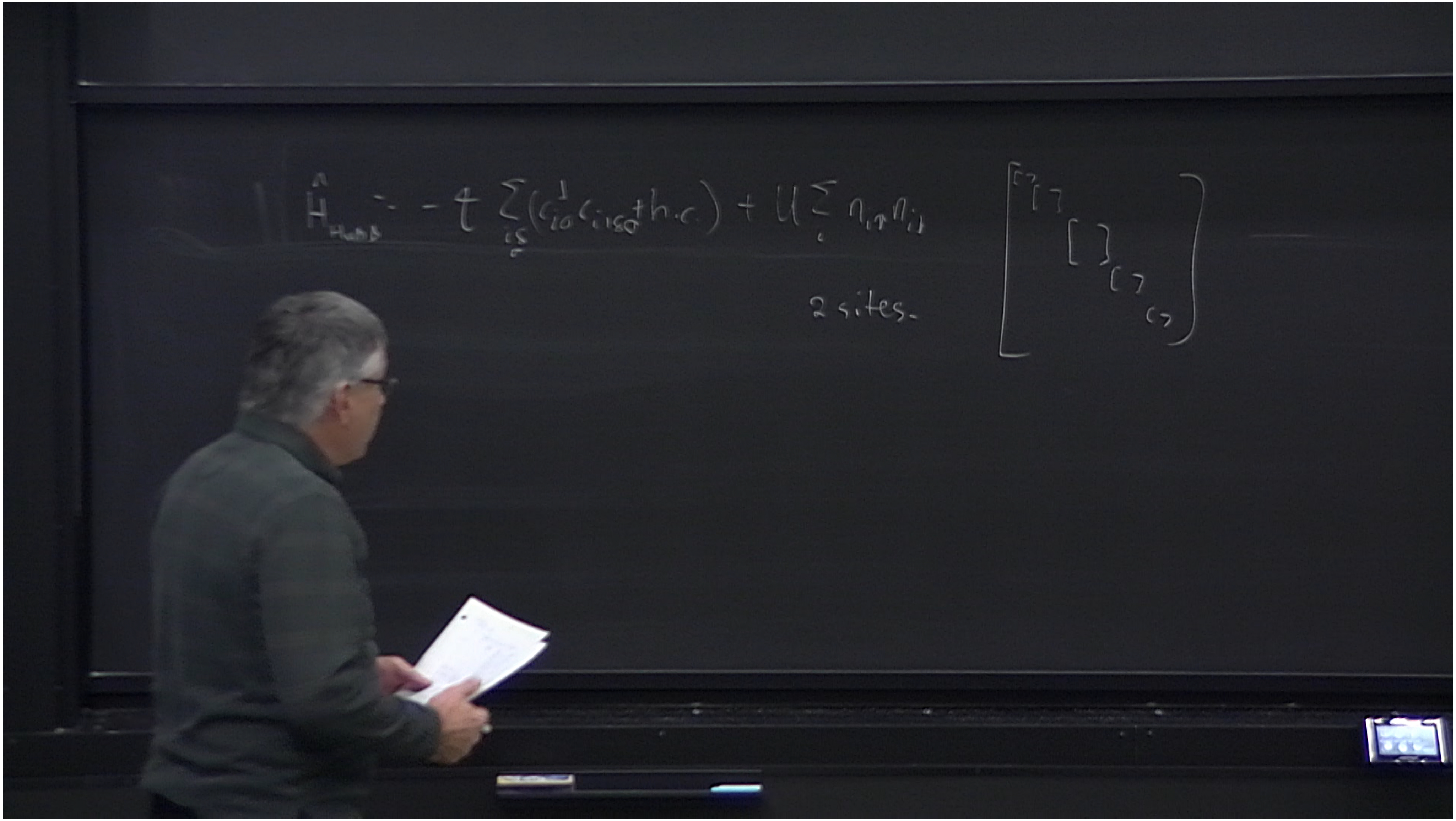
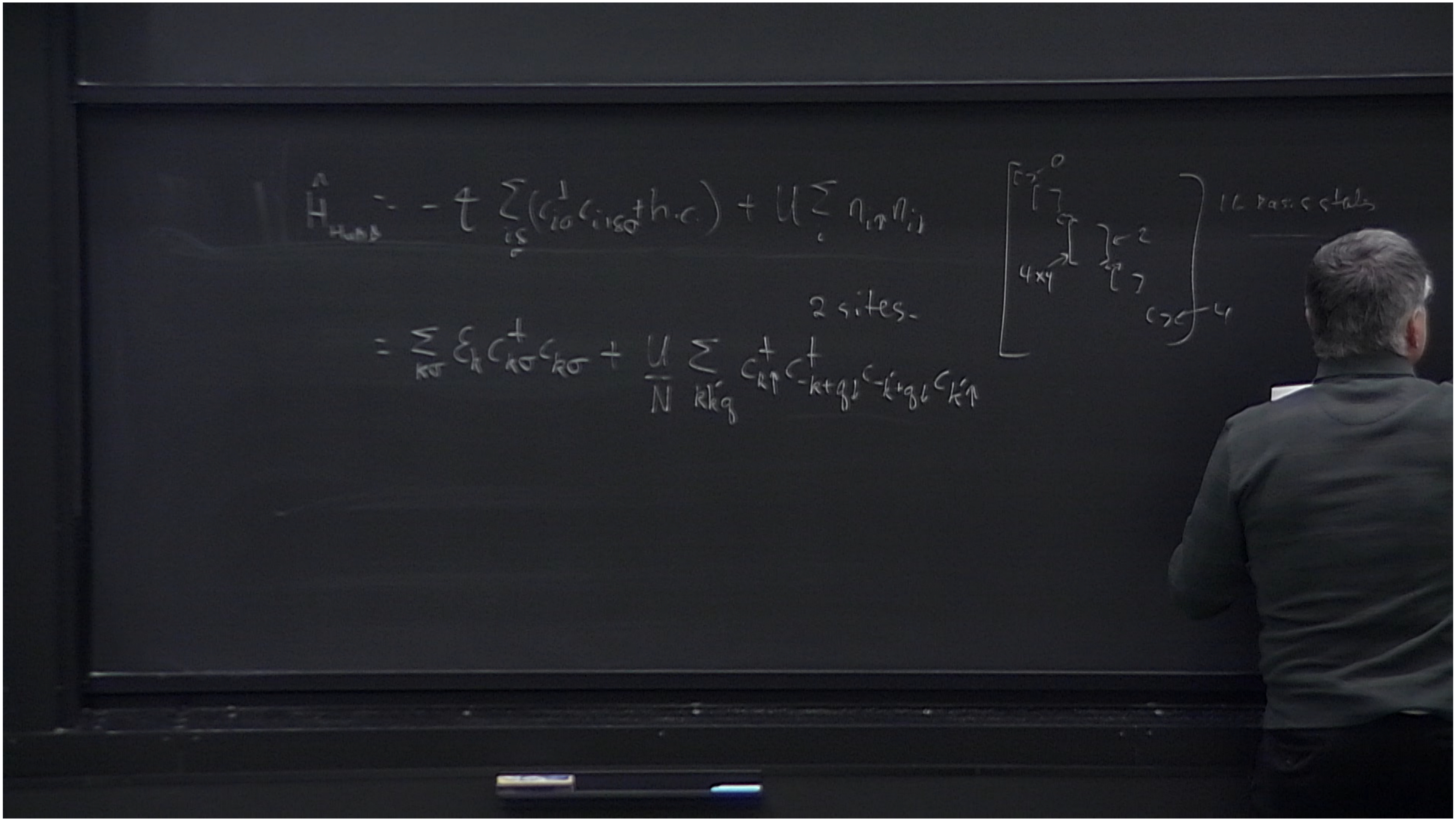
Title: PSI 2016/2017 Condensed Matter - Lecture 13

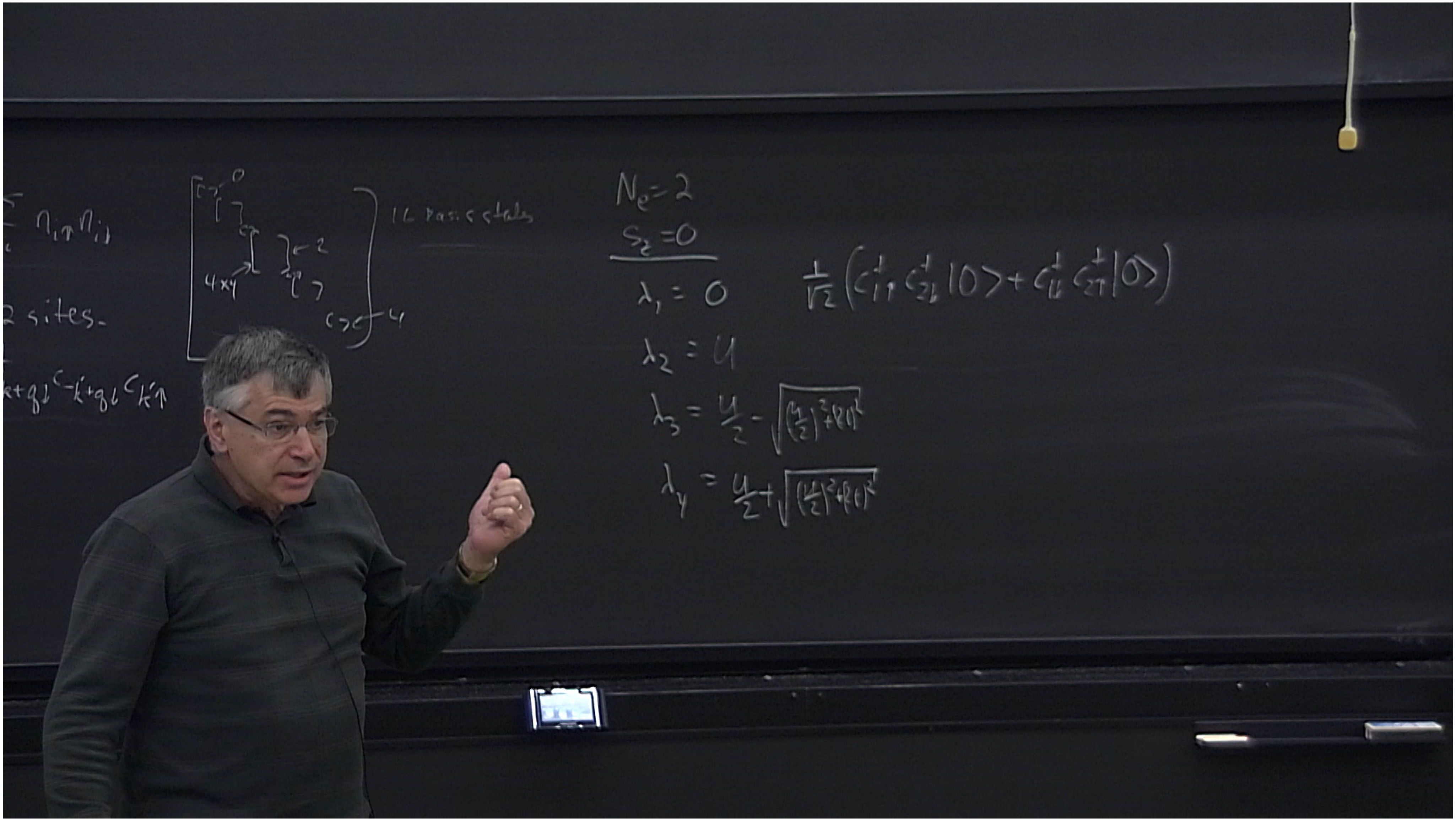
Date: Nov 23, 2016 10:45 AM

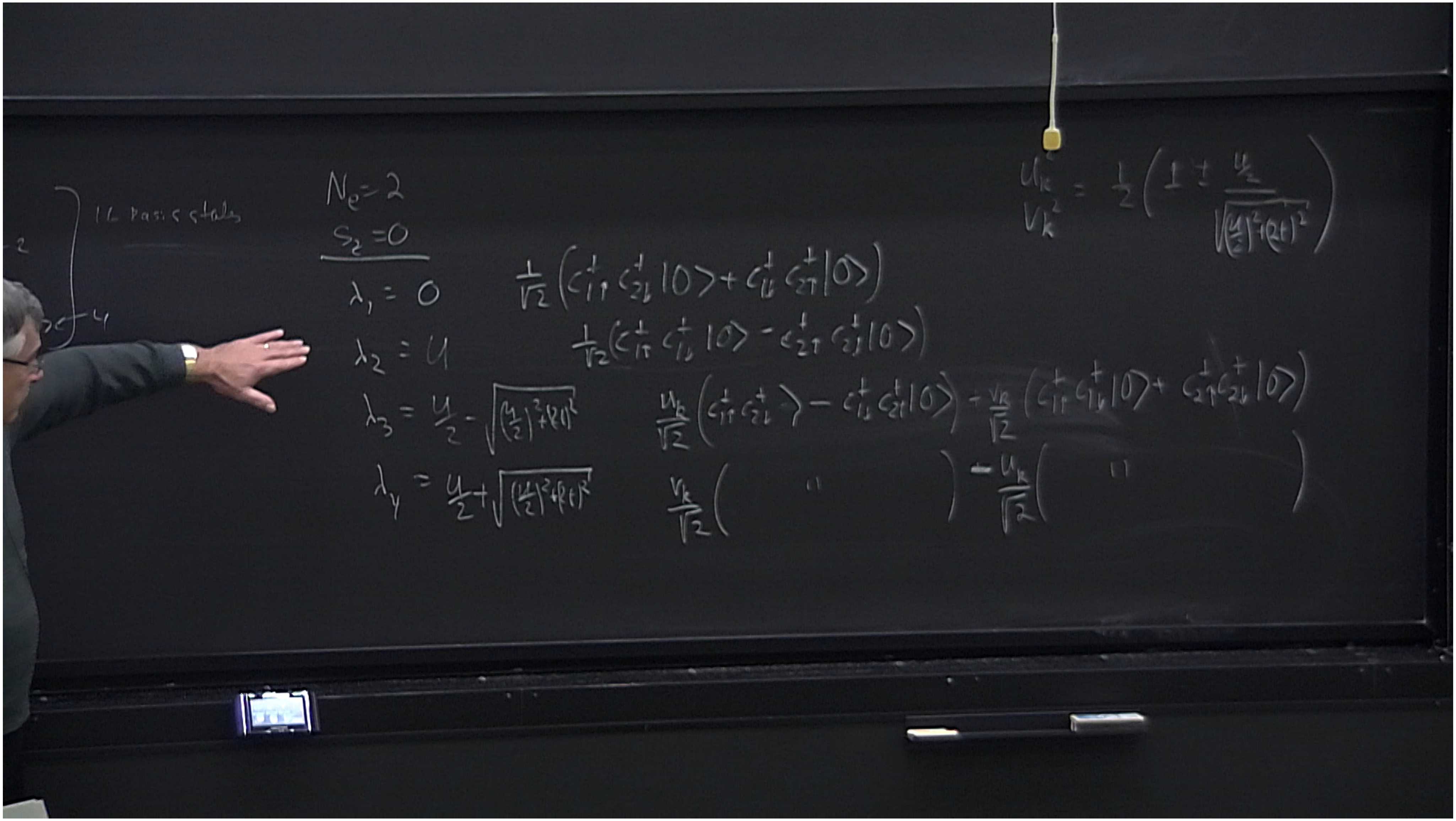
URL: http://pirsa.org/16110064

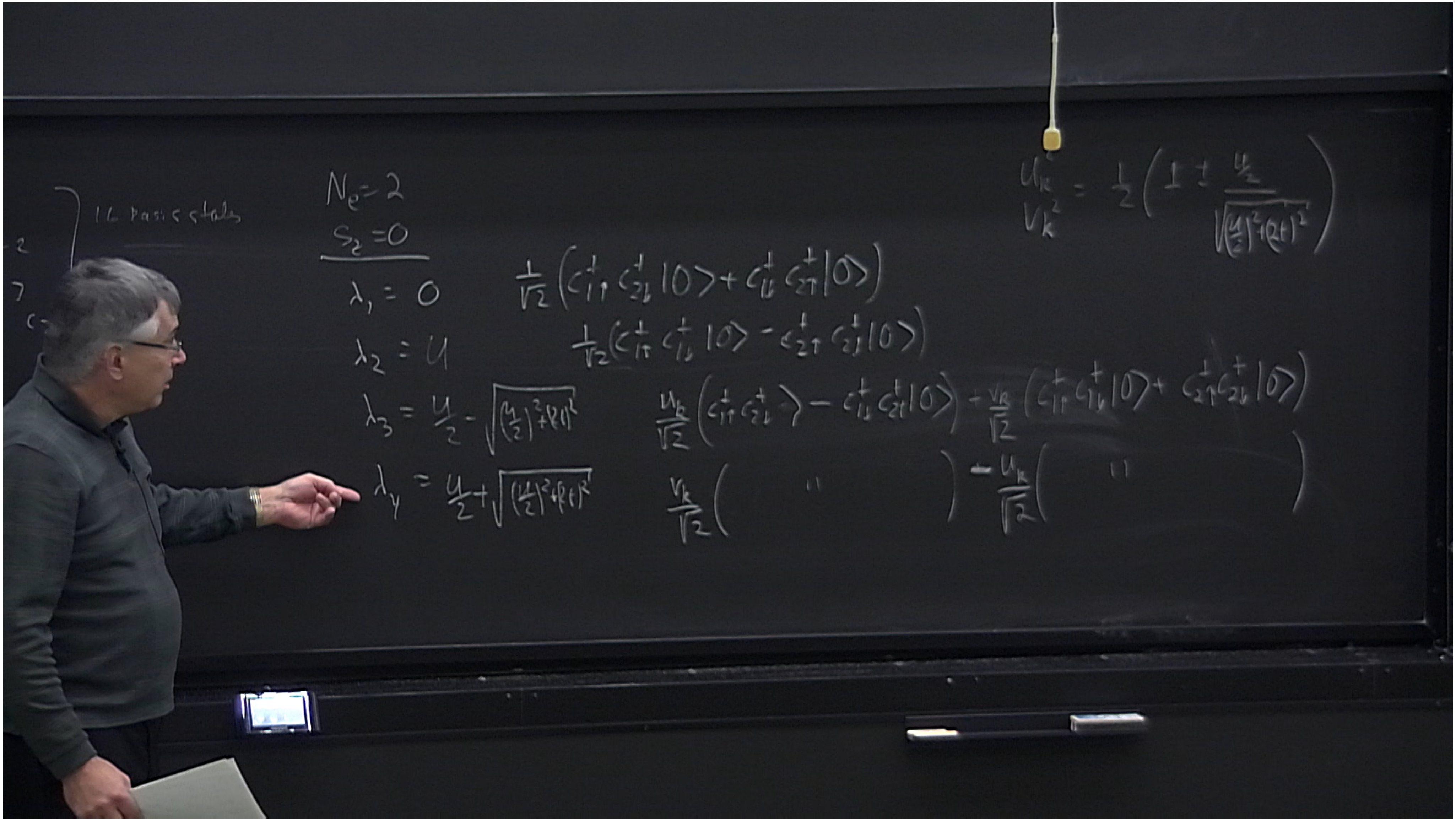
Abstract:

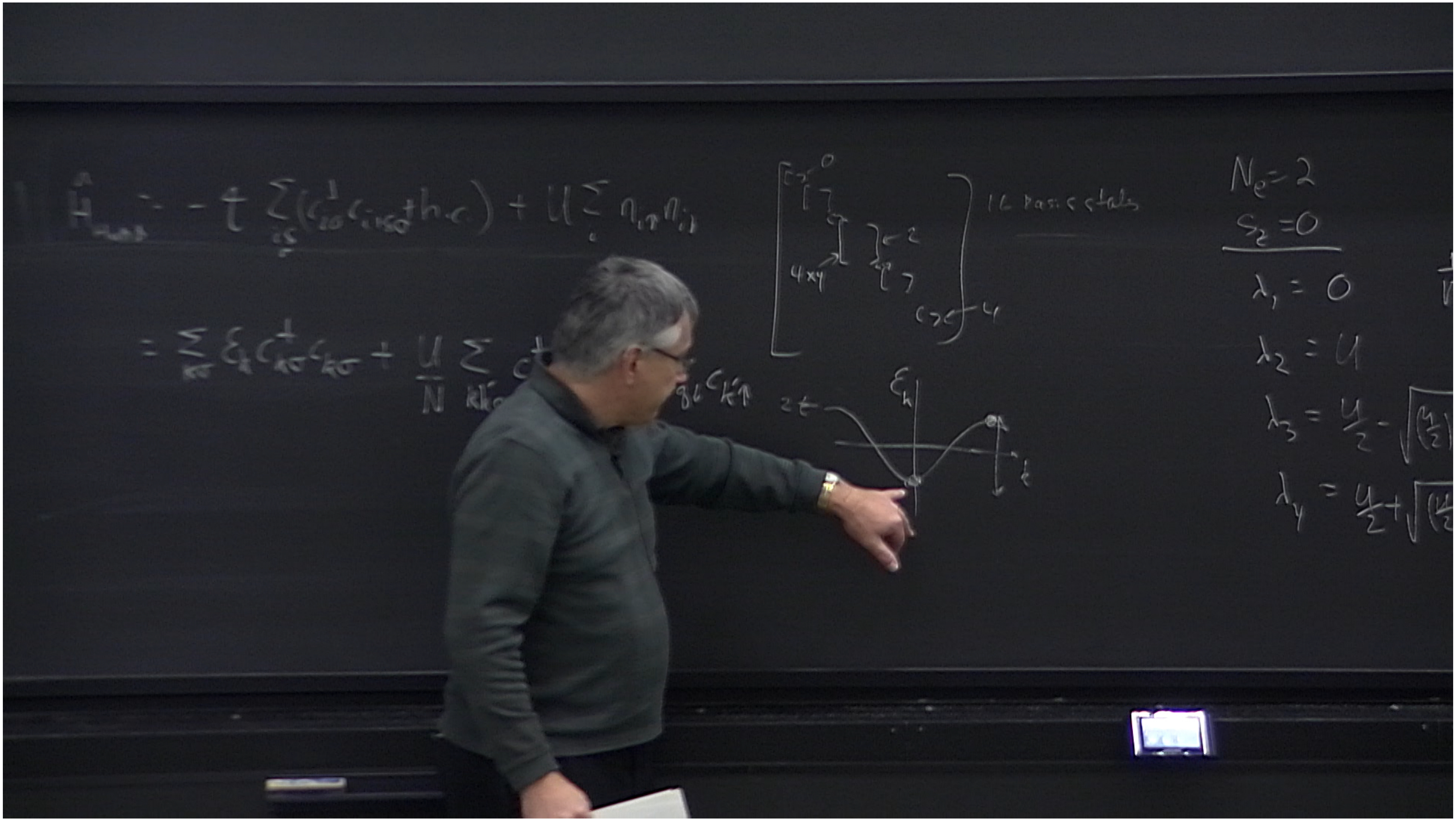

2 sites.

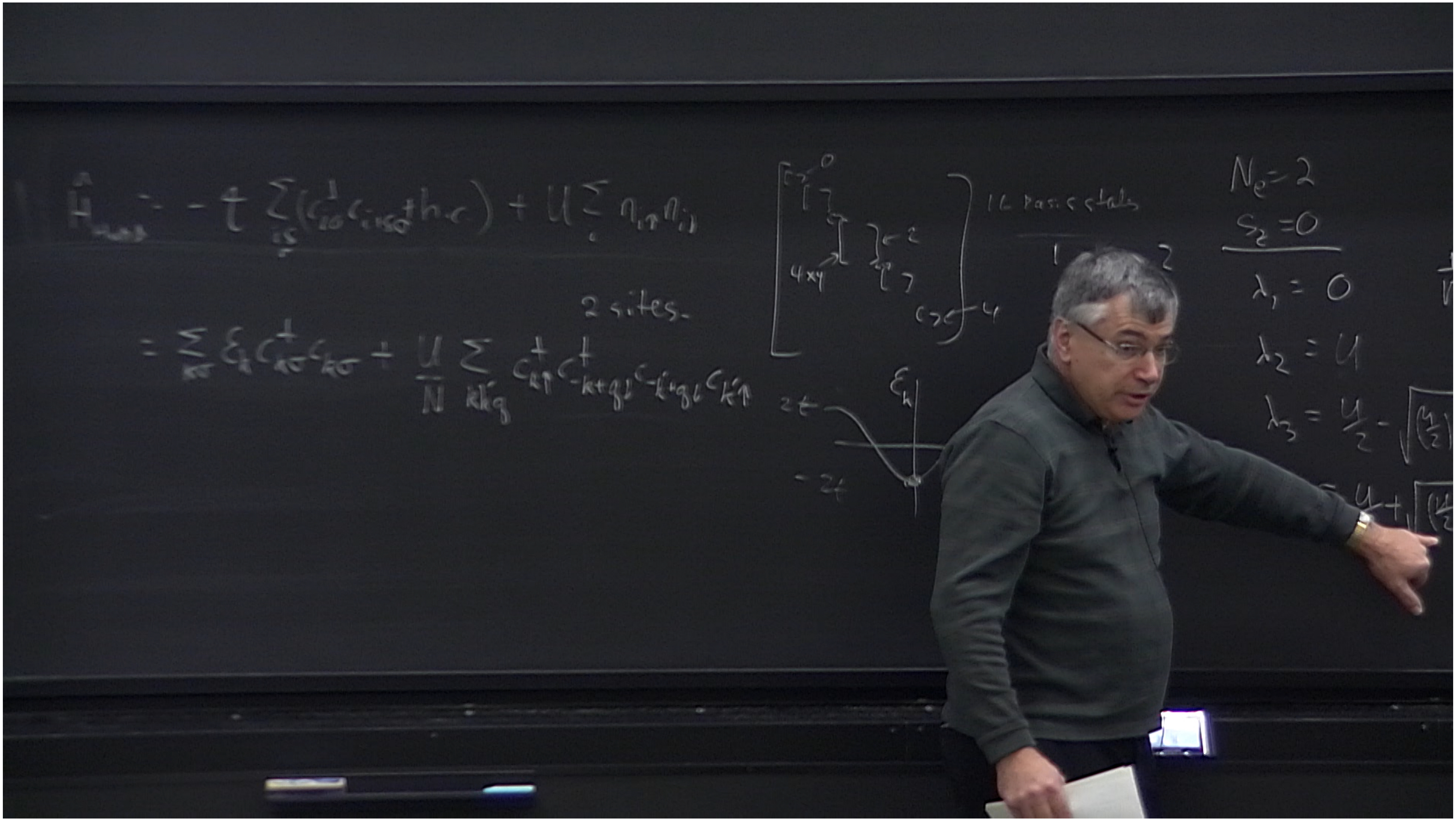

$\hat{H}_{Hubb} = -t \sum_{i\delta\sigma} (c^\dagger_{i\sigma} c_{i+\delta\sigma} + h.c.) + U \sum_i n_{i\uparrow} n_{i\downarrow}$
2 sites.
$= \sum_{k\sigma} \varepsilon_k c^\dagger_{k\sigma} c_{k\sigma} + \frac{U}{N} \sum_{kk'q} c^\dagger_{k\uparrow} c^\dagger_{-k+q\downarrow} c_{-k'+q\downarrow} c_{k'\uparrow}$
16 basis states
0
2
4
4x4

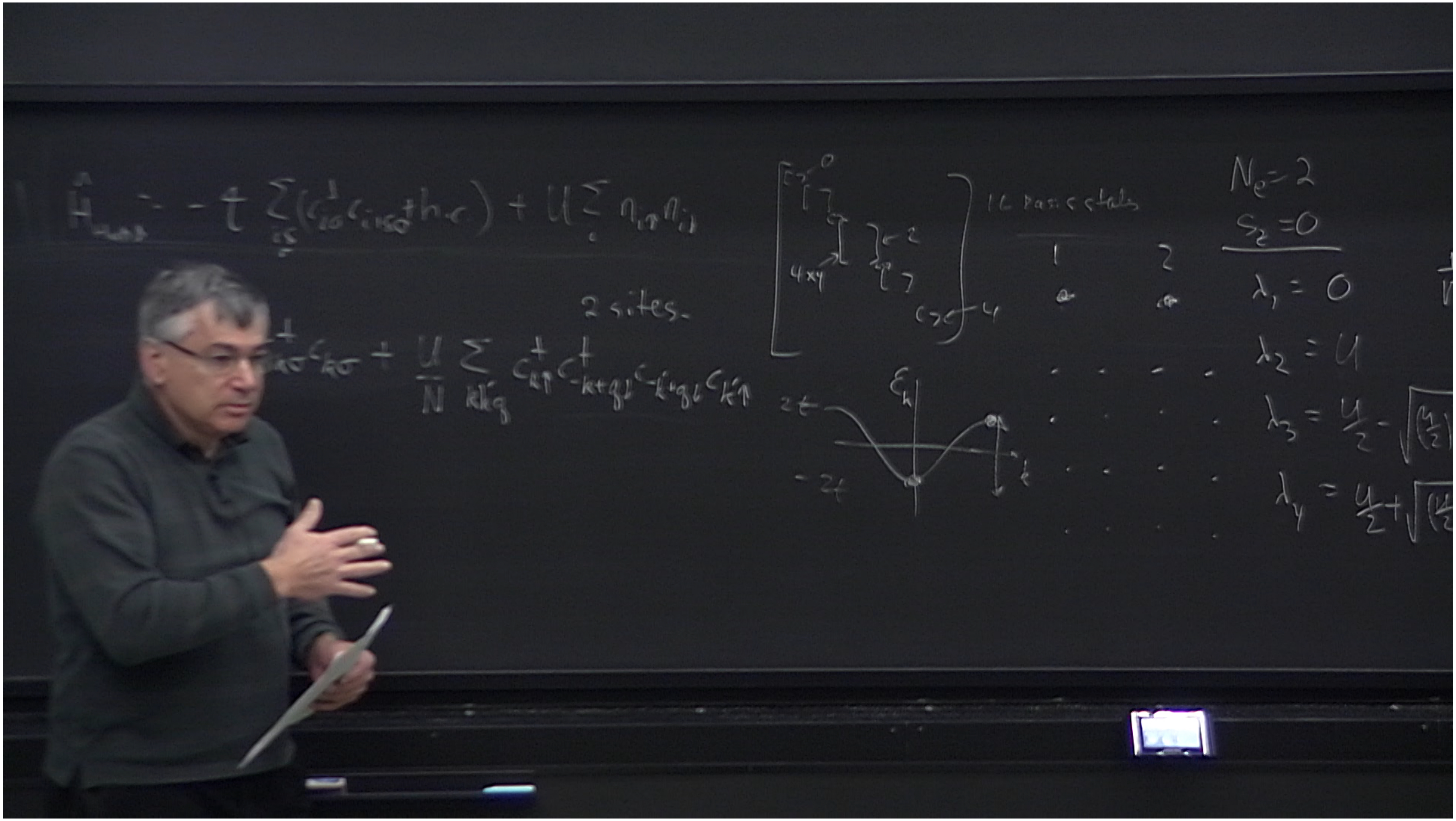

16 basis states
2 sites
4x4
N_e = 2
S_z = 0
λ_1 = 0
λ_2 = U
λ_3 = U/2 − √((U/2)^2 + (2t)^2)
λ_4 = U/2 + √((U/2)^2 + (2t)^2)

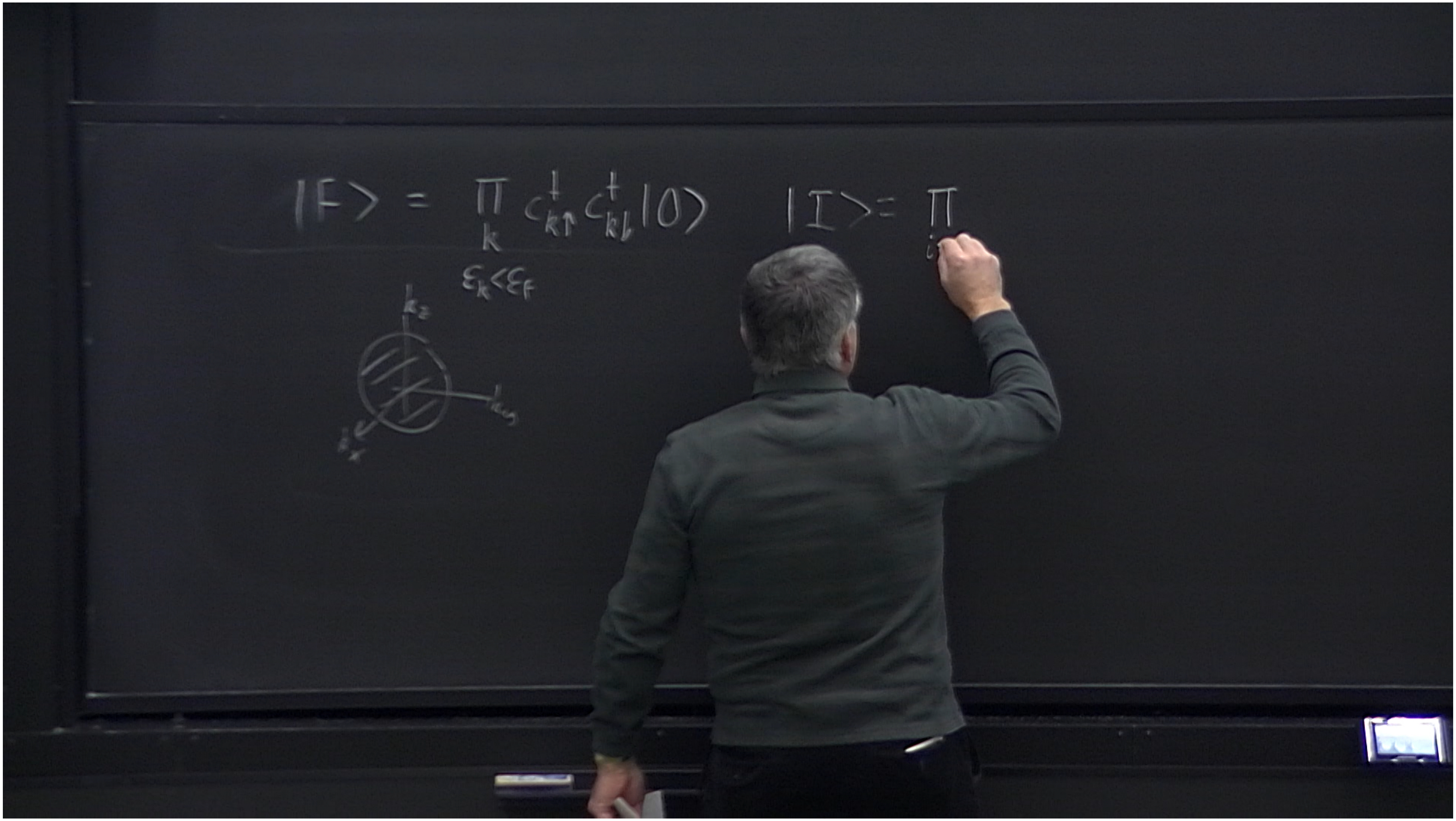

16 basis states
$N_e = 2$
$S_z = 0$
$\lambda_1 = 0$
$\frac{1}{\sqrt{2}}\left(c^\dagger_{1\uparrow} c^\dagger_{2\downarrow}|0\rangle + c^\dagger_{1\downarrow} c^\dagger_{2\uparrow}|0\rangle\right)$
$\lambda_2 = U$
$\frac{1}{\sqrt{2}}\left(c^\dagger_{1\uparrow} c^\dagger_{1\downarrow}|0\rangle - c^\dagger_{2\uparrow} c^\dagger_{2\downarrow}|0\rangle\right)$
$\lambda_3 = \frac{U}{2} - \sqrt{\left(\frac{U}{2}\right)^2 + (2t)^2}$
$\lambda_4 = \frac{U}{2} + \sqrt{\left(\frac{U}{2}\right)^2 + (2t)^2}$
$\frac{u_k}{\sqrt{2}}\left(c^\dagger_{1\uparrow} c^\dagger_{2\downarrow}\rangle - c^\dagger_{1\downarrow} c^\dagger_{2\uparrow}|0\rangle\right) + \frac{v_k}{\sqrt{2}}\left(c^\dagger_{1\uparrow} c^\dagger_{1\downarrow}|0\rangle + c^\dagger_{2\uparrow} c^\dagger_{2\downarrow}|0\rangle\right)$
$\frac{v_k}{\sqrt{2}}\left(\quad '' \quad \right) - \frac{u_k}{\sqrt{2}}\left(\quad '' \quad \right)$
$\begin{matrix} u_k^2 \\ v_k^2 \end{matrix} = \frac{1}{2}\left(1 \pm \frac{U/2}{\sqrt{\left(\frac{U}{2}\right)^2 + (2t)^2}}\right)$

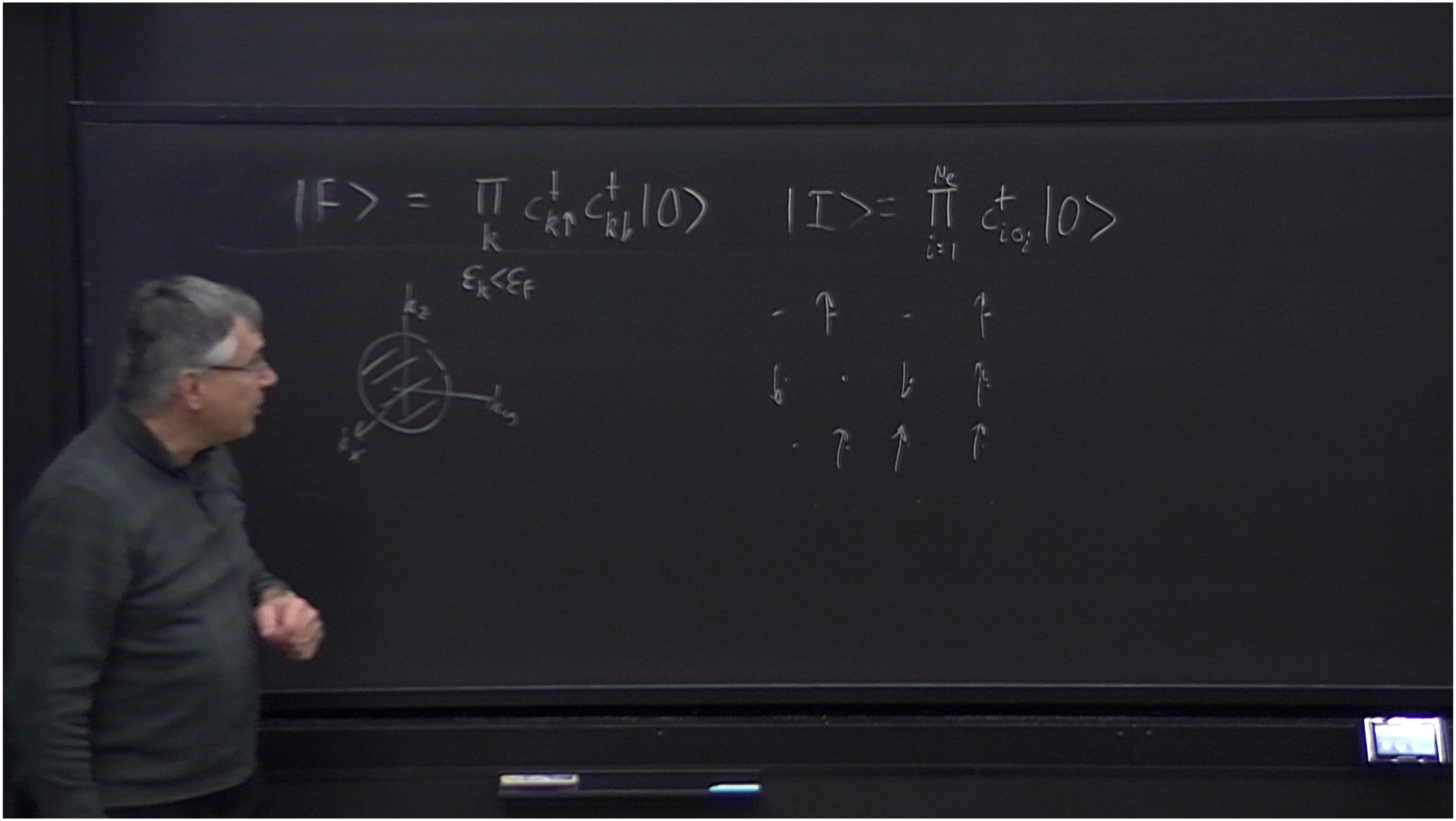

16 basis states
N_e = 2
S_z = 0
λ_1 = 0
λ_2 = U
λ_3 = U/2 − √((U/2)^2 + (2t)^2)
λ_4 = U/2 + √((U/2)^2 + (2t)^2)
1/√2 (c†_{1↑} c†_{2↓}|0> + c†_{1↓} c†_{2↑}|0>)
1/√2 (c†_{1↑} c†_{1↓}|0> − c†_{2↑} c†_{2↓}|0>)
u_k/√2 (c†_{1↑} c†_{2↓}|0> − c†_{1↓} c†_{2↑}|0>) + v_k/√2 (c†_{1↑} c†_{1↓}|0> + c†_{2↑} c†_{2↓}|0>)
v_k/√2 (") − u_k/√2 (")
u_k^2, v_k^2 = 1/2 (1 ± (U/2)/√((U/2)^2 + (2t)^2))

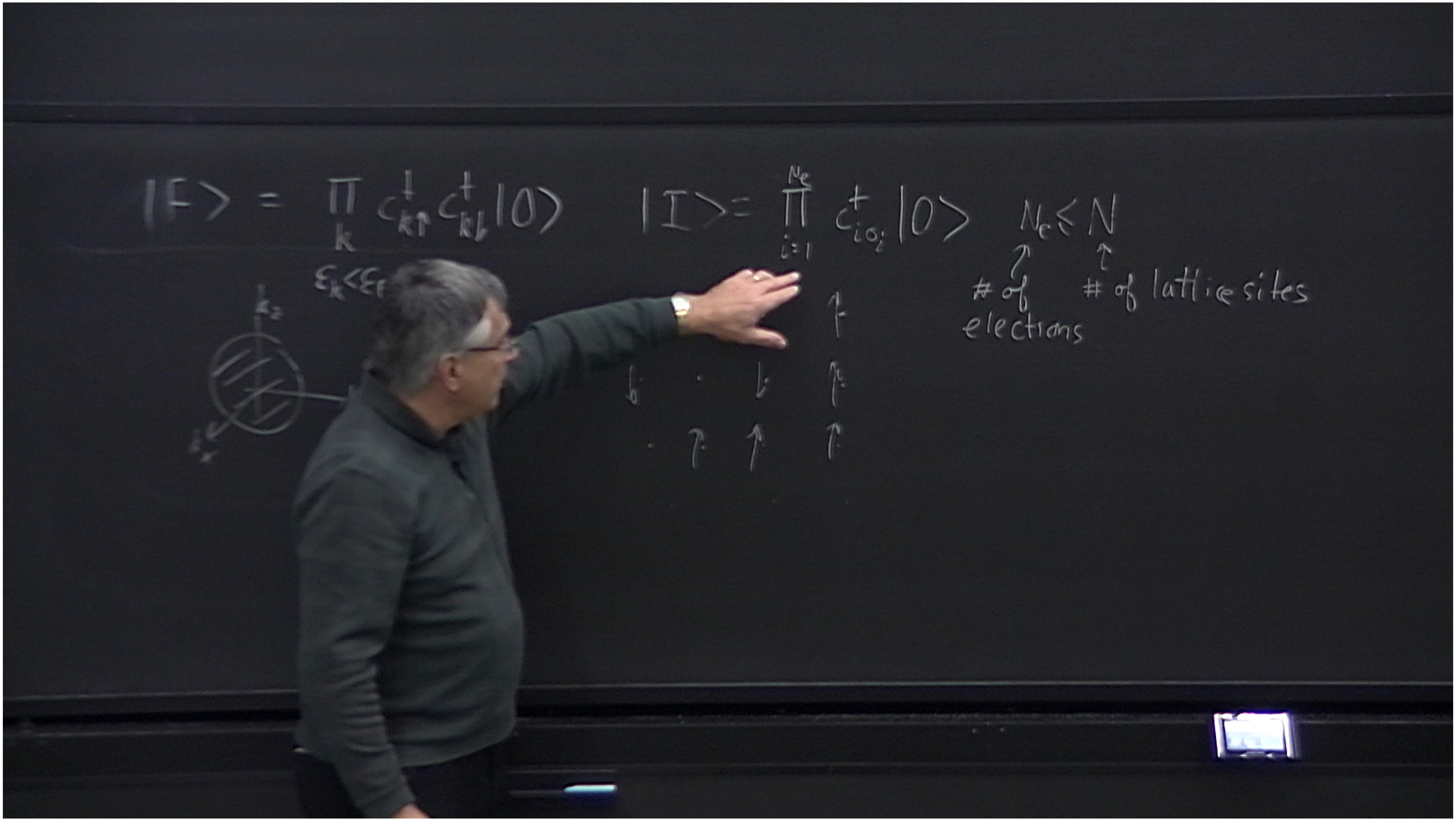

16 basis states
N_e = 2
S_z = 0
λ_1 = 0
λ_2 = U
4x4

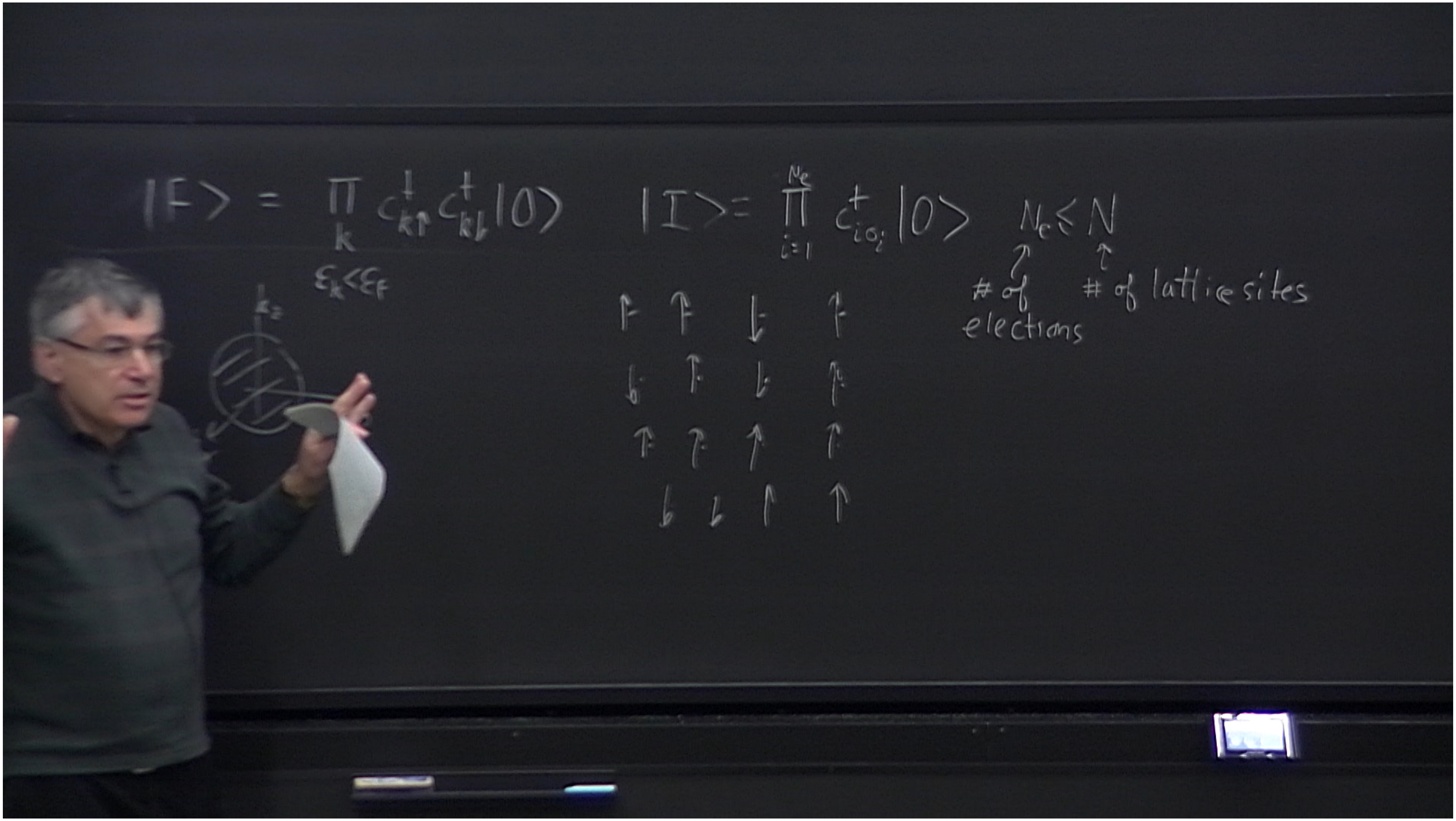

2 sites.
16 basis states
4x4
Ne = 2
Sz = 0
λ1 = 0
λ2 = U

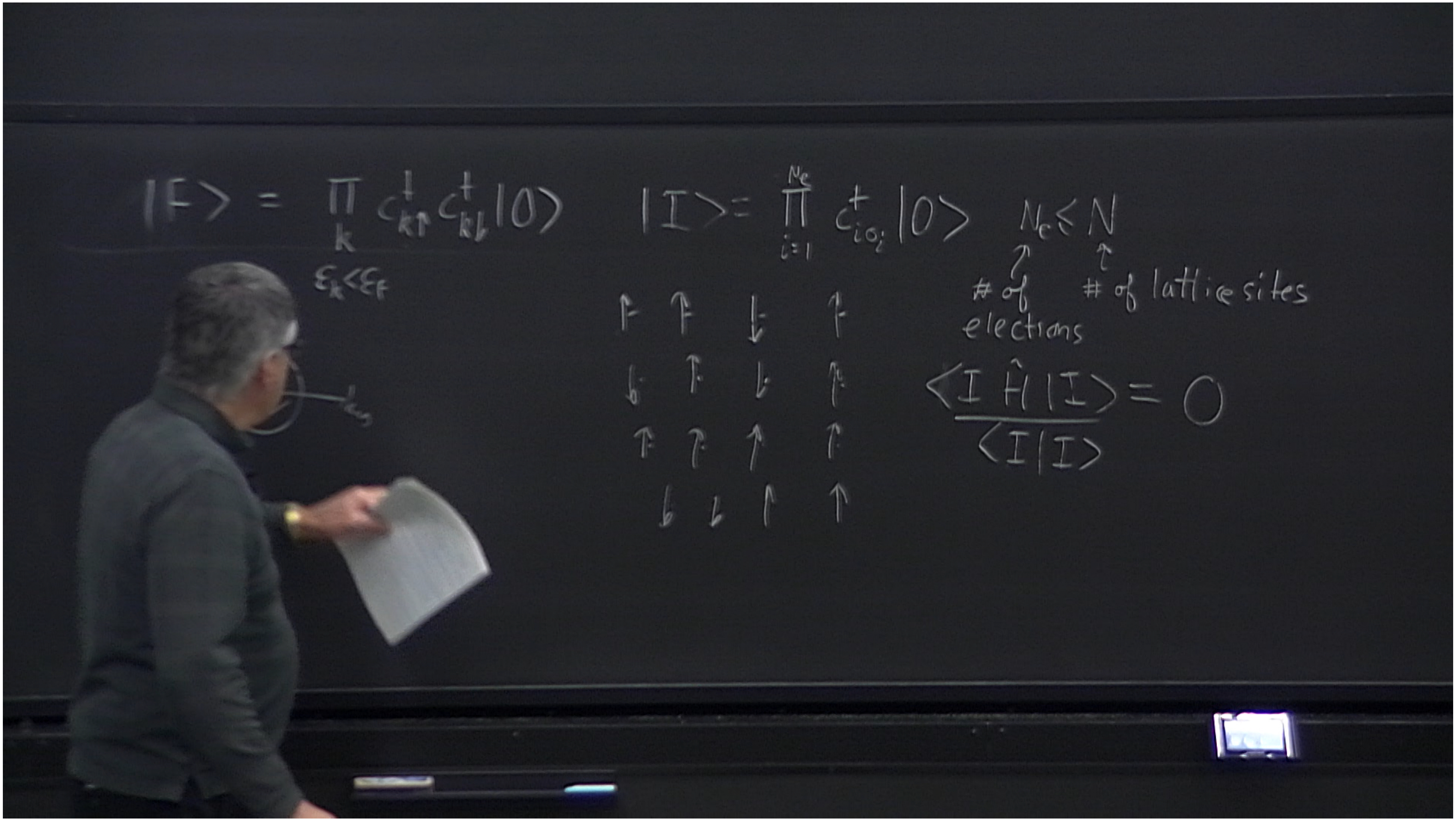

2 sites
16 basis states
N_e = 2
S_z = 0
λ_1 = 0
λ_2 = U


|F> = Π_k c†_{k↑} c†_{k↓} |0>
ε_k<ε_F
|I>= Π_i
k_z
k_y
k_x


|F> = Π c†k↑ c†k↓ |0>
k
εk<εF
kz
ky
kx
|I>= Π c†iσi |0>
Ne
i=1


|F> = ∏ c†k↑ c†k↓ |0>
k
εk<εF
kz
|I>= ∏ c†iσi |0>
Ne
i=1
Ne ≤ N
of
elections
# of lattice sites


|F> = Π c†k↑ c†k↓ |0>
k
εk<εF
kz
|I> = Π c† iσi |0>
Ne
i=1
Ne ≤ N
of
elections
# of lattice sites


|F> = Π c†kↁ c†k↓ |0>
k
εk<εF
|I> = Π (i=1 to Ne) c†iσi |0>
Ne ≤ N
# of electrons
# of lattice sites
<I Ĥ |I> / <I|I> = 0

2 dimensions

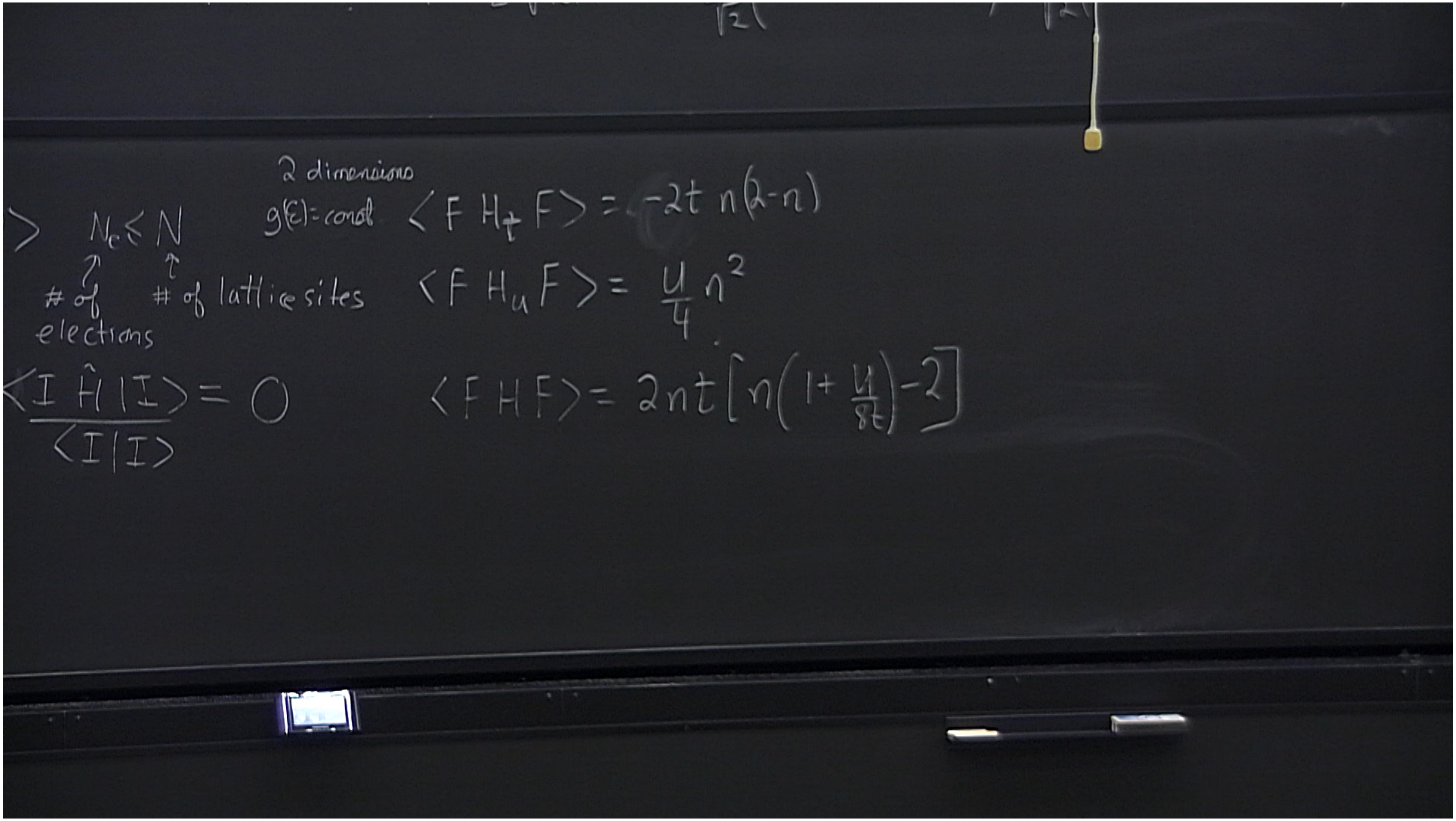
$g(\varepsilon) = \text{const}$ $\quad \langle F \, H_t \, F \rangle = -2t \, n(2-n)$

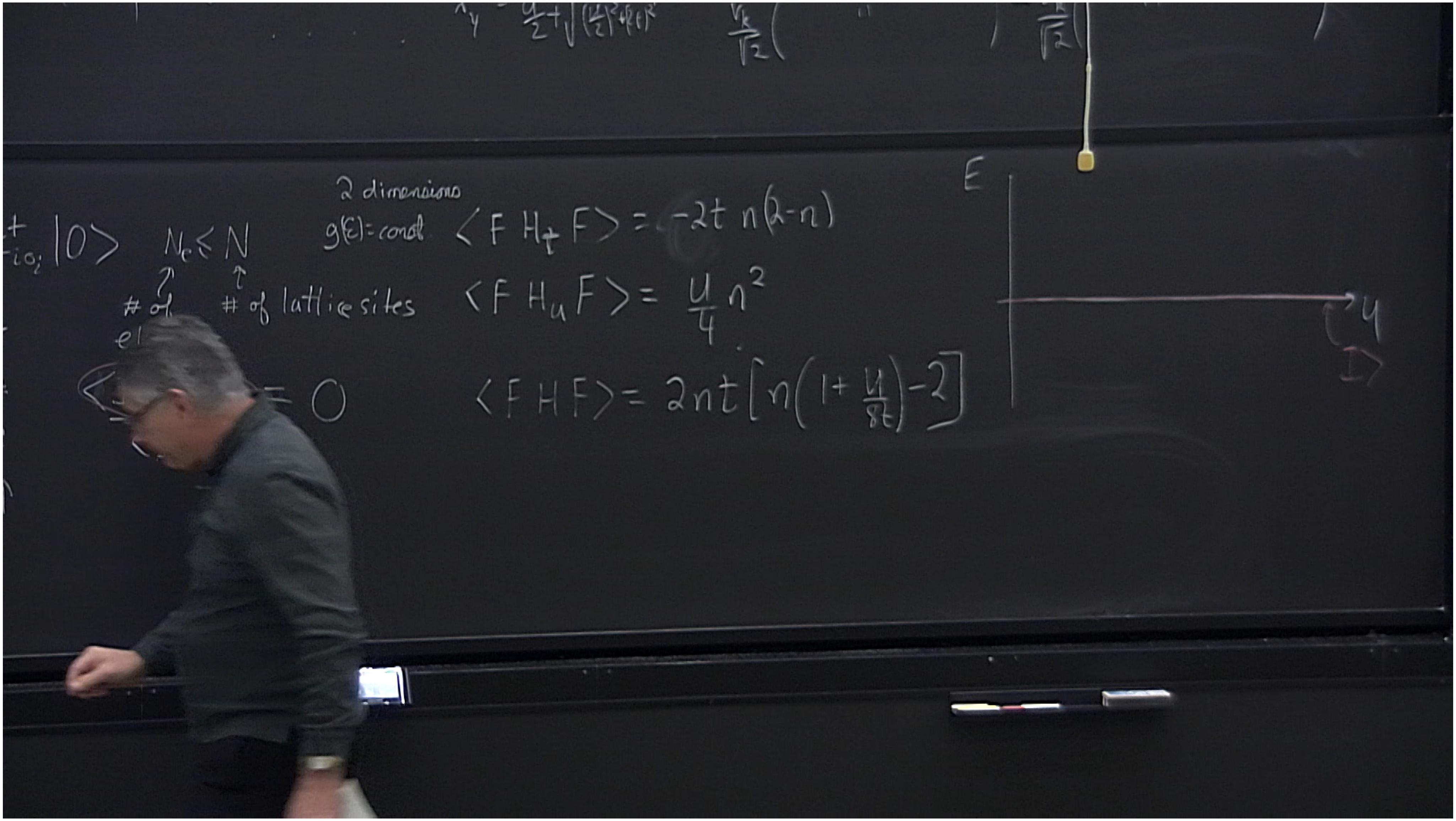
$\rangle \quad N_e \leq N$

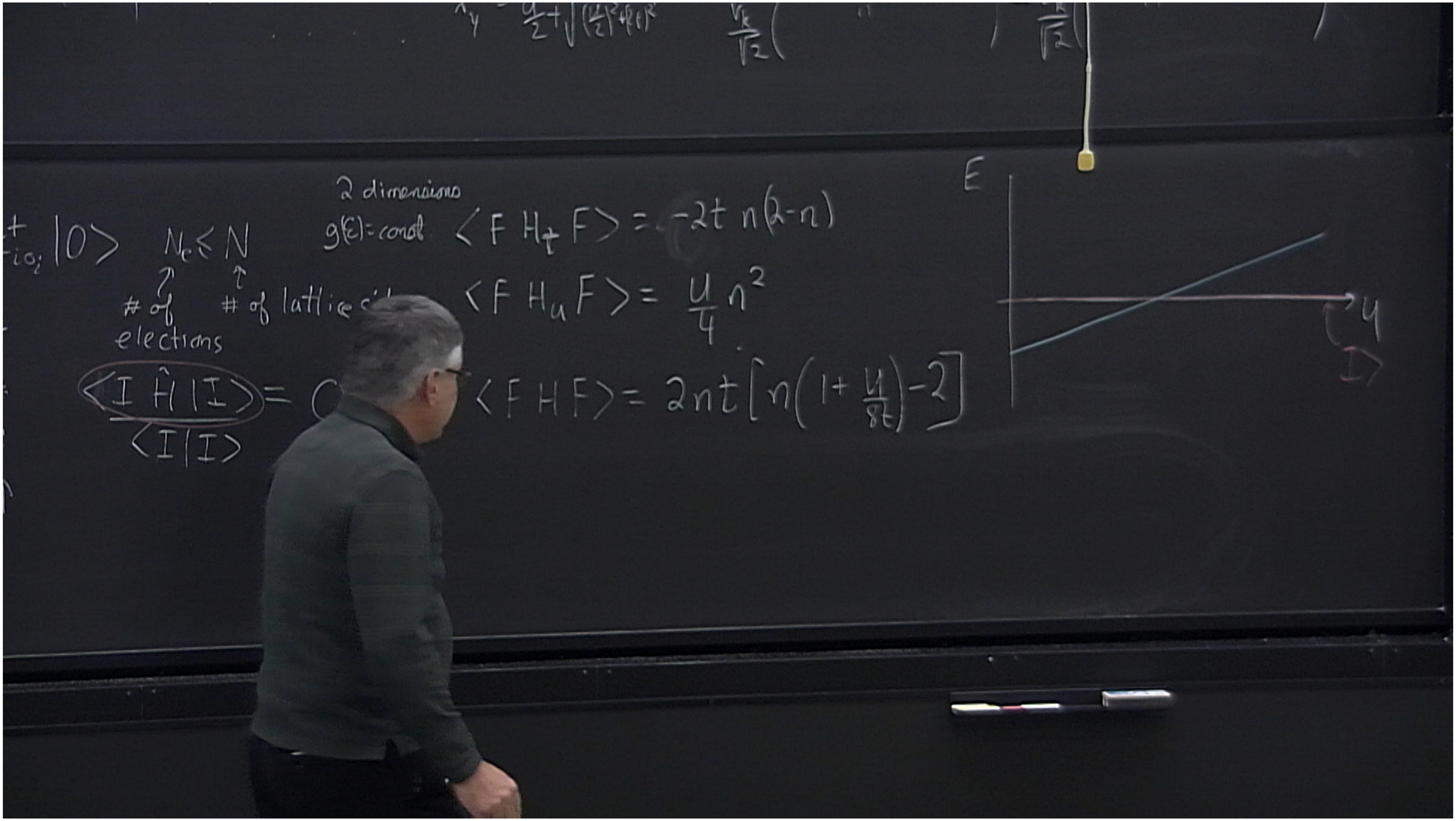
N_e: # of elections

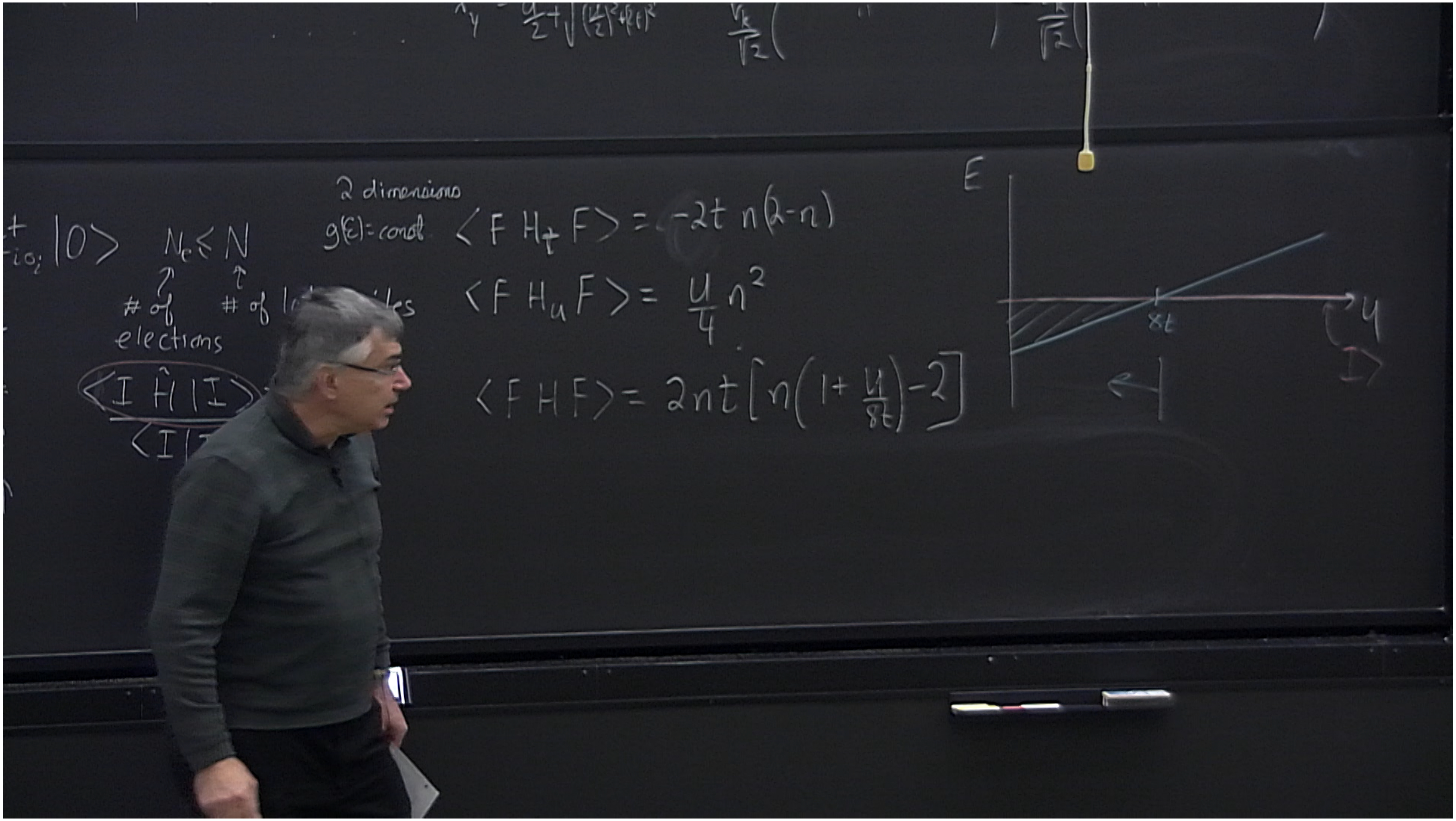
N: # of lattice sites

$$\frac{\langle I \, \hat{H} \, | I \rangle}{\langle I | I \rangle} = 0$$

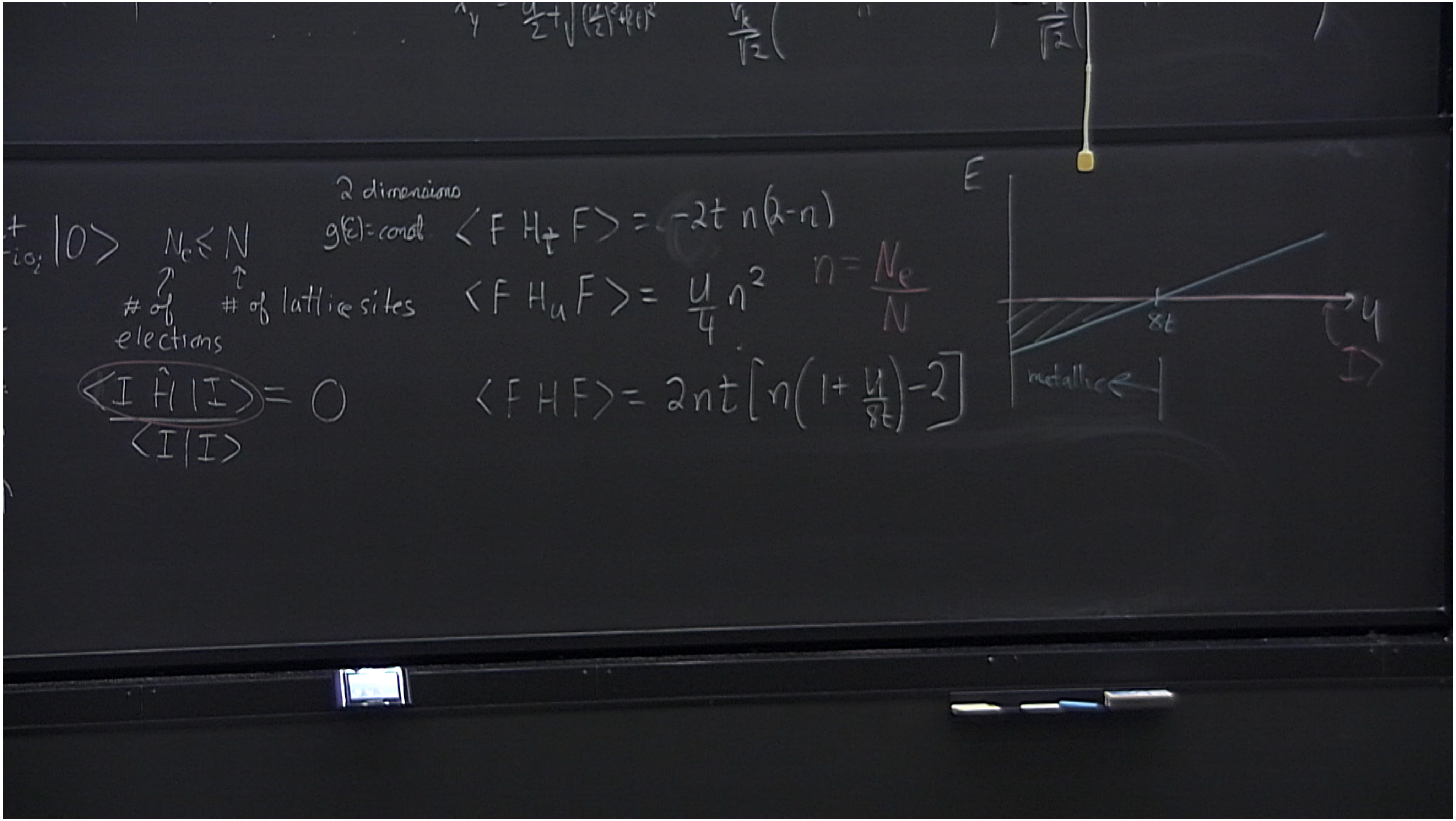

2 dimensions
g(ε) = const
⟨F H_t F⟩ = -2t n(2-n)
N_e ≤ N
# of electrons
# of lattice sites
⟨F H_u F⟩ = U/4 n^2
⟨I Ĥ I⟩ / ⟨I|I⟩ = 0
⟨F H F⟩ = 2nt[n(1+ U/8t) - 2]

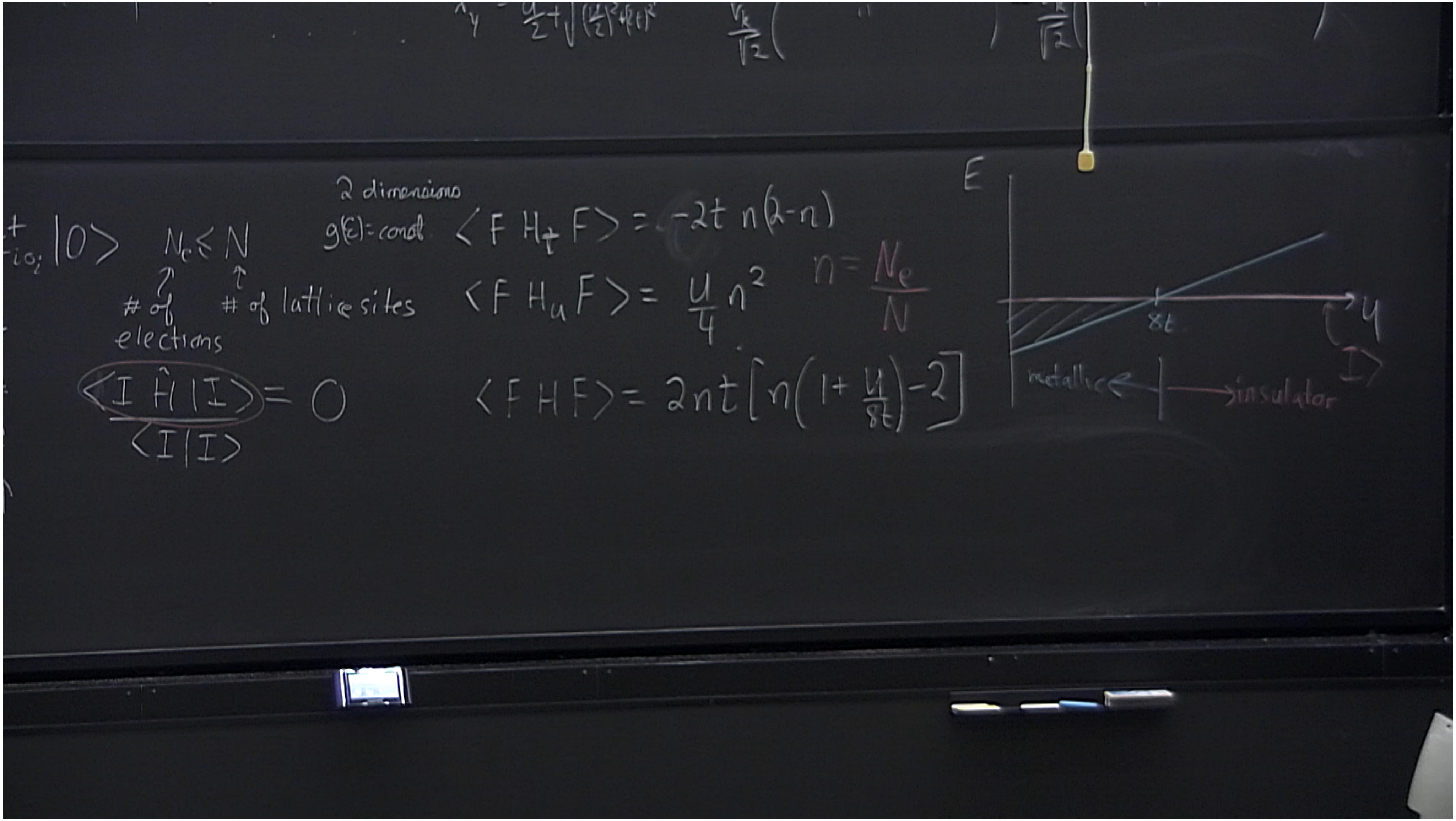

2 dimensions
g(E) = const
⟨F H_t F⟩ = -2t n(2-n)
N_e ≤ N
# of lattice sites
⟨F H_U F⟩ = U/4 n^2
⟨F H F⟩ = 2nt[n(1 + U/8t) - 2]
E
U

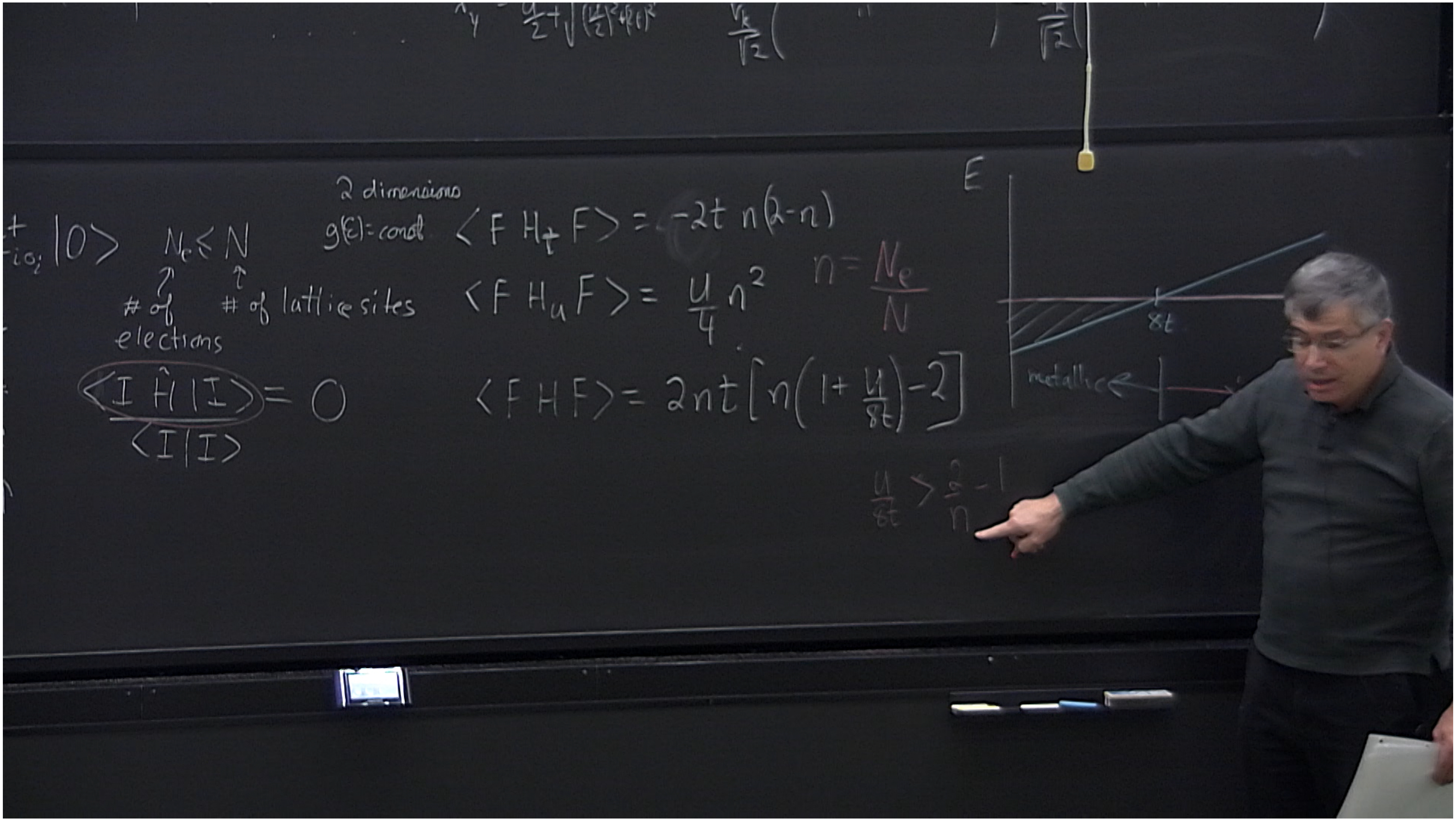

2 dimensions
g(ε)=const ⟨F H_t F⟩ = -2t n(2-n)
N_e ≤ N
# of electrons
# of lattice sites
⟨F H_u F⟩ = U/4 n^2
⟨I|Ĥ|I⟩ / ⟨I|I⟩ =
⟨F H F⟩ = 2nt[n(1+ U/8t)-2]
E
U
|I⟩

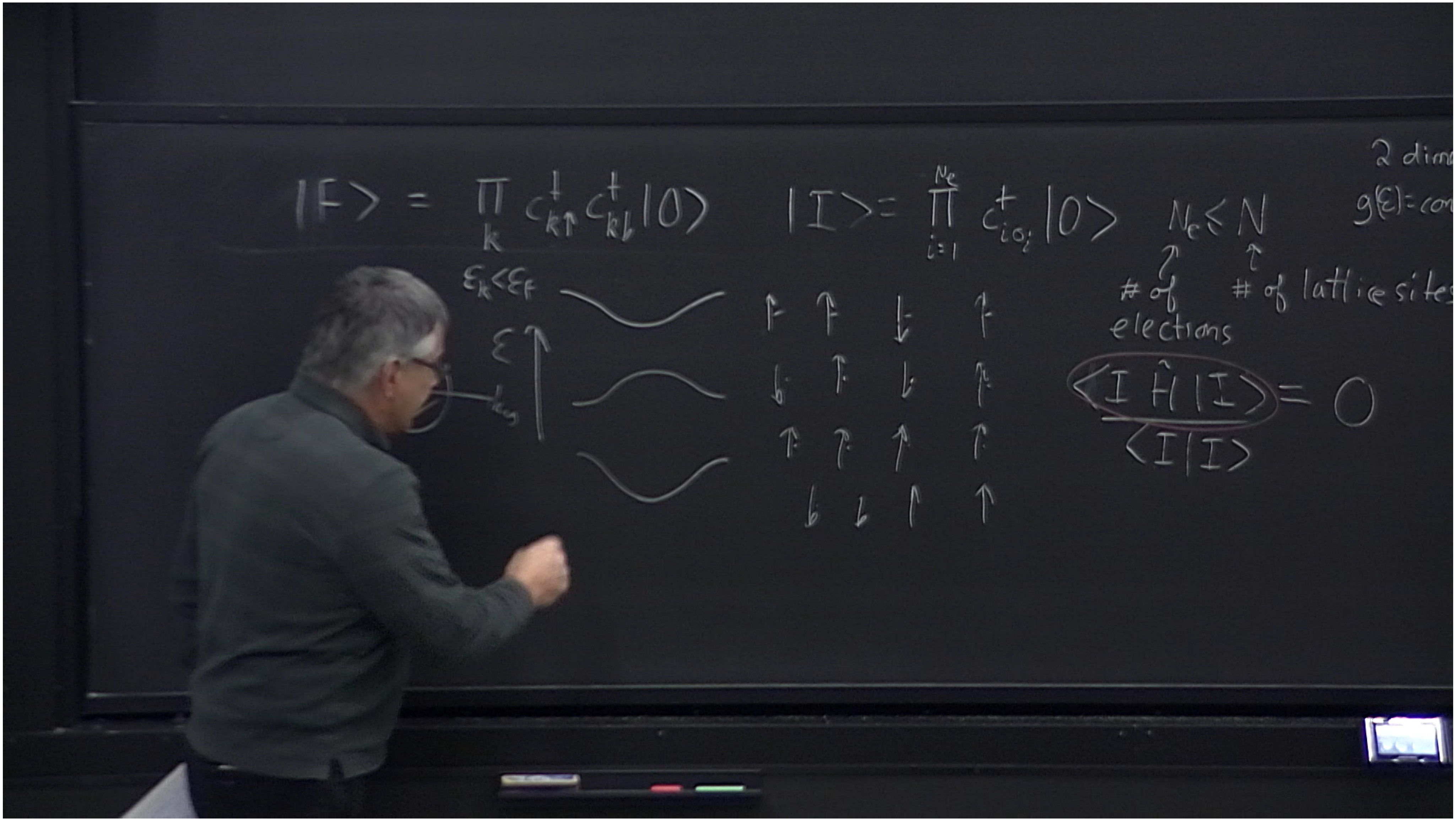


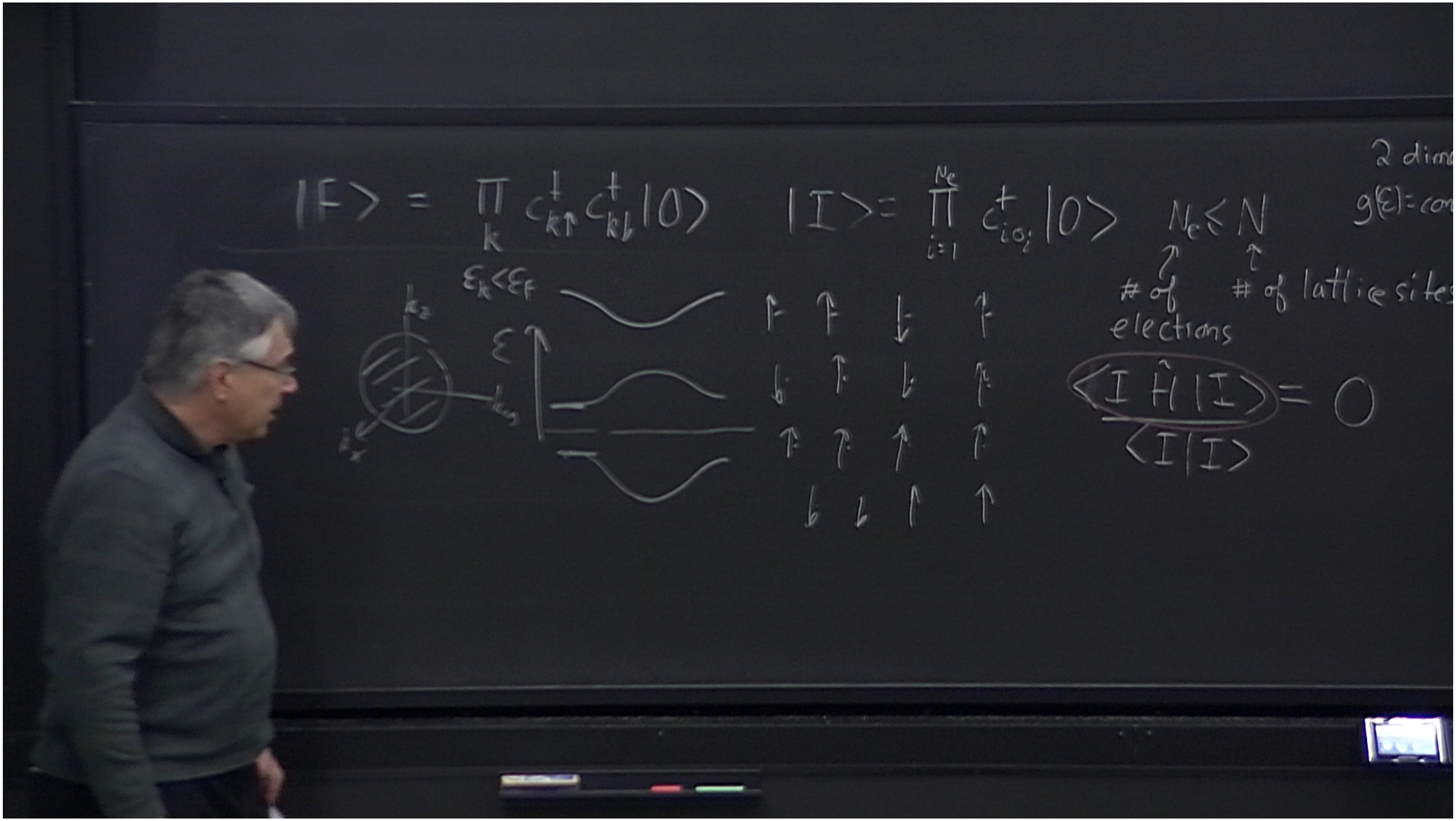
2 dimensions
g(E)=const
<F H_t F> = -2t n(2-n)
N_e ≤ N
# of elections
<F H_u F> = U/4 n^2
<F H F> = 2nt[n(1+ U/8t)-2]
E
8t
U


2 dimensions
g(E) = const
⟨F H_t F⟩ = -2t n(2-n)
N_e ≤ N
# of electrons
# of lattice sites
⟨F H_u F⟩ = U/4 n^2
n = N_e / N
⟨I Ĥ I⟩ / ⟨I|I⟩ = 0
⟨F H F⟩ = 2nt[n(1 + U/8t) - 2]
E
8t
U
metallic
|I⟩

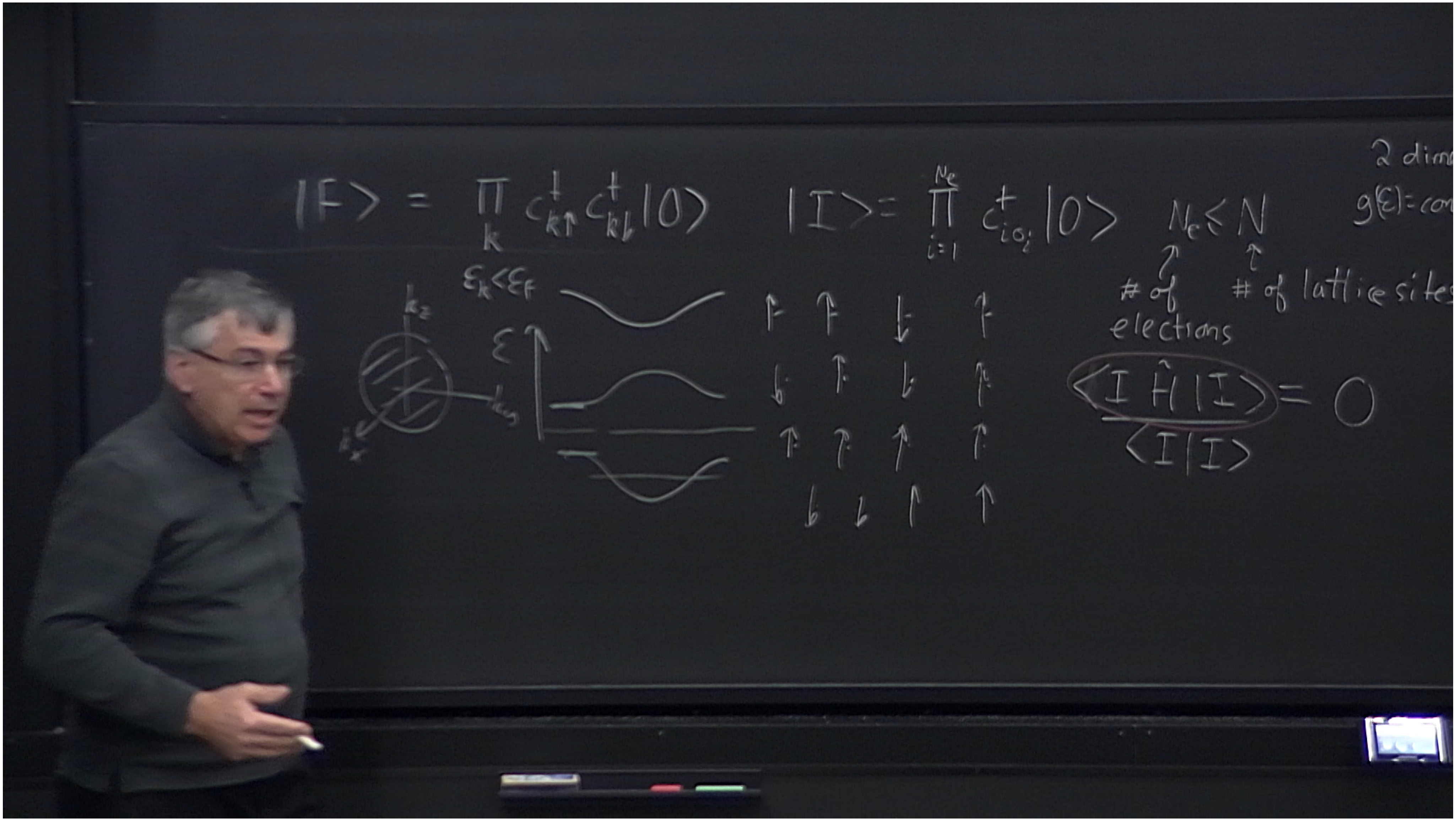

2 dimensions
g(E) = const
⟨F H_t F⟩ = -2t n(2-n)
N_e ≤ N
# of electrons
# of lattice sites
⟨F H_u F⟩ = U/4 n^2
n = N_e / N
⟨I Ĥ I⟩ / ⟨I|I⟩ = 0
⟨F H F⟩ = 2nt[n(1 + U/8t) - 2]
E
8t
U
|I⟩
metallic
insulator

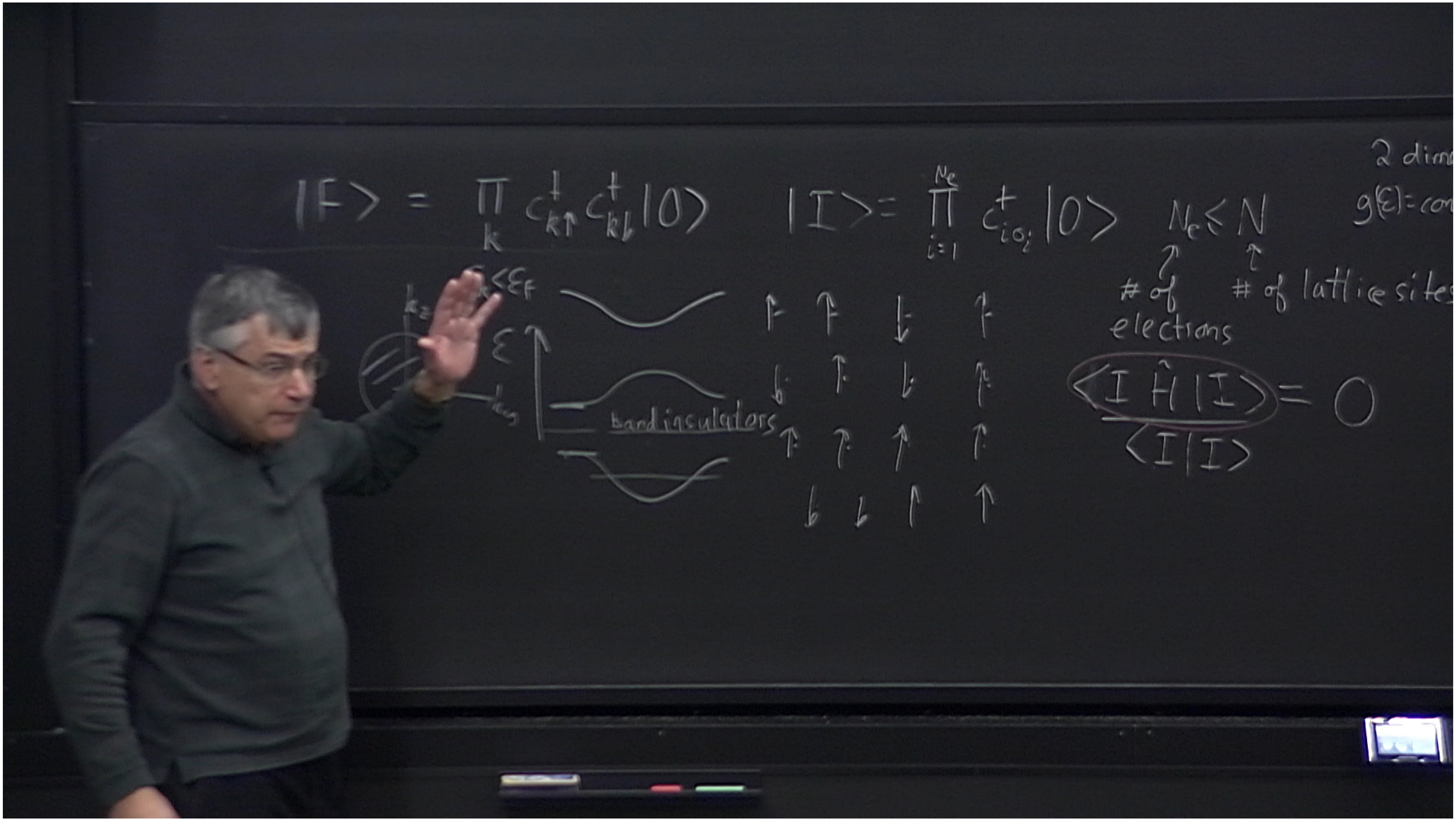

2 dimensions
g(E) = const
⟨F H_t F⟩ = -2t n(2-n)
N_e ≤ N
# of electrons
# of lattice sites
⟨F H_u F⟩ = U/4 n^2
n = N_e/N
⟨I|Ĥ|I⟩ / ⟨I|I⟩ = 0
⟨F H F⟩ = 2nt[n(1 + U/8t) - 2]
U/8t > 2/n - 1
E
8t
metallic


|F> = Π c†k↑ c†k↓ |0>
k
εk<εF
|I>= Π c†iσi |0>
Ne
i=1
Ne ≤ N
# of electrons
# of lattice sites
<I Ĥ |I> / <I|I> = 0

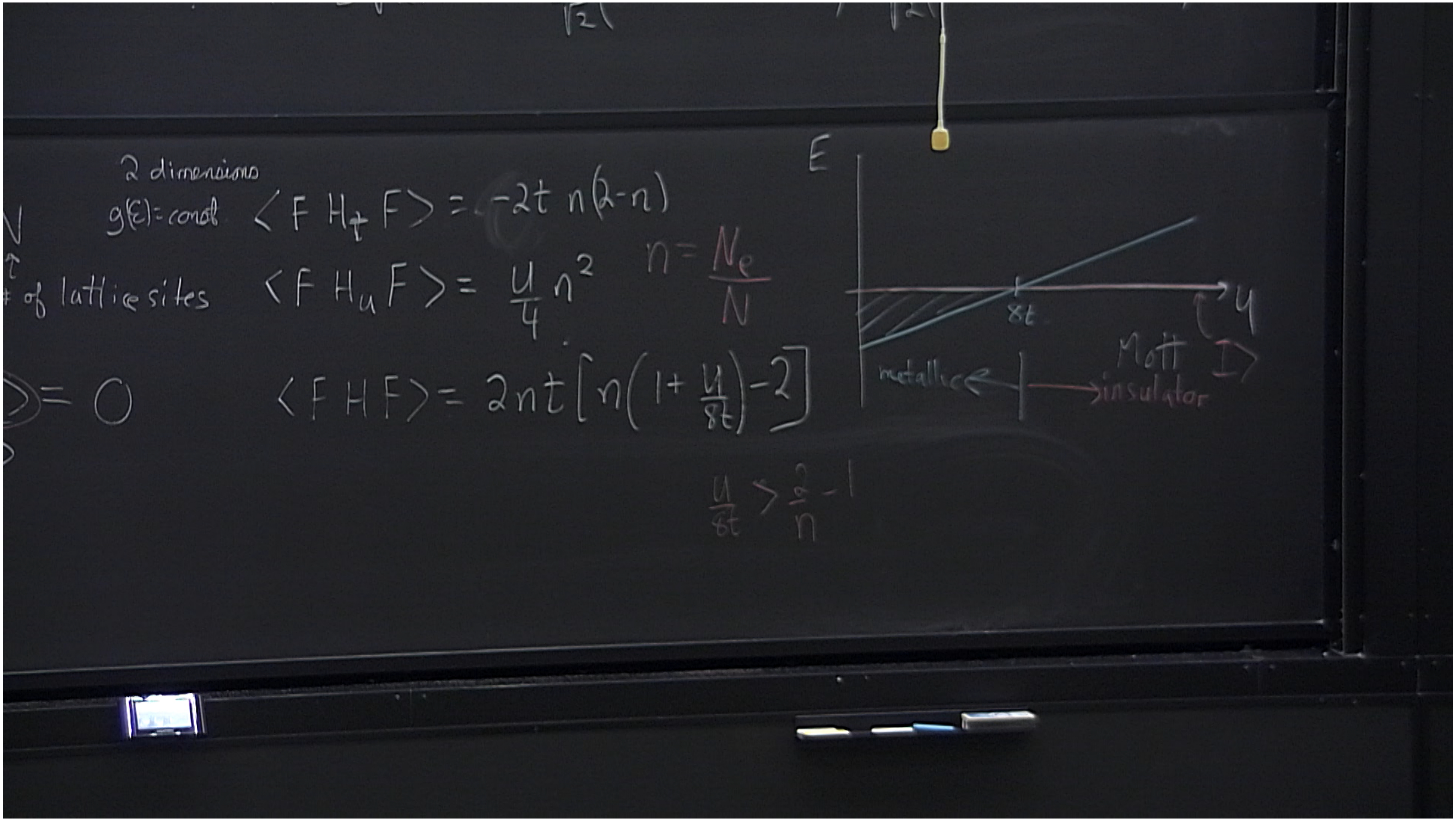


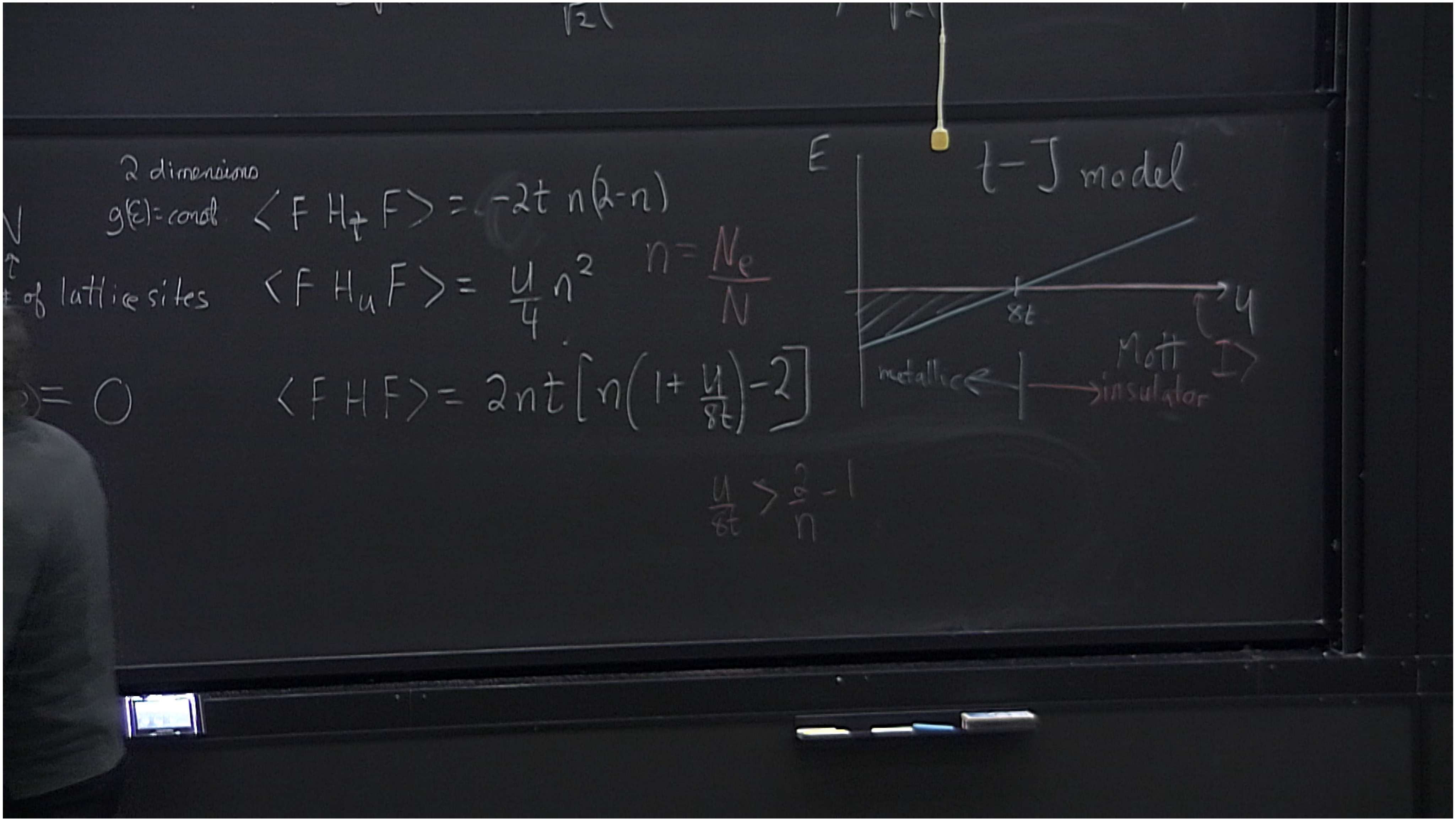
|F> = Π_k c†_{k↑} c†_{k↓} |0>
ε_k < ε_F
|I> = Π_{i=1}^{N_e} c†_{iσ_i} |0>
N_e ≤ N
# of electrons
# of lattice sites
<I|Ĥ|I> / <I|I> = 0


|F> = Π c†kↈ c†k↓ |0>
εk<εF
|I> = Π c†iσi |0>
Ne ≤ N
# of electrons
# of lattice sites
<I|Ĥ|I> / <I|I> = 0
2 dim
g(ε) = con



|F> = Π c† c† |0>
|I>= Π c† |0>
Ne ≤ N
# of electrons
# of lattice sites
2 dim
g(E)= con
band insulators
<I|Ĥ|I> = 0
<I|I>


2 dimensions
g(E) = const
⟨F H_t F⟩ = -2t n(2-n)
# of lattice sites
⟨F H_u F⟩ = U/4 n^2
n = N_e / N
⟨F H F⟩ = 2nt [n(1 + U/8t) - 2]
U/8t > 2/n - 1
E
U
8t
Mott I
metallic
insulator

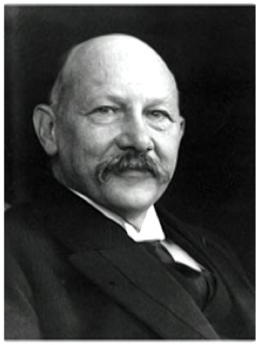


2 dimensions
g(ε)=const
< F H_t F> = -2t n(2-n)
n = N_e / N
# of lattice sites
< F H_u F> = U/4 n^2
= 0
< F H F> = 2nt[n(1+ U/8t)-2]
U/8t > 2/n -1
E
t-J model
8t
U
metallic
Mott
insulator

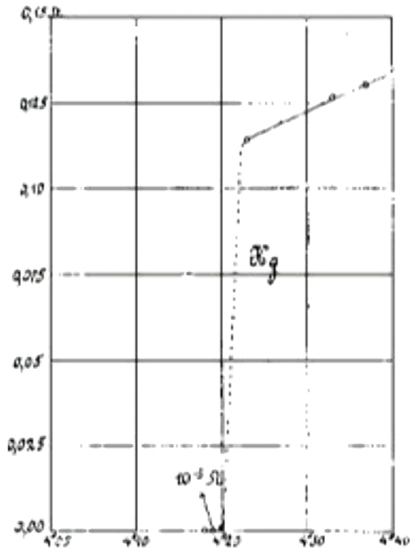
Superconductivity

Kamerlingh Onnes, H.,
"The Superconductivity of Mercury." *Comm. Phys. Lab. Univ. Leiden; Nos. 122 and 124, 1911.*

Gilles Holst

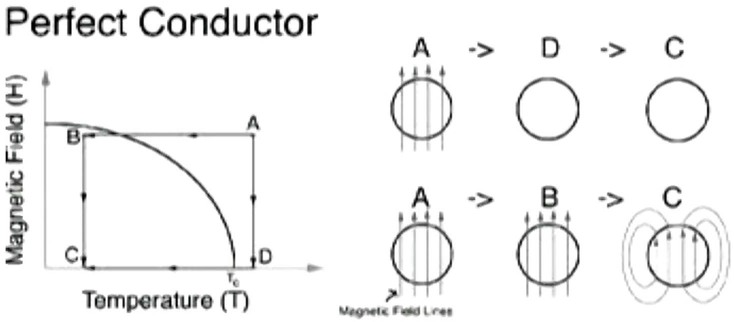


Heike Kamerlingh Onnes



Walther Meißner
1882 - 1974

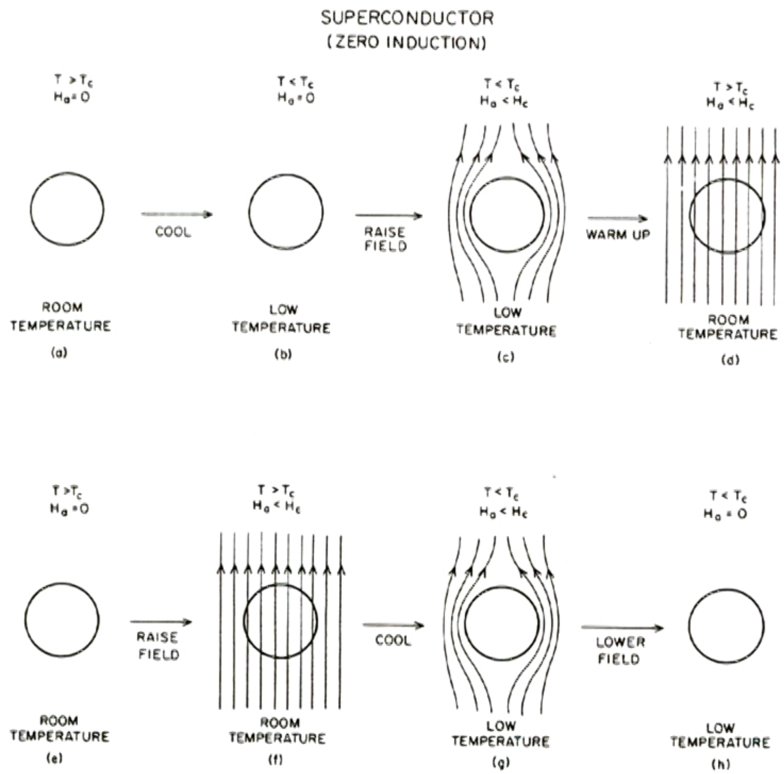
Meissner-Ochsenfeld Effect



Robert Ochsenfeld
1901 - 1993

Walther Meißner
1882 - 1974

Meissner-Ochsenfeld Effect

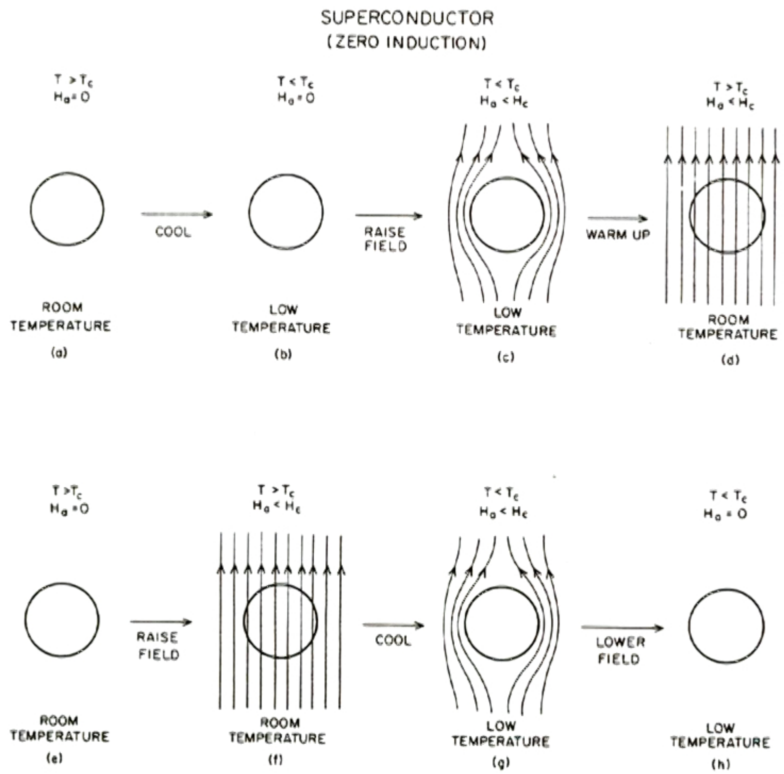


Robert Ochsenfeld
1901 - 1993

Dahl, p.180

Walther Meißner
1882 - 1974

Meissner-Ochsenfeld Effect



Robert Ochsenfeld
1901 - 1993

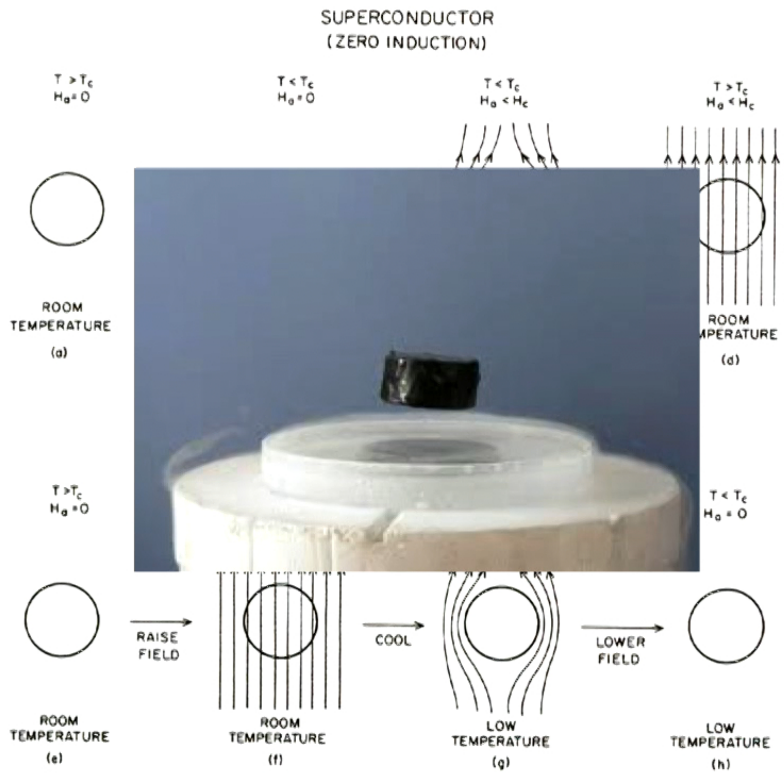
Flux exclusion
(no big deal)

Flux expulsion
(big deal !)

Dahl, p.180

Walther Meißner
1882 - 1974

Meissner-Ochsenfeld Effect

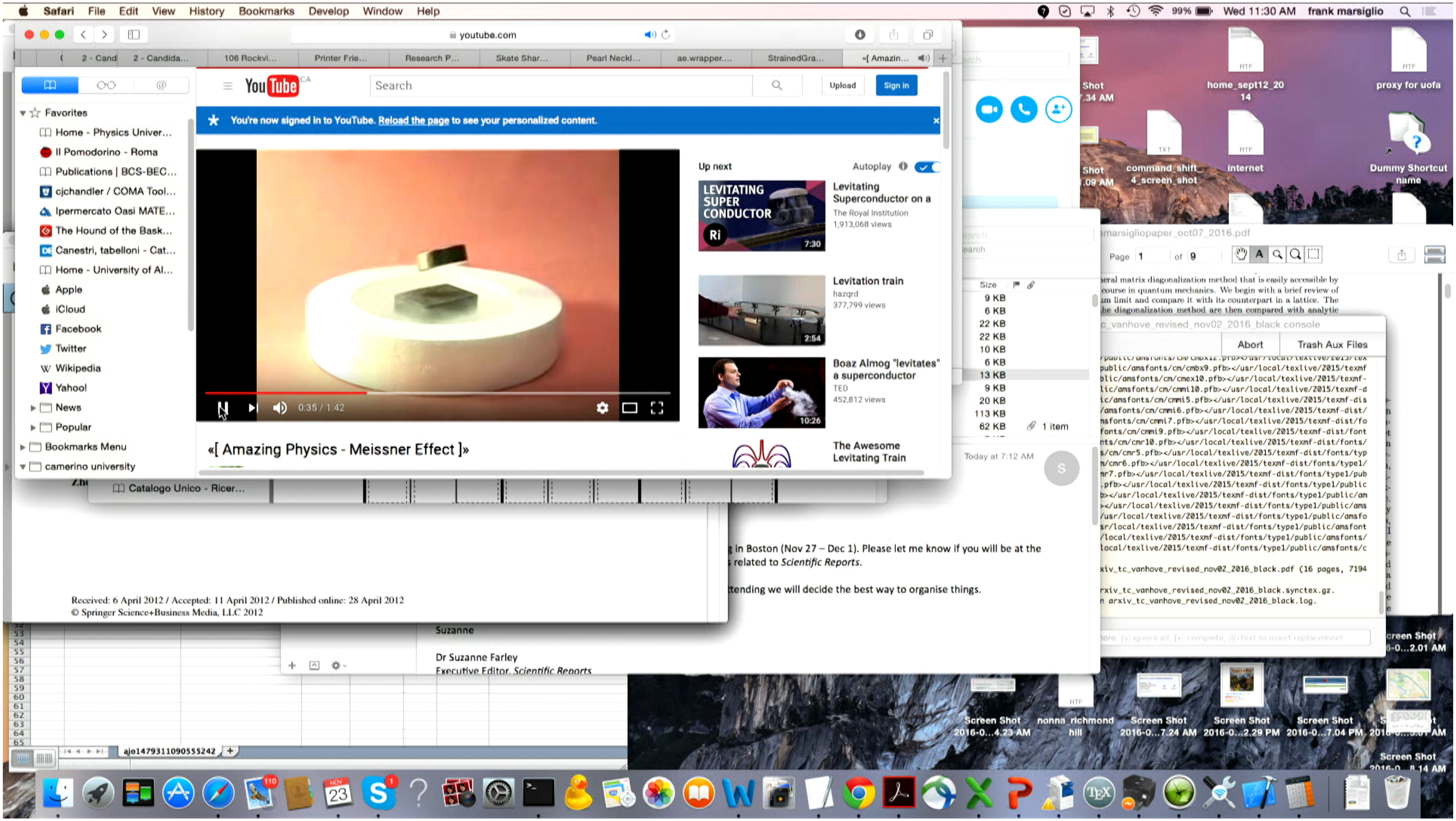


Robert Ochsenfeld
1901 - 1993

Flux exclusion
(no big deal)

Flux expulsion
(big deal !)

Dahl, p.180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Il Pomodorino - Roma
Publications | BCS-BEC...
cjchandler / COMA Tool...
Ipermercato Oasi MATE...
The Hound of the Bask...
Canestri, tabelloni - Cat...
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iCloud
Facebook
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Yahoo!
News
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Bookmarks Menu
camerino university
Catalogo Unico - Ricer...
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0:35 / 1:42
«[Amazing Physics - Meissner Effect]»
Up next
Autoplay
Levitating Superconductor on a
The Royal Institution
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Levitation train
hazqrd
377,799 views
Boaz Almog "levitates" a superconductor
TED
452,812 views
The Awesome Levitating Train
Received: 6 April 2012 / Accepted: 11 April 2012 / Published online: 28 April 2012
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in Boston (Nov 27 – Dec 1). Please let me know if you will be at the
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Dr Suzanne Farley
Executive Editor, Scientific Reports
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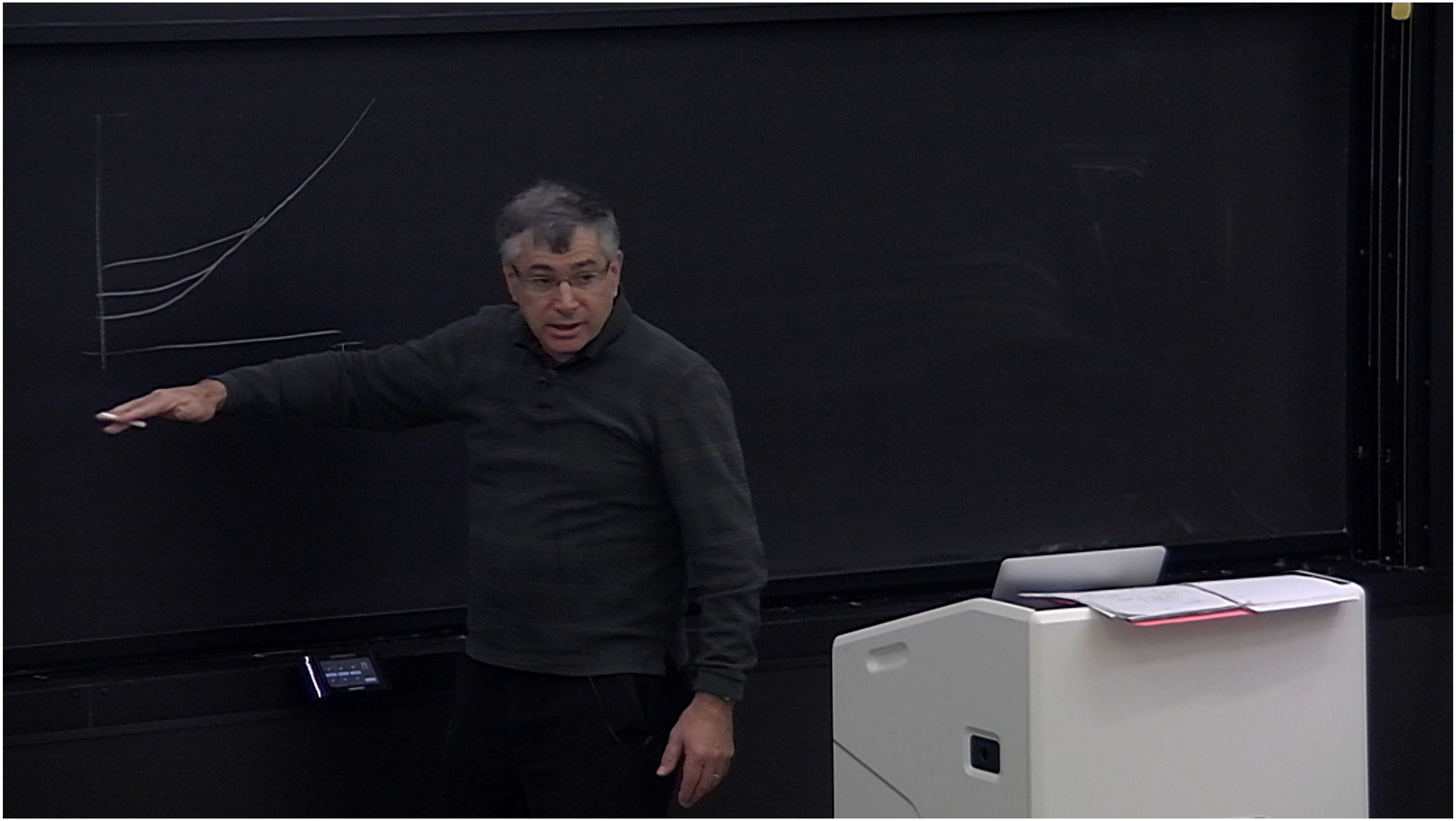
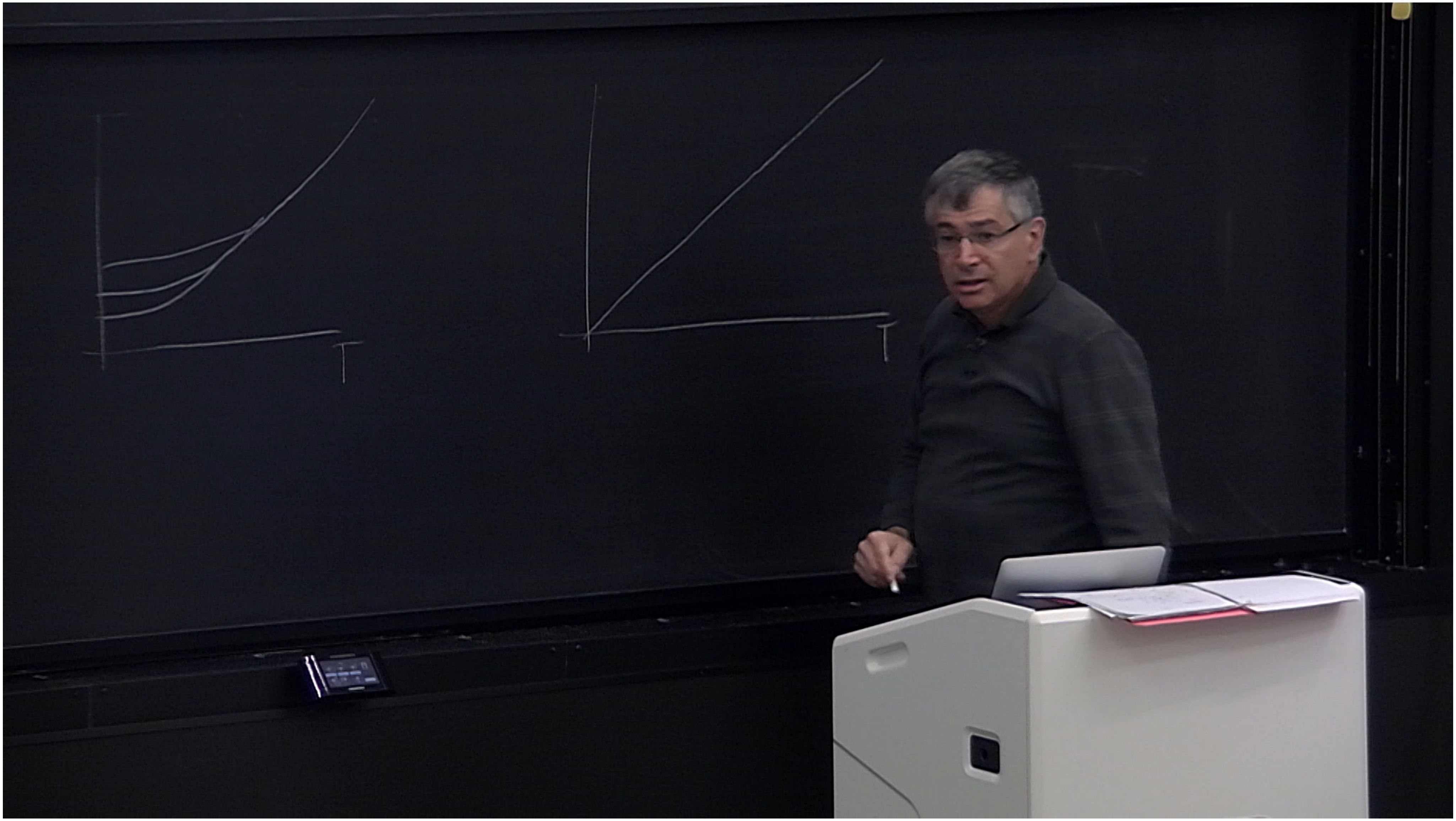
Trash Aux Files
home_sept12_20 14
proxy for uofa
command_shift_4_screen_shot
internet
Dummy Shortcut name
Screen Shot
nonna_richmond hill


T

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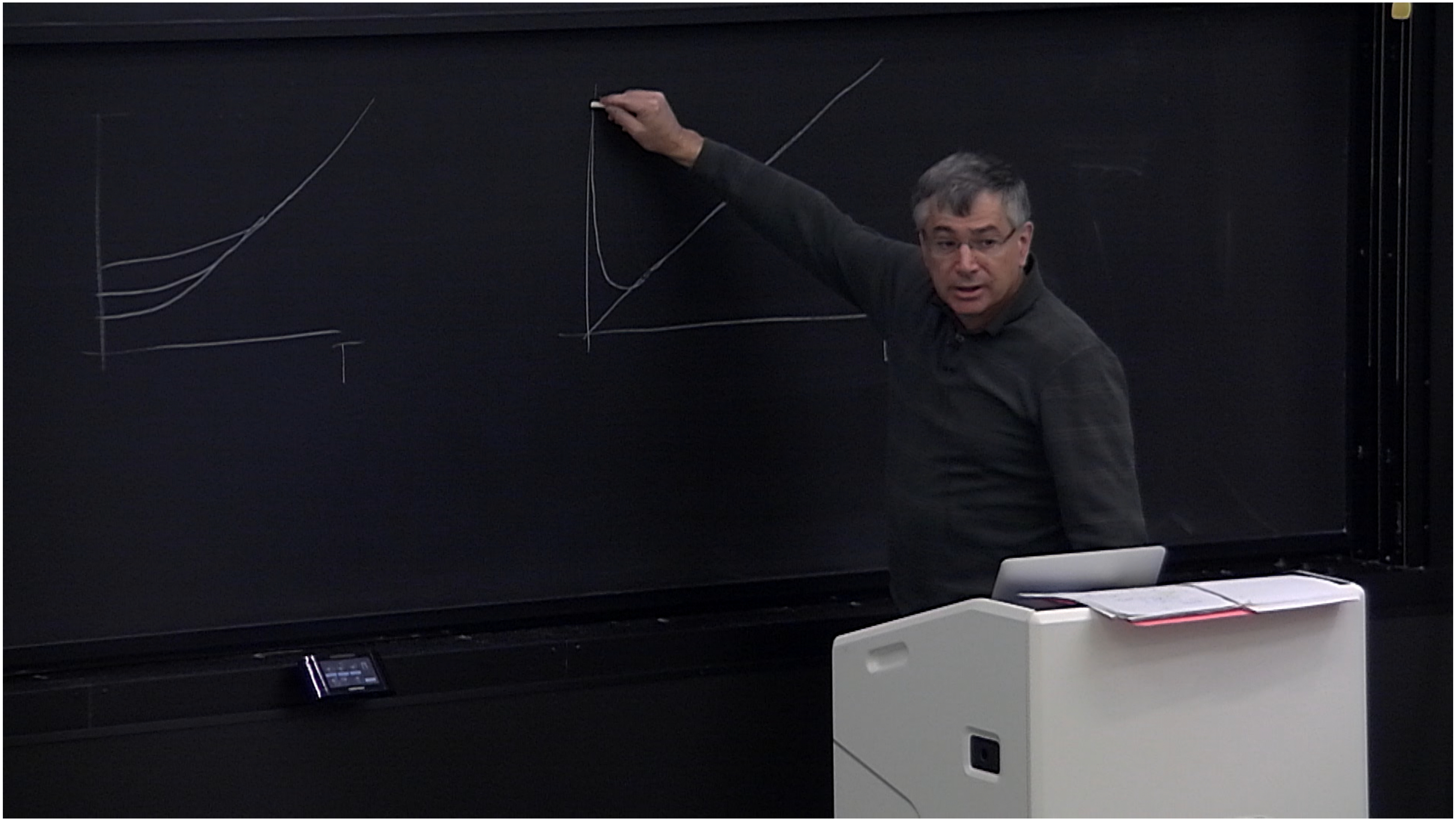
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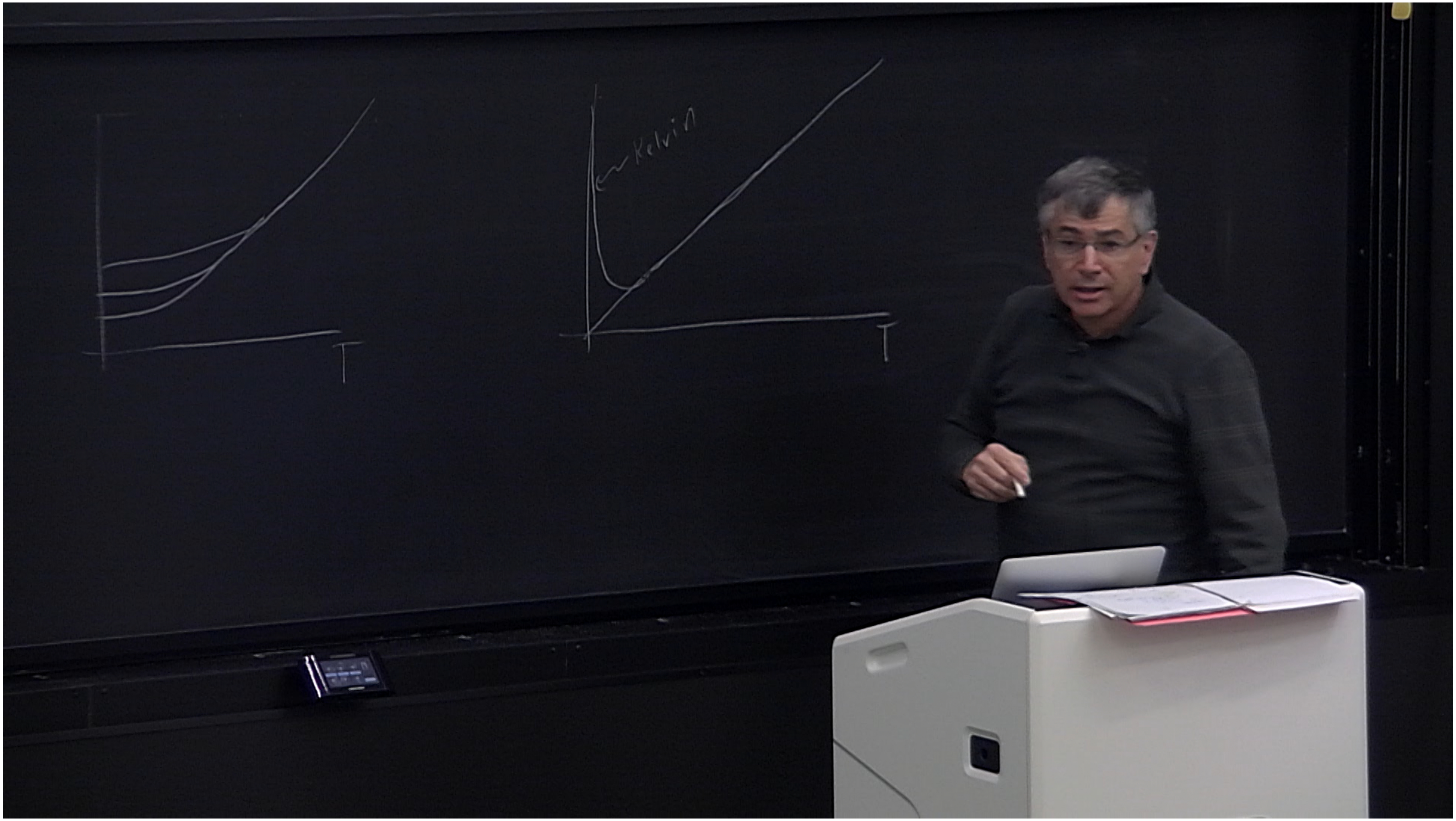
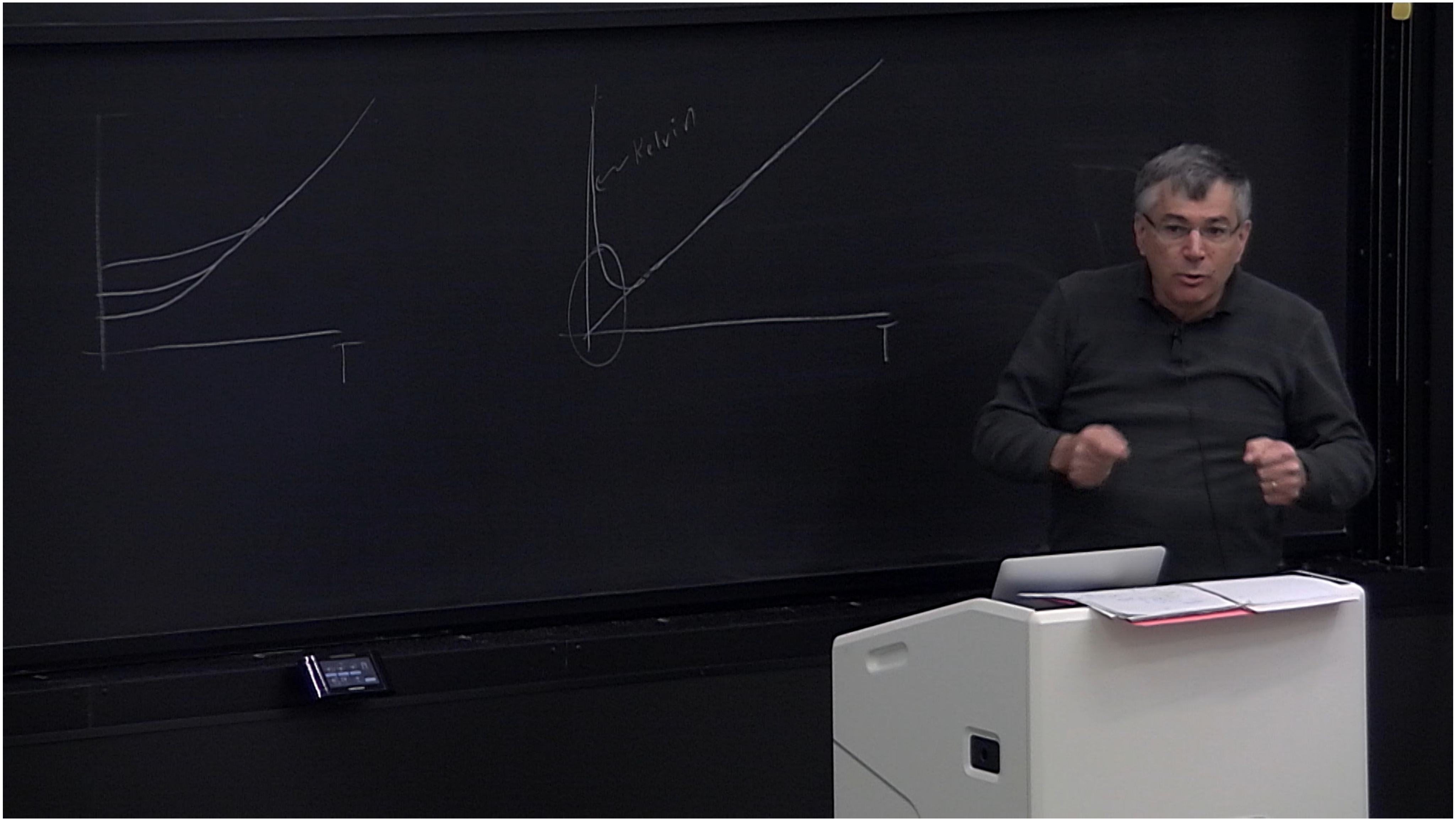
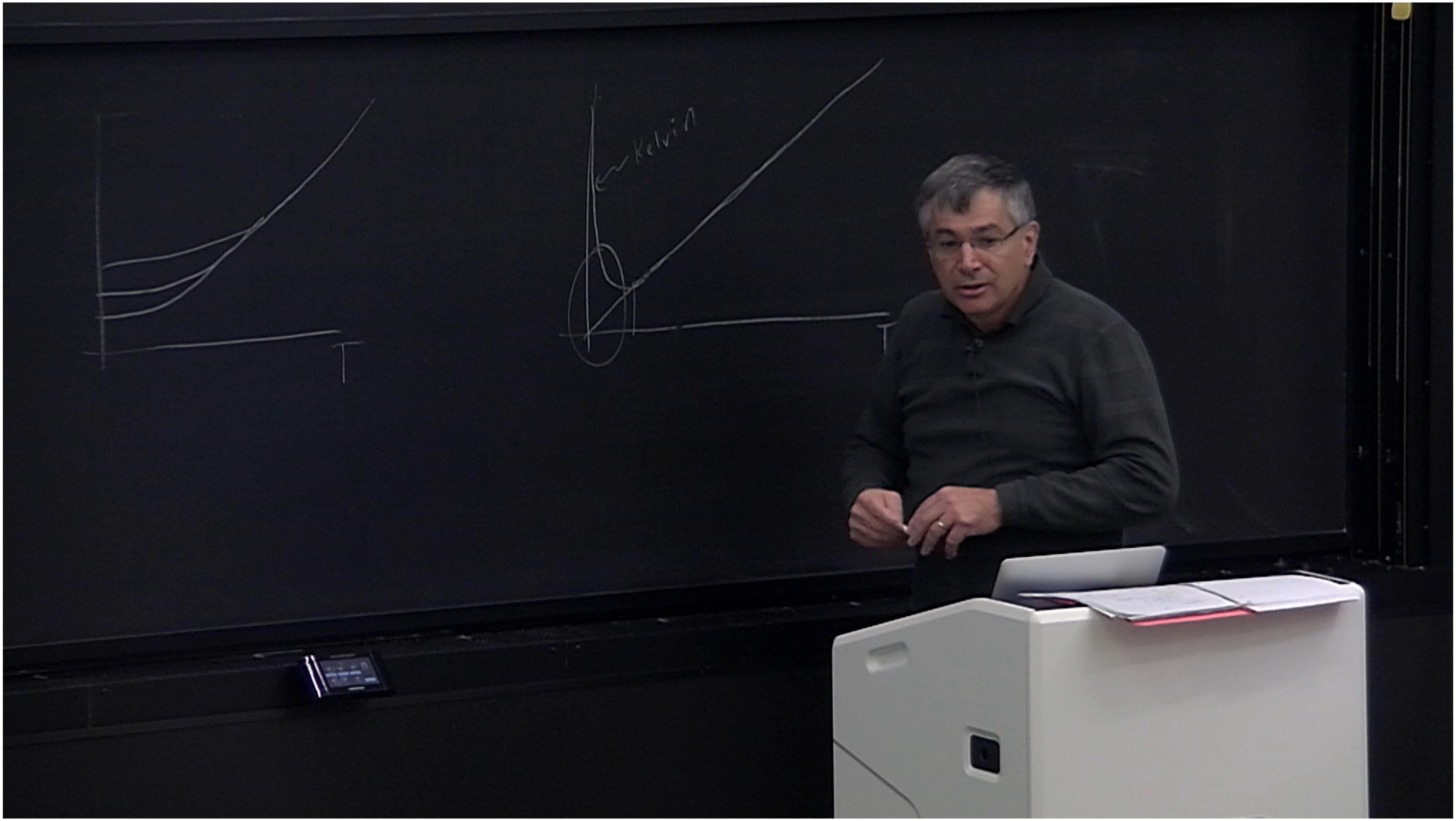

Kelvin
T
T



T
Kelvin
T

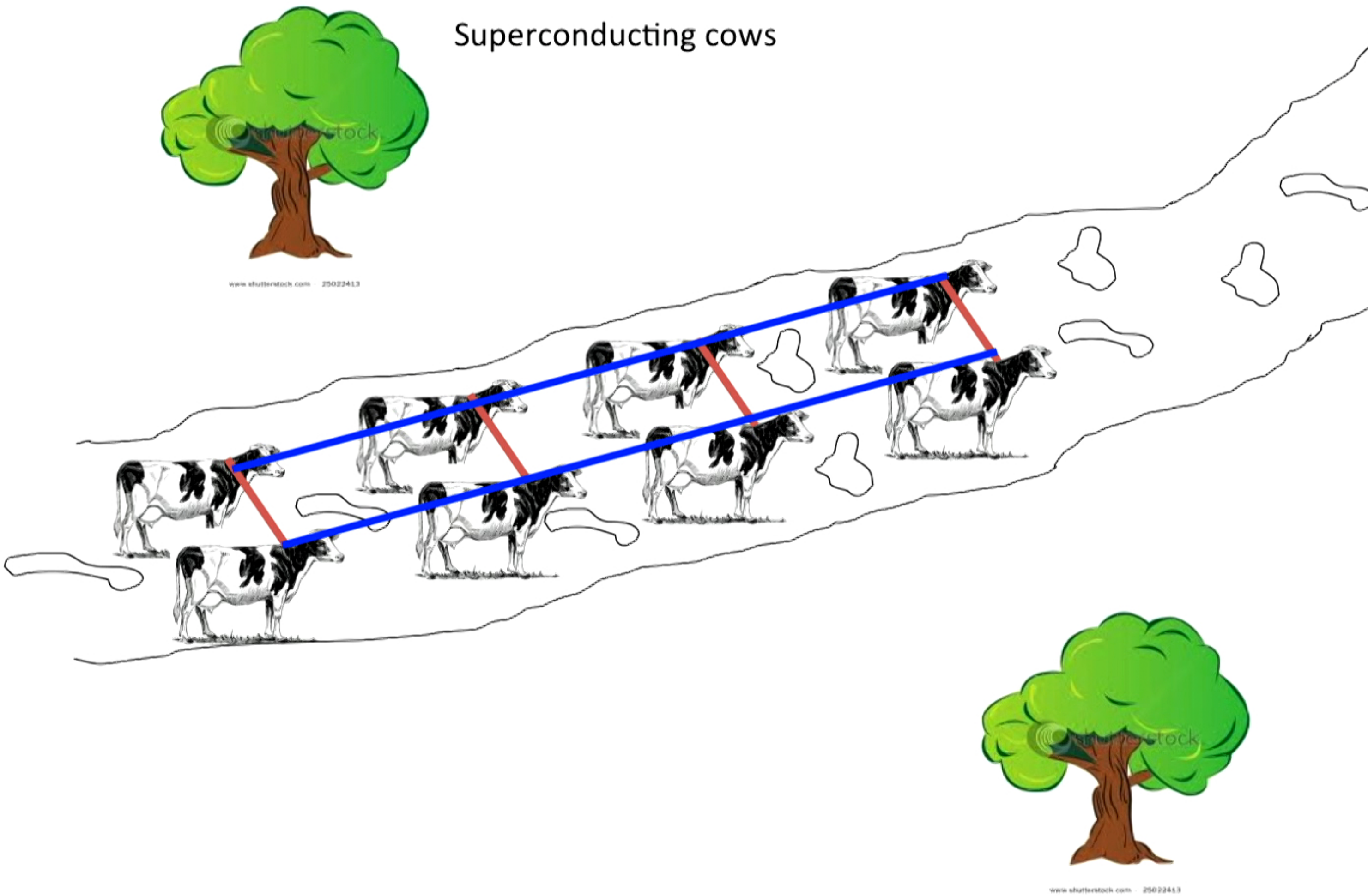

Kelvin
T
T

What else happened between 1933 and the `modern era'?

What else happened between 1933 and the `modern era'?

Heinz and Fritz London, 1935

Superconducting cows



What else happened between 1933 and the `modern era'?

Heinz and Fritz London, 1935

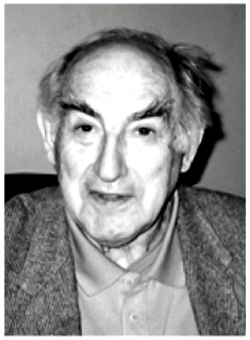
Lev Shubnikov, 1935

What else happened between 1933 and the `modern era'?

Heinz and Fritz London, 1935

Lev Shubnikov, 1935

Vitaly Ginzburg and



Lev Landau, 1950

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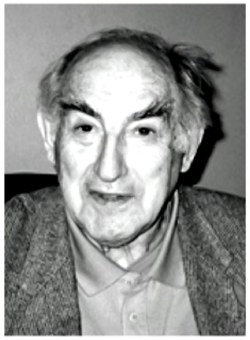
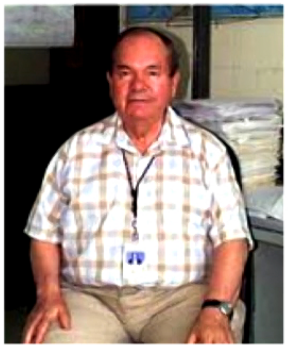
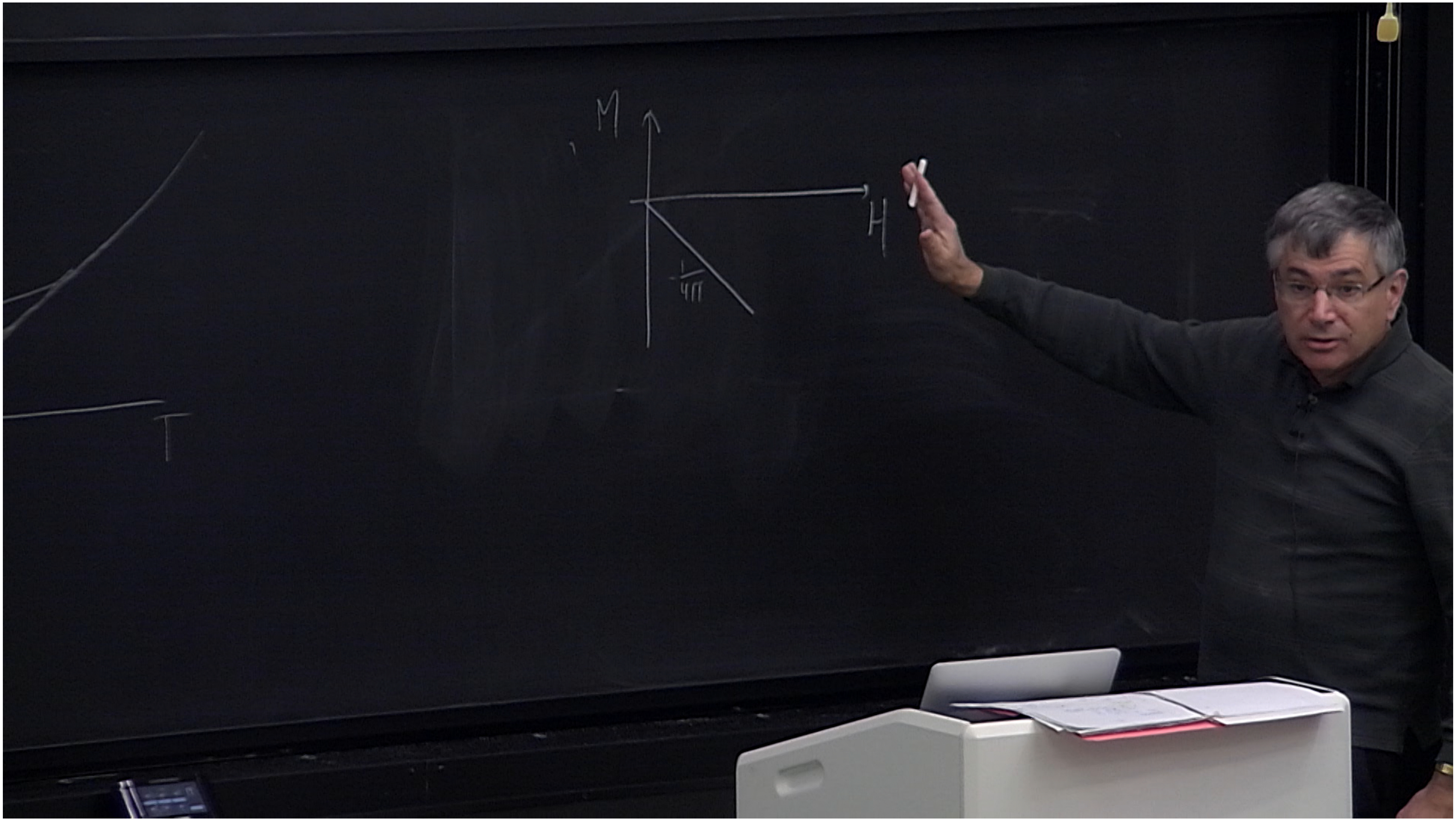


Alexei A. Abrikosov 1956




M
H
$-\frac{1}{4\pi}$
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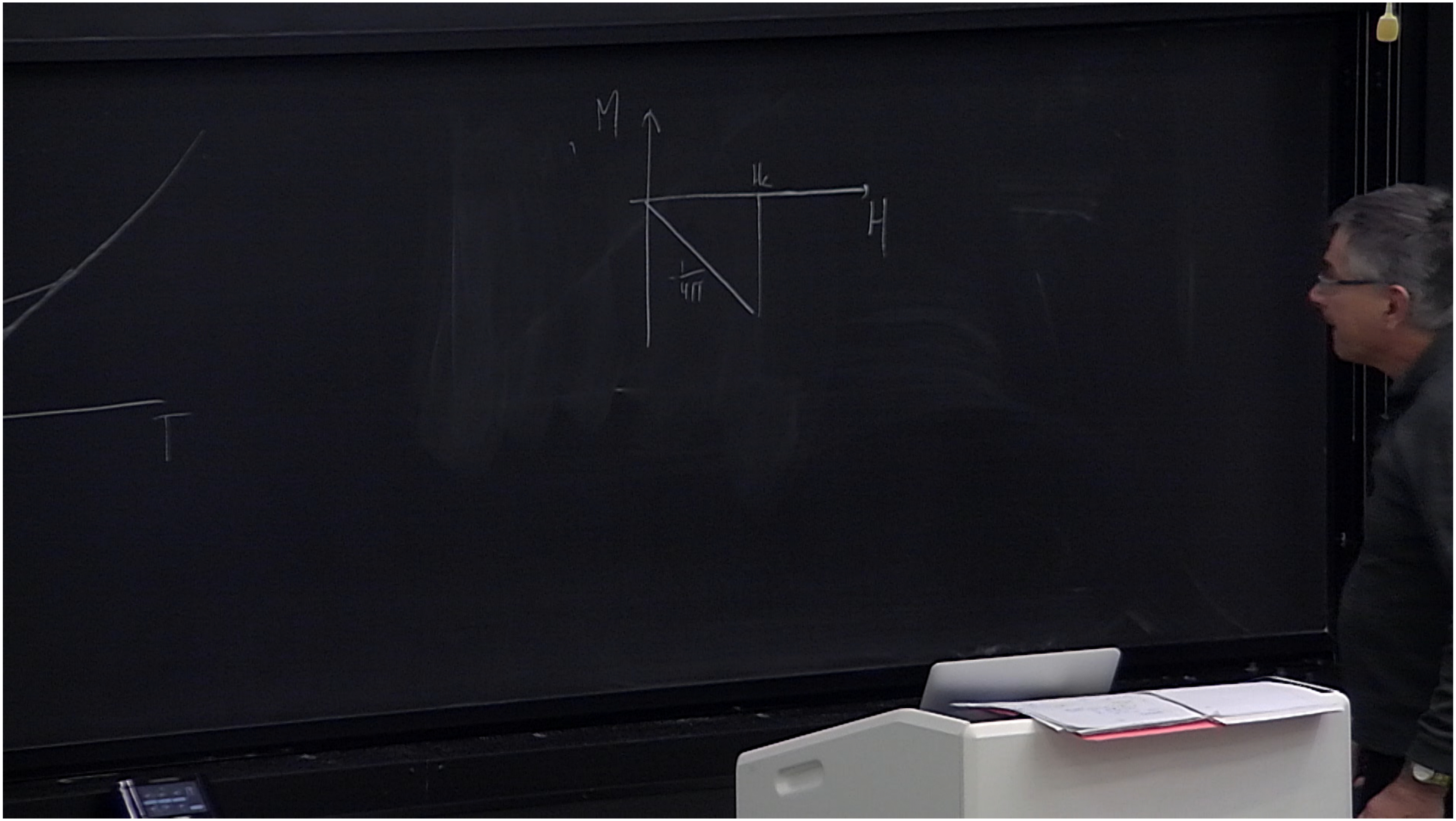
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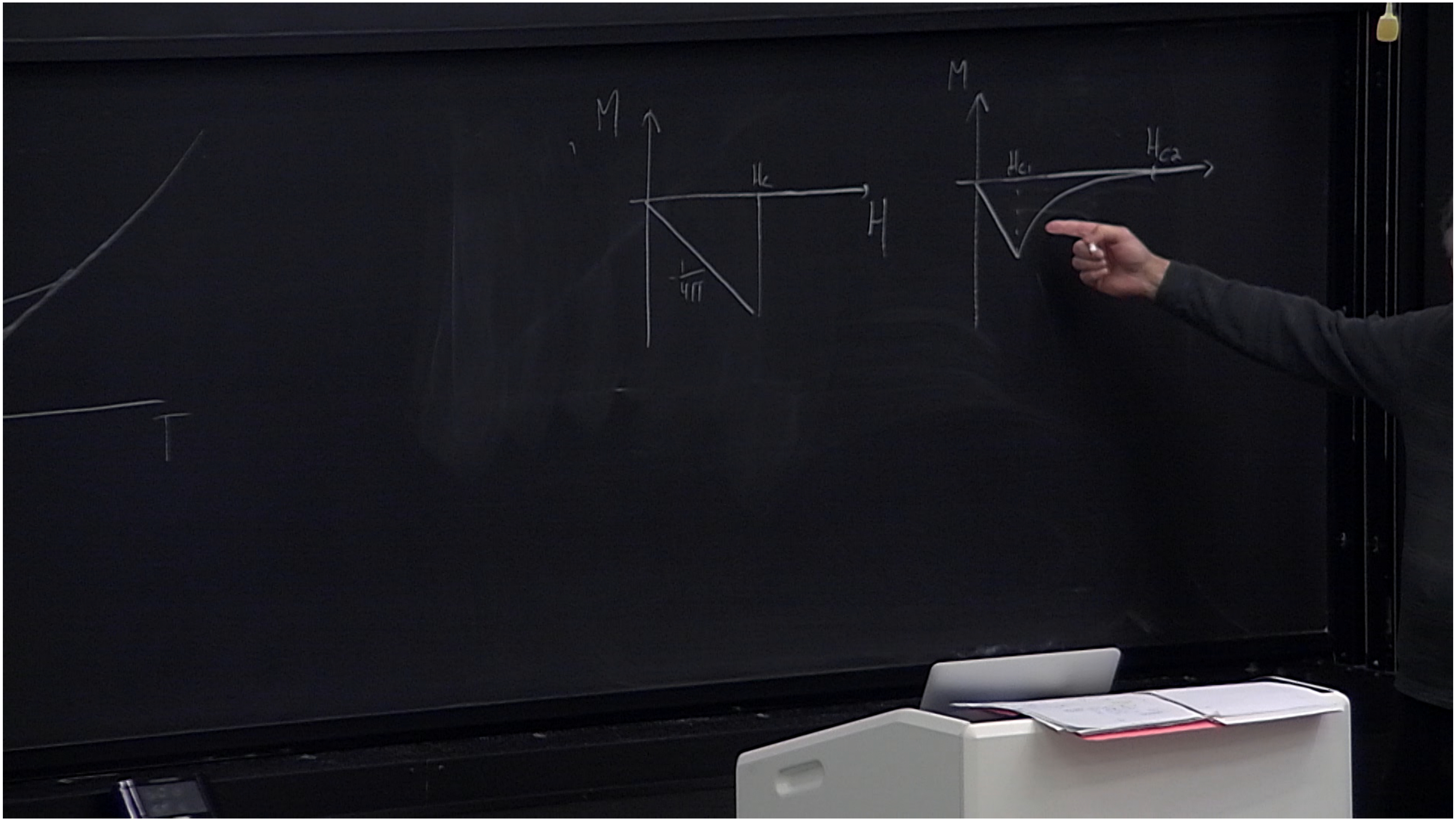
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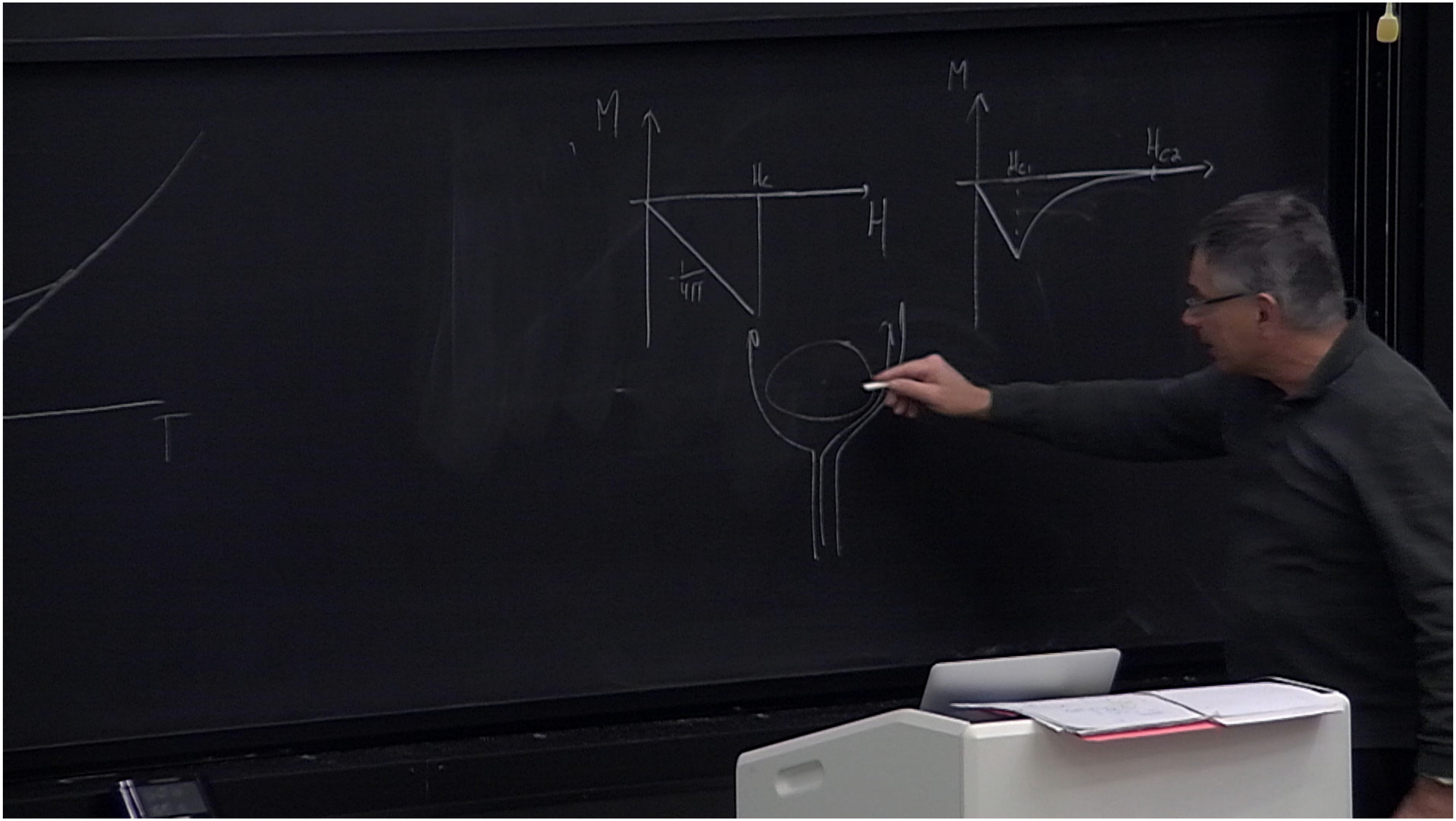
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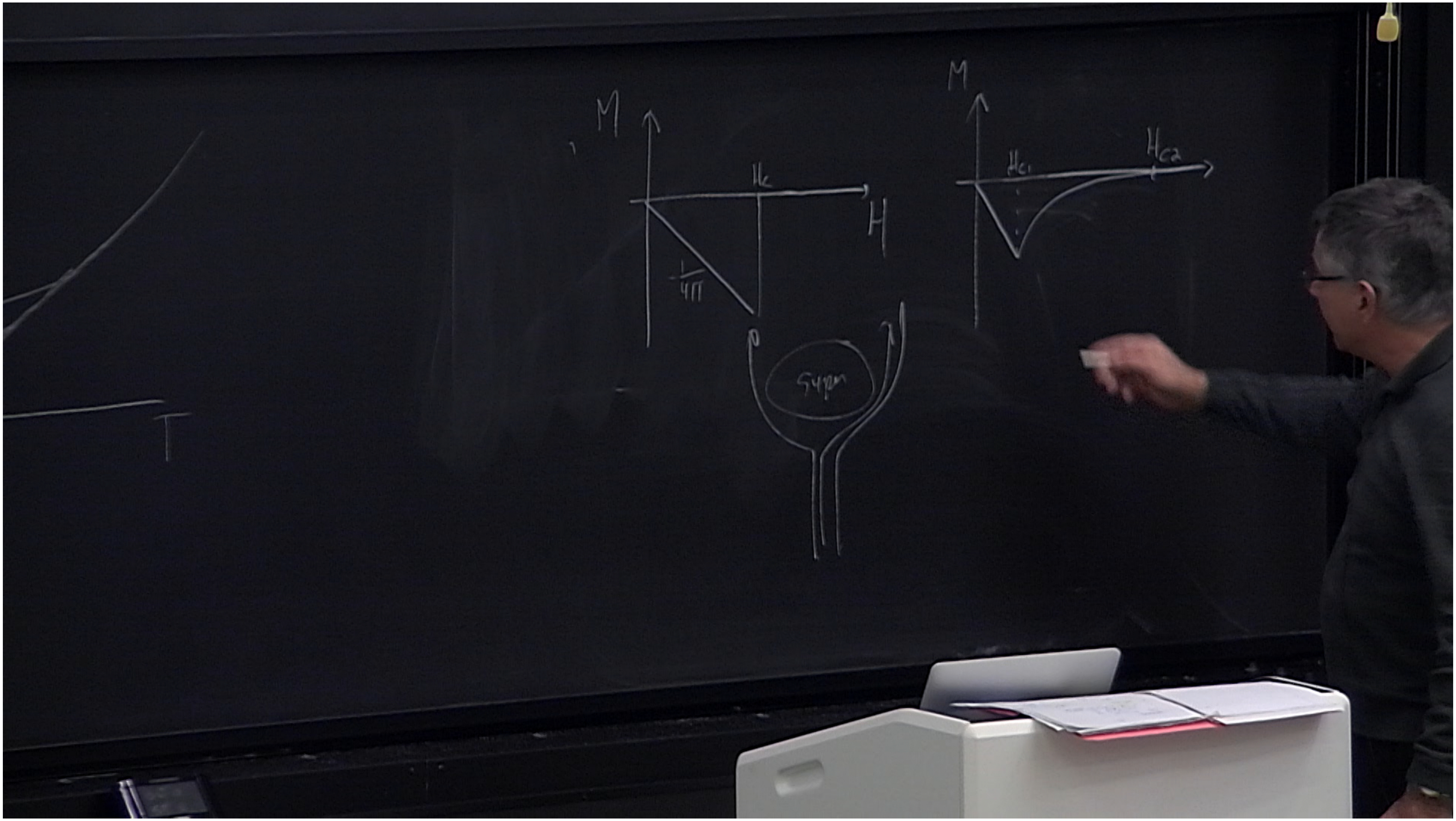

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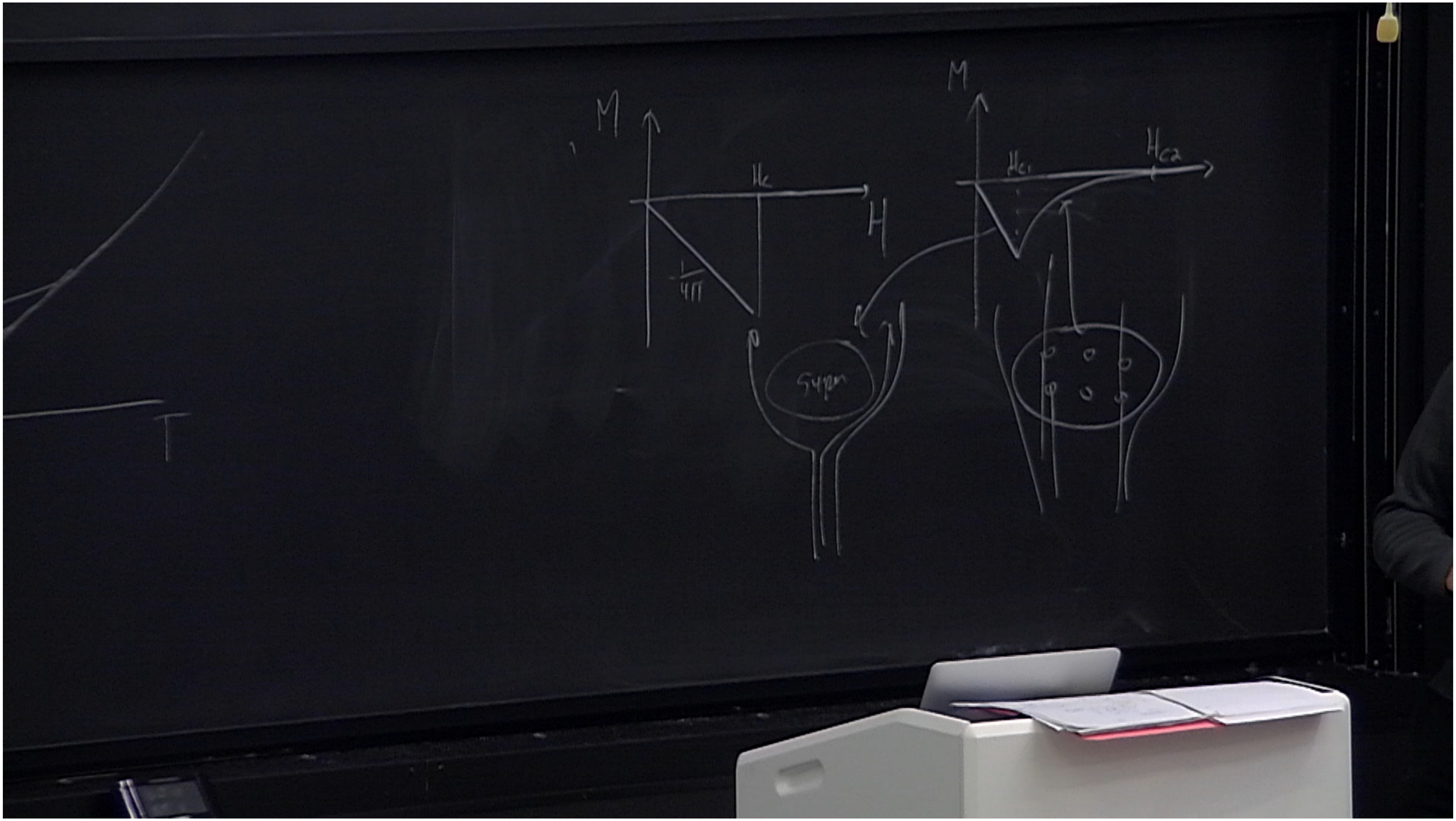
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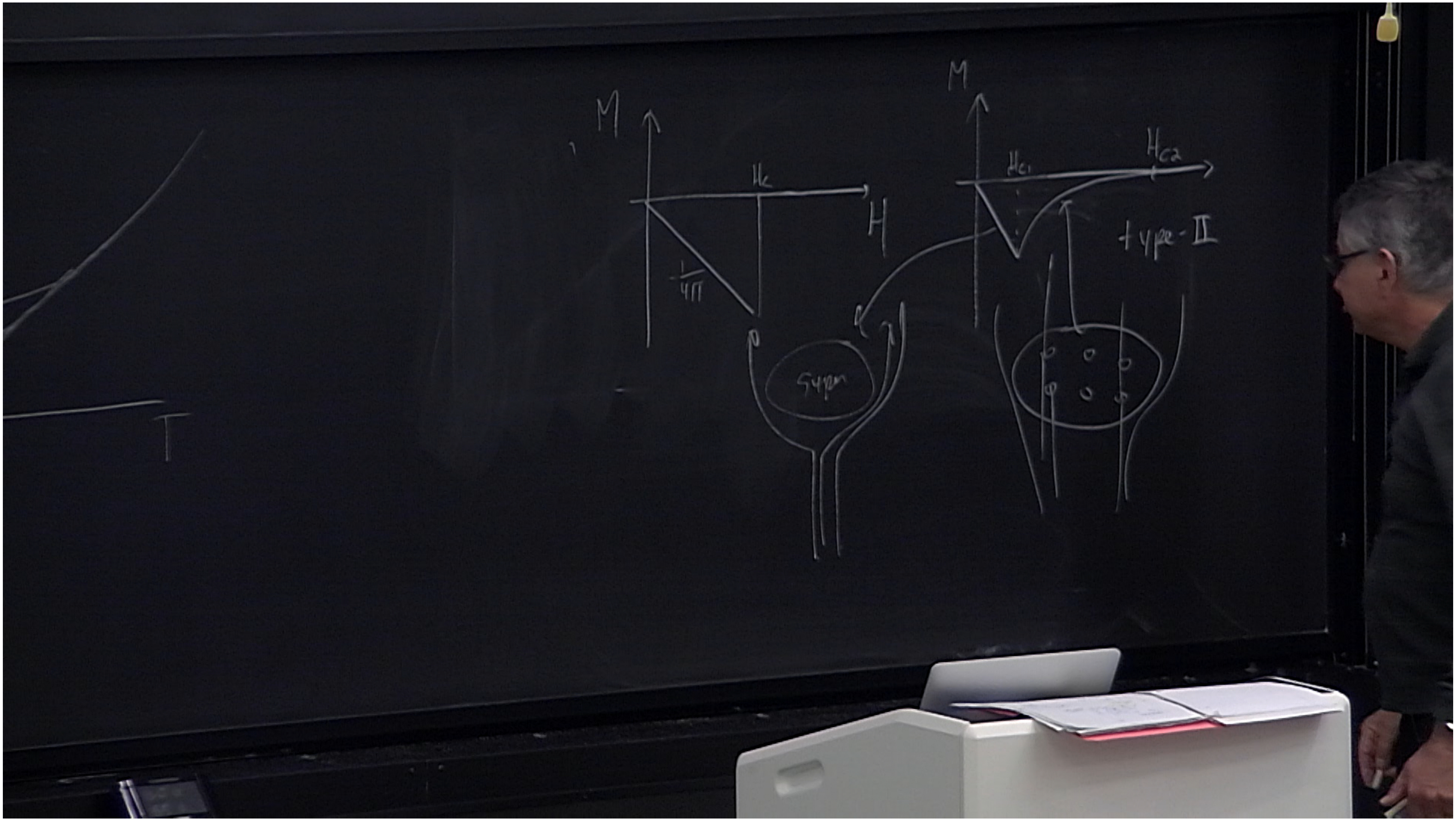
M
H
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H_{c1}
H_{c2}
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T

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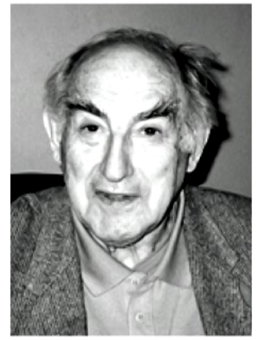

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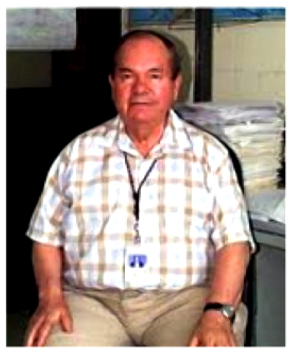
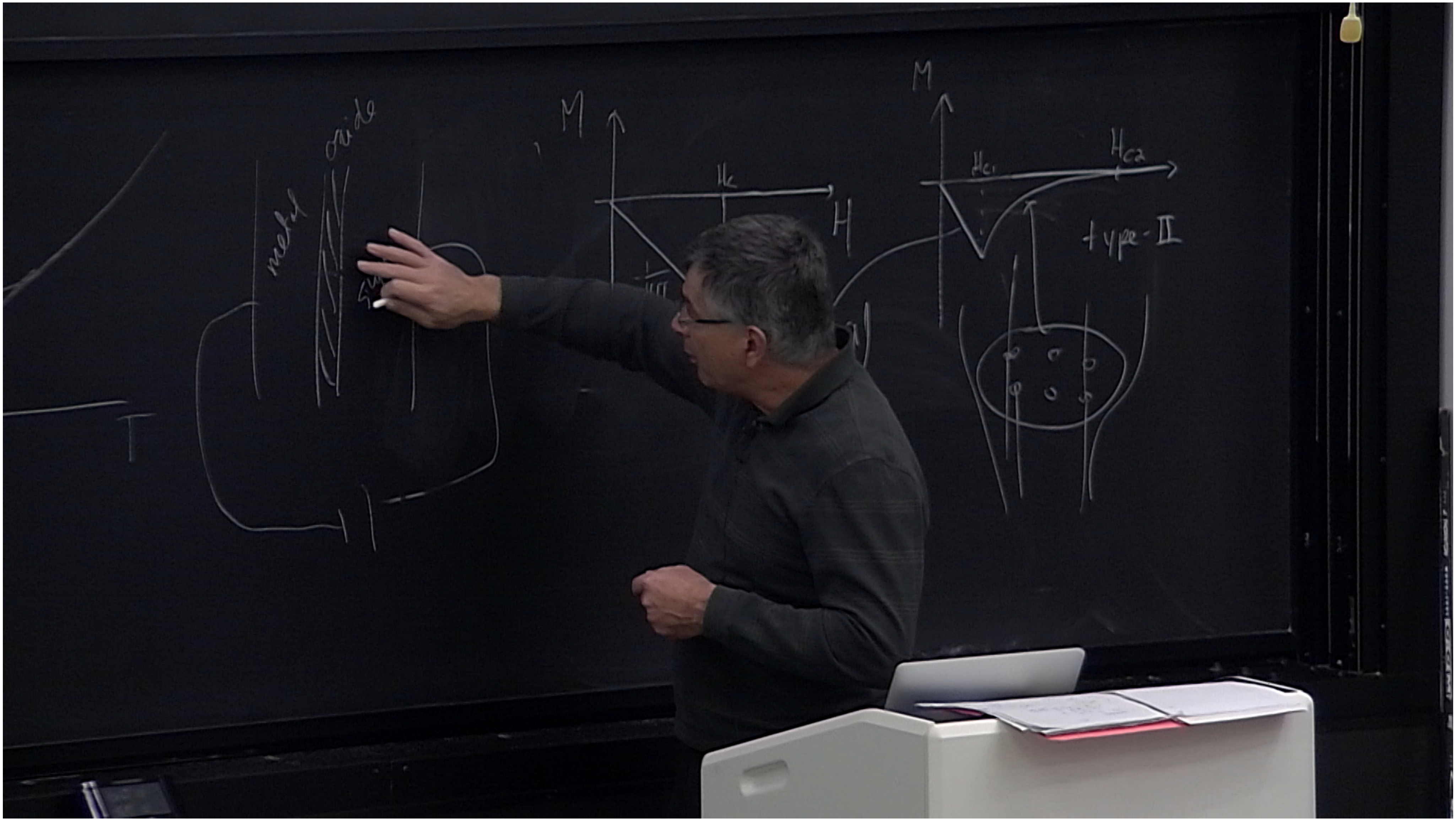
Alexei A. Abrikosov 1956



Brian Josephson 1962


metal
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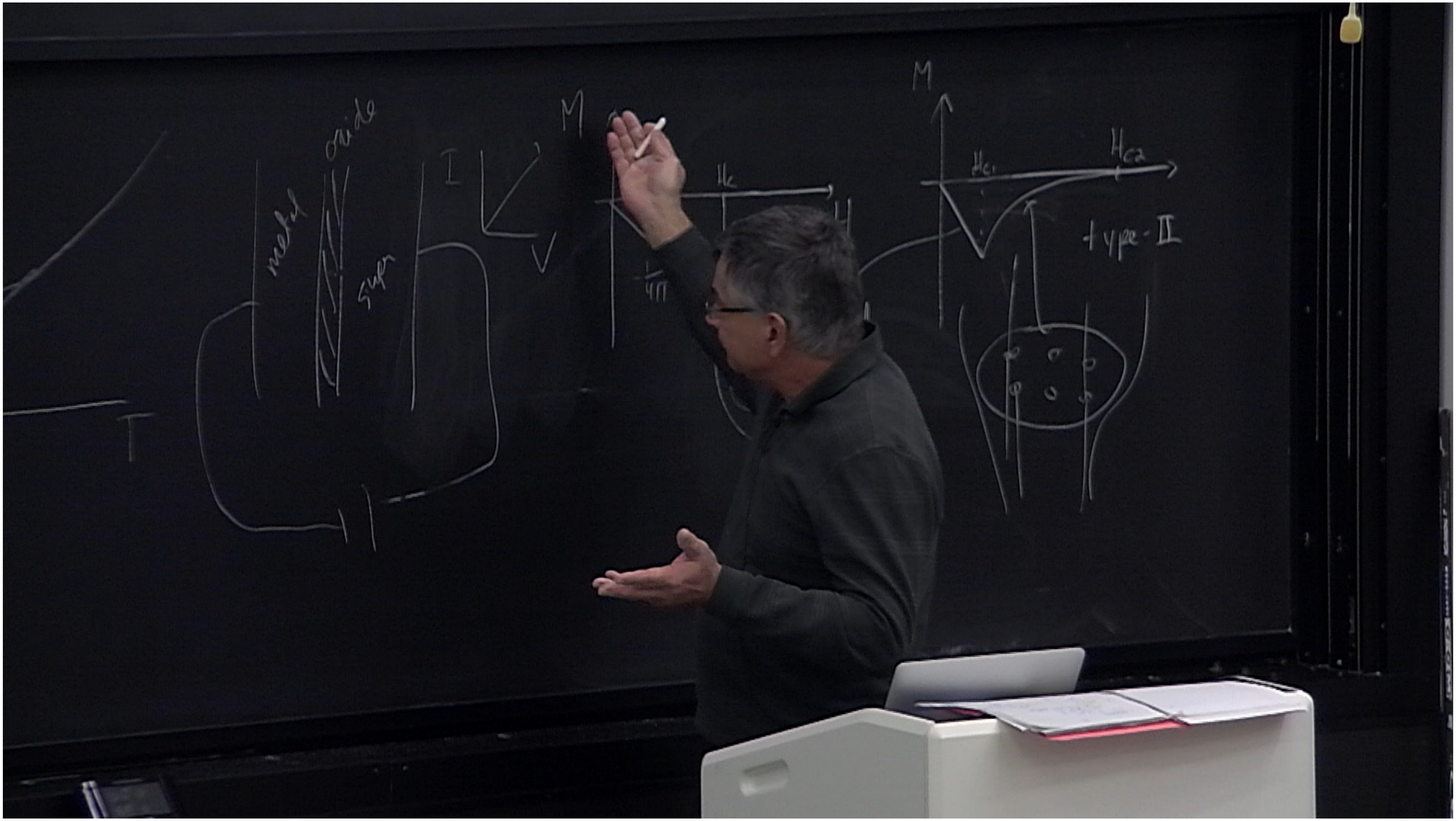
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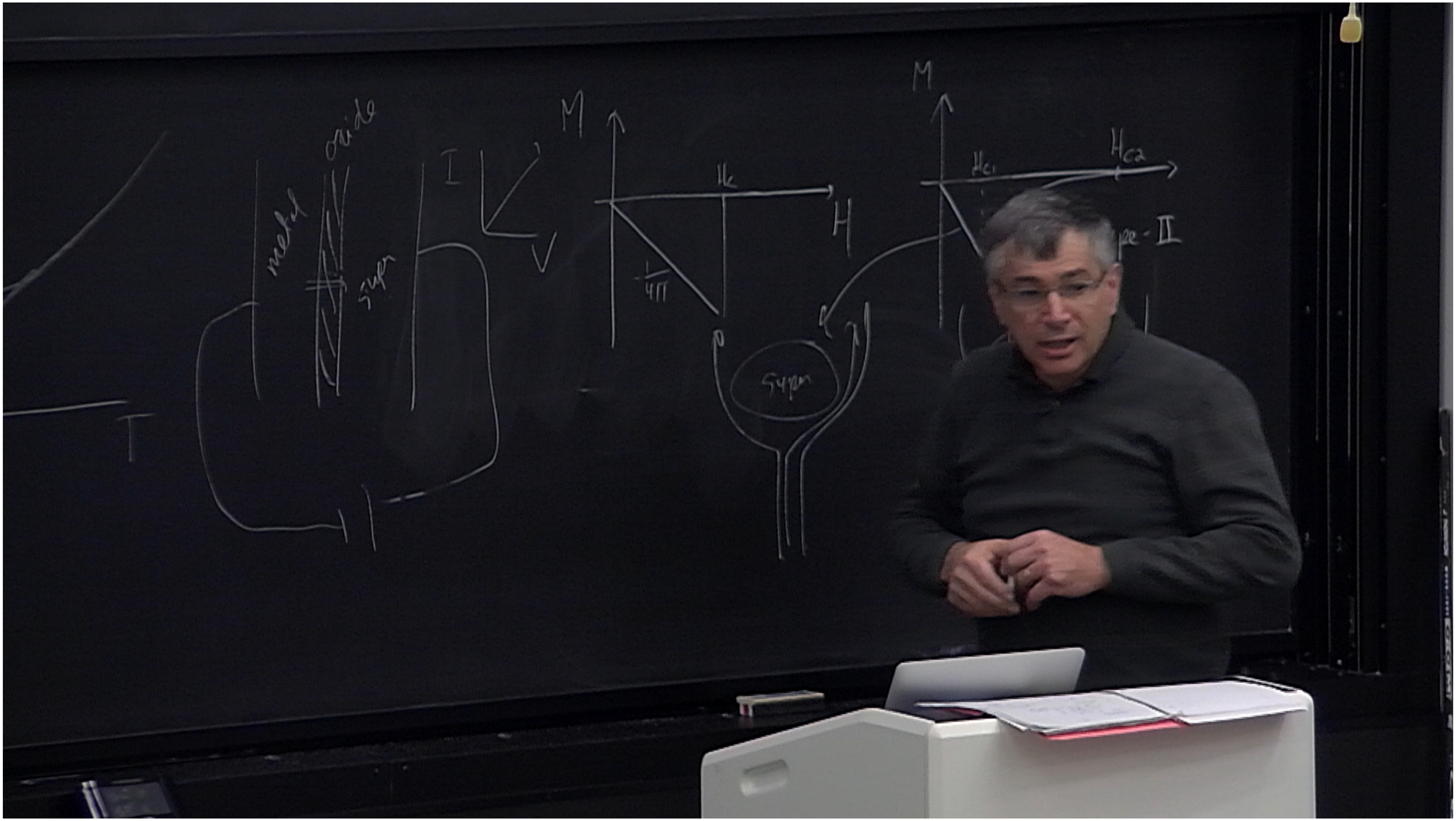
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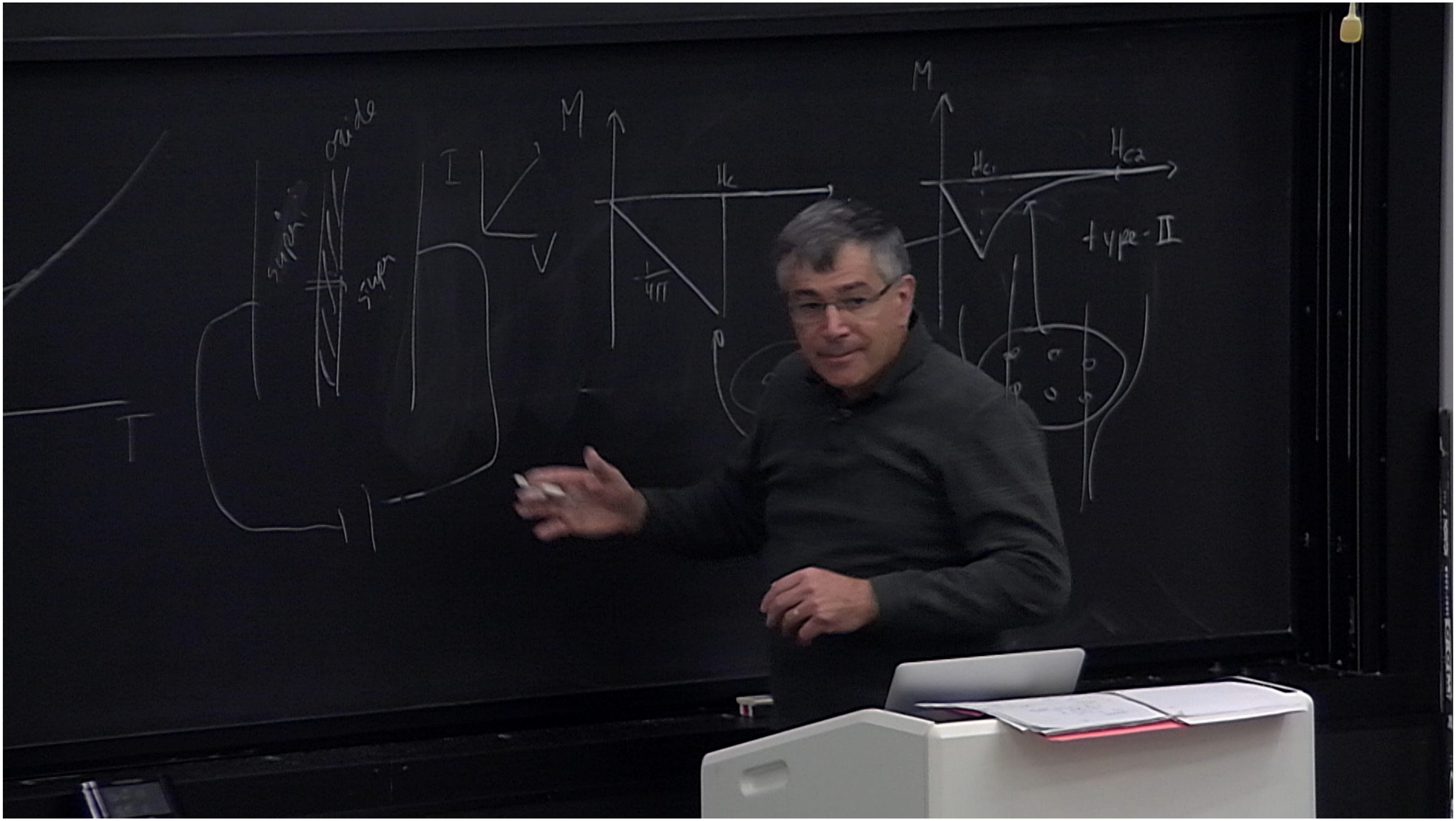

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H_c
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Messungen mit Hilfe von flüssigem Helium. XIII.
Kontaktwiderstand zwischen Supraleitern und Nichtsupraleitern.

Von **R. Holm** und **W. Meissner** in Berlin-Charlottenburg.

Mit 4 Abbildungen. (Eingegangen am 26. Januar 1932.)

Zeitschrift für Physik, Bd. 133, S. 499—503 (1952).

Versuche zur Supraleitung an Kontakten.

Von

ISOLDE DIETRICH *.

Mit 7 Figuren im Text.

(Eingegangen am 2. Juli 1952.)

Kontakte zwischen Kontaktgliedern des Supraleiters Tantal mit einer isolierenden Fremdschicht aus TiO_2 oder CeO_2 bekannter Dicke werden supraleitend. Die Abhängigkeit der Übergangskurve von der Dicke der Schicht und der Belastungsstromstärke wird untersucht.

3. Zwischen Supraleitern aus gleichem oder verschiedenem Material (geprüft wurde Sn und Pb) ist ein supraleitender Kontakt ohne Verschweißung der Materialien möglich. Bei Eintritt der Supraleitfähigkeit verschwindet auch der Widerstand der Störschicht.

3. Between superconductors of the same or different materials (...)
superconductivity is possible without welding them. When
this superconductivity occurs, the resistance of the layer
(contact region between the superconductors) disappears.

Versuche zur Supraleitung an Kontakten.

Von

Isolde Dietrich*.

Mit 7 Figuren im Text.

(Eingegangen am 2. Juli 1952.)

Kontakte zwischen Kontaktgliedern des Supraleiters Tantal mit einer isolierenden Fremdschicht aus TiO_2 oder CeO_2 bekannter Dicke werden supraleitend. Die Abhängigkeit der Übergangskurve von der Dicke der Schicht und der Belastungsstromstärke wird untersucht.

DIRECT MEASUREMENT OF THE SUPERCONDUCTING ENERGY GAP

James Nicol, Sidney Shapiro, and Paul H. Smith
Advanced Research Division, Arthur D. Little, Incorporated, Cambridge, Massachusetts

(Received October 27, 1960)

3. Between su
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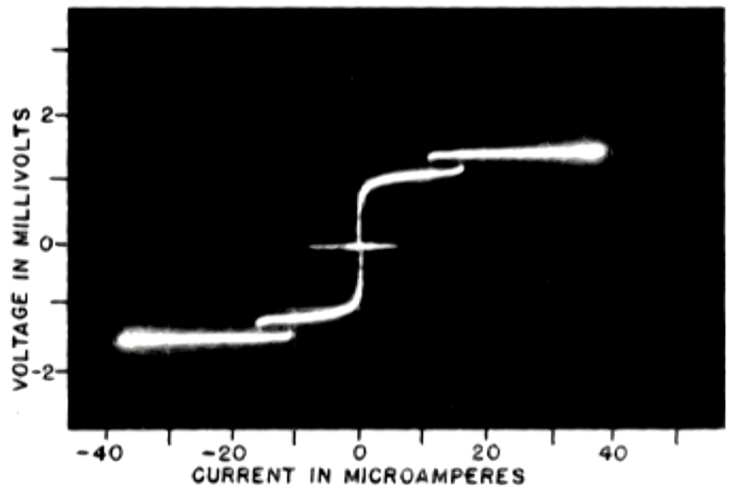
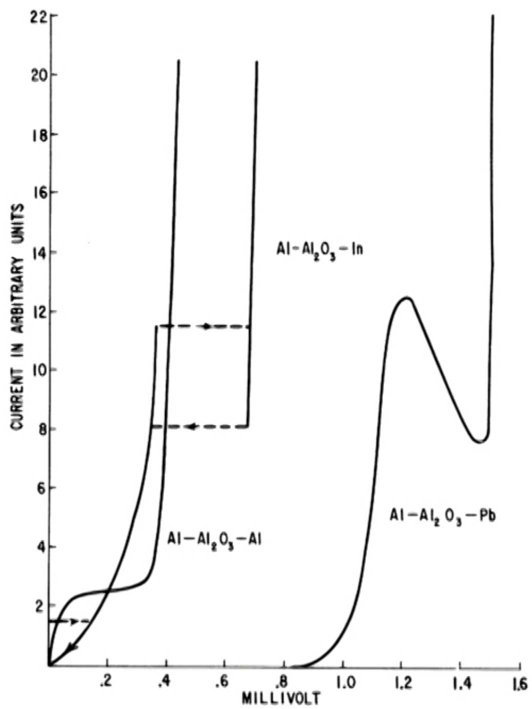


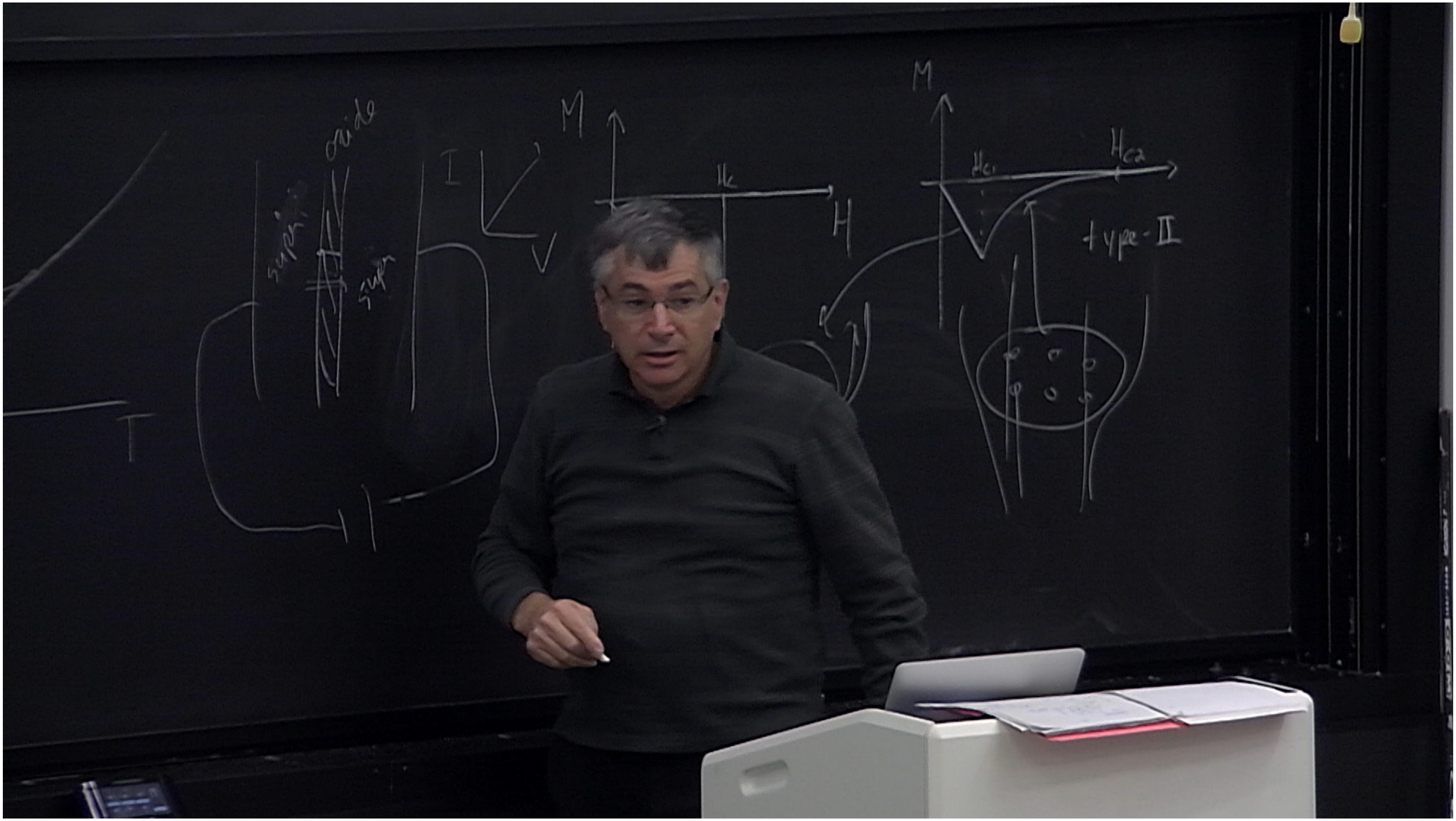
FIG. 1. Voltage vs tunneling current for an Al-Al_2O_3-Pb sandwich at 1°K.

ELECTRON TUNNELING BETWEEN TWO SUPERCONDUCTORS

Ivar Giaever
General Electric Research Laboratory, Schenectady, New York
(Received October 31, 1960)



was not traced out. Also, as is apparent from the low-current behavior of this sample, the oxide film is pierced by a superconductive bridge. When the current is increased the bridge goes normal, and its conductivity is too low to affect the general characteristics of the tunneling. When the current is decreased, the bridge remains normal at a lower current due to Joule heating.


oxide
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type-II

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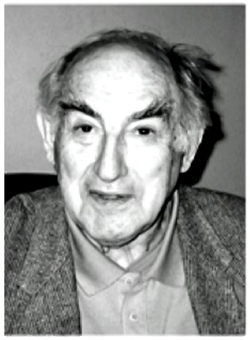
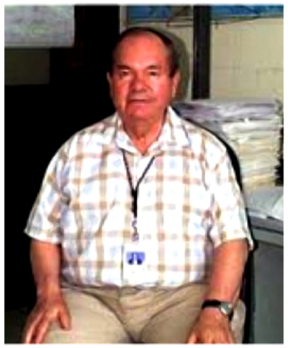
Vitaly Ginzburg and Lev Landau, 1950



Alexei A. Abrikosov 1956



Brian Josephson 1962

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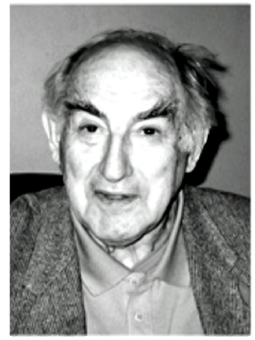
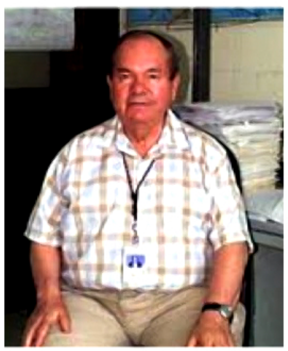


Alexei A. Abrikosov 1956



J. Bardeen L.N. Cooper J.R. Schrieffer
1957

Brian Josephson 1962

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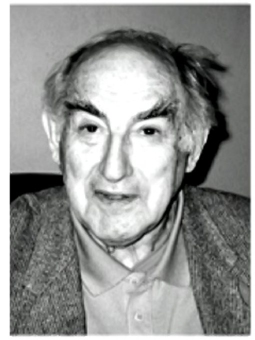
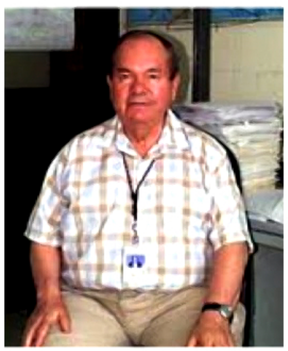
Vitaly Ginzburg and Lev Landau, 1950



Alexei A. Abrikosov 1956



J. Bardeen L.N. Cooper J.R. Schrieffer
195

Brian Josephson 1962

1986

J. Georg Bednorz K. Alexander Müller

A case study ---- high temperature superconductivity

Bednorz, J. G., and K. A. Müller, 1986, Z. Phys. B **64**, 189.

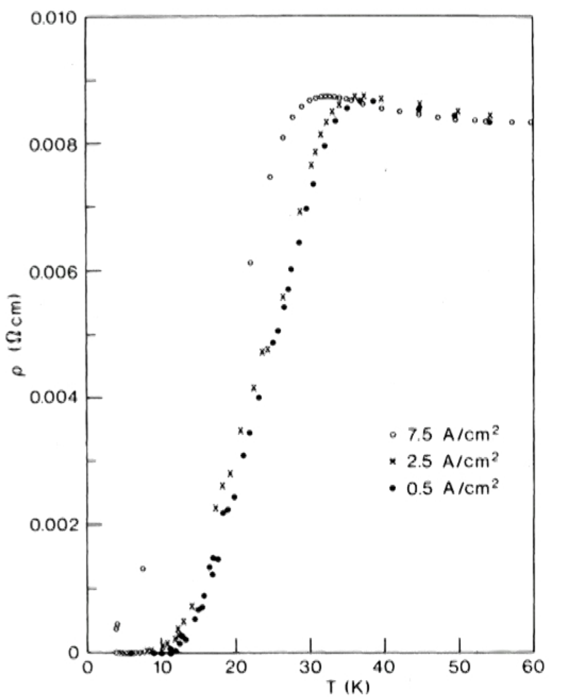
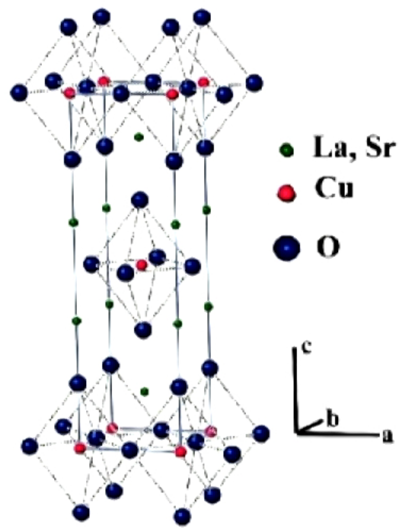
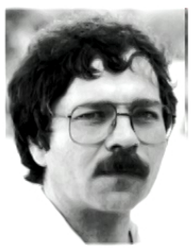
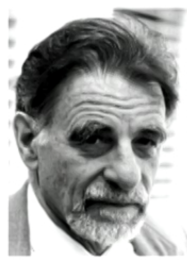


FIG. 5. Low-temperature resistivity of a sample with x(Ba) = 0.75, recorded for different current densities. From Bednorz and Müller (1986), © Springer-Verlag 1986.



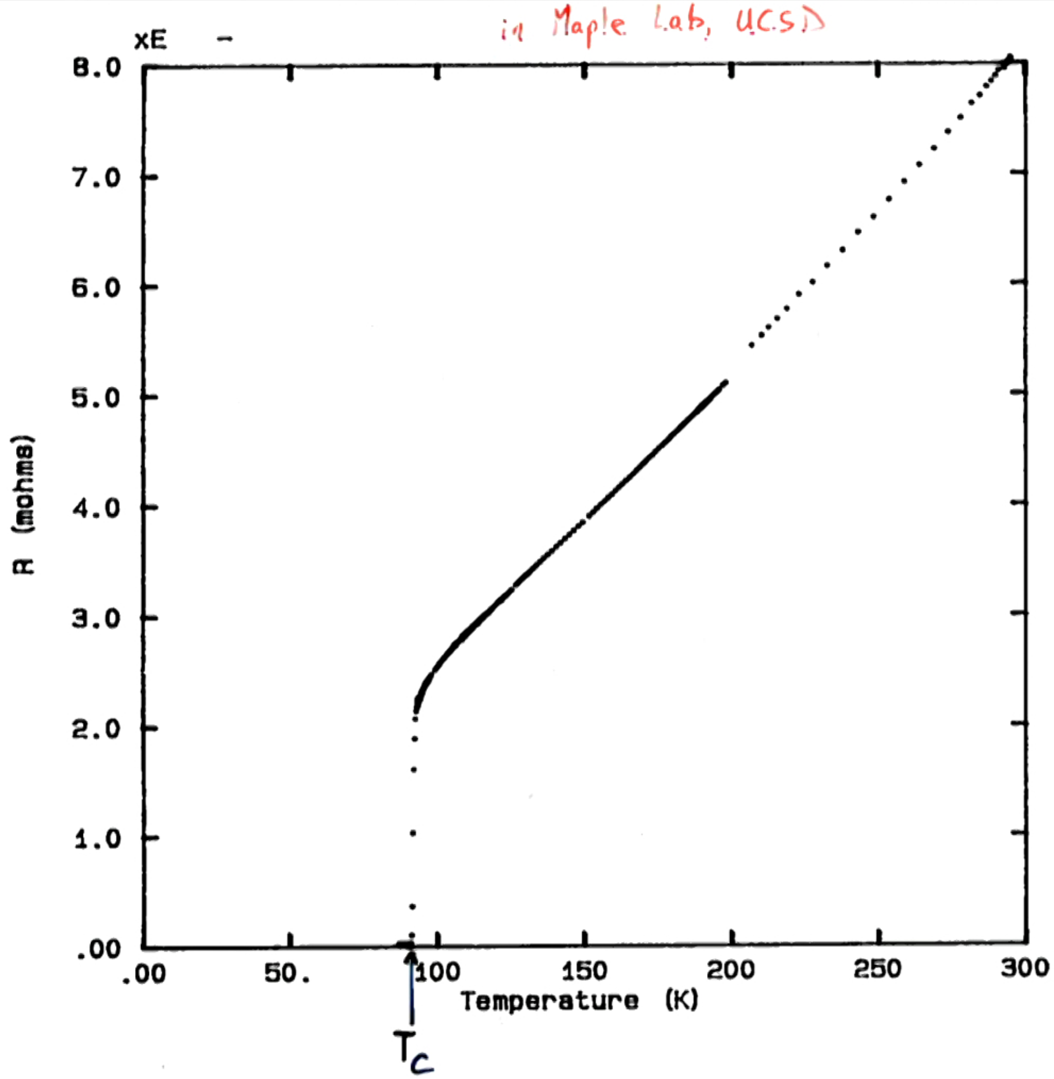


J. Georg Bednorz



K. Alexander Müller

in Maple Lab, UCSD



powder !

PHYSICAL REVIEW VOLUME 114, NUMBER 3 MAY 1, 1959

Heat Capacity of Aluminum between 0.1°K and 4.0°K*

NORMAN E. PHILLIPS
Department of Chemistry and Radiation Laboratory, University of California, Berkeley, California

(Received December 1, 1958)

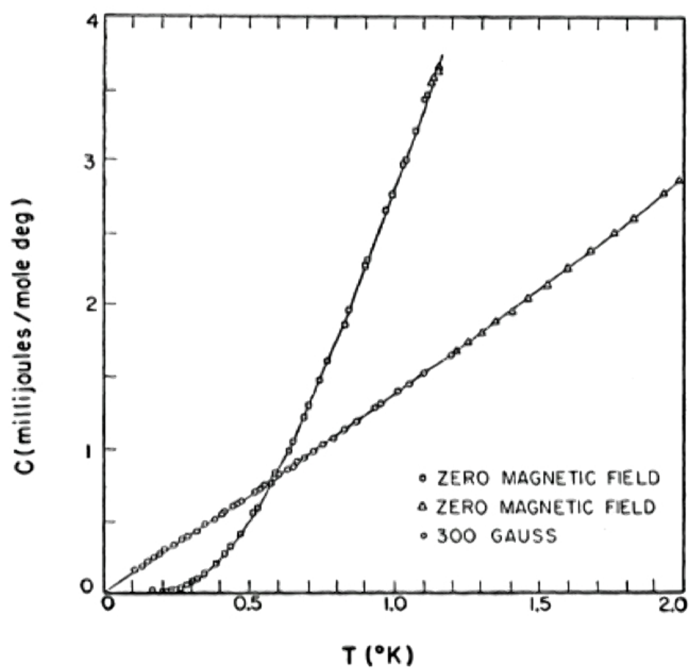


FIG. 4. Heat capacity of aluminum from 0.1 to 2.0°K. The two experiments in the adiabatic demagnetization range are designated by squares for the normal state and circles for the superconducting state. The triangles represent points taken at liquid helium temperatures.

Superconductivity

Charles P. Poole, Jr.

Horacio A. Farach

Richard J. Creswick

Department of Physics and Astronomy
University of South Carolina
Columbia, South Carolina

Ruslan Prozorov

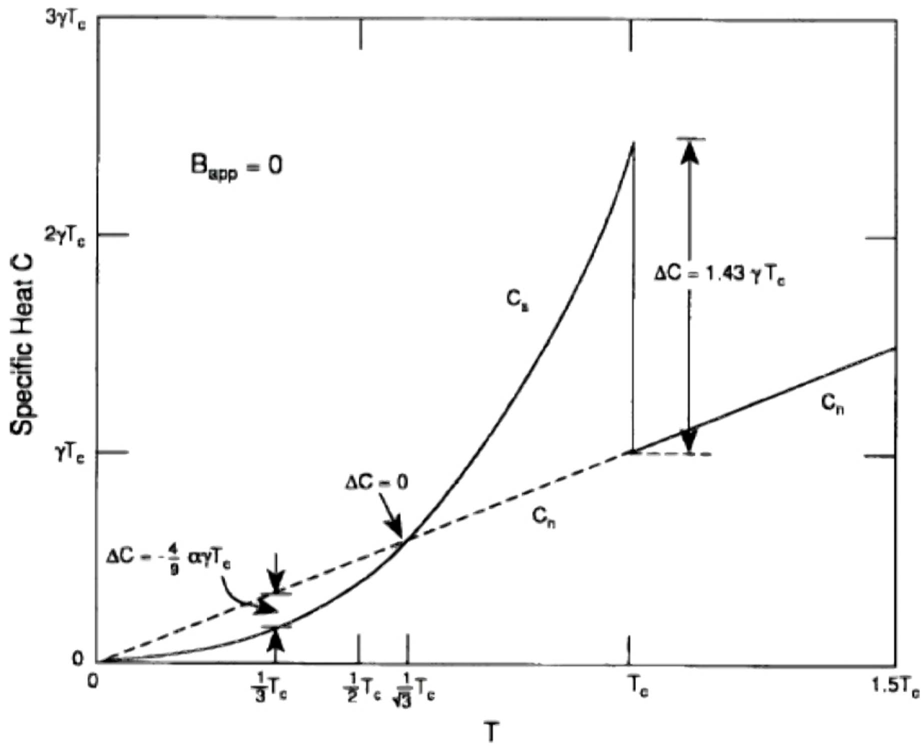


Figure 4.7 Temperature dependence of the normal-state C_n (- - -) and superconducting-state C_s (—) specific heats. The figure shows the specific heat jump $1.43\gamma T_c$ of Eq. (4.9) that is predicted by the BCS theory, the crossover point at $T = T_c/\sqrt{3}$, and the maximum negative jump $0.44\alpha\gamma T_c$ at $T = T_c/3$. In this and the following 12 figures it is assumed that only the linear electronic term γT exists in the normal state (i.e, $AT^3 = 0$).

Charles P. Poole, Jr.
Horacio A. Farach
Richard J. Creswick
Department of Physics and Astronomy
University of South Carolina
Columbia, South Carolina
Ruslan Prozorov

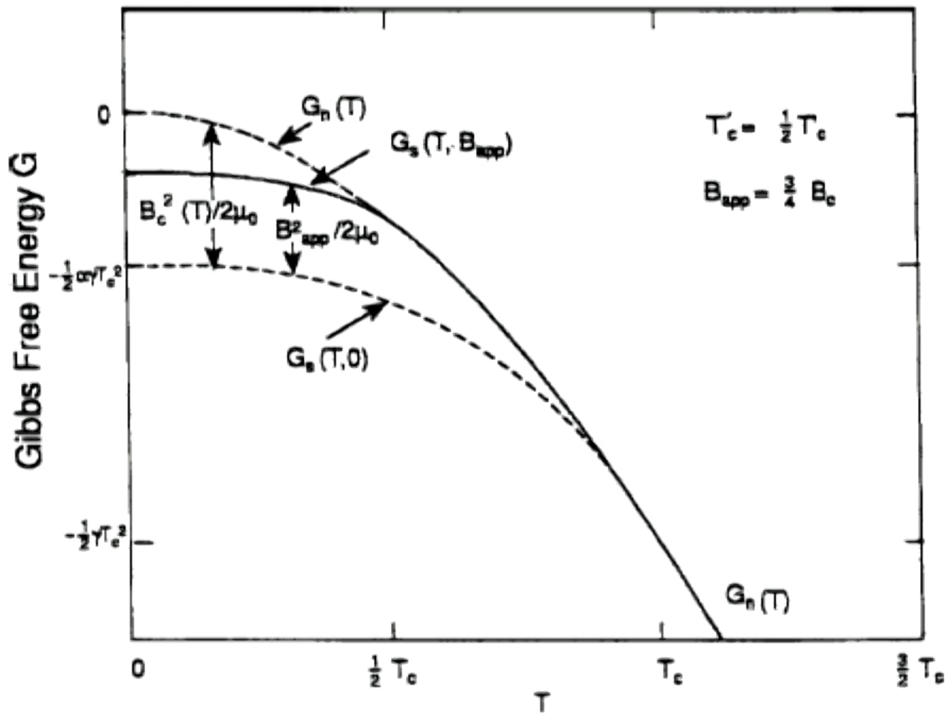
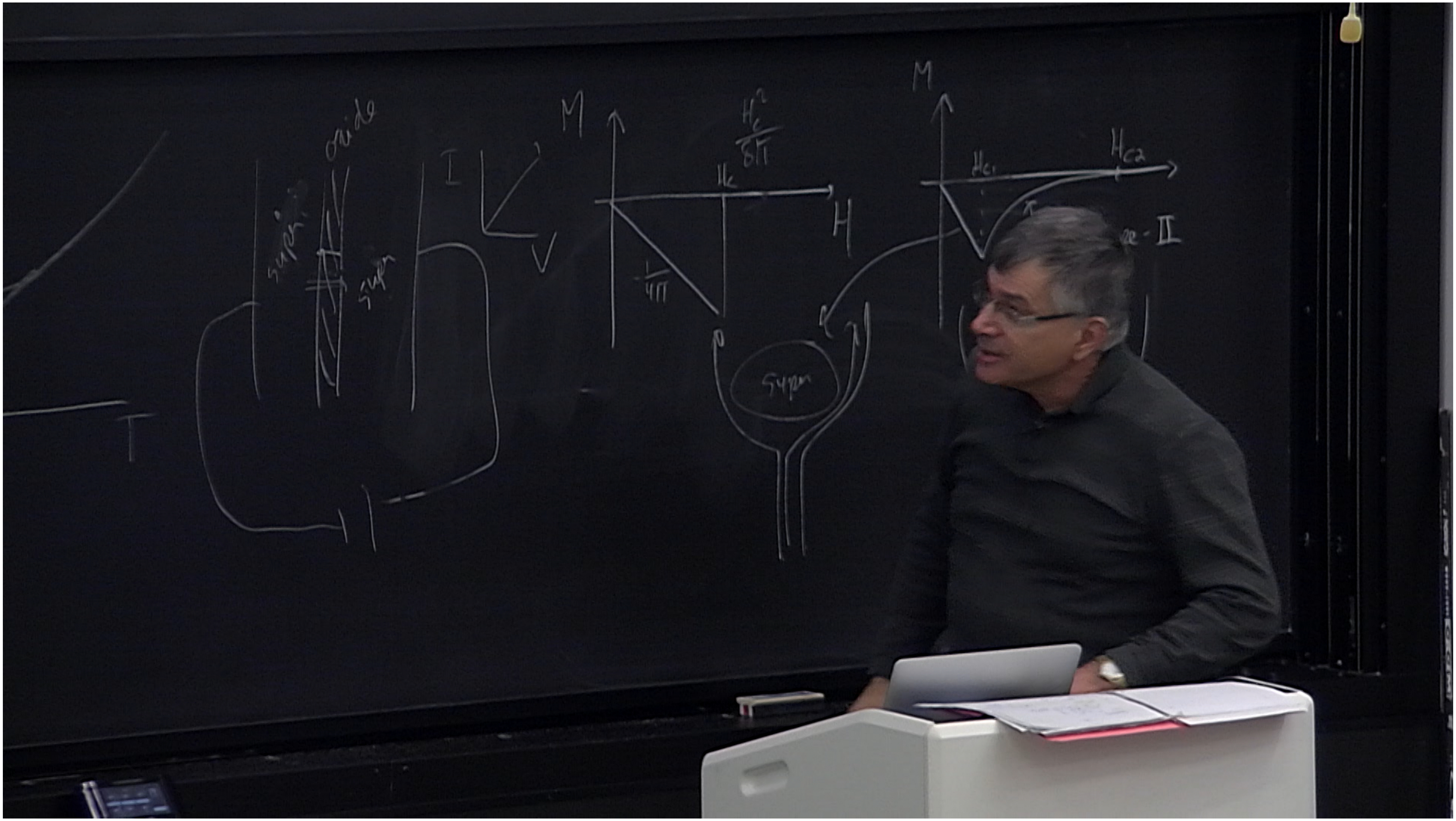


Figure 4.11 Effect of an applied magnetic field $B_{app} = 0.75B_c$ on the Gibbs free energy $G_s(T, B)$ in the superconducting state. In this and the succeeding figures dashed curves are used to indicate both the normal-state extrapolation below T_c' and the zero-field superconducting state behavior, where T_c' denotes the transition temperature when there is a field present.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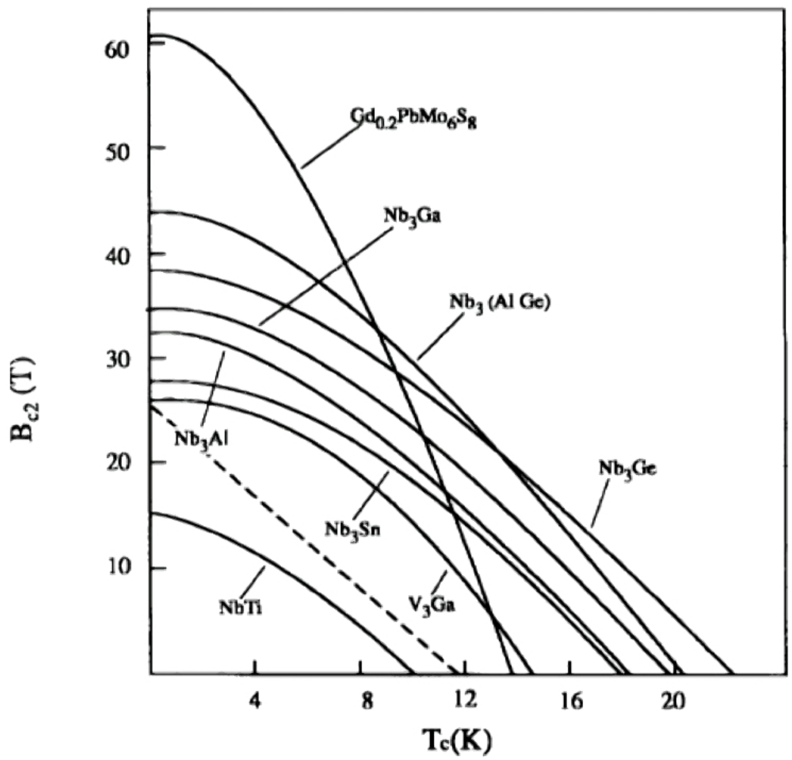

Figure 5.26 Relation between upper-critical field B_{c2} and temperature for the best classical superconductors, some of which are used for fabricating commercial magnets. In the high-temperature limit ($2/3T_c < T < T_c$) many of the curves have a slope that is close to the value 1.83 T/K of the Pauli limit (dashed curve) (Wilson, 1983, p. 302).

Superconductivity

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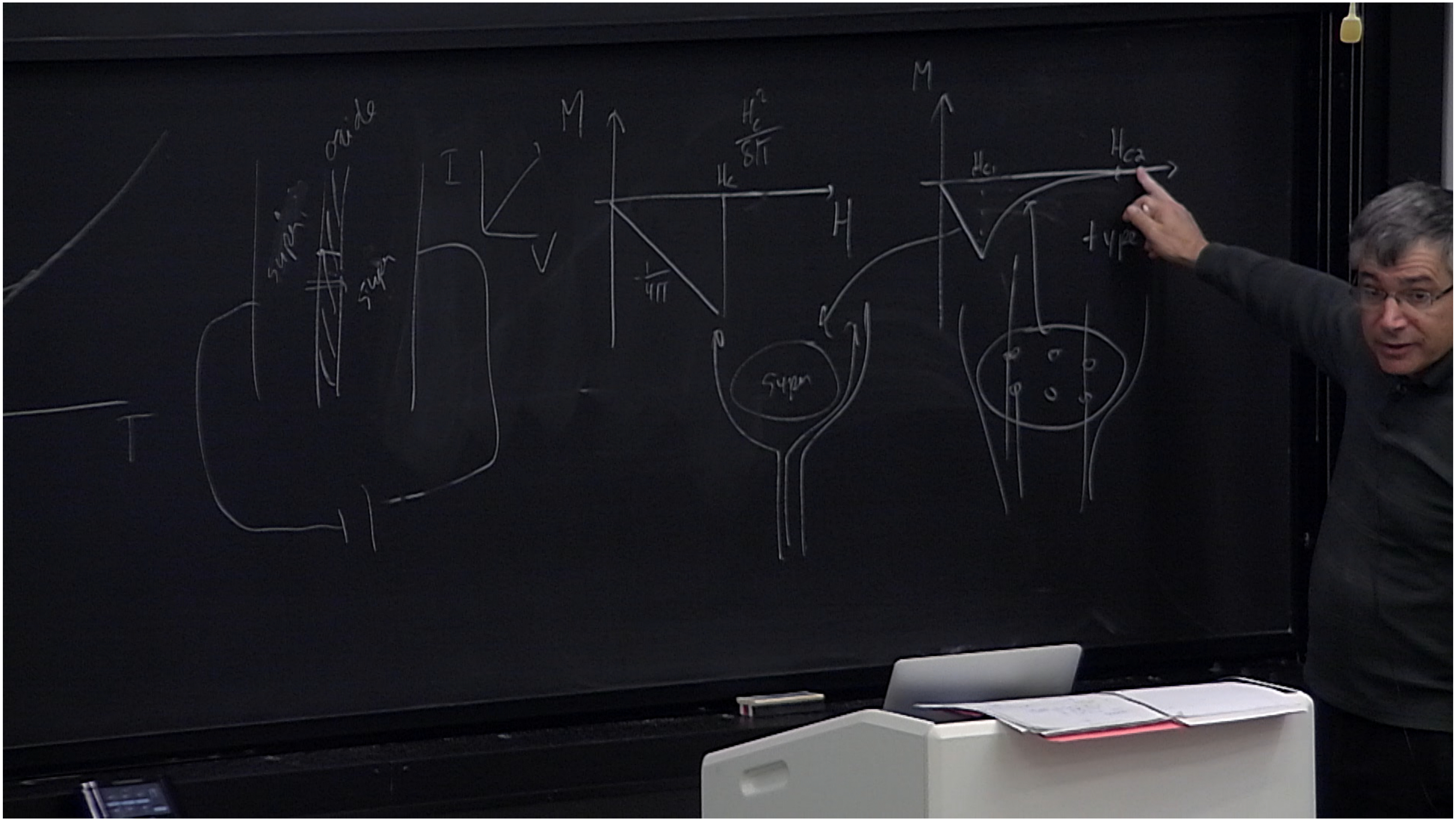

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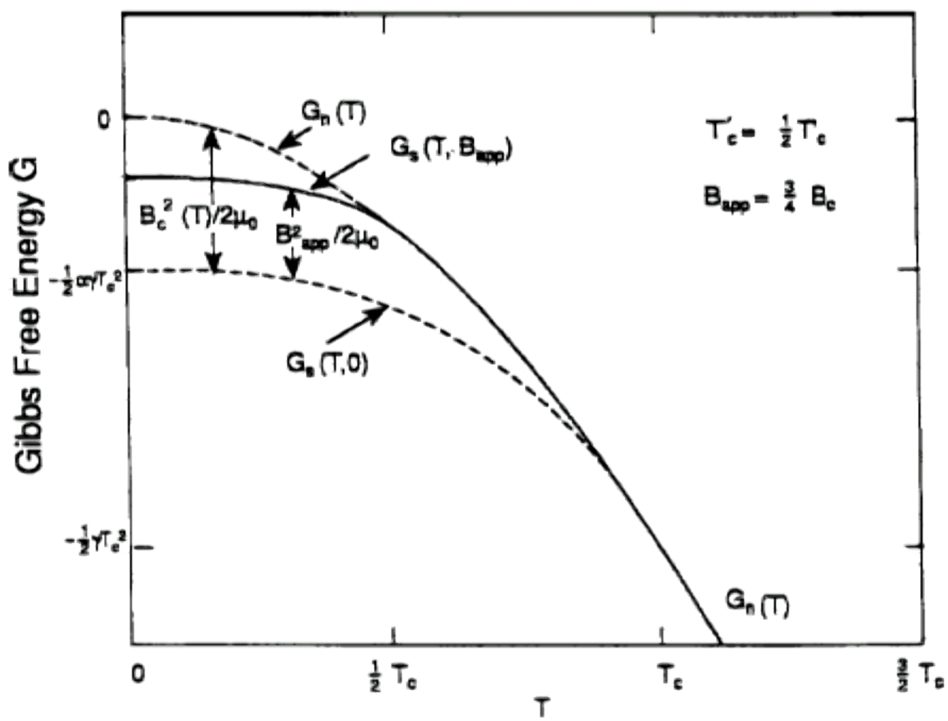

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Superconductivity

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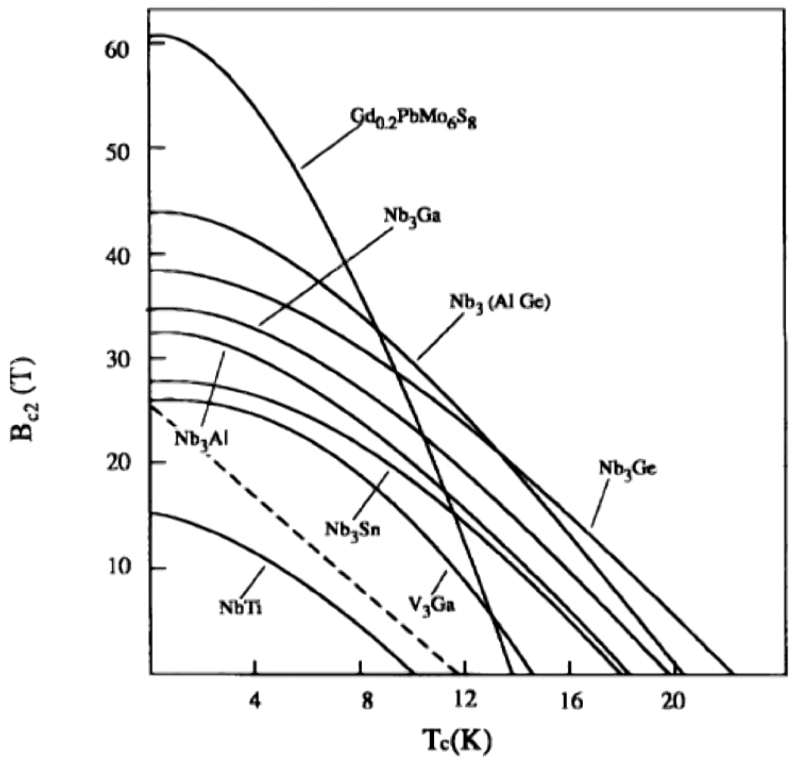

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PHYSICAL REVIEW VOLUME 122, NUMBER 4 MAY 15, 1961

Study of Superconductors by Electron Tunneling

IVAR GIAEVER AND KARL MEGERLE
General Electric Research Laboratory, Schenectady, New York

(Received January 3, 1961)

PHYSICAL REVIEW VOLUME 122, NUMBER 4 MAY 15, 1961

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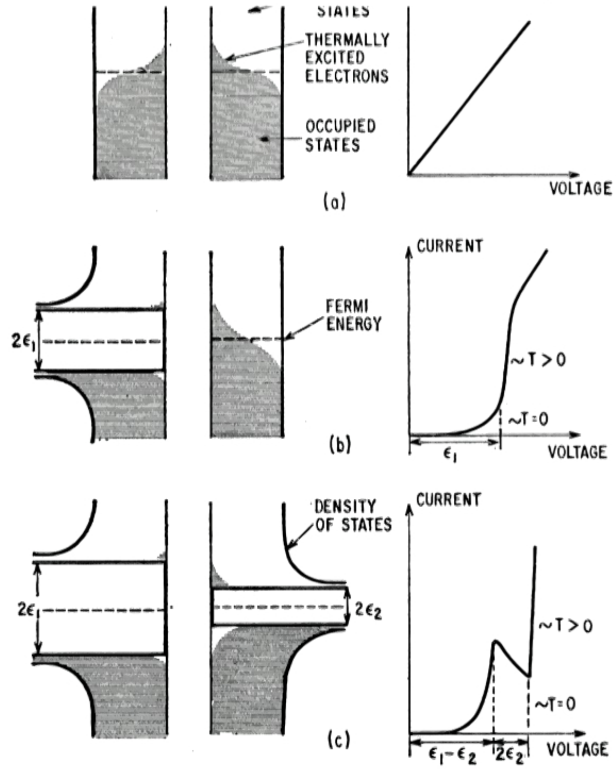

FIG. 4. Energy diagram displaying the density of states and the current-voltage characteristics for the three cases. (a) Both metals in the normal state. (b) One metal in the normal state and one in the superconducting state. (c) Both metals in the superconducting state.

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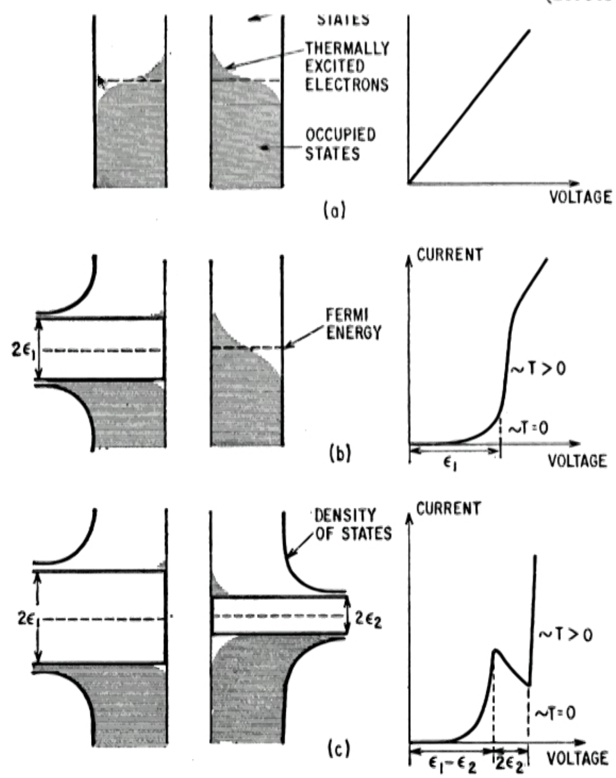

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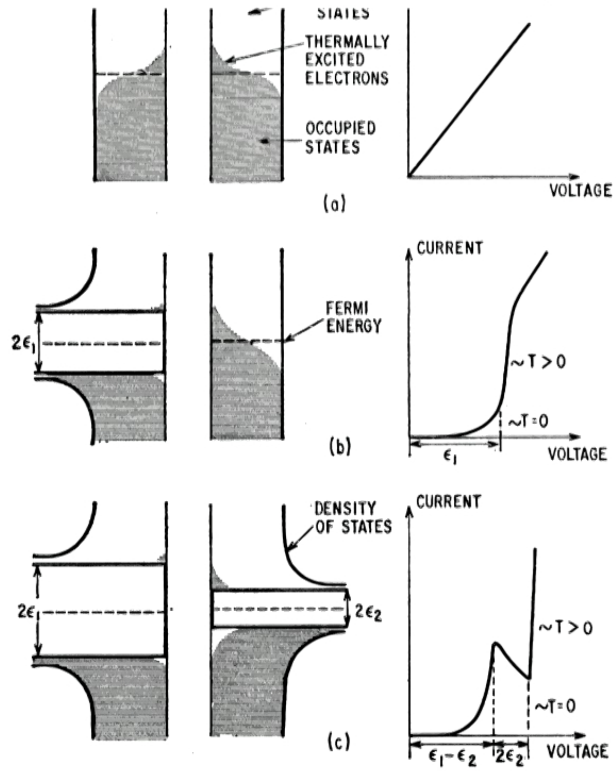

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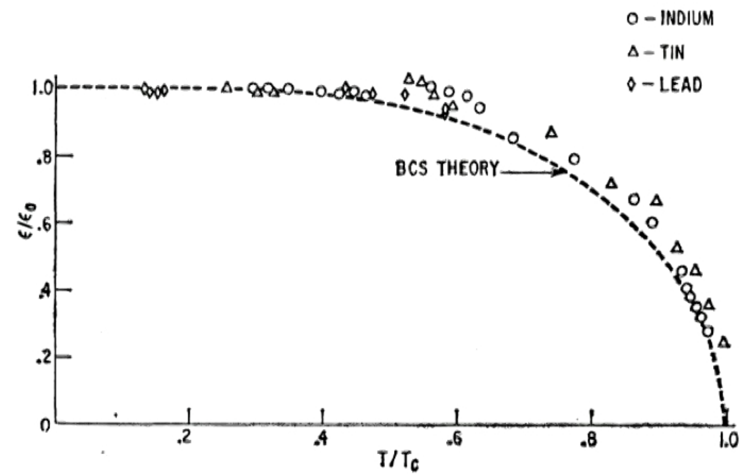
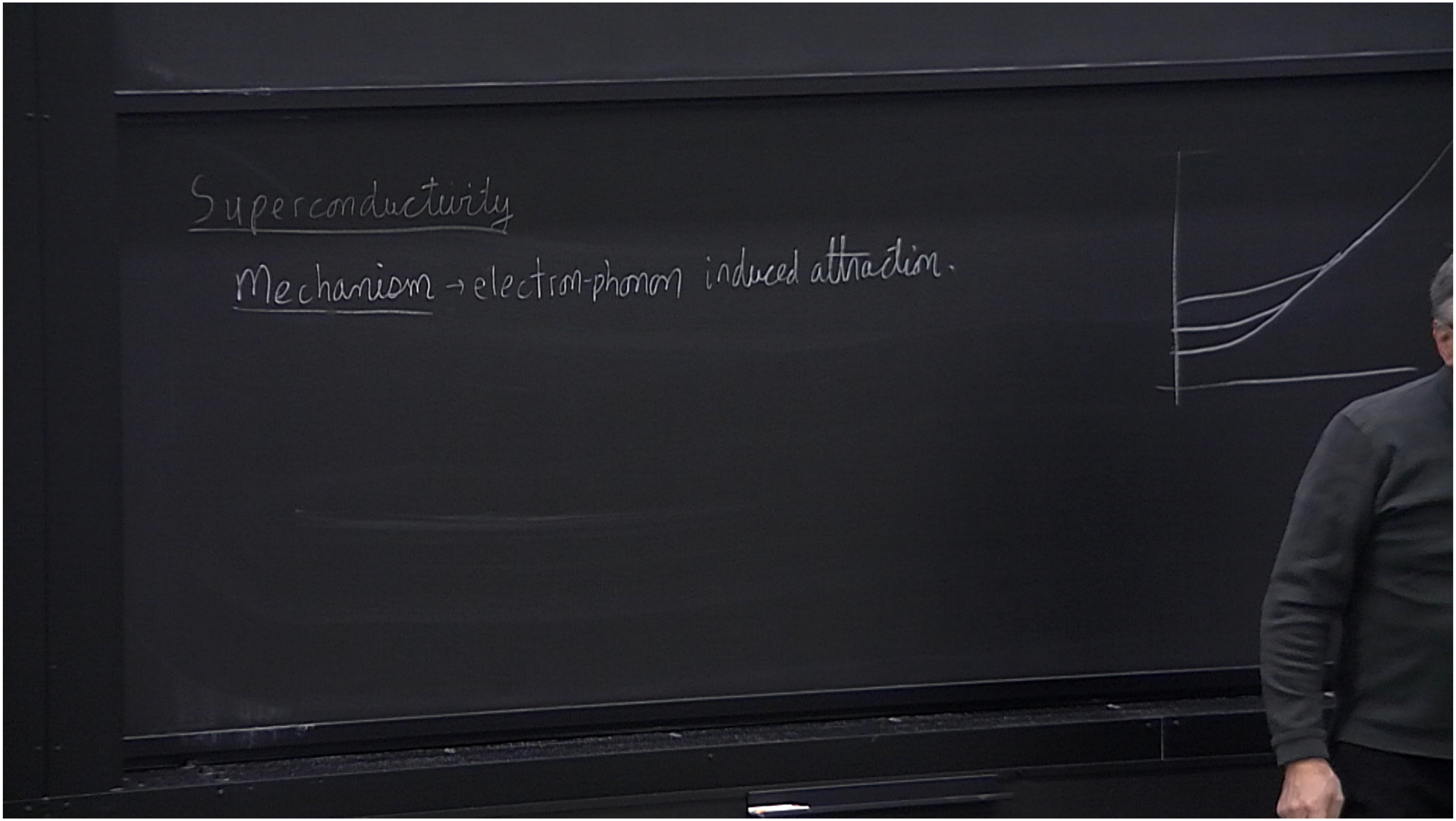
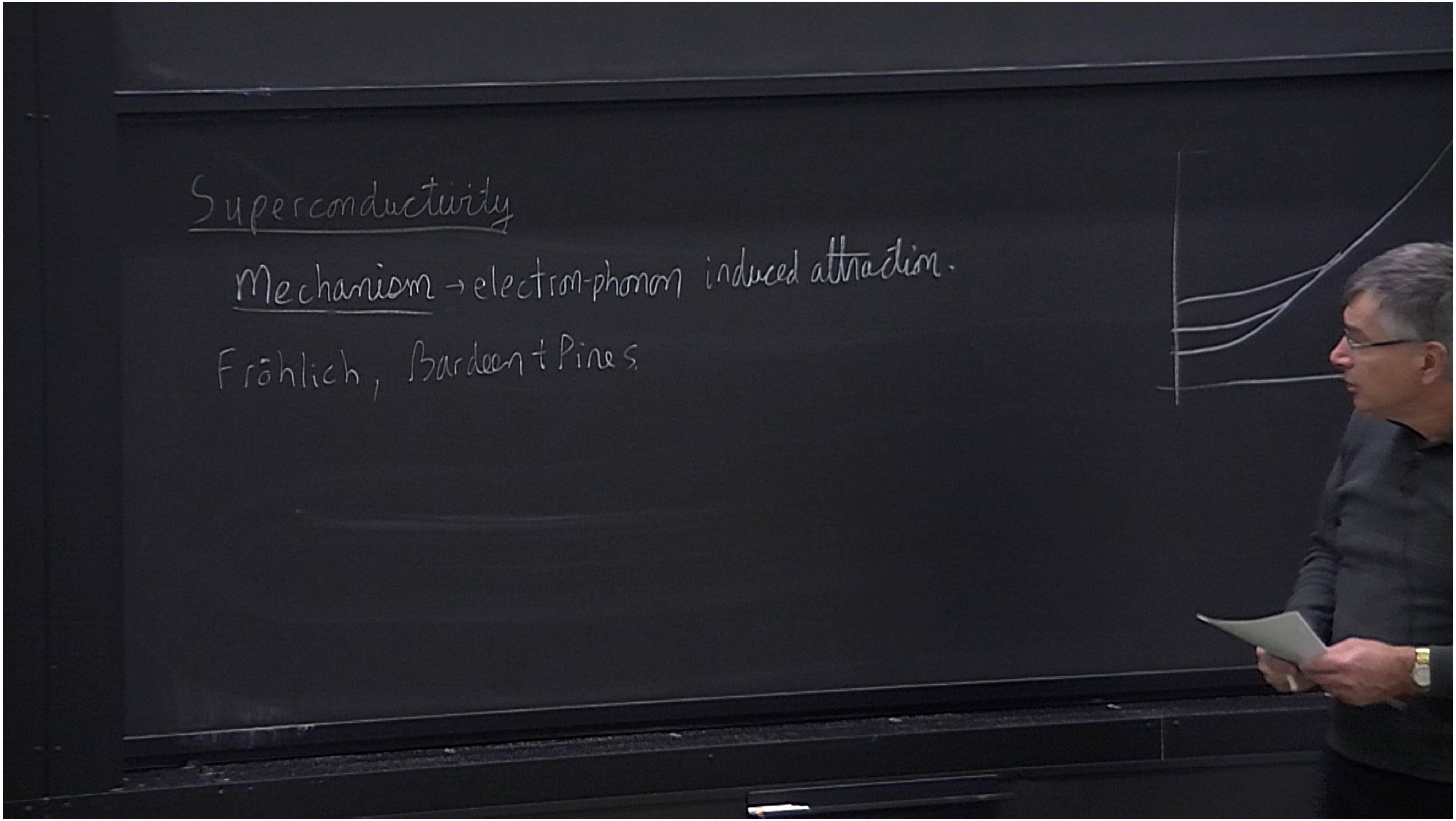


FIG. 11. The energy gap of Pb, Sn, and In films as a function of reduced temperature, compared with the Bardeen-Cooper-Schrieffer theory.


Superconductivity
Mechanism → electron-phonon induced attraction.


Superconductivity
Mechanism → electron-phonon induced attraction.
Fröhlich, Bardeen + Pines

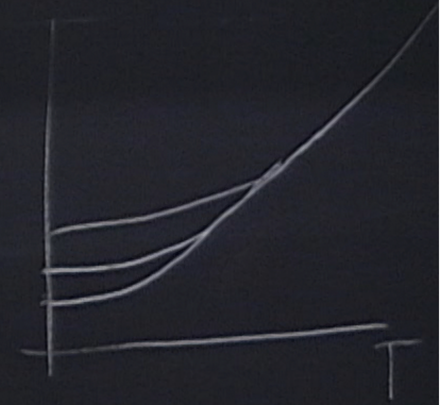
Superconductivity

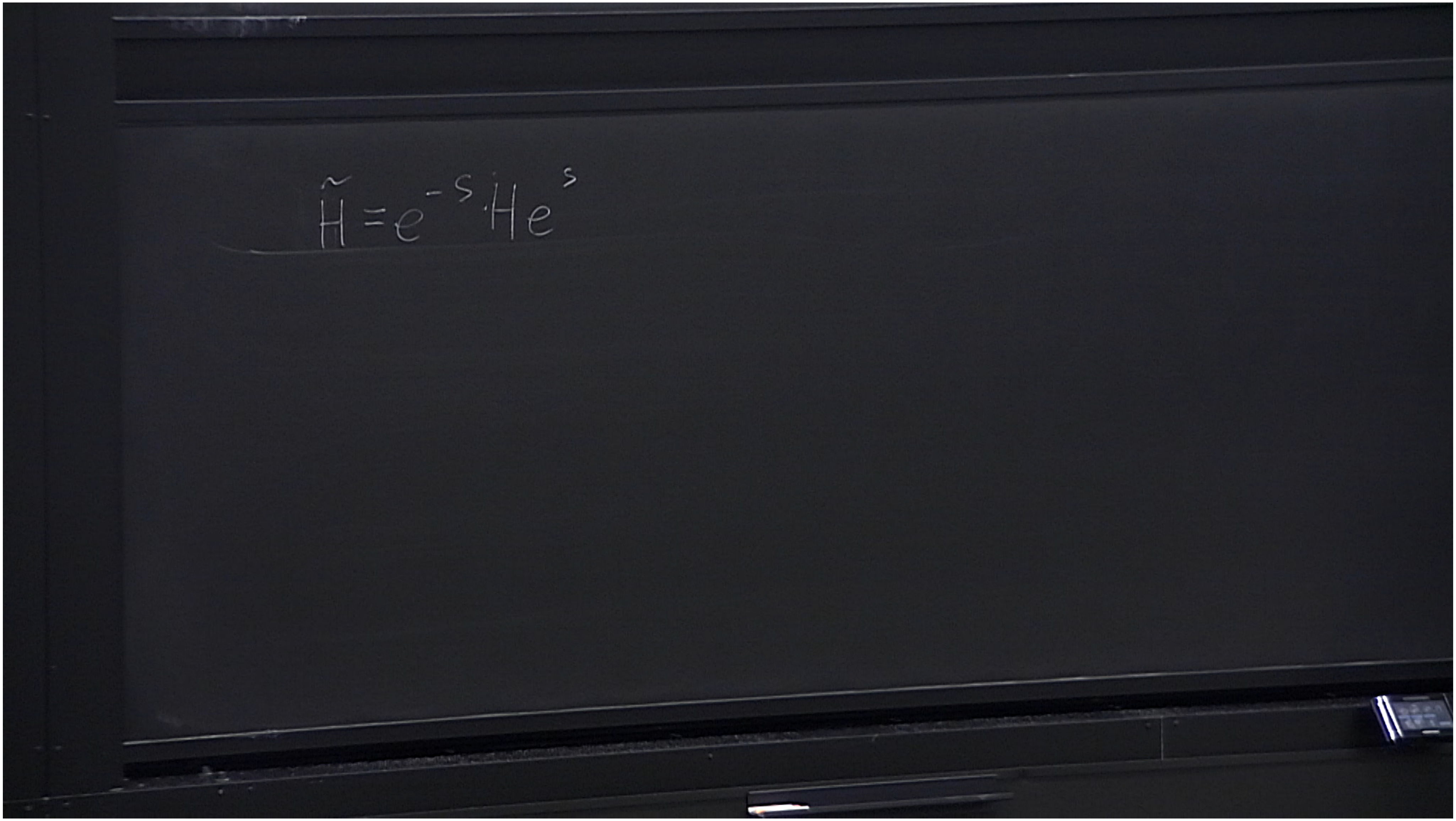
Mechanism → electron-phonon induced attraction.

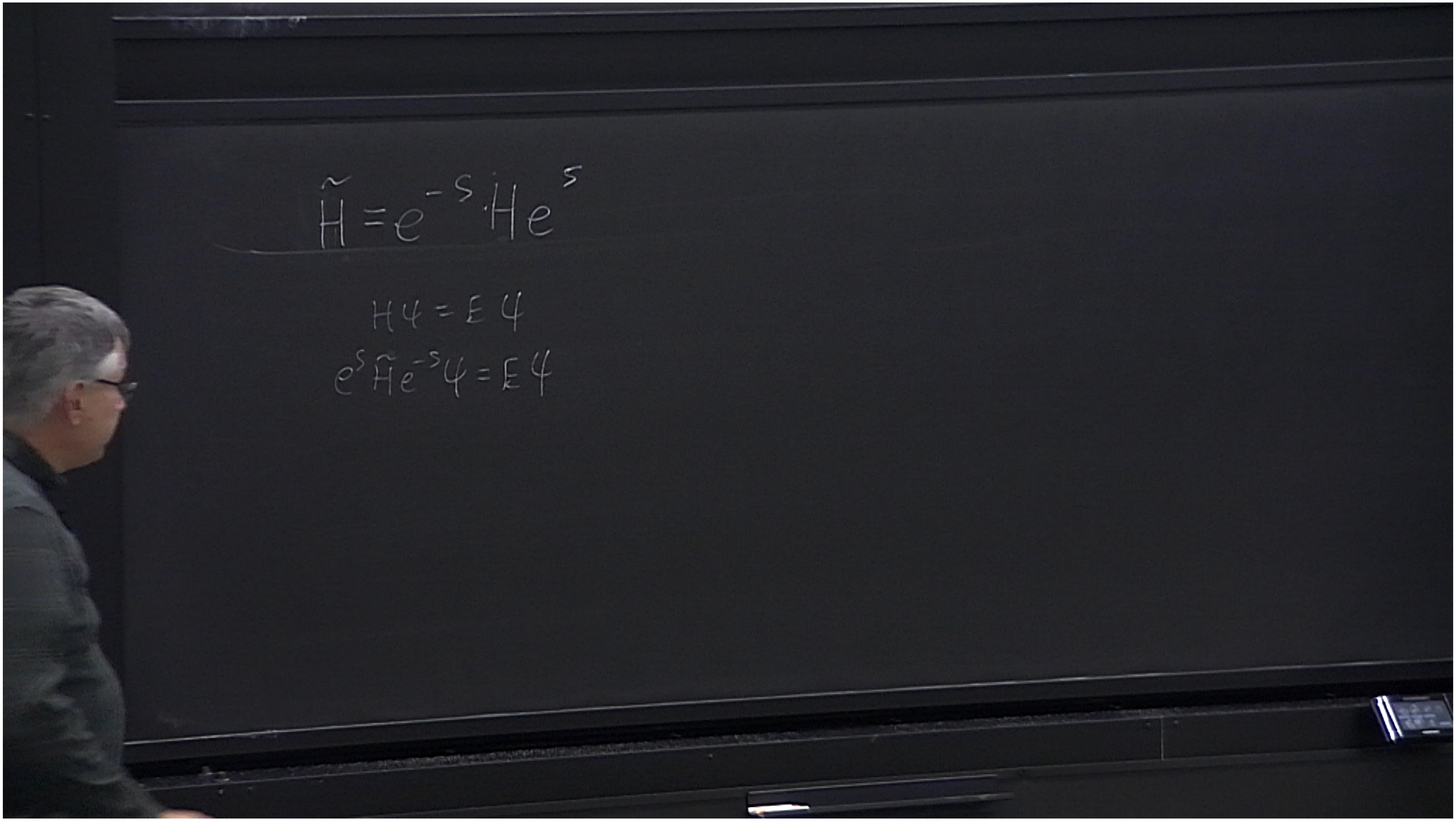
Fröhlich, Bardeen + Pines

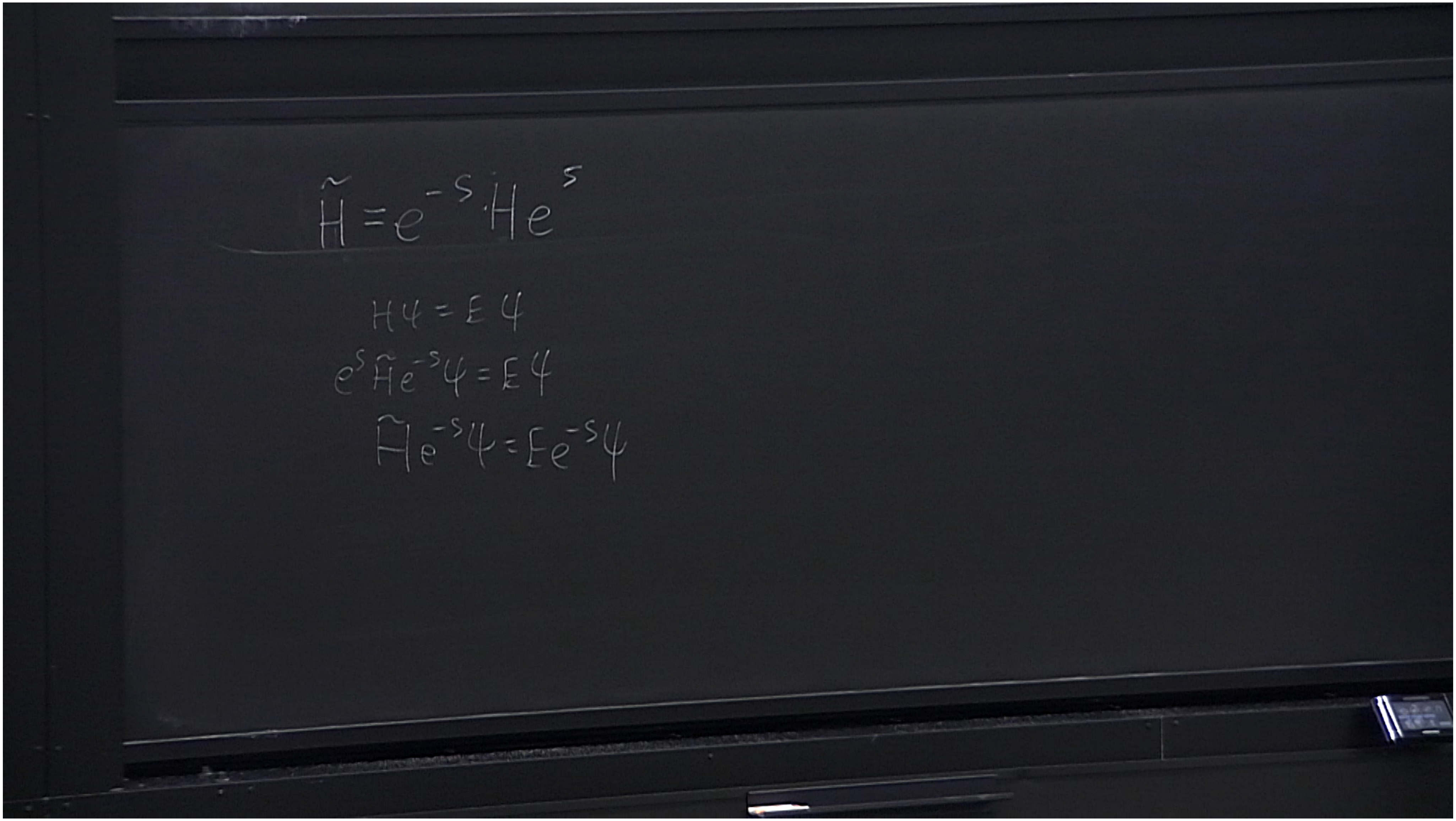
$$H = \sum_{k\sigma} \varepsilon_k c^\dagger_{k\sigma} c_{k\sigma} + \sum_q \omega_q a^\dagger_q a_q + \frac{1}{\sqrt{N}} \sum_{kq\sigma} M_q \left(a_q + a^\dagger_{-q}\right) c^\dagger_{p+q\sigma} c_{p\sigma}$$

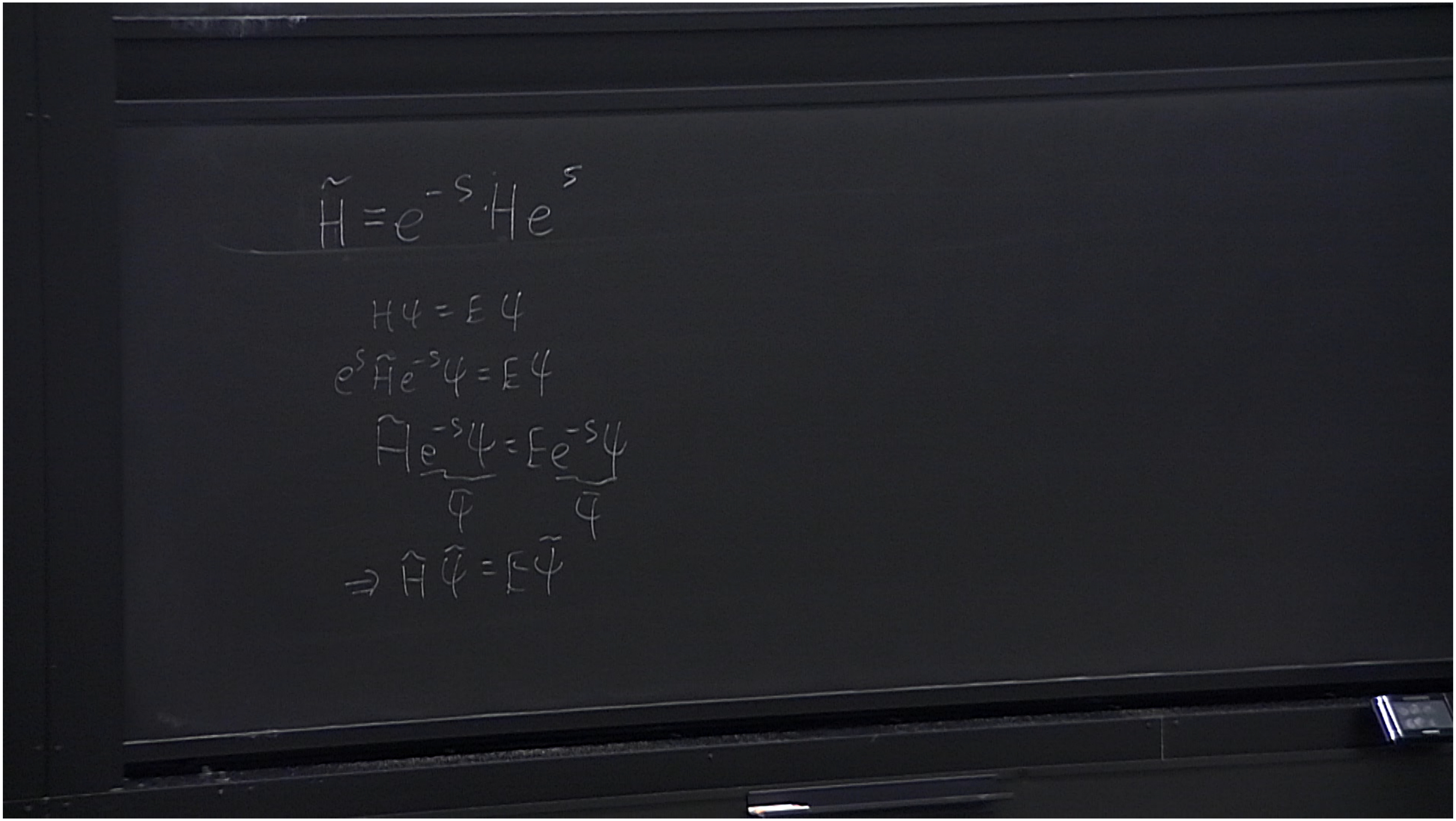
$M_q = g\,\omega_E$ (Holstein)




$\tilde{H} = e^{-S} \cdot H e^{S}$


$\tilde{H} = e^{-S} \cdot H e^{S}$
$H\psi = E\psi$
$e^{S} \tilde{H} e^{-S} \psi = E\psi$


$\tilde{H} = e^{-S} H e^{S}$
$H\psi = E\psi$
$e^{S}\tilde{H}e^{-S}\psi = E\psi$
$\tilde{H}e^{-S}\psi = Ee^{-S}\psi$


$\tilde{H} = e^{-S} H e^{S}$
$H\psi = E\psi$
$e^{S}\tilde{H}e^{-S}\psi = E\psi$
$\tilde{H}\underbrace{e^{-S}\psi}_{\tilde{\psi}} = E\underbrace{e^{-S}\psi}_{\tilde{\psi}}$
$\Rightarrow \tilde{H}\tilde{\psi} = E\tilde{\psi}$

$$\tilde{H} = e^{-S} H e^{S}$$

$$e^{-S} H e^{S} = \hat{H} + [H, S] + \frac{1}{2}[[H, S], S] + \dots$$

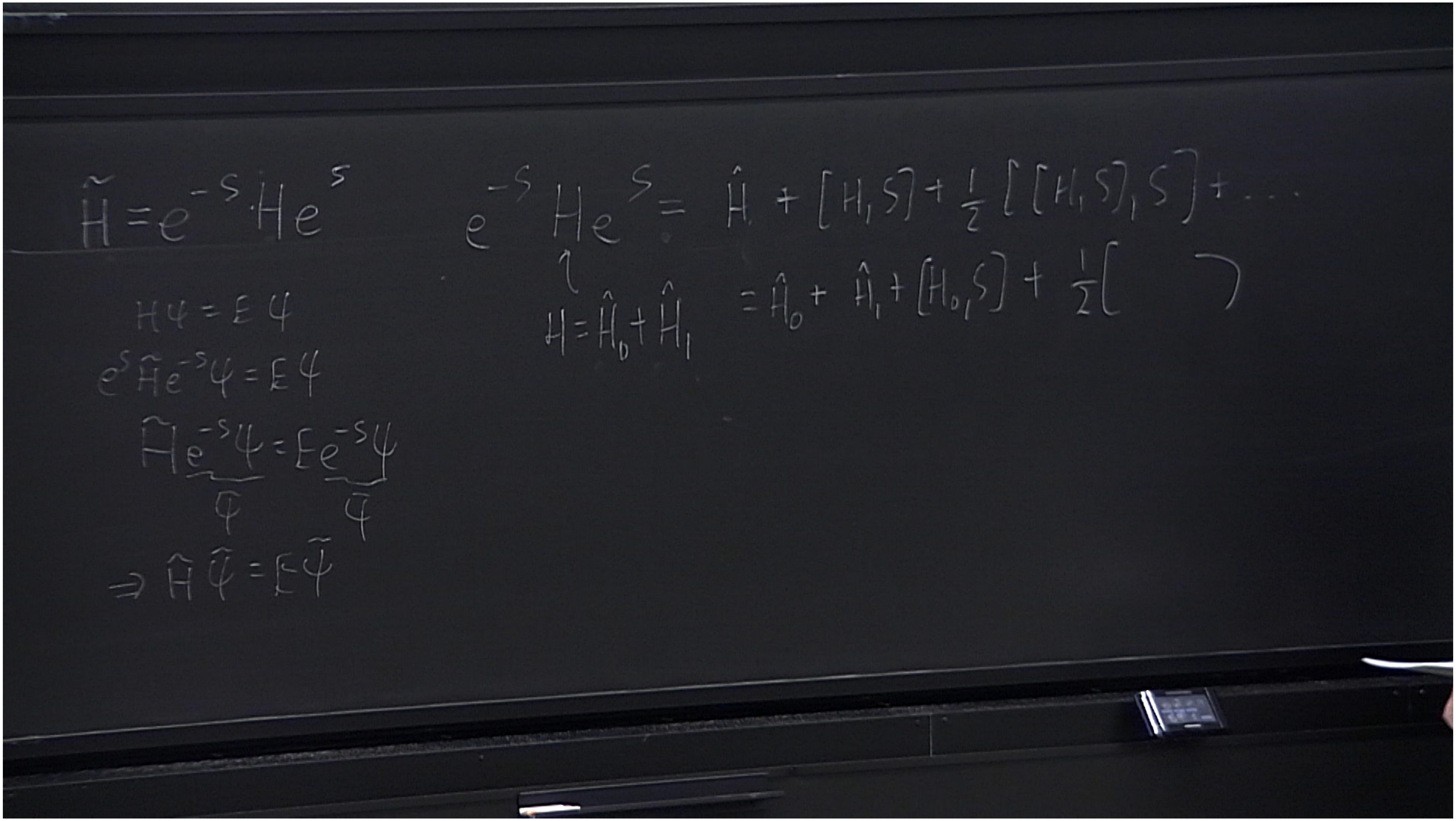
$$H = \hat{H}_0 + \hat{H}_1$$

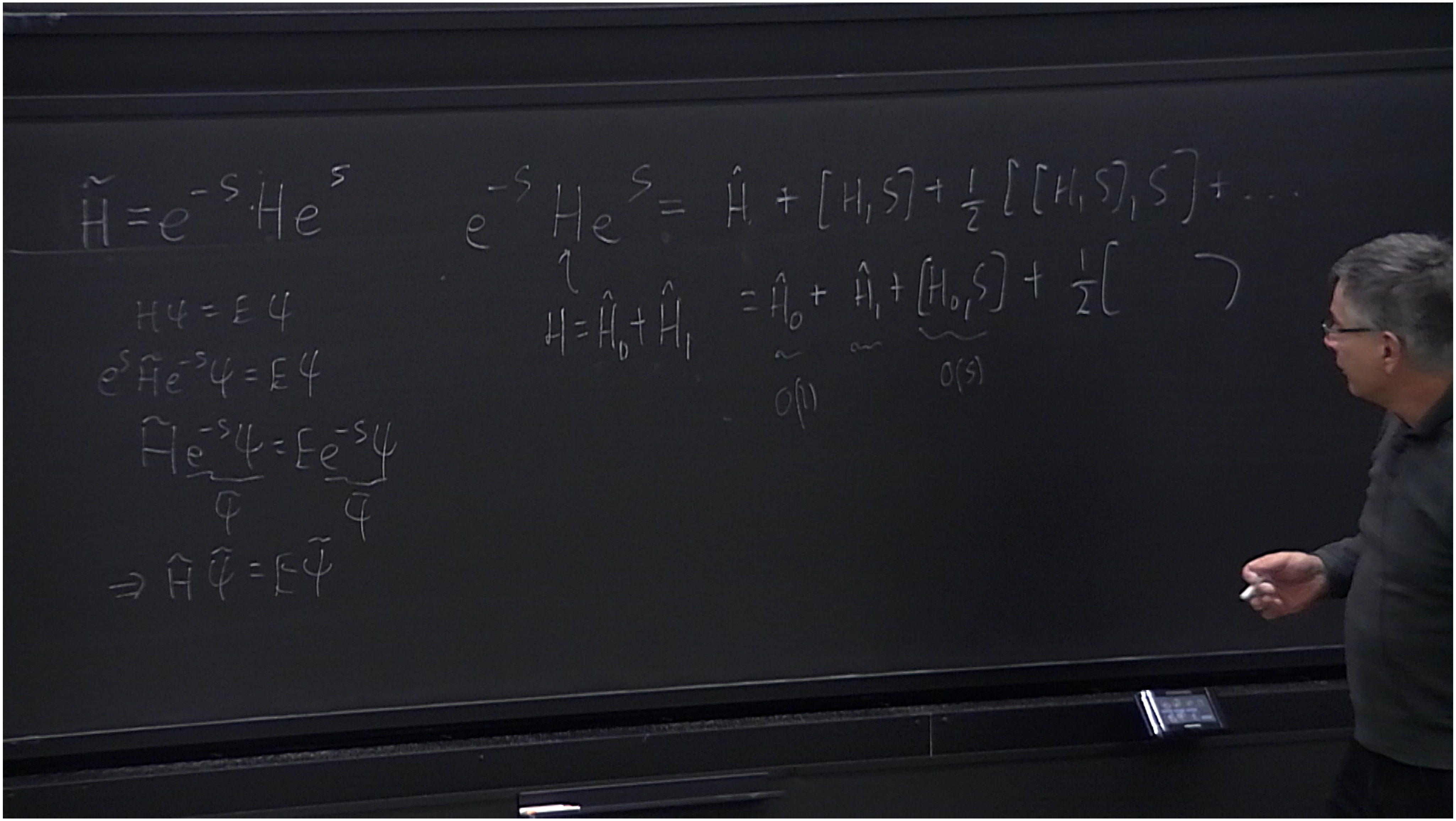
$$H\psi = E\psi$$

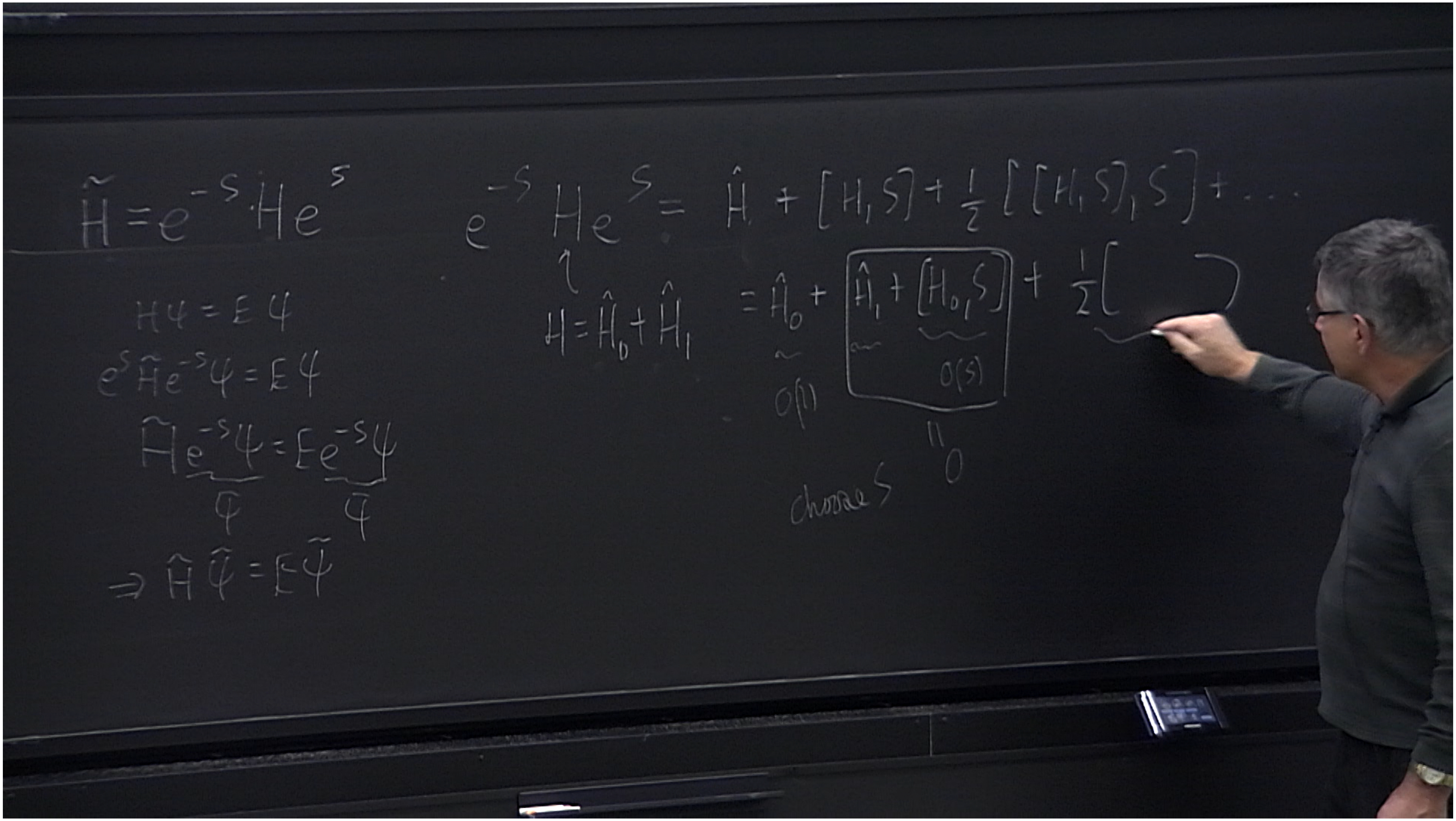
$$e^{S}\tilde{H}e^{-S}\psi = E\psi$$

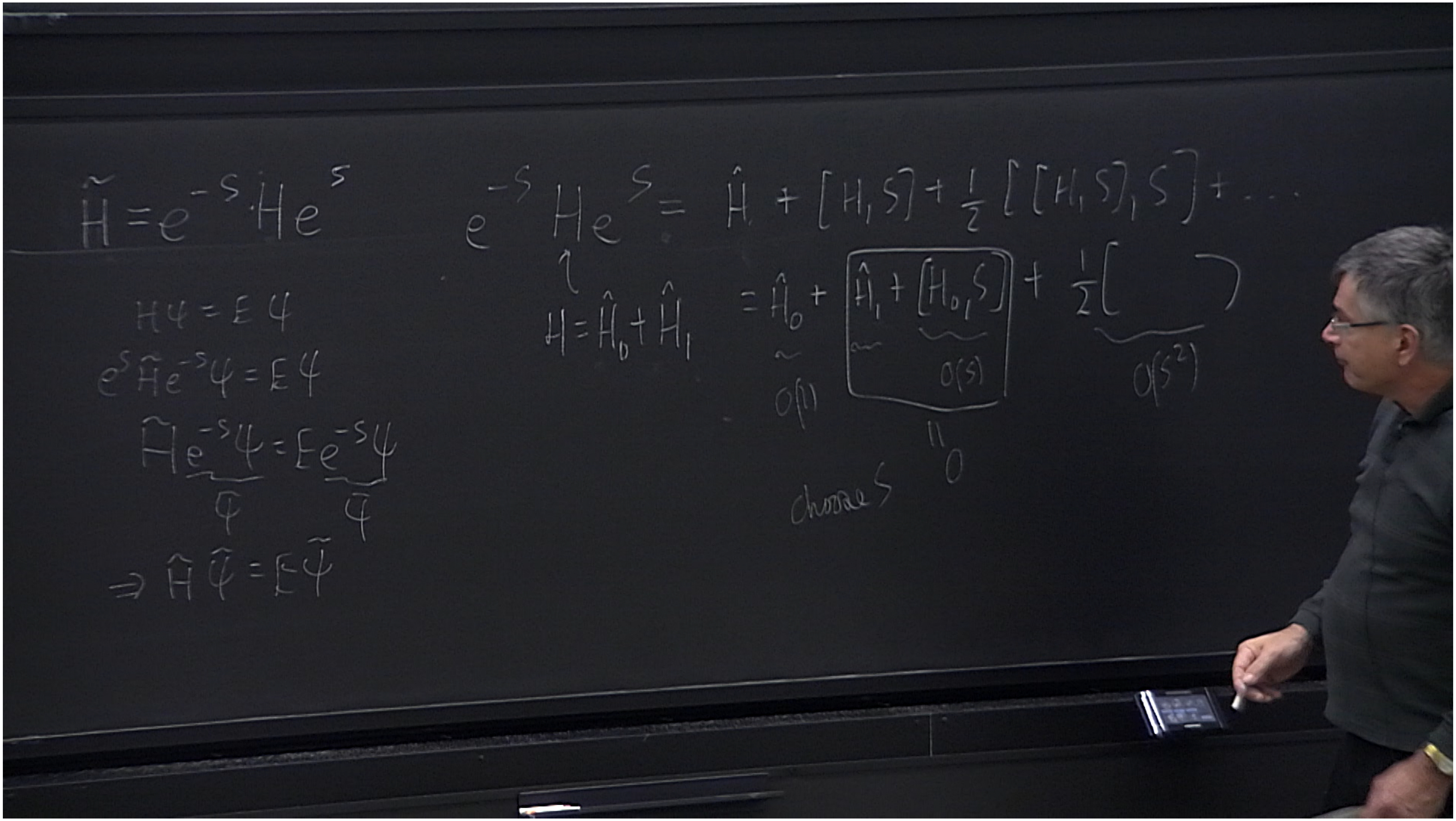
$$\tilde{H}\underbrace{e^{-S}\psi}_{\tilde{\psi}} = E\underbrace{e^{-S}\psi}_{\tilde{\psi}}$$

$$\Rightarrow \hat{H}\tilde{\psi} = E\tilde{\psi}$$

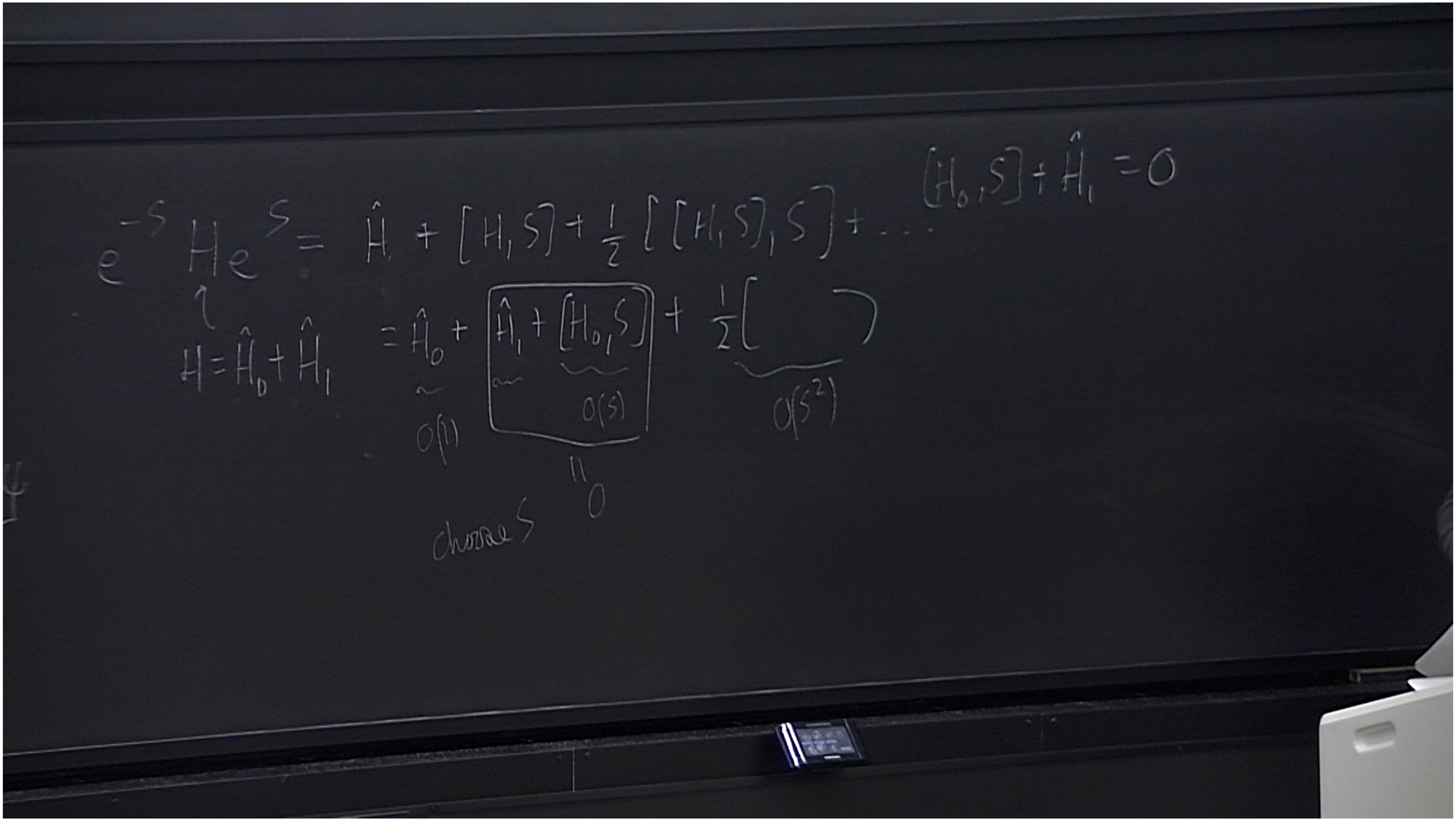

$\tilde{H} = e^{-S} H e^{S}$
$e^{-S} H e^{S} = \hat{H} + [H, S] + \frac{1}{2}[[H, S], S] + \dots$
$= \hat{H}_0 + \hat{H}_1 + [H_0, S] + \frac{1}{2}[\quad]$
$H = \hat{H}_0 + \hat{H}_1$
$H\psi = E\psi$
$e^{S}\tilde{H}e^{-S}\psi = E\psi$
$\tilde{H}e^{-S}\psi = Ee^{-S}\psi$
$\tilde{\psi} \quad \tilde{\psi}$
$\Rightarrow \tilde{H}\tilde{\psi} = E\tilde{\psi}$

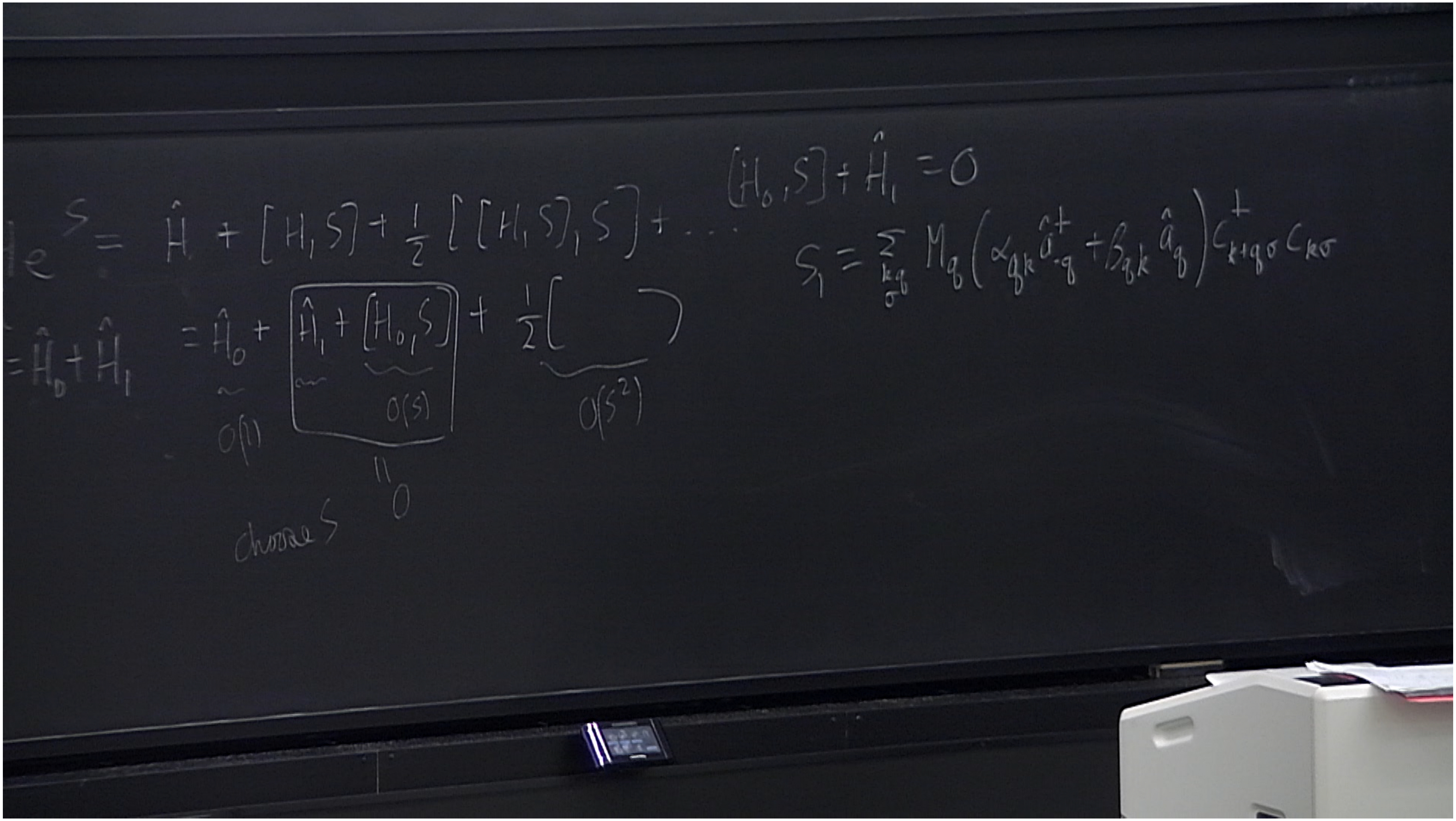

$\tilde{H} = e^{-S} H e^{S}$
$e^{-S} H e^{S} = \hat{H} + [H, S] + \frac{1}{2}[[H, S], S] + \dots$
$H = \hat{H}_0 + \hat{H}_1$
$= \hat{H}_0 + \hat{H}_1 + [H_0, S] + \frac{1}{2}[\quad]$
$O(1)$
$O(S)$
$H\psi = E\psi$
$e^{S}\tilde{H}e^{-S}\psi = E\psi$
$\tilde{H}e^{-S}\psi = Ee^{-S}\psi$
$\Rightarrow \tilde{H}\tilde{\psi} = E\tilde{\psi}$

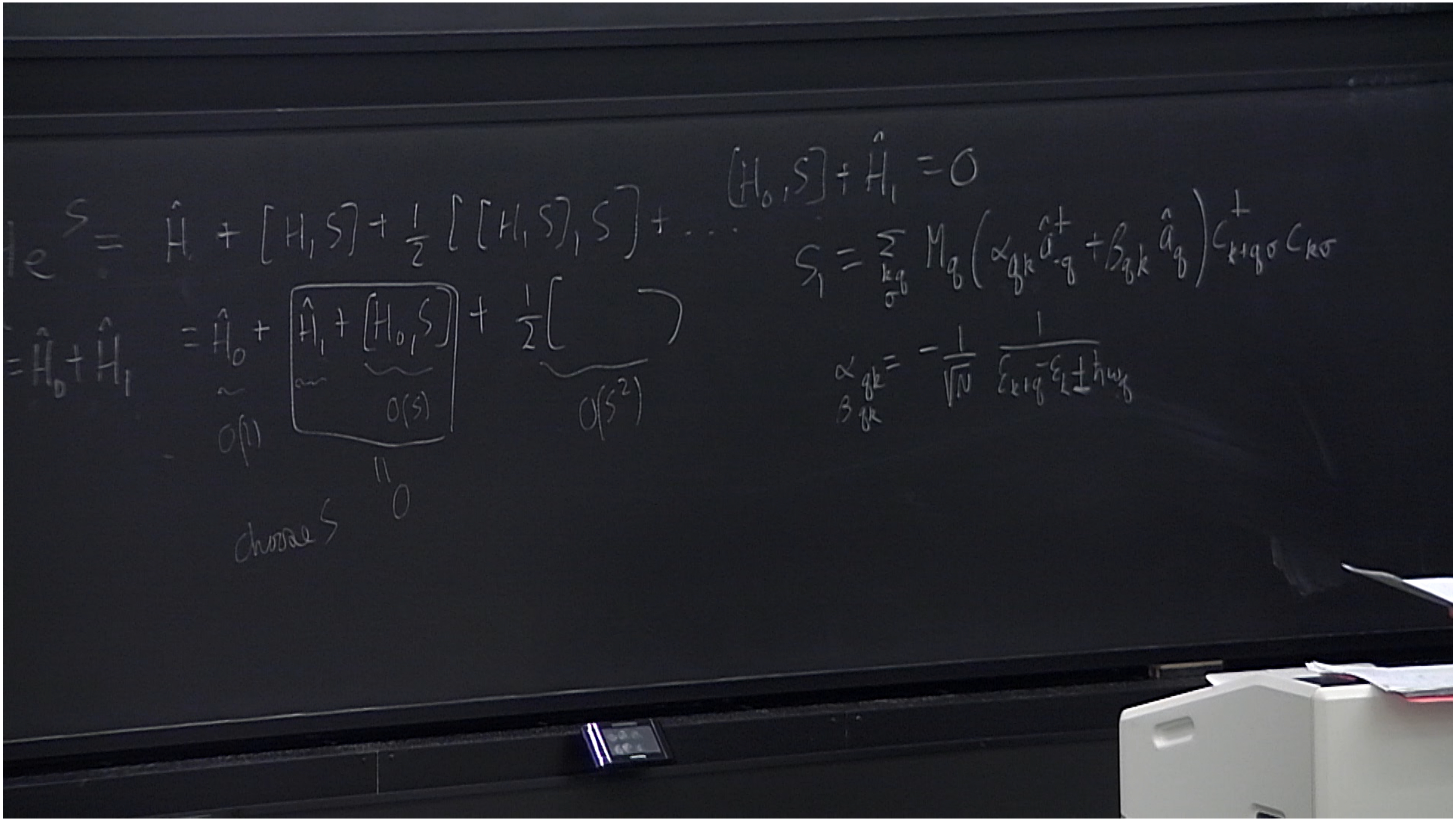

H̃ = e^{-S} H e^{S}
e^{-S} H e^{S} = Ĥ + [H, S] + 1/2 [[H, S], S] + ...
H = Ĥ_0 + Ĥ_1
= Ĥ_0 + Ĥ_1 + [H_0, S] + 1/2 [ ]
O(1)
O(S)
= 0
choose S
Hψ = Eψ
e^{S} H̃ e^{-S} ψ = Eψ
H̃ e^{-S} ψ = E e^{-S} ψ
⇒ H̃ ψ̃ = E ψ̃



$\tilde{H} = e^{-S} H e^{S}$
$e^{-S} H e^{S} = \hat{H} + [H, S] + \frac{1}{2}[[H, S], S] + \dots$
$H = \hat{H}_0 + \hat{H}_1$
$= \hat{H}_0 + \hat{H}_1 + [H_0, S] + \frac{1}{2}[\ ]$
$O(1)$
$O(S)$
$O(S^2)$
$= 0$
choose S
$H\psi = E\psi$
$e^{S}\tilde{H}e^{-S}\psi = E\psi$
$\tilde{H}e^{-S}\psi = Ee^{-S}\psi$
$\tilde{\psi}$
$\Rightarrow \tilde{H}\tilde{\psi} = E\tilde{\psi}$


$[H_0, S] + \hat{H}_1 = 0$
$e^{-S} H e^{S} = \hat{H} + [H, S] + \frac{1}{2}[[H, S], S] + \ldots$
$H = \hat{H}_0 + \hat{H}_1$
$= \hat{H}_0 + \hat{H}_1 + [H_0, S] + \frac{1}{2}[\quad]$
$O(1)$
$O(S)$
$O(S^2)$
$= 0$
choose S


[H_0, S] + Ĥ_1 = 0
e^S = Ĥ + [H, S] + 1/2 [[H, S], S] + ...
S_1 = Σ_{kqσ} M_q (α_{qk} â†_{-q} + β_{qk} â_q) c†_{k+qσ} c_{kσ}
= Ĥ_0 + Ĥ_1 = Ĥ_0 + Ĥ_1 + [H_0, S] + 1/2 [ ]
O(1)
O(S)
O(S^2)
0
choose S


$[H_0, S] + \hat{H}_1 = 0$
$He^S = \hat{H} + [H, S] + \frac{1}{2}[[H, S], S] + \dots$
$S_1 = \sum_{kq\sigma} M_q (\alpha_{qk} \hat{a}^\dagger_{-q} + \beta_{qk} \hat{a}_q) c^\dagger_{k+q\sigma} c_{k\sigma}$
$= \hat{H}_0 + \hat{H}_1$
$= \hat{H}_0 + \hat{H}_1 + [H_0, S] + \frac{1}{2}[\ ]$
$O(1)$
$O(S)$
$O(S^2)$
$= 0$
choose S
$\alpha_{qk}, \beta_{qk} = -\frac{1}{\sqrt{N}} \frac{1}{\varepsilon_{k+q} - \varepsilon_k \pm \hbar\omega_q}$

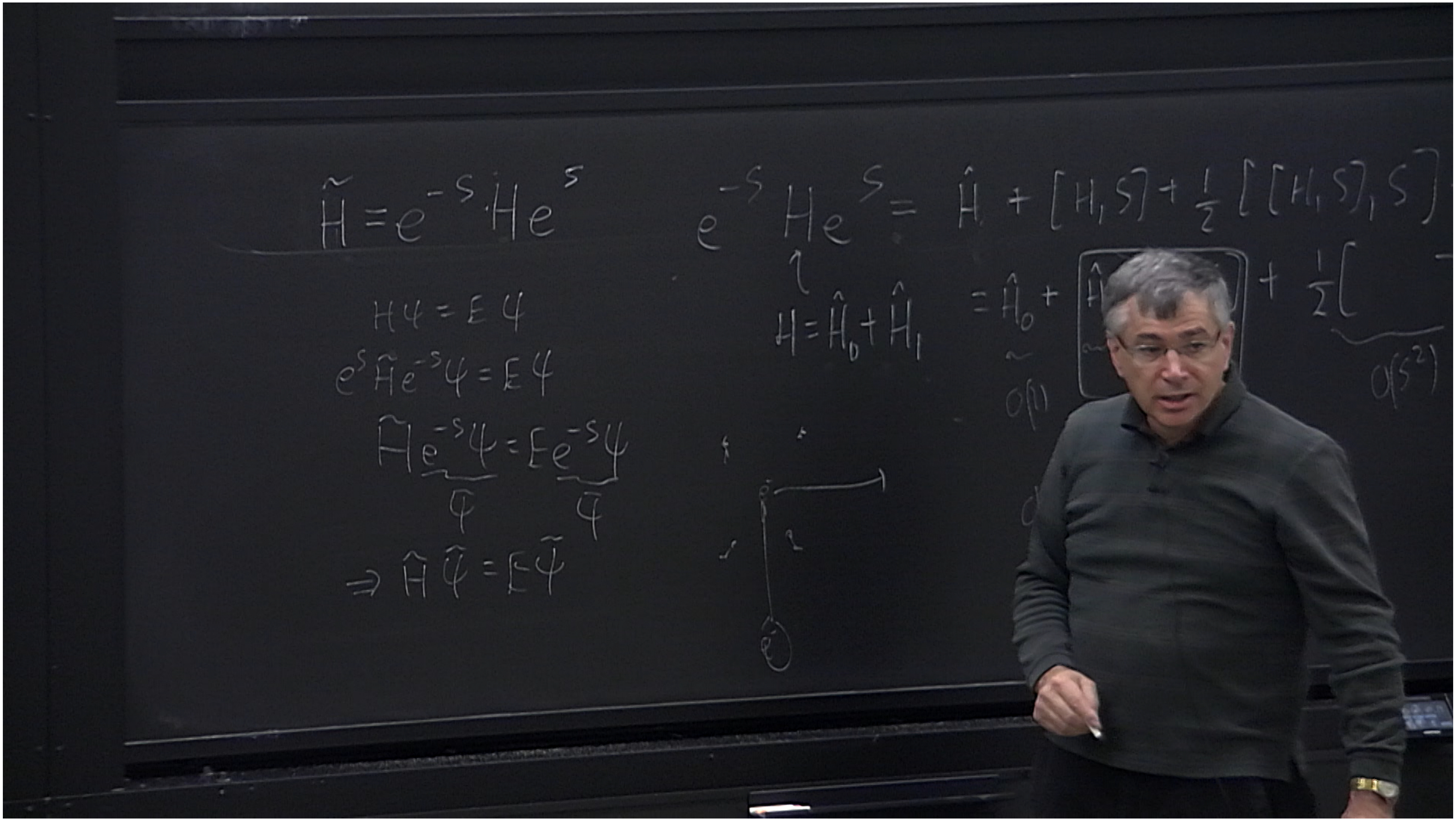
$$[H_0, S] + \hat{H}_1 = 0$$

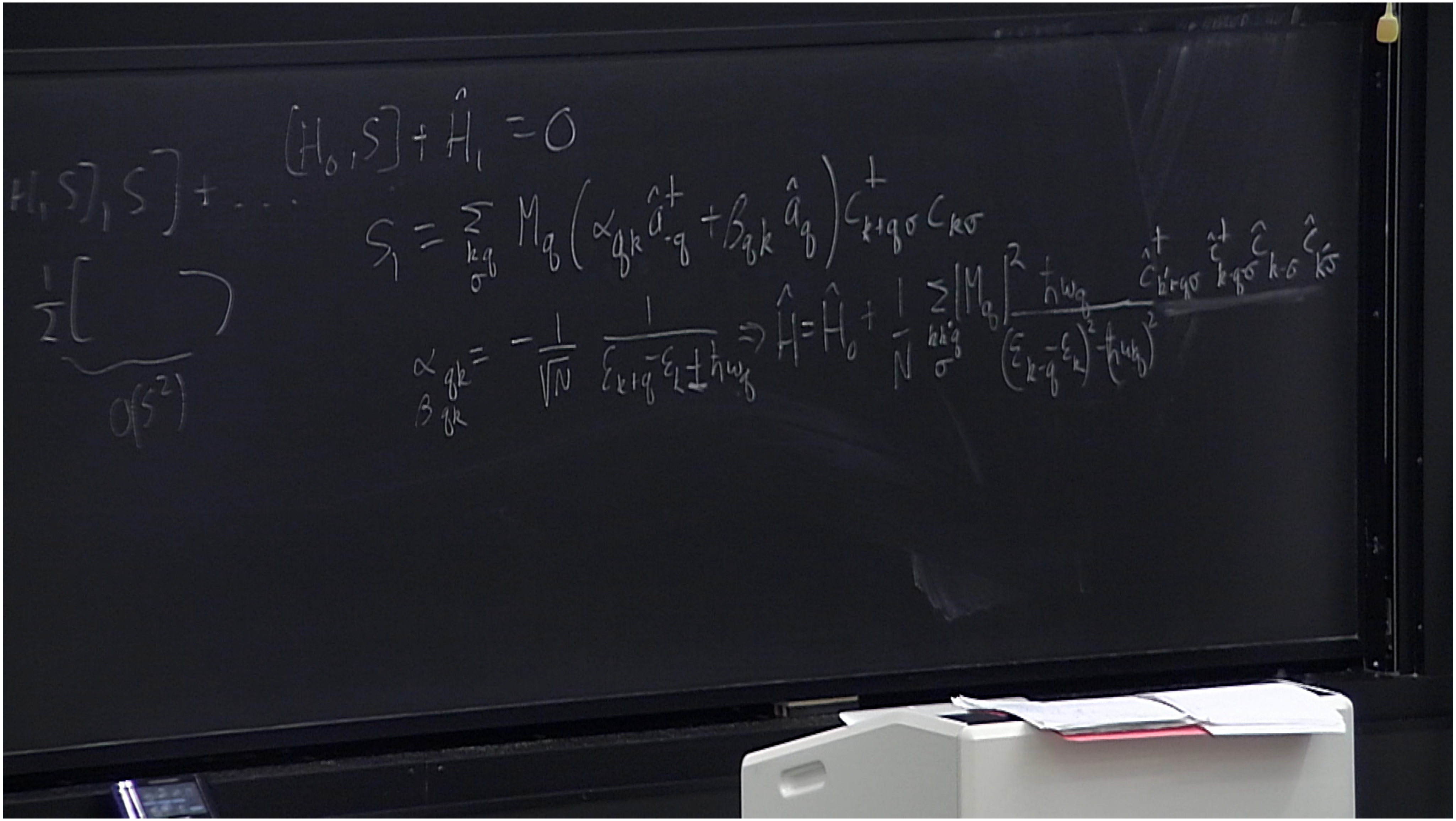
$$[[H_1, S], S] + \dots$$

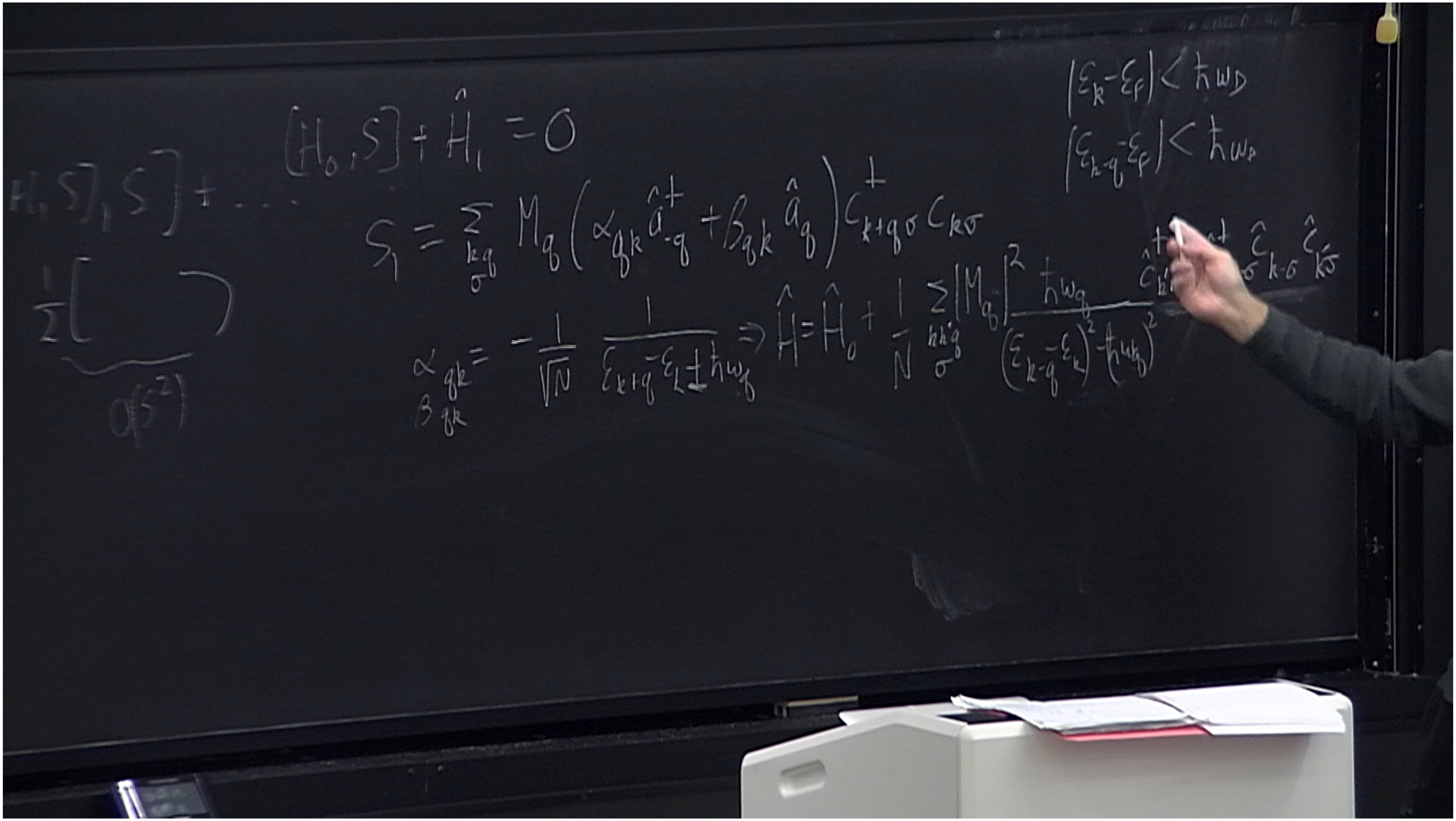
$$\underbrace{\frac{1}{2}[\quad]}_{O(S^2)}$$

$$S_1 = \sum_{\substack{kq\\ \sigma}} M_q \left(\alpha_{qk} \hat{a}^\dagger_{-q} + \beta_{qk} \hat{a}_q \right) c^\dagger_{k+q\sigma} c_{k\sigma}$$

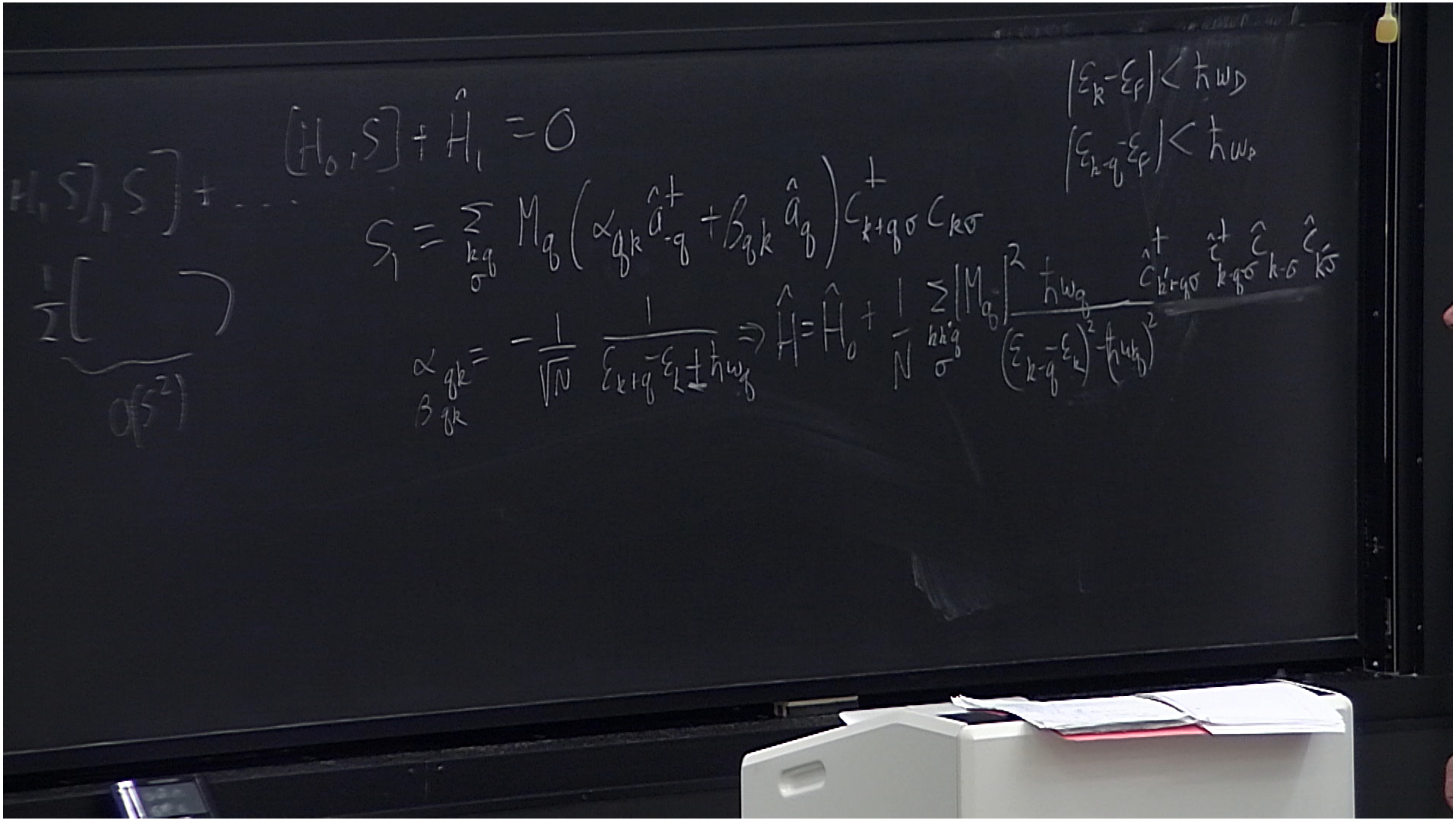
$$\begin{matrix}\alpha_{qk} \\ \beta_{qk}\end{matrix} = -\frac{1}{\sqrt{N}} \frac{1}{\varepsilon_{k+q} - \varepsilon_k \pm \hbar\omega_q} \Rightarrow \hat{H} = \hat{H}_0 + \frac{1}{N} \sum_{\substack{kk'q\\ \sigma}} |M_q|^2 \frac{\hbar\omega_q}{(\varepsilon_{k-q} - \varepsilon_k)^2 - (\hbar\omega_q)^2} \hat{c}^\dagger_{k'+q\sigma} \hat{c}^\dagger_{k-q\sigma'} \hat{c}_{k\sigma'} \hat{c}_{k'\sigma}$$


$\tilde{H} = e^{-S} H e^{S}$
$e^{-S} H e^{S} = \hat{H} + [H, S] + \frac{1}{2}[[H, S], S]$
$H\psi = E\psi$
$e^{S}\tilde{H}e^{-S}\psi = E\psi$
$\tilde{H}e^{-S}\psi = E e^{-S}\psi$
$\Rightarrow \tilde{H}\tilde{\psi} = E\tilde{\psi}$
$H = \hat{H}_0 + \hat{H}_1$
$= \hat{H}_0 +$
$+ \frac{1}{2}[$
$O(1)$
$O(S^2)$


$[H_0, S] + \hat{H}_1 = 0$
$[[H_1, S], S] + \dots$
$S_1 = \sum_{kq\sigma} M_q \left(\alpha_{qk} \hat{a}^{\dagger}_{-q} + \beta_{qk} \hat{a}_q \right) c^{\dagger}_{k+q\sigma} c_{k\sigma}$
$\frac{1}{2}[\quad]$ $O(S^2)$
$\alpha_{qk}, \beta_{qk} = -\frac{1}{\sqrt{N}} \frac{1}{\varepsilon_{k+q} - \varepsilon_k \pm \hbar\omega_q}$
$\Rightarrow \hat{H} = \hat{H}_0 + \frac{1}{N} \sum_{kk'q\sigma} |M_q|^2 \frac{\hbar\omega_q}{(\varepsilon_{k-q} - \varepsilon_k)^2 - (\hbar\omega_q)^2} \hat{c}^{\dagger}_{k'+q\sigma} \hat{c}^{\dagger}_{k-q\sigma'} \hat{c}_{k\sigma'} \hat{c}_{k'\sigma}$



[H0, S] + Ĥ1 = 0
S1 = Σ Mq (αqk â†-q + βqk âq) c†k+qσ ckσ
|εk − εF| < ħωD
|εk-q − εF| < ħωD
αqk, βqk = − 1/√N · 1/(εk+q − εk ± ħωq)
⇒ Ĥ = Ĥ0 + 1/N Σ |Mq|² ħωq / ((εk-q − εk)² − (ħωq)²)
O(S²)


$[H_0, S] + \hat{H}_1 = 0$
$|\varepsilon_k - \varepsilon_F| < \hbar\omega_D$
$|\varepsilon_{k-q} - \varepsilon_F| < \hbar\omega_D$
$S_1 = \sum_{kq\sigma} M_q \left(\alpha_{qk} \hat{a}^{\dagger}_{-q} + \beta_{qk} \hat{a}_q\right) c^{\dagger}_{k+q\sigma} c_{k\sigma}$
$\alpha_{qk}, \beta_{qk} = -\frac{1}{\sqrt{N}} \frac{1}{\varepsilon_{k+q} - \varepsilon_k \pm \hbar\omega_q}$
$\Rightarrow \hat{H} = \hat{H}_0 + \frac{1}{N} \sum_{kk'q\sigma} |M_q|^2 \frac{\hbar\omega_q}{(\varepsilon_{k-q} - \varepsilon_k)^2 - (\hbar\omega_q)^2} \hat{c}^{\dagger}_{k'+q\sigma} \hat{c}^{\dagger}_{k-q\sigma} \hat{c}_{k\sigma} \hat{c}_{k'\sigma}$
$O(S^2)$