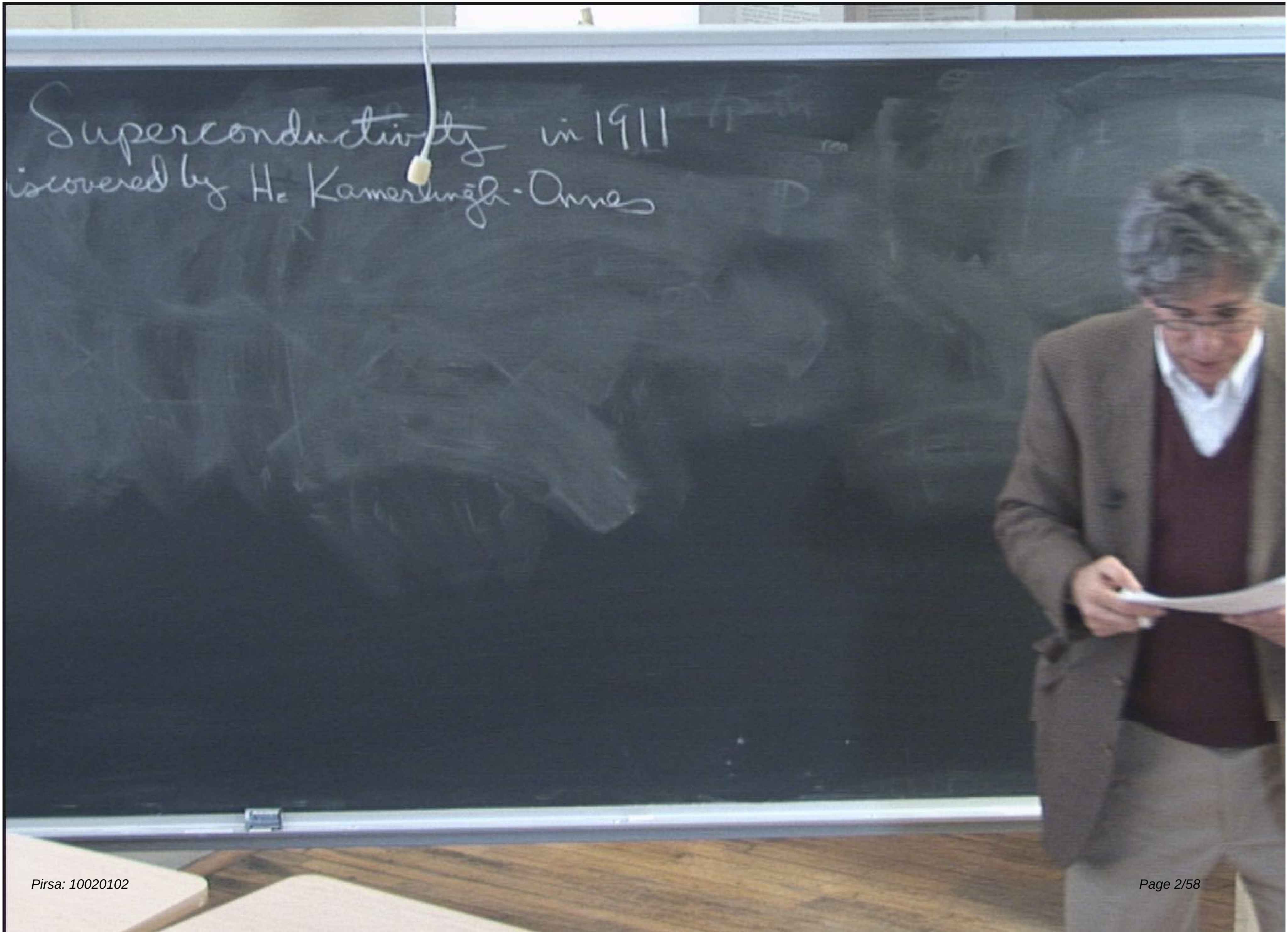
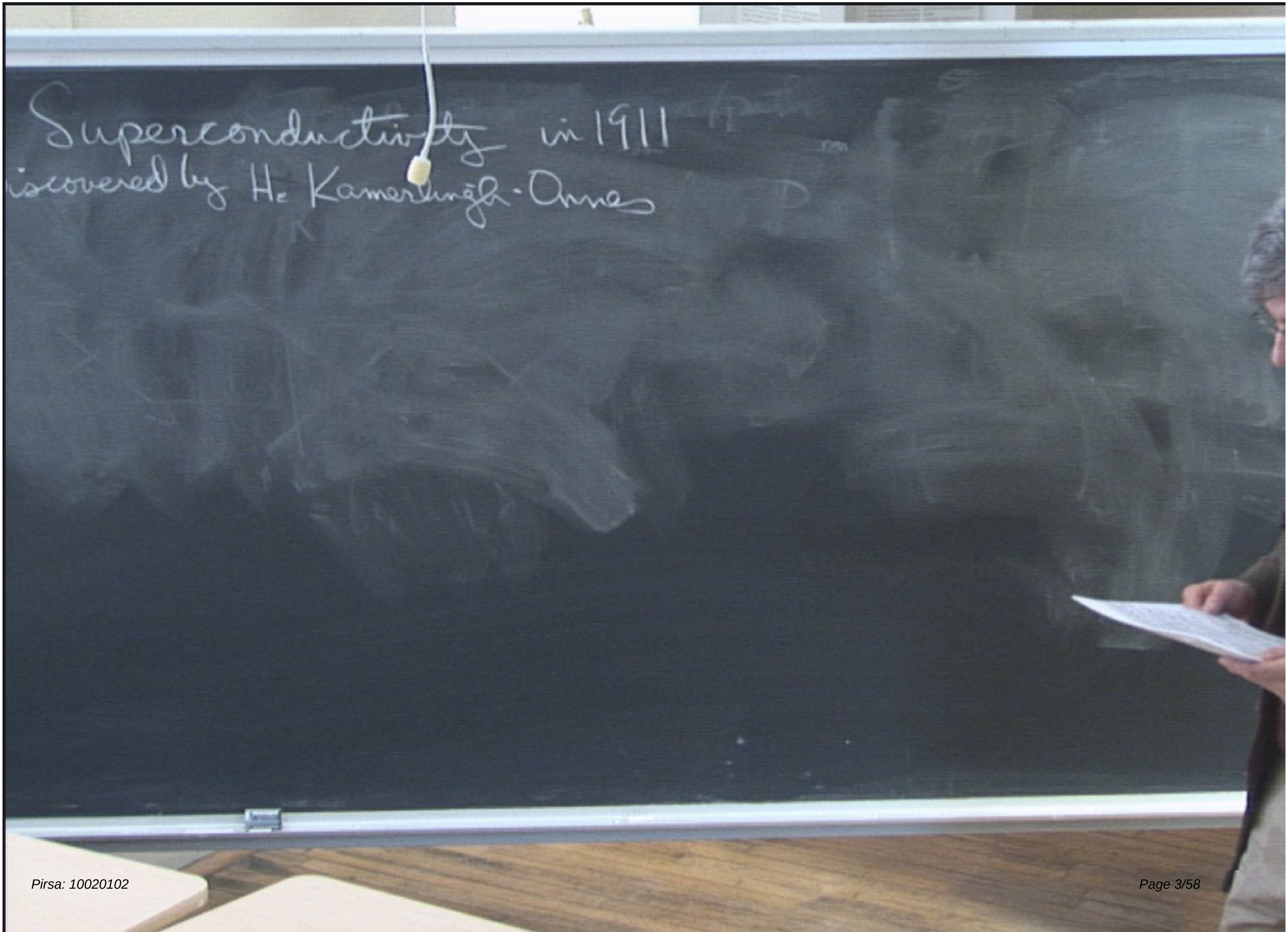
Title: Condensed Matter II - Lecture 6

Date: Feb 23, 2010 10:10 AM

URL: http://pirsa.org/10020102

Abstract:


Superconductivity in 1911
iscovered by H. Kamerlingh-Onnes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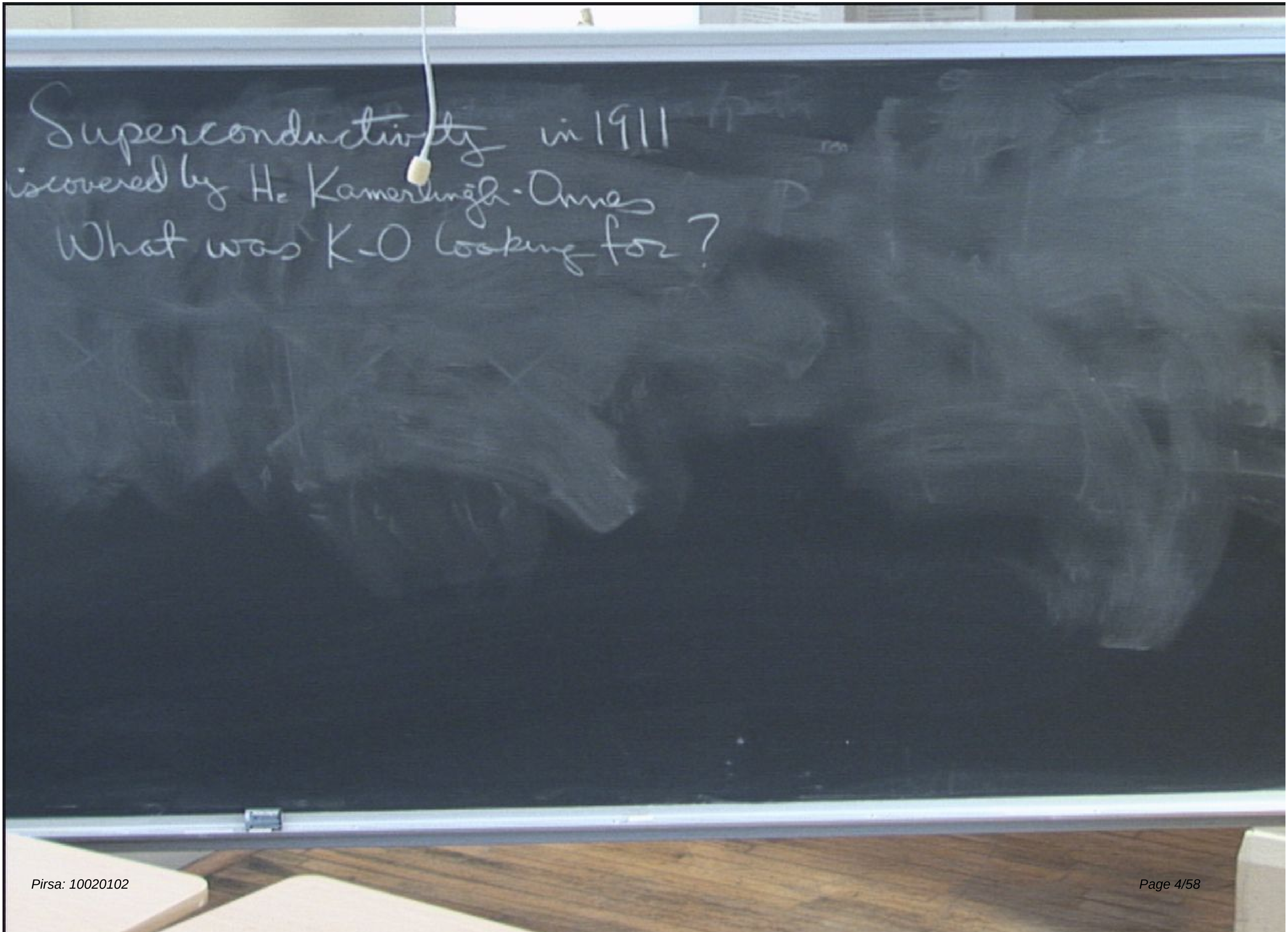
Superconductivity in 1911
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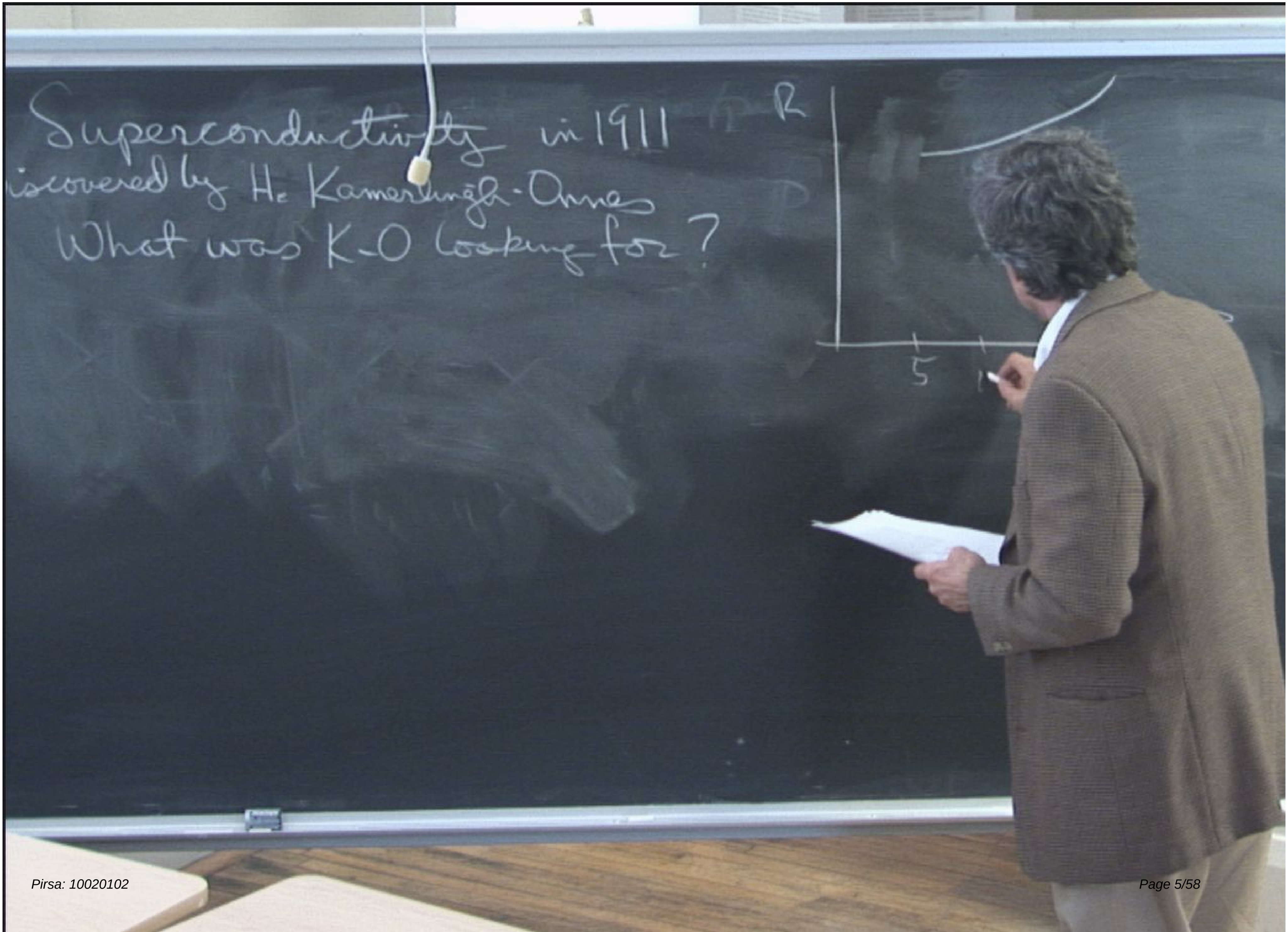
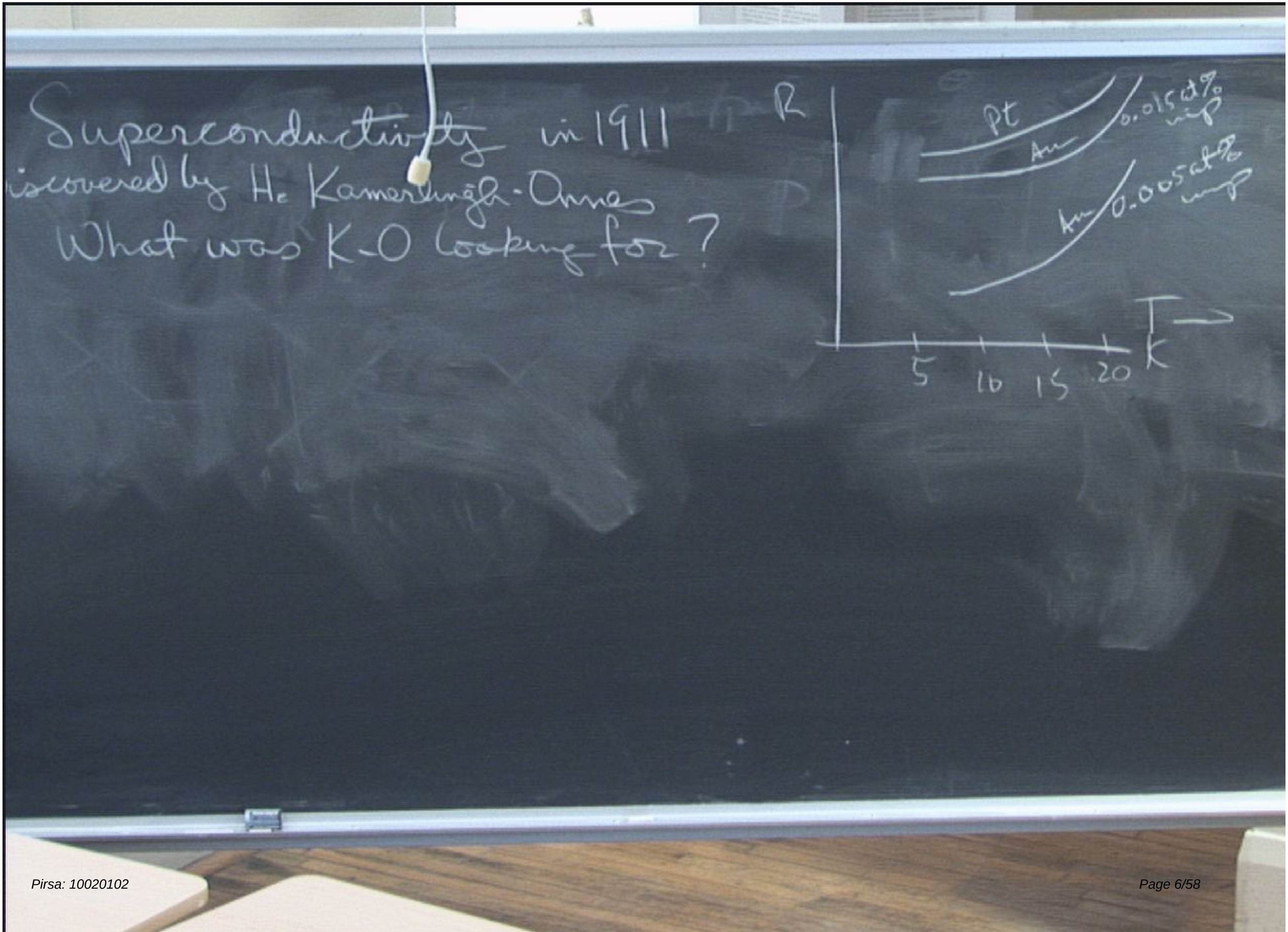
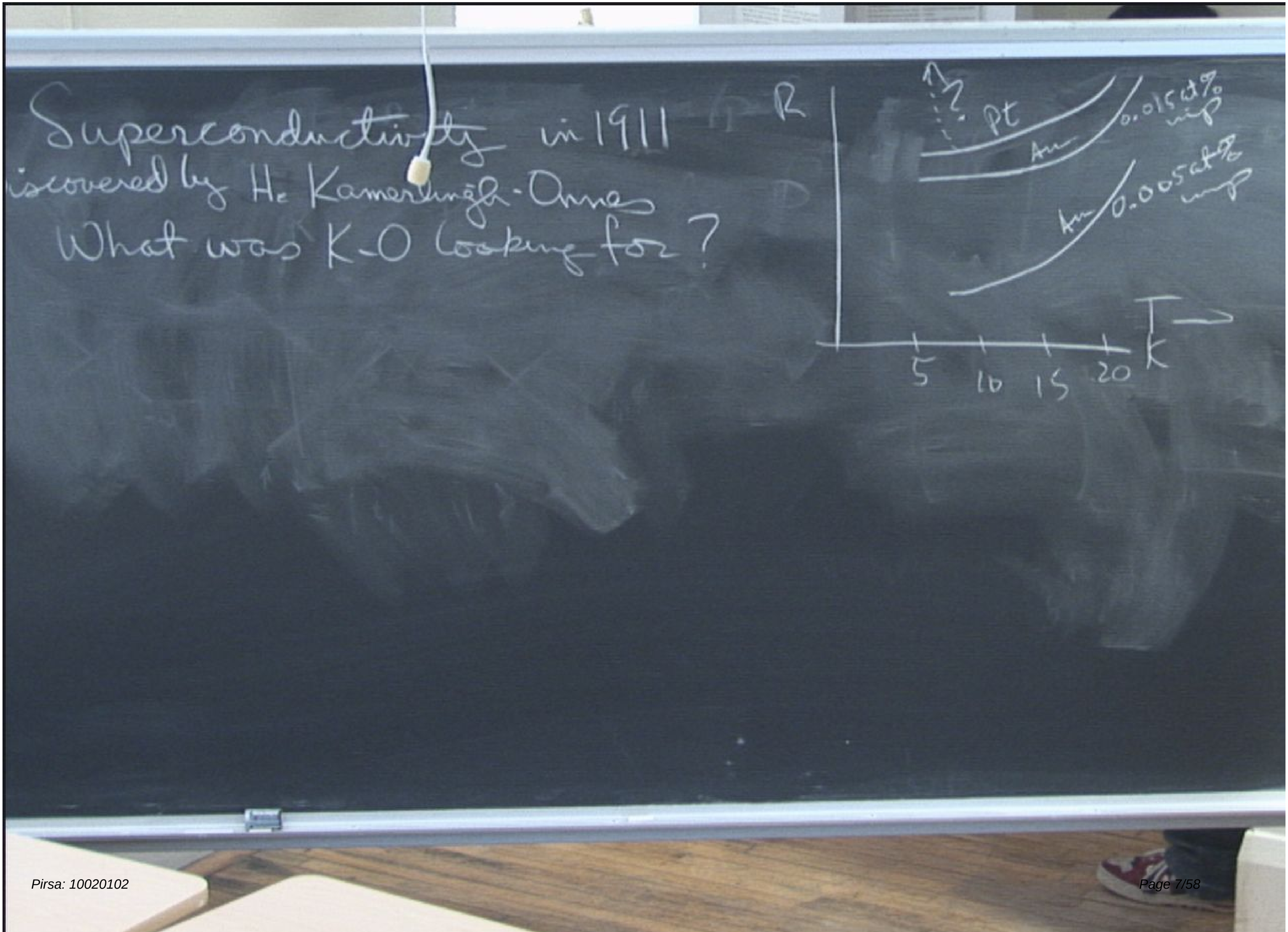
What was K-O looking for?


Superconductivity in 1911
iscovered by H. Kamerlingh-Onnes
What was K-O looking for?
R
5


Superconductivity in 1911
iscovered by H. Kamerlingh-Onnes
What was K-O looking for?
R
Pt
Au
0.015 at% imp
Au
0.005 at% imp
T →
5
10
15
20
K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R
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Au
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5
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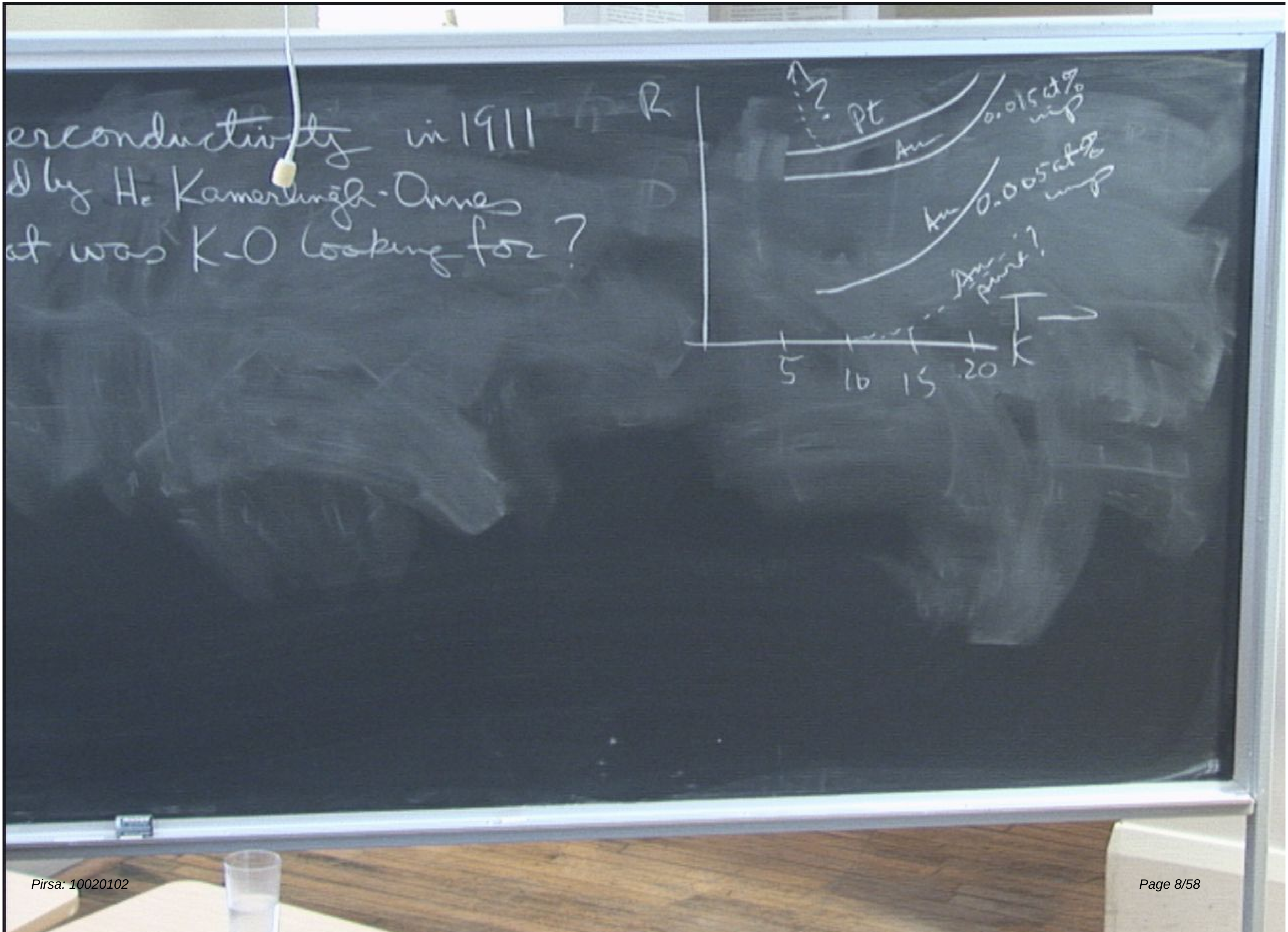
K
T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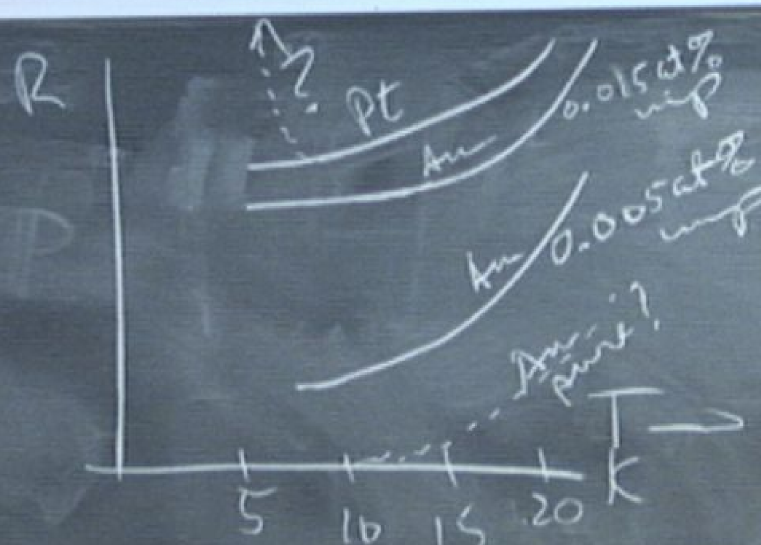
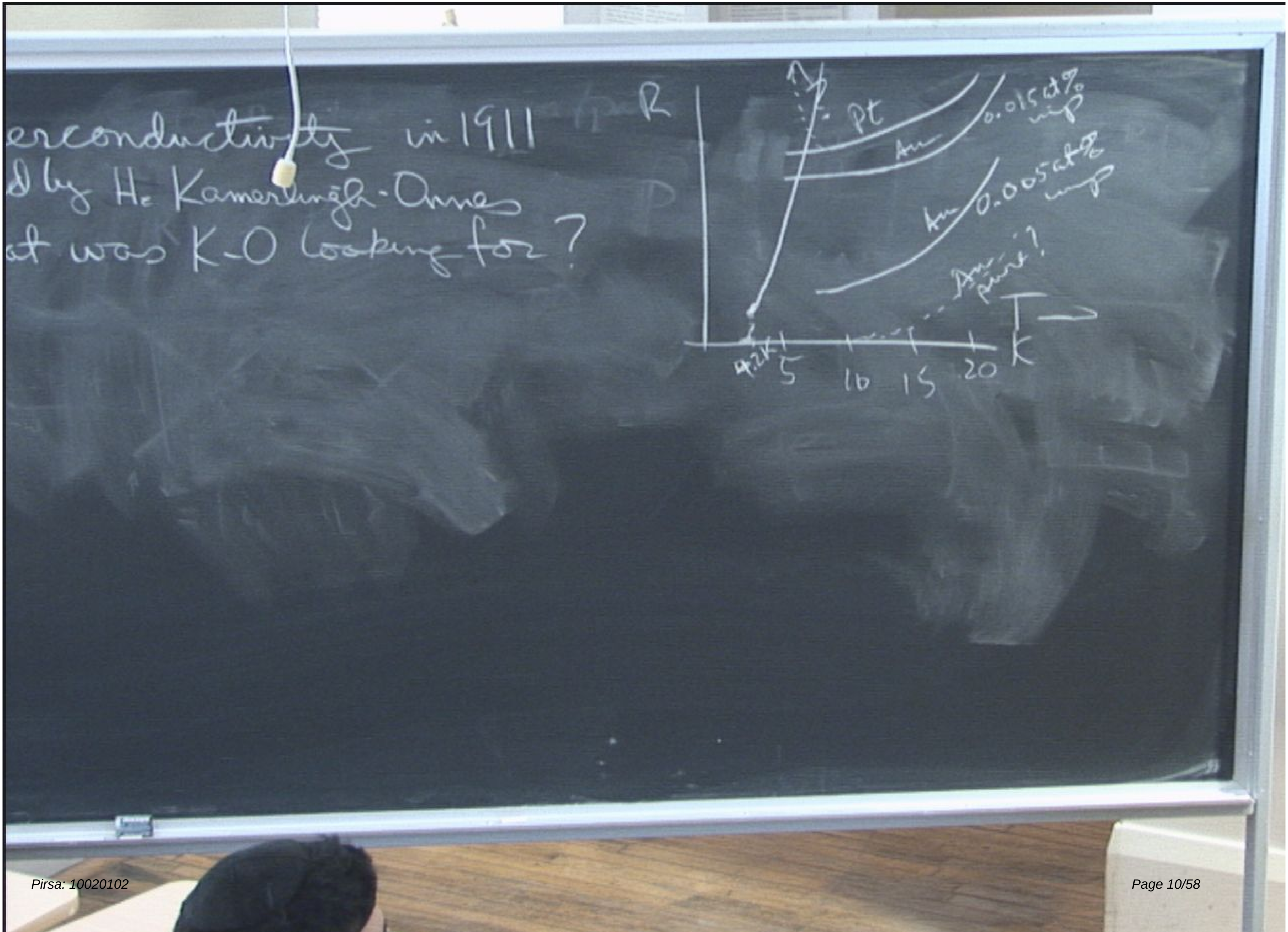
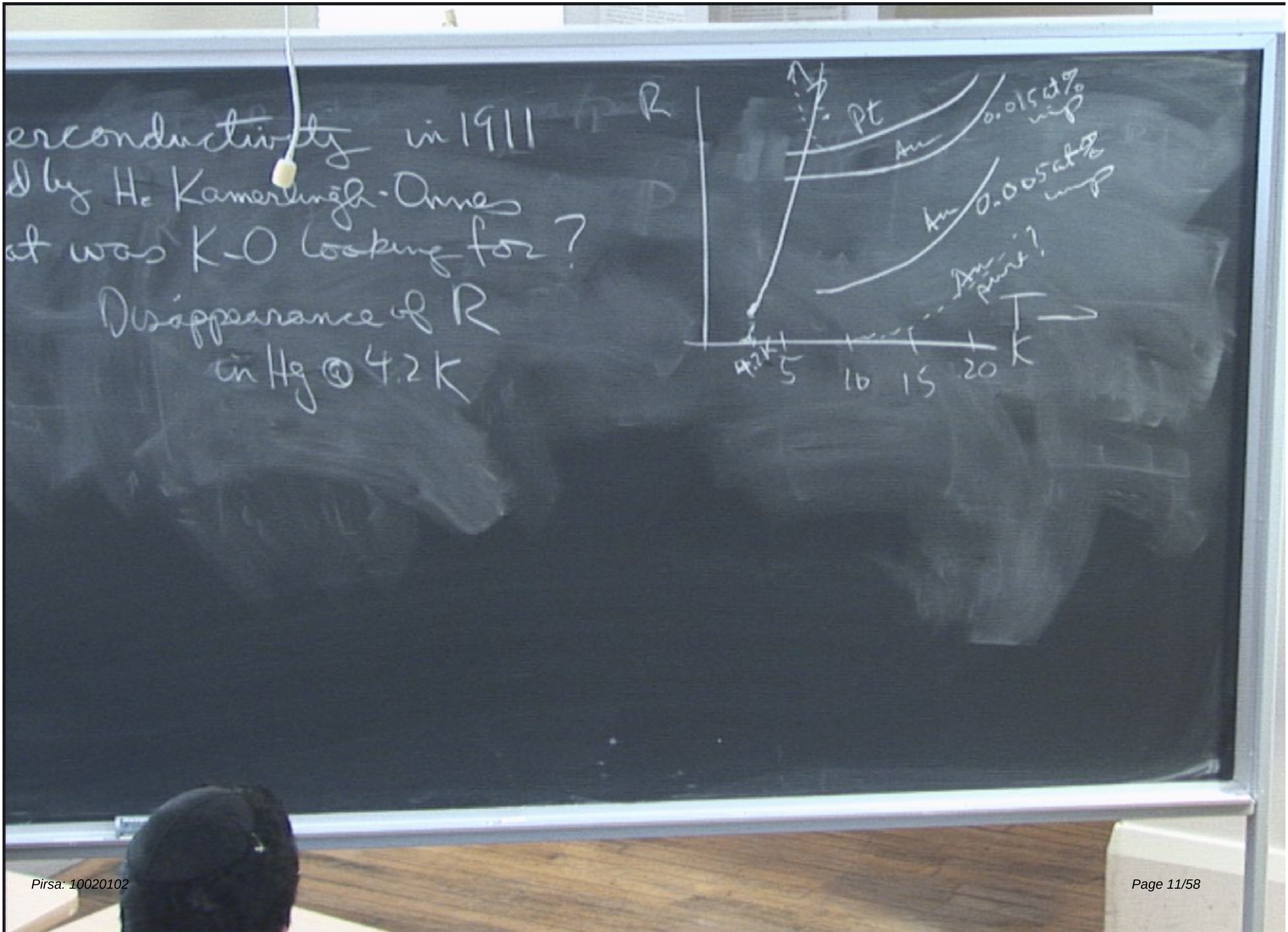
at was K-O looking for?
R
pt
Au
0.015 at% imp
Au
0.005 at% imp
Au pure?
T
5
10
15
20
K

…erconductivity in 1911
…d by H. Kamerlingh-Onnes
…at was K-O looking for?

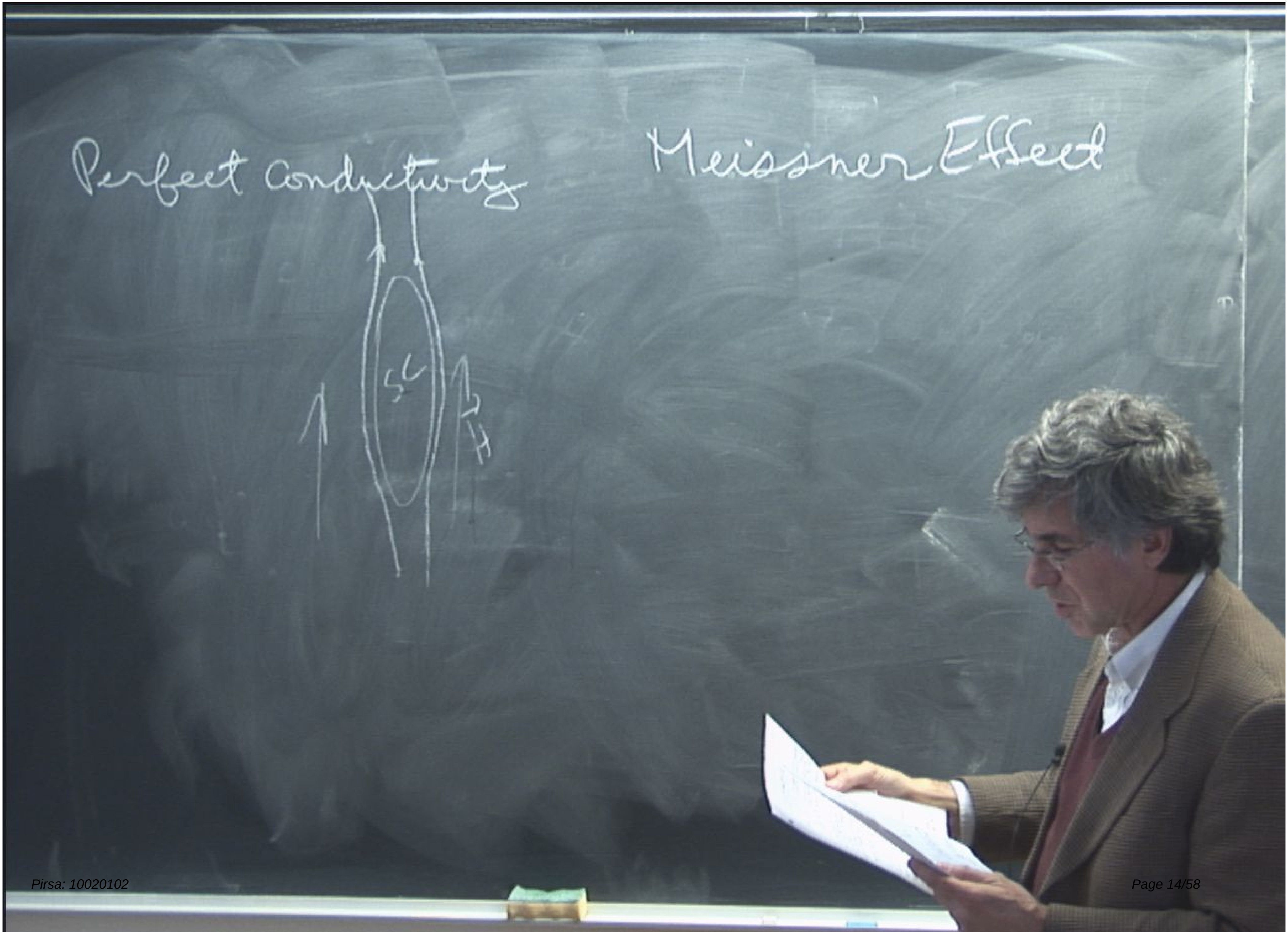


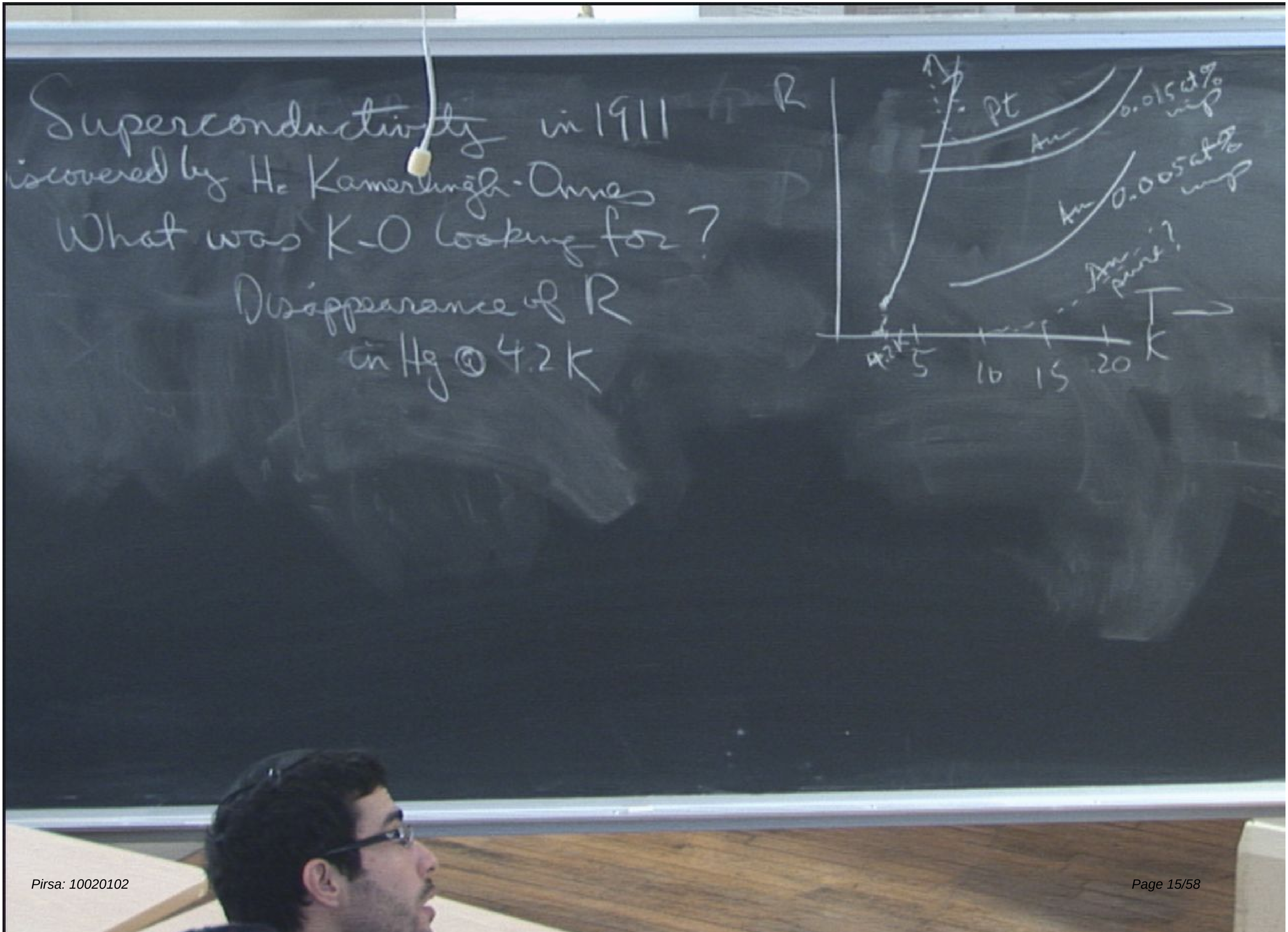

erconductivity in 1911
d by H. Kamerlingh-Onnes
at was K-O looking for?
R
Pt
Au
0.015 at% imp
Au
0.005 at% imp
Au pure?
T
4.2K
5
10
15
20
K


erconductivity in 1911
d by H. Kamerlingh-Onnes
at was K-O looking for?
Disappearance of R
in Hg @ 4.2 K
R
Pt
Au
0.015 at% imp
Au
0.005 at% imp
Au pure?
T
K
4.2K
5
10
15
20

Perfect conductivity

Perfect conductivity


Perfect conductivity
Meissner Effect
SC
H


Superconductivity in 1911
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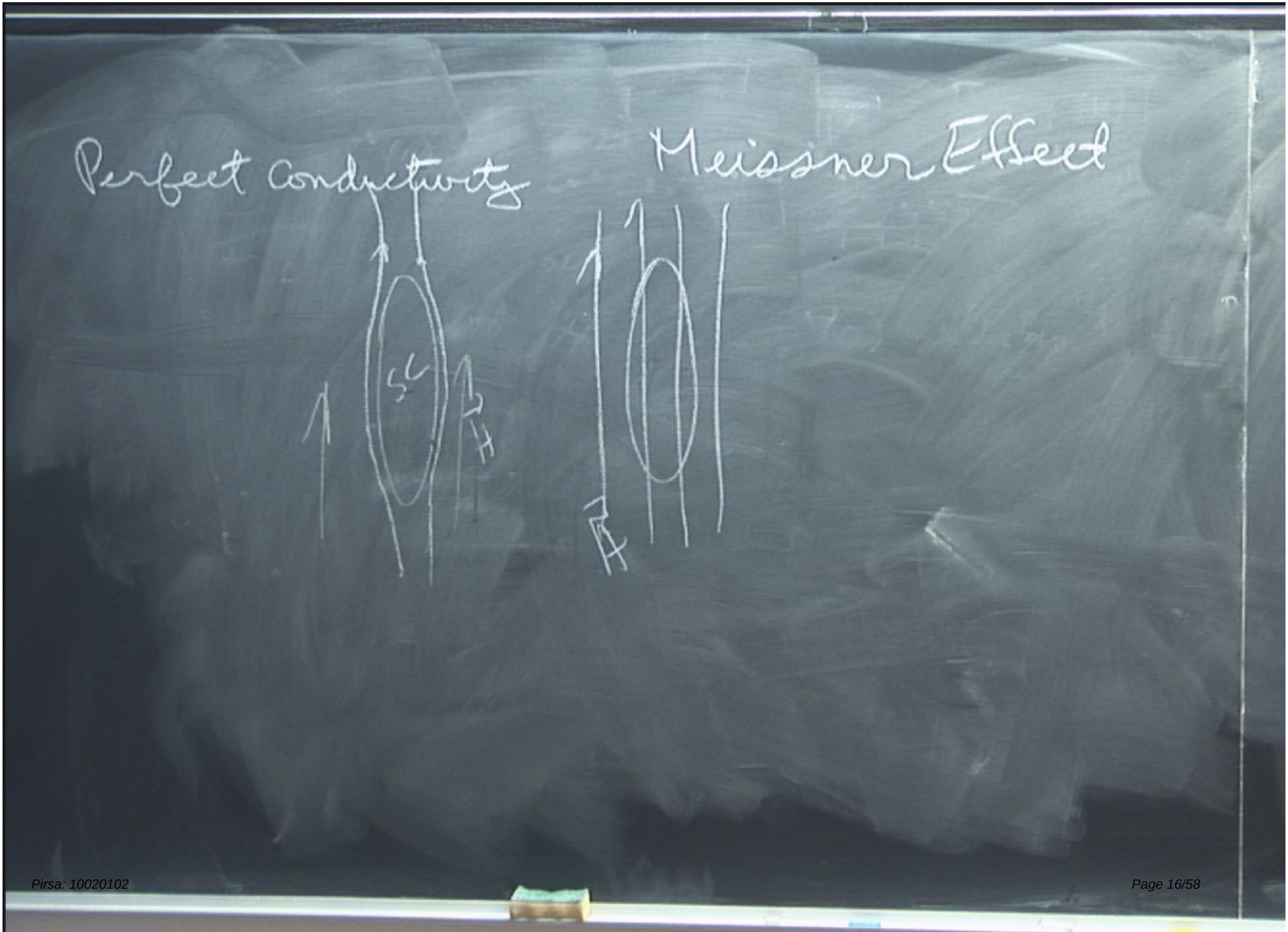
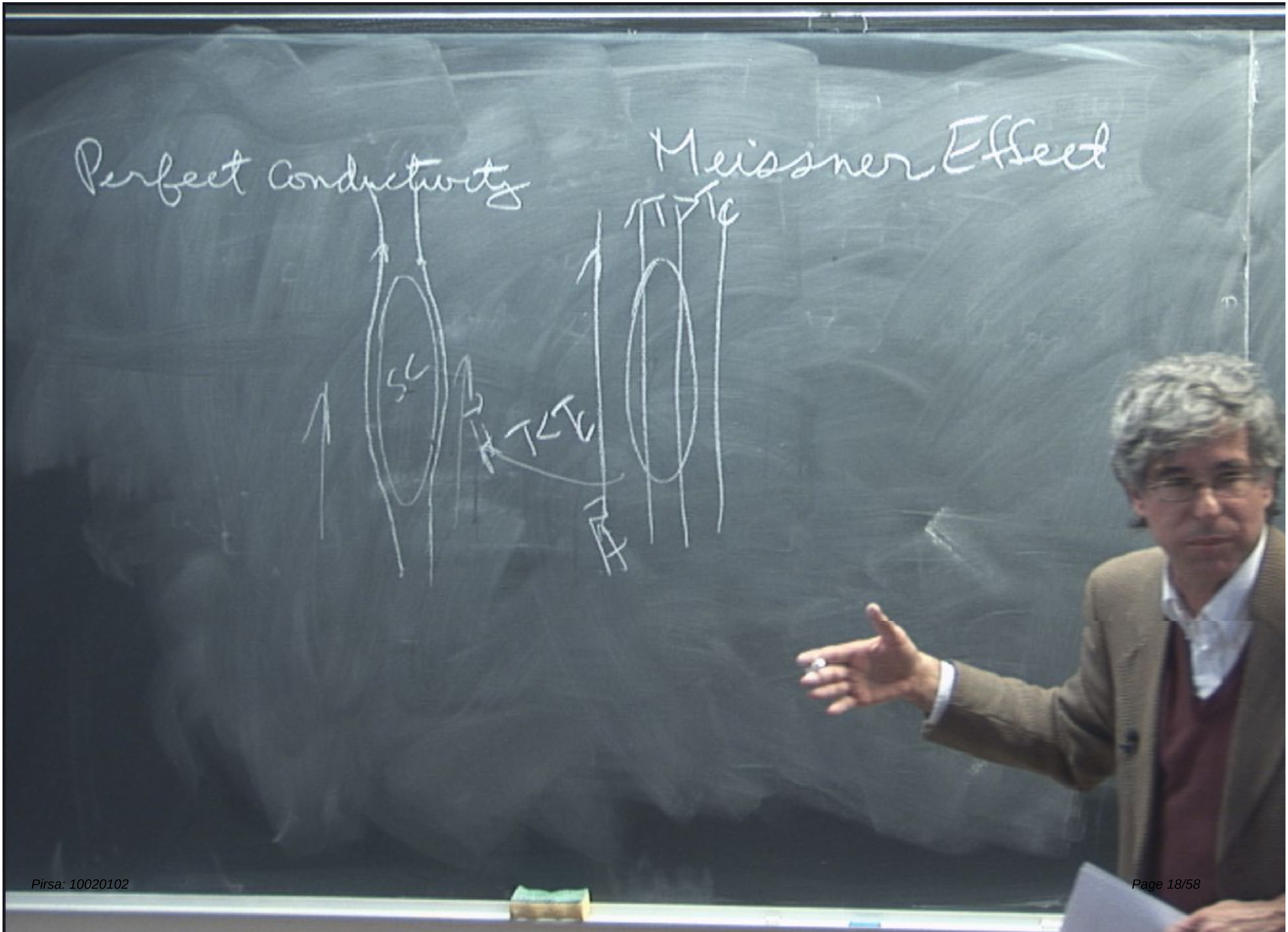
What was K-O looking for?
Disappearance of R
in Hg @ 4.2 K
R
Pt
Au
0.015 at% imp
Au
0.005 at% imp
Au pure?
T
K
5
10
15
20


Perfect Conductivity
Meissner Effect
SC
H
H

Perfect conductivity

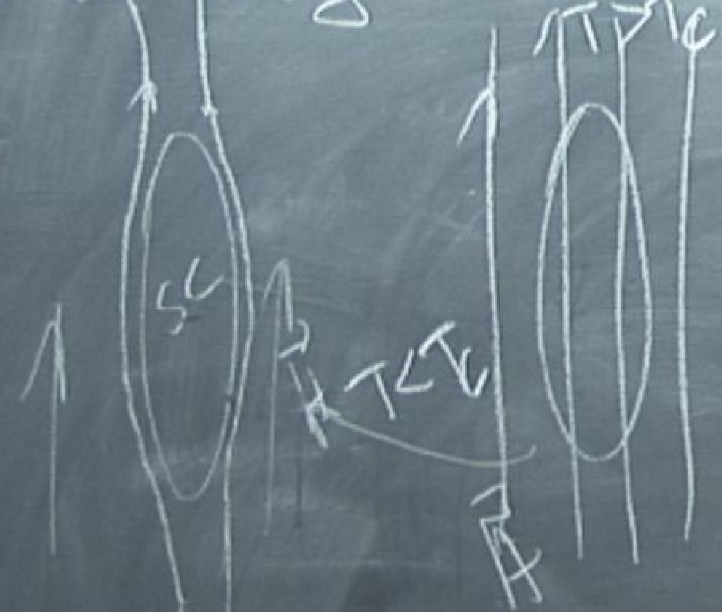
Meissner Effect


Perfect conductivity
Meissner Effect
SC
T<Tc
T>Tc

Perfect Conductivity   Meissner Effect

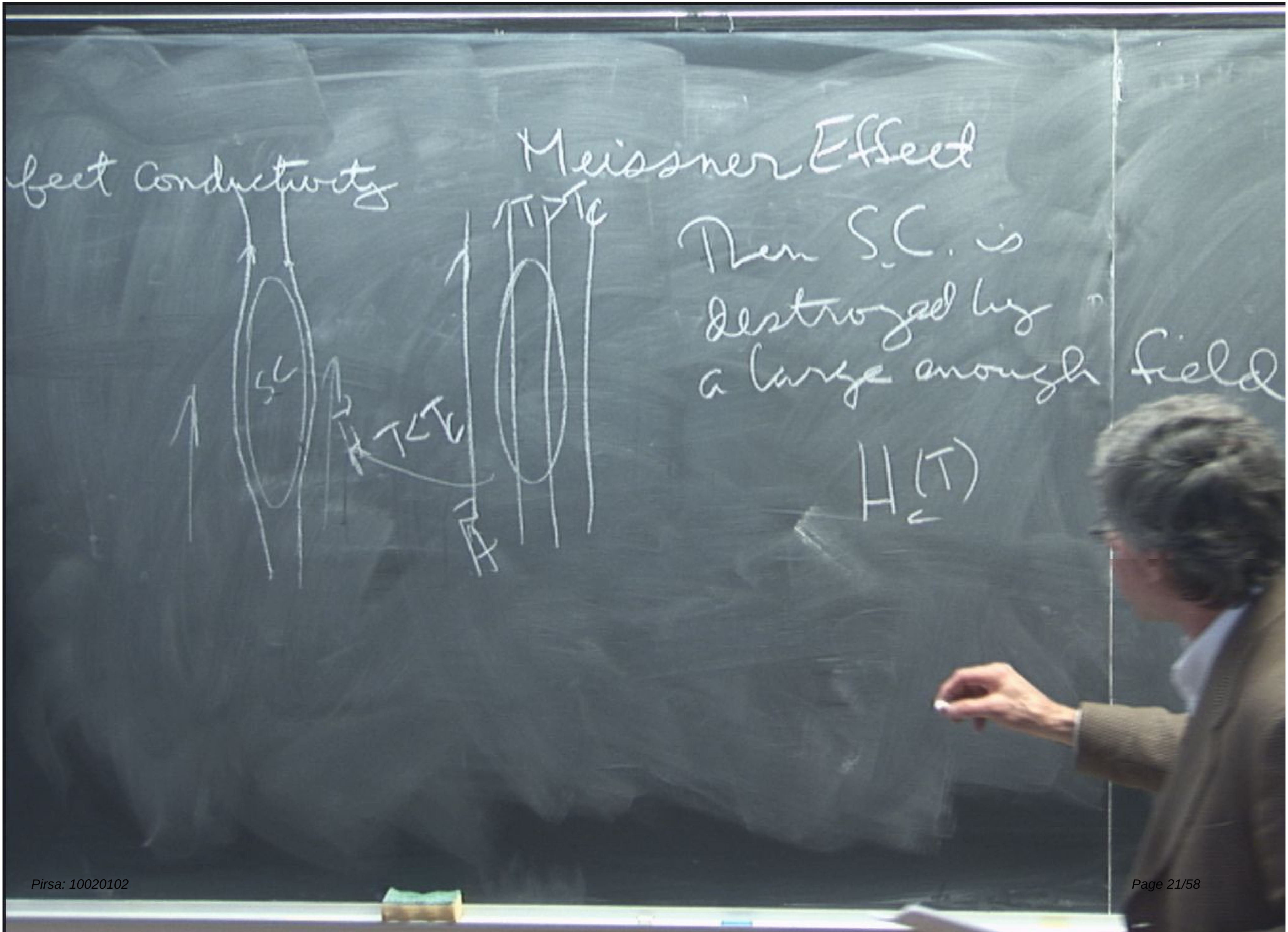
...fect conductivity

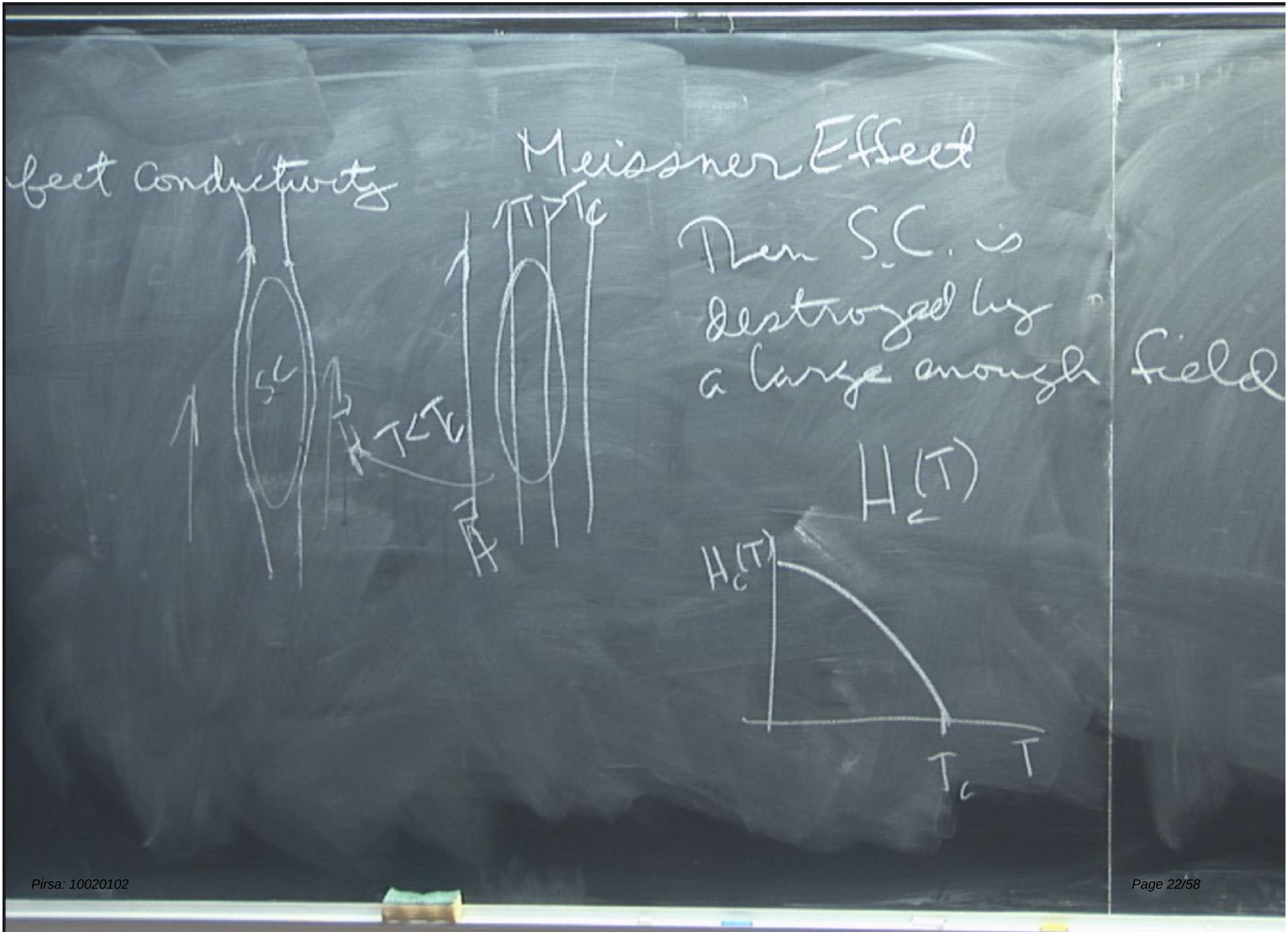
Meissner Effect



Then S.C. is destroyed by a large enough field

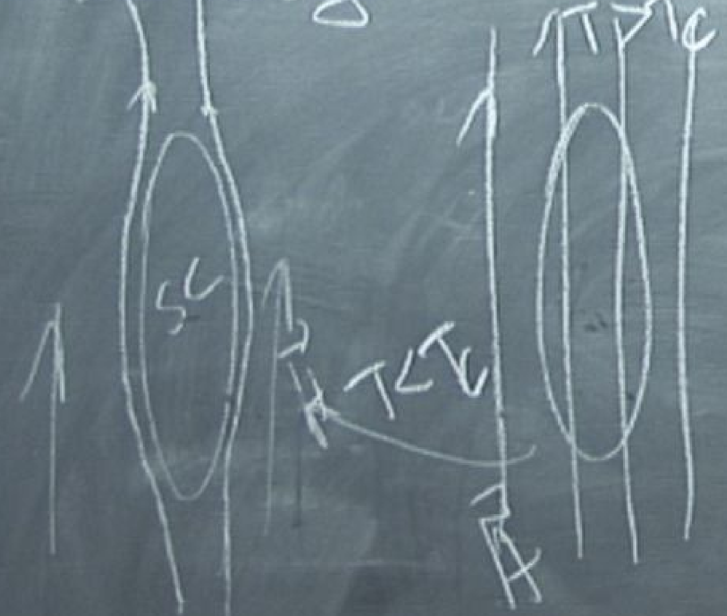
H_c


fect conductivity
Meissner Effect
SC
T<Tc
T>Tc
Then S.C. is destroyed by a large enough field
Hc(T)


fect conductivity
Meissner Effect
T > Tc
SC
T < Tc
H
Then S.C. is
destroyed by
a large enough field
Hc(T)
Hc(T)
Tc
T

fect Conductivity

Meissner Effect



Then S.C. is destroyed by a large enough field

$H_c(T)$


Type I, II
ield

Type I, II

eld

$$f_s(T) - f_n(T) = -\frac{H_c^2(T)}{8\pi}$$

Type I, II

eld

$$f_s(T) - f_n(T) = -\frac{H_c^2(T)}{8\pi}$$

Type I, II

London

ield

$$f_s(T) - f_n(T) = -\frac{H_c^2(T)}{8\pi}$$

Type I, II

London Equations

eld

$$f_s(T) - f_n(T) = -\frac{H_c^2(T)}{8\pi}$$

Type (I), II

London Equations

Conjectured

$$\langle \vec{P} \rangle_{\substack{S.C.\\ \text{Ground} \\ \text{State}}} = 0$$

ield

$$f_s(T) - f_n(T) = -\frac{H_c^2(T)}{8\pi}$$

Type I, II

London Equations

Conjectured

ield

$$f_s(T) - f_n(T) = -\frac{H_c^2(T)}{8\pi}$$

$$\langle \vec{p} \rangle_{S.C.} = 0 = m\langle \vec{v}_s \rangle + \frac{e\vec{A}}{c}$$

S.C. Ground State

Type I, II

...eld

$$f_s(T) - f_n(T) = -\frac{H_c^2(T)}{8\pi}$$

London Equations

Conjectured

$$\langle \vec{p} \rangle_{S.C.} = 0 = m\langle \vec{v}_s \rangle + \frac{e\vec{A}}{c}$$

S.C. Ground State

$$\therefore \vec{J}_s = e n_s \langle \vec{v}_s \rangle$$

Supercurrent density

Type (I), II

London Equations

Conjectured

$$\langle \vec{p} \rangle_{s.c.} = 0 = m\langle \vec{v}_s \rangle + \frac{e\vec{A}}{c}$$

S.C. Ground State

ignore ... of S.C.

ield

$$f_s(T) - f_n(T) = -\frac{H_c^2(T)}{8\pi}$$

$$\therefore \vec{J}_s = e n_s \langle \vec{v}_s \rangle = -\frac{e^2 n_s \vec{A}}{mc}$$

Supercurrent density

Type (I), II

...eld

$$f_s(T) - f_n(T) = -\frac{H_c^2(T)}{8\pi}$$

London Equations

Conjectured

$$\langle \vec{p} \rangle_{S.C.} = 0 = m\langle \vec{v}_s \rangle + \frac{e\vec{A}}{c}$$

S.C. Ground State

$$\therefore \vec{J}_s = e n_s \langle \vec{v}_s \rangle = -\frac{e^2 n_s \vec{A}}{mc}$$

Supercurrent density

Makes sense London gauge

$$\vec{\nabla} \cdot \vec{A} = 0$$

Type I, II

...eld

$$f_s(T) - f_n(T) = -\frac{H_c^2(T)}{8\pi}$$

London Equations

Conjectured

$$\langle \vec{p} \rangle_{S.C.} = 0 = m\langle \vec{v}_s \rangle + \frac{e\vec{A}}{c}$$

S.C. Ground State

$$\therefore \vec{J}_s = e n_s \langle \vec{v}_s \rangle = -\frac{e^2 n_s \vec{A}}{mc}$$

Supercurrent density

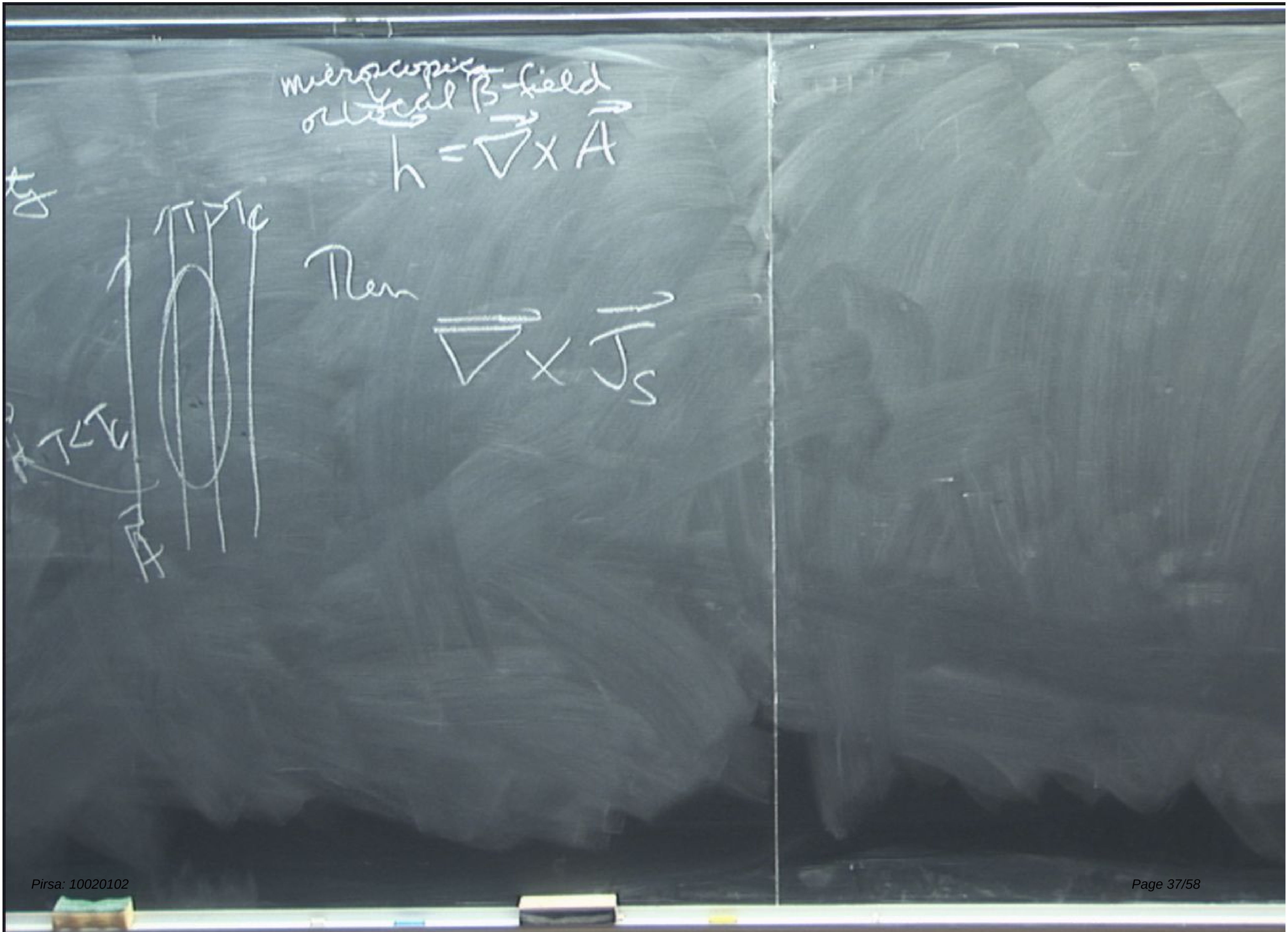
Makes sense London gauge

$\vec{\nabla}\cdot\vec{A} = 0$ and $\vec{A} \to 0$ inside

microscopic
local B-field

$$h = \vec{\nabla} \times \vec{A}$$

microscopic B-field
or local
$$h = \vec{\nabla} \times \vec{A}$$


microscopic B-field
local
h = ∇ × A
T > T_c
T < T_c
Then
∇ × J_s

microscopic
local B-field

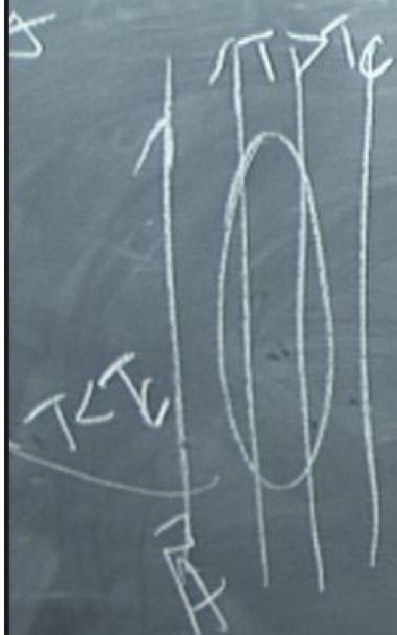
$$\vec{h} = \vec{\nabla} \times \vec{A}$$

Then

$$\vec{\nabla} \times \vec{J}_s = \vec{h}$$

~~microscopic~~ local B-field

$$h = \vec{\nabla} \times \vec{A}$$



Then

$$\vec{\nabla} \times \vec{J}_s = -\frac{e^2 n_s}{mc} \vec{h}$$

microscopic local B-field

$$\vec{h} = \vec{\nabla} \times \vec{A}$$

Then

$$\vec{\nabla} \times \vec{J}_s = -\frac{e^2 n_s}{mc}\vec{h}$$

From Maxwell

$$\vec{\nabla} \times \vec{h} = \frac{4\pi}{c}\vec{J}$$

microscopic local B-field

$$h = \vec{\nabla} \times \vec{A}$$

From Maxwell

$$\vec{\nabla} \times \vec{h} = \frac{4\pi}{c} \vec{J}$$

Then

$$\vec{\nabla} \times \vec{J}_s = -\frac{e^2 n_s}{mc} \vec{h}$$

$$\vec{\nabla} \times \vec{\nabla} \times \vec{h} = -\frac{4\pi}{c} \frac{e^2 n_s}{mc} \vec{h}$$

microscopic local B-field

$$\vec{h} = \vec{\nabla} \times \vec{A}$$

From Maxwell

$$\vec{\nabla} \times \vec{h} = \frac{4\pi \vec{J}}{c}$$

Then

$$\vec{\nabla} \times \vec{J}_s = -\frac{e^2 n_s}{mc} \vec{h}$$

$$\vec{\nabla} \times \vec{\nabla} \times \vec{h} = -\frac{4\pi}{c} \frac{e^2 n_s}{mc} \vec{h}$$

~~microscopic~~ or local B-field

$$\vec{h} = \vec{\nabla} \times \vec{A}$$

From Maxwell

$$\vec{\nabla} \times \vec{h} = \frac{4\pi}{c} \vec{J}$$

Then

$$\vec{\nabla} \times \vec{J}_s = -\frac{e^2 n_s}{mc} \vec{h}$$

$$\vec{\nabla} \times \vec{\nabla} \times \vec{h} = -\frac{4\pi}{c} \frac{e^2 n_s}{mc} \vec{h}$$

$$+\nabla^2 \vec{h} = +\frac{4\pi e^2 n_s}{mc^2} \vec{h}$$

microscopic
local B-field

$$\vec{h} = \vec{\nabla} \times \vec{A}$$

From Maxwell

$$\vec{\nabla} \times \vec{h} = \frac{4\pi \vec{J}}{c}$$

Then

$$\vec{\nabla} \times \vec{J}_s = -\frac{e^2 n_s}{mc}\vec{h}$$

$$\vec{\nabla} \times \vec{\nabla} \times \vec{h} = -\frac{4\pi}{c}\frac{e^2 n_s}{mc}\vec{h}$$

$$+\nabla^2 \vec{h} = +\frac{4\pi e^2 n_s}{mc^2}\vec{h} = \frac{1}{\lambda_L^2}\vec{h}$$

...oscopic
...ocal B-field

$$\vec{h} = \vec{\nabla} \times \vec{A}$$

From Maxwell

$$\vec{\nabla} \times \vec{h} = \frac{4\pi}{c}\vec{J}$$

Lon...

Cong...

$\langle \vec{p}$ ...

...lem

$$\vec{\nabla} \times \vec{J}_S = -\frac{e^2 n_s}{mc}\vec{h}$$

$$\vec{\nabla} \times \vec{\nabla} \times \vec{h} = -\frac{4\pi}{c}\frac{e^2 n_s}{mc}\vec{h}$$

$$+\nabla^2 \vec{h} = +\frac{4\pi e^2 n_s}{mc^2}\vec{h} = \frac{1}{\lambda_L^2}\vec{h}$$

London Penetration Length

Mak...

microscopic
local B-field
$$h = \vec{\nabla} \times \vec{A}$$

Perfect conductivity

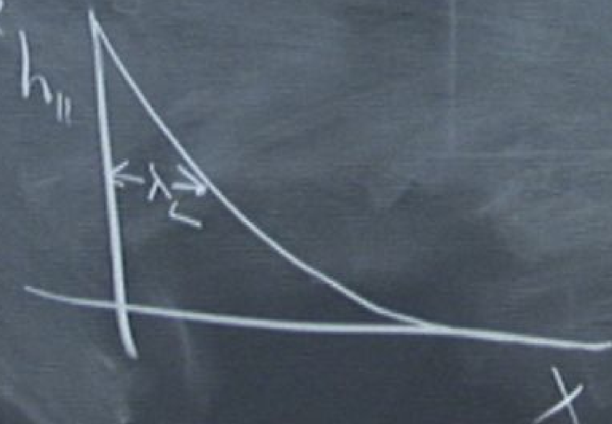
Then

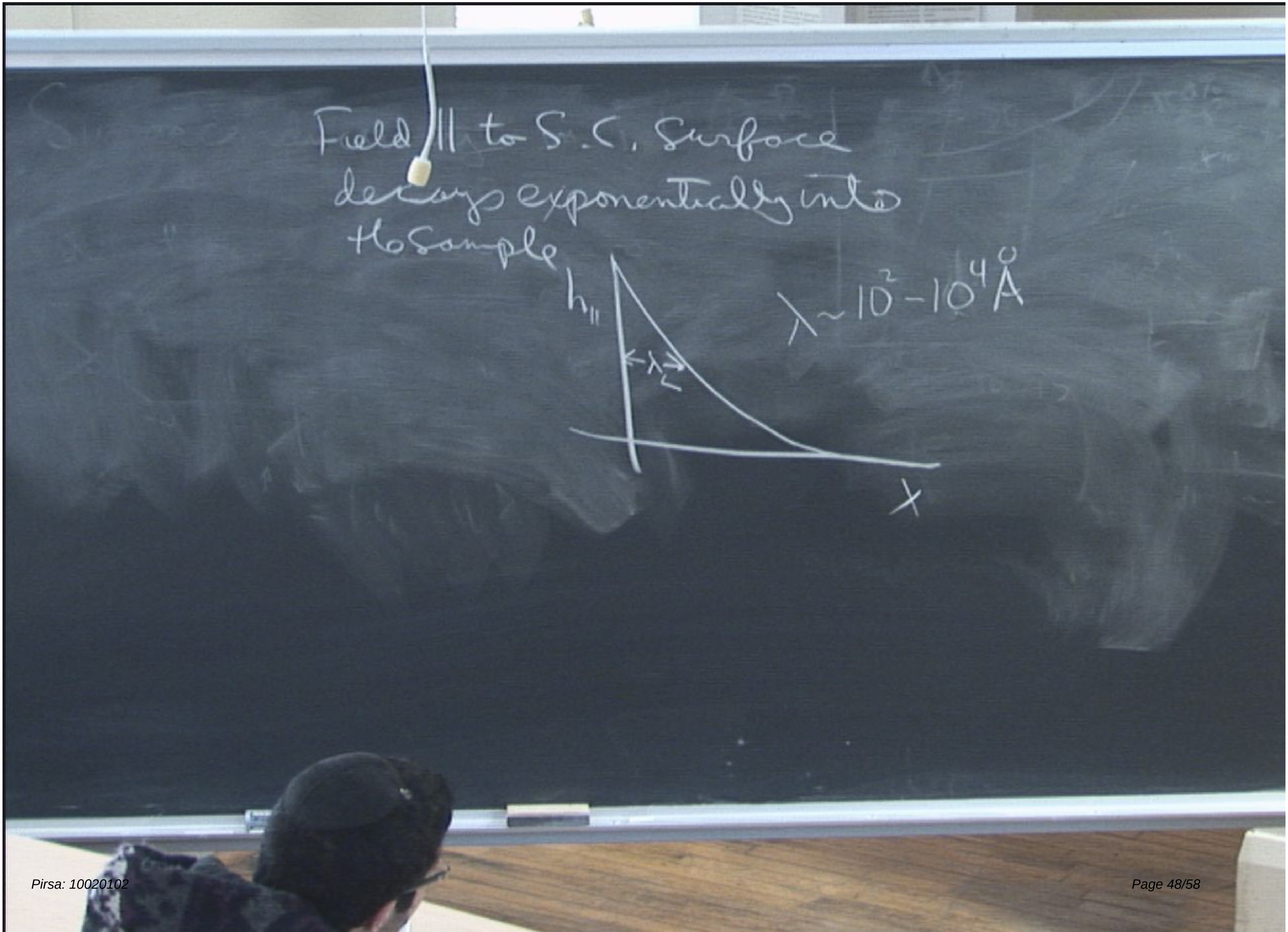
$$\vec{\nabla} \times \vec{J}_S = -\frac{e^2 n_s}{mc} \ldots$$

$$\vec{\nabla} \times \vec{\nabla} \times \vec{h} = - \frac{4\pi}{c} \ldots$$

$$+\nabla^2 \vec{h} = + \frac{4\pi}{m} \ldots$$

Field $\parallel$ to S.C. surface
decays exponentially into
the sample




Field || to S.C. surface
decays exponentially into
the sample
$h_{\parallel}$
λ_L
$\lambda \sim 10^2 - 10^4$ Å
x

From Maxwell

$$\vec{\nabla} \times \vec{h} = \frac{4\pi \vec{J}}{c}$$

$$\vec{h}$$

$$\frac{4\pi e^2 n_s}{mc} \vec{h}$$

$$\frac{4\pi e^2 n_s}{mc^2} \vec{h} = \frac{1}{\lambda_L^2} \vec{h}$$

London Penetration Length

London Equations

Conjectured

$$\langle \vec{p} \rangle_{S.C.} = 0 = m\langle \vec{v}_s \rangle + \frac{e\vec{A}}{c}$$

S.C. Ground State

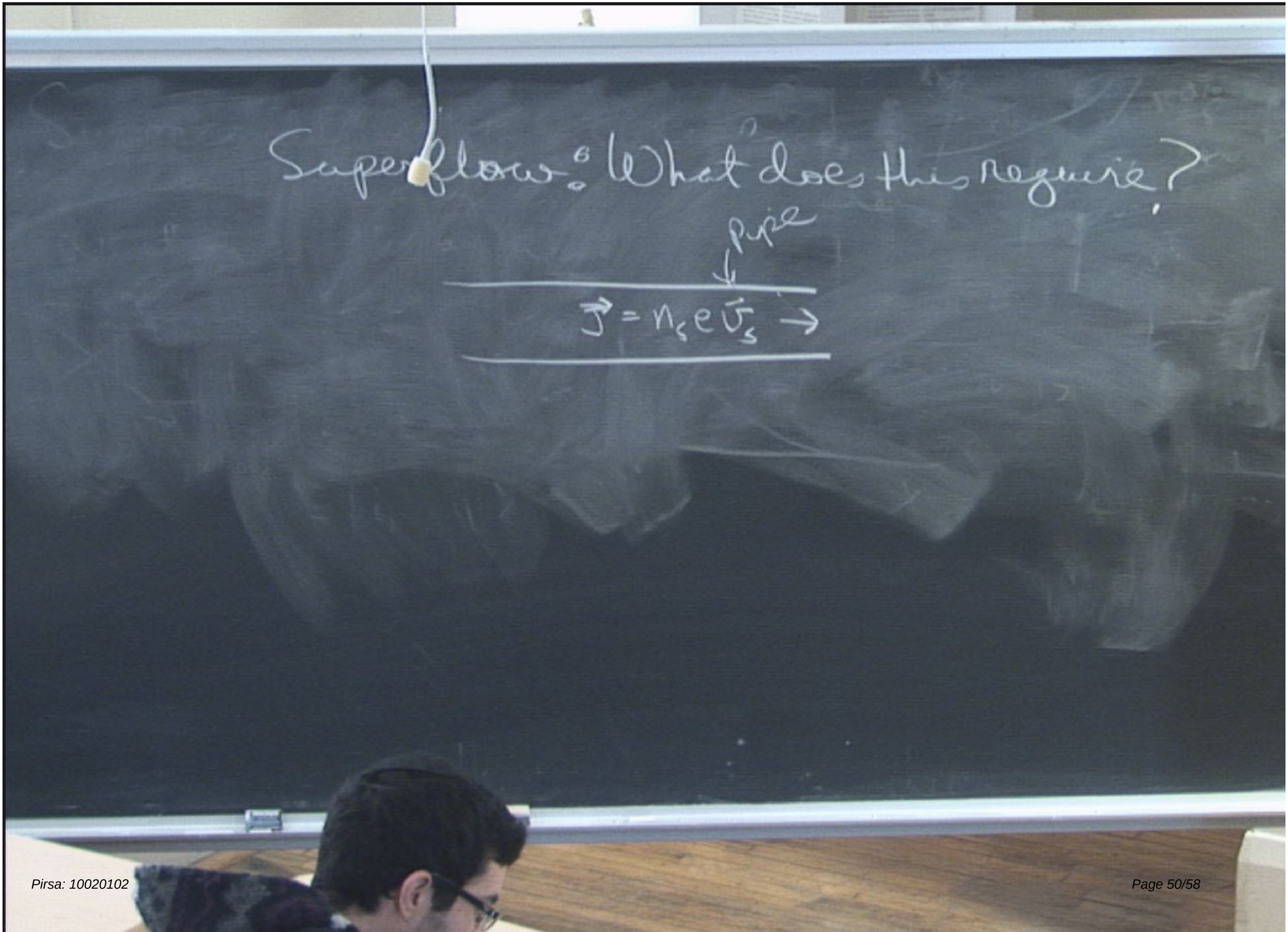
Ignore S.C.

$$\therefore \vec{J}_s = e n_s \langle \vec{v}_s \rangle = -\frac{e^2 n_s \vec{A}}{mc}$$

Supercurrent density

Makes sense London gauge

$\vec{\nabla} \cdot \vec{A} = 0$ and $\vec{A} \to 0$ inside

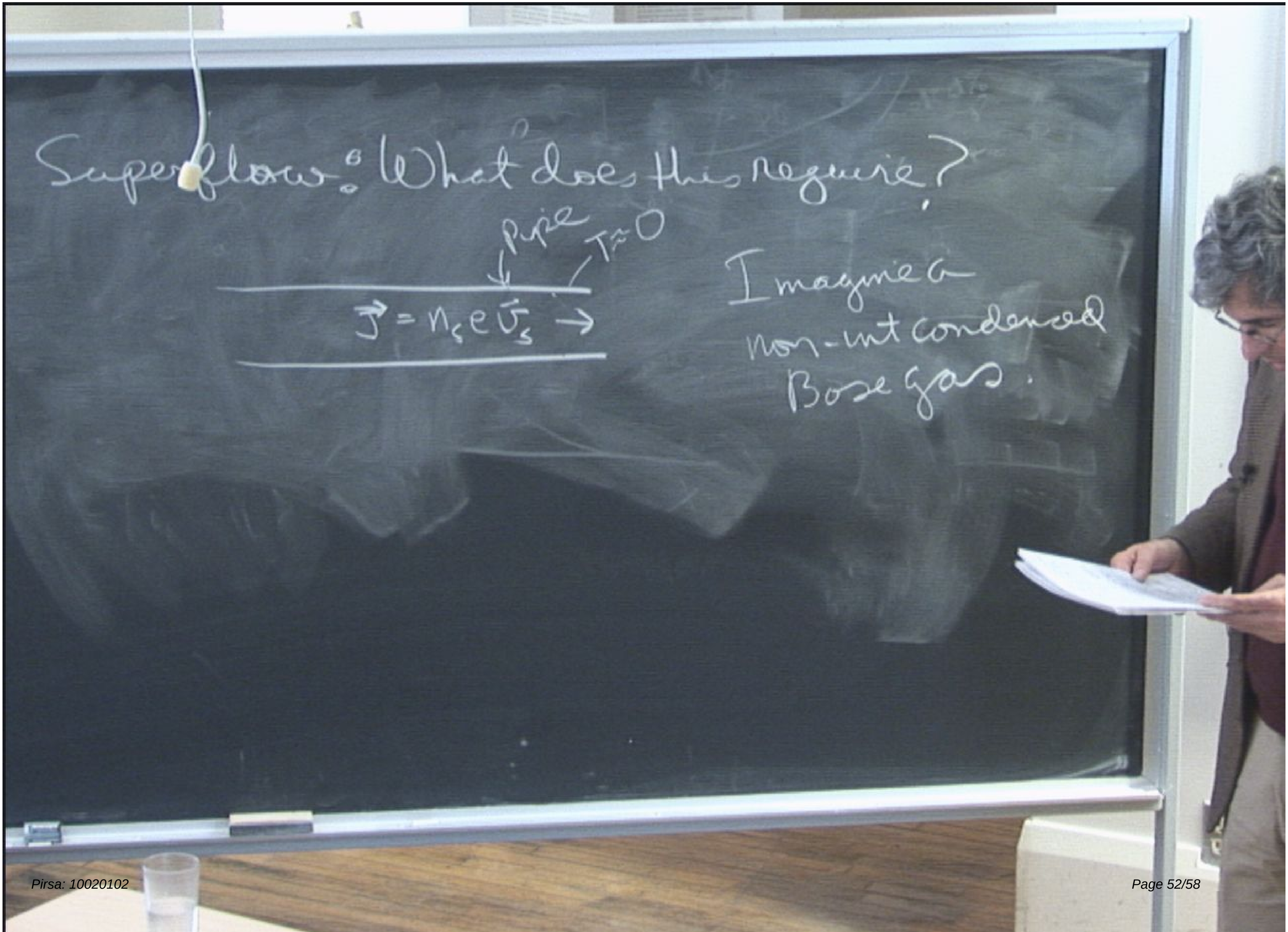

Superflow: What does this require?
pipe
$\vec{J} = n_s e \vec{v}_s \rightarrow$

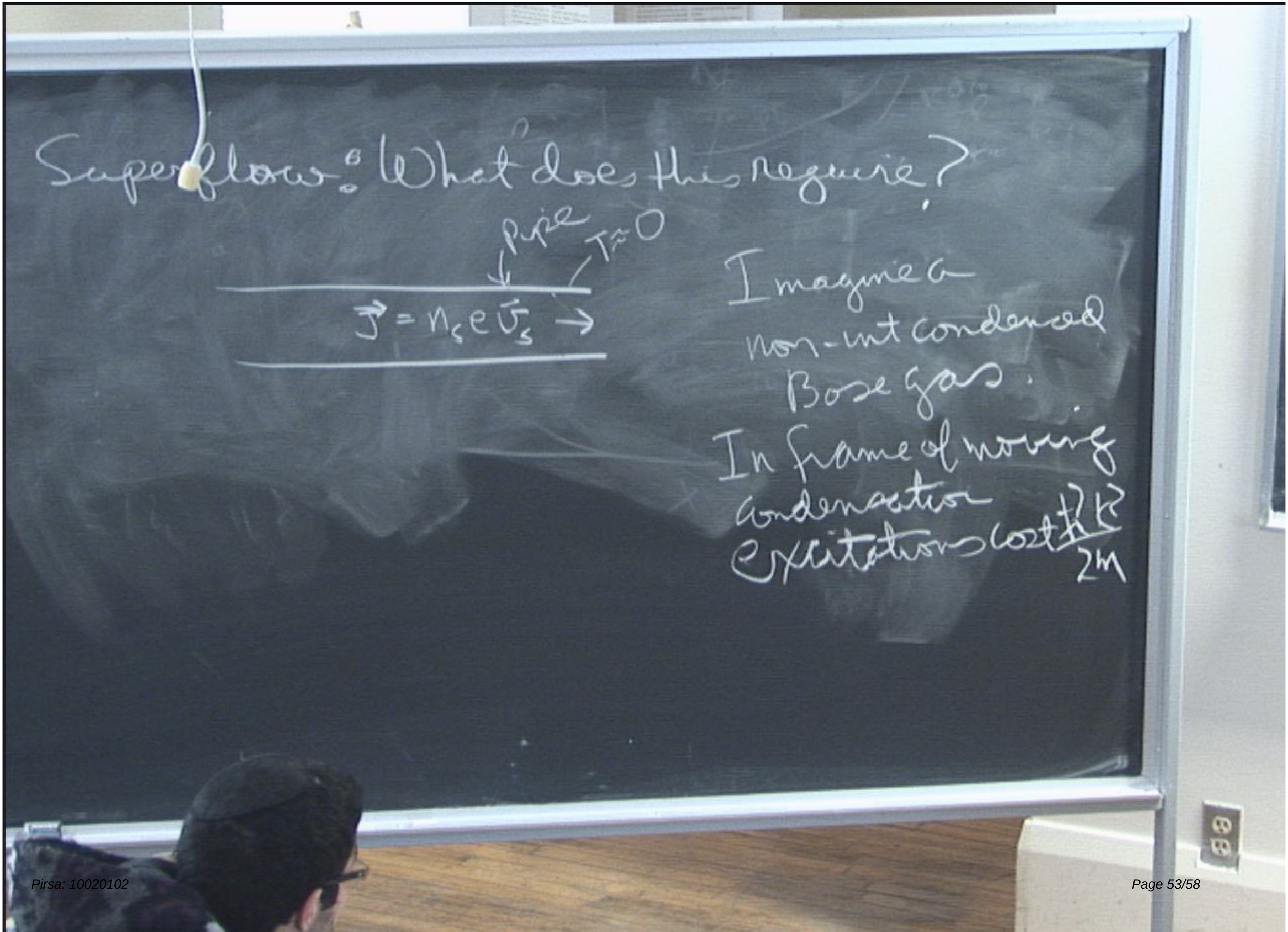
Superflow: What does this require?

pipe

$T \approx 0$

$\vec{J} = n_s e \vec{v}_s \rightarrow$


Superflow: What does this require?
pipe
T≈0
J = n_s e v_s →
Imagine a
non-int condensed
Bose gas.


Superflow: What does this require?
pipe
$T \approx 0$
$\vec{J} = n_s e \vec{v}_s \rightarrow$
Imagine a
non-int condensed
Bose gas:
In frame of moving
condensation
excitations cost $\frac{\hbar^2 k^2}{2m}$

Superflow: What does this require?

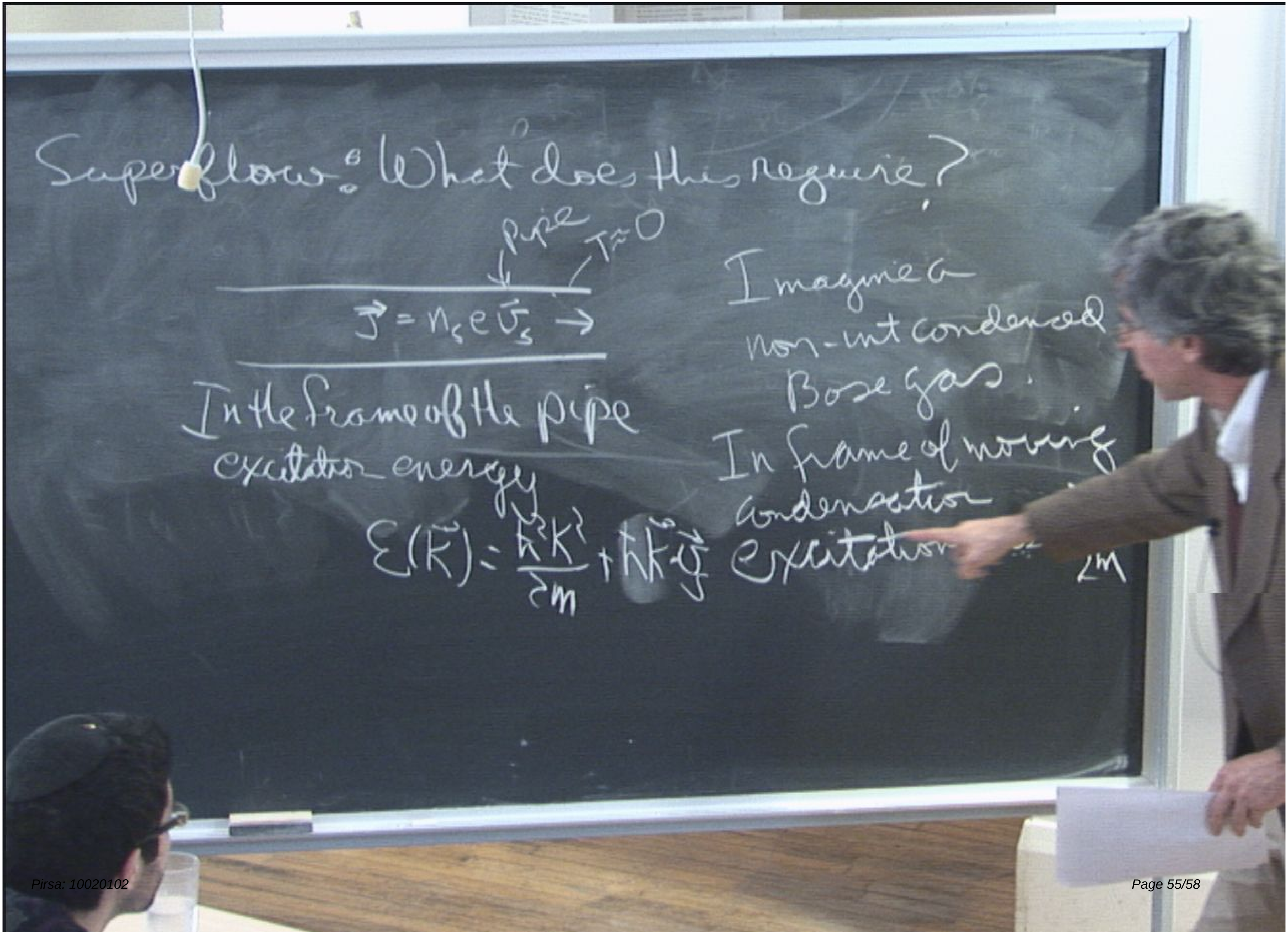
pipe

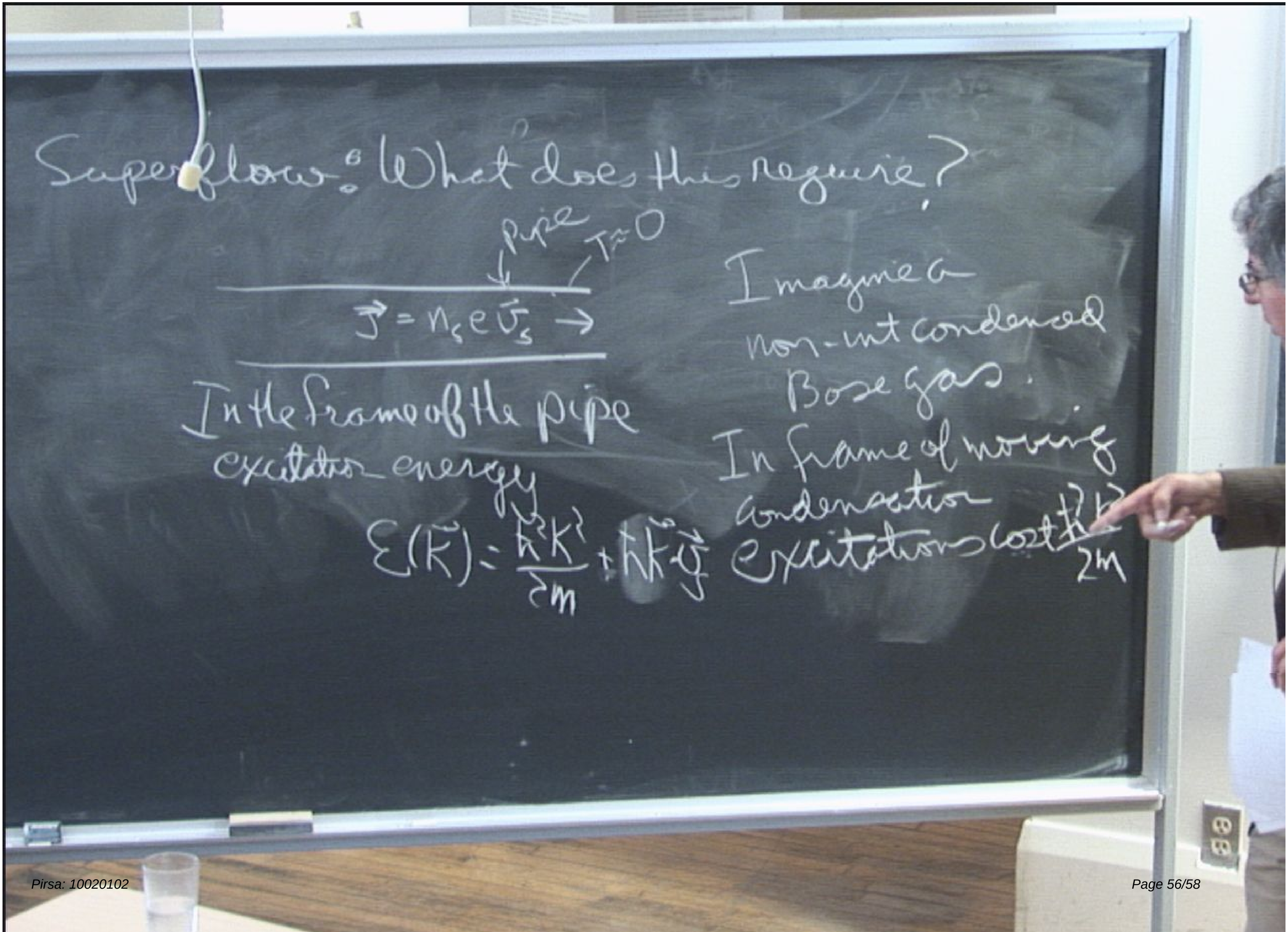
$T \approx 0$

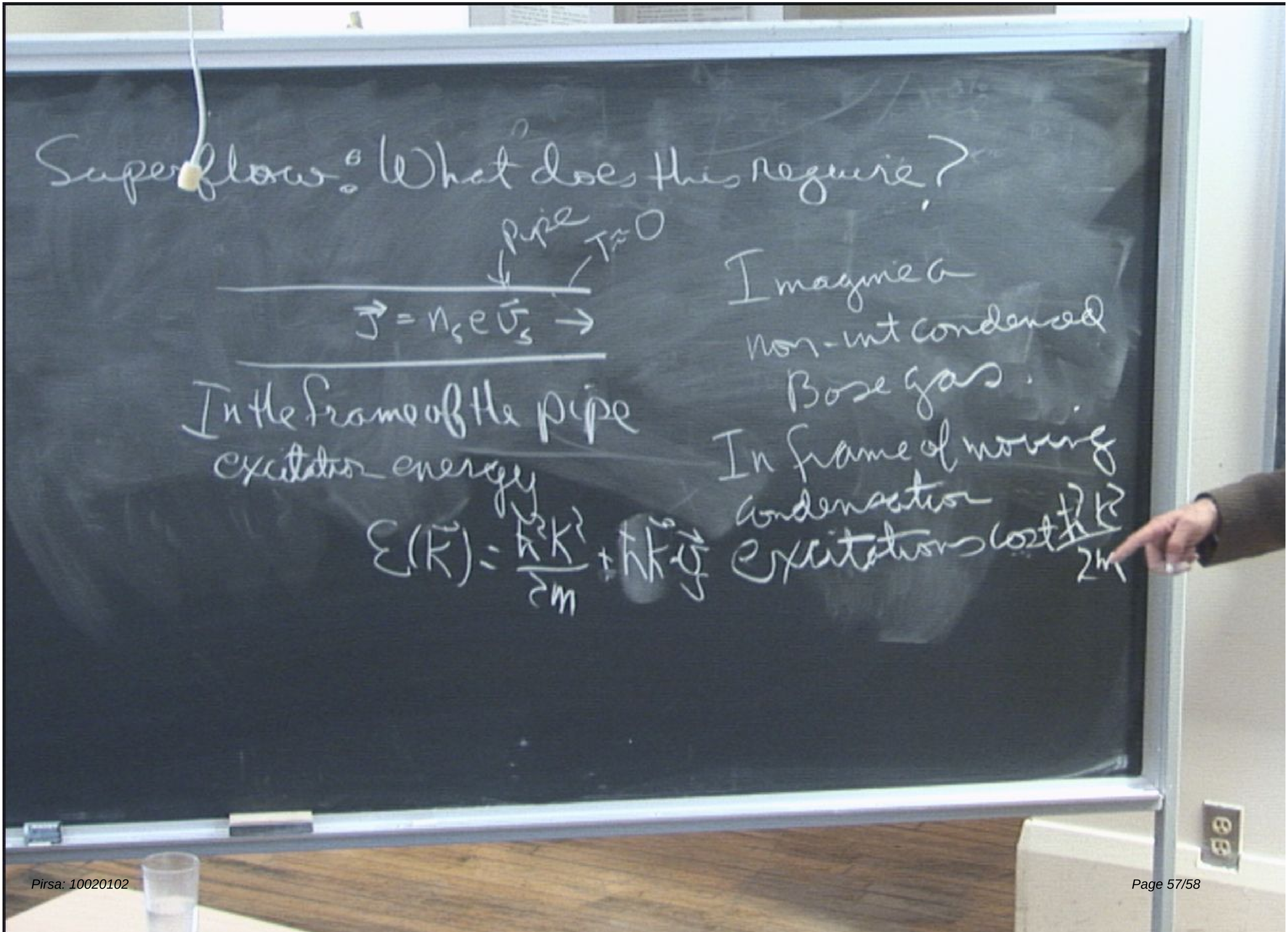
$\vec{J} = n_s e \vec{v}_s \rightarrow$

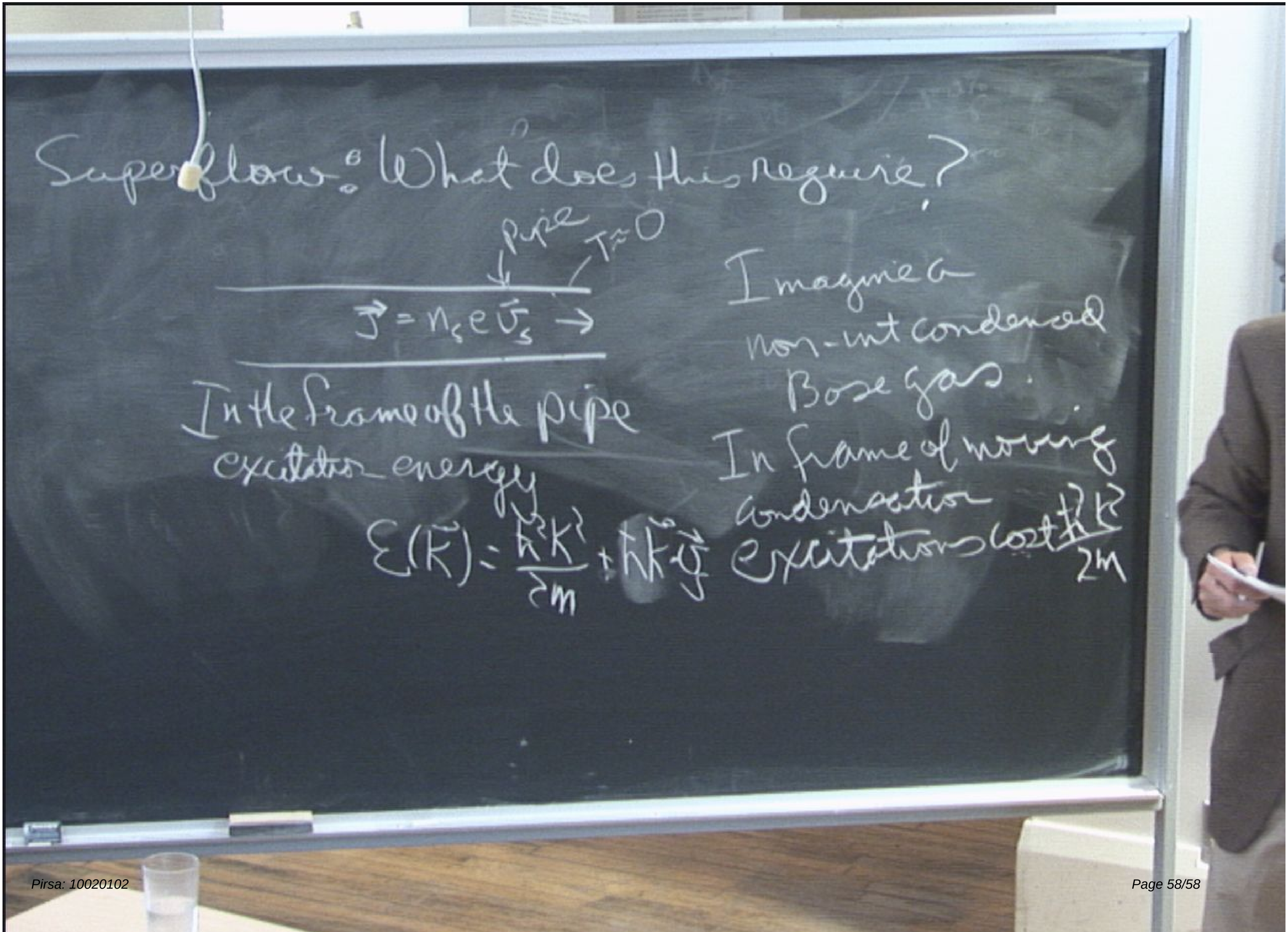
Imagine a
non-int condensed
Bose gas:

In frame of moving
condensation
excitations cost $\frac{\hbar^2 k^2}{2m}$


Superflow: What does this require?
pipe
T ≈ 0
$\vec{J} = n_s e \vec{v}_s$
In the frame of the pipe
excitation energy
$\mathcal{E}(\vec{k}) = \frac{\hbar^2 k^2}{2m} + \hbar \vec{k} \cdot \vec{v}$
Imagine a
non-int condensed
Bose gas.
In frame of moving
condensation
excitation
2m


Superflow: What does this require?
pipe
T≈0
$\vec{J} = n_s e \vec{v}_s \rightarrow$
In the frame of the pipe
excitation energy
$\mathcal{E}(\vec{k}) = \frac{\hbar^2 k^2}{2m} + \hbar\vec{k}\cdot\vec{v}$
Imagine a
non-int condensed
Bose gas.
In frame of moving
condensation
excitations cost $\frac{\hbar^2 k^2}{2m}$


Superflow: What does this require?
pipe
$T \approx 0$
$\vec{J} = n_s e \vec{v}_s$
In the frame of the pipe
excitation energy
$\varepsilon(\vec{k}) = \frac{\hbar^2 k^2}{2m} + \hbar \vec{k} \cdot \vec{v}$
Imagine a
non-int condensed
Bose gas.
In frame of moving
condensate
excitations cost $\frac{\hbar^2 k^2}{2m}$


Superflow: What does this require?
pipe
$T \approx 0$
$\vec{J} = n_s e \vec{v}_s \rightarrow$
In the frame of the pipe
excitation energy
$\mathcal{E}(\vec{k}) = \frac{\hbar^2 k^2}{2m} + \hbar \vec{k} \cdot \vec{v}$
Imagine a
non-int condensed
Bose gas.
In frame of moving
condensation
excitations cost $\frac{\hbar^2 k^2}{2m}$