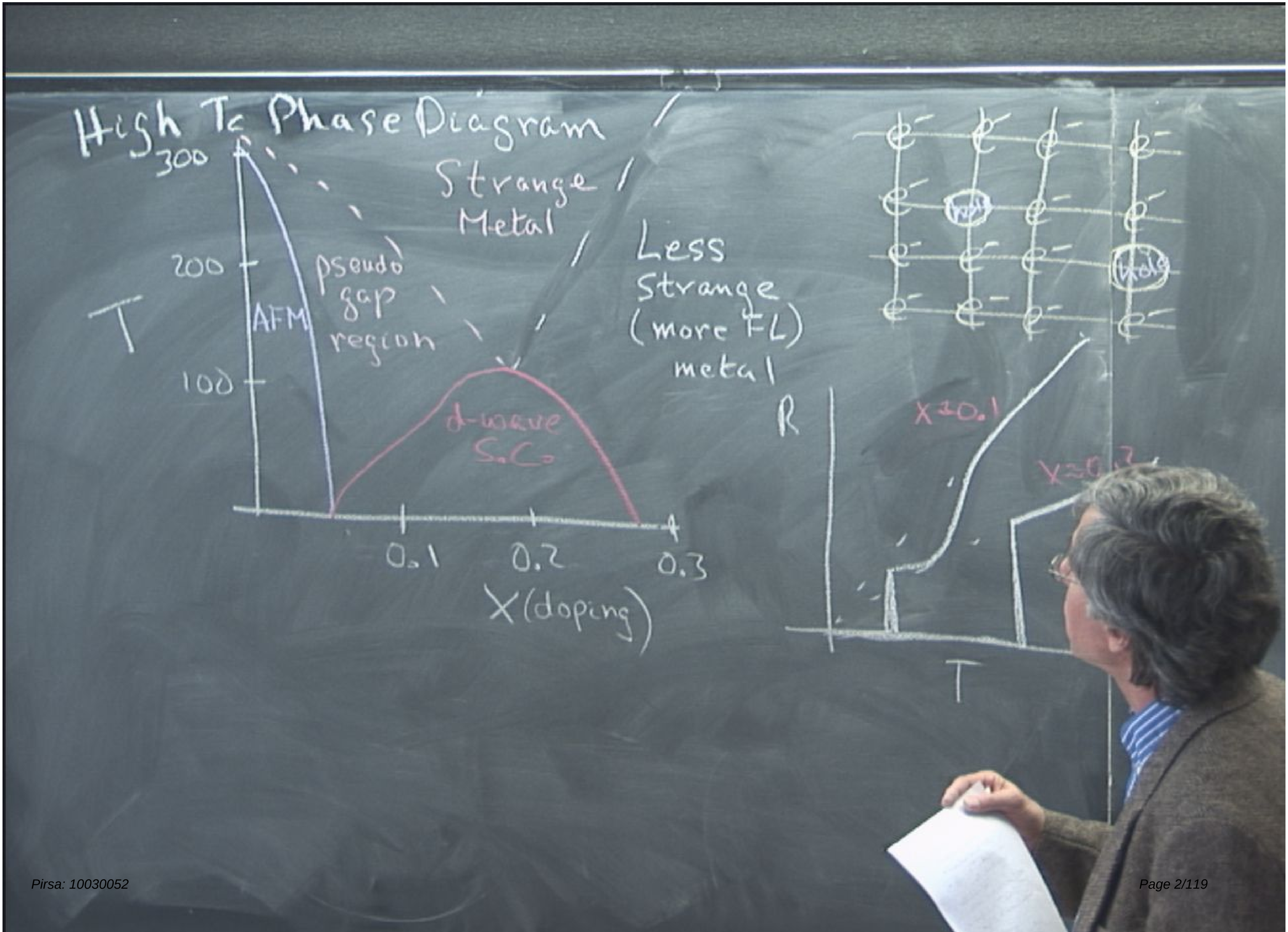
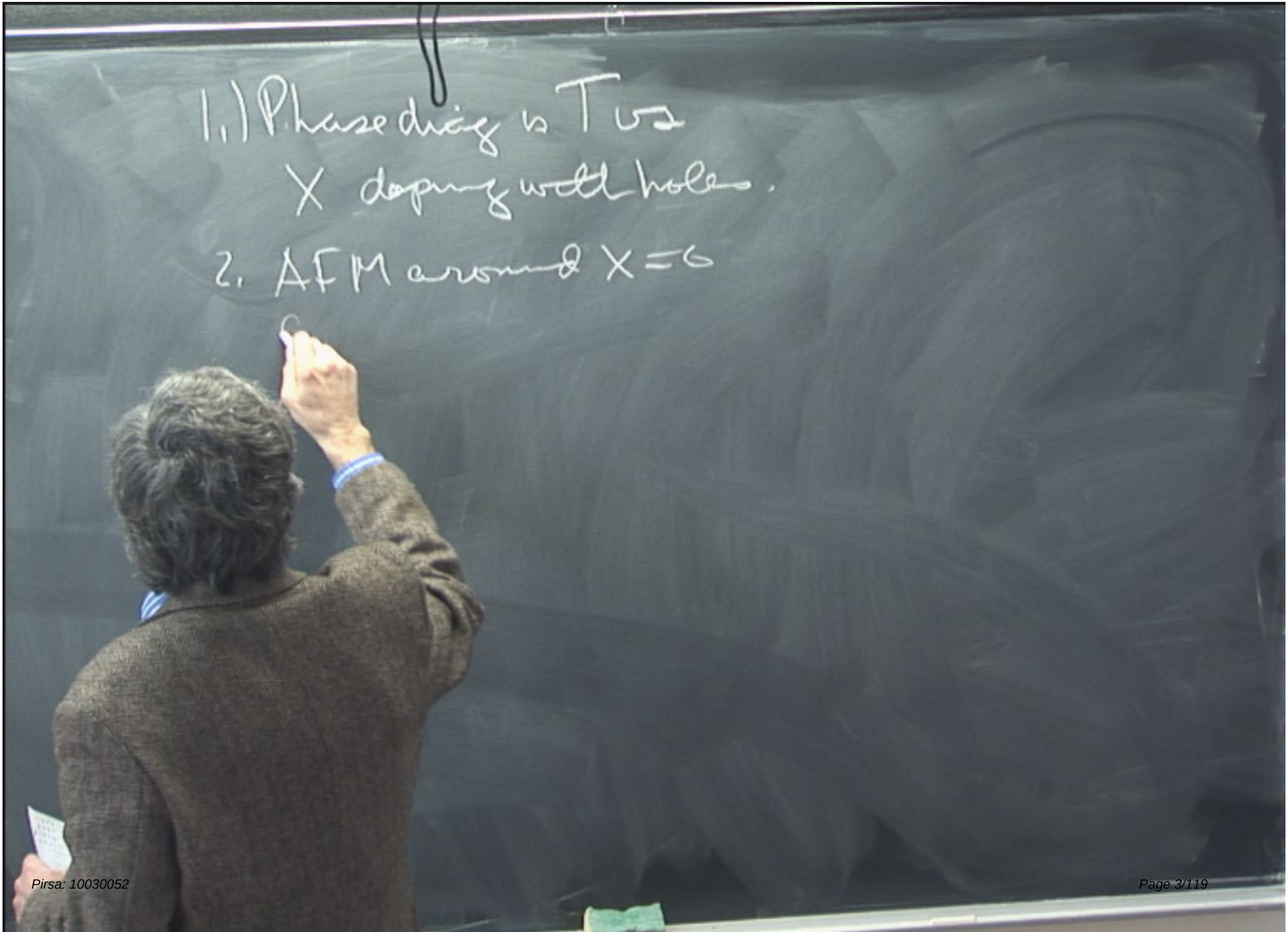
Title: Condensed Matter II - Lecture 14

Date: Mar 05, 2010 11:10 AM

URL: http://pirsa.org/10030052

Abstract:


High Tc Phase Diagram
300
200
100
T
AFM
pseudo gap region
Strange Metal
Less Strange (more FL) metal
d-wave S.C.
0.1
0.2
0.3
X (doping)
R
T
X≈0.1
hole


1.) Phase diag is T vs
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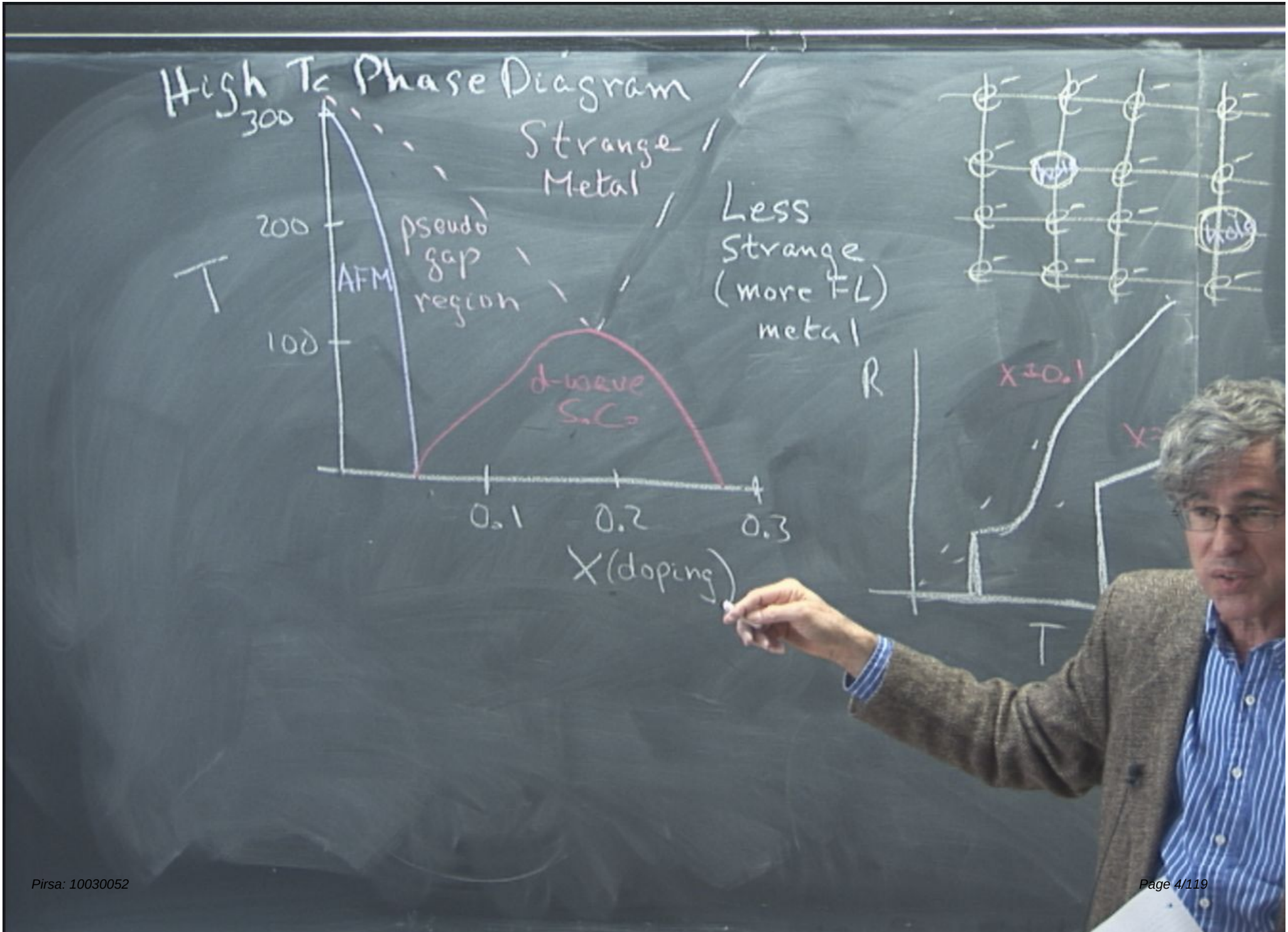
2. AFM around X=0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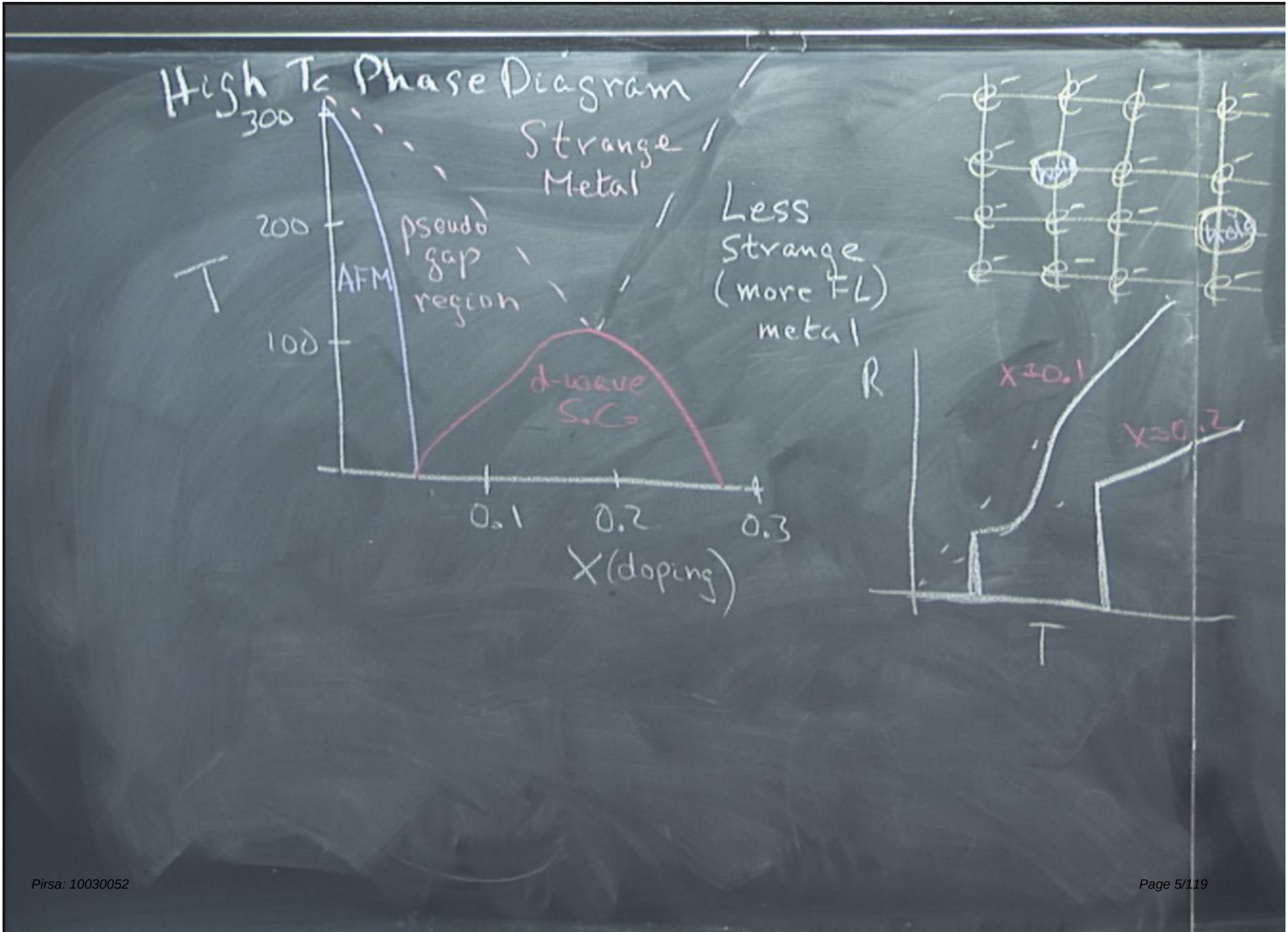
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2. AFM around X=0
quickly destroyed by hole

3. d-wave S.c.
n_s, and $T_c \to 0$ at
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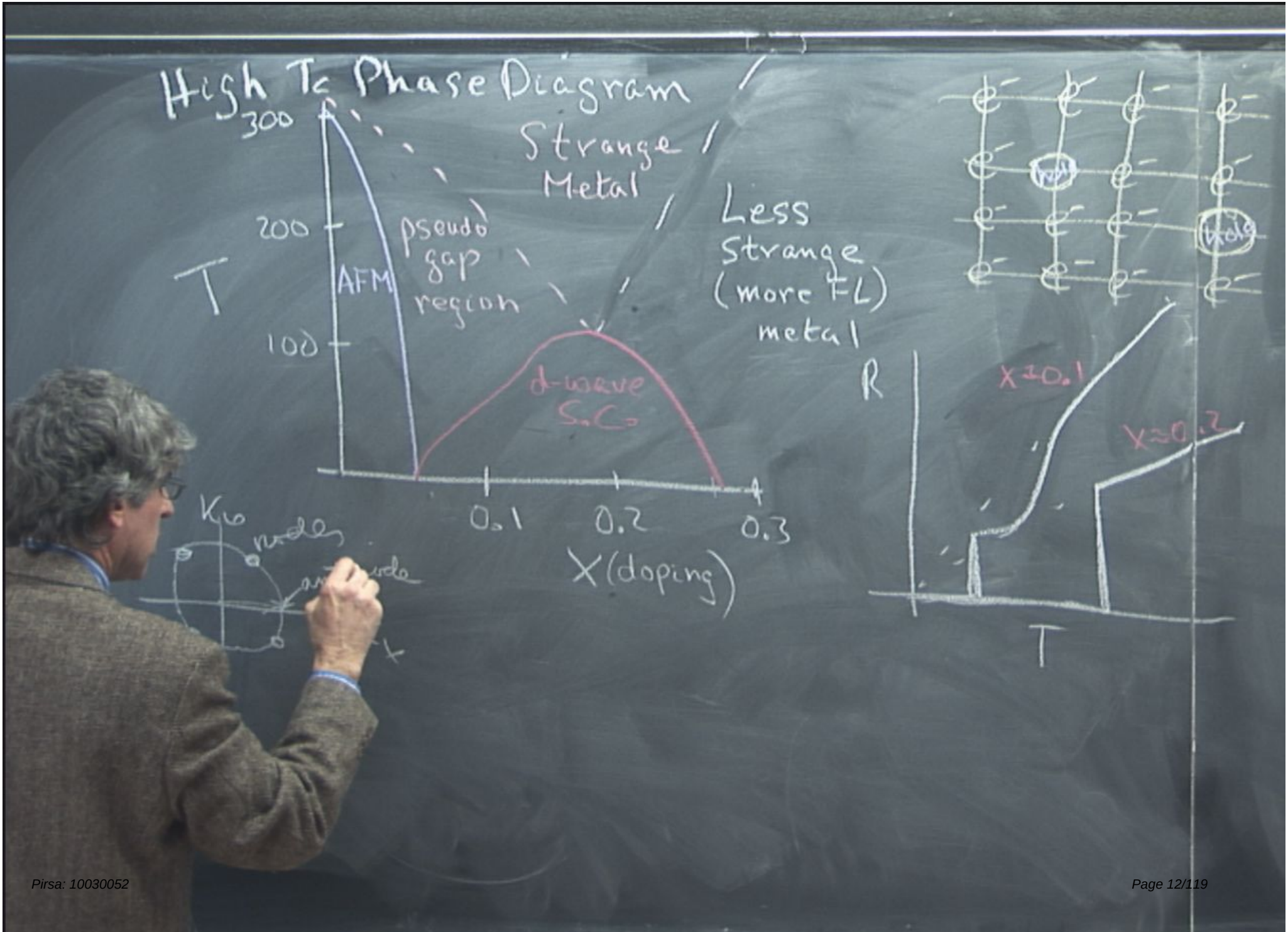
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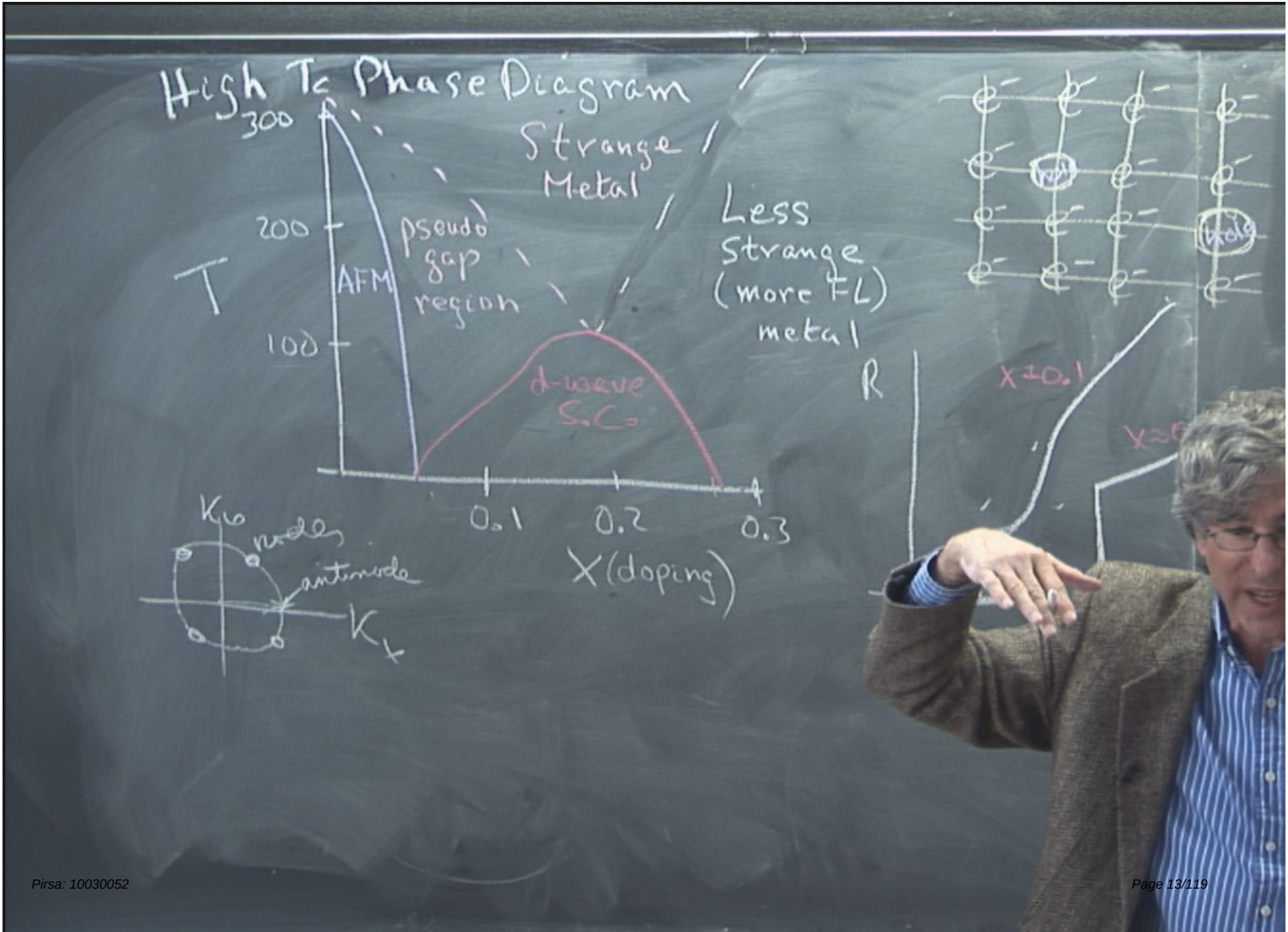
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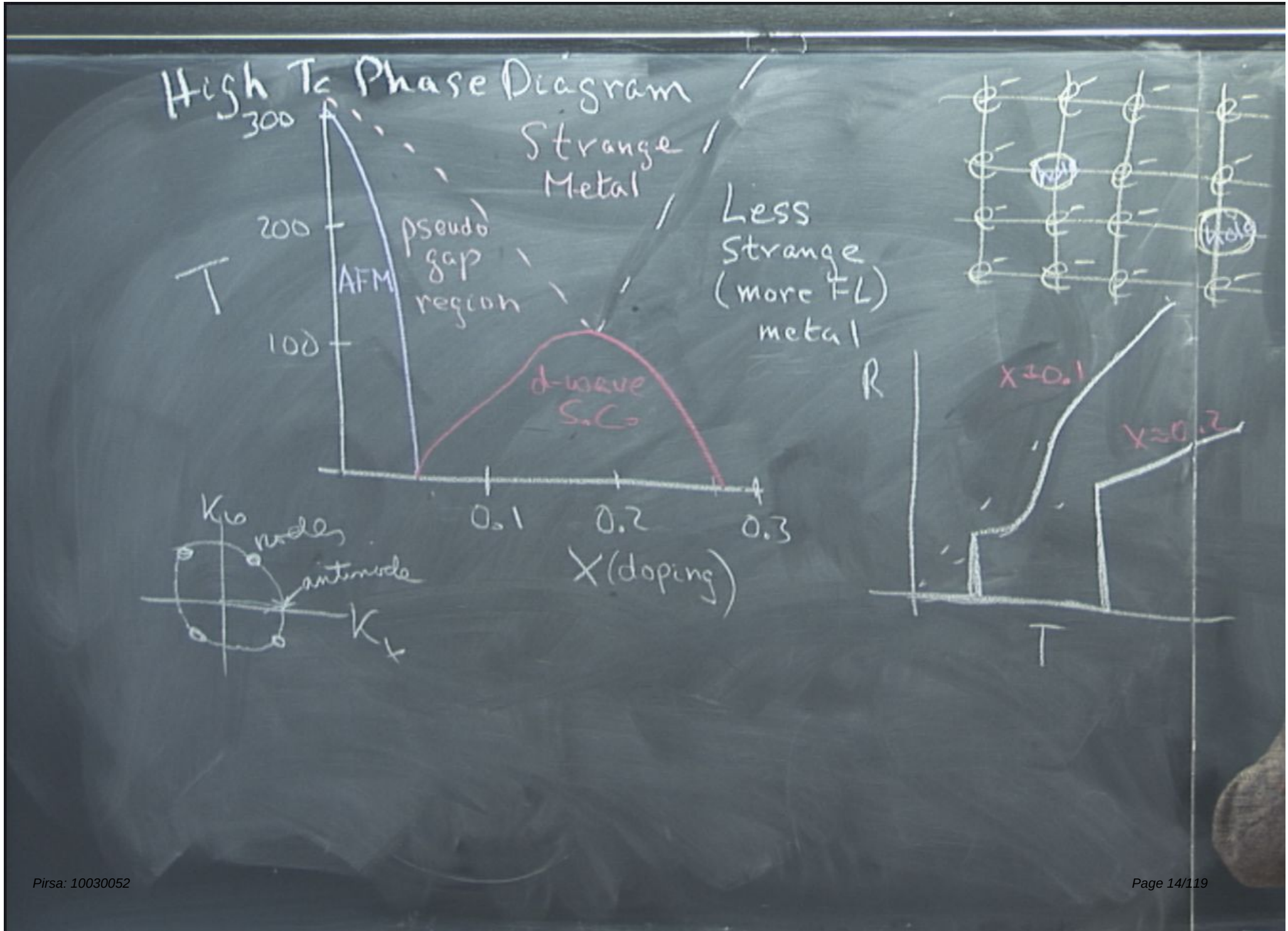
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K_1
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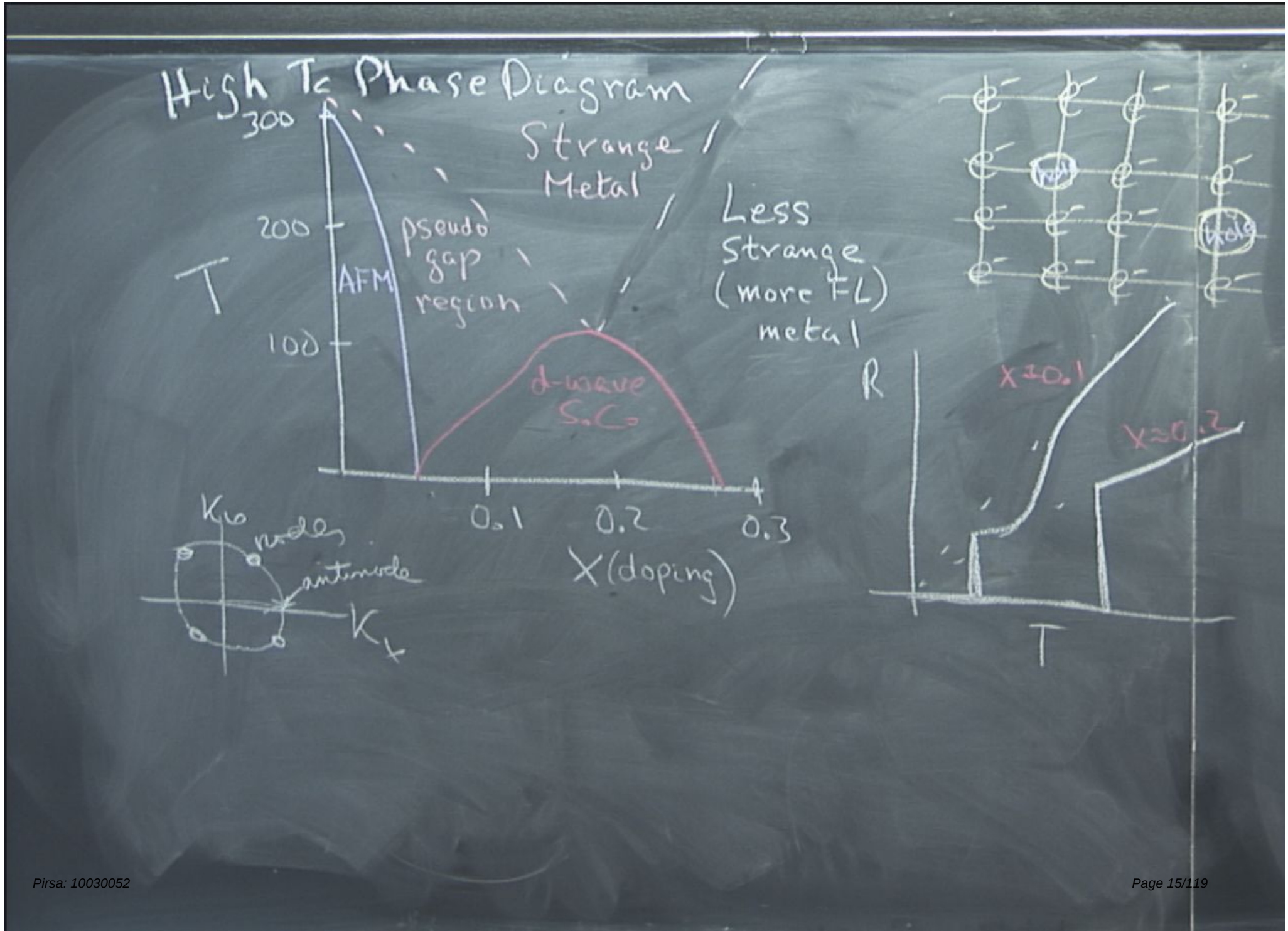
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K_t
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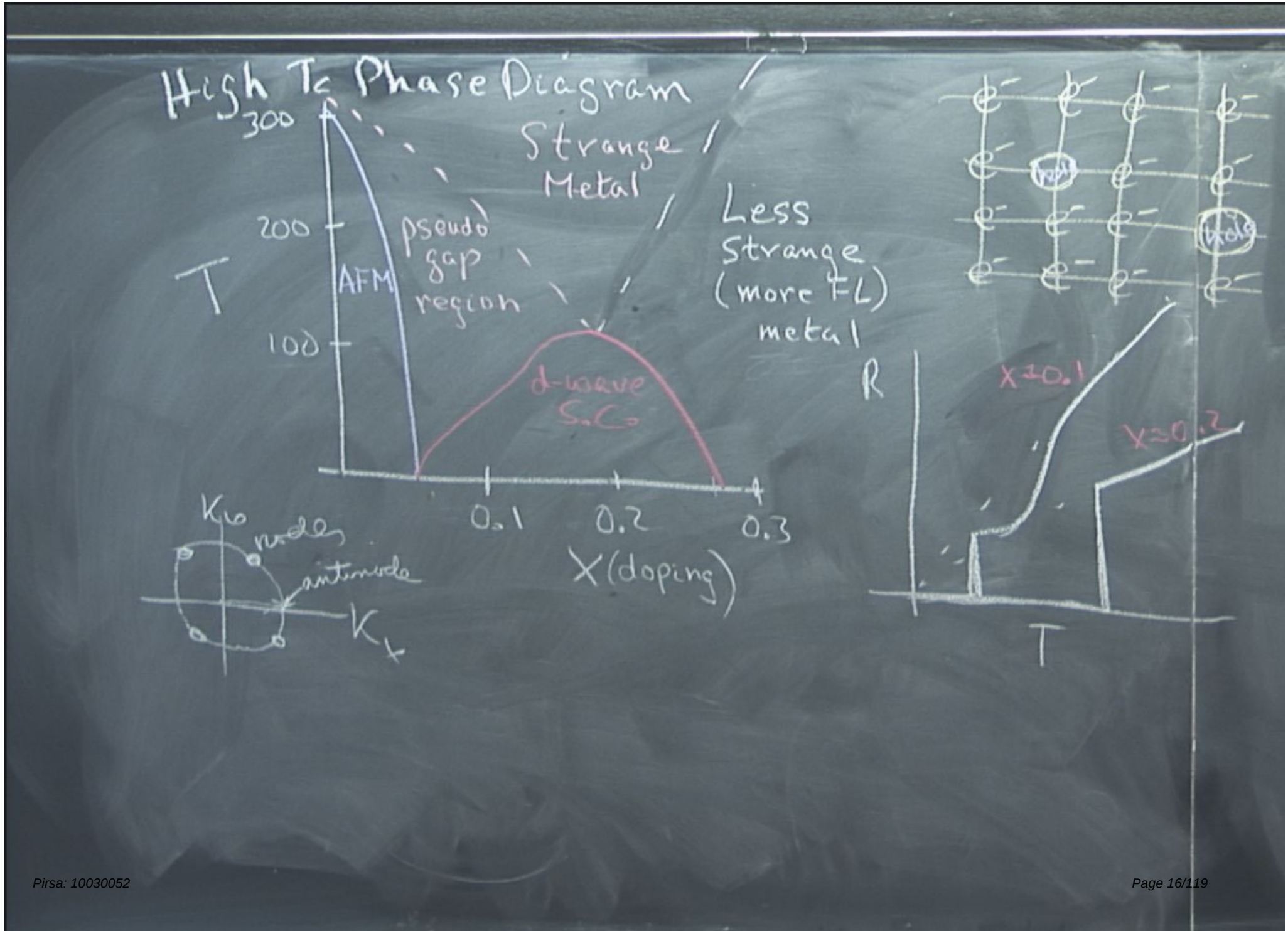
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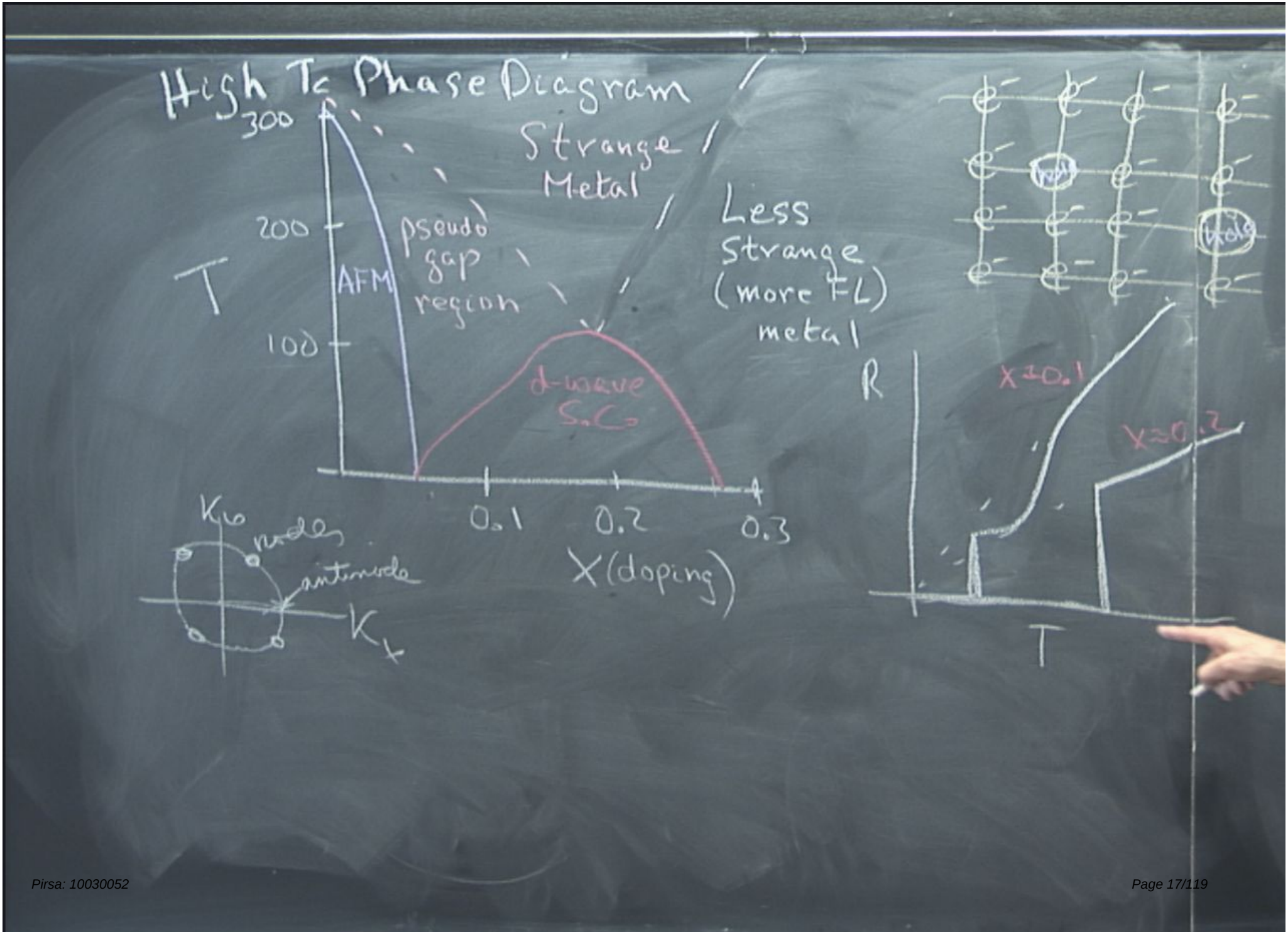
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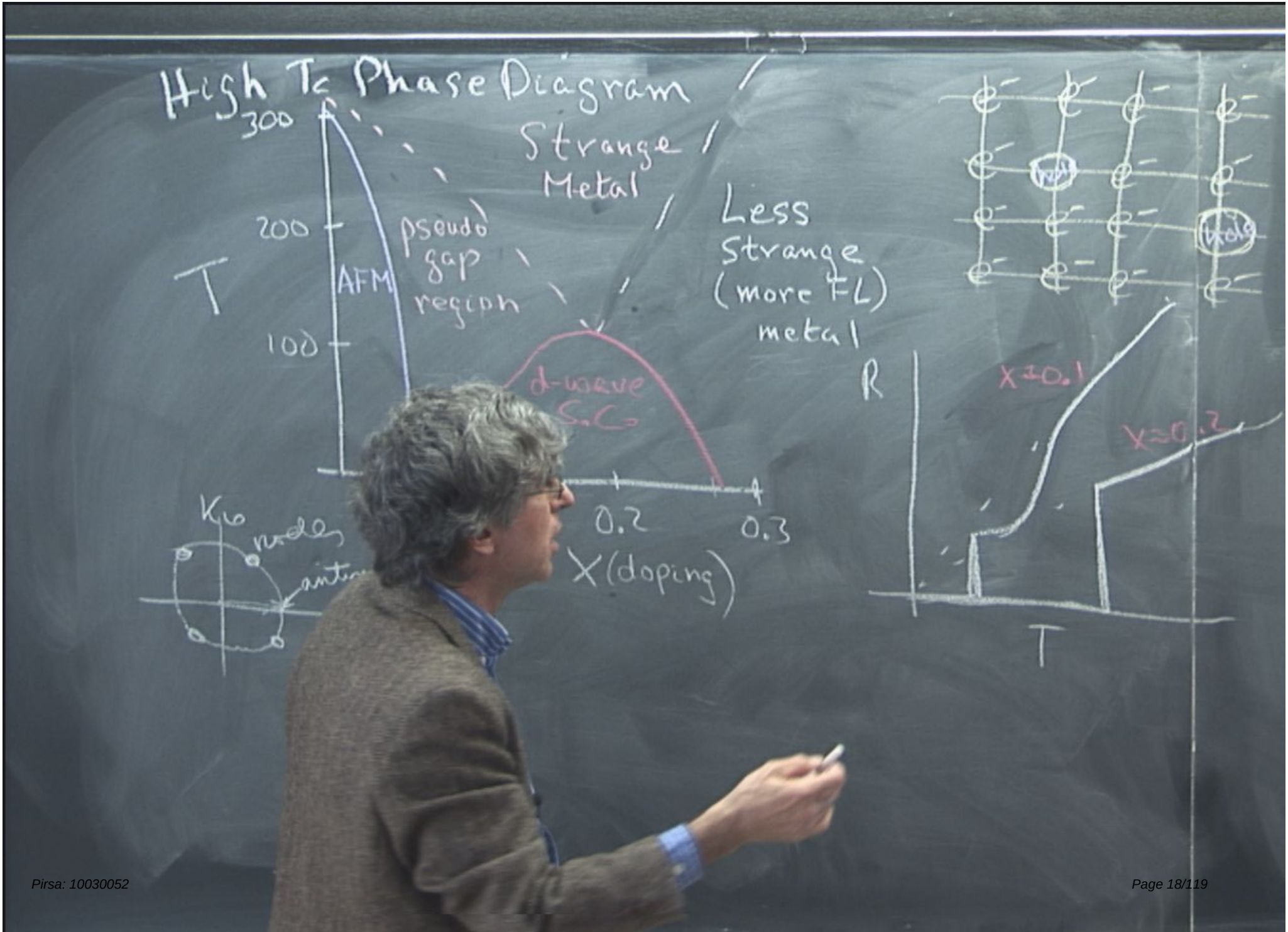
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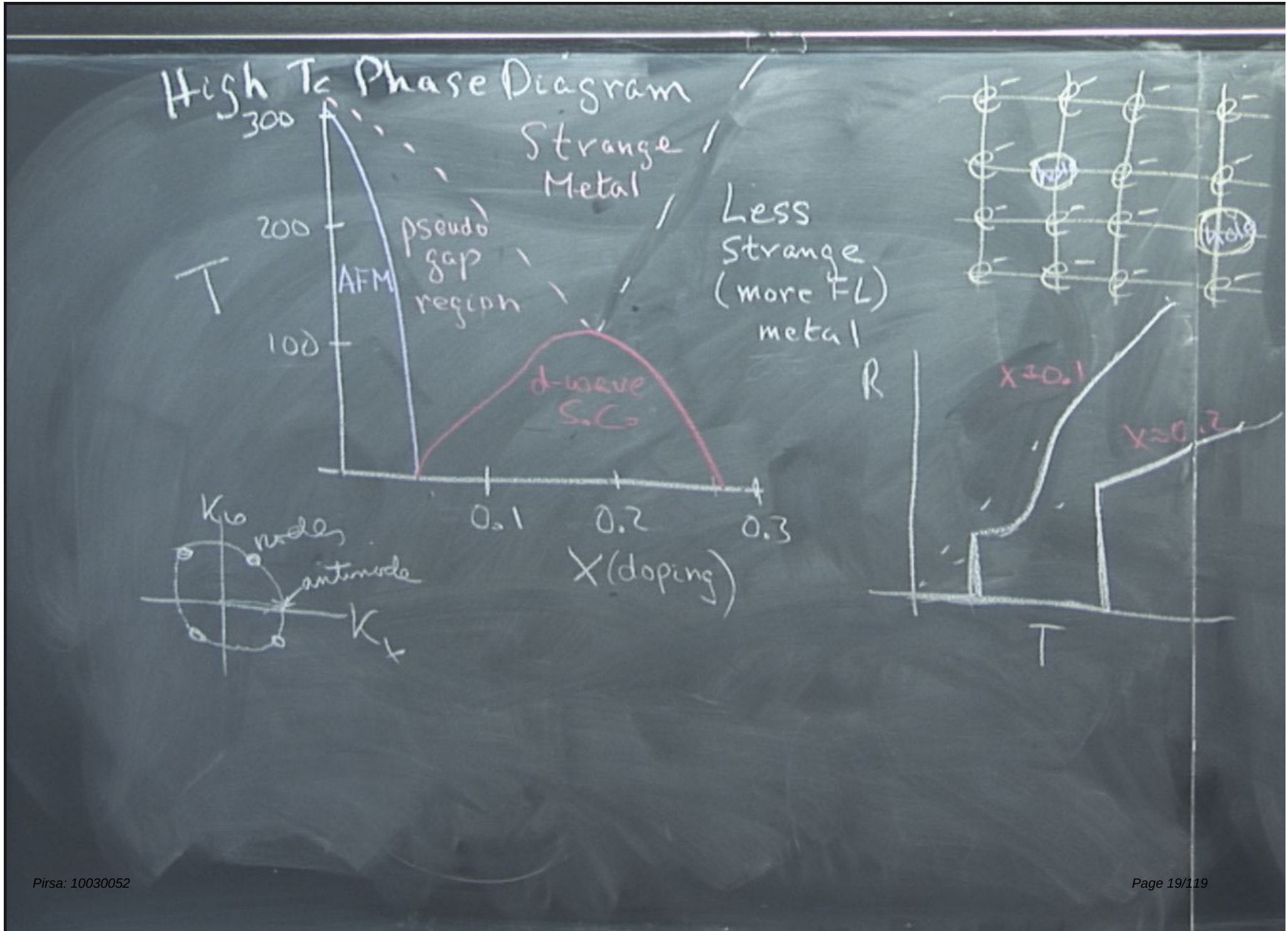
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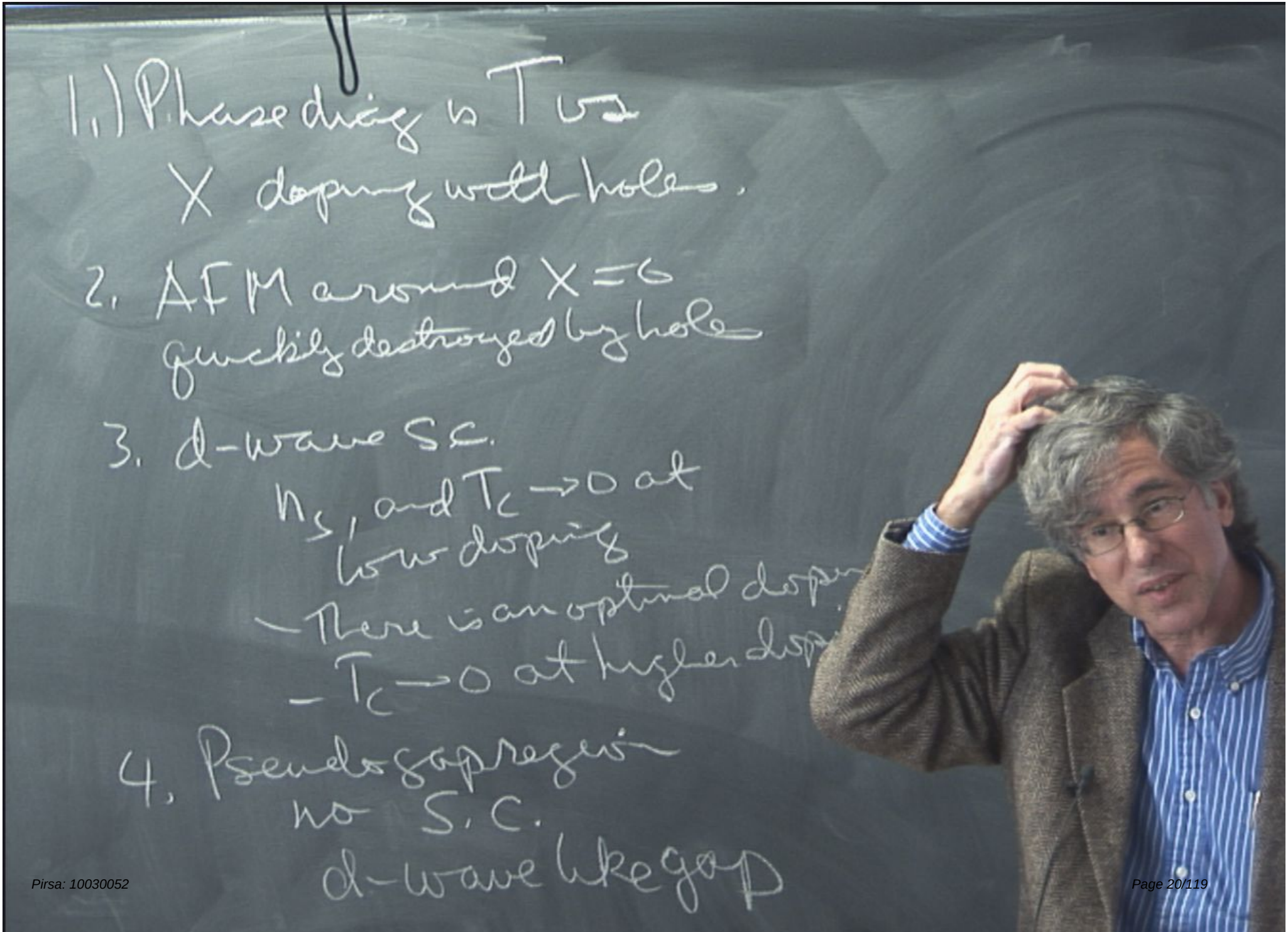
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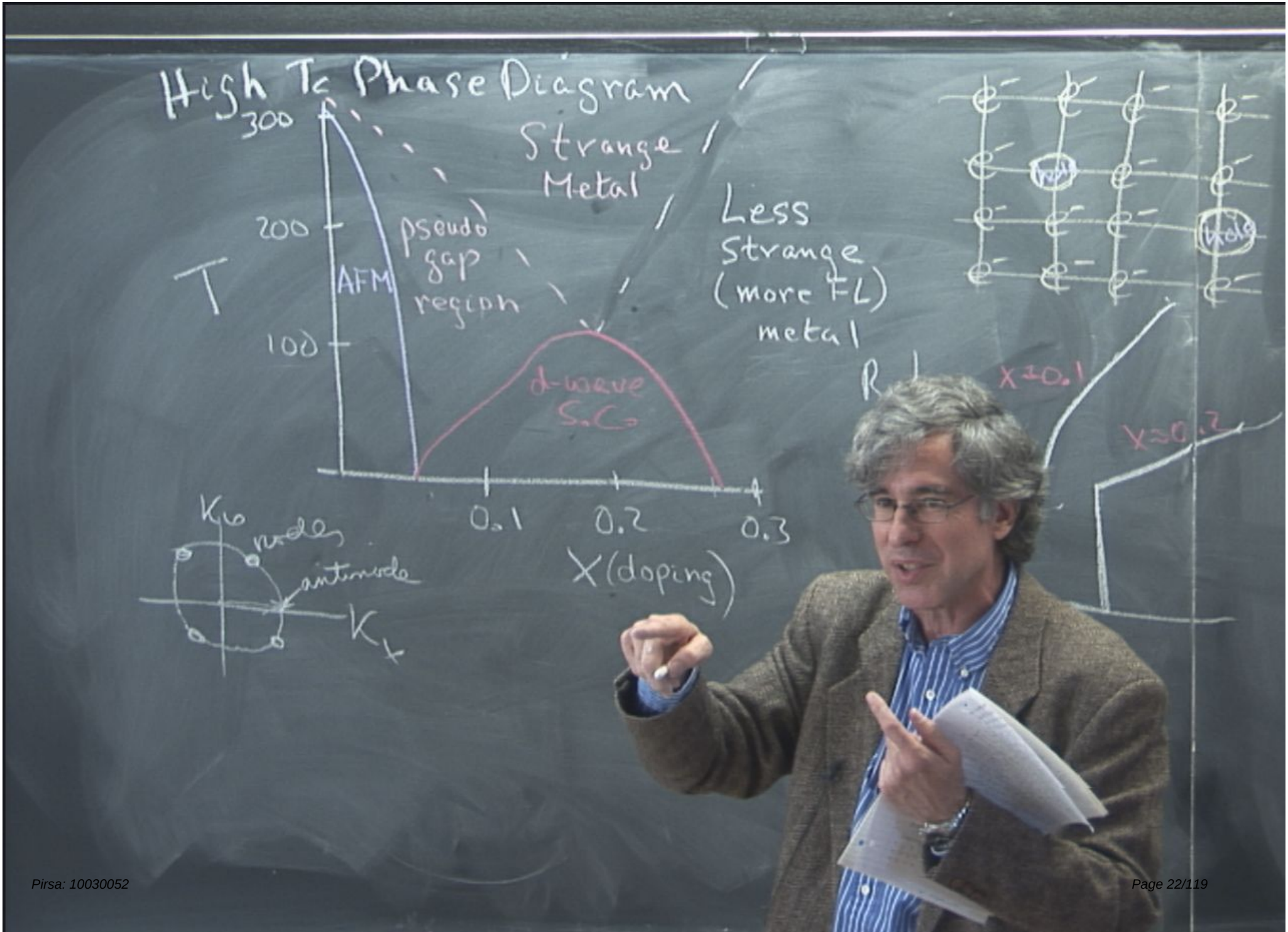
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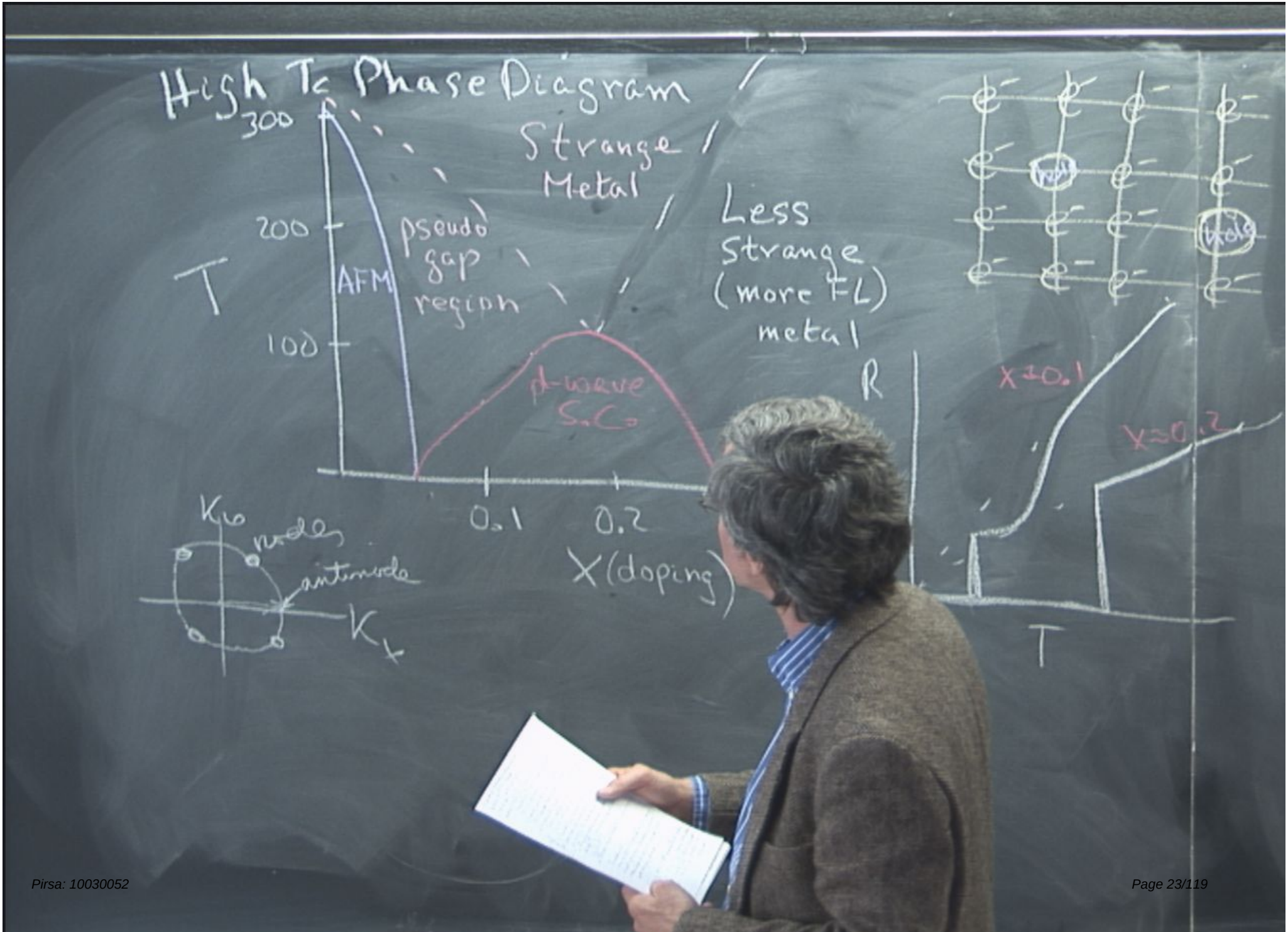
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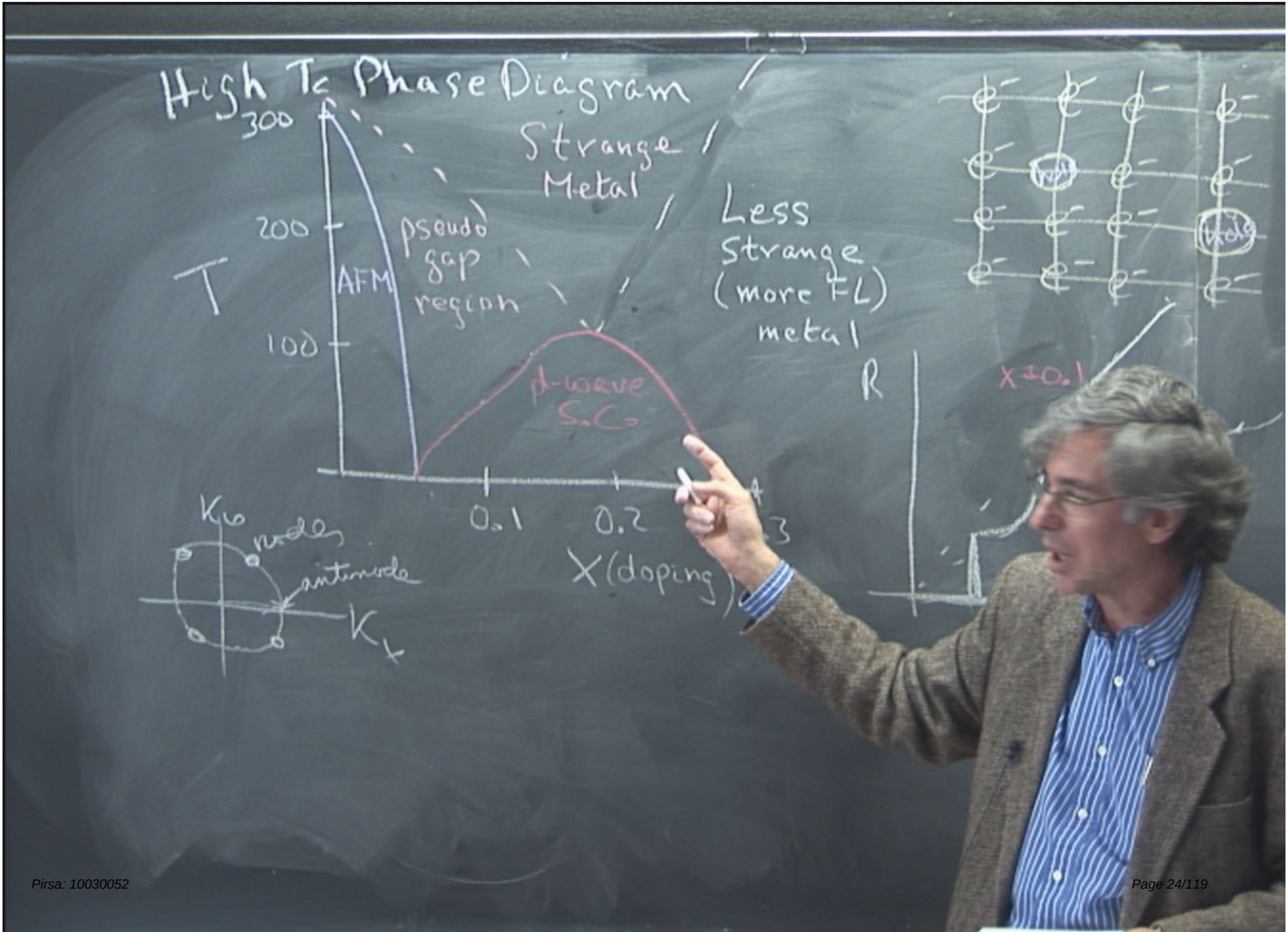
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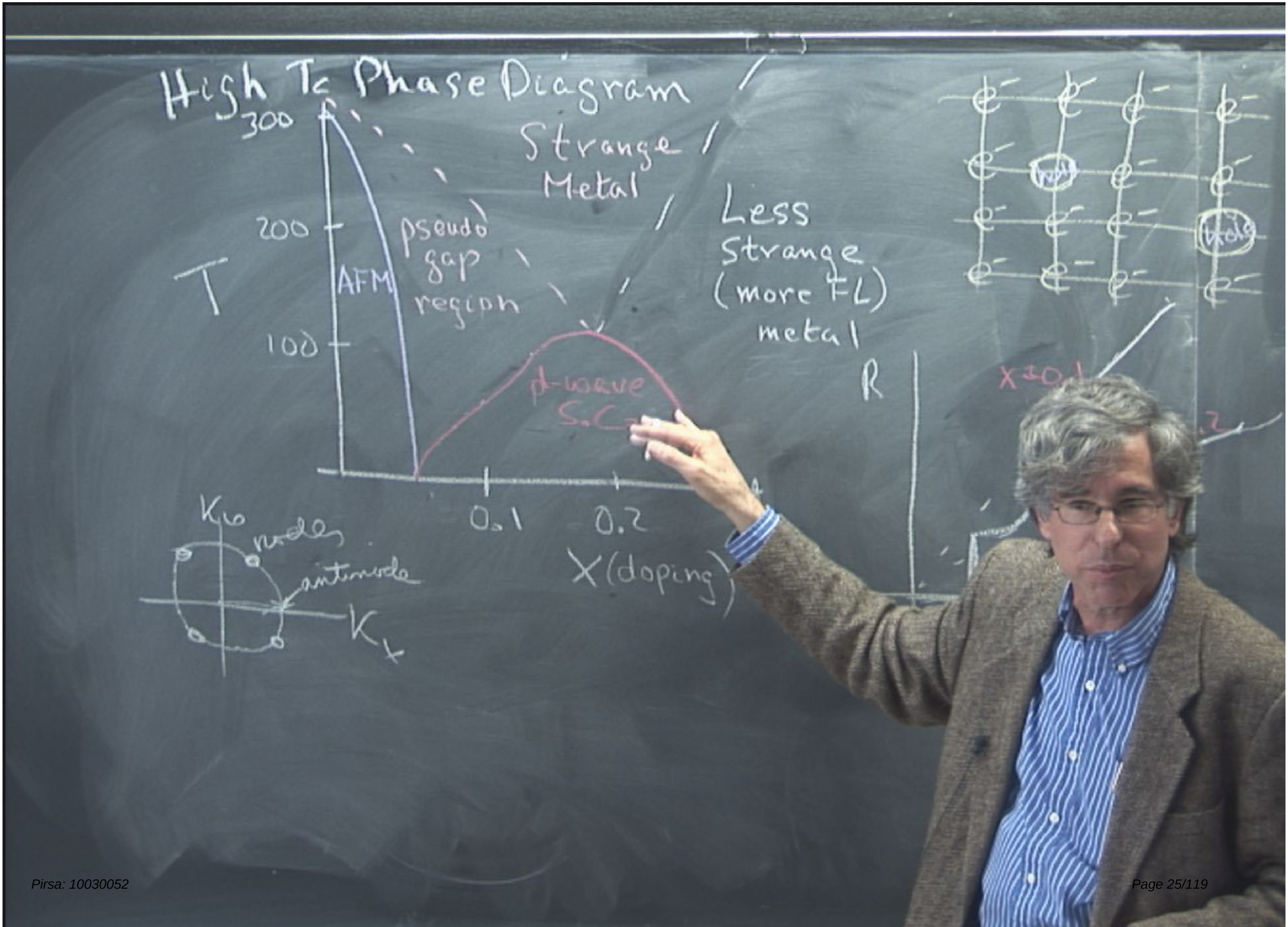
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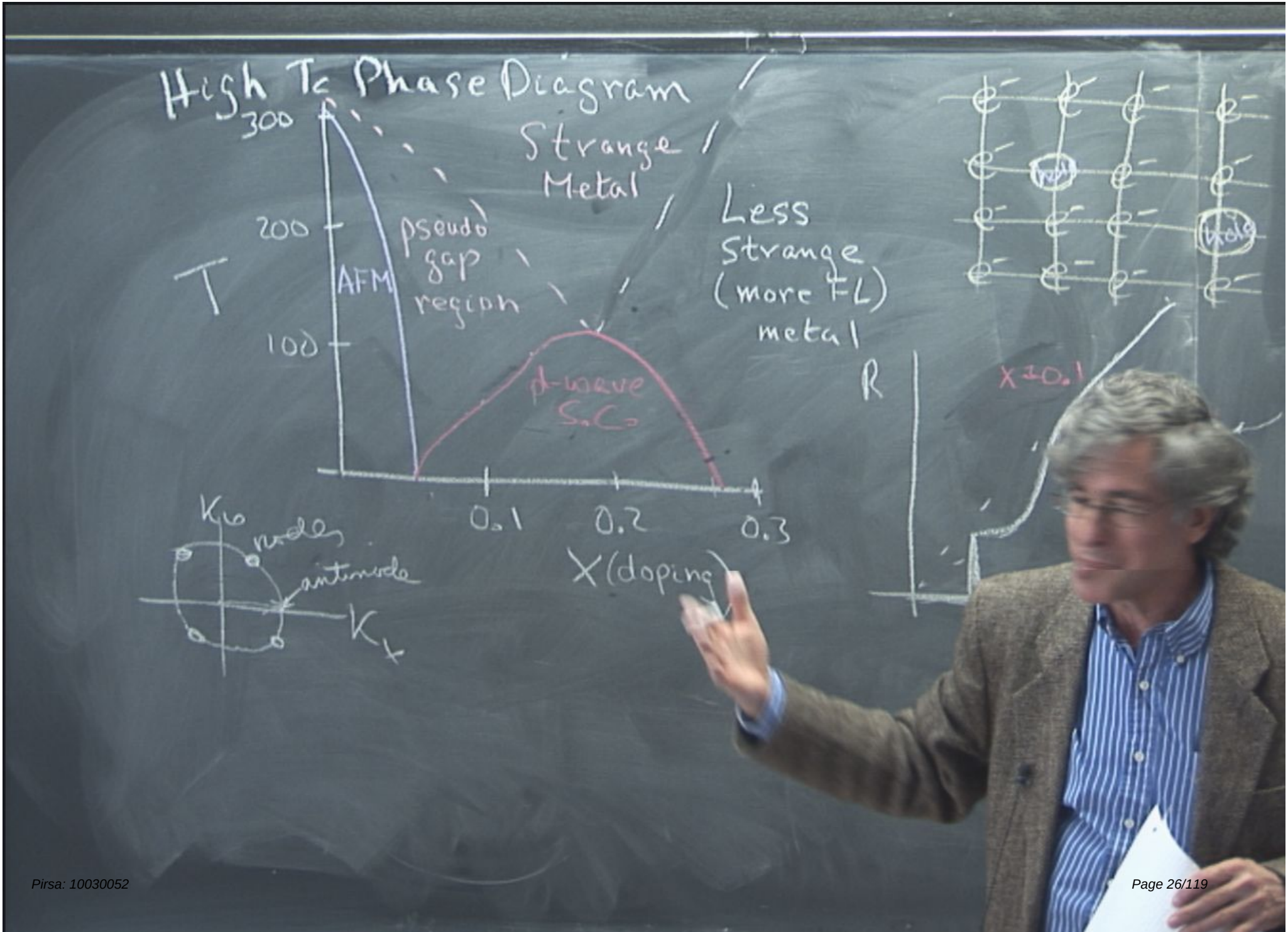
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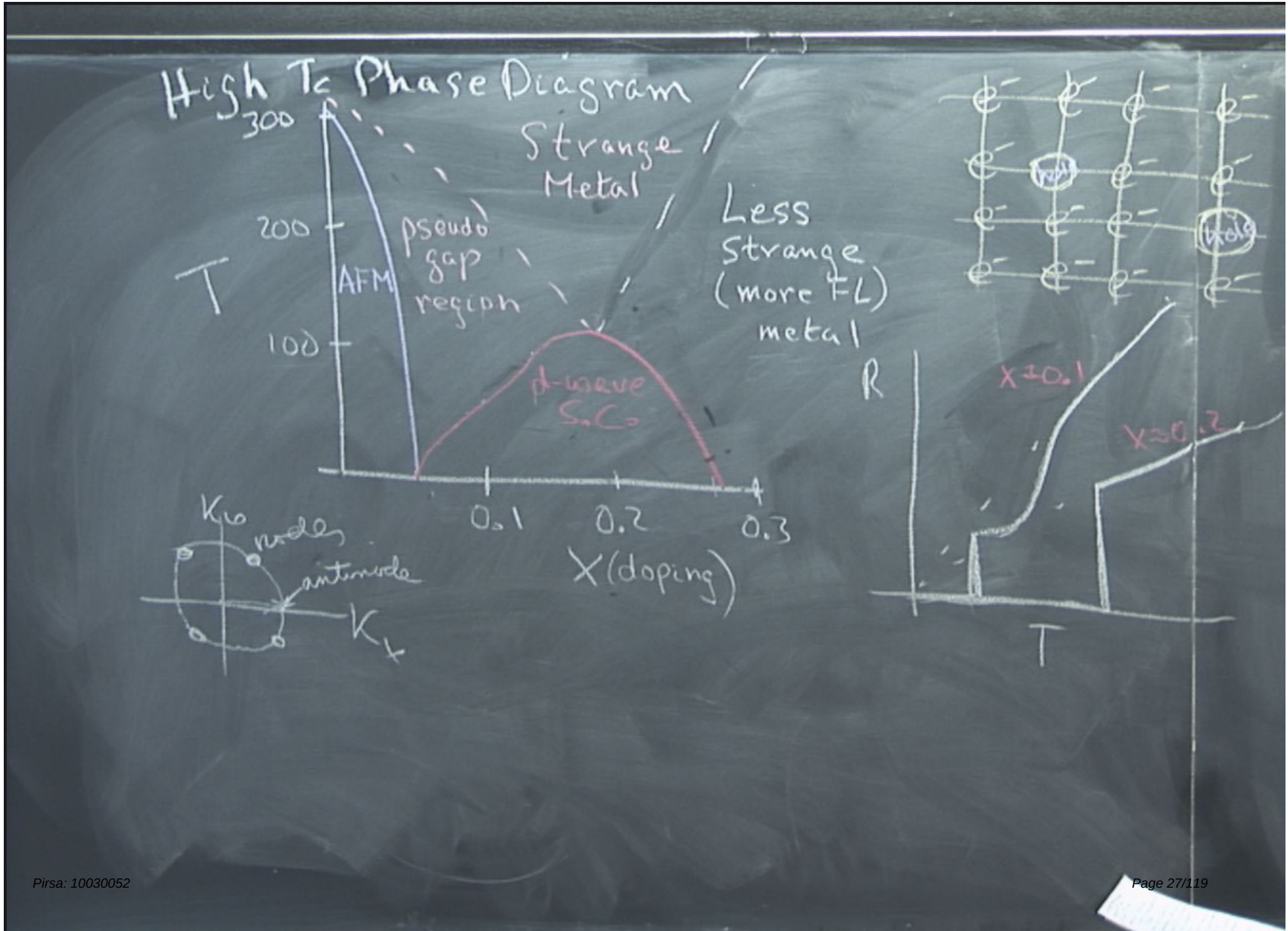
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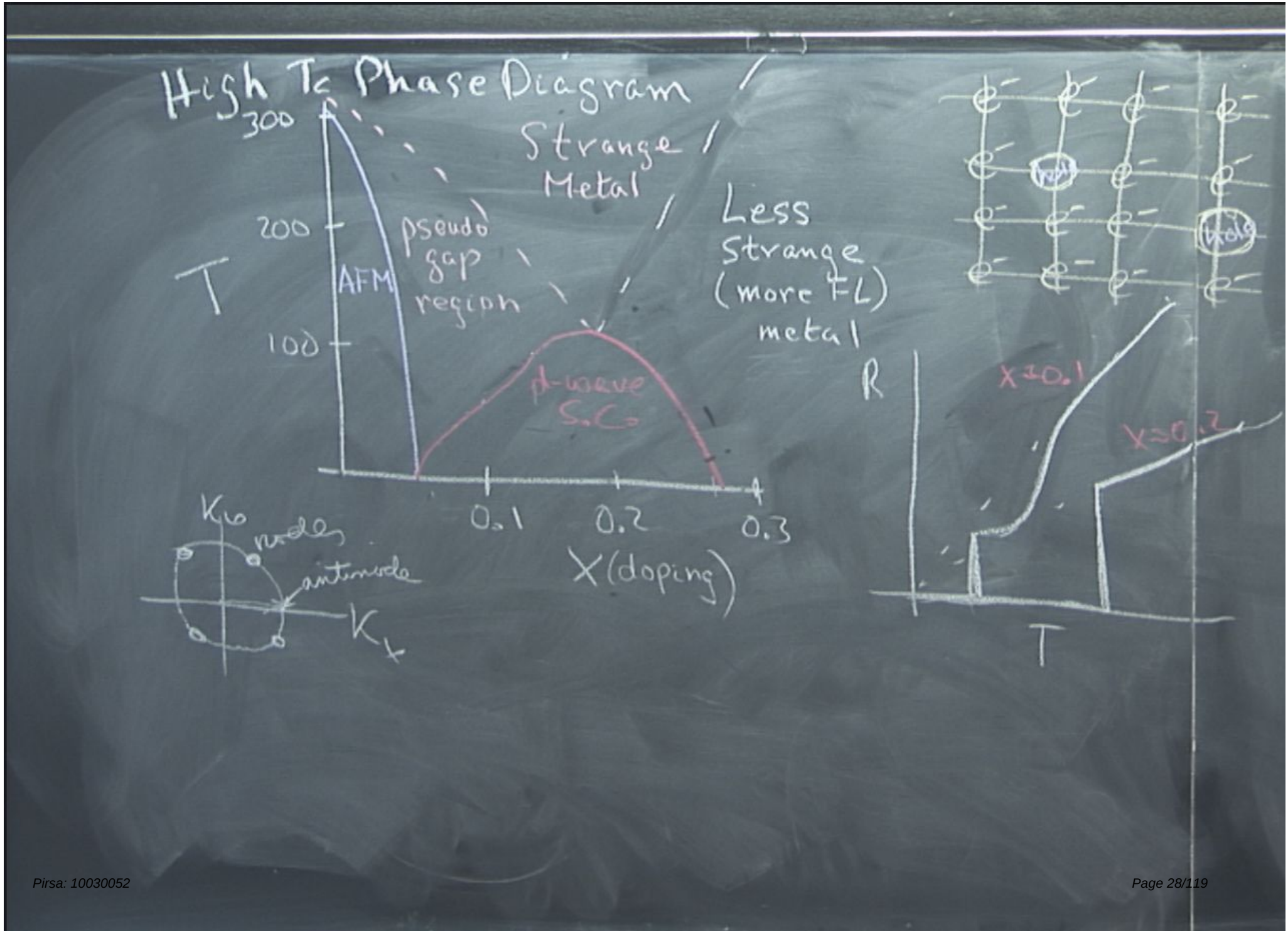
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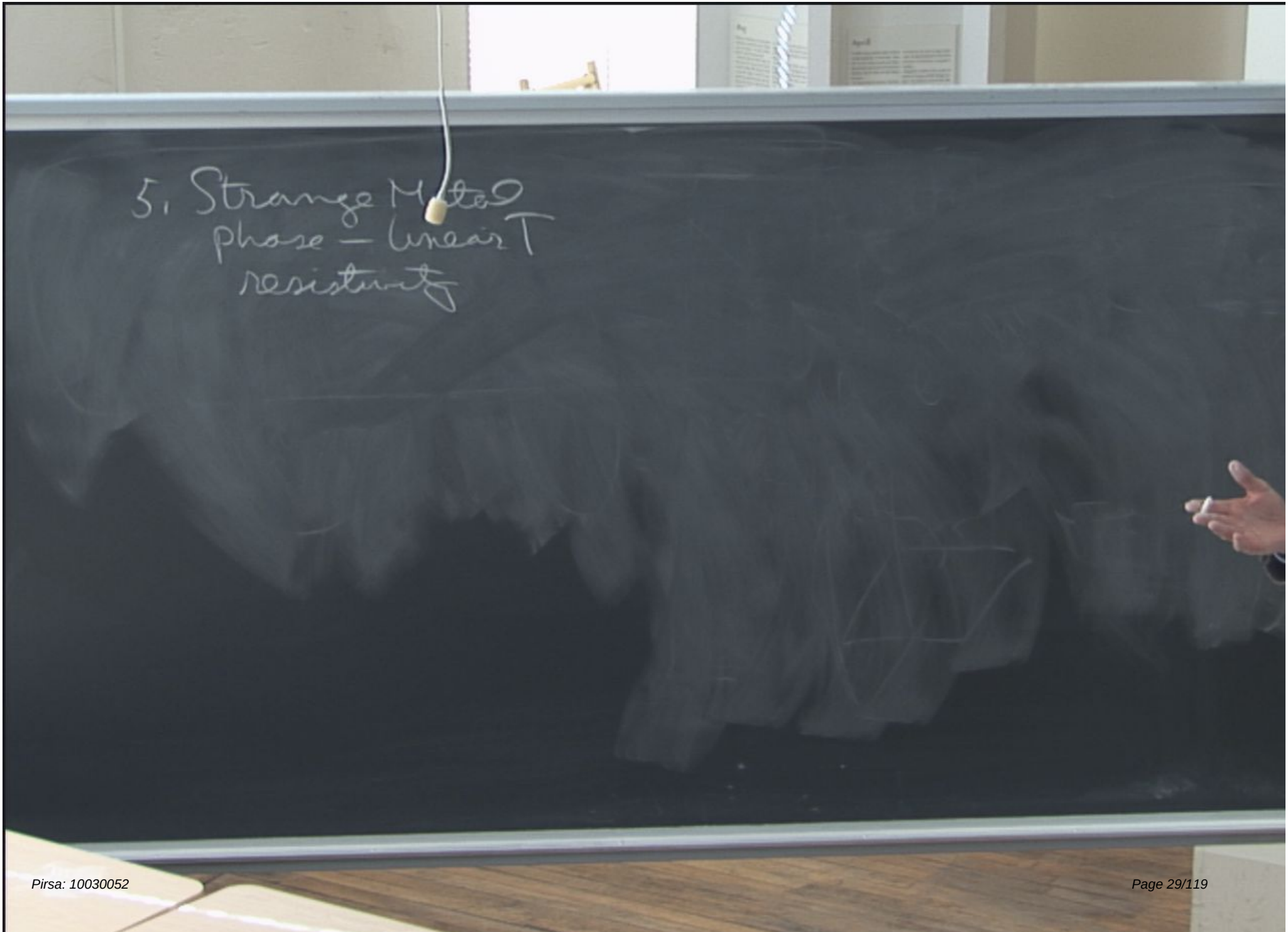
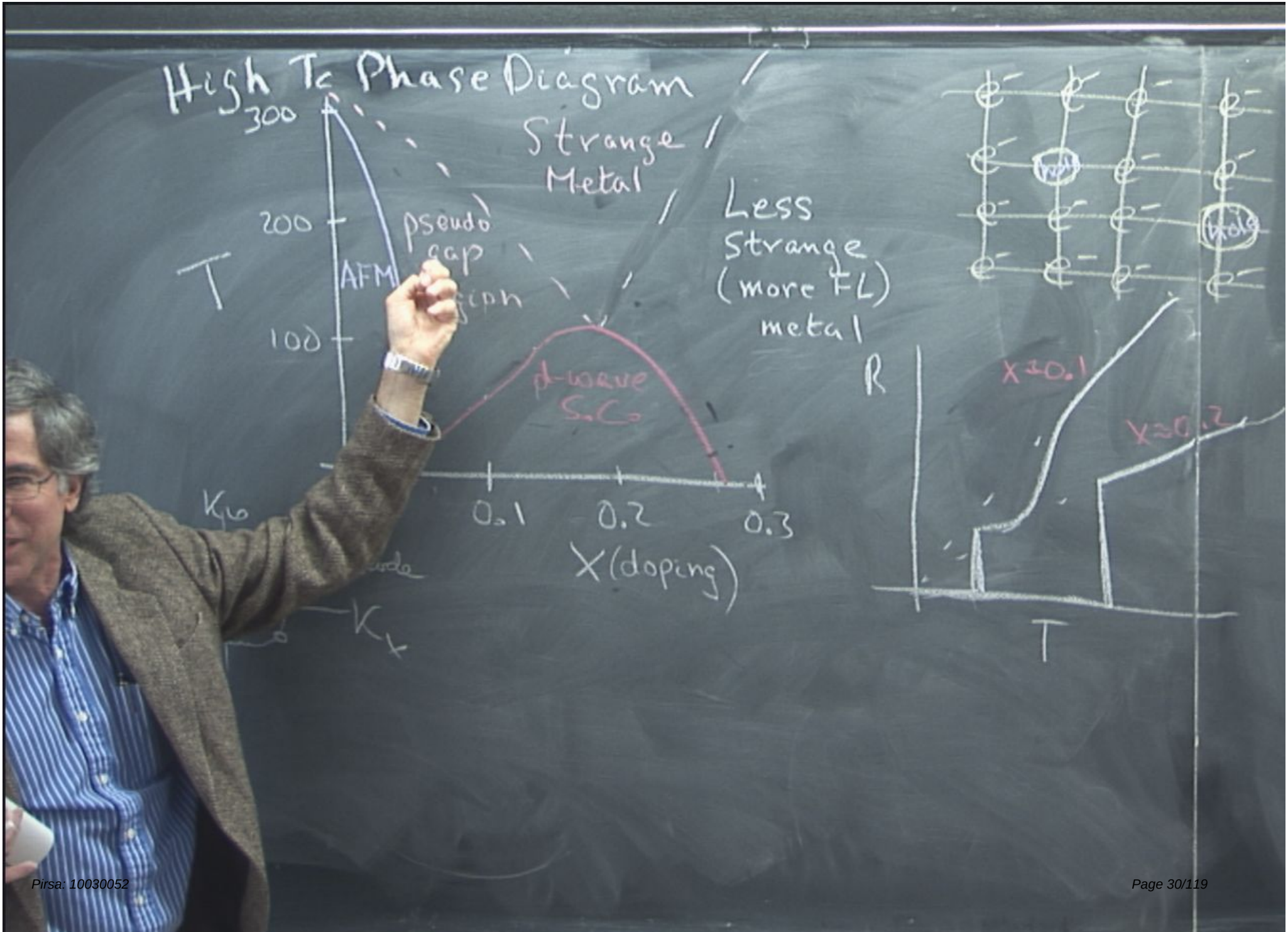

5. Strange Metal
phase — linear T
resistivity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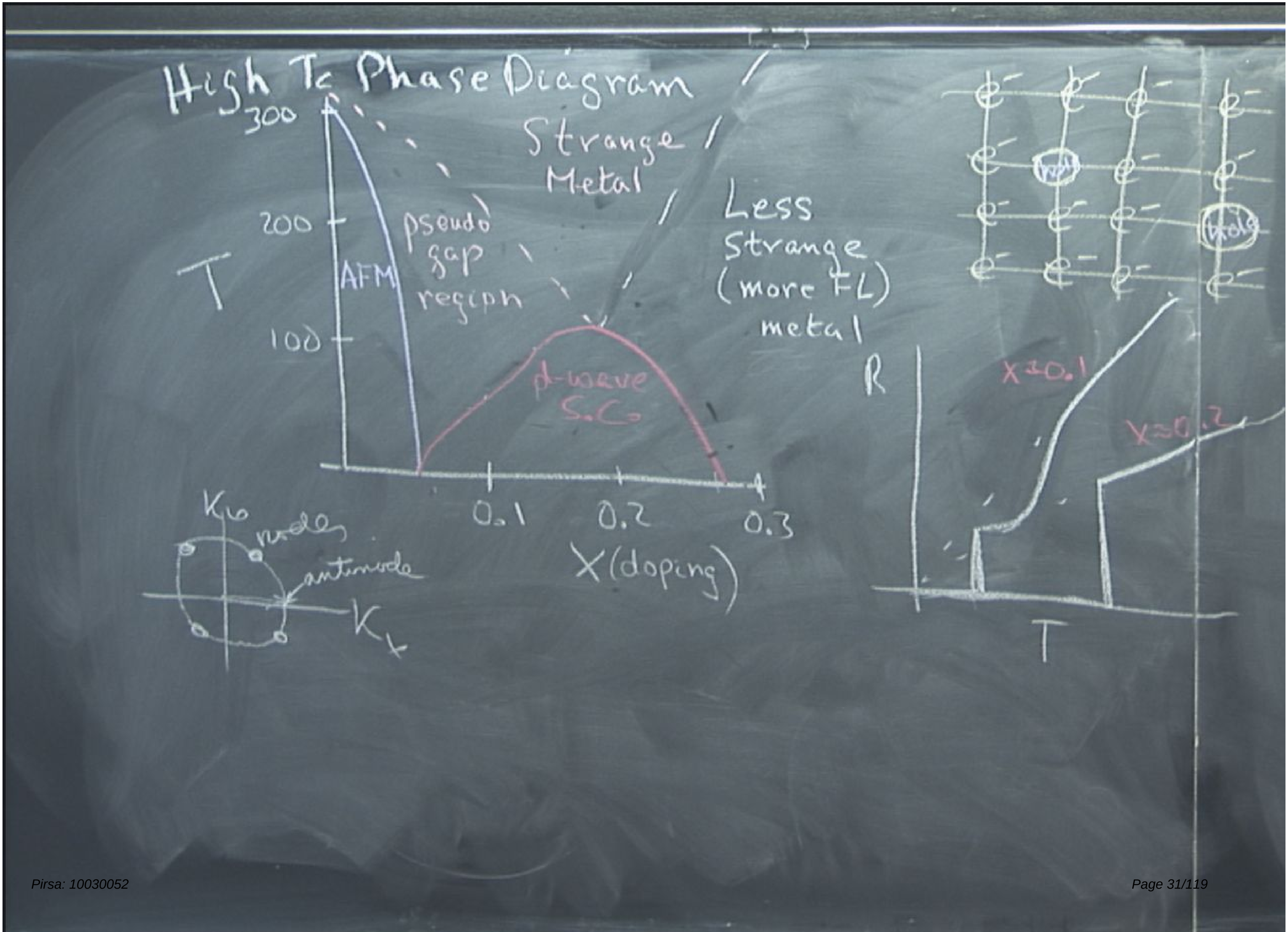
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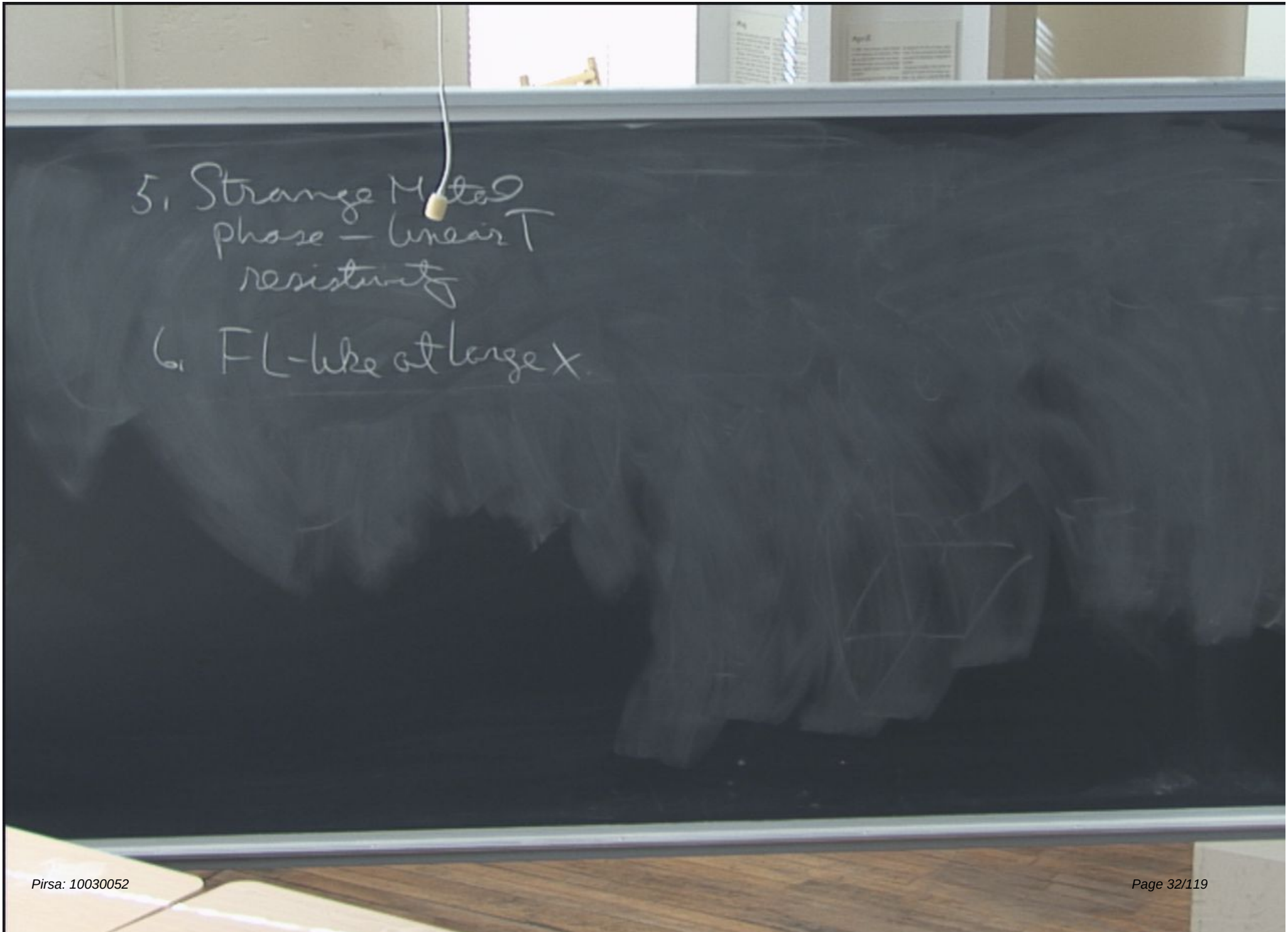
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5. Strange Metal phase — linear T resistivity

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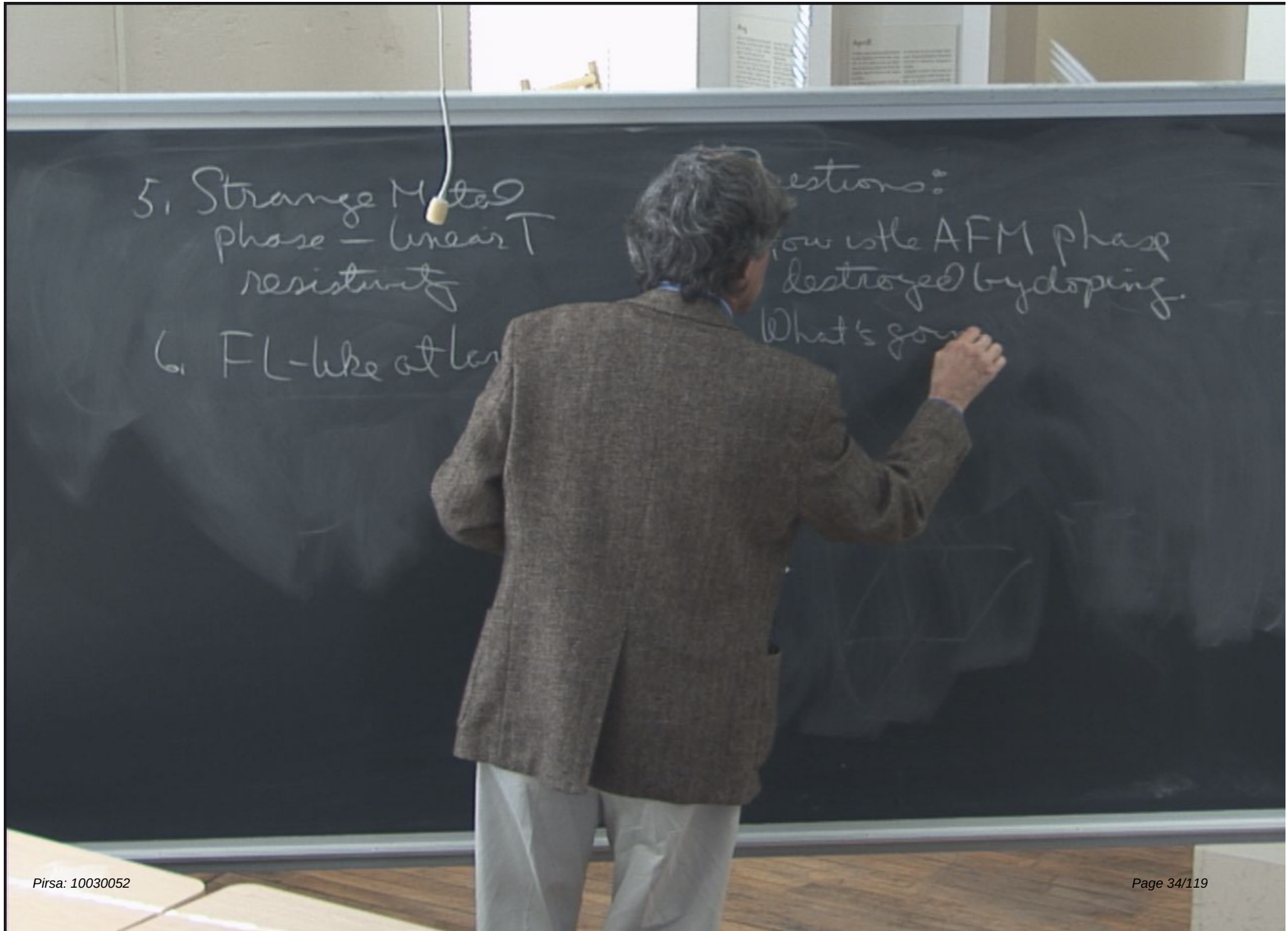
Questions:

— How is the AFM phase destroyed by doping.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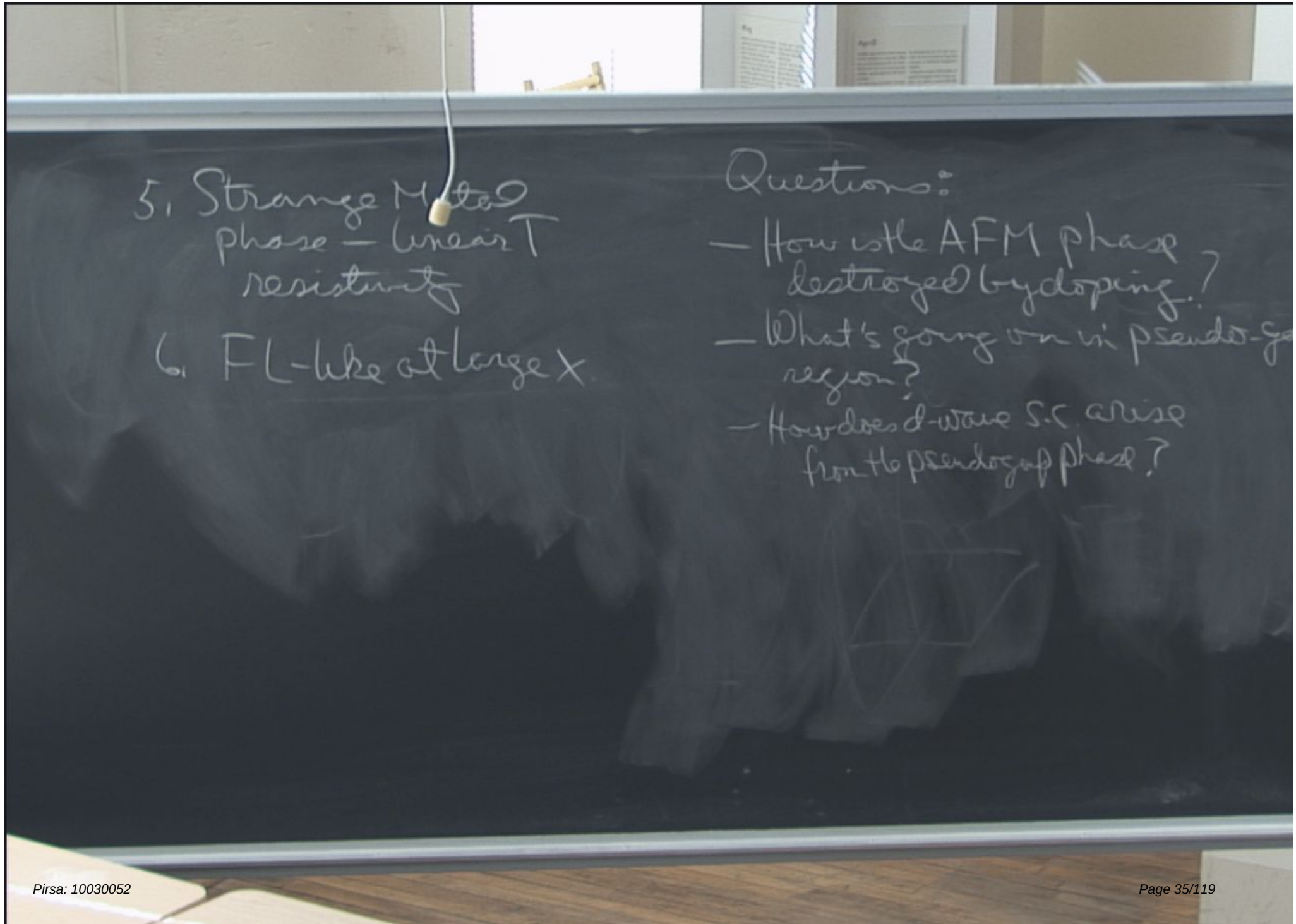
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— How does d-wave S.C arise
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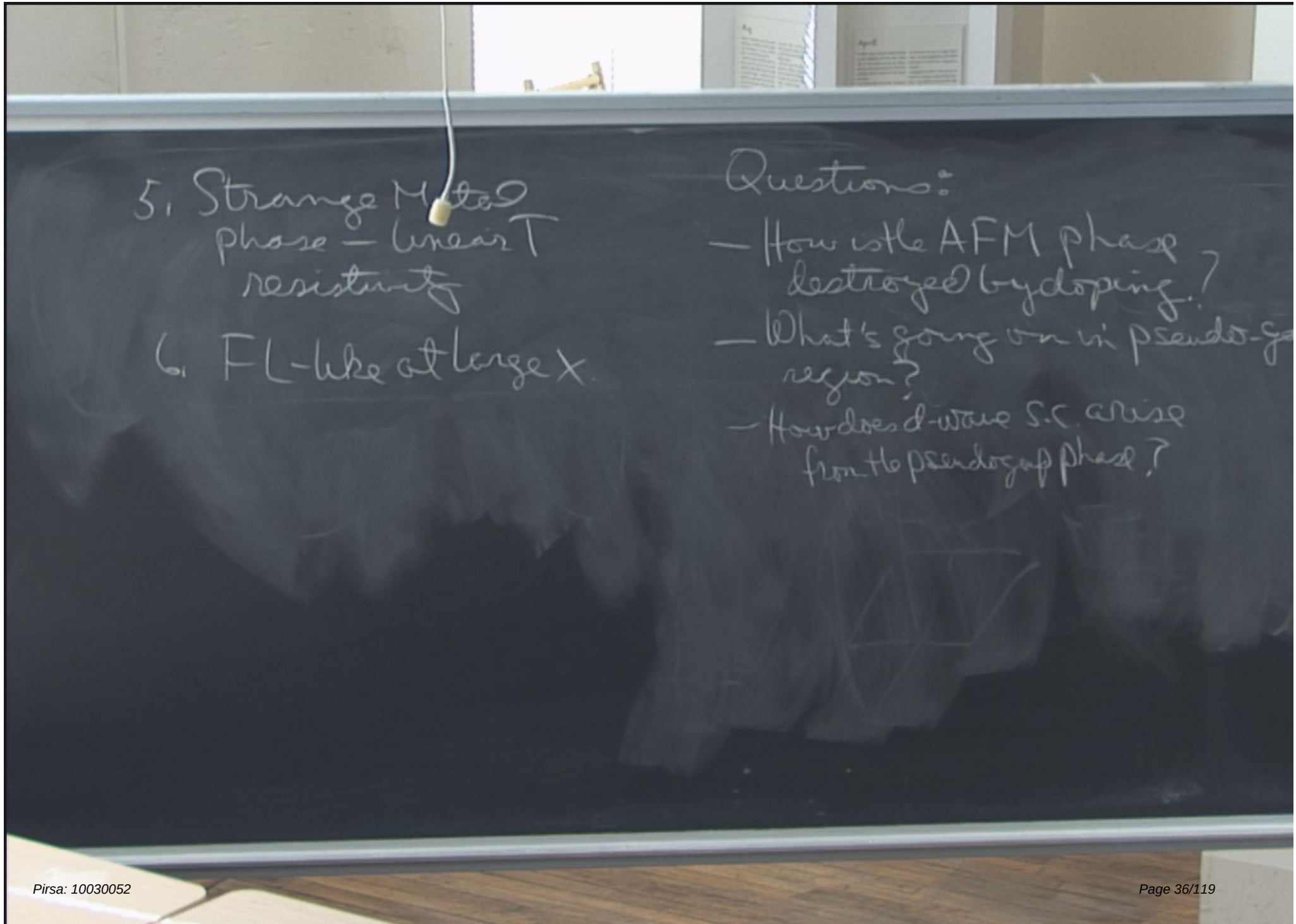
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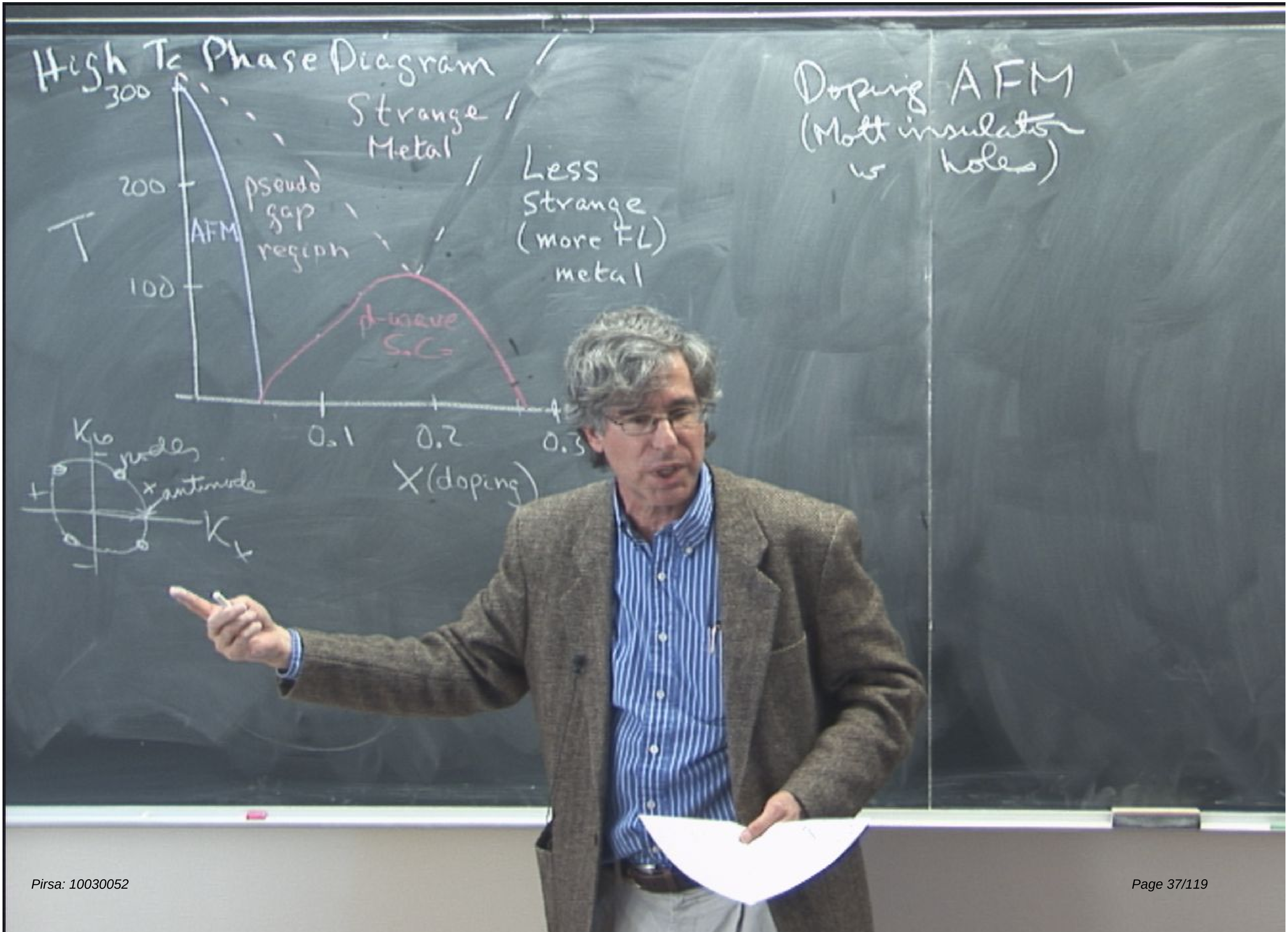
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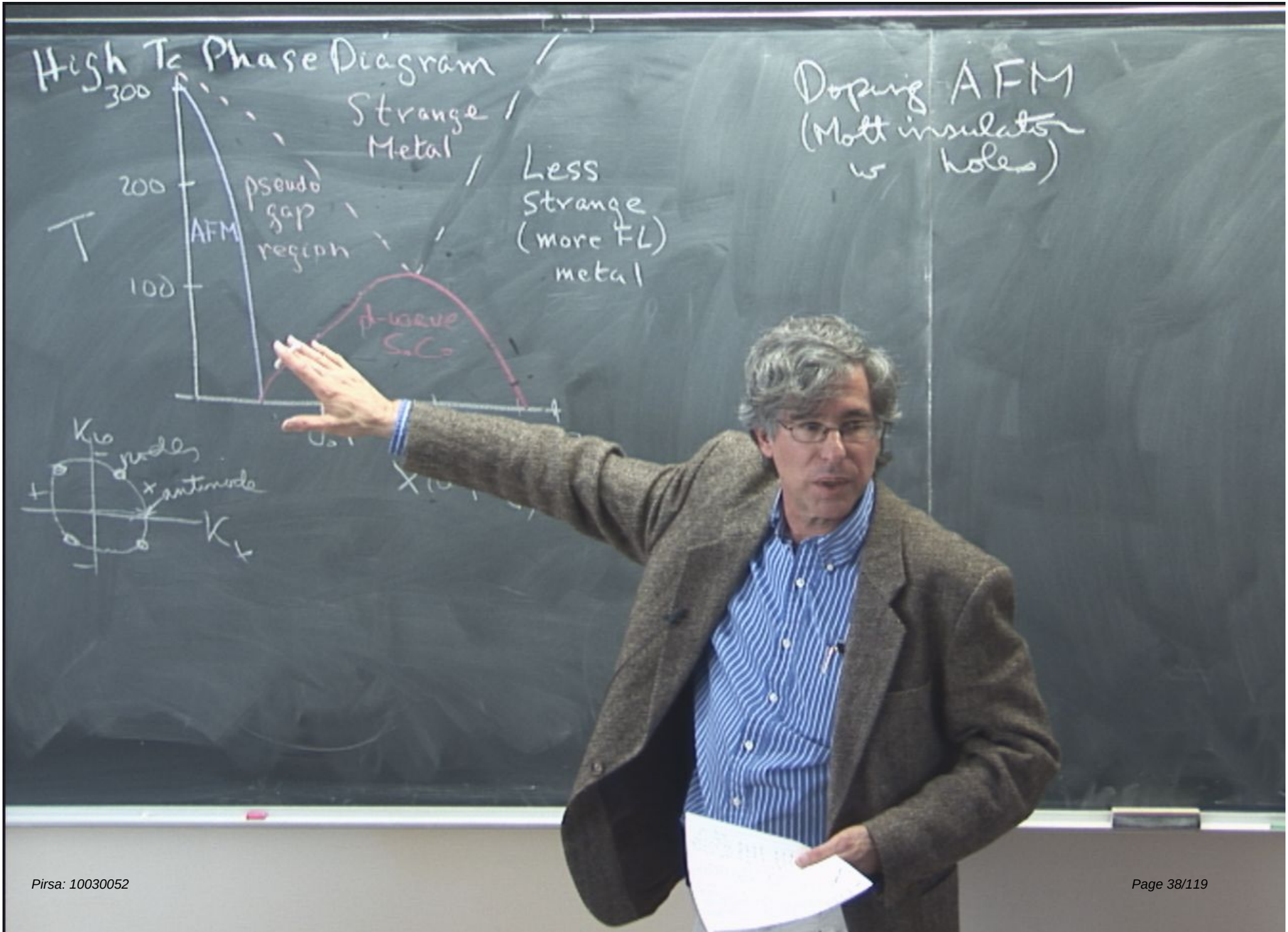
Doping AFM
(Mott insulator w holes)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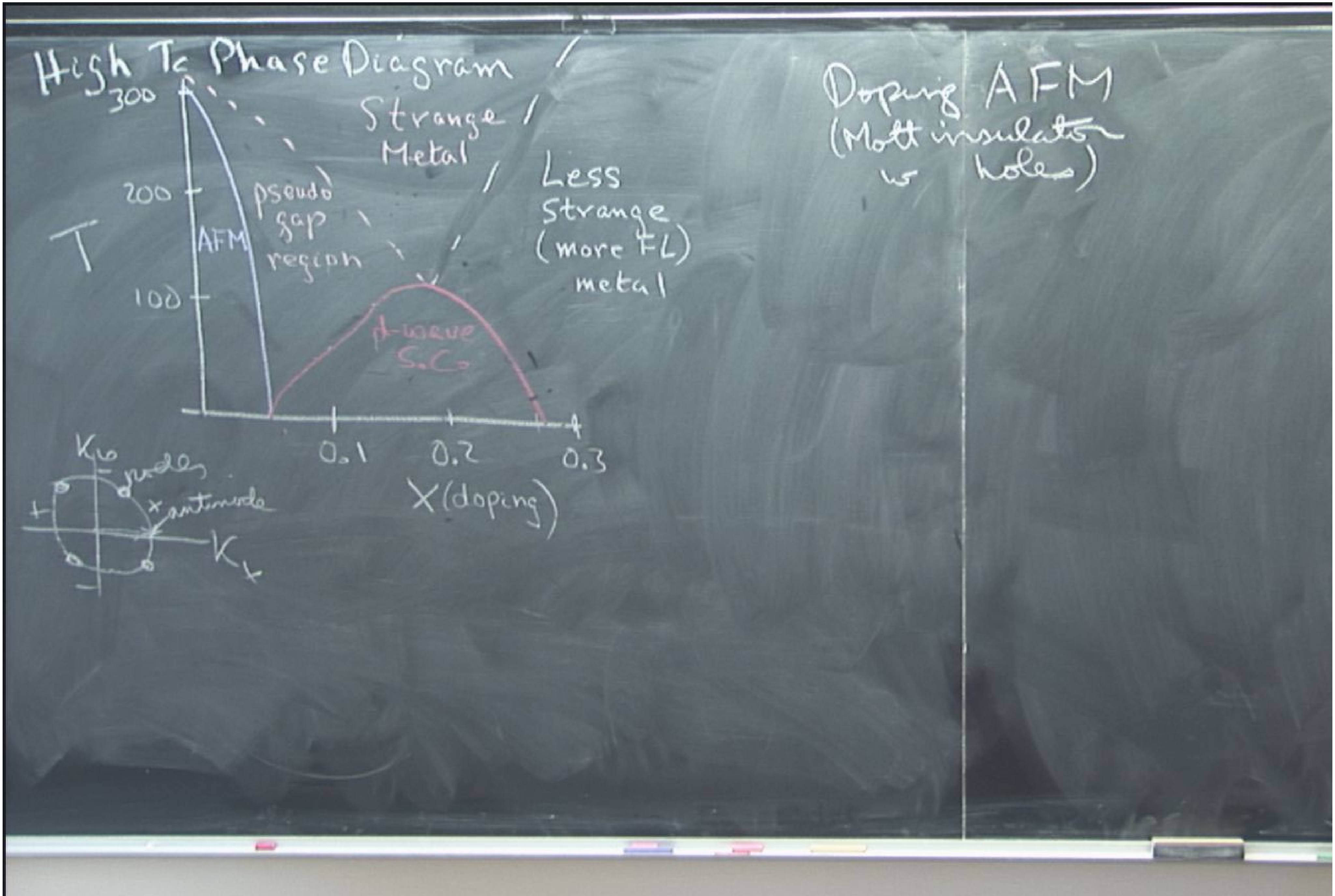
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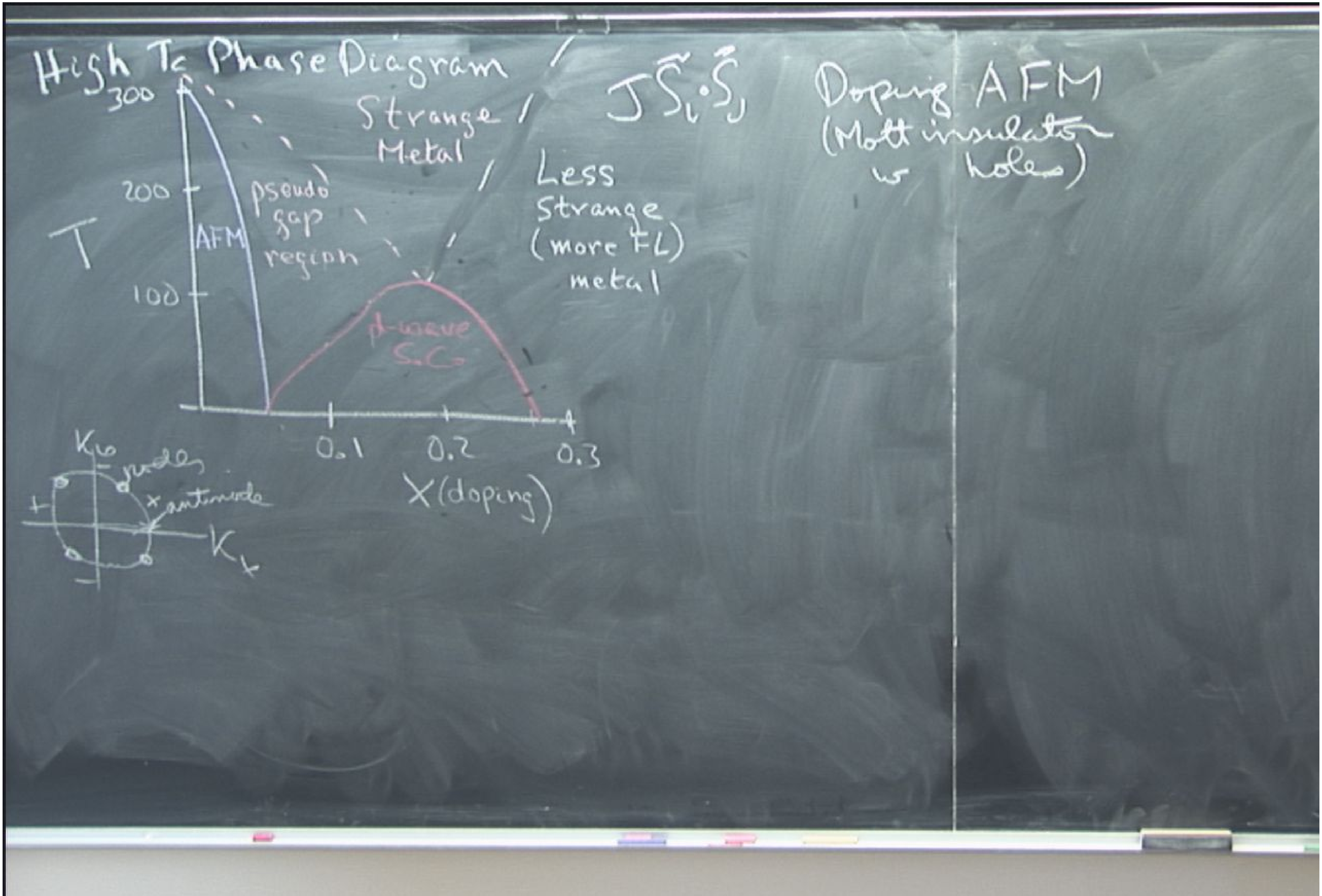
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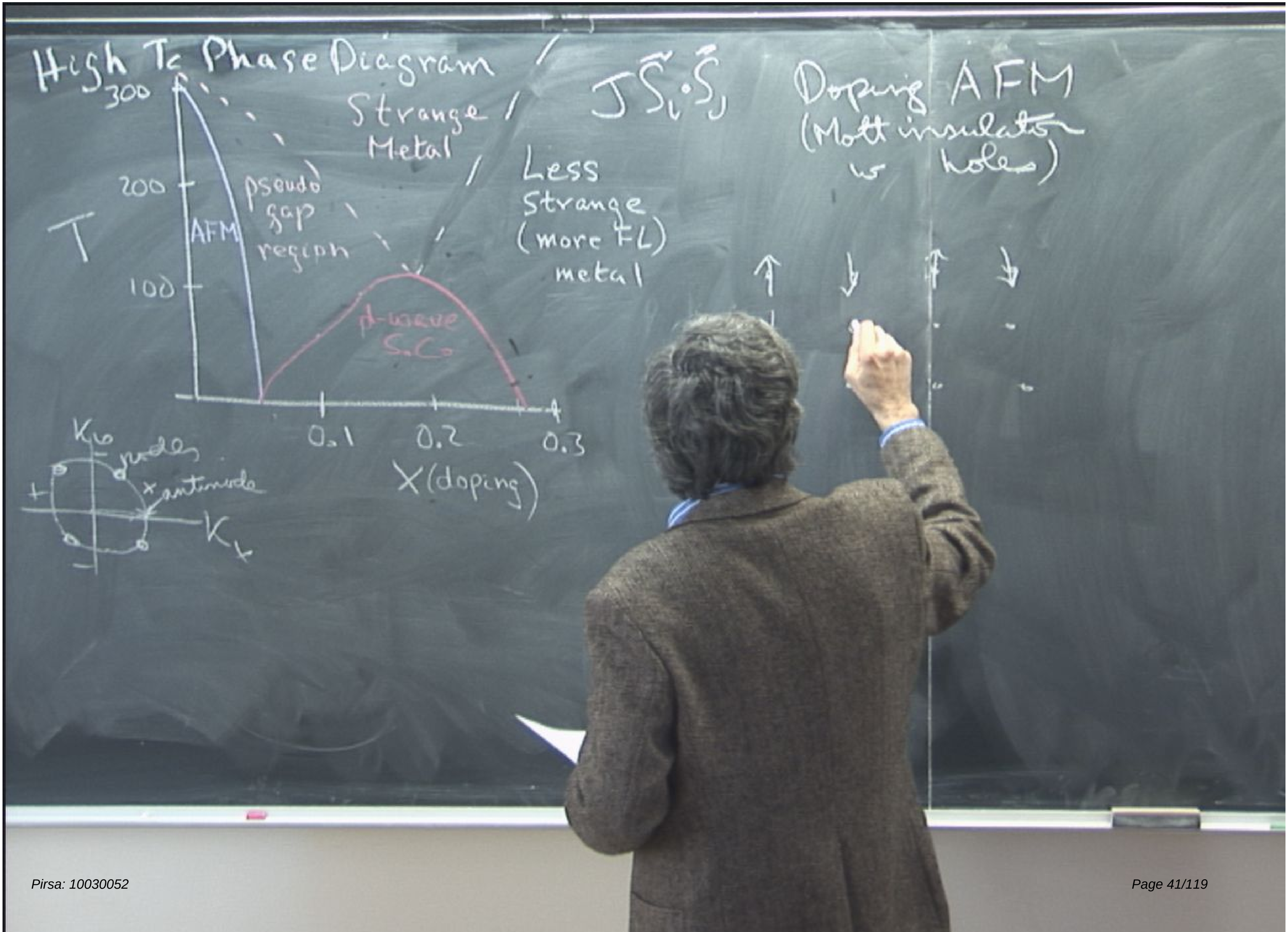
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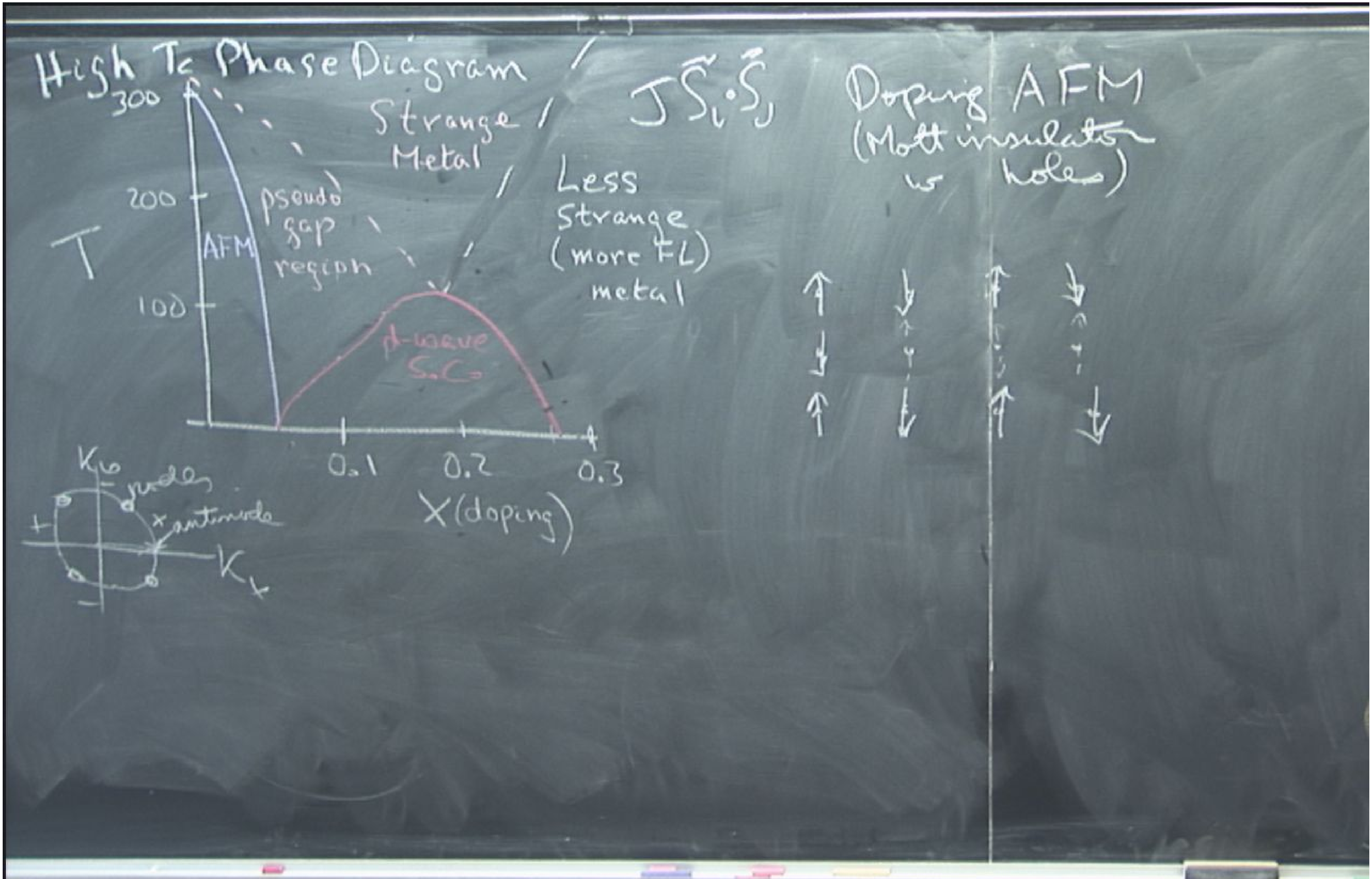
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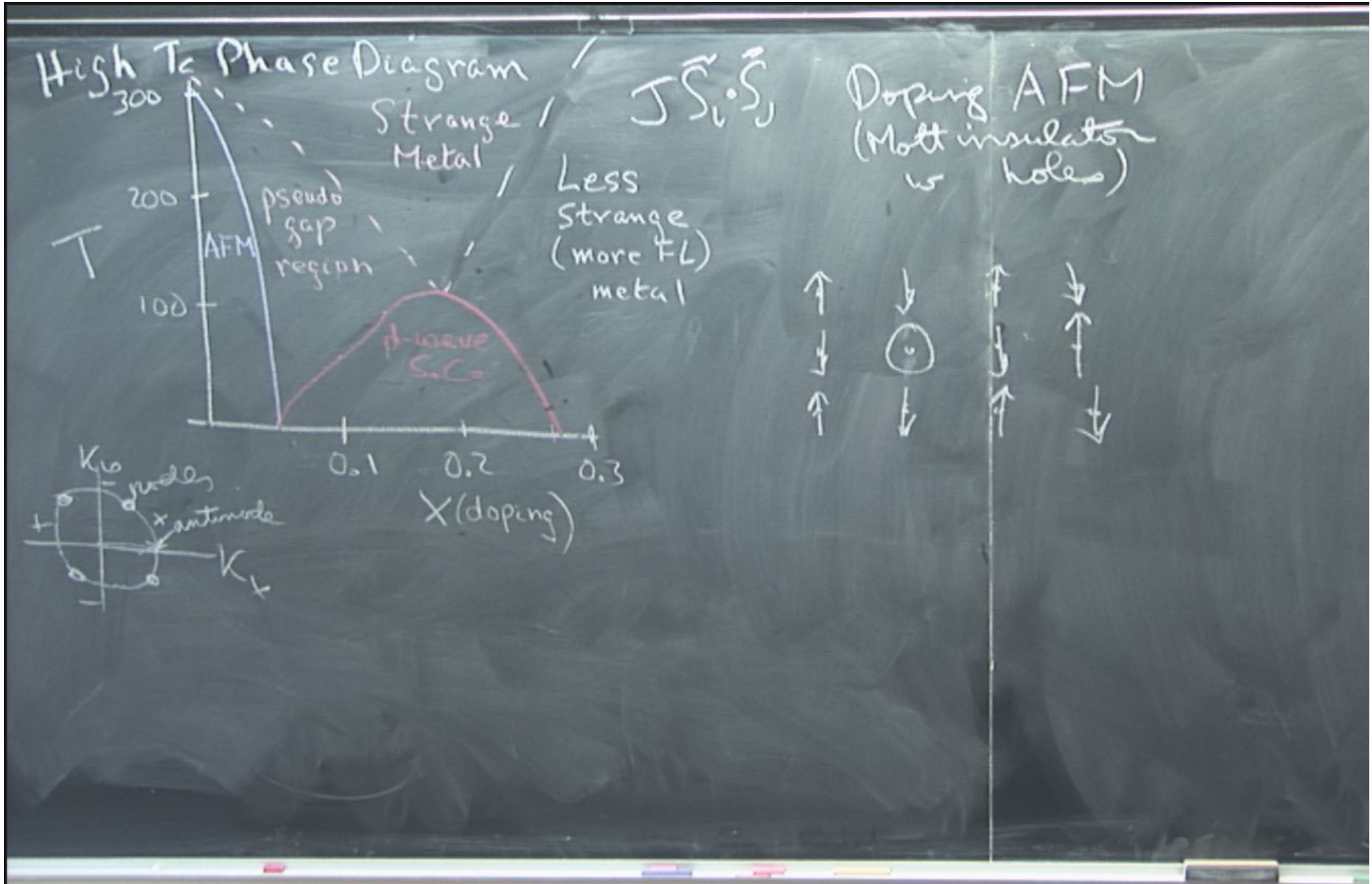
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$J\vec{S}_i \cdot \vec{S}_j$
Doping
AFM
(Mott insulator
vs holes)
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Metal
Less
Strange
(more FL)
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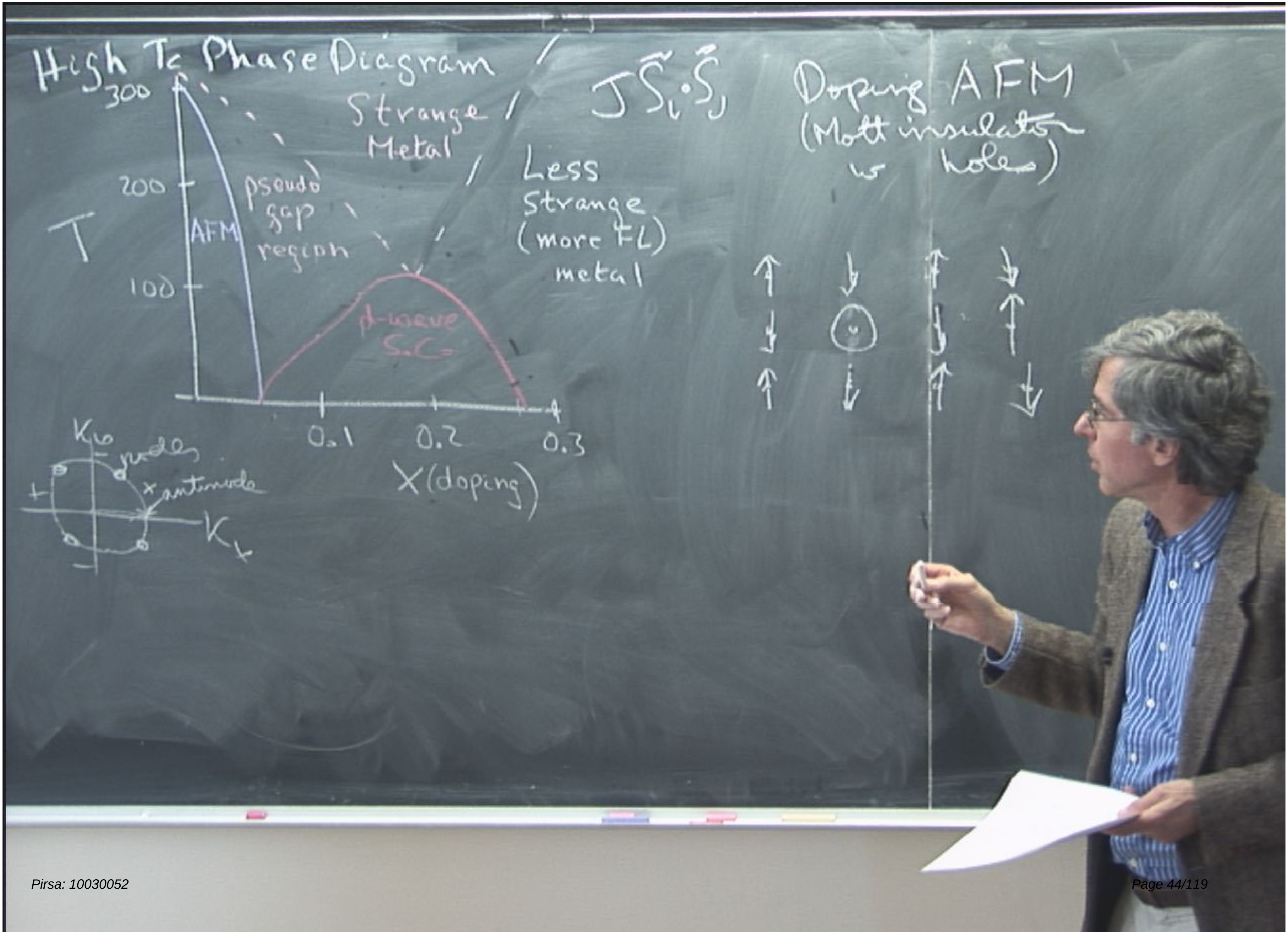
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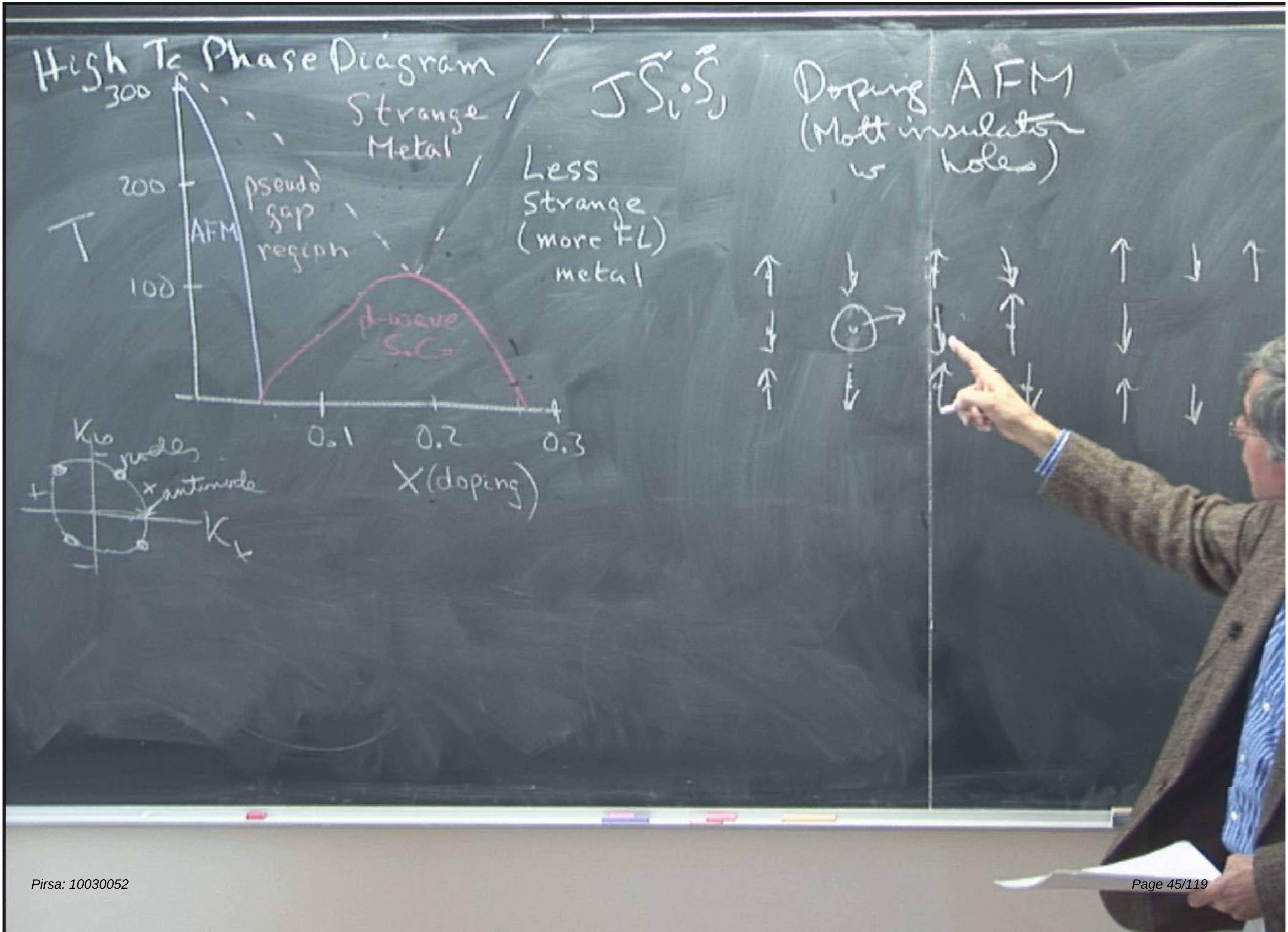
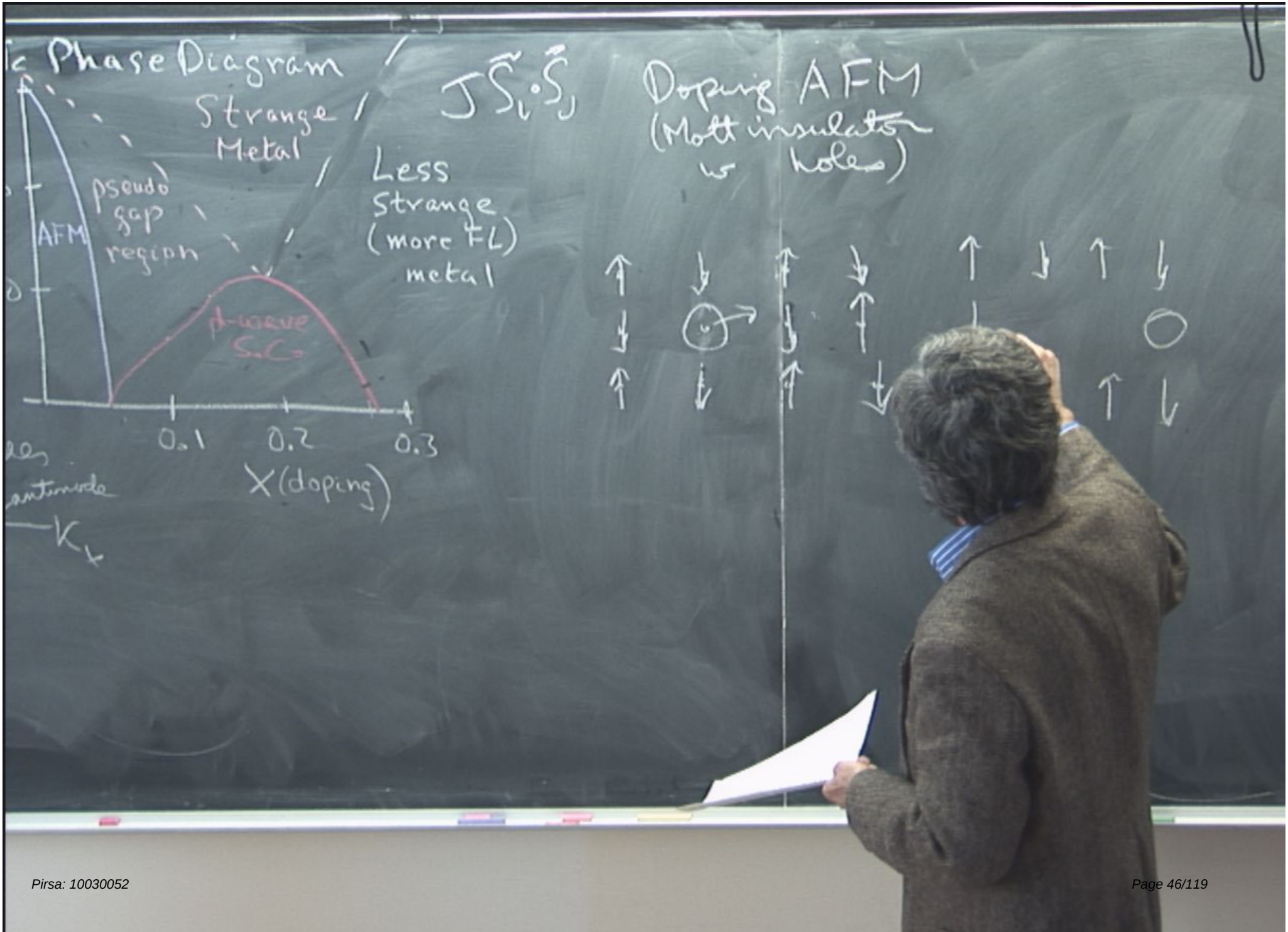
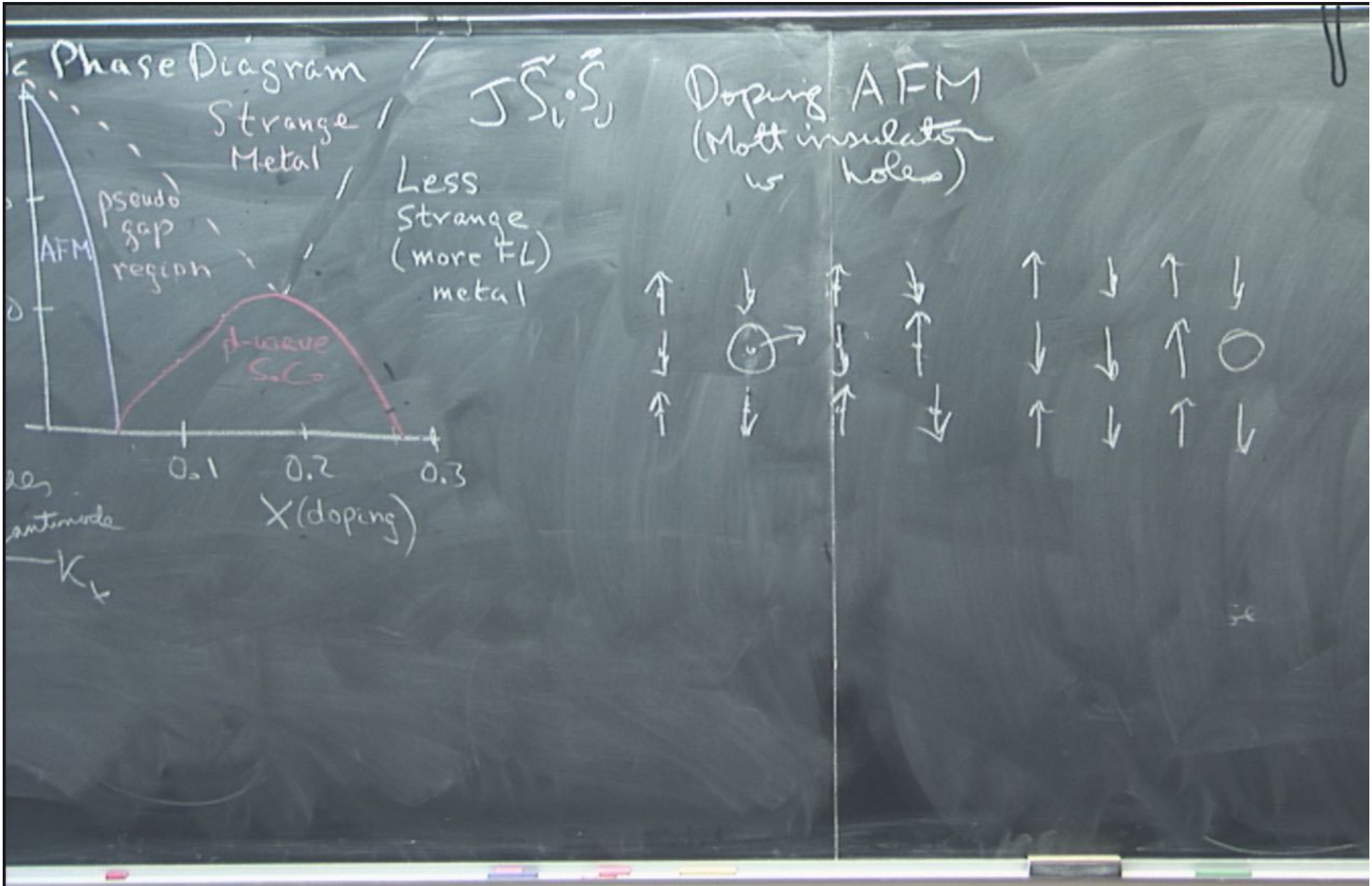
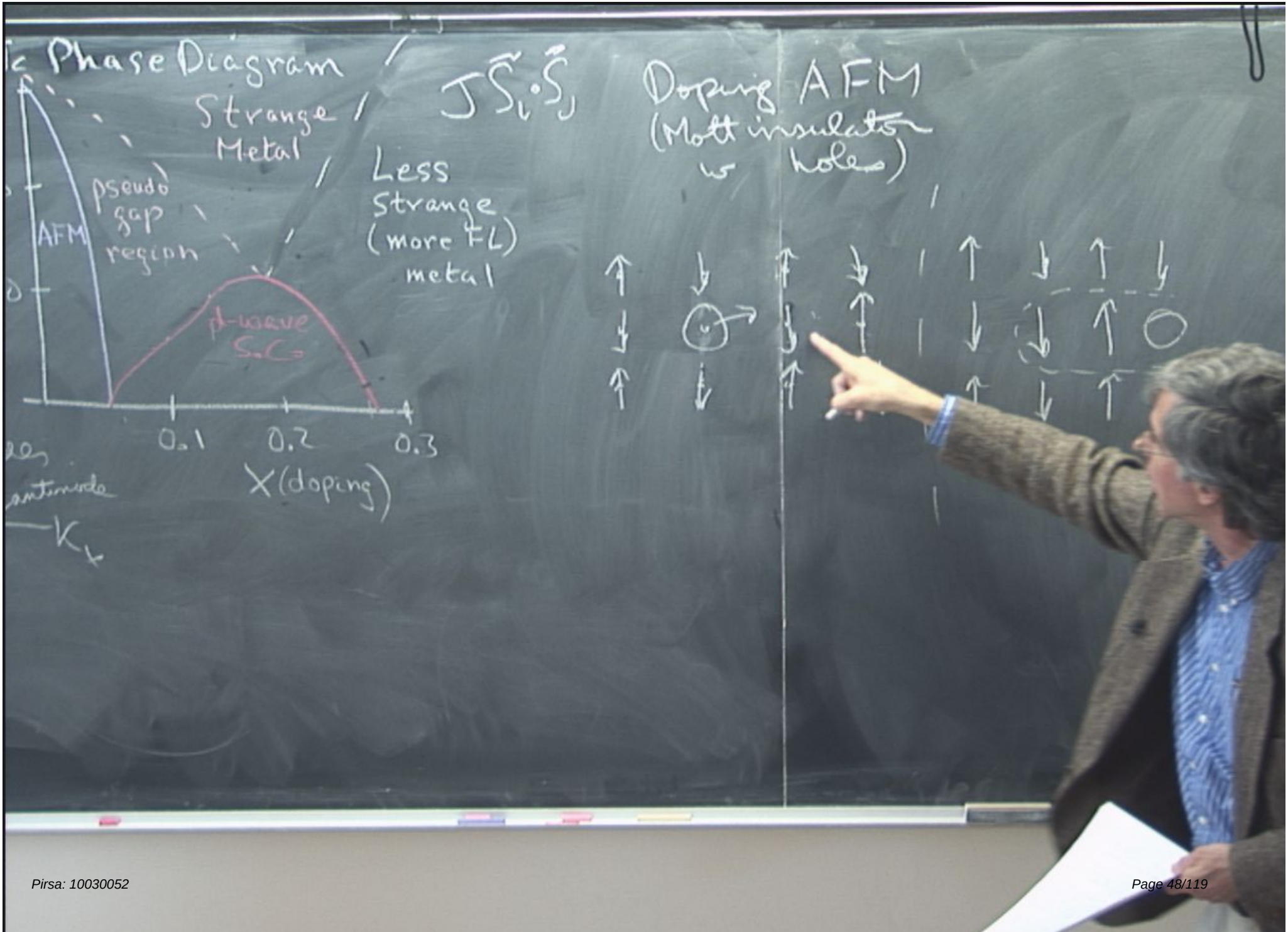
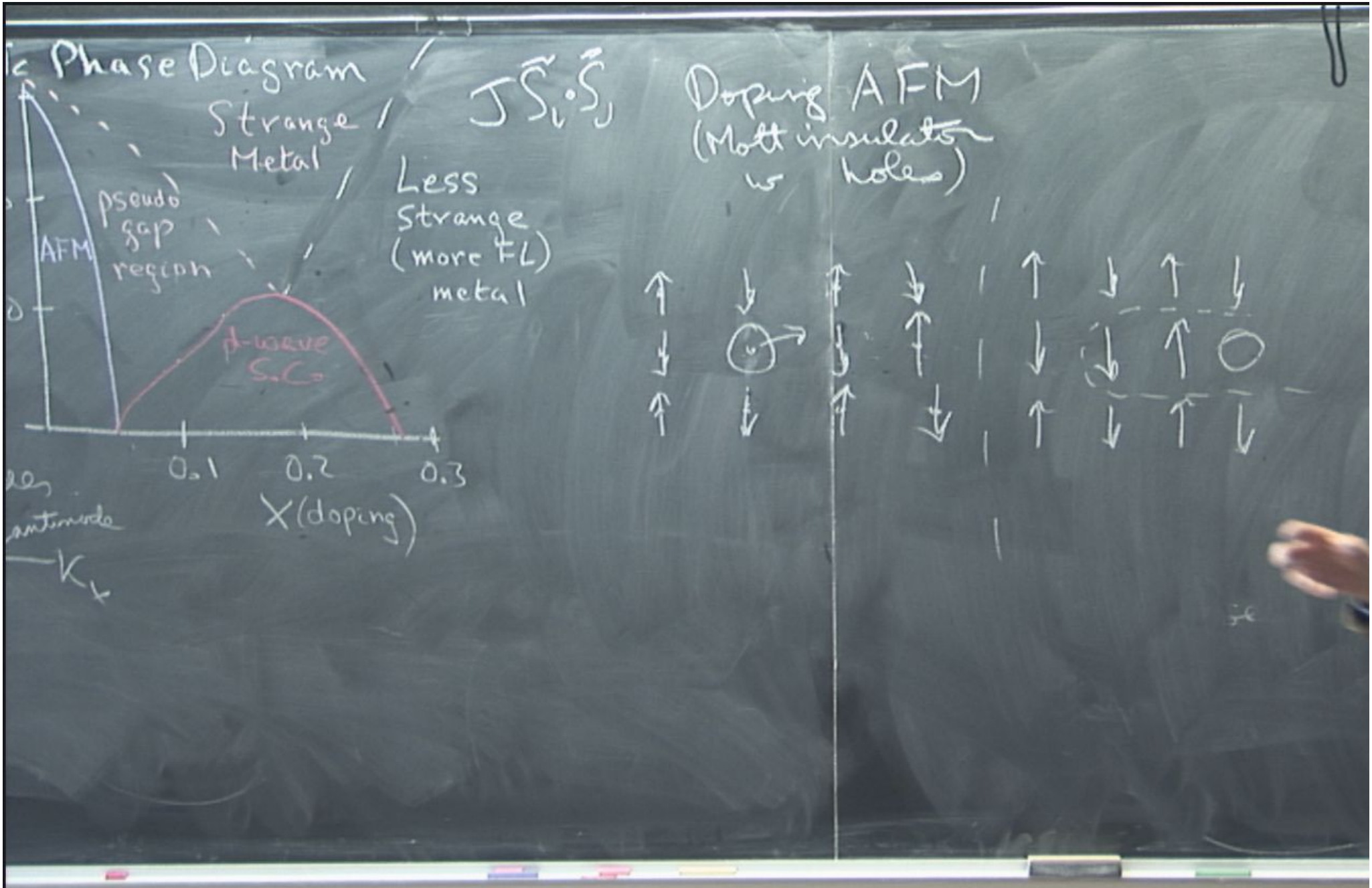
Doping AFM
(Mott insulator w holes)

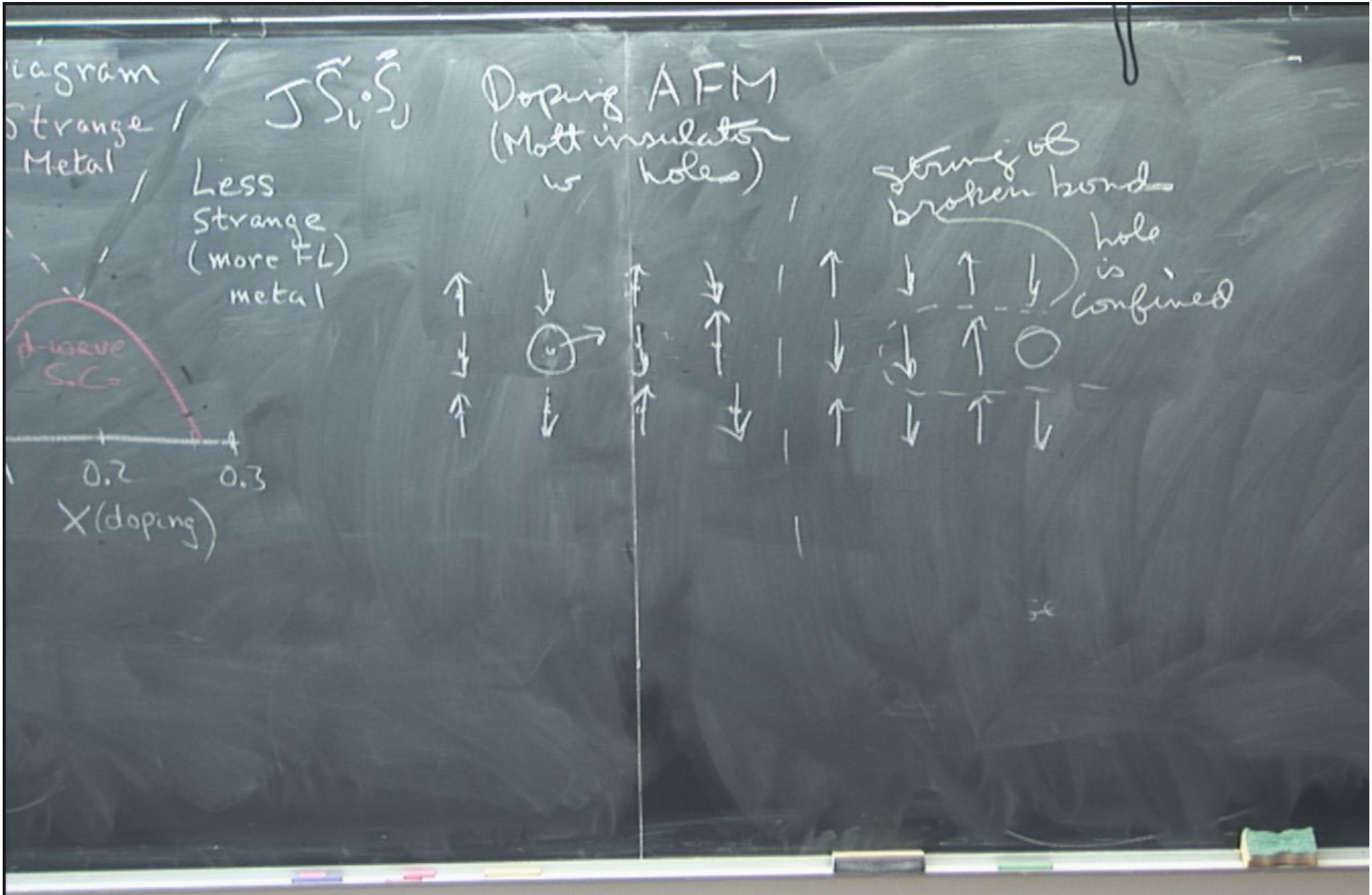

High Tc Phase Diagram
300
200
100
T
AFM
pseudo gap region
Strange Metal
Less Strange (more FL) metal
d-wave S.C.
0.1
0.2
0.3
X(doping)
nodes
antinode
JS_i·S_j
Doping AFM
(Mott insulator w holes)

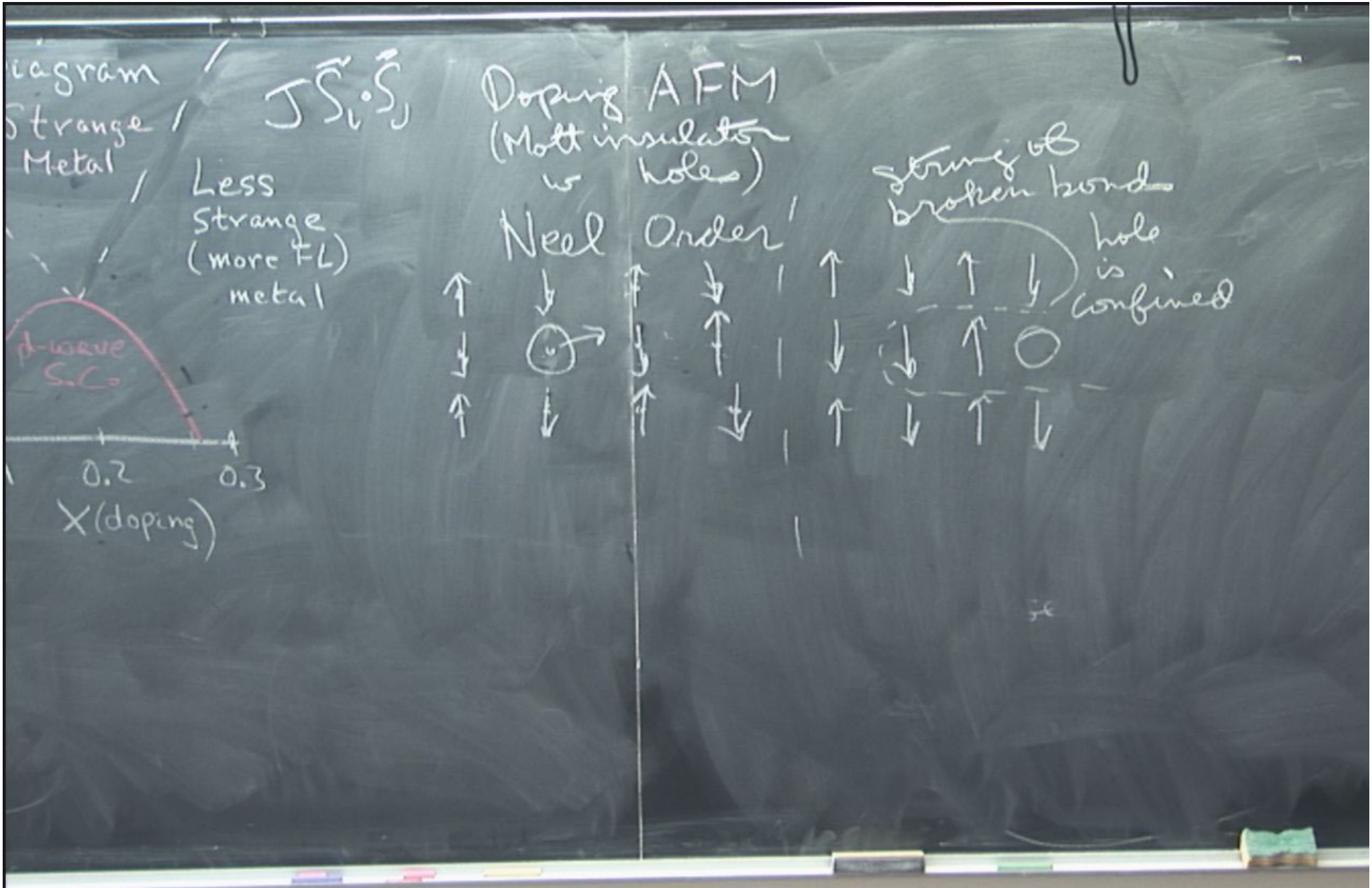

c Phase Diagram
Strange Metal
$J\vec{S}_i \cdot \vec{S}_j$
Doping AFM
(Mott insulator
w holes)
pseudo gap region
AFM
Less Strange (more FL) metal
d-wave S.C.
0.1
0.2
0.3
X(doping)

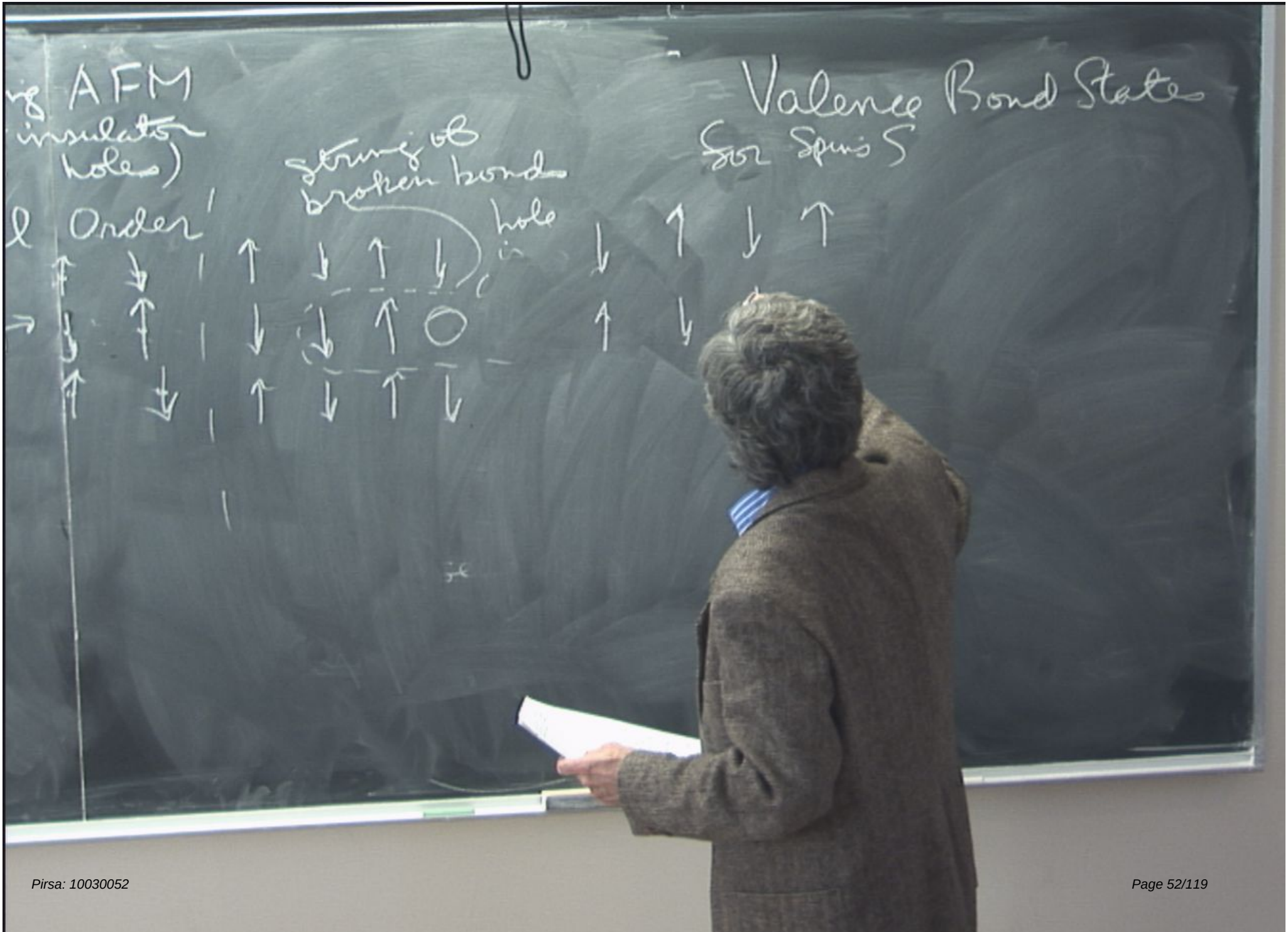

c Phase Diagram
Strange Metal
$J\vec{S}_i \cdot \vec{S}_j$
Doping AFM
(Mott insulator w holes)
Less Strange (more FL) metal
pseudo gap region
AFM
d-wave S.C.
0.1
0.2
0.3
X(doping)
K_L

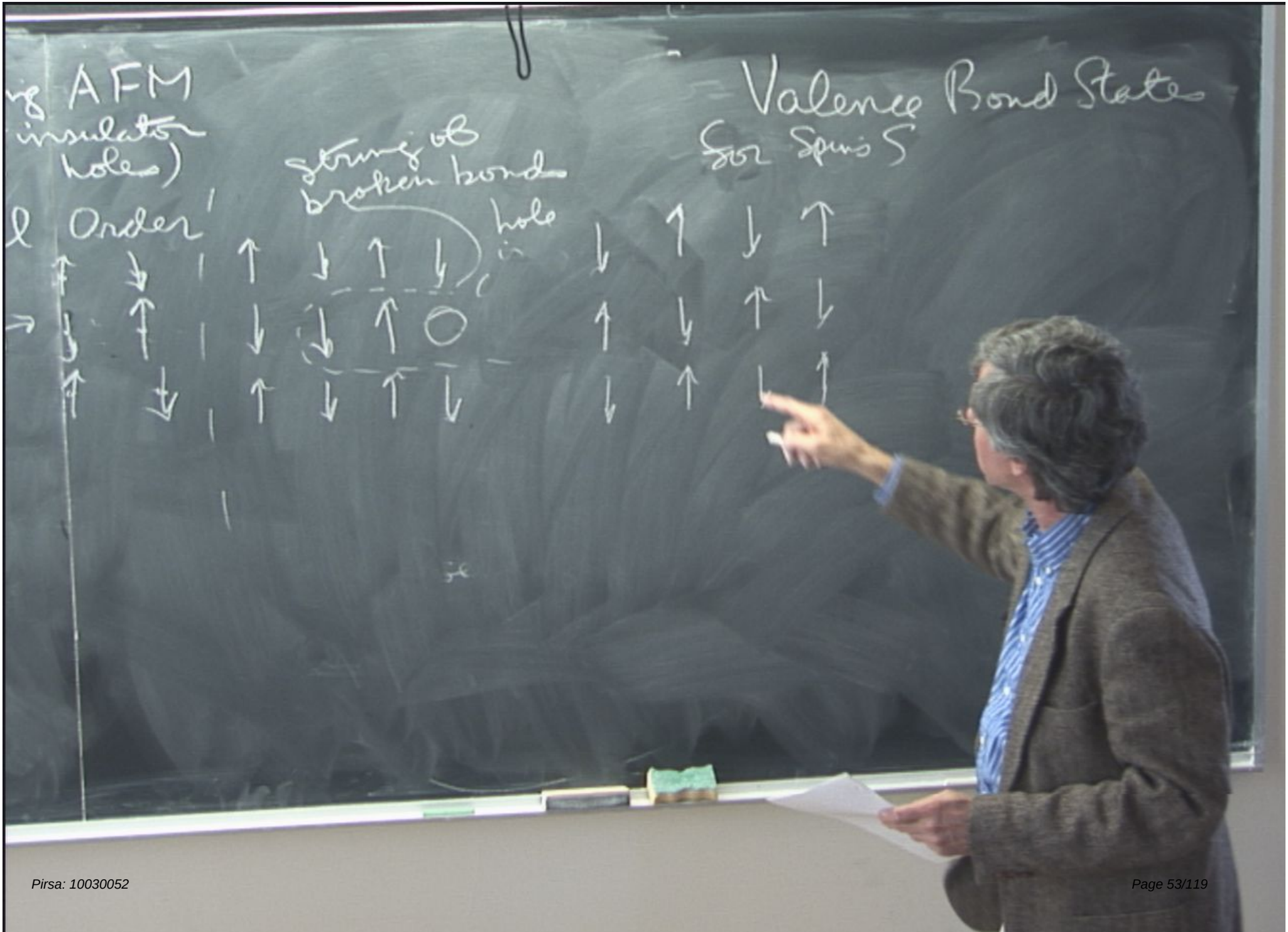

c Phase Diagram
Strange Metal
$J\vec{S}_i \cdot \vec{S}_j$
Doping AFM
(Mott insulator
holes)
Less Strange (more FL) metal
pseudo gap region
AFM
d-wave S.C.
0.1
0.2
0.3
X(doping)

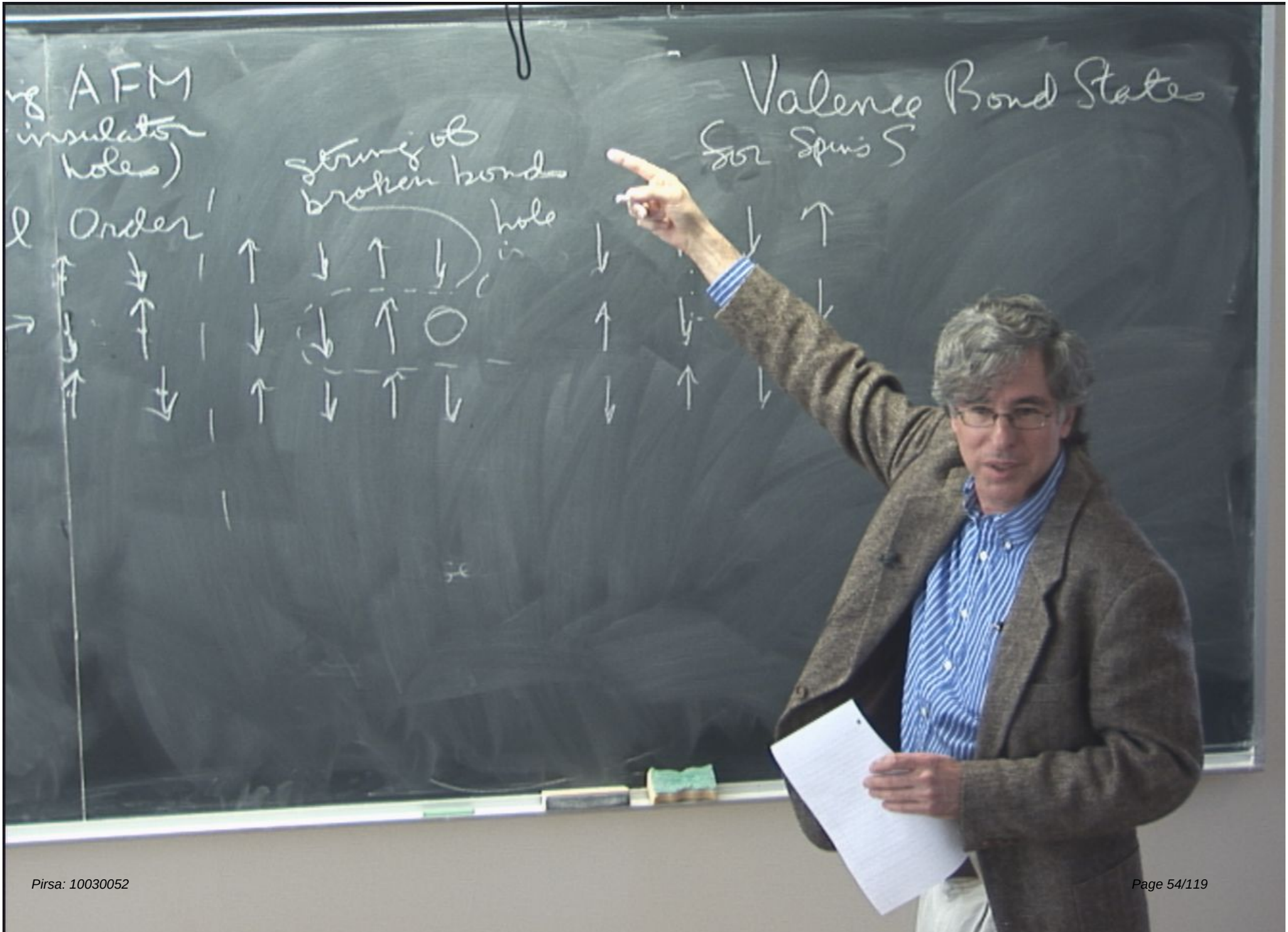

c Phase Diagram
Strange Metal
$J\vec{S}_i \cdot \vec{S}_j$
Doping
AFM
(Mott insulator
w holes)
pseudo gap region
AFM
Less Strange (more FL) metal
d-wave S.C.
0.1
0.2
0.3
X(doping)

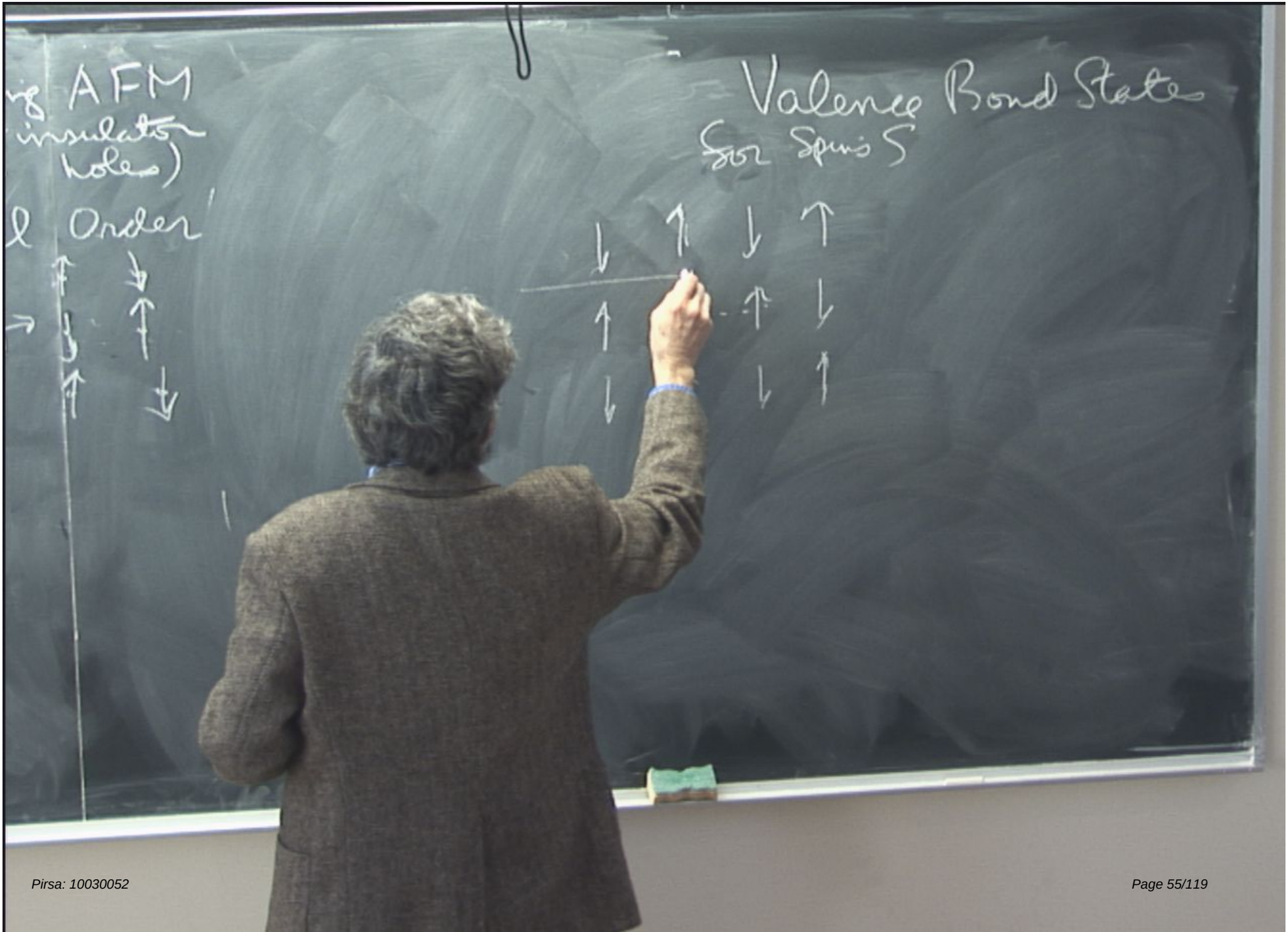

iagram
Strange
Metal
Less
Strange
(more FL)
metal
d-wave
SC
0.2
0.3
X(doping)
$J\vec{S}_i \cdot \vec{S}_j$
Doping AFM
(Mott insulator
w holes)
string of
broken bonds
hole
is
confined

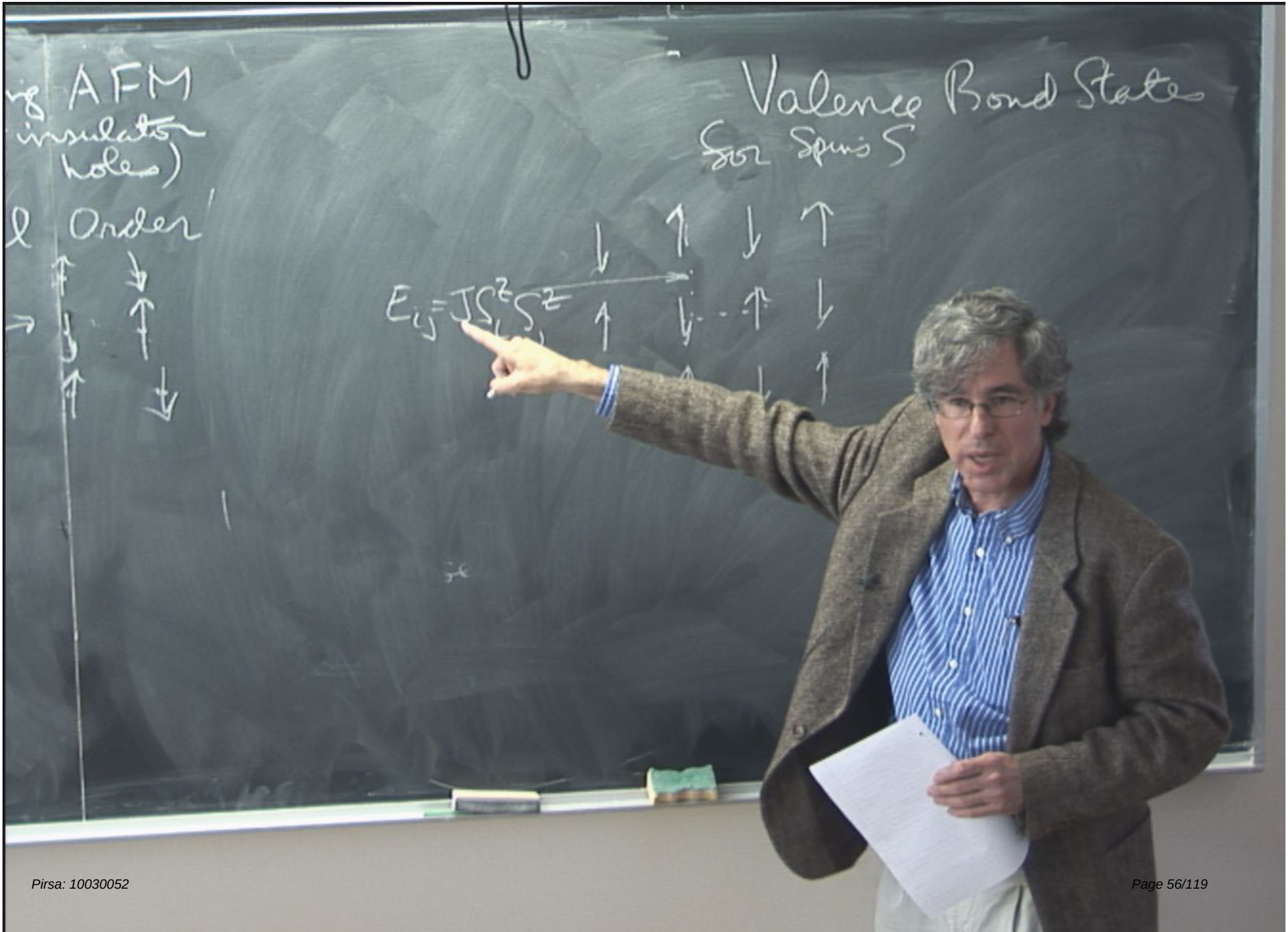

iagram
Strange
Metal
$J\vec{S}_i \cdot \vec{S}_j$
Doping AFM
(Mott insulator
w holes)
Less
Strange
(more FL)
metal
Neel Order
string of
broken bonds
hole
is
confined
d-wave
SC
0.2
0.3
X(doping)

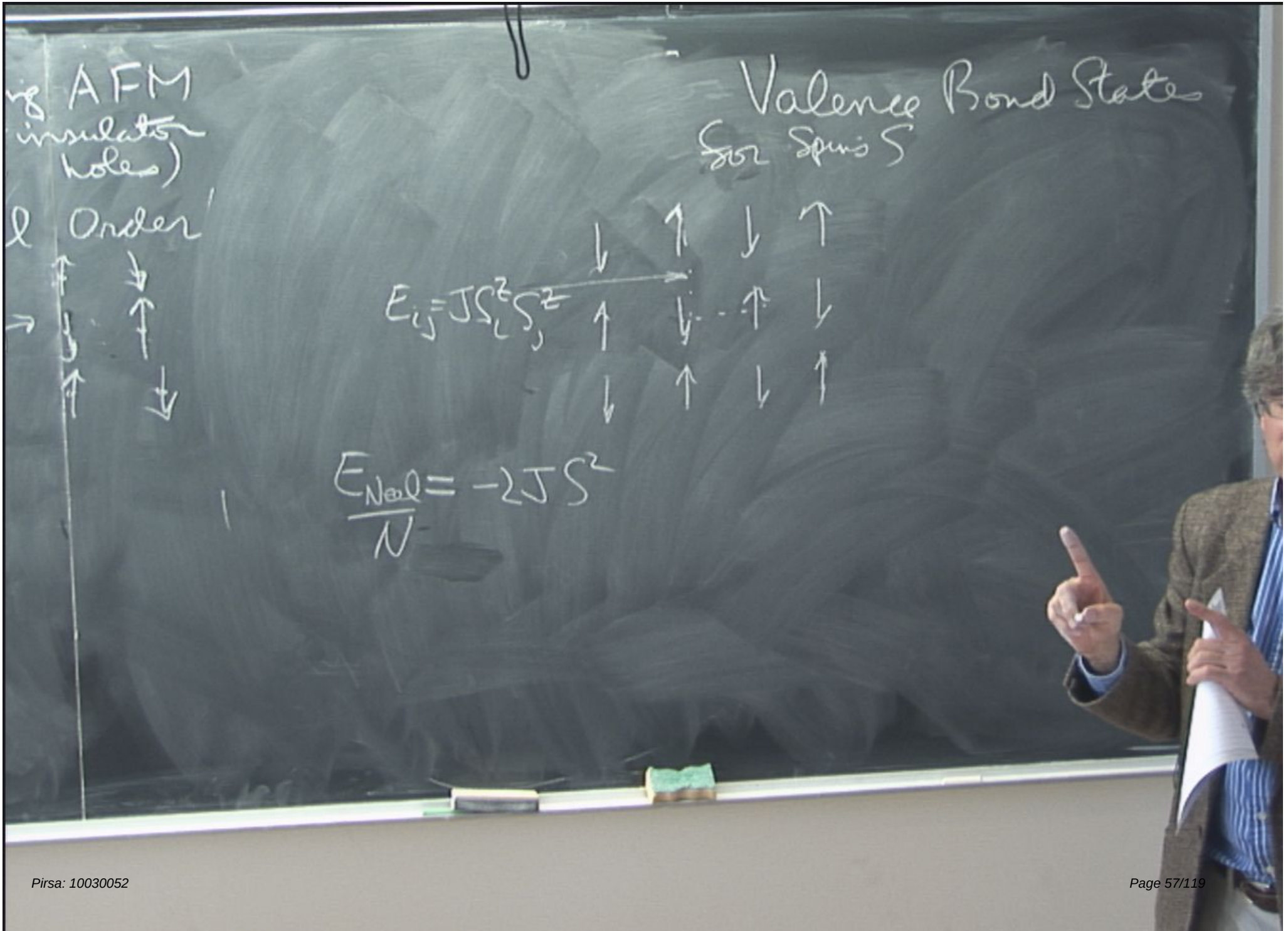

AFM
insulator
holes)
Order
string of
broken bonds
hole
Valence Bond State
for Spin S

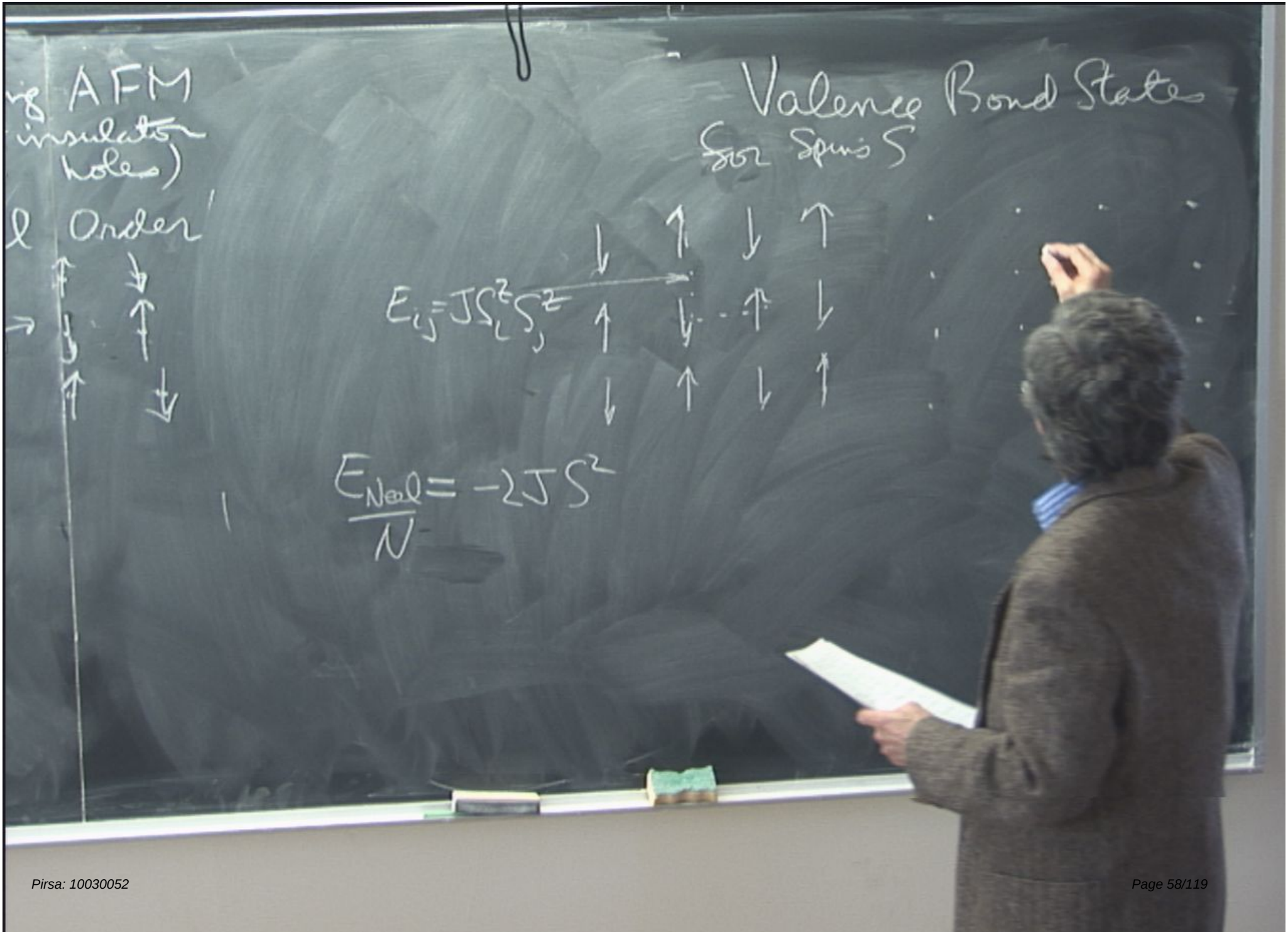

AFM
insulator
holes)
Order
string of
broken bond
hole
Valence Bond State
for Spin 5

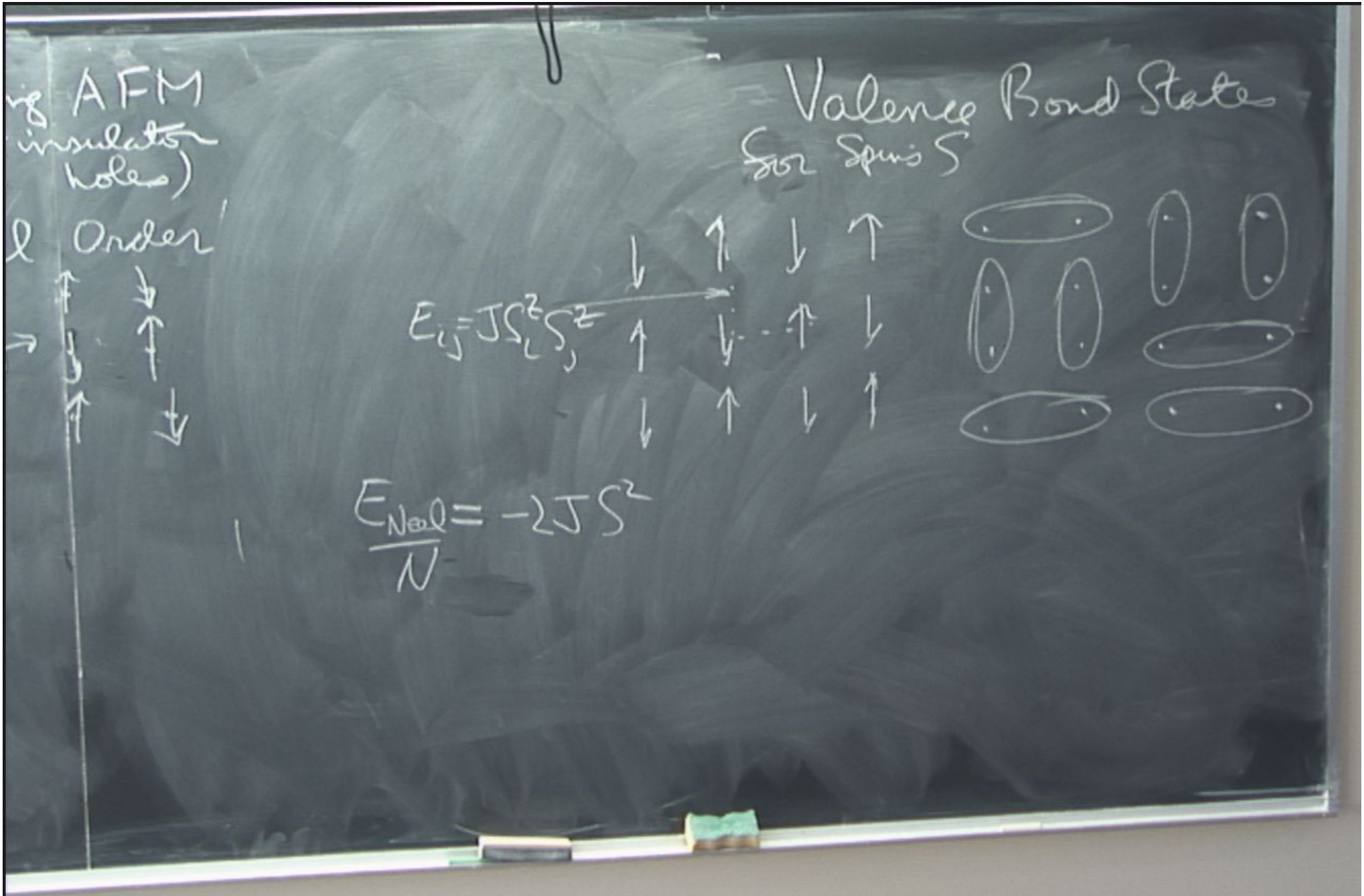

AFM
insulator
holes)
Order
string of
broken bonds
hole
is
Valence Bond State
for Spin 5

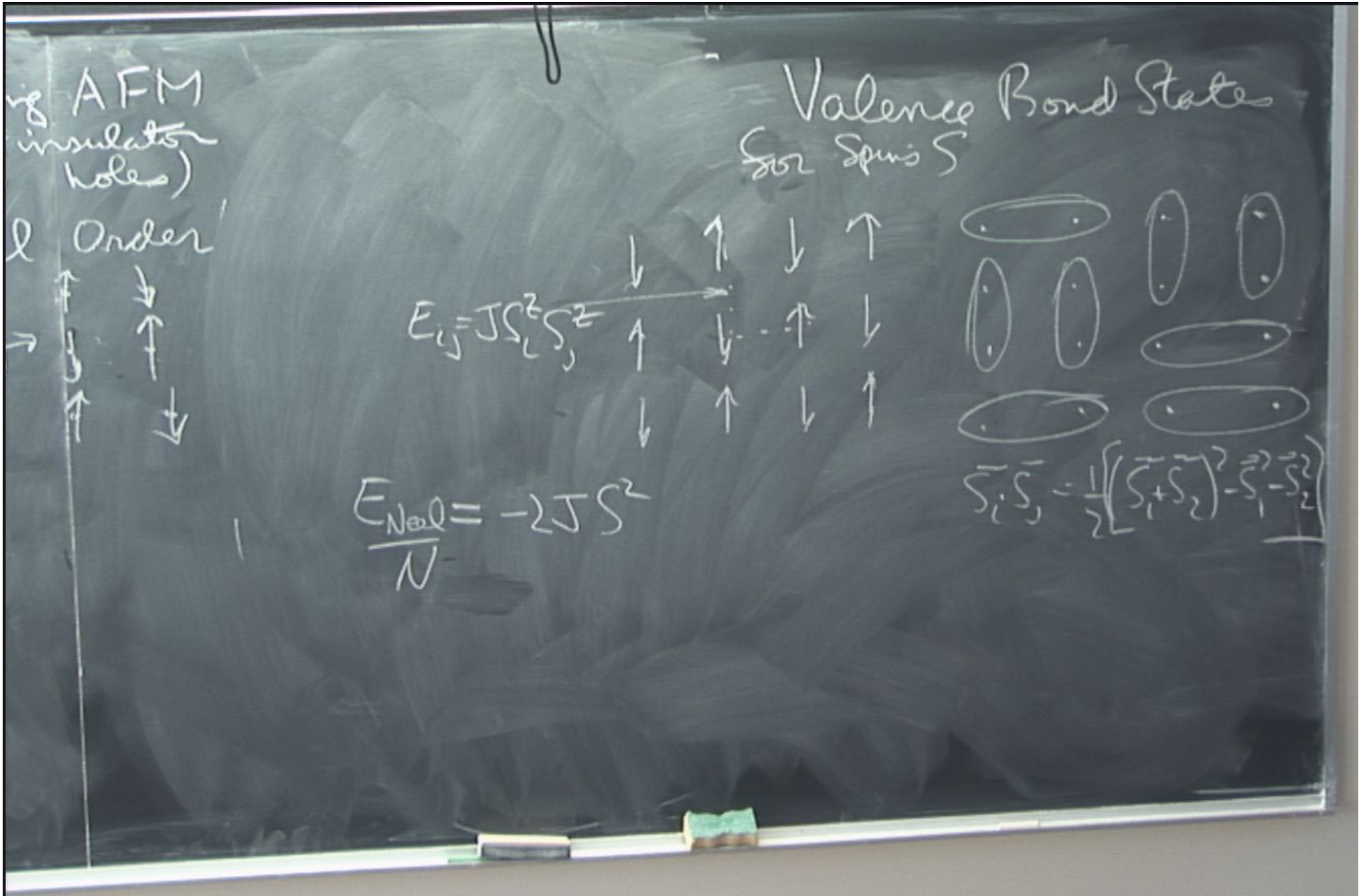

AFM
insulator
holes)
Order
Valence Bond State
for Spin S

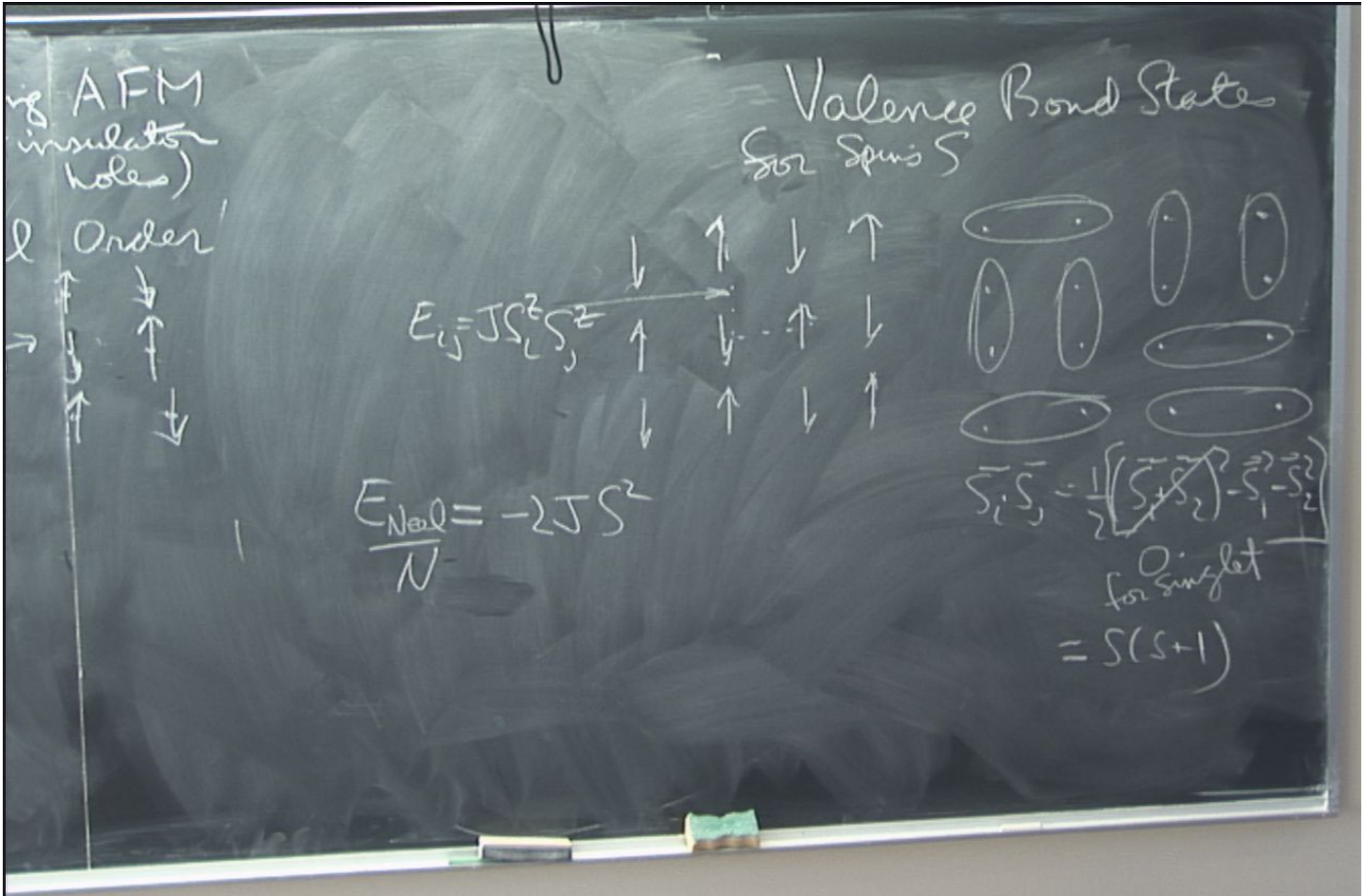

AFM
insulator
holes)
Order
Valence Bond State
for Spin S
$E_{ij} = JS_i^z S_j^z$

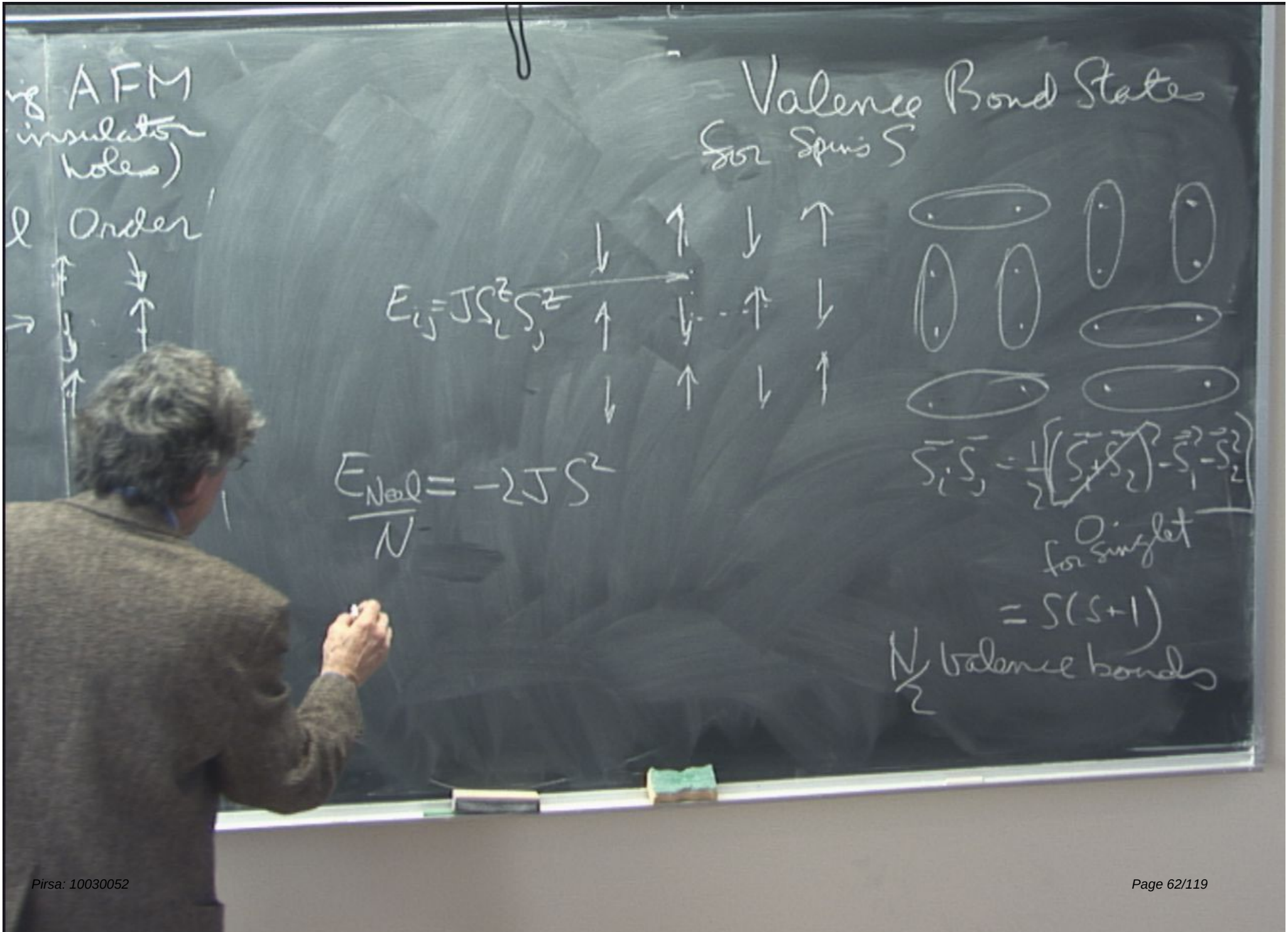

AFM
insulator
holes)
Order
Valence Bond State
Spin S
$E_{ij} = J S_i^z S_j^z$
$\frac{E_{Neel}}{N} = -2JS^2$

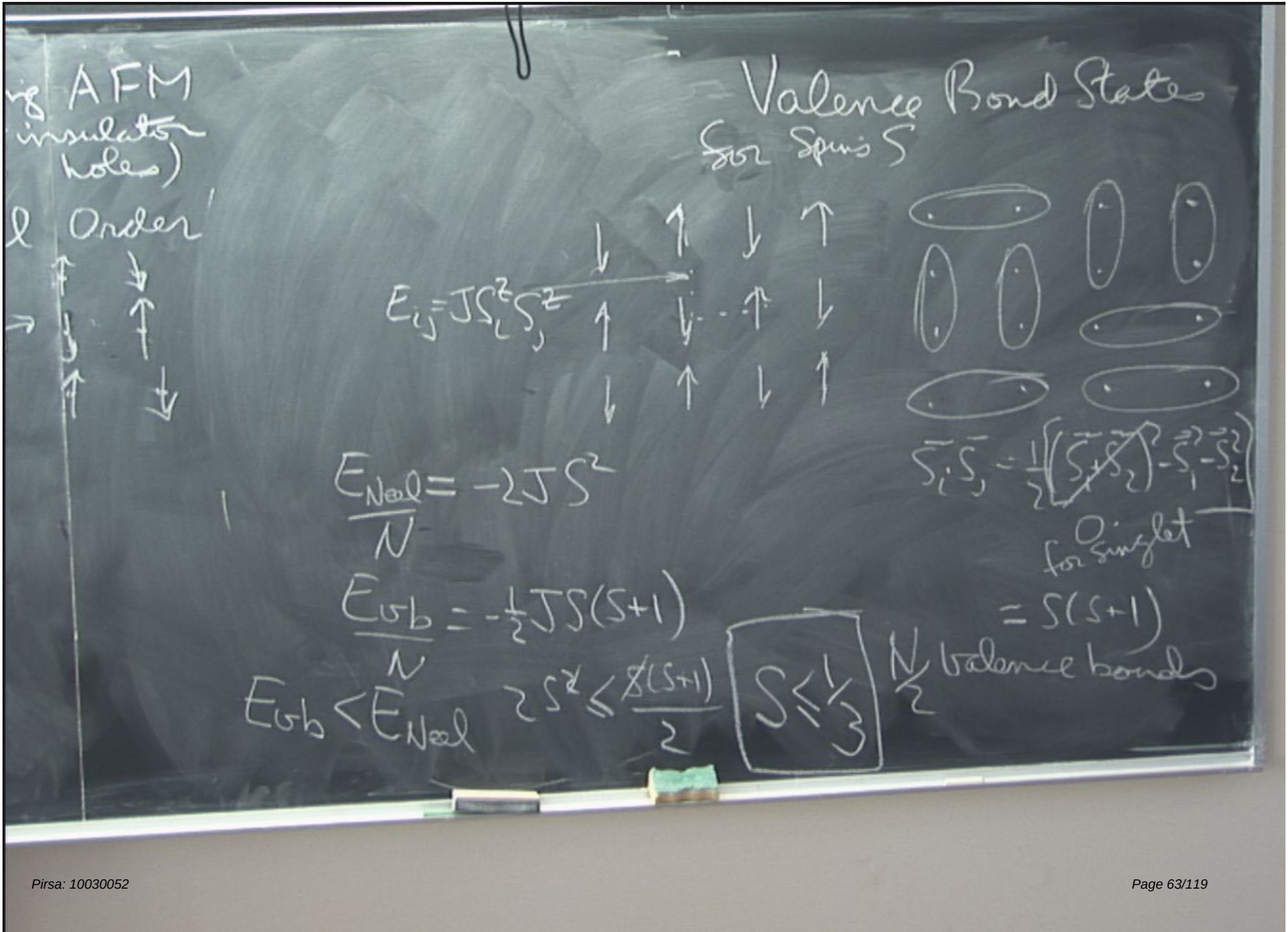

AFM
insulator
holes)
Order
Valence Bond States
Spin S
$E_{ij} = J S_i^z S_j^z$
$\frac{E_{Neel}}{N} = -2JS^2$

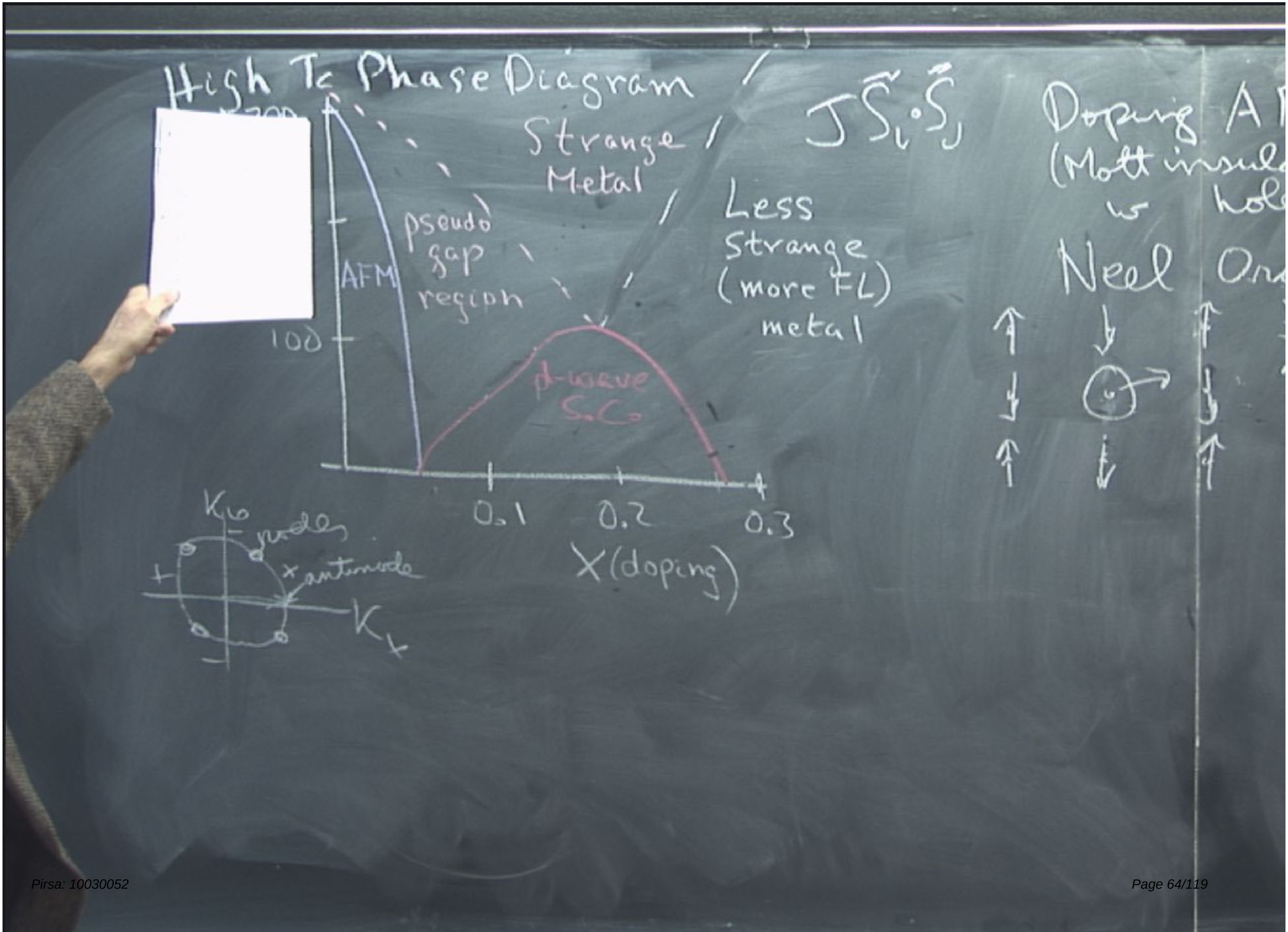

AFM
insulator
holes)
Order
Valence Bond State
For Spin S
$E_{ij} = J S_i^z S_j^z$
$\frac{E_{Neel}}{N} = -2JS^2$

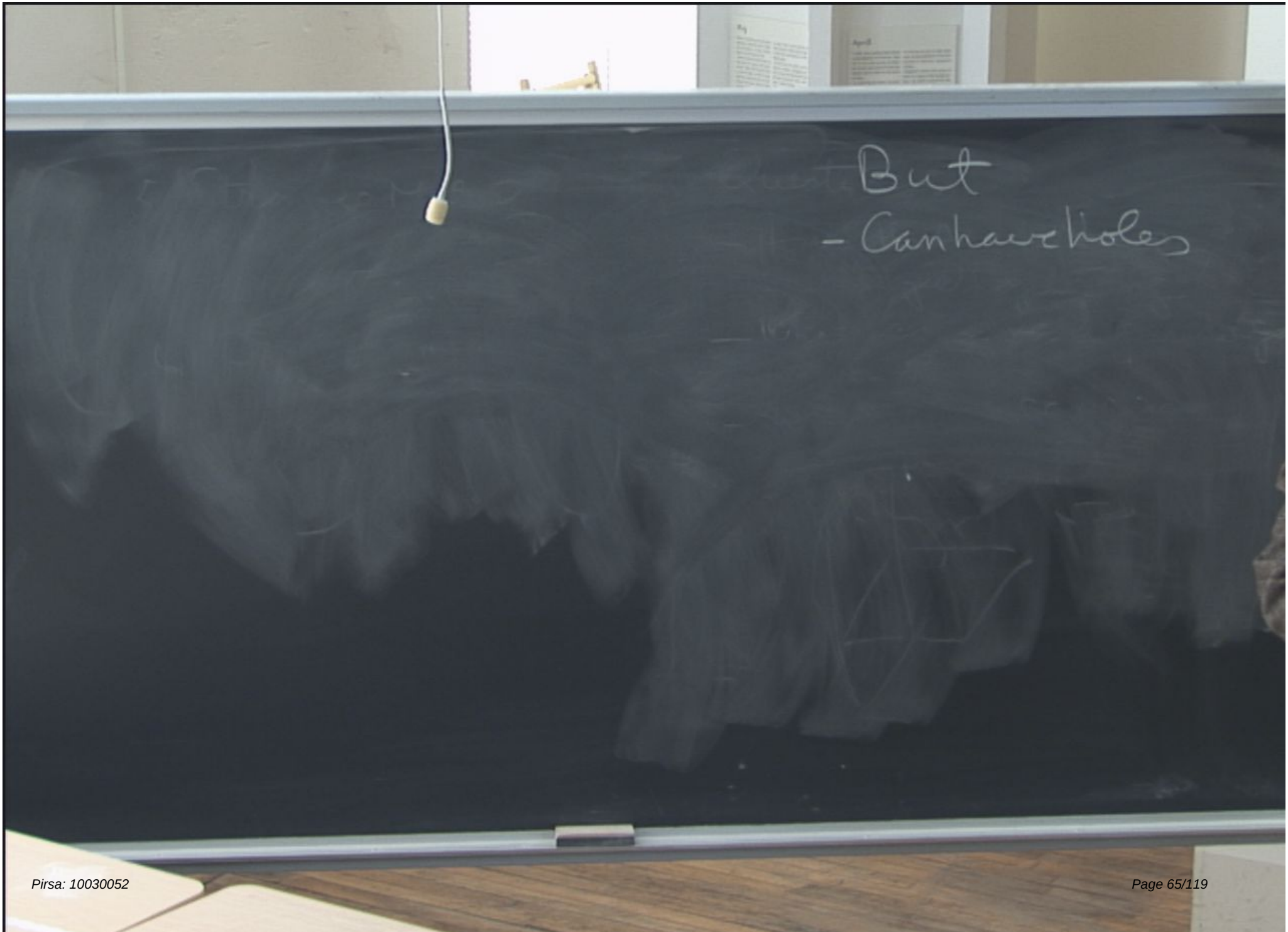

AFM
insulator
holes)
Order
Valence Bond State
Spin S
$E_{ij} = J S_i^z S_j^z$
$E_{Neel} = -2JS^2$
$\frac{E_{Neel}}{N}$
$\vec{S}_i \vec{S}_j = \frac{1}{2}\left[(\vec{S}_1 + \vec{S}_2)^2 - \vec{S}_1^2 - \vec{S}_2^2\right]$


AFM
insulator
holes)
Order
$E_{ij} = JS_i^z S_j^z$
$\frac{E_{Neel}}{N} = -2JS^2$
Valence Bond State
For Spin S
$\vec{S}_i \vec{S}_j = \frac{1}{2}\left[(\vec{S}_1 + \vec{S}_2)^2 - \vec{S}_1^2 - \vec{S}_2^2\right]$
for singlet
$= S(S+1)$


AFM
insulator
holes)
Order
$E_{ij} = J S_i^z S_j^z$
$\frac{E_{Neel}}{N} = -2JS^2$
Valence Bond State
for Spin S
$\vec{S}_i \vec{S}_j = \frac{1}{2}\left[(\vec{S}_1 + \vec{S}_2)^2 - \vec{S}_1^2 - \vec{S}_2^2\right]$
0 for singlet
$= S(S+1)$
$\frac{N}{2}$ valence bonds


AFM
insulator
holes)
Order
Valence Bond States
for Spin S
$E_{ij} = J S_i^z S_j^z$
$\frac{E_{Neel}}{N} = -2JS^2$
$\frac{E_{vb}}{N} = -\frac{1}{2}JS(S+1)$
$E_{vb} < E_{Neel}$
$2S^2 \leq \frac{S(S+1)}{2}$
$S \leq \frac{1}{3}$
$\vec{S}_i \vec{S}_j = \frac{1}{2}\left[(\vec{S}_1+\vec{S}_2)^2 - \vec{S}_1^2 - \vec{S}_2^2\right]$
0 for singlet
$= S(S+1)$
$\frac{N}{2}$ valence bonds

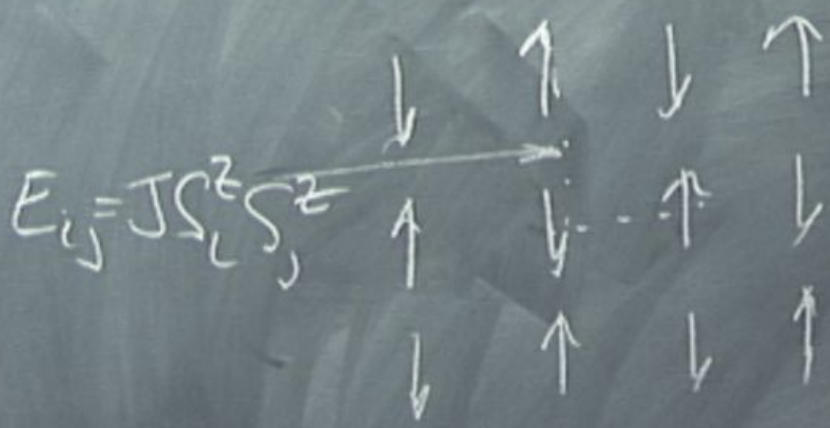

High Tc Phase Diagram
Strange Metal
Less Strange (more FL) metal
pseudo gap region
AFM
100
d-wave S.C.
0.1
0.2
0.3
X (doping)
nodes
antinode
$J\vec{S}_i\cdot\vec{S}_j$
Neel


But
- Can have holes

Valence Bond States

For Spin $\frac{1}{2}$

$E_{ij} = J S_i^z S_j^z$



$\vec{S}_i \vec{S}_j = \frac{1}{2}\left[(\vec{S}_i + \vec{S}_j)^2 - \vec{S}_i^2 - \vec{S}_j^2\right]$

for Singlet $= S(S+1)$

$\frac{E_{Neel}}{N} = -2JS^2$

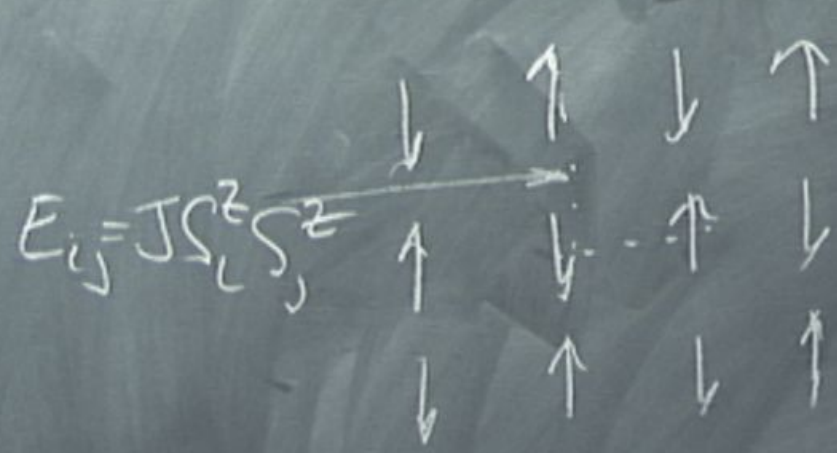
$\frac{E_{Vb}}{N} = -\frac{1}{2}JS(S+1)$

$N/2$ valence bonds

$E_{Vb} < E_{Neel}$ $\quad 2S^2 \leq \frac{S(S+1)}{2}$ $\quad S \leq \frac{1}{3}$

Valence Bond States

For Spin $\frac{1}{2}$



$E_{ij} = J S_i^z S_j^z$

$\vec{S}_i \cdot \vec{S}_j = \frac{1}{2}\left[(\vec{S}_i + \vec{S}_j)^2 - \vec{S}_i^2 - \vec{S}_j^2\right]$

for Singlet $= S(S+1)$

$\frac{E_{Neel}}{N} = -2JS^2$

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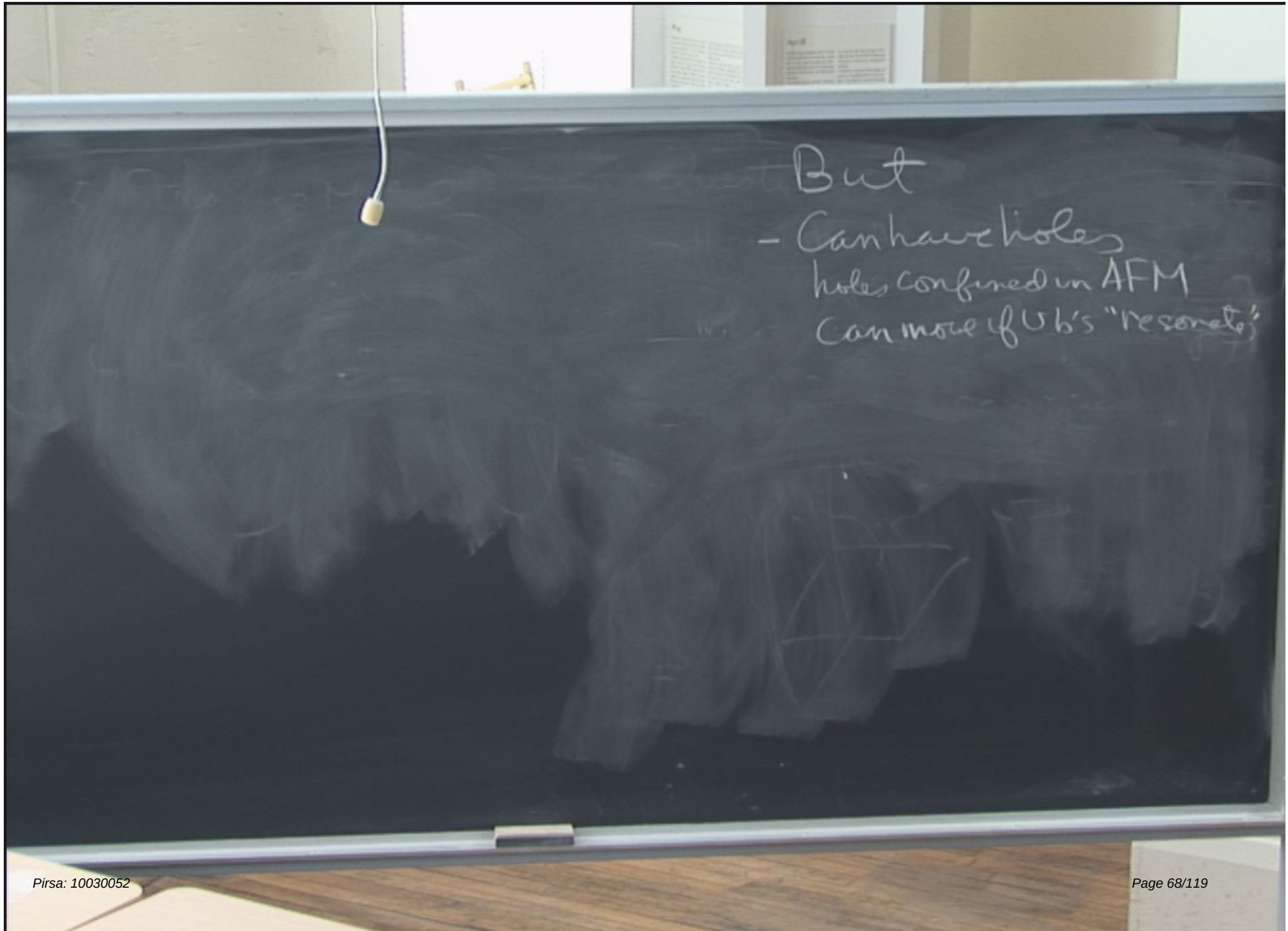
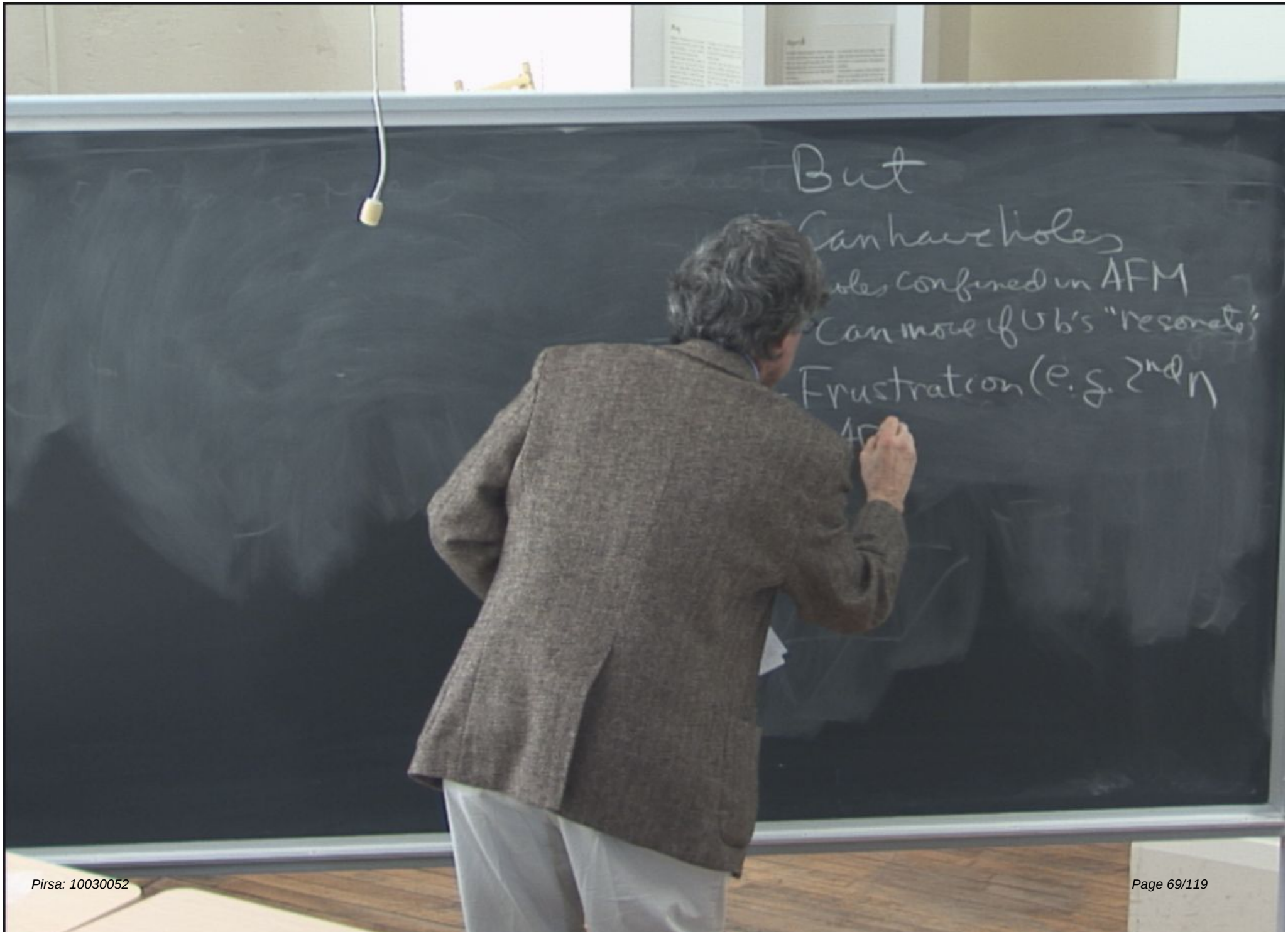
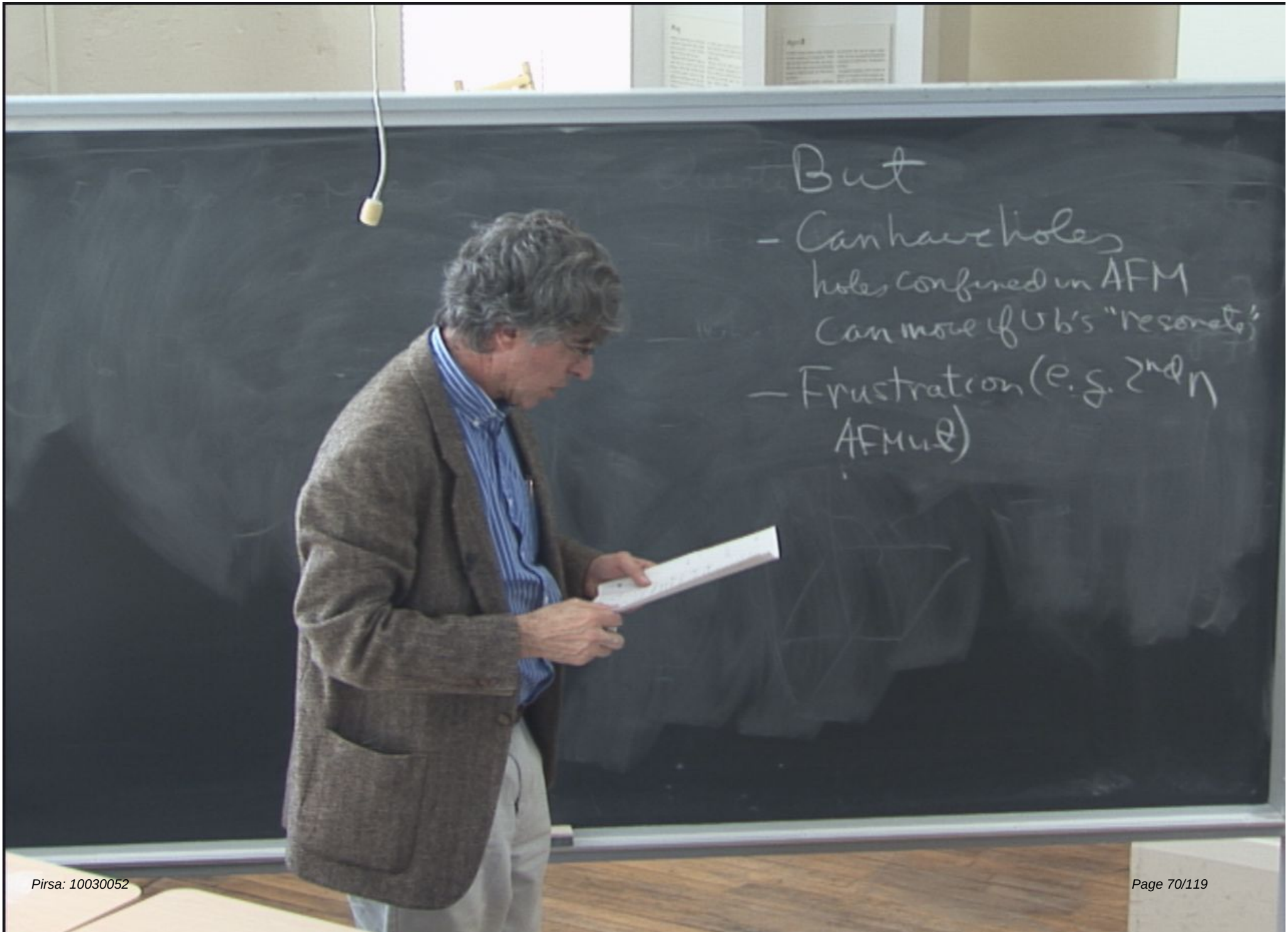
$\frac{N}{2}$ valence bonds

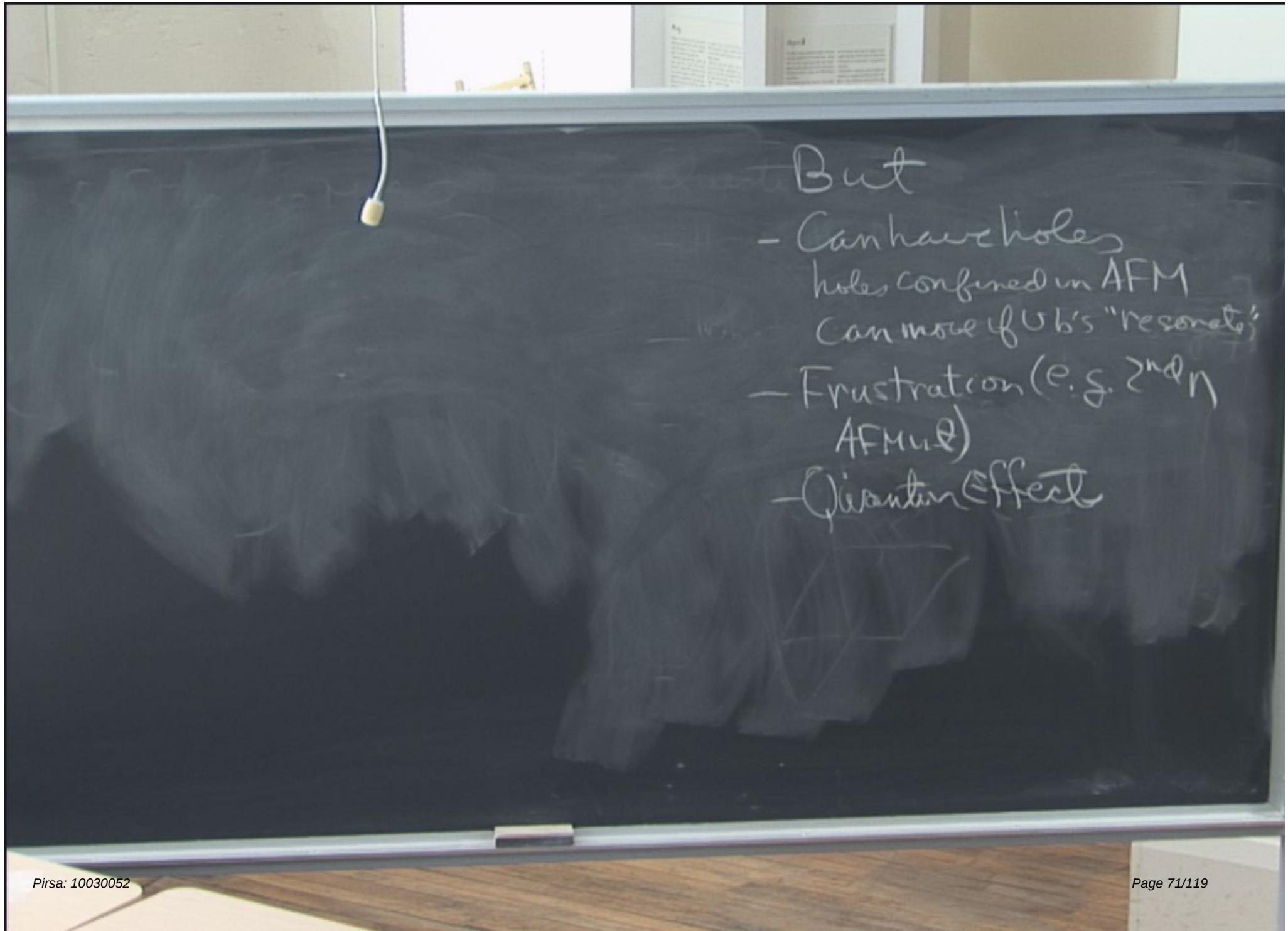
$E_{Vb} < E_{Neel} \quad 2S^2 \leq S(S+1)$

$S \leq 1$


But
- Can have holes
holes confined in AFM
Can move if Ub's "resonate"

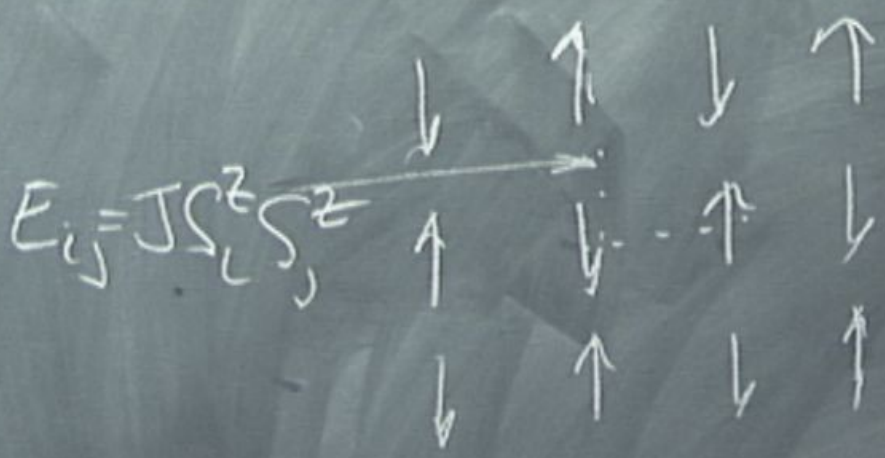

But
can have holes
confined in AFM
can move if U b's "resonate"
Frustration (e.g. 2nd n


But
- Can have holes
holes confined in AFM
Can move if Ub's "resonate"
- Frustration (e.g. 2nd n
AFM u.c.)

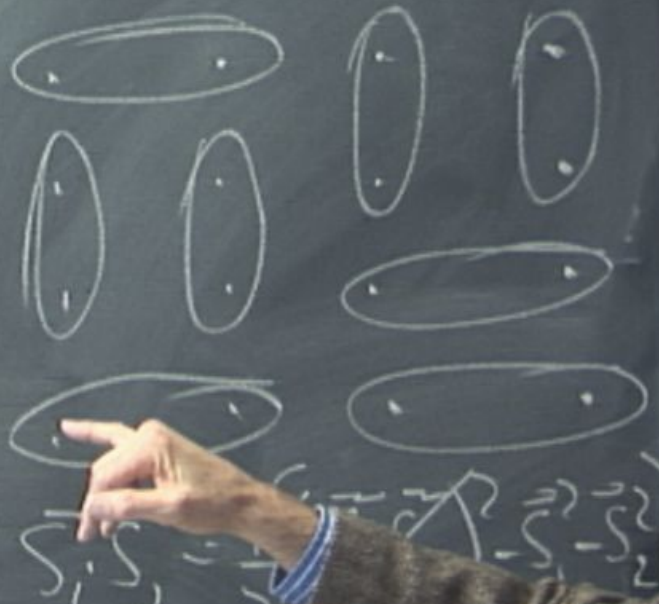

But
- Can have holes
holes confined in AFM
Can move if U b's "resonate"
- Frustration (e.g. 2nd n
AFM u.c.)
- Quantum Effects

Valence Bond States

For Spin S



$E_{ij} = J S_i^z S_j^z$



$S_i \cdot S_j = \frac{1}{2}\left[(\vec{S}_i + \vec{S}_j)^2 - \vec{S}_i^2 - \vec{S}_j^2\right]$

$E_{Neel} = -2JS^2$

$\frac{E_{Neel}}{N}$

$\frac{E_{vb}}{N} = -\frac{1}{2}JS(S+1)$

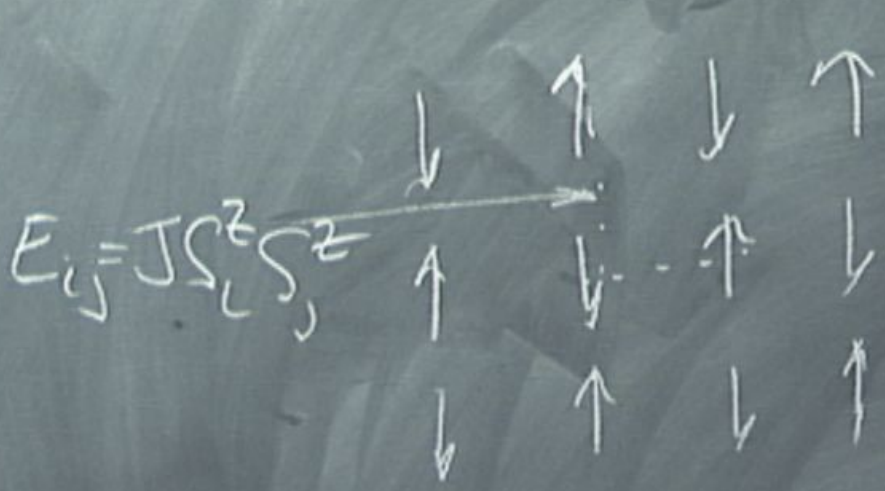
for Singlet $= S(S+1)$

$\frac{N}{2}$ valence bonds

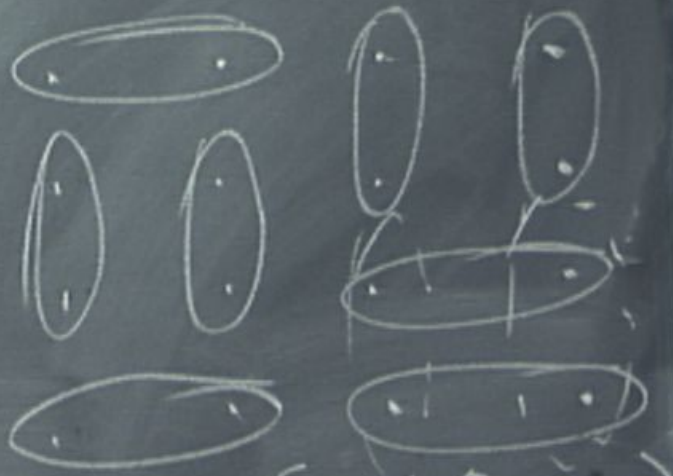
$E_{vb} < E_{Neel}$ $\quad 2S^2 \leq \frac{S(S+1)}{2}$ $\quad S \leq \frac{1}{3}$

Valence Bond States

For Spins S



$E_{ij} = J S_i^z S_j^z$



$\vec{S}_i \cdot \vec{S}_j = \frac{1}{2}\left[(\vec{S}_1 + \vec{S}_2)^2 - \vec{S}_1^2 - \vec{S}_2^2\right]$

$= 0$ for singlet

$= S(S+1)$

$\frac{N}{2}$ valence bonds

$E_{Neel} = -2JS^2$

$\frac{E_{Neel}}{N}$

$\frac{E_{vb}}{N} = -\frac{1}{2}JS(S+1)$

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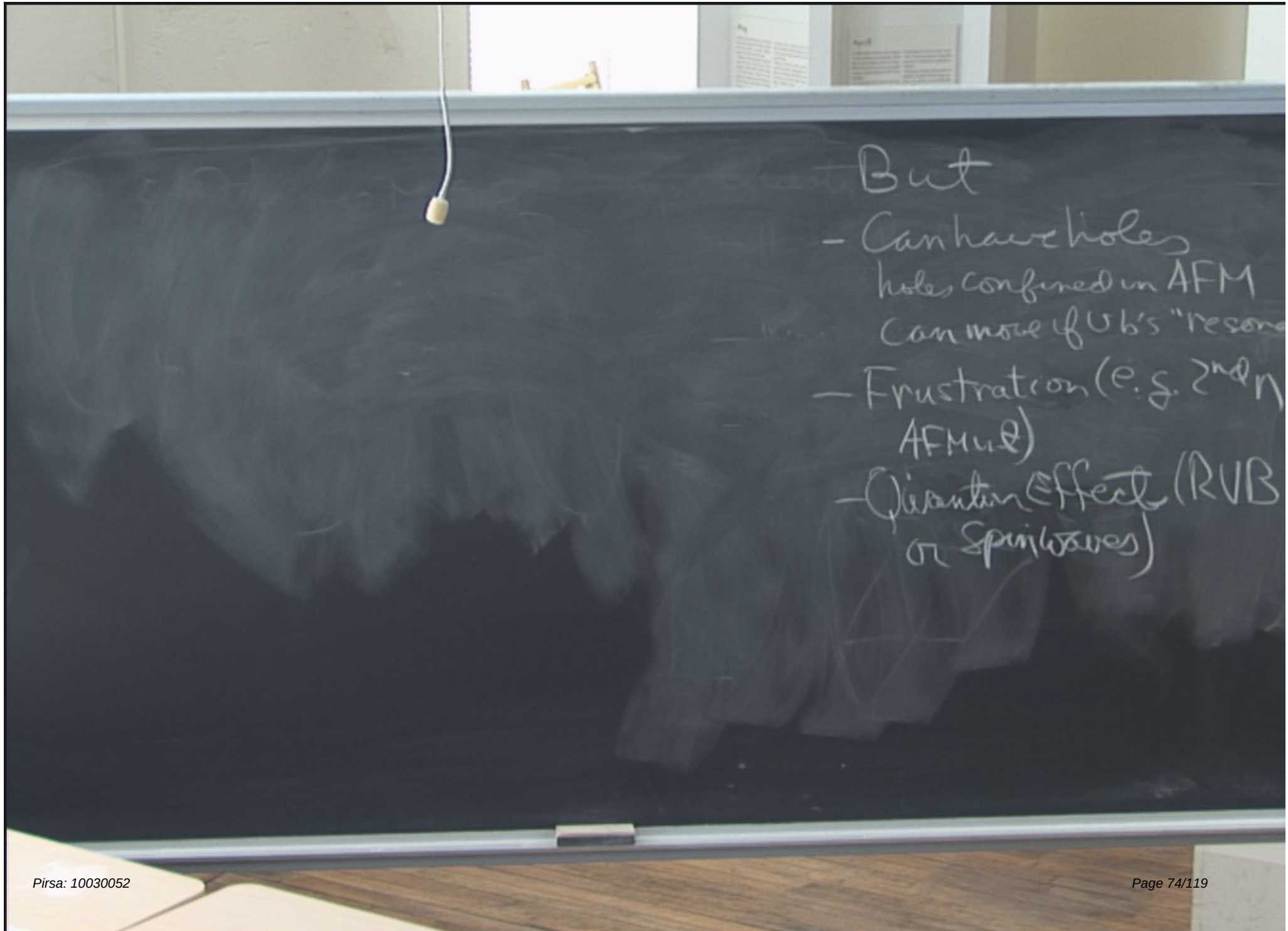
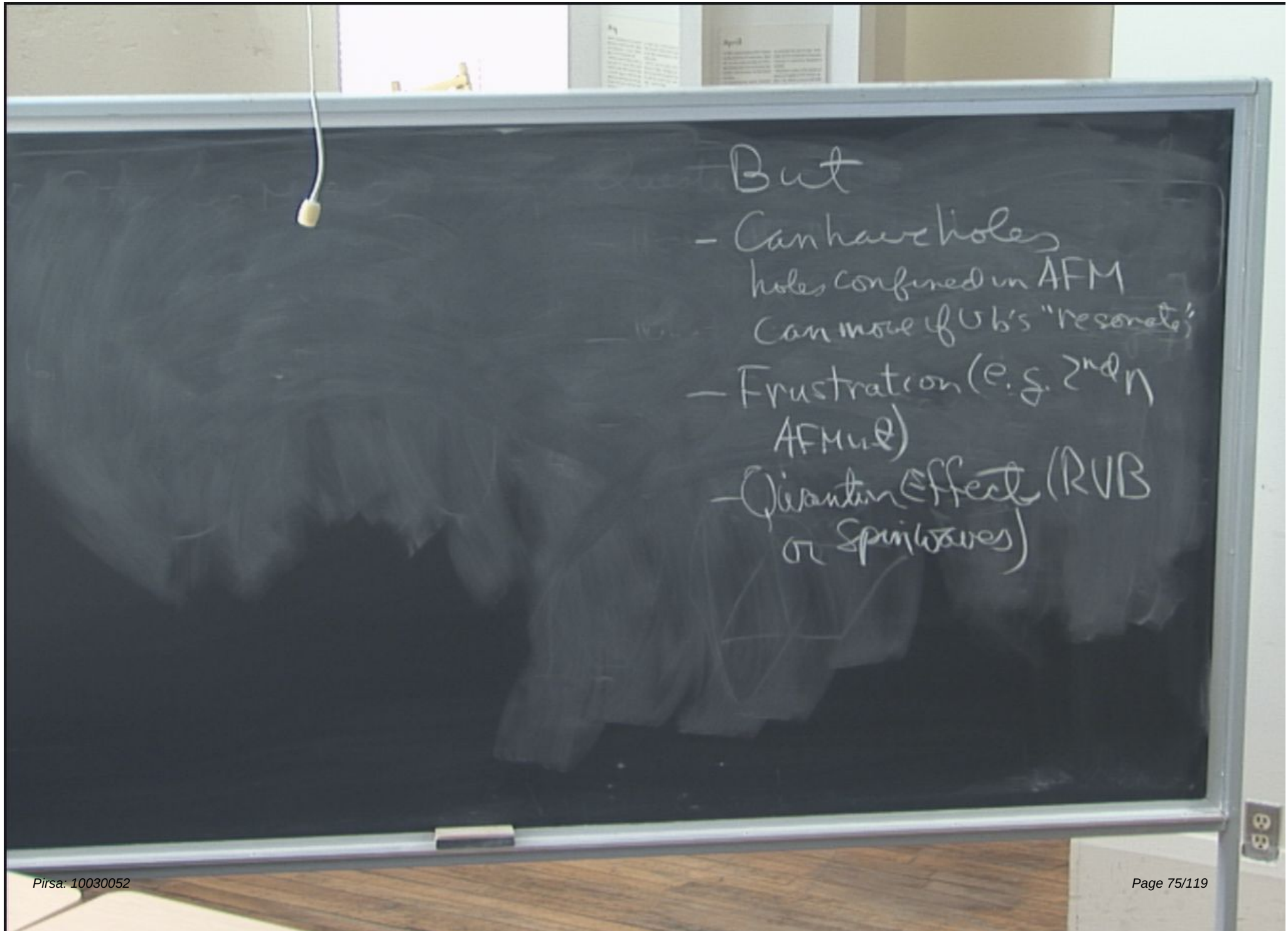
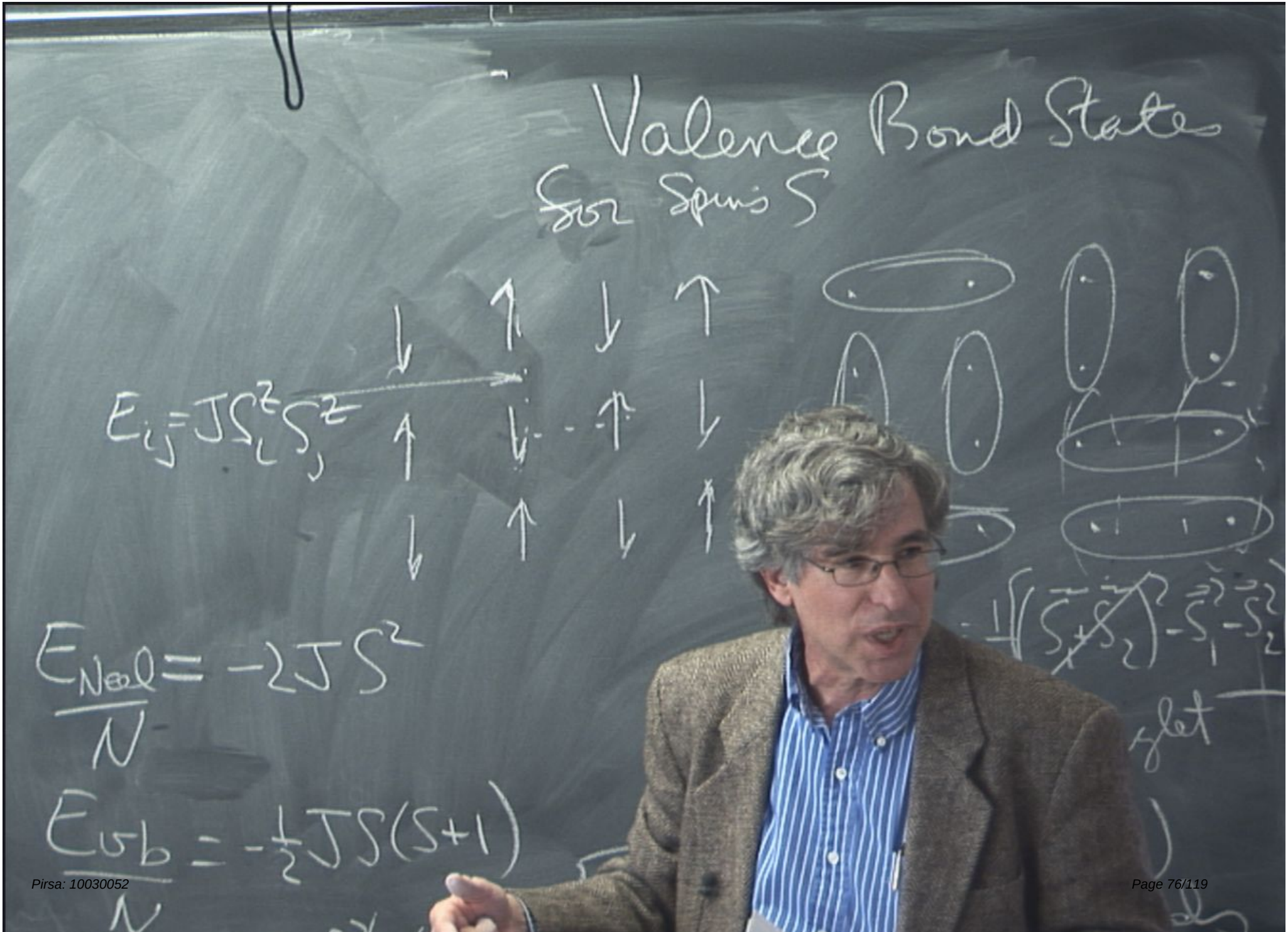
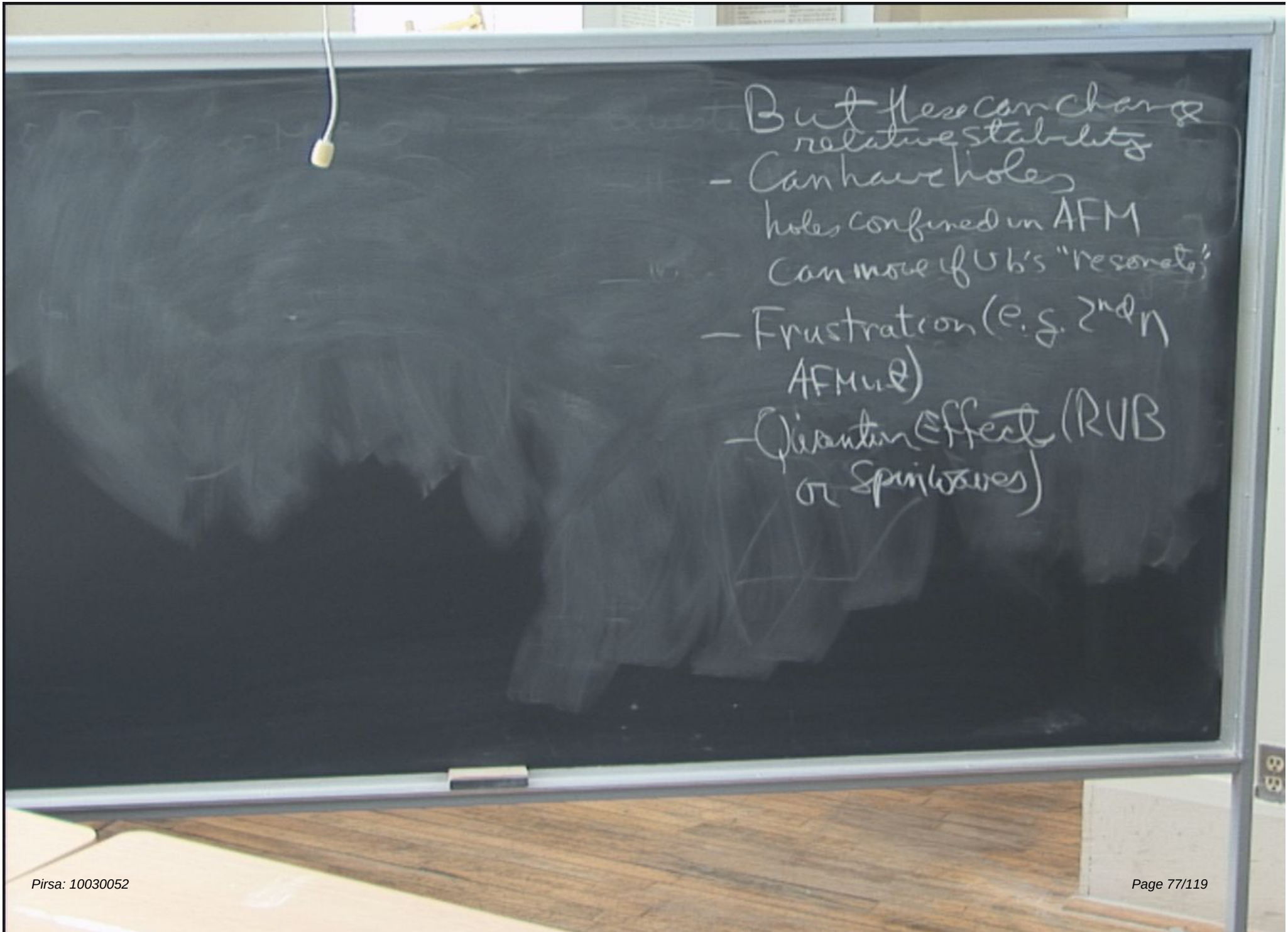
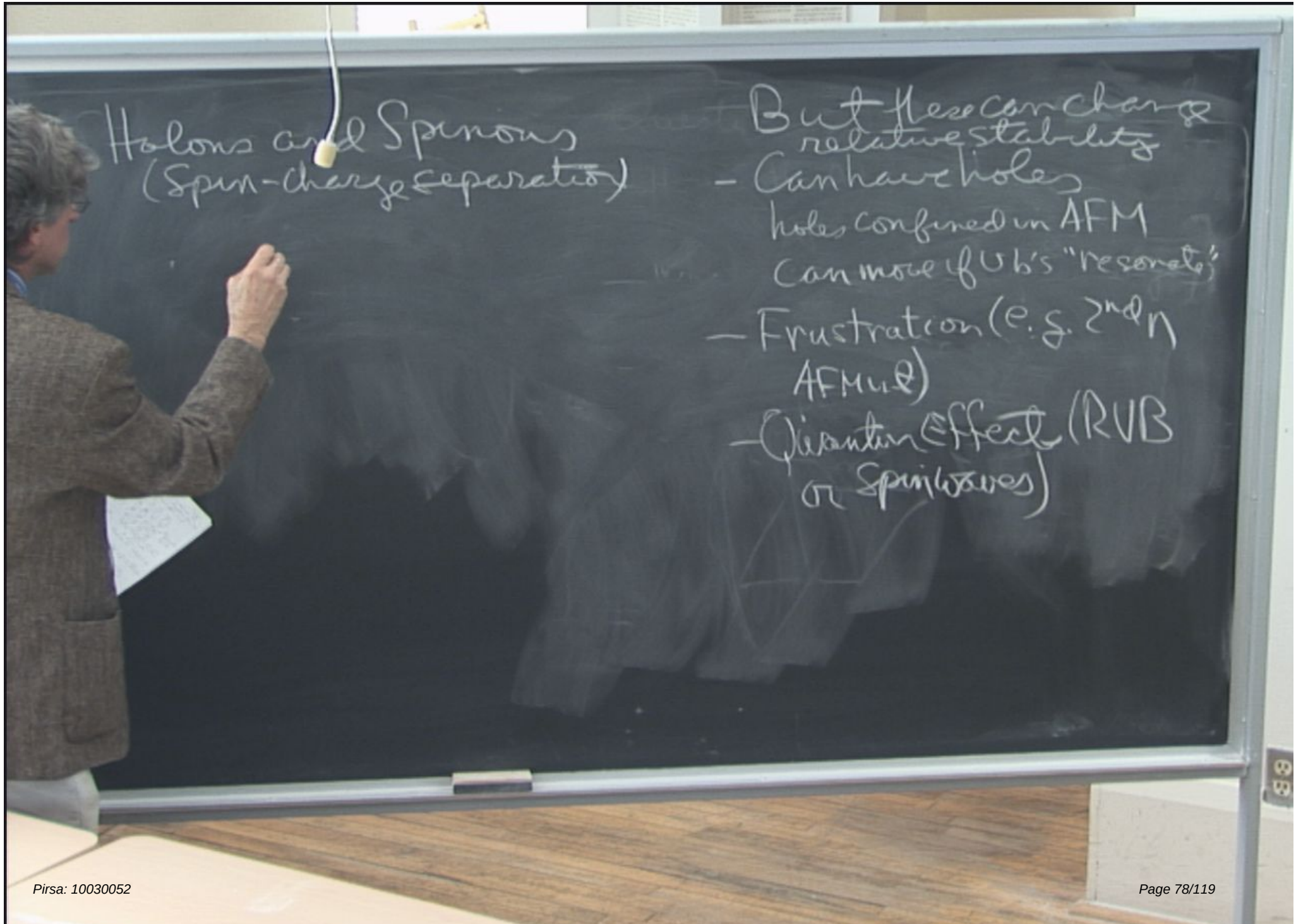

But
- Can have holes
holes confined in AFM
Can move if Ub's "reson
- Frustration (e.g. 2nd n
AFM u.l)
- Quantum effects (RVB
or Spin waves)


But
- Can have holes
holes confined in AFM
Can move if U b's "resonate"
- Frustration (e.g. 2nd n
AFM u.c.)
- Quantum effects (RVB
or Spin waves)

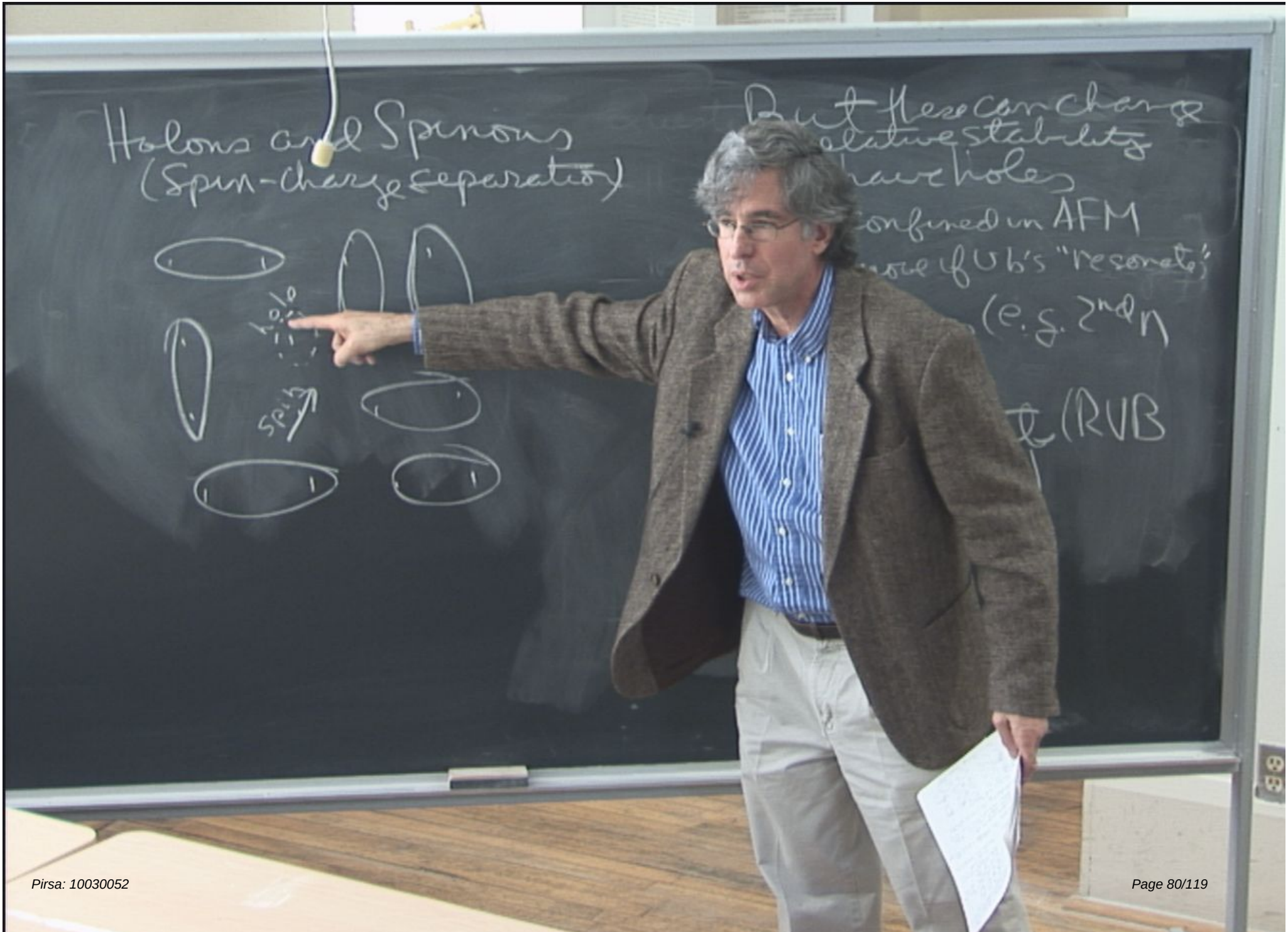

Valence Bond States
For Spins S
$E_{ij} = JS_i^z S_j^z$
$\frac{E_{Neel}}{N} = -2JS^2$
$\frac{E_{VB}}{N} = -\frac{1}{2}JS(S+1)$

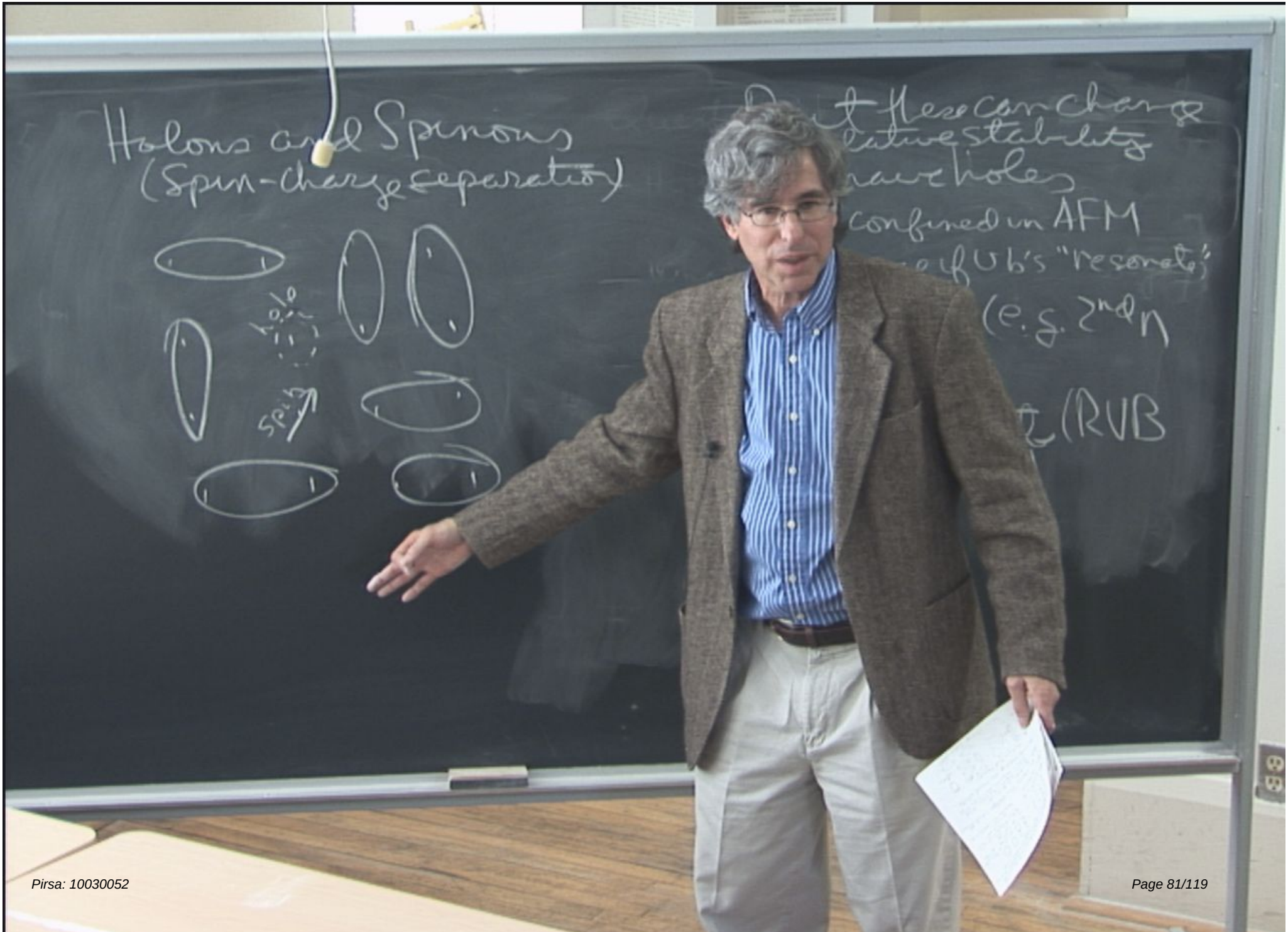

But these can change relative stabilities
- Can have holes
holes confined in AFM
Can move if Ub's "resonate"
- Frustration (e.g. 2nd n AFM in 2)
- Quantum effects (RVB or Spin waves)

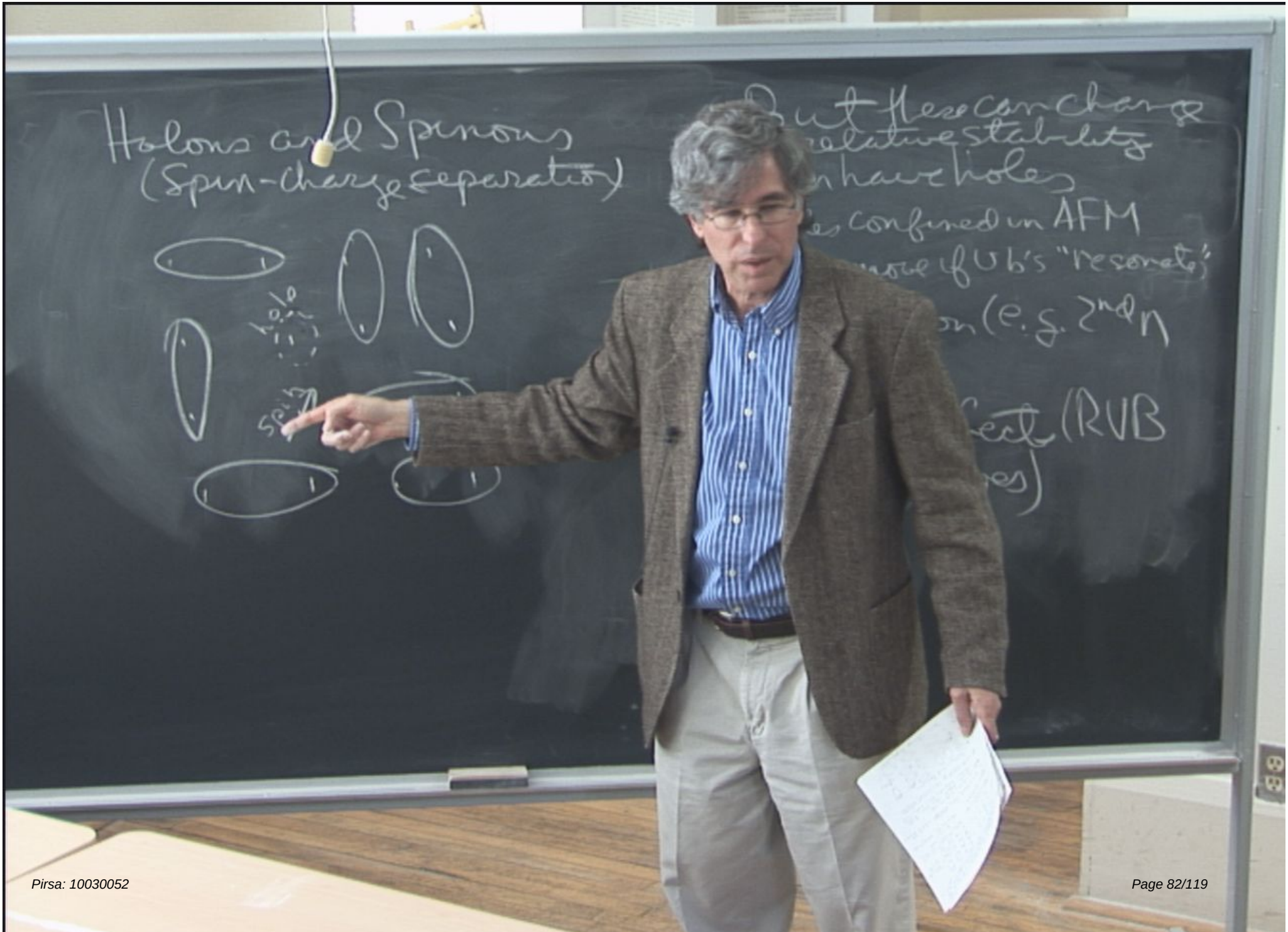

Holons and Spinons
(Spin-charge separation)
But these can change
relative stability
- Can have holes
holes confined in AFM
Can move if Ub's "resonate"
- Frustration (e.g. 2nd n
AFM u.c.)
- Quantum effects (RVB
or Spin waves)

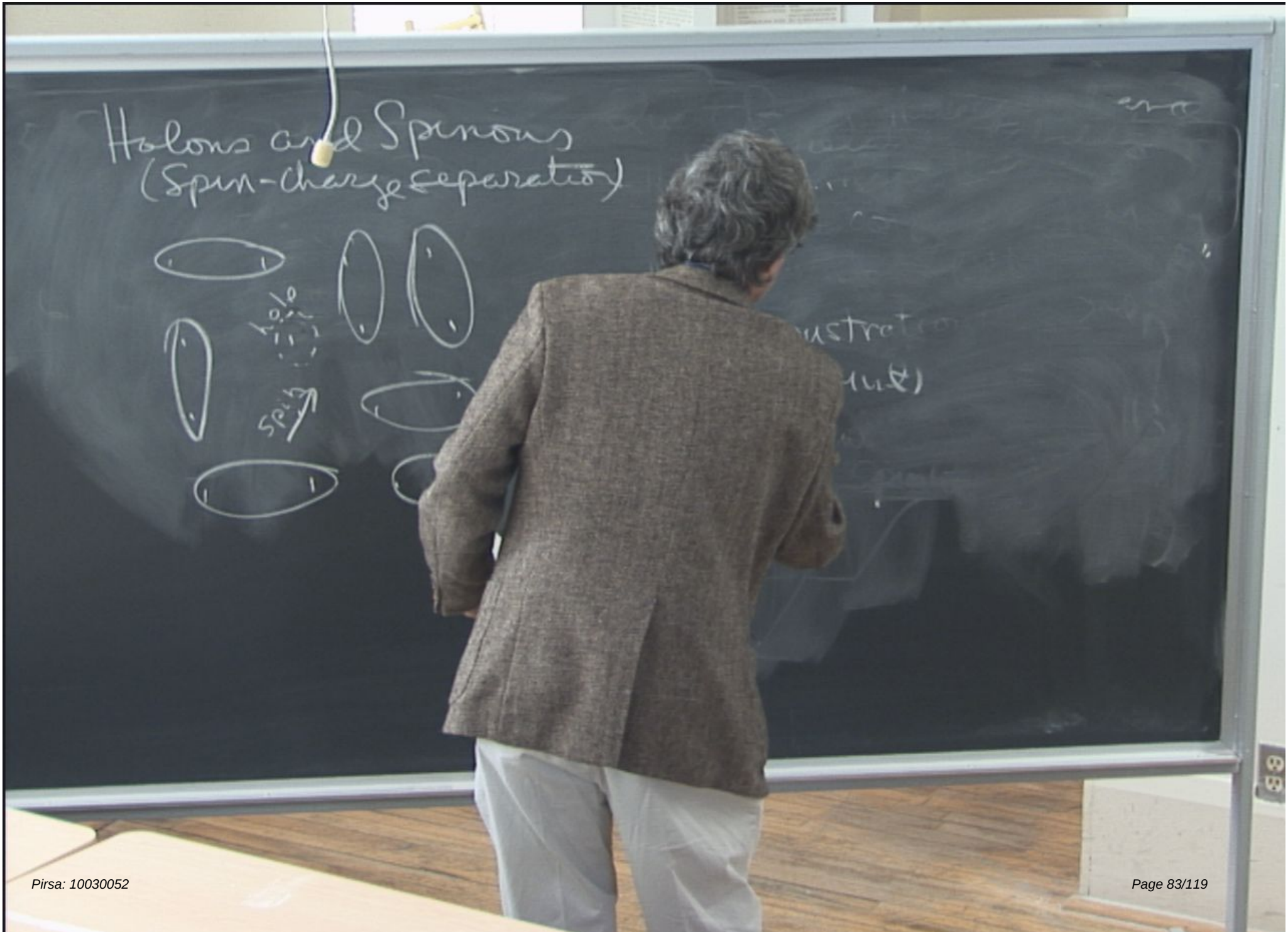
Holons and Spinons
(Spin-charge separation)

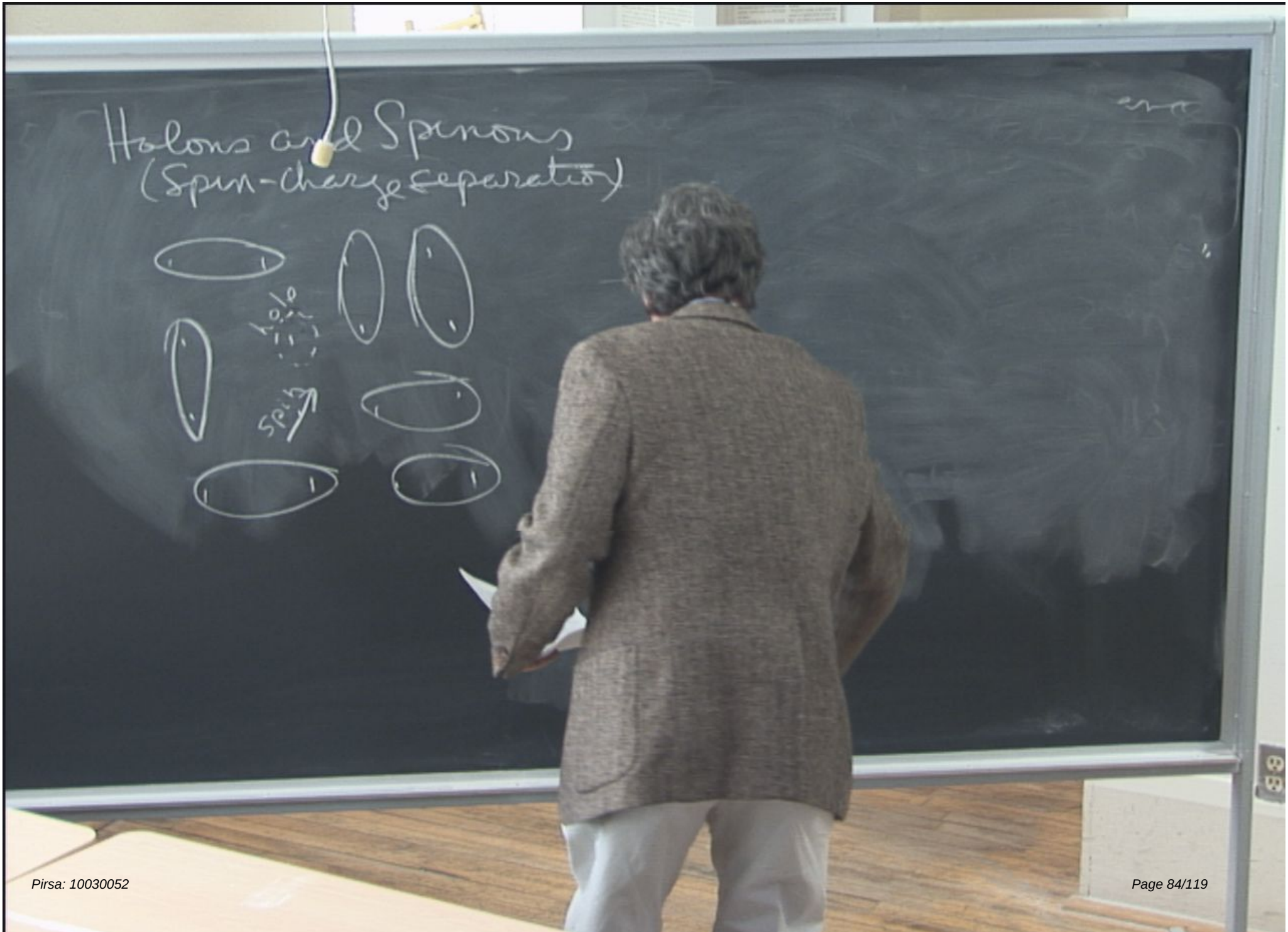
But these can change
relative stability
- Can have holes
holes confined in AFM
Can move if U b's "resonate"
- Frustration (e.g. 2nd n
AFM u2)
- Quantum effects (RVB
or Spin waves)

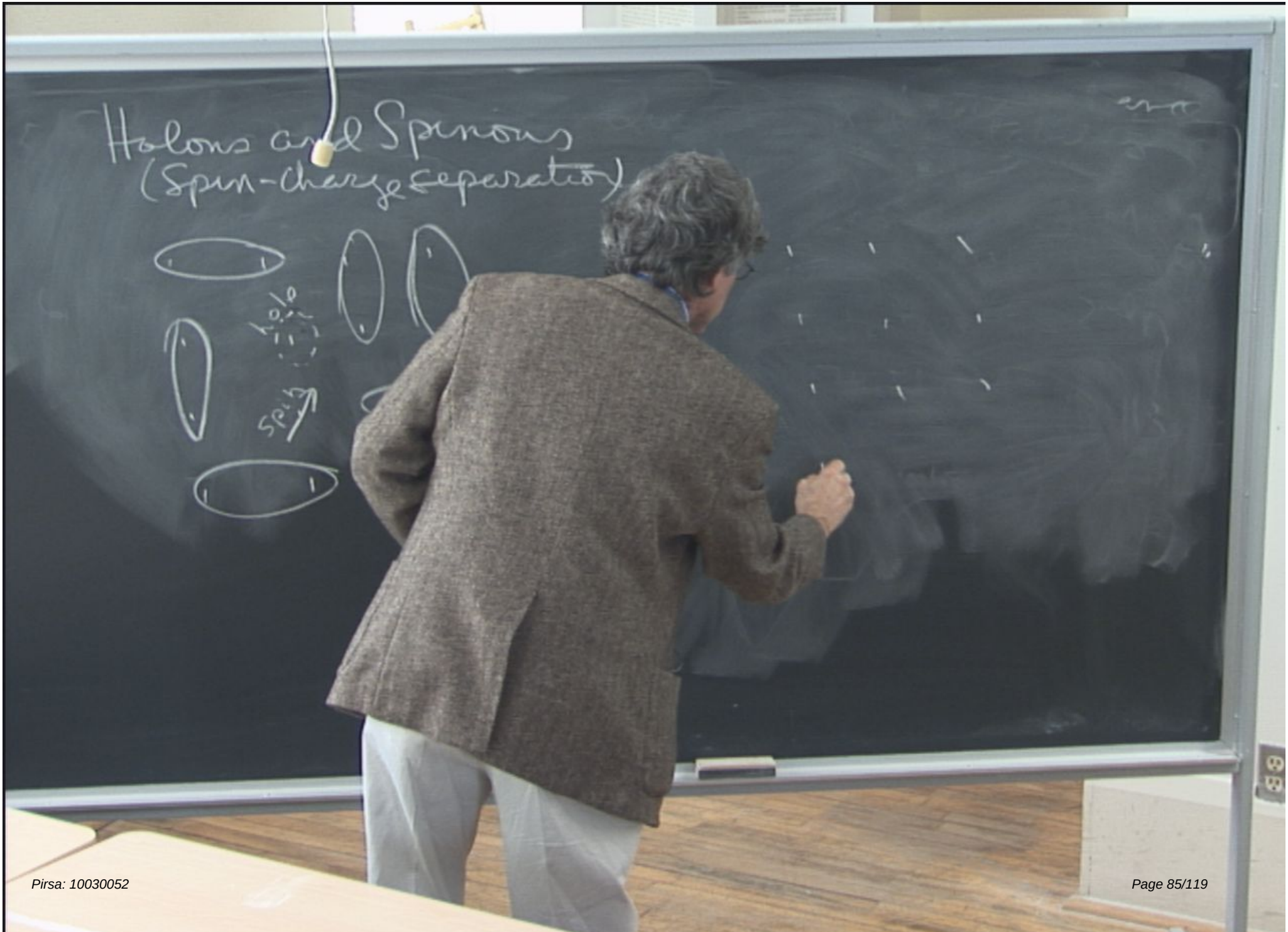

Holons and Spinons
(Spin-Charge Separation)
But these can change
confined in AFM
(e.g. 2nd n
(RVB

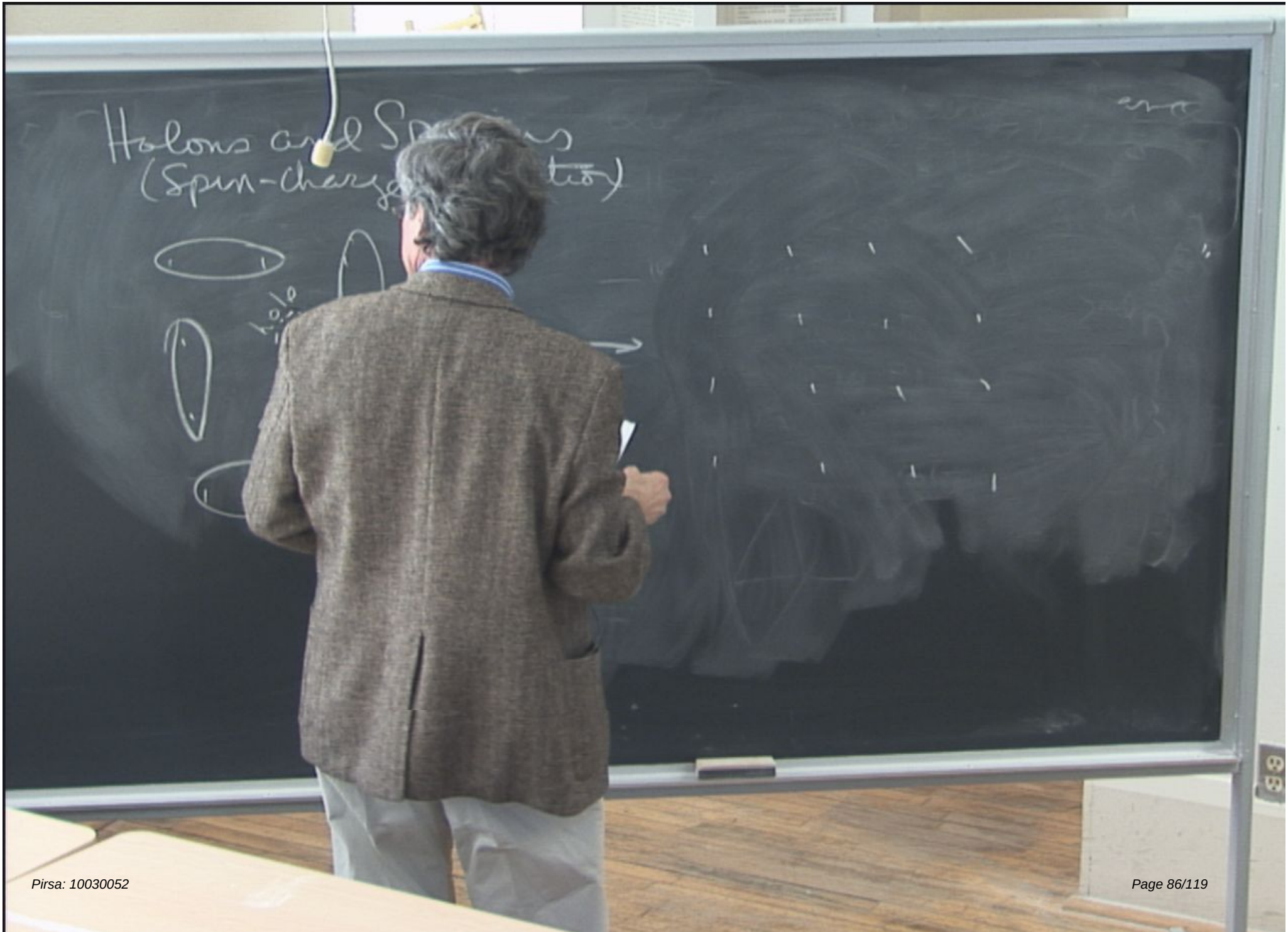

Holons and Spinons
(Spin-charge seperation)
hole
spin
confined in AFM
(e.g. 2nd n
(RVB

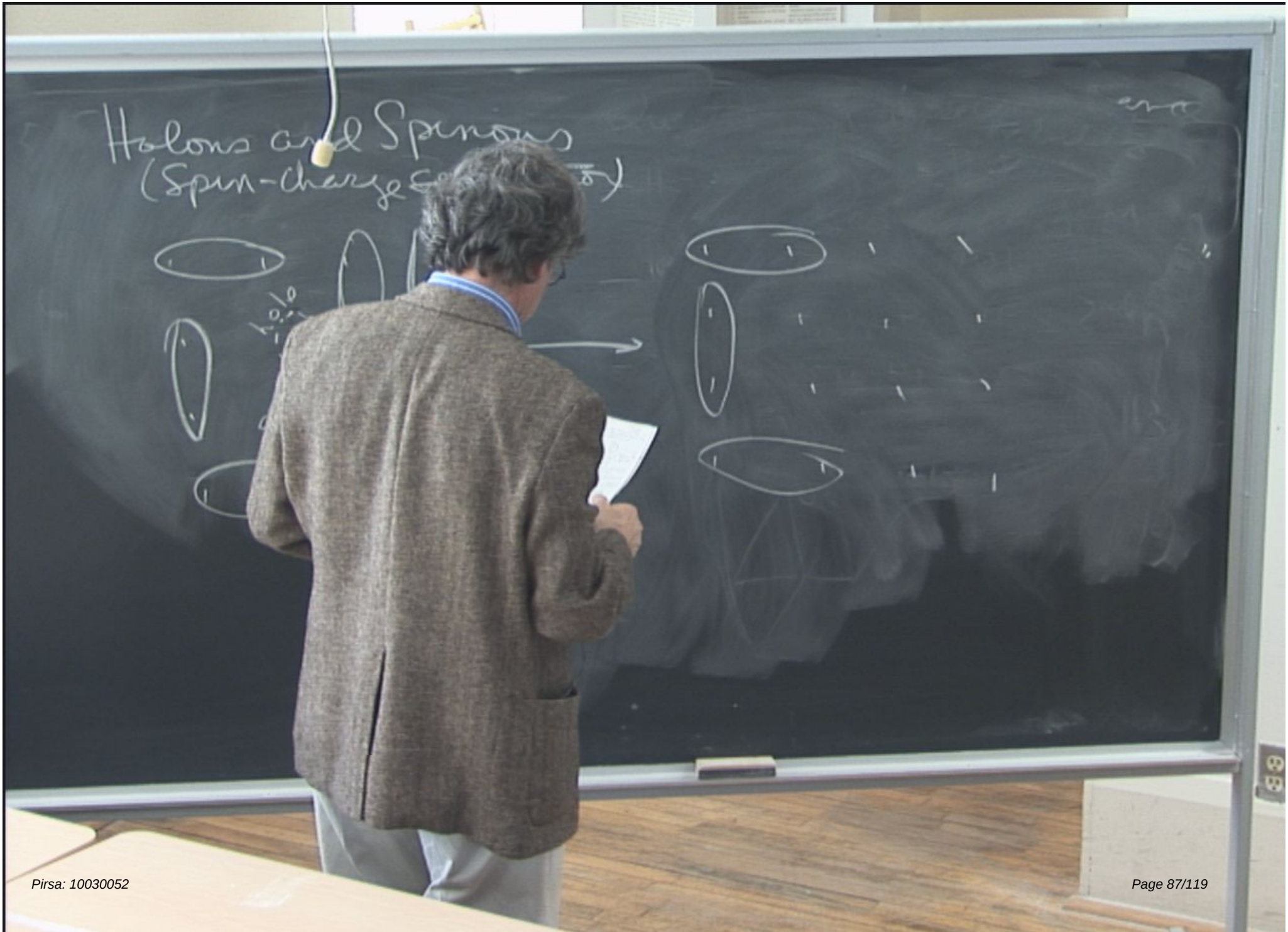

Holons and Spinons
(Spin-Charge Separation)
hole
spin
confined in AFM
(RVB

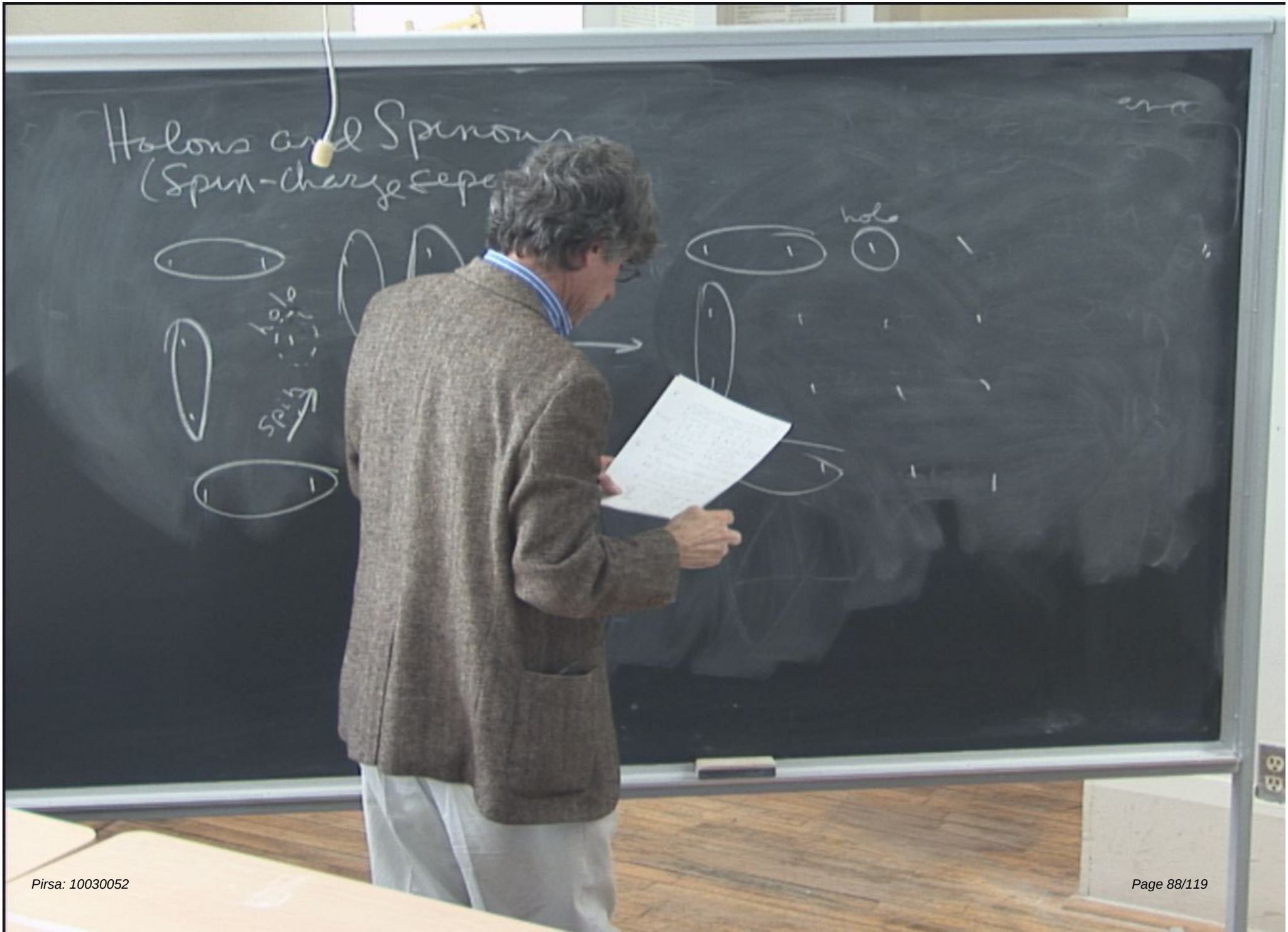

Holons and Spinons
(Spin-charge separation)
hole
spin

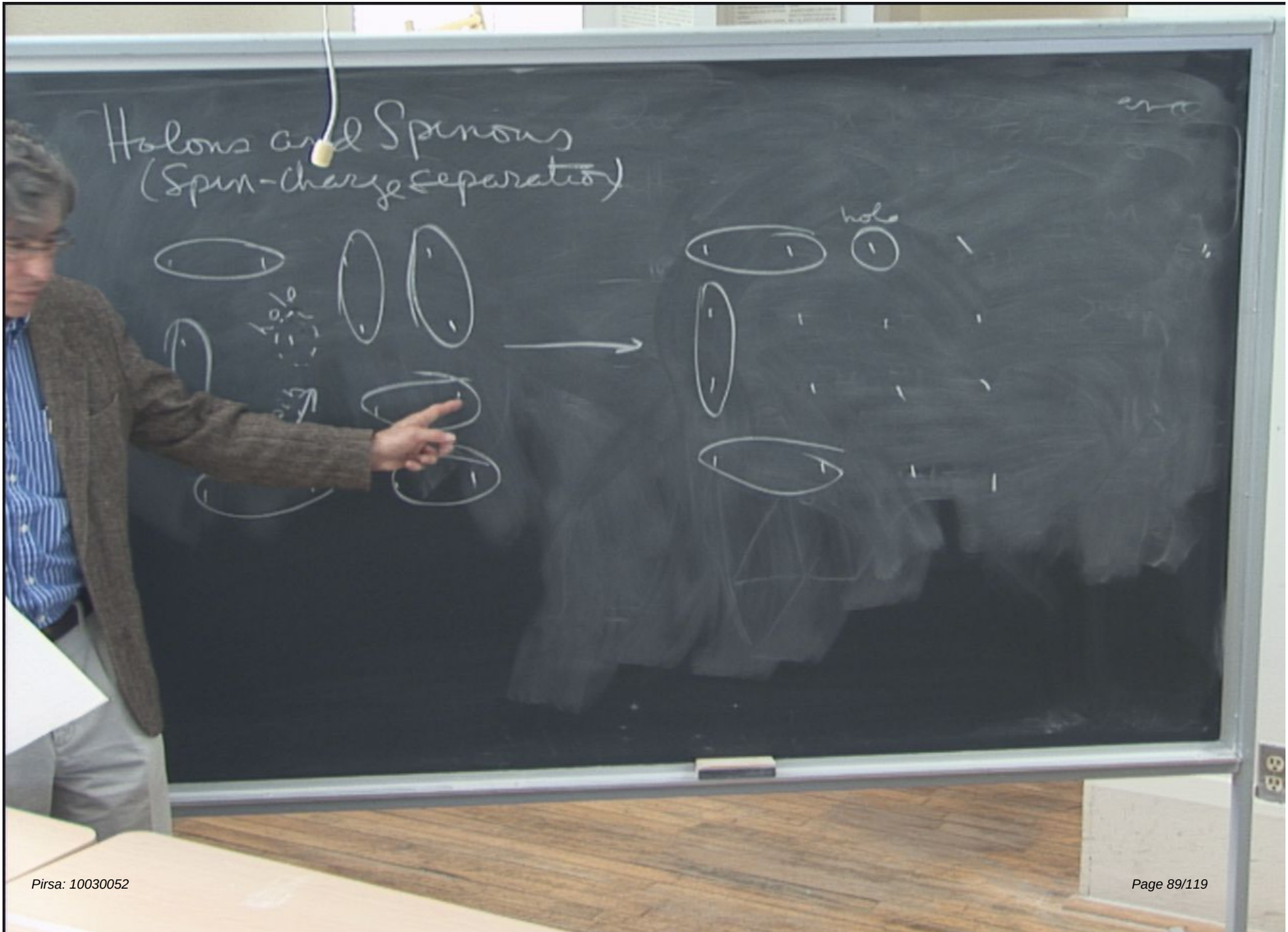

Holons and Spinons
(Spin-charge separation)
hole
spin

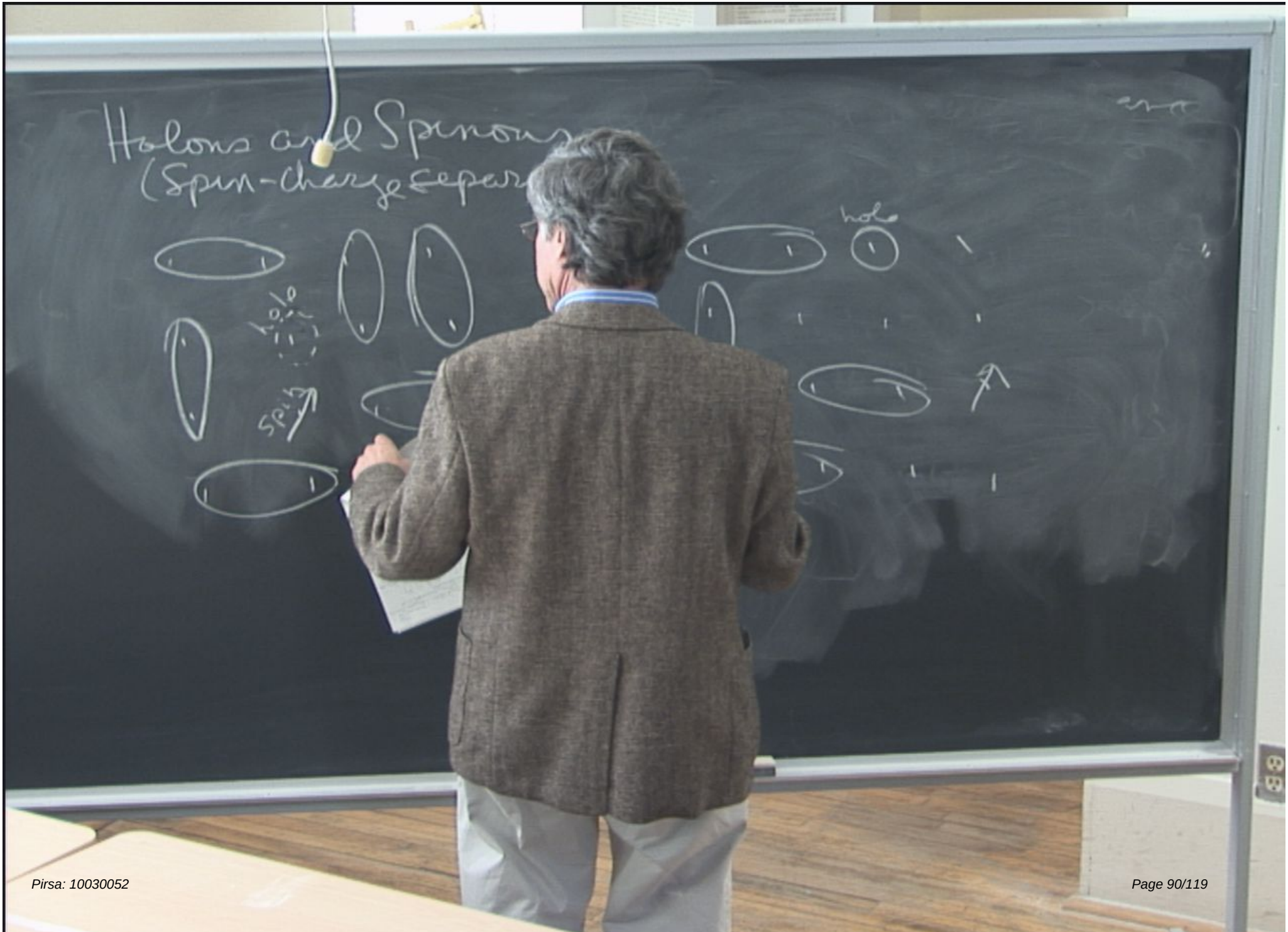

Holons and Spinons
(Spin-charge separation)
hole
spin

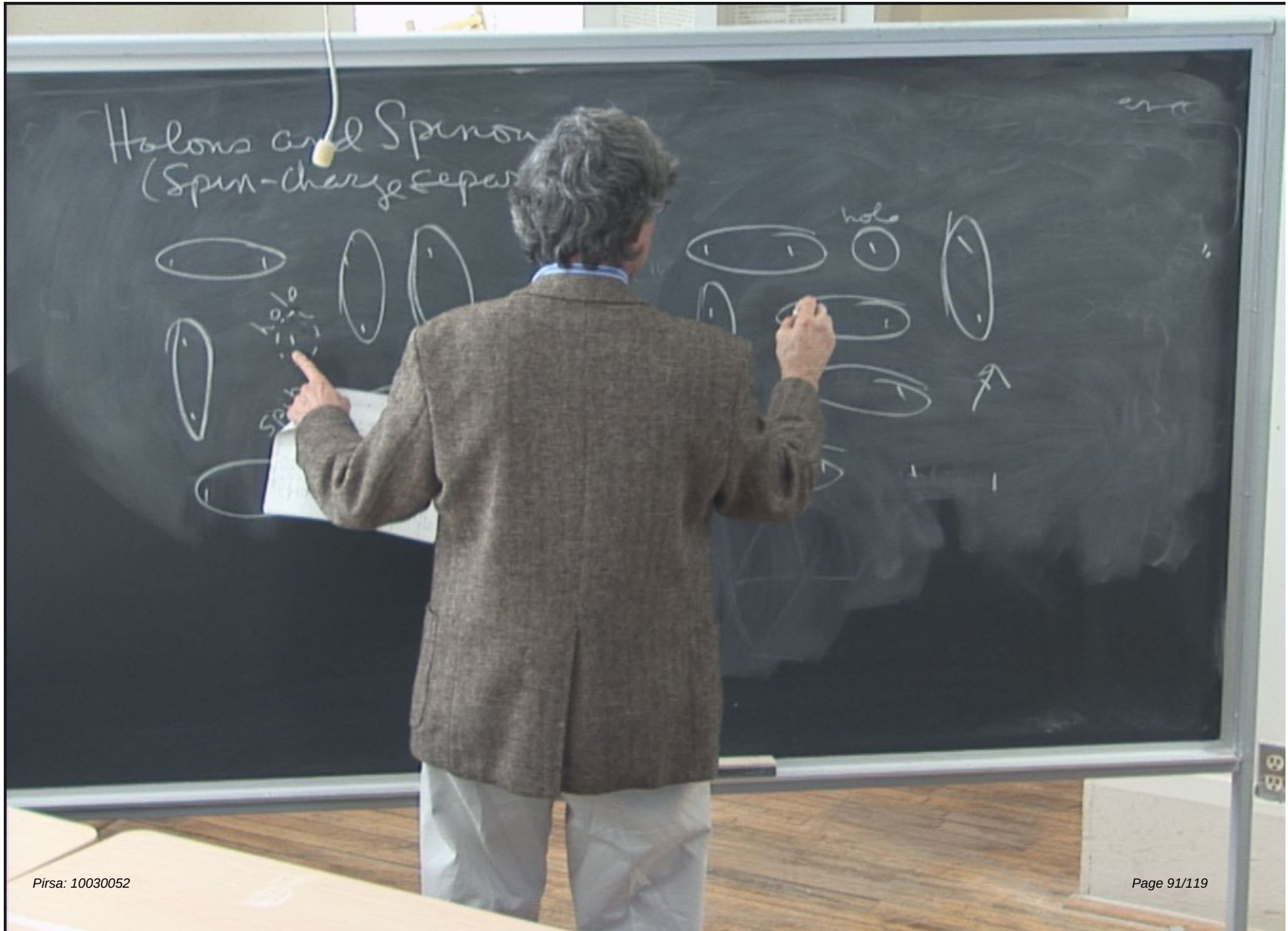

Holons and S
(Spin-charg
tio)

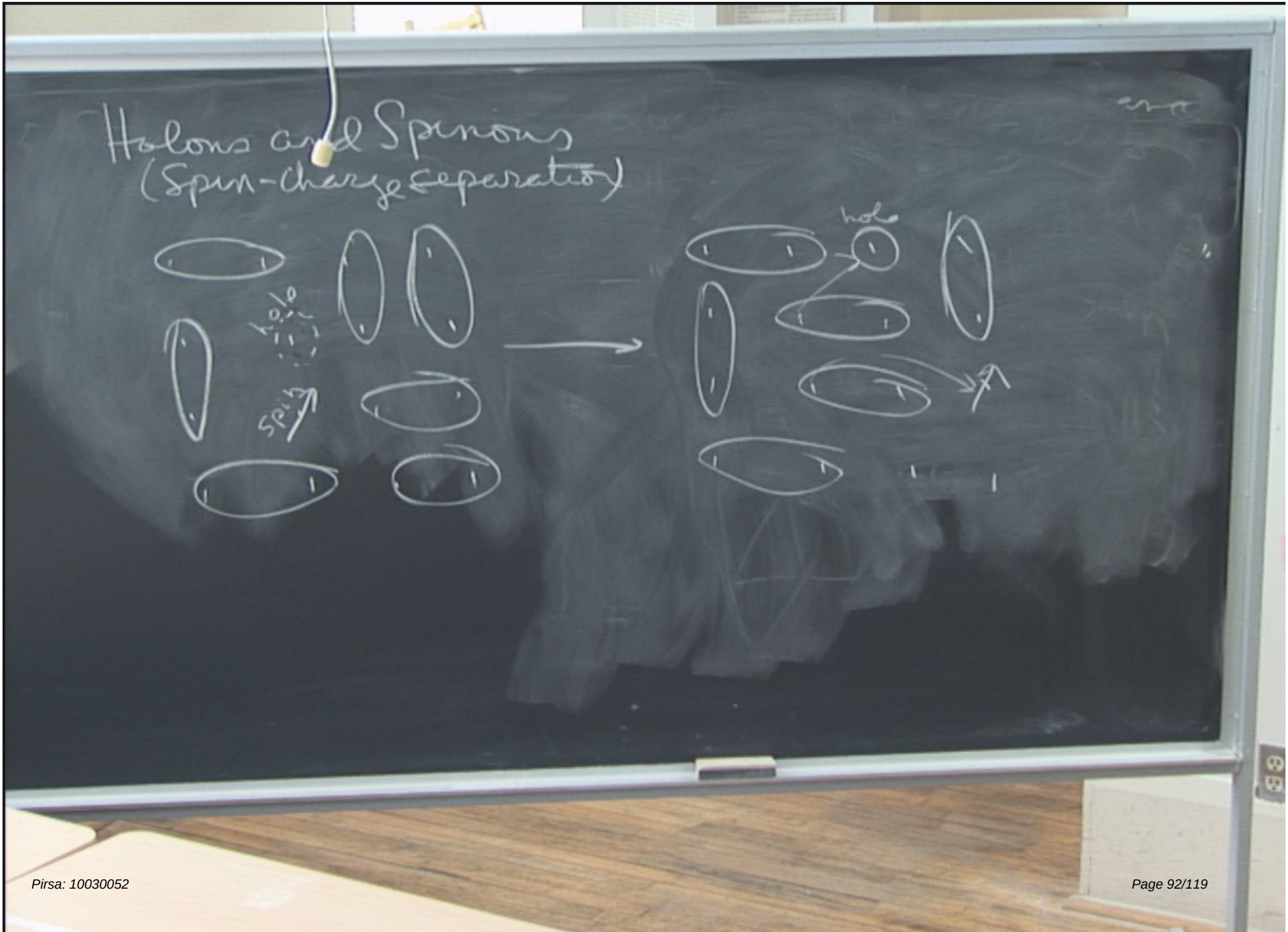

Holons and Spinons


Holons and Spinons
hole
hole
spin

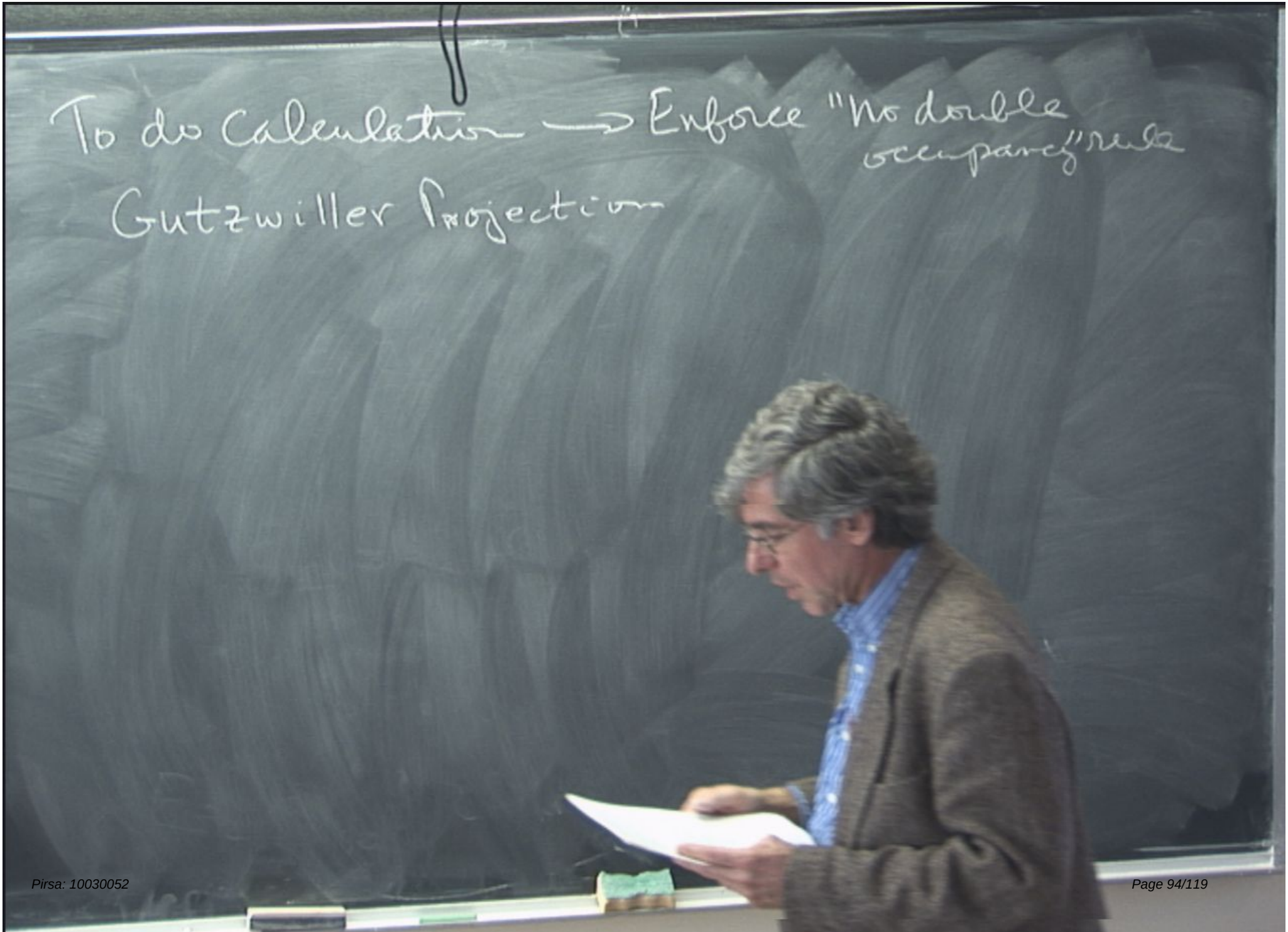

Holons and Spinons
(Spin-charge separation)
hole


Holons and Spinons
hole
spin


Holons and Spinon
(Spin-charge seper
hole


Holons and Spinons
(Spin-charge separation)
hole
spin
hole

To do Calculation → Enforce "No double occupancy" rule

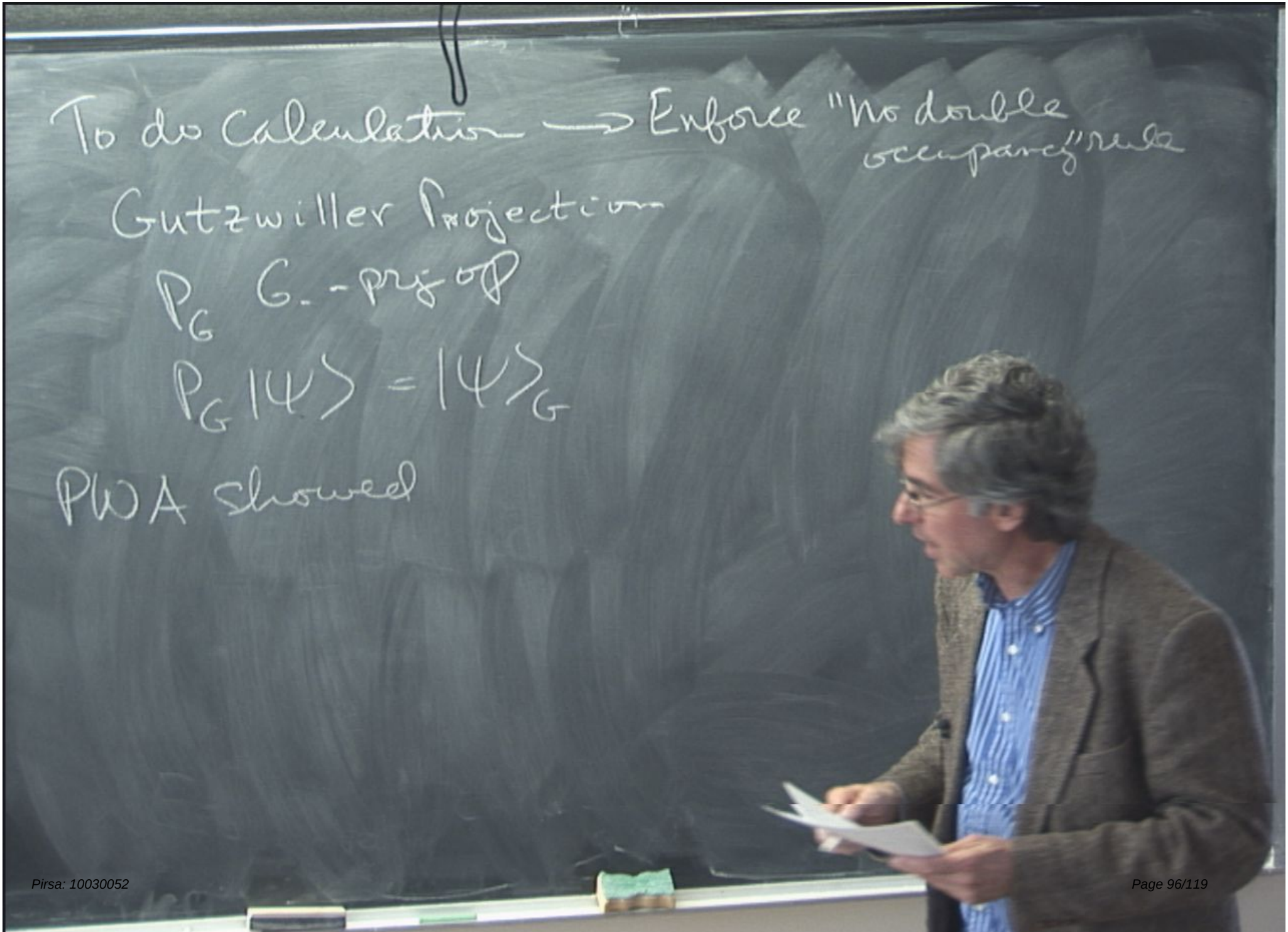

To do Calculation → Enforce "No double occupancy" rule
Gutzwiller Projection

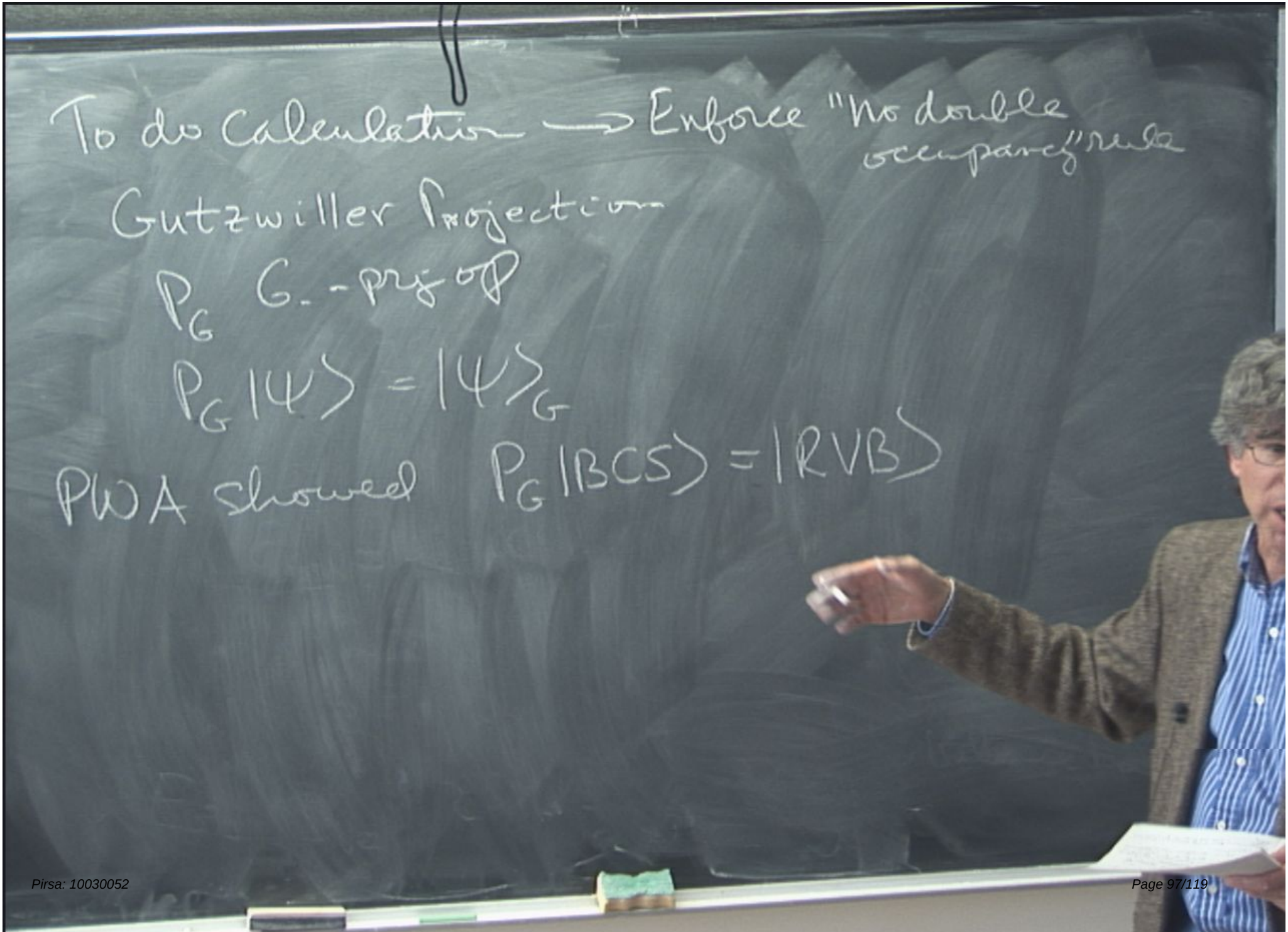
To do Calculation → Enforce "No double occupancy" rule

Gutzwiller Projection

P_G G.-proj. op

$P_G |\psi\rangle = |\psi\rangle_G$


To do Calculation → Enforce "No double occupancy" rule
Gutzwiller Projection
P_G G.-proj. op
$P_G|\psi\rangle = |\psi\rangle_G$
PWA showed


To do Calculation → Enforce "No double occupancy" rule
Gutzwiller Projection
P_G G.-proj of
$P_G|\Psi\rangle = |\Psi\rangle_G$
PWA showed $P_G|BCS\rangle = |RVB\rangle$

To do Calculation → Enforce "No double occupancy" rule

Gutzwiller Projection

P_G G.-proj. of Ψ

$P_G|\Psi\rangle = |\Psi\rangle_G$

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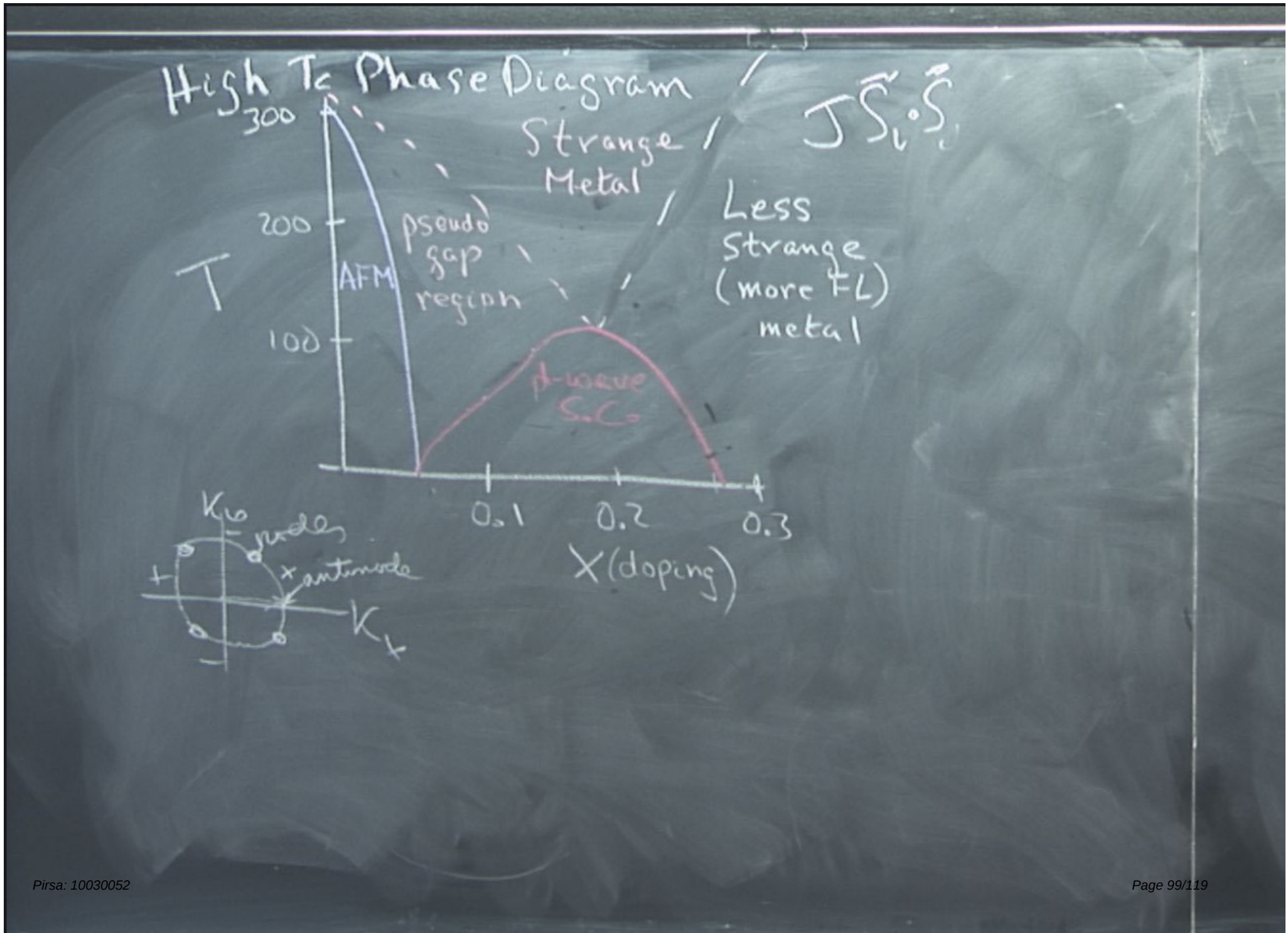
High Tc Phase Diagram
300
200
100
T
AFM
pseudo gap region
Strange Metal
Less Strange (more FL) metal
d-wave S.C.
0.1
0.2
0.3
X (doping)
$J\vec{S}_i \cdot \vec{S}_j$
K_0
nodes
antinode
K_x

To do Calculation → Enforce "No double occupancy" rule

Gutzwiller Projection

P_G G.-proj. op

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PWA showed $P_G|BCS\rangle = |RVB\rangle$

$P_G|$d-wave BCS$\rangle$ has a d-wave gap.

QMC results

→ Gutzwiller MFT.

To do Calculation → Enforce "No double occupancy" rule

Gutzwiller Projection

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$\mathcal{H}_{eff} =$

To do Calculation → Enforce "No double occupancy" rule

Gutzwiller Projection

P_G G.-proj op

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PWA showed $P_G|BCS\rangle = |RVB\rangle$

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QMC results

→ Gutzwiller MFT.

$H_{eff} = g_t T + g_J J \sum_{ij} \vec{S}_i \cdot \vec{S}_j$

To do Calculation → Enforce "No double occupancy" rule

Gutzwiller Projection

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Gutzwiller Projection

P_G G.-proj op

$P_G|\psi\rangle = |\psi\rangle_G$

PWA showed $P_G|BCS\rangle = |RVB\rangle$ Variational energy

$P_G|$d-wave BCS$\rangle$ has a d-wave gap.

QMC results

→ Gutzwiller MFT.

$H_{eff} = g_t \sum_{ij} t_{ij} + g_J J \sum_{ij} \vec{S}_i \cdot \vec{S}_j$

$g_t = \frac{x}{1+x}$

To do Calculation → Enforce "No double occupancy" rule

Gutzwiller Projection

P_G G.-proj op

$P_G|\Psi\rangle = |\Psi\rangle_G$

PWA showed $P_G|BCS\rangle = |RVB\rangle$ Variational energy

$P_G|$d-wave BCS$\rangle$ has a d-wave gap.

QMC results

→ Gutzwiller MFT.

$$\mathcal{H}_{eff} = g_t \boxed{T} + g_s J \sum_{ij} \vec{S}_i \cdot \vec{S}_j$$

$$g_t = \frac{x}{1+x} \qquad g_s = \frac{4}{(1+x)^2}$$

To do calculation → Enforce "No double occupancy" rule

Gutzwiller Projection

P_G G.-proj. op

$P_G|\psi\rangle = |\psi\rangle_G$

PWA showed $P_G|BCS\rangle = |RVB\rangle$ Kinetic energy

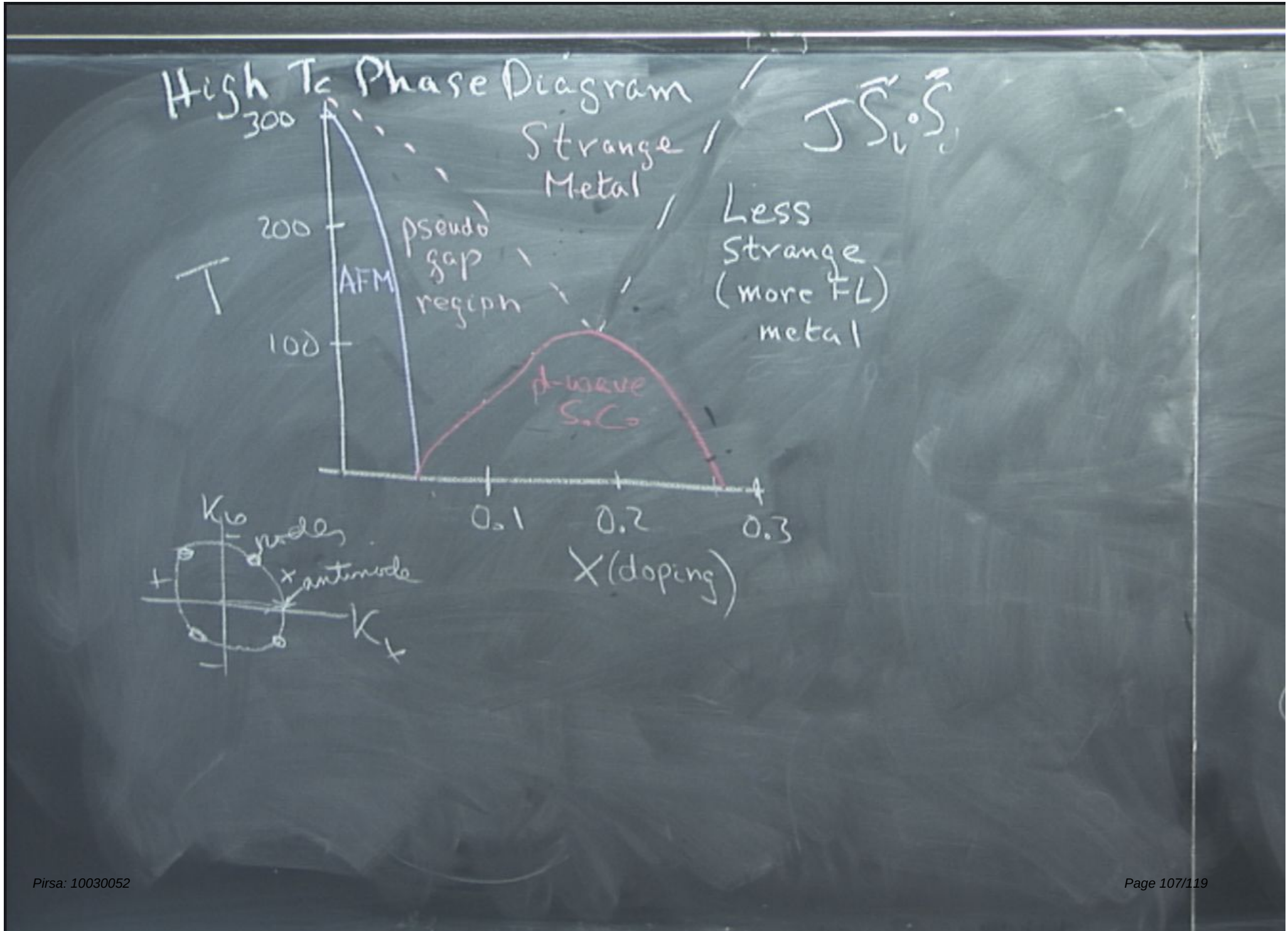
$P_G|d\text{-wave BCS}\rangle$ has a d-wave gap.

QMC results

→ Gutzwiller MFT.

$$\mathcal{H}_{eff} = g_t \sum_{ij\sigma} (c^\dagger_{i\sigma} c_{j\sigma} + \text{h.c.}) + g_s J \sum_{ij} \vec{S}_i \cdot \vec{S}_j$$

$$g_t = \frac{x}{1+x} \qquad g_s = \frac{4}{(1+x)^2}$$


High Tc Phase Diagram
$J\vec{S}_i \cdot \vec{S}_j$
300
200
100
T
AFM
pseudo gap regiph
Strange Metal
Less Strange (more FL) metal
d-wave S.C.
0.1
0.2
0.3
X(doping)
K_0
nodes
antinode
K_+

To do Calculation → Enforce "No double occupancy" rule

Gutzwiller Projection

P_G G.-proj op

"Plain Vanilla RVB"

$P_G|\psi\rangle = |\psi\rangle_G$

PWA showed $P_G|BCS\rangle = |RVB\rangle$

$P_G|d\text{-wave BCS}\rangle$ has a d-wave gap.

variation energy

QMC results

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To do calculation → Enforce "No double occupancy" rule

Gutzwiller Projection

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"Plain Vanilla RVB"

PWA showed $P_G|BCS\rangle = |RVB\rangle$ Variational energy

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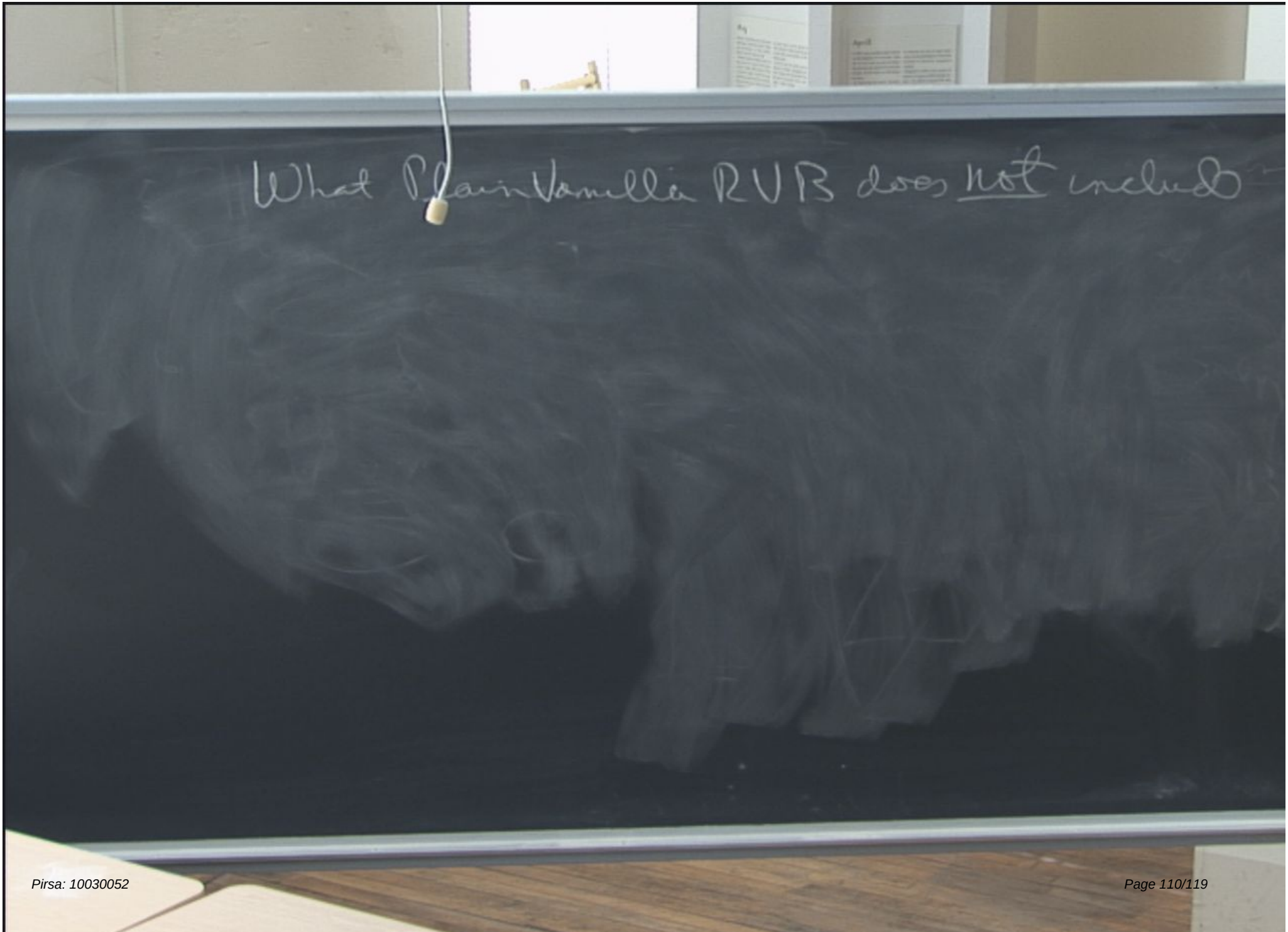
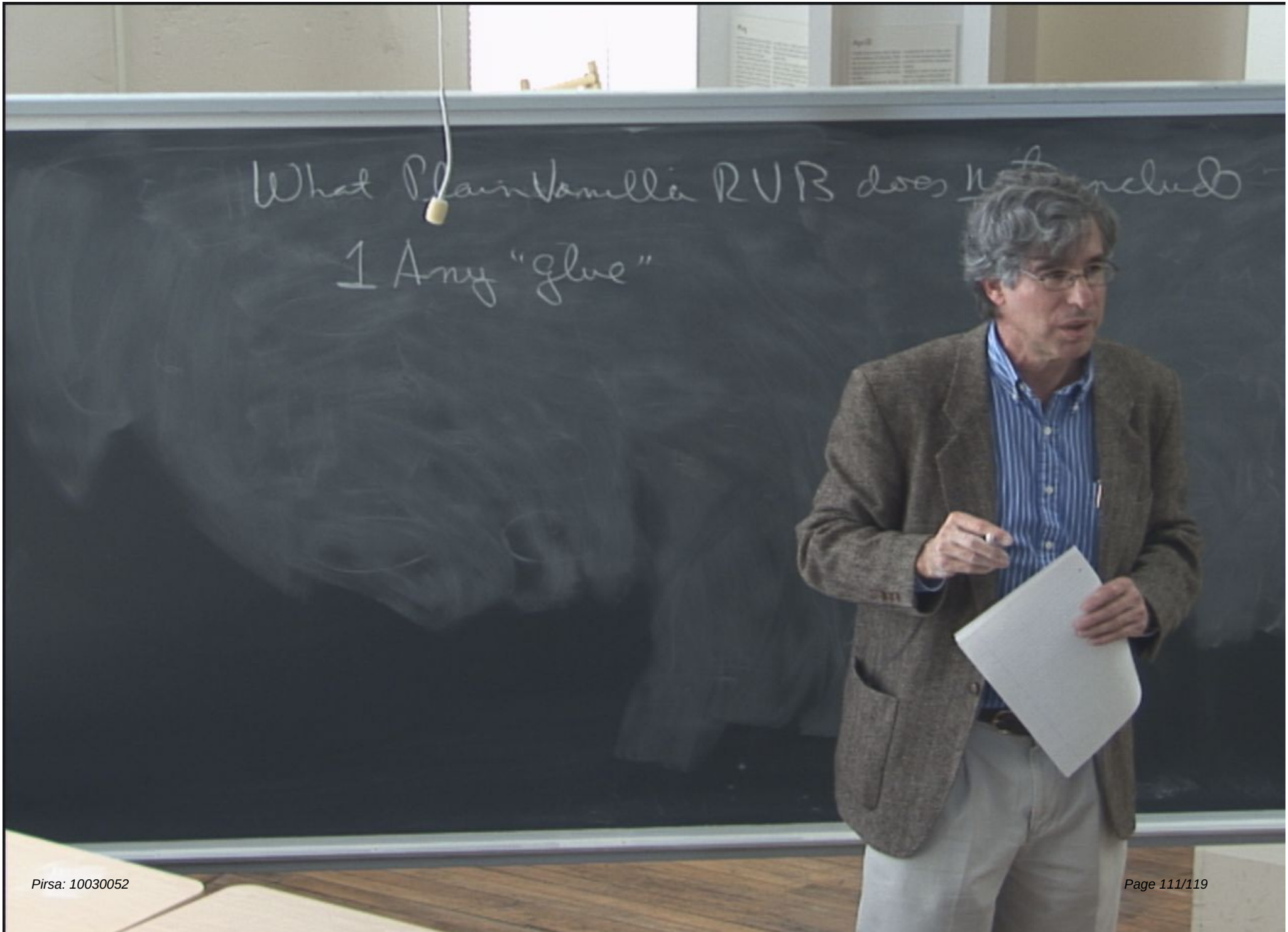
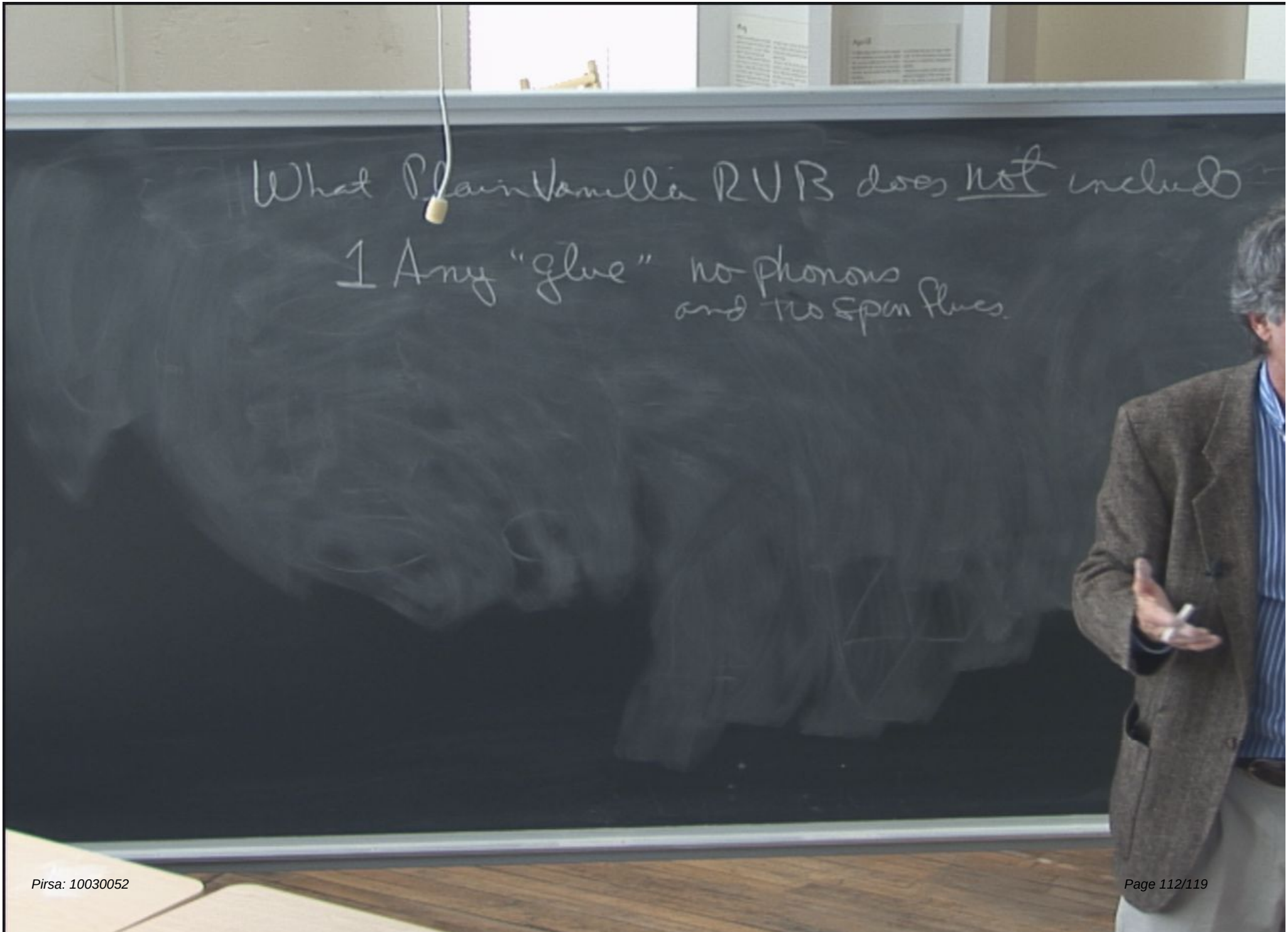
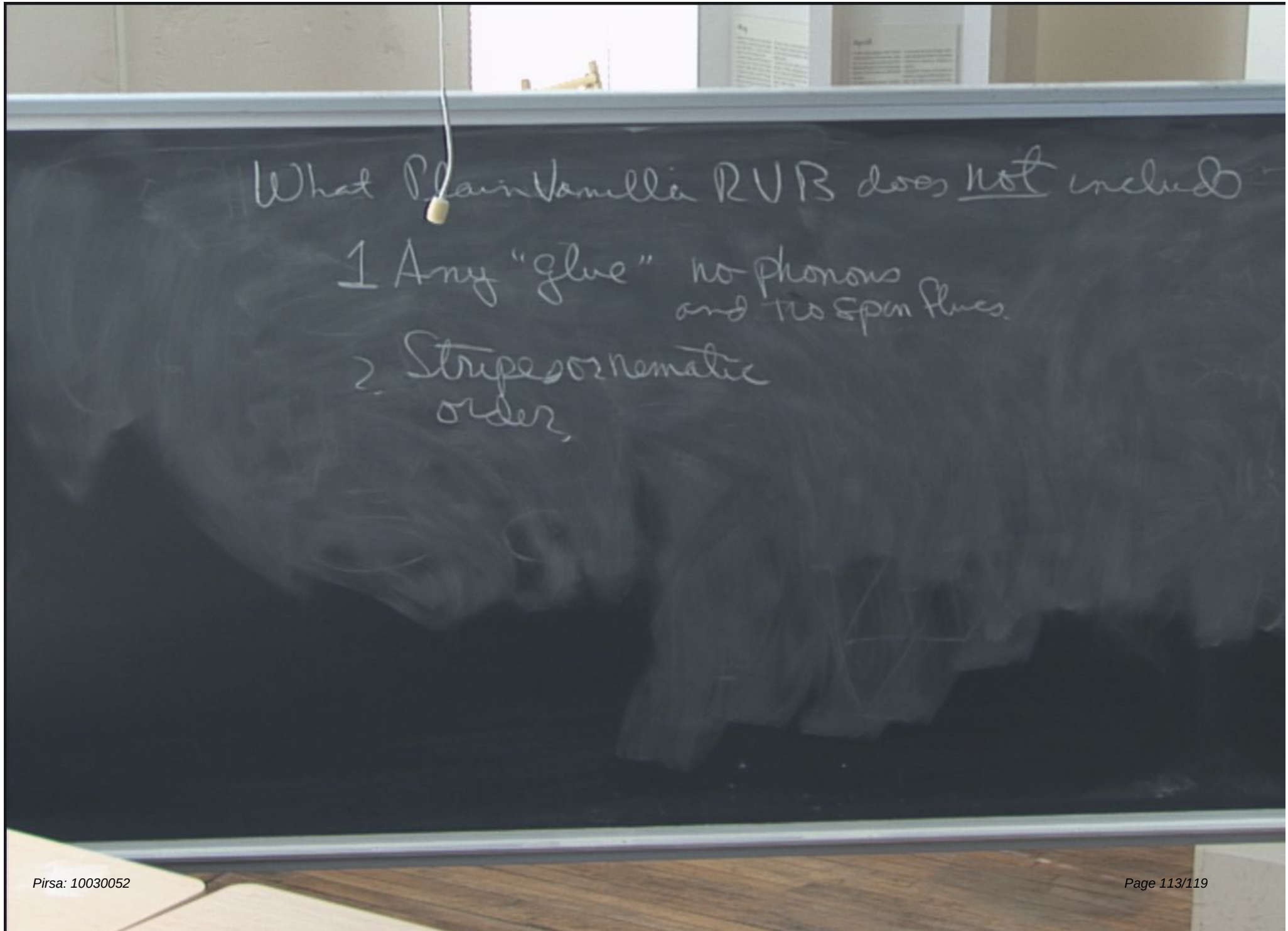
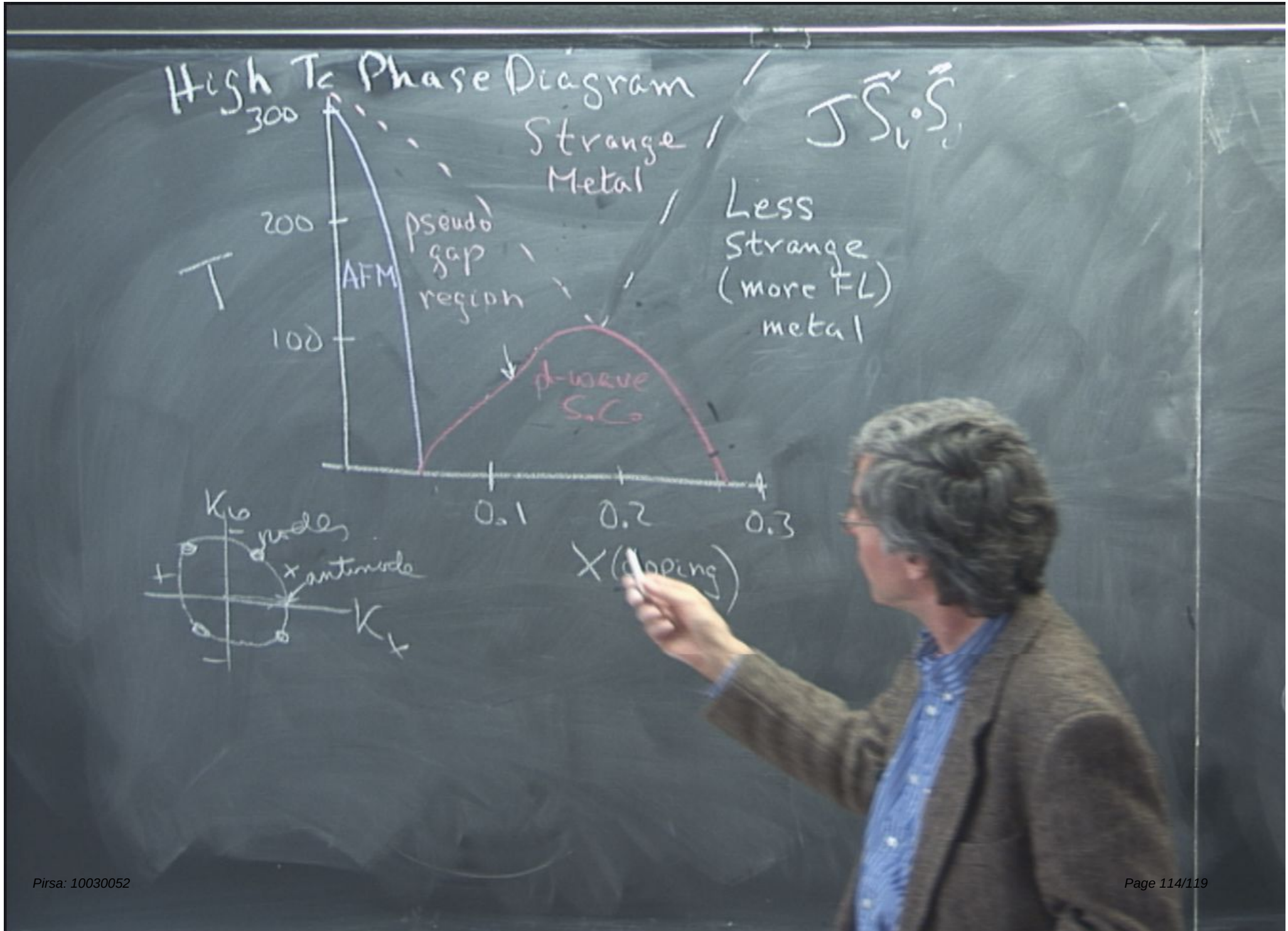
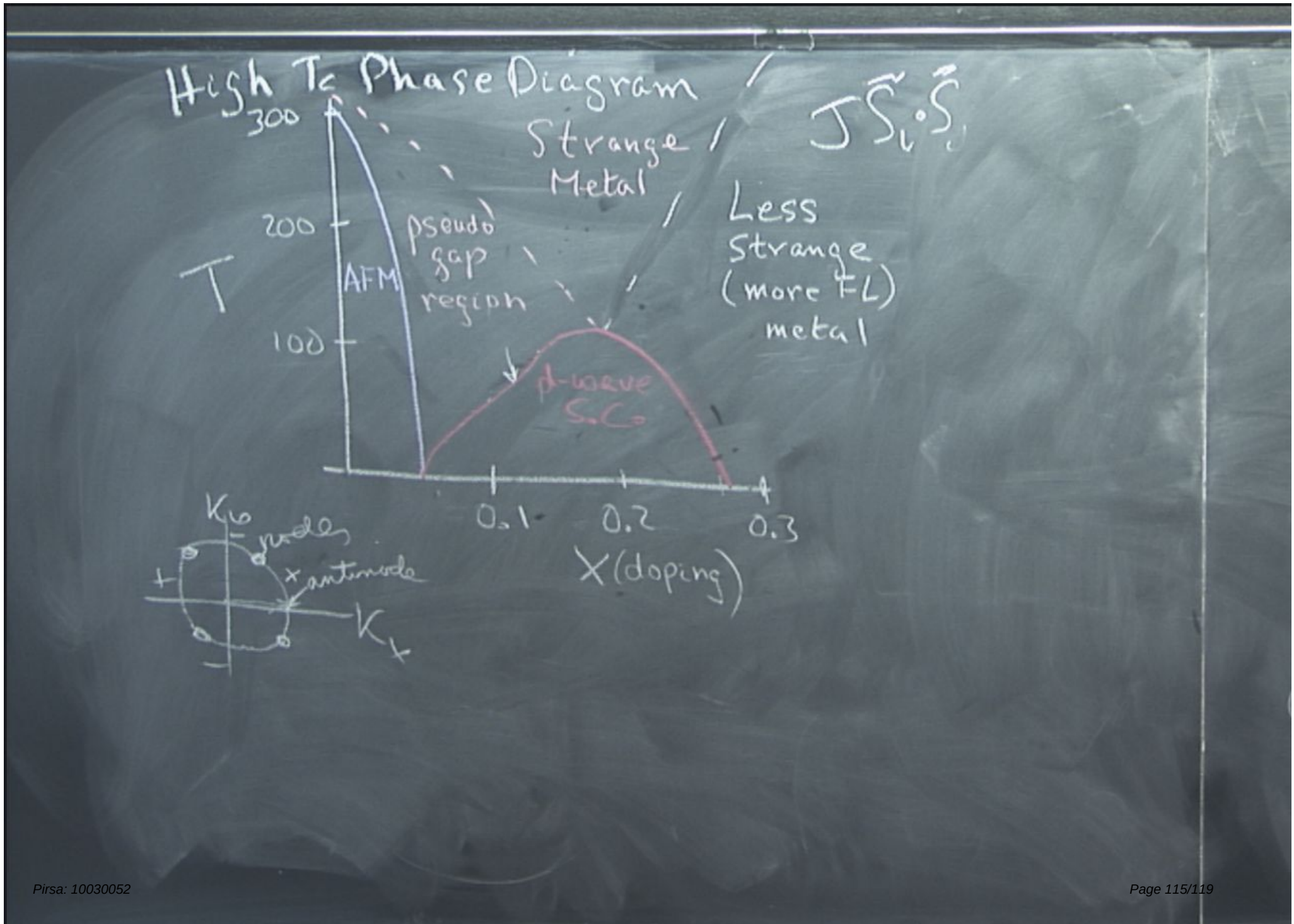

What Plain Vanilla RVB does not include


What Plain Vanilla RVB does not include
1 Any "glue"


What Plain Vanilla RVB does not include
1 Any "glue" no phonons
and no spin flues.


What Plain Vanilla RVB does not include
1 Any "glue" no phonons and no spin flucs.
2. Stripes or nematic order.


High Tc Phase Diagram
300
200
100
T
AFM
pseudo gap region
Strange Metal
Less Strange (more FL) metal
d-wave S.C.
0.1
0.2
0.3
X (doping)
nodes
antinode
K_y
K_x
$J\vec{S}_i \cdot \vec{S}_j$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$J\vec{S}_i \cdot \vec{S}_j$
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Less Strange (more FL) metal
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200
100
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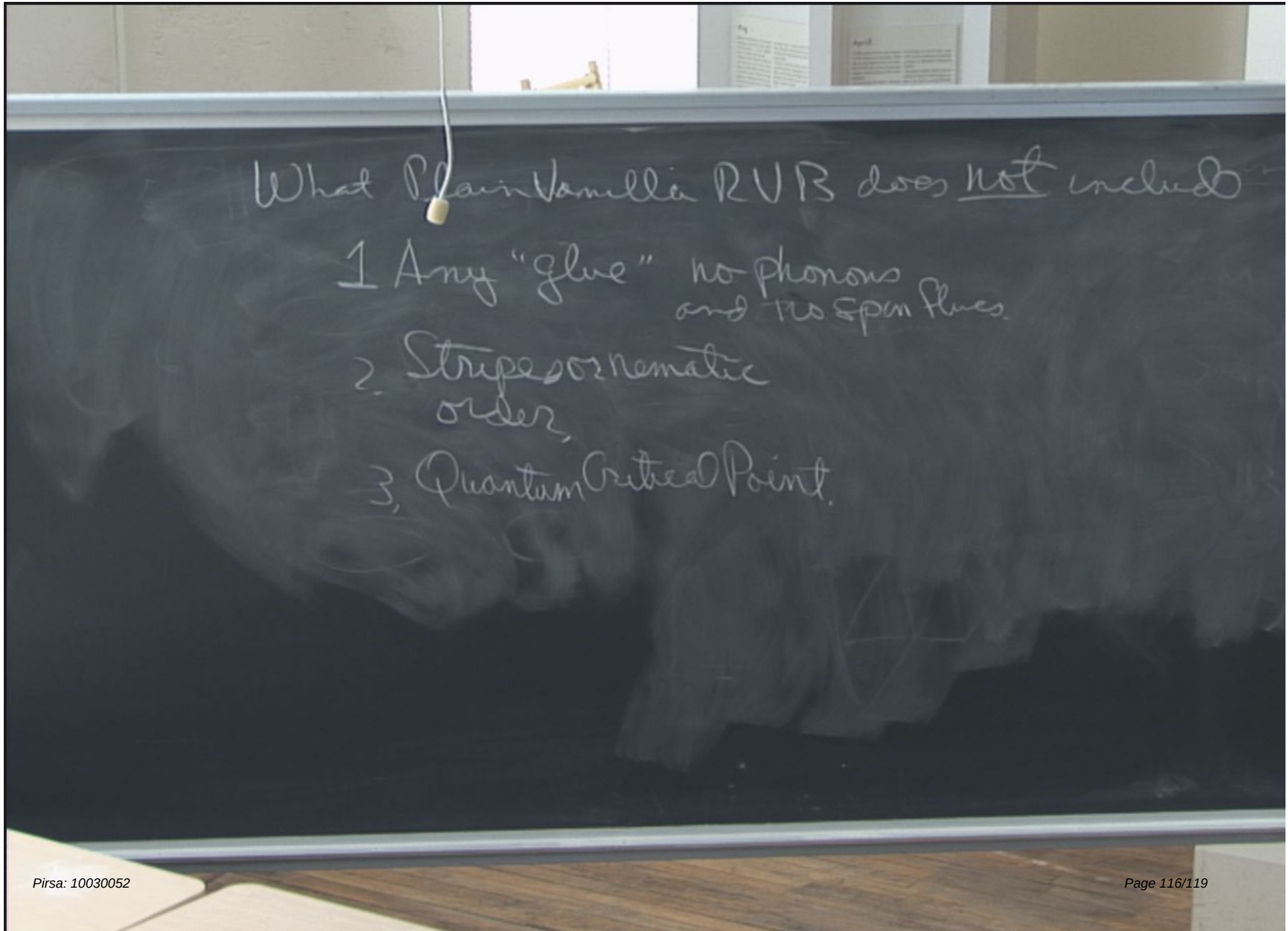
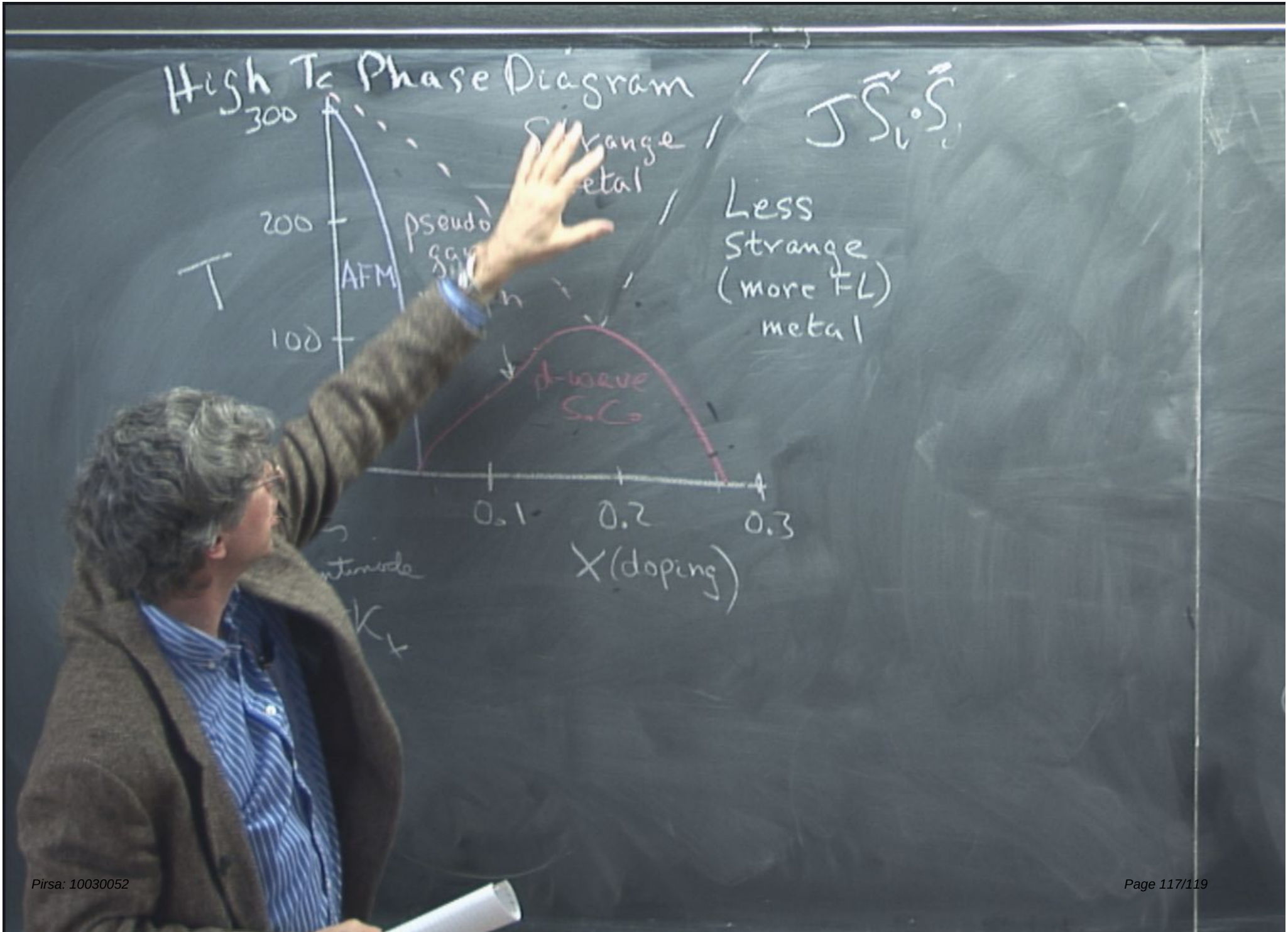

What Plain Vanilla RVB does not include
1 Any "glue" no phonons and no spin flues.
2. Stripes or nematic order.
3. Quantum Critical Point.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Less
Strange
(more FL)
metal
d-wave
S.C.
0.1
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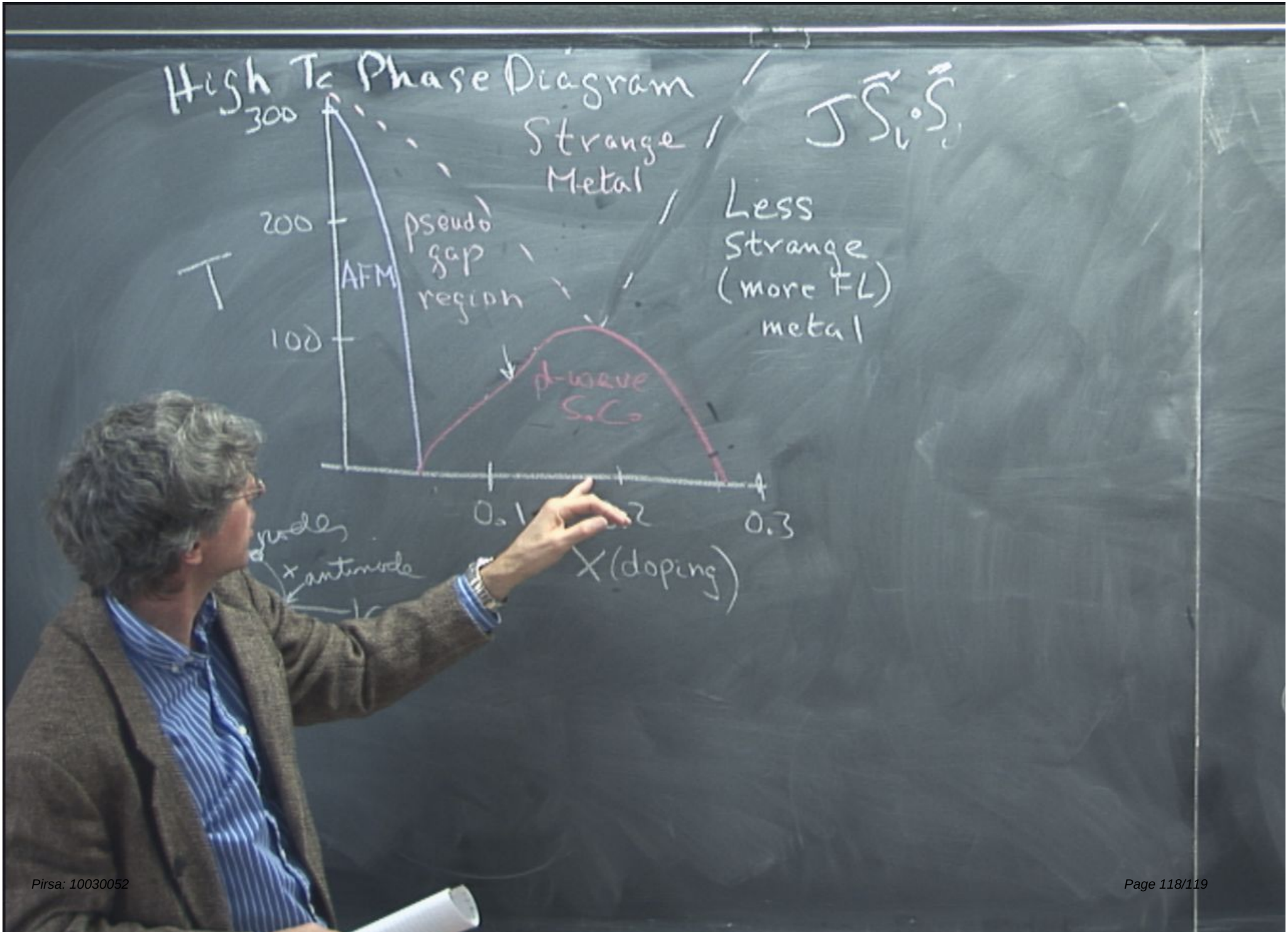
0.3
X(doping)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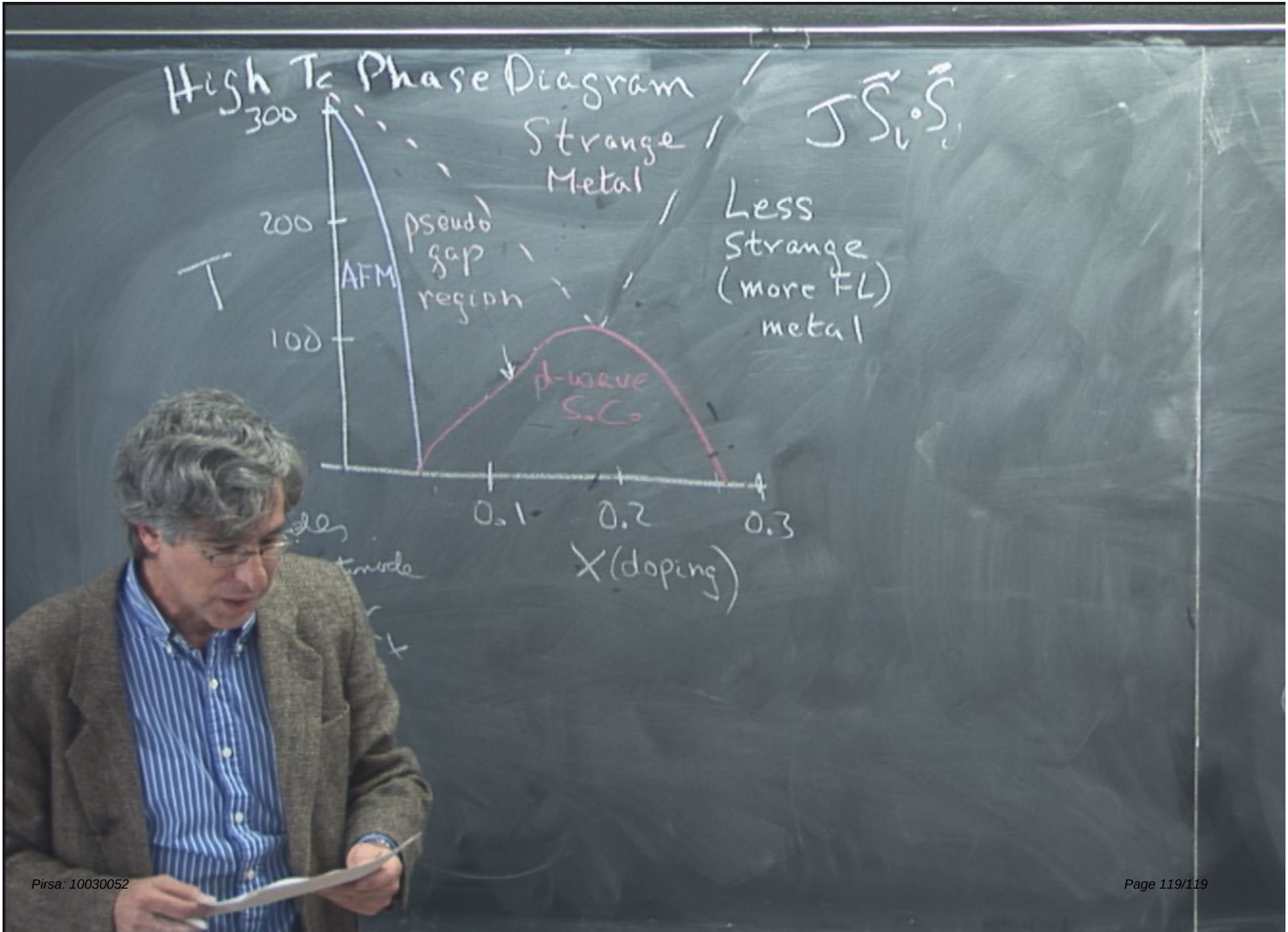
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