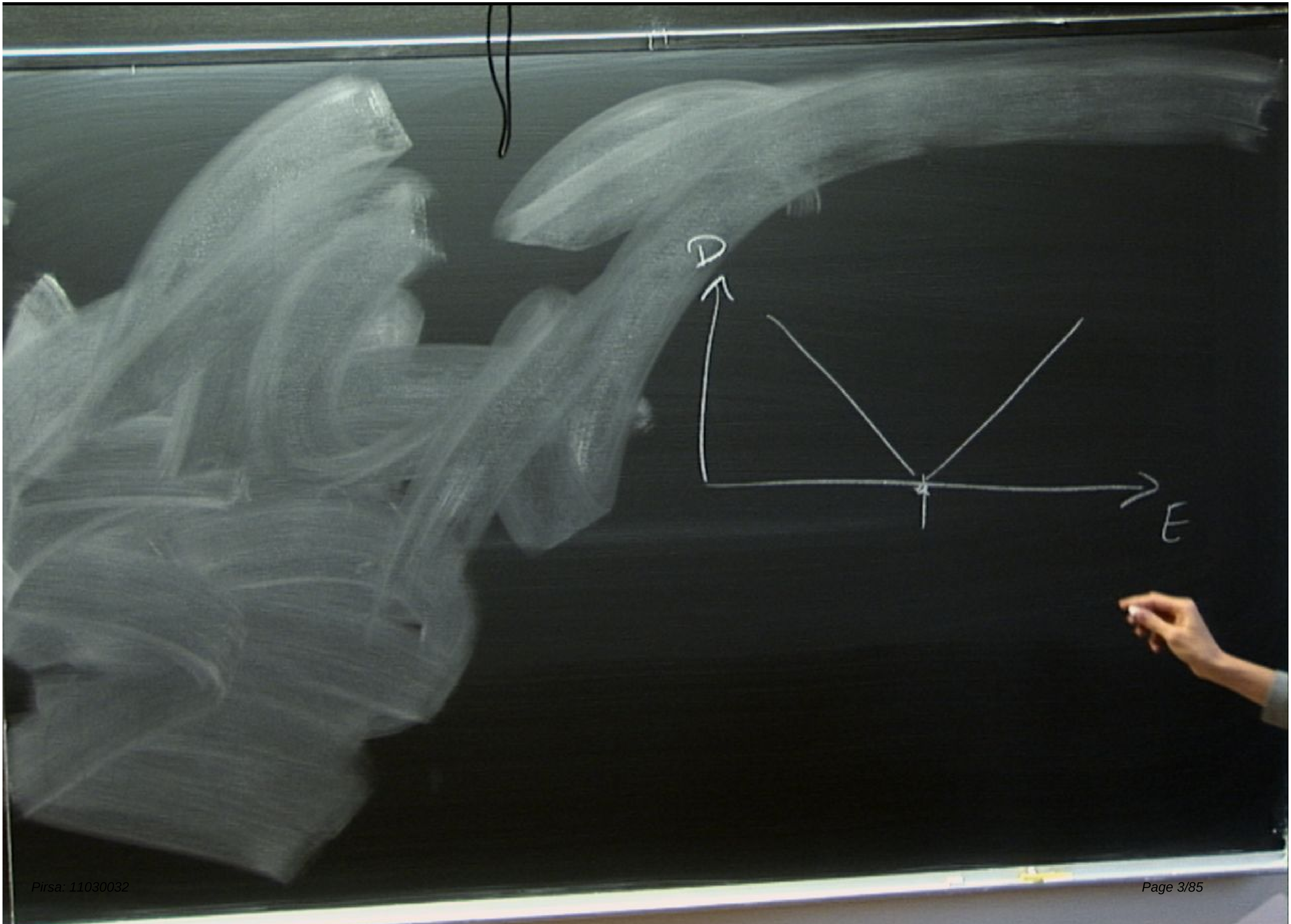
Title: Explorations in Condensed Matter - Lecture 3

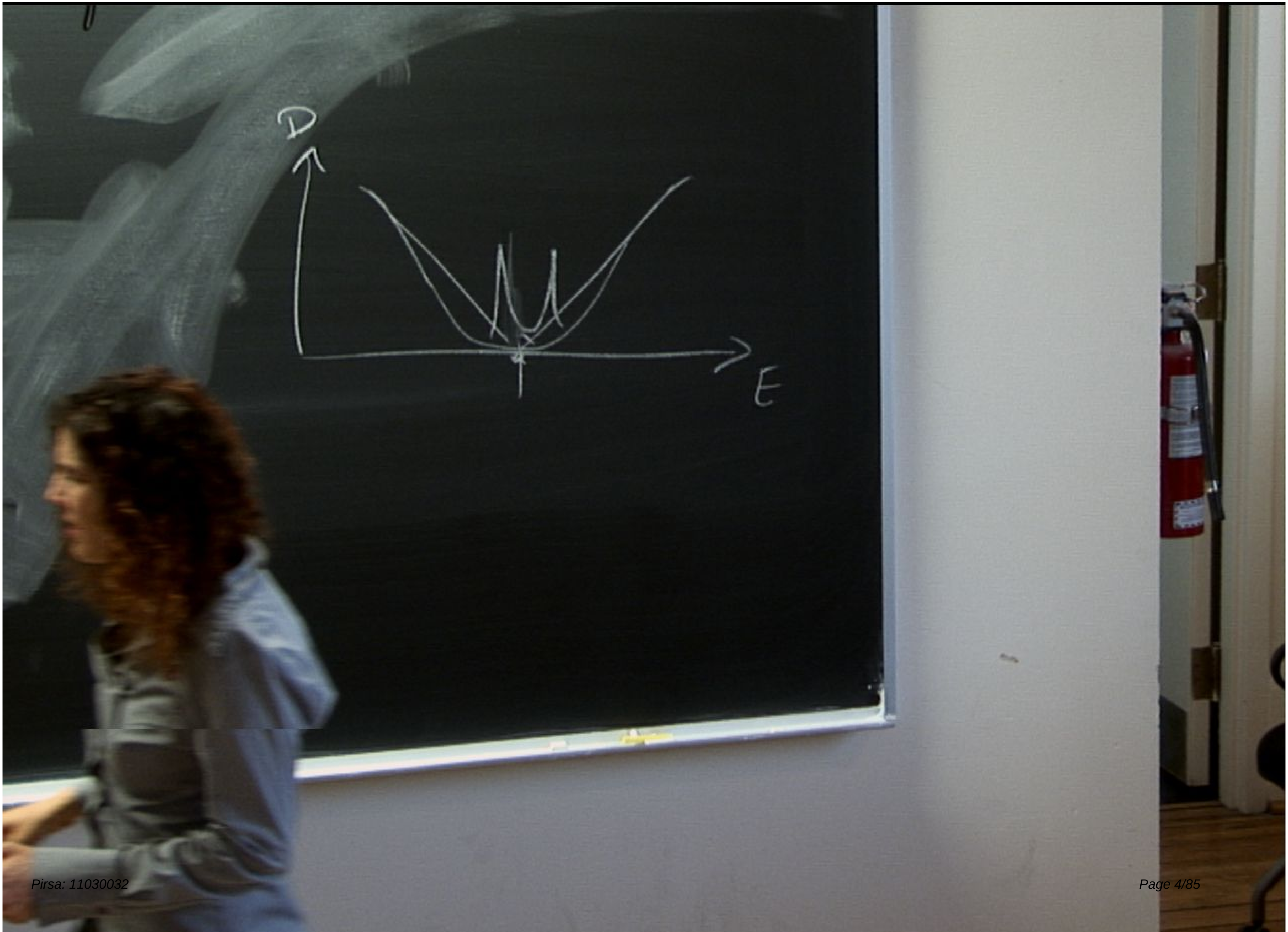
Date: Mar 16, 2011 10:15 AM

URL: http://pirsa.org/11030032

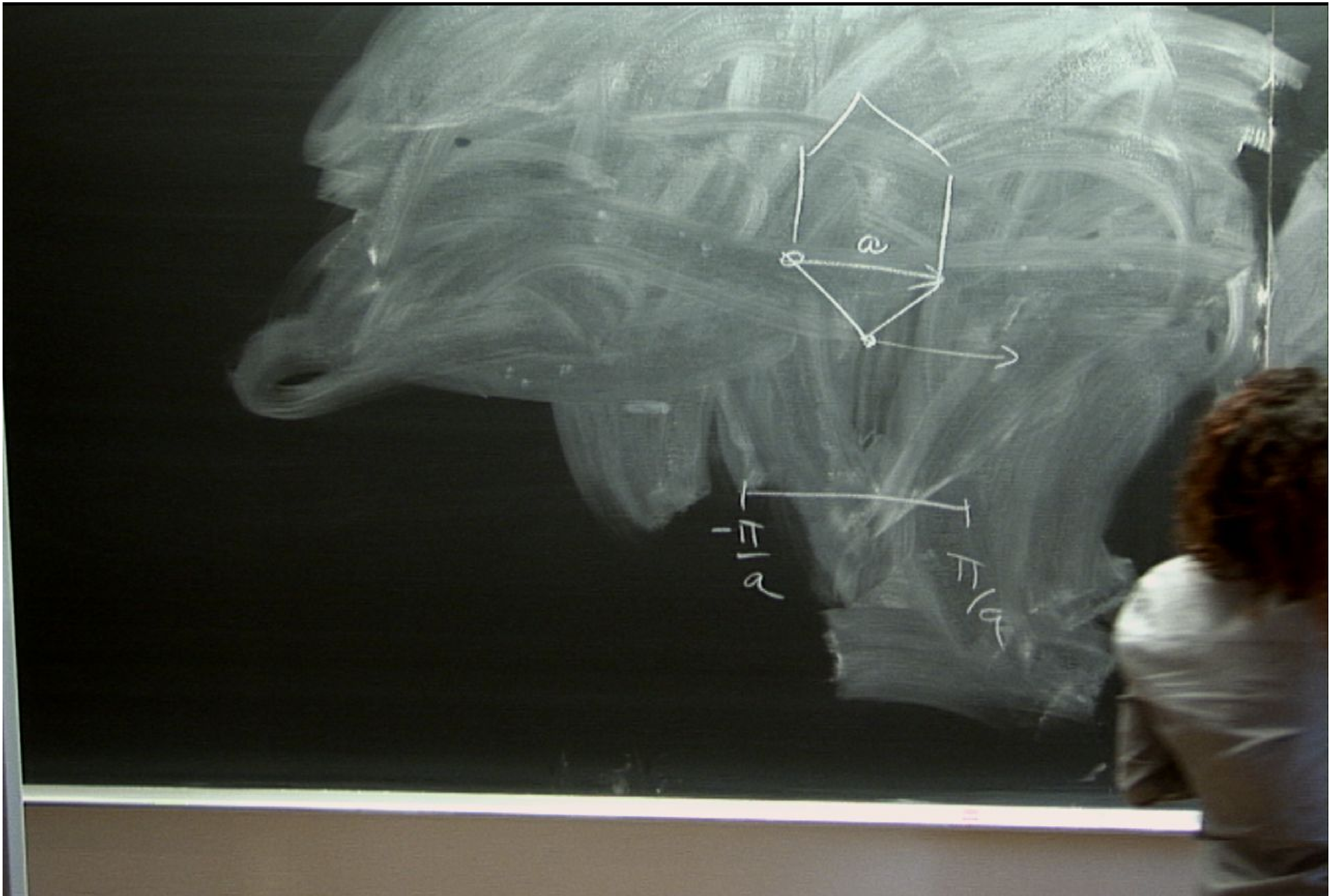
Abstract:

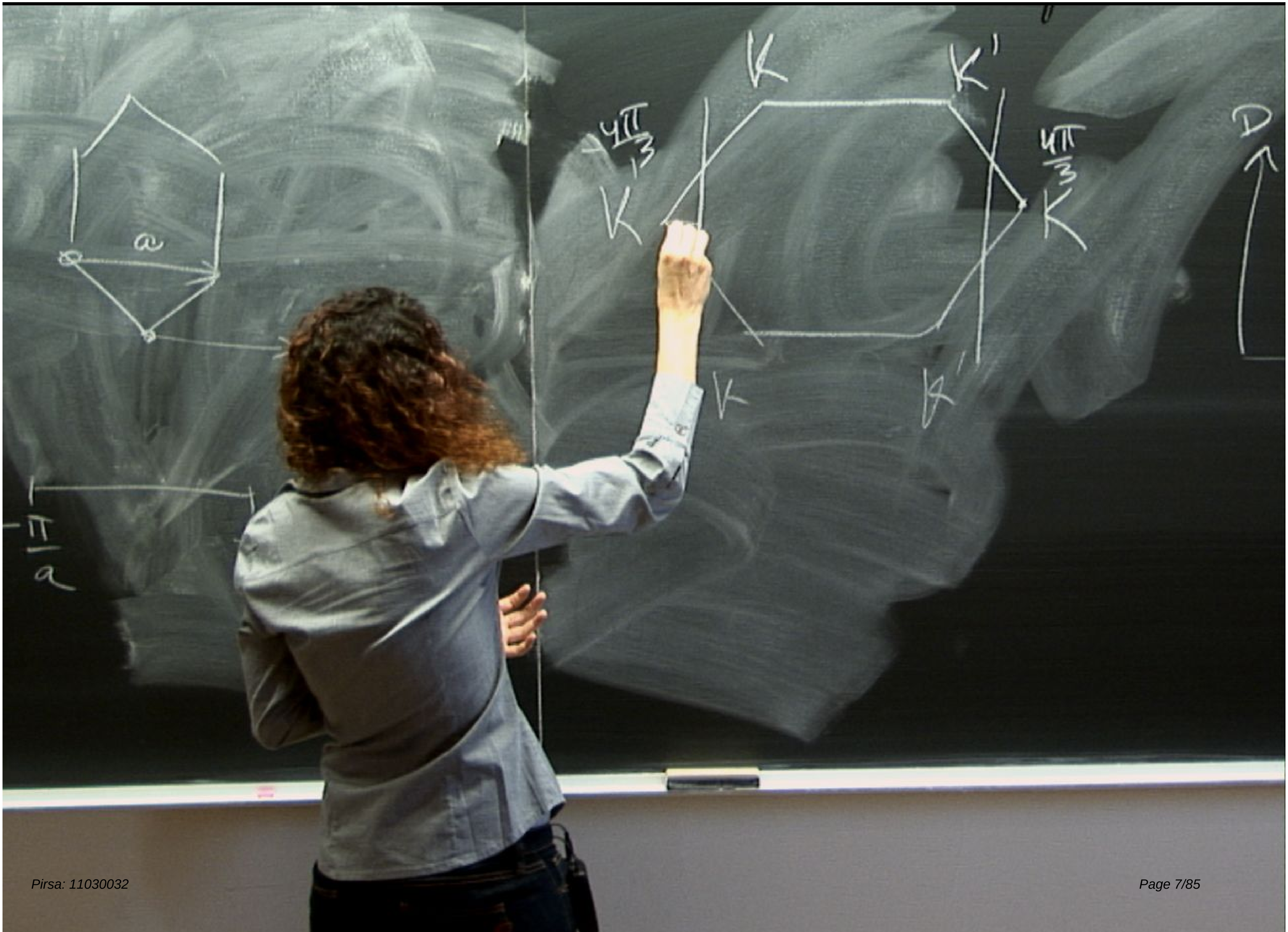
perimeter scholars
international

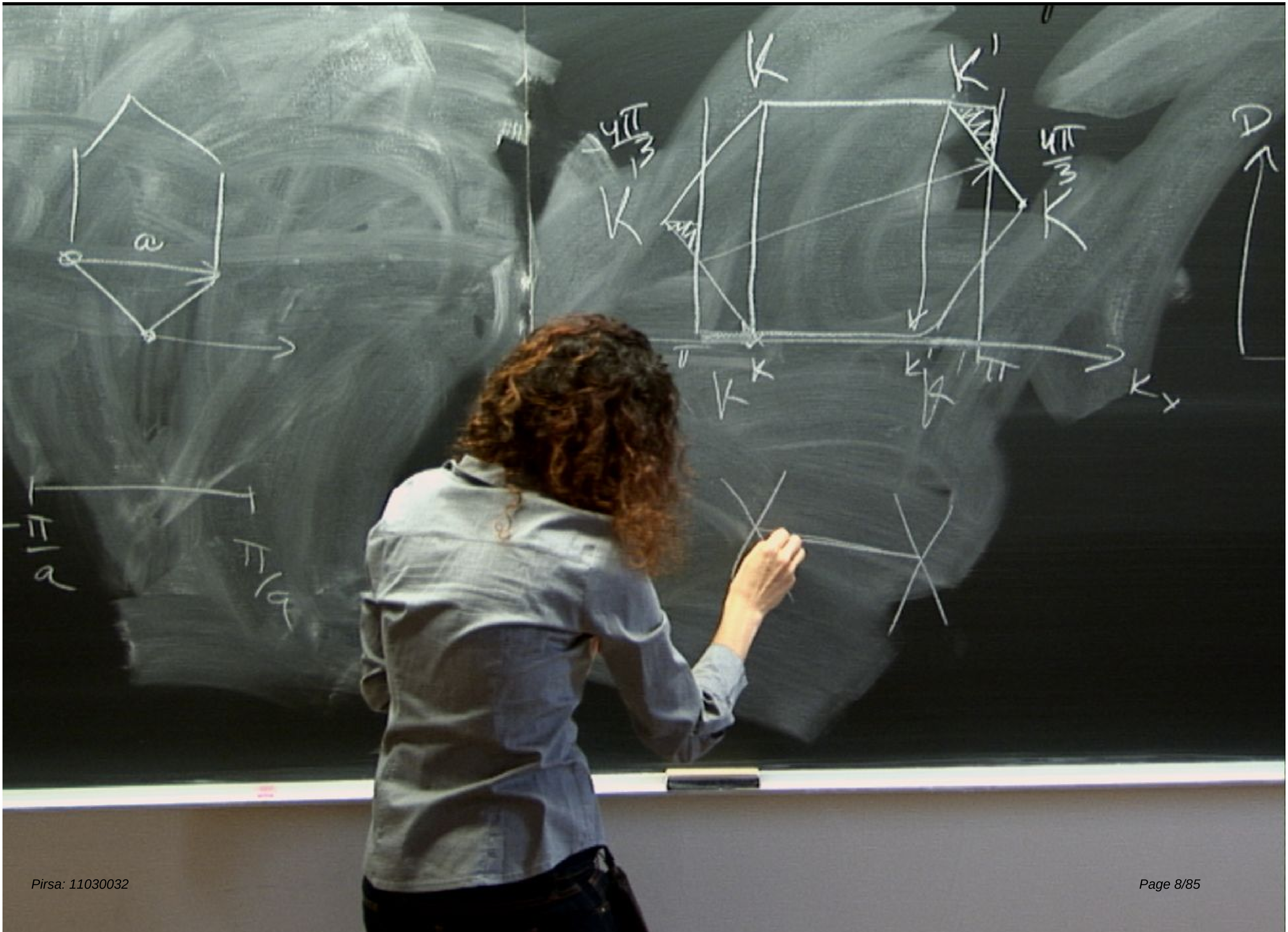

D
E


D
E

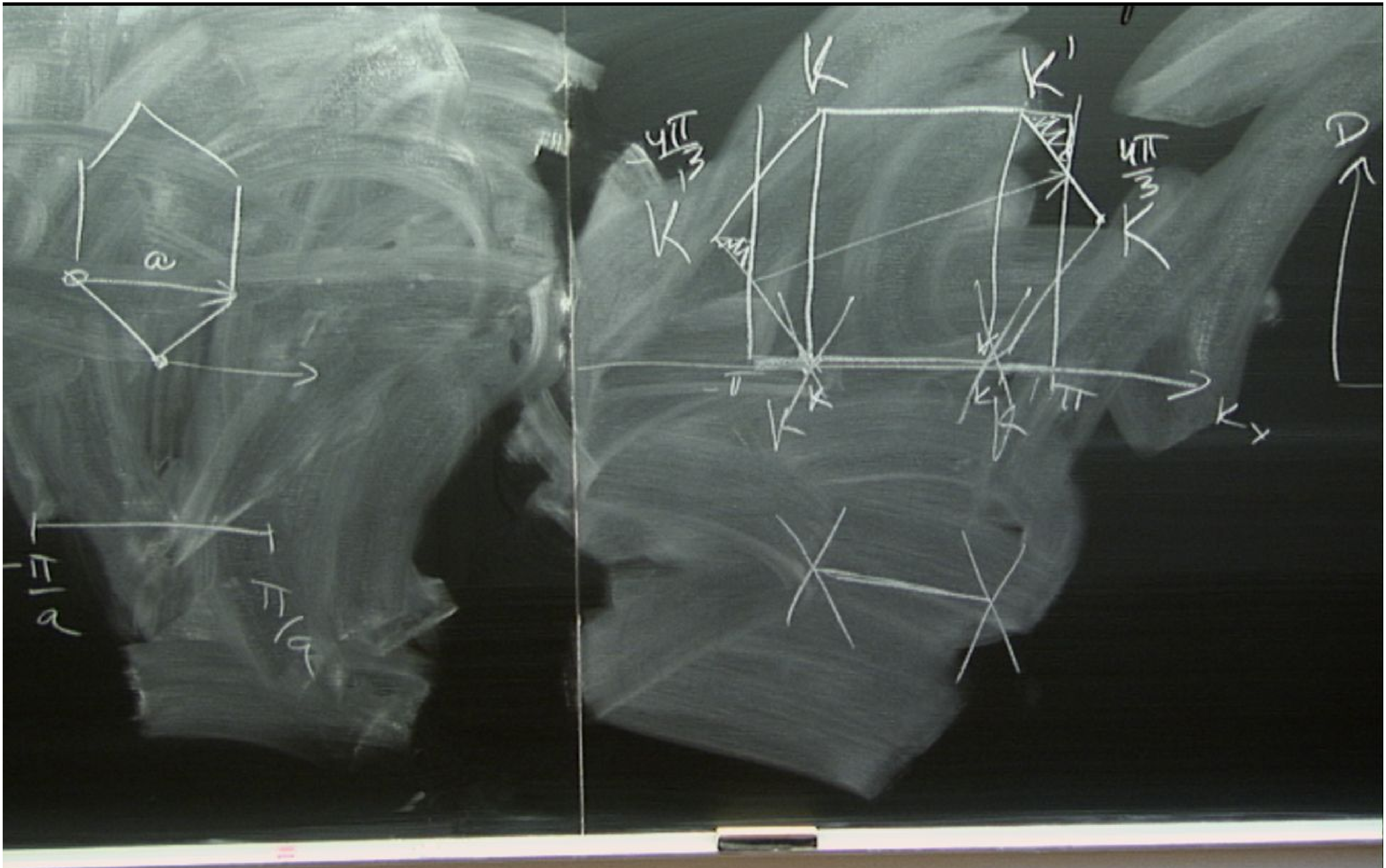

K
K'
K'
K
K
K'
D
E

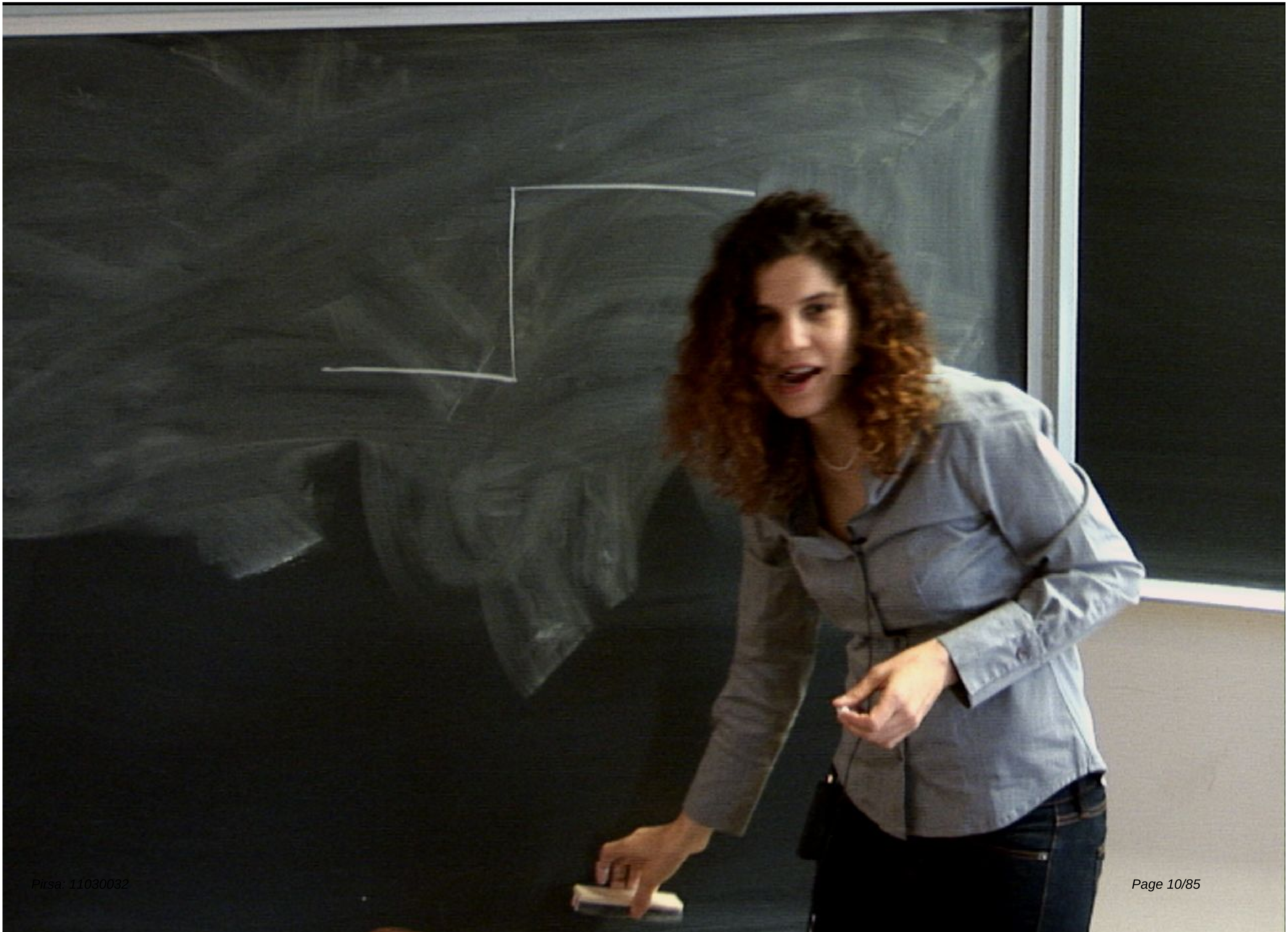

a
-π/a
π/a

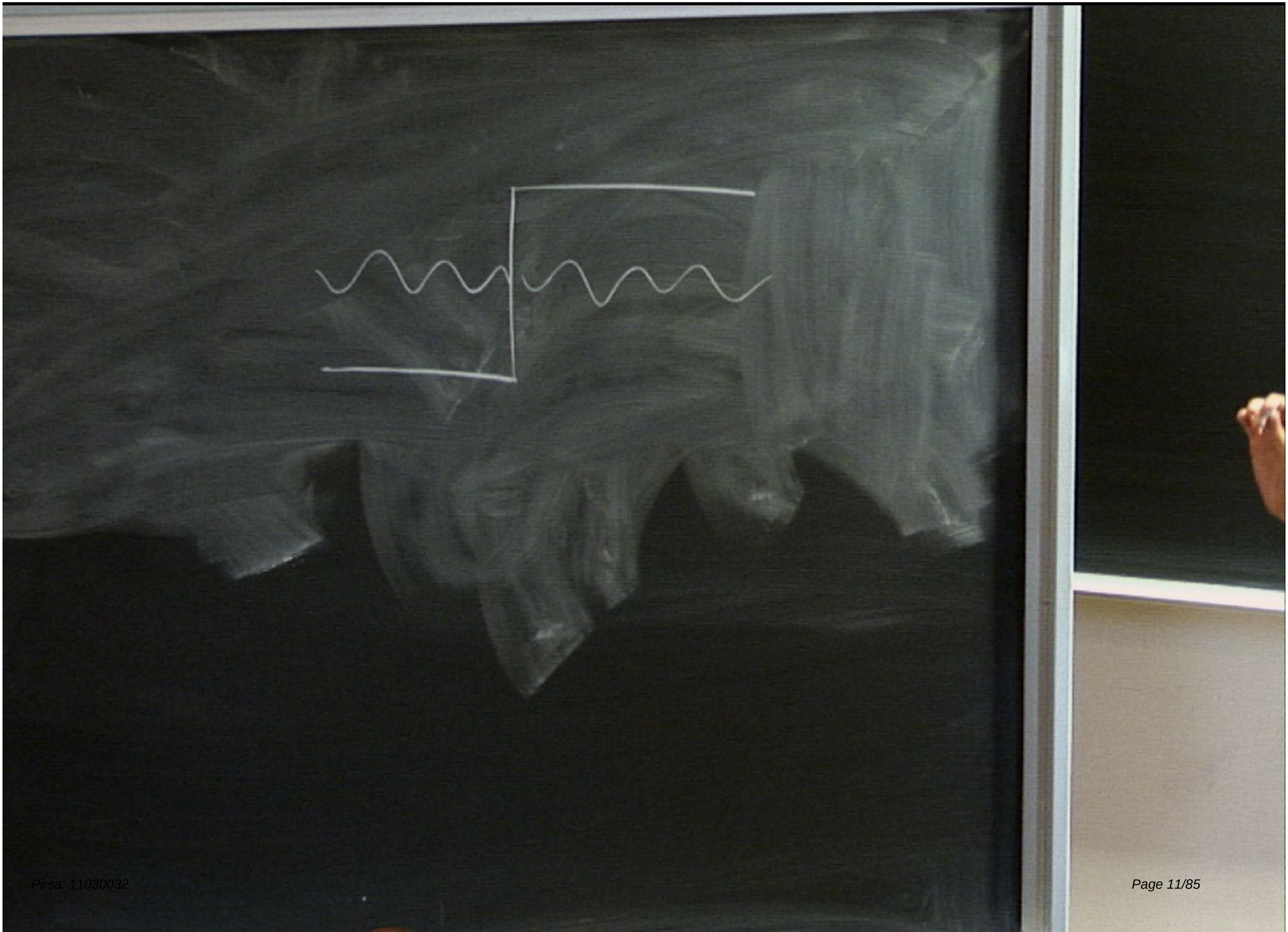

K
K'
4π/3
4π/3
K
K
K
K'
a
π/a
D

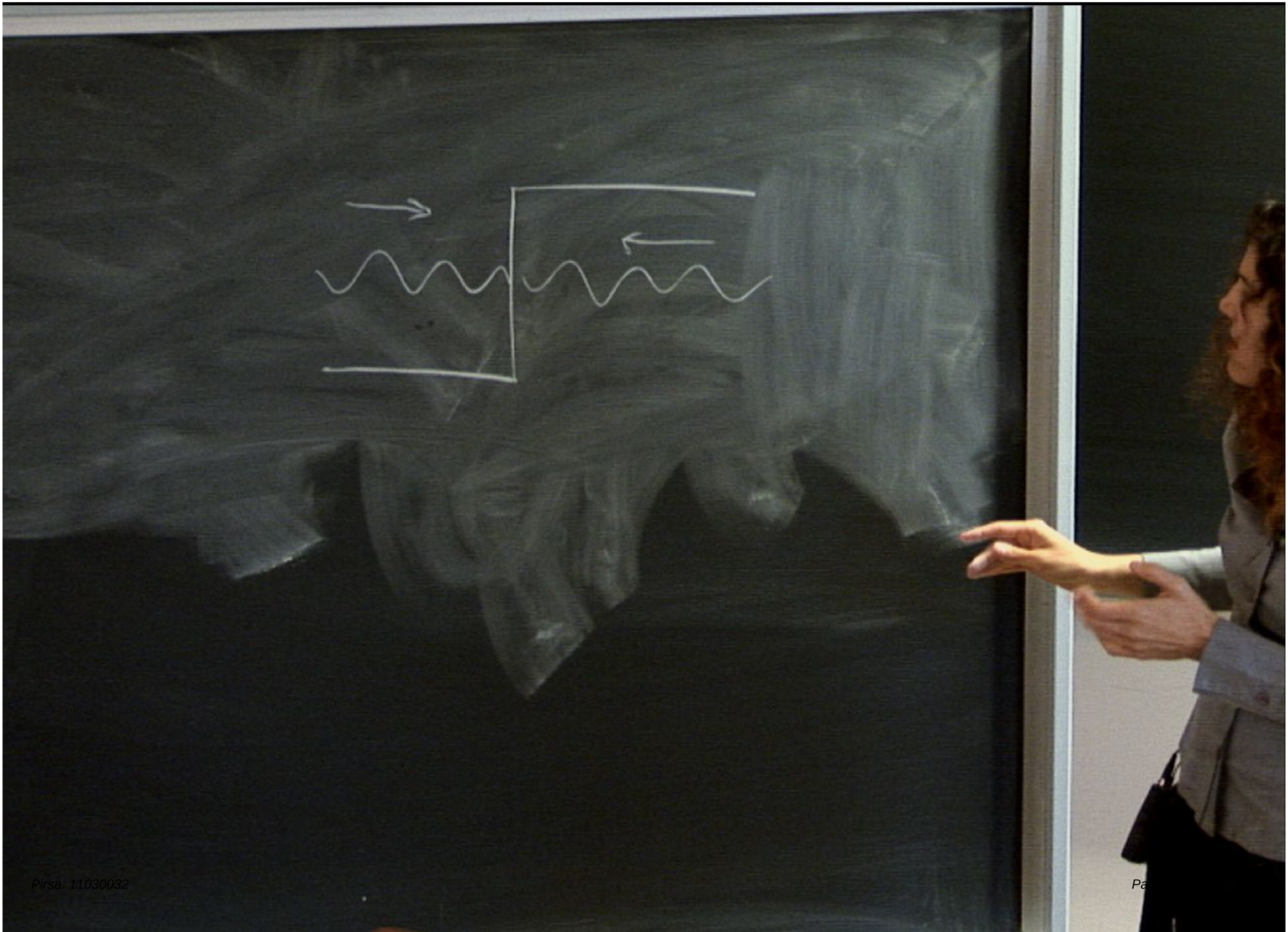


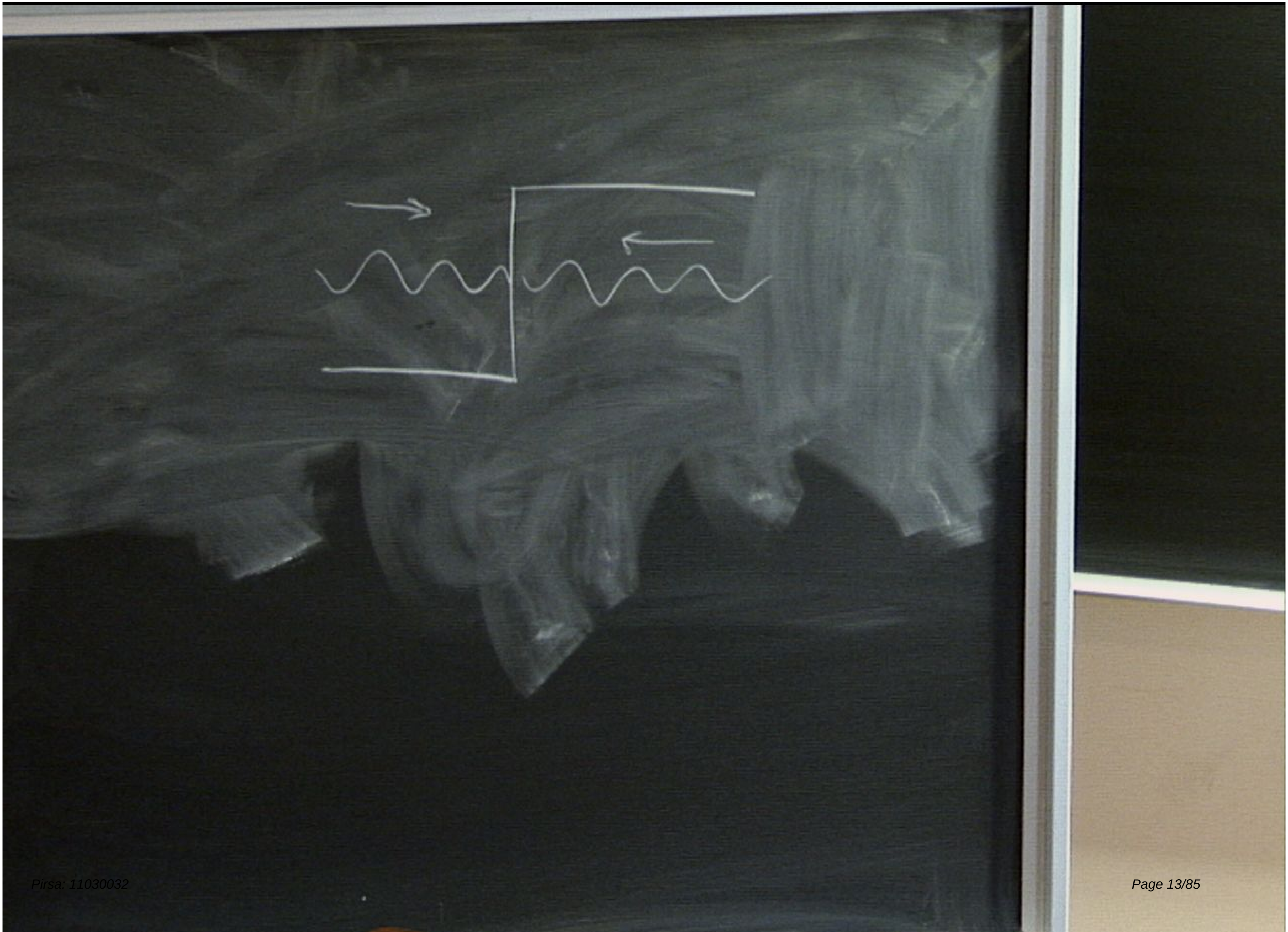
a
K
K'
4π/3
D
k_x
-π/a
π/a


a
$-\pi/a$
π/a
K
K'
$4\pi/3$
$4\pi/3$
K
K
$-\pi$
π
k_x
D

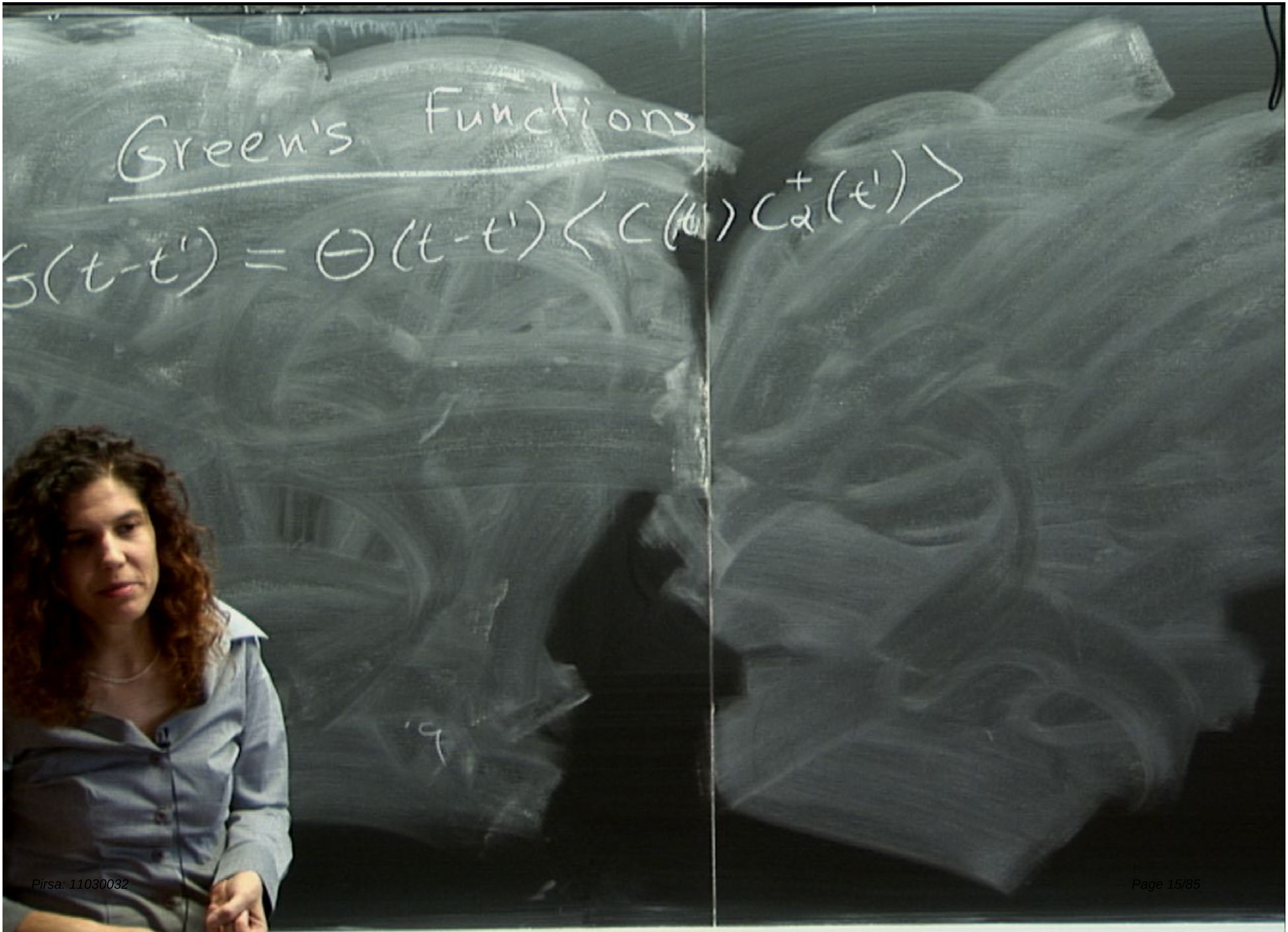


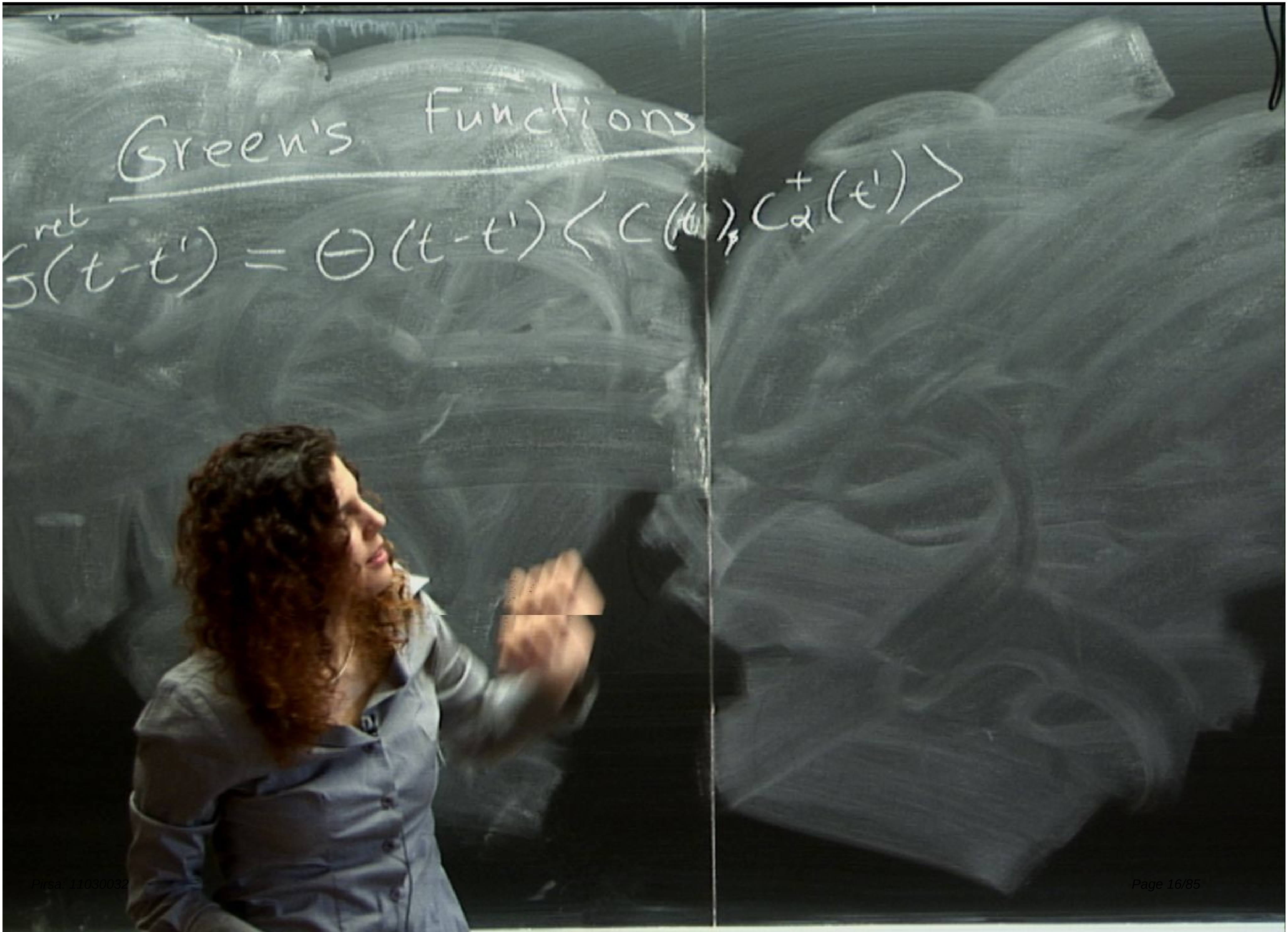







Green's Functions


Green's Functions
G(t-t') = Θ(t-t') < c(t) c_α^+(t') >


Green's Functions
$G^{ret}(t-t') = \Theta(t-t')\langle c(t), c_\alpha^+(t')\rangle$

Green's Functions

$$G^{ret}(t-t') = \Theta(t-t')\langle c(t), c^{+}_{\alpha}(t')\rangle$$

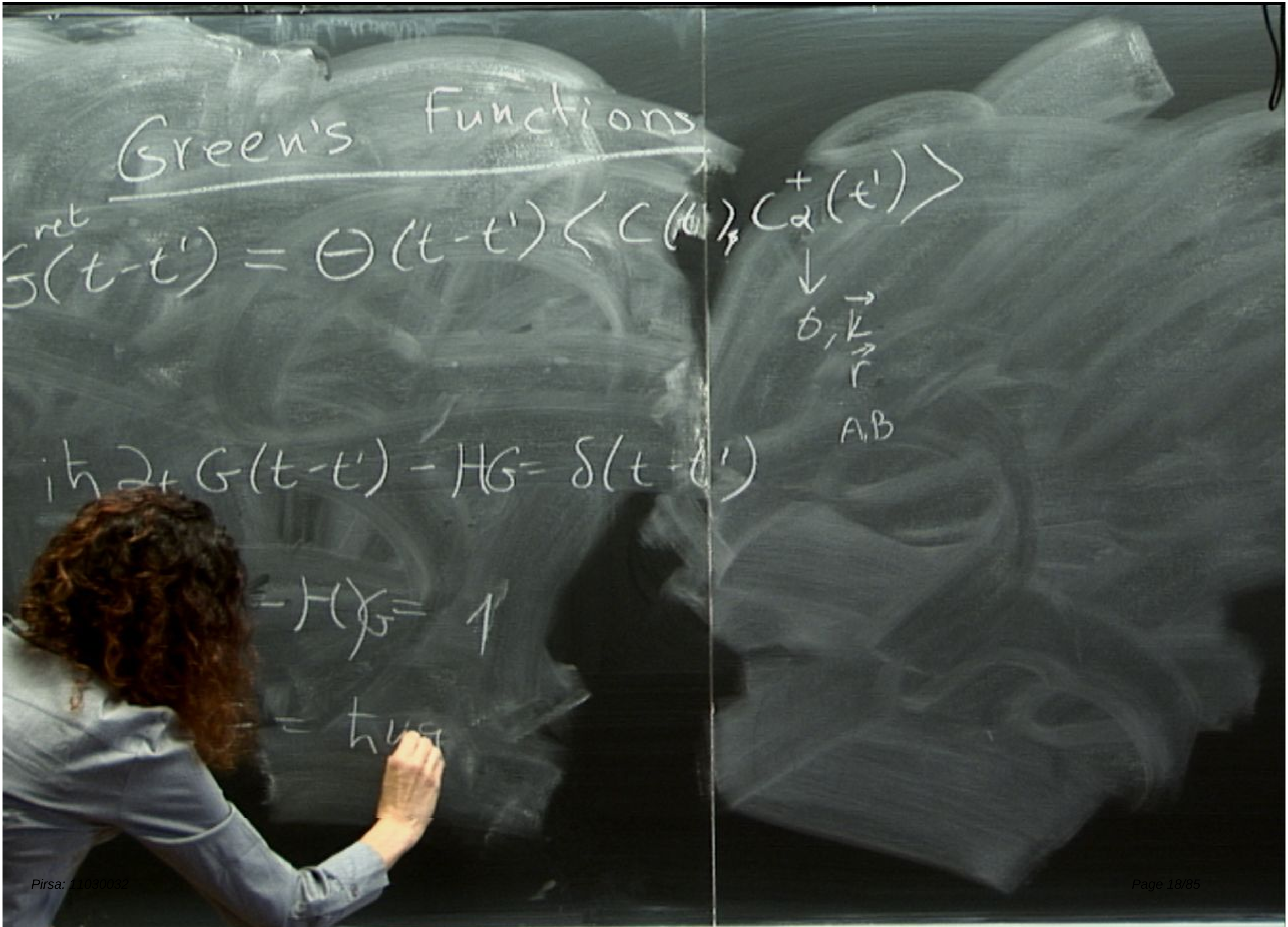
$\downarrow$

$\sigma, \vec{k}$

$\vec{r}$

A,B

$$i\hbar\partial_t G(t-t') - H = \delta(t-t')$$


Green's Functions
G ret (t-t') = Θ(t-t') < C(t), C α + (t') >
σ, k
r
A,B
iħ∂t G(t-t') - HG = δ(t-t')
-H( )G = 1
= ħω

Green's Functions

$$G^{ret}(t-t') = \Theta(t-t')\langle c(t), c_\alpha^{+}(t')\rangle$$

$\alpha \downarrow$ $\sigma, \vec{k}$, $\vec{r}$, A, B

$$i\hbar\partial_t G(t-t') - HG = \delta(t-t')$$

$$(\hbar\omega - H)G = 1$$

$$G = (\hbar\omega - H)^{-1}$$

Green's Functions

$$G^{ret}(t-t') = \Theta(t-t')\langle c(t), c_\alpha^+(t')\rangle$$

$\alpha \rightarrow \sigma, \vec{k}$

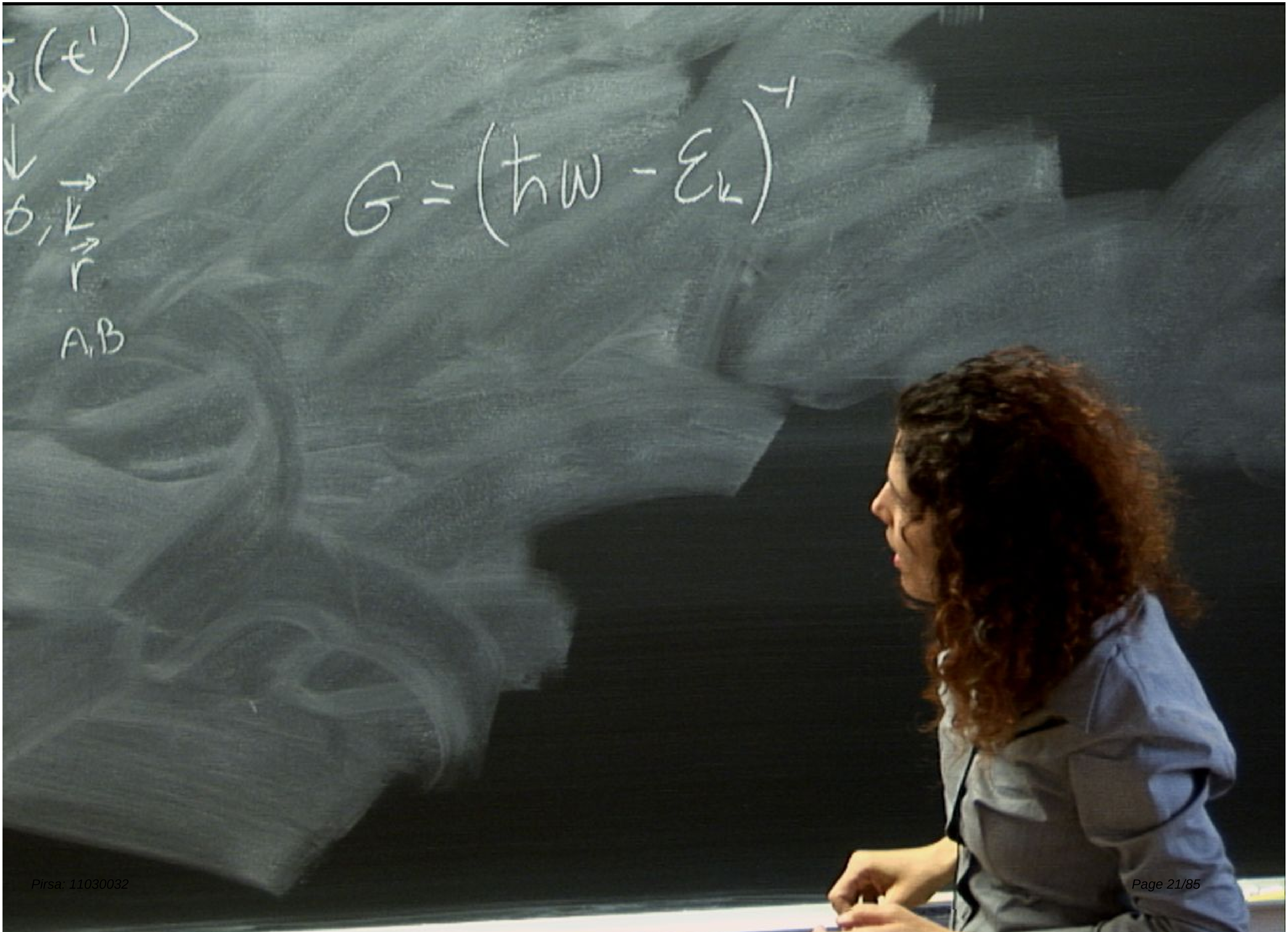
$\vec{r}$

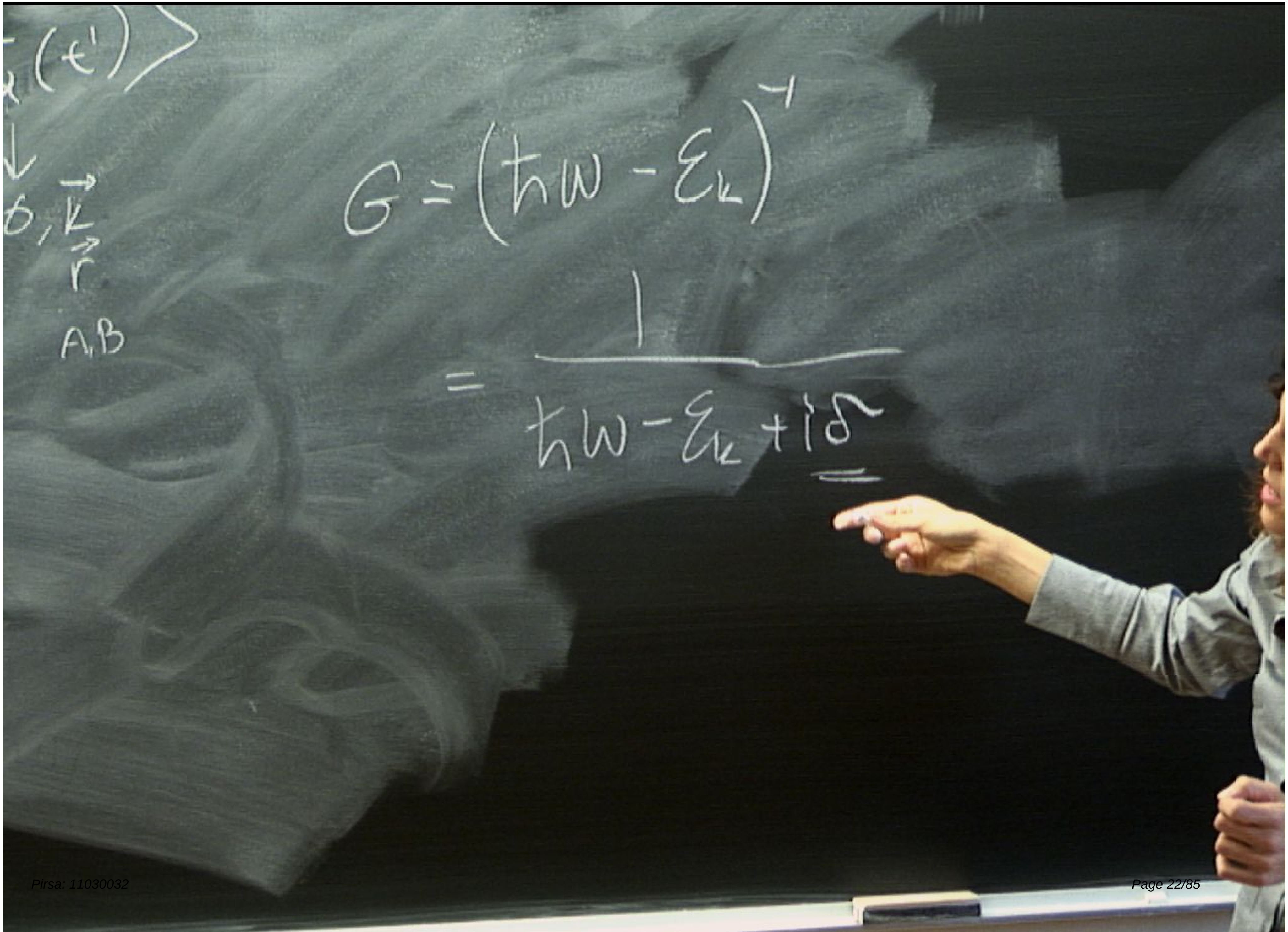
A, B

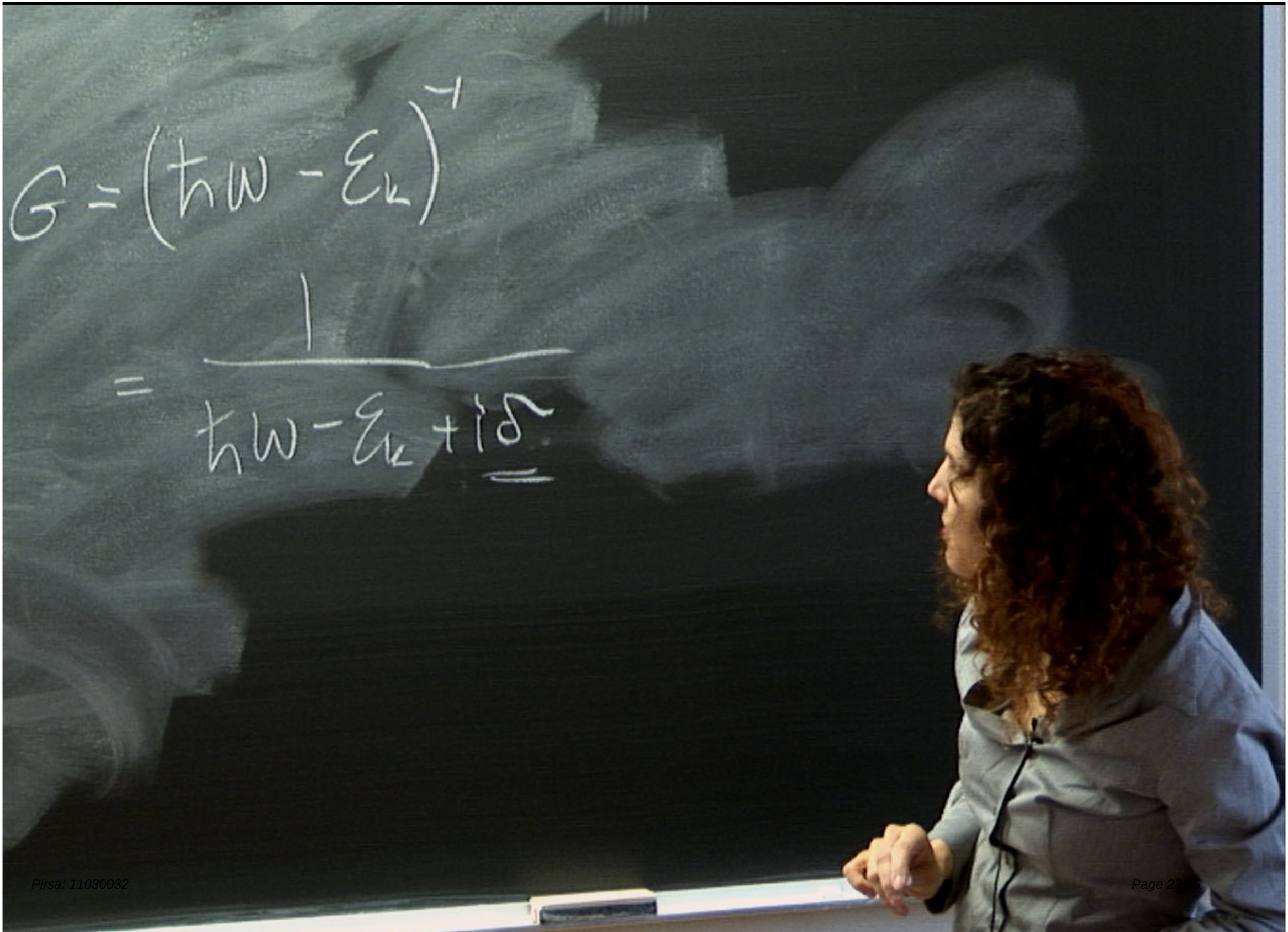
$$i\hbar\partial_t G(t-t') - HG = \delta(t-t')$$

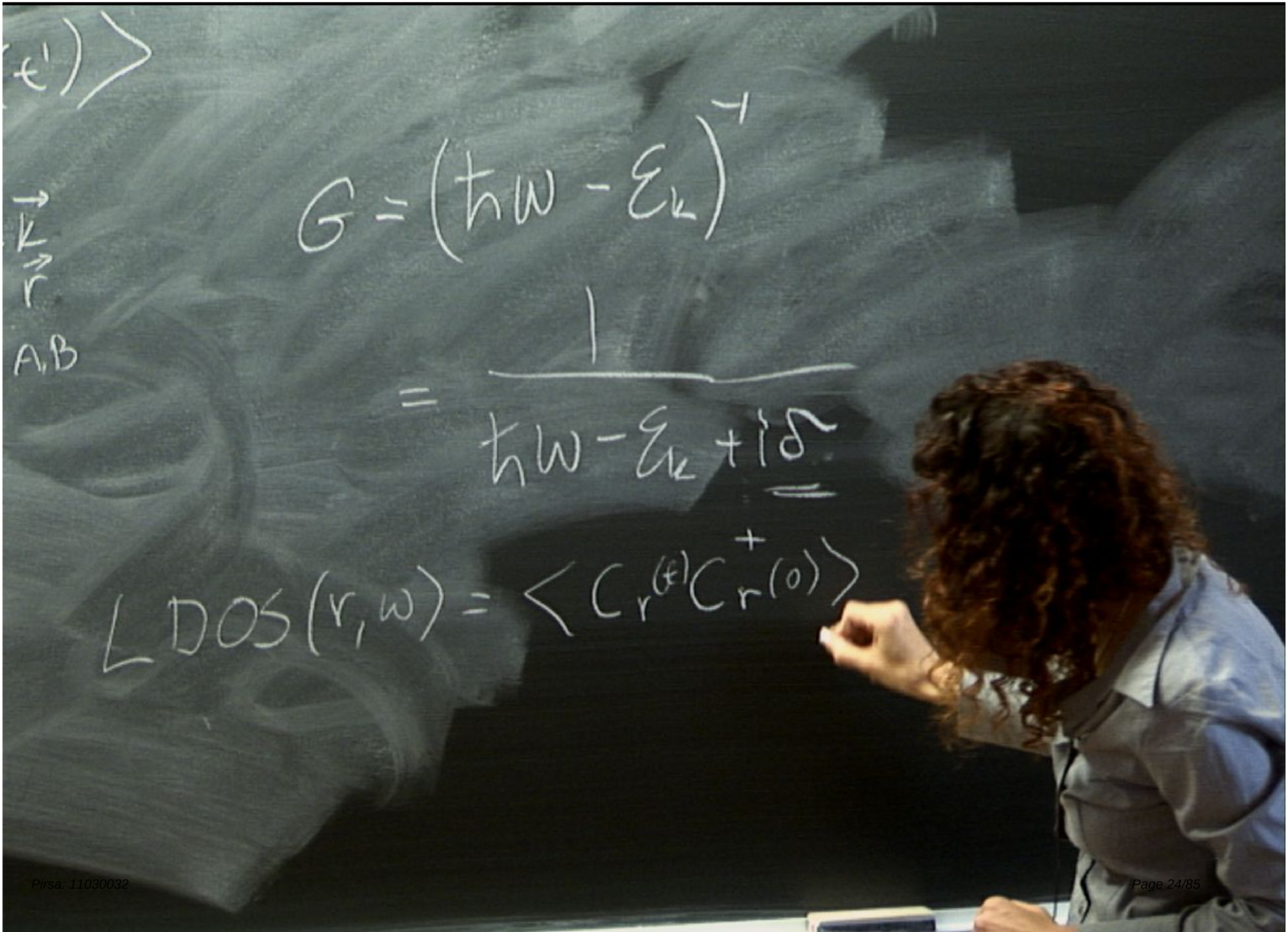
$$(\hbar\omega - H)G = 1$$

$$G = (\hbar\omega - H)^{-1}$$


G = (ħω - Ɛk)⁻¹
A,B


(t')
$G = (\hbar\omega - \varepsilon_k)^{-1}$
$= \frac{1}{\hbar\omega - \varepsilon_k + i\delta}$
A, B


$G = (\hbar\omega - \varepsilon_k)^{-1}$
$= \frac{1}{\hbar\omega - \varepsilon_k + i\delta}$


G = (ħω - ε_k)^-1
= 1 / (ħω - ε_k + iδ)
LDOS(r,ω) = <c_r(t) c_r^+(0)>
k
r
A,B

$(t')\rangle$

$\vec{k}$

$\vec{r}$

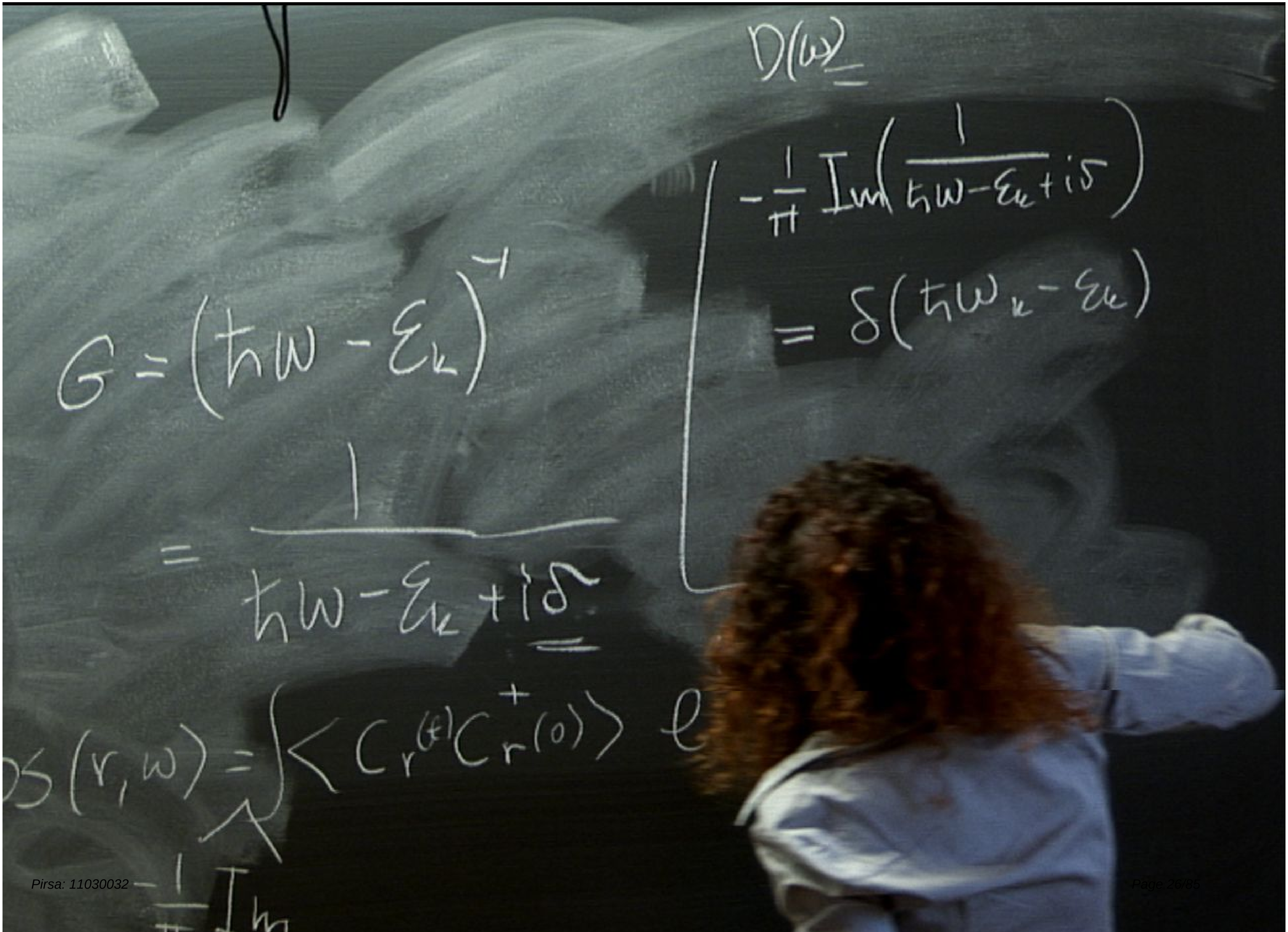
A, B

$$G = (\hbar\omega - \varepsilon_k)^{-1}$$

$$= \frac{1}{\hbar\omega - \varepsilon_k + i\delta}$$

$$LDOS(r,\omega) = \int \langle C_r(t) C_r^+(0)\rangle e^{i\omega t} dt$$

$$-\frac{1}{\pi} Im$$


D(ω)
G = (ħω - ε_k)^{-1}
= 1 / (ħω - ε_k + iδ)
-1/π Im(1 / (ħω - ε_k + iδ))
= δ(ħω_k - ε_k)
S(r, ω) = ∫ <C_r(t) C_r^+(0)> e

$$D(\omega) = -\frac{1}{\pi}\sum_k \mathrm{Im}\left(\frac{1}{\hbar\omega - \varepsilon_k + i\delta}\right)$$

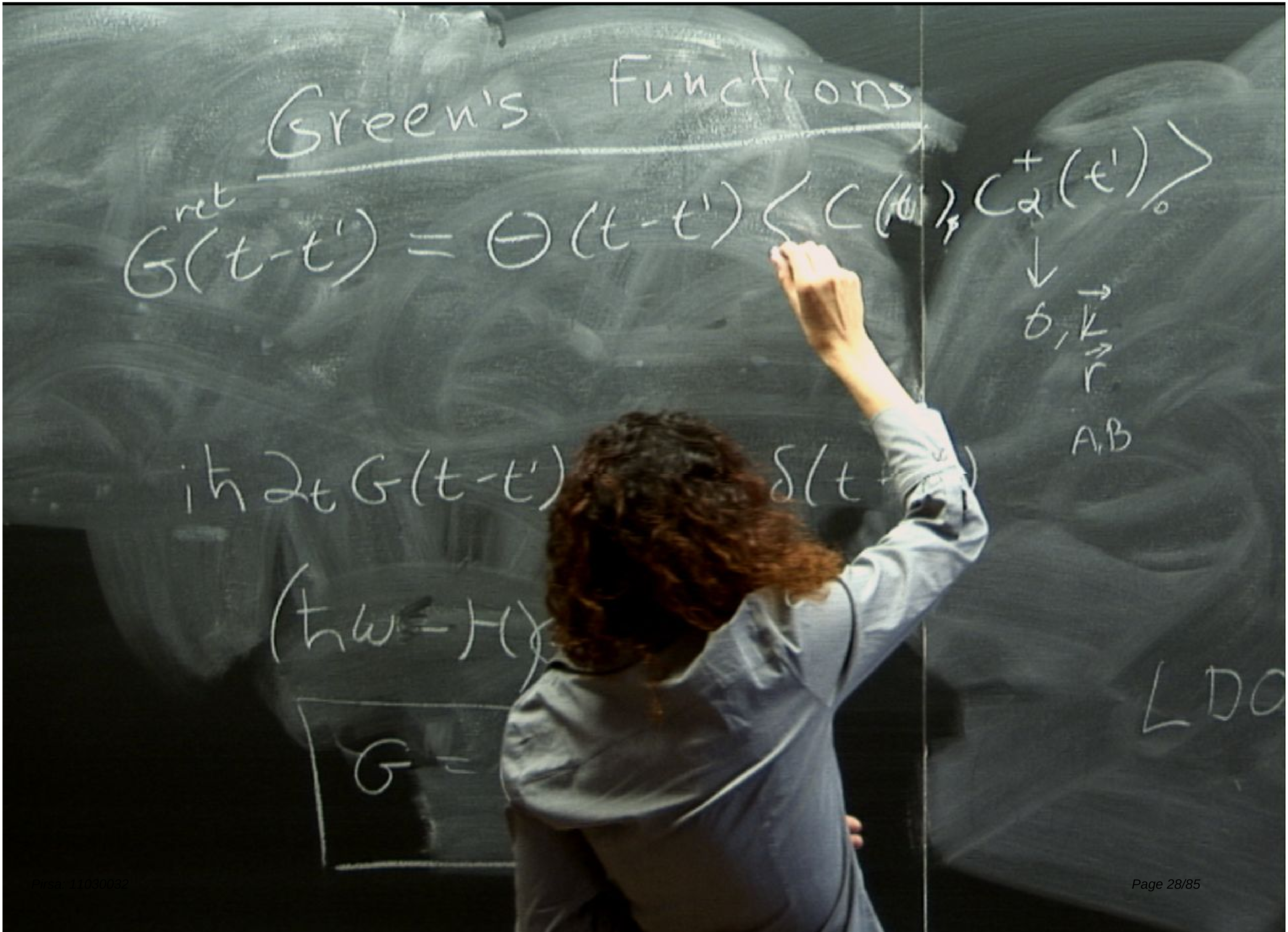
$$= \sum_k \delta(\hbar\omega_k - \varepsilon_k)$$

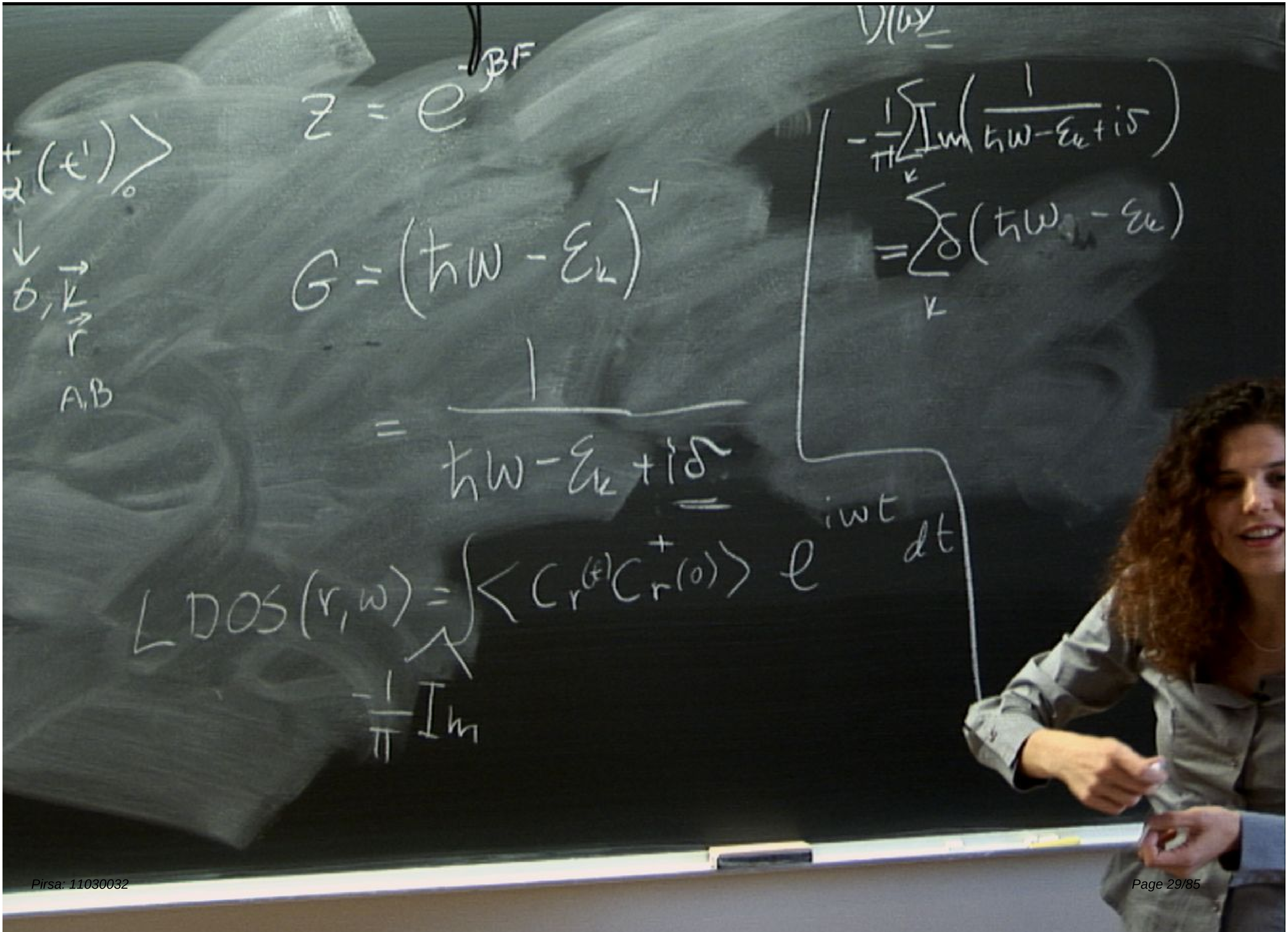
$$G = (\hbar\omega - \varepsilon_k)^{-1}$$

$$= \frac{1}{\hbar\omega - \varepsilon_k + i\delta}$$

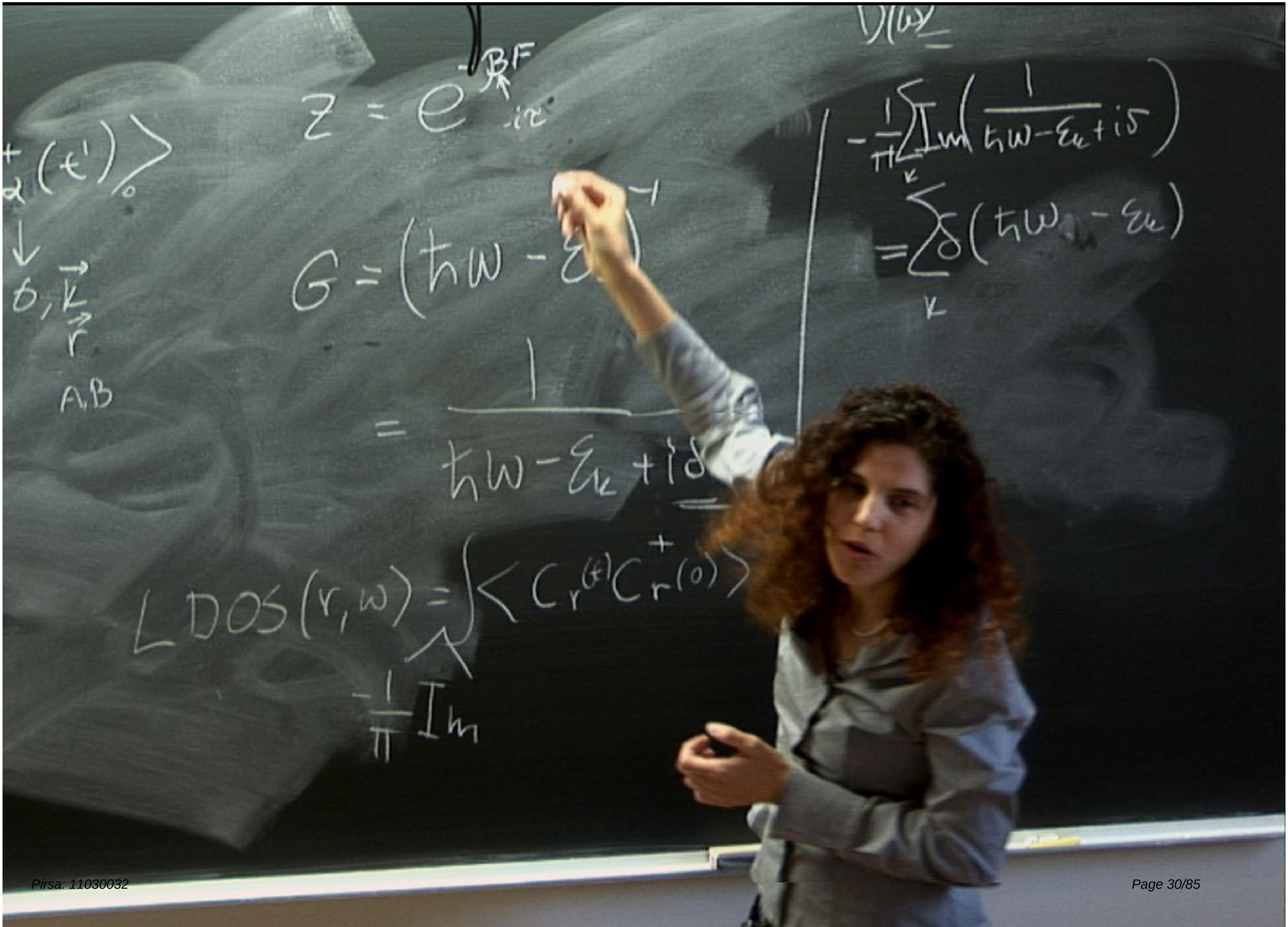
$$DOS(r,\omega) = \int \langle c_r(t) c_r^{+}(0)\rangle e^{i\omega t}\, dt$$

$$= -\frac{1}{\pi}\mathrm{Im}$$


Green's Functions
G ret (t-t') = Θ(t-t') < C(t), C+α(t') >0
σ, k
r
A,B
iħ∂t G(t-t')
δ(t
(ħω-H(
G =
LDO



Z = e^{-βF}
G = (ħω - ε_k)^{-1}
= 1 / (ħω - ε_k + iδ)
LDOS(r,ω) = ∫ <C_r(t) C_r^+(0)> e^{iωt} dt
-1/π Im
-1/π Σ_k Im(1 / (ħω - ε_k + iδ))
= Σ_k δ(ħω - ε_k)
A,B


Z = e
G = (ħω - ε
= 1 / (ħω - εk + iδ)
LDOS(r, ω) =
-1/π Im
A,B
-1/π Σk Im (1 / (ħω - εk + iδ))
= Σk δ(ħω - εk)

$c^{+}_{\alpha}(t')\rangle_0$

$\downarrow$

$\sigma, \vec{k}$

$\vec{r}$

A,B

$$Z = e^{-\beta F}, \quad \beta \to i\tau$$

$$G = (\hbar\omega - \varepsilon_k)^{-1} = \frac{1}{\hbar\omega - \varepsilon_k + i\delta}$$

$$LDOS(r,\omega) = \int \langle c_r(t)\, c_r^{+}(0)\rangle\, e^{i\omega t}\, dt$$

$$-\frac{1}{\pi}\,\mathrm{Im}$$

$$D(\omega) = -\frac{1}{\pi}\sum_k \mathrm{Im}\left(\frac{1}{\hbar\omega - \varepsilon_k + i\delta}\right) = \sum_k \delta(\hbar\omega - \varepsilon_k)$$

$D(\omega)$

$\alpha^{+}(t')\rangle_0$

$\downarrow$

$\sigma, \vec{k}$

$\vec{r}$

A, B

$Z = e^{-\beta F}_{i\tau}$

$G = (\hbar\omega - \varepsilon_k)^{-1}$

$= \dfrac{1}{\hbar\omega - \varepsilon_k + i\delta}$

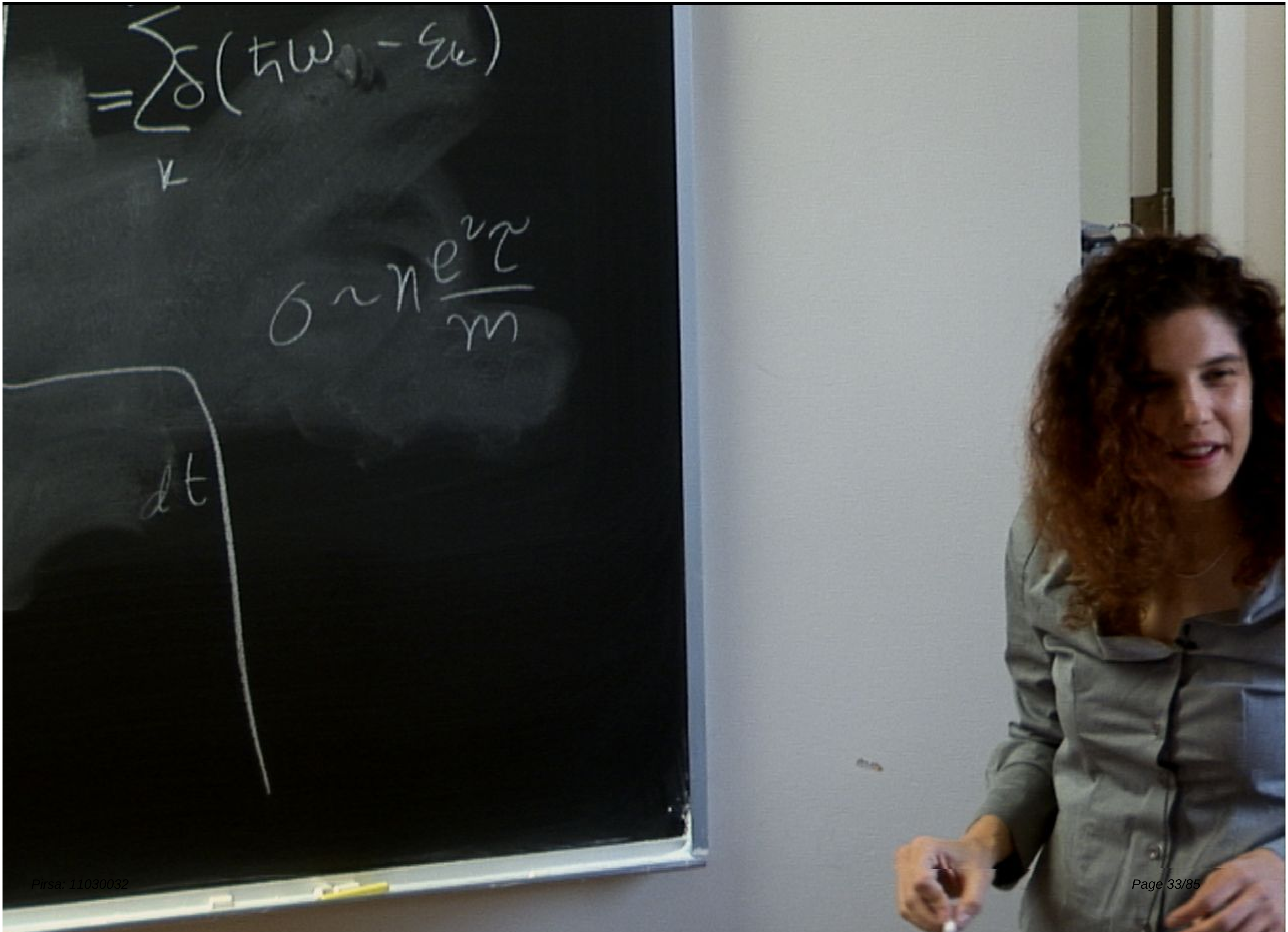
$\boxed{\omega + i\delta \to i\omega}$

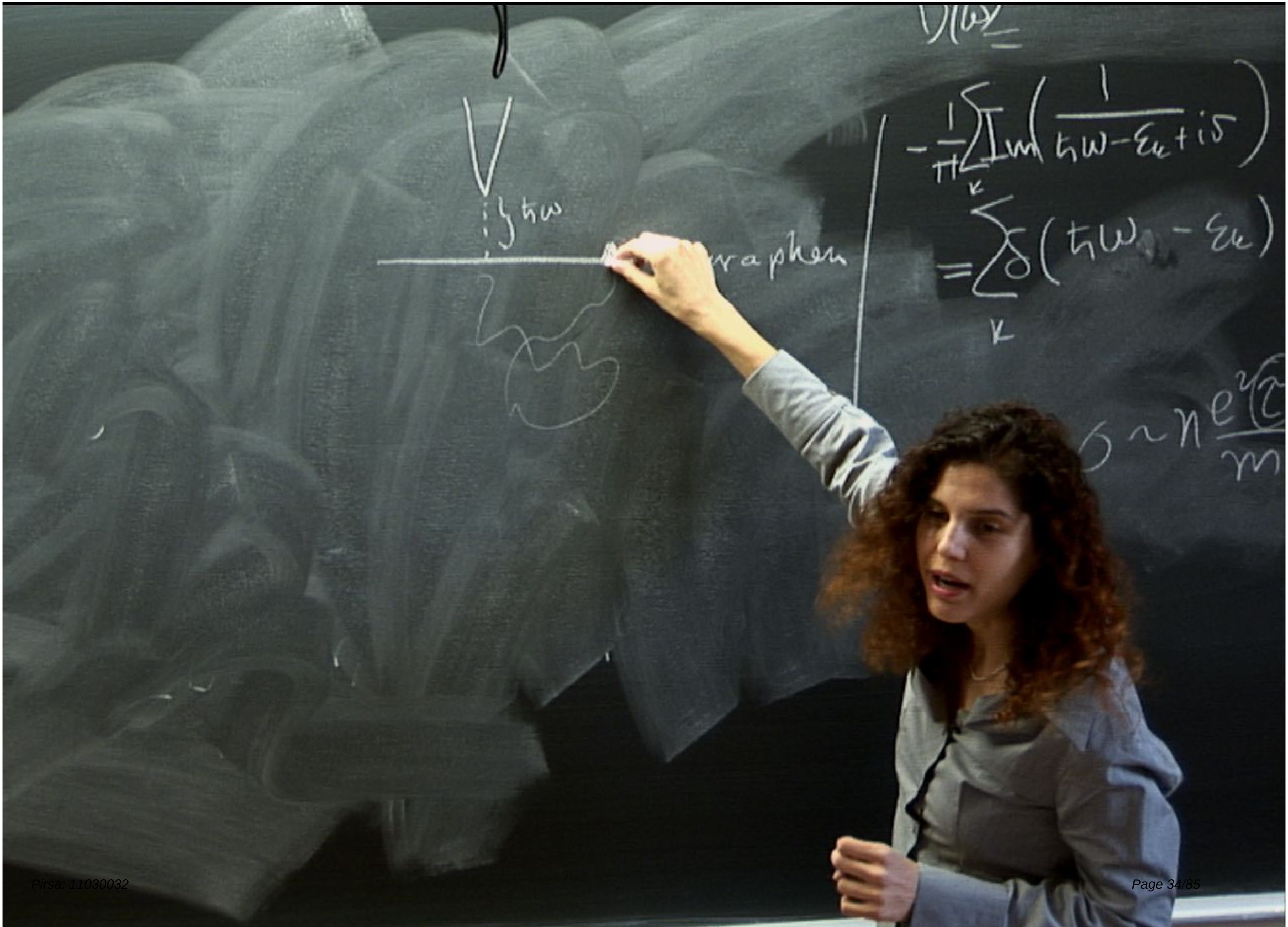
$-\frac{1}{\pi}\sum_k \mathrm{Im}\left(\frac{1}{\hbar\omega - \varepsilon_k + i\delta}\right)$

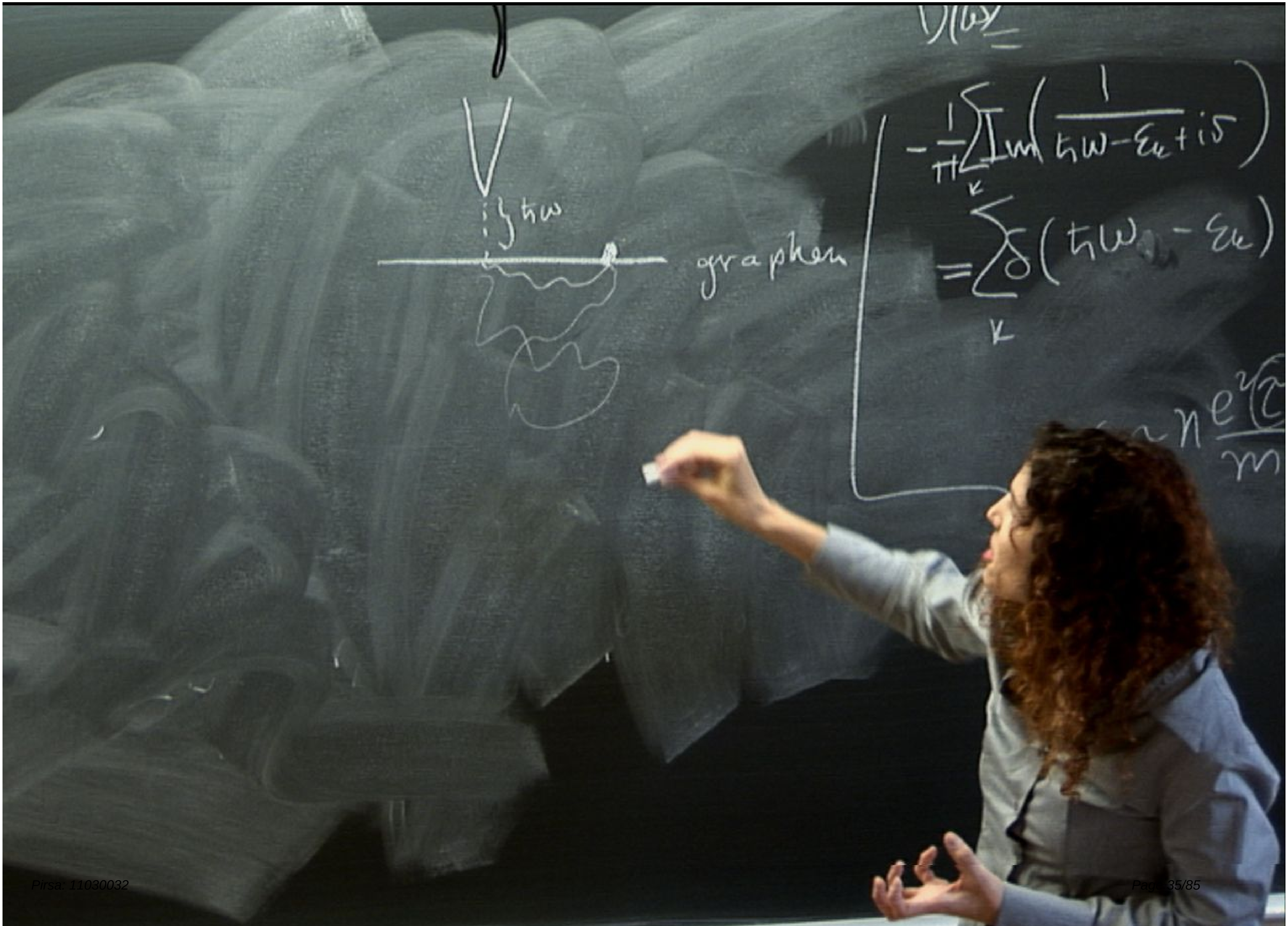
$= \sum_k \delta(\hbar\omega - \varepsilon_k)$

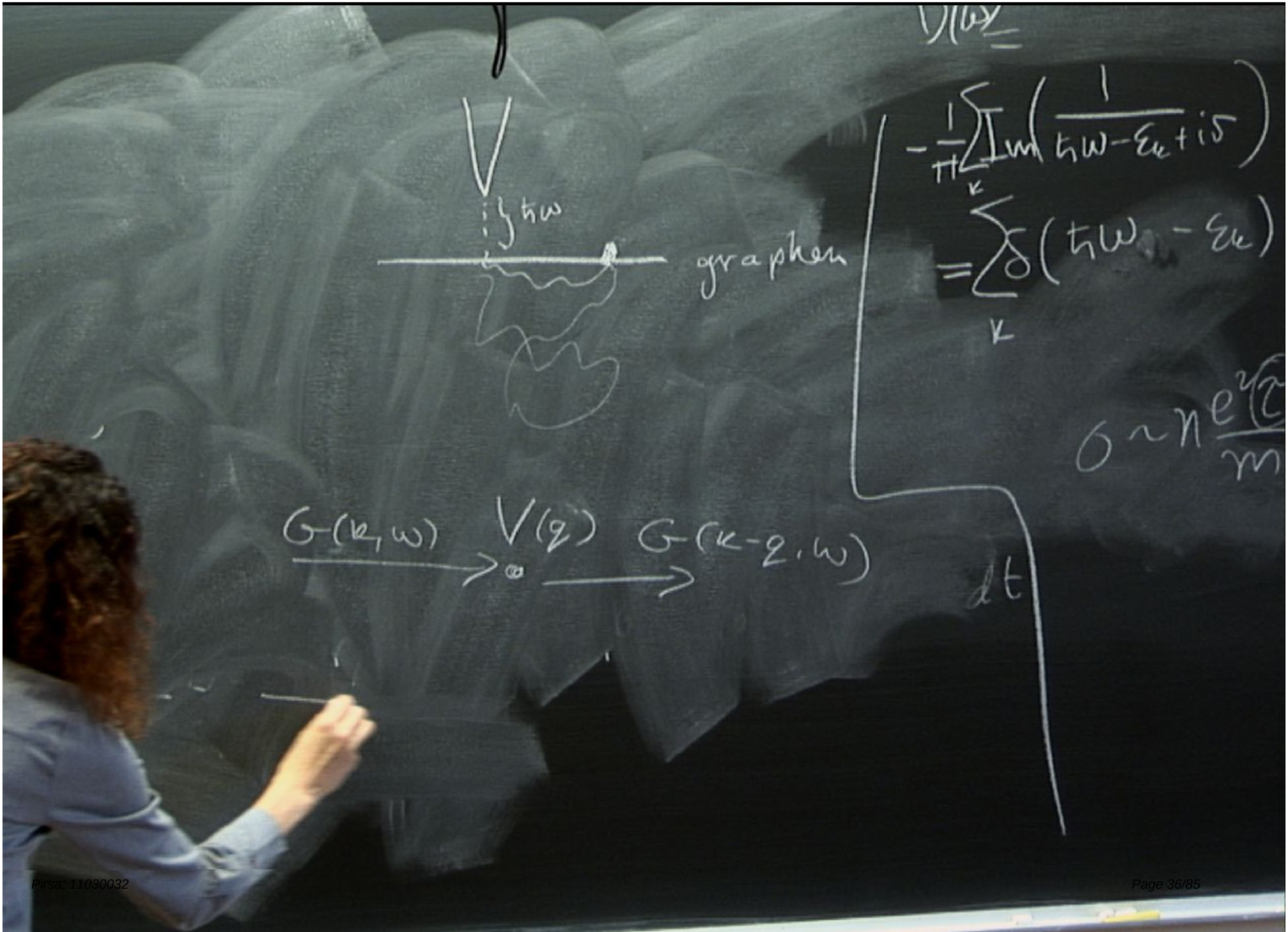
$LDOS(r,\omega) = \int \langle C_r(t) C_r^{+}(0)\rangle e^{i\omega t} dt$

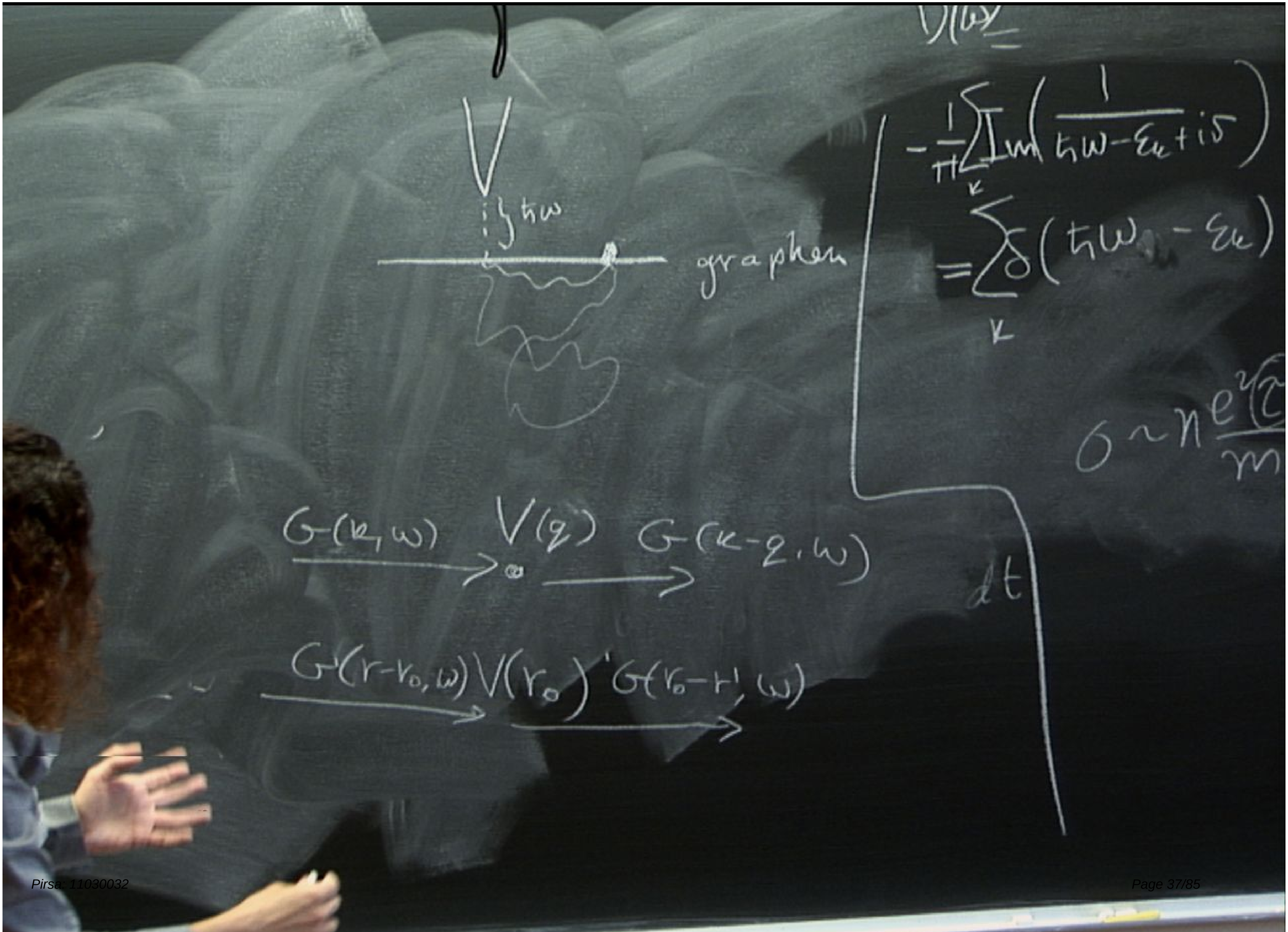
$-\frac{1}{\pi}\mathrm{Im}$


$= \sum_k \delta(\hbar\omega - \varepsilon_k)$
$\sigma \sim n \frac{e^2 \tau}{m}$
dt


$-\frac{1}{\pi}\sum_k \mathrm{Im}\left(\frac{1}{\hbar\omega-\varepsilon_k+i\delta}\right)$
$=\sum_k \delta(\hbar\omega-\varepsilon_k)$


graphen


D(ω)
V
ħω
graphen
-1/π ∑_k Im(1/(ħω - ε_k + iδ))
= ∑_k δ(ħω - ε_k)
σ ~ n e²τ/m
G(k, ω)
V(q)
G(k-q, ω)
dt

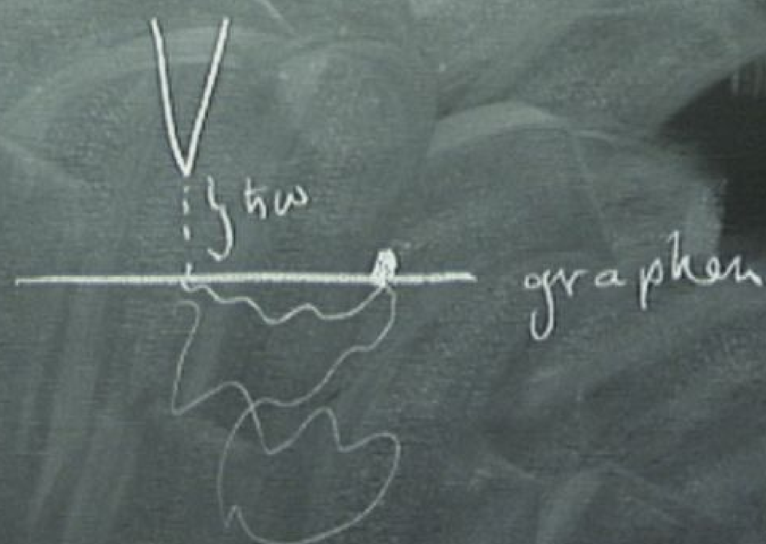


$-\frac{1}{\pi}\sum_k \mathrm{Im}\left(\frac{1}{\hbar\omega - \varepsilon_k + i\delta}\right)$
$= \sum_k \delta(\hbar\omega - \varepsilon_k)$
$\hbar\omega$
graphen
$\sigma \sim n\frac{e^2\tau}{m}$
$G(k,\omega)$ $V(q)$ $G(k-q,\omega)$
$G(r-r_0,\omega)\,V(r_0)\,G(r_0-r',\omega)$
dt

$D(\omega) =$

$$-\frac{1}{\pi}\sum_k \mathrm{Im}\left(\frac{1}{\hbar\omega-\varepsilon_k+i\delta}\right)$$

$$=\sum_k \delta(\hbar\omega-\varepsilon_k)$$

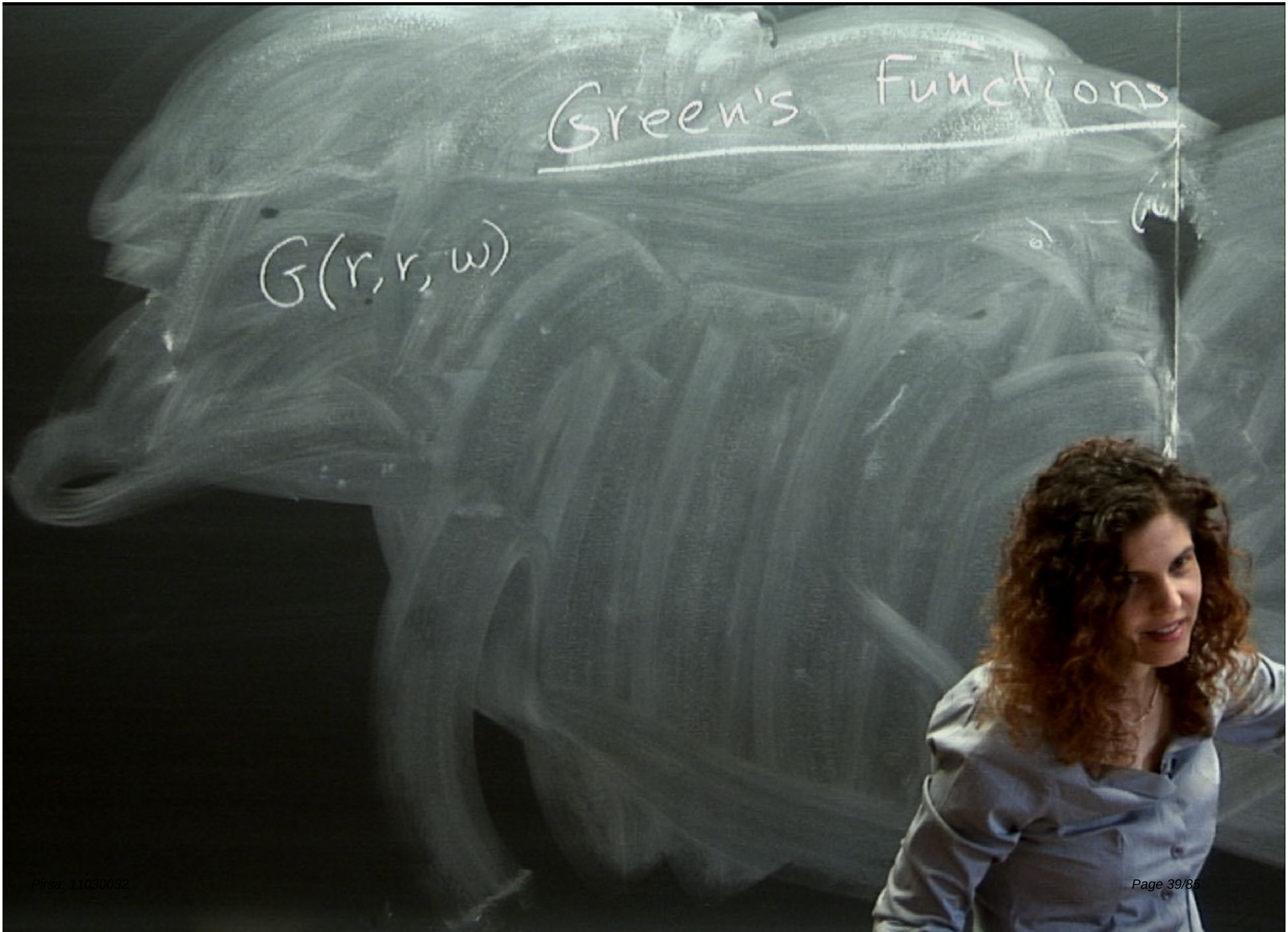


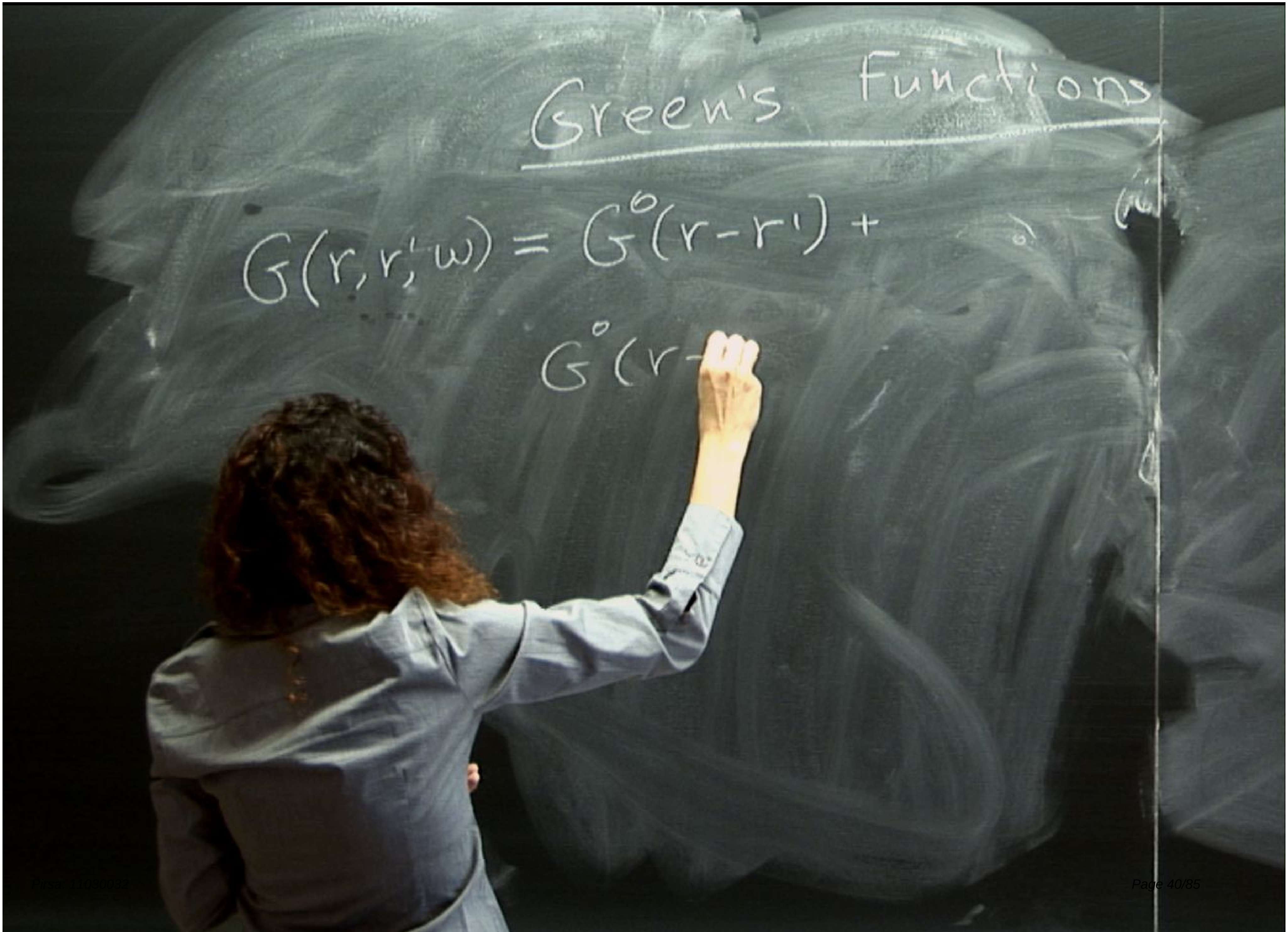
$$\sigma \sim n\frac{e^2\tau}{m}$$

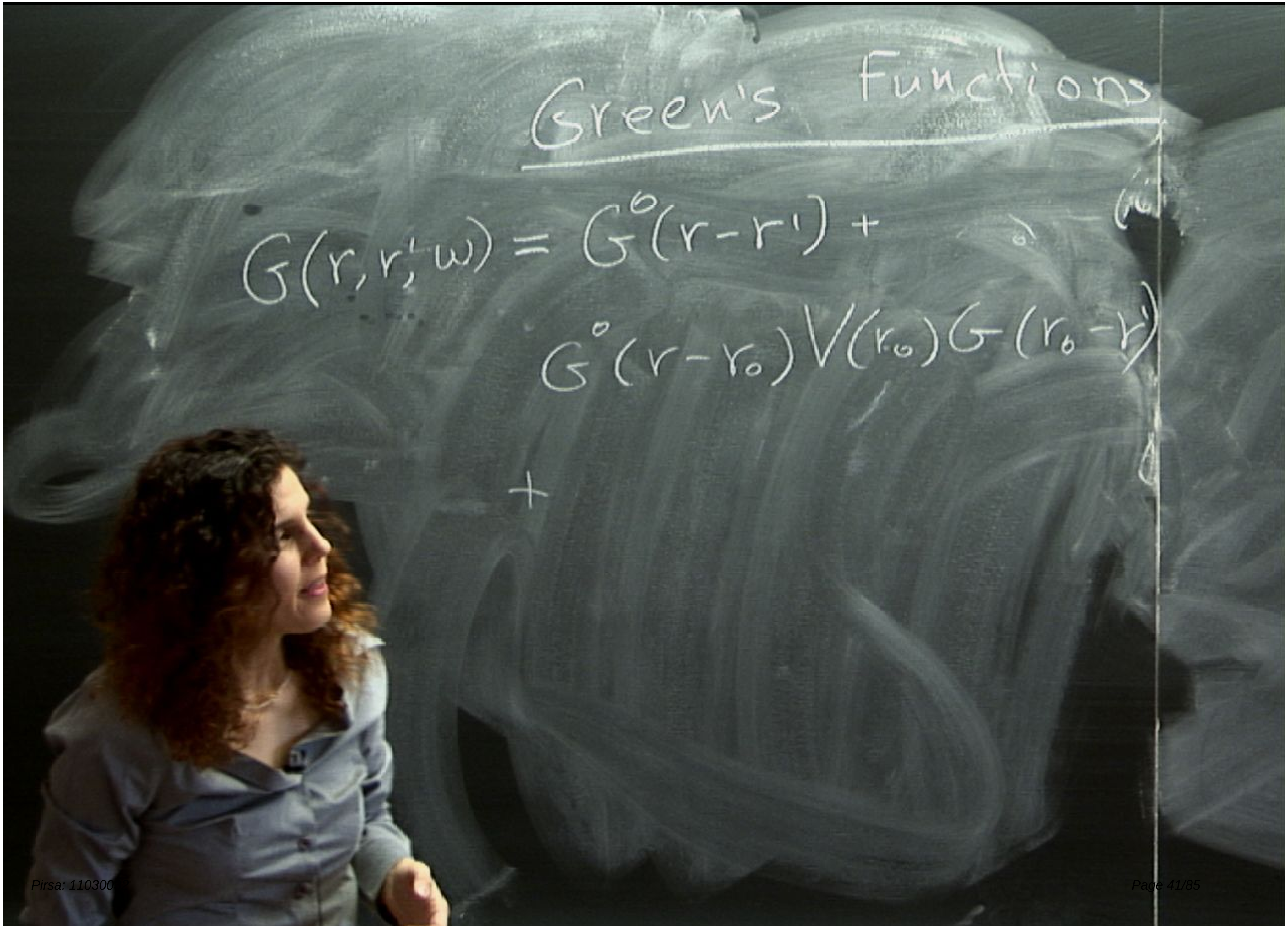
$$G(k,\omega)\quad V(q)\quad G(k-q,\omega)$$

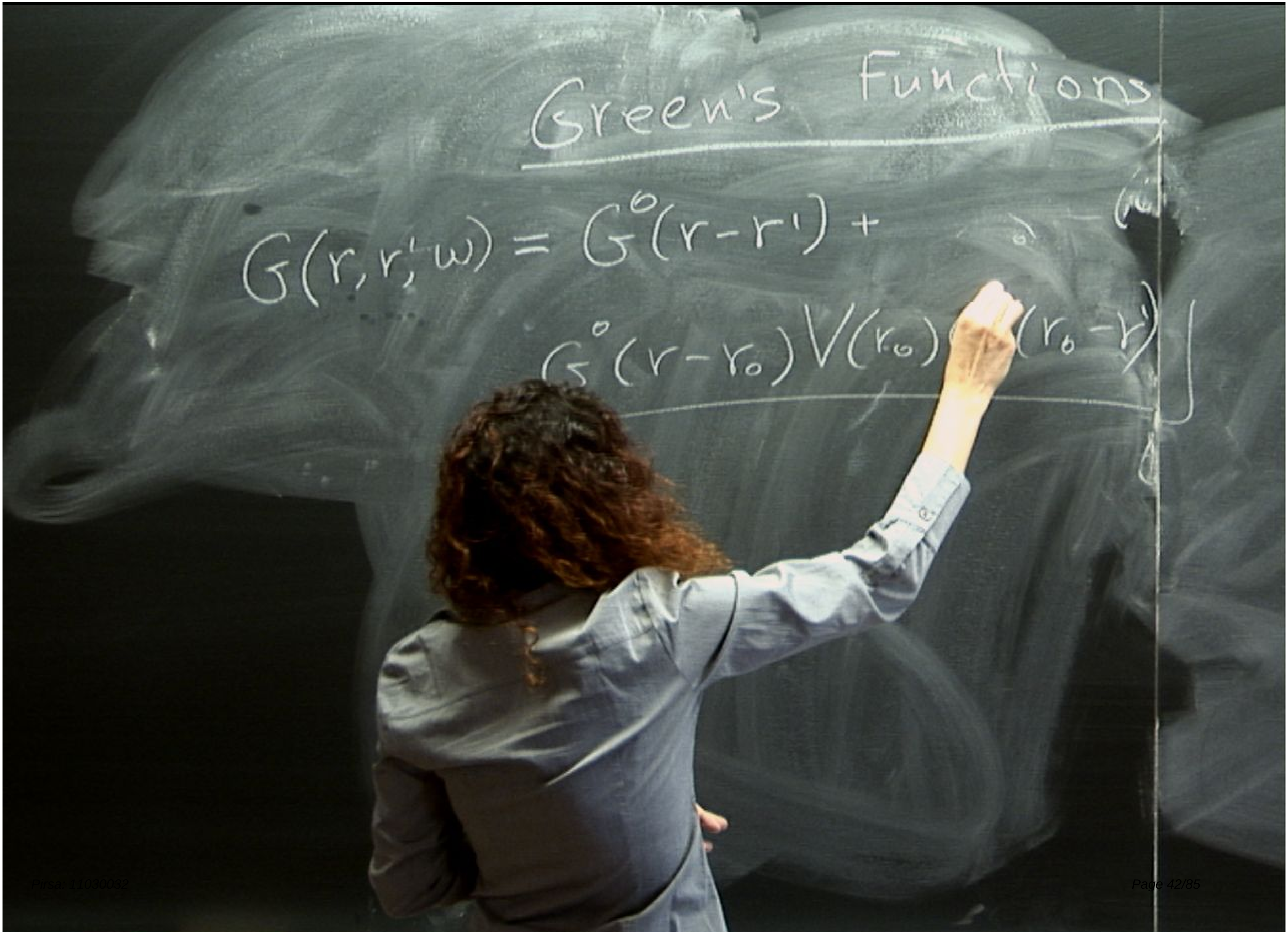
$$G(r-r_0,\omega)\,V(r_0)\,G(r_0-r',\omega)$$

dt


Green's Functions
G(r,r,ω)

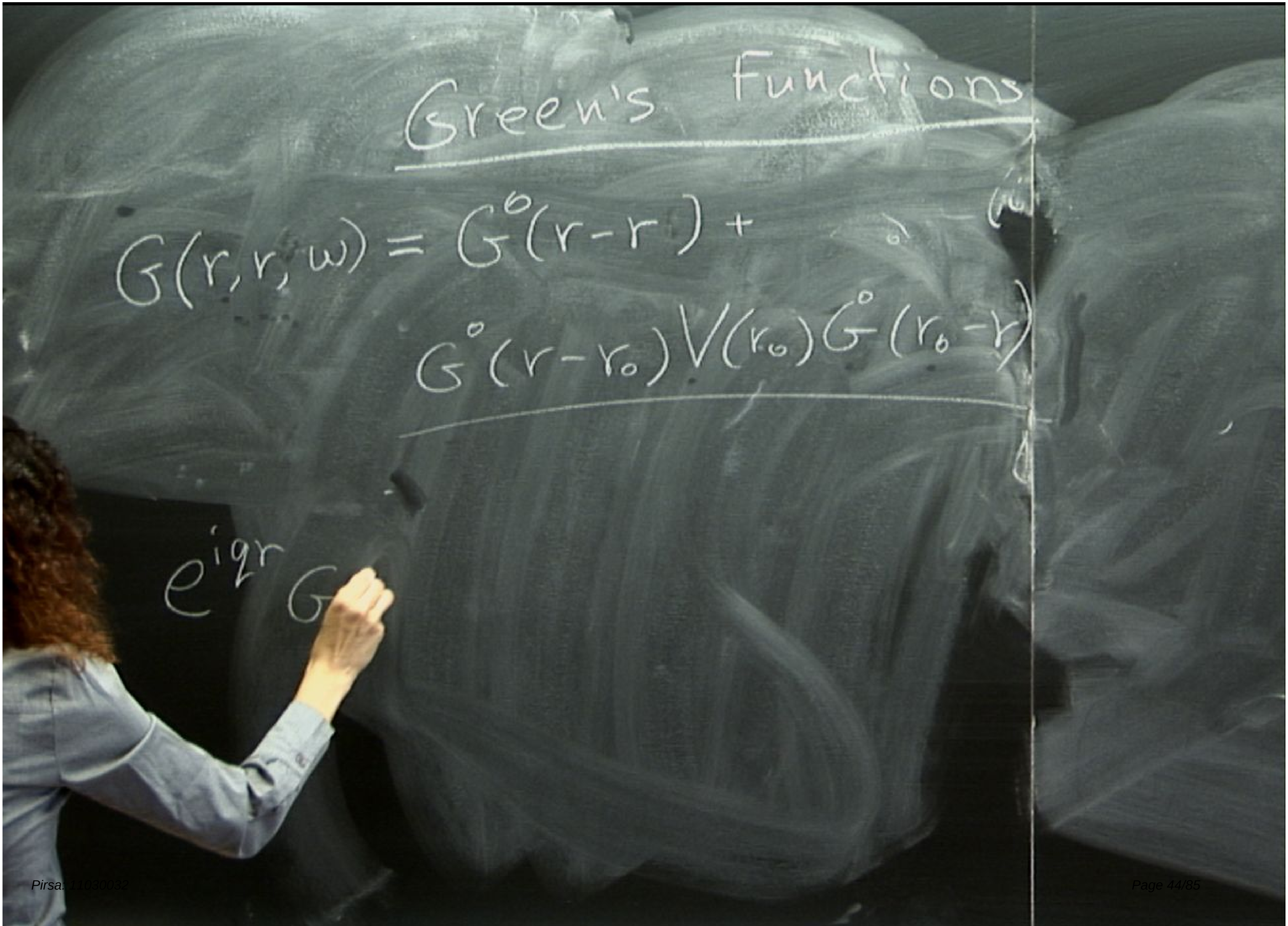

Green's Functions
G(r,r';ω) = G⁰(r−r') +
G⁰(r−

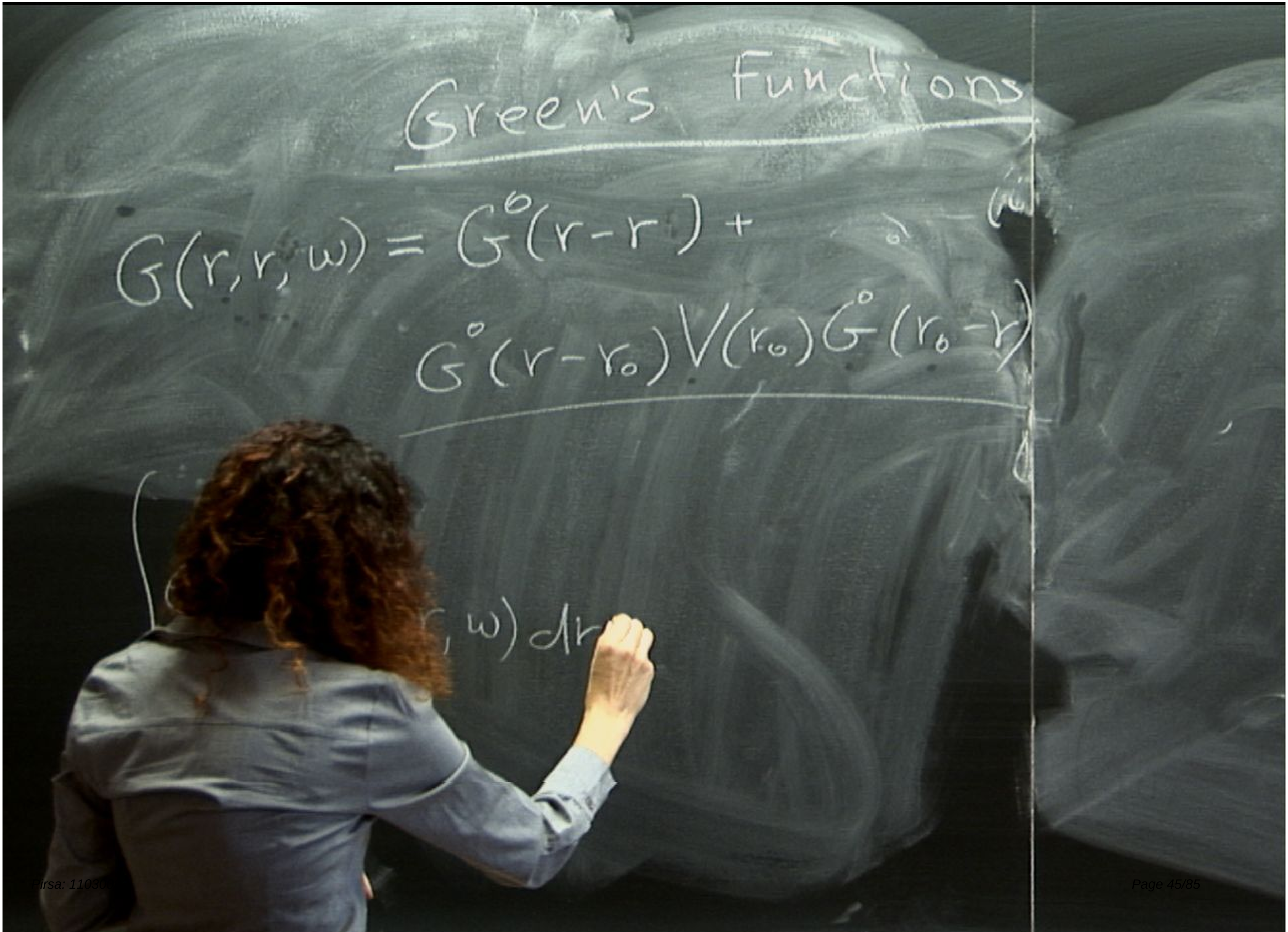

Green's Functions
G(r,r';ω) = G^0(r-r') +
G^0(r-r_0)V(r_0)G(r_0-r')
+

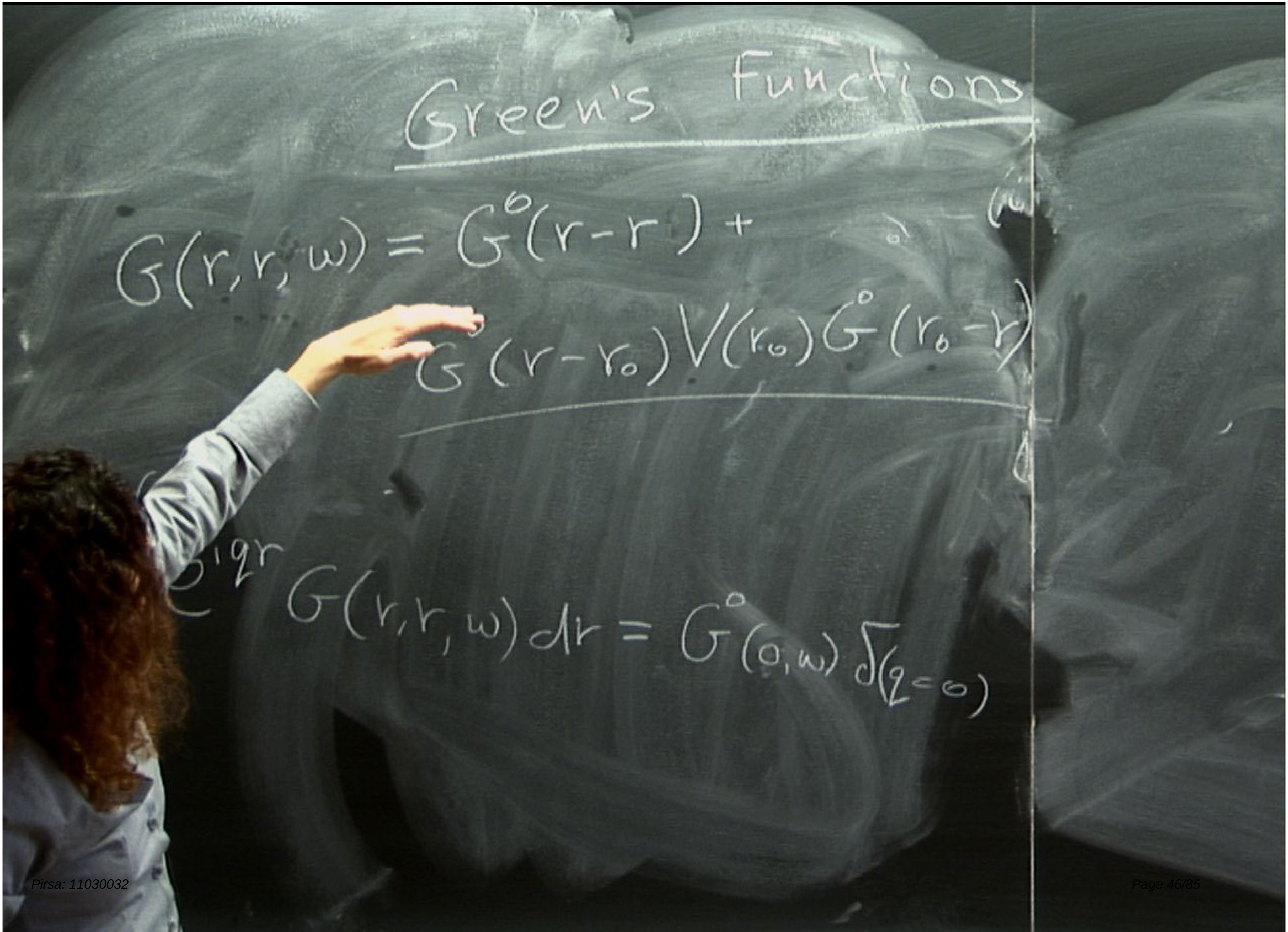

Green's Functions
G(r,r';ω) = G°(r−r') +
G°(r−r₀)V(r₀)
(r₀−r')

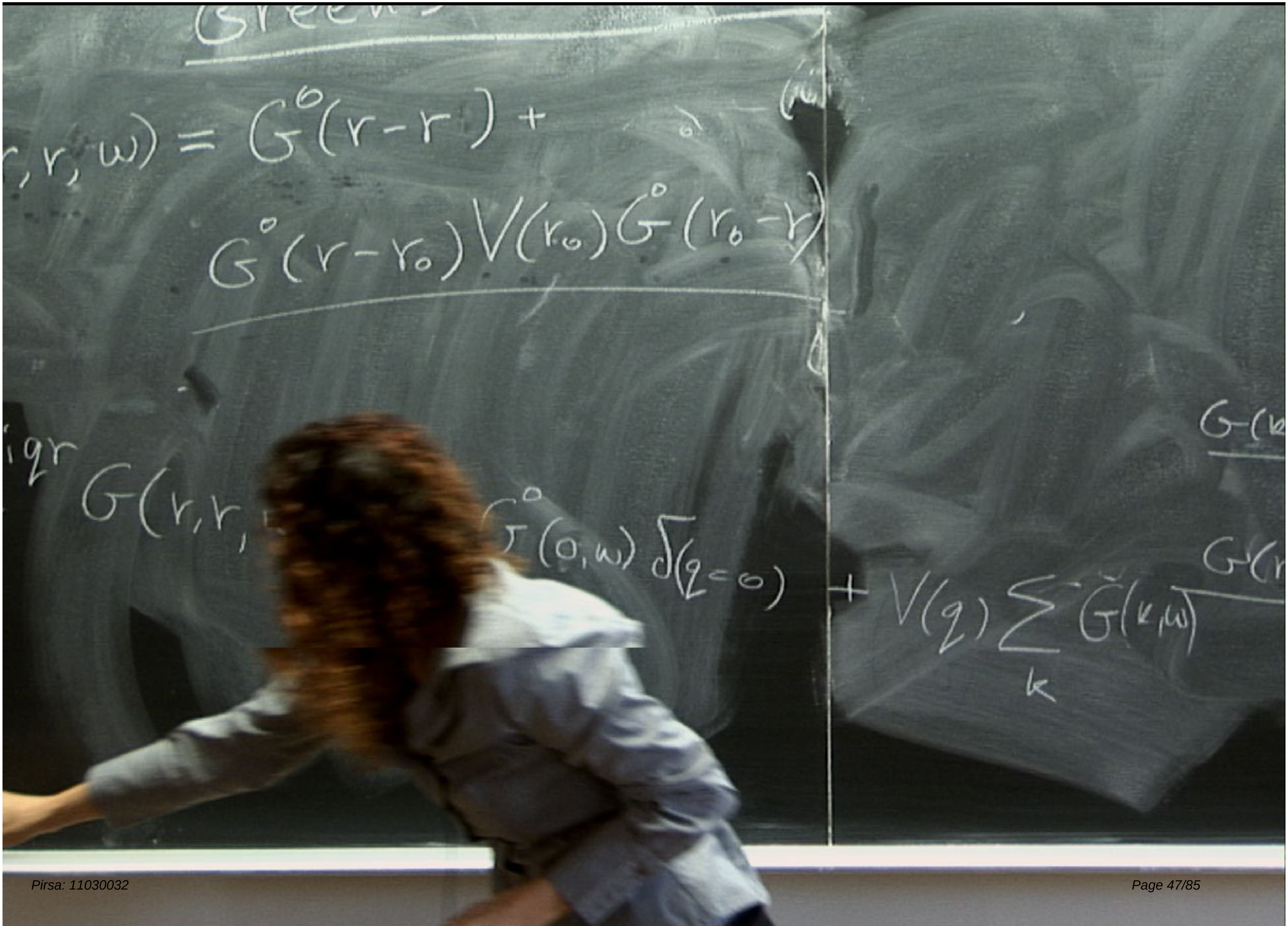
Green's Functions

$$G(r,r,\omega) = G^0(r-r) + G^0(r-r_0)\,V(r_0)\,G^0(r_0-r)$$

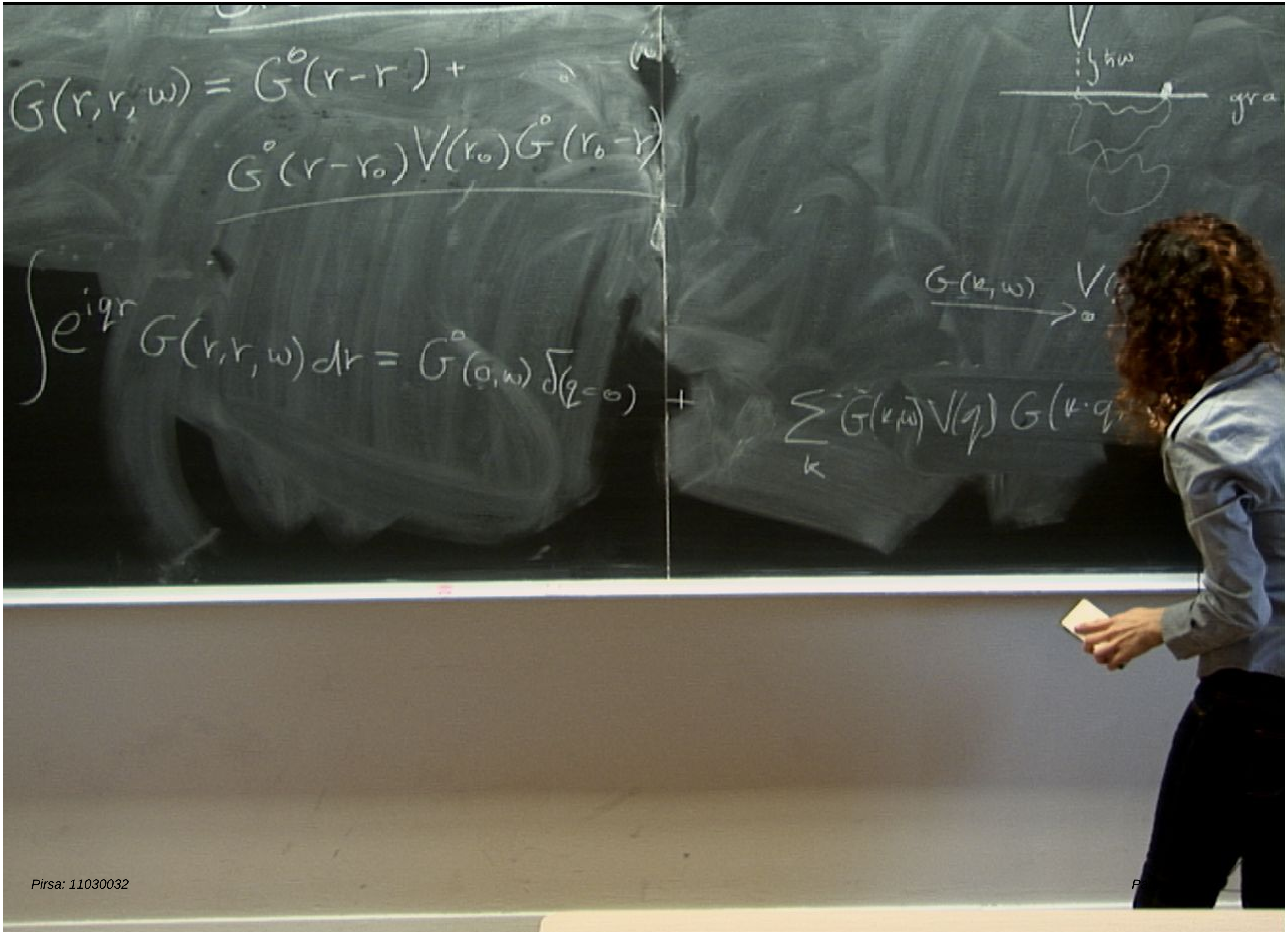

Green's Functions
G(r,r,ω) = G^0(r-r) +
G^0(r-r_0)V(r_0)G^0(r_0-r)
e^{iqr} G


Green's Functions
G(r,r',ω) = G°(r−r') +
G°(r−r₀)V(r₀)G°(r₀−r')
ω) dr

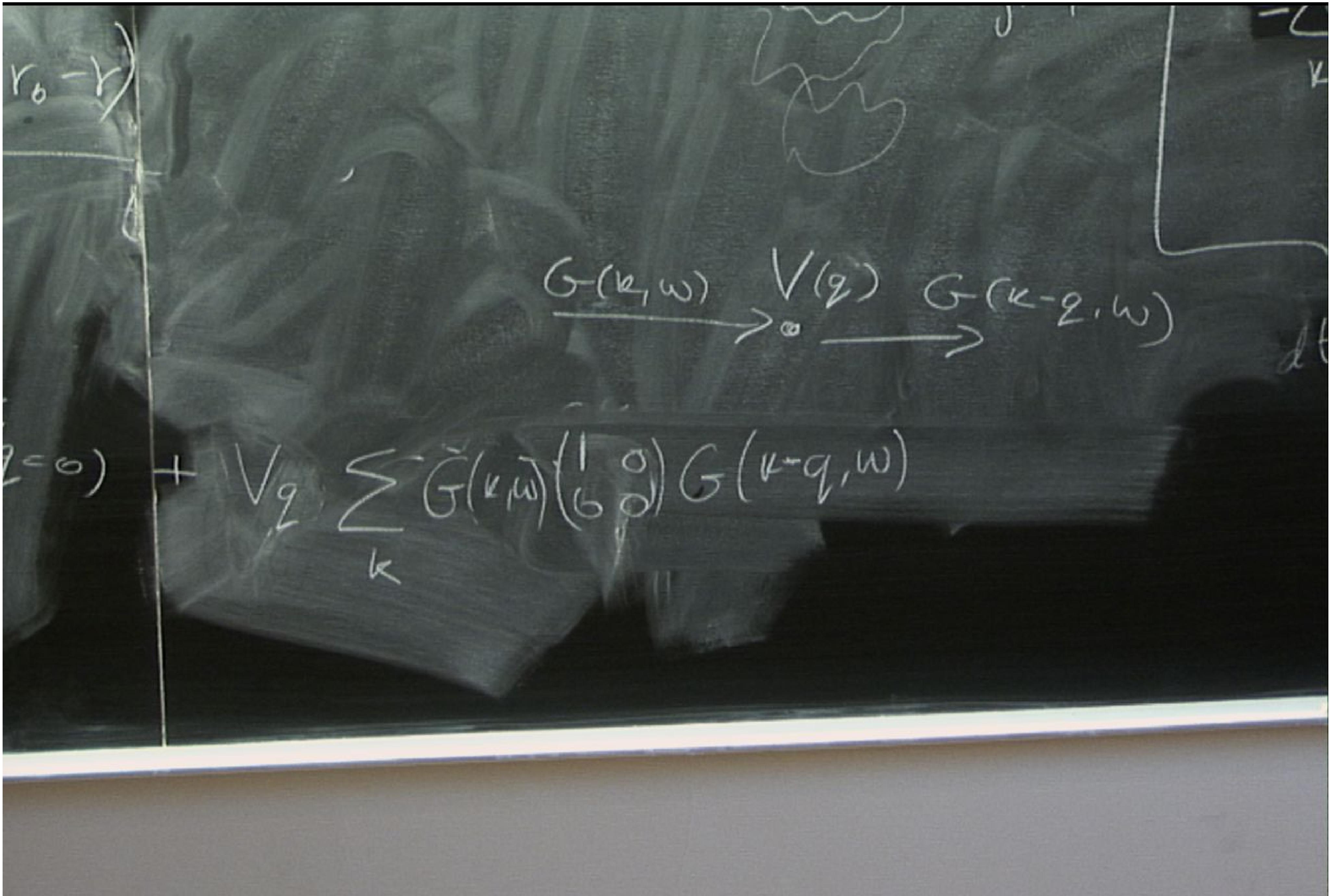

Green's Functions
G(r,r,ω) = G°(r-r) +
G(r-r₀)V(r₀)G°(r₀-r)
e^{iqr} G(r,r,ω) dr = G°(0,ω) δ(q=0)

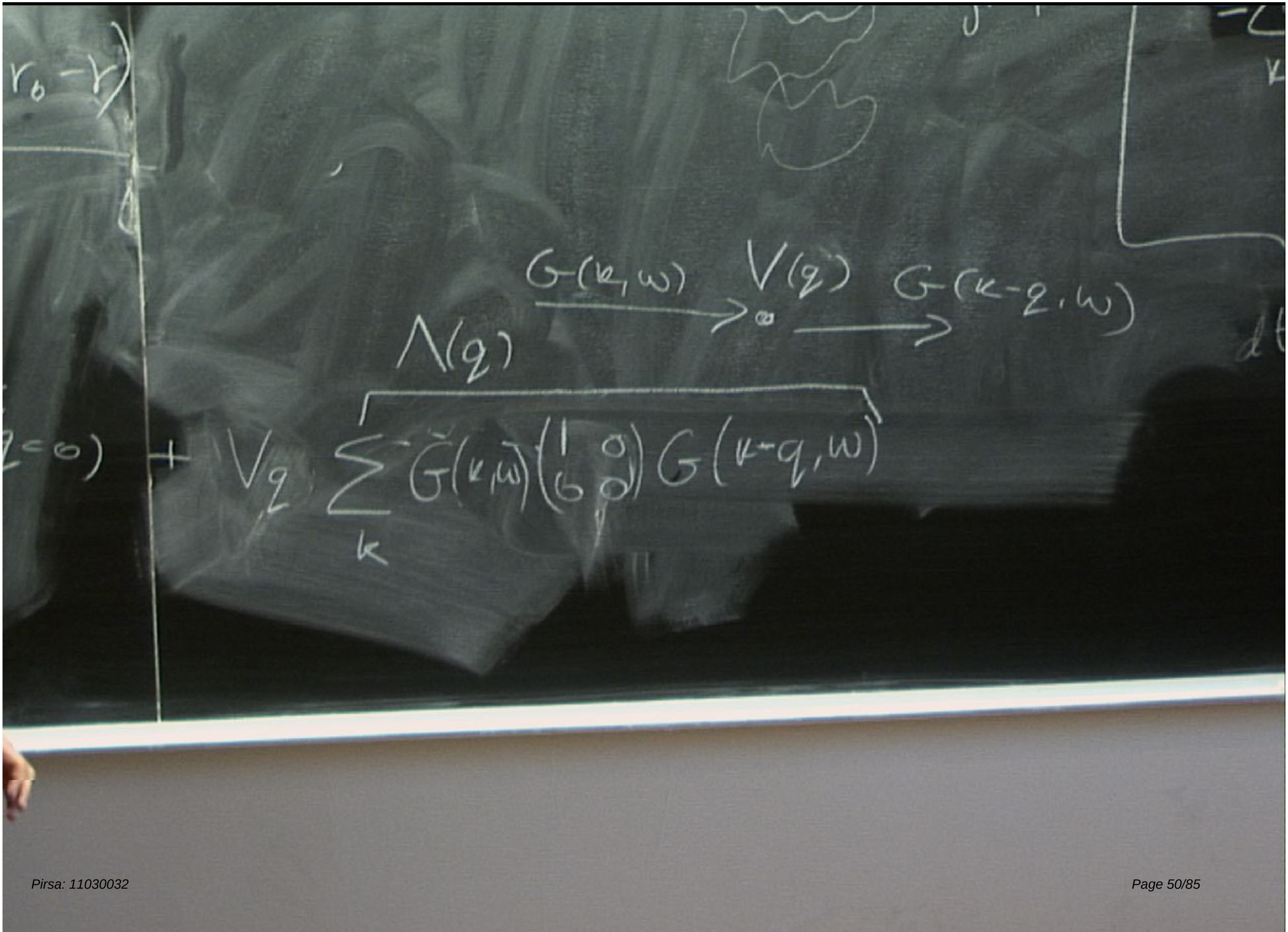


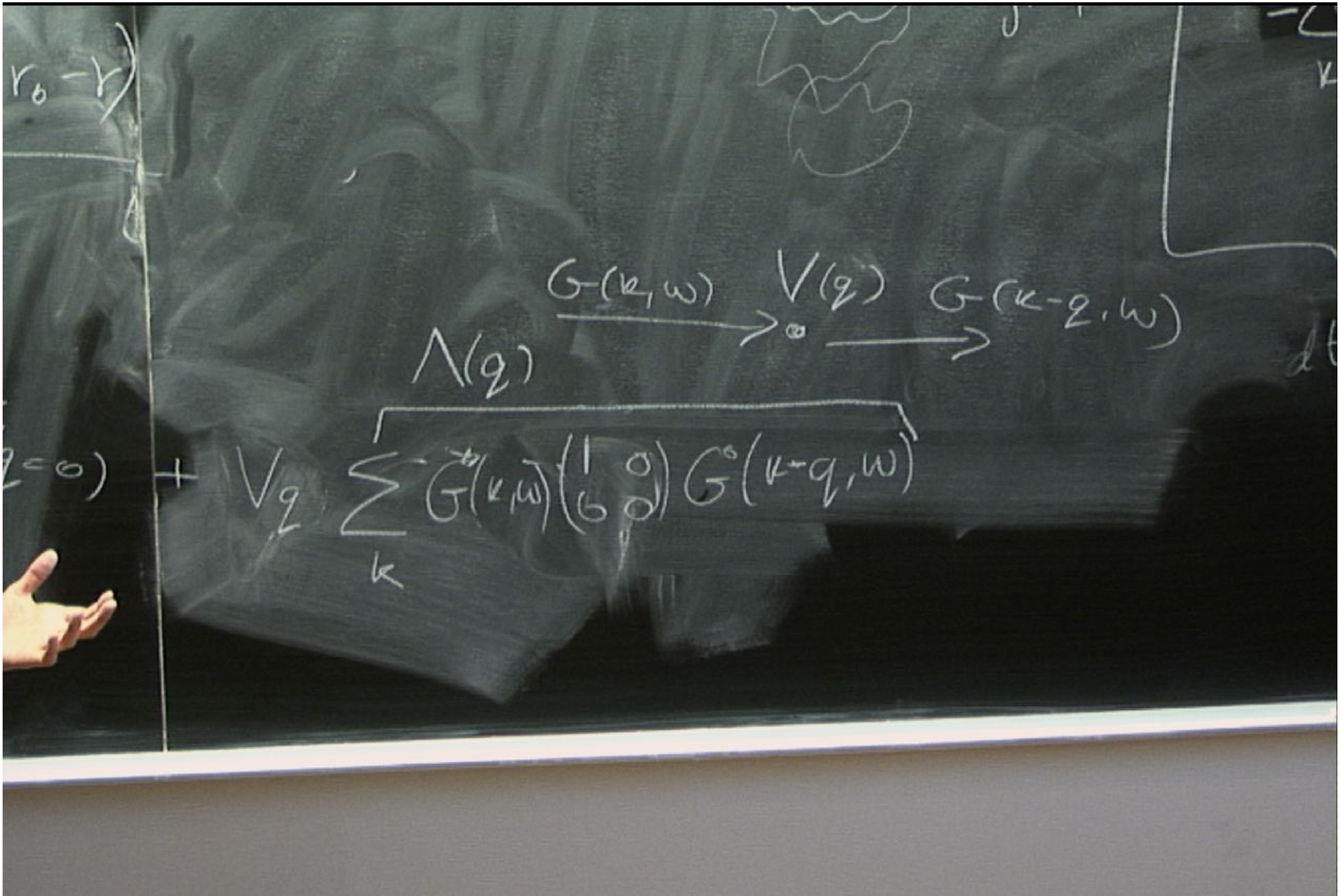
$= G^0(r-r) +$
$G^0(r-r_0)V(r_0)G^0(r_0-r)$
$G(r,r,$
$G^0(0,\omega)\,\delta(q=0)$
$+ V(q)\sum_k G(k,\omega)$

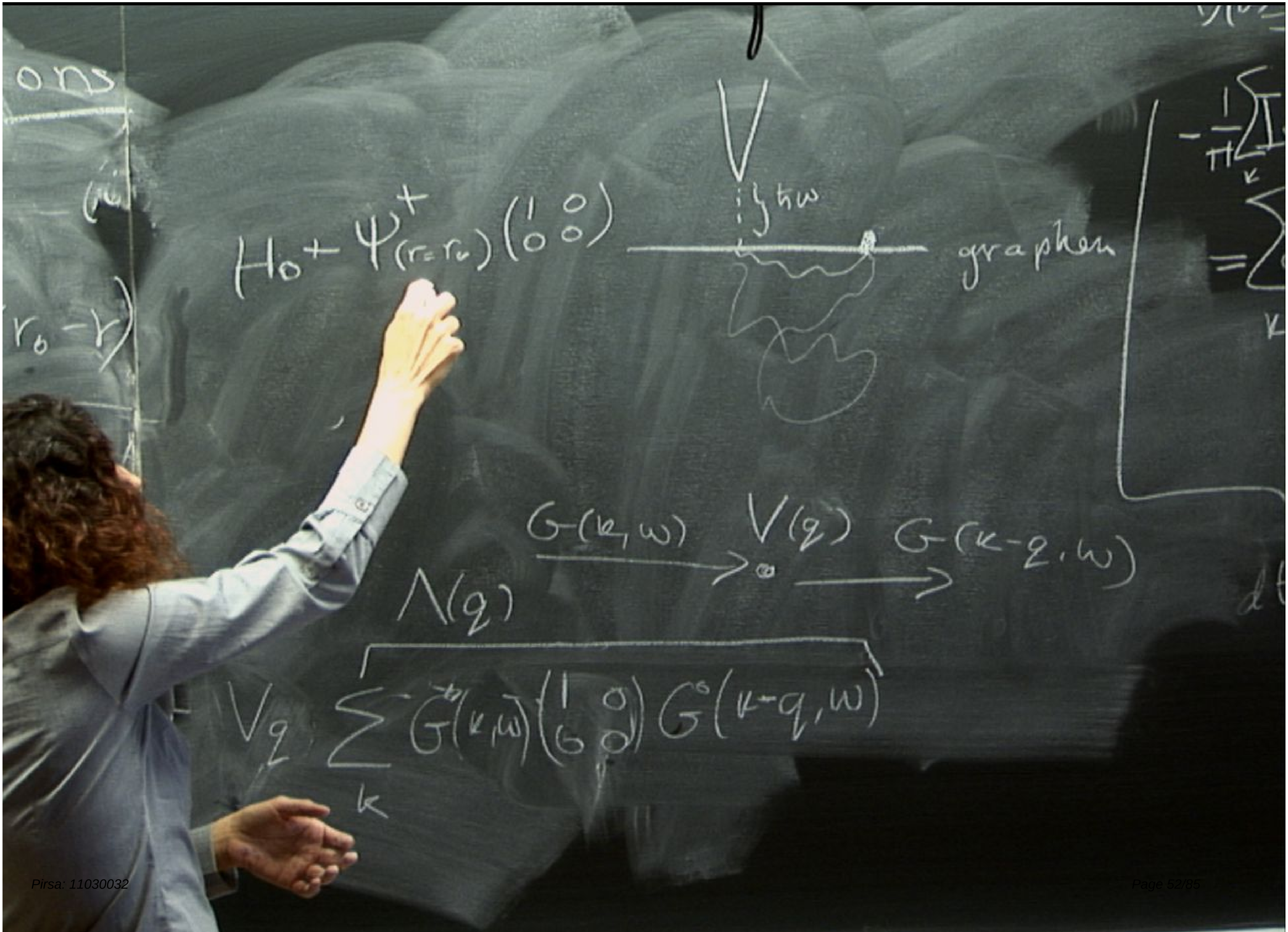


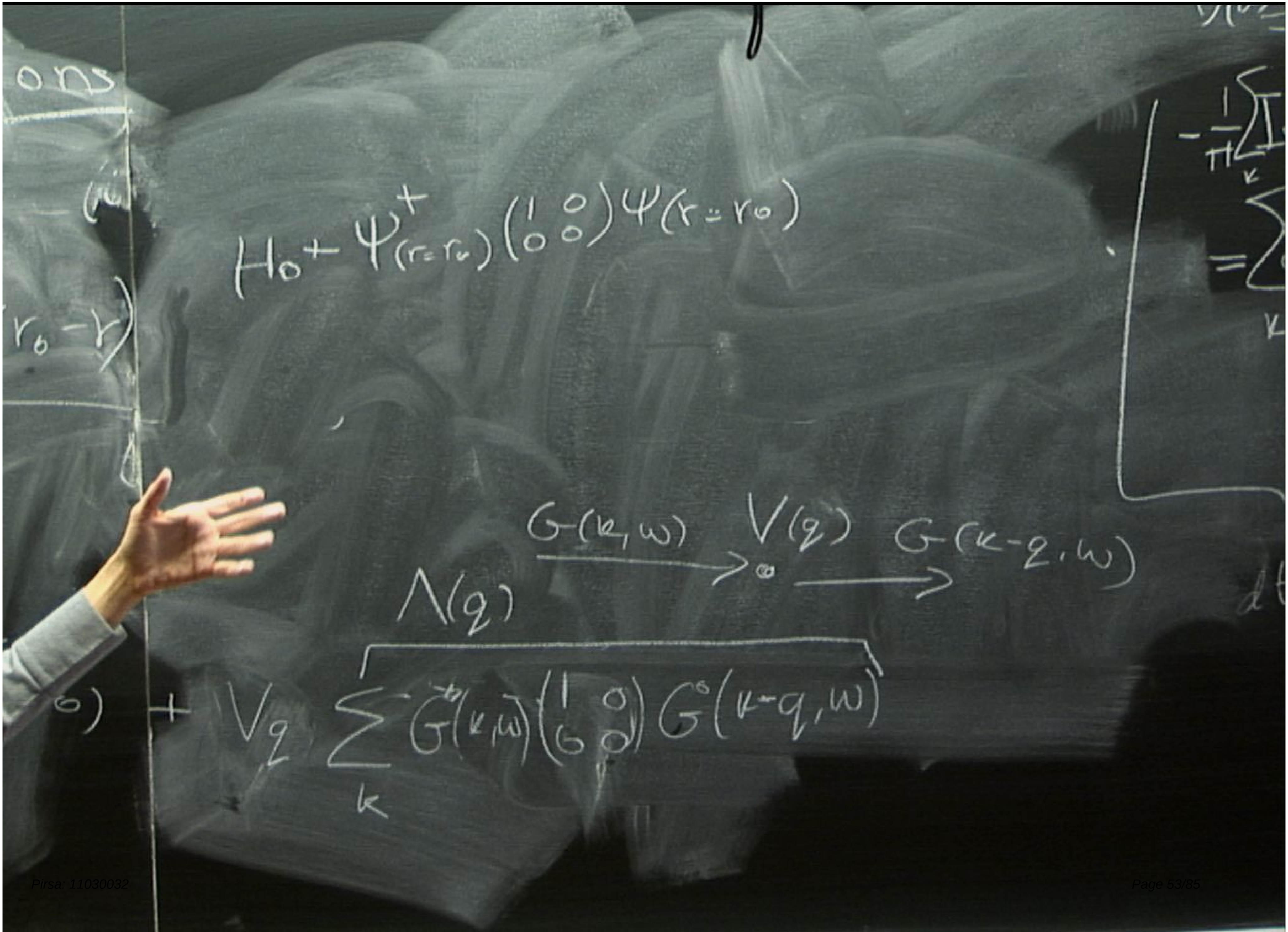
G(r,r,ω) = G°(r−r) +
G°(r−r₀)V(r₀)G°(r₀−r)
∫e^{iqr} G(r,r,ω) dr = G°(0,ω) δ(q=0) +
Σ_k G(k,ω)V(q) G(k·q
G(k,ω)
V(
ħω
gra

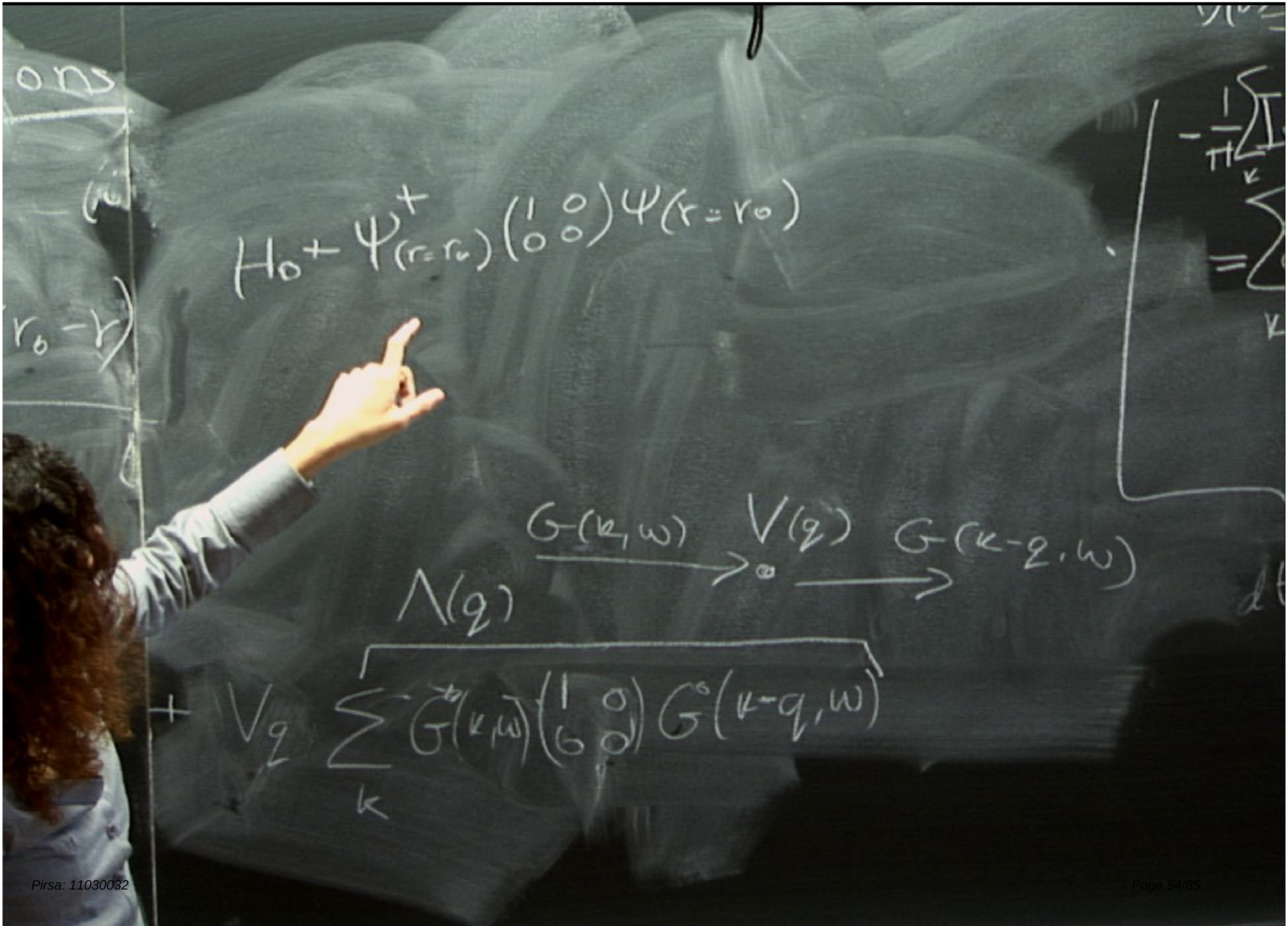

r₀ − r
G(k,ω) V(q) G(k−q,ω)
+ V_q Σ_k G̃(k,ω) (1 0 / 0 0) G(k−q,ω)

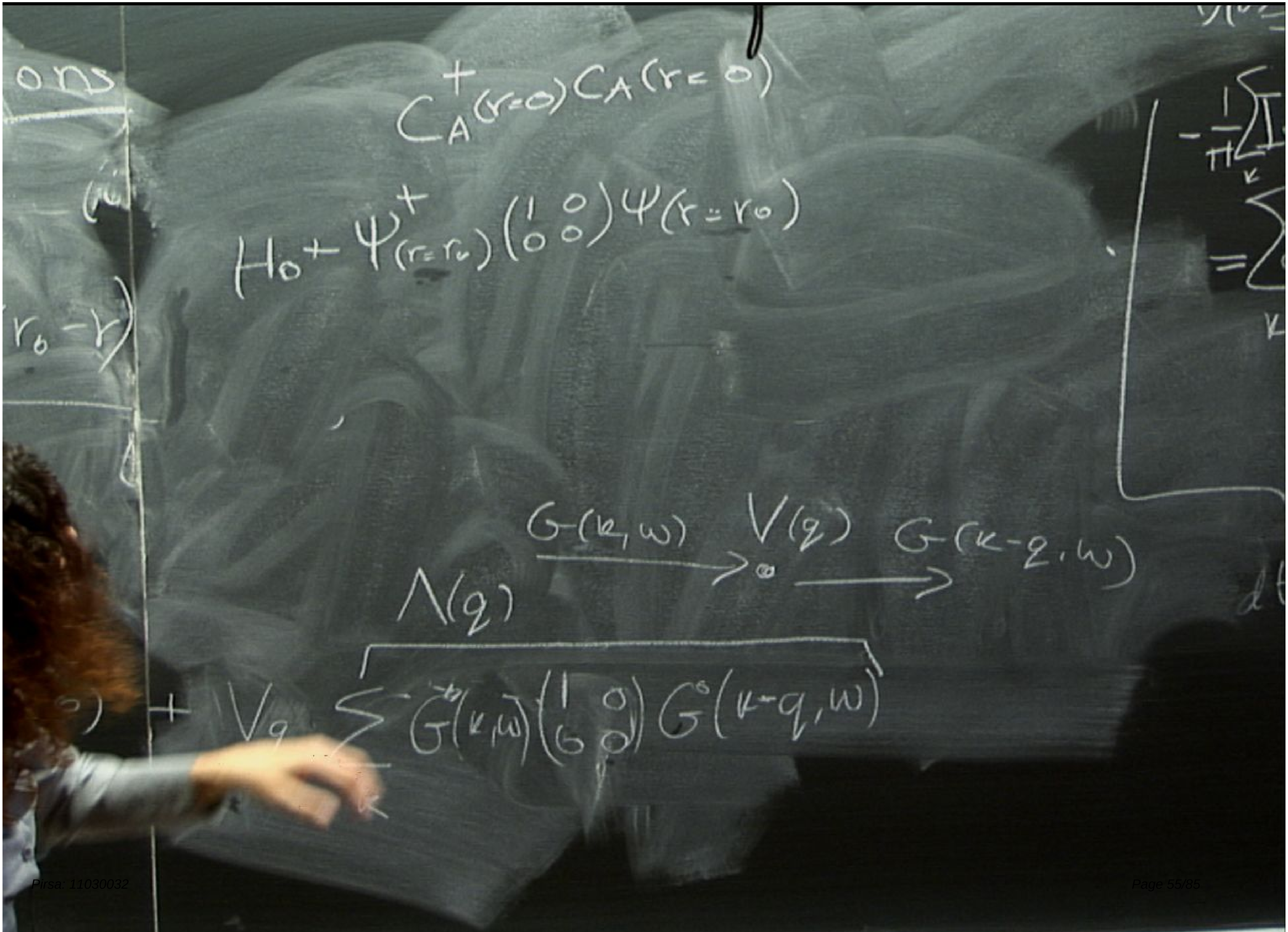

G(k,ω) V(q) G(k-q,ω)
Λ(q)
+ V_q Σ_k G̃(k,ω) (1 0 / 0 0) G(k-q,ω)


G(k,ω)
V(q)
G(k-q,ω)
Λ(q)
+ V_q Σ_k G(k,ω) (1 0; 0 0) G°(k-q,ω)


H0 + ψ+(r=r0) (1 0 / 0 0)
V
graphen
G(k,ω)
V(q)
G(k-q,ω)
Λ(q)
Vq Σk G(k,ω) (1 0 / 0 0) G°(k-q,ω)


ons
$H_0 + \psi^{+}_{(r=r_0)} \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix} \psi(r=r_0)$
$r_0 - r)$
$G(k,\omega)$
$V(q)$
$G(k-q,\omega)$
$\Lambda(q)$
$+ V_q \sum_k G(k,\omega) \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix} G^0(k-q,\omega)$


H0 + ψ+(r=r0) (1 0 / 0 0) ψ(r=r0)
G(k,ω) V(q) G(k−q,ω)
Λ(q)
+ Vq Σk G(k,ω) (1 0 / 0 0) G0(k−q,ω)



$C_A^\dagger(r=0)C_A(r=0)$
$H_0 + \psi^\dagger_{(r=r_0)}\begin{pmatrix}1&0\\0&0\end{pmatrix}\psi(r=r_0)$
$G(k,\omega)$ $V(q)$ $G(k-q,\omega)$
$\Lambda(q)$
$+ V_q \sum \vec{G}(k,\omega)\begin{pmatrix}1&0\\0&0\end{pmatrix}G^0(k-q,\omega)$

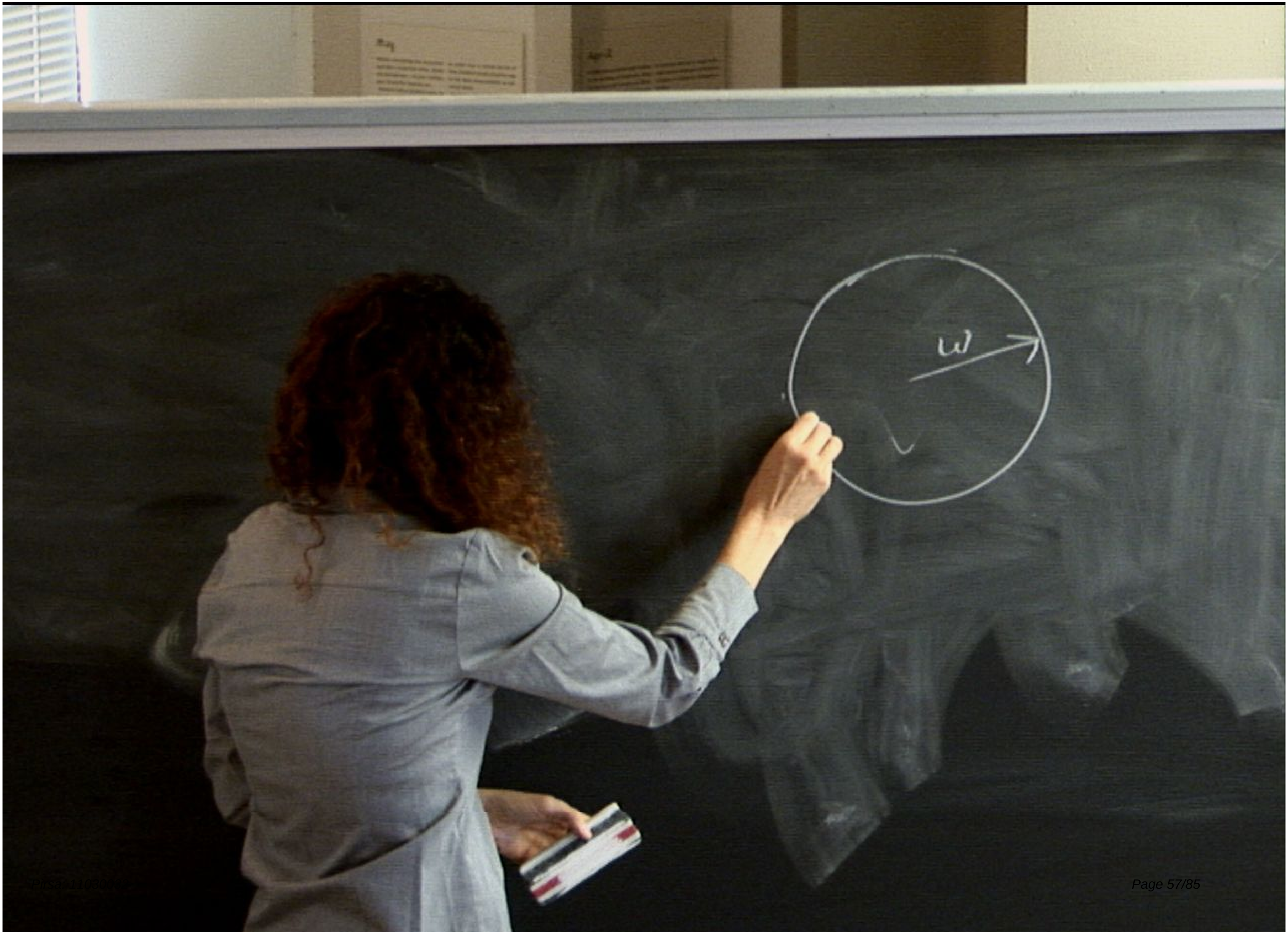
$C_A^\dagger(r=0)\,C_A(r=0)$

$H_0 + \psi^\dagger_{(r=r_0)} \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix} \psi(r=r_0)$

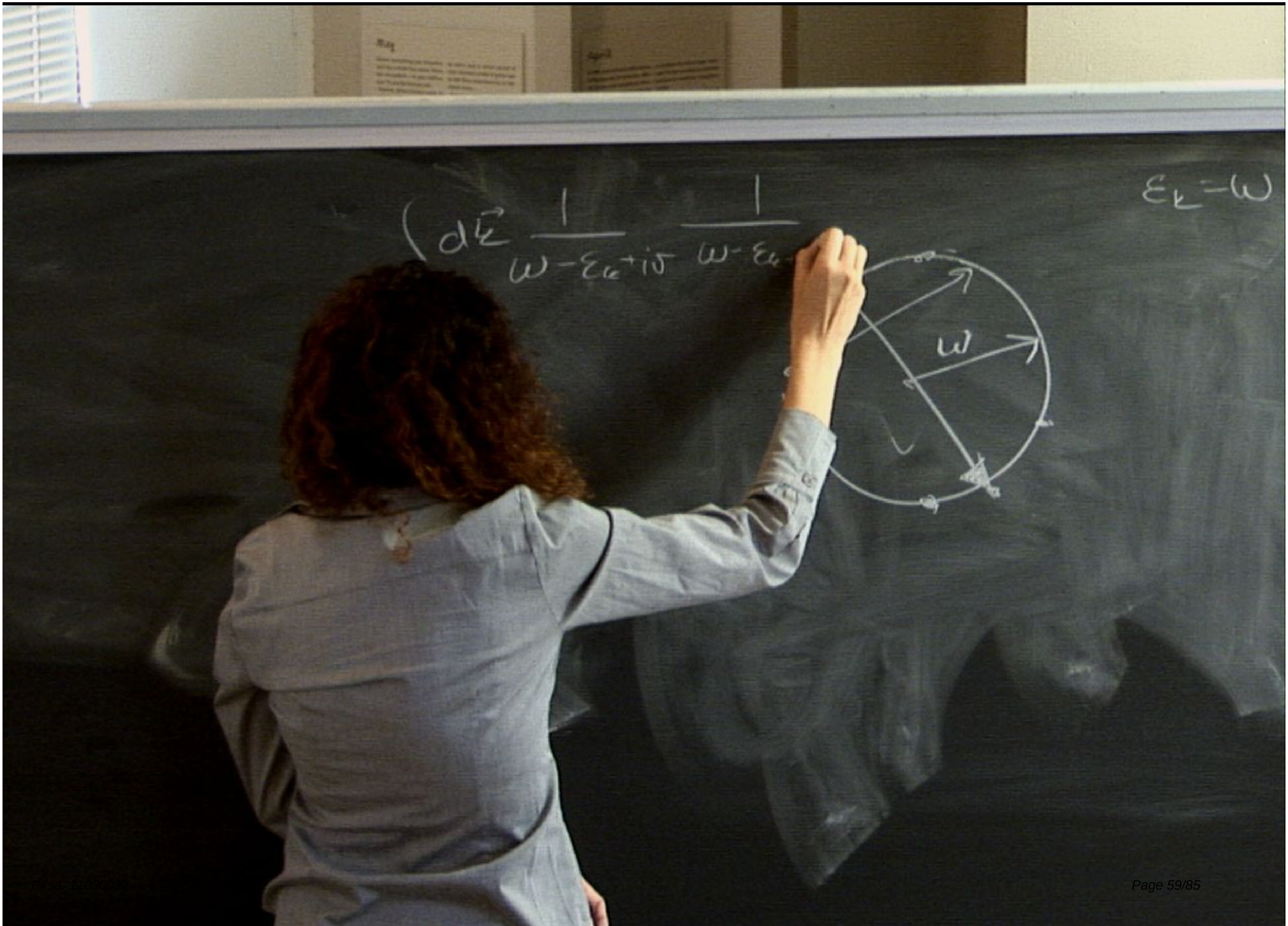
$G(k,\omega) \quad V(q) \quad G(k-q,\omega)$

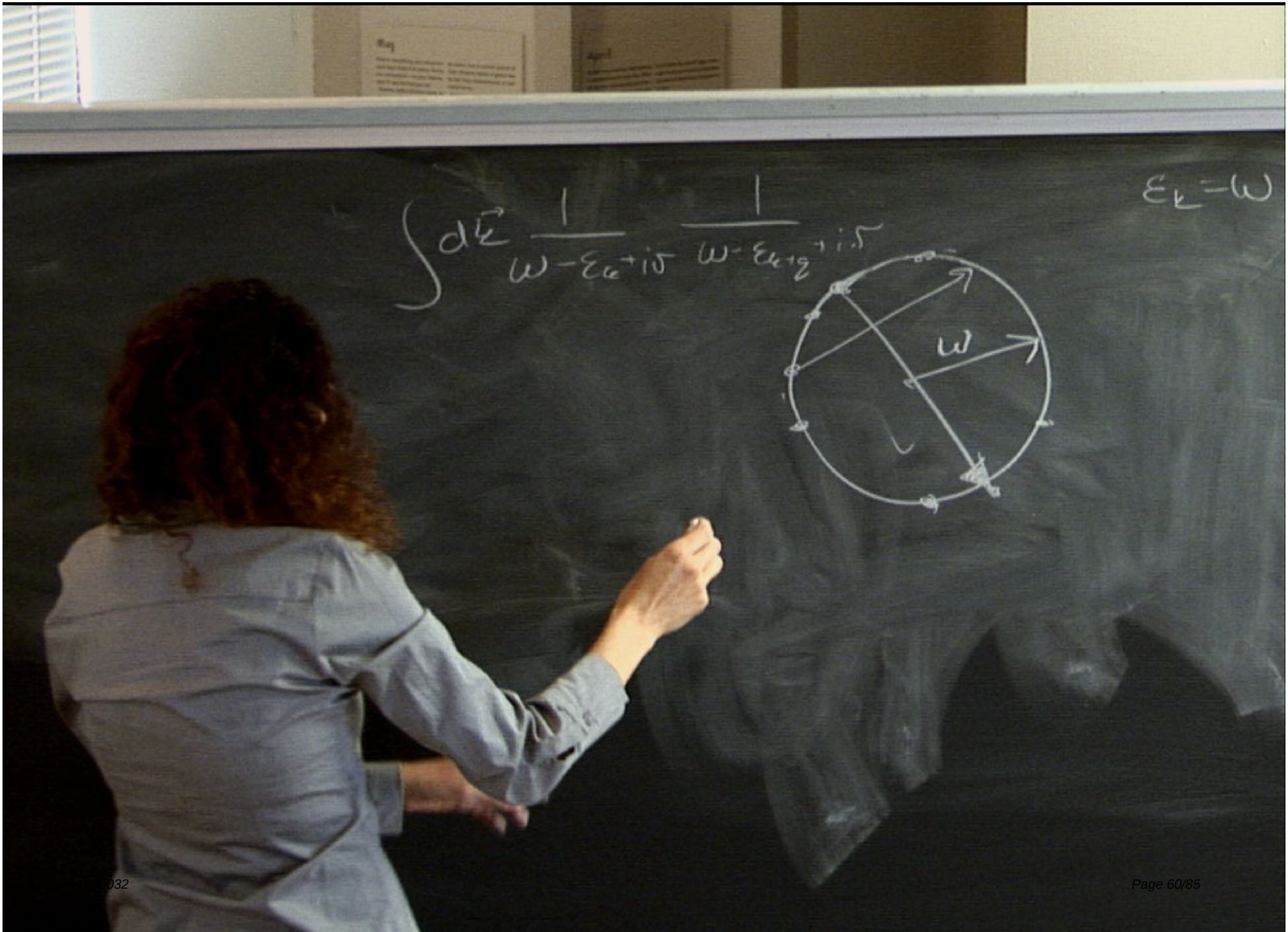
$\Lambda(q)$

$+\; V_q \sum_k \vec{G}(k,\omega) \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix} G^0(k-q,\omega)$

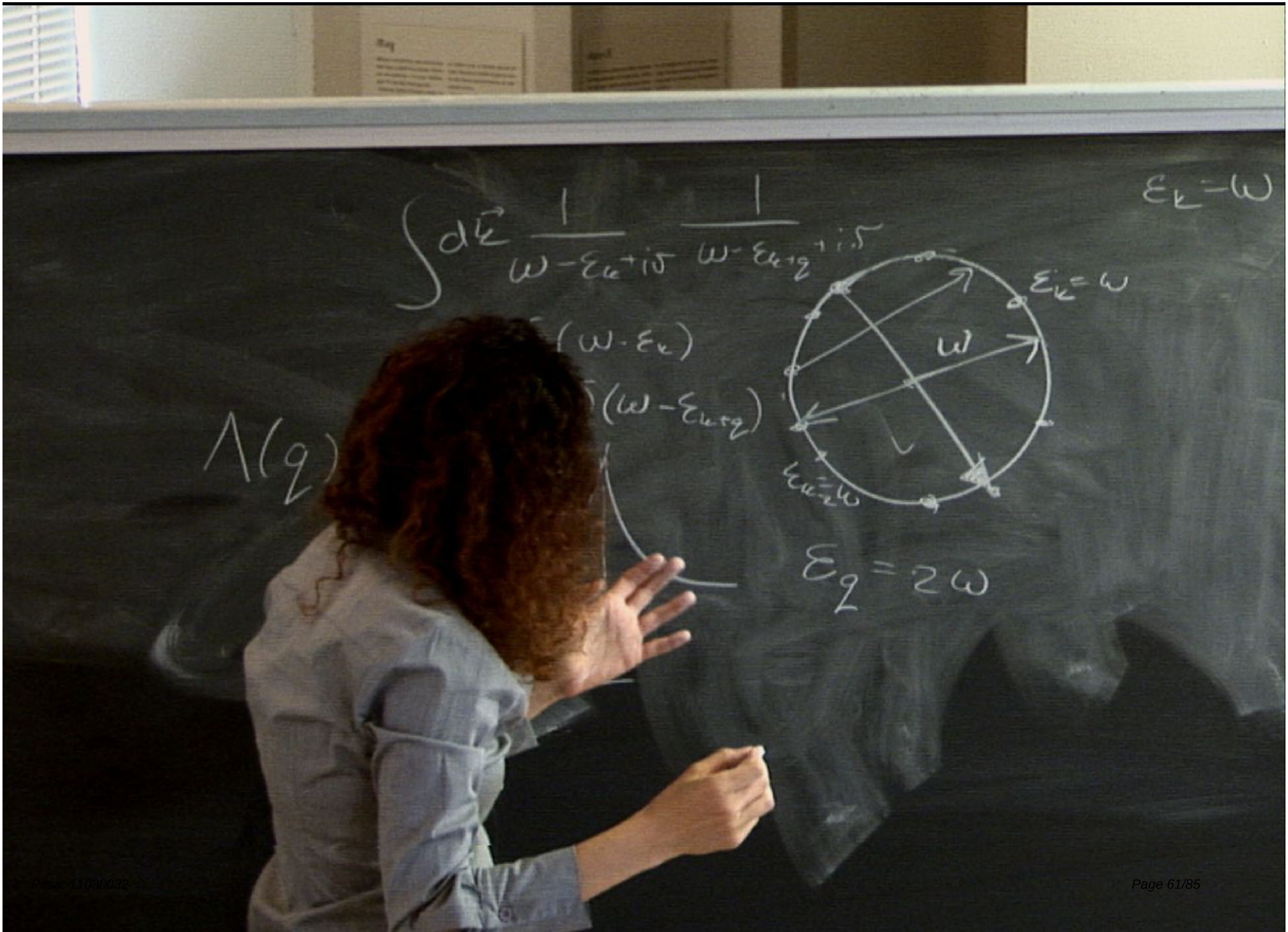

ω

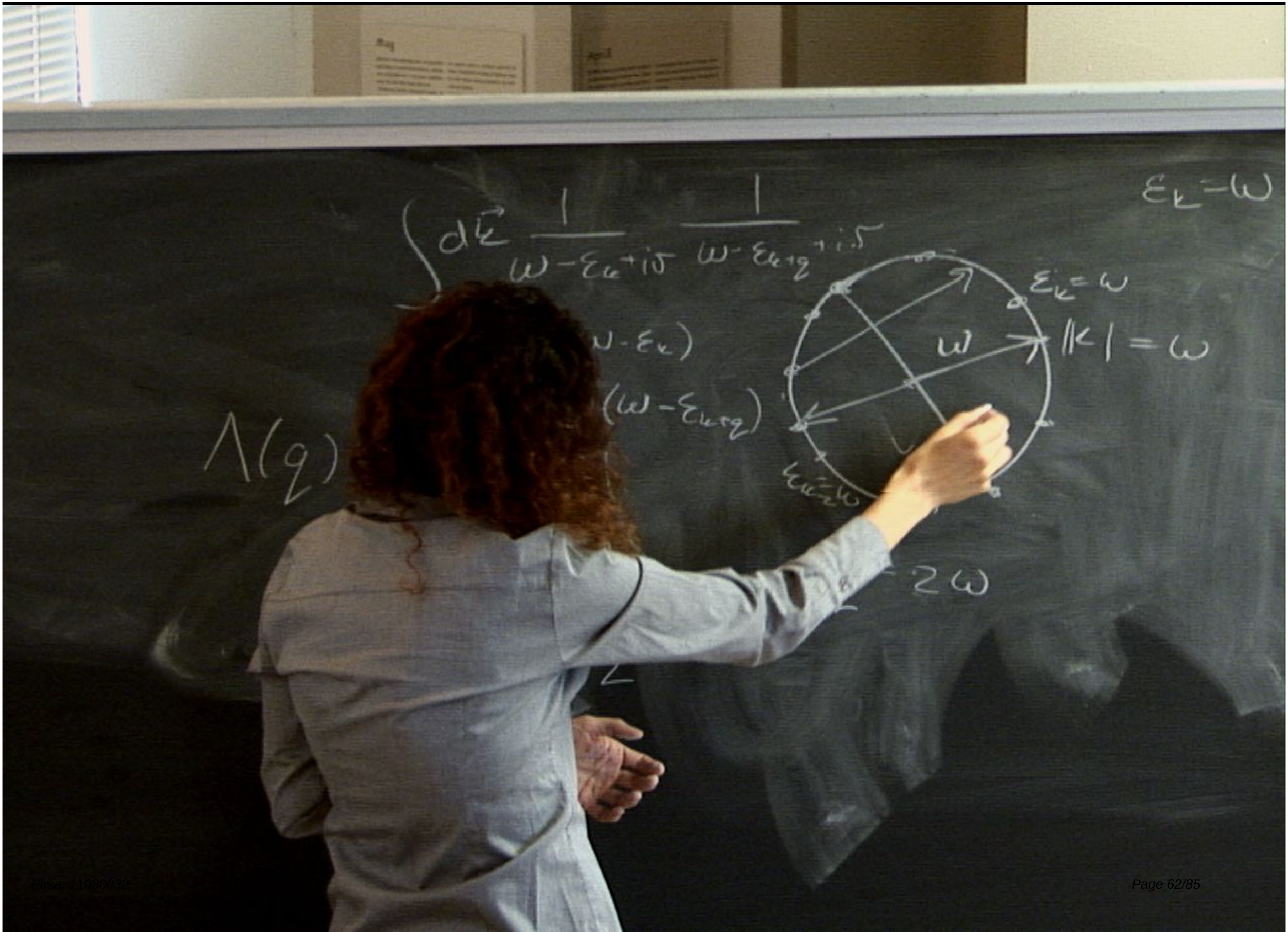

$\varepsilon_k = -\omega$
ω


$\varepsilon_k = -\omega$
ω

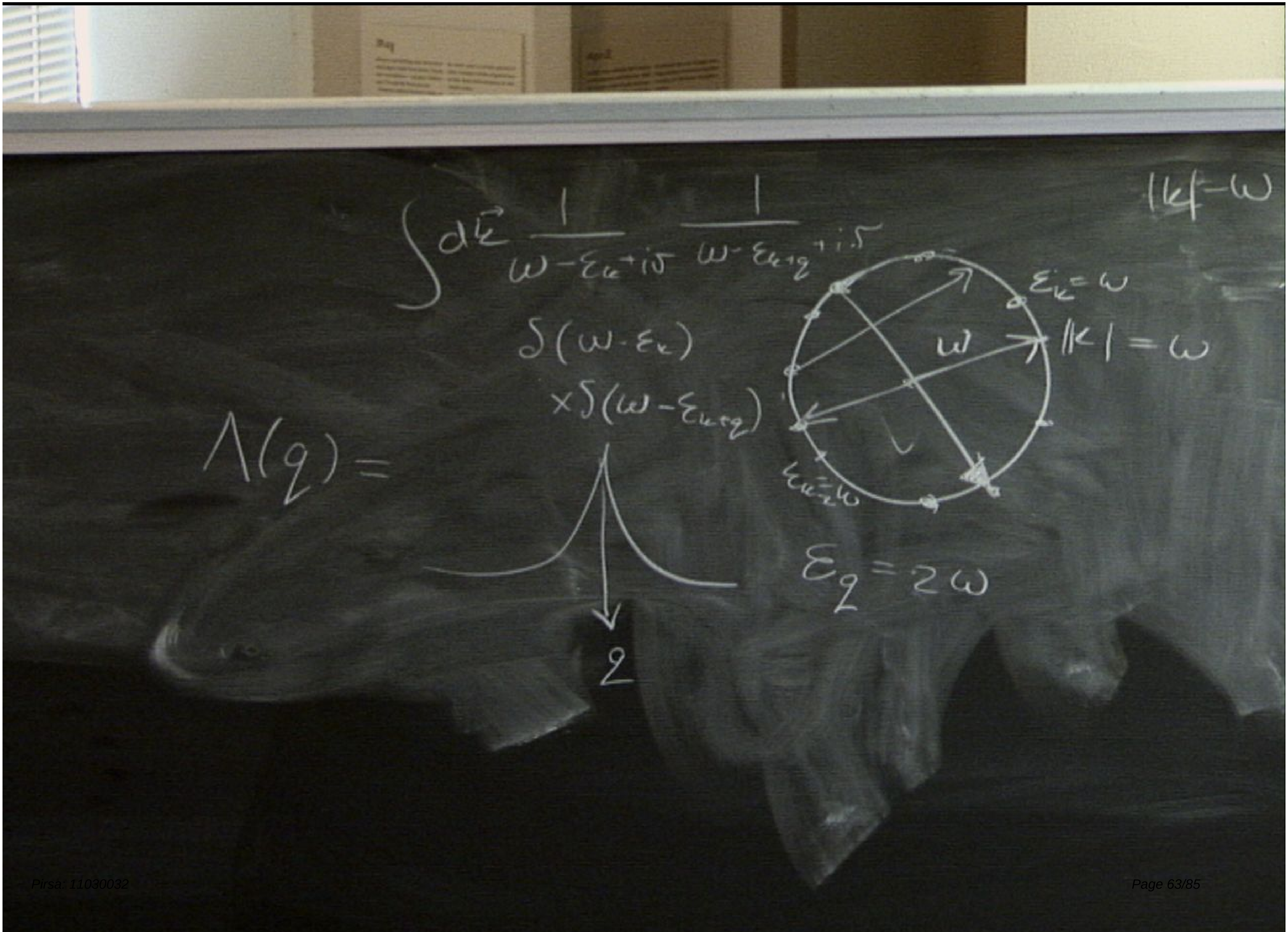


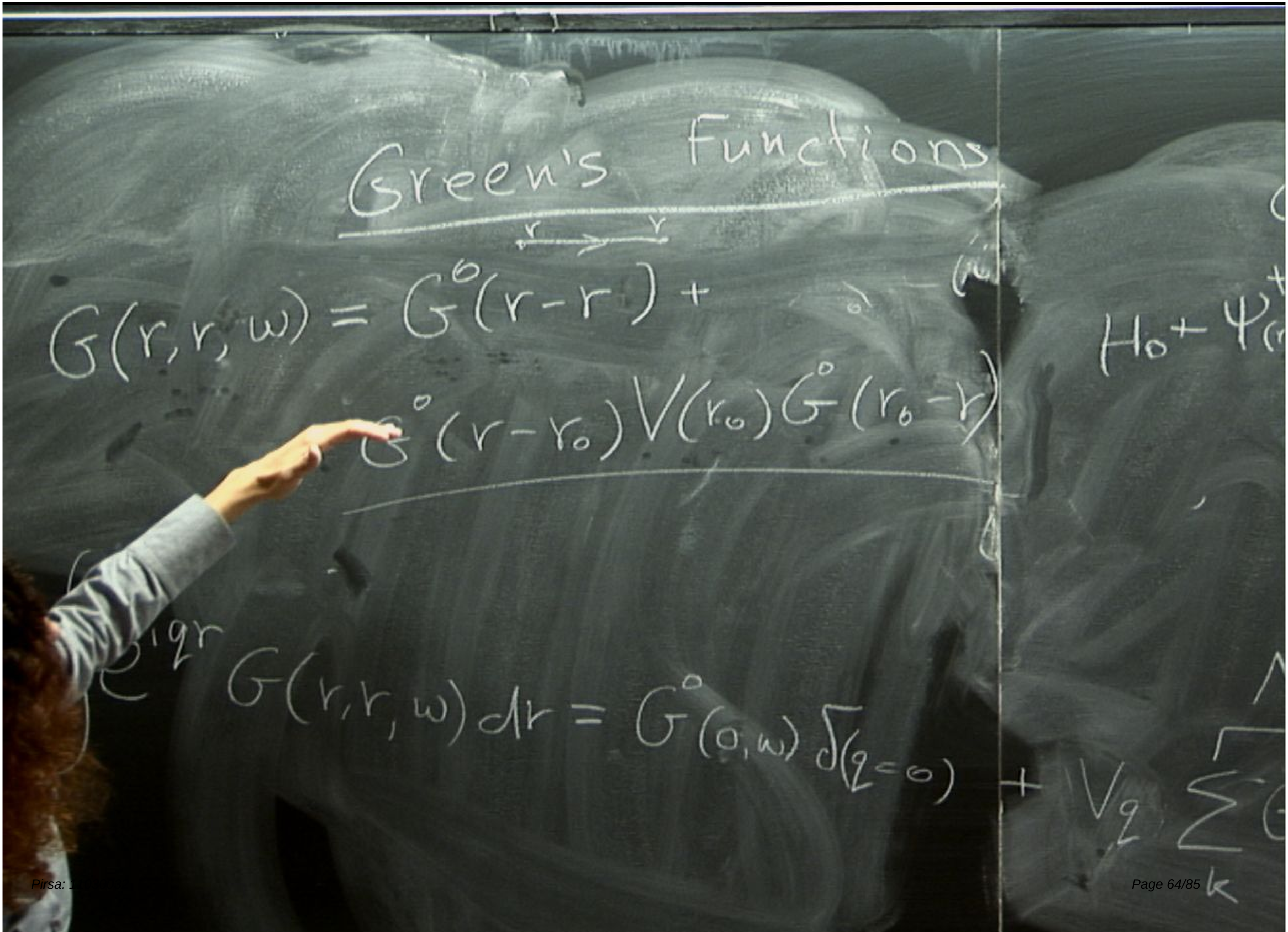
$\int d\vec{k} \frac{1}{\omega - \varepsilon_k + i\delta} \frac{1}{\omega - \varepsilon_{k+q} + i\delta}$
$\varepsilon_k = -\omega$
ω

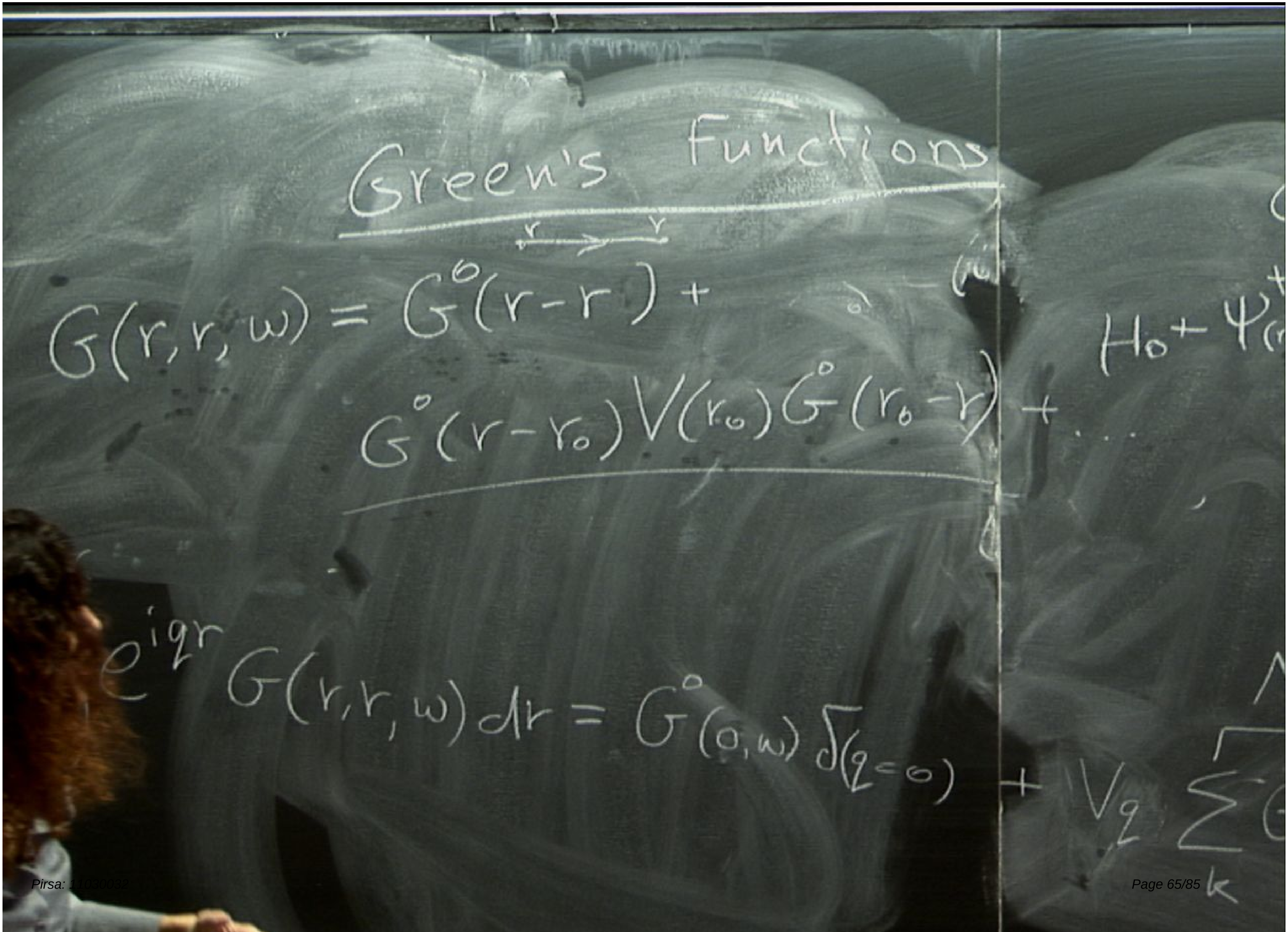

Ek = -ω
Ek = ω
ω
Λ(q)
Eq = 2ω



$\int d\vec{k} \frac{1}{\omega - \varepsilon_k + i\delta} \frac{1}{\omega - \varepsilon_{k+q} + i\delta}$
$\varepsilon_k = -\omega$
$\varepsilon_k = \omega$
$|k| = \omega$
ω
$(\omega - \varepsilon_{k+q})$
$\Lambda(q)$
2ω


|k|=ω
∫dk 1/(ω−ε_k+iδ) 1/(ω−ε_{k+q}+iδ)
δ(ω−ε_k)
×δ(ω−ε_{k+q})
Λ(q) =
ε_k=ω
|k|=ω
ω
ε_q=2ω
q


Green's Functions
G(r,r,ω) = G⁰(r−r) +
G⁰(r−r₀)V(r₀)G⁰(r₀−r)
e^{iqr} G(r,r,ω)dr = G⁰(0,ω) δ(q=0) + V_q Σ_k
H₀ + Ψ

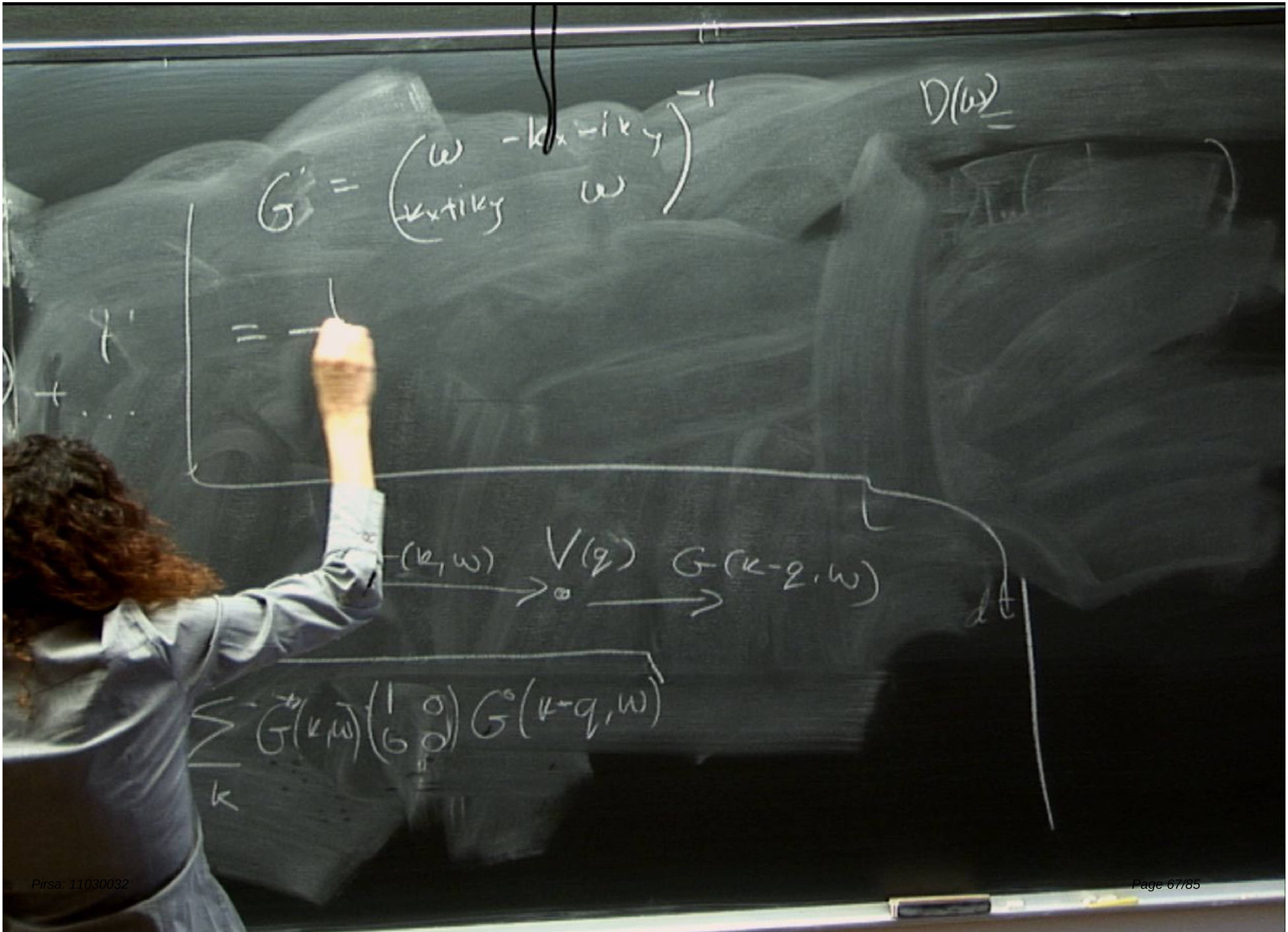

Green's Functions
G(r,r,ω) = G°(r−r) +
G°(r−r₀)V(r₀)G°(r₀−r) + . . .
H₀+Ψ
e^{iqr} G(r,r,ω) dr = G°(0,ω) δ(q=0) + V_q Σ_k

Green's Functions

$$G(r,r,\omega) = G^0(r-r) + G^0(r-r_0)\,V(r_0)\,G^0(r_0-r) + \dots$$

$$\int e^{iqr}\, G(r,r,\omega)\, dr = G^0(0,\omega)\,\delta(q=0) + V_q \sum_k G \dots$$

$H_0 + \Psi \dots$


D(ω)
V(q)
G(k-q, ω)
k

$D(\omega) =$

$$G^{-1} = \begin{pmatrix} i\omega & -k_x - ik_y \\ k_x + ik_y & i\omega \end{pmatrix}^{-1}$$

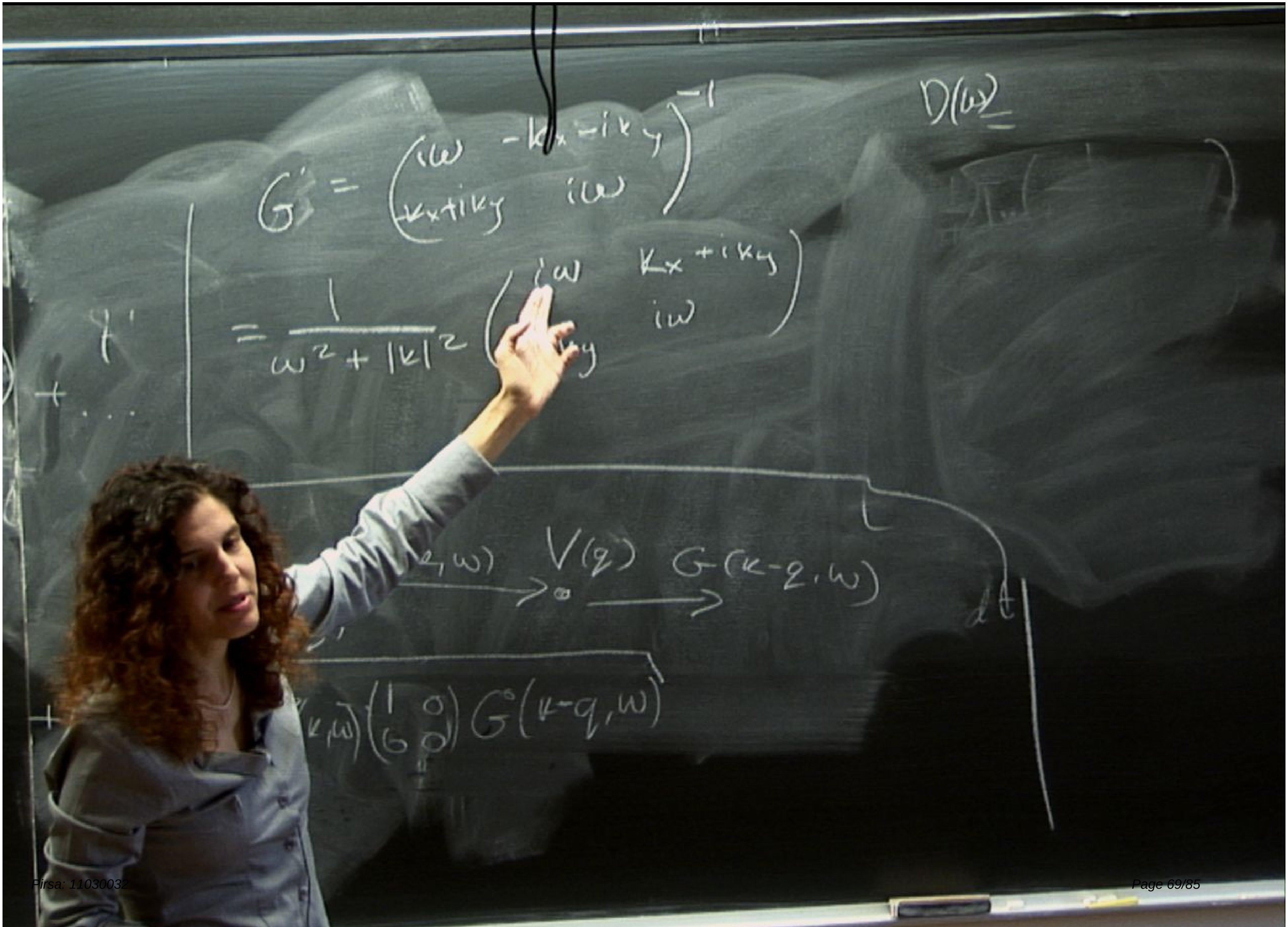
$$= \frac{1}{\omega^2 + |k|^2} \begin{pmatrix} i\omega & k_x + ik_y \\ k_x - ik_y & i\omega \end{pmatrix}$$

$$G(k,\omega) \quad V(q) \quad G(k-q,\omega)$$

$$\Lambda(q)$$

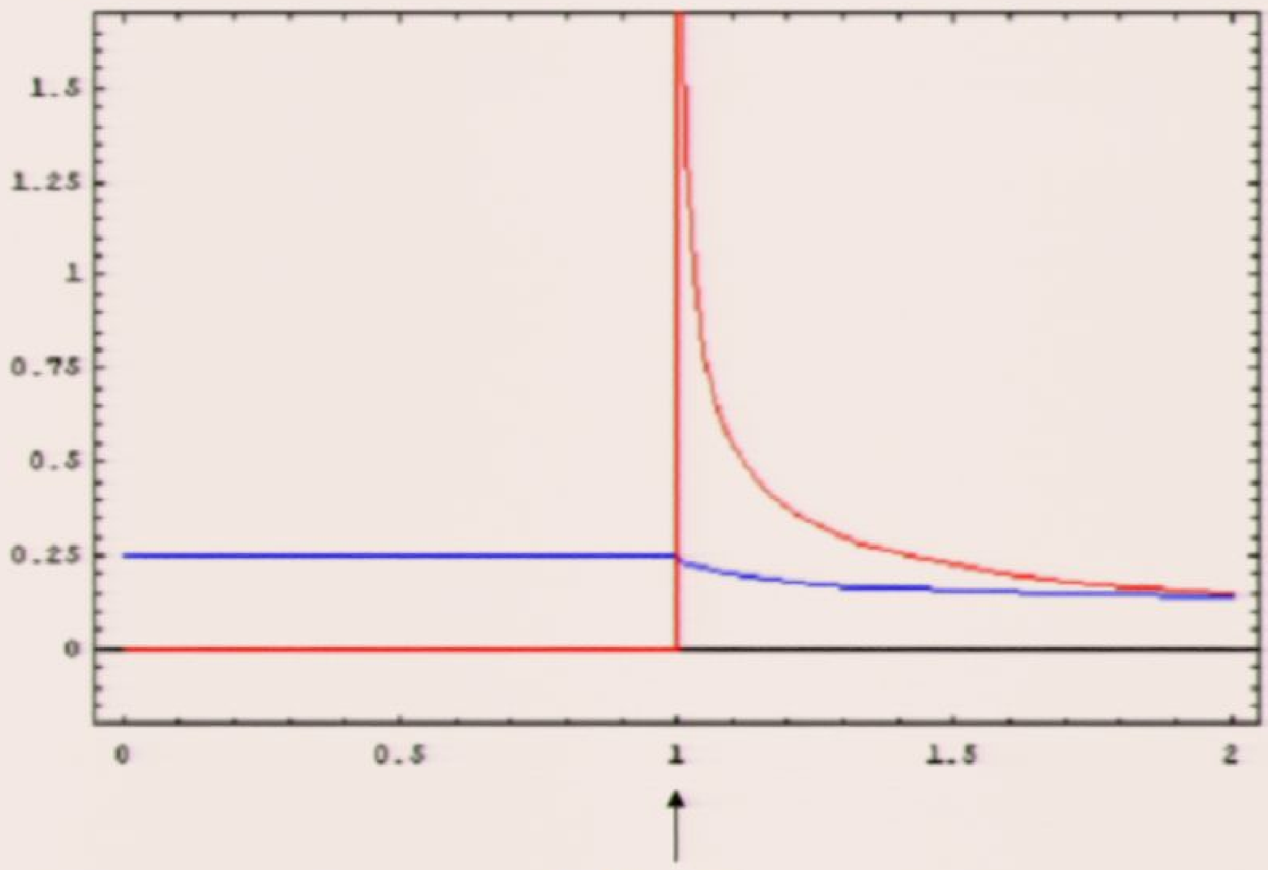
$$+ \; V_q \sum_k G^0(k,\omega) \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix} G^0(k-q,\omega)$$

dt


D(ω)
V(q)
G(k-q,ω)

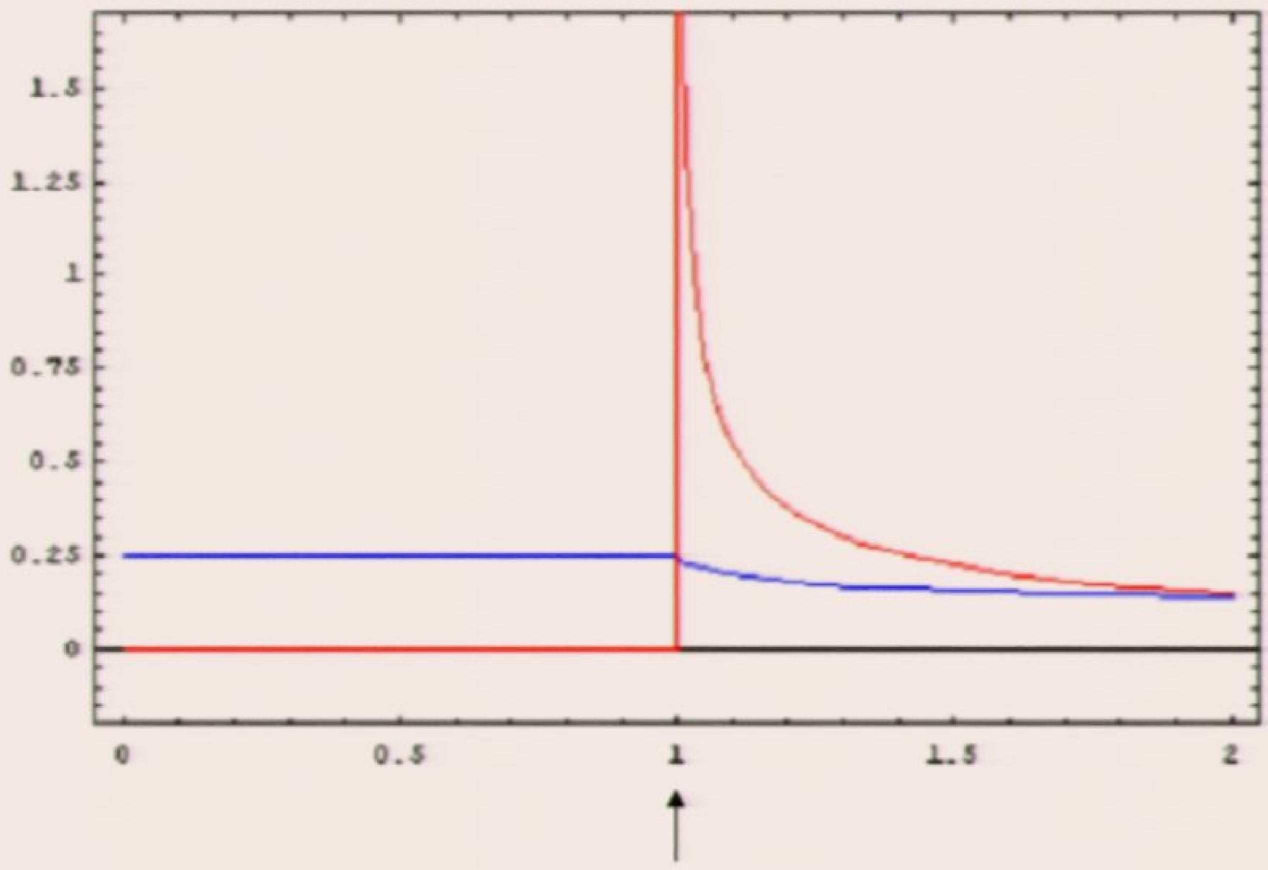
Same valley scattering Analytic results

LDOS = non-chiral ,
chiral



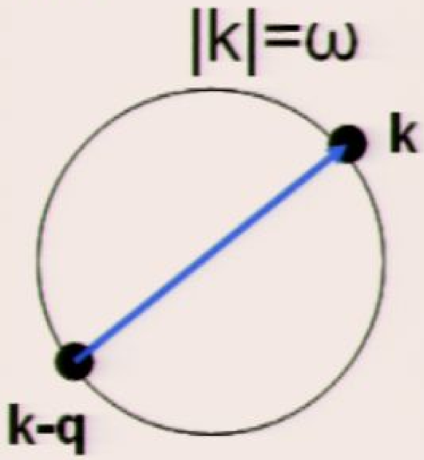
Same valley scattering Analytic results

LDOS = non-chiral ,
chiral



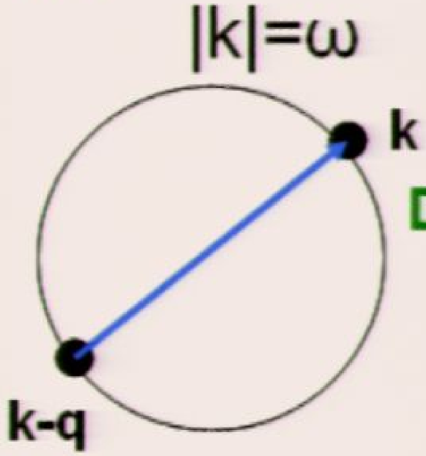
Heuristic Picture
Intra-valley scattering

E(k) near the valley



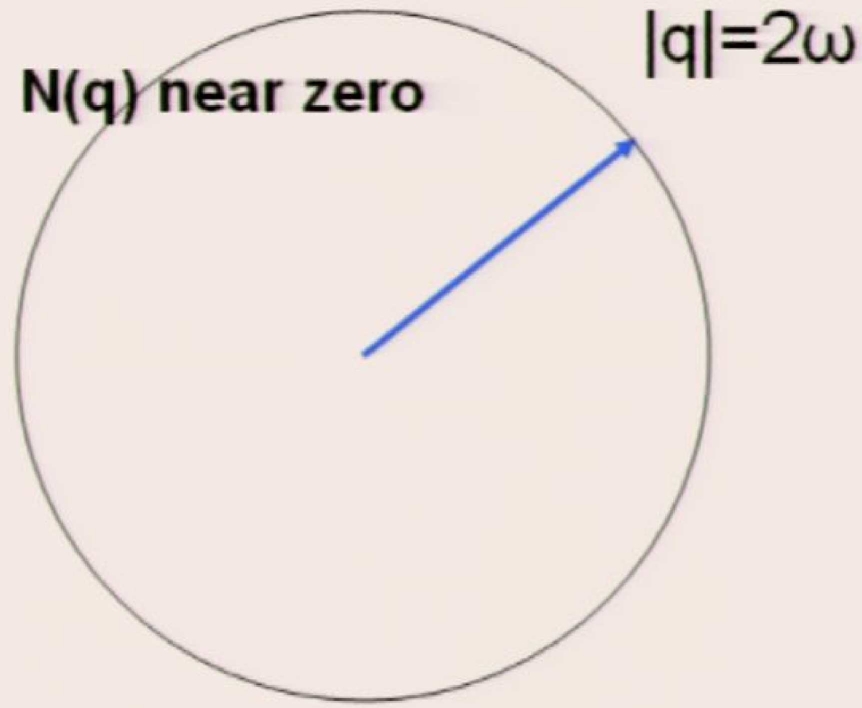
Heuristic Picture
Intra-valley scattering

E(k) near the valley



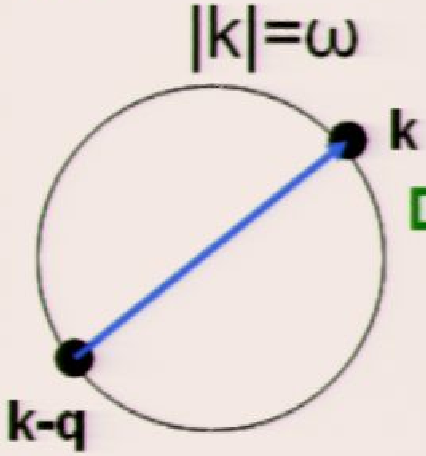
Dominant process

N(q) near zero



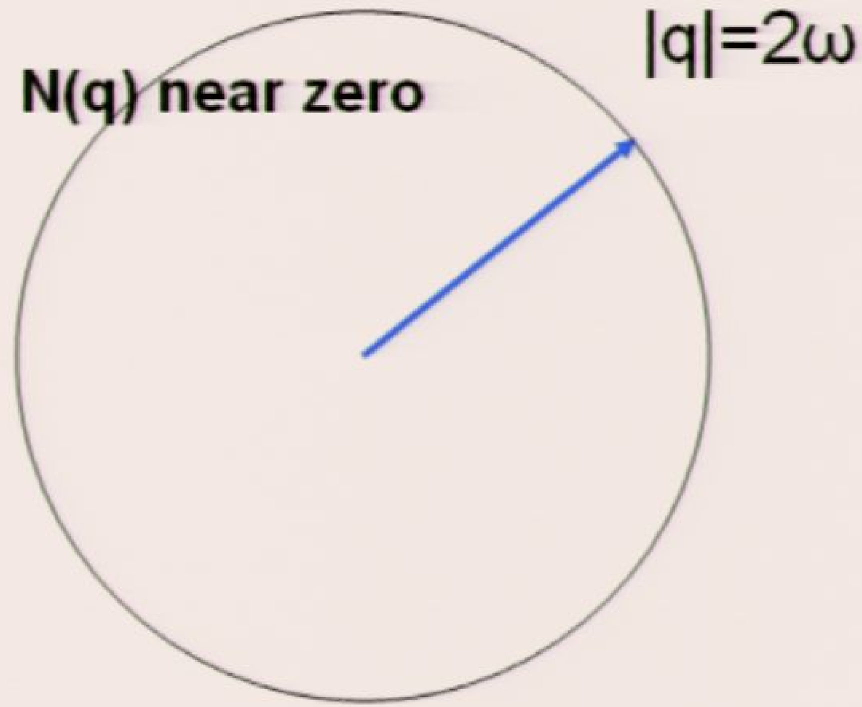
Heuristic Picture
Intra-valley scattering

E(k) near the valley



Dominant process

N(q) near zero

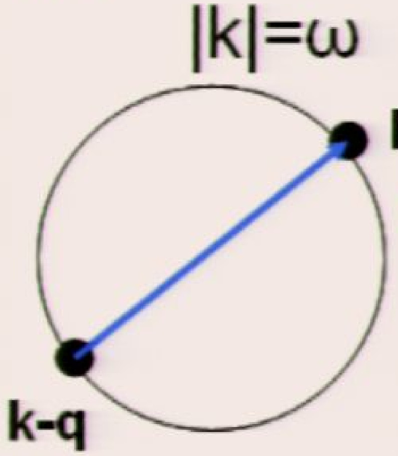


Process probability

$$\langle \psi_k | \sigma_{0/3} | \psi_{k-q} \rangle$$

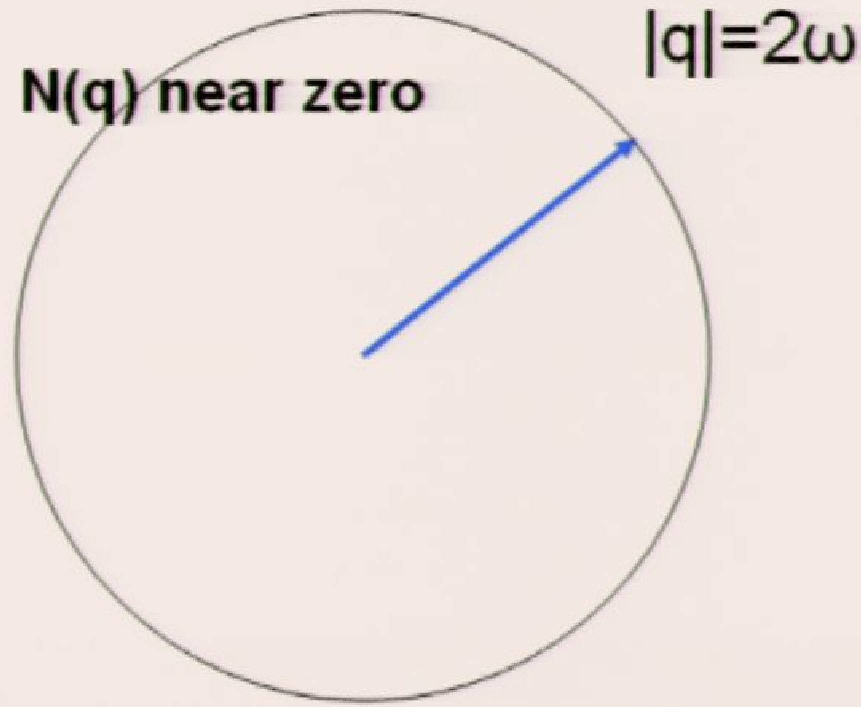
Heuristic Picture
Intra-valley scattering

E(k) near the valley



Dominant process

N(q) near zero

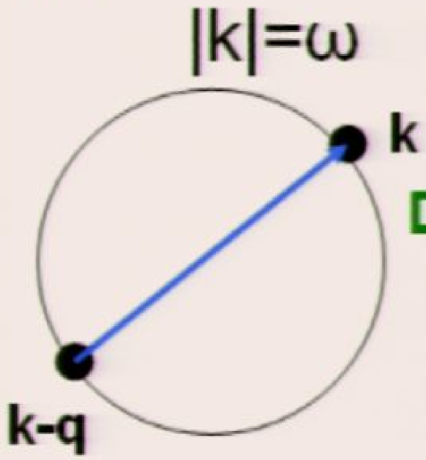


Process probability

$$\begin{pmatrix}1 & e^{i\phi_k}\end{pmatrix}\begin{pmatrix}1 & 0\\ 0 & \pm 1\end{pmatrix}\begin{pmatrix}1\\ e^{-i\phi_{k-q}}\end{pmatrix} = 1 \pm e^{i\phi_{k,k-q}} = 1 \pm e^{i\pi}$$

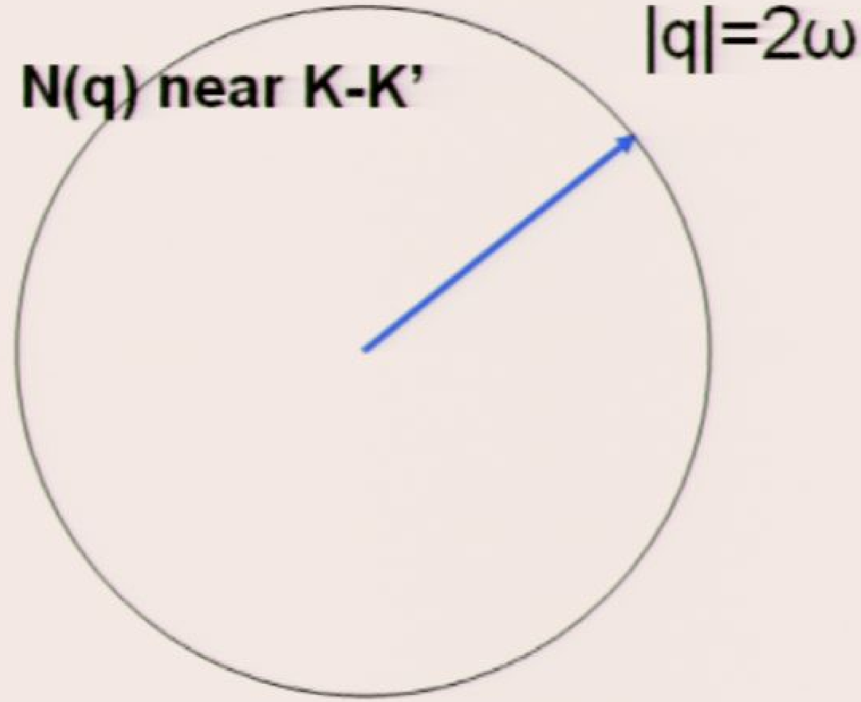
Heuristic Picture
Inter-valley scattering

E(k) near the valleys



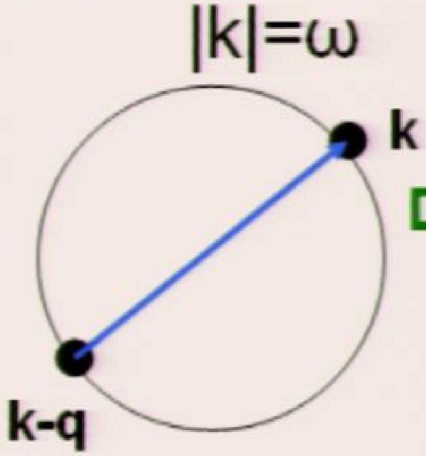
Dominant process

N(q) near K-K'



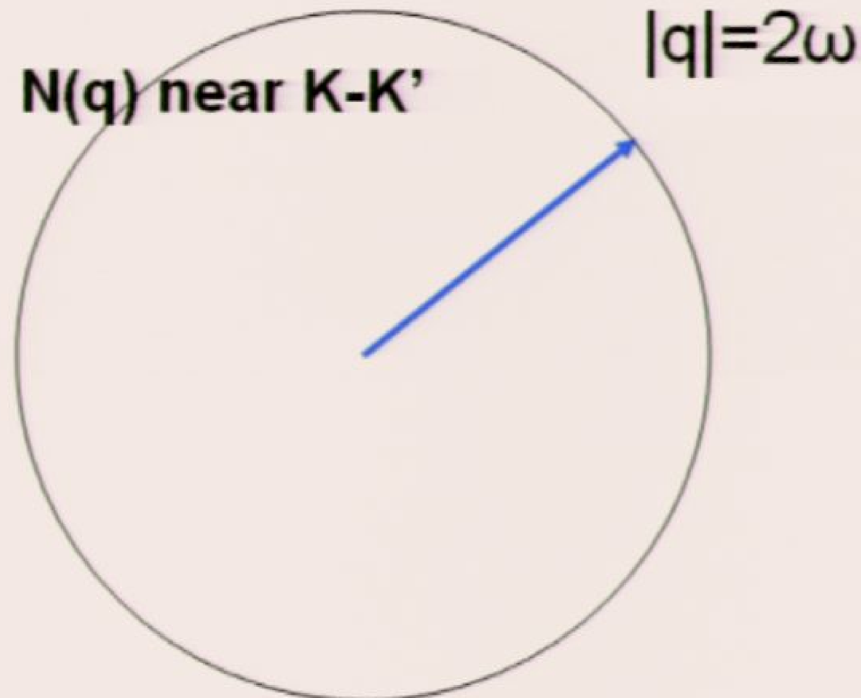
Heuristic Picture
Inter-valley scattering

E(k) near the valleys



Dominant process

N(q) near K-K'



Process probability (due to chirality)

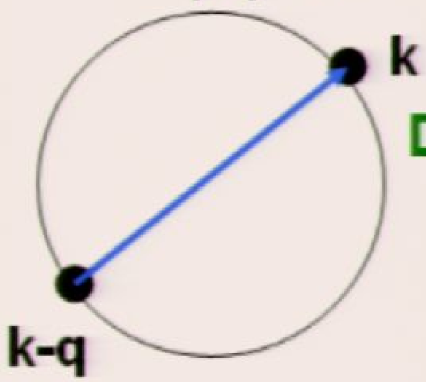
$$\langle \psi_k | \sigma_{0/3} | \psi'_{k-q} \rangle$$

Heuristic Picture

Inter-valley scattering

E(k) near the valleys

|k|=ω



Dominant process

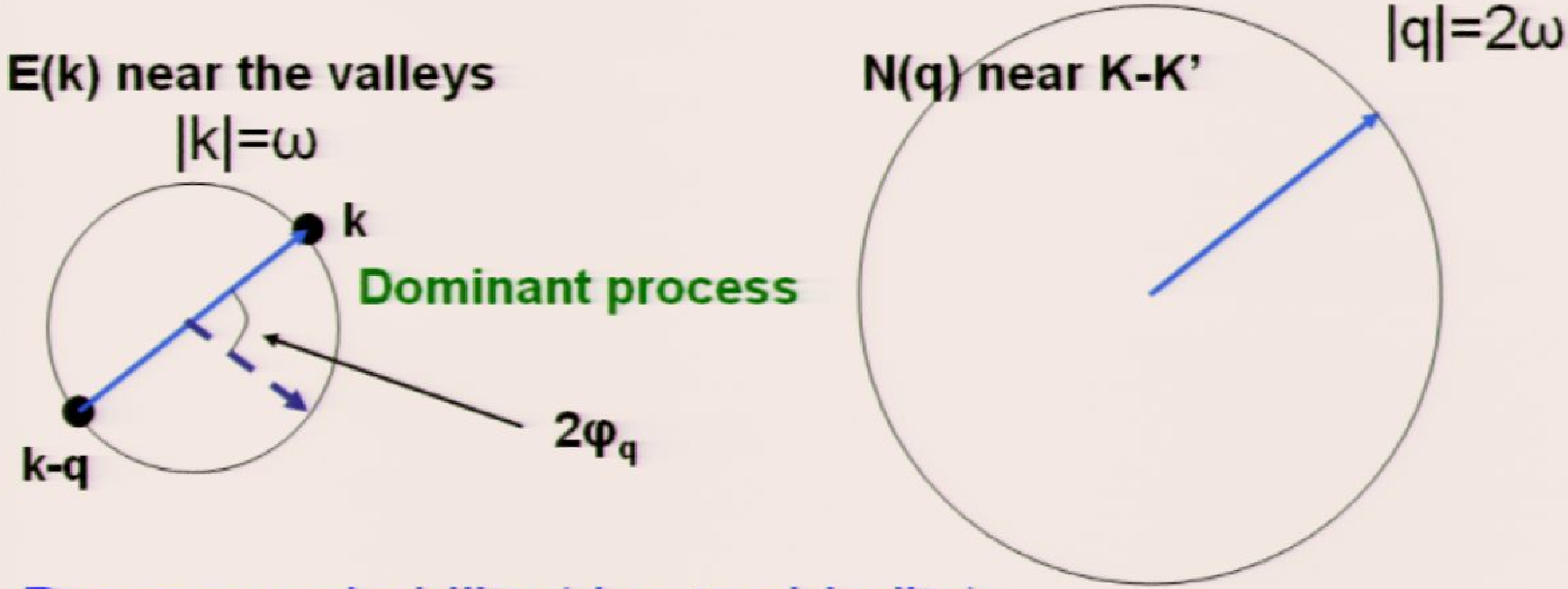
N(q) near K-K'

|q|=2ω

Process probability (due to chirality)

$$\begin{pmatrix}1 & e^{i\phi_k}\end{pmatrix}\begin{pmatrix}1 & 0\\ 0 & \pm 1\end{pmatrix}\begin{pmatrix}1\\ e^{-i\phi'_{k-q}}\end{pmatrix}$$

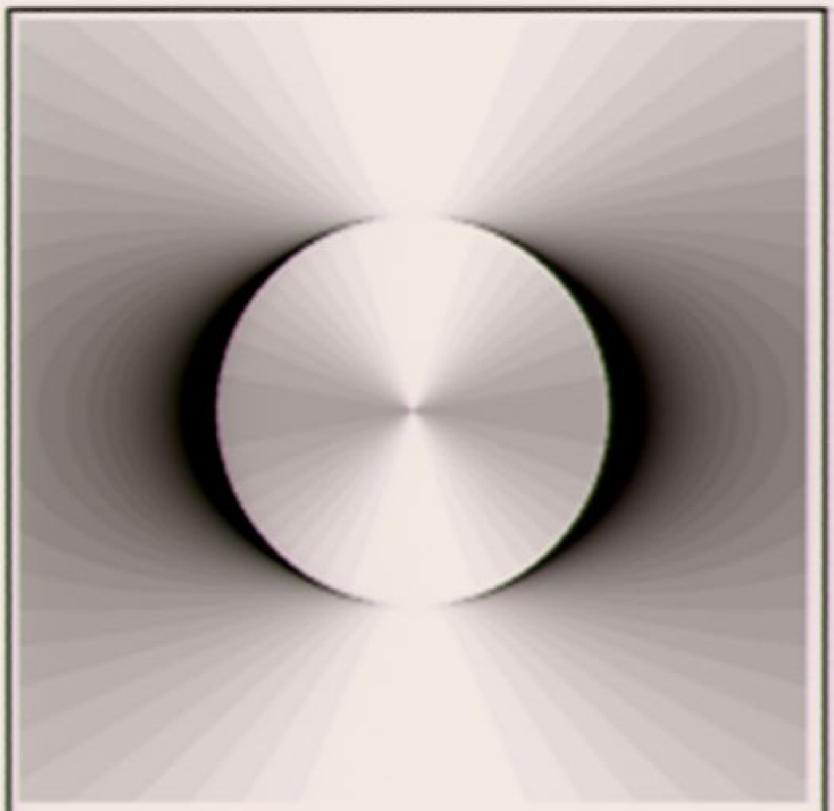
Heuristic Picture
Inter-valley scattering



Process probability (due to chirality)

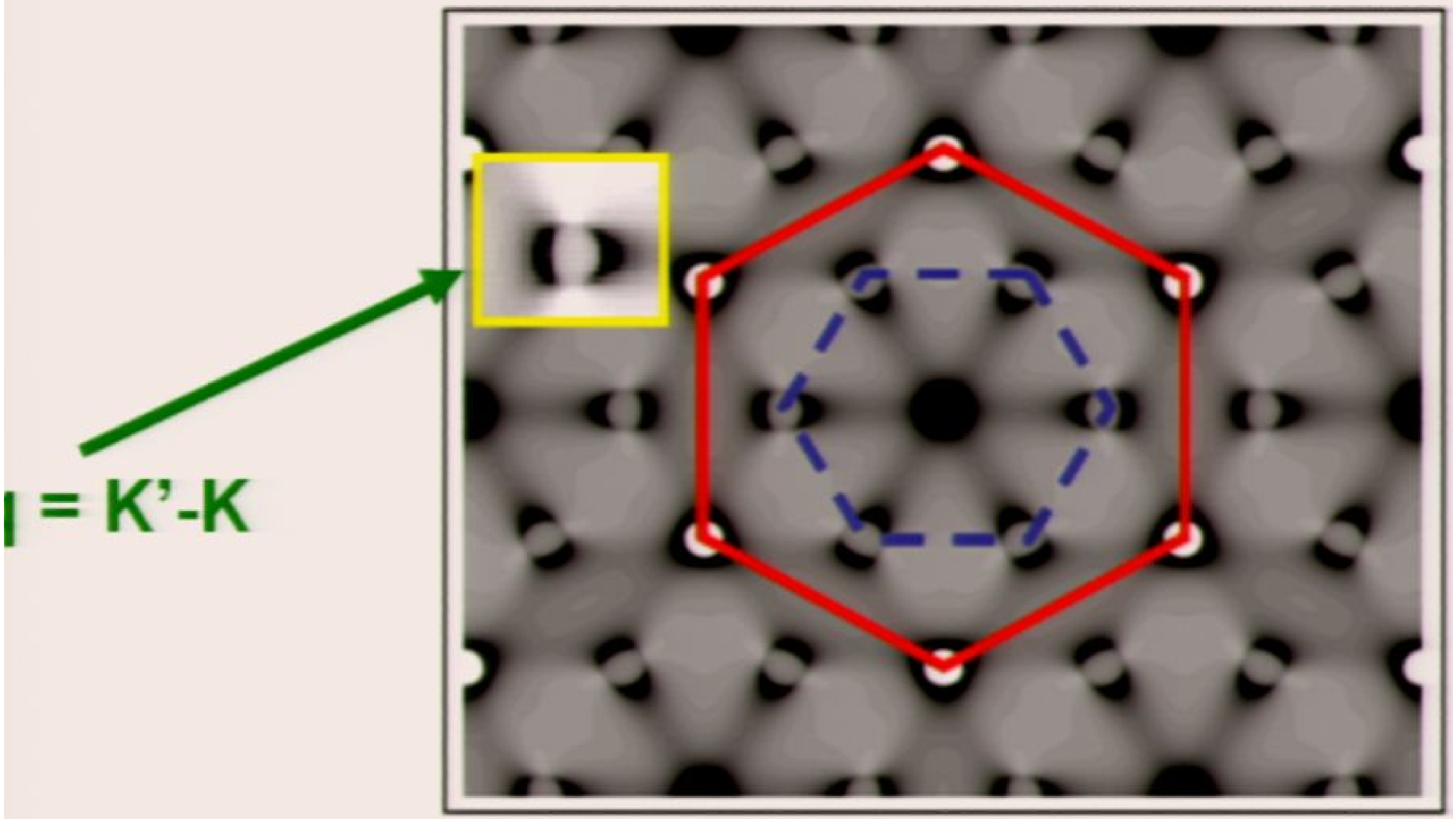
$$1 \pm e^{2i\phi_q} \rightarrow \begin{cases} 2\cos^2(\phi_q) & \sigma_0 \\ 2\sin^2(\phi_q) & \sigma_3 \end{cases}$$

Inter-valley scattering
Analytic results



Numerical Simulation

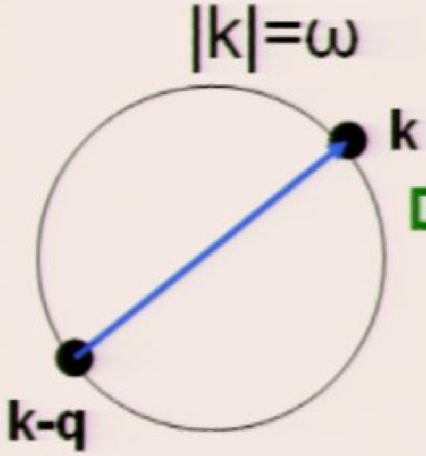
Re(δN(q))



End of slide show, click to exit.

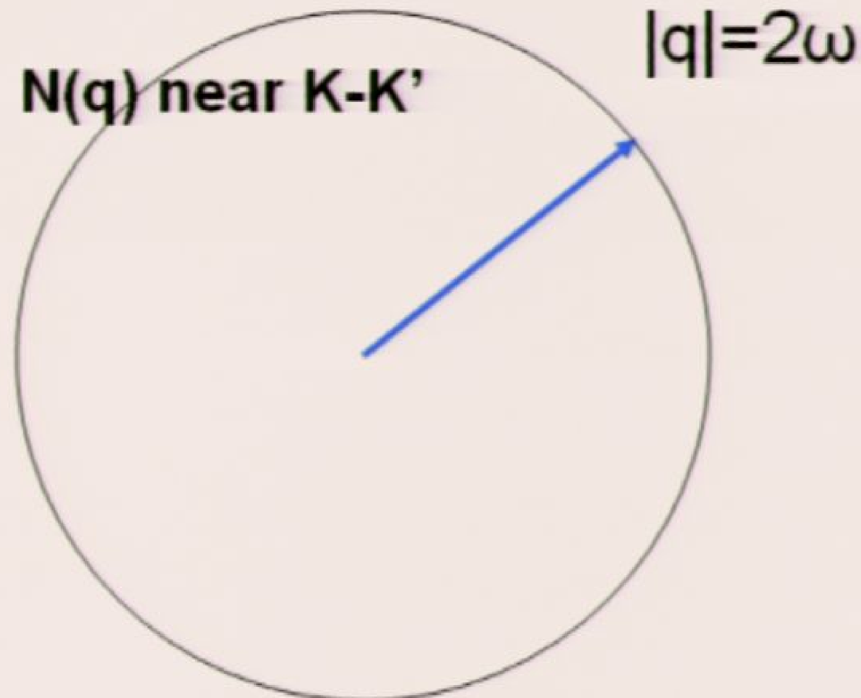
Heuristic Picture
Inter-valley scattering

E(k) near the valleys



Dominant process

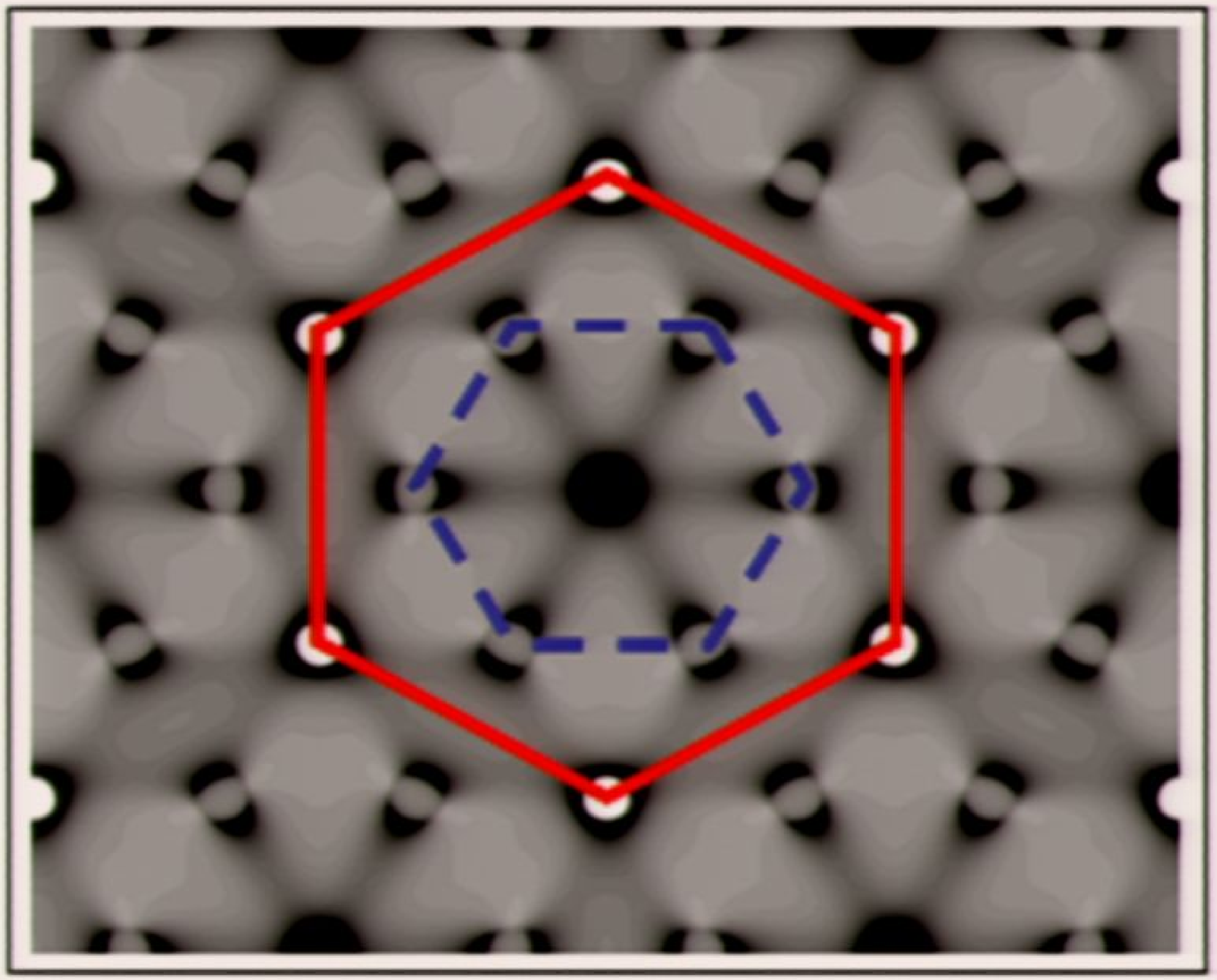
N(q) near K-K'

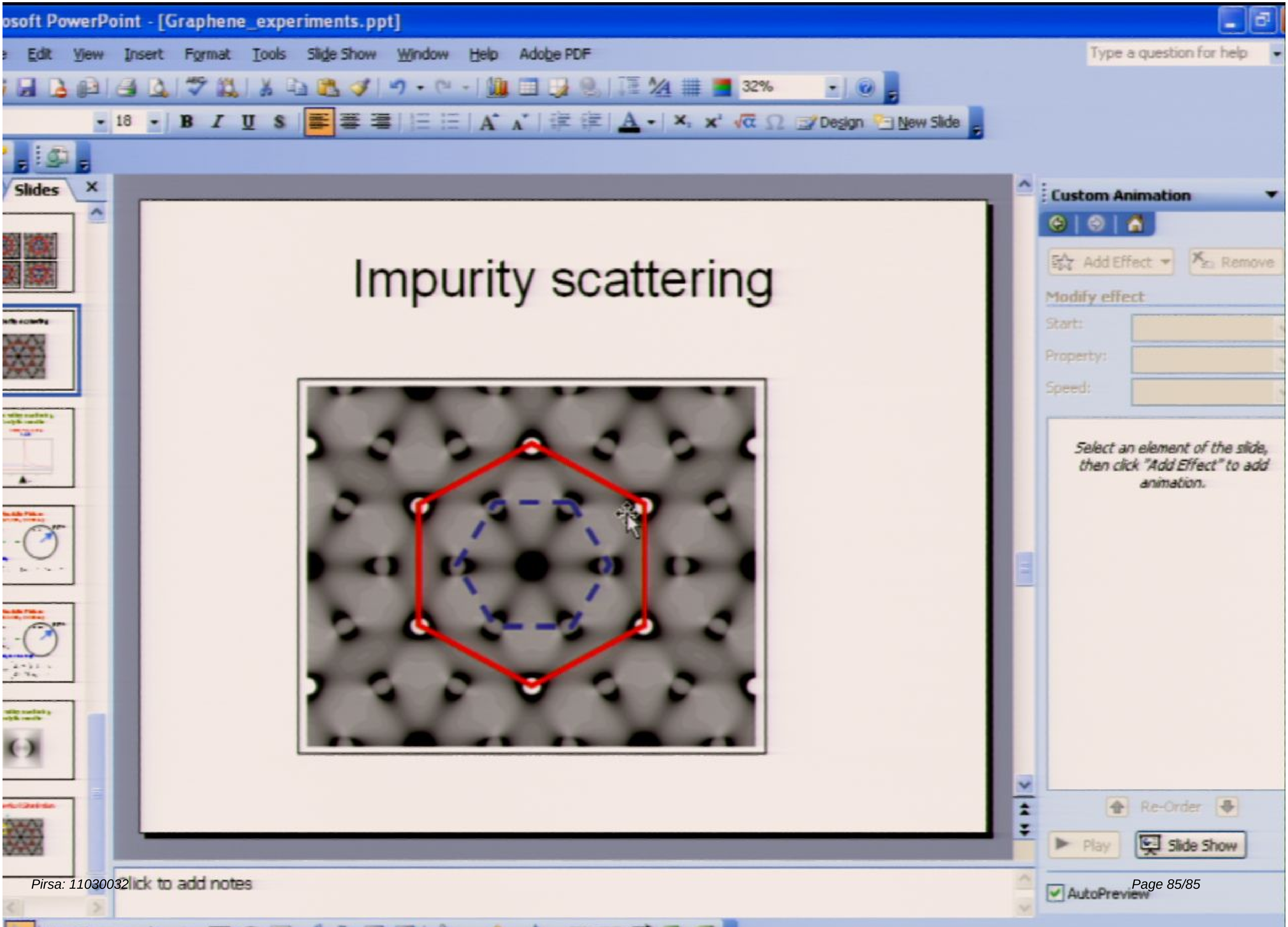


Process probability (due to chirality)

$$\begin{pmatrix}1 & e^{i\phi_k}\end{pmatrix}\begin{pmatrix}1 & 0\\ 0 & \pm 1\end{pmatrix}\begin{pmatrix}1\\ e^{-i\phi'_{k-q}}\end{pmatrix}$$

Impurity scattering




osoft PowerPoint - [Graphene_experiments.ppt]
Edit View Insert Format Tools Slide Show Window Help Adobe PDF
Type a question for help
32%
18
Design New Slide
Slides
Impurity scattering
Custom Animation
Add Effect
Remove
Modify effect
Start:
Property:
Speed:
Select an element of the slide, then click "Add Effect" to add animation.
Re-Order
Play
Slide Show
AutoPreview
Click to add notes