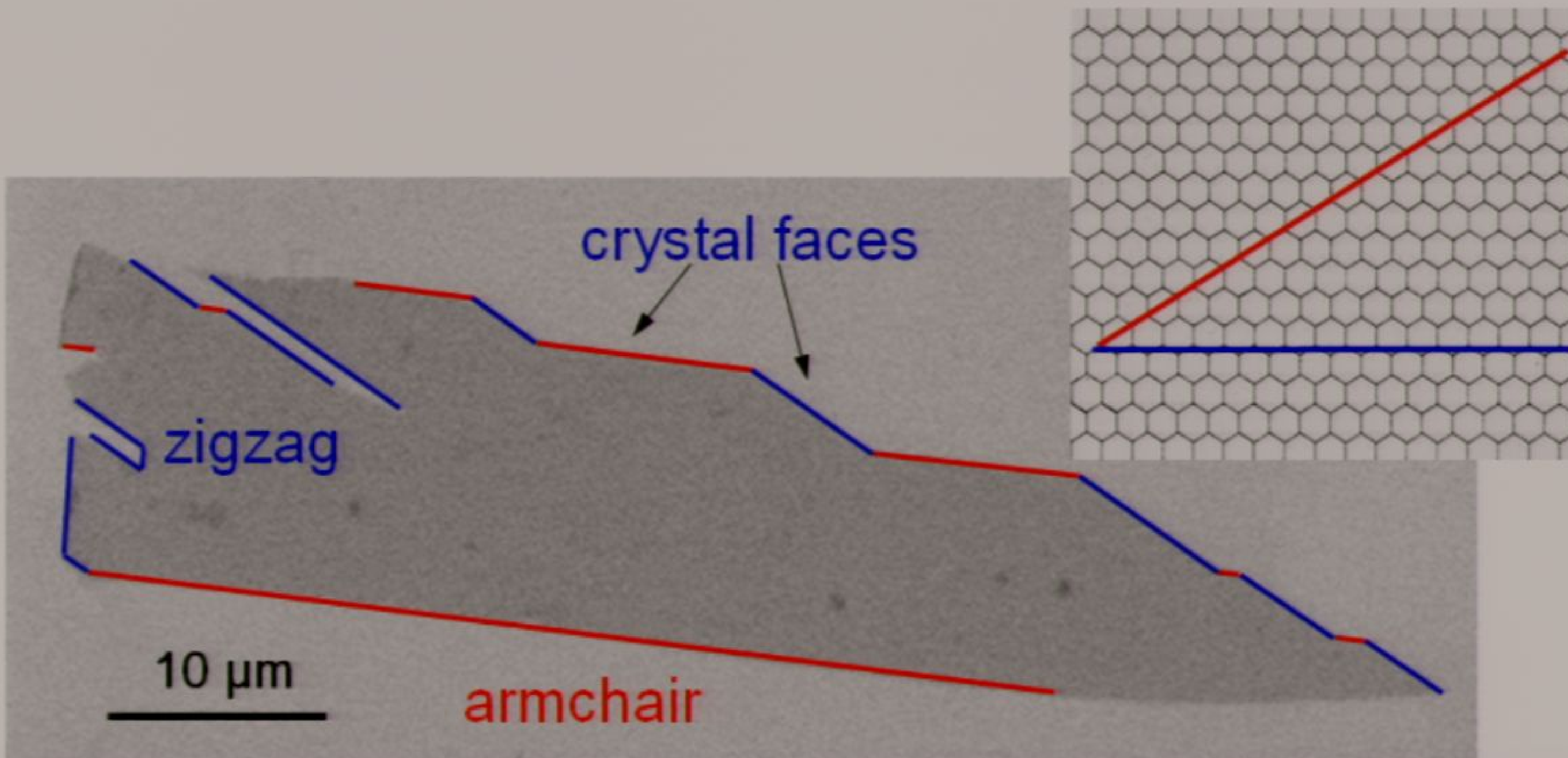
Title: Explorations in Condensed Matter - Lecture 1

Date: Mar 14, 2011 10:15 AM

URL: http://pirsa.org/11030030

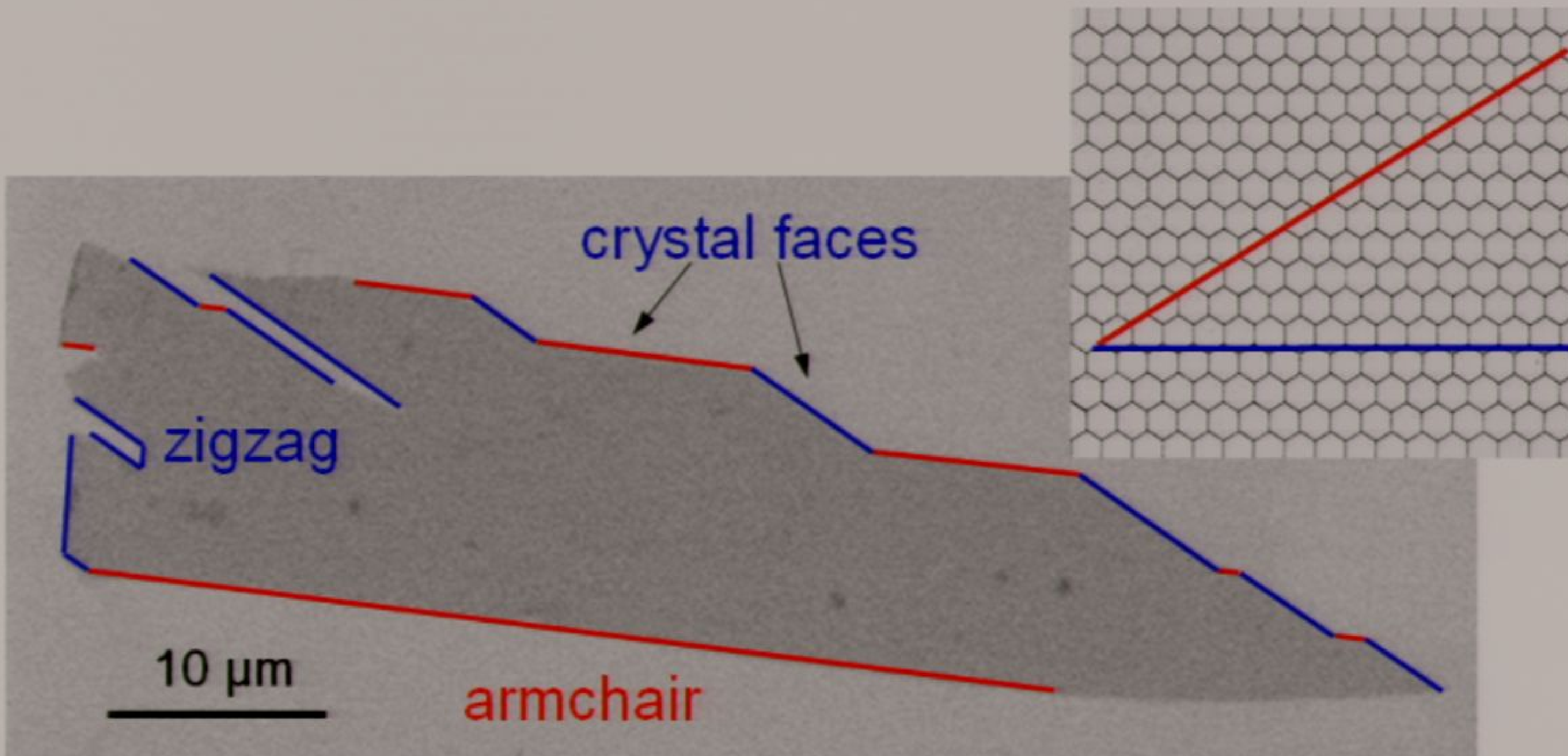
Abstract:

First Crystals
Geim and Novoselov 2004



not just flakes

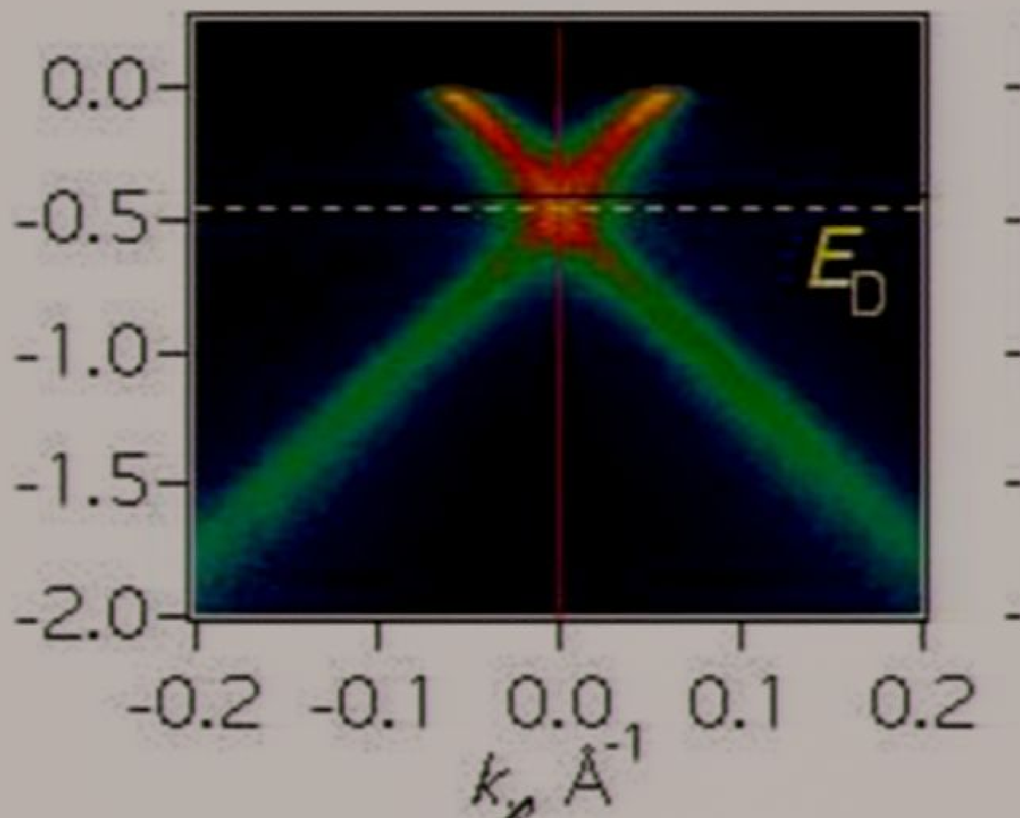
First Crystals
Geim and Novoselov 2004



not just flakes

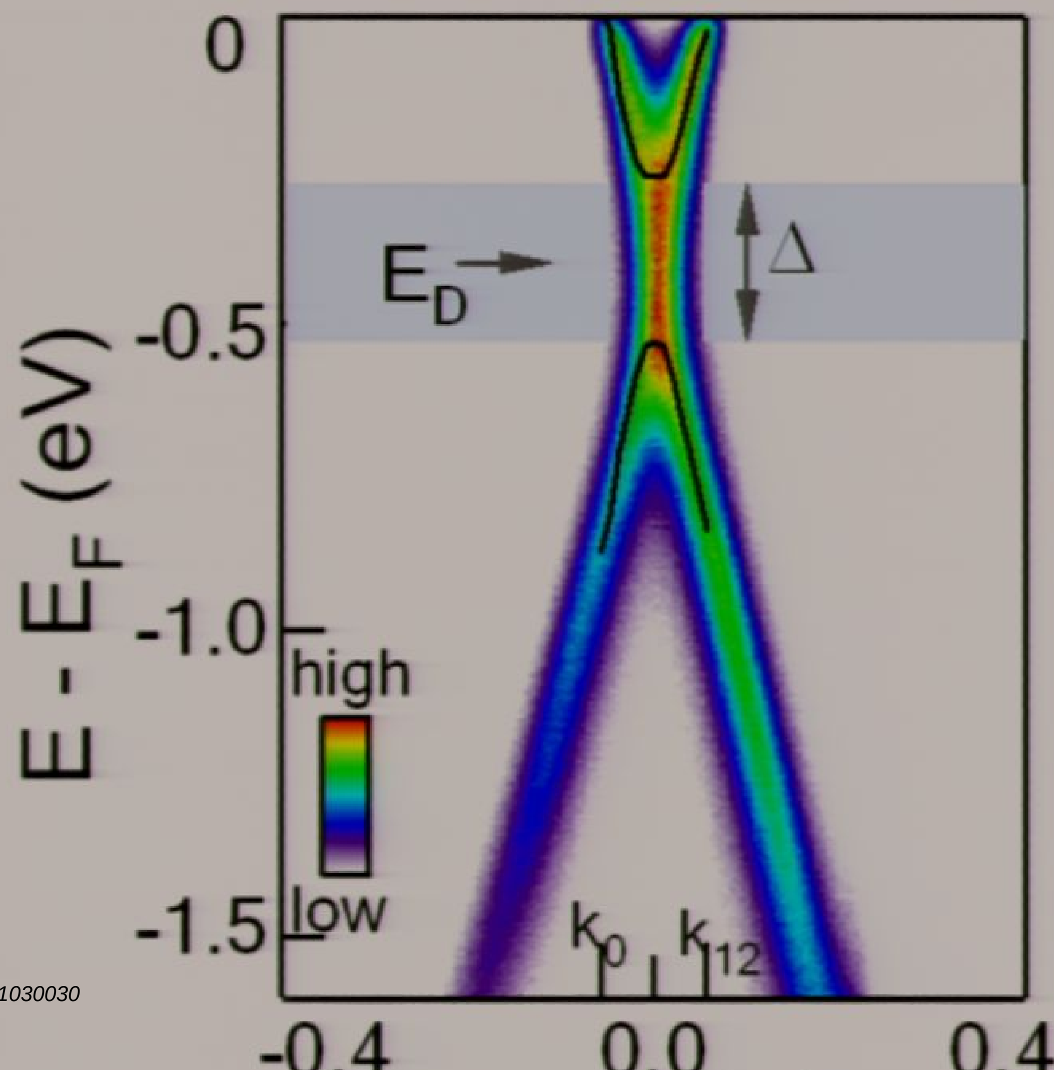
Suspended graphene

Single Layer – Dirac cone dispersion



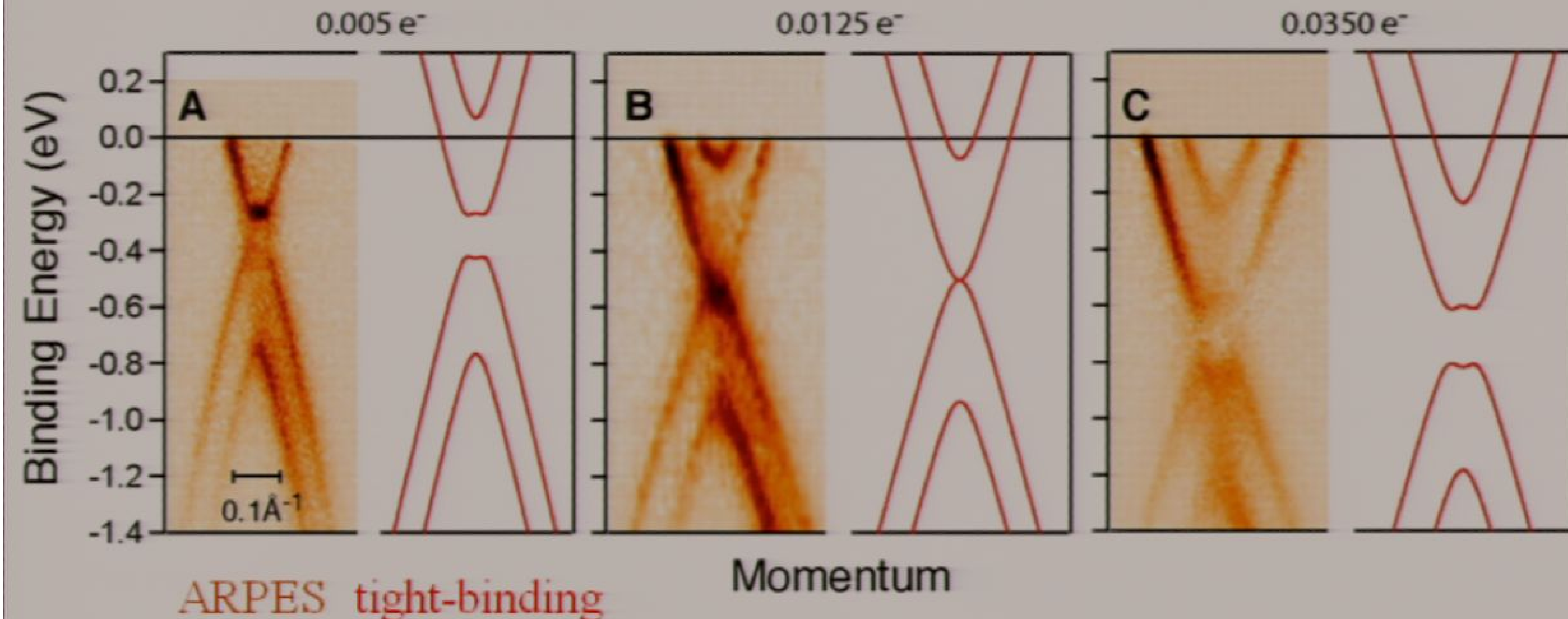
Varchon *et. al*, Phys. Rev. Lett. 2007

Induced gap



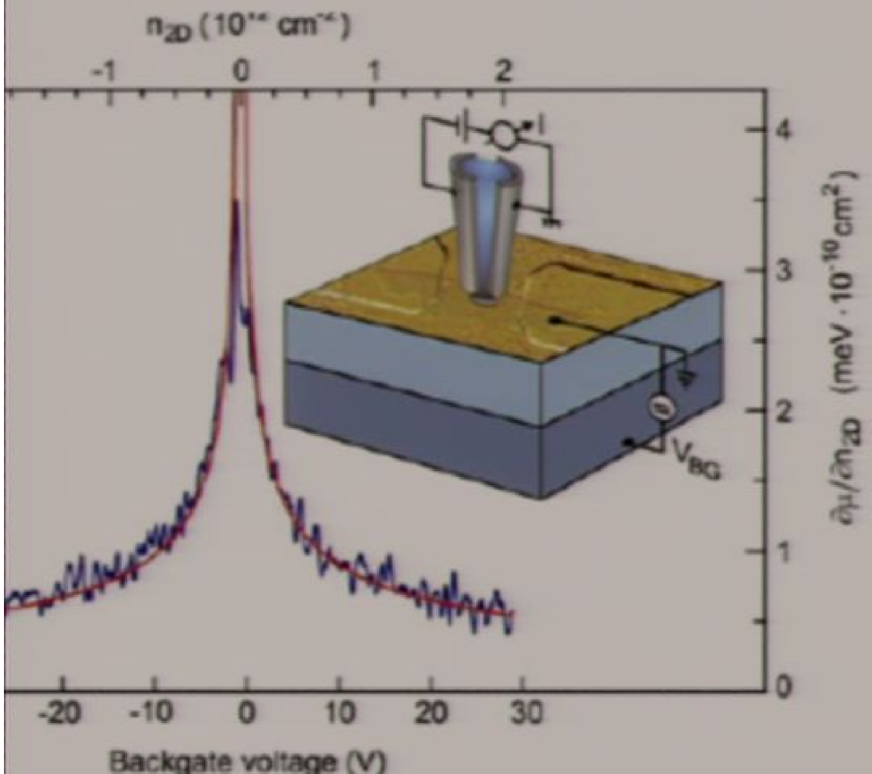
Zhou *et al.*
Nature Materials **6**, 770 (2007)

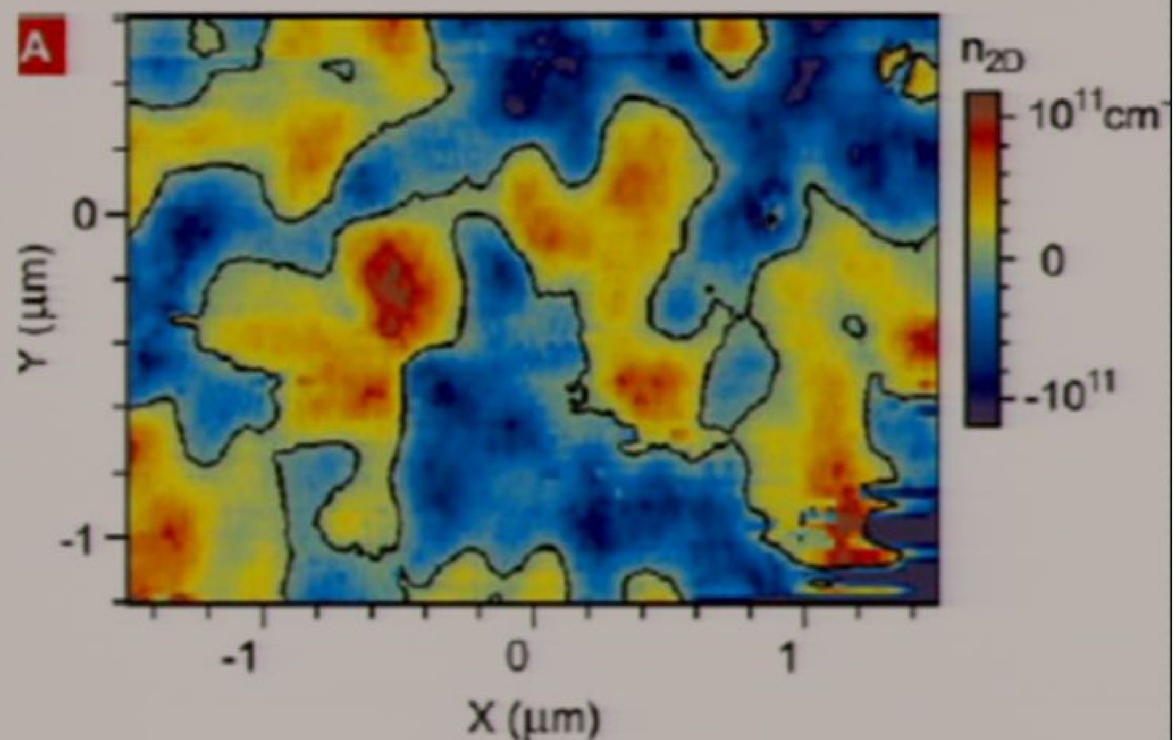
Graphene Bilayer – ARPES



Ohta et al. Science **313**, 951 (2006)

Electron-hole puddles





Martin *et al.* Nature Physics 2008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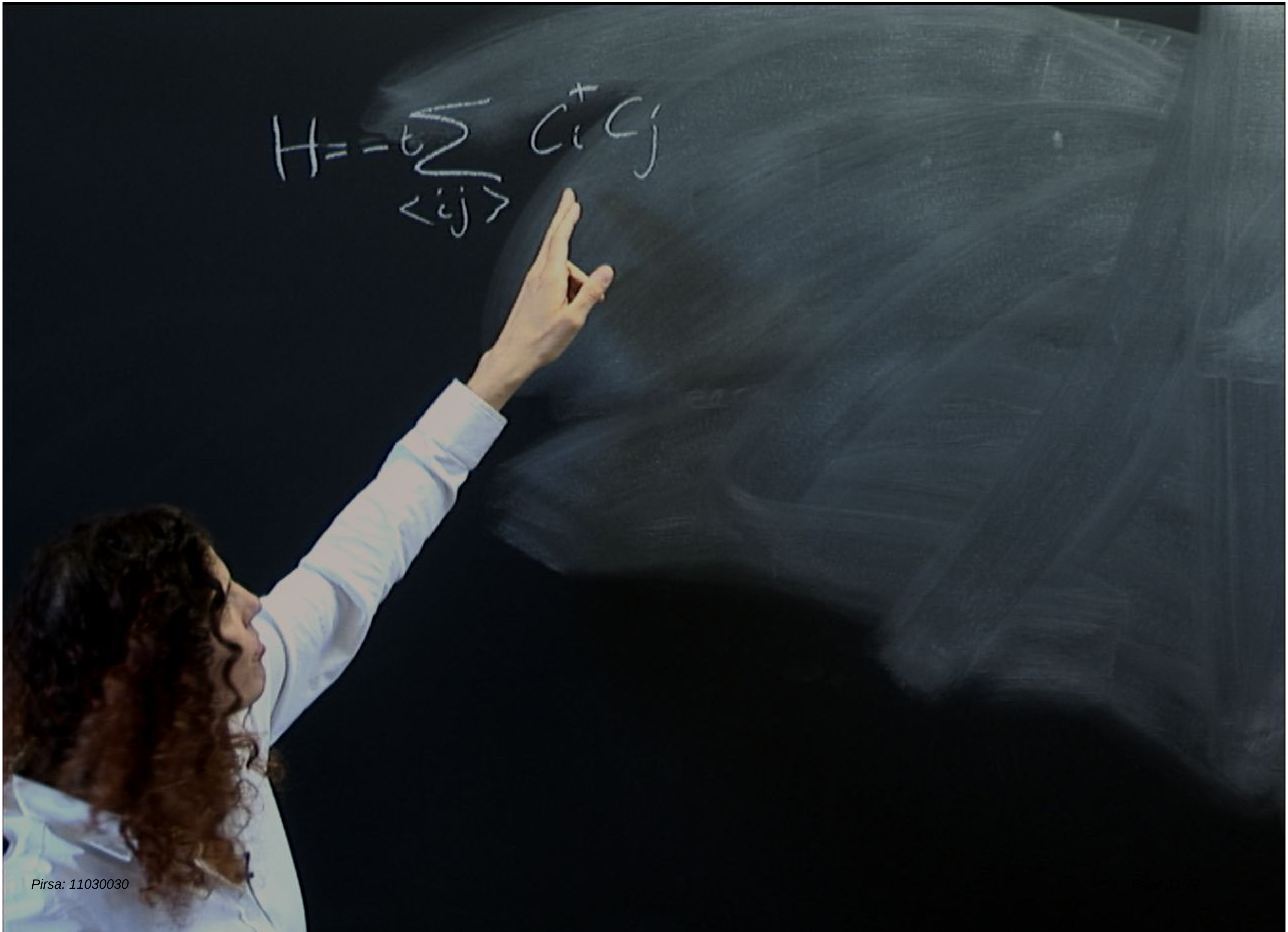
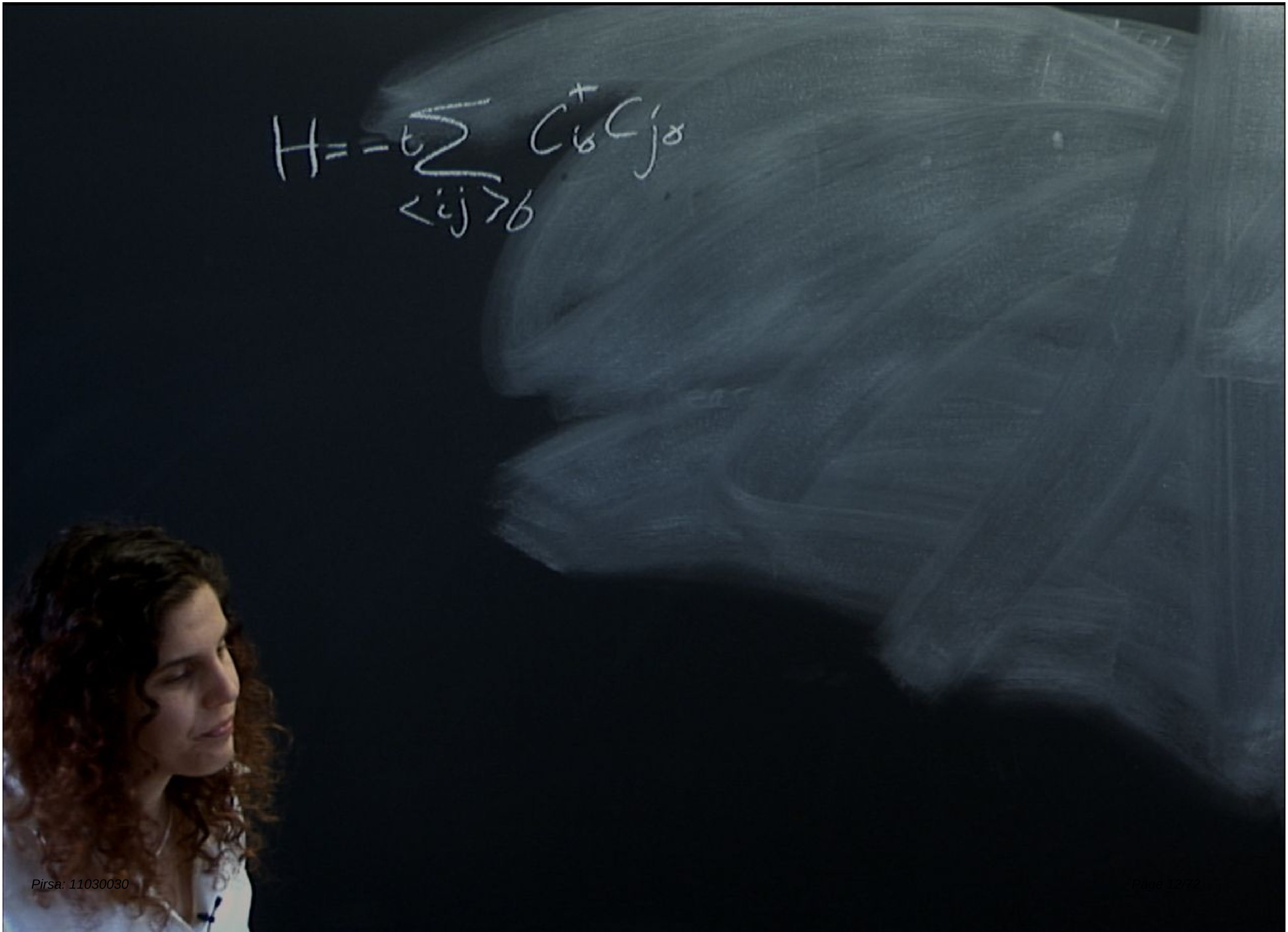
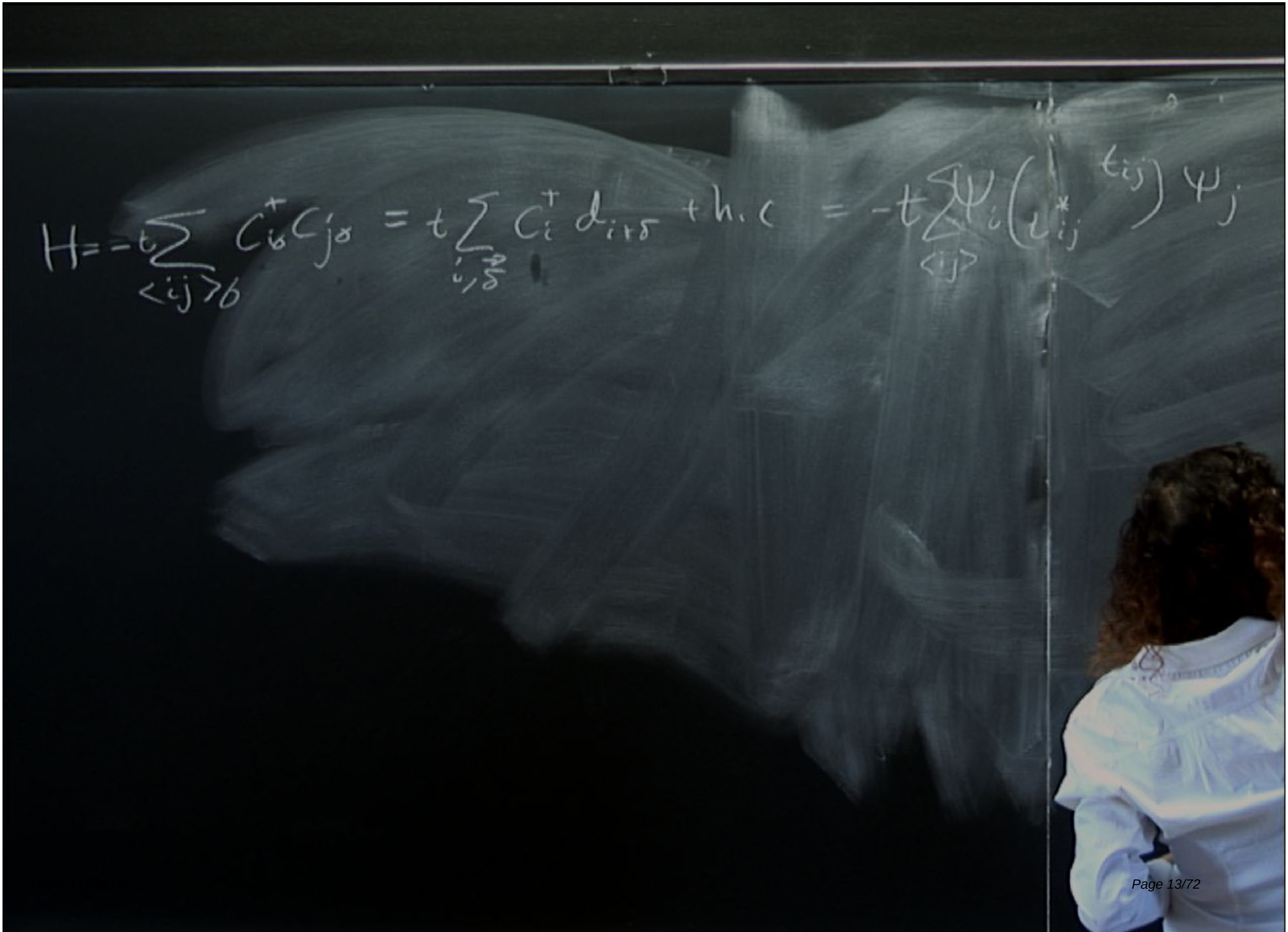
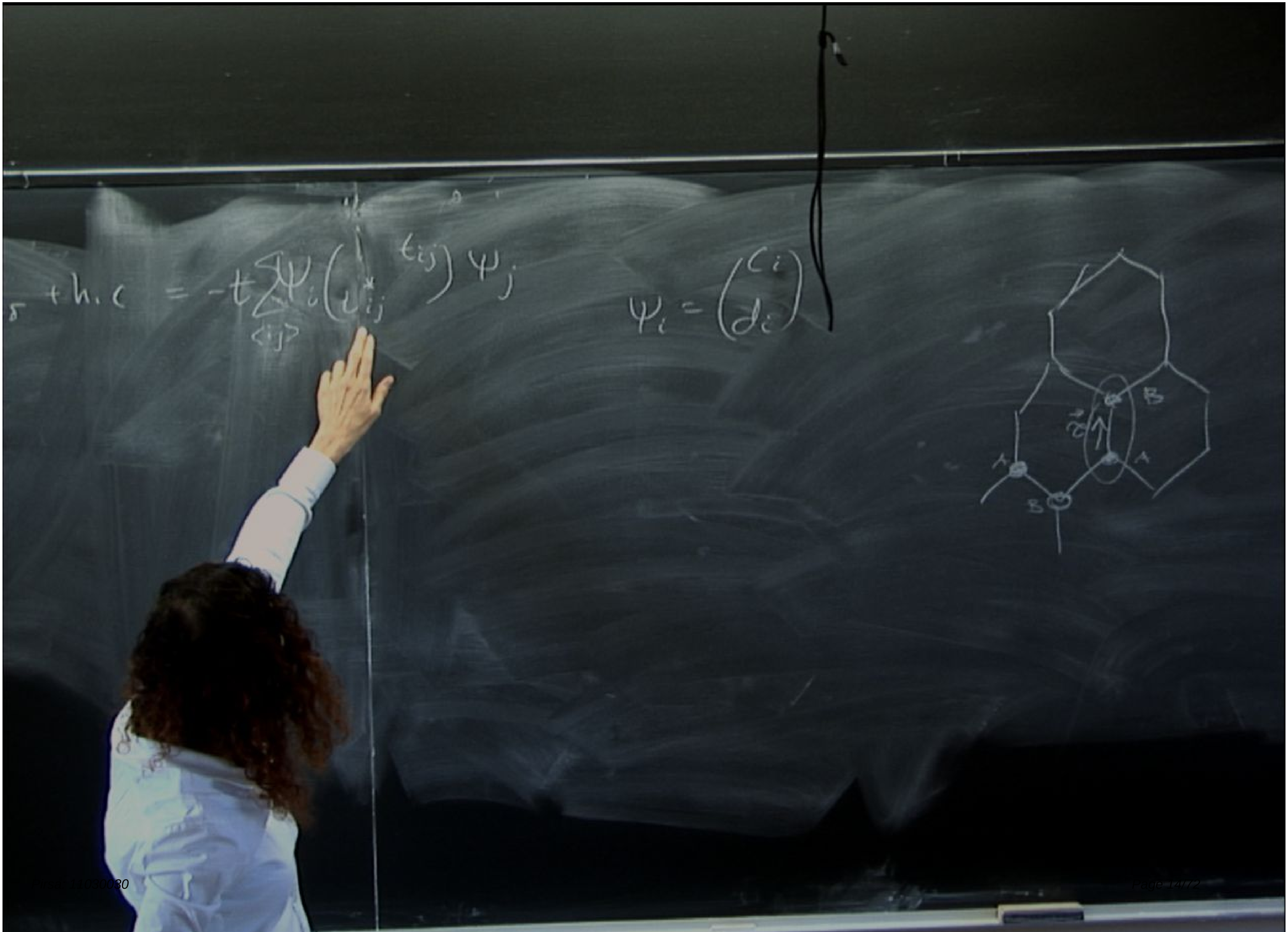
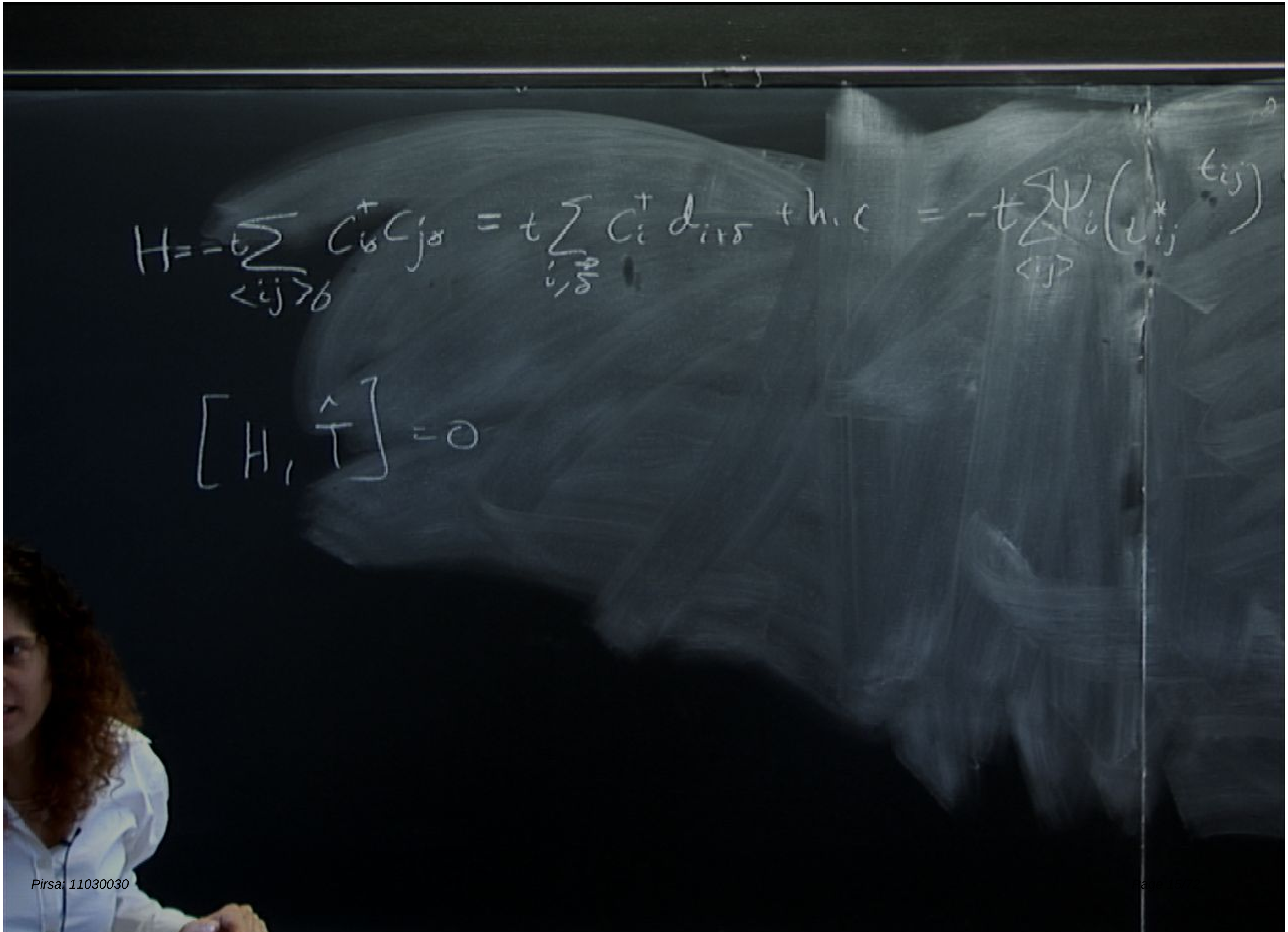

$H = -t \sum_{\langle ij \rangle} c_i^{+} c_j$


$H = -t \sum_{\langle ij \rangle \sigma} c^{\dagger}_{i\sigma} c_{j\sigma}$

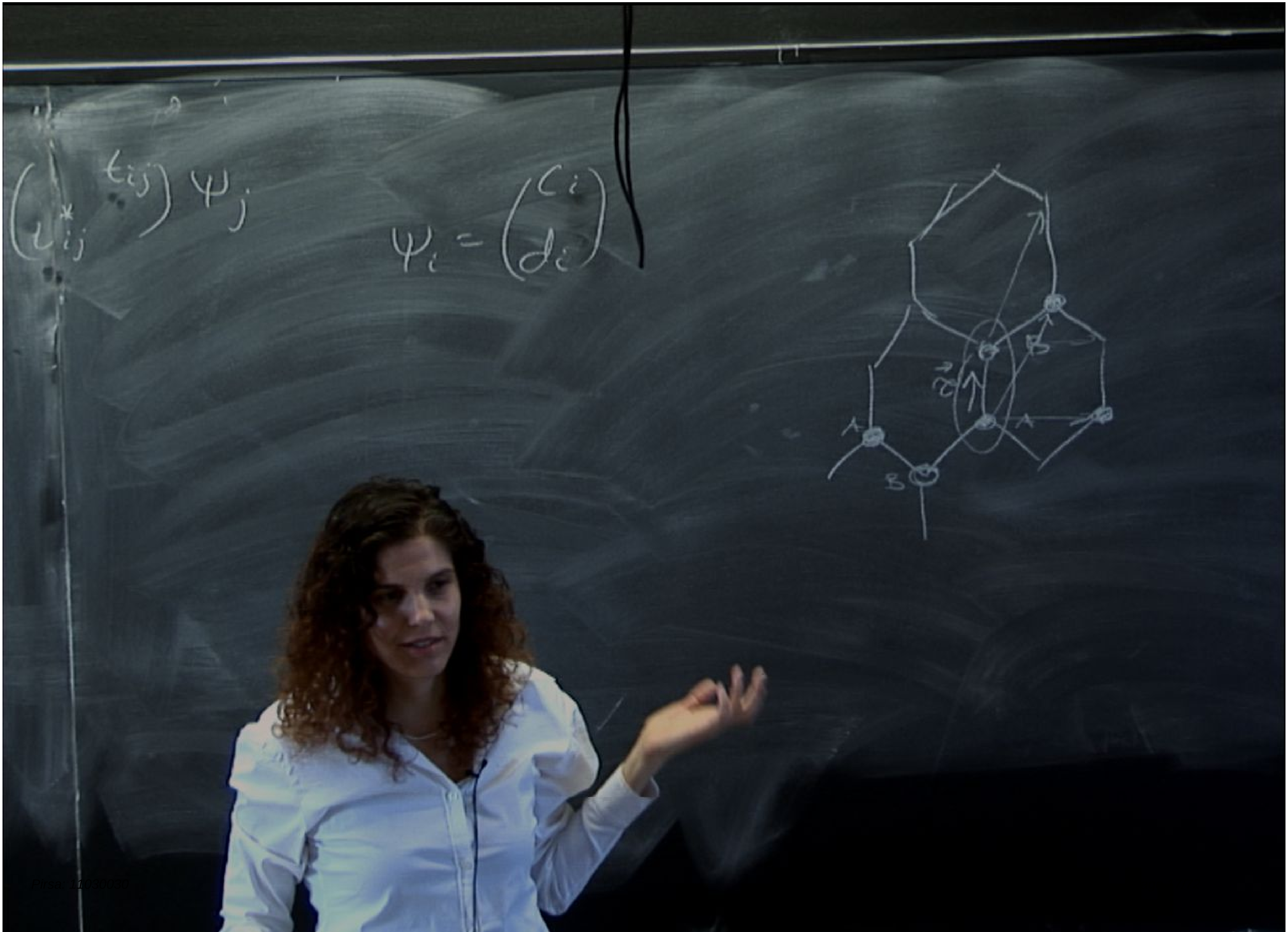

$H = -t \sum_{\langle ij \rangle \sigma} c^{\dagger}_{i\sigma} c_{j\sigma} = t \sum_{i, \vec{\delta}} c^{\dagger}_{i} d_{i+\delta} + h.c = -t \sum_{\langle ij \rangle} \psi_i \begin{pmatrix} & t_{ij} \\ t^{*}_{ij} & \end{pmatrix} \psi_j$

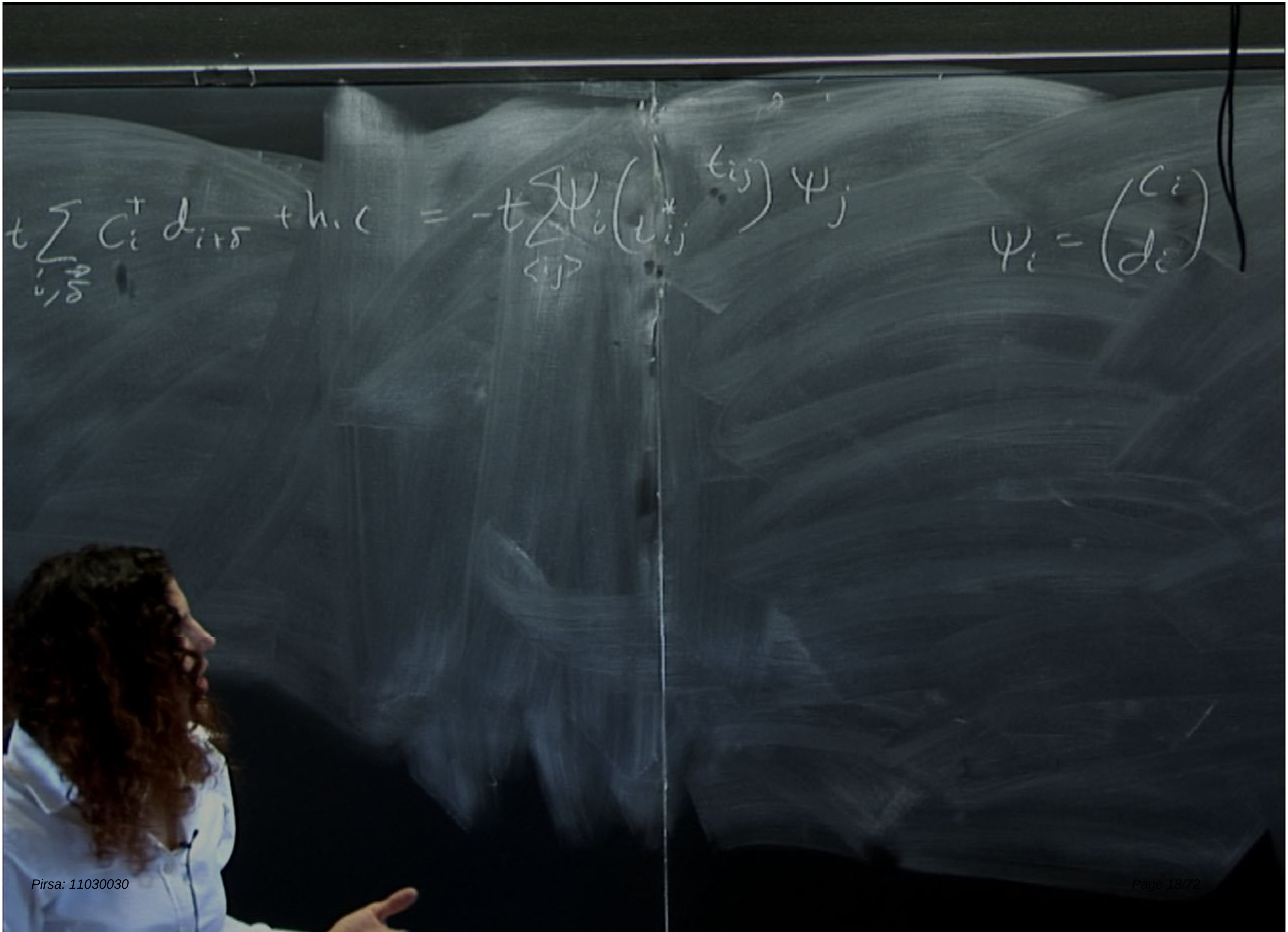

+ h.c
ψi = (ci di)
A
B
A
B

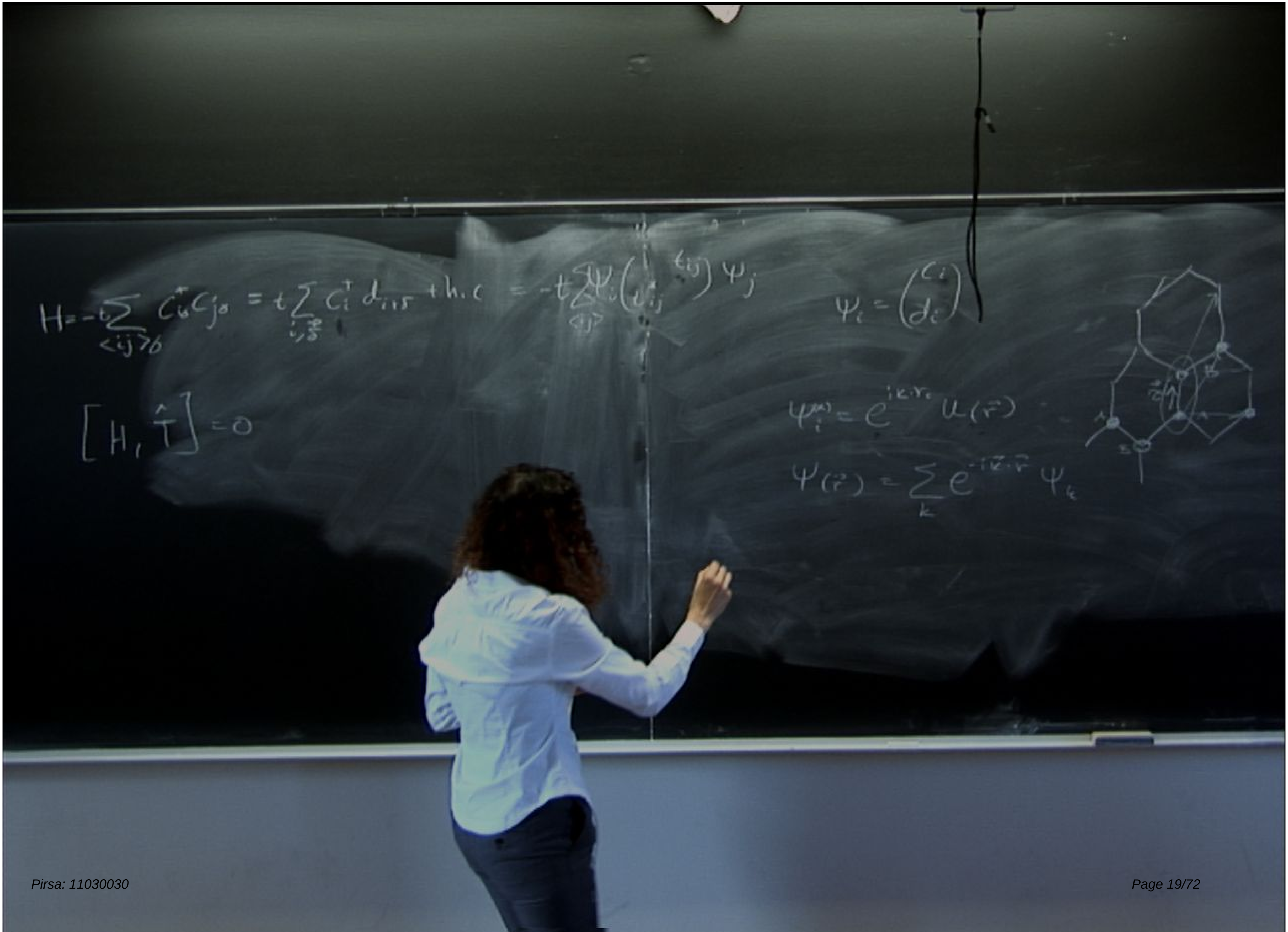

[H, T̂] = 0

$$H = -t \sum_{\langle ij \rangle \sigma} c^{\dagger}_{i\sigma} c_{j\sigma} = t \sum_{i, \vec{\delta}} c^{\dagger}_{i} d_{i+\delta} + h.c. = -t \sum_{\langle ij \rangle} \psi_i \left(t^{*}_{ij} \quad t_{ij} \right)$$

$$[H, \hat{T}] = 0$$

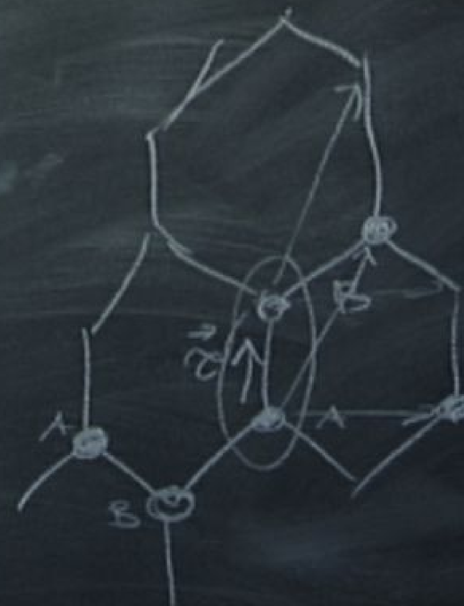

t_ij) ψ_j
t*_ij
ψ_i = (c_i d_i)
A
B
A
B


t ∑ c_i^† d_{i+δ} + h.c = -t ∑ Ψ_i (t_{ij}^* t_{ij}) Ψ_j
i,δ
⟨ij⟩
Ψ_i = (c_i d_i)



$\begin{pmatrix} & t_{ij} \\ t^*_{ij} & \end{pmatrix} \psi_j$

$$\psi_i = \begin{pmatrix} c_i \\ d_i \end{pmatrix}$$



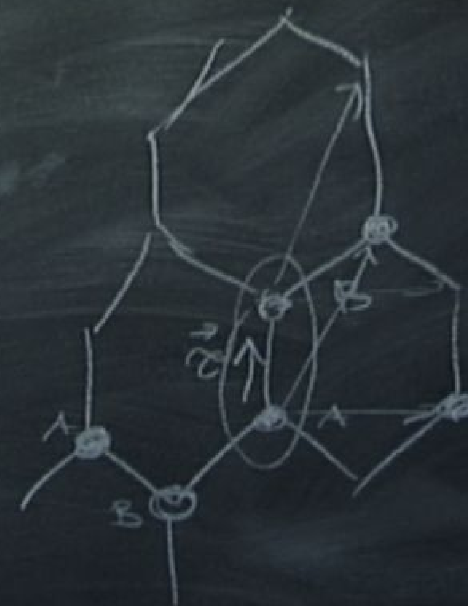
$$\psi_i^{(k)} = e^{ik\cdot r_i} u(\vec{r})$$

$$\psi(\vec{r}) = \sum_k e^{-i\vec{k}\cdot\vec{r}} \psi_k$$

$$\psi^\dagger(r_i)\psi(r_j) = \sum_{p,k} e^{i(p-k)\cdot r_i - ik\cdot\vec{\delta}}$$

$$t_{ij}) \psi_j$$

$$\psi_i = \begin{pmatrix} c_i \\ d_i \end{pmatrix}$$

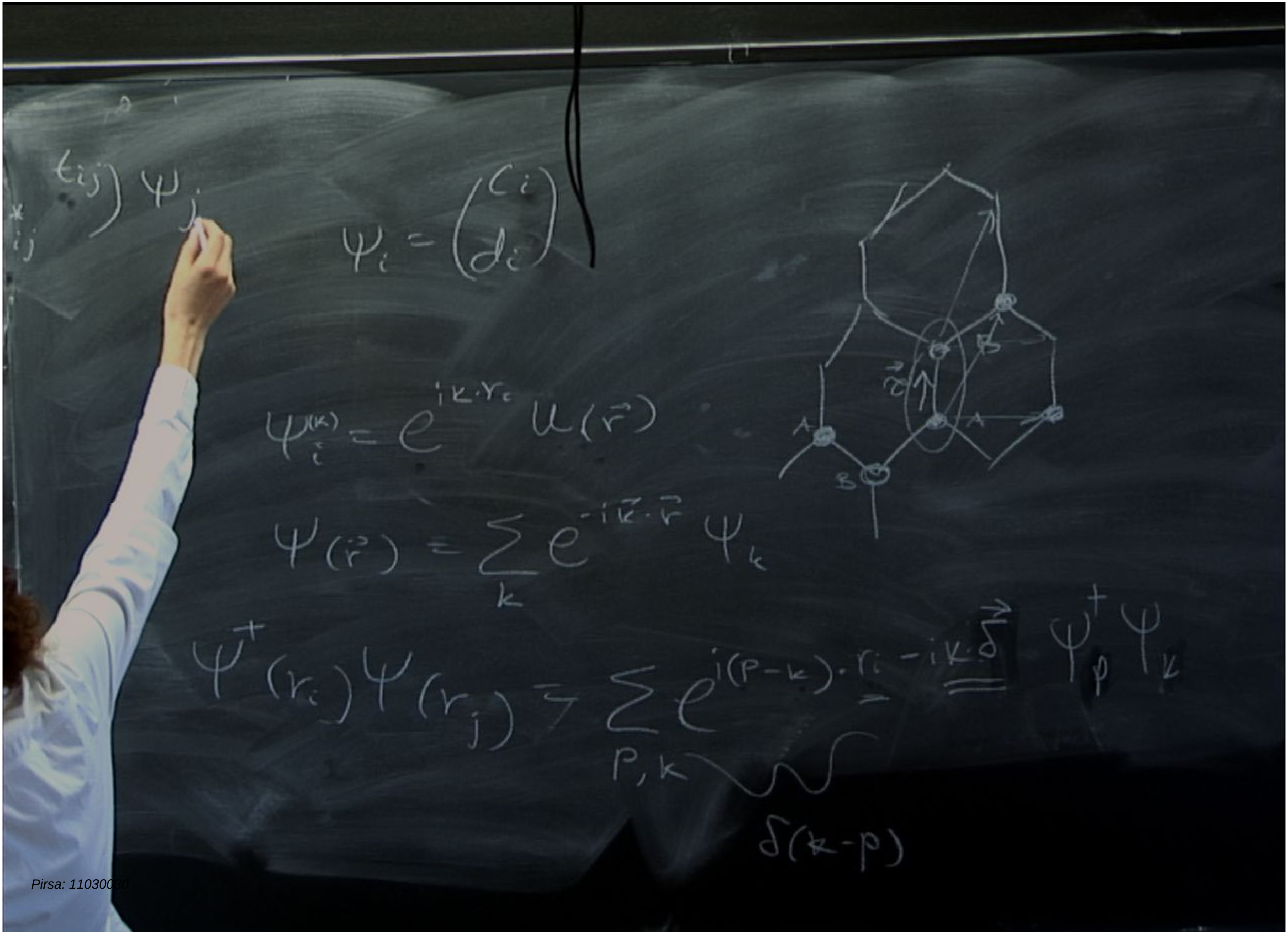


$$\psi_i^{(k)} = e^{i k \cdot r_i} u(\vec{r})$$

$$\psi(\vec{r}) = \sum_k e^{-i \vec{k} \cdot \vec{r}} \psi_k$$

$$\psi^\dagger(r_i) \psi(r_j) = \sum_{p,k} e^{i(p-k) \cdot r_i - i k \cdot \vec{\delta}} \psi_p^\dagger \psi_k$$

$$\delta(k-p)$$


$t_{ij}) \Psi_j$
$\Psi_i = \begin{pmatrix} c_i \\ d_i \end{pmatrix}$
$\Psi_i^{(k)} = e^{ik\cdot r_i} u(\vec{r})$
$\Psi(\vec{r}) = \sum_k e^{-i\vec{k}\cdot\vec{r}} \Psi_k$
$\Psi^\dagger(r_i)\Psi(r_j) = \sum_{p,k} e^{i(p-k)\cdot r_i - ik\cdot\vec{\delta}} \Psi_p^\dagger \Psi_k$
$\delta(k-p)$
A
B
A
$\vec{\delta}$

$$t_{ij}) \psi_j =$$

$$\psi_i = \begin{pmatrix} c_i \\ d_i \end{pmatrix}$$

$$\psi_i^{(k)} = e^{i k \cdot r_i} u(\vec{r})$$

$$\psi(\vec{r}) = \sum_k e^{-i \vec{k} \cdot \vec{r}} \psi_k$$

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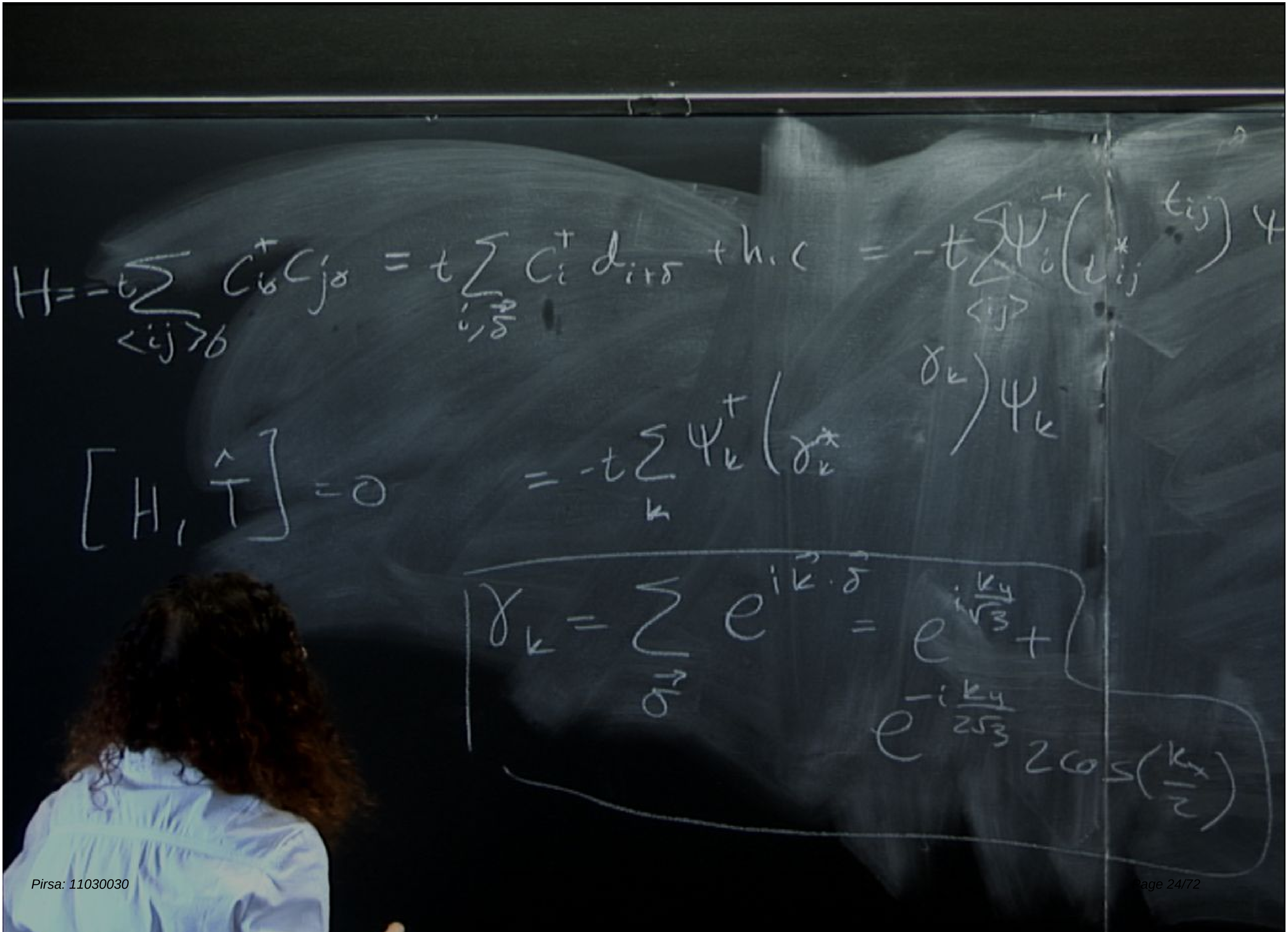
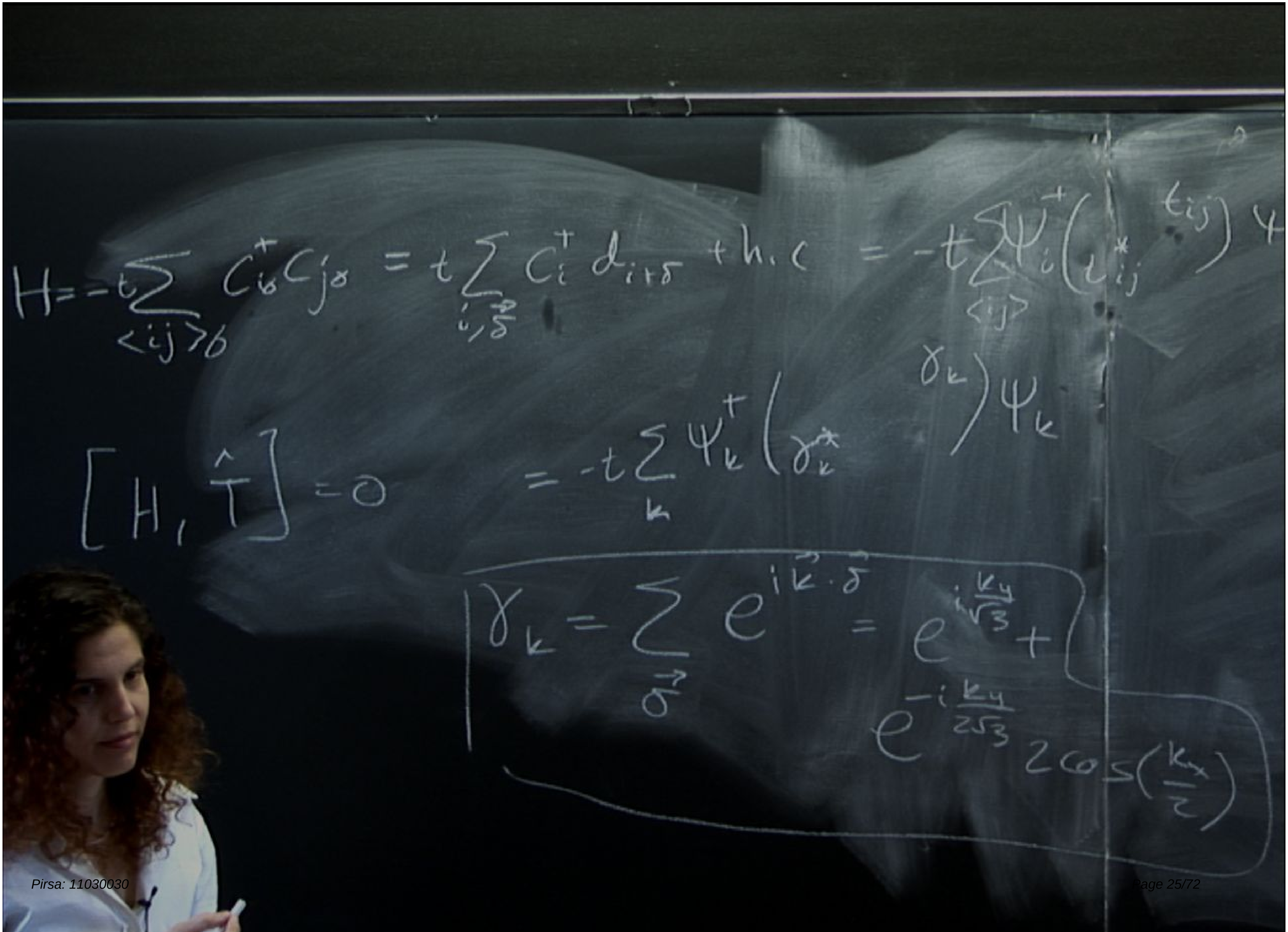
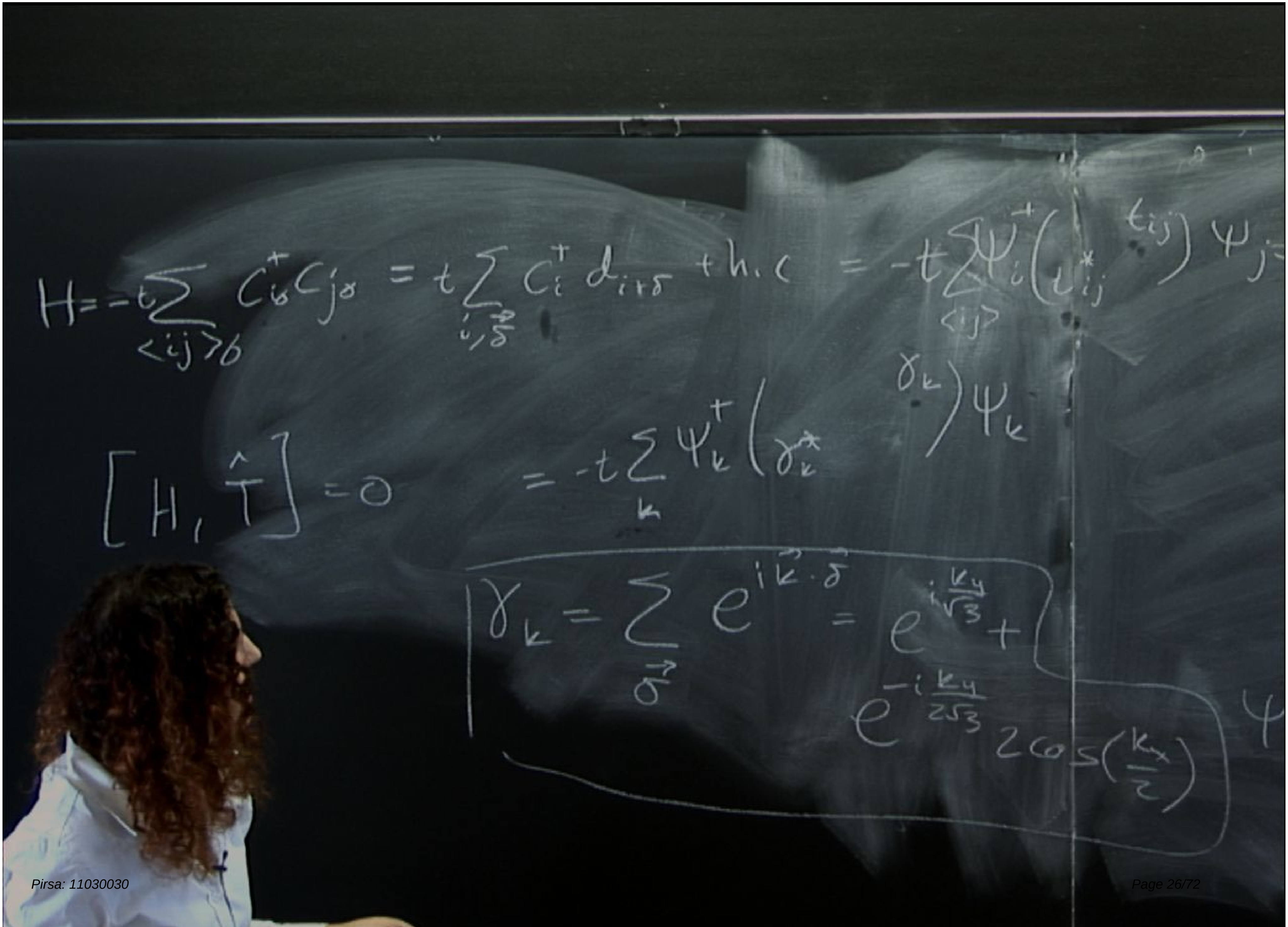
$$\delta(k-p)$$


$H = -t \sum_{\langle ij \rangle \sigma} c^\dagger_{i\sigma} c_{j\sigma} = t \sum_{i,\vec\delta} c^\dagger_i d_{i+\delta} + h.c. = -t \sum_{\langle ij \rangle} \Psi^\dagger_i \begin{pmatrix} & t_{ij} \\ t^*_{ij} & \end{pmatrix} \Psi$
$= -t \sum_k \Psi^\dagger_k \begin{pmatrix} & \gamma_k \\ \gamma^*_k & \end{pmatrix} \Psi_k$
$[H, \hat{T}] = 0$
$\gamma_k = \sum_{\vec\delta} e^{i\vec{k}\cdot\vec{\delta}} = e^{i\frac{k_y}{\sqrt{3}}} + e^{-i\frac{k_y}{2\sqrt{3}}} 2\cos\left(\frac{k_x}{2}\right)$


$H = -t \sum_{\langle ij \rangle \sigma} c_{i\sigma}^{+} c_{j\sigma} = t \sum_{i,\vec{\delta}} c_i^{+} d_{i+\delta} + h.c = -t \sum_{\langle ij \rangle} \Psi_i^{+} \left(t_{ij}^{*} \quad t_{ij} \right) \Psi$
$= -t \sum_{k} \Psi_k^{+} \left(\gamma_k^{*} \quad \gamma_k \right) \Psi_k$
$[H, \hat{T}] = 0$
$\gamma_k = \sum_{\vec{\delta}} e^{i\vec{k}\cdot\vec{\delta}} = e^{i\frac{k_y}{\sqrt{3}}} + e^{-i\frac{k_y}{2\sqrt{3}}} 2\cos\left(\frac{k_x}{2}\right)$


H = -t ∑_{<ij>σ} c†_{iσ} c_{jσ} = t ∑_{i,δ} c†_i d_{i+δ} + h.c = -t ∑_{<ij>} Ψ†_i (t*_ij t_ij) Ψ_j
= -t ∑_k Ψ†_k (γ*_k γ_k) Ψ_k
[H, T̂] = 0
γ_k = ∑_δ e^{i k·δ} = e^{i k_y/√3} + e^{-i k_y/(2√3)} 2cos(k_x/2)

$$H = -t\sum_{\langle ij\rangle\sigma} c^{\dagger}_{i\sigma} c_{j\sigma} = t\sum_{i,\vec{\delta}} c_i^{\dagger} d_{i+\delta} + h.c. = -t\sum_{\langle ij\rangle}\Psi_i^{\dagger} \begin{pmatrix} & t_{ij} \\ t^{*}_{ij} & \end{pmatrix}\Psi_j$$

$$= -t\sum_{k} \Psi_k^{\dagger} \begin{pmatrix} & \gamma_k \\ \gamma_k^{*} & \end{pmatrix}\Psi_k$$

$$[H, \hat{T}] = 0$$

$$\gamma_k = \sum_{\vec{\delta}} e^{i\vec{k}\cdot\vec{\delta}} = e^{i\frac{k_y}{\sqrt{3}}} + e^{-i\frac{k_y}{2\sqrt{3}}}\, 2\cos\left(\frac{k_x}{2}\right)$$

$$\hat{H}^2 = \begin{pmatrix} |\gamma_k|^2 & \\ & |\gamma_k|^2 \end{pmatrix}$$

$$H = -t \sum_{\langle ij \rangle \sigma} c^{\dagger}_{i\sigma} c_{j\sigma} = t \sum_{i, \vec{\delta}} c^{\dagger}_{i} d_{i+\delta} + h.c. = -t \sum_{\langle ij \rangle} \Psi^{\dagger}_{i} \begin{pmatrix} & t_{ij} \\ t^{*}_{ij} & \end{pmatrix} \Psi_{j}$$

$$= -t \sum_{k} \Psi^{\dagger}_{k} \begin{pmatrix} & \gamma_k \\ \gamma^{*}_{k} & \end{pmatrix} \Psi_{k}$$

$$[H, \hat{T}] = 0$$

$$\gamma_k = \sum_{\vec{\delta}} e^{i \vec{k} \cdot \vec{\delta}} = e^{i \frac{k_y}{\sqrt{3}}} + e^{-i \frac{k_y}{2\sqrt{3}}} \, 2\cos\left(\frac{k_x}{2}\right)$$

$$\hat{H}^2 = \begin{pmatrix} |\gamma_k|^2 & \\ & |\gamma_k|^2 \end{pmatrix}$$

$$E_k = \pm |\gamma_k|$$

$$H = -t\sum_{\langle ij\rangle\sigma} c^\dagger_{i\sigma} c_{j\sigma} = t\sum_{i,\vec\delta} c^\dagger_i d_{i+\delta} + h.c. = -t\sum_{\langle ij\rangle} \Psi^\dagger_i \begin{pmatrix} & t_{ij} \\ t^*_{ij} & \end{pmatrix} \Psi_j$$

$$= -t\sum_{k} \Psi^\dagger_k \begin{pmatrix} & \gamma_k \\ \gamma^*_k & \end{pmatrix} \Psi_k$$

$$[H, \hat{T}] = 0$$

$$\gamma_k = \sum_{\vec\delta} e^{i\vec{k}\cdot\vec{\delta}} = e^{i\frac{k_y}{\sqrt{3}}} + e^{-i\frac{k_y}{2\sqrt{3}}}\, 2\cos\left(\frac{k_x}{2}\right)$$

$$H^2 = \begin{pmatrix} |\gamma_k|^2 & \\ & |\gamma_k|^2 \end{pmatrix}$$

$$E_k = \pm|\gamma_k|$$

$$H = -t \sum_{\langle ij \rangle \sigma} c_{i\sigma}^\dagger c_{j\sigma} = t \sum_{i,\vec{\delta}} c_i^\dagger d_{i+\delta} + h.c. = -t \sum_{\langle ij \rangle} \psi_i^\dagger \begin{pmatrix} & t_{ij} \\ t_{ij}^* & \end{pmatrix} \psi_j$$

$$= -t \sum_k \psi_k^\dagger \begin{pmatrix} & \gamma_k \\ \gamma_k^* & \end{pmatrix} \psi_k$$

$$[H, \hat{T}] = 0$$

$$\gamma_k = \sum_{\vec{\delta}} e^{i\vec{k}\cdot\vec{\delta}} = e^{i\frac{k_y}{\sqrt{3}}} + e^{-i\frac{k_y}{2\sqrt{3}}} 2\cos\left(\frac{k_x}{2}\right)$$

$$\hat{H}^2 = \begin{pmatrix} |\gamma_k|^2 & \\ & |\gamma_k|^2 \end{pmatrix}$$

$$E_k = \pm |\gamma_k|$$

$$H = -t \sum_{\langle ij \rangle \sigma} c_{i\sigma}^\dagger c_{j\sigma} = t \sum_{i, \vec{\delta}} c_i^\dagger d_{i+\delta} + h.c. = -t \sum_{\langle ij \rangle} \Psi_i^\dagger \begin{pmatrix} & t_{ij} \\ t_{ij}^* & \end{pmatrix} \Psi_j$$

$$= -t \sum_k \Psi_k^\dagger \begin{pmatrix} & \gamma_k \\ \gamma_k^* & \end{pmatrix} \Psi_k$$

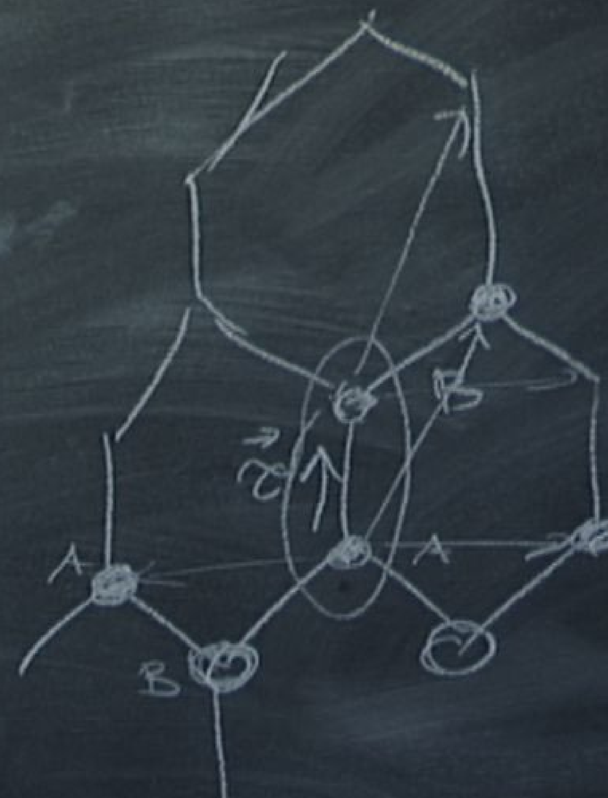
$$[H, \hat{T}] = 0$$

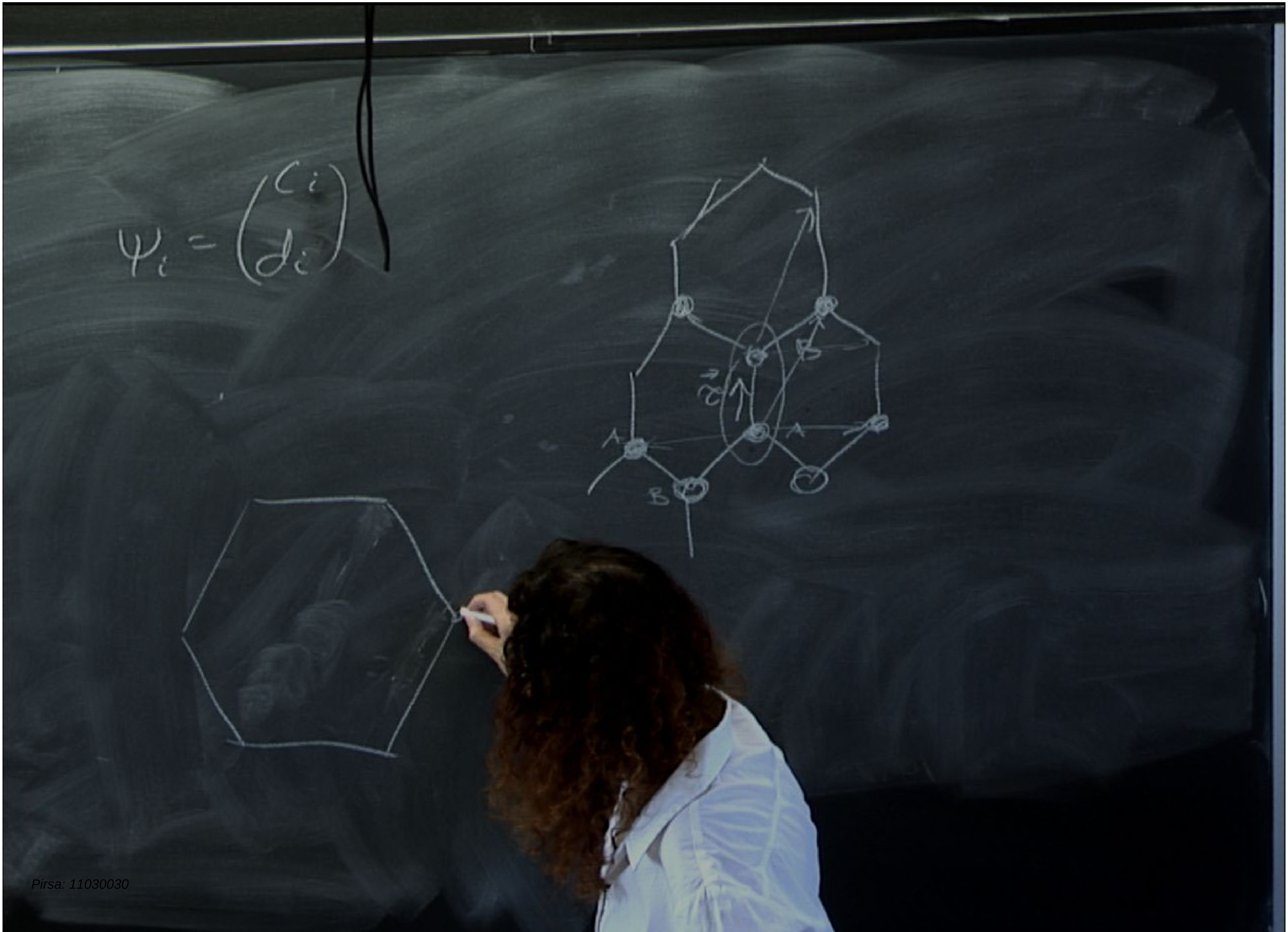
$$\gamma_k = \sum_{\vec{\delta}} e^{i \vec{k} \cdot \vec{\delta}} = e^{i \frac{k_y}{\sqrt{3}}} + e^{-i \frac{k_y}{2\sqrt{3}}} 2\cos\left(\frac{k_x}{2}\right)$$

$$\hat{H}^2 = \begin{pmatrix} |\gamma_k|^2 & \\ & |\gamma_k|^2 \end{pmatrix}$$

$$E_k = \pm |\gamma_k|$$

$$\Psi_i = \begin{pmatrix} c_i \\ d_i \end{pmatrix}$$

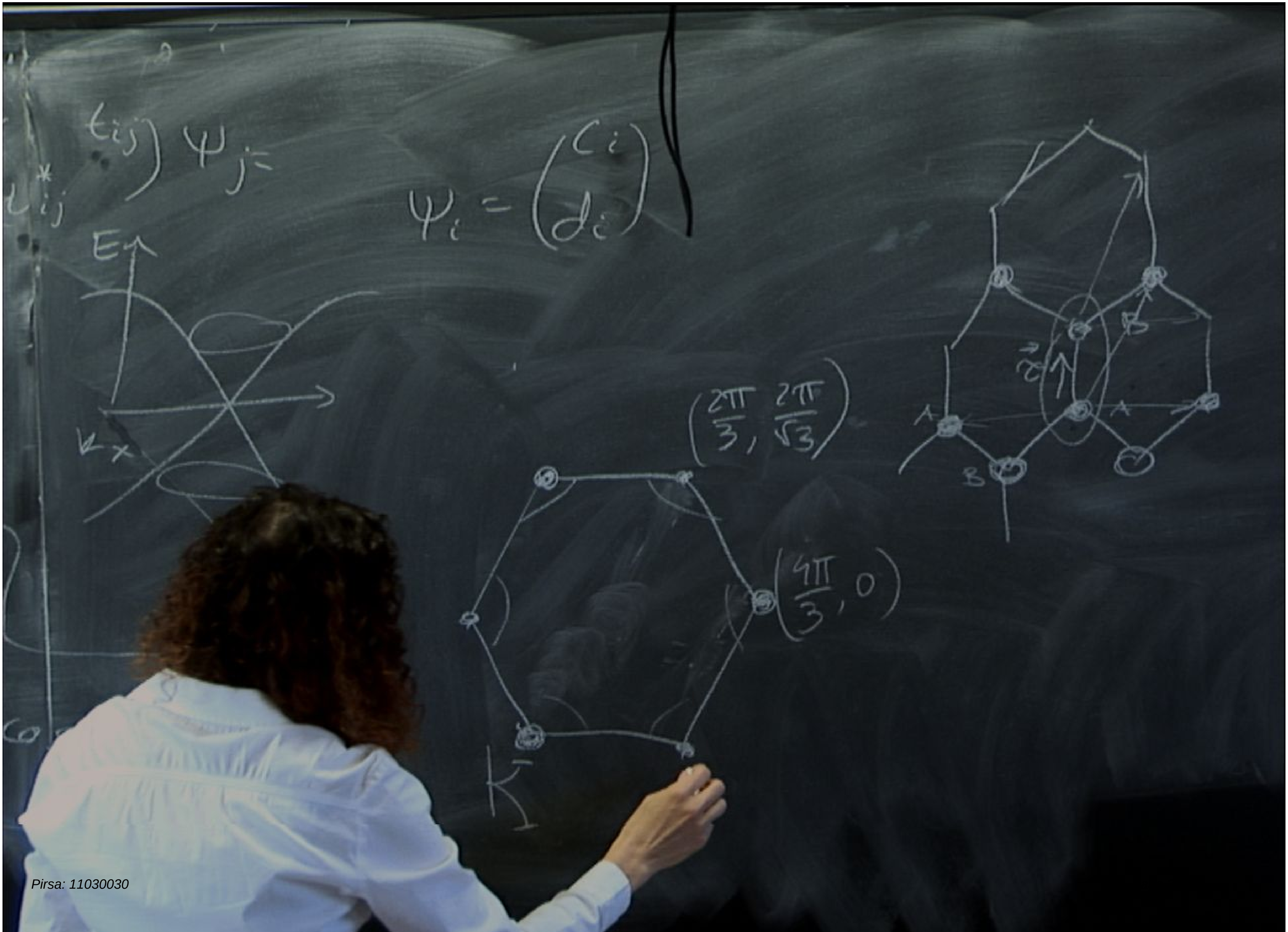



$\Psi_i = \begin{pmatrix} c_i \\ d_i \end{pmatrix}$
A
B
A
B
$\vec{\tau}$

$$\Psi_i = \begin{pmatrix} c_i \\ d_i \end{pmatrix}$$

$$\left(\frac{2\pi}{3}, \frac{2\pi}{\sqrt{3}}\right)$$

$$\left(\frac{4\pi}{3}, 0\right)$$



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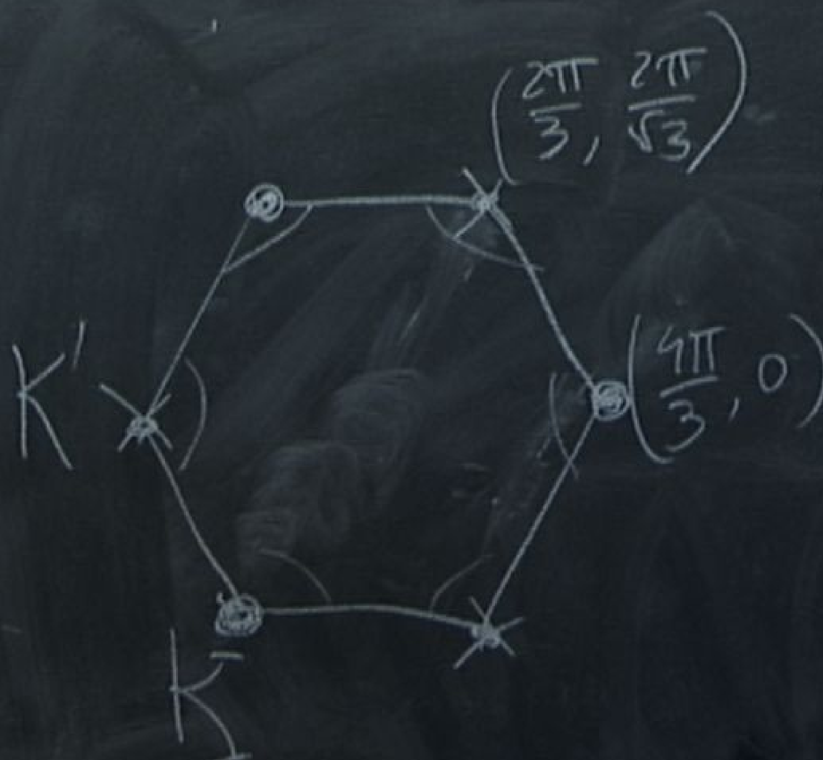
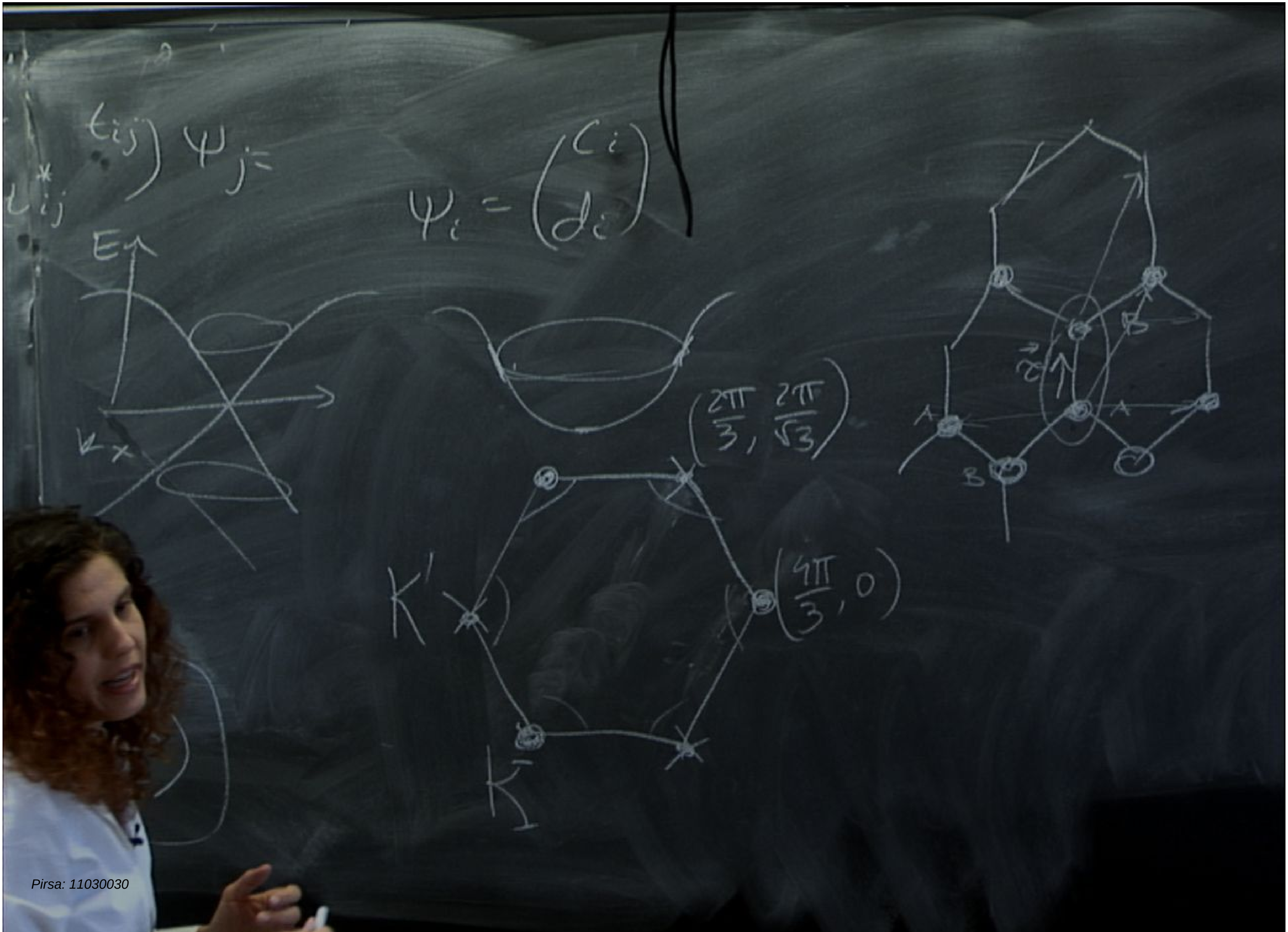
$t_{ij}) \psi_j =$

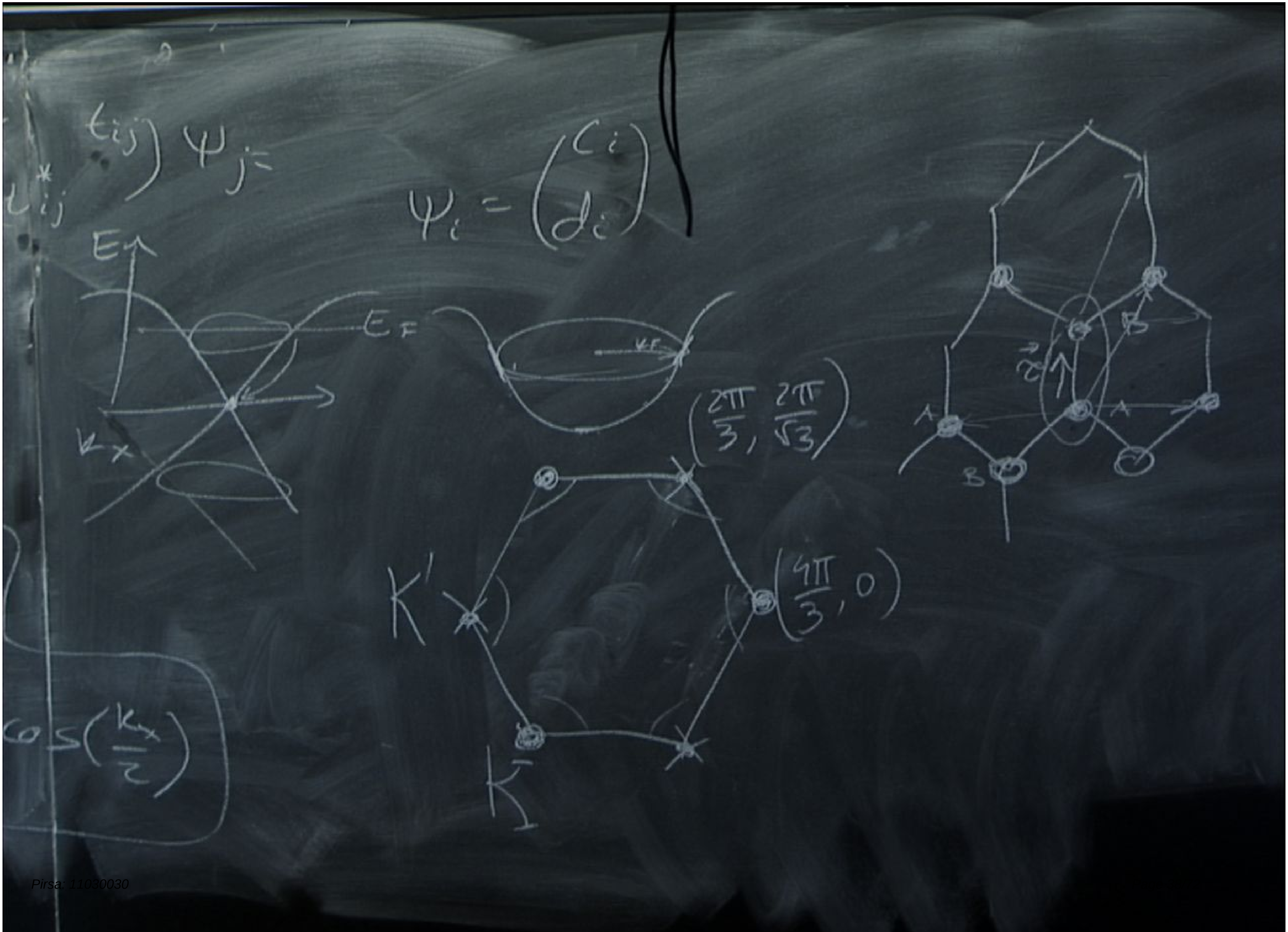
t^*_{ij}

$\psi_i = \begin{pmatrix} c_i \\ d_i \end{pmatrix}$

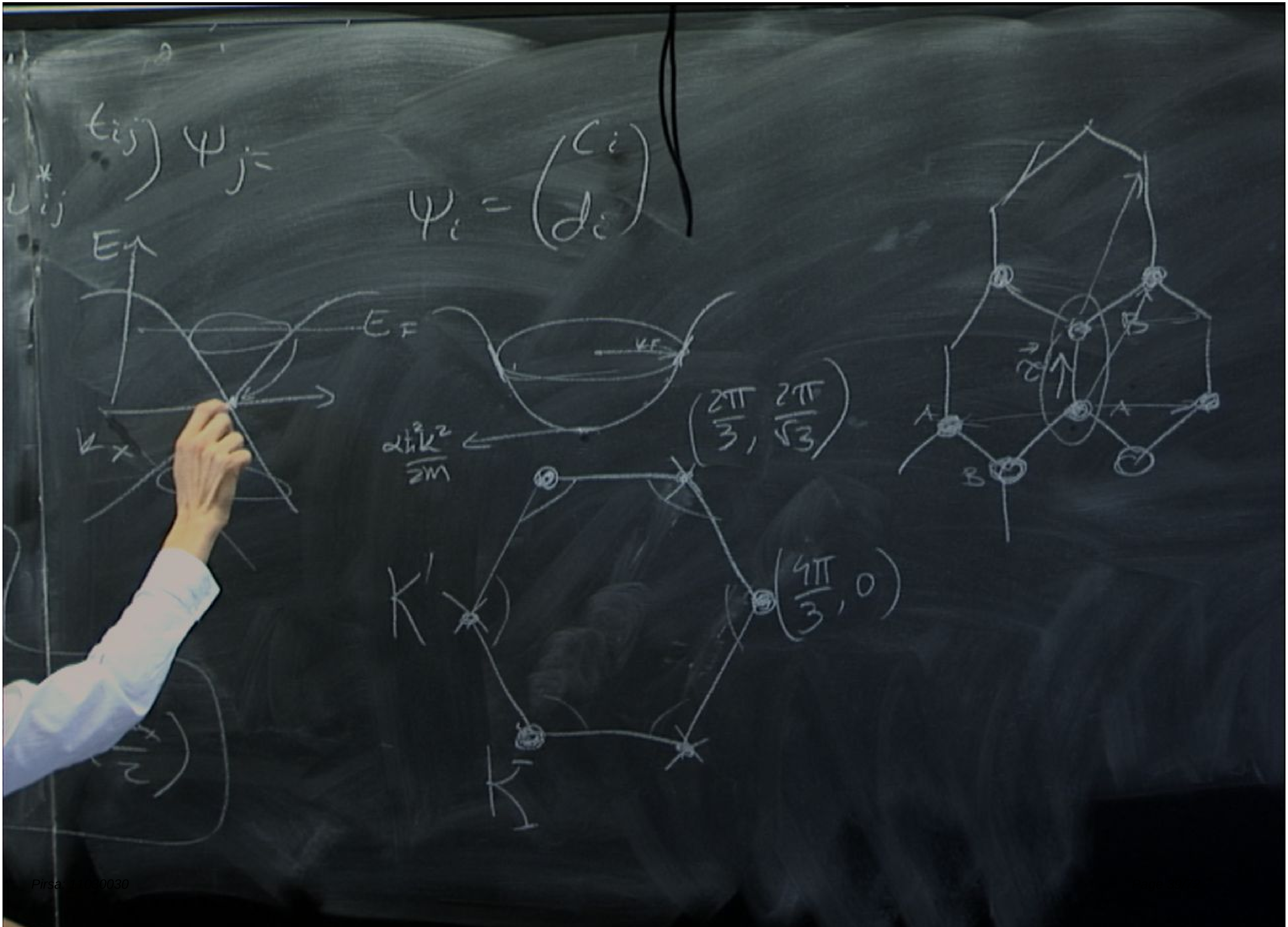


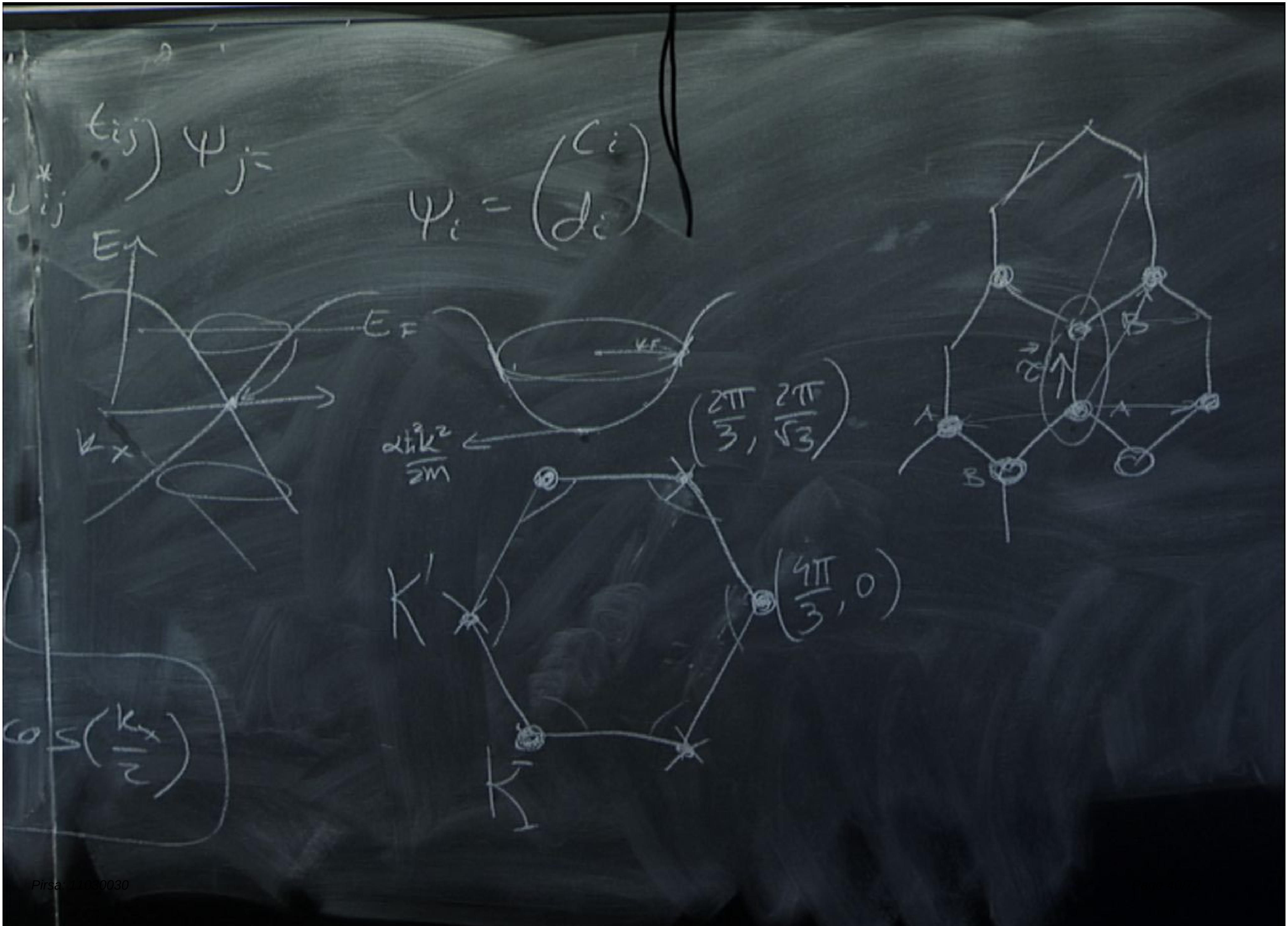
$\cos\left(\frac{k_x}{2}\right)$

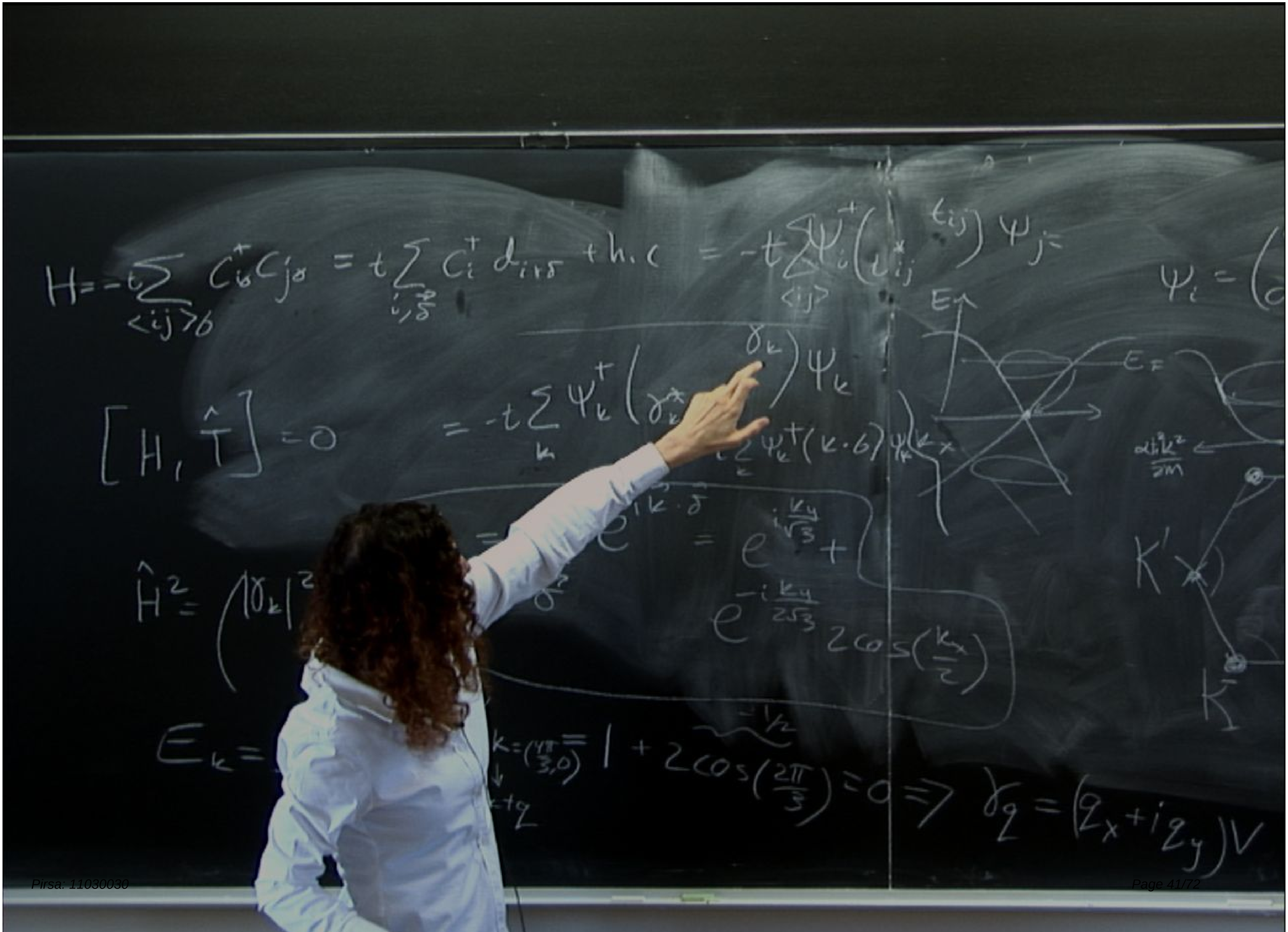

ψ_i = (c_i, d_i)
E
k_x
(2π/3, 2π/√3)
(4π/3, 0)
K'
K
A
B



$t_{ij})\,\psi_j =$
t^*_{ij}
$\psi_i = \begin{pmatrix} c_i \\ d_i \end{pmatrix}$
E
k_x
E_F
v_F
$\left(\frac{2\pi}{3}, \frac{2\pi}{\sqrt{3}}\right)$
$\left(\frac{4\pi}{3}, 0\right)$
K'
K
A
B
$\cos\left(\frac{k_x}{2}\right)$


$\psi_i = \begin{pmatrix} c_i \\ d_i \end{pmatrix}$
E
E_F
v_F
k_x
$\frac{\alpha \hbar^2 k^2}{2m}$
$\left(\frac{2\pi}{3}, \frac{2\pi}{\sqrt{3}}\right)$
$\left(\frac{4\pi}{3}, 0\right)$
K'
K
A
B


t_ij) ψ_j =
ψ_i = (c_i d_i)
E
E_F
k_x
v_F
αħ²k²/2m
(2π/3, 2π/√3)
(4π/3, 0)
K'
K
A
B
τ
cos(k_x/2)


[H, T̂] = 0
E_F
K'
K

$$H = -t \sum_{\langle ij \rangle \sigma} c_{i\sigma}^{\dagger} c_{j\sigma} = t \sum_{i,\vec{\delta}} c_i^{\dagger} d_{i+\delta} + h.c. = -t \sum_{\langle ij \rangle} \psi_i^{\dagger} \begin{pmatrix} & t_{ij} \\ t_{ij}^{*} & \end{pmatrix} \psi_j$$

$$= -t \sum_k \psi_k^{\dagger} \begin{pmatrix} & \gamma_k \\ \gamma_k^{*} & \end{pmatrix} \psi_k$$

$$\Rightarrow -t \sum_k \psi_k^{\dagger} (k \cdot \sigma) \psi_k$$

$$[H, \hat{T}] = 0$$

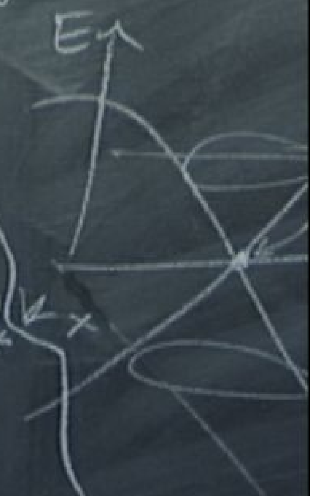
$$\gamma_k = \sum_{\vec{\delta}} e^{i \vec{k} \cdot \vec{\delta}} = e^{i \frac{k_y}{\sqrt{3}}} + e^{-i \frac{k_y}{2\sqrt{3}}} 2\cos\left(\frac{k_x}{2}\right)$$

$$\hat{H}^2 = \begin{pmatrix} |\gamma_k|^2 & \\ & |\gamma_k|^2 \end{pmatrix}$$

$$E_k = \pm |\gamma_k|$$

$$\gamma_{k=(\frac{4\pi}{3},0)} = 1 + 2\cos\left(\frac{2\pi}{3}\right) = 0 \Rightarrow \gamma_q =$$

$k \to k+q$, $-1/2$



$$H = -t\sum_{\langle ij\rangle\sigma} c^\dagger_{i\sigma} c_{j\sigma} = t\sum_{i,\vec\delta} c_i^\dagger d_{i+\delta} + h.c. = -t\sum_{\langle ij\rangle} \Psi_i^\dagger \begin{pmatrix} & t_{ij} \\ t^*_{ij} & \end{pmatrix}\Psi_j =$$

$$\Psi_i = (c \ldots$$

$$= -t\sum_k \Psi_k^\dagger \begin{pmatrix} & \gamma_k \\ \gamma_k^* & \end{pmatrix} \Psi_k$$

$$\Rightarrow -t\sum_k \Psi_k^\dagger (k\cdot\sigma)\Psi_k \quad k\times$$

$$[H, \hat{T}] = 0$$

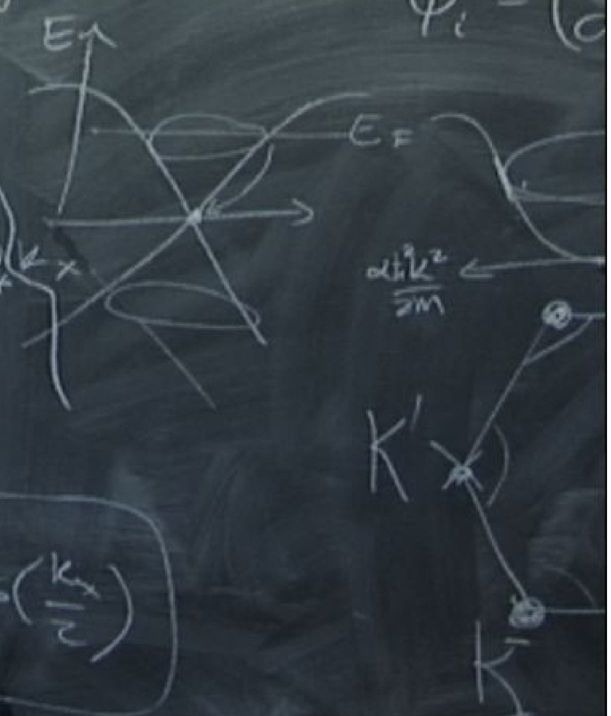
$$\gamma_k = \sum_{\vec\delta} e^{i\vec k\cdot\vec\delta} = e^{i\frac{k_y}{\sqrt{3}}} + e^{-i\frac{k_y}{2\sqrt{3}}}\, 2\cos\left(\frac{k_x}{2}\right)$$

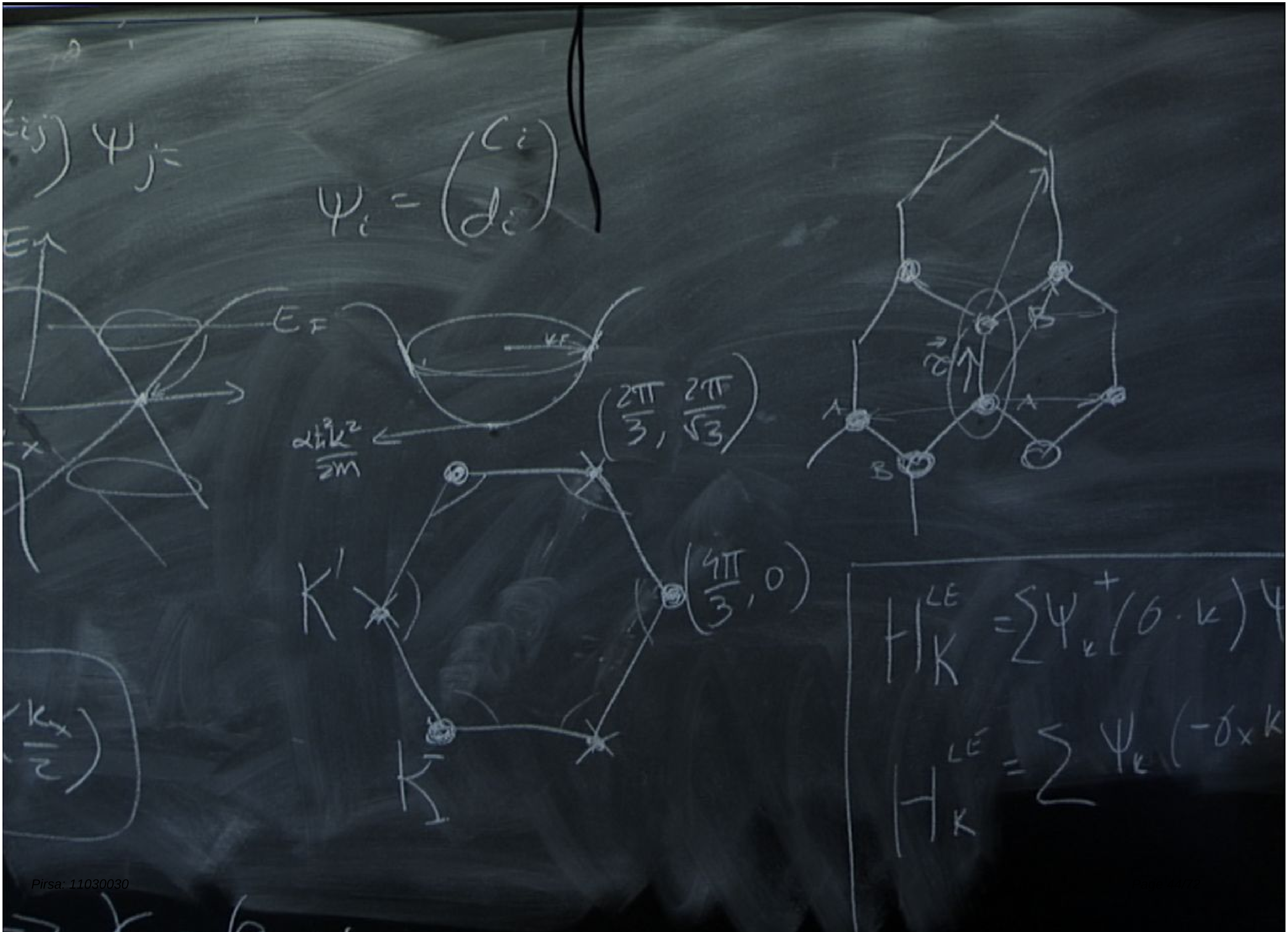
$$\hat{H}^2 = \begin{pmatrix} |\gamma_k|^2 & \\ & |\gamma_k|^2 \end{pmatrix}$$

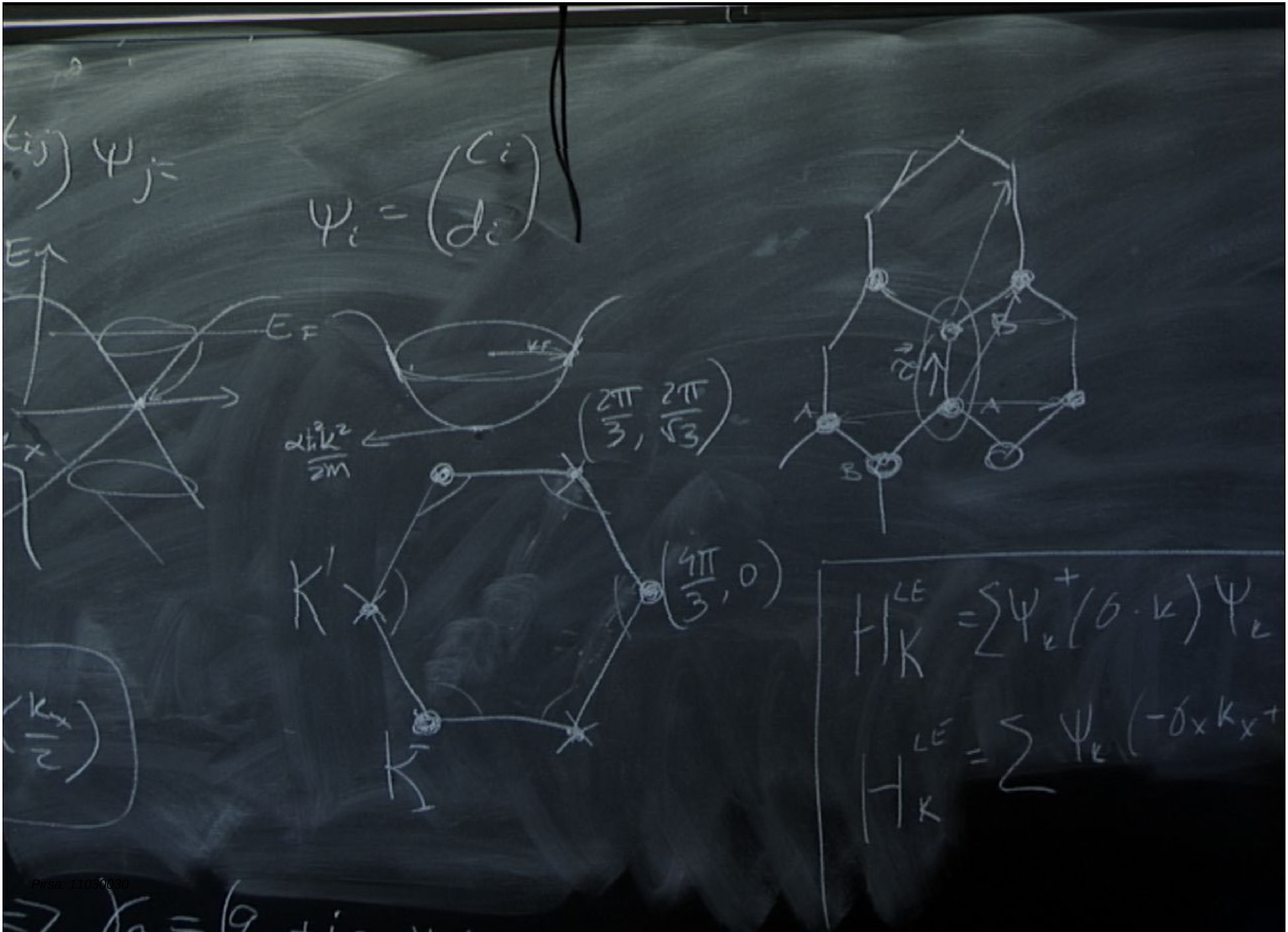
$$E_k = \pm|\gamma_k|$$

$$\gamma_{k=(\frac{4\pi}{3},0)} = 1 + 2\underbrace{\cos\left(\frac{2\pi}{3}\right)}_{-1/2} = 0 \Rightarrow \gamma_q = (q_x + i q_y)V$$

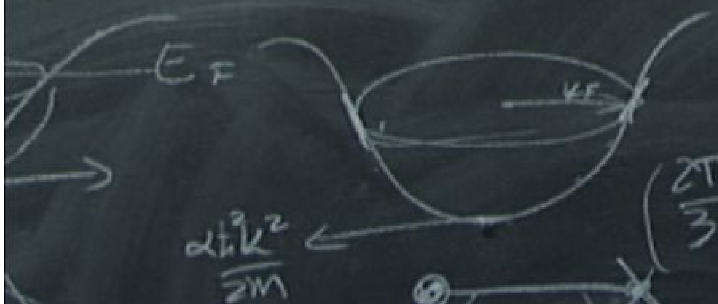
$$k \to k+q$$

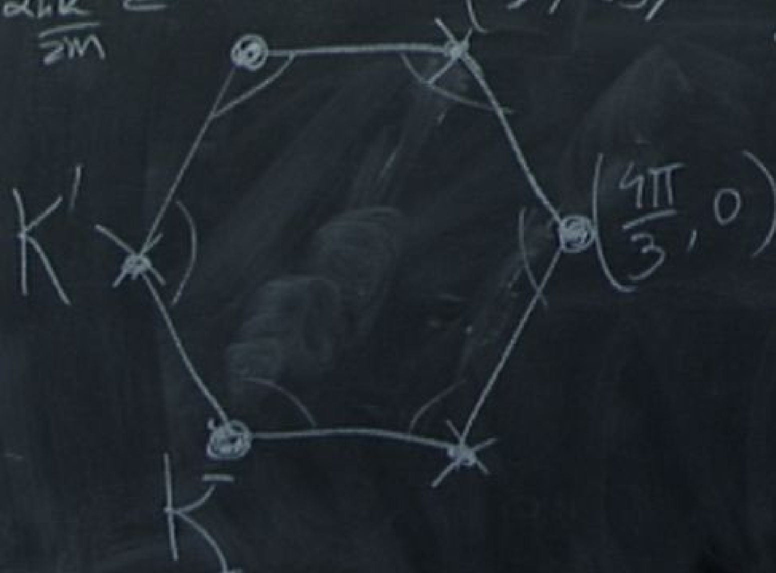


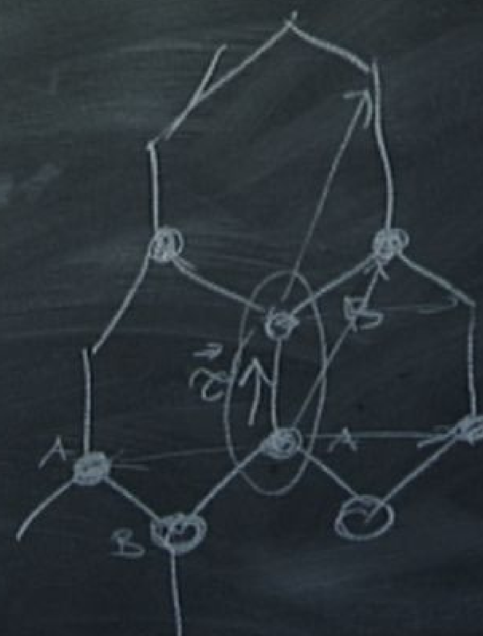

Ψi = (ci / di)
E
EF
vF
αħ²k²/2m
(2π/3, 2π/√3)
(4π/3, 0)
K'
K
A
B
H_K^LE = Σ Ψk† (σ·k) Ψ
H_K^LE = Σ Ψk (−σx k


Ψi = (ci di)
EF
K'
K
(2π/3, 2π/√3)
(4π/3, 0)
A
B
HK LE = Σ Ψk+ (σ · k) Ψk

$$\Psi_i = \begin{pmatrix} c_i \\ d_i \end{pmatrix}$$

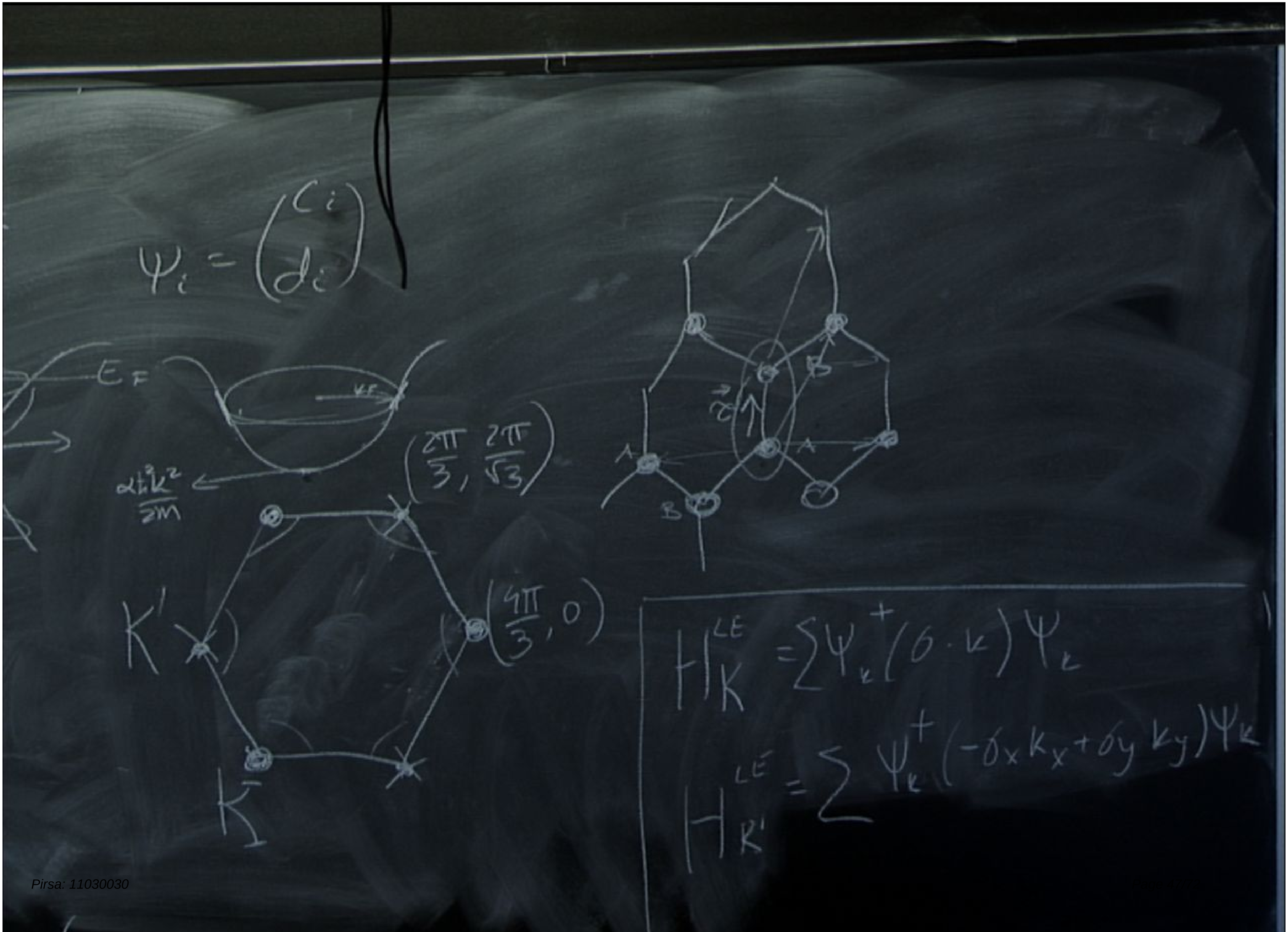


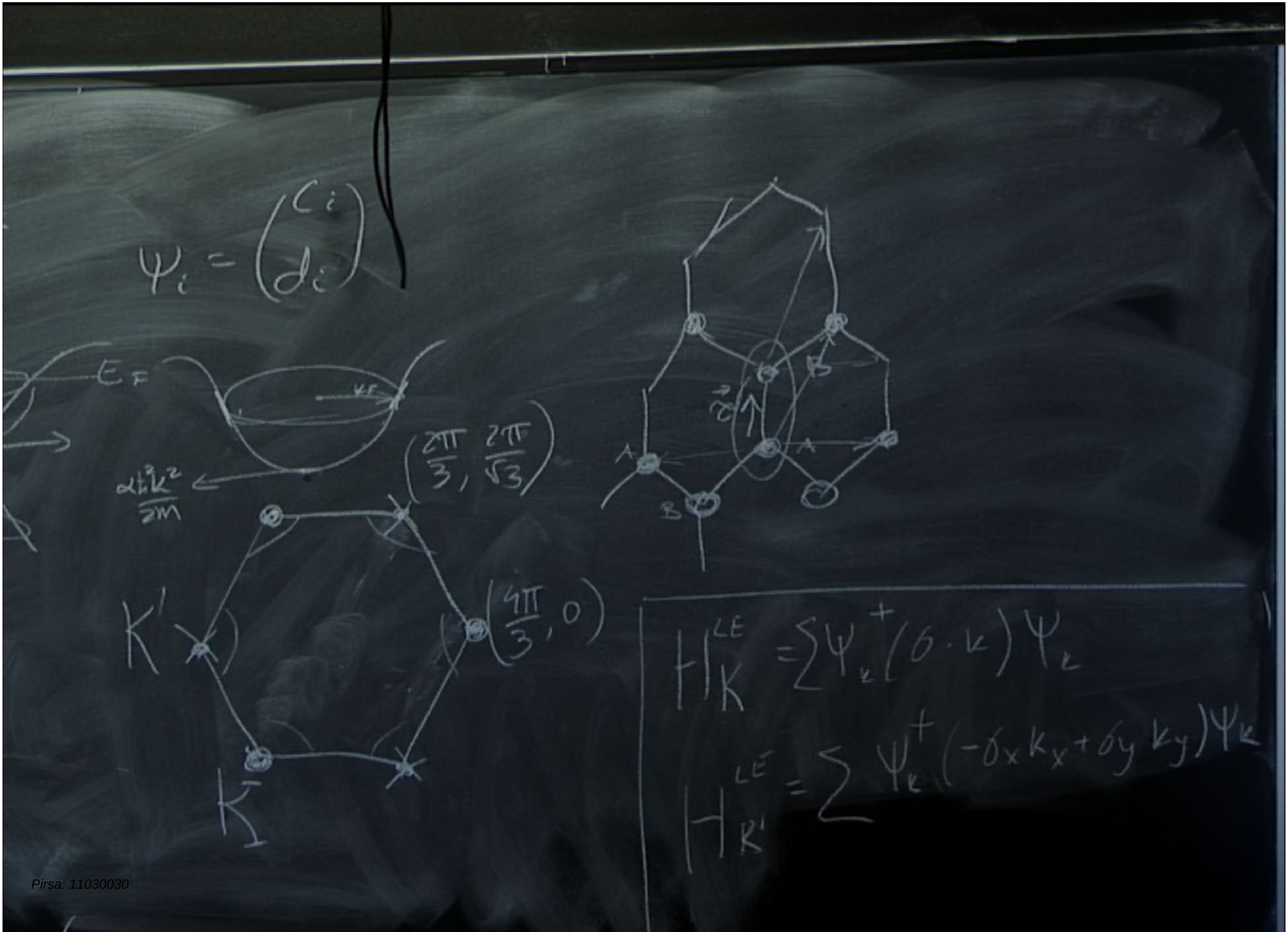


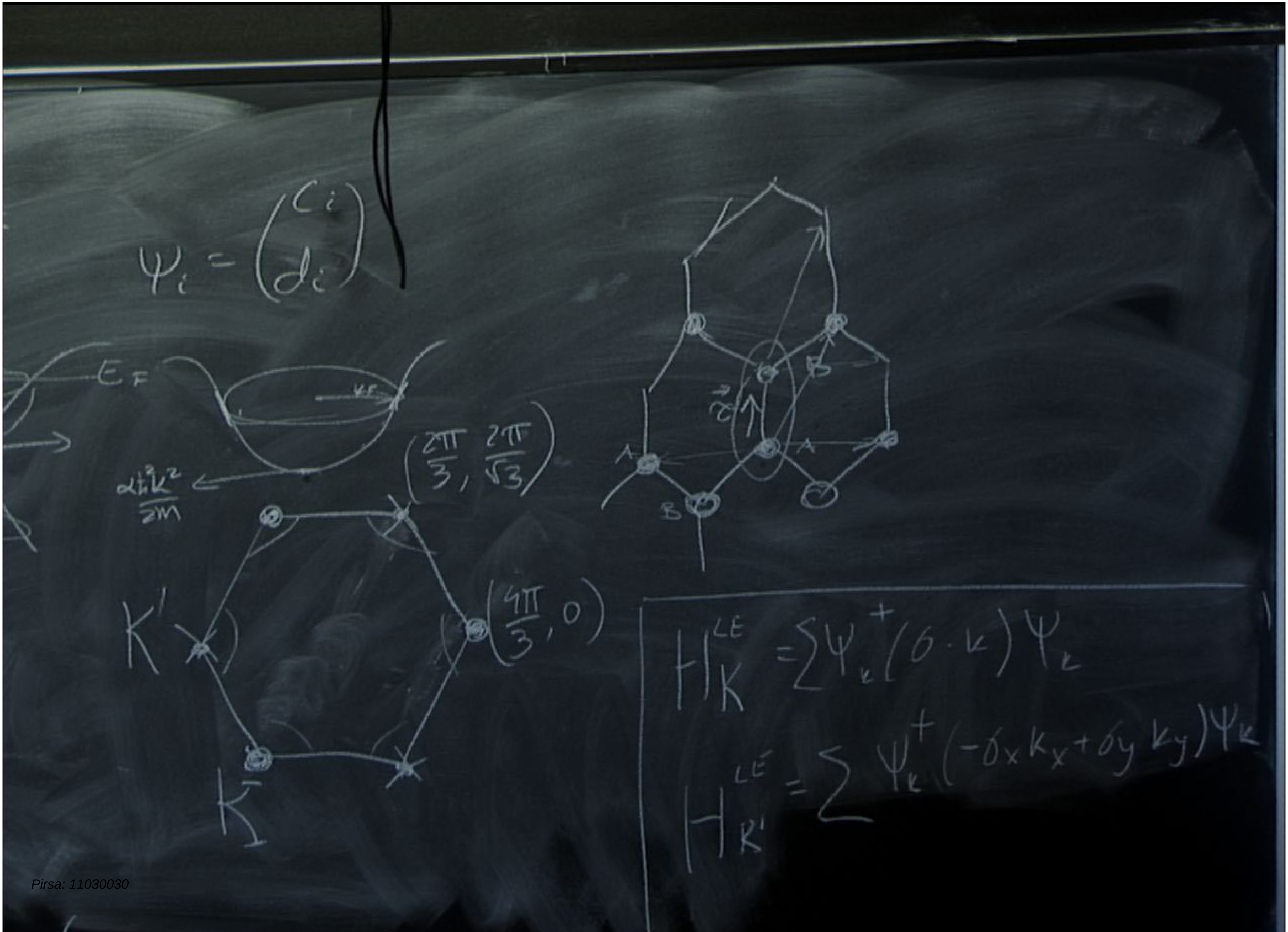


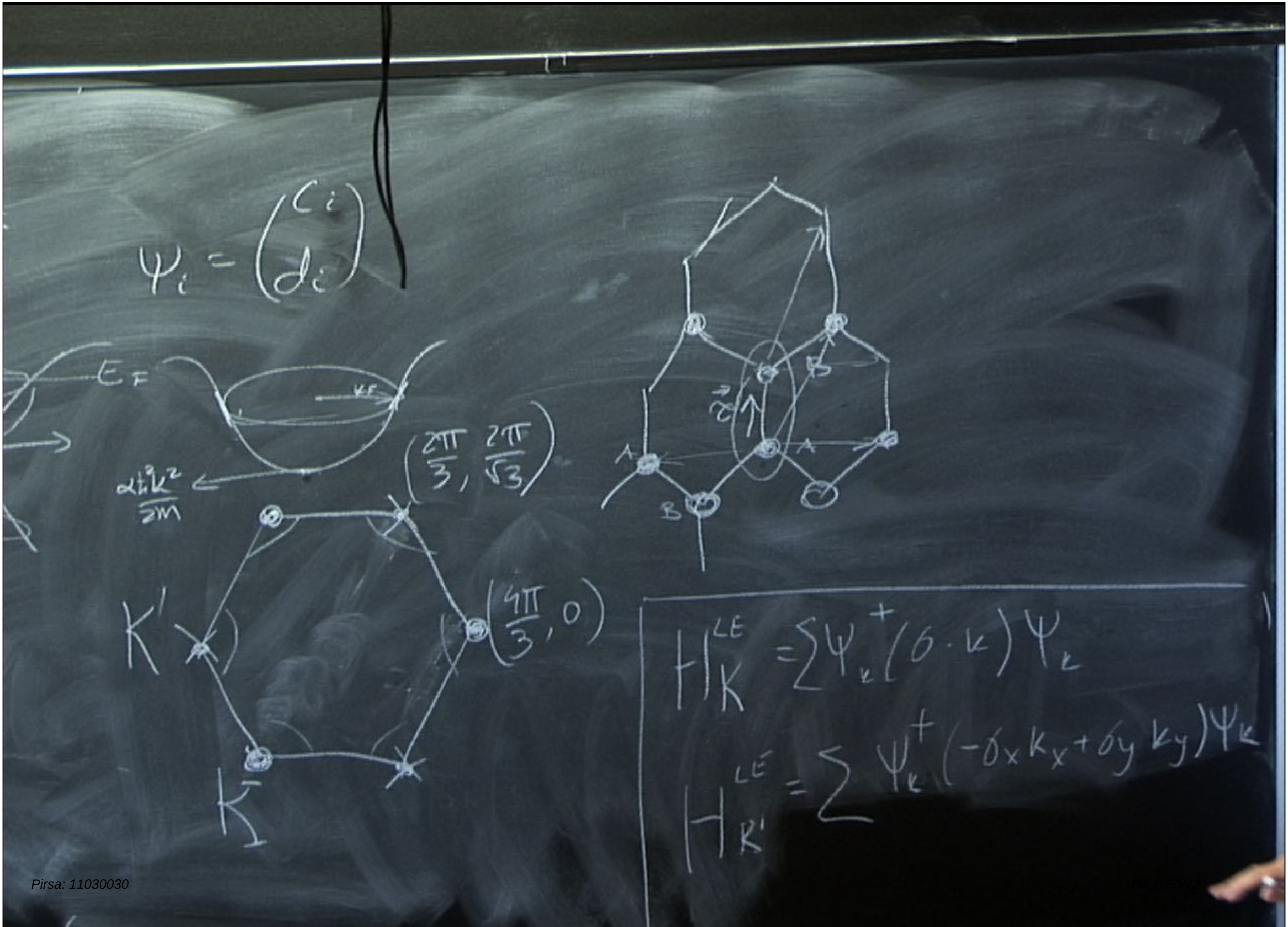
$$H_K^{LE} = \sum \Psi_k^\dagger (\sigma \cdot k) \Psi_k$$

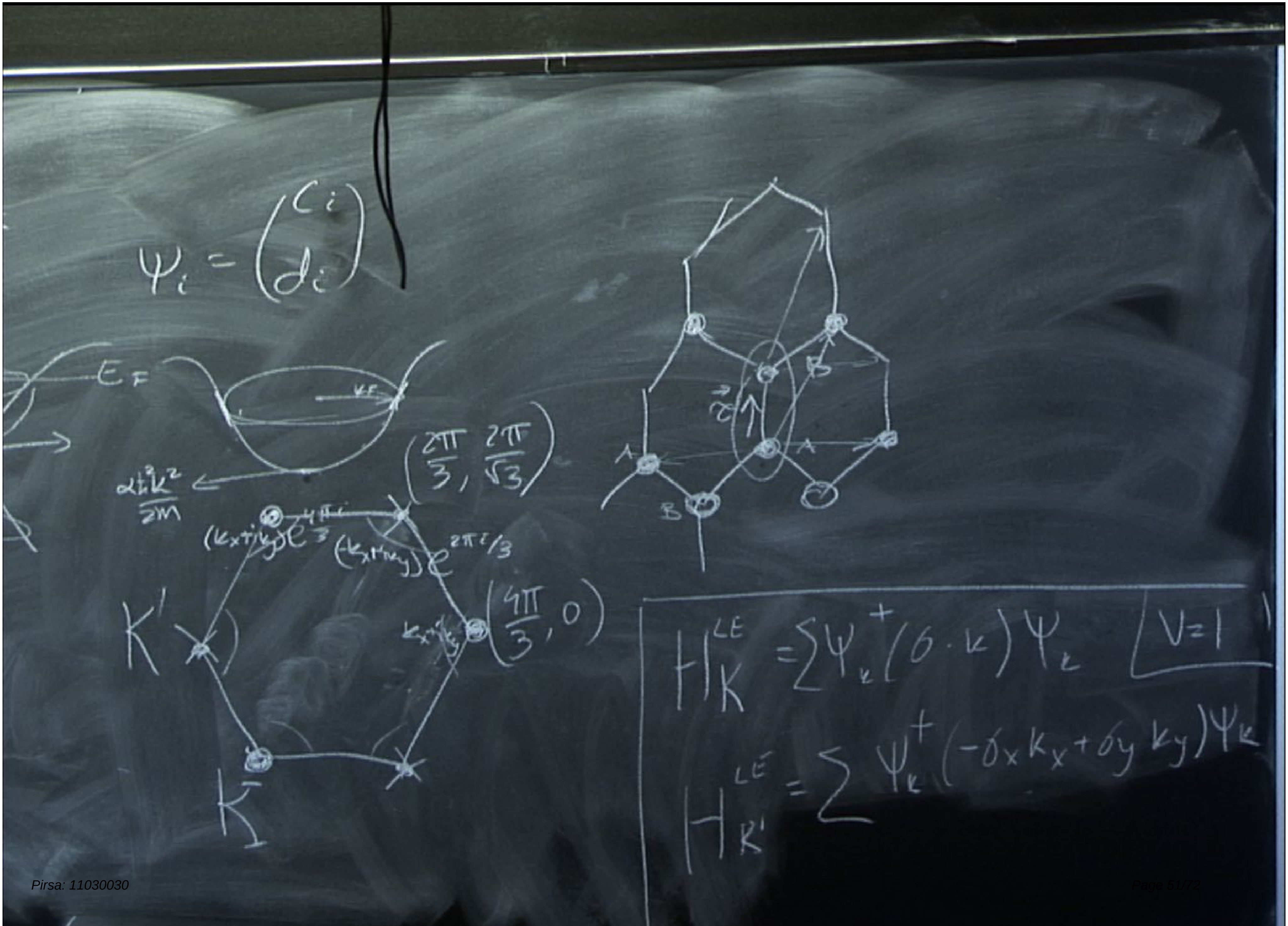
$$H_{K'}^{LE} = \sum \Psi_k^\dagger (-\sigma_x k_x + \sigma_y k_y) \Psi_k$$

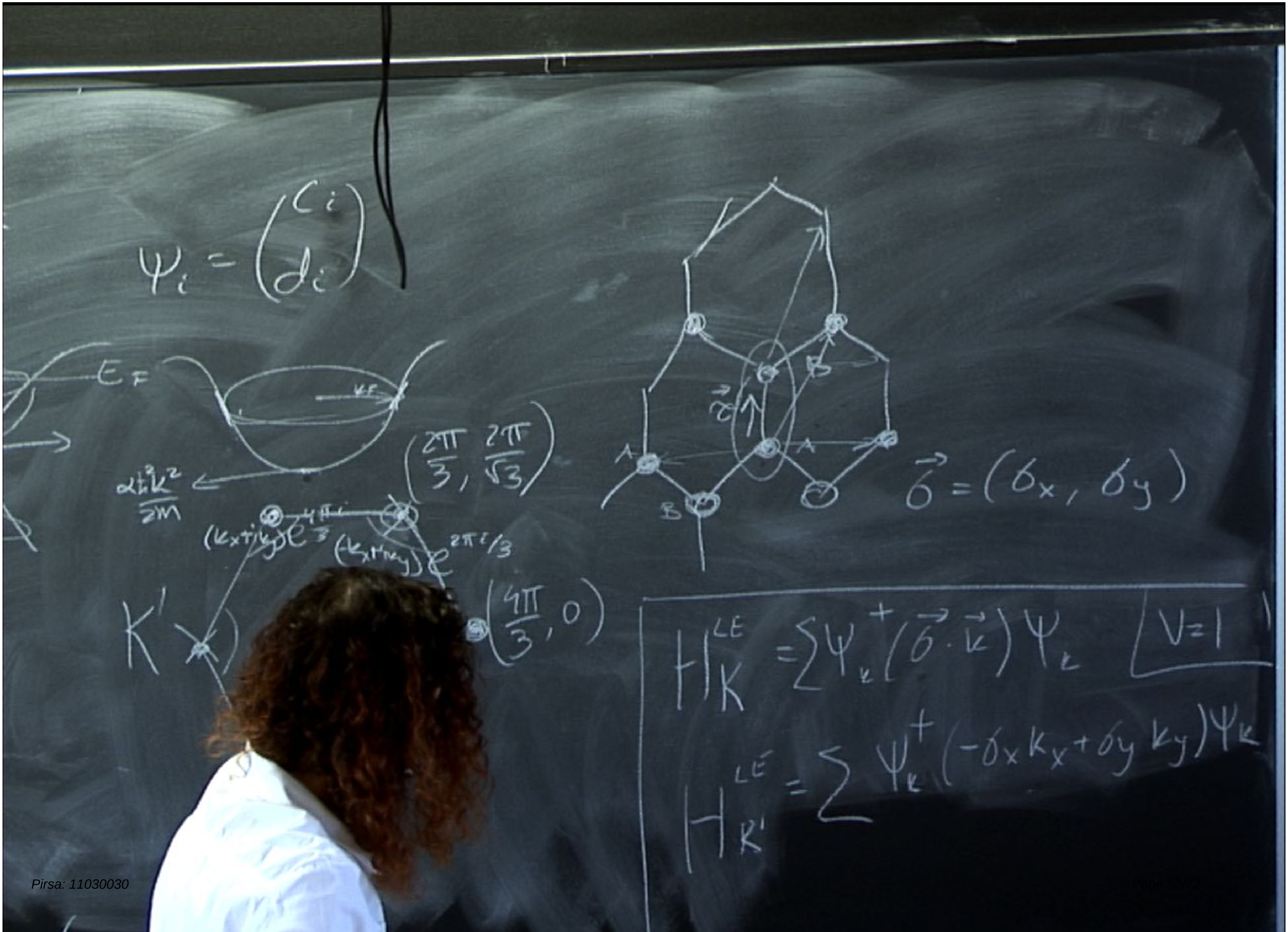

Ψi = (ci / di)
EF
vF
ħ²k²/2m
(2π/3, 2π/√3)
(4π/3, 0)
K'
K
A
B
HK^LE = Σ Ψk† (σ·k) Ψk
HK'^LE = Σ Ψk† (−σx kx + σy ky) Ψk


$\Psi_i = \begin{pmatrix} c_i \\ d_i \end{pmatrix}$
E_F
v_F
$\frac{\alpha \hbar^2 k^2}{2m}$
$\left(\frac{2\pi}{3}, \frac{2\pi}{\sqrt{3}}\right)$
$\left(\frac{4\pi}{3}, 0\right)$
K'
K
A
B
$\vec{a}$
$H_K^{LE} = \sum \Psi_k^\dagger (\sigma \cdot k) \Psi_k$
$H_{K'}^{LE} = \sum \Psi_k^\dagger (-\sigma_x k_x + \sigma_y k_y) \Psi_k$

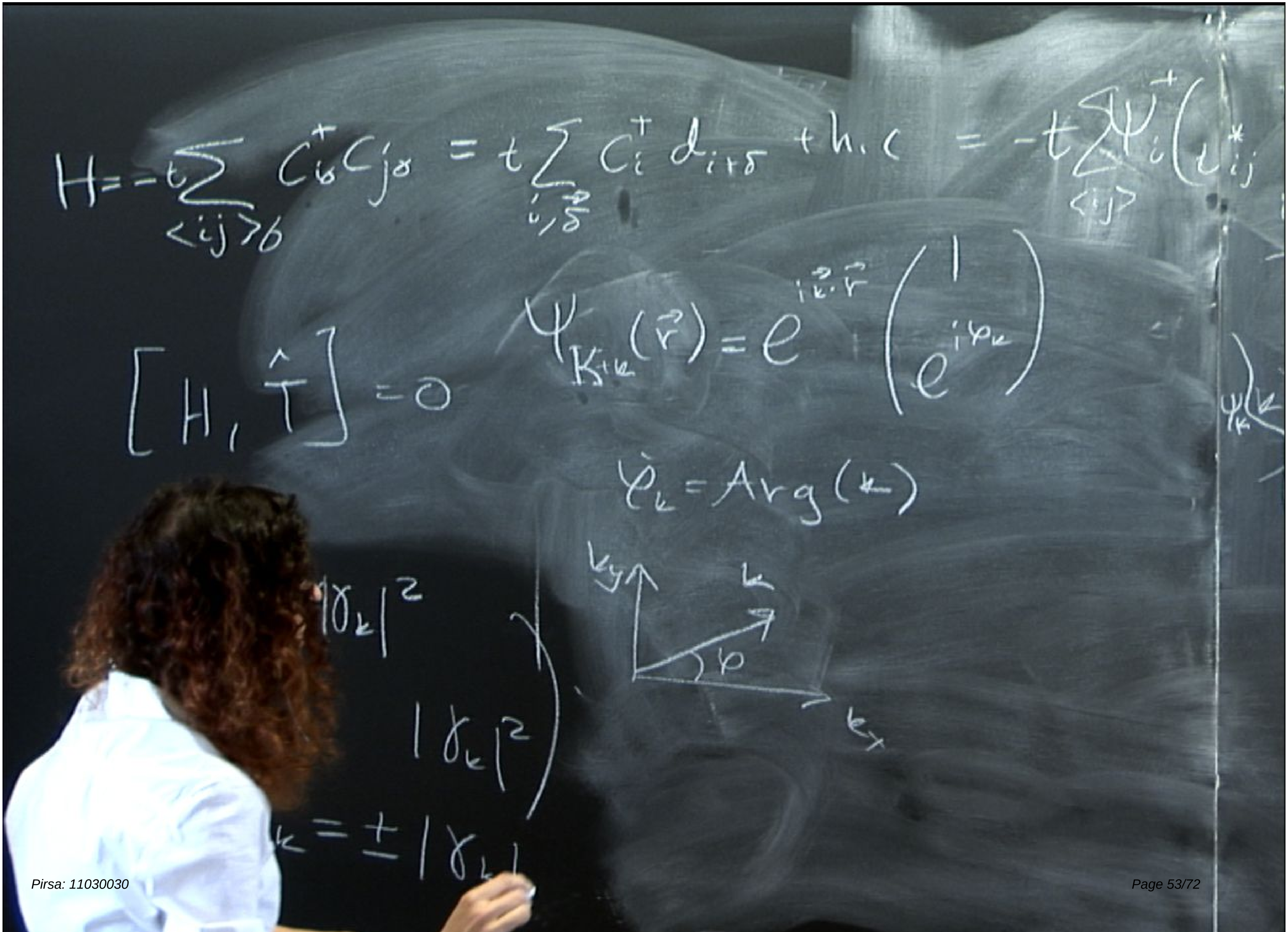

Ψi = (ci di)
EF
vF
αℏ²k²/2m
(2π/3, 2π/√3)
(4π/3, 0)
K'
K
A
B
A
B
A
a
H^LE_K = Σ Ψ†k (σ·k) Ψk
H^LE_K' = Σ Ψ†k (−σx kx + σy ky) Ψk

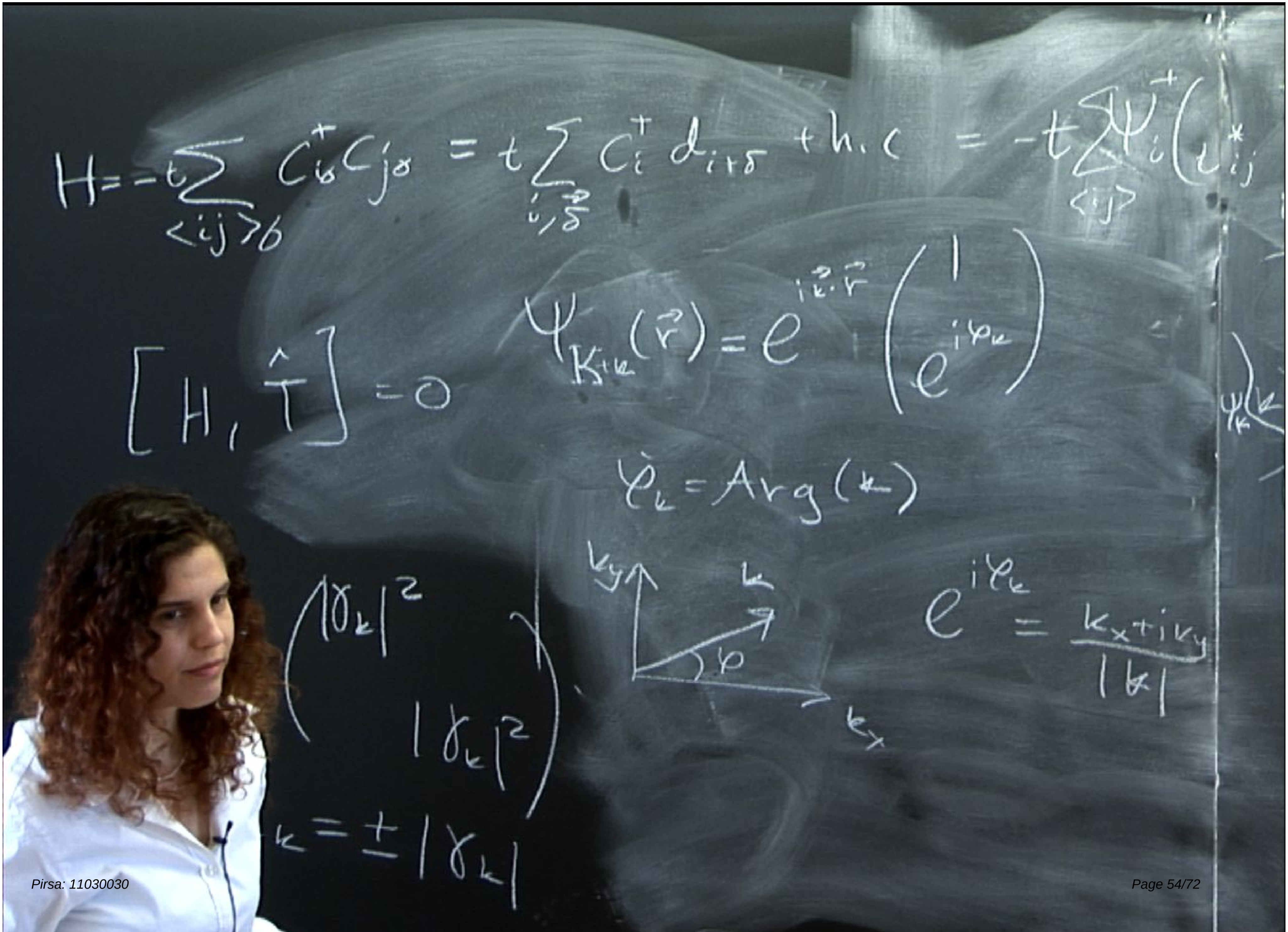

Ψi = (ci di)
EF
vF
αℏ²k²/2m
(2π/3, 2π/√3)
(4π/3, 0)
K'
K
A
B
H^LE_K = Σ Ψ_k^+ (σ·k) Ψ_k
H^LE_K' = Σ Ψ_k^+ (−σx kx + σy ky) Ψk

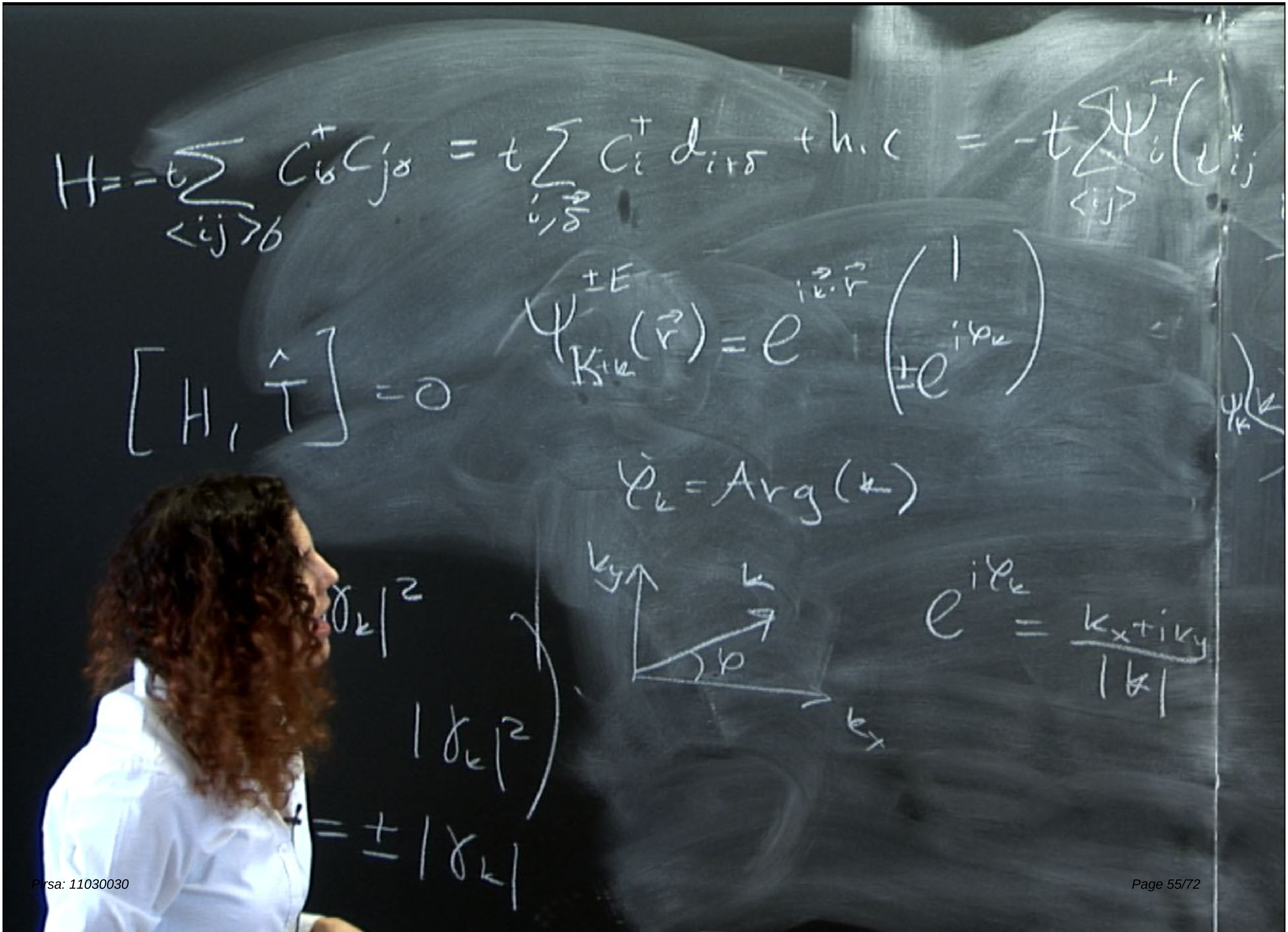

$\Psi_i = \begin{pmatrix} c_i \\ d_i \end{pmatrix}$
E_F
v_F
$\frac{\alpha \hbar^2 k^2}{2m}$
$\left(\frac{2\pi}{3}, \frac{2\pi}{\sqrt{3}}\right)$
$\left(\frac{4\pi}{3}, 0\right)$
K'
K
A
B
$H_K^{LE} = \sum \Psi_k^\dagger (\sigma \cdot k) \Psi_k$
$V=1$
$H_{K'}^{LE} = \sum \Psi_k^\dagger (-\sigma_x k_x + \sigma_y k_y) \Psi_k$

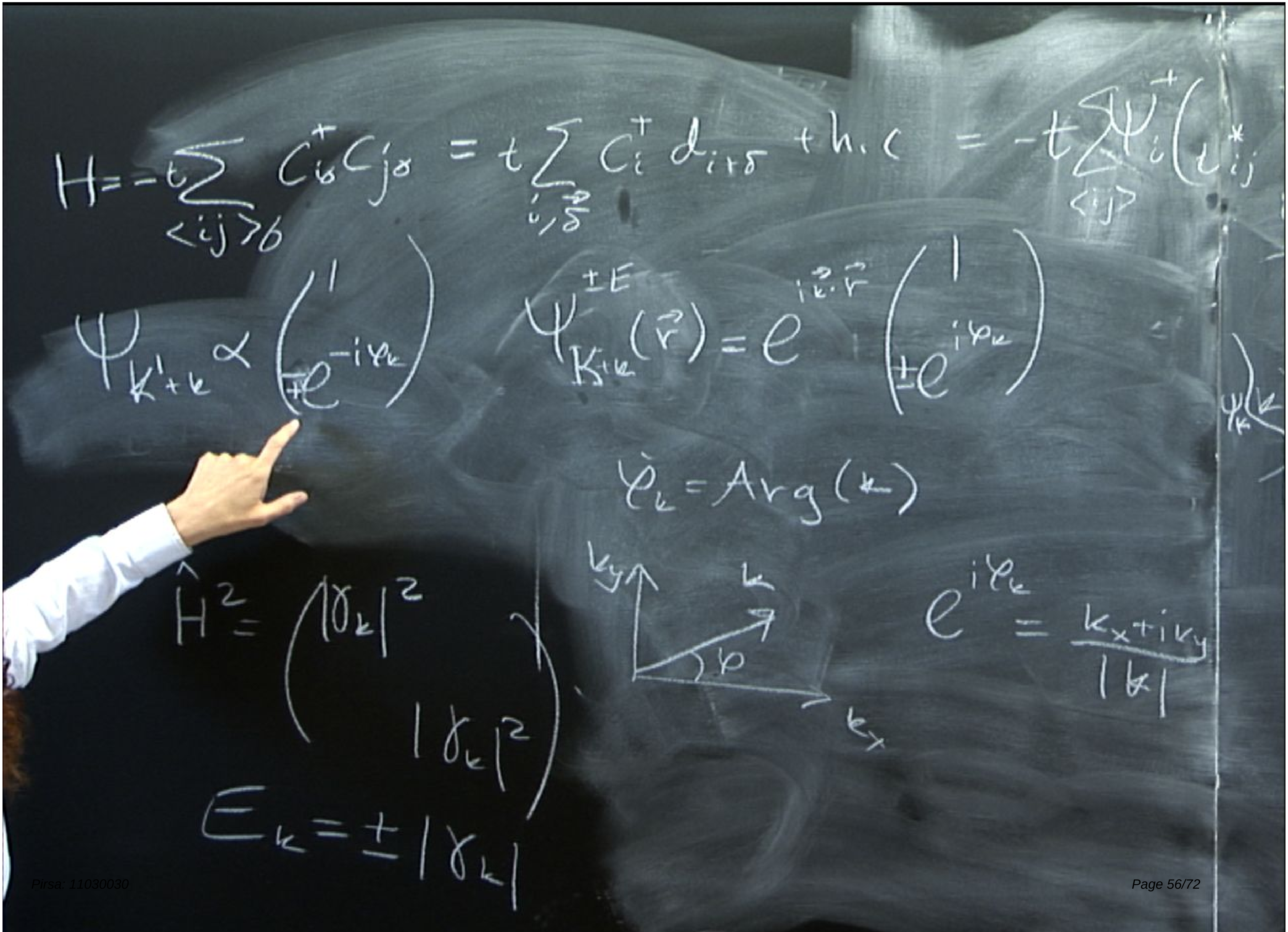


Ψi = (ci, di)
EF
vF
(2π/3, 2π/√3)
αħ²k²/2m
(kx+iky) e
(kx+iky) e^{2πi/3}
K'
(4π/3, 0)
A
B
σ⃗ = (σx, σy)
H_K^{LE} = Σ Ψk† (σ⃗ · k⃗) Ψk
v=1
H_{K'}^{LE} = Σ Ψk† (−σx kx + σy ky) Ψk


H = -t Σ_{<ij>σ} c†_{iσ} c_{jσ} = t Σ_{i,δ} c†_i d_{i+δ} + h.c = -t Σ_{<ij>} ψ†_i (t*_{ij}
[H, T̂] = 0
ψ_{K+k}(r) = e^{i k·r} (1, e^{iφ_k})
φ_k = Arg(k)
k_y
k
φ
k_x
|γ_k|²
|γ_k|²
k = ± |γ_k|


$H = -t \sum_{\langle ij \rangle \sigma} c^\dagger_{i\sigma} c_{j\sigma} = t \sum_{i,\vec{\delta}} c^\dagger_i d_{i+\delta} + h.c = -t \sum_{\langle ij \rangle} \psi^\dagger_i (t^*_{ij}$
$[H, \hat{T}] = 0$
$\psi_{K+k}(\vec{r}) = e^{i\vec{k}\cdot\vec{r}} \begin{pmatrix} 1 \\ e^{i\varphi_k} \end{pmatrix}$
$\varphi_k = Arg(k)$
k_y
k
φ
k_x
$e^{i\varphi_k} = \frac{k_x + i k_y}{|k|}$
$|\gamma_k|^2$
$|\gamma_k|^2$
$_k = \pm |\gamma_k|$


$H = -t \sum_{\langle ij \rangle \sigma} c^{\dagger}_{i\sigma} c_{j\sigma} = t \sum_{i,\vec{\delta}} c^{\dagger}_{i} d_{i+\delta} + h.c = -t \sum_{\langle ij \rangle} \Psi^{\dagger}_{i} (t^{*}_{ij}$
$[H, \hat{T}] = 0$
$\Psi^{\pm E}_{K+k}(\vec{r}) = e^{i\vec{k}\cdot\vec{r}} \begin{pmatrix} 1 \\ \pm e^{i\varphi_k} \end{pmatrix}$
$\varphi_k = Arg(k)$
k_y
k
φ
k_x
$e^{i\varphi_k} = \frac{k_x + ik_y}{|k|}$
$|\gamma_k|^2$
$|\gamma_k|^2$
$= \pm |\gamma_k|$


H = -t Σ_{<ij>σ} c†_{iσ} c_{jσ} = t Σ_{i,δ} c†_i d_{i+δ} + h.c = -t Σ_{<ij>} Ψ†_i (t*_{ij}
Ψ_{K'+k} ∝ (1, ±e^{-iφ_k})
Ψ^{±E}_{K+k}(r) = e^{ik·r} (1, ±e^{iφ_k})
φ_k = Arg(k)
k_y
k
φ
k_x
e^{iφ_k} = (k_x + ik_y) / |k|
Ĥ² = (|γ_k|² , |γ_k|²)
E_k = ± |γ_k|

$$H = -t\sum_{\langle ij\rangle\sigma} c^\dagger_{i\sigma} c_{j\sigma} = t\sum_{i,\vec{\delta}} c^\dagger_i d_{i+\delta} + h.c. = -t\sum_{\langle ij\rangle} \Psi^\dagger_i \left(t^*_{ij} \right.$$

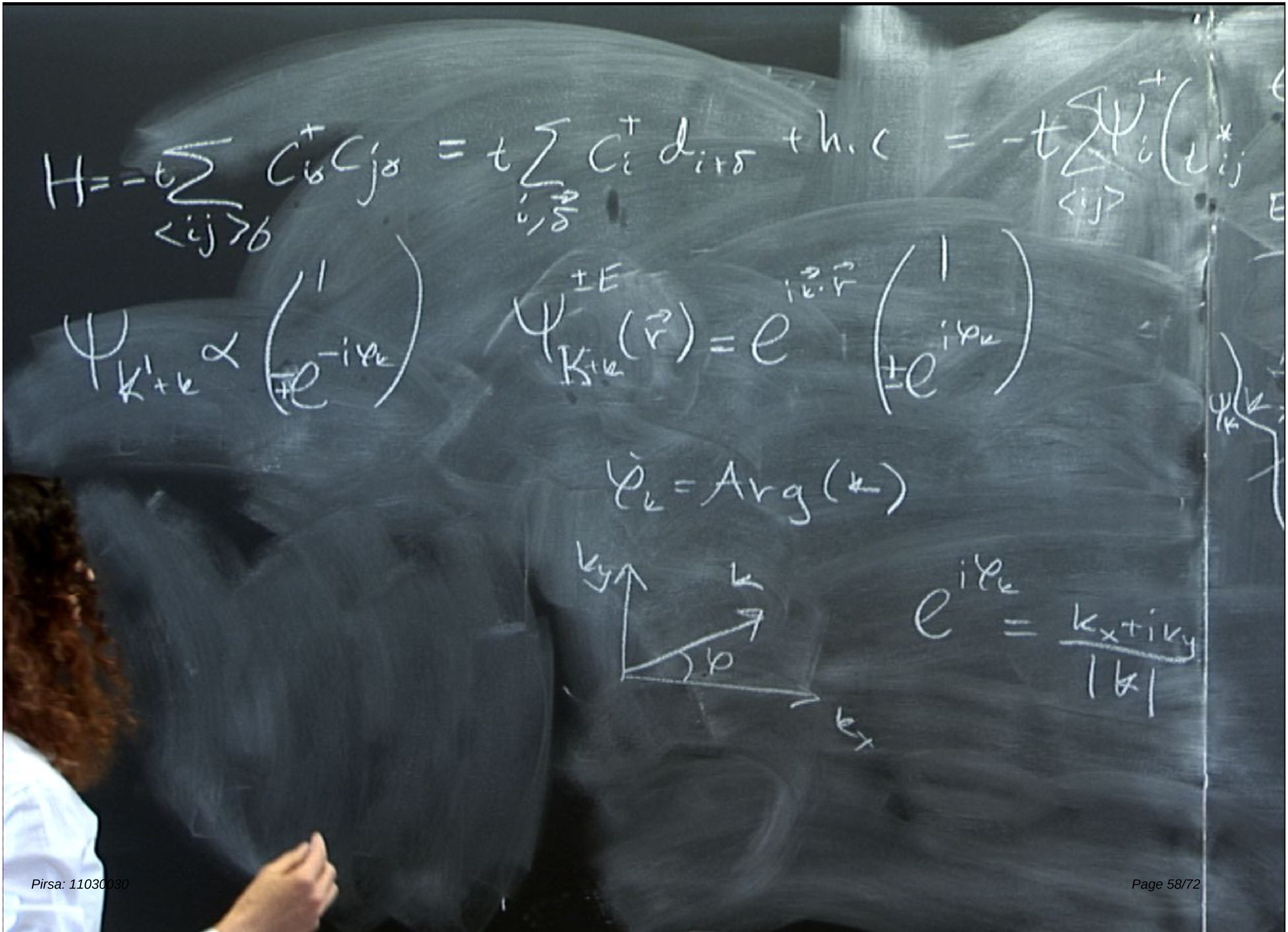
$$\Psi_{K'+k} \propto \begin{pmatrix} 1 \\ \mp e^{-i\varphi_k} \end{pmatrix} \qquad \Psi^{\pm E}_{K+k}(\vec{r}) = e^{i\vec{k}\cdot\vec{r}} \begin{pmatrix} 1 \\ \pm e^{i\varphi_k} \end{pmatrix}$$

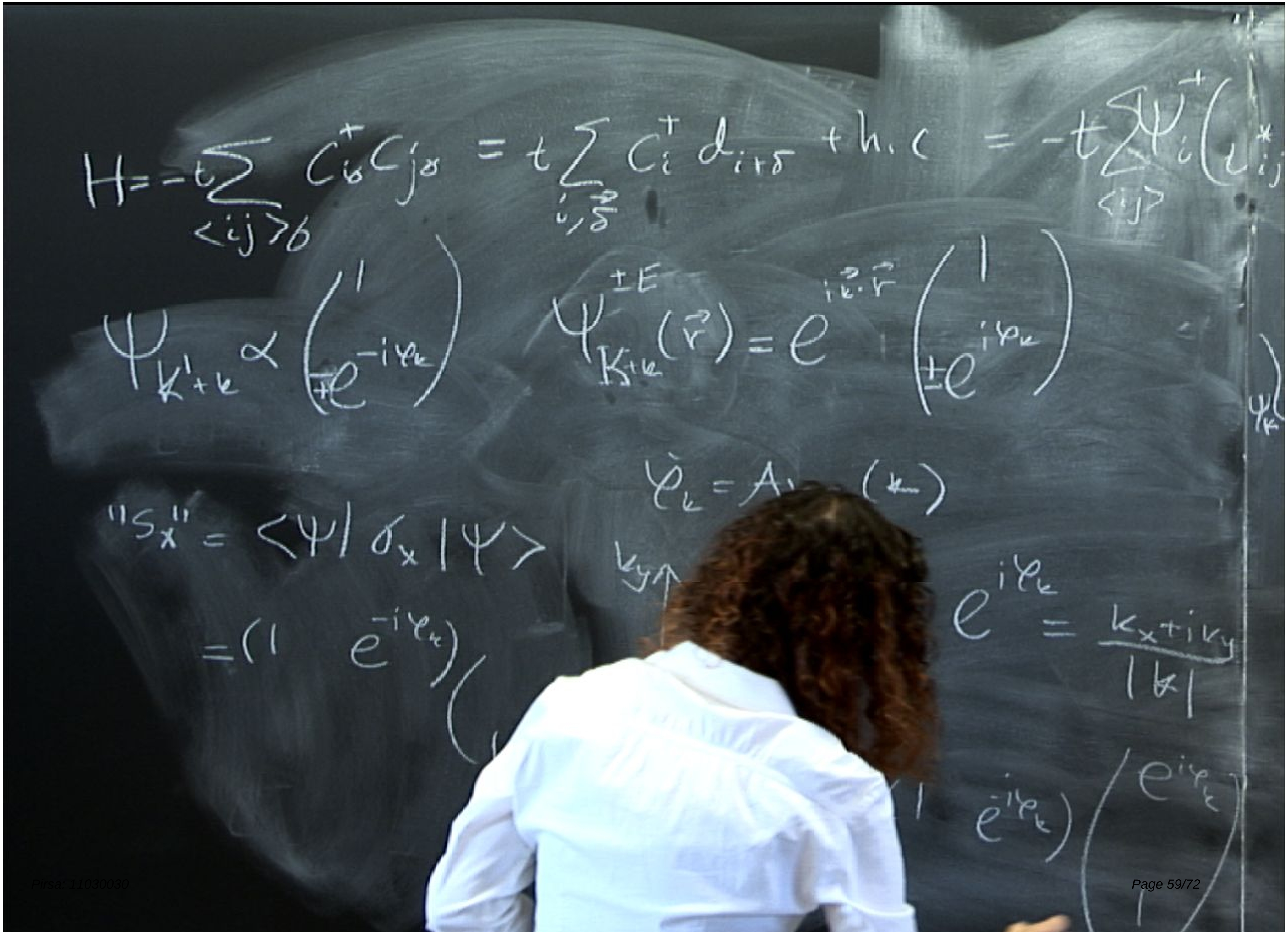
$$\varphi_k = \mathrm{Arg}(k)$$

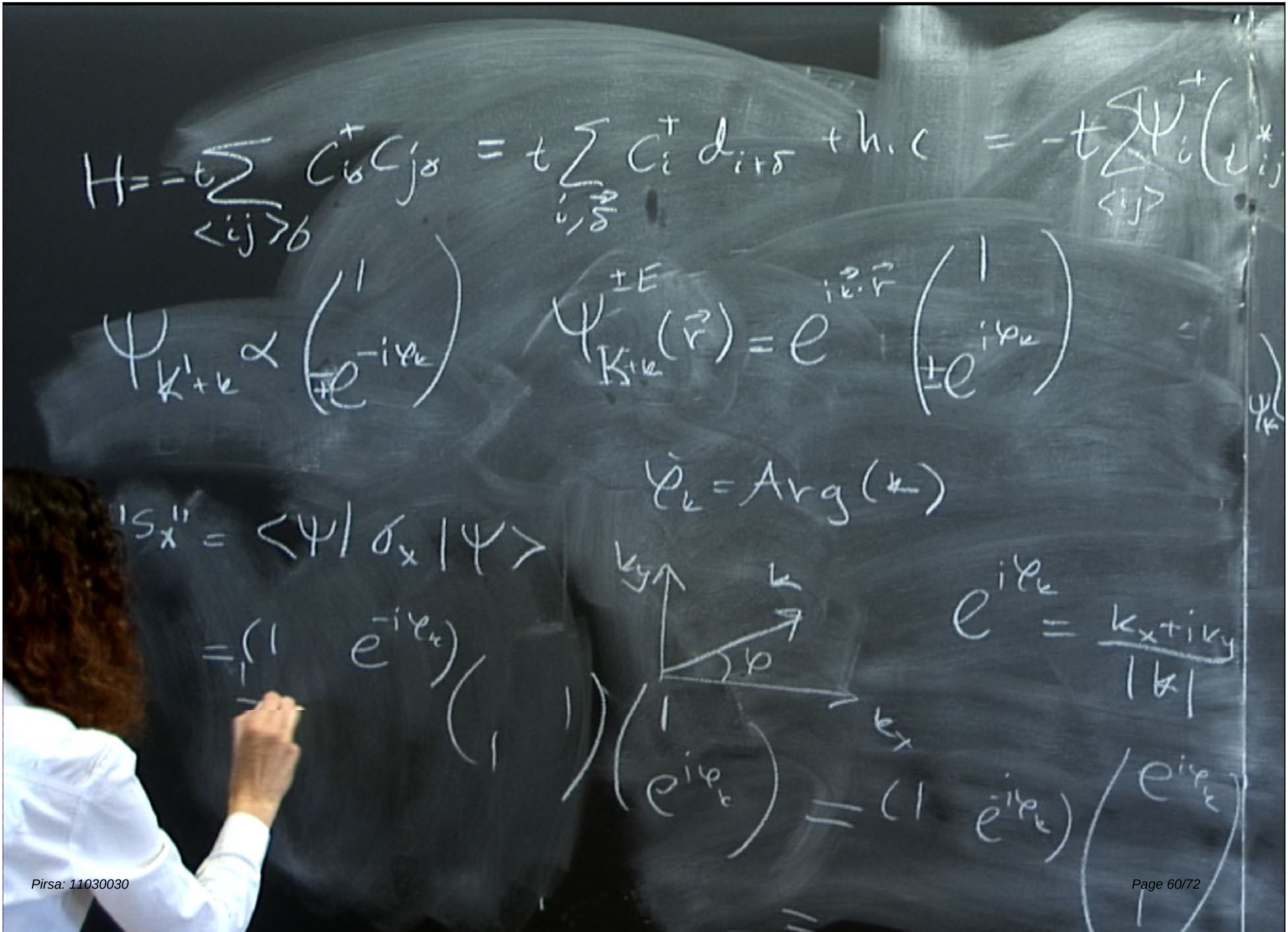
$$\hat{H}^2 = \begin{pmatrix} |\gamma_k|^2 & \\ & |\gamma_k|^2 \end{pmatrix}$$

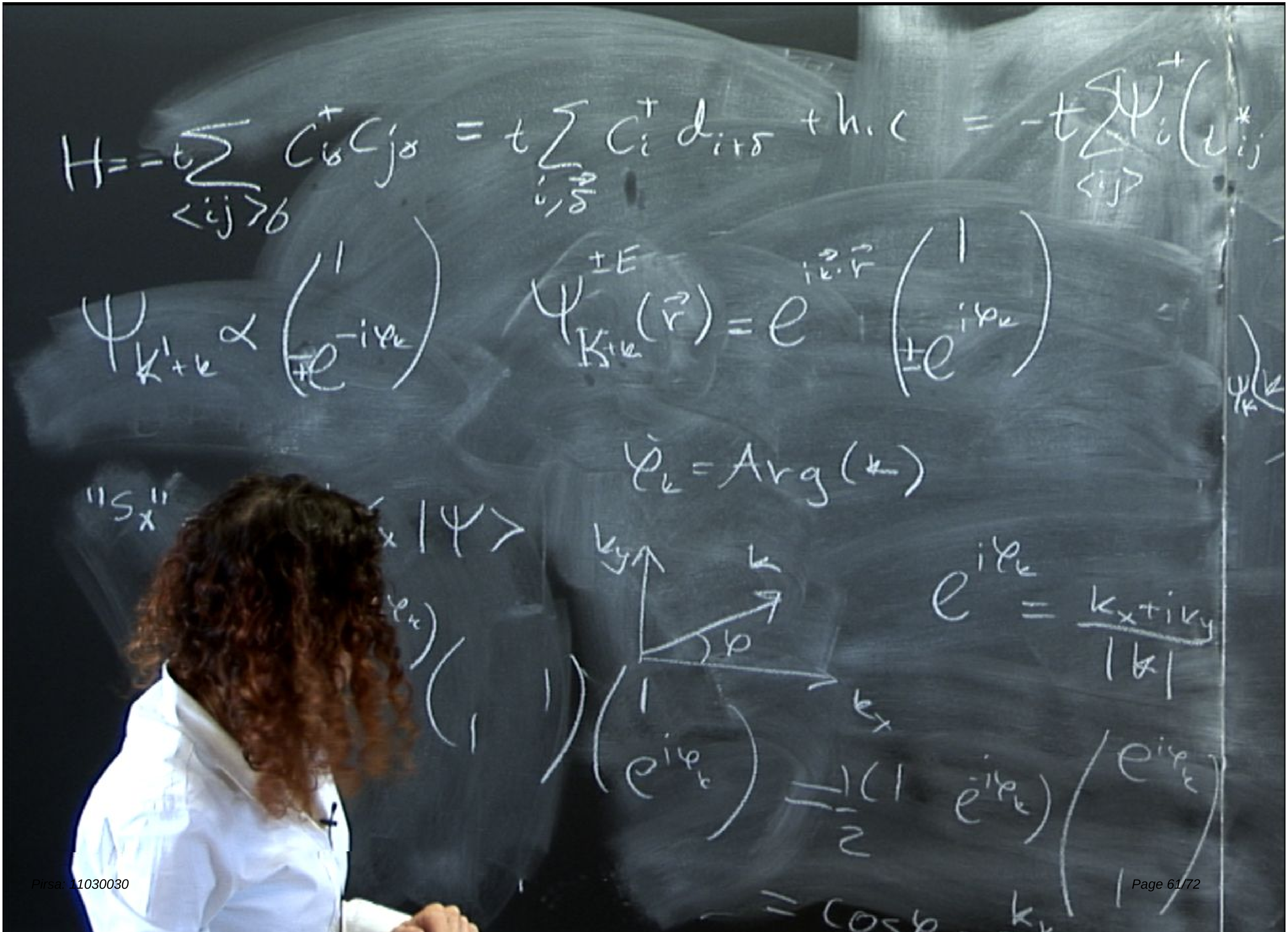
$$e^{i\varphi_k} = \frac{k_x + i k_y}{|k|}$$

$$E_k = \pm|\gamma_k|$$

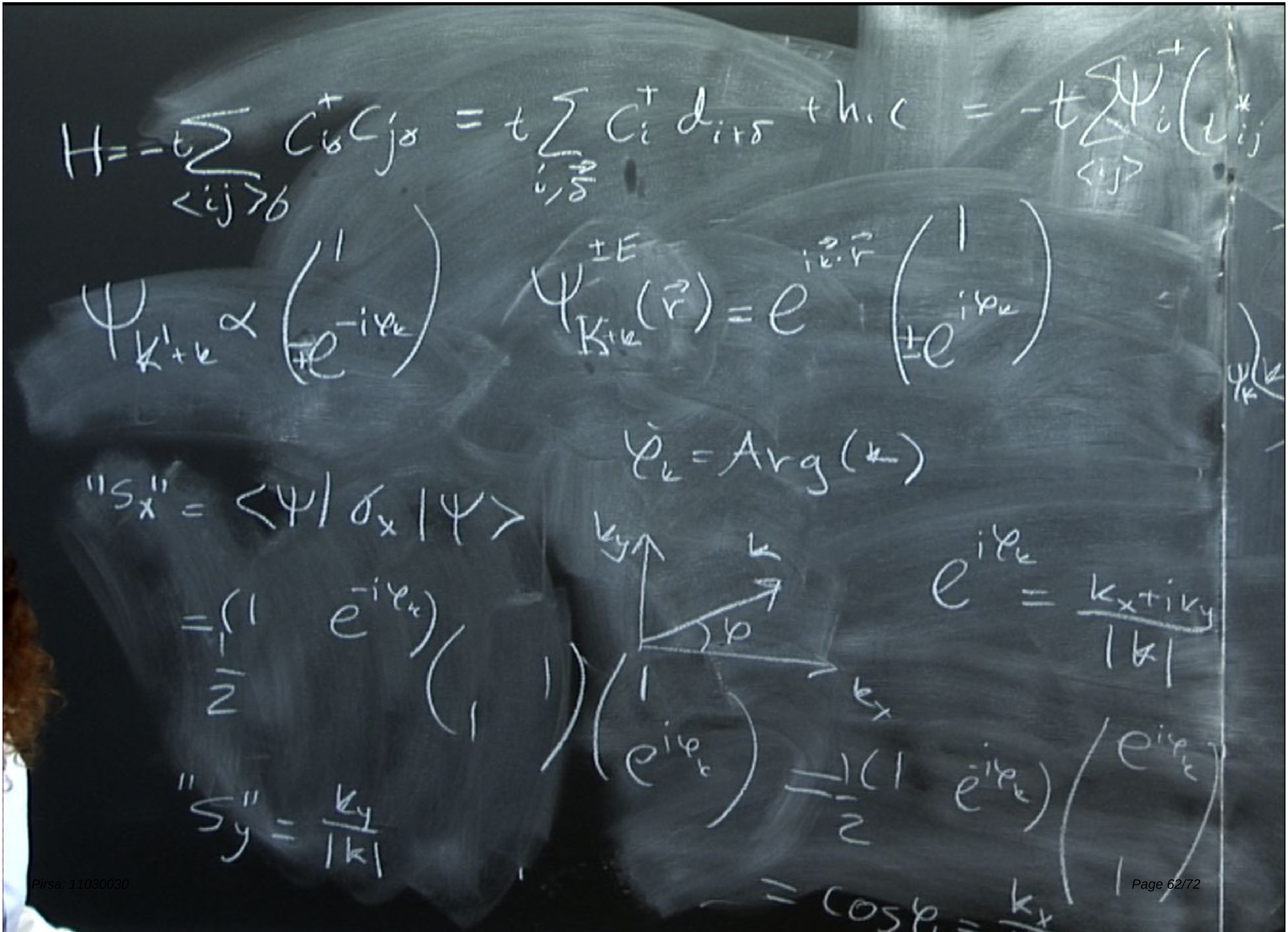

$H = -t \sum_{\langle ij \rangle \sigma} c^{\dagger}_{i\sigma} c_{j\sigma} = t \sum_{i,\vec{\delta}} c^{\dagger}_i d_{i+\delta} + h.c. = -t \sum_{\langle ij \rangle} \psi^{\dagger}_i (\ldots$
$\psi_{K'+k} \propto \begin{pmatrix} 1 \\ \mp e^{-i\varphi_k} \end{pmatrix}$
$\psi^{\pm E}_{K+k}(\vec{r}) = e^{i\vec{k}\cdot\vec{r}} \begin{pmatrix} 1 \\ \pm e^{i\varphi_k} \end{pmatrix}$
$\varphi_k = \mathrm{Arg}(k)$
k_y
k
φ
k_x
$e^{i\varphi_k} = \frac{k_x + i k_y}{|k|}$

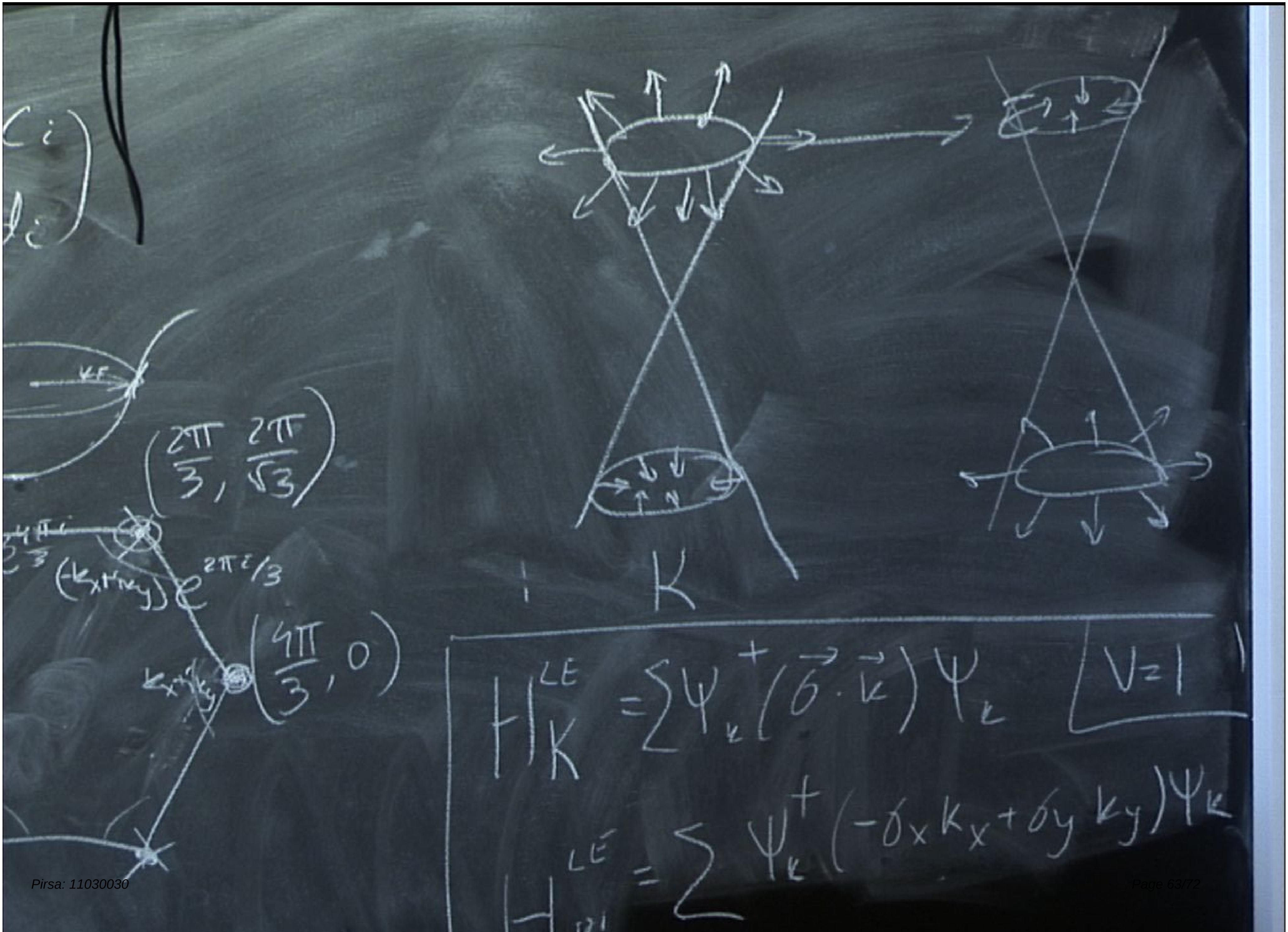

H = -t ∑_{<ij>σ} c†_{iσ} c_{jσ} = t ∑_{i,δ} c†_i d_{i+δ} + h.c = -t ∑_{<ij>} ψ†_i (
ψ_{K'+k} ∝ (1, ±e^{-iφ_k})
ψ^{±E}_{K+k}(r) = e^{i k·r} (1, ±e^{iφ_k})
φ_k = A
"S_x" = <ψ| σ_x |ψ>
k_y
= (1 e^{-iφ_k})
e^{iφ_k} = (k_x + i k_y) / |k|
(1 e^{-iφ_k}) (e^{iφ_k}

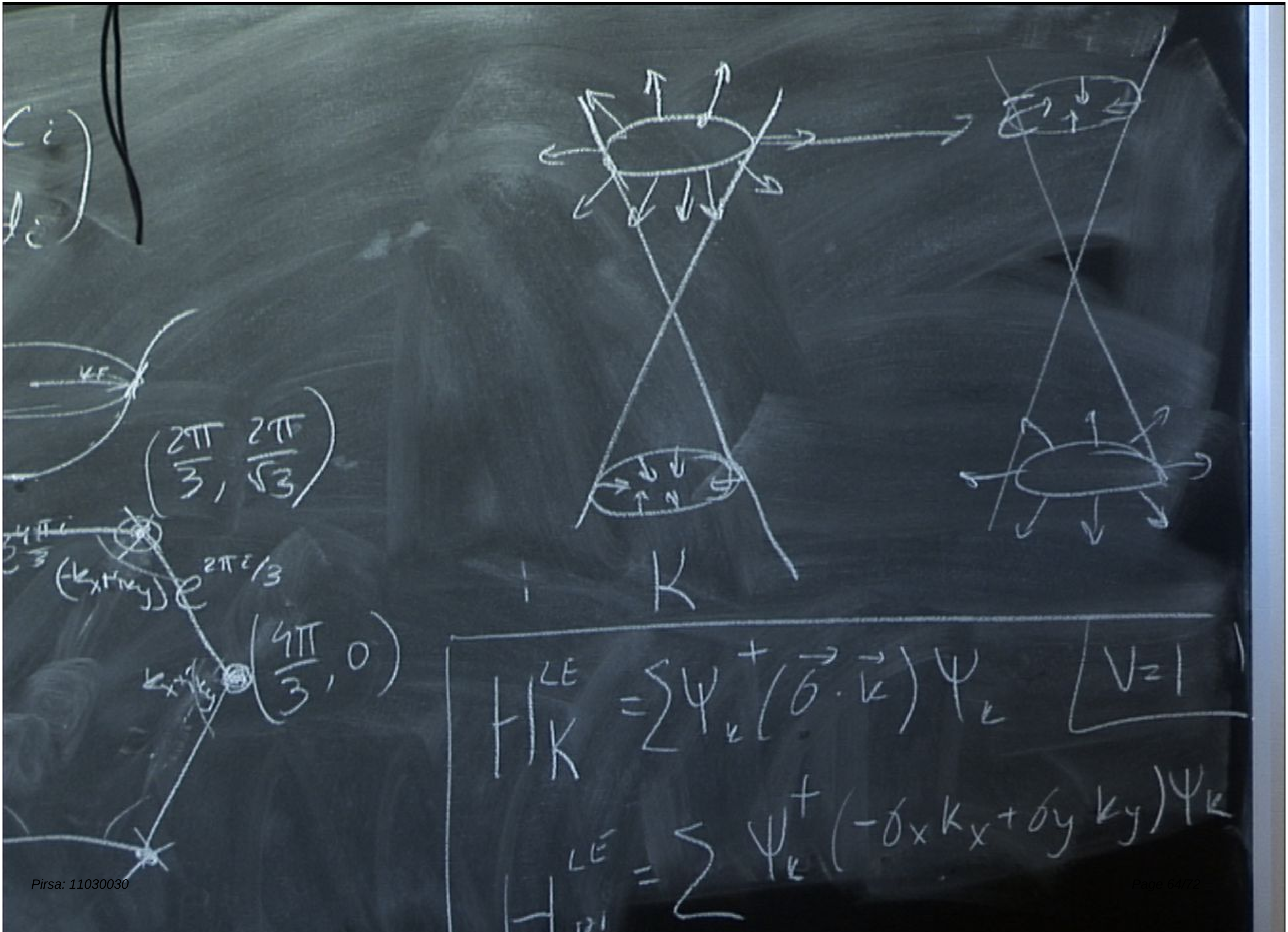

H = -t ∑_{<ij>σ} c†_{iσ} c_{jσ} = t ∑_{i,δ} c†_i d_{i+δ} + h.c = -t ∑_{<ij>} Ψ†_i
Ψ_{K'+k} ∝ (1, ∓e^{-iφ_k})
Ψ^{±E}_{K+k}(r) = e^{i k·r} (1, ±e^{iφ_k})
φ_k = Arg(k)
"S_x" = <Ψ| σ_x |Ψ>
= (1 e^{-iφ_k}) (1 ; 1) (1 ; e^{iφ_k}) = (1 e^{-iφ_k}) (e^{iφ_k} ; 1)
k_y
k
φ
k_x
e^{iφ_k} = (k_x + i k_y) / |k|



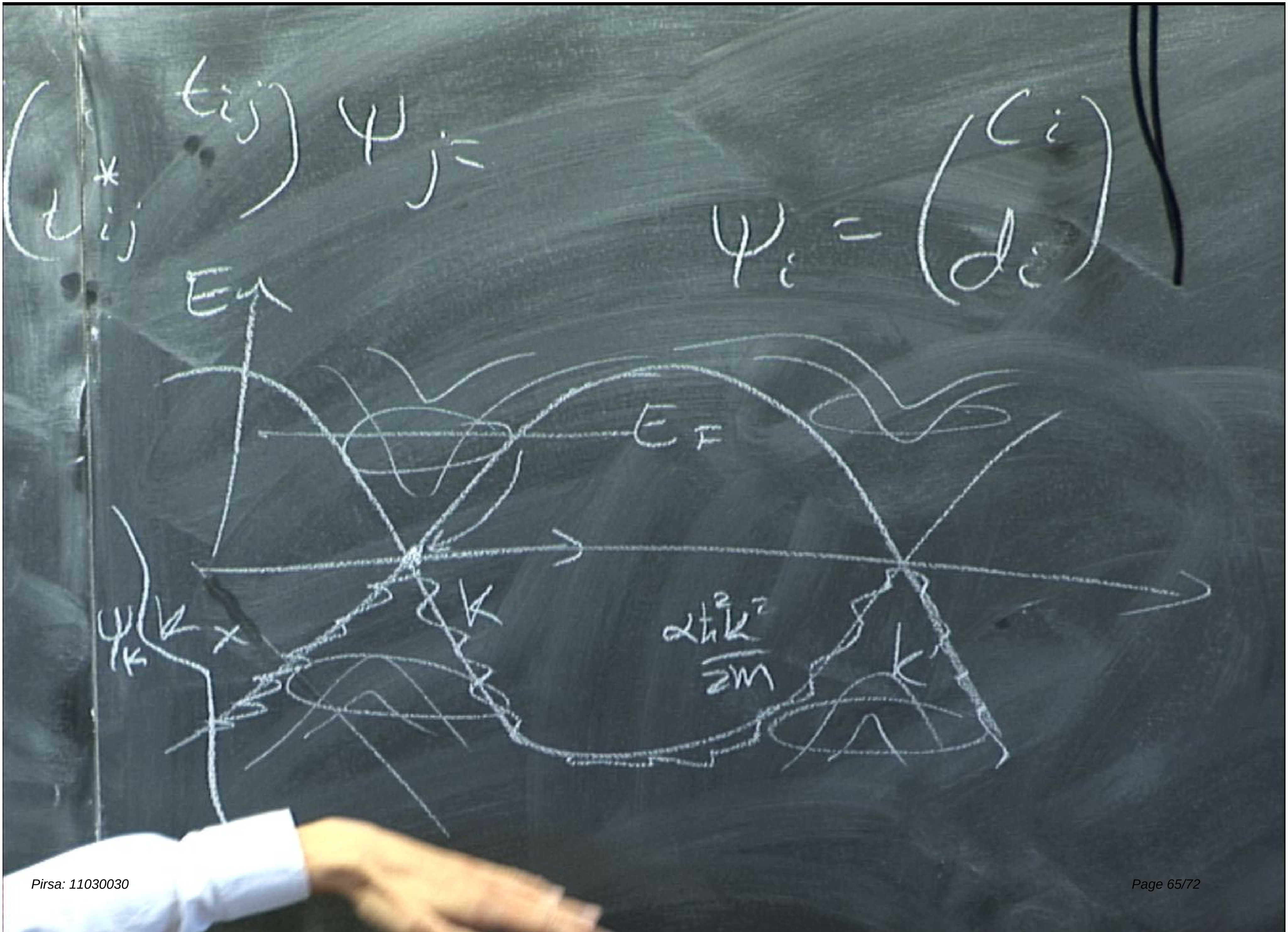
H = -t Σ_{<ij>σ} c†_{iσ} c_{jσ} = t Σ_{i,δ} c†_i d_{i+δ} + h.c = -t Σ_{<ij>} Ψ†_i (
Ψ_{K'+k} ∝ (1, ∓e^{-iφ_k})
Ψ^{±E}_{K+k}(r) = e^{ik·r} (1, ±e^{iφ_k})
φ_k = Arg(k)
"S_x"
k_y
k
φ
k_x
e^{iφ_k} = (k_x + ik_y)/|k|

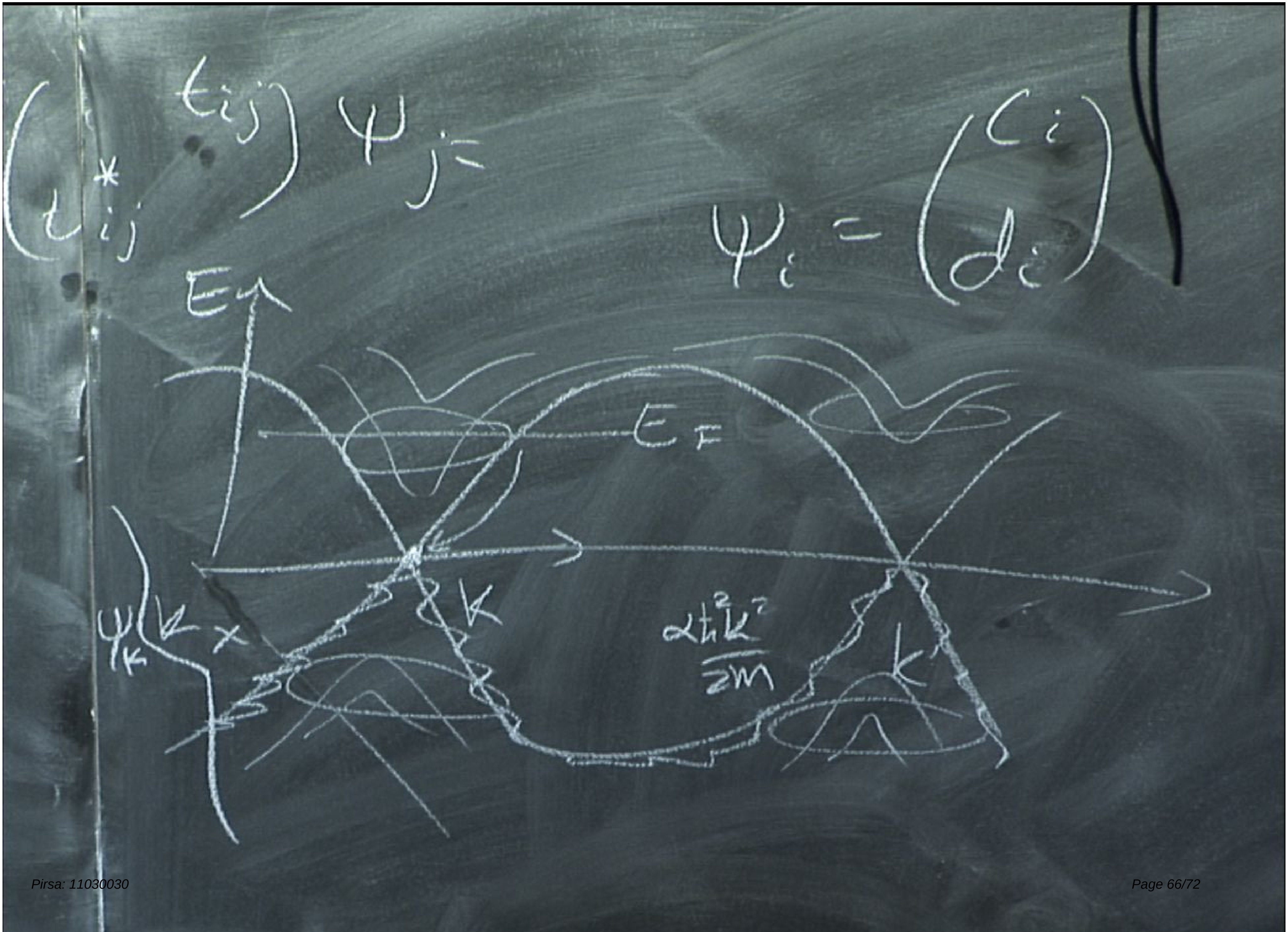

$H = -t \sum_{\langle ij \rangle \sigma} c^\dagger_{i\sigma} c_{j\sigma} = t \sum_{i,\vec{\delta}} c^\dagger_i d_{i+\delta} + h.c = -t \sum_{\langle ij \rangle} \Psi^\dagger_i ($
$\Psi_{K'+k} \propto \begin{pmatrix} 1 \\ \pm e^{-i\varphi_k} \end{pmatrix}$
$\Psi^{\pm E}_{K+k}(\vec{r}) = e^{i\vec{k}\cdot\vec{r}} \begin{pmatrix} 1 \\ \pm e^{i\varphi_k} \end{pmatrix}$
$\varphi_k = \mathrm{Arg}(k)$
$"S_x" = \langle \Psi | \sigma_x | \Psi \rangle$
$= \frac{1}{2} (1 \quad e^{-i\varphi_k}) \begin{pmatrix} & 1 \\ 1 & \end{pmatrix} \begin{pmatrix} 1 \\ e^{i\varphi_k} \end{pmatrix}$
k_y
k
φ
k_x
$e^{i\varphi_k} = \frac{k_x + i k_y}{|k|}$
$= \frac{1}{2} (1 \quad e^{-i\varphi_k}) \begin{pmatrix} e^{i\varphi_k} \\ 1 \end{pmatrix}$
$"S_y" = \frac{k_y}{|k|}$
$= \cos\varphi_k = \frac{k_x}{}$


K
$\left(\frac{2\pi}{3}, \frac{2\pi}{\sqrt{3}}\right)$
$e^{2\pi i/3}$
$(-k_x+ik_y)$
$\left(\frac{4\pi}{3}, 0\right)$
k_F
$H_K^{LE} = \sum \Psi_k^\dagger (\vec{\sigma}\cdot\vec{k}) \Psi_k$
$v=1$
$= \sum \Psi_k^\dagger (-\sigma_x k_x + \sigma_y k_y) \Psi_k$
$H^{LE} = \sum$

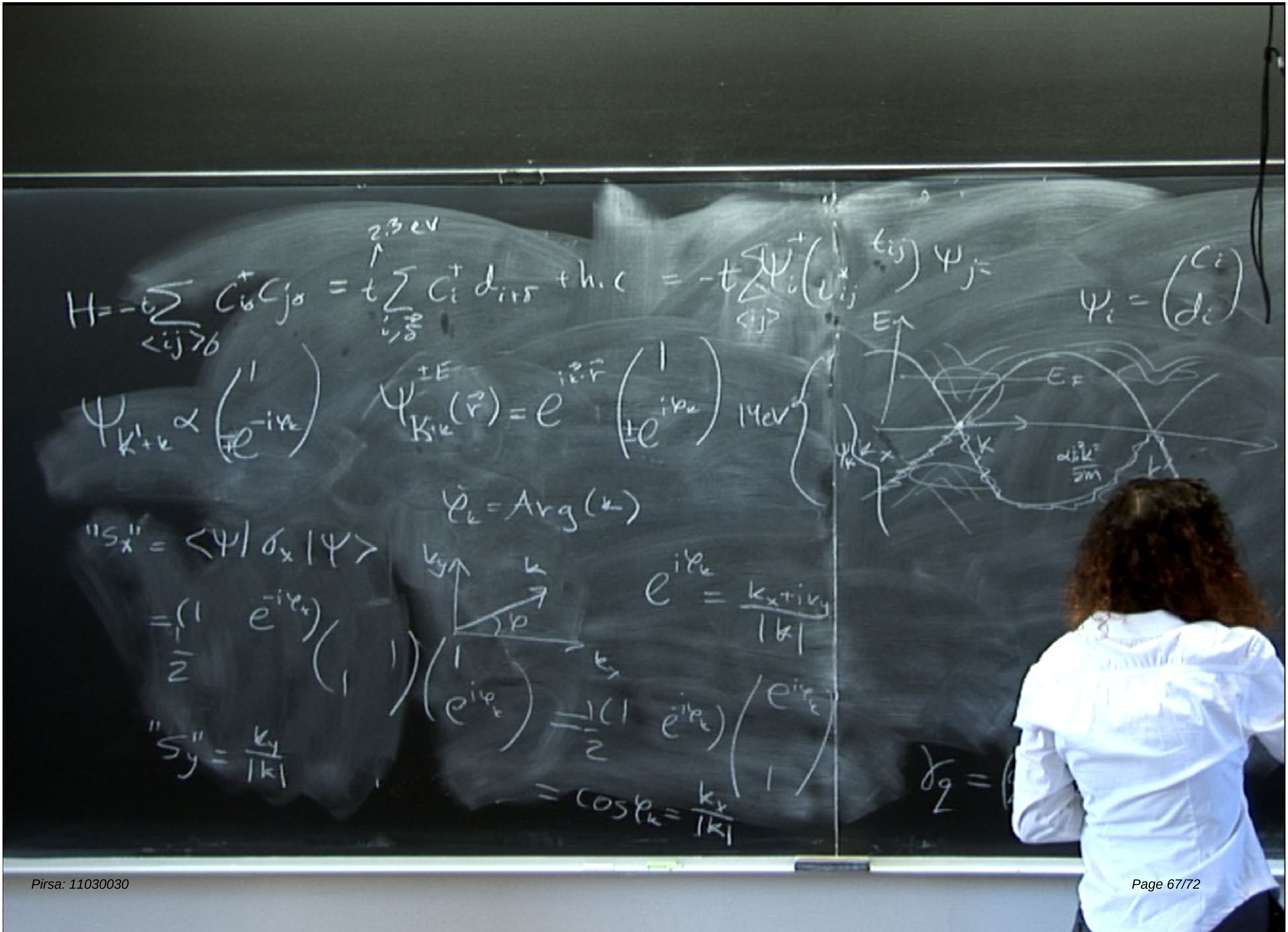


$\left(\frac{2\pi}{3}, \frac{2\pi}{\sqrt{3}}\right)$
$e^{2\pi i/3}$
$\left(\frac{4\pi}{3}, 0\right)$
K
$H_K^{LE} = \sum \Psi_k^\dagger (\vec{\sigma} \cdot \vec{k}) \Psi_k$
$v = 1$
$H^{LE} = \sum \Psi_k^\dagger (-\sigma_x k_x + \sigma_y k_y) \Psi_k$

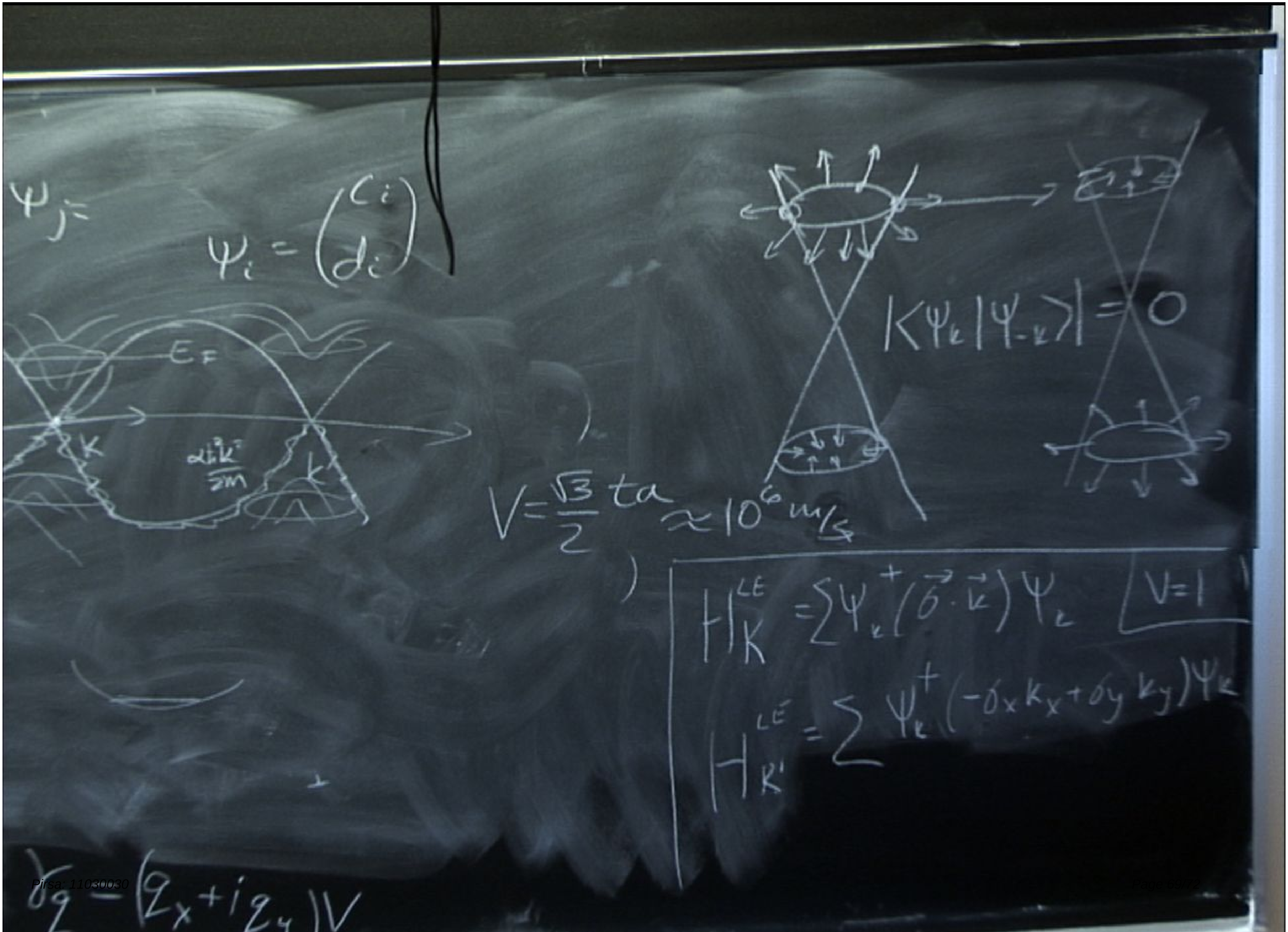

t_ij
t*_ij
ψ_j =
ψ_i = (c_i d_i)
E
E_F
k
k'
ψ_k
x
αħ²k²/2m

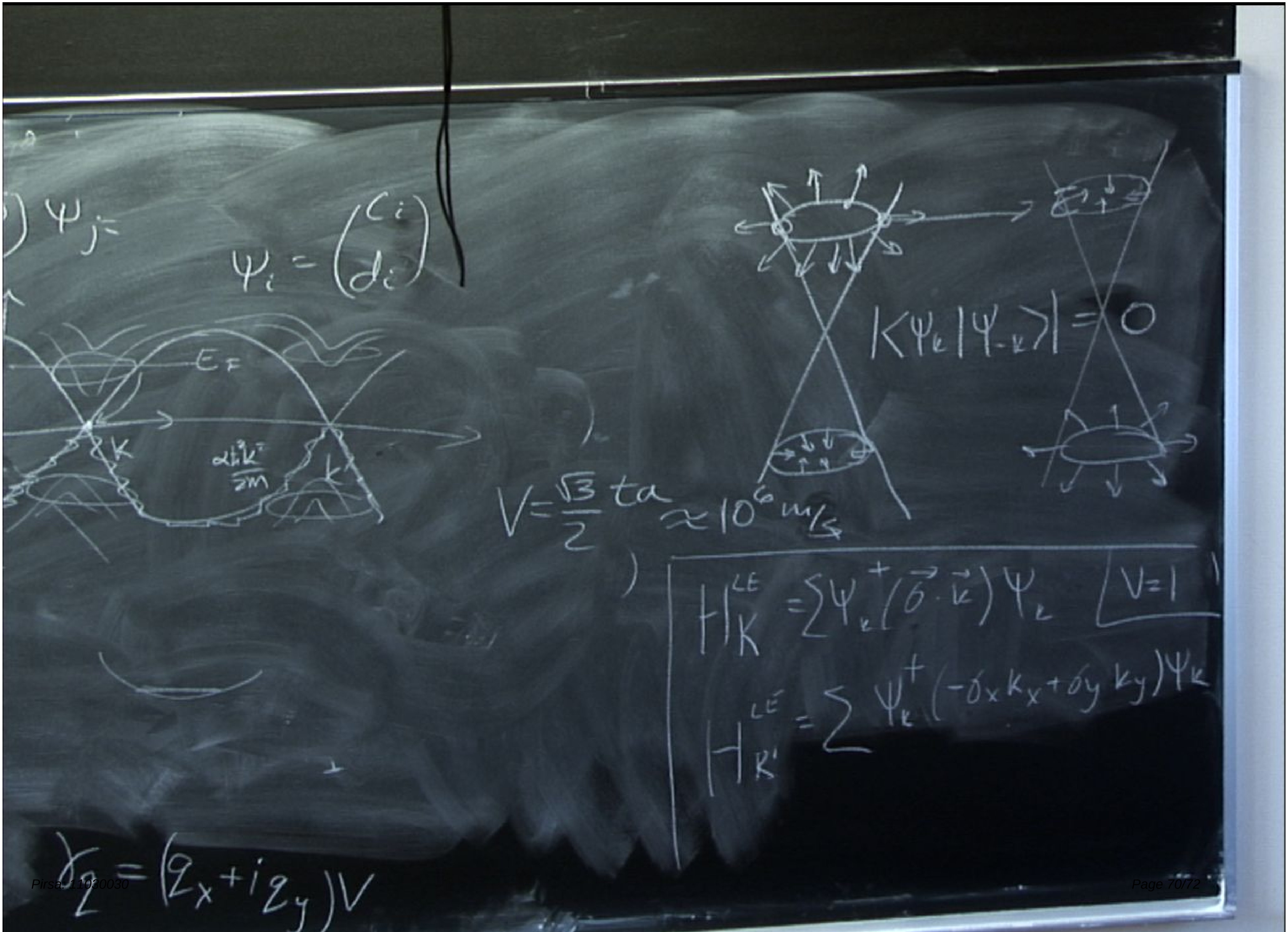


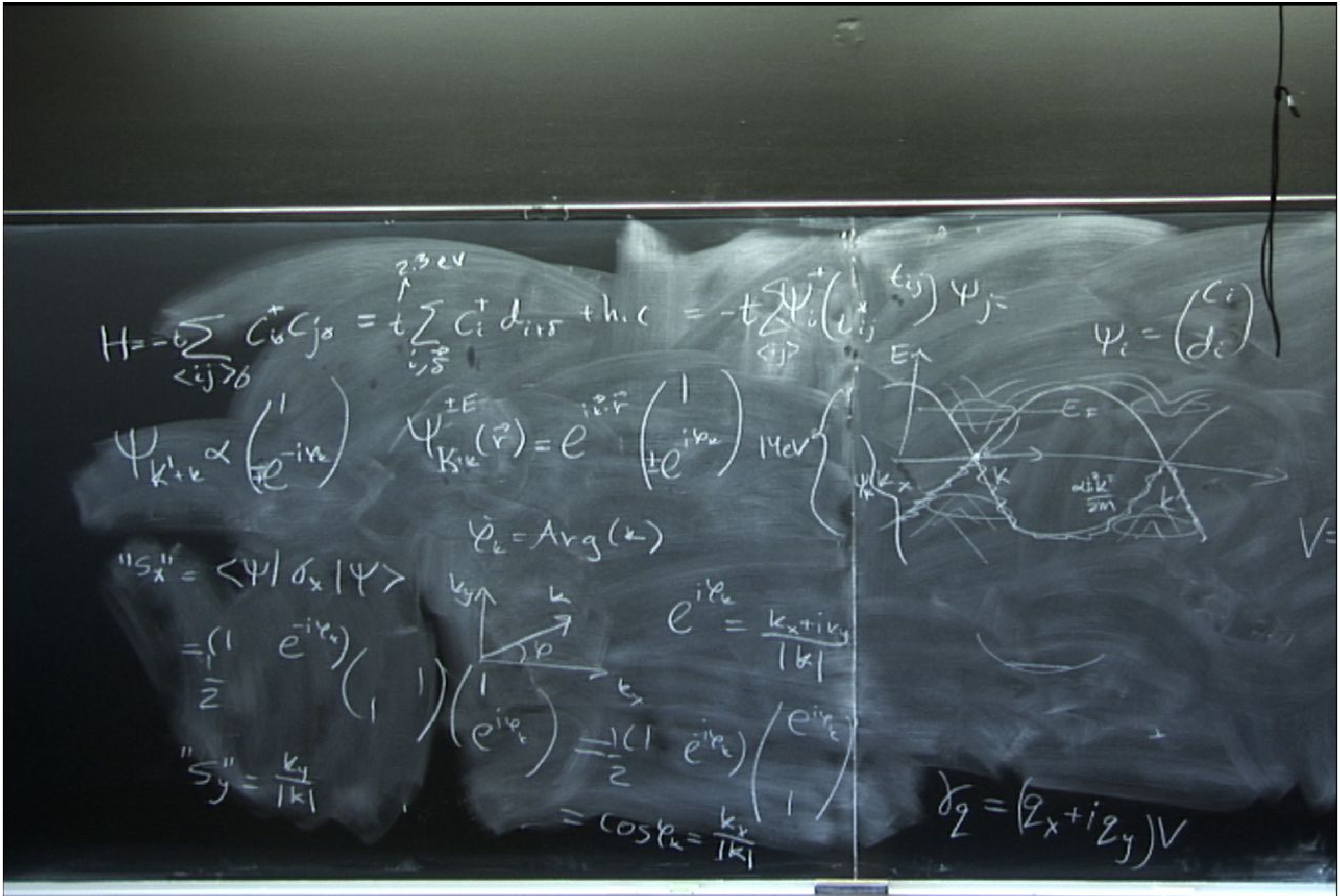
t_ij
t*_ij
ψ_j =
ψ_i = (c_i d_i)
E
E_F
ψ_k
x
k
ħ²k²/2m
k'


2.3 eV
$H = -t \sum_{\langle ij \rangle \sigma} c^\dagger_{i\sigma} c_{j\sigma} = t \sum_{i,\vec\delta} c^\dagger_i d_{i+\delta} + h.c. = -t \sum_{\langle ij \rangle} \Psi^\dagger_i (\ \ t_{ij}) \Psi_j$
$\Psi_i = \begin{pmatrix} c_i \\ d_i \end{pmatrix}$
$\Psi_{K'+k} \propto \begin{pmatrix} 1 \\ \pm e^{-i\varphi_k} \end{pmatrix}$
$\Psi^{\pm E}_{K+k}(\vec r) = e^{i\vec k \cdot \vec r} \begin{pmatrix} 1 \\ \pm e^{i\varphi_k} \end{pmatrix}$
14 eV
E_F
$\varphi_k = \mathrm{Arg}(k)$
"S_x" $= \langle \Psi | \sigma_x | \Psi \rangle$
$e^{i\varphi_k} = \frac{k_x + i k_y}{|k|}$
k_y
k_x
φ
$= \frac{1}{2} (1 \ \ e^{-i\varphi_k}) \begin{pmatrix} & 1 \\ 1 & \end{pmatrix} \begin{pmatrix} 1 \\ e^{i\varphi_k} \end{pmatrix}$
$= \frac{1}{2} (1 \ \ e^{i\varphi_k}) \begin{pmatrix} e^{i\varphi_k} \\ 1 \end{pmatrix}$
$= \cos\varphi_k = \frac{k_x}{|k|}$
"S_y" $= \frac{k_y}{|k|}$
$\gamma_q =$


2.3 eV
14eV
$\varphi_k = \mathrm{Arg}(k)$
"S_x" = ⟨ψ| σ_x |ψ⟩
"S_y" = $\frac{k_y}{|k|}$


ψj =
ψi = (ci di)
EF
K
K'
ħ²k²/2m
V = √3/2 ta ≈ 10⁶ m/s
|⟨ψk|ψ-k⟩| = 0
H_K^LE = Σ ψk+ (σ⃗·k⃗) ψk
V=1
H_K'^LE = Σ ψk+ (−σx kx + σy ky) ψk
γq = (qx + i qy) V


Ψi = (ci di)
EF
K
K'
|<Ψk|Ψ-k>| = 0
V = √3/2 ta ≈ 10^6 m/s
H_K^LE = ΣΨk^+ (σ·k) Ψk
V=1
H_K'^LE = Σ Ψk^+ (-σx kx + σy ky) Ψk
γ2 = (qx + i qy)V

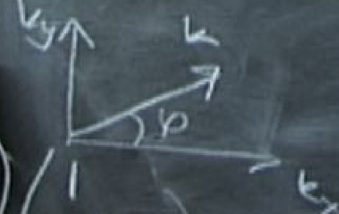

2.3 eV
h.c
ψi = (ci di)
E
EF
1 eV
φk = Arg(k)
"Sx" = <ψ| σx |ψ>
ky
kx
e^{iφk} = (kx + i ky)/|k|
= cos φk = kx/|k|
"Sy" = ky/|k|
γq = (qx + i qy)V

$$H = -t \sum_{\langle ij \rangle \sigma} c^\dagger_{i\sigma} c_{j\sigma} = \underset{2.3\,\text{eV}}{t} \sum_{i,\vec{\delta}} c^\dagger_i d_{i+\delta} + h.c. = -t \sum_{\langle ij \rangle} \Psi_i^\dagger \begin{pmatrix} & t_{ij} \\ t^*_{ij} & \end{pmatrix} \Psi_j$$

$$\Psi_i = \begin{pmatrix} c_i \\ d_i \end{pmatrix}$$

$$\Psi_{K'+k} \propto \begin{pmatrix} 1 \\ \pm e^{-i\varphi_k} \end{pmatrix} \qquad \Psi^{\pm E}_{K+k}(\vec{r}) = e^{i\vec{k}\cdot\vec{r}} \begin{pmatrix} 1 \\ \pm e^{i\varphi_k} \end{pmatrix} \quad 1\,\text{eV}$$

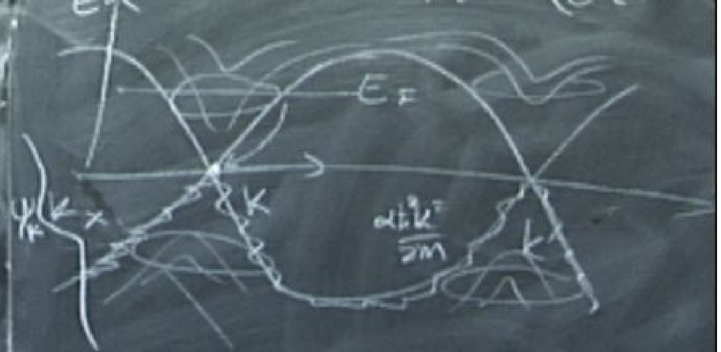
$$\varphi_k = \mathrm{Arg}(k)$$



$$e^{i\varphi_k} = \frac{k_x + i k_y}{|k|}$$

$$\text{"}S_x\text{"} = \langle \Psi | \sigma_x | \Psi \rangle = \frac{1}{2} \begin{pmatrix} 1 & e^{-i\varphi_k} \end{pmatrix} \begin{pmatrix} & 1 \\ 1 & \end{pmatrix} \begin{pmatrix} 1 \\ e^{i\varphi_k} \end{pmatrix} = \frac{1}{2} \begin{pmatrix} 1 & e^{-i\varphi_k} \end{pmatrix} \begin{pmatrix} e^{i\varphi_k} \\ 1 \end{pmatrix} = \cos\varphi_k = \frac{k_x}{|k|}$$

$$\text{"}S_y\text{"} = \frac{k_y}{|k|}$$



$$\gamma_q = (q_x + i q_y) V$$