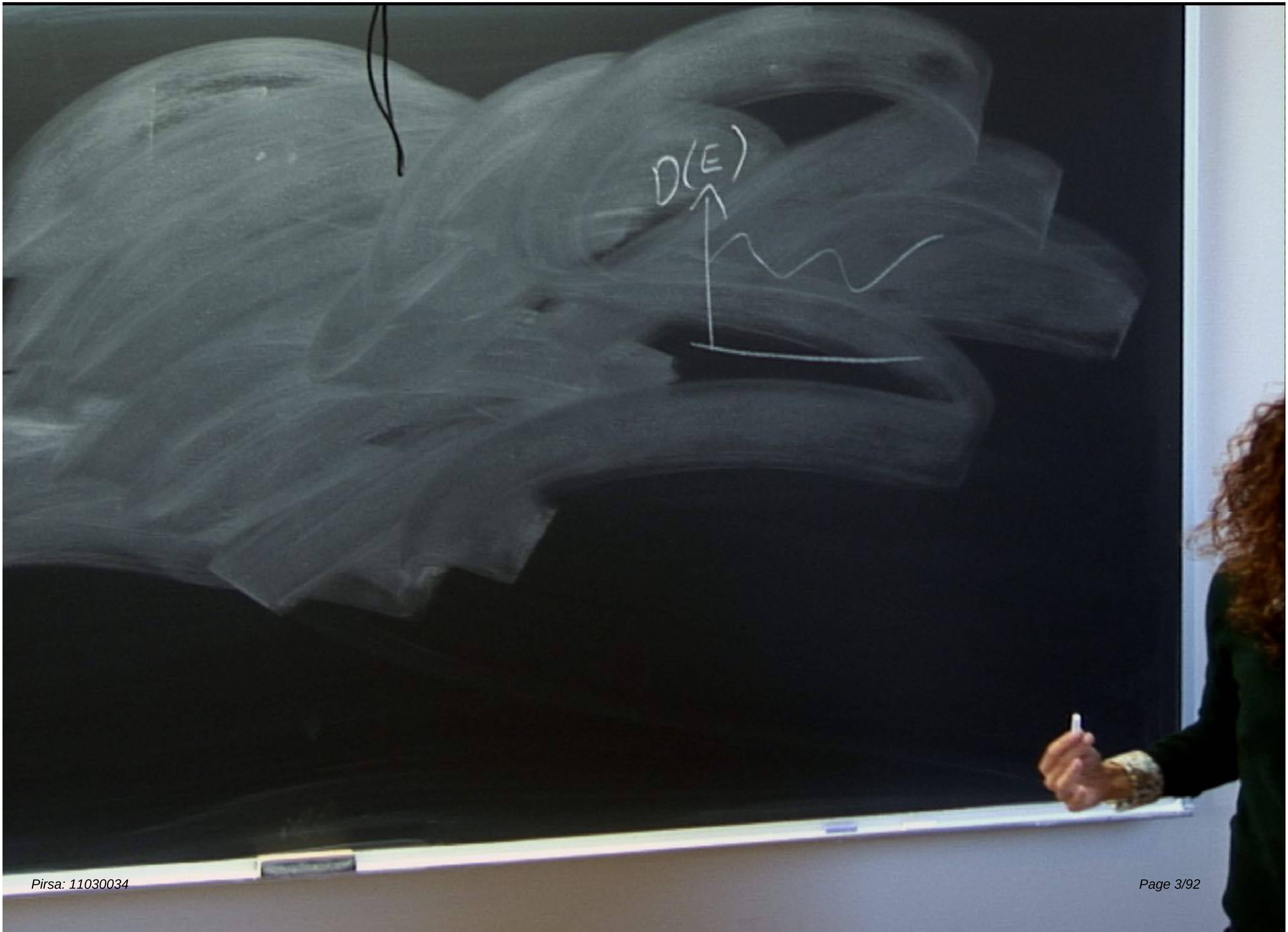
Title: Explorations in Condensed Matter - Lecture 5

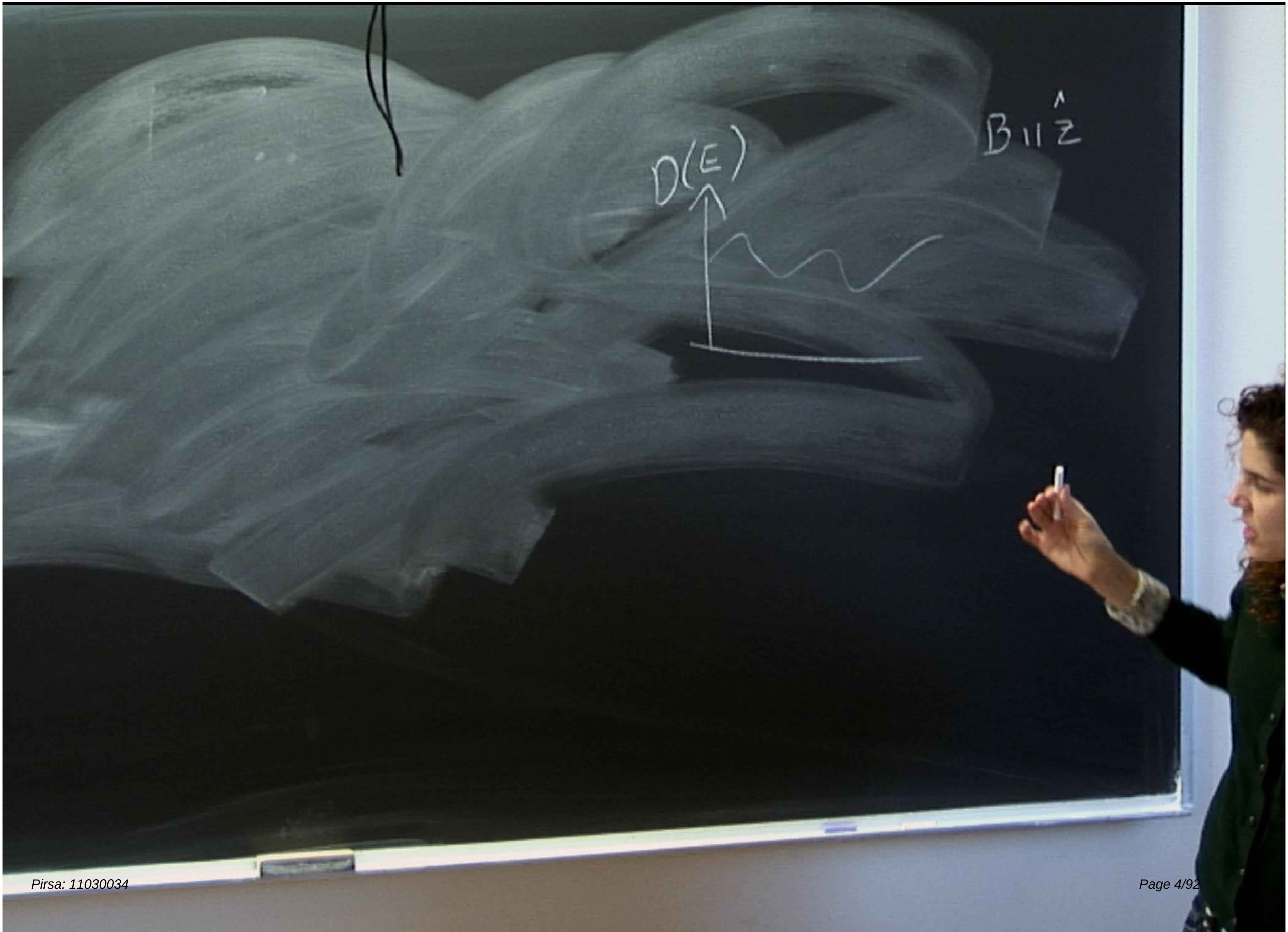
Date: Mar 18, 2011 10:15 AM

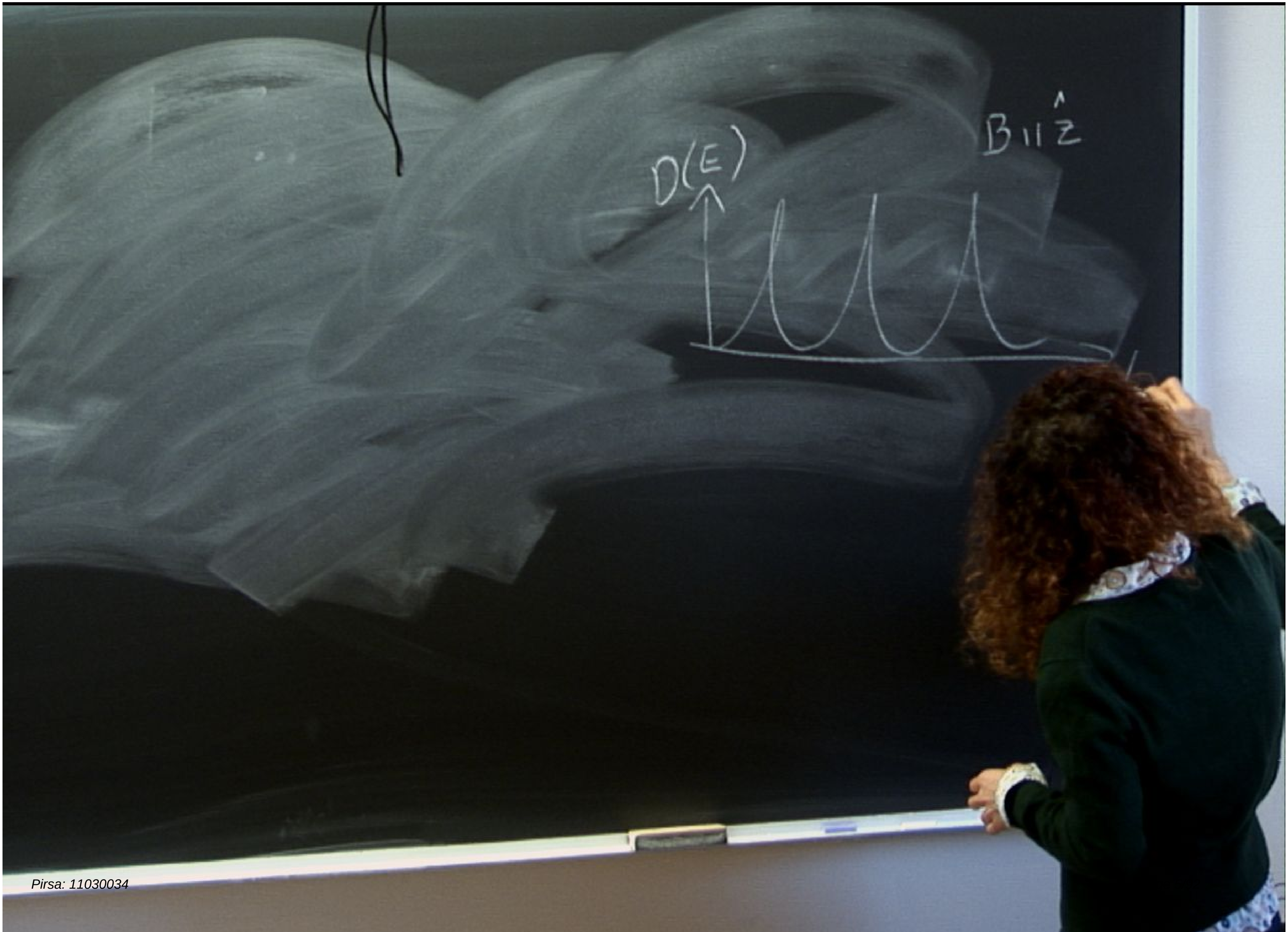
URL: http://pirsa.org/11030034

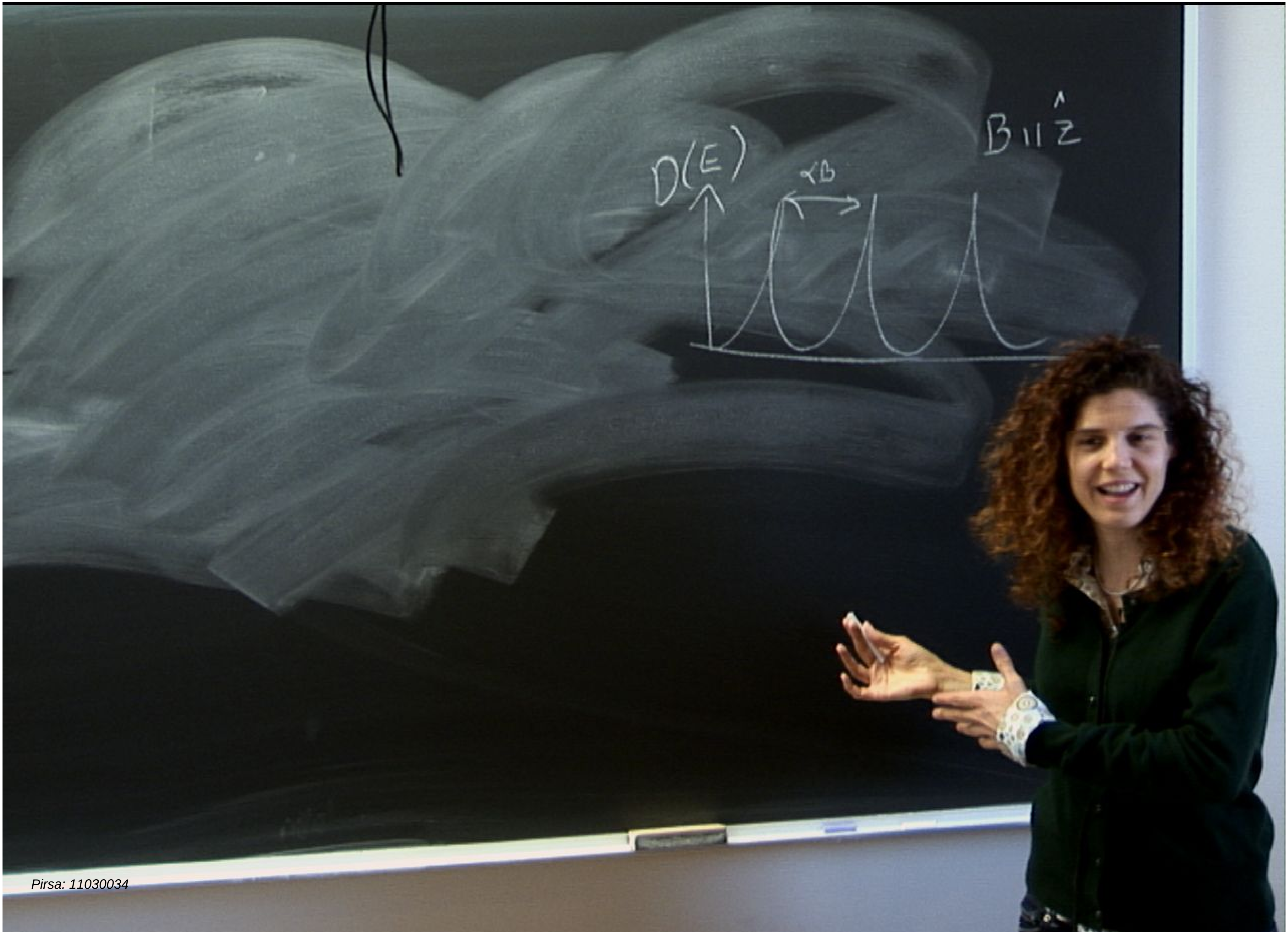
Abstract:

perimeter scholars
international


D(E)

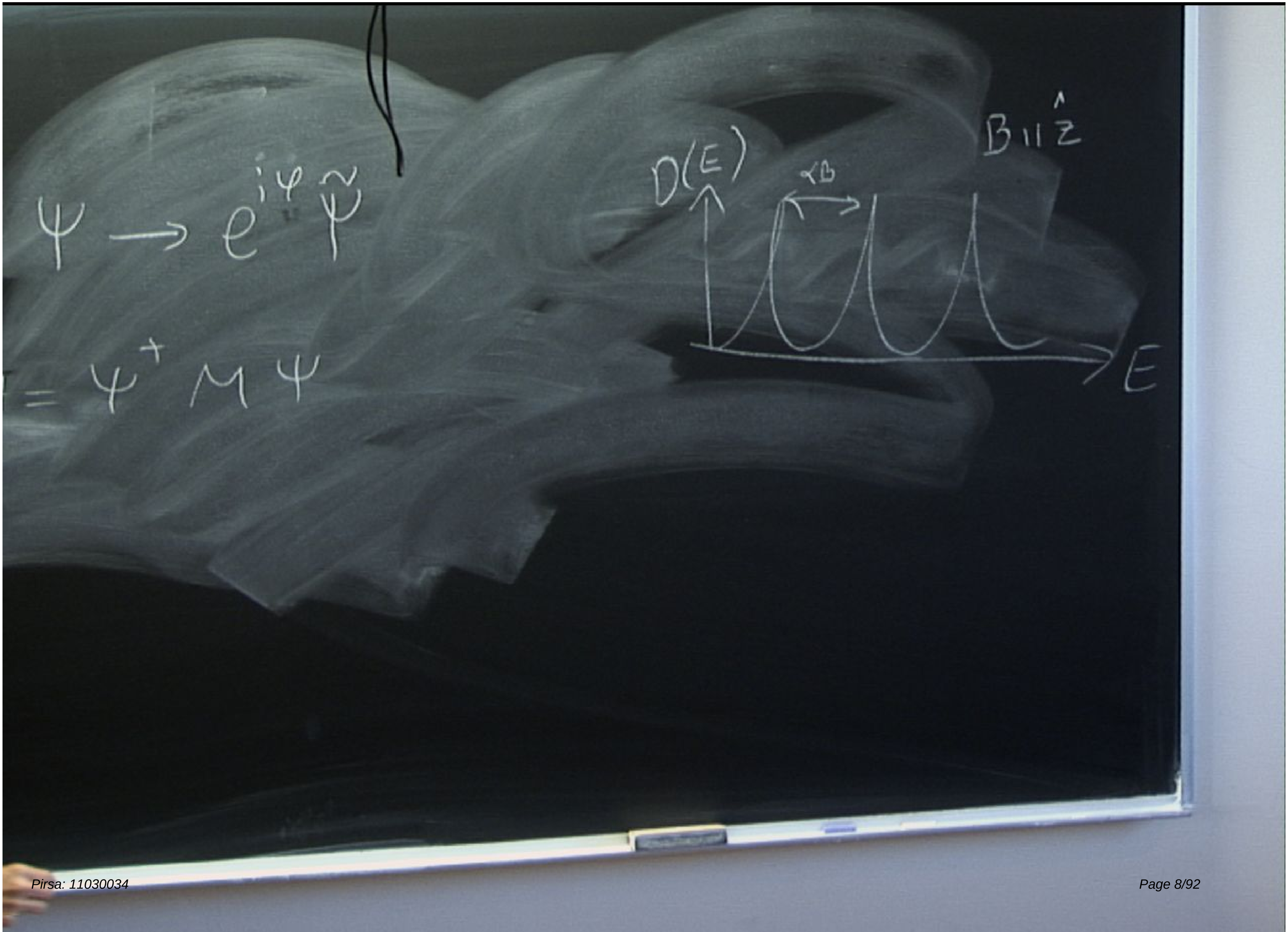

D(E)
B || ẑ

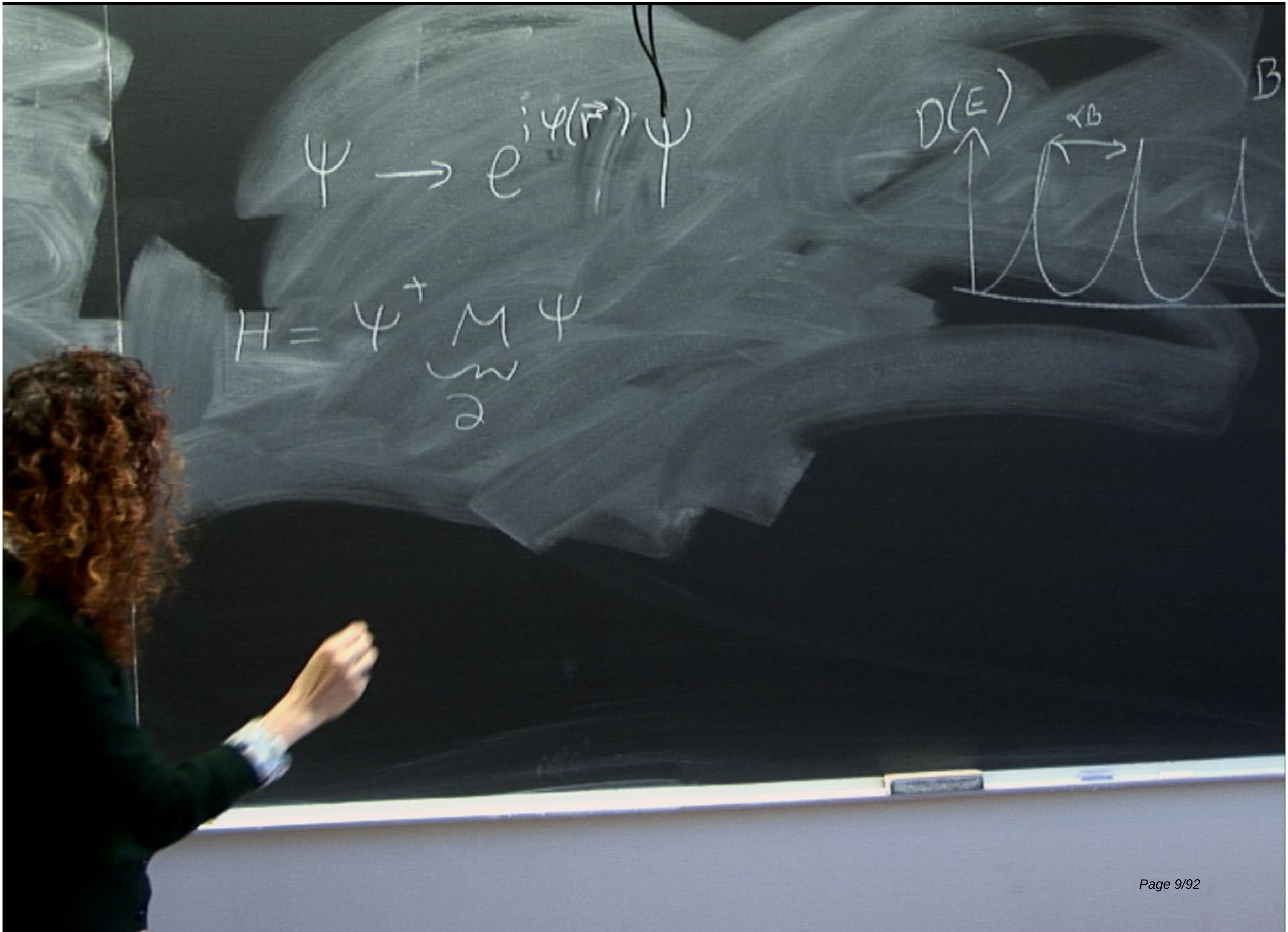

D(E)
B ∥ ẑ

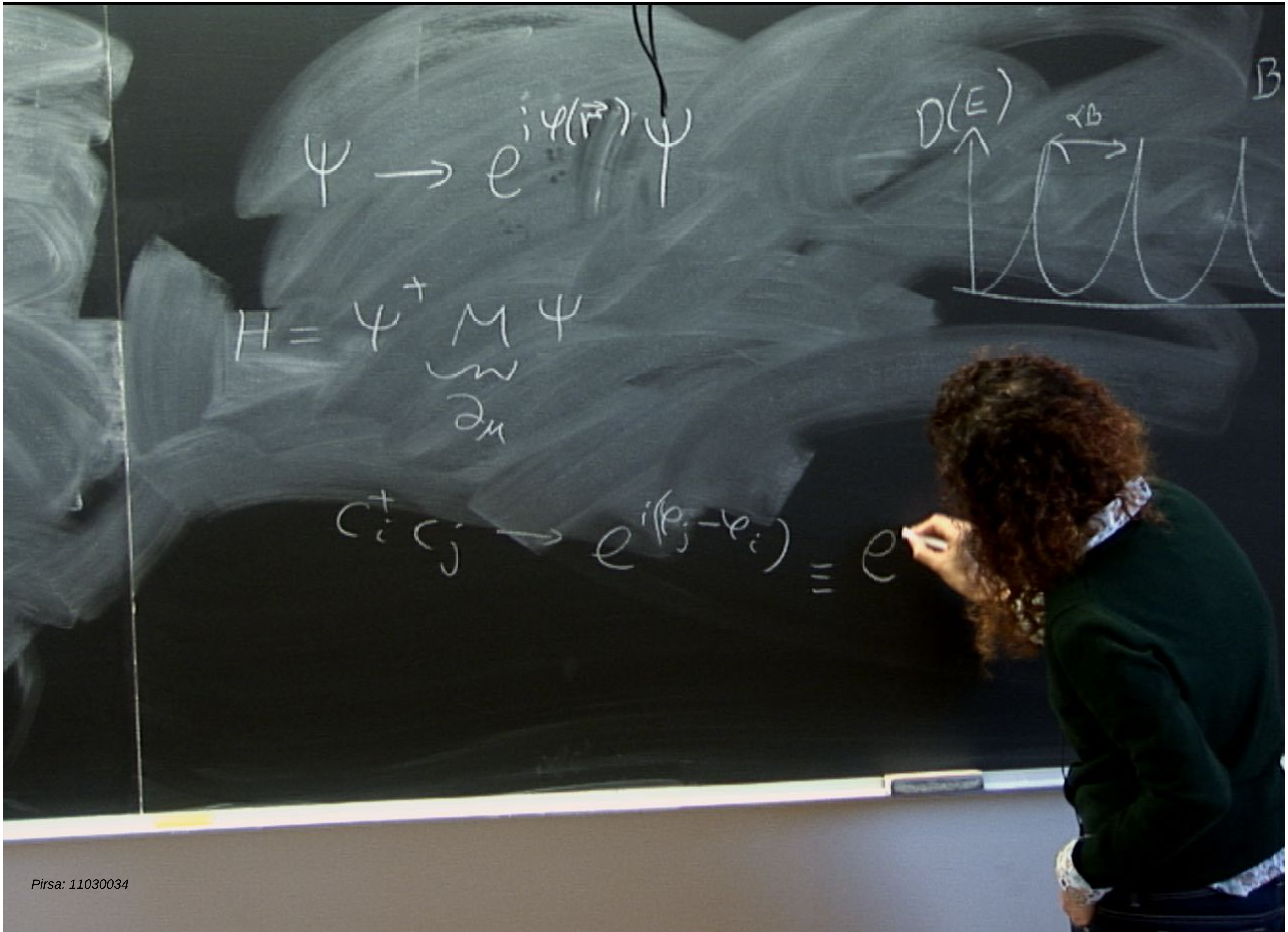


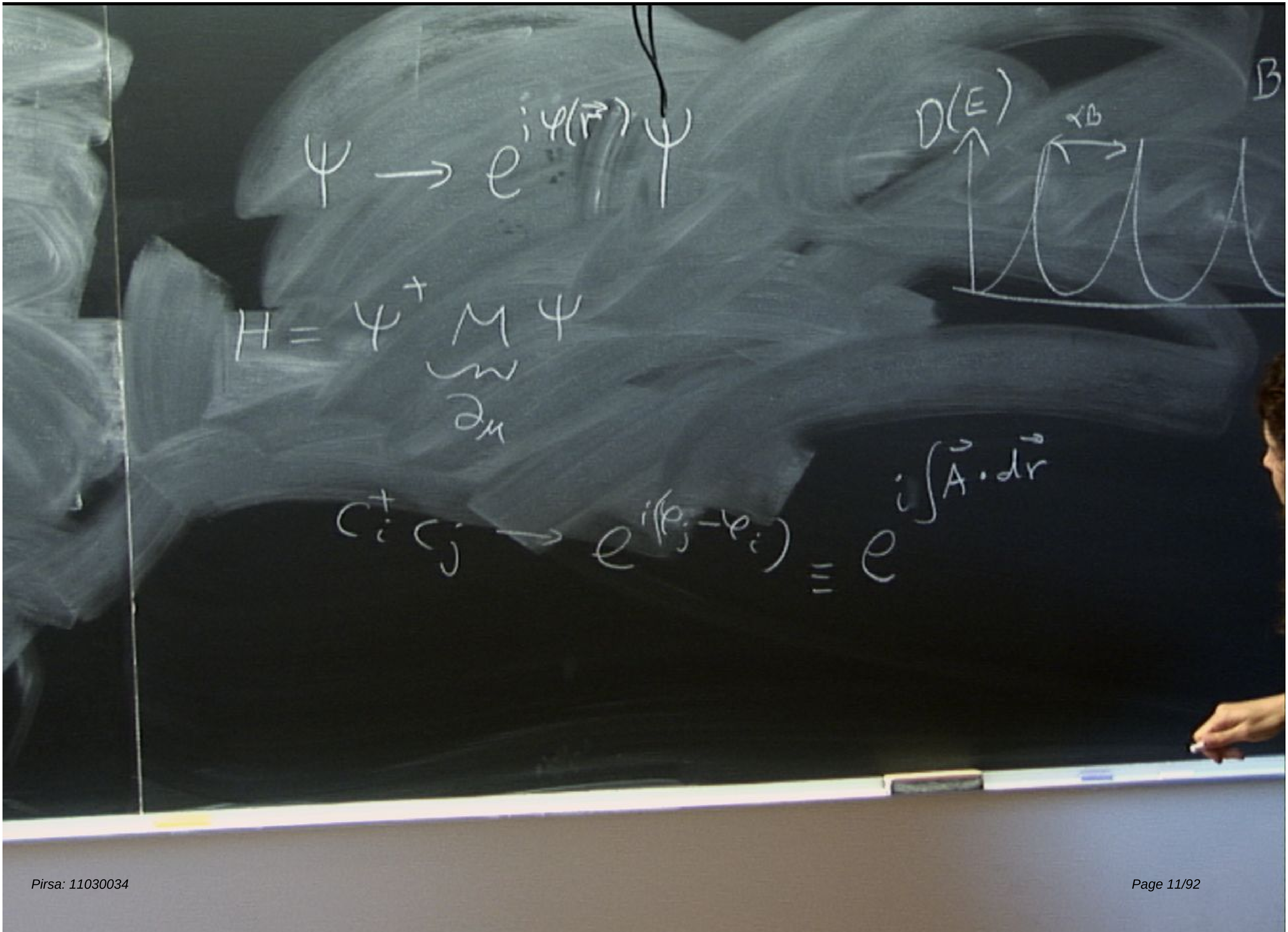
Pirsa: 11030034

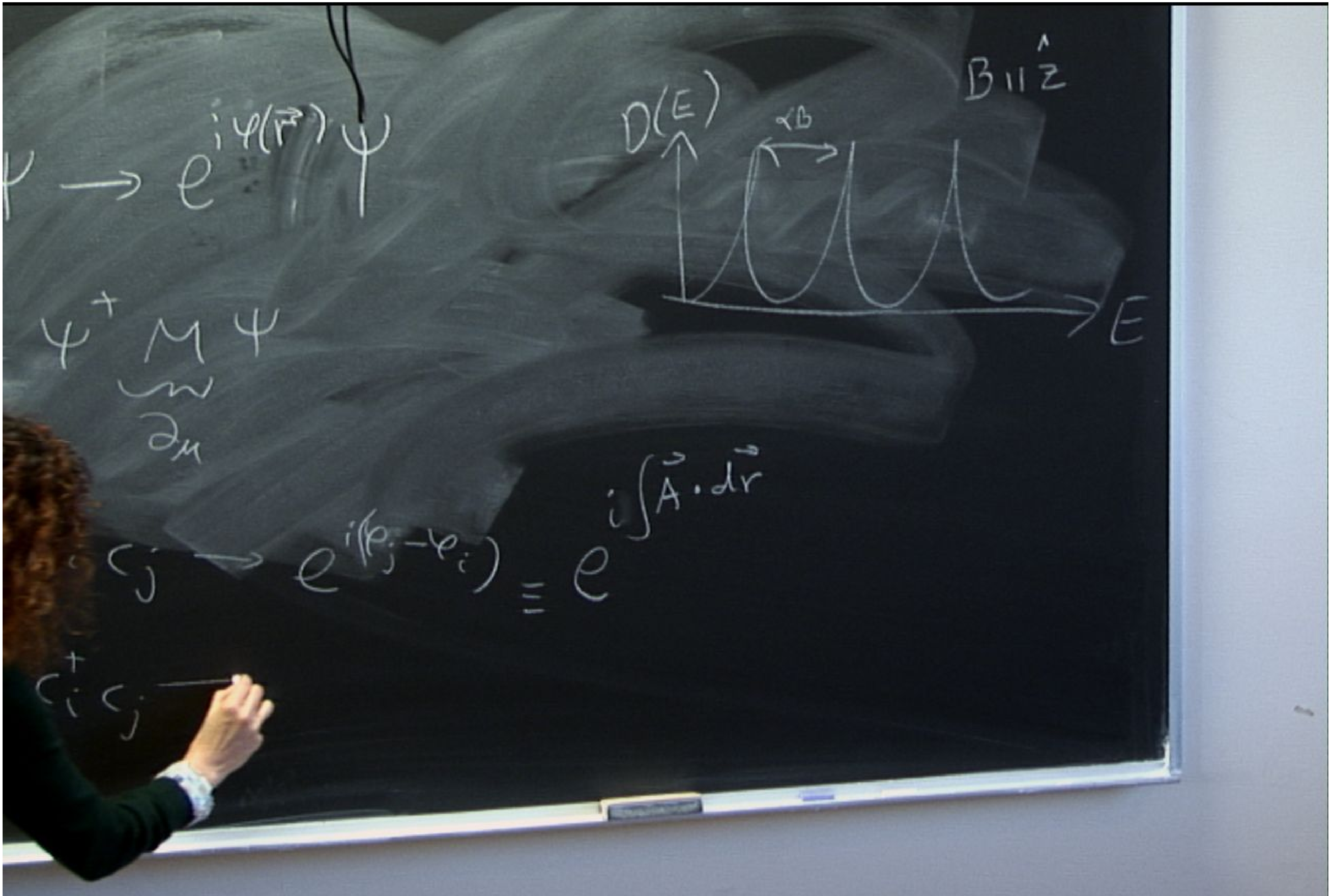

ψ → e^{iφ} ψ
D(E)
∝B
B ∥ ẑ
E

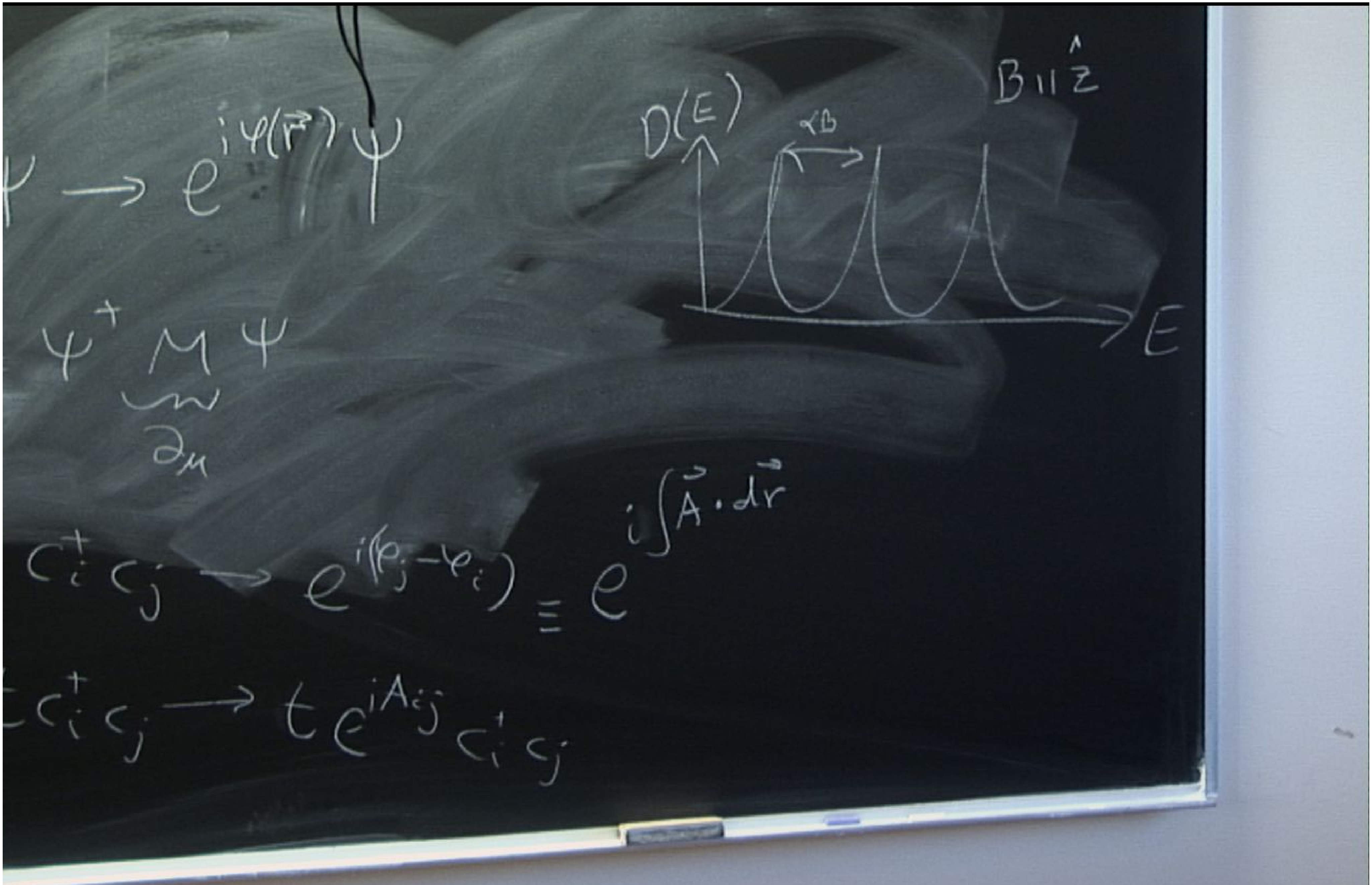

ψ → e^{iφ} ψ̃
= ψ† M ψ
D(E)
ωB
B ∥ ẑ
E

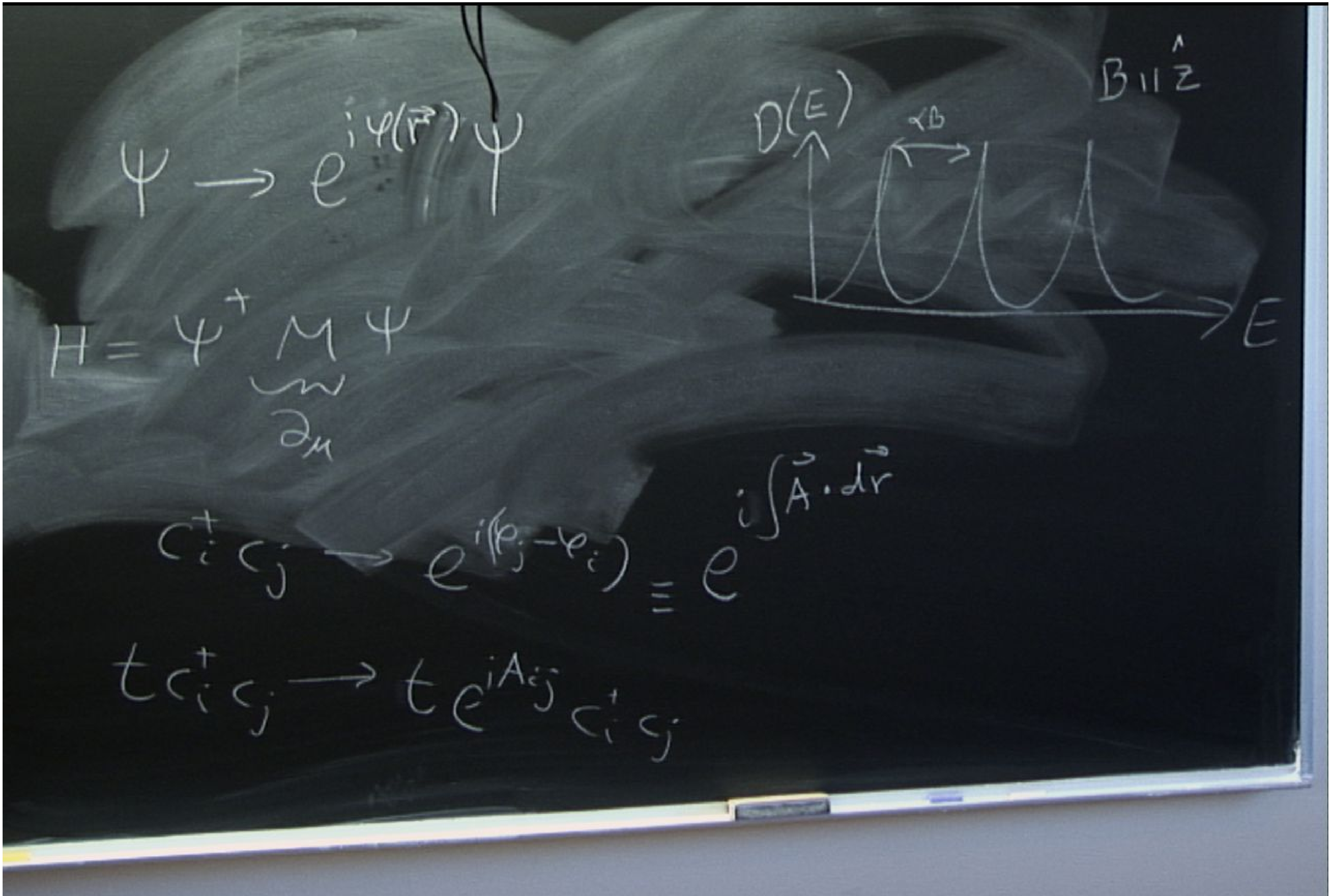

Ψ → e^{iφ(r⃗)} Ψ
H = Ψ† M Ψ
2
D(E)
∝B
B

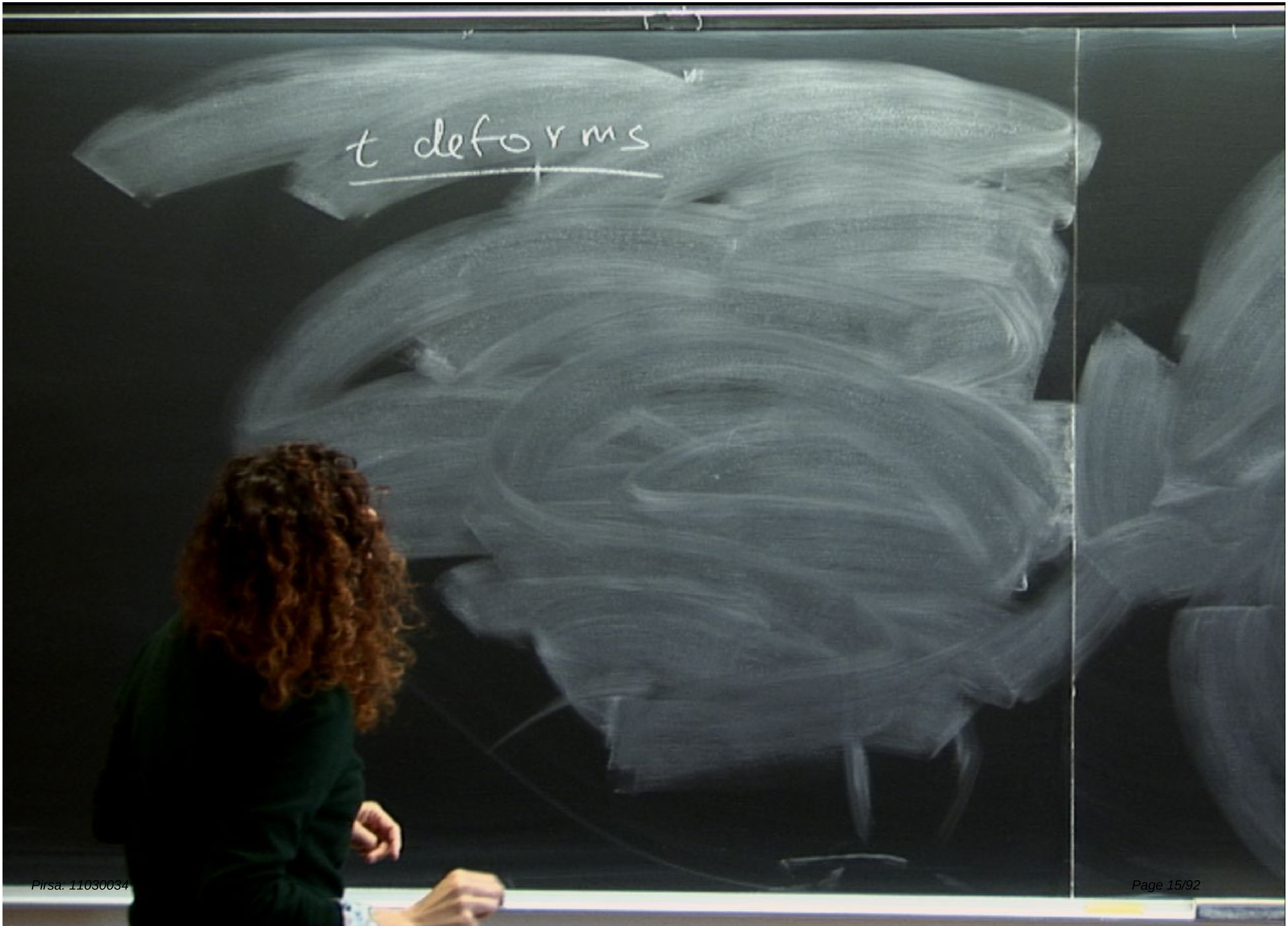

Ψ → e^{iφ(r⃗)} Ψ
D(E)
∝B
B
H = Ψ† M Ψ
∂μ
c_i† c_j → e^{i(φ_j − φ_i)} ≡ e

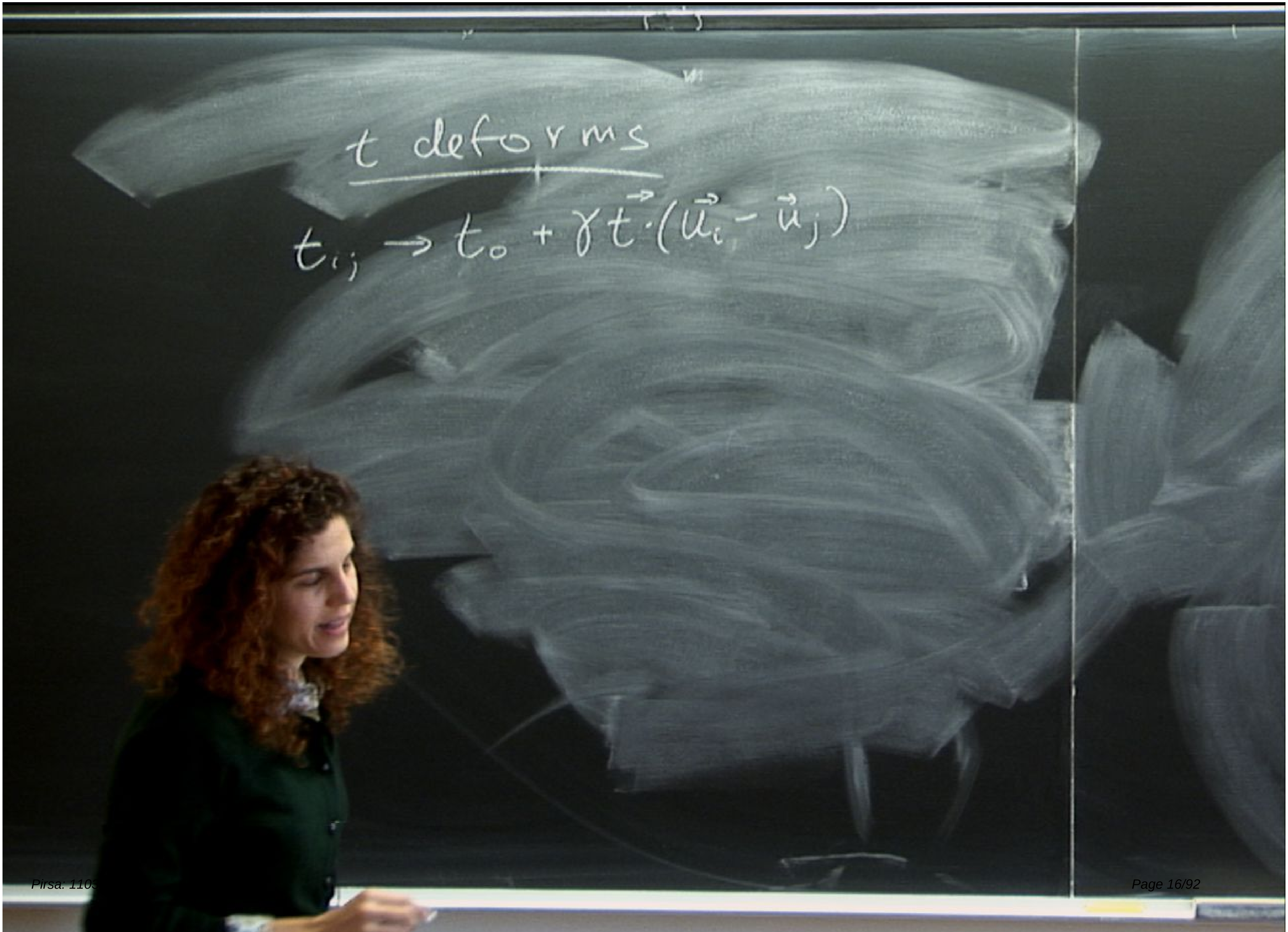

$\Psi \to e^{i\varphi(\vec{r})}\Psi$
$H = \Psi^{\dagger} M \Psi$
∂_μ
$c_i^{\dagger} c_j \to e^{i(\varphi_j - \varphi_i)} \equiv e^{i\int \vec{A}\cdot d\vec{r}}$
D(E)
$\propto B$
B

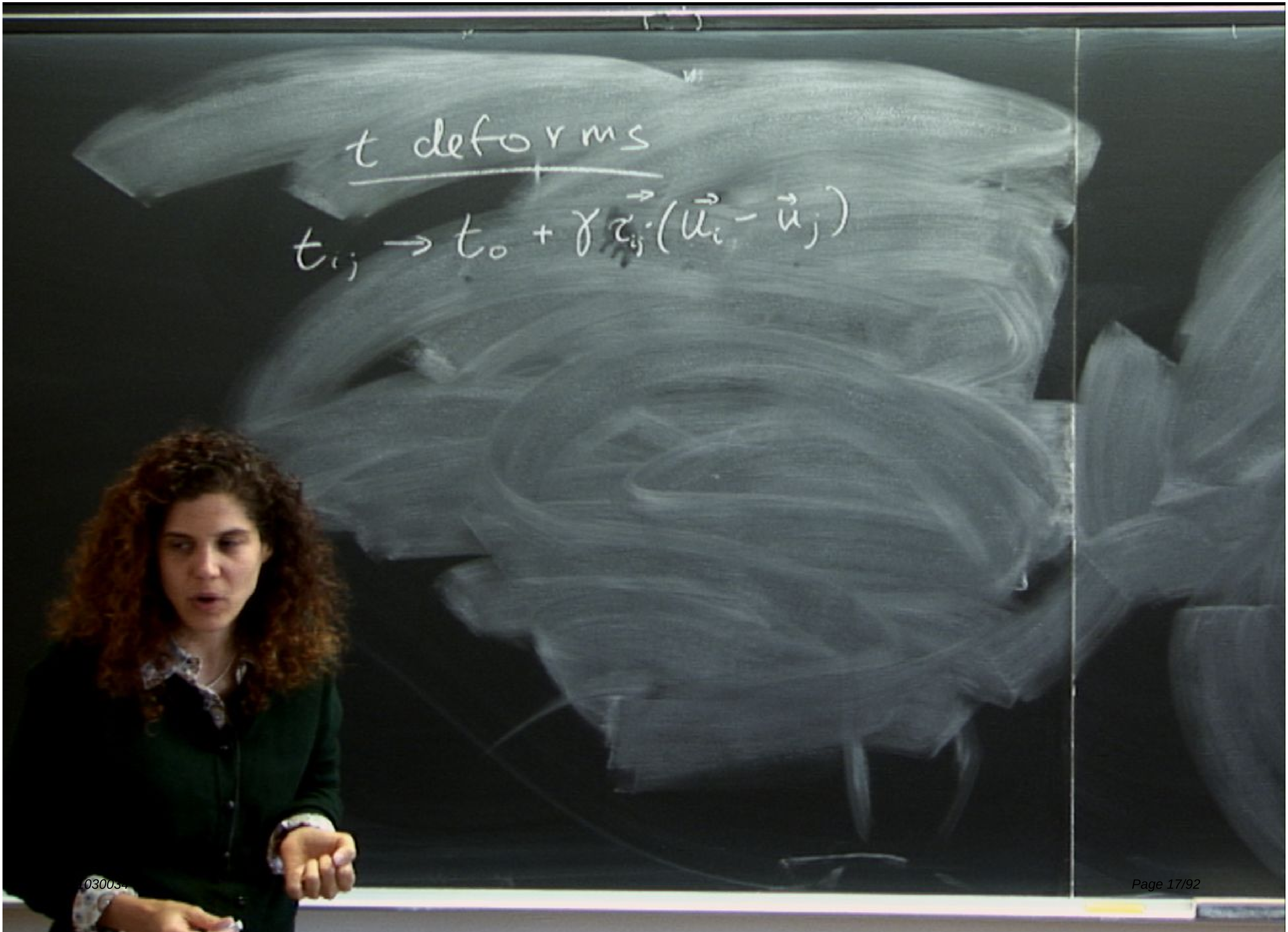

ψ → e^{iφ(r⃗)} ψ
ψ† M ψ
∂_μ
D(E)
∝B
B ∥ ẑ
E
c_j → e^{i(φ_j − φ_i)} ≡ e^{i∫A⃗·dr⃗}
c_i† c_j

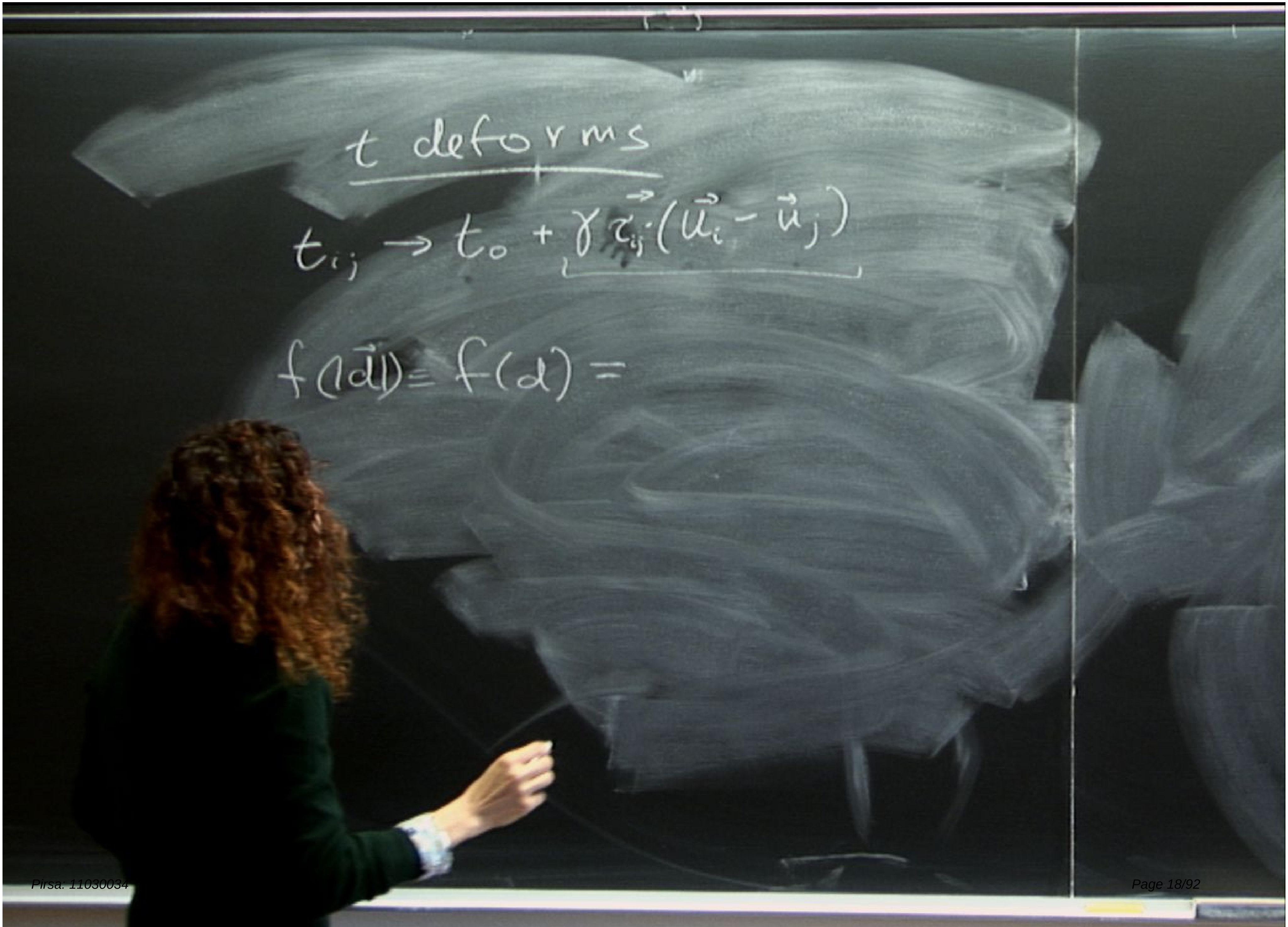

ψ → e^{iφ(r⃗)} ψ
D(E)
∝B
B ∥ ẑ
E
ψ† M ψ
∂_μ
e^{i∫A⃗·dr⃗}
c_i† c_j → e^{i(φ_j − φ_i)} ≡ e
t c_i† c_j → t e^{iA_ij} c_i† c_j

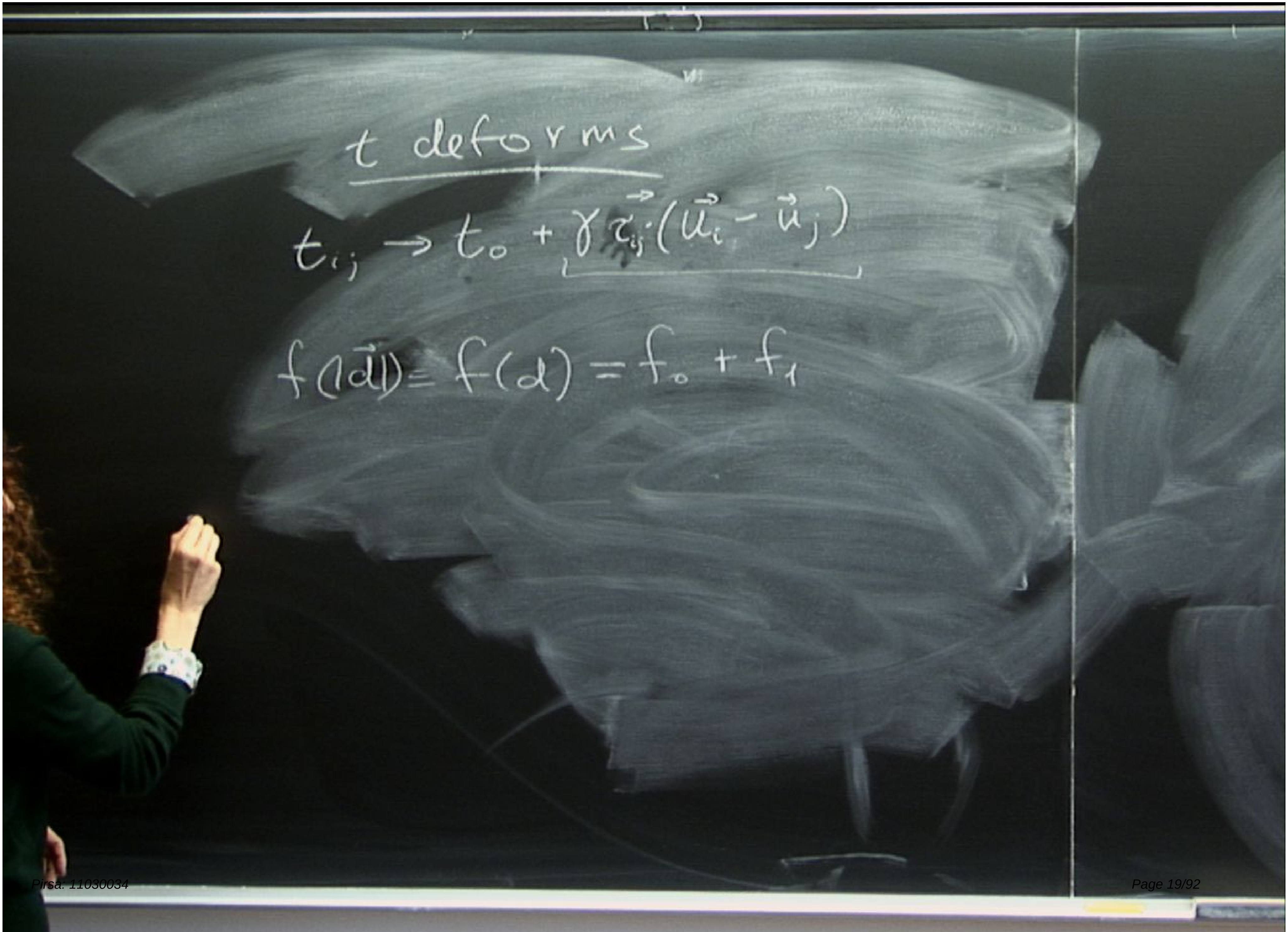

$\Psi \to e^{i\varphi(\vec{r})}\Psi$
$H = \Psi^\dagger M \Psi$
∂_μ
$c_i^\dagger c_j \to e^{i(\varphi_j - \varphi_i)} \equiv e^{i\int \vec{A}\cdot d\vec{r}}$
$t c_i^\dagger c_j \to t e^{iA_{ij}} c_i^\dagger c_j$
D(E)
$\propto B$
$B \parallel \hat{z}$
E

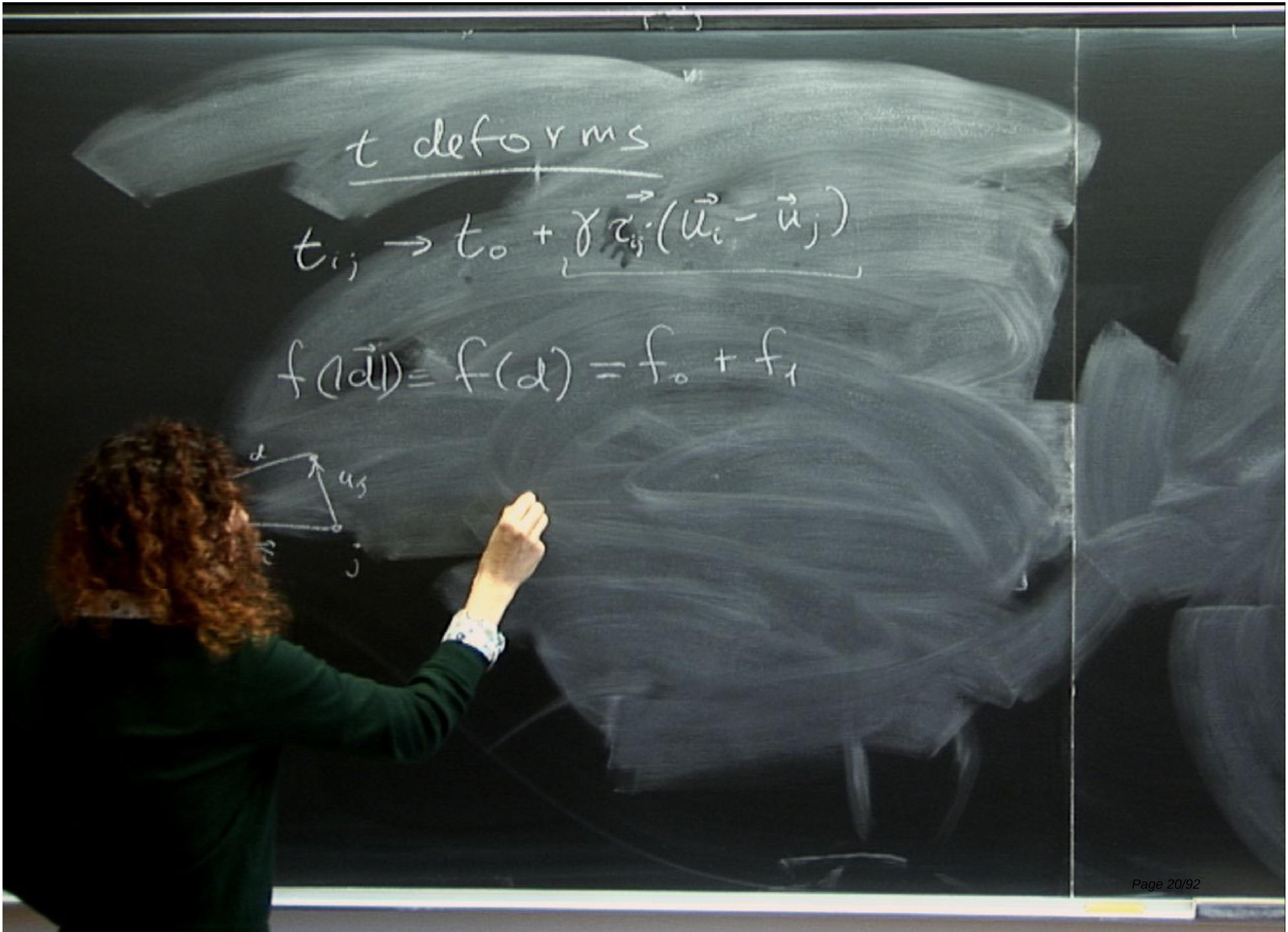

t deforms


t deforms
$t_{ij} \to t_0 + \gamma \vec{t} \cdot (\vec{u}_i - \vec{u}_j)$


t deforms
$t_{ij} \to t_0 + \gamma \vec{r}_{ij} \cdot (\vec{u}_i - \vec{u}_j)$


t deforms
$t_{ij} \to t_0 + \gamma \vec{r}_{ij} \cdot (\vec{u}_i - \vec{u}_j)$
$f(|\vec{d}|) = f(d) =$

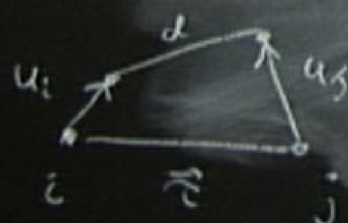

t deforms
t_ij → t_0 + γ τ_ij · (u_i − u_j)
f(|d|) = f(d) = f_0 + f_1


t deforms
$t_{ij} \to t_0 + \gamma \vec{\tau}_{ij} \cdot (\vec{u}_i - \vec{u}_j)$
$f(|\vec{d}|) = f(d) = f_0 + f_1$
d
u_j
j

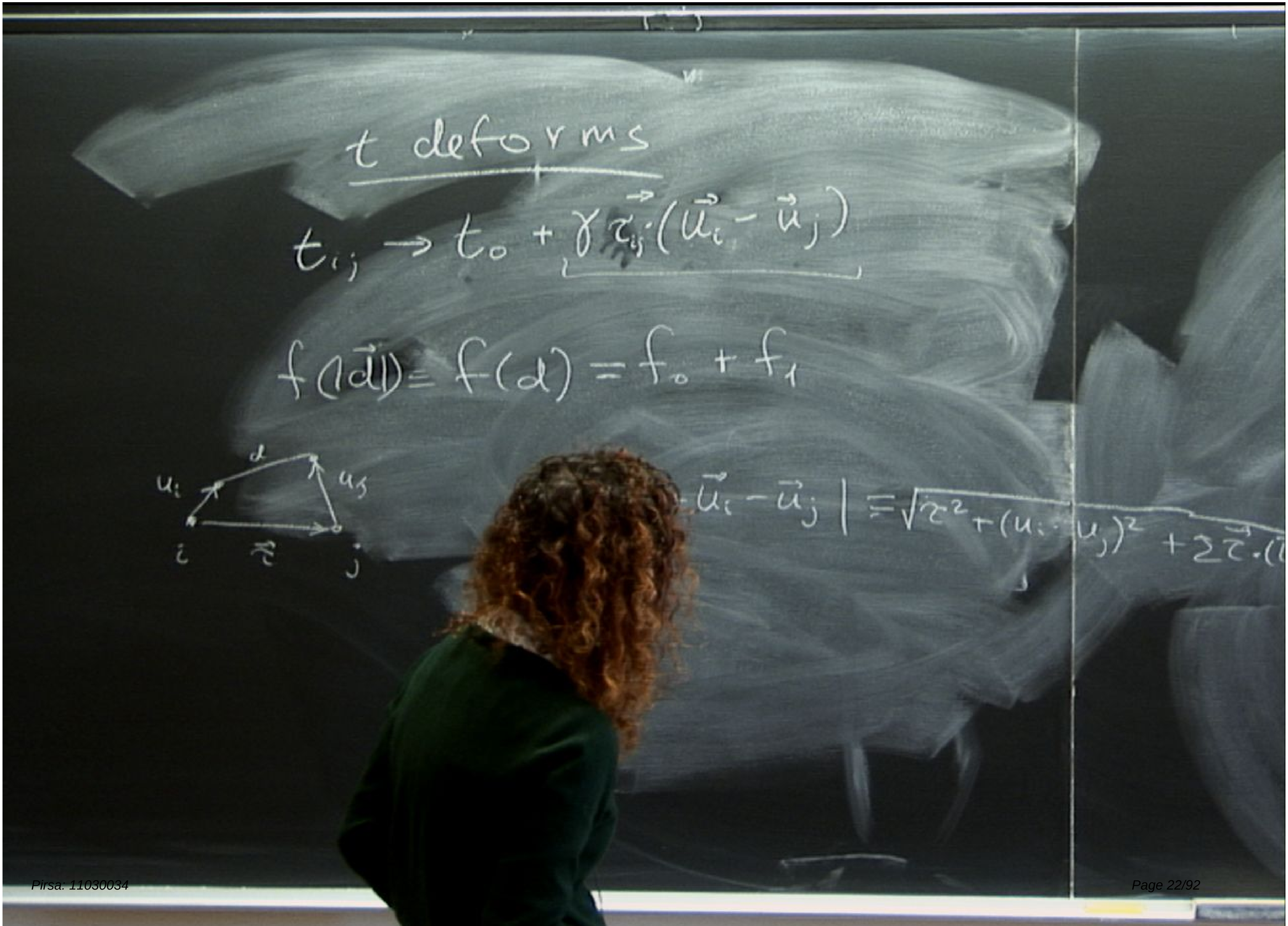
t deforms

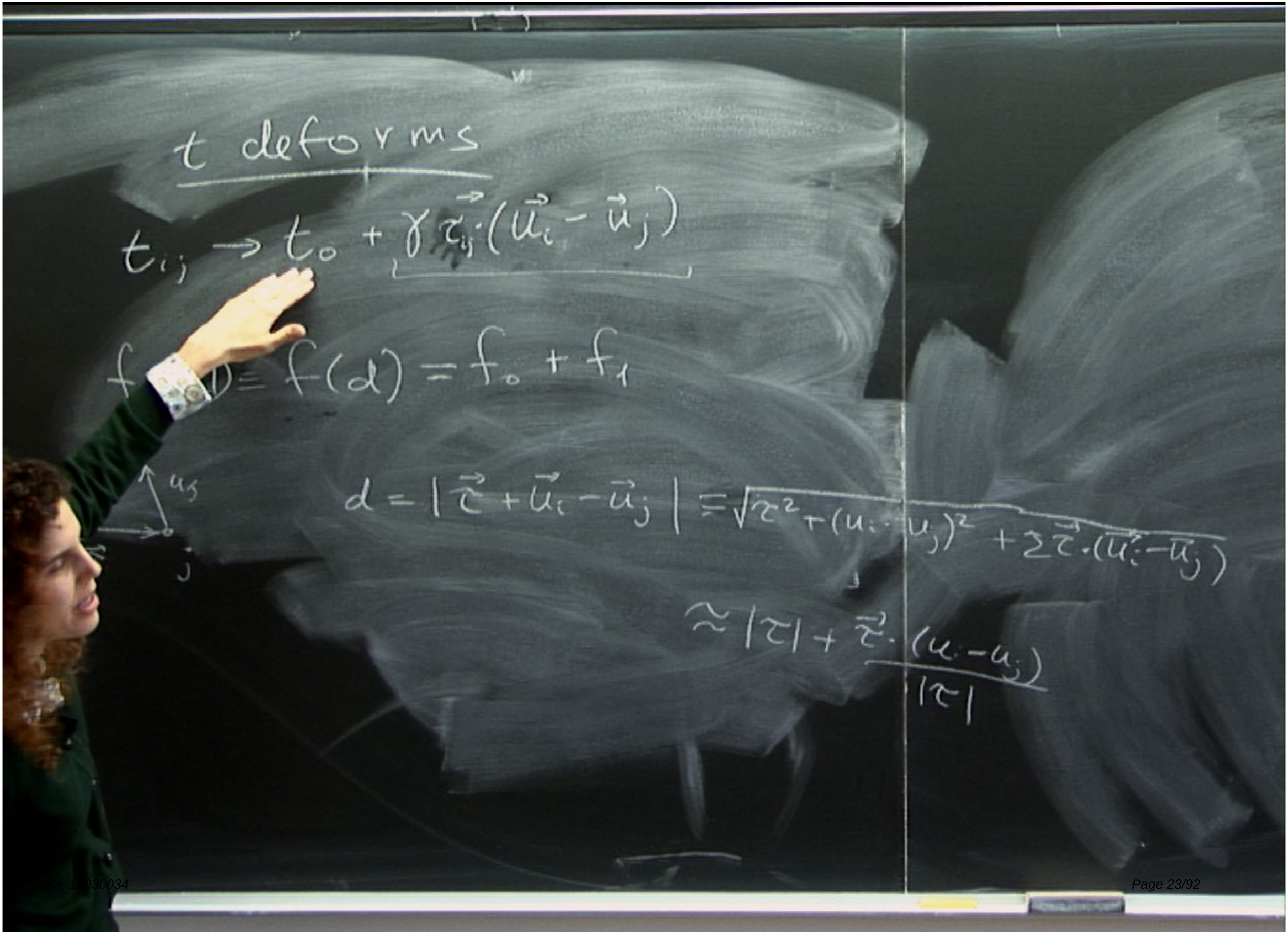
$$t_{ij} \to t_0 + \gamma \vec{\tau}_{ij} \cdot (\vec{u}_i - \vec{u}_j)$$

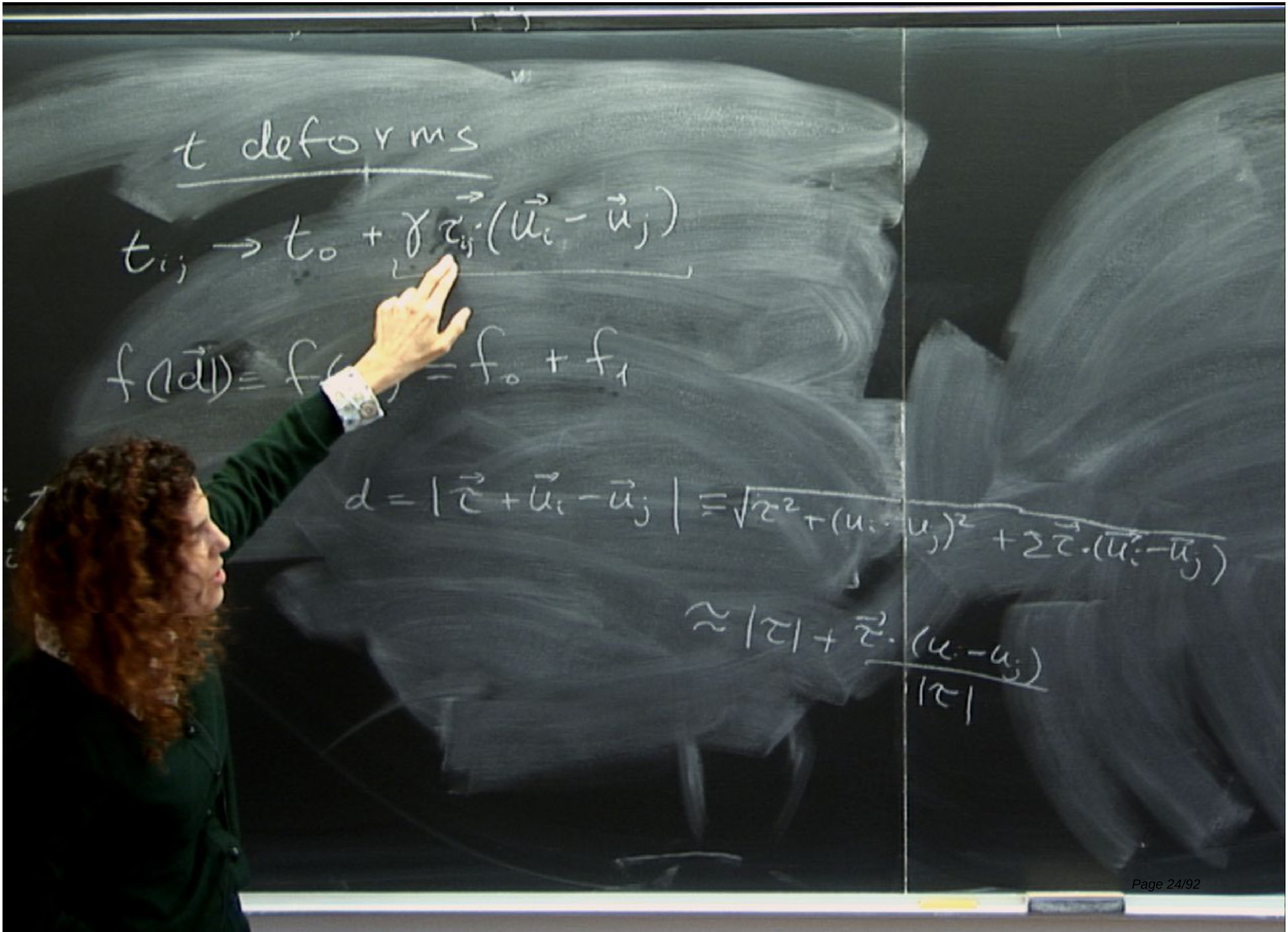
$$f(|\vec{d}|) = f(d) = f_0 + f_1$$

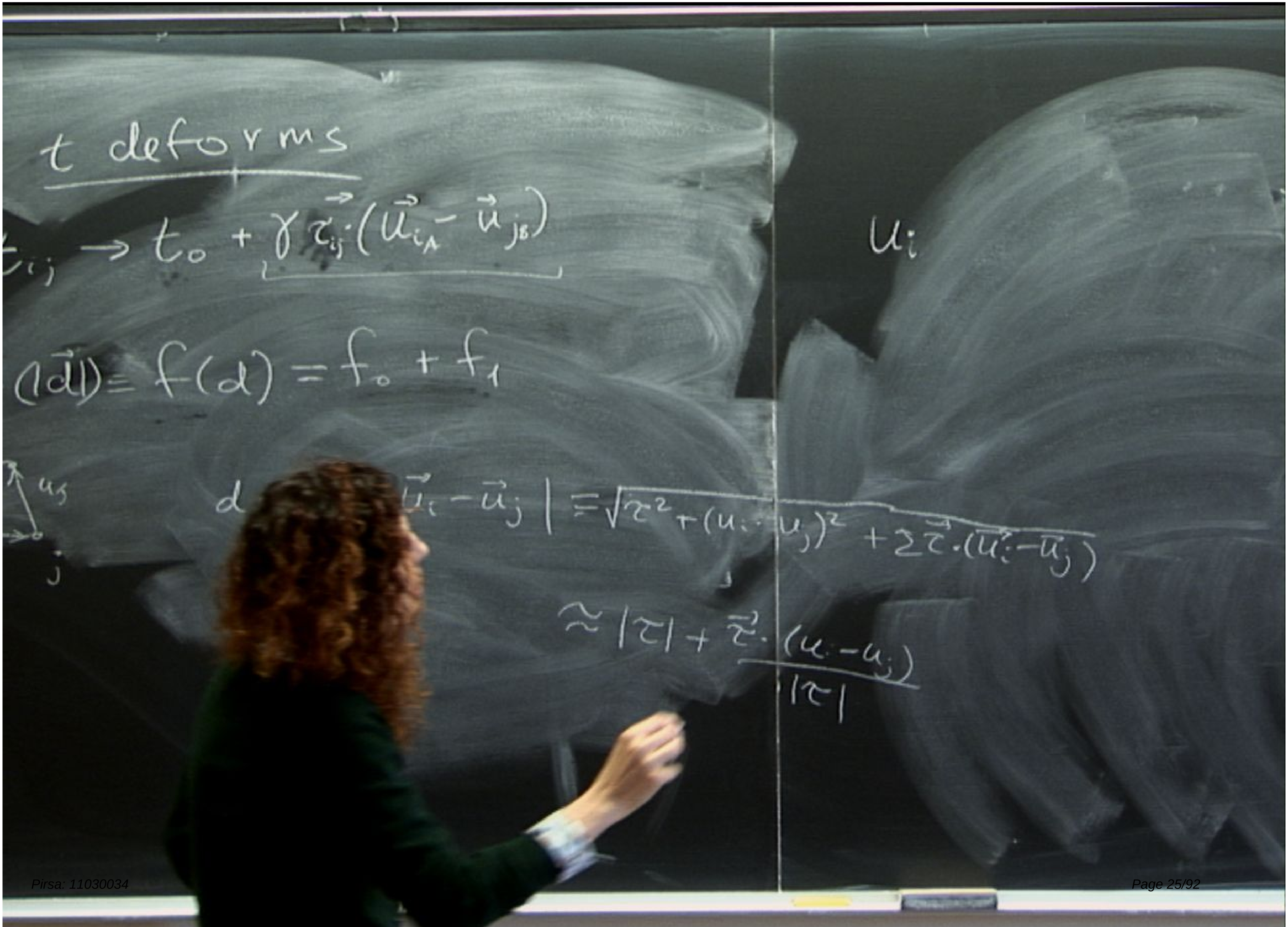


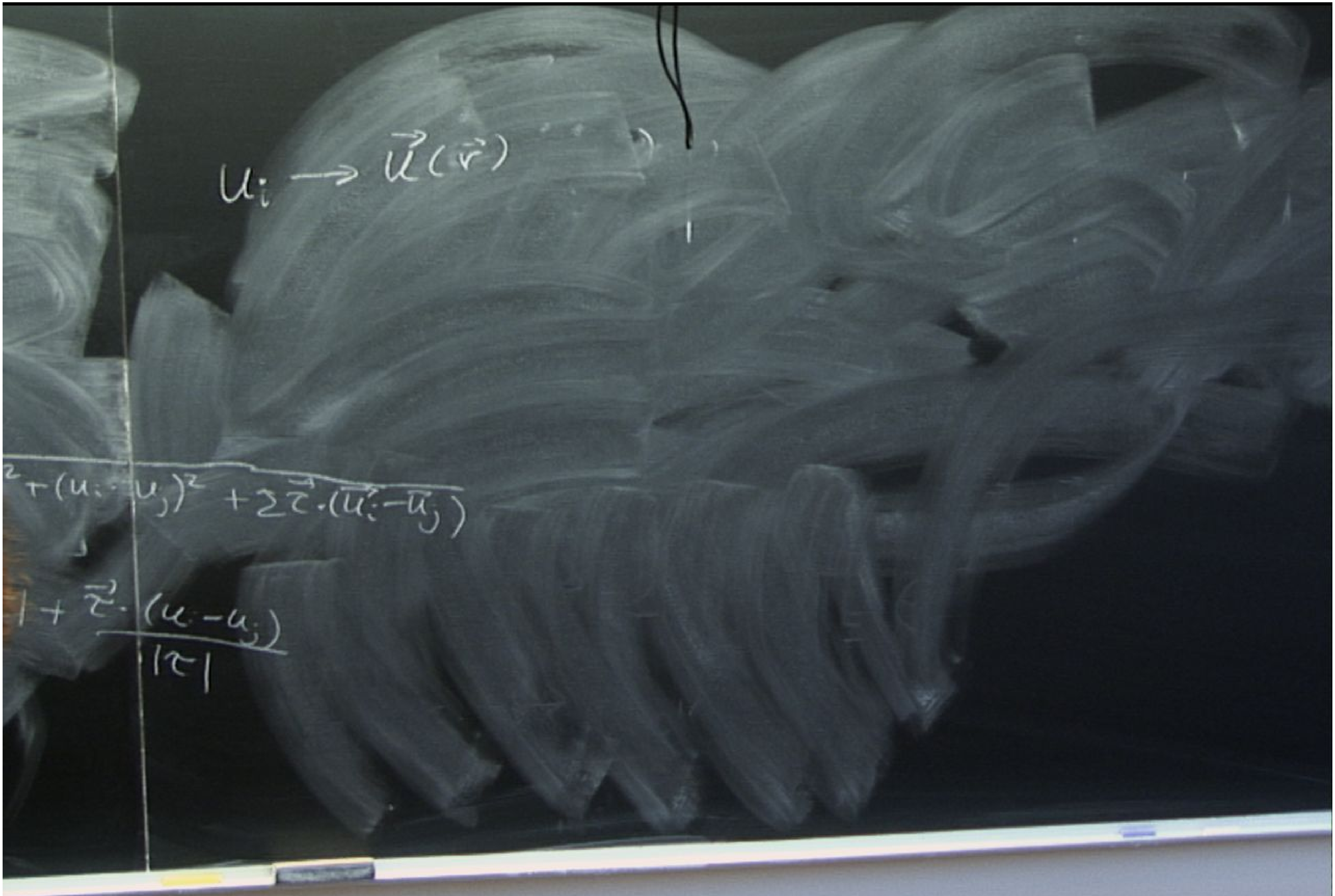
$$d = |\vec{\tau} + \vec{u}_i - \vec{u}_j|$$

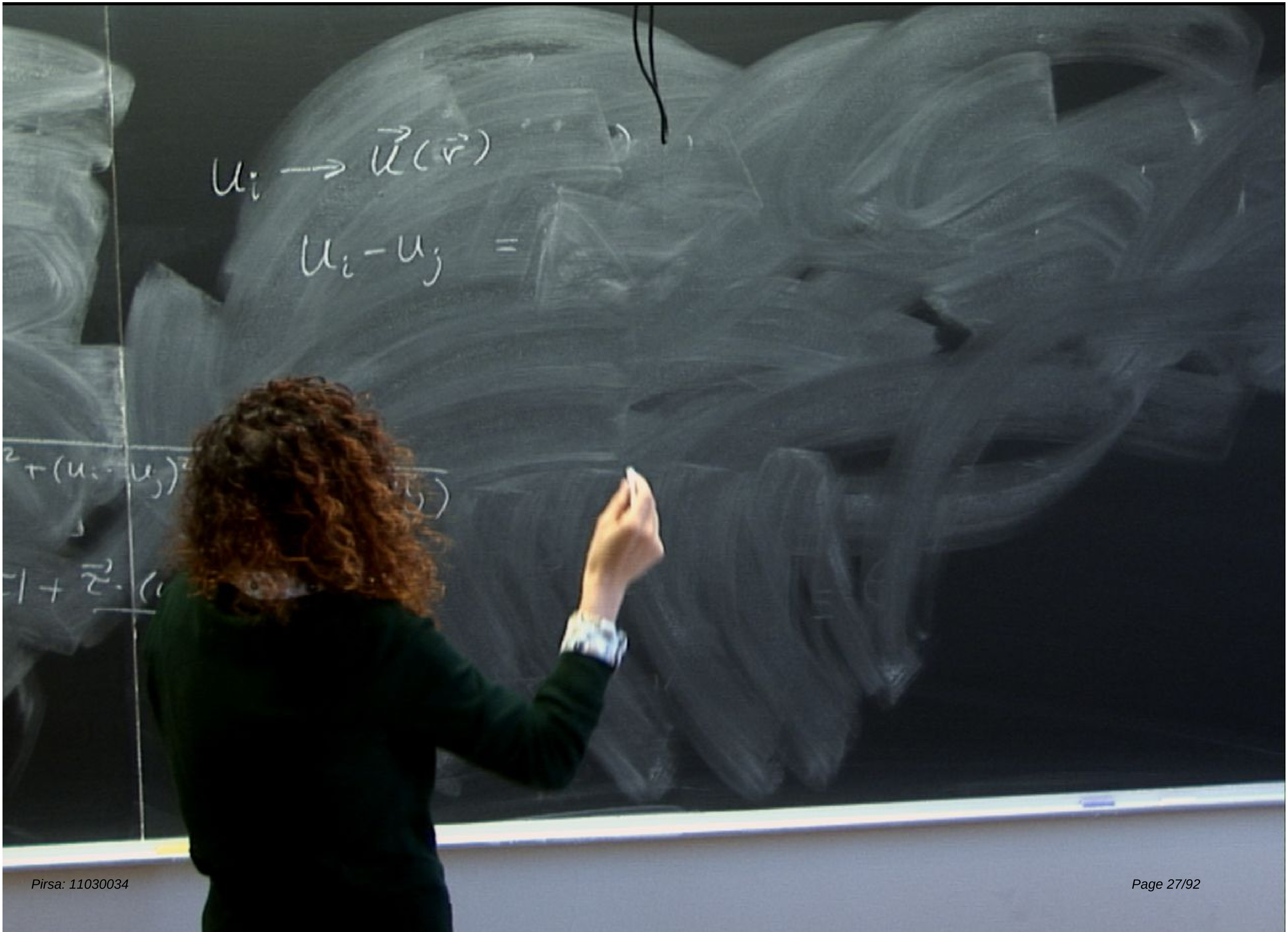

t deforms
$t_{ij} \to t_0 + \gamma \vec{\tau}_{ij} \cdot (\vec{u}_i - \vec{u}_j)$
$f(|\vec{d}|) = f(d) = f_0 + f_1$
u_i
d
u_j
i
$\vec{\tau}$
j
$\vec{u}_i - \vec{u}_j \,| = \sqrt{\tau^2 + (u_i - u_j)^2} + 2\vec{\tau}\cdot($

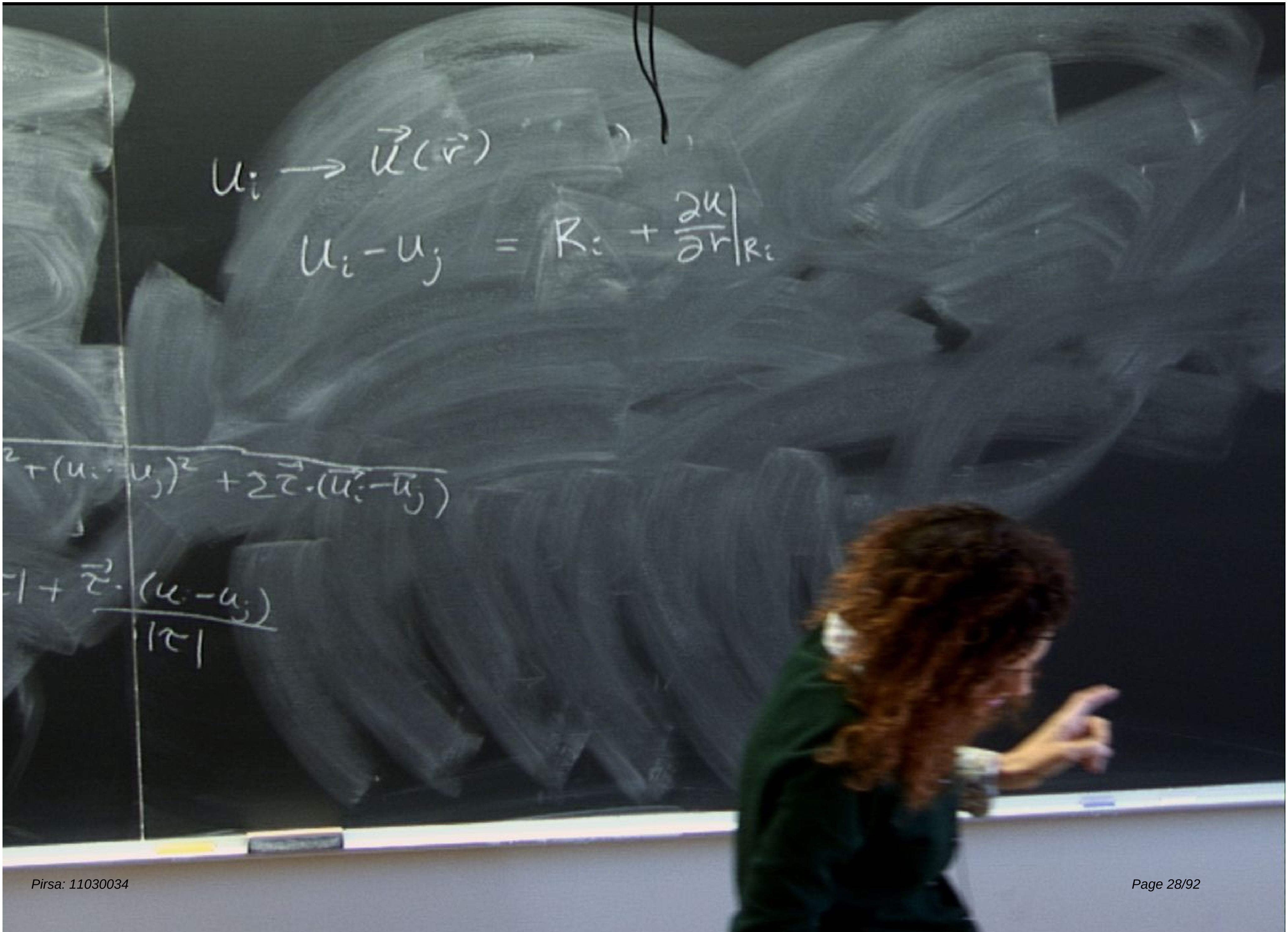

t deforms
t_ij → t_0 + γ τ_ij · (u_i − u_j)
f = f(d) = f_0 + f_1
u_j
j
d = | τ + u_i − u_j | = √(τ² + (u_i − u_j)² + 2 τ · (u_i − u_j))
≈ |τ| + τ · (u_i − u_j) / |τ|

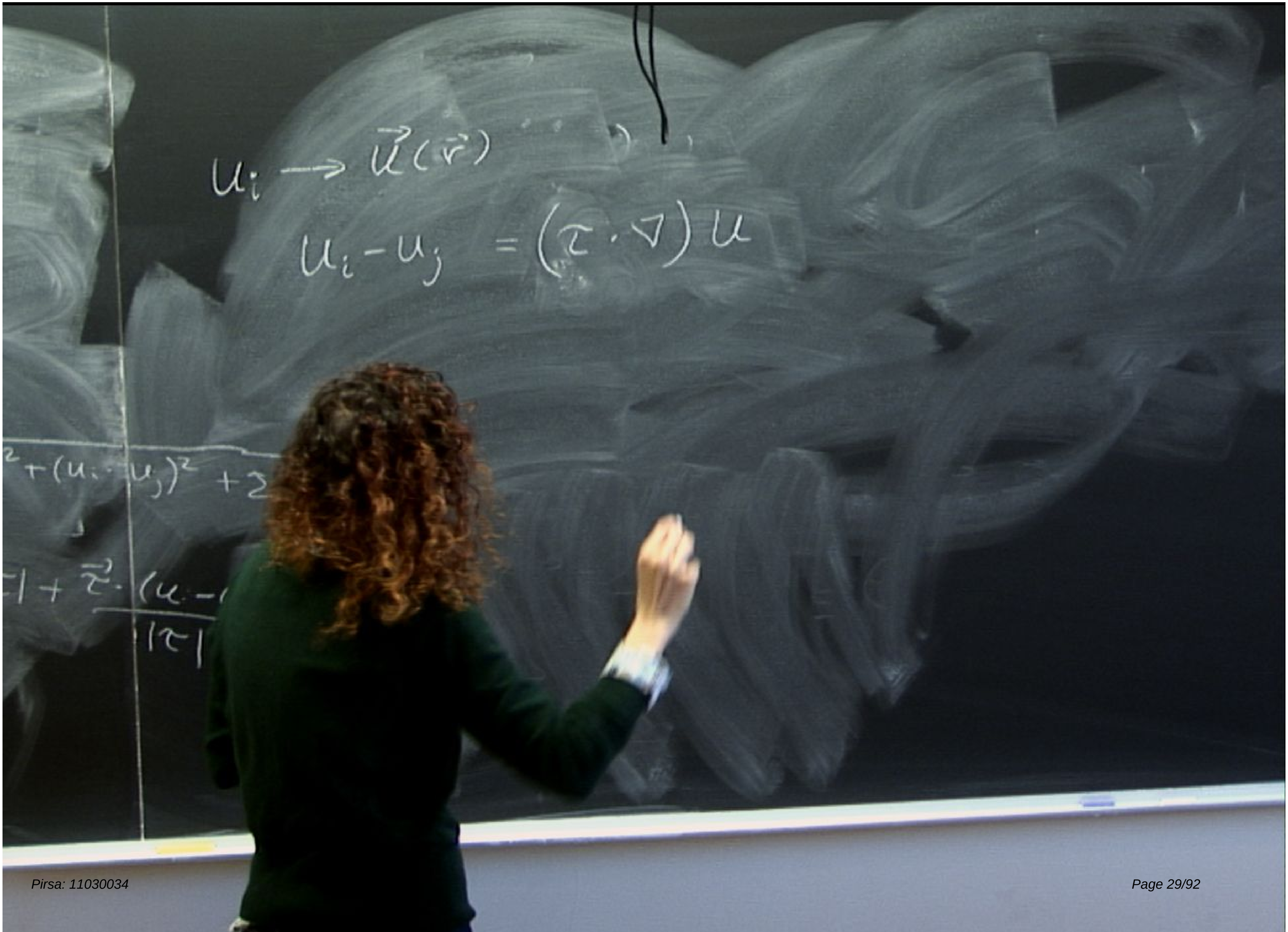

t deforms
t_ij → t_0 + γ τ_ij·(u_i − u_j)
f(|d|) = f( ) = f_0 + f_1
d = |τ + u_i − u_j| = √(τ² + (u_i − u_j)² + 2τ·(u_i − u_j))
≈ |τ| + τ·(u_i − u_j) / |τ|


t deforms
$t_{ij} \to t_0 + \gamma \vec{\tau}_{ij} \cdot (\vec{u}_{iA} - \vec{u}_{jB})$
$(|\vec{d}|) = f(d) = f_0 + f_1$
u_i
u_j
j
$d = |\vec{\tau} + \vec{u}_i - \vec{u}_j| = \sqrt{\tau^2 + (u_i - u_j)^2 + 2\vec{\tau}\cdot(\vec{u}_i - \vec{u}_j)}$
$\approx |\tau| + \vec{\tau} \cdot \frac{(u_i - u_j)}{|\tau|}$

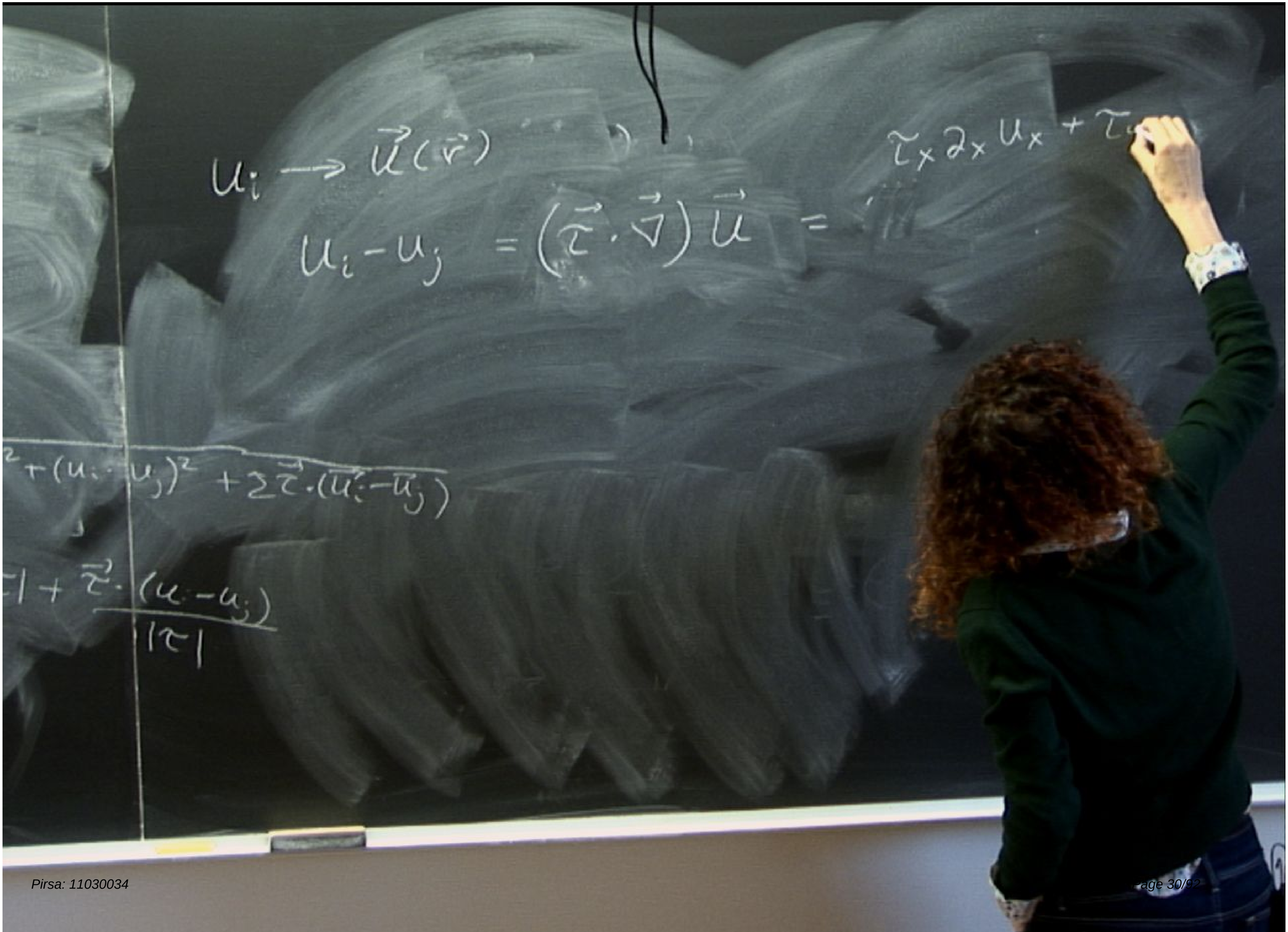

u_i → u⃗(r⃗)
² + (u_i − u_j)² + Σ τ⃗·(u⃗_i − u⃗_j)
+ τ⃗·(u_i − u_j) / |τ|

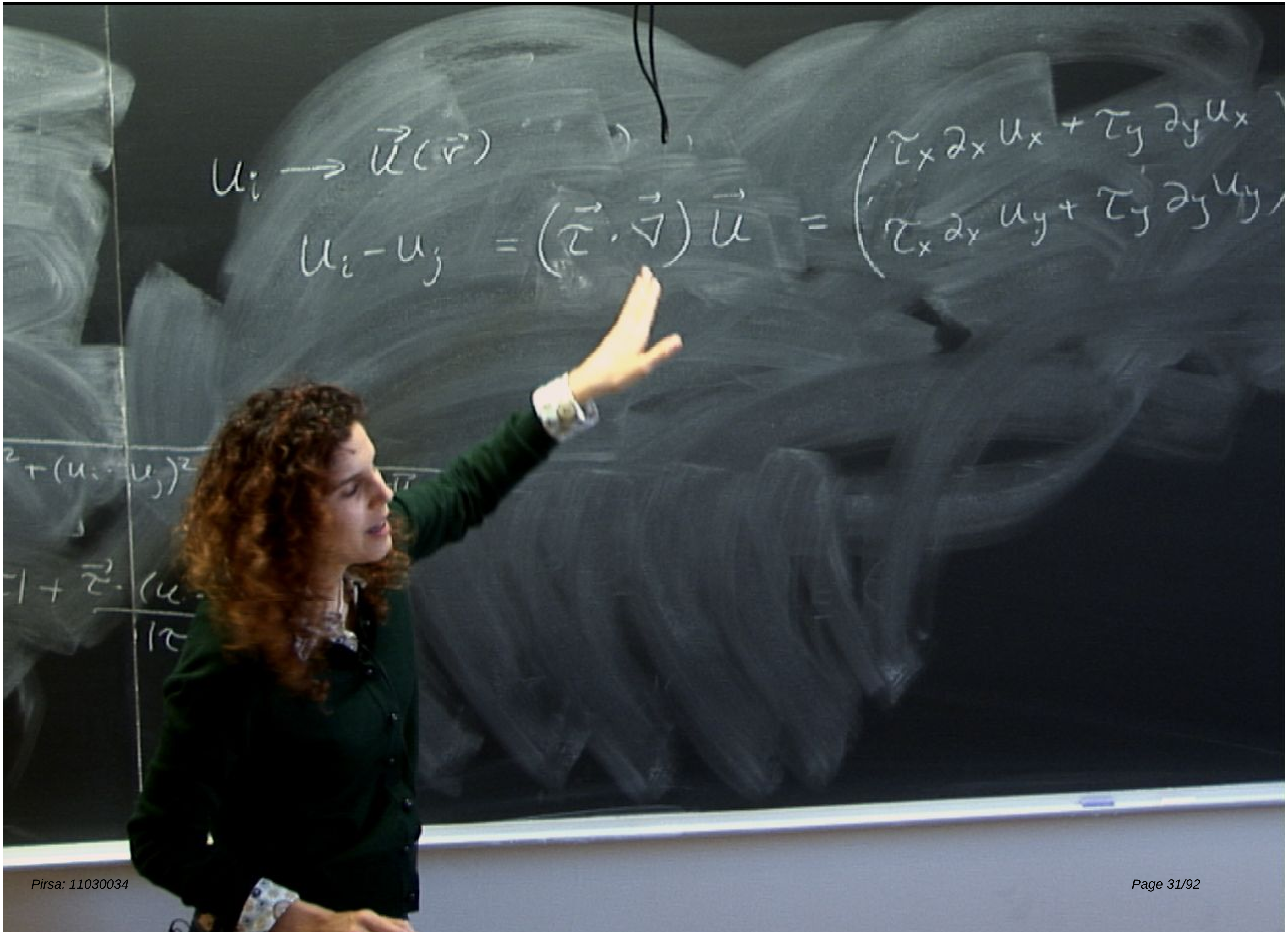

$u_i \to \vec{u}(\vec{r})$
$u_i - u_j =$

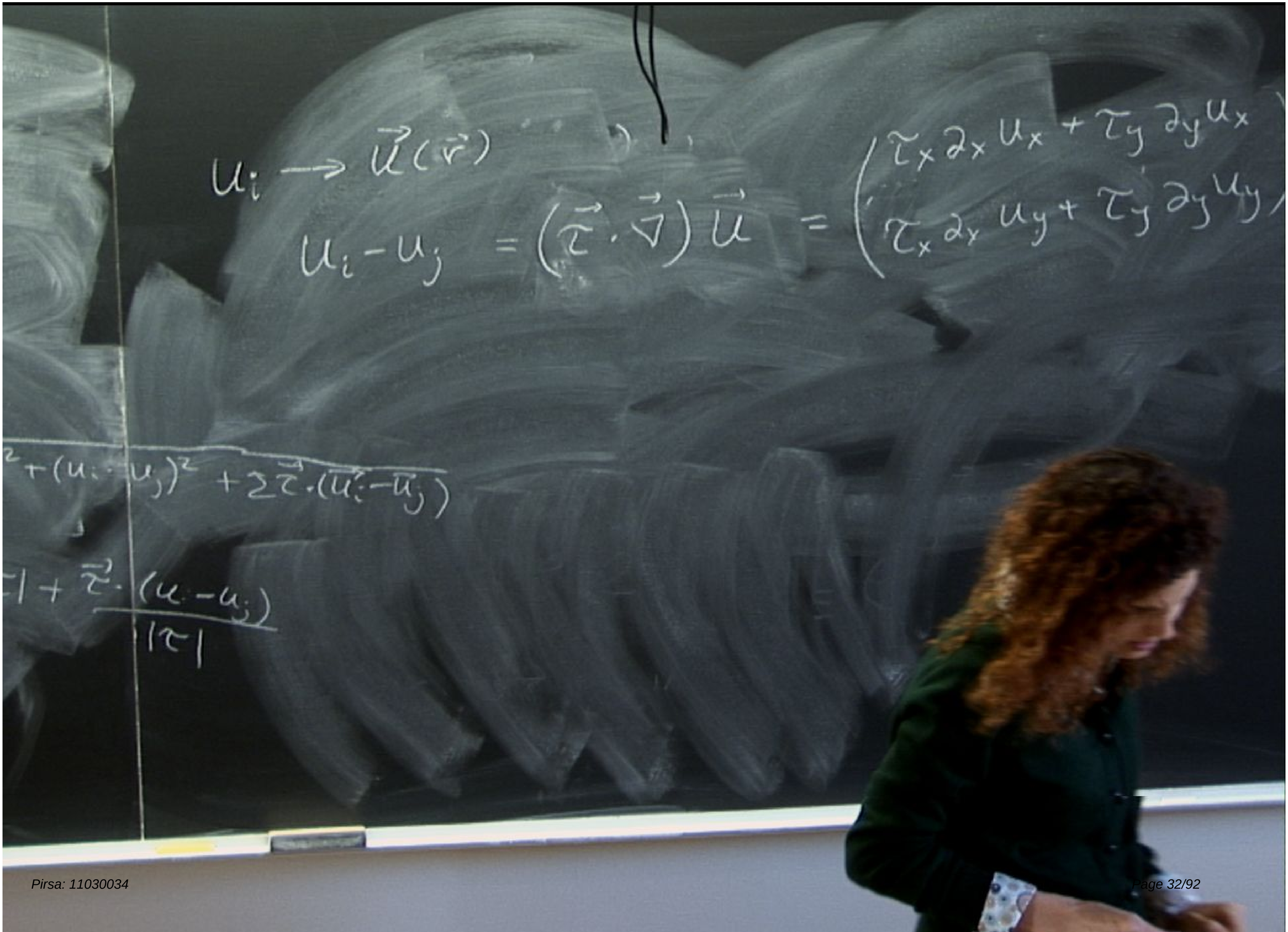

u_i → u(r)
u_i − u_j = R_i + ∂u/∂r|R_i

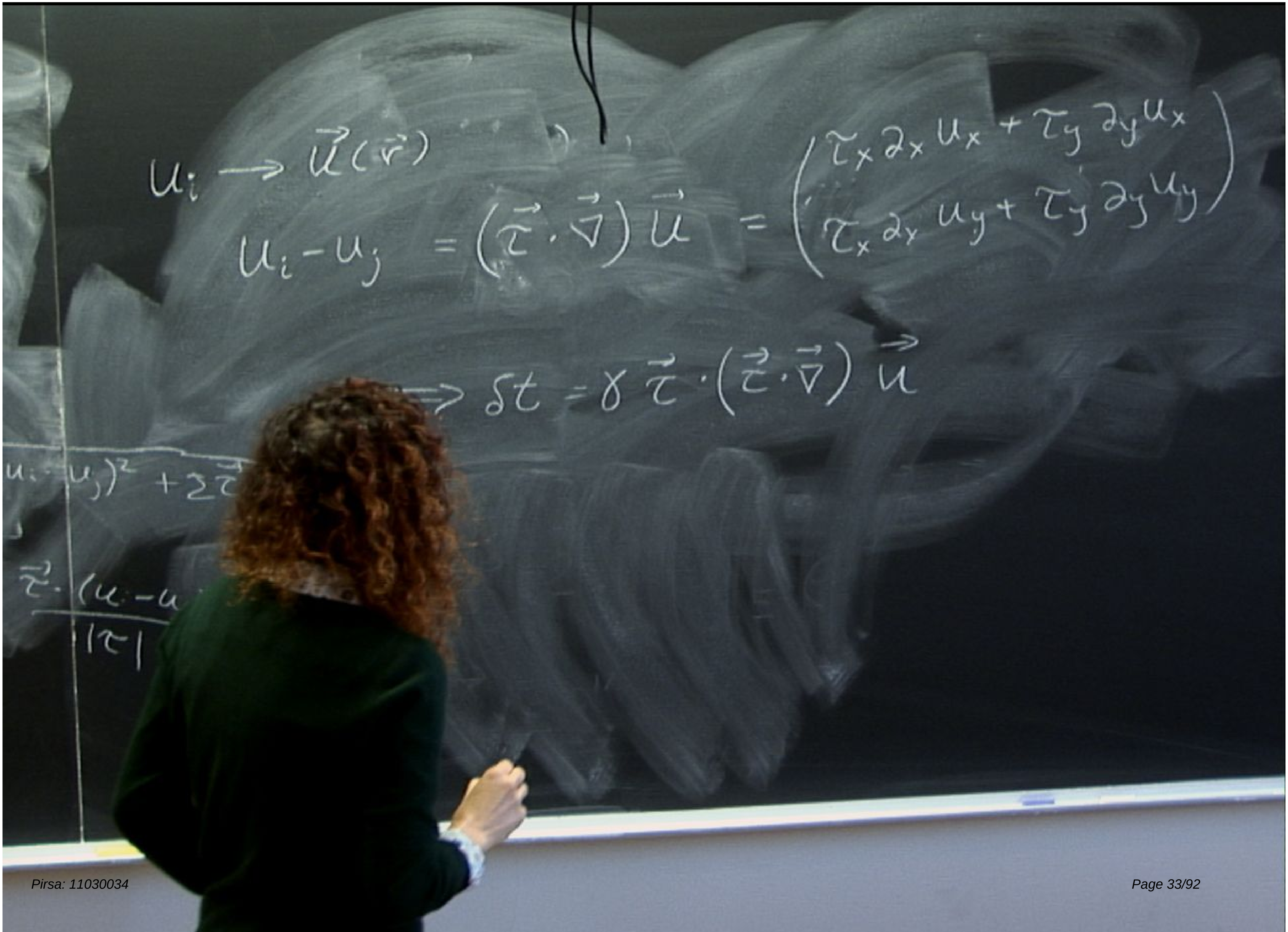


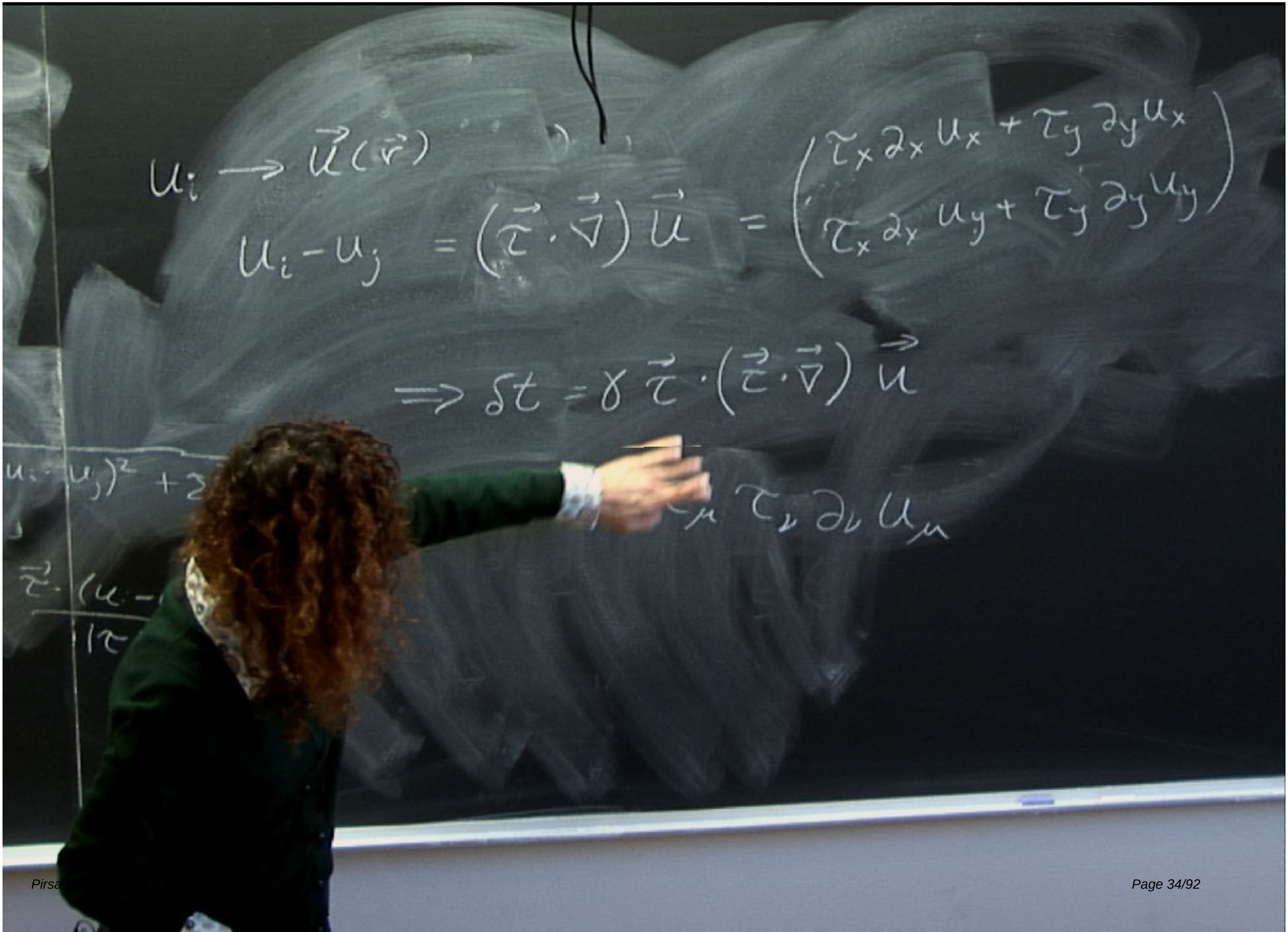
$u_i \longrightarrow \vec{u}(\vec{r})$
$u_i - u_j = (\tau \cdot \nabla) u$

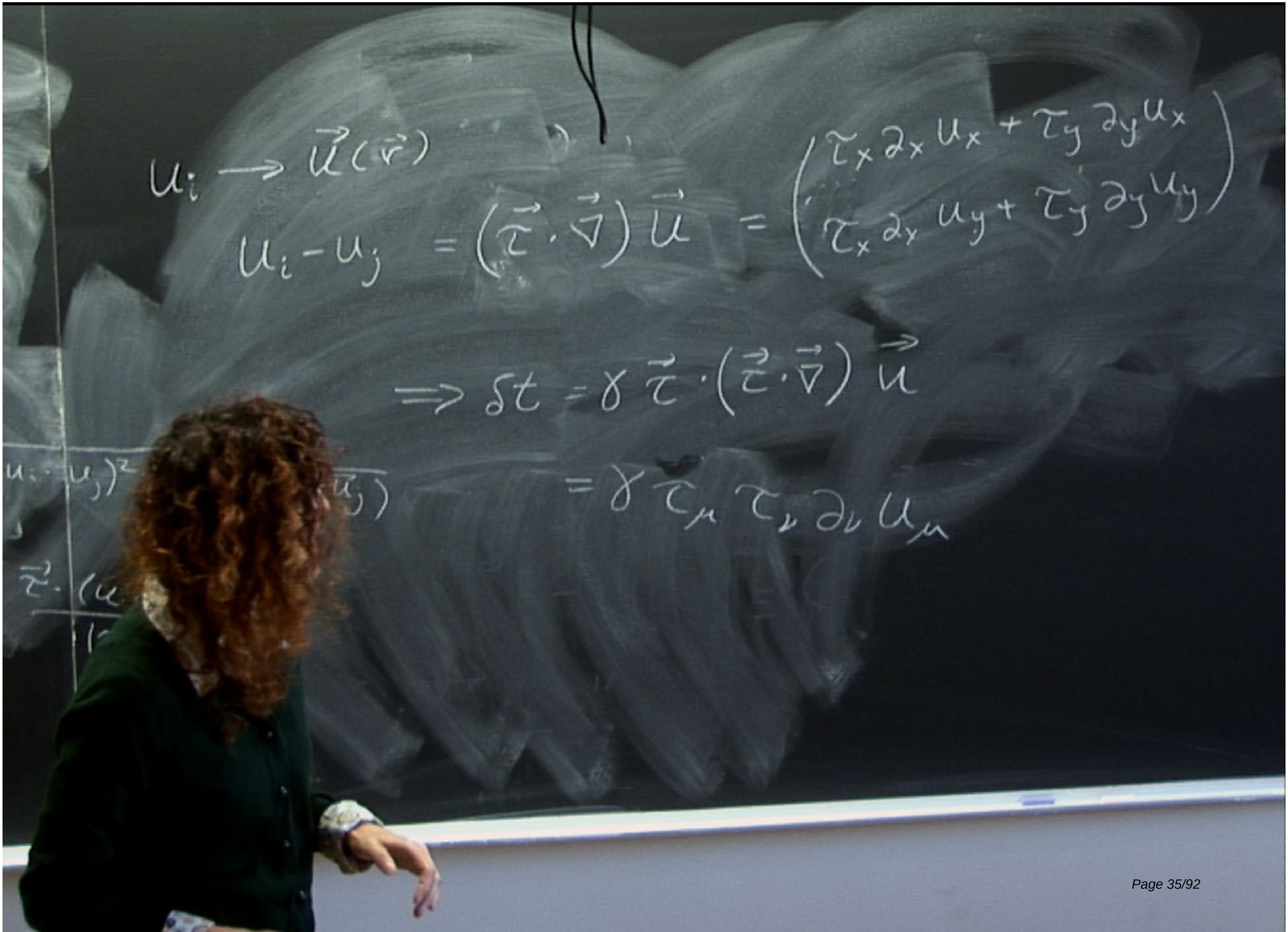

u_i → u⃗(r⃗)
u_i − u_j = (τ⃗ · ∇⃗) u⃗ =
τ_x ∂_x u_x + τ
+ (u_i − u_j)² + 2 τ⃗ · (u⃗_i − u⃗_j)
| + τ⃗ · (u_i − u_j) / |τ|

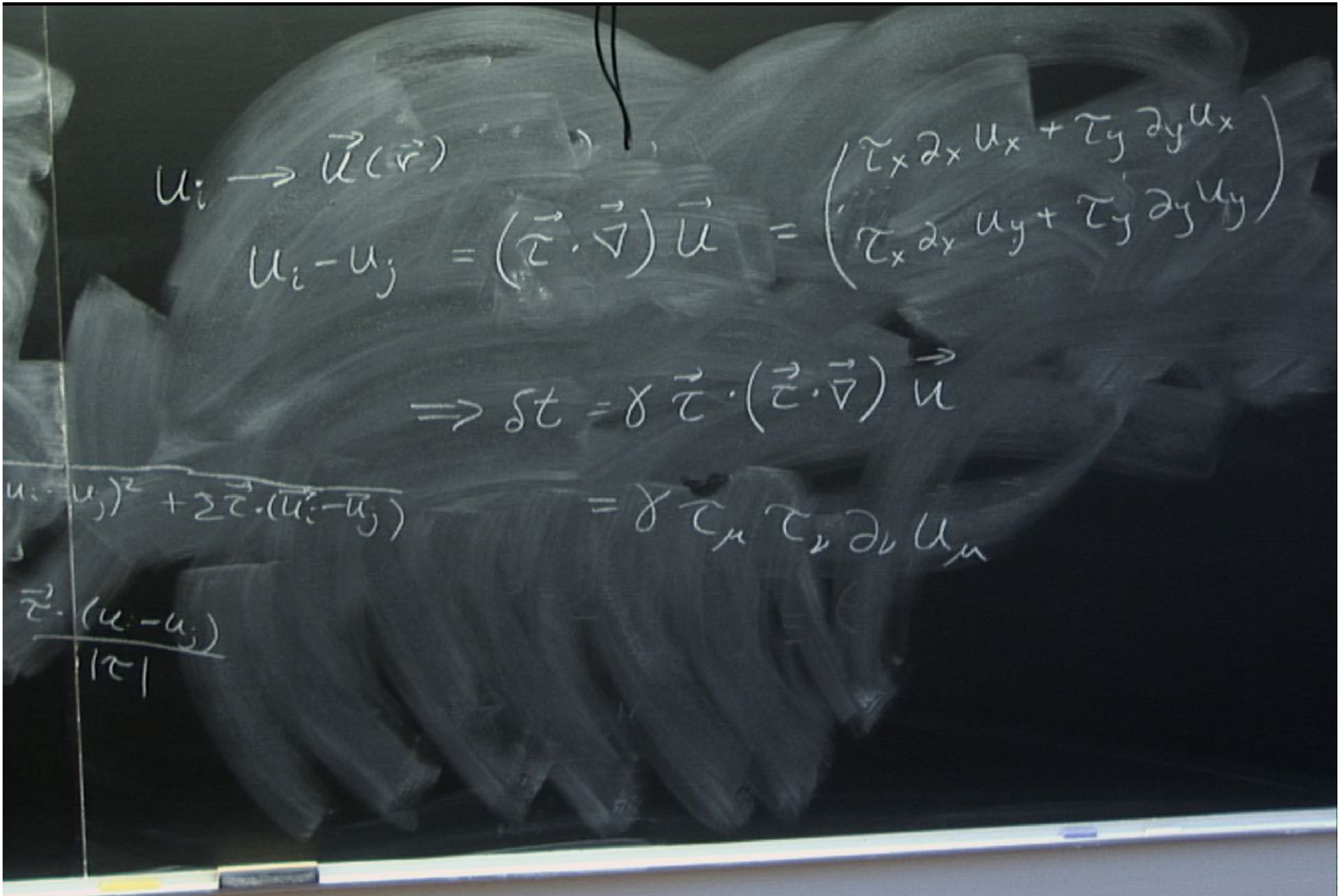

$u_i \longrightarrow \vec{u}(\vec{r})$
$u_i - u_j = (\vec{\tau}\cdot\vec{\nabla})\,\vec{u} = \begin{pmatrix} \tau_x \partial_x u_x + \tau_y \partial_y u_x \\ \tau_x \partial_x u_y + \tau_y \partial_y u_y \end{pmatrix}$

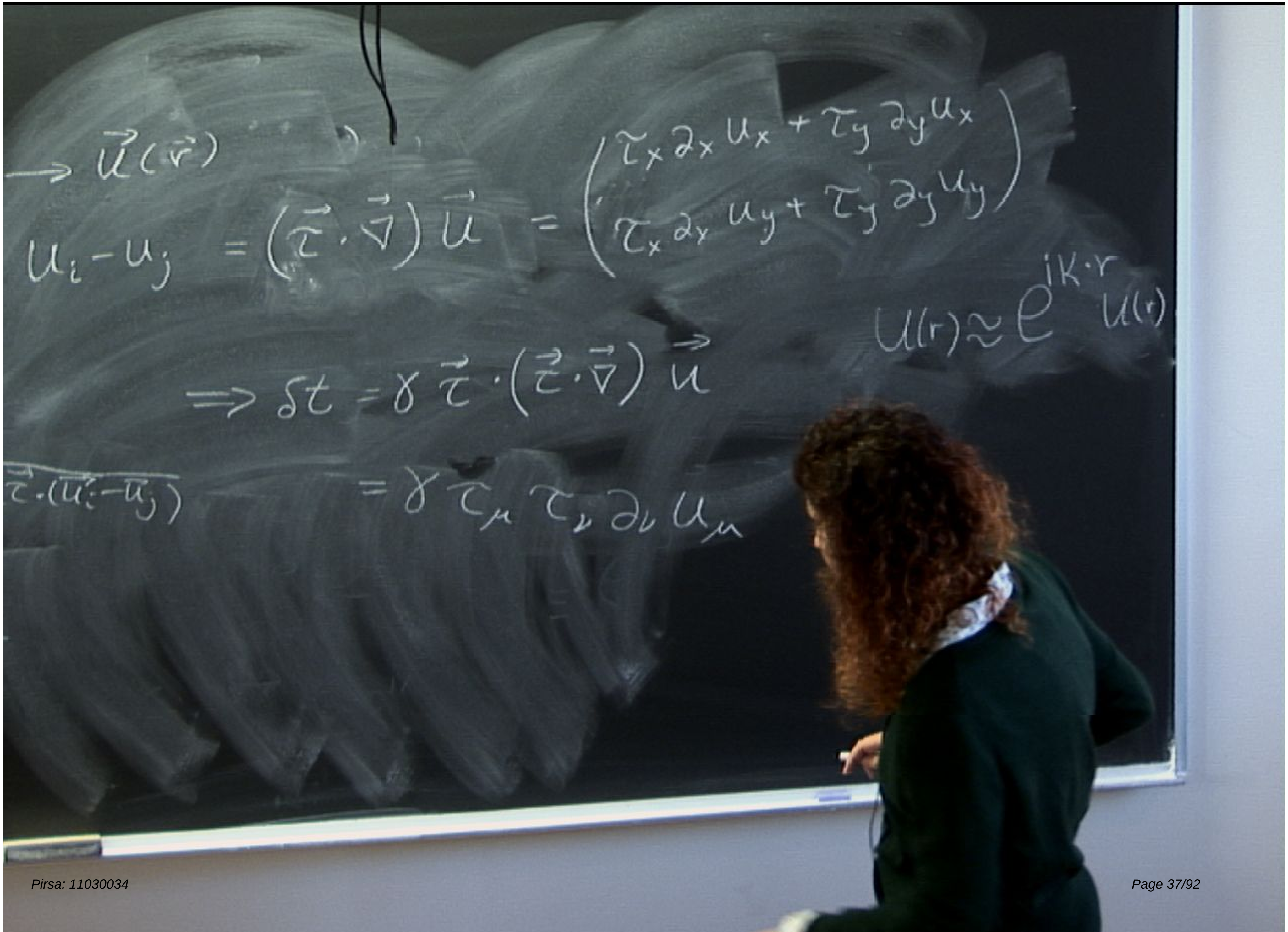

u_i → u⃗(r⃗)
u_i − u_j = (τ⃗ · ∇⃗) u⃗ = (τ_x ∂_x u_x + τ_y ∂_y u_x
τ_x ∂_x u_y + τ_y ∂_y u_y
+ (u_i − u_j)^2 + 2τ⃗·(u⃗_i − u⃗_j)
+ τ⃗·(u_i − u_j) / |τ|

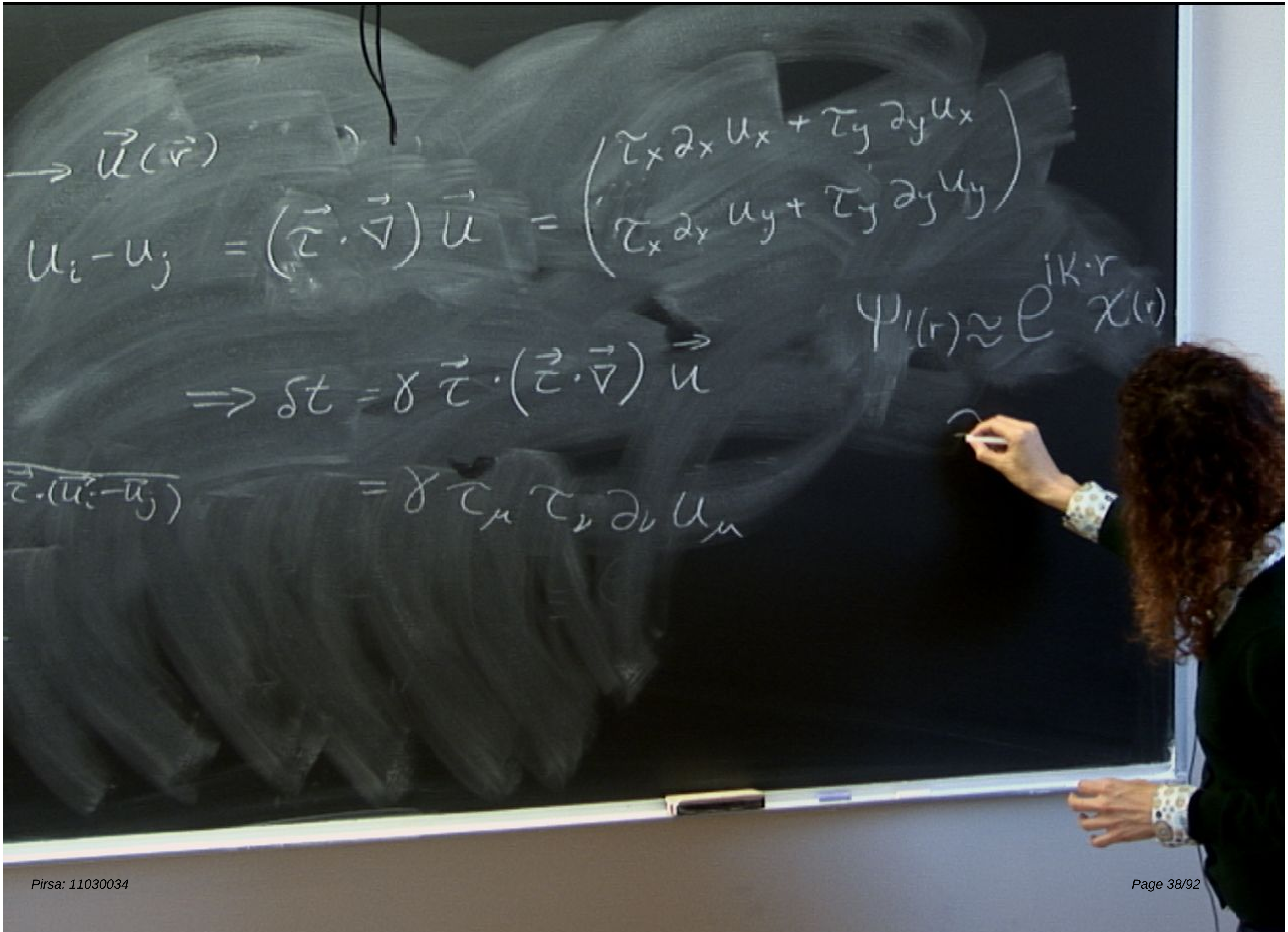

u_i → u(r)
u_i − u_j = (τ · ∇) u = (τ_x ∂_x u_x + τ_y ∂_y u_x, τ_x ∂_x u_y + τ_y ∂_y u_y)
⇒ δt = γ τ · (τ · ∇) u

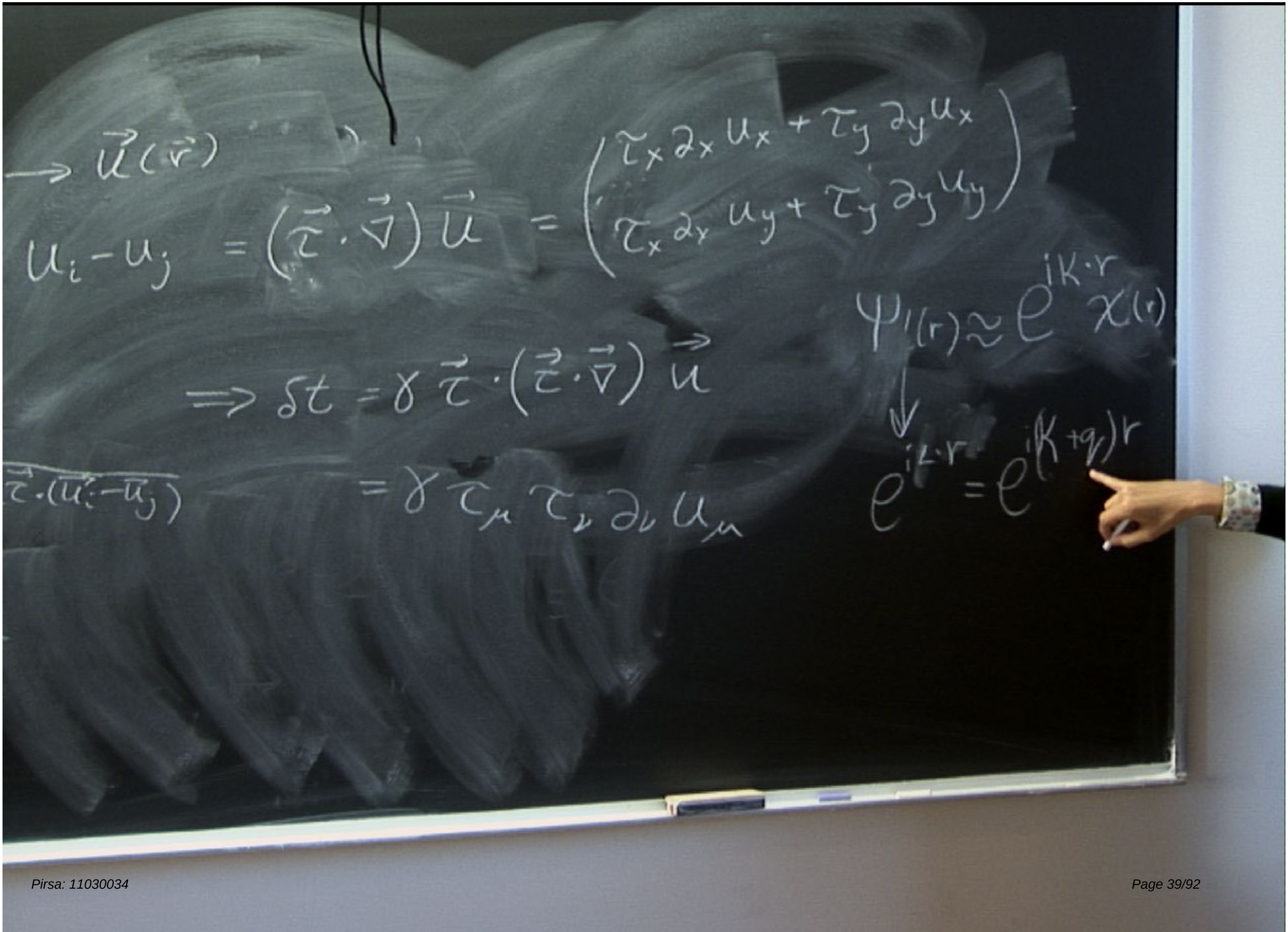

$u_i \longrightarrow \vec{u}(\vec{r})$
$u_i - u_j = (\vec{\tau}\cdot\vec{\nabla})\vec{u} = \begin{pmatrix} \tau_x \partial_x u_x + \tau_y \partial_y u_x \\ \tau_x \partial_x u_y + \tau_y \partial_y u_y \end{pmatrix}$
$\Longrightarrow \delta t = \gamma\, \vec{\tau}\cdot(\vec{\tau}\cdot\vec{\nabla})\vec{u}$
$\tau_\nu \partial_\nu u_\mu$

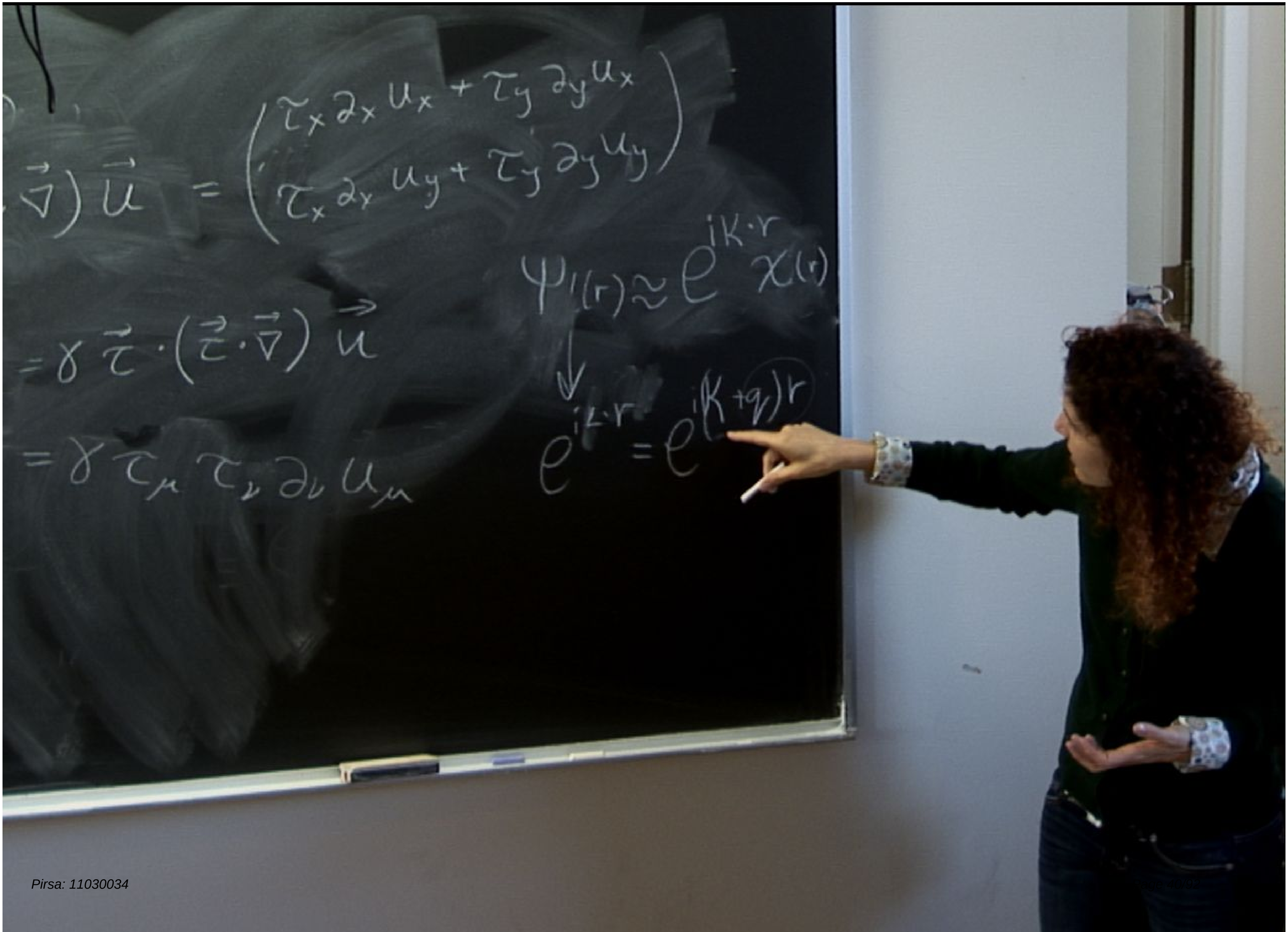

$u_i \longrightarrow \vec{u}(\vec{r})$
$u_i - u_j = (\vec{\tau} \cdot \vec{\nabla}) \vec{u} = \begin{pmatrix} \tau_x \partial_x u_x + \tau_y \partial_y u_x \\ \tau_x \partial_x u_y + \tau_y \partial_y u_y \end{pmatrix}$
$\Longrightarrow \delta t = \gamma \vec{\tau} \cdot (\vec{\tau} \cdot \vec{\nabla}) \vec{u}$
$= \gamma \tau_\mu \tau_\nu \partial_\nu u_\mu$

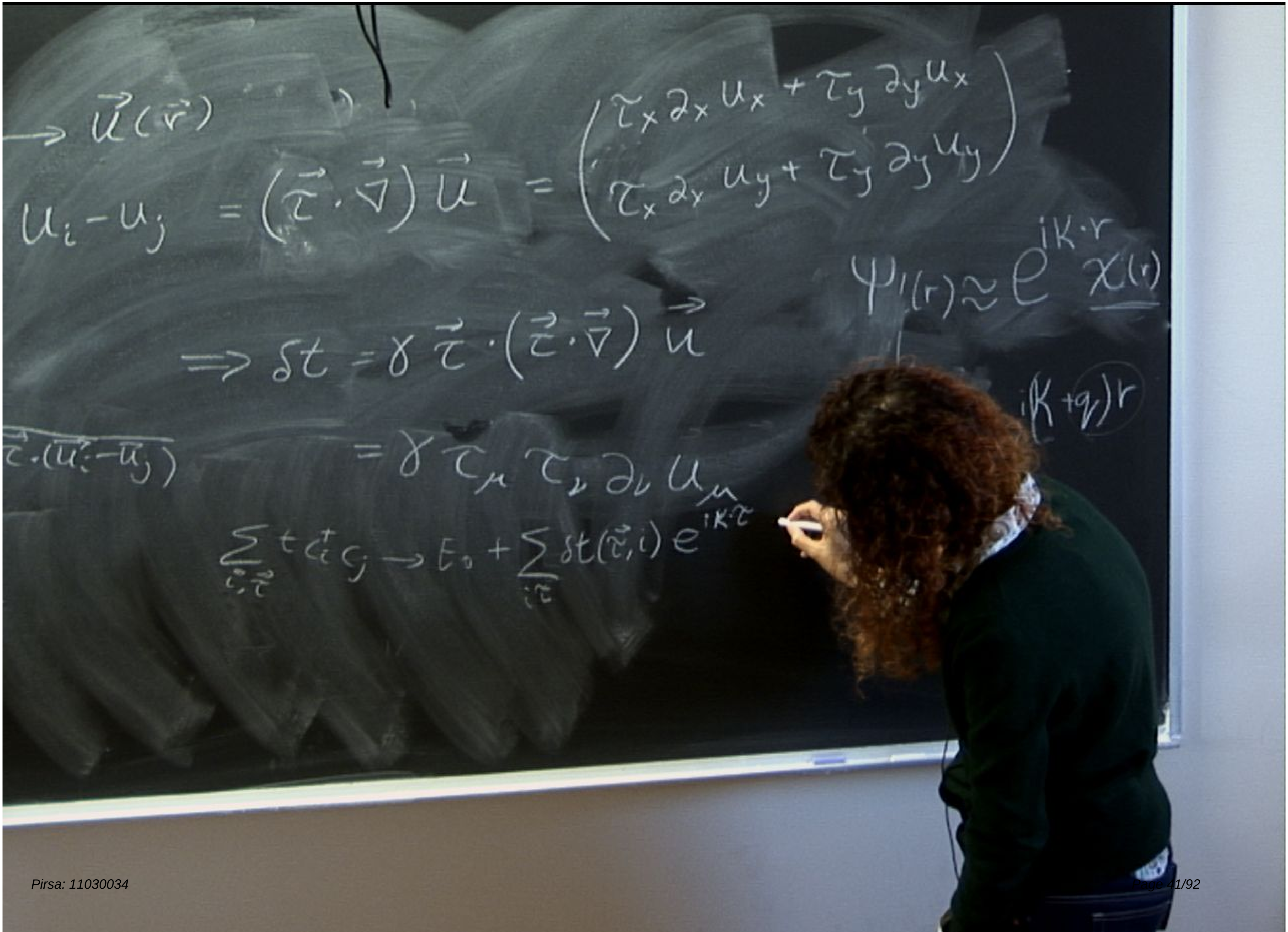

$u_i \longrightarrow \vec{u}(\vec{r})$
$u_i - u_j = (\vec{\tau}\cdot\vec{\nabla})\vec{u} = \begin{pmatrix} \tau_x \partial_x u_x + \tau_y \partial_y u_x \\ \tau_x \partial_x u_y + \tau_y \partial_y u_y \end{pmatrix}$
$\Longrightarrow \delta t = \gamma\, \vec{\tau}\cdot(\vec{\tau}\cdot\vec{\nabla})\vec{u}$
$= \gamma\, \tau_\mu \tau_\nu \partial_\nu u_\mu$
$u_j)^2 + \Sigma \vec{\tau}\cdot(\vec{u}_i - \vec{u}_j)$
$\frac{\vec{\tau}\cdot(u_i - u_j)}{|\tau|}$

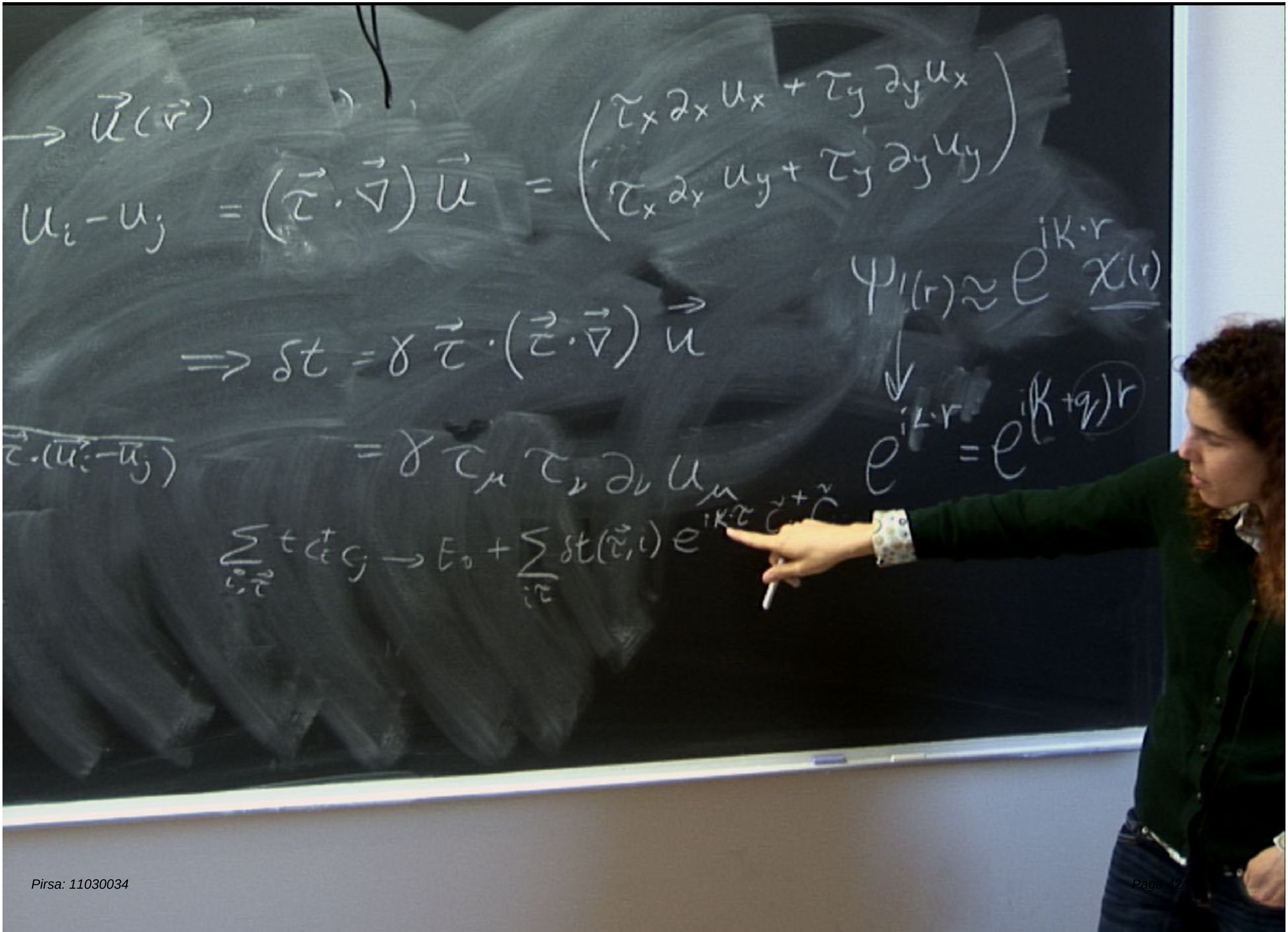

→ u(r)
u_i − u_j = (τ · ∇) u = (τ_x ∂_x u_x + τ_y ∂_y u_x ; τ_x ∂_x u_y + τ_y ∂_y u_y)
u(r) ≈ e^{ik·r} u(r)
⟹ δt = γ τ · (τ · ∇) u
τ · (u_i − u_j) = γ τ_μ τ_ν ∂_ν u_μ


$\longrightarrow \vec{u}(\vec{r})$
$u_i - u_j = (\vec{\tau}\cdot\vec{\nabla})\vec{u} = \begin{pmatrix} \tau_x \partial_x u_x + \tau_y \partial_y u_x \\ \tau_x \partial_x u_y + \tau_y \partial_y u_y \end{pmatrix}$
$\Psi_{l}(r) \approx e^{ik\cdot r} \chi(r)$
$\Longrightarrow \delta t = \gamma \vec{\tau}\cdot(\vec{\tau}\cdot\vec{\nabla})\vec{u}$
$\vec{\tau}\cdot(\vec{u}_i - \vec{u}_j) = \gamma \tau_\mu \tau_\nu \partial_\nu u_\mu$


→ u⃗(r⃗)
u_i − u_j = (τ⃗ · ∇⃗) u⃗ = (τ_x ∂_x u_x + τ_y ∂_y u_x ; τ_x ∂_x u_y + τ_y ∂_y u_y)
⇒ δt = γ τ⃗ · (τ⃗ · ∇⃗) u⃗
τ⃗ · (u⃗_i − u⃗_j)
= γ τ_μ τ_ν ∂_ν u_μ
Ψ(r) ≈ e^{iK·r} χ(r)
e^{iK·r} = e^{i(K+q)r}

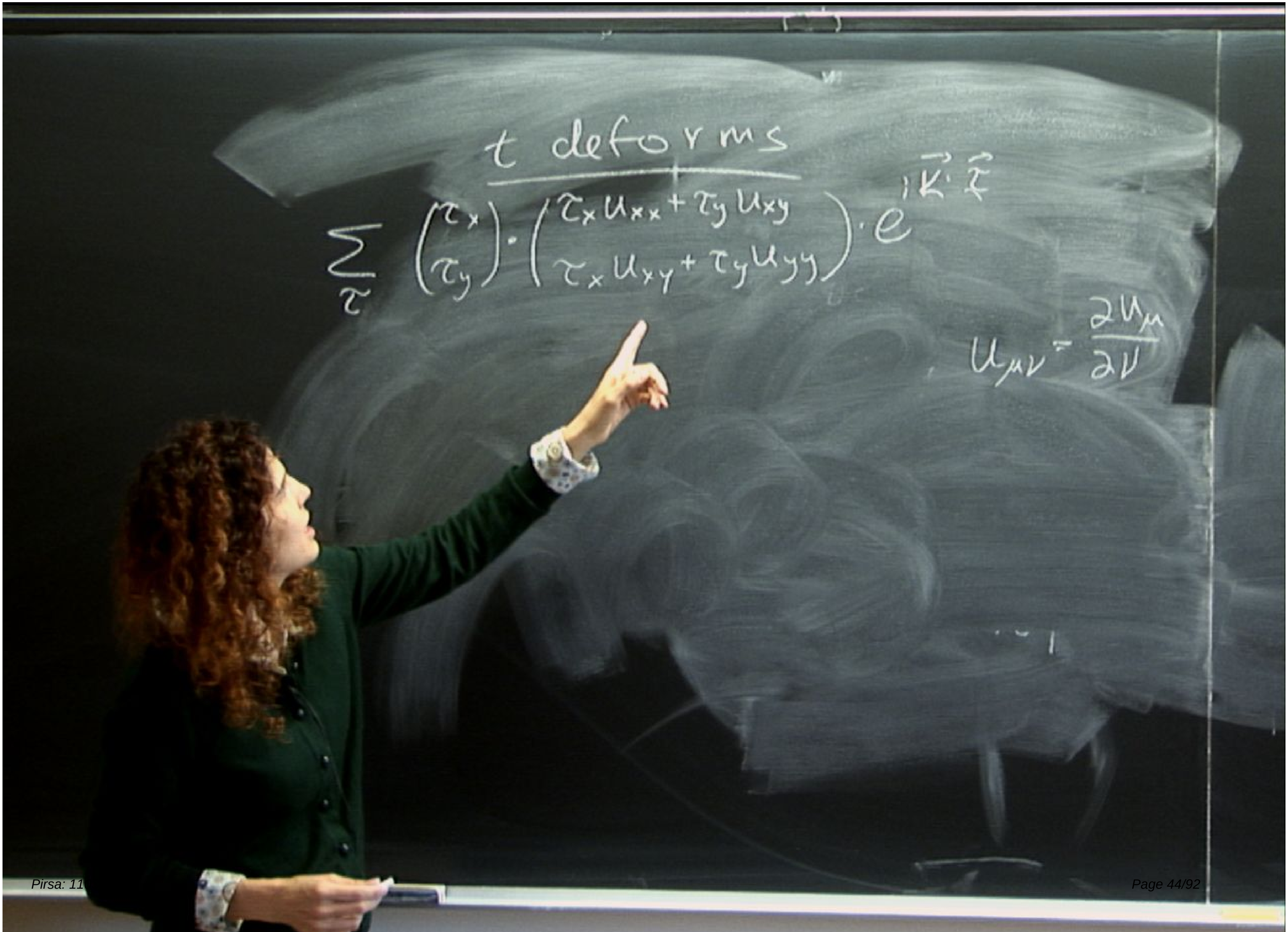

$\vec{\nabla})\,\vec{u} = \begin{pmatrix} \tau_x \partial_x u_x + \tau_y \partial_y u_x \\ \tau_x \partial_x u_y + \tau_y \partial_y u_y \end{pmatrix}$
$= \gamma\, \vec{\tau} \cdot (\vec{\tau} \cdot \vec{\nabla})\, \vec{u}$
$= \gamma\, \tau_\mu \tau_\nu \partial_\nu u_\mu$
$\psi(r) \approx e^{iK\cdot r} \chi(r)$
$e^{iK\cdot r} = e^{i(K+q)r}$


→ u⃗(r⃗)
u_i − u_j = (τ⃗·∇⃗) u⃗ = (τ_x ∂_x u_x + τ_y ∂_y u_x ; τ_x ∂_x u_y + τ_y ∂_y u_y)
ψ'(r) ≈ e^{iK·r} χ(r)
⟹ δt = γ τ⃗·(τ⃗·∇⃗) u⃗
τ⃗·(u⃗_i − u⃗_j)
= γ τ_μ τ_ν ∂_ν u_μ
i(K+q)r
Σ_{i,τ⃗} t c_i† c_j → t_0 + Σ_{i,τ⃗} δt(τ⃗,i) e^{iK·τ}

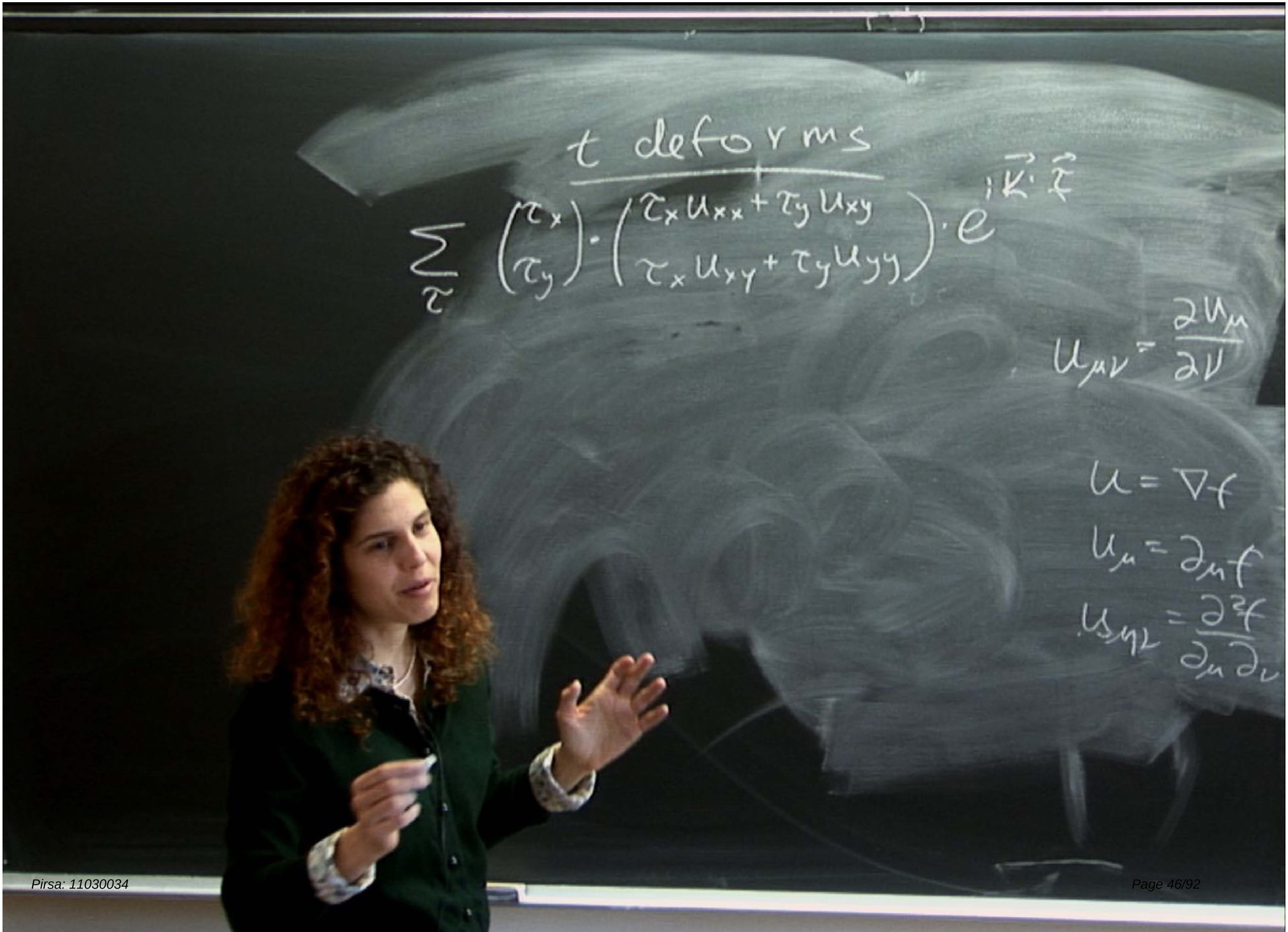

→ u(r)
u_i − u_j = (τ·∇) u = (τx ∂x ux + τy ∂y ux, τx ∂x uy + τy ∂y uy)
⟹ δt = γ τ·(τ·∇) u
τ·(u_i − u_j) = γ τμ τν ∂ν uμ
Ψ(r) ≈ e^{iK·r} χ(r)
e^{iK·r} = e^{i(K+q)r}
Σ t c_i† c_j → t_0 + Σ δt(τ, i) e^{iK·τ}

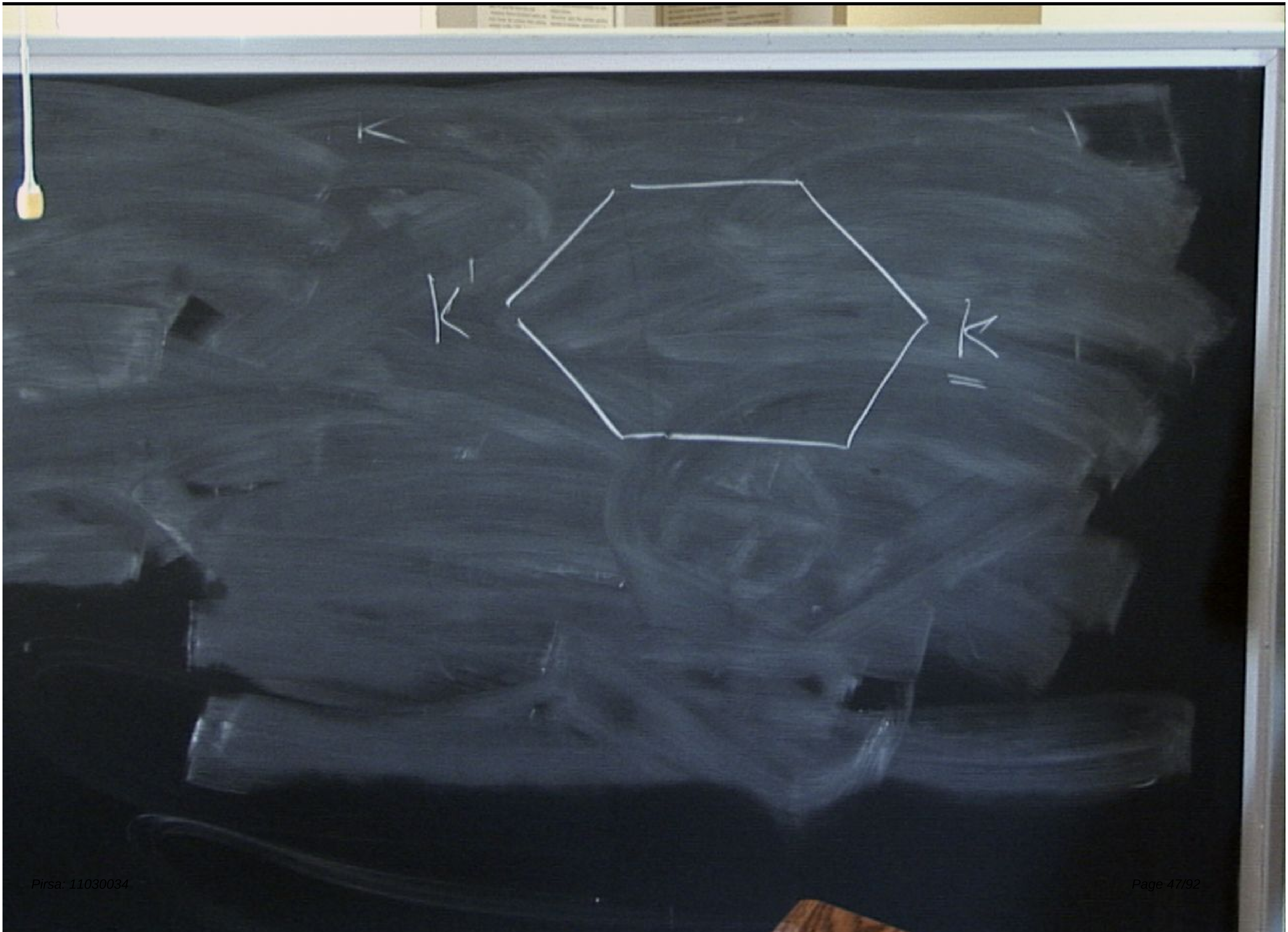
t deforms

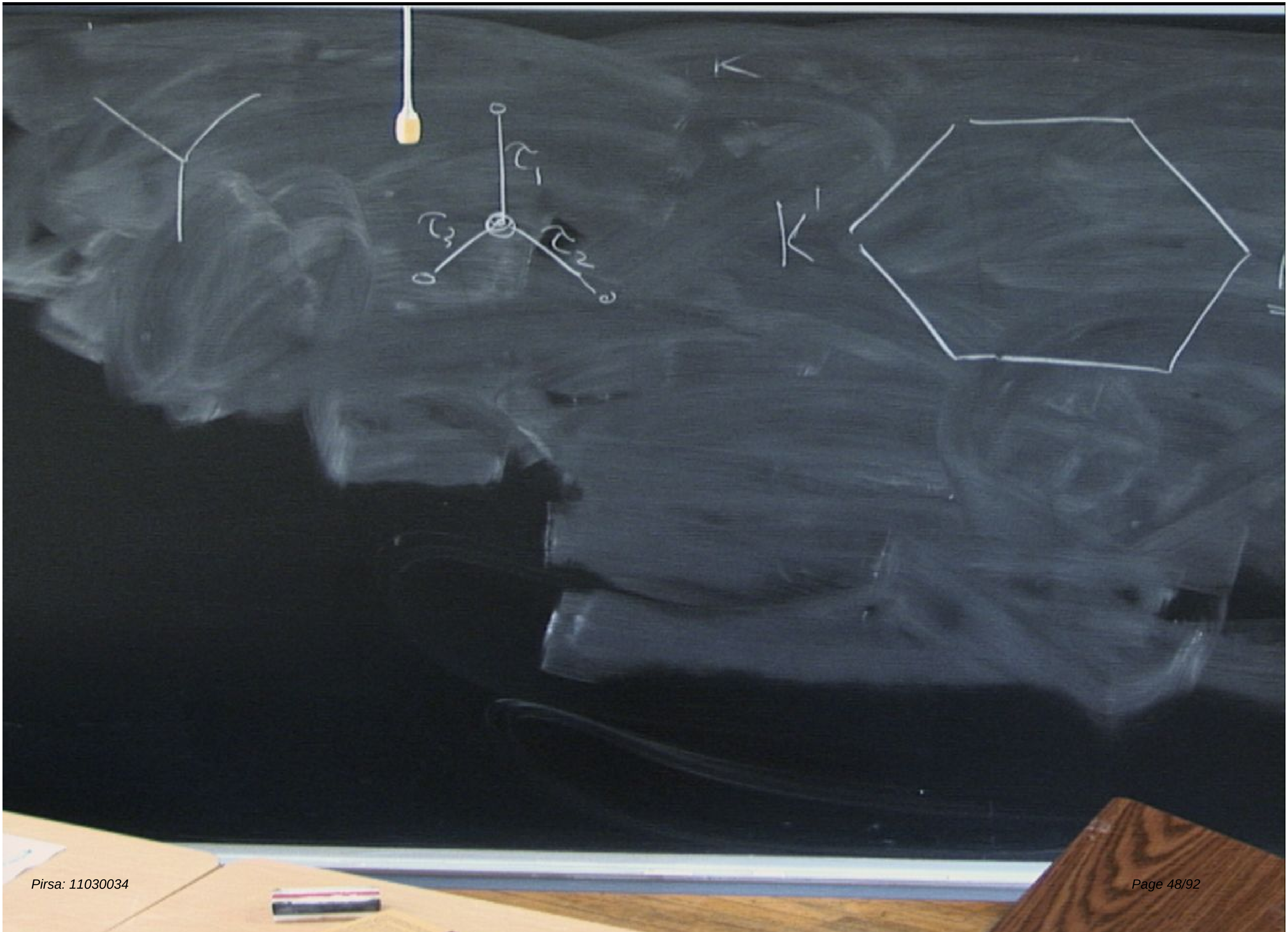
$$\sum_{\tau} \begin{pmatrix} \tau_x \\ \tau_y \end{pmatrix}$$

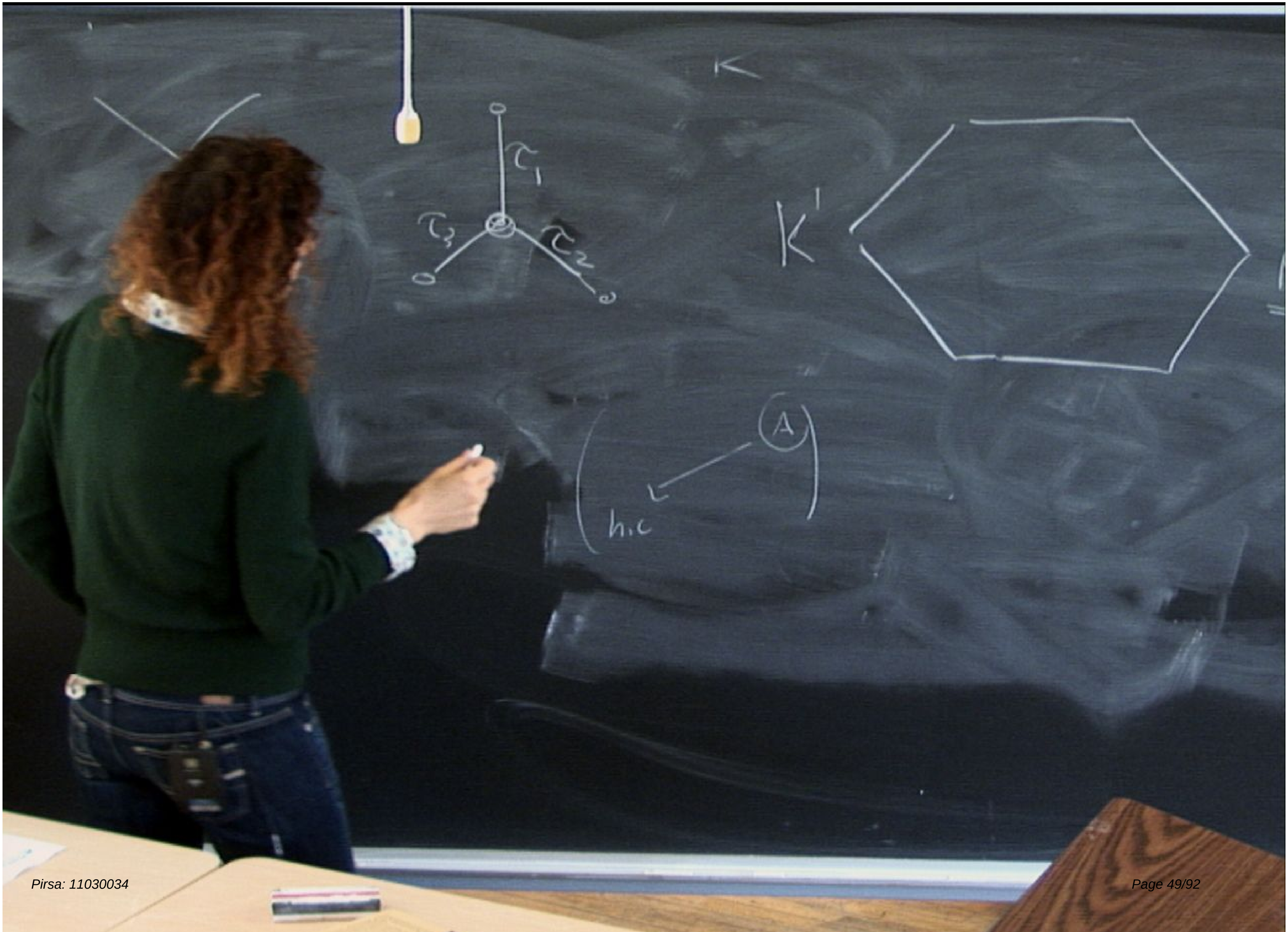

t deforms
$\sum_{\tau} \begin{pmatrix} \tau_x \\ \tau_y \end{pmatrix} \cdot \begin{pmatrix} \tau_x u_{xx} + \tau_y u_{xy} \\ \tau_x u_{xy} + \tau_y u_{yy} \end{pmatrix} \cdot e^{i\vec{k}\cdot\vec{\tau}}$
$u_{\mu\nu} = \frac{\partial u_\mu}{\partial \nu}$

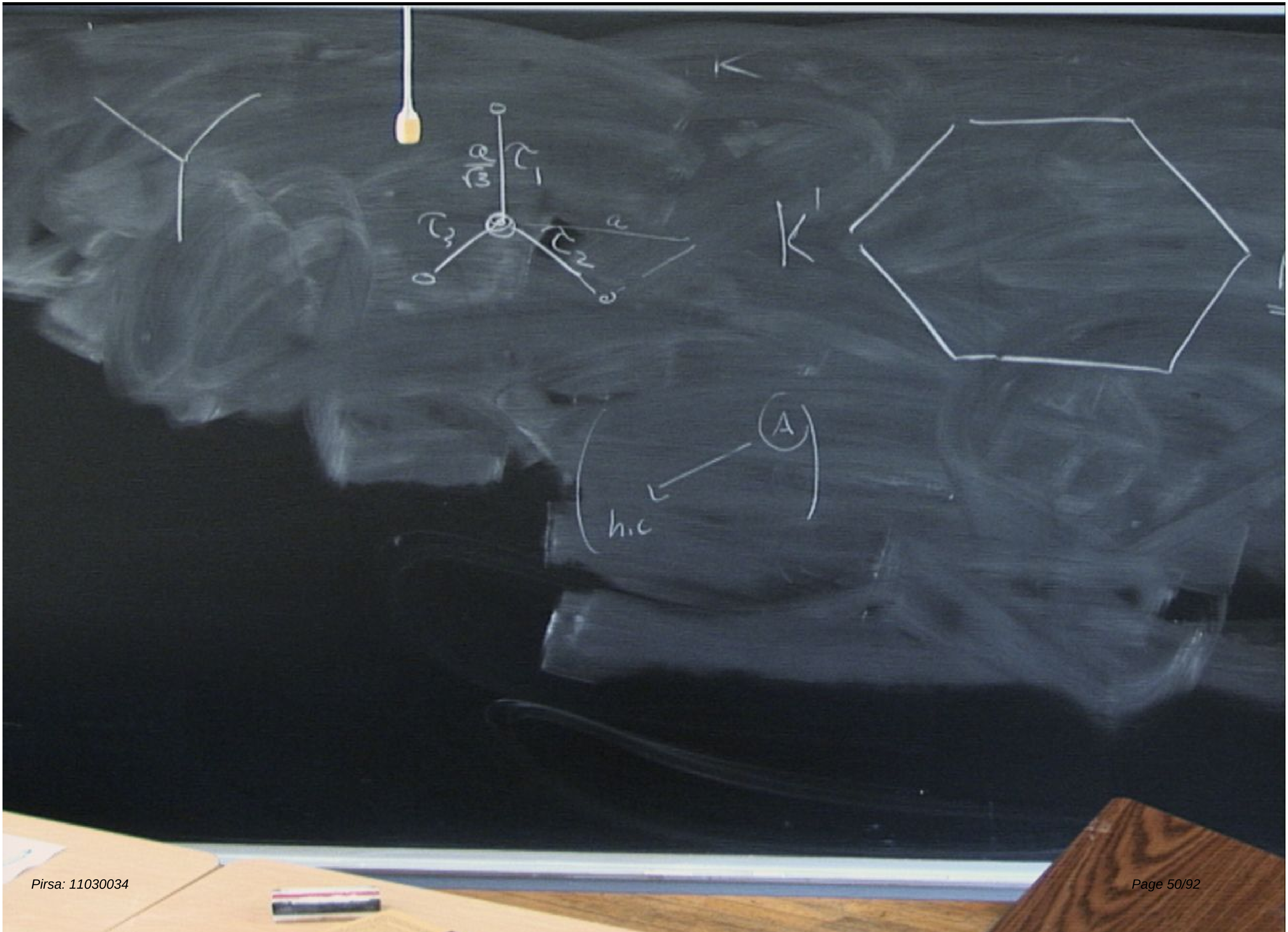

t deforms
u = ∇f


t deforms
$\sum_\tau \begin{pmatrix}\tau_x \\ \tau_y\end{pmatrix} \cdot \begin{pmatrix}\tau_x u_{xx} + \tau_y u_{xy} \\ \tau_x u_{xy} + \tau_y u_{yy}\end{pmatrix} \cdot e^{i\vec{k}\cdot\vec{\tau}}$
$u_{\mu\nu} = \frac{\partial u_\mu}{\partial \nu}$
$u = \nabla f$
$u_\mu = \partial_\mu f$
$u_{\mu\nu} = \frac{\partial^2 f}{\partial_\mu \partial_\nu}$


K'
K


K
τ_1
τ_3
τ_2
K'


τ1
τ3
τ2
K
K'
A
h.c


K
K'
a/√3
τ1
τ2
τ3
a
A
h.c

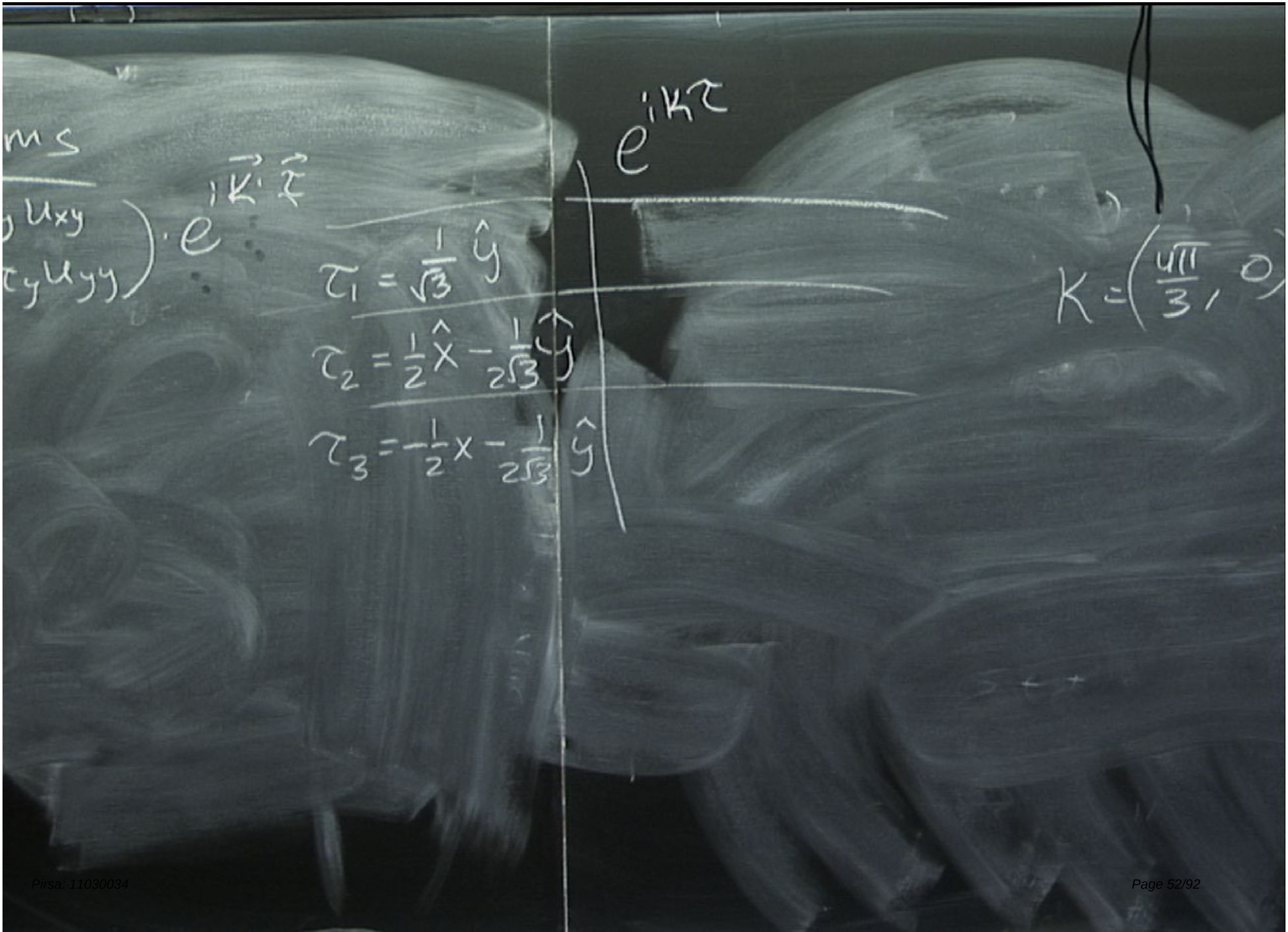
t deforms

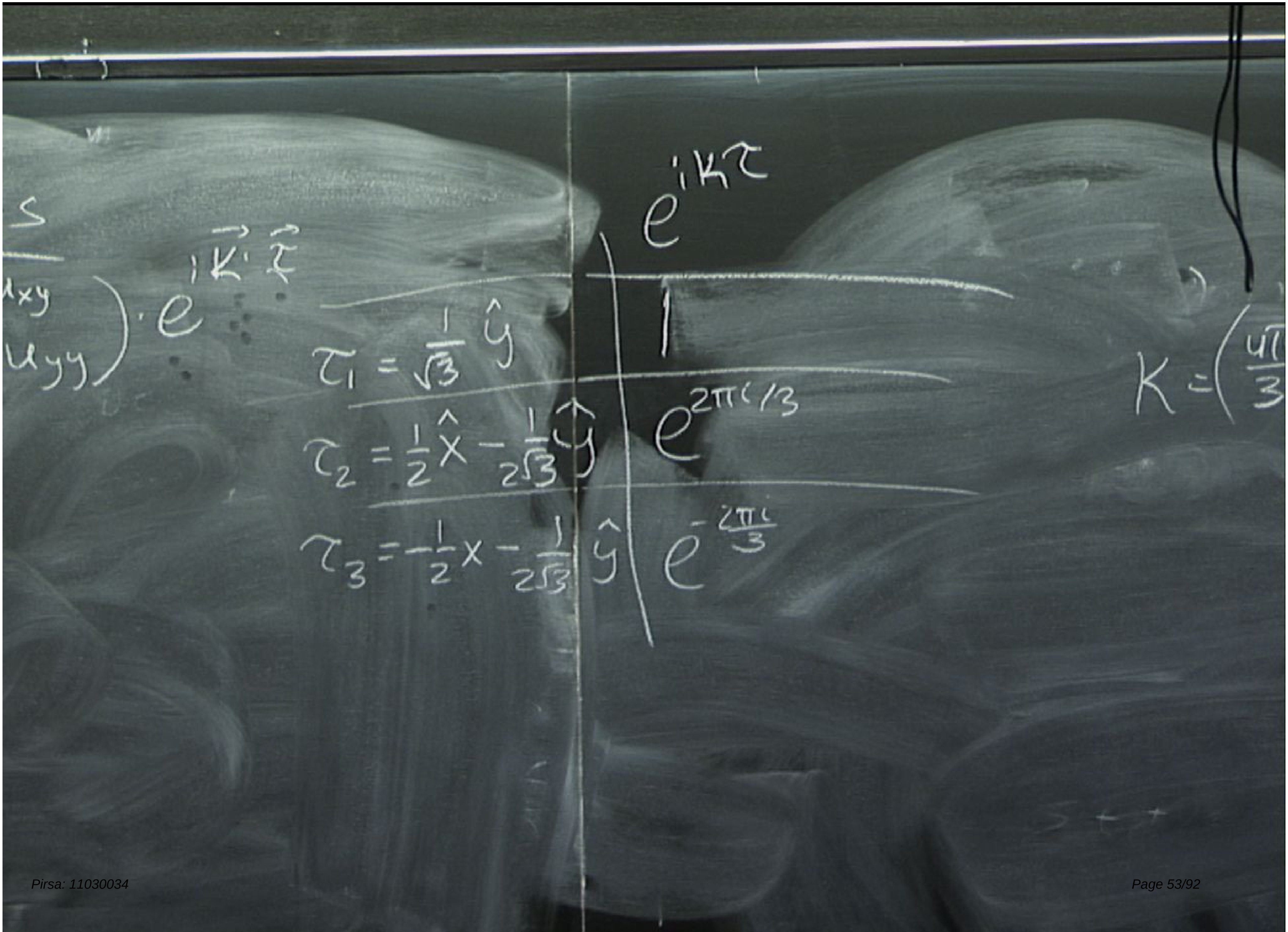
$$\sum_{\tau} \begin{pmatrix}\tau_x \\ \tau_y\end{pmatrix} \cdot \begin{pmatrix}\tau_x u_{xx} + \tau_y u_{xy} \\ \tau_x u_{xy} + \tau_y u_{yy}\end{pmatrix} \cdot e^{i\vec{K}\cdot\vec{\tau}}$$

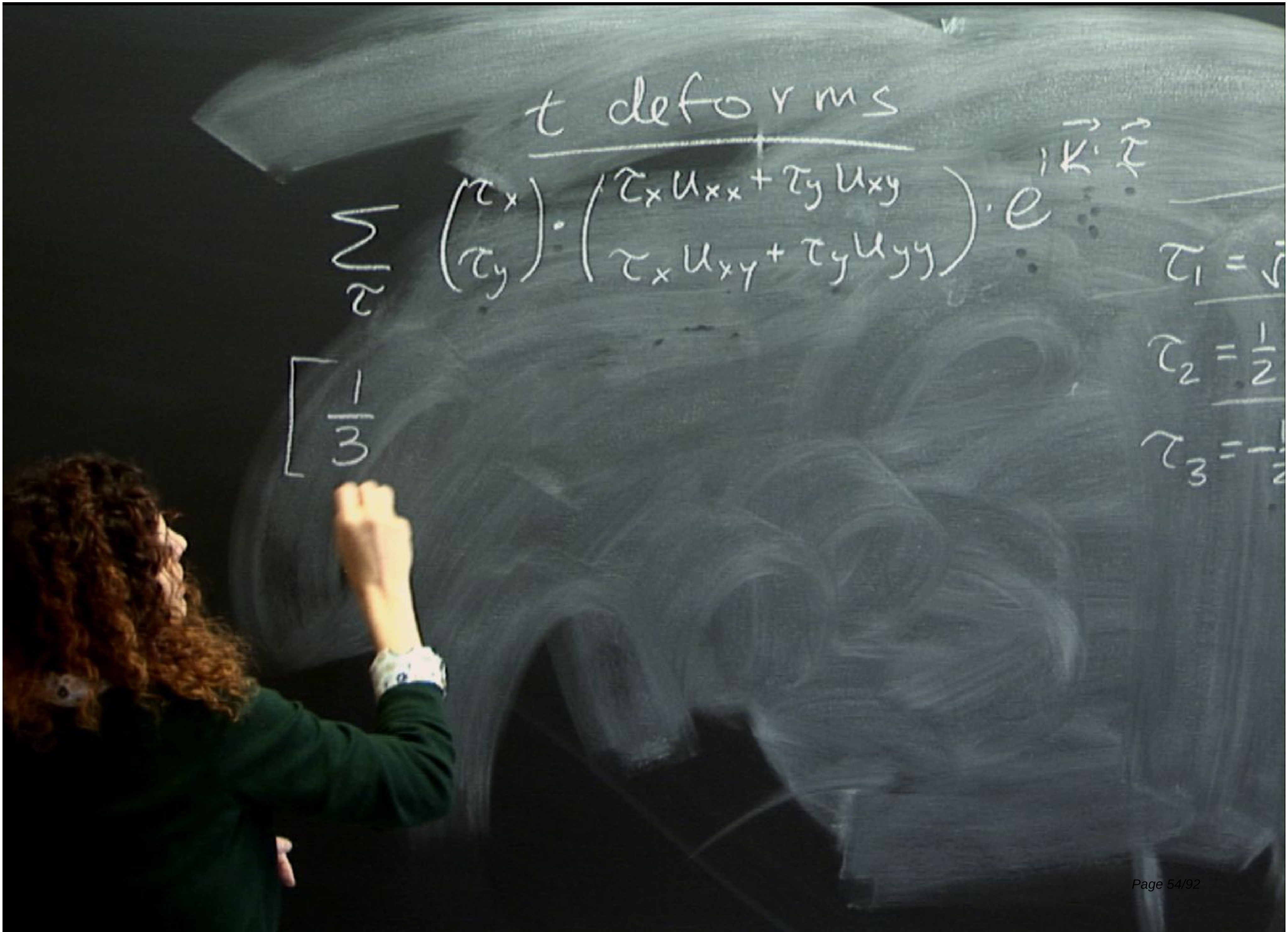
$$\tau_1 = \frac{1}{\sqrt{3}}\hat{y}$$

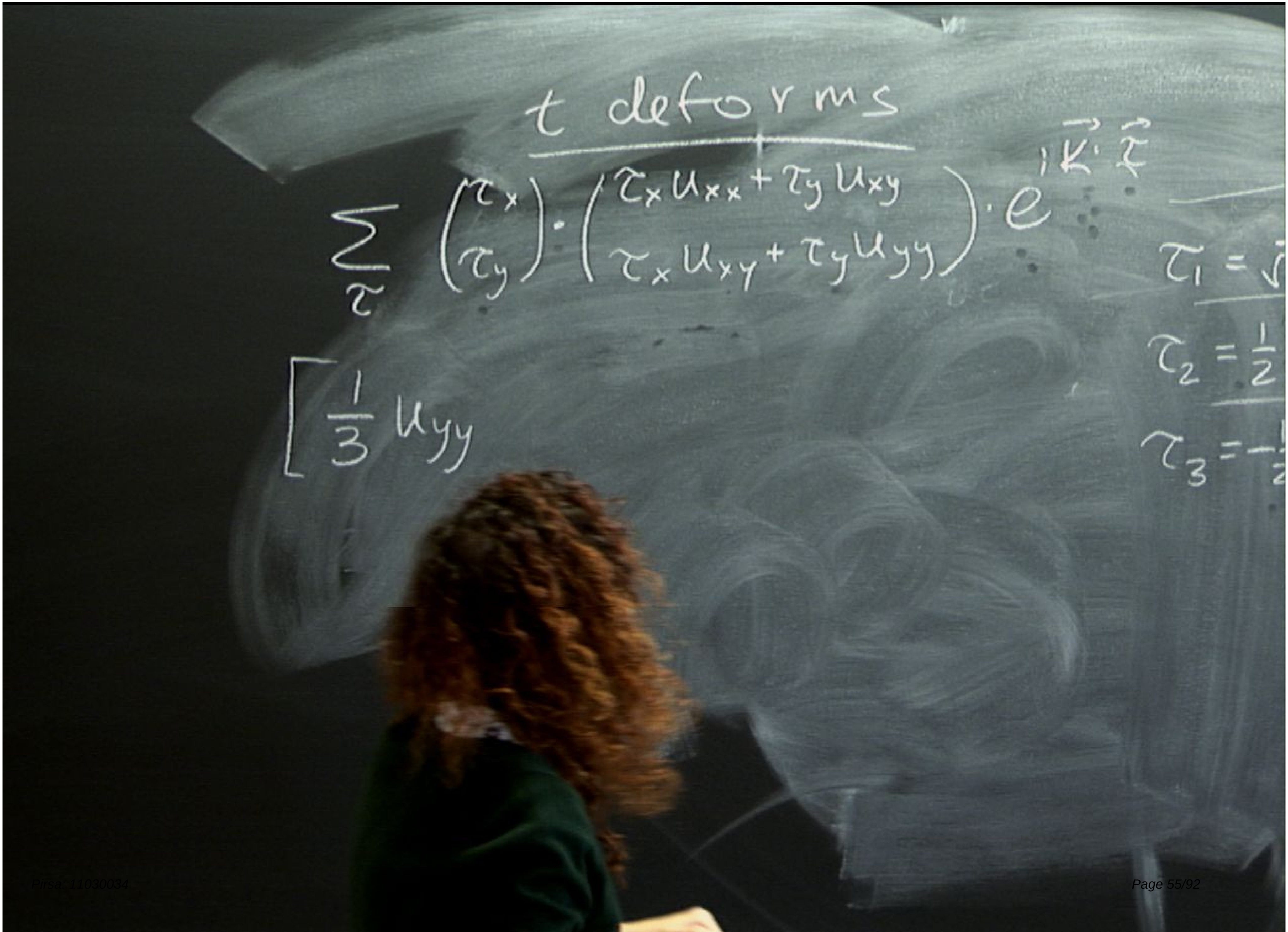
$$\tau_2 = \frac{1}{2}\hat{x} - \frac{1}{2\sqrt{3}}\hat{y}$$

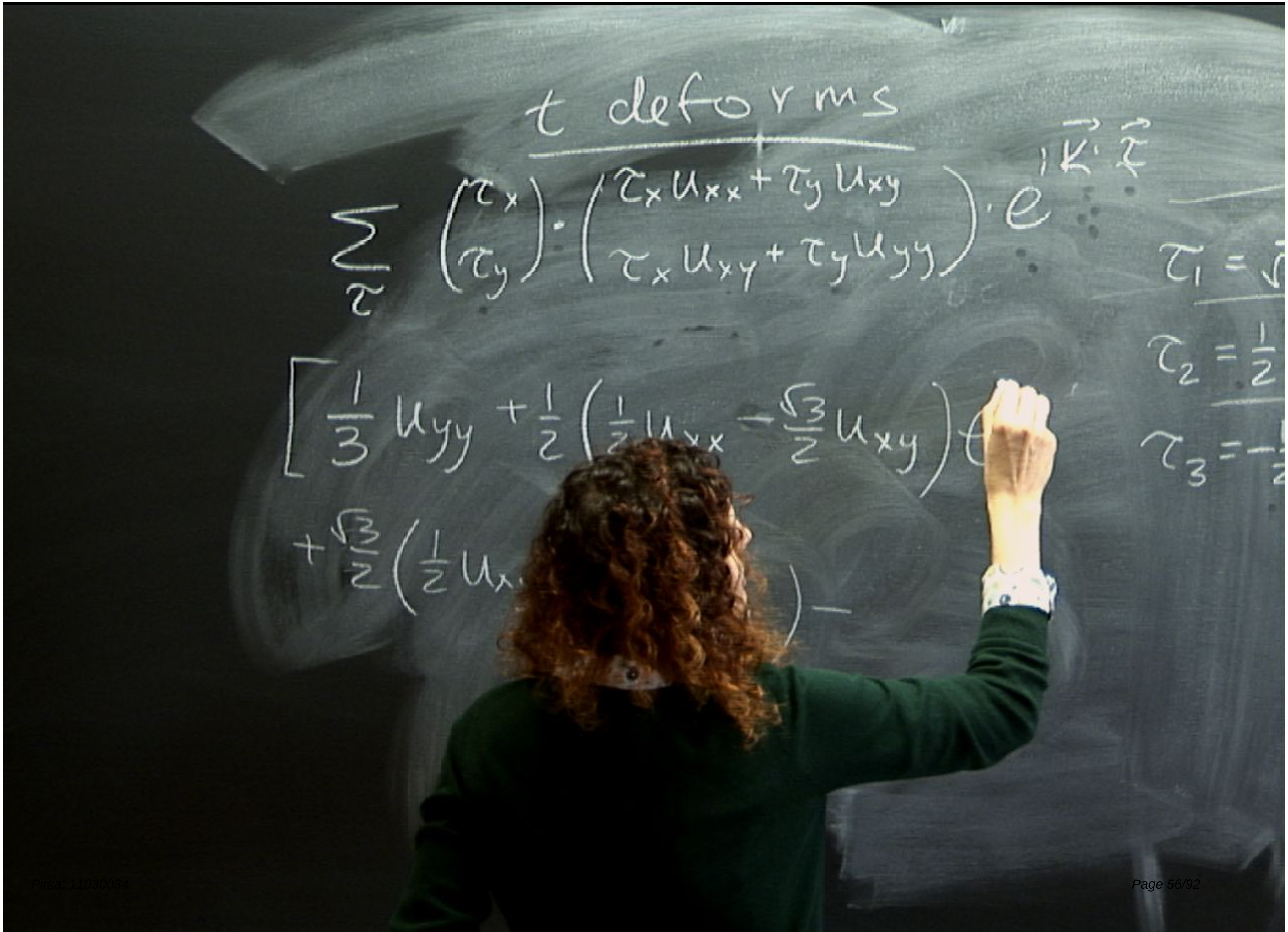
$$\tau_3 = -\frac{1}{2}x - \frac{1}{2\sqrt{3}}\hat{y}$$

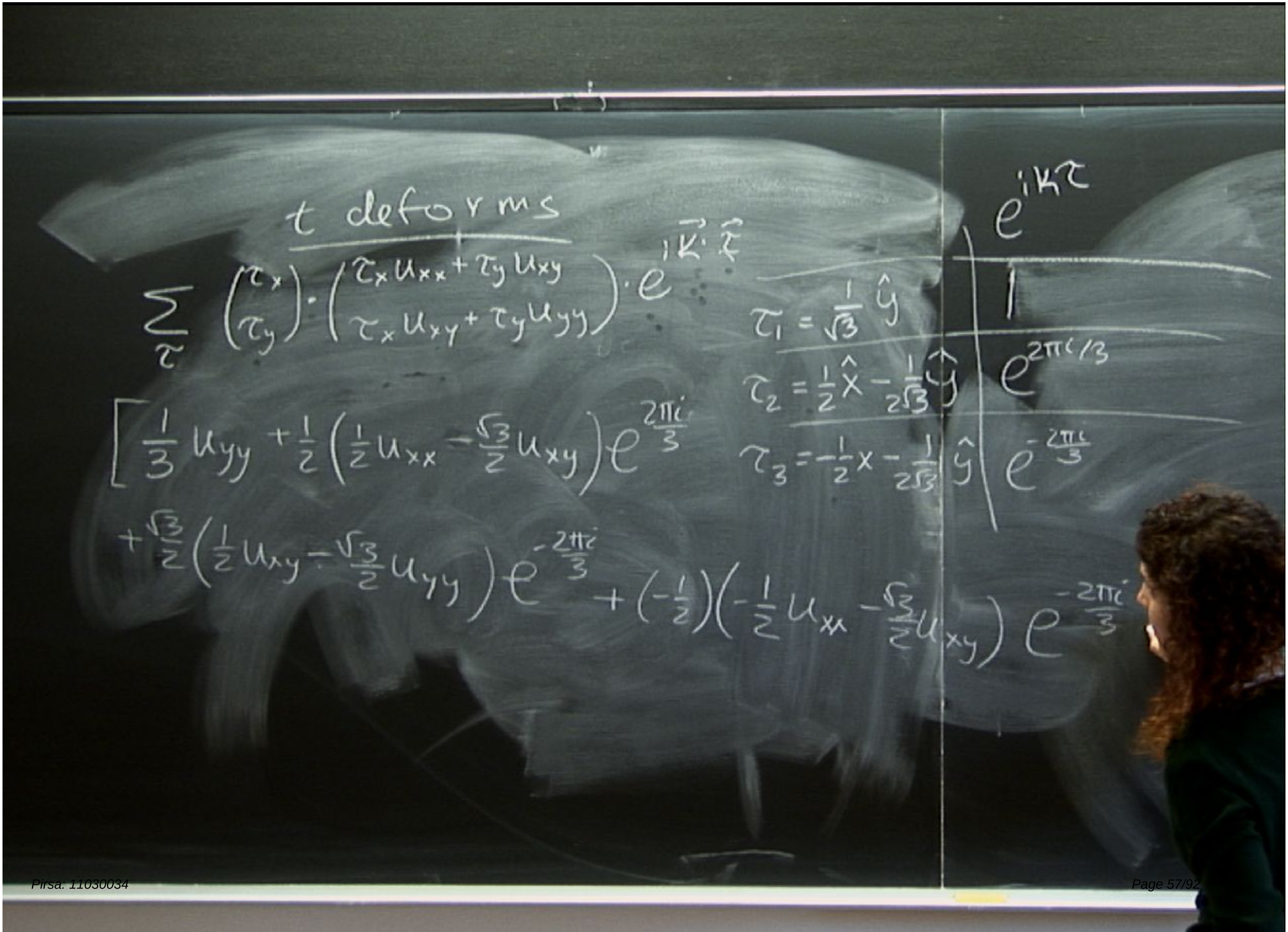

ms
$\cdot e^{i\vec{K}\cdot\vec{\tau}}$
$\tau_1 = \frac{1}{\sqrt{3}}\hat{y}$
$\tau_2 = \frac{1}{2}\hat{x} - \frac{1}{2\sqrt{3}}\hat{y}$
$\tau_3 = -\frac{1}{2}x - \frac{1}{2\sqrt{3}}\hat{y}$
$e^{ik\tau}$
$K = (\frac{4\pi}{3}, 0)$

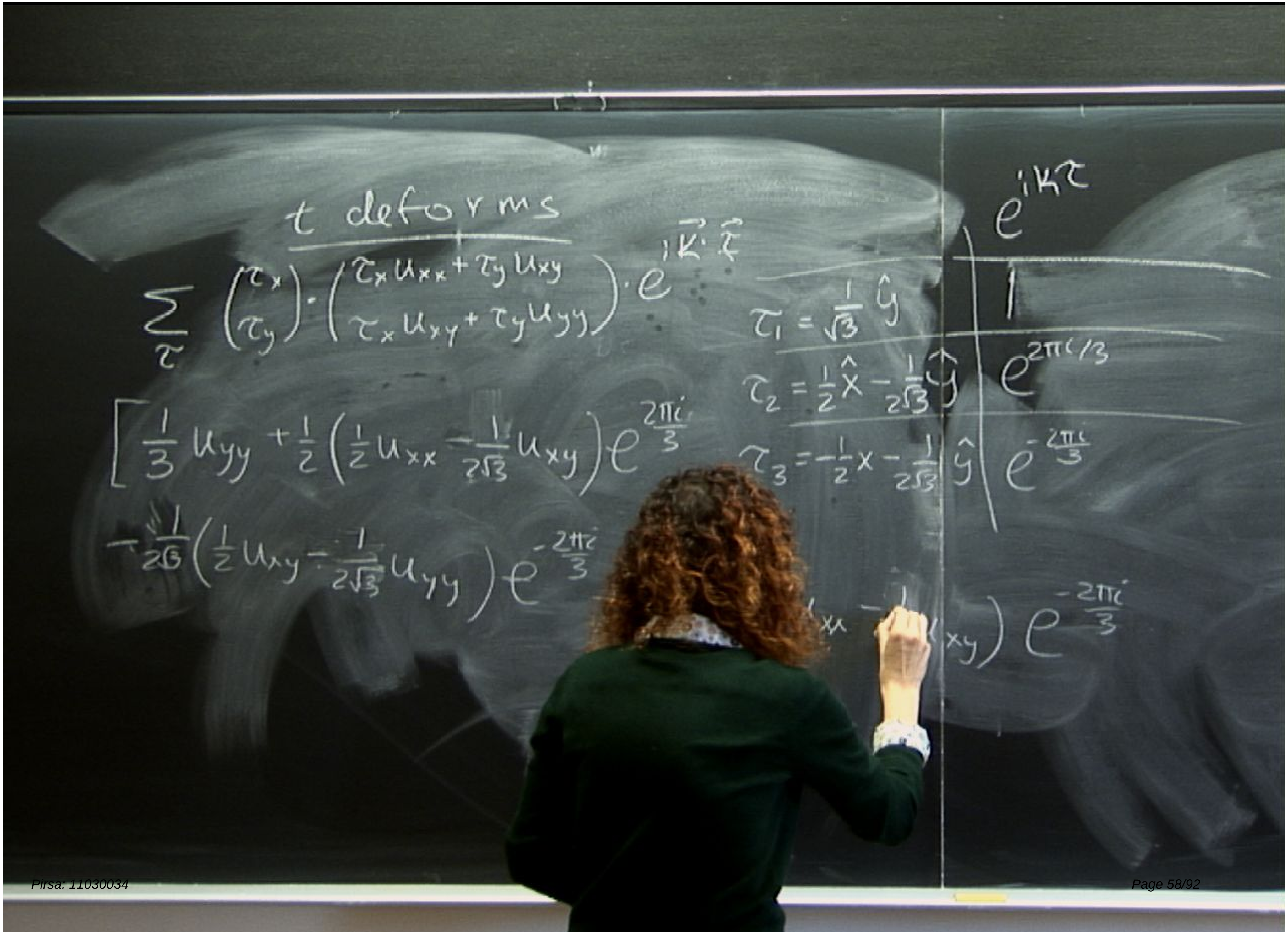

$e^{i\vec{K}\cdot\vec{\tau}}$
$\tau_1 = \frac{1}{\sqrt{3}}\hat{y}$
$\tau_2 = \frac{1}{2}\hat{x} - \frac{1}{2\sqrt{3}}\hat{y}$
$\tau_3 = -\frac{1}{2}x - \frac{1}{2\sqrt{3}}\hat{y}$
$e^{iK\tau}$
1
$e^{2\pi i/3}$
$e^{-\frac{2\pi i}{3}}$

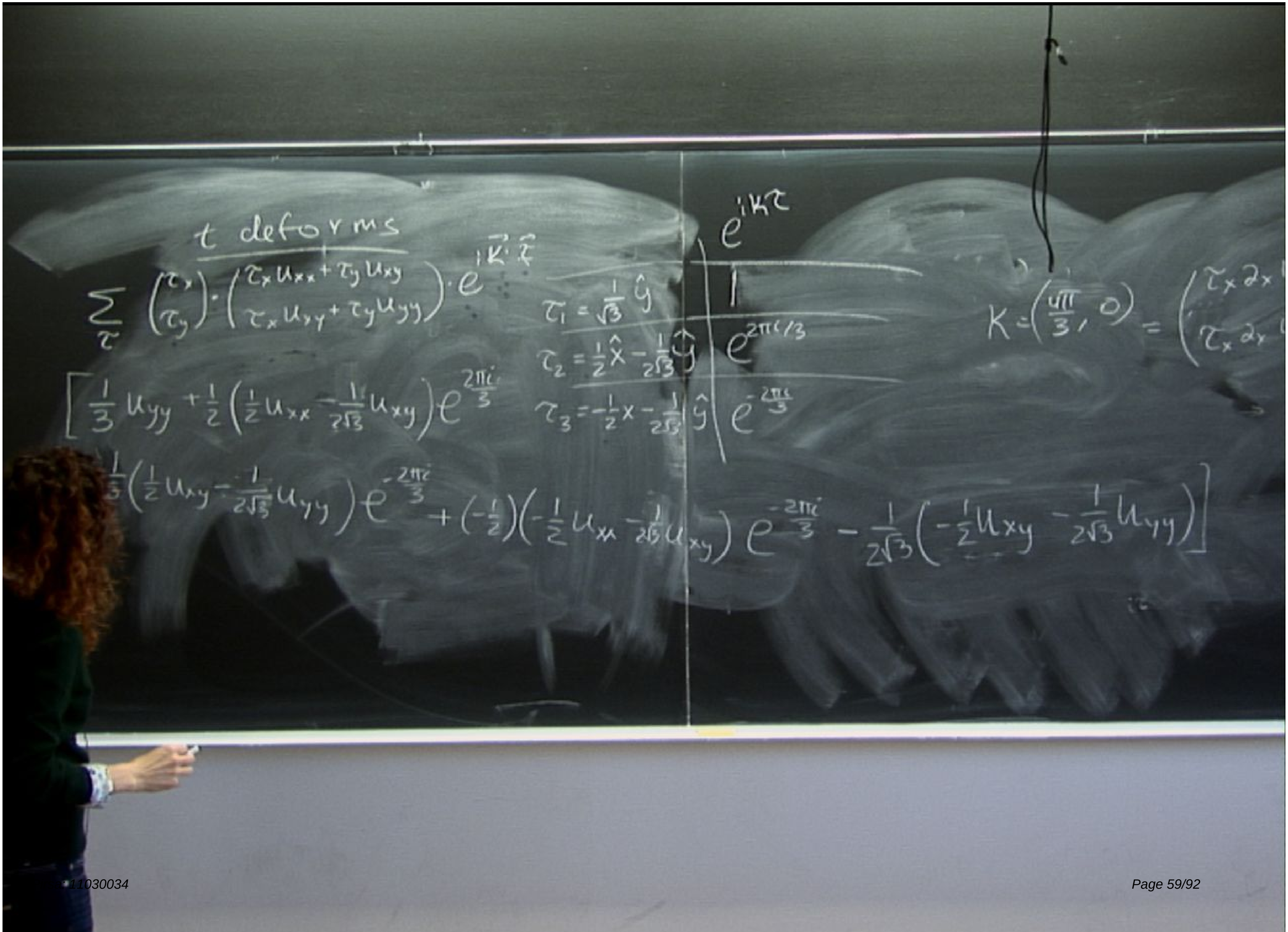

t deforms
Σ_τ (τx, τy) · (τx uxx + τy uxy, τx uxy + τy uyy) · e^{iK·τ}
τ1 =
τ2 = 1/2
τ3 = −
[1/3

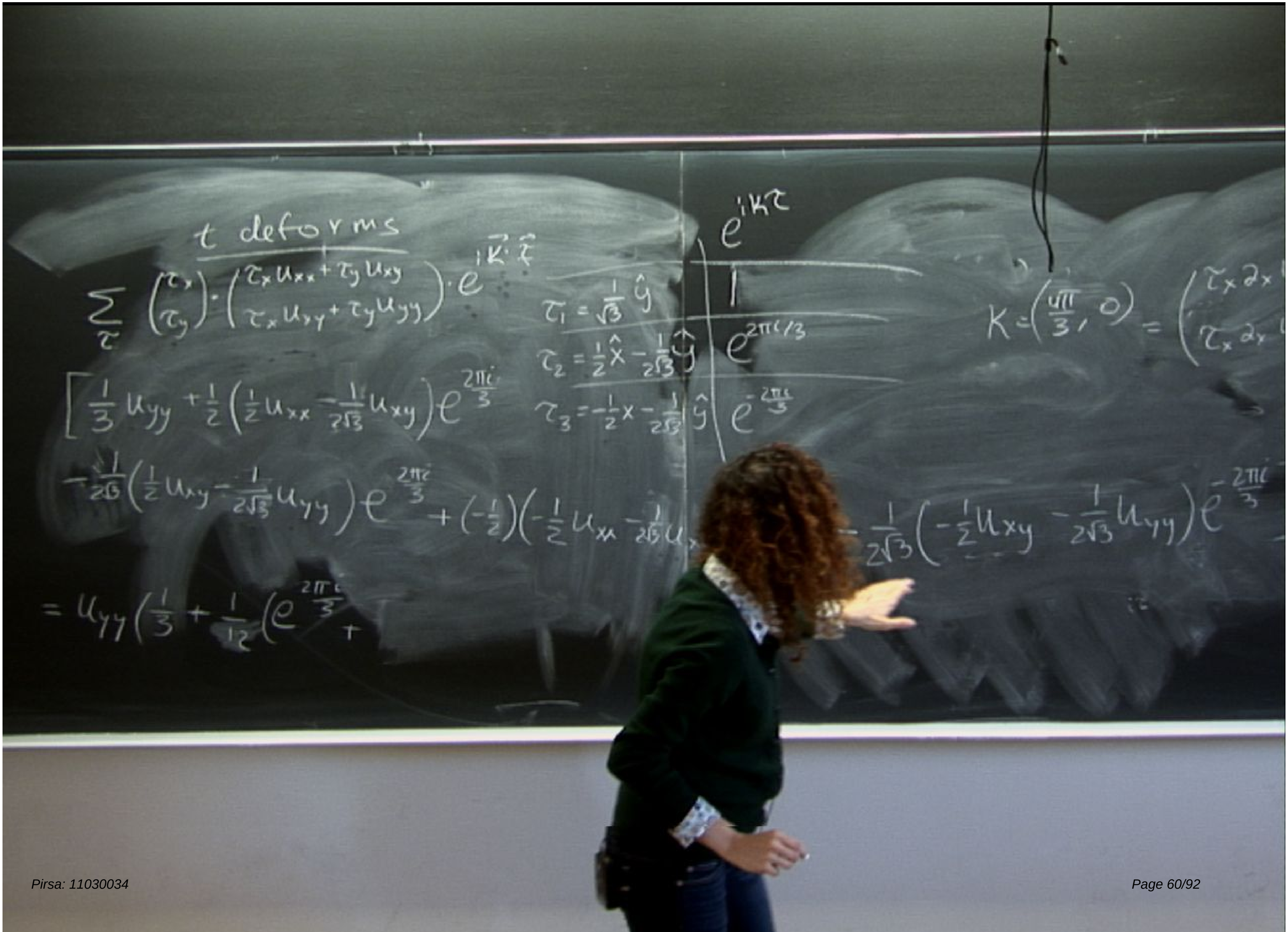

t deforms
$\sum_{\tau} \begin{pmatrix} \tau_x \\ \tau_y \end{pmatrix} \cdot \begin{pmatrix} \tau_x u_{xx} + \tau_y u_{xy} \\ \tau_x u_{xy} + \tau_y u_{yy} \end{pmatrix} \cdot e^{i\vec{K}\cdot\vec{\tau}}$
$\left[\frac{1}{3} u_{yy} \right.$
$\tau_1 =$
$\tau_2 = \frac{1}{2}$
$\tau_3 = -$

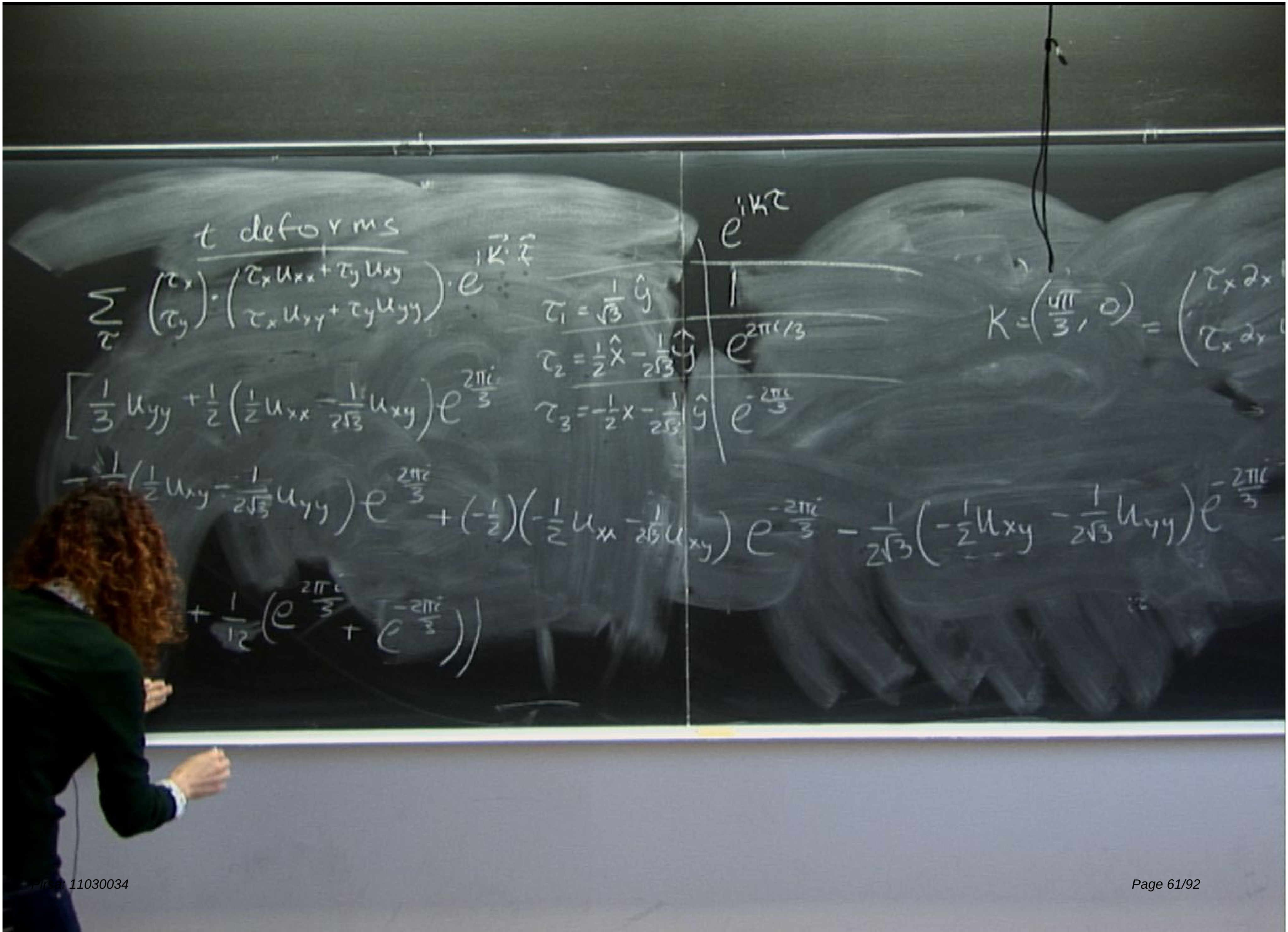

t deforms

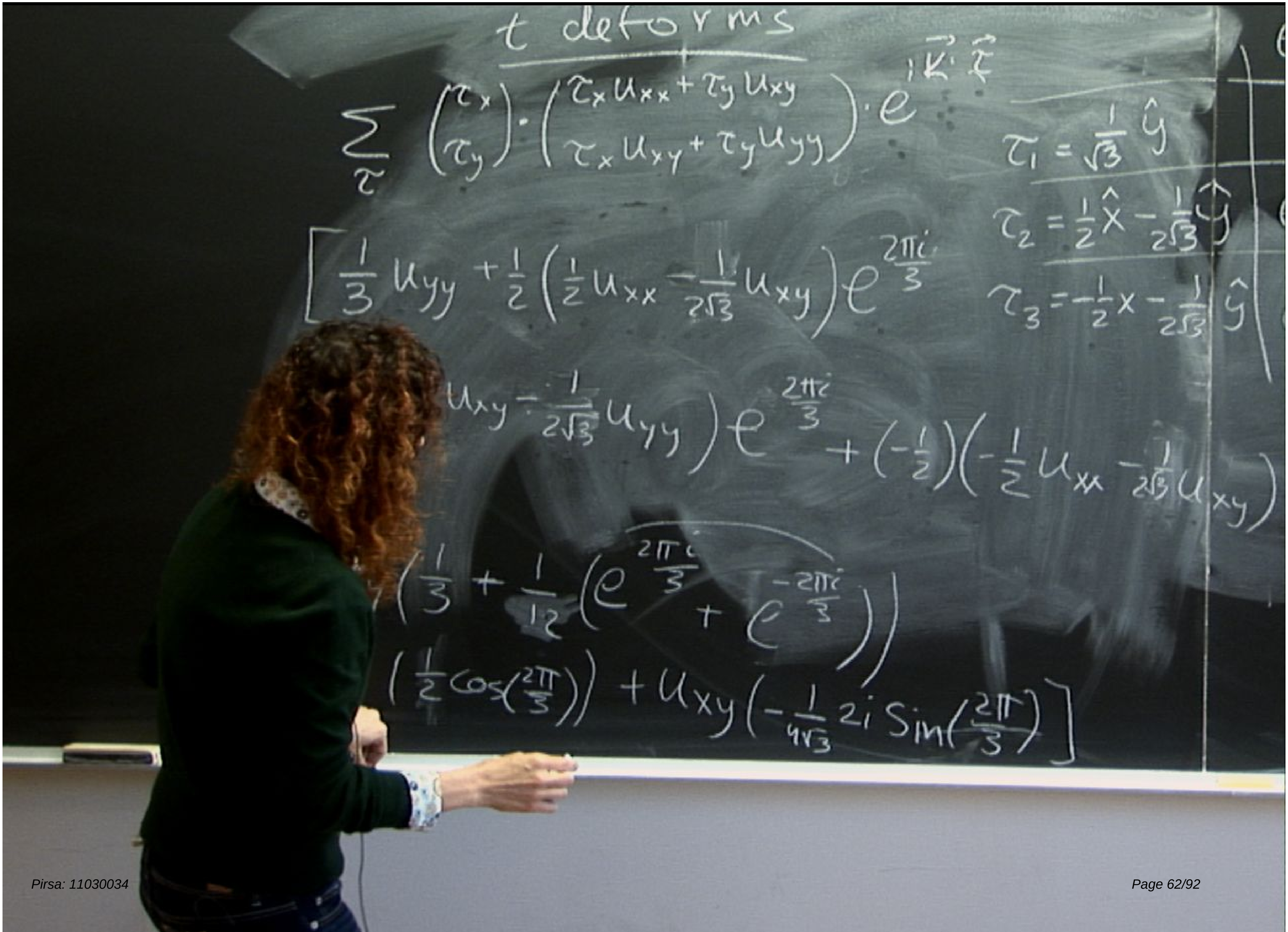

t deforms
$\sum_{\tau} \begin{pmatrix} \tau_x \\ \tau_y \end{pmatrix} \cdot \begin{pmatrix} \tau_x u_{xx} + \tau_y u_{xy} \\ \tau_x u_{xy} + \tau_y u_{yy} \end{pmatrix} \cdot e^{i\vec{K}\cdot\vec{\tau}}$
$\tau_1 = \frac{1}{\sqrt{3}} \hat{y}$
$\tau_2 = \frac{1}{2}\hat{x} - \frac{1}{2\sqrt{3}}\hat{y}$
$\tau_3 = -\frac{1}{2}x - \frac{1}{2\sqrt{3}}\hat{y}$
$e^{iK\tau}$
1
$e^{2\pi i/3}$
$e^{-\frac{2\pi i}{3}}$
$\Big[\frac{1}{3}u_{yy} + \frac{1}{2}\left(\frac{1}{2}u_{xx} - \frac{\sqrt{3}}{2}u_{xy}\right)e^{\frac{2\pi i}{3}}$
$+\frac{\sqrt{3}}{2}\left(\frac{1}{2}u_{xy} - \frac{\sqrt{3}}{2}u_{yy}\right)e^{-\frac{2\pi i}{3}} + \left(-\frac{1}{2}\right)\left(-\frac{1}{2}u_{xx} - \frac{\sqrt{3}}{2}u_{xy}\right)e^{-\frac{2\pi i}{3}}$

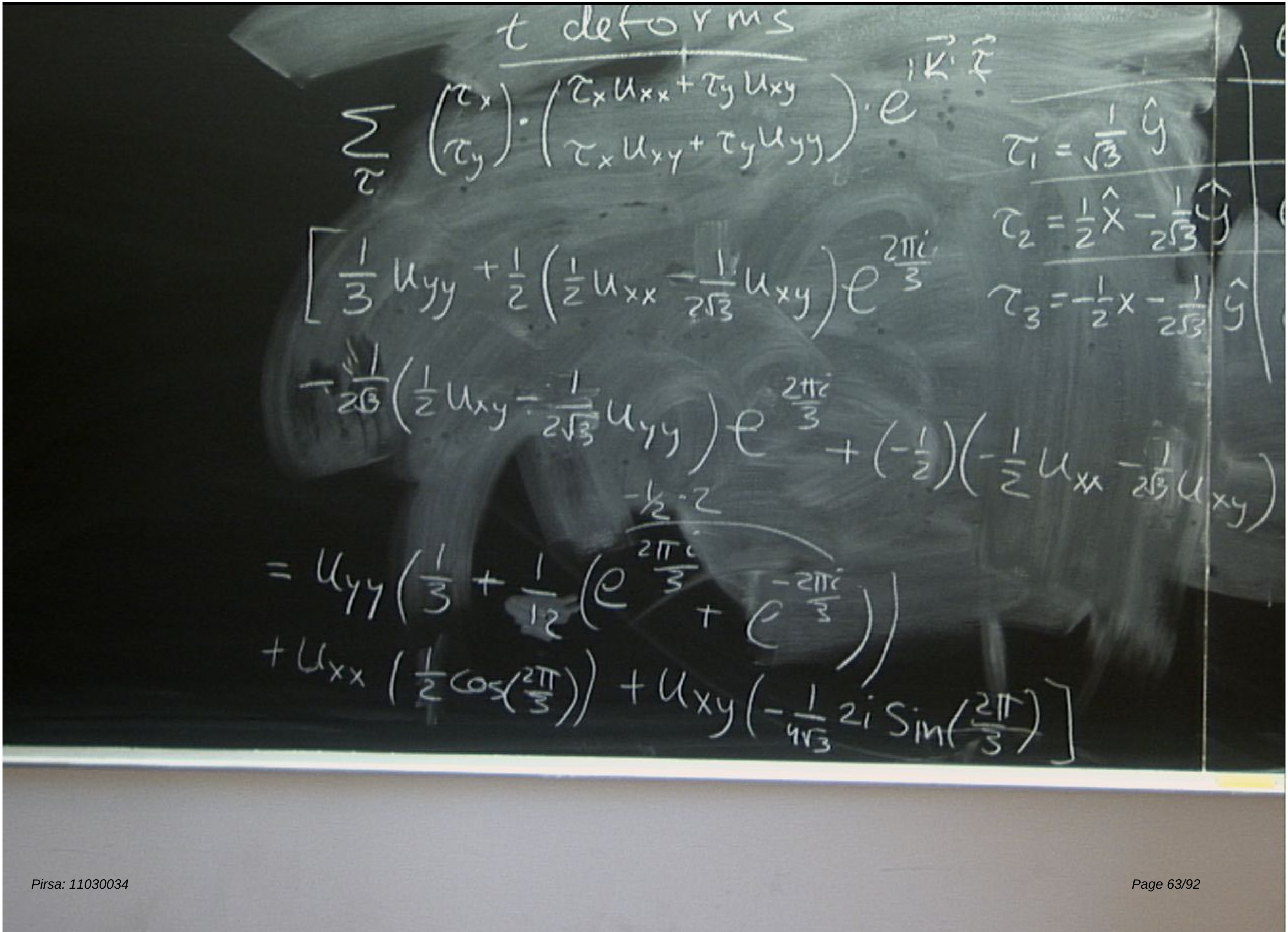

t deforms
$\sum_\tau \begin{pmatrix}\tau_x\\ \tau_y\end{pmatrix}\cdot\begin{pmatrix}\tau_x u_{xx}+\tau_y u_{xy}\\ \tau_x u_{xy}+\tau_y u_{yy}\end{pmatrix}\cdot e^{i\vec{K}\cdot\vec{\tau}}$
$\Big[\frac{1}{3}u_{yy}+\frac{1}{2}\Big(\frac{1}{2}u_{xx}-\frac{1}{2\sqrt{3}}u_{xy}\Big)e^{\frac{2\pi i}{3}}$
$-\frac{1}{2\sqrt{3}}\Big(\frac{1}{2}u_{xy}-\frac{1}{2\sqrt{3}}u_{yy}\Big)e^{-\frac{2\pi i}{3}}$
$\tau_1=\frac{1}{\sqrt{3}}\hat{y}$
$\tau_2=\frac{1}{2}\hat{x}-\frac{1}{2\sqrt{3}}\hat{y}$
$\tau_3=-\frac{1}{2}x-\frac{1}{2\sqrt{3}}\hat{y}$
$e^{iK\tau}$
1
$e^{2\pi i/3}$
$e^{-\frac{2\pi i}{3}}$
$u_{xy})\,e^{-\frac{2\pi i}{3}}$


t deforms
Σ_τ (τx, τy) · (τx uxx + τy uxy, τx uxy + τy uyy) · e^{i K·τ}
τ1 = 1/√3 ŷ
τ2 = 1/2 x̂ − 1/(2√3) ŷ
τ3 = −1/2 x − 1/(2√3) ŷ
e^{iKτ}
1
e^{2πi/3}
e^{−2πi/3}
K = (4π/3, 0)
[1/3 uyy + 1/2 (1/2 uxx − 1/(2√3) uxy) e^{2πi/3}
+ (−1/2)(−1/2 uxx − 1/(2√3) uxy) e^{−2πi/3} − 1/(2√3) (−1/2 uxy − 1/(2√3) uyy)]


t deforms
e^{ikτ}
K = (4π/3, 0)


t deforms
$\sum_\tau \begin{pmatrix}\tau_x\\ \tau_y\end{pmatrix}\cdot\begin{pmatrix}\tau_x u_{xx}+\tau_y u_{xy}\\ \tau_x u_{xy}+\tau_y u_{yy}\end{pmatrix}\cdot e^{i\vec{K}\cdot\vec{\tau}}$
$\tau_1 = \frac{1}{\sqrt{3}}\hat{y}$
$\tau_2 = \frac{1}{2}\hat{x} - \frac{1}{2\sqrt{3}}\hat{y}$
$\tau_3 = -\frac{1}{2}x - \frac{1}{2\sqrt{3}}\hat{y}$
$e^{iK\tau}$
1
$e^{2\pi i/3}$
$e^{-\frac{2\pi i}{3}}$
$K = \left(\frac{4\pi}{3}, 0\right) =$
$\left[\frac{1}{3}u_{yy} + \frac{1}{2}\left(\frac{1}{2}u_{xx} - \frac{1}{2\sqrt{3}}u_{xy}\right)e^{\frac{2\pi i}{3}}\right.$
$\left(\frac{1}{2}u_{xy} - \frac{1}{2\sqrt{3}}u_{yy}\right)e^{\frac{2\pi i}{3}} + \left(-\frac{1}{2}\right)\left(-\frac{1}{2}u_{xx} - \frac{1}{2\sqrt{3}}u_{xy}\right)e^{-\frac{2\pi i}{3}} - \frac{1}{2\sqrt{3}}\left(-\frac{1}{2}u_{xy} - \frac{1}{2\sqrt{3}}u_{yy}\right)e^{-\frac{2\pi i}{3}}$
$+ \frac{1}{12}\left(e^{\frac{2\pi i}{3}} + e^{-\frac{2\pi i}{3}}\right)\Big)$


t deforms
τ_x u_xx + τ_y u_xy
τ_x u_xy + τ_y u_yy
τ_1 = 1/√3 ŷ
τ_2 = 1/2 x̂ − 1/(2√3) ŷ
τ_3 = −1/2 x − 1/(2√3) ŷ


t deforms
Σ_τ (τ_x, τ_y) · (τ_x u_xx + τ_y u_xy, τ_x u_xy + τ_y u_yy) · e^{iK·τ}
τ_1 = 1/√3 ŷ
τ_2 = 1/2 x̂ − 1/(2√3) ŷ
τ_3 = −1/2 x − 1/(2√3) ŷ
[1/3 u_yy + 1/2 (1/2 u_xx − 1/(2√3) u_xy) e^{2πi/3}
− 1/(2√3) (1/2 u_xy − 1/(2√3) u_yy) e^{2πi/3} + (−1/2)(−1/2 u_xx − 1/(2√3) u_xy)
= u_yy (1/3 + 1/12 (e^{2πi/3} + e^{−2πi/3}))
+ u_xx (1/2 cos(2π/3)) + u_xy (−1/(4√3) 2i sin(2π/3))]

$e^{ik\tau}$

1

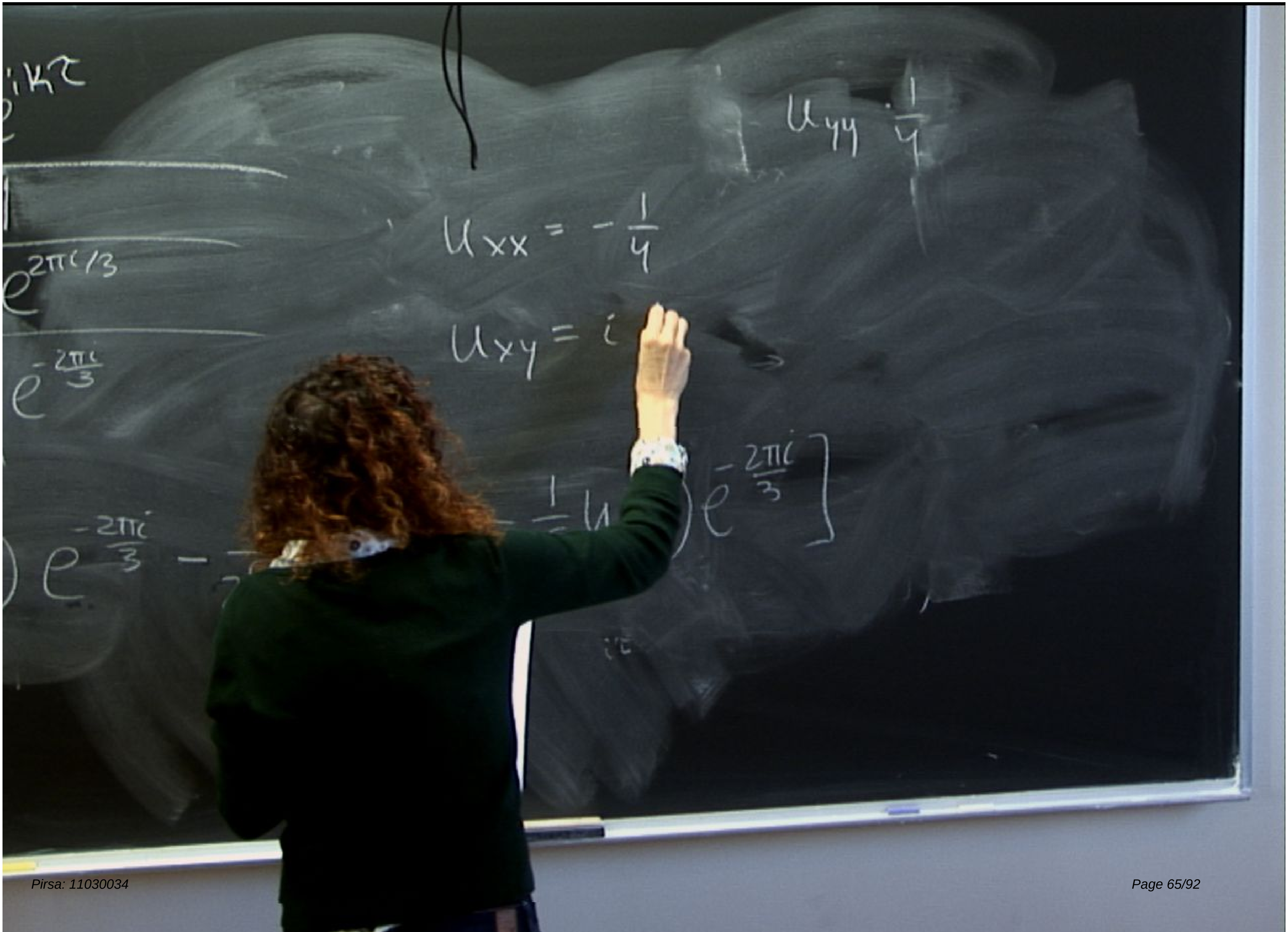
$\hat{y}$ $e^{2\pi i/3}$

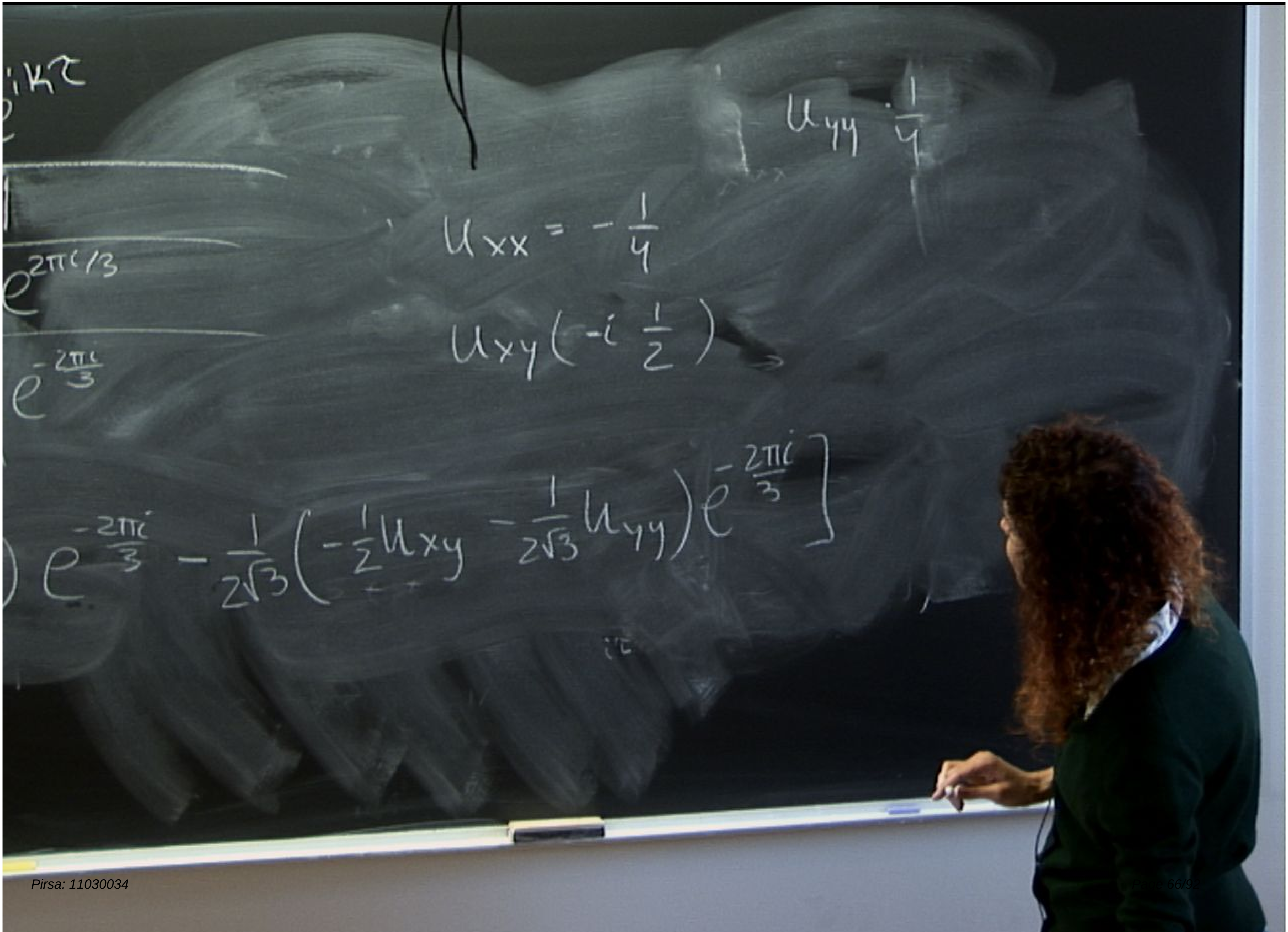
$\frac{1}{\sqrt{3}}\hat{y}$ $e^{-\frac{2\pi i}{3}}$

$u_{yy}\left(\frac{1}{3}-\frac{1}{6}\right) = u_{yy}\cdot\frac{1}{6}$

$u_{xx} =$

$u_{xy})\, e^{-\frac{2\pi i}{3}} - \frac{1}{2\sqrt{3}}\left(-\frac{1}{2}u_{xy} - \frac{1}{2\sqrt{3}}u_{yy}\right)e^{-\frac{2\pi i}{3}}\Big]$


ikτ
e^{2πi/3}
e^{-2πi/3}
U_yy 1/4
U_xx = - 1/4
U_xy = i
e^{-2πi/3}


u_yy 1/4
u_xx = -1/4
u_xy (-i 1/2)
e^{2πi/3}
e^{-2πi/3}
) e^{-2πi/3} - 1/(2√3) (-1/2 u_xy - 1/(2√3) u_yy) e^{-2πi/3}]

$e^{ik\tau}$

$e^{2\pi i/3}$

$e^{-\frac{2\pi i}{3}}$

$u_{yy}\ \frac{1}{4}$

$u_{xx} = -\frac{1}{4}$

$u_{xy}\left(-i\,\frac{1}{2}\right)$

$\psi^\dagger(\nabla\cdot\sigma)\psi$

$-i\hbar(\partial_x - i\partial_y)$

$u_{xx} - u_{yy} = A_x$

$$) e^{-\frac{2\pi i}{3}} - \frac{1}{2\sqrt{3}}\left(-\frac{1}{2}u_{xy} - \frac{1}{2\sqrt{3}}u_{yy}\right)e^{-\frac{2\pi i}{3}}\Big]$$

$e^{ik\tau}$

$e^{2\pi i/3}$

$e^{-\frac{2\pi i}{3}}$

$u_{xx} = -\frac{1}{4}$

$u_{yy}\ \frac{1}{4}$

$u_{xy}\left(-i\,\frac{1}{2}\right)$

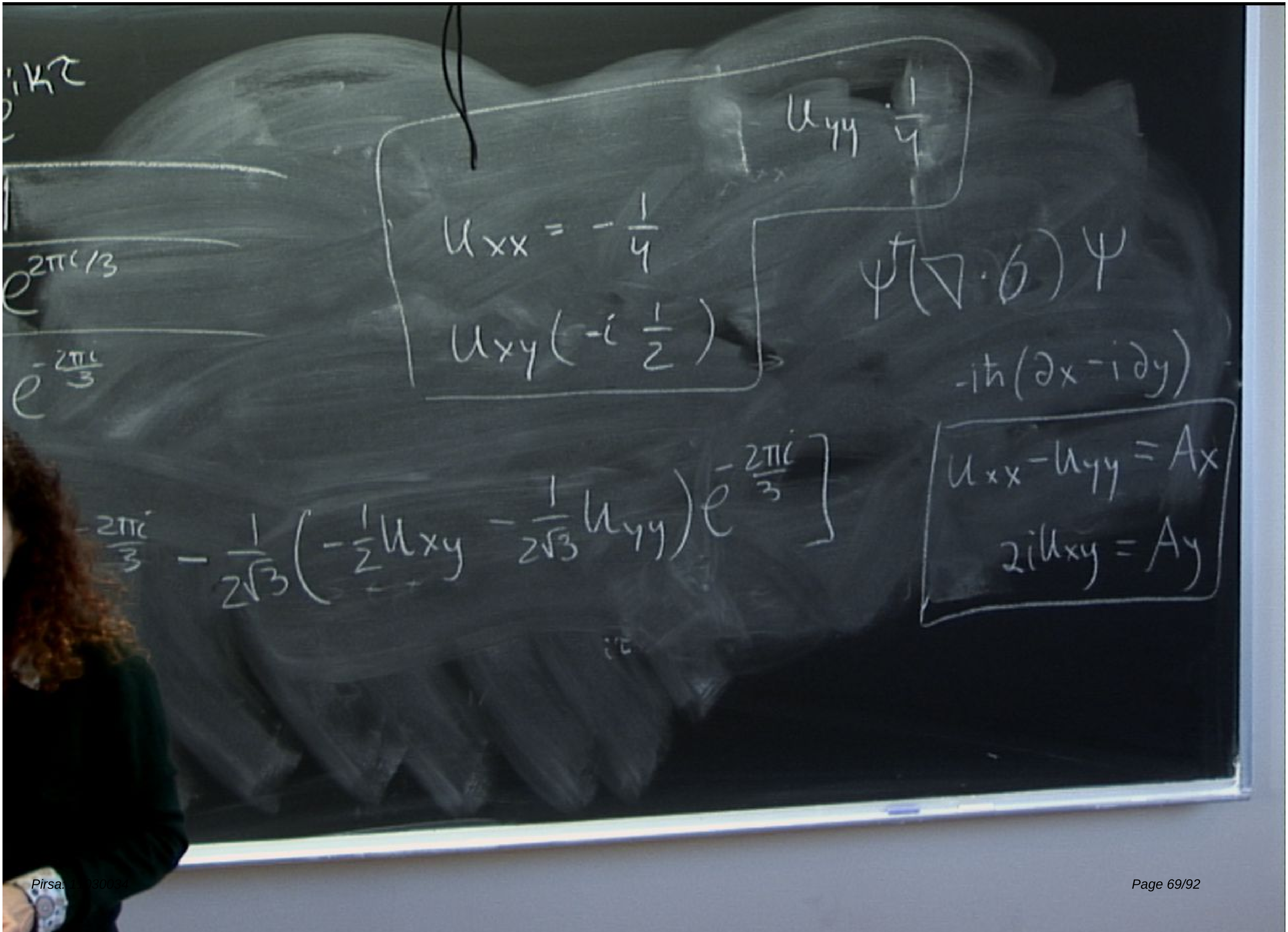
$\psi^\dagger(\nabla\cdot\sigma)\psi$

$-i\hbar(\partial_x - i\partial_y)$

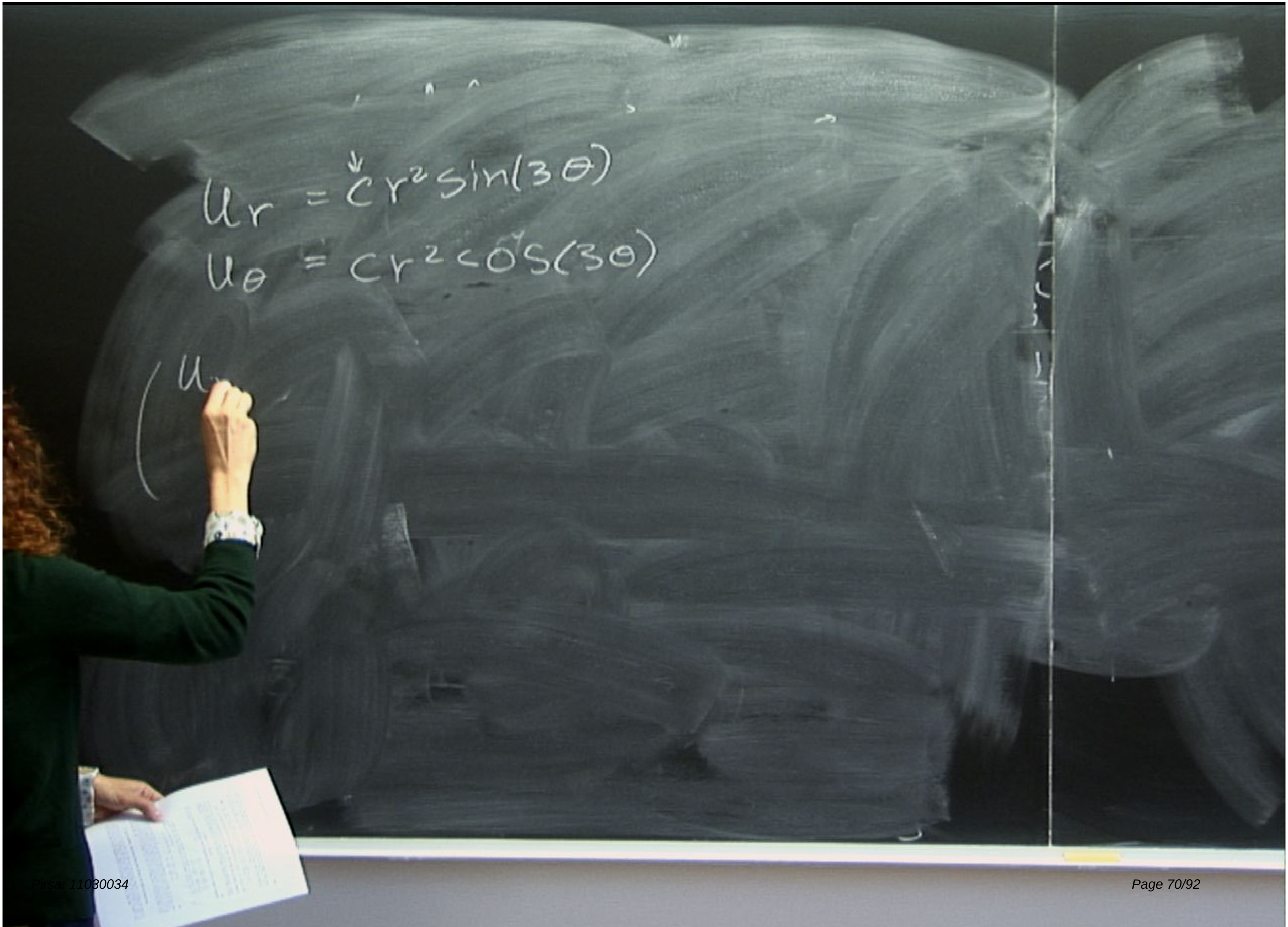
$) e^{-\frac{2\pi i}{3}} - \frac{1}{2\sqrt{3}}\left(-\frac{1}{2}u_{xy} - \frac{1}{2\sqrt{3}}u_{yy}\right)e^{-\frac{2\pi i}{3}}]$

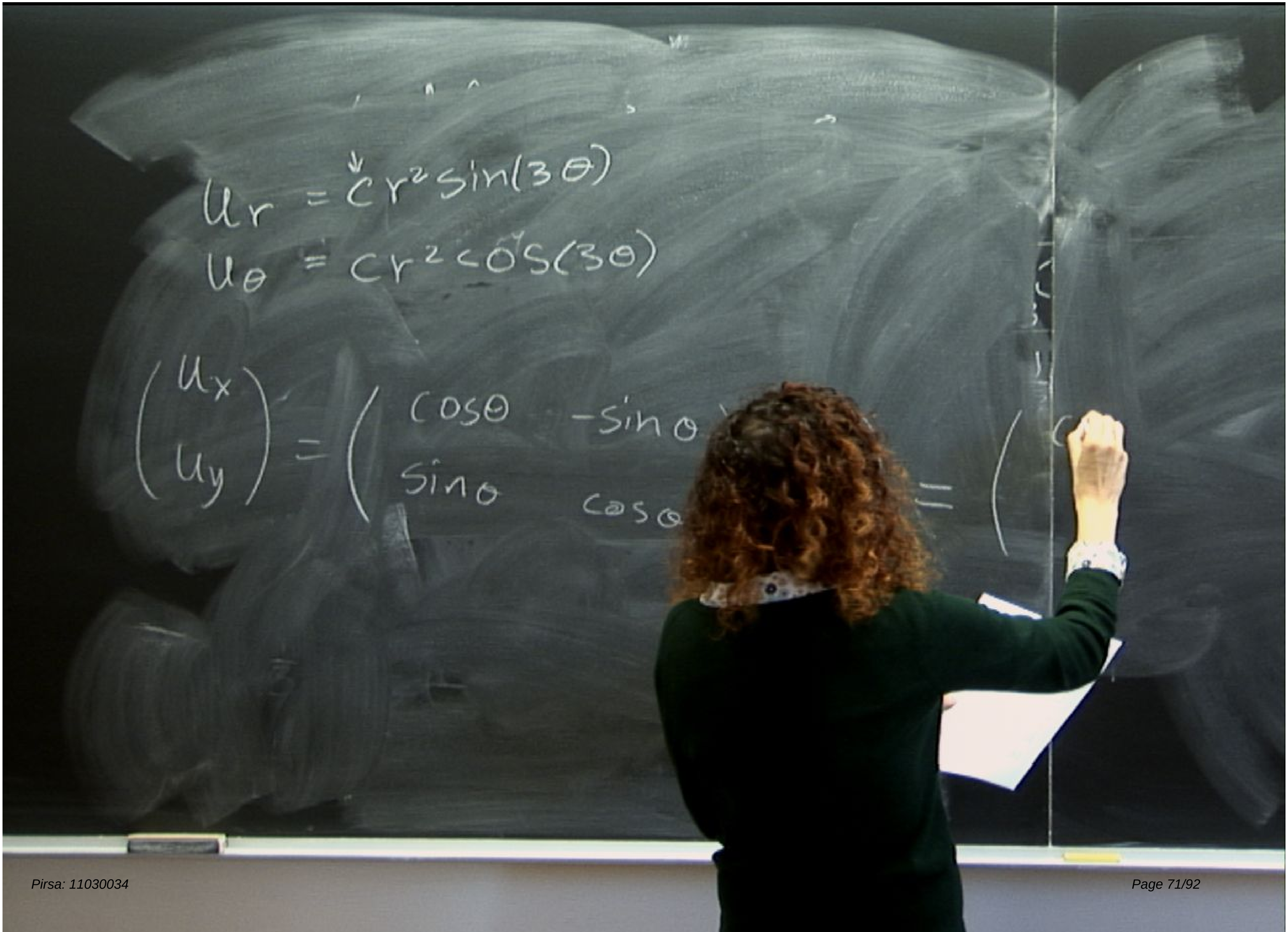
$u_{xx} - u_{yy} = A_x$

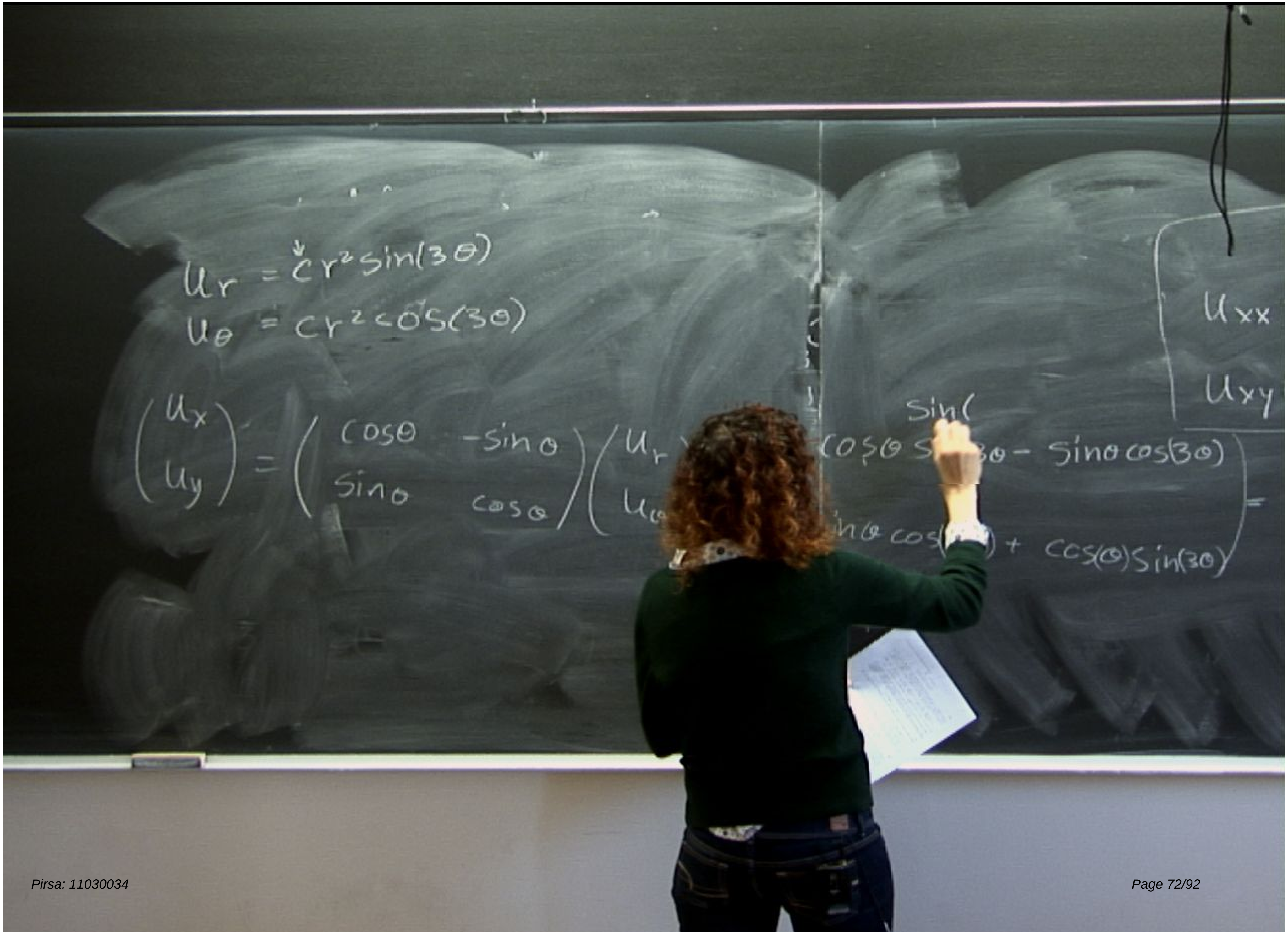
$2iu_{xy} = A_y$



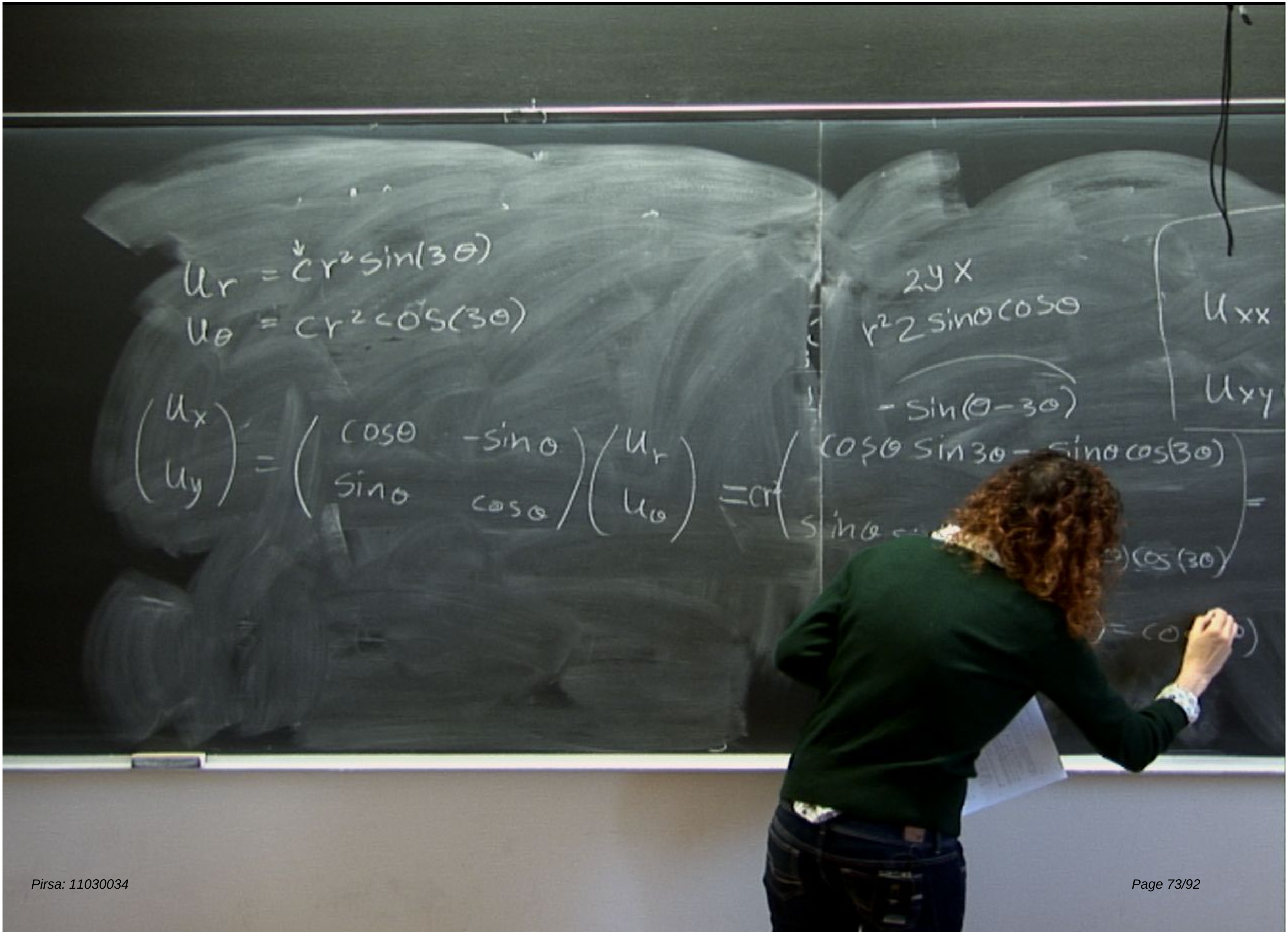
$e^{ik\tau}$
$e^{2\pi i/3}$
$e^{-\frac{2\pi i}{3}}$
$u_{yy}\ \frac{1}{4}$
$u_{xx} = -\frac{1}{4}$
$u_{xy}(-i\ \frac{1}{2})$
$\psi^{\dagger}(\nabla\cdot\sigma)\psi$
$-i\hbar(\partial_x - i\partial_y)$
$u_{xx} - u_{yy} = A_x$
$2iu_{xy} = A_y$
$-\frac{1}{2\sqrt{3}}\left(-\frac{1}{2}u_{xy} - \frac{1}{2\sqrt{3}}u_{yy}\right)e^{-\frac{2\pi i}{3}}\Big]$

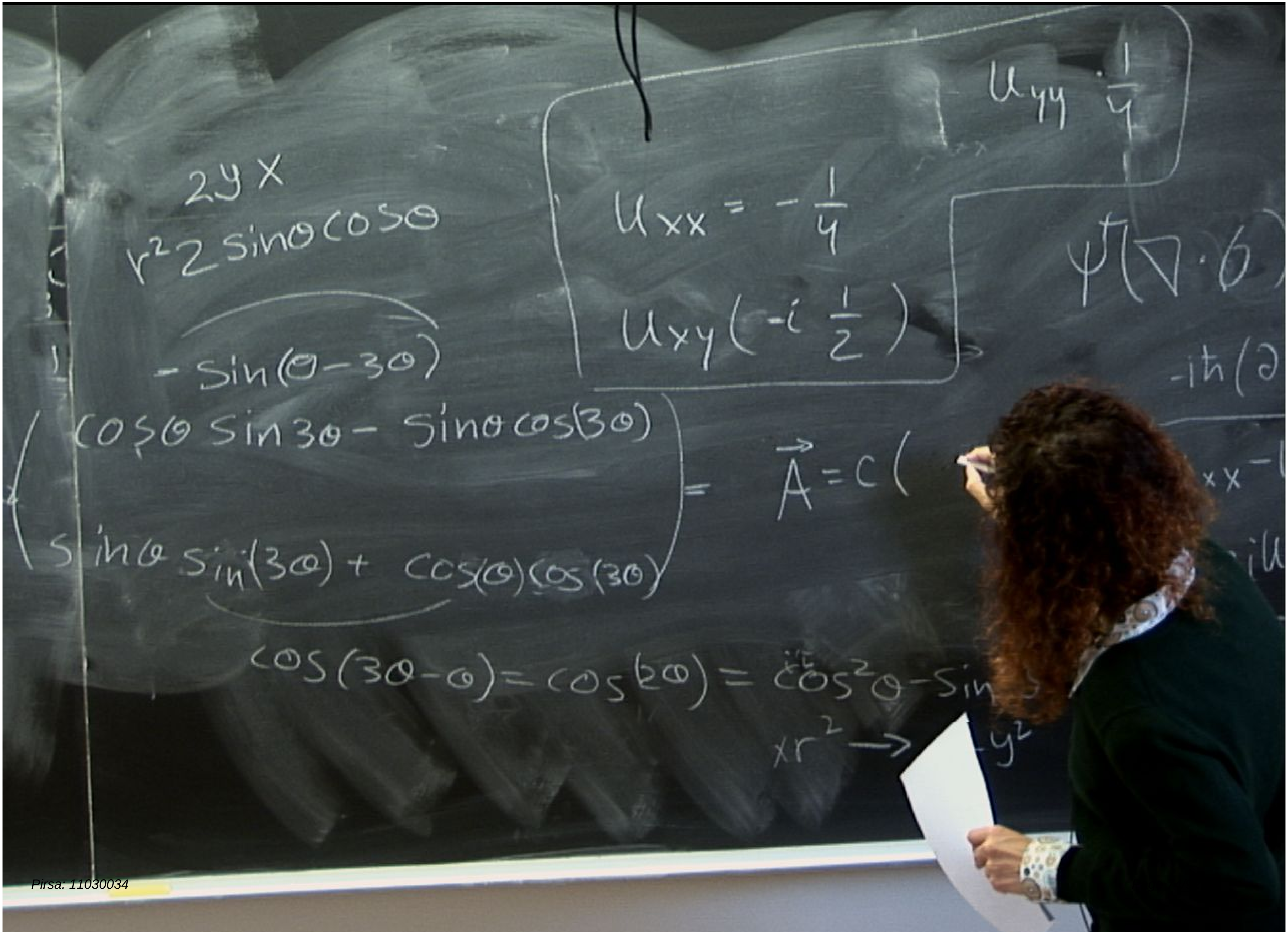

u_r = c r^2 sin(3θ)
u_θ = c r^2 cos(3θ)


u_r = c r^2 sin(3θ)
u_θ = c r^2 cos(3θ)
(u_x u_y) = (cosθ -sinθ sinθ cosθ)



ur = cr²sin(3θ)
uθ = cr²cos(3θ)
ux
uy
cosθ -sinθ
sinθ cosθ
ur
sin(
cosθ s 3θ - sinθ cos(3θ)
+ cos(θ)sin(3θ)
uxx
uxy


ur = c r² sin(3θ)
uθ = c r² cos(3θ)
2yx
r² 2 sinθ cosθ
-sin(θ-3θ)
uxx
uxy
ux uy = cosθ -sinθ sinθ cosθ ur uθ = cr²
cosθ sin3θ - sinθ cos(3θ)


u_yy 1/4
2yx
r^2 2 sinθ cosθ
u_xx = −1/4
u_xy (−i 1/2)
ψ†(∇·σ
− sin(θ−3θ)
−iħ(∂
cosθ sin3θ − sinθ cos(3θ)
= A = c(
sinθ sin(3θ) + cos(θ)cos(3θ)
cos(3θ−θ) = cos(2θ) = cos^2θ − sin
xr^2 → y^2

$2yx$

$r^2 2\sin\theta\cos\theta$

$-\sin(\theta - 3\theta)$

$\cos\theta\sin 3\theta - \sin\theta\cos(3\theta)$

$\sin\theta\sin(3\theta) + \cos(\theta)\cos(3\theta)$

$\cos(3\theta - \theta) = \cos(2\theta) = \cos^2\theta - \sin^2\theta$

$x r^2 \rightarrow x^2 - y^2$

$u_{yy}\ \frac{1}{4}$

$u_{xx} = -\frac{1}{4}$

$u_{xy}\left(-i\,\frac{1}{2}\right)$

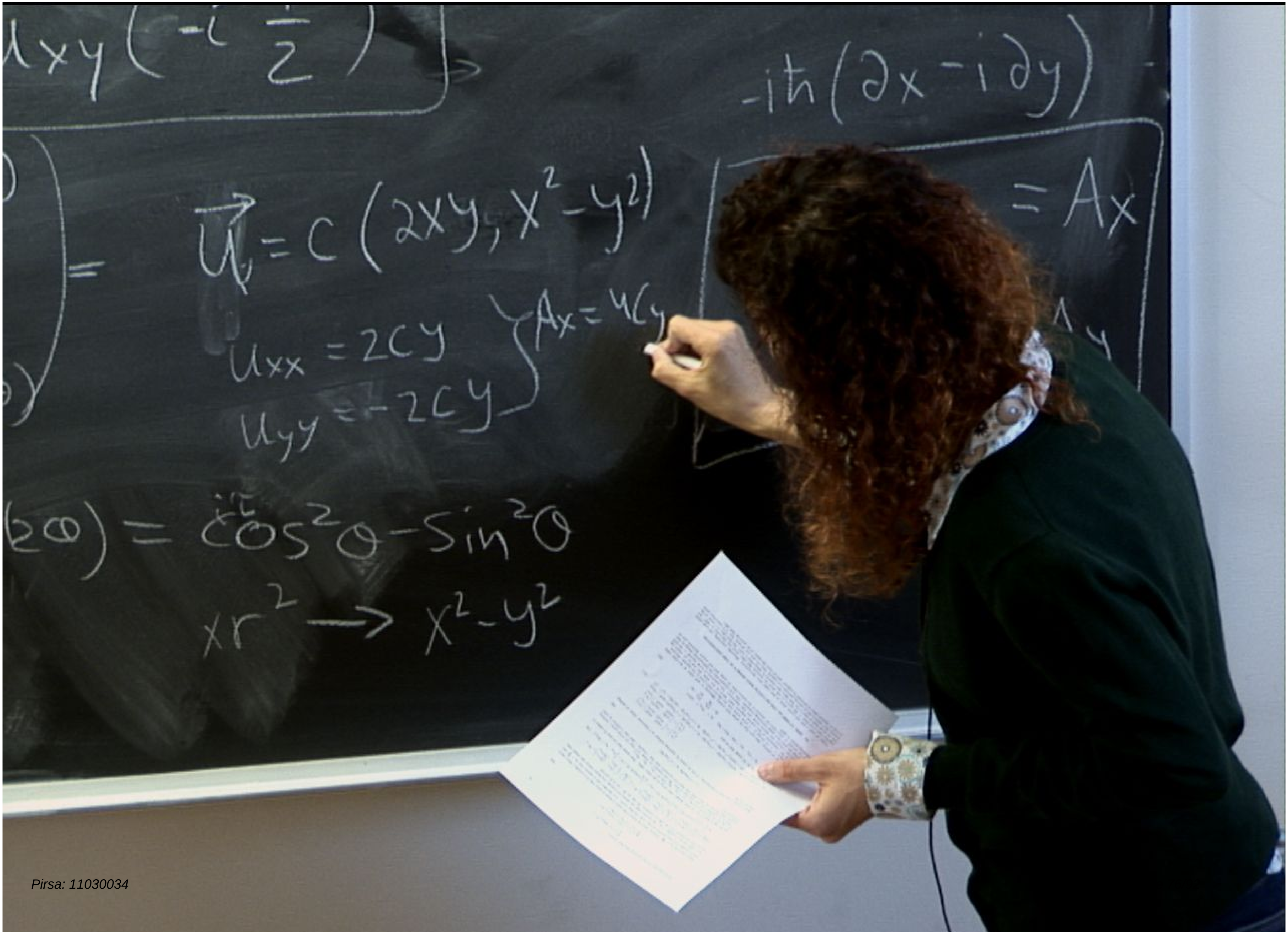
$\psi^\dagger(\nabla\cdot\sigma$

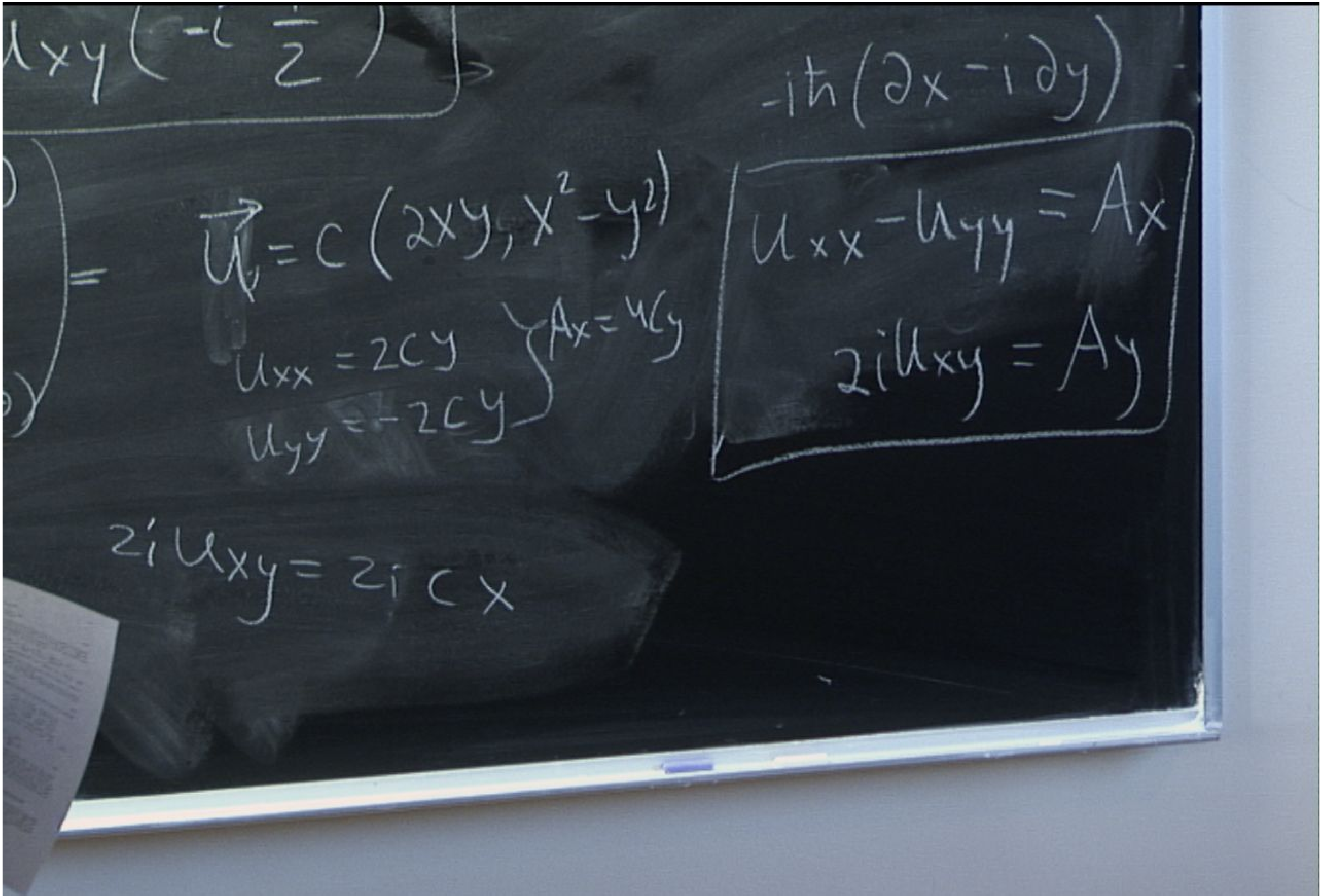
$-i\hbar(\partial$

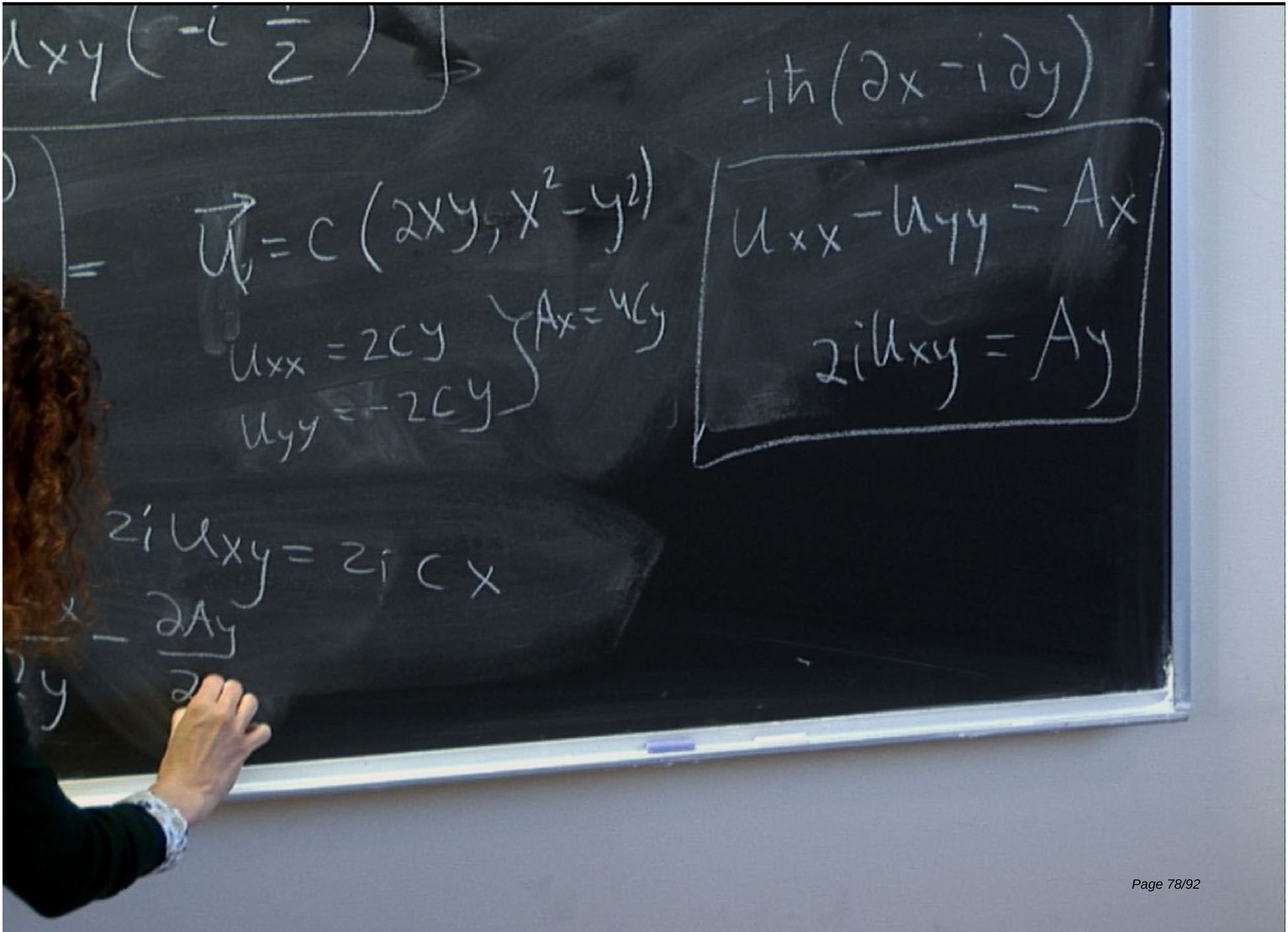
$\vec{u} = c\,(2xy, x^2 - y^2)$

$u_{xx} -$

$2iu$


-iħ(∂x - i∂y)
u⃗ = c(2xy, x² - y²)
= Ax
Ax = u(y
uxx = 2cy
uyy = -2cy
= cos²θ - sin²θ
xr² → x² - y²


-iħ(∂x - i∂y)
u = c(2xy, x² - y²)
uxx = 2cy
uyy = -2cy
Ax = 4cy
uxx - uyy = Ax
2iuxy = Ay
2iuxy = 2icx


$-i\hbar(\partial x - i\partial y)$
$\vec{u} = c(2xy, x^2 - y^2)$
$u_{xx} = 2cy$
$u_{yy} = -2cy$
$A_x = 4cy$
$u_{xx} - u_{yy} = A_x$
$2iu_{xy} = A_y$
$2iu_{xy} = 2icx$

$u_{xy}\left(-i\,\frac{1}{2}\right)$

$-i\hbar(\partial_x - i\partial_y)$

$\cos(3\theta)$

$[\text{illegible}])\cos(3\theta)$

$= \quad \vec{u} = c\,(2xy,\, x^2 - y^2)$

$u_{xx} = 2cy$

$u_{yy} = -2cy$

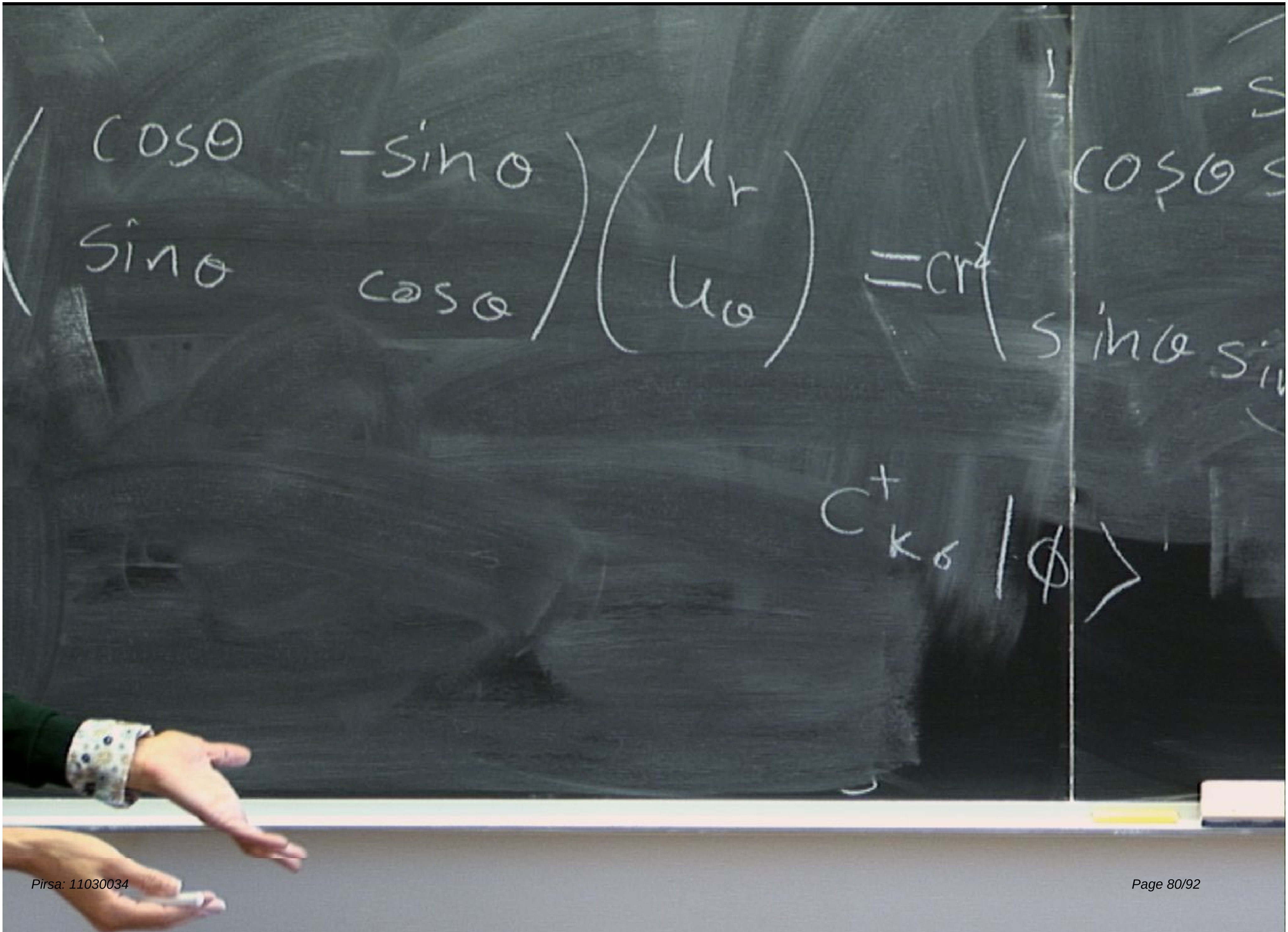
$A_x = 4cy$

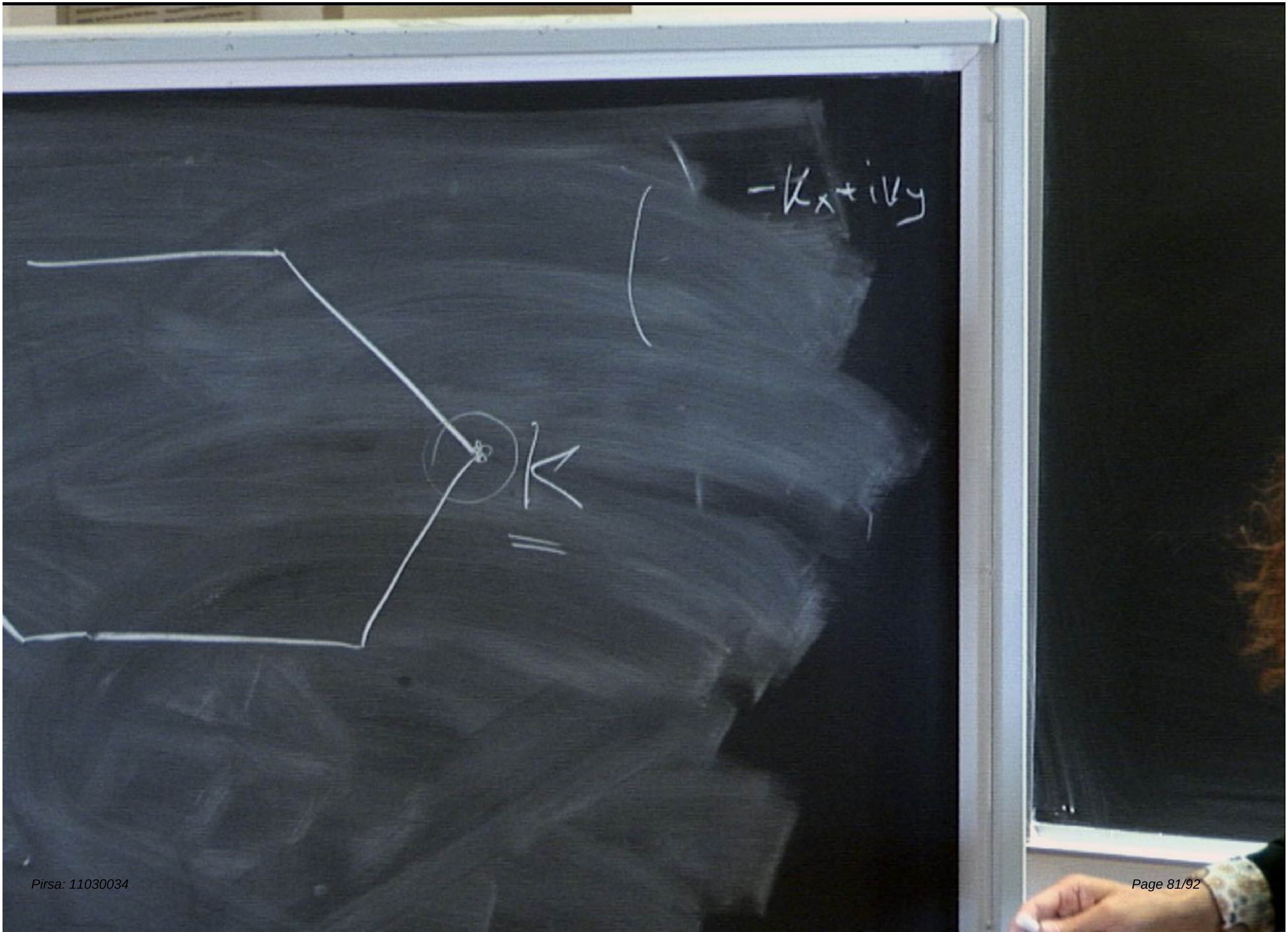
$$u_{xx} - u_{yy} = A_x$$

$$2iu_{xy} = A_y$$

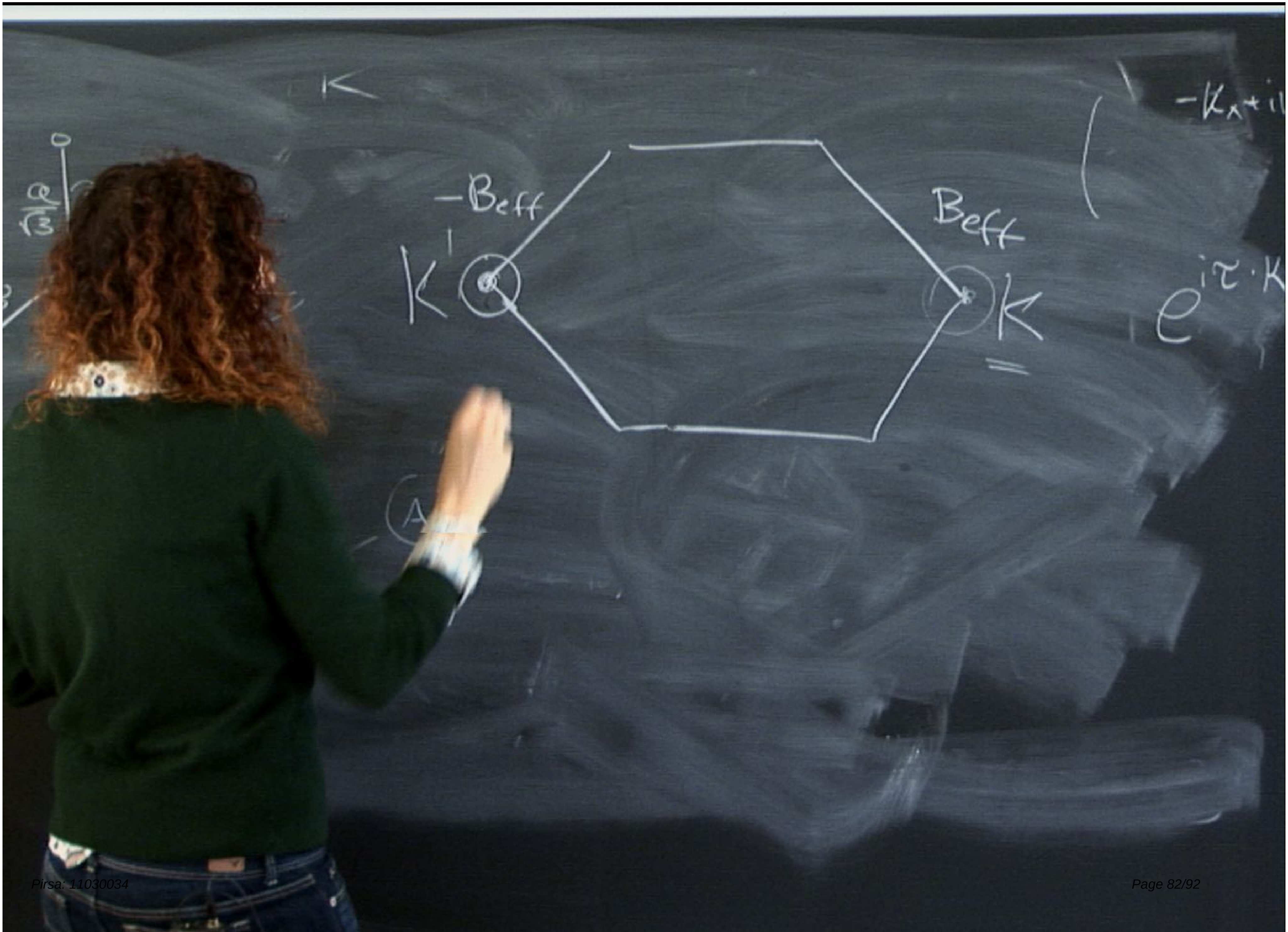
$2iu_{xy} = 2icx$

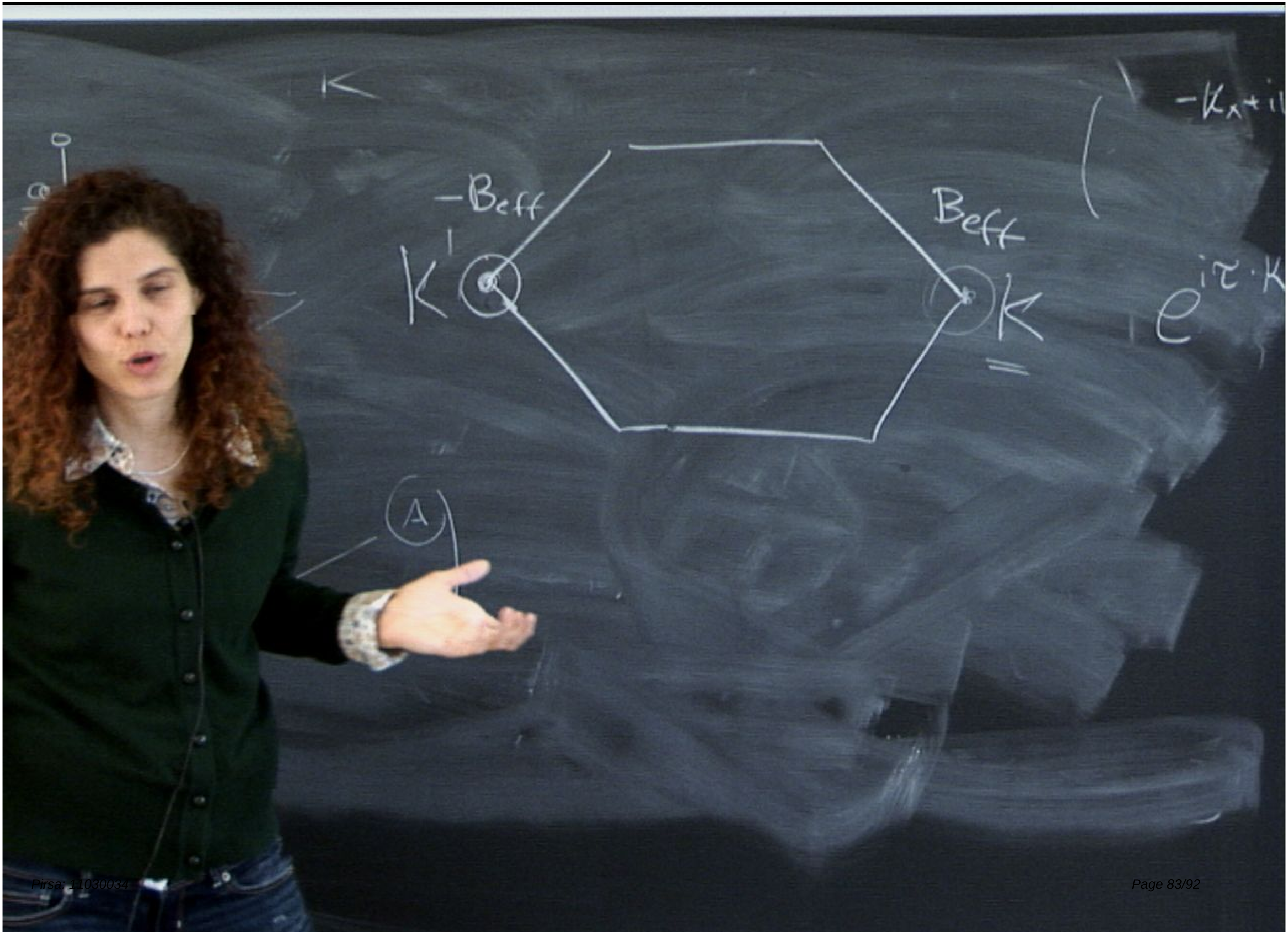
$$\frac{\partial A_x}{\partial y} - \frac{\partial A_y}{\partial x} = 2c$$


cosθ −sinθ
sinθ cosθ
u_r
u_θ
=cr²
cosθ
sinθ
c†_{kσ} |φ⟩

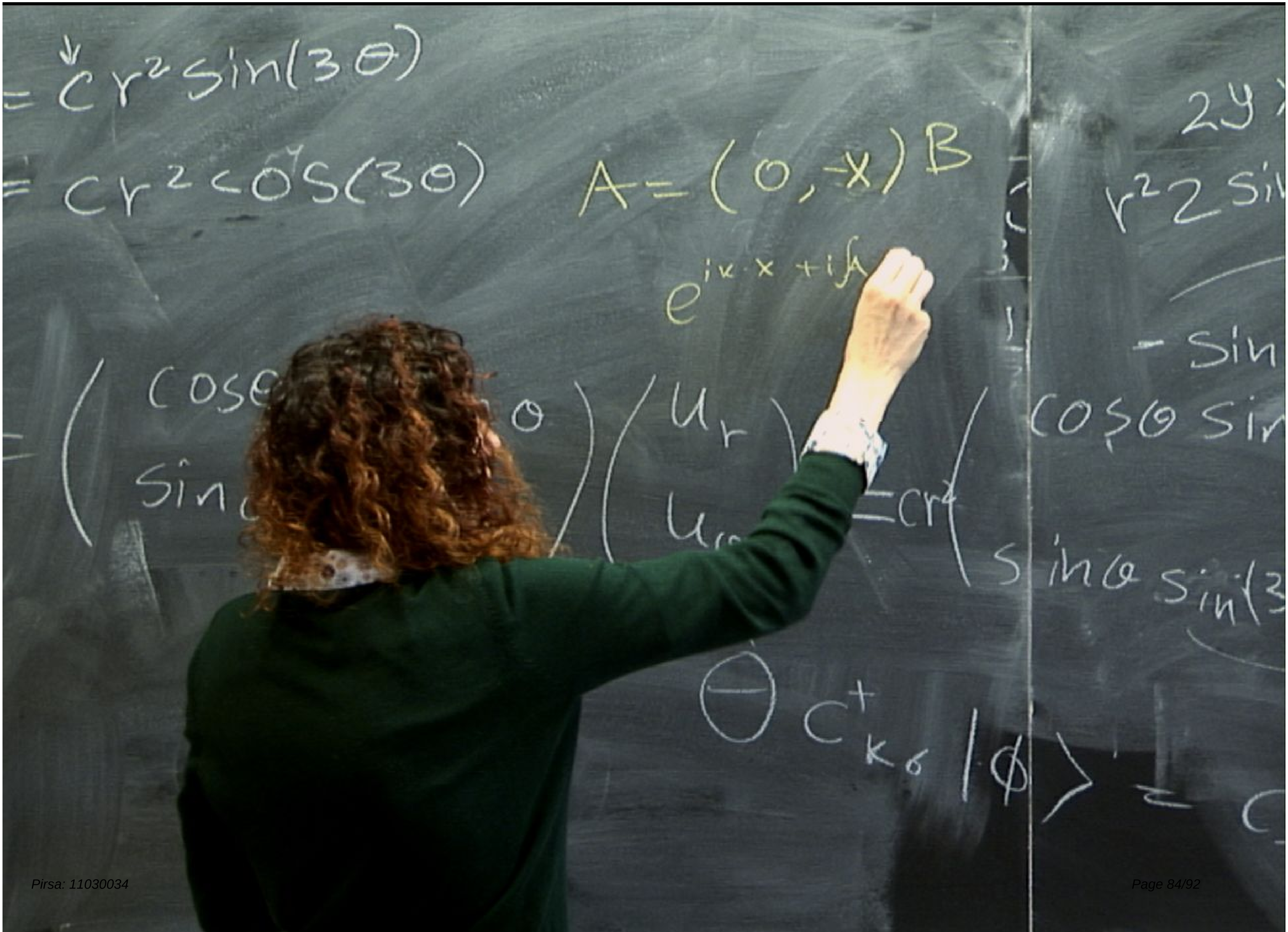


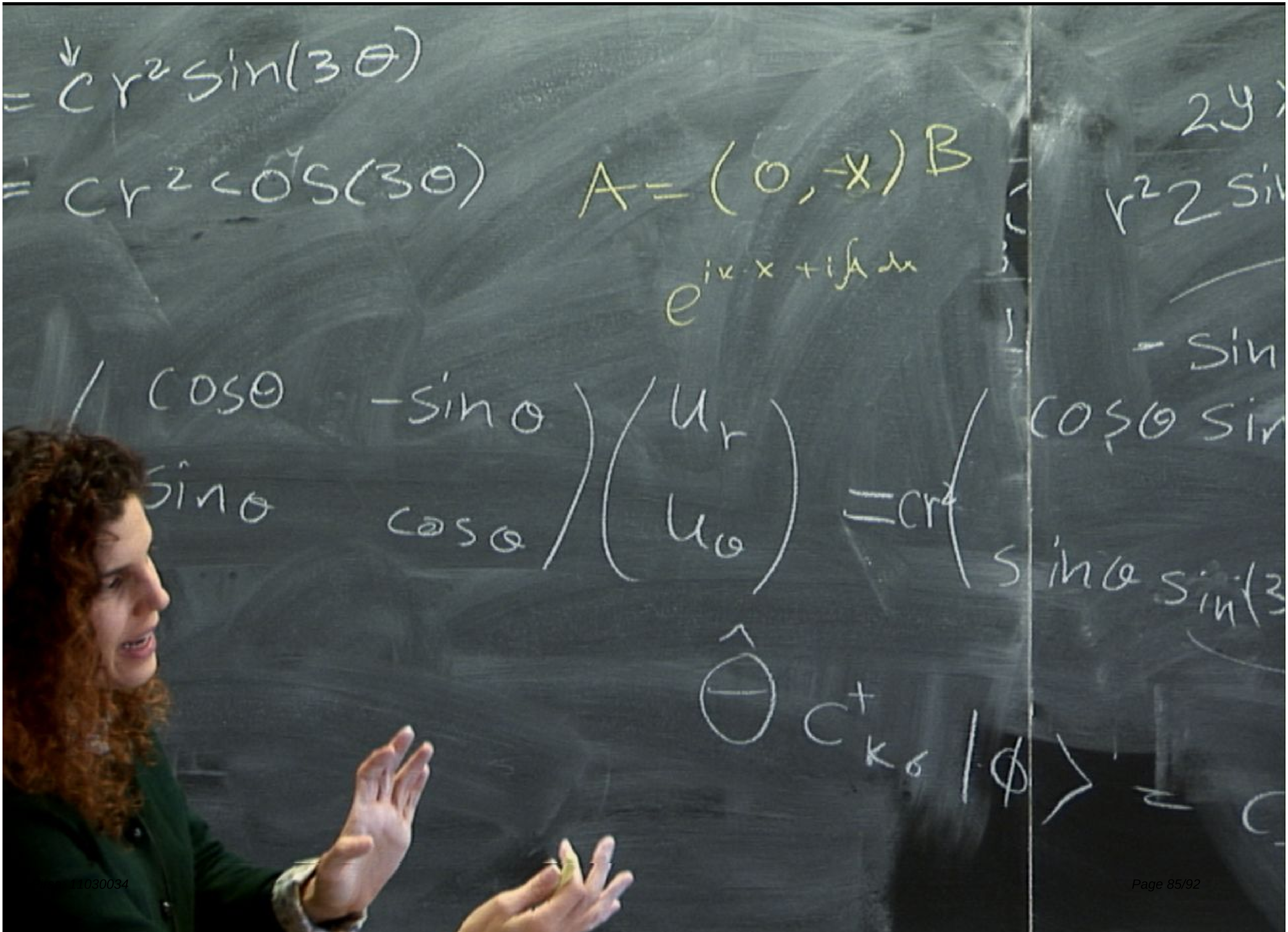
$-k_x + ik_y$
K

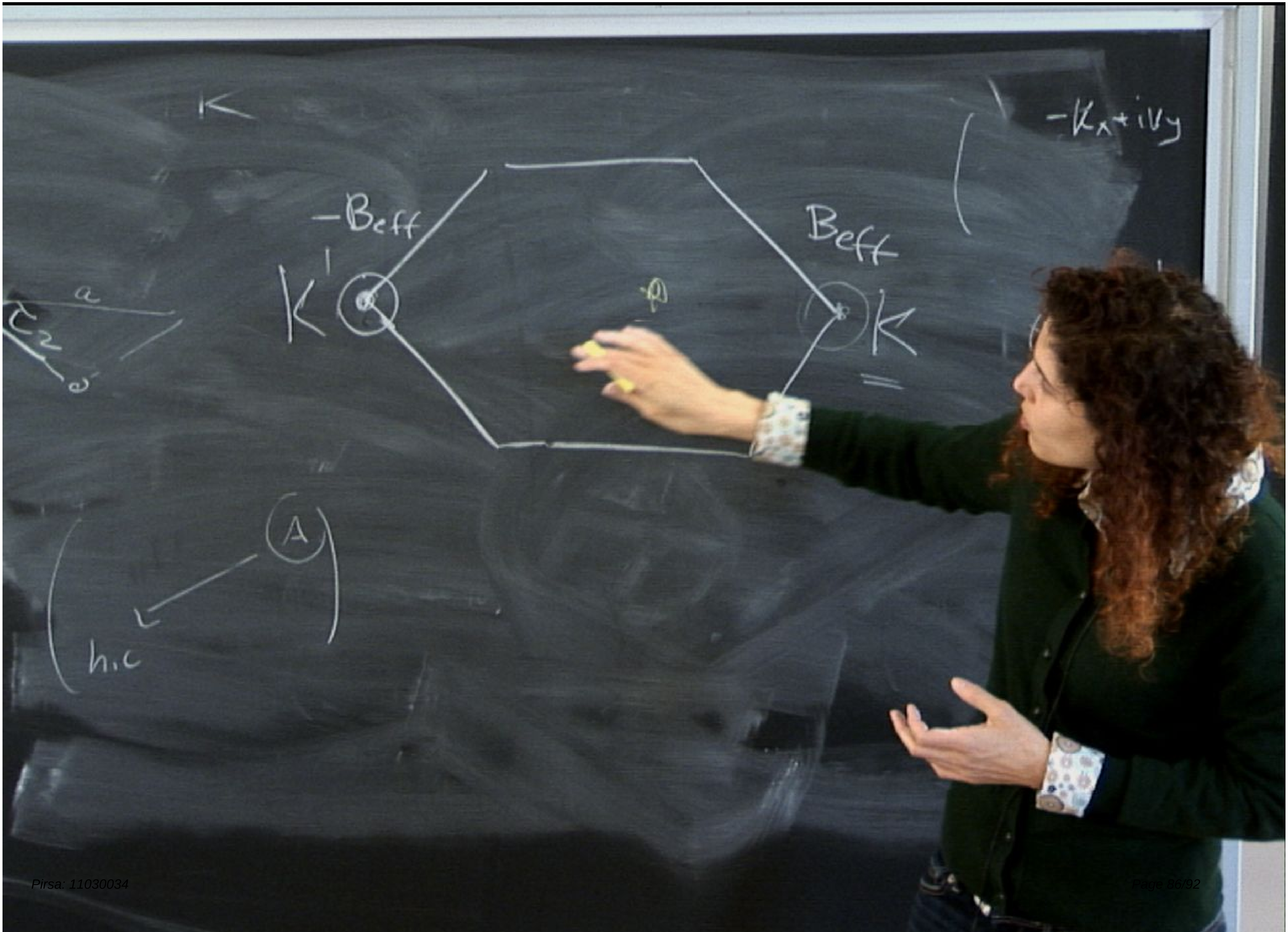

K
-Beff
Beff
K'
K



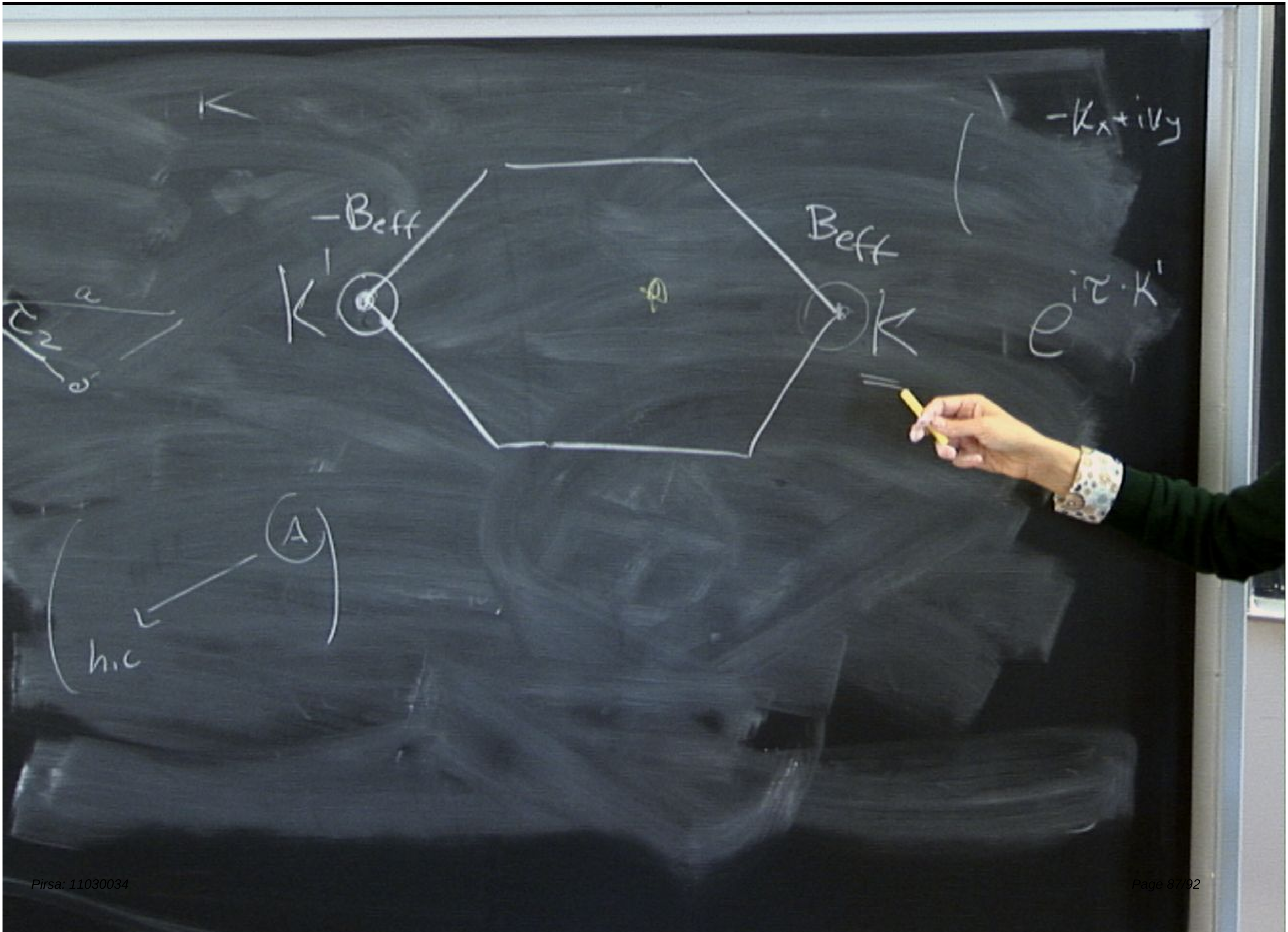
K
$-B_{eff}$
B_{eff}
K'
K
$e^{i\tau\cdot K}$
A

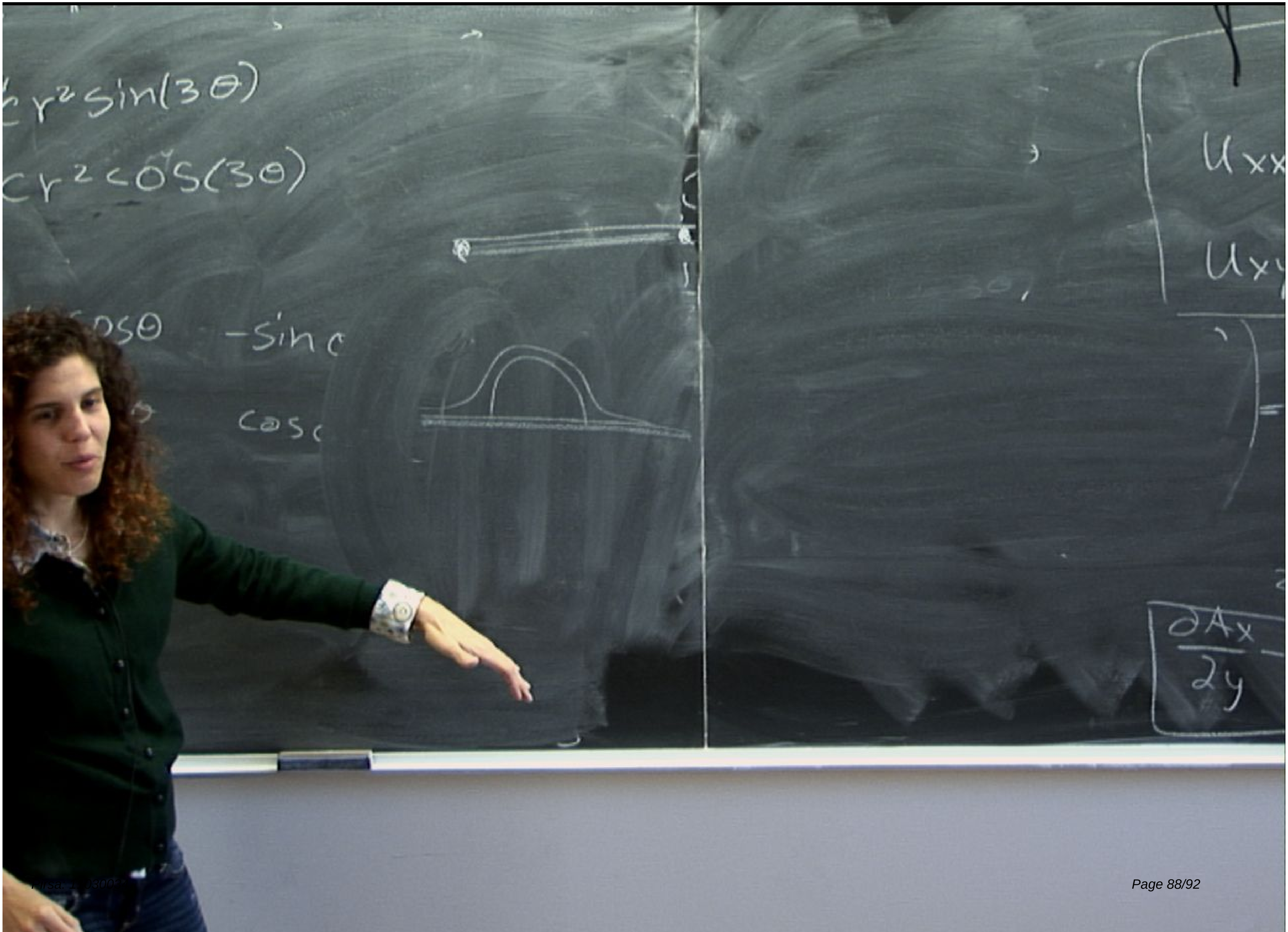

= cr²sin(3θ)
= cr²cos(3θ)
A = (0, -x) B
2y
r²2 sin
- sin
cos θ sin



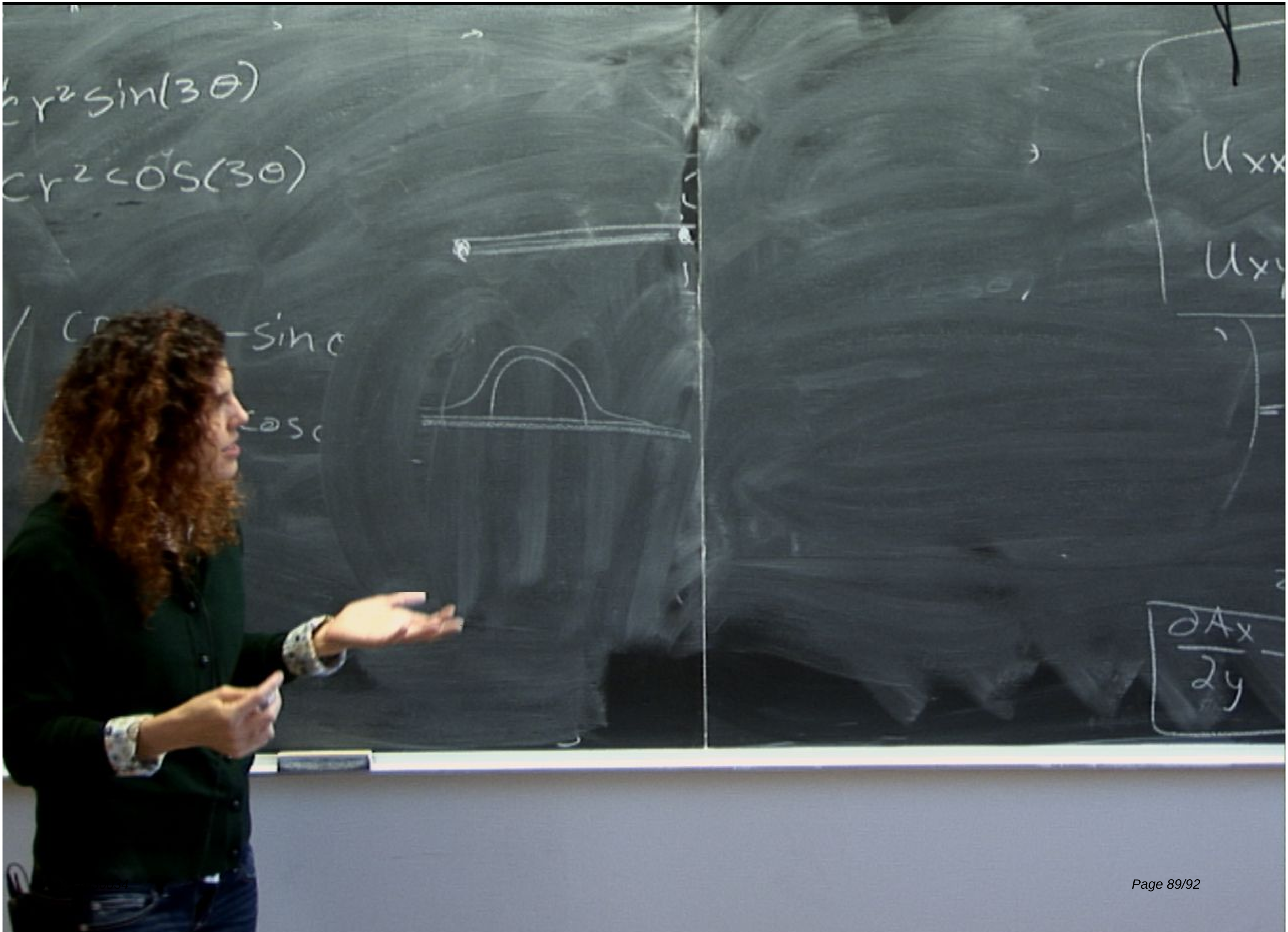


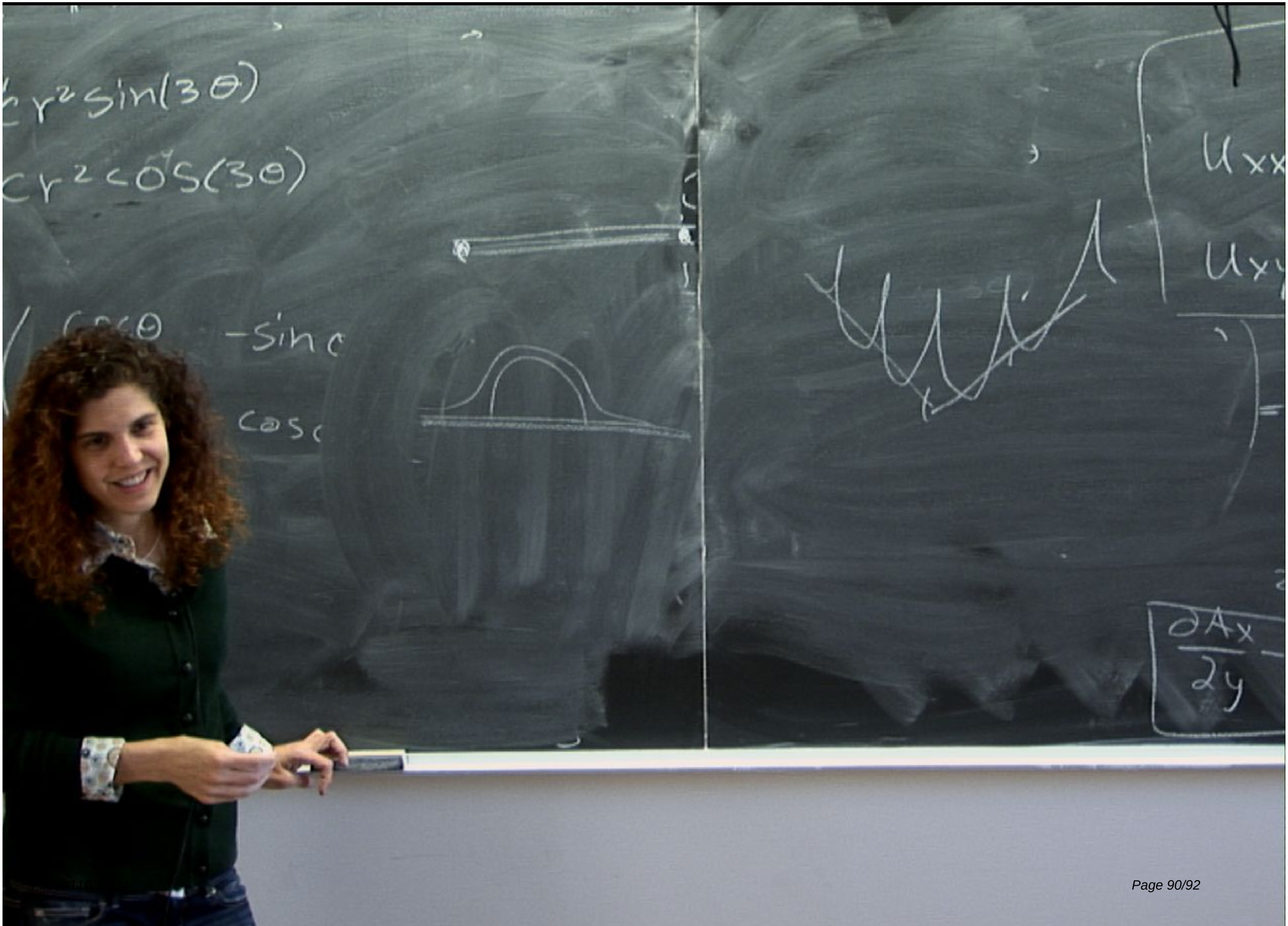
-Beff
Beff
K'
K
h.c
A

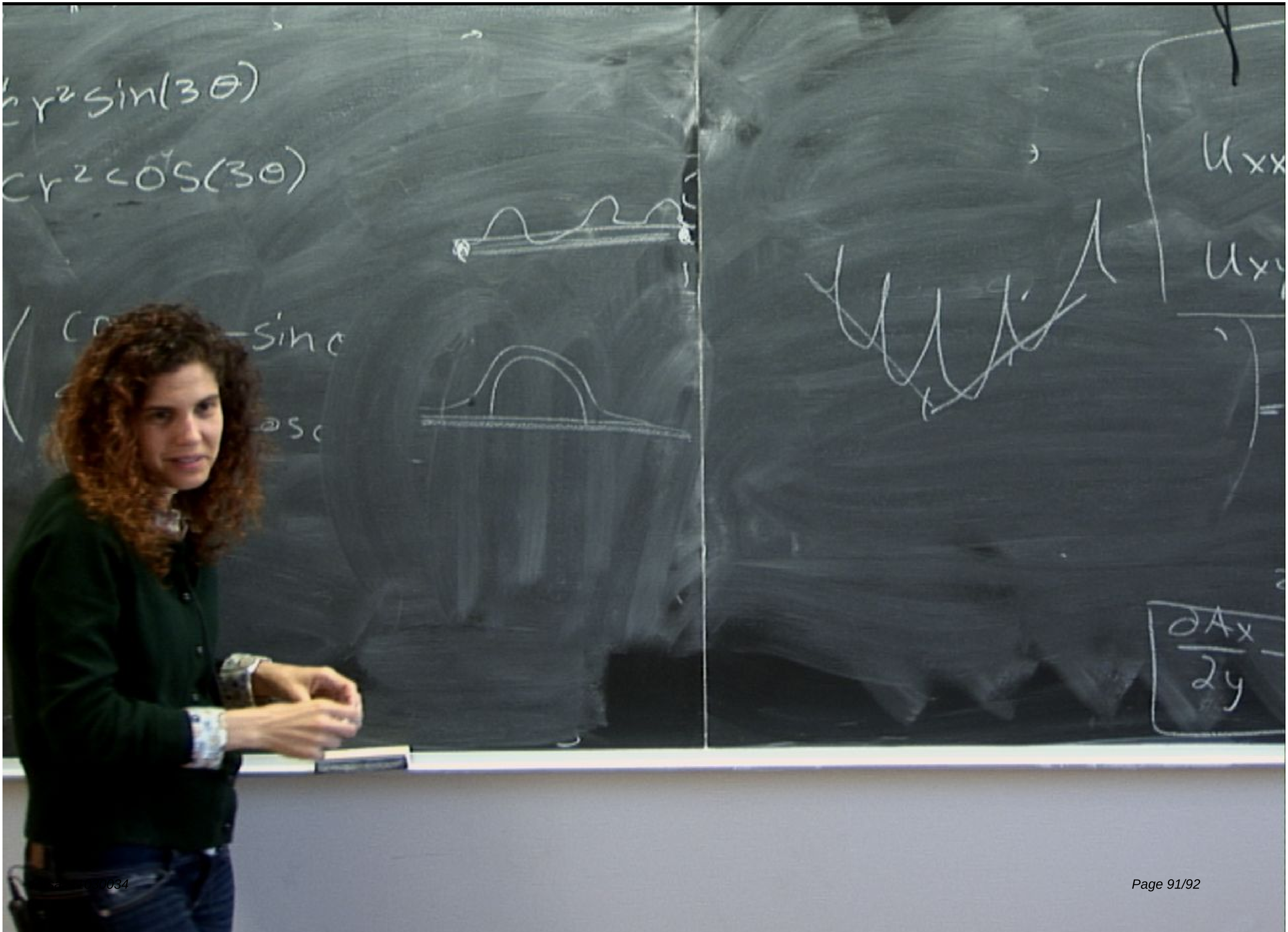

K
$-B_{eff}$
B_{eff}
K'
K
$-K_x + iK_y$
$e^{i\tau \cdot K'}$
a
τ_2
A
h.c

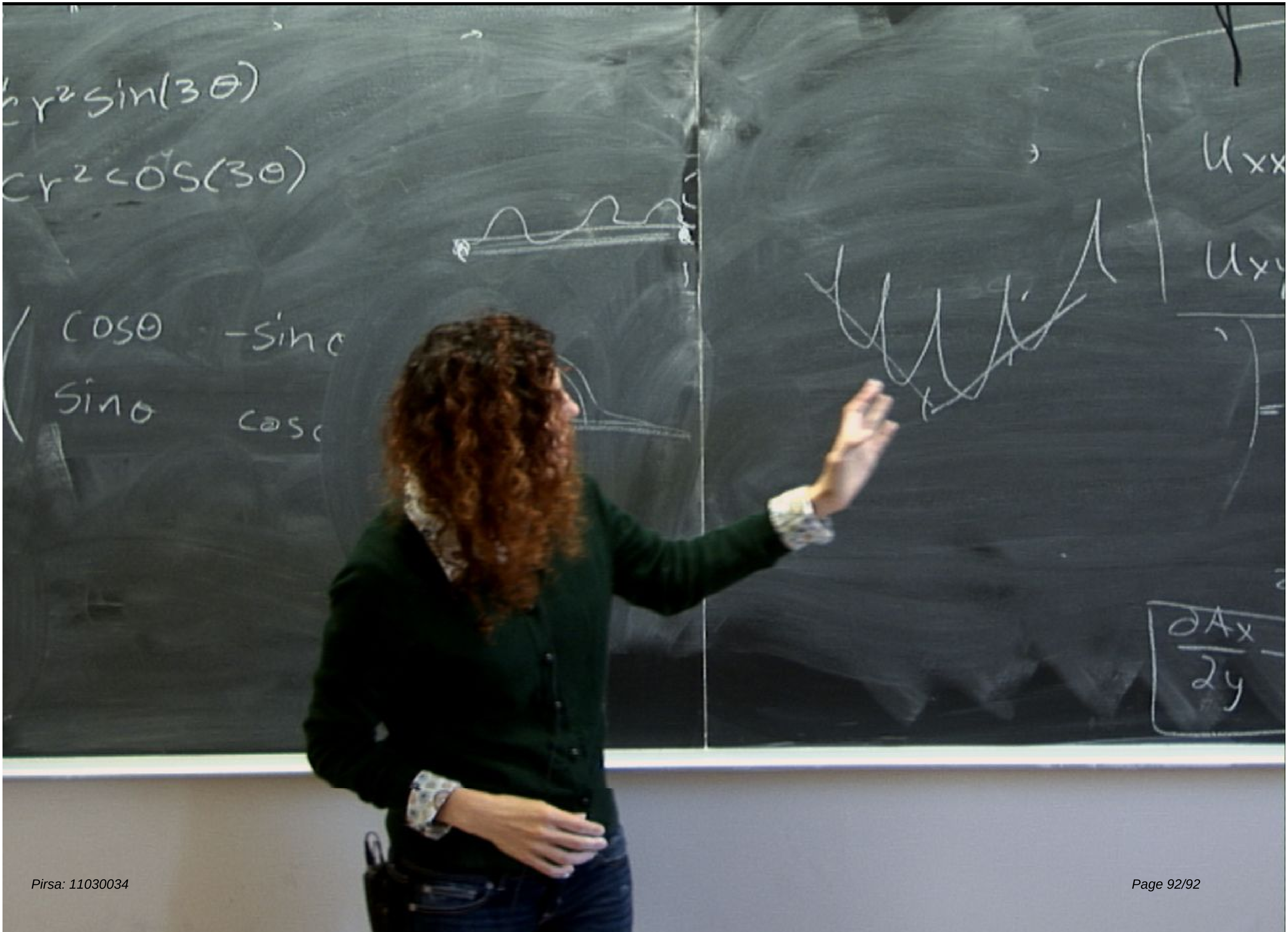


r²sin(3θ)
r²cos(3θ)
-sin
cos
u_{xx}
u_{xy}
∂Ax / ∂y


r²sin(3θ)
cr²cos(3θ)
-sin
cos
Uxx
Uxy
∂Ax
∂y


r²sin(3θ)
cr²cos(3θ)
-sin
cos
∂Ax
∂y


r²sin(3θ)
cr²cos(3θ)
sin
Uxx
Uxy
∂Ax
∂y


r²sin(3θ)
cr²cos(3θ)
cosθ
-sin
sinθ
cos
uxx
uxy
∂Ax
∂y