Title: Emergence and Effective Field Theories in Gravitational Physics

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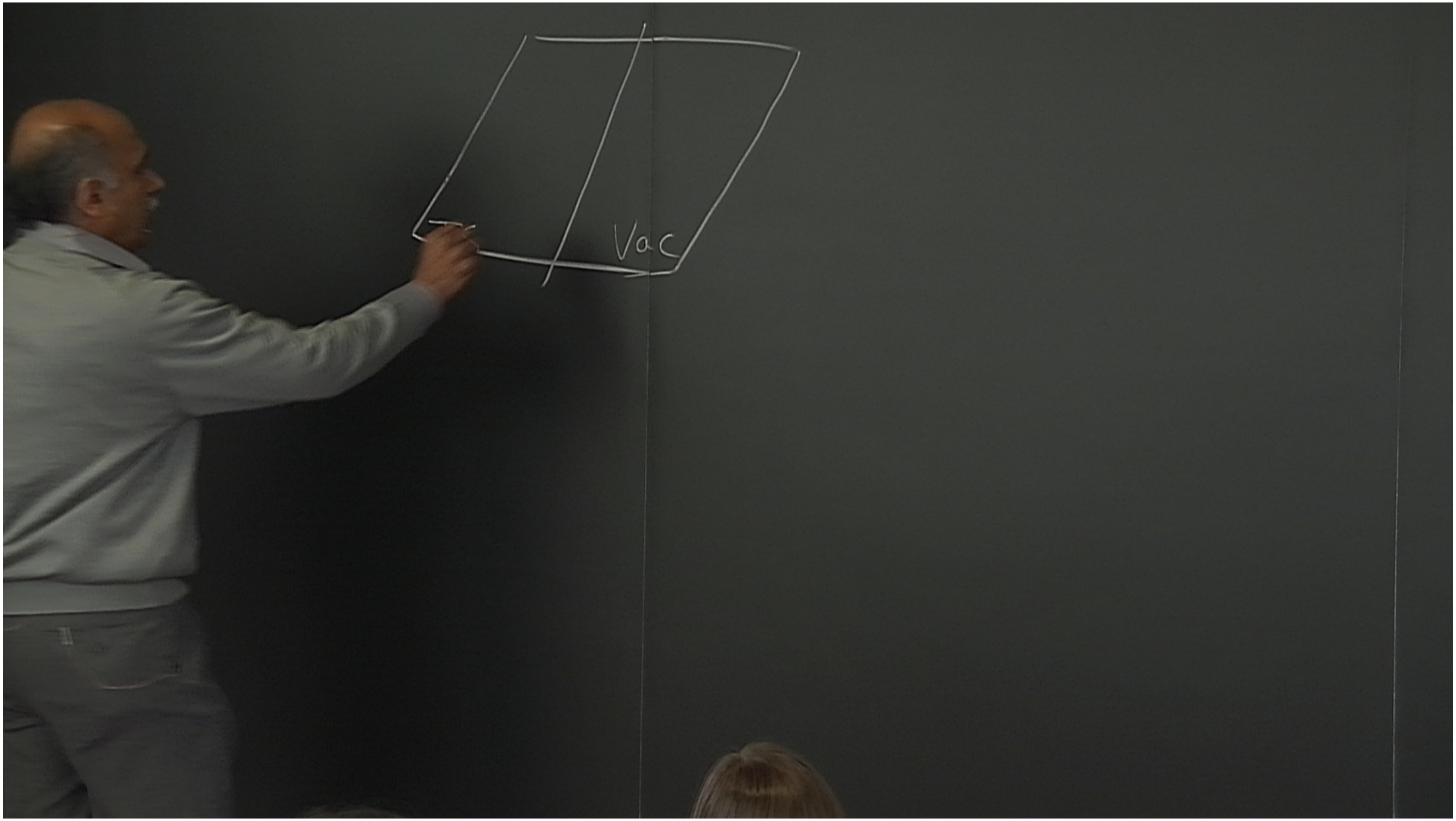
Abstract: This paper has two aims. The first is to improve upon the diverse and often muddled philosophical characterizations of emergence by articulating reasonably precise necessary and sufficient conditions for a phenomenon to count as emergent in physics. Central to this account of emergence is the idea that emergent phenomena cannot be explained reductively. The second aim of the paper is to apply this account to the use of effective field theories in gravitational physics. Effective field theories have recently been applied to model the inspiral trajectories (and other features) of two compact, massive objects orbiting each other, with excellent predictive success. The calculational machinery has been ported from quantum field theory, but the physical interpretation is significantly different. The paper concludes that this application of effective field theories to gravitational physics is clearly not a case of emergence.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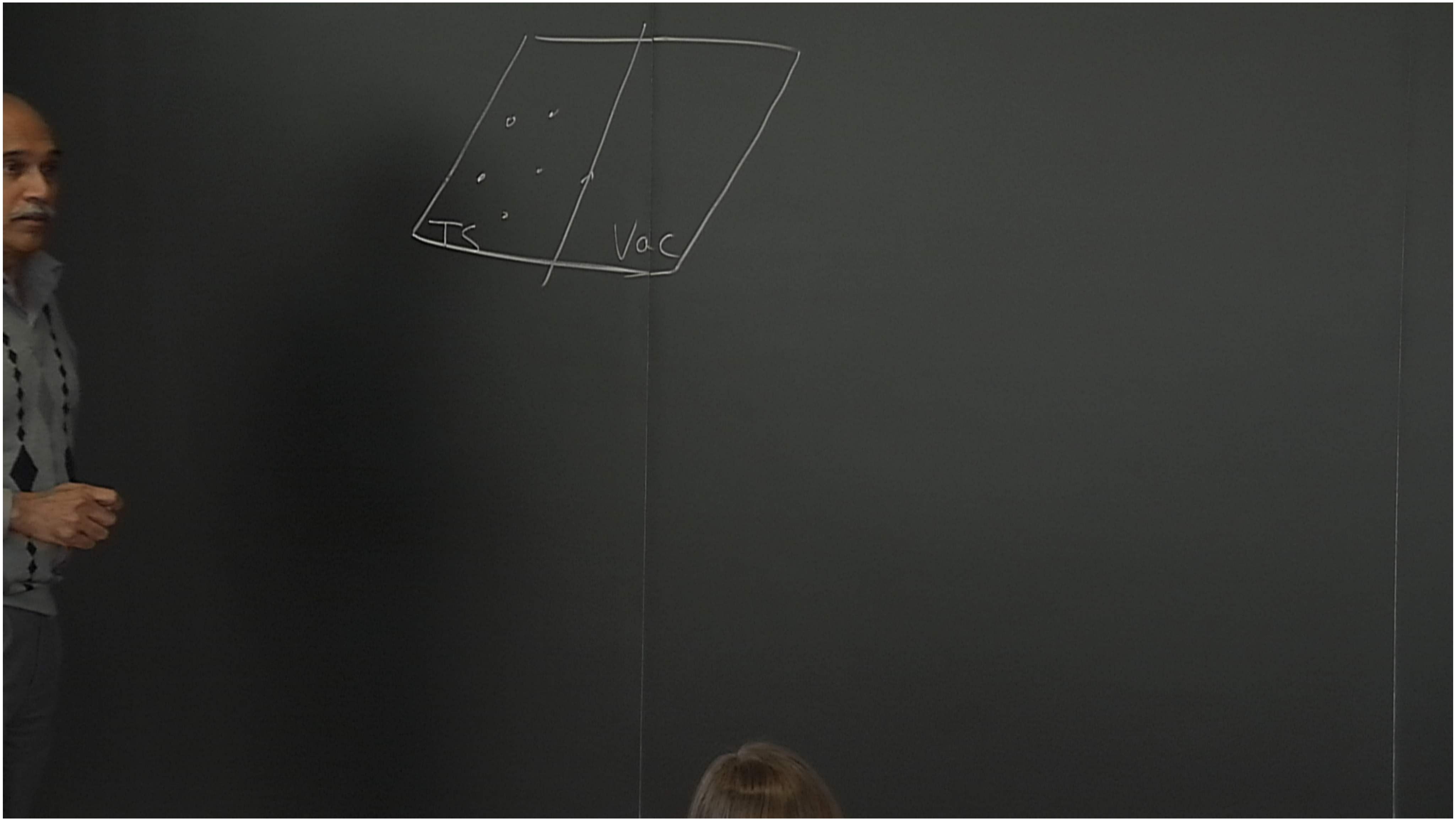
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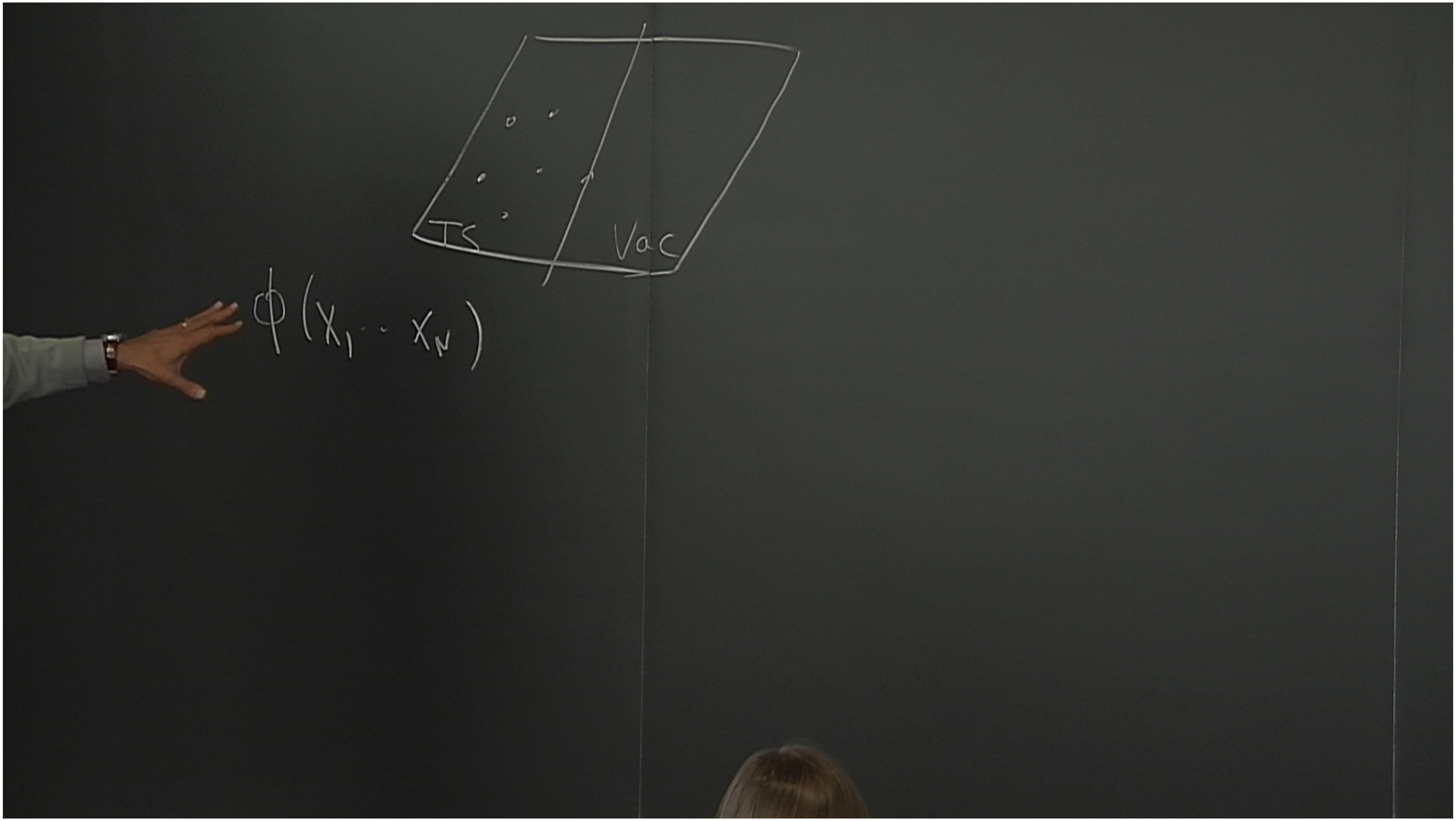
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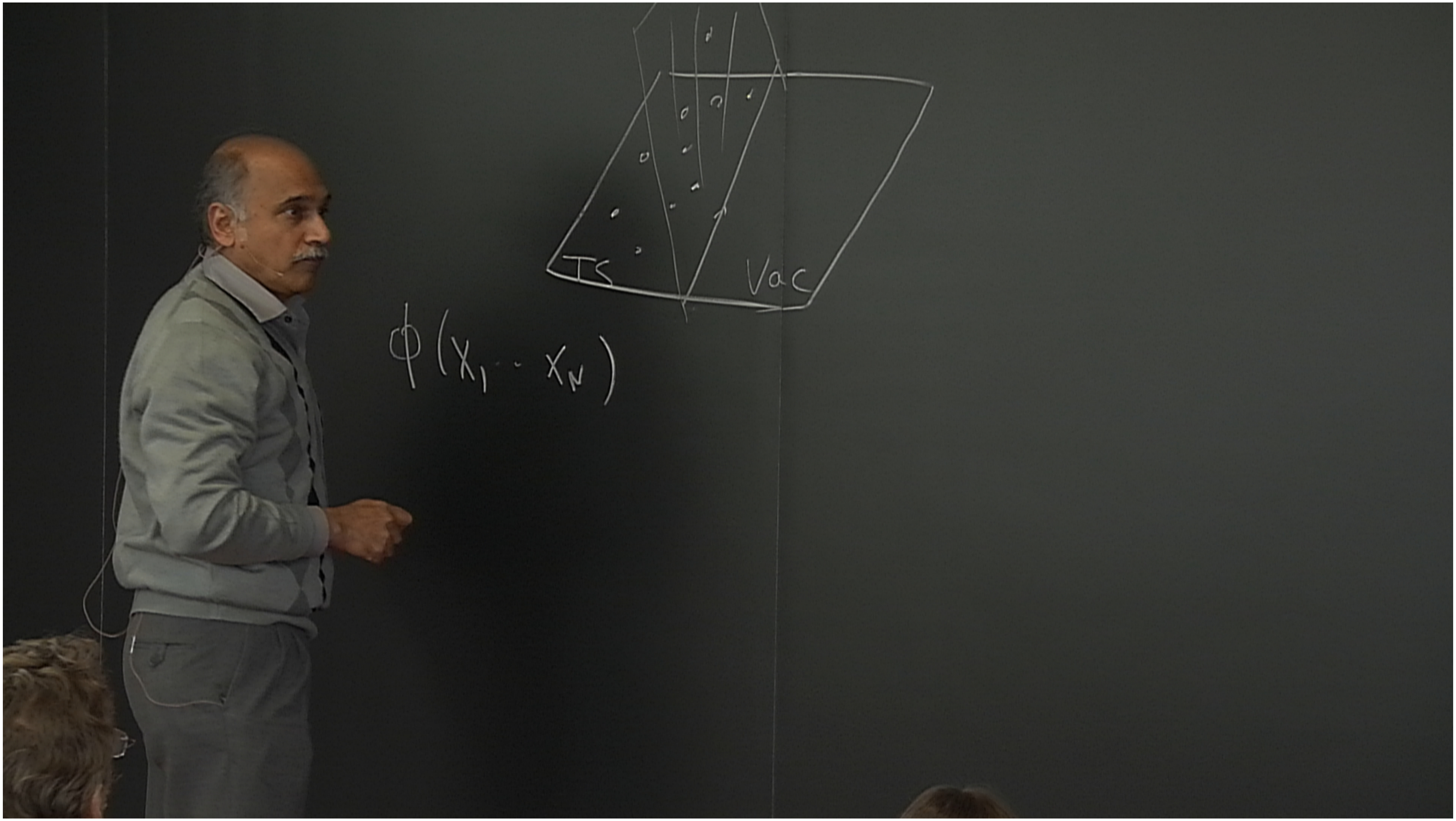
ϕ(x1 .. xN)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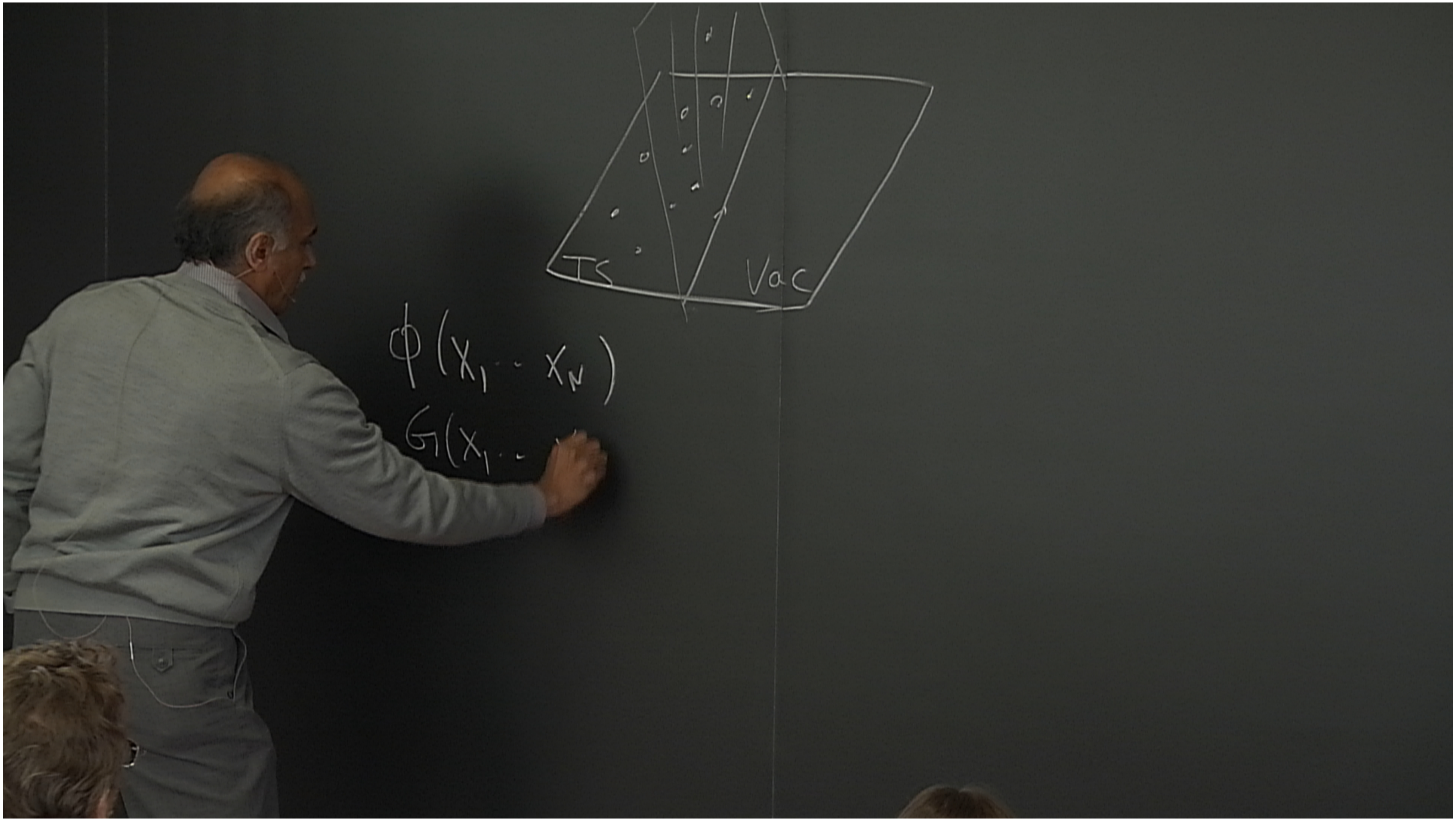
φ(x1 .. xN)



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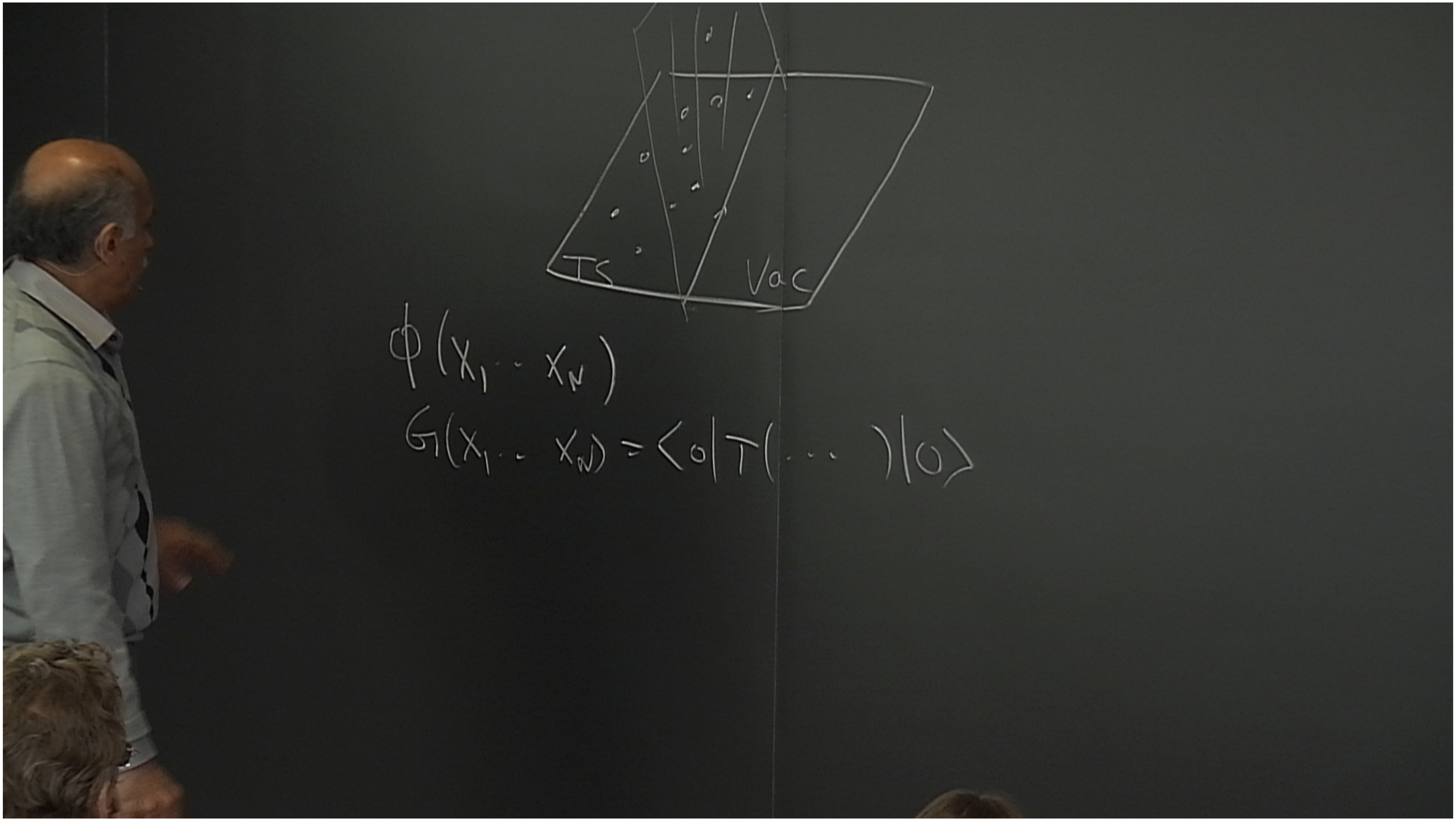
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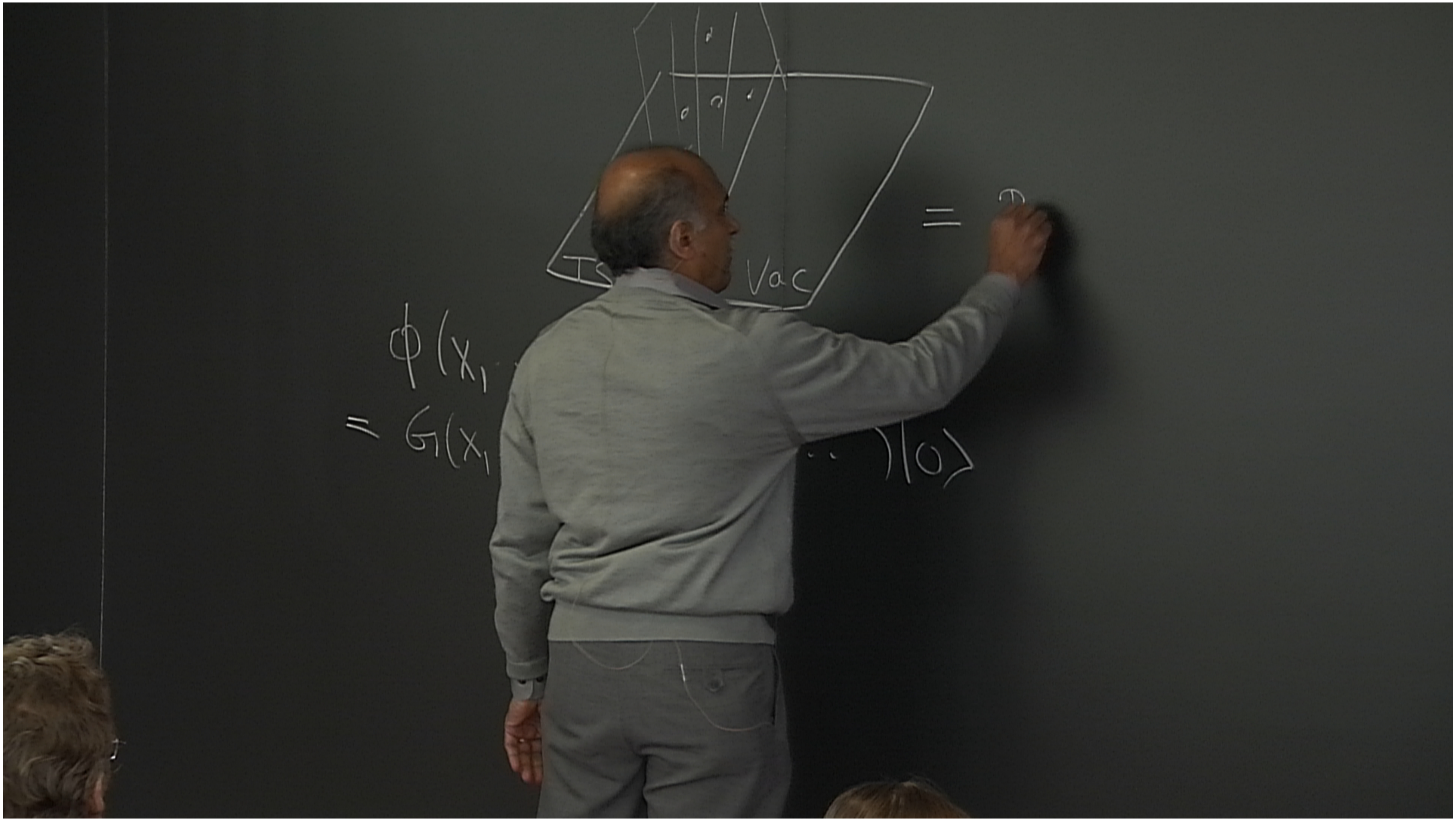
φ(x1 ... xN)
G(x1 ... xN) = <0|T(...)|0>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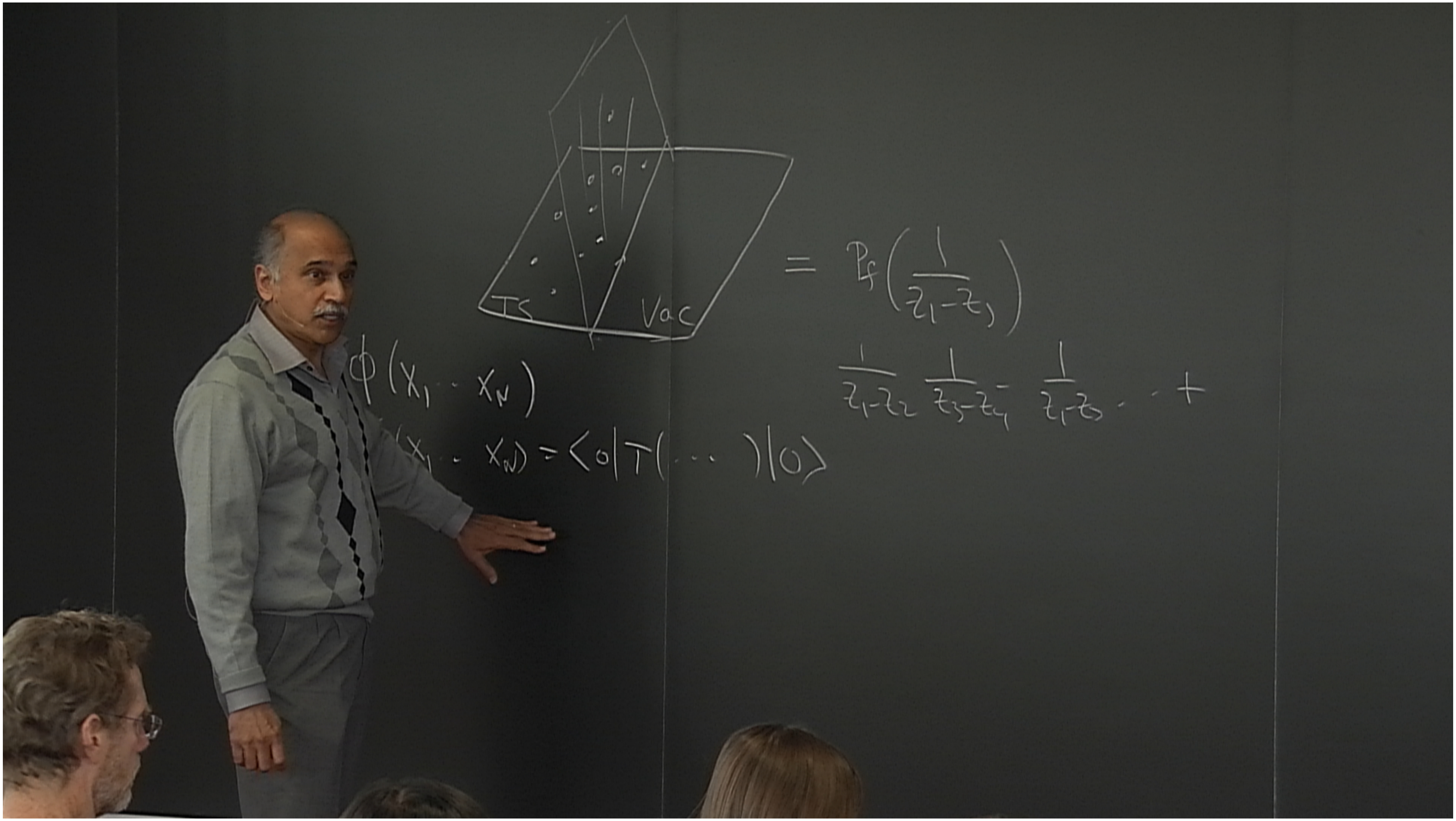
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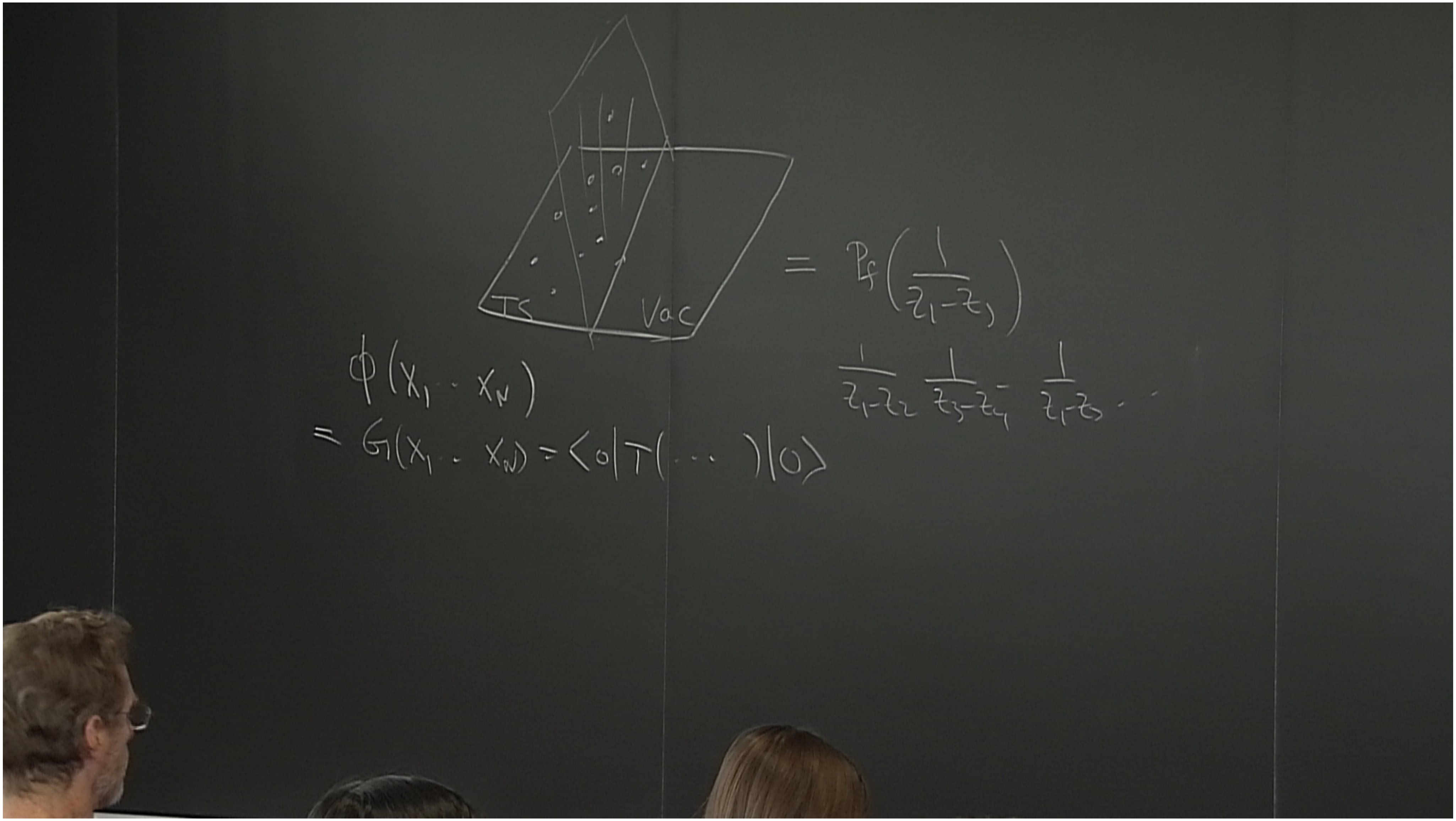
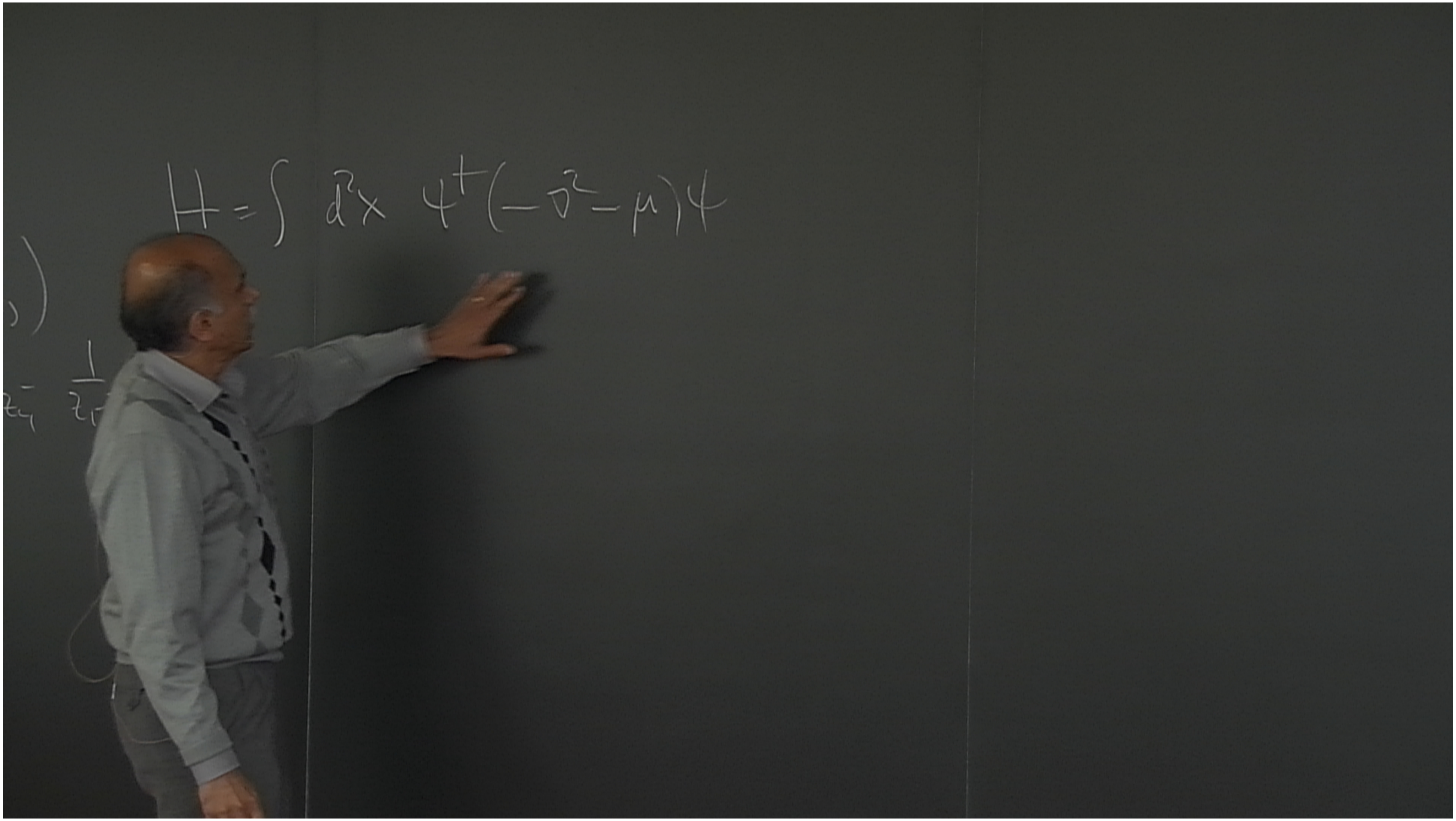
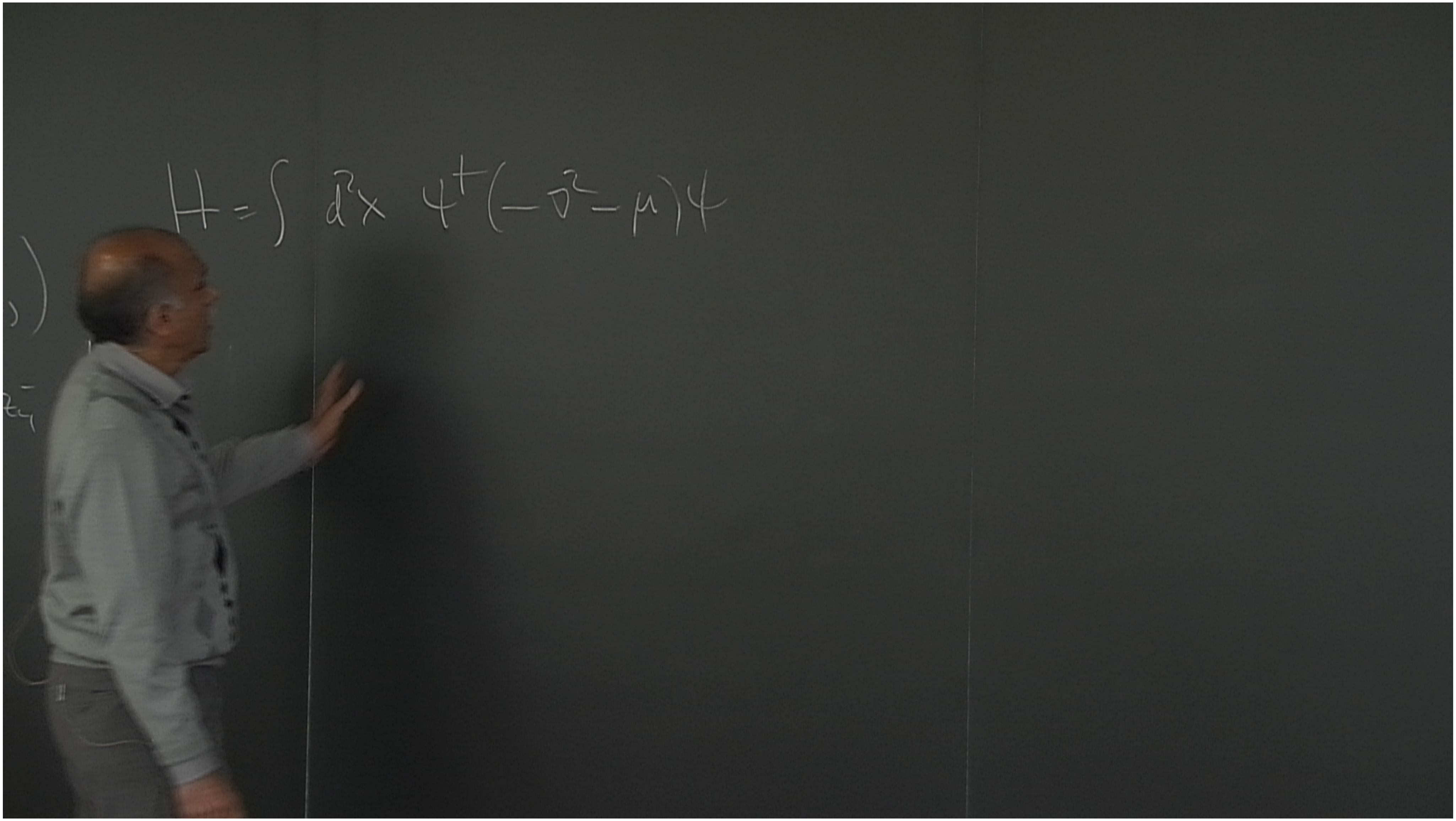
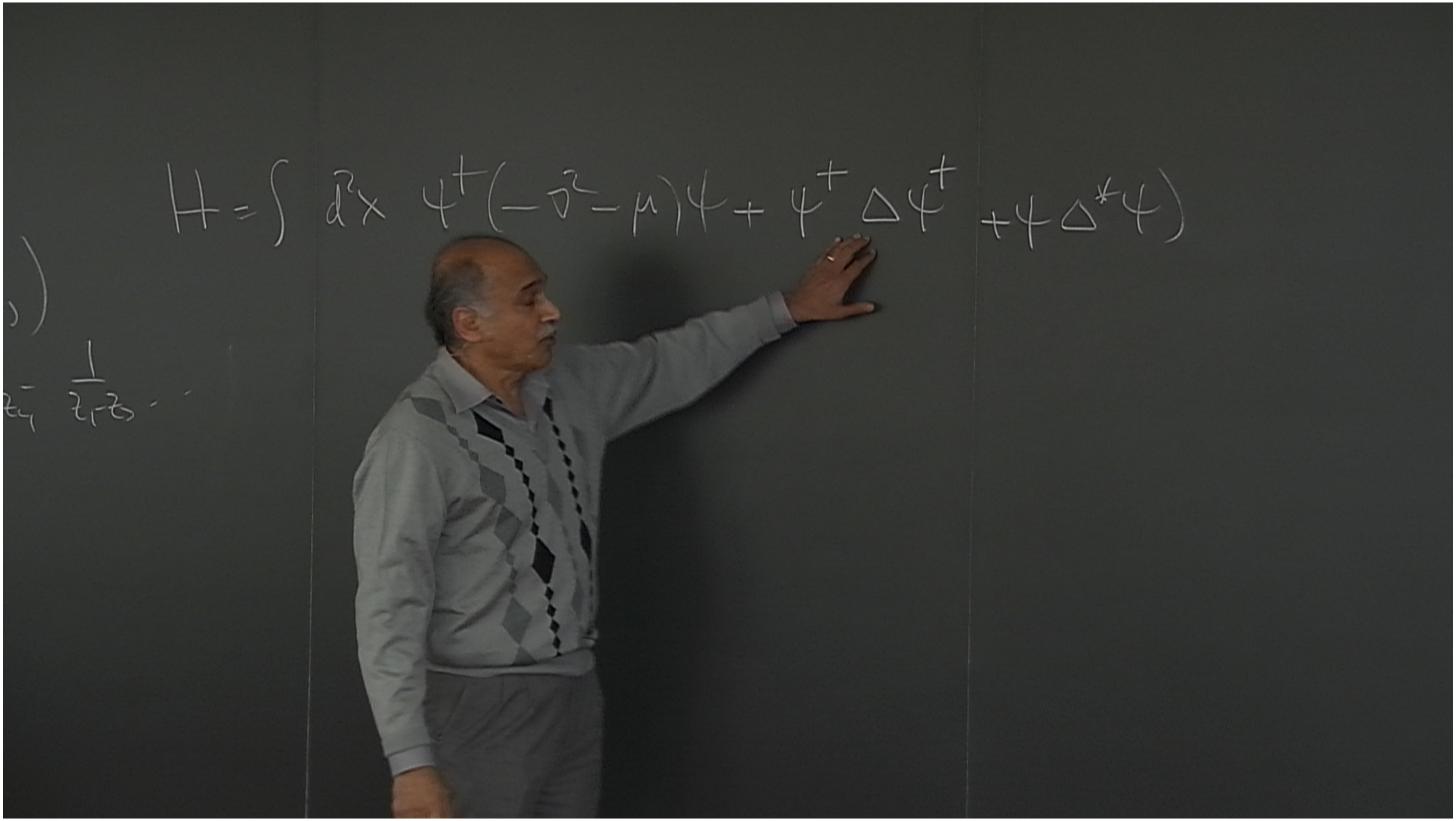
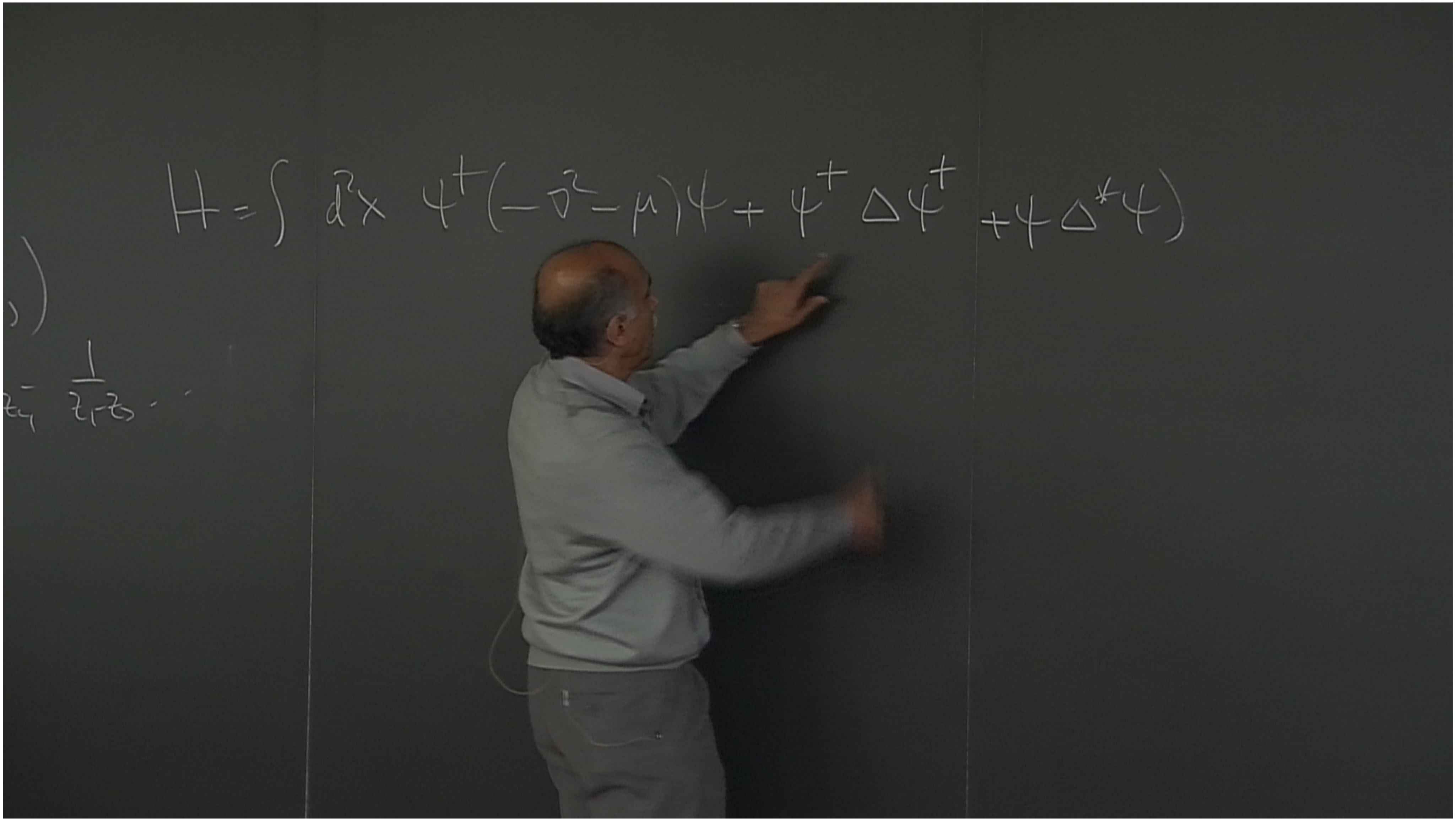
Vac
$= Pf\left(\frac{1}{z_1 - z_j}\right)$
$\frac{1}{z_1-z_2}\frac{1}{z_3-z_4} - \frac{1}{z_1-z_3}\cdots +$
$\phi(x_1 \cdots x_N)$
$(x_1 \cdots x_N) = \langle 0|T(\cdots)|0\rangle$

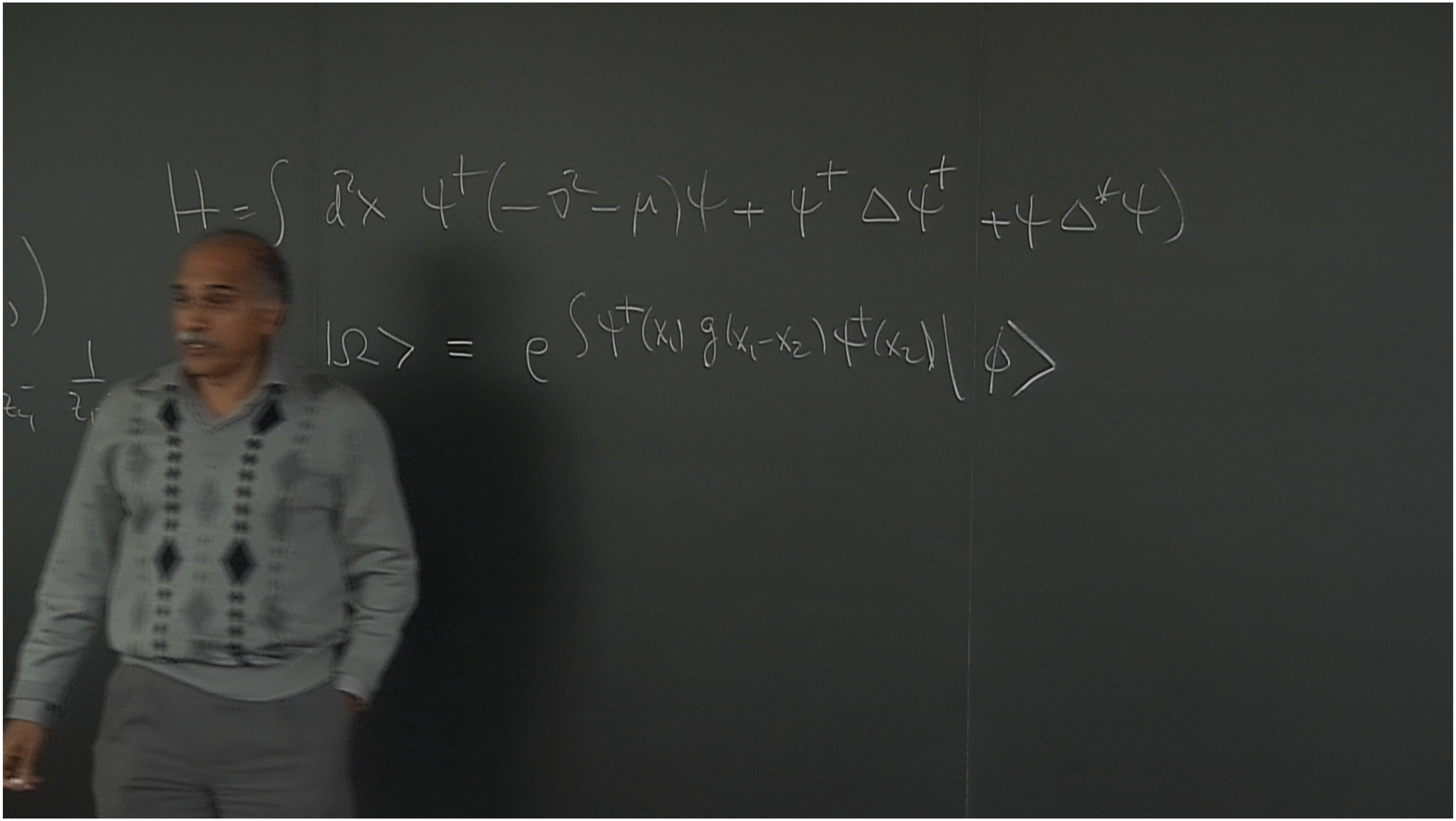

TS
Vac
= Pf(1 / (z_i - z_j))
1/(z1-z2) 1/(z3-z4) - 1/(z1-z3) . . .
φ(x1 .. xN)
= G(x1 .. xN) = <0|T(. . .)|0>

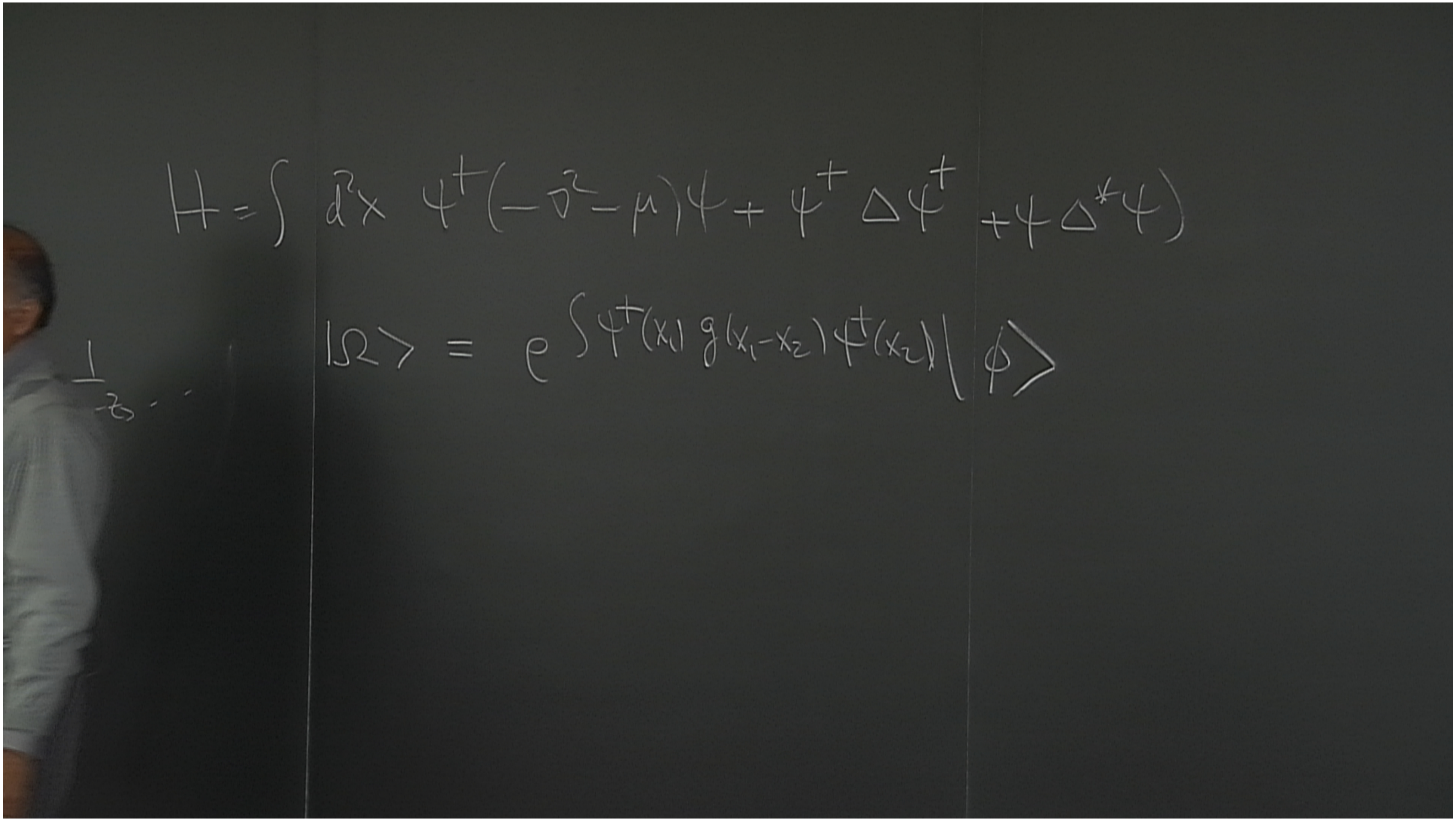

$H = \int d^2x \; \psi^\dagger(-\nabla^2 - \mu)\psi$

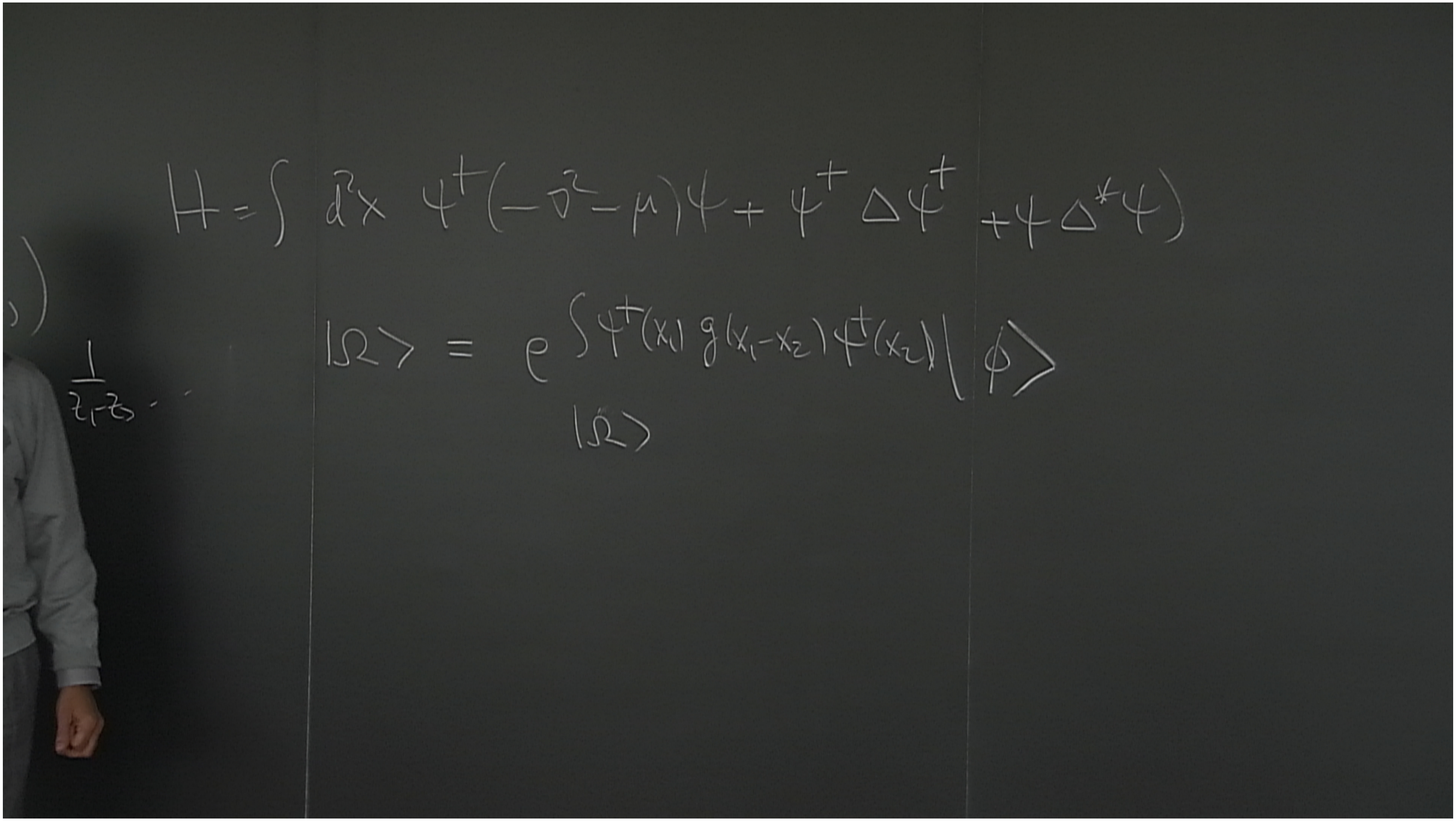

$H = \int d^2x \, \psi^\dagger (-\nabla^2 - \mu) \psi$

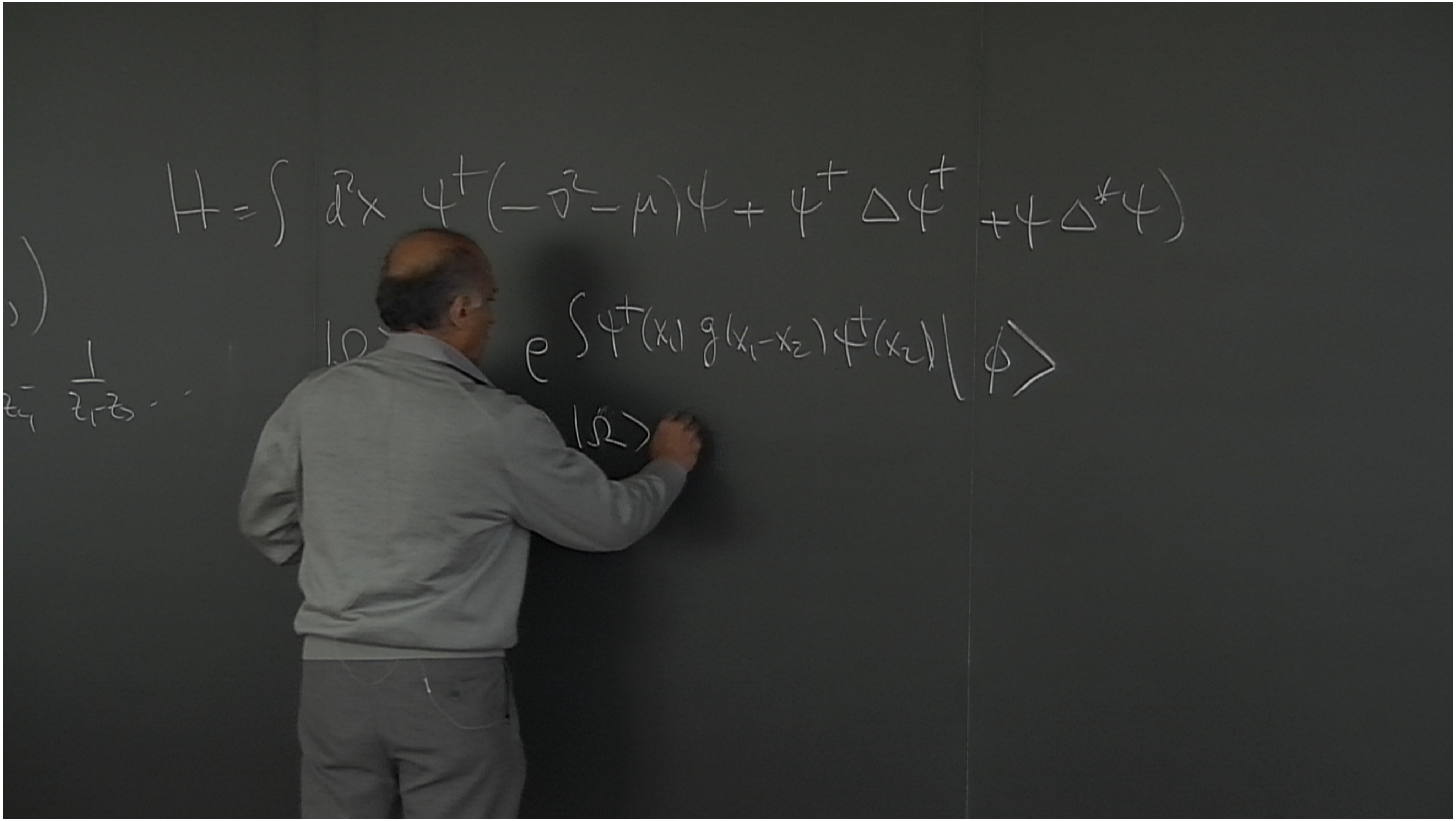

H = ∫ d²x ψ†(−∇² − μ)ψ + ψ† Δ ψ† + ψ Δ* ψ)

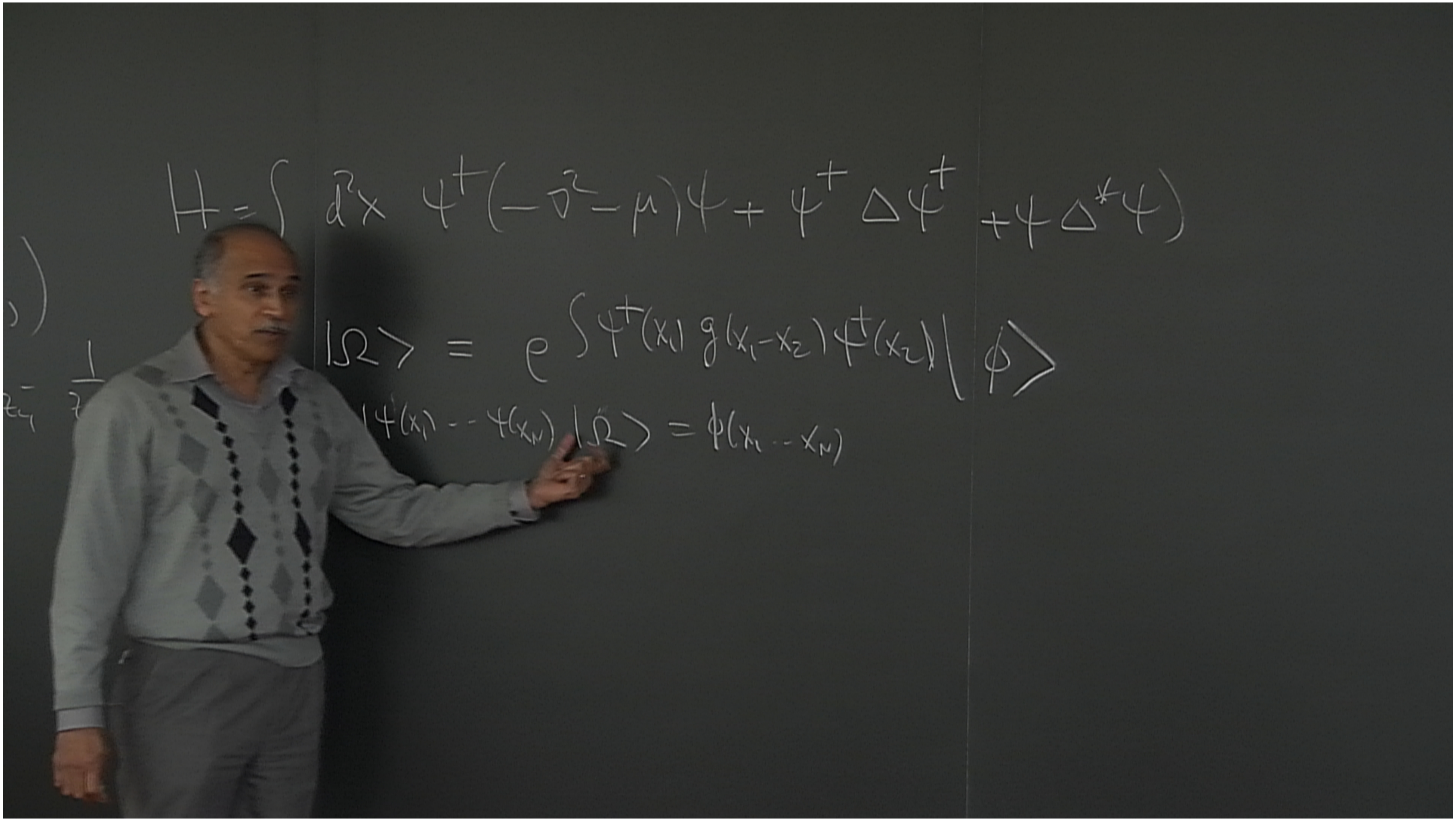

$H = \int d^2x \; \psi^\dagger(-\nabla^2 - \mu)\psi + \psi^\dagger \Delta \psi^\dagger + \psi \Delta^* \psi)$

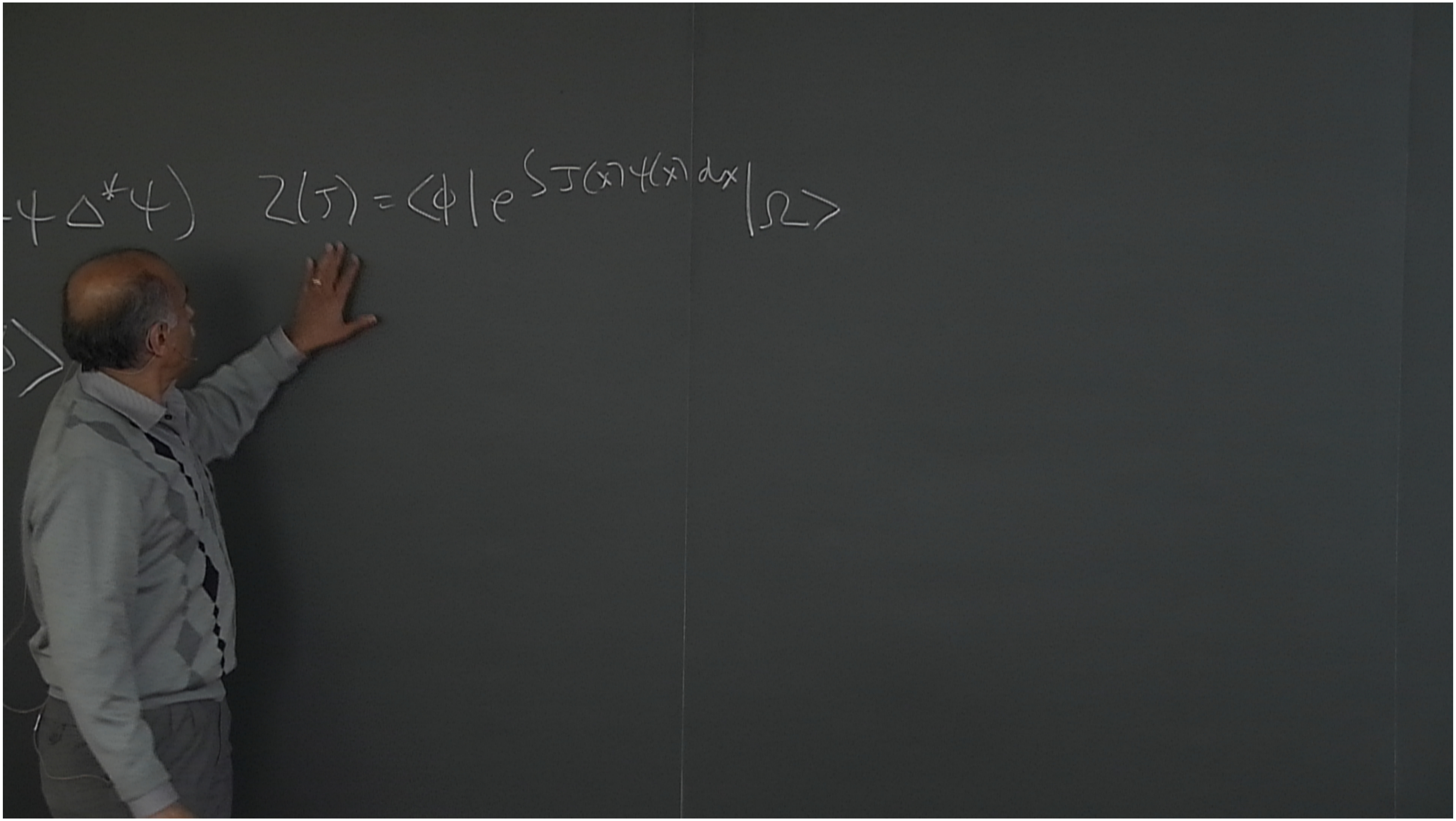

$H = \int d^2x\, \psi^\dagger(-\nabla^2 - \mu)\psi + \psi^\dagger \Delta \psi^\dagger + \psi \Delta^* \psi)$
$|\Omega\rangle = e^{\int \psi^\dagger(x_1)\, g(x_1 - x_2)\, \psi^\dagger(x_2)}|\phi\rangle$


$H = \int d^2x\, \psi^\dagger(-\nabla^2 - \mu)\psi + \psi^\dagger \Delta \psi^\dagger + \psi \Delta^* \psi)$
$|\Omega\rangle = e^{\int \psi^\dagger(x_1)\, g(x_1 - x_2)\, \psi^\dagger(x_2)} |\phi\rangle$


$H = \int d^2x \; \psi^\dagger(-\nabla^2 - \mu)\psi + \psi^\dagger \Delta \psi^\dagger + \psi \Delta^* \psi)$
$|\Omega\rangle = e^{\int \psi^\dagger(x_1)\, g(x_1 - x_2)\, \psi^\dagger(x_2)} |\phi\rangle$
$|\Omega\rangle$
$\frac{1}{z_1 - z_2} \cdots$

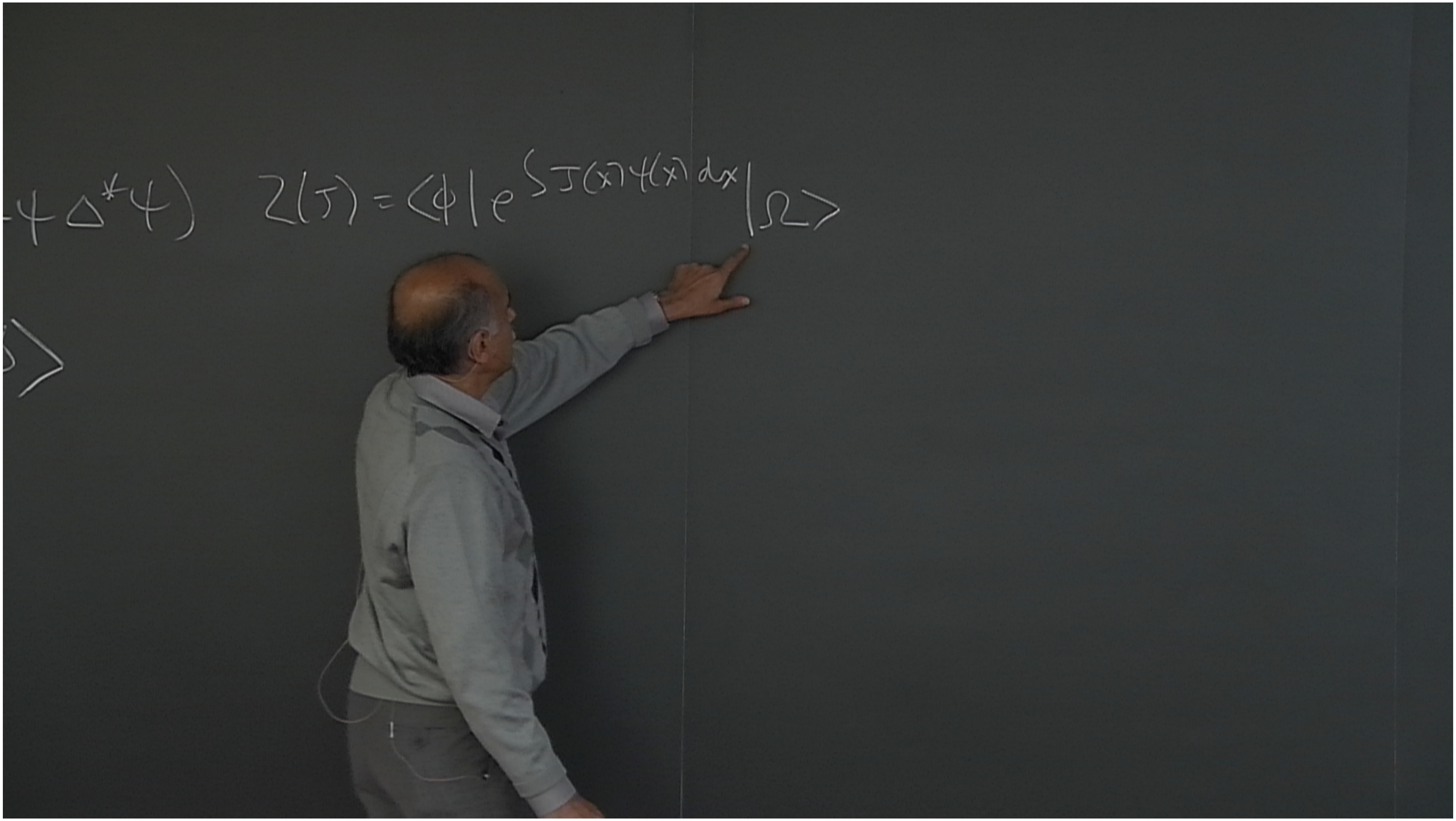

H = ∫ d²x ψ†(−∇² − μ)ψ + ψ† Δ ψ† + ψ Δ* ψ)
e ∫ψ†(x₁) g(x₁−x₂) ψ†(x₂) | φ>

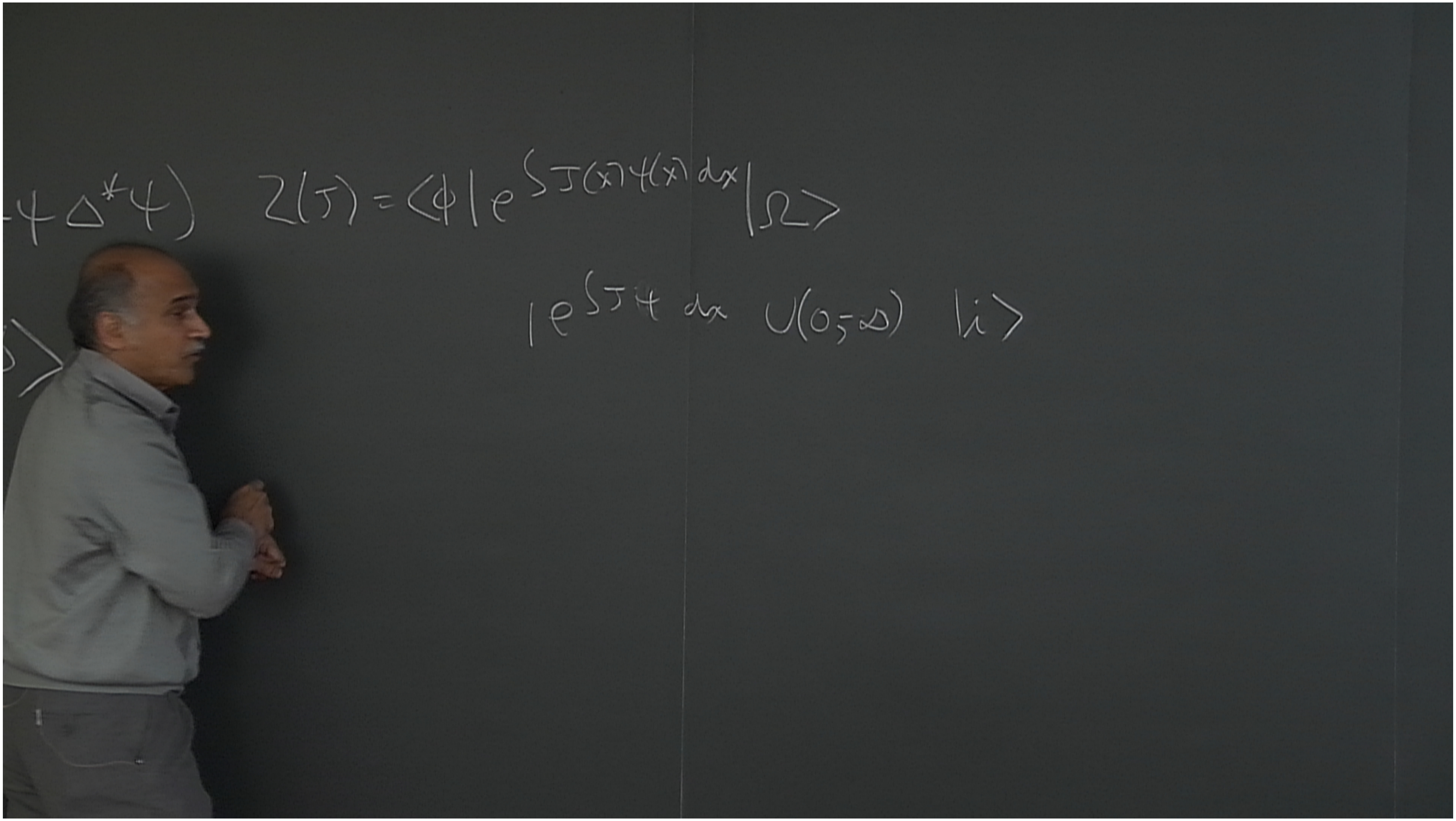

H = ∫ d²x ψ†(−∇²−μ)ψ + ψ† Δ ψ† + ψ Δ* ψ)
|Ω> = e^∫ψ†(x₁) g(x₁−x₂) ψ†(x₂) |φ>
ψ(x₁) .. ψ(x_N) |Ω> = φ(x₁ .. x_N)

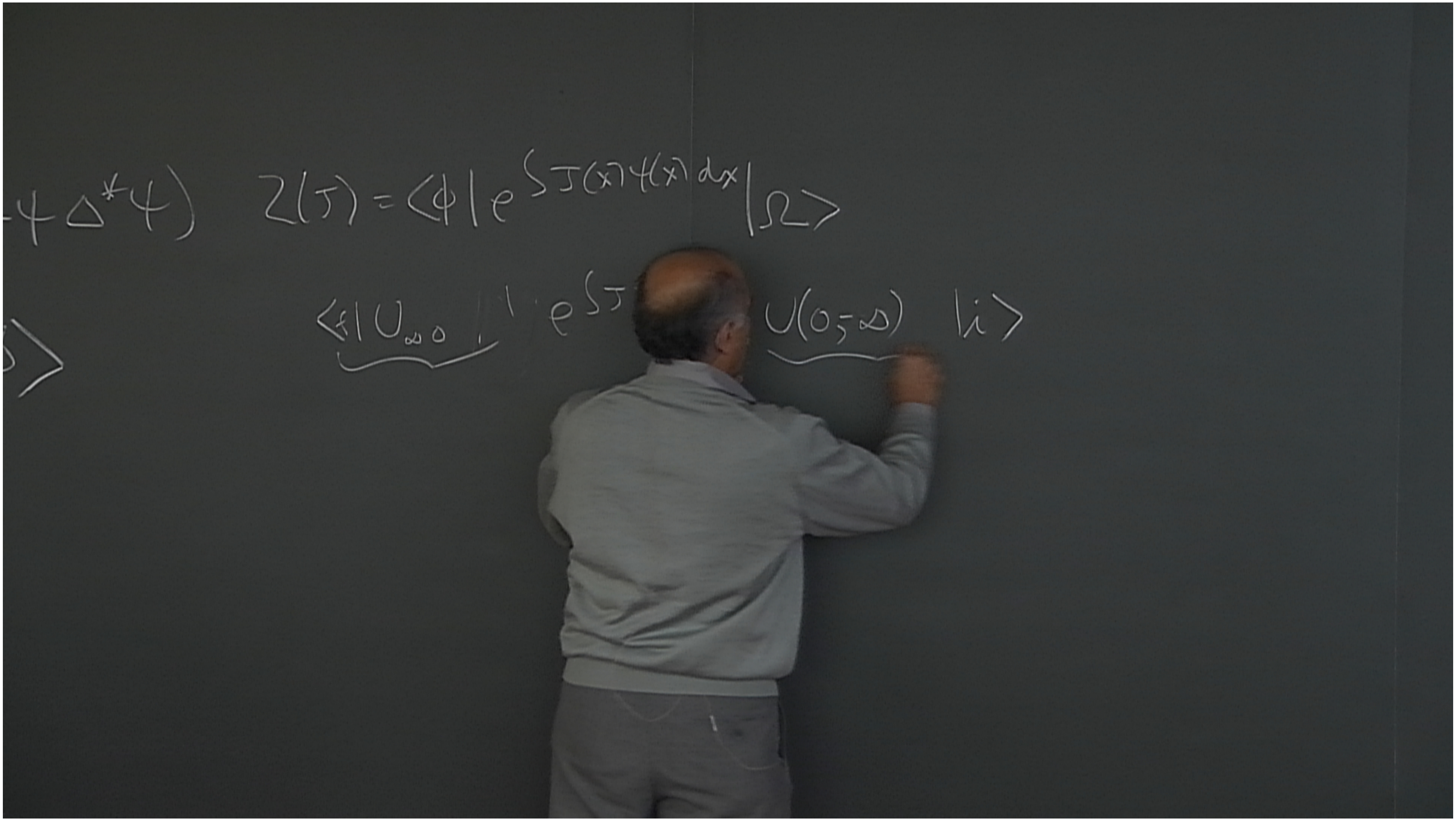

$\psi + \Delta^{*}\psi)$
$Z(J) = \langle \phi | e^{\int J(x)\psi(x)\,dx} | \Omega \rangle$

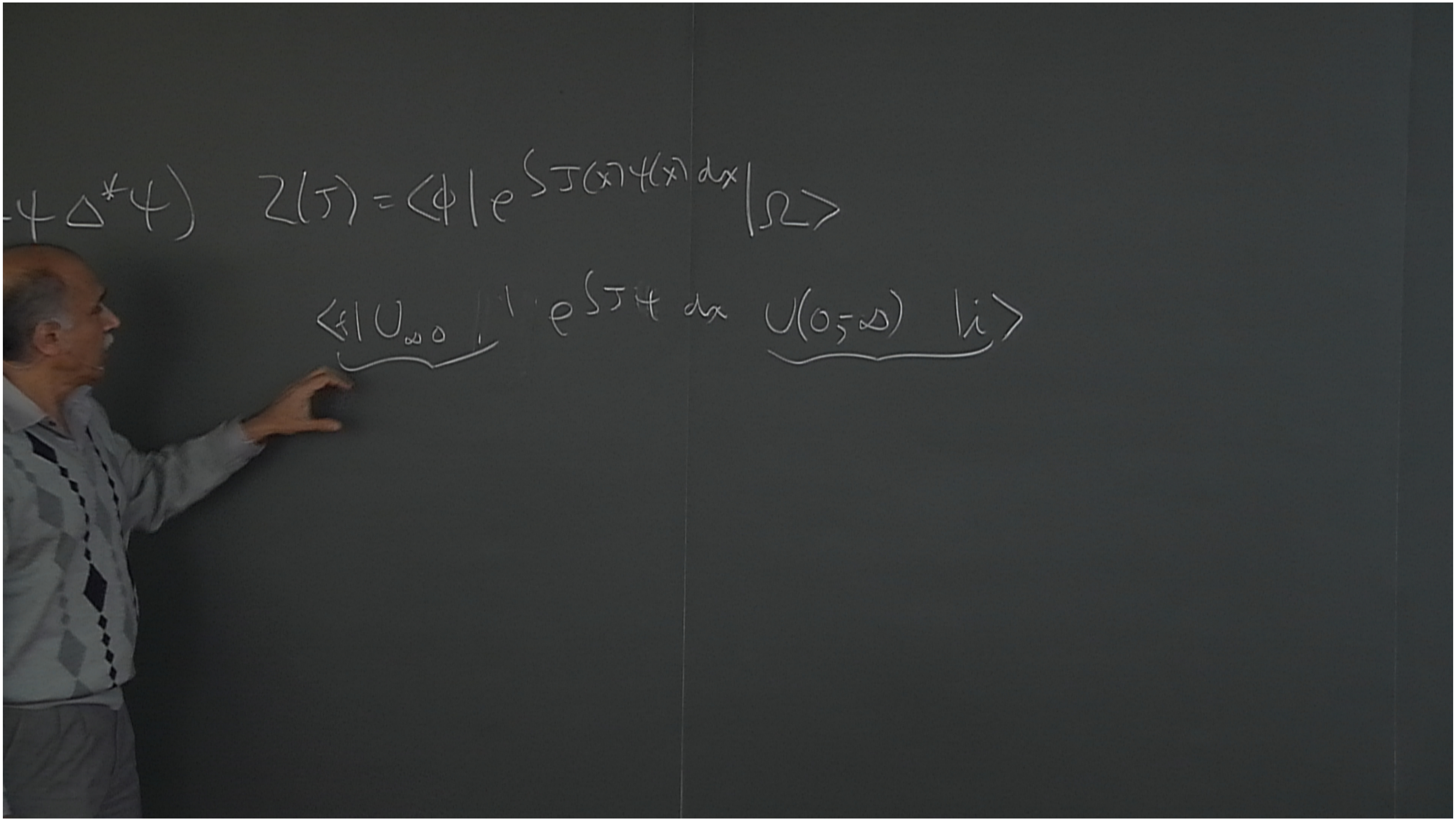
$-\psi + \Delta^* \psi)$ $\quad Z(J) = \langle \phi | e^{\int J(x)\psi(x)\,dx} | \Omega \rangle$

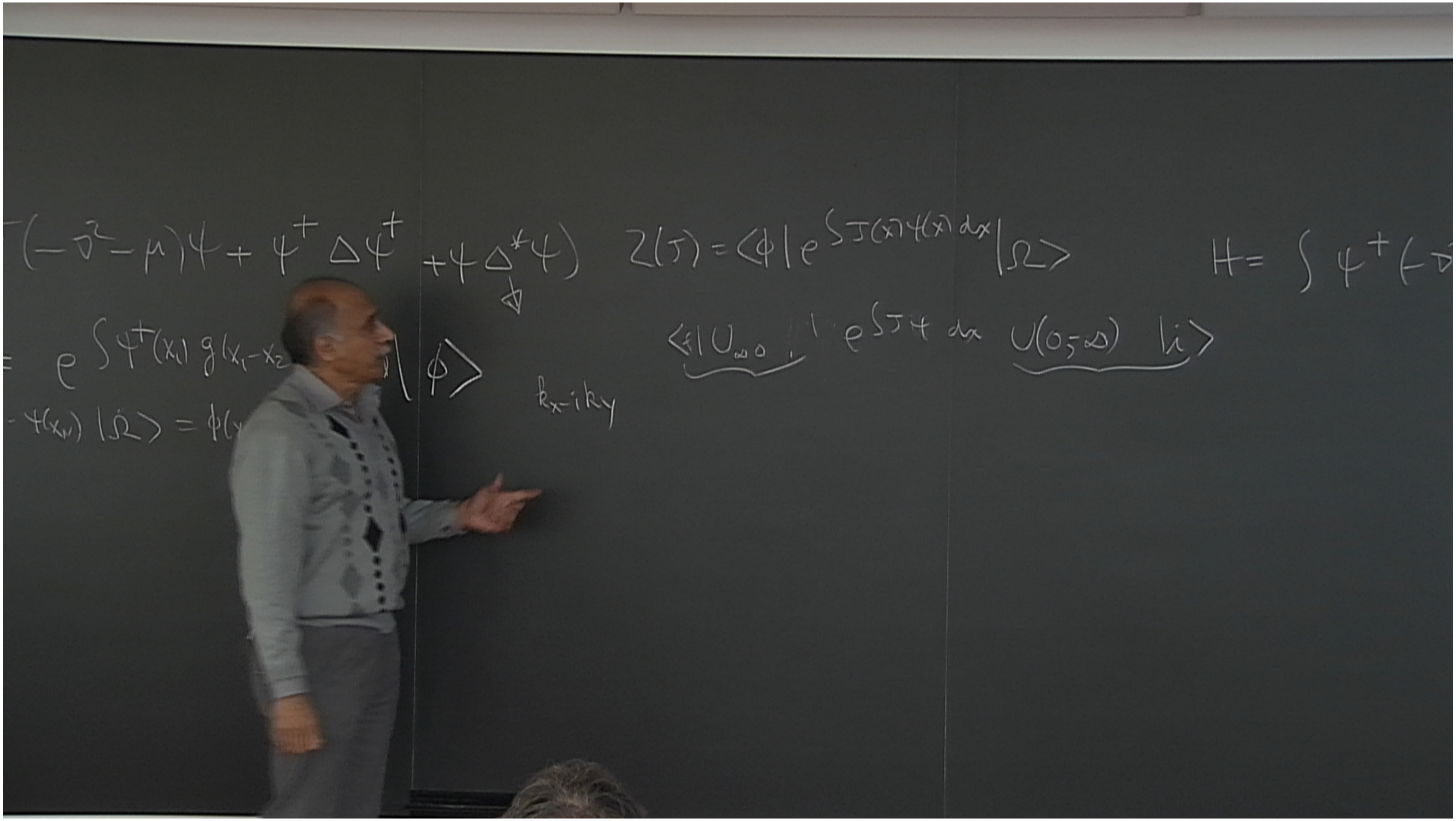
$\rangle$

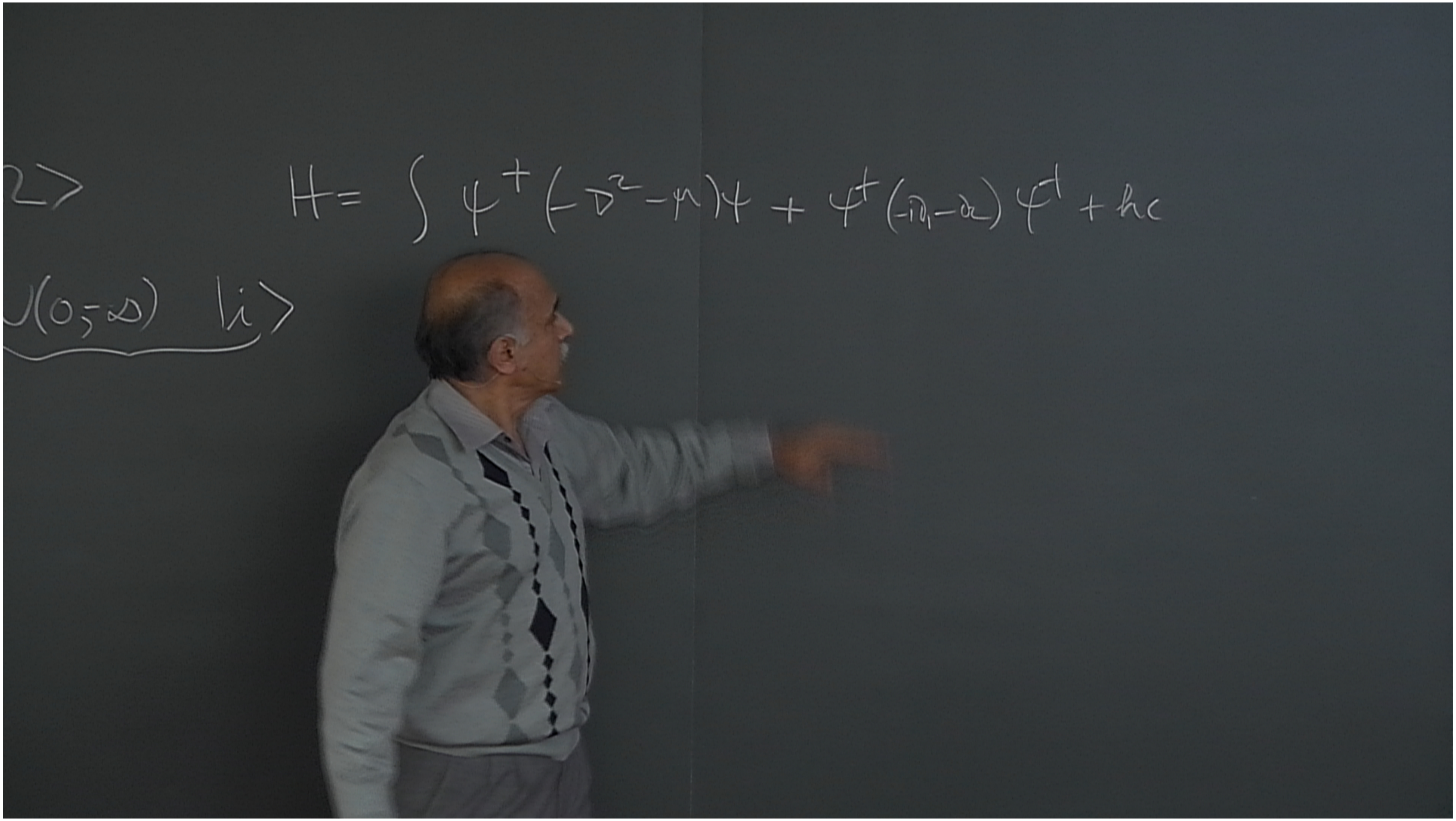

Z(J) = <φ| e∫J(x)ψ(x)dx |Ω>

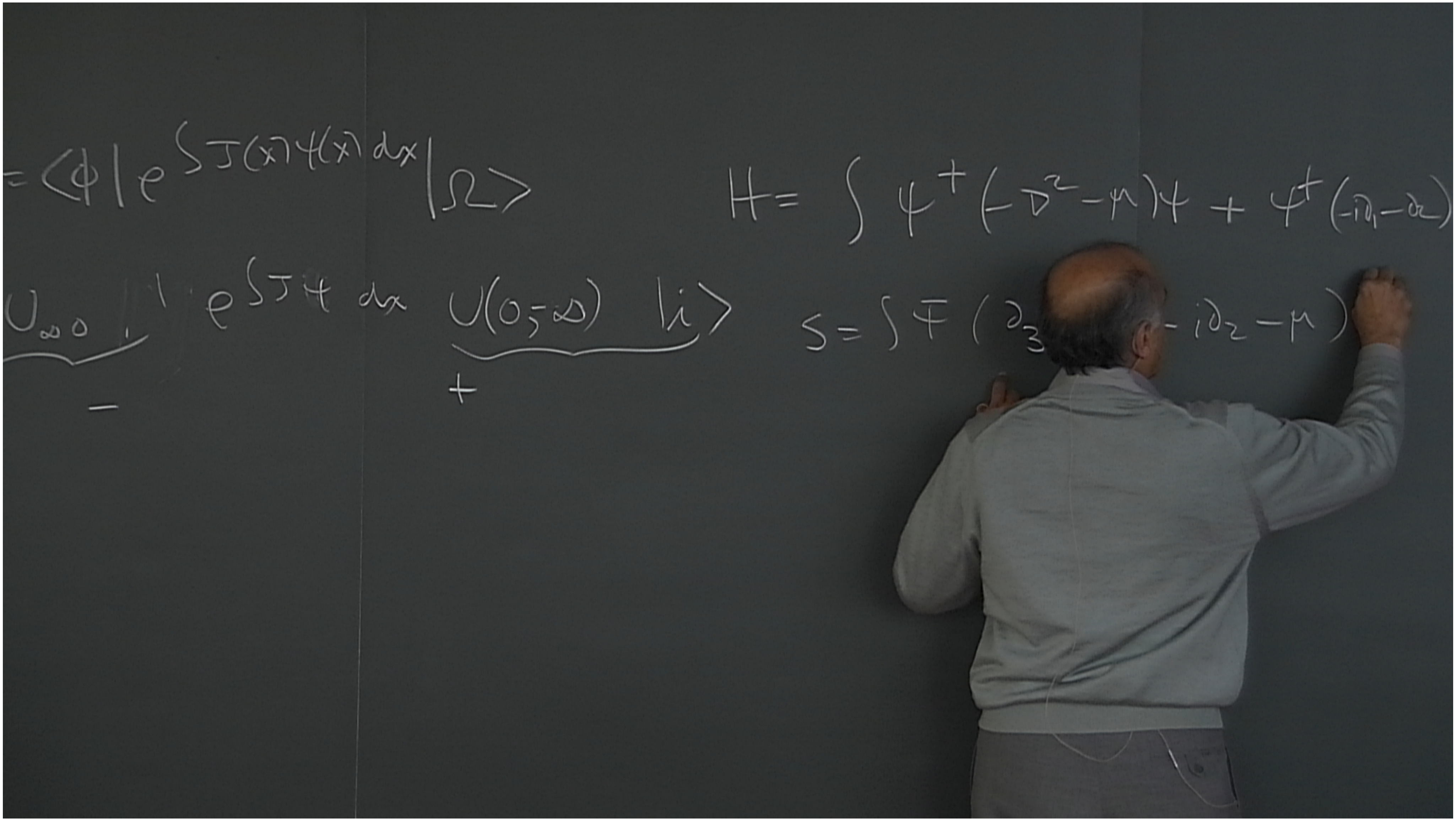

Z(J) = ⟨φ| e^{∫J(x)φ(x) dx} |Ω⟩
| e^{∫Jφ dx} U(0,-∞) |i⟩

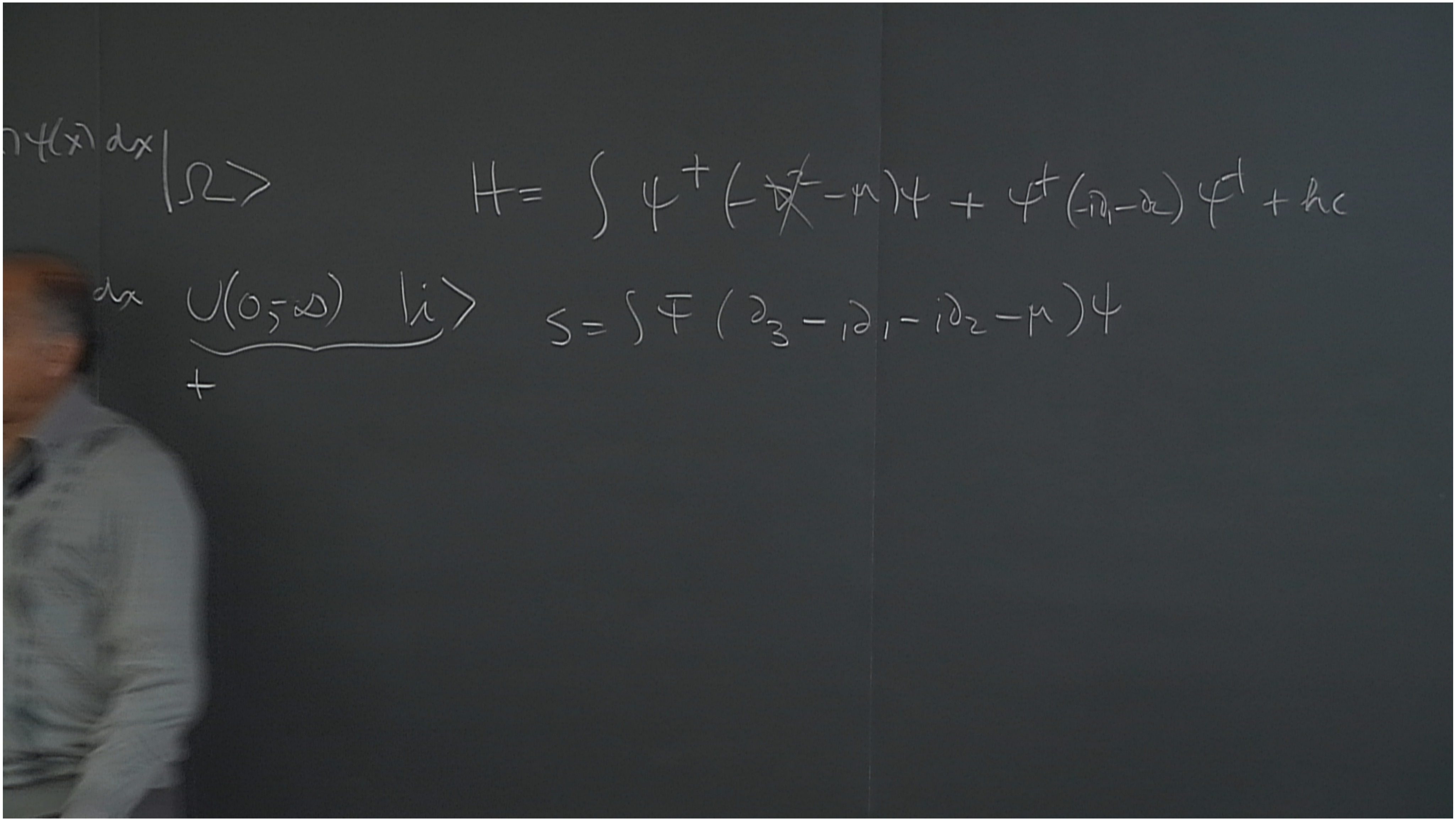

Z(J) = ⟨Φ| e^{∫J(x)ψ(x)dx} |Ω⟩
⟨f| U∞0 e^{∫J U(0,-∞) |i⟩

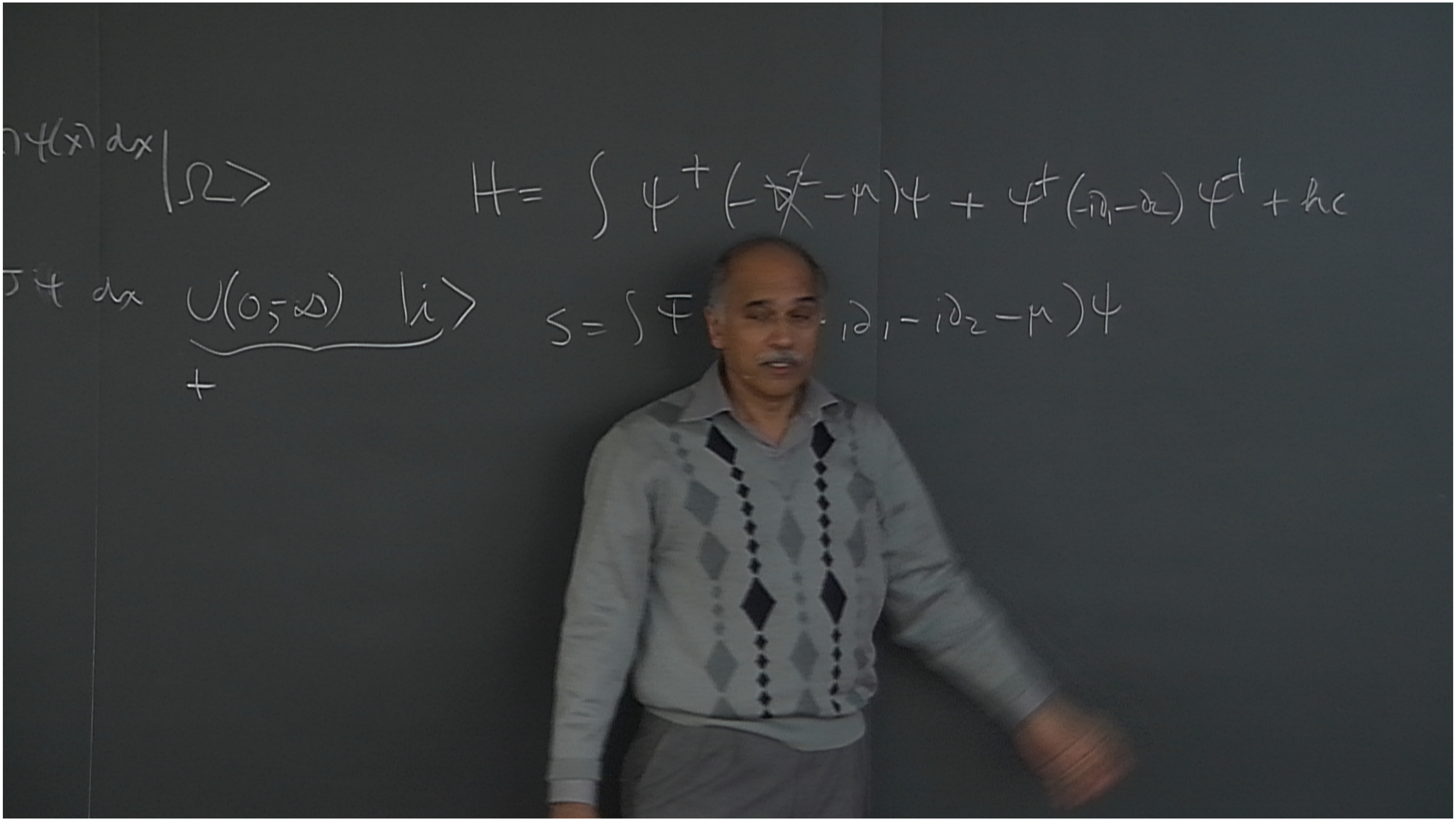

Z(J) = ⟨Φ| e^{∫J(x)ψ(x) dx} |Ω⟩
⟨f| U_{∞0} e^{∫Jψ dx} U(0,-∞) |i⟩

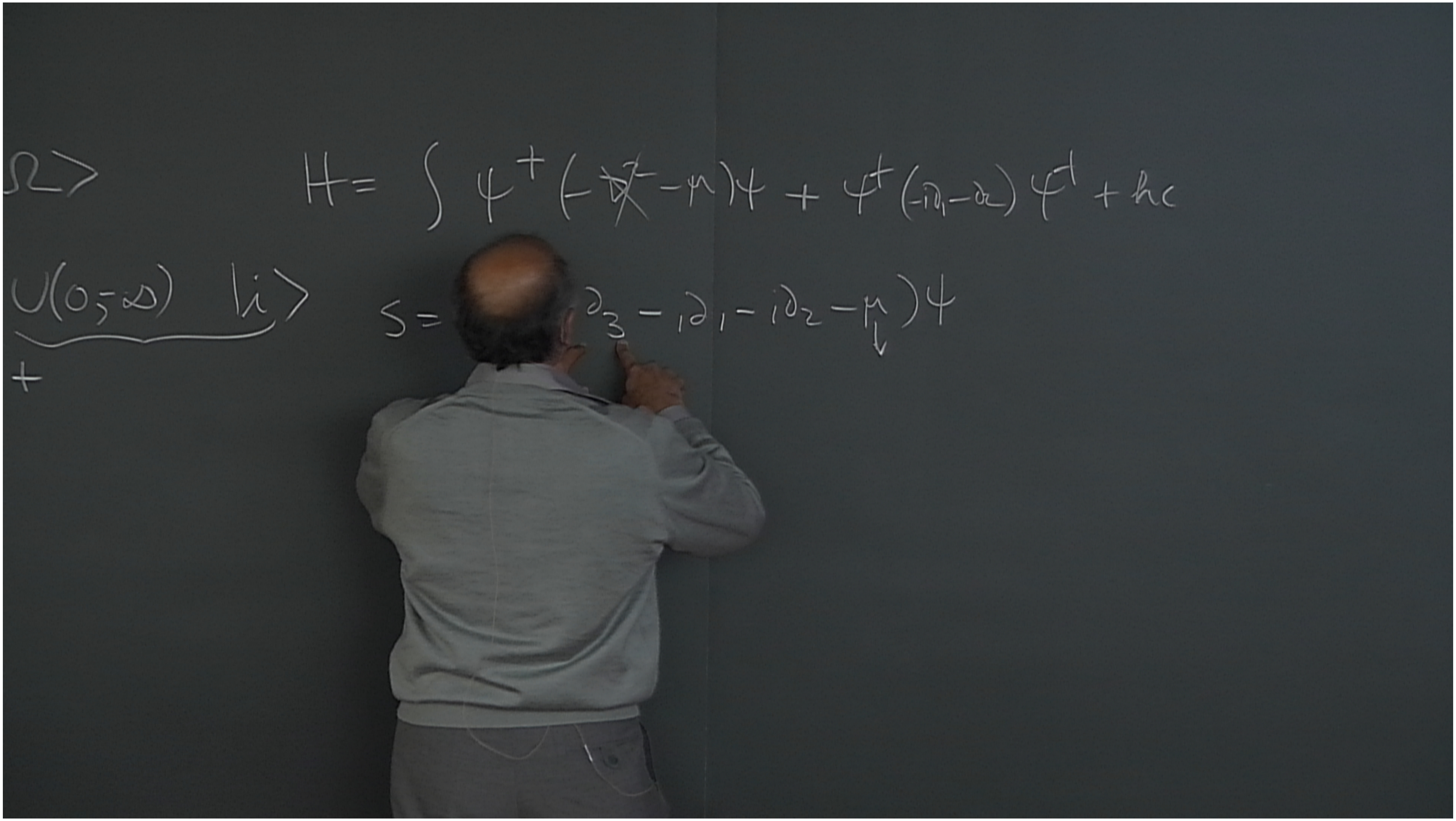

Z(J) = ⟨φ| e^{∫J(x)ψ(x) dx} |Ω⟩
H = ∫ ψ⁺ (−∇
kx−iky

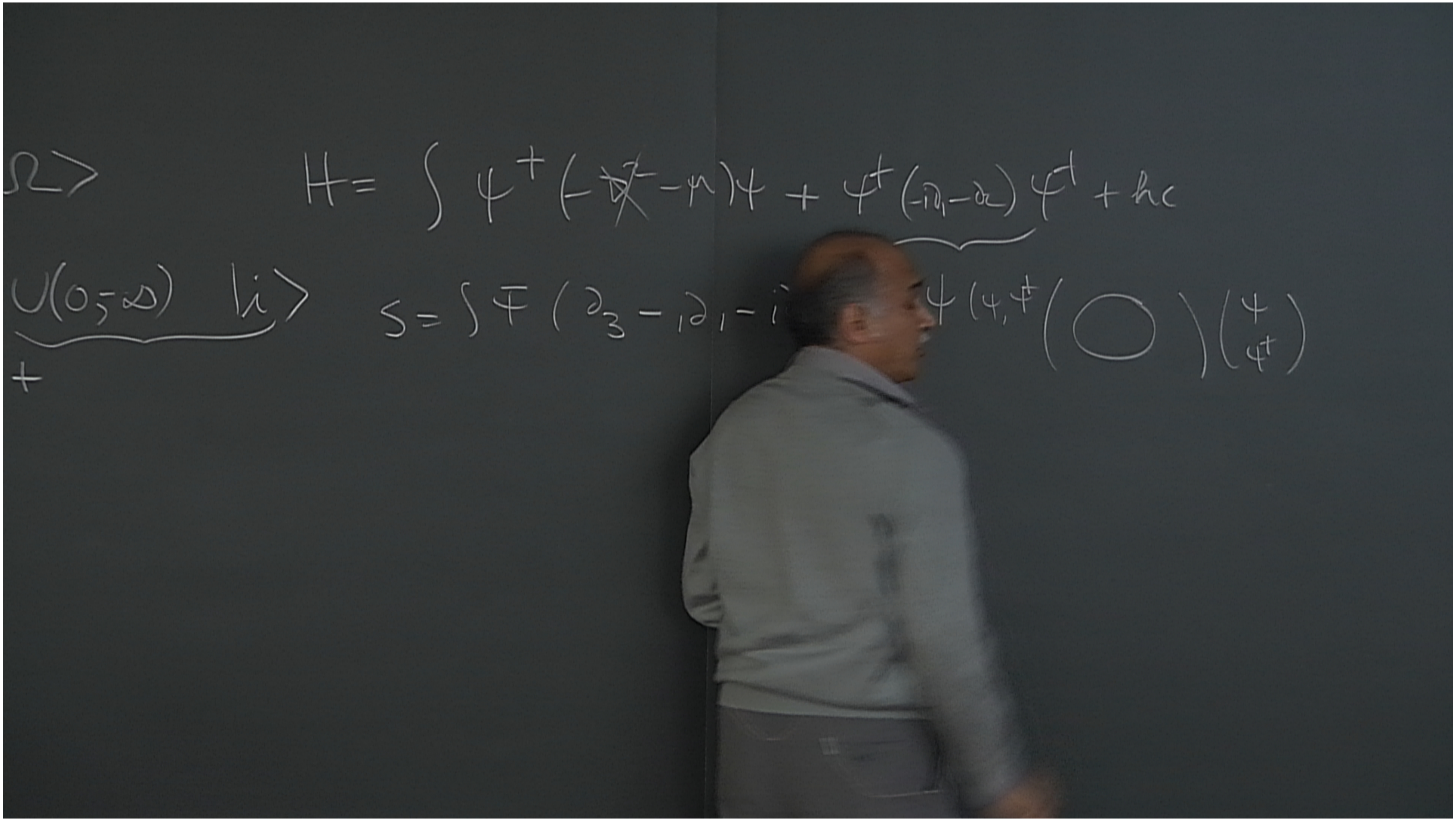

H = ∫ ψ† (−∇² − μ)ψ + ψ† (−i∂₁ − ∂₂) ψ† + hc

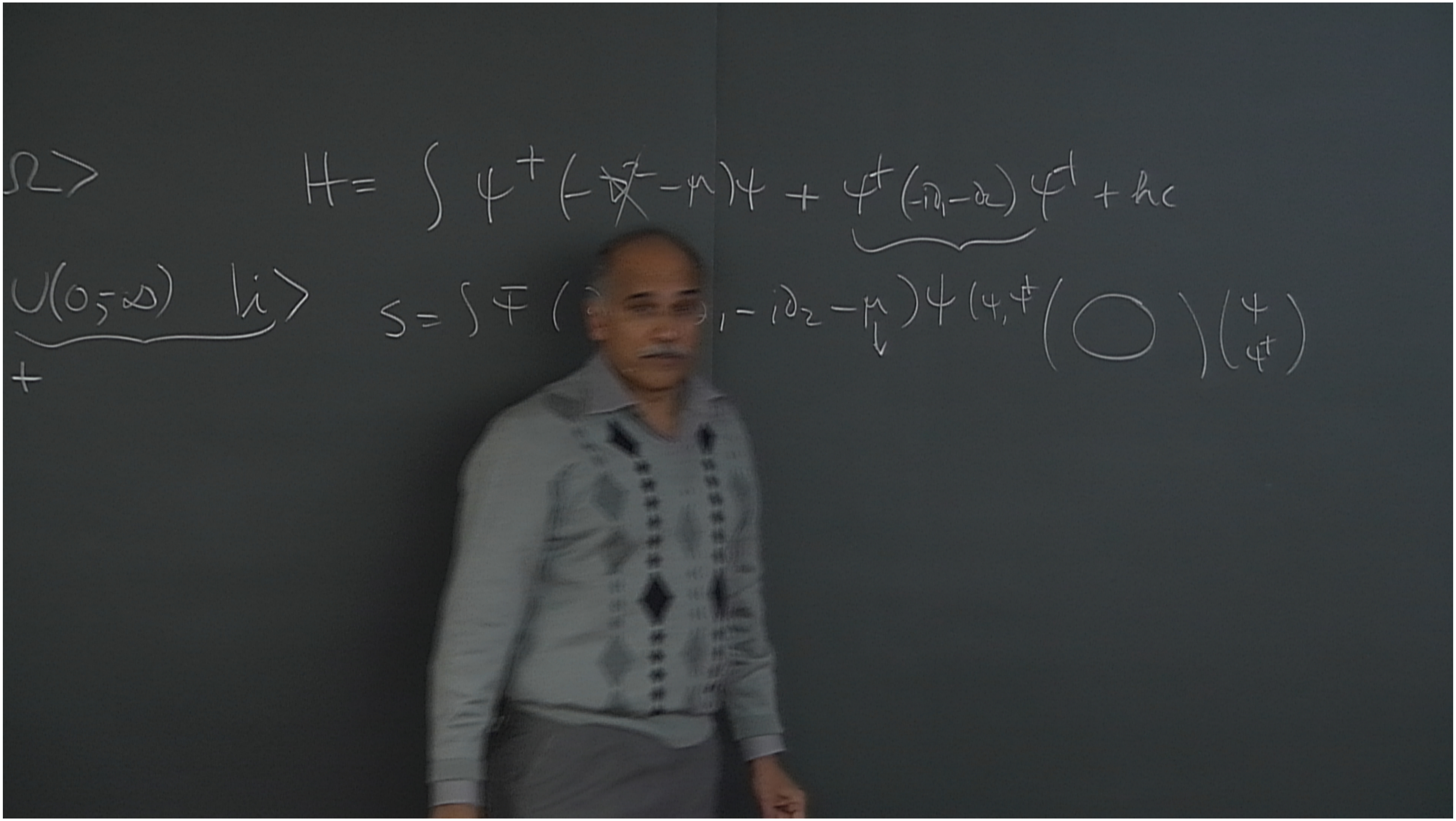


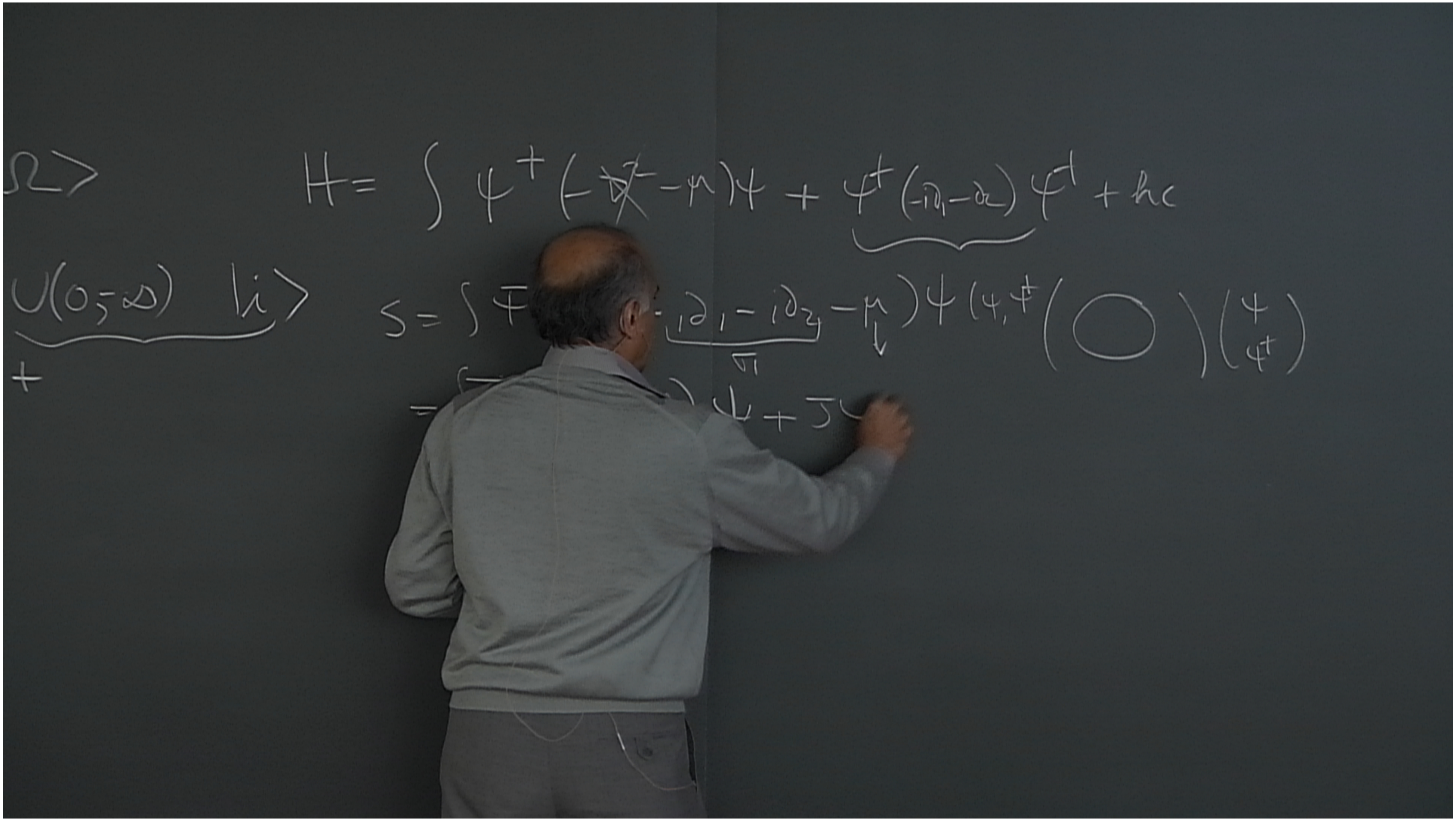

$\psi(x)\, dx\, |\Omega\rangle$
$H = \int \psi^\dagger(-\partial^2 - \mu)\psi + \psi^\dagger(-i\partial_1 - \partial_2)\psi^\dagger + hc$
$dx\ U(0,-\infty)\ |i\rangle$
$S = \int \bar{\psi}(\partial_3 - i\partial_1 - i\partial_2 - \mu)\psi$
+











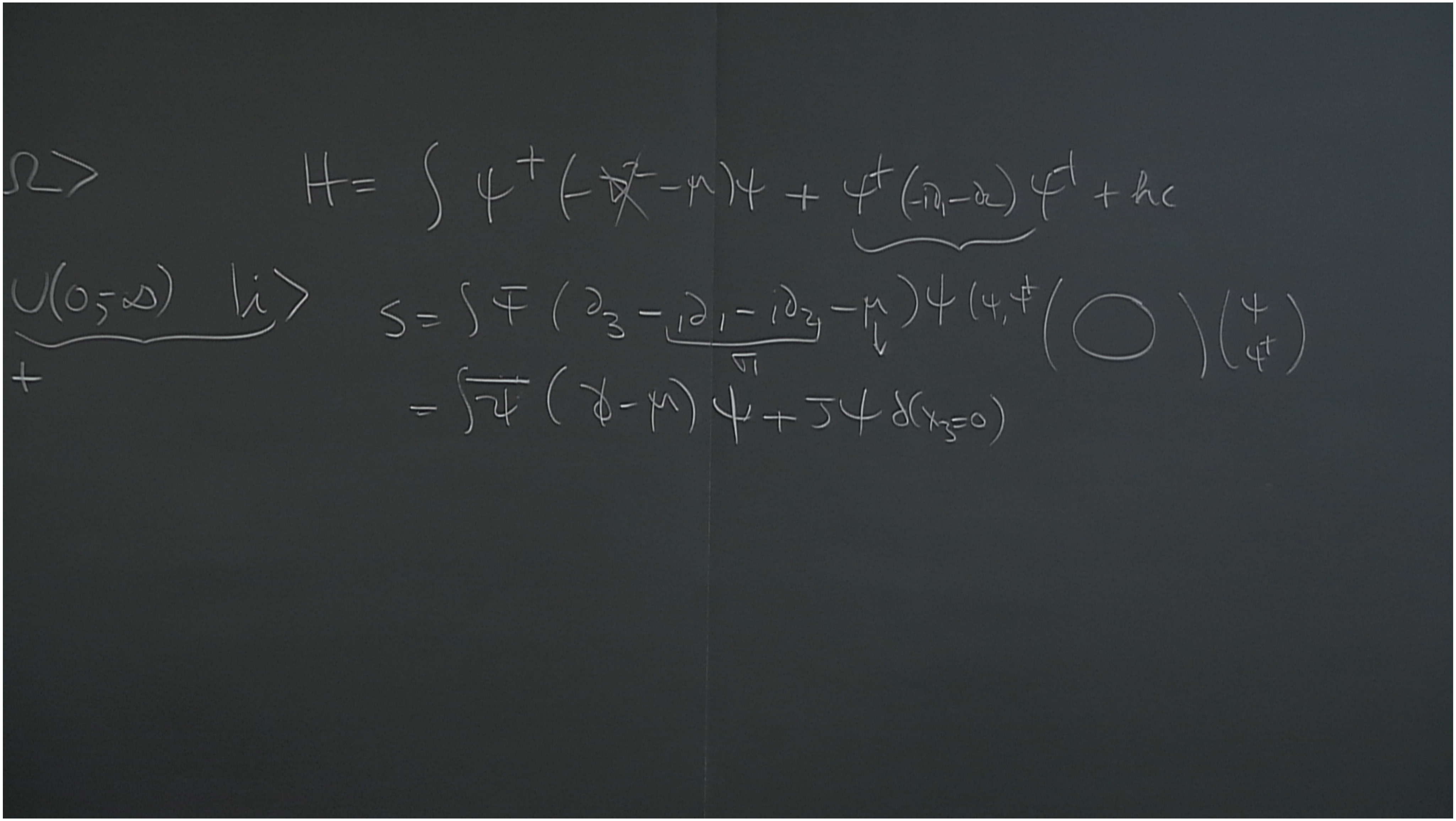
$|\Omega\rangle$

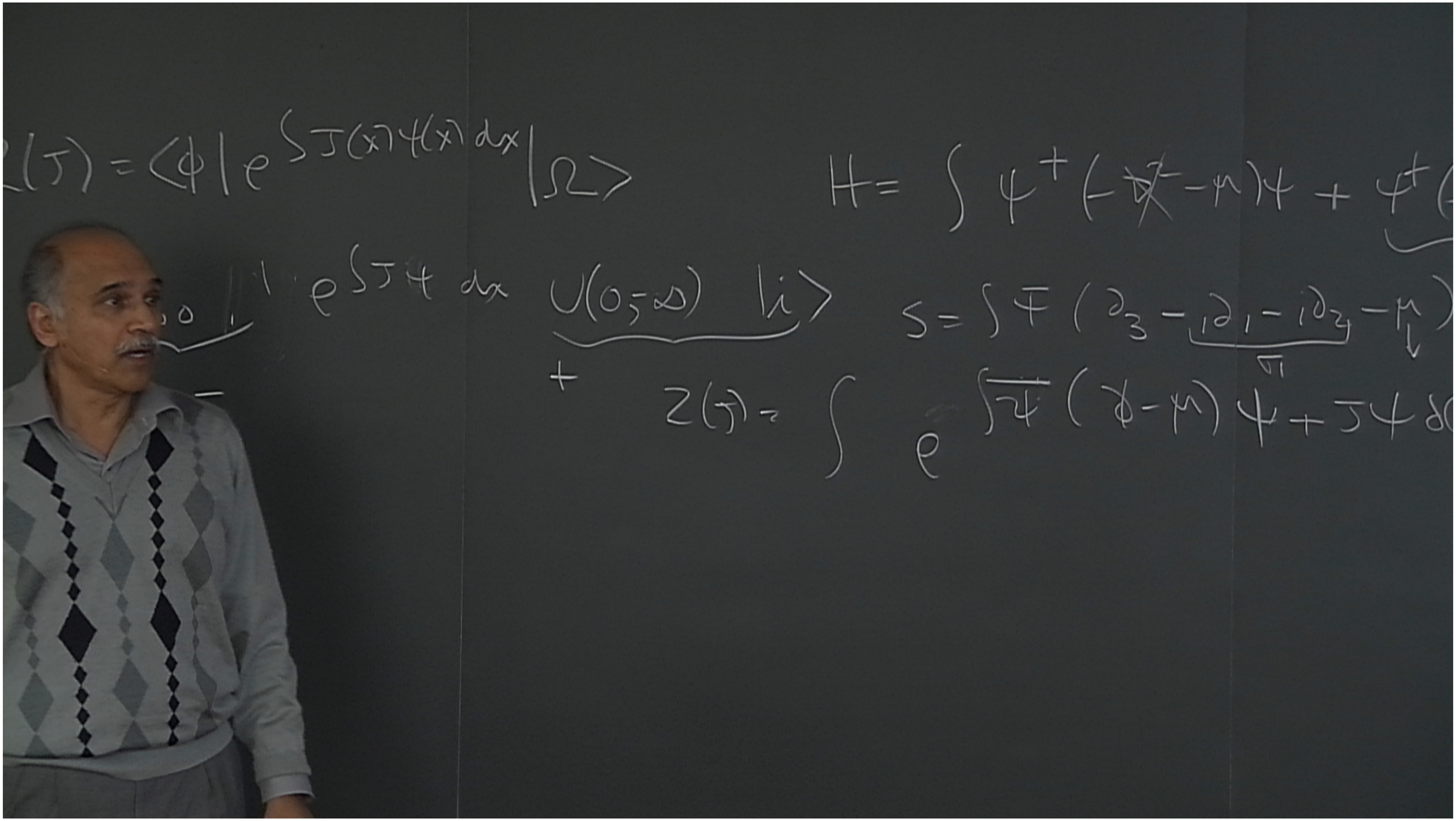
$$H = \int \psi^{\dagger}\left(-\partial^{2} - \mu\right)\psi + \psi^{\dagger}\left(-i\partial_1 - \partial_2\right)\psi^{\dagger} + hc$$

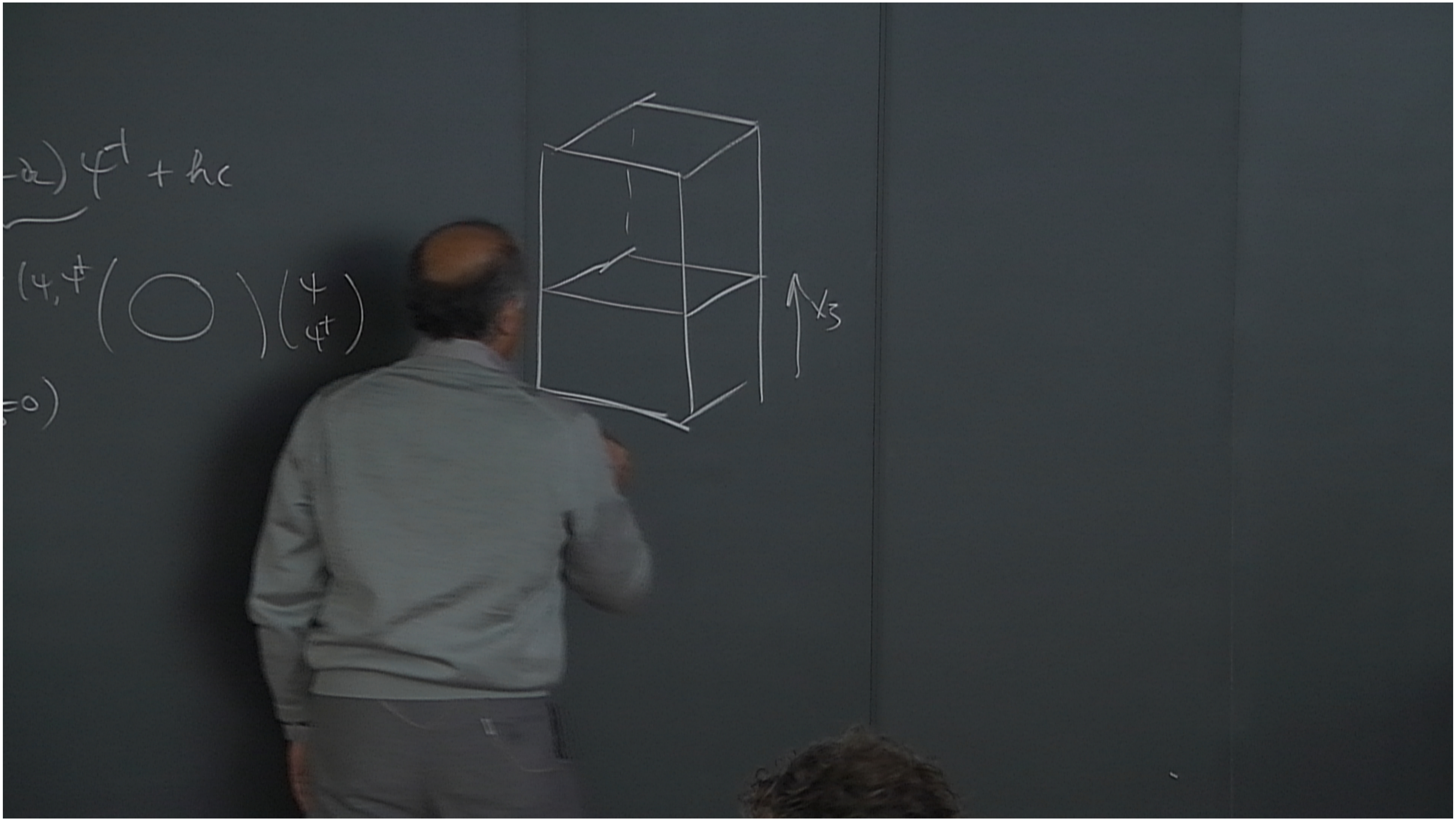
$U(0,-\infty)\,|i\rangle$

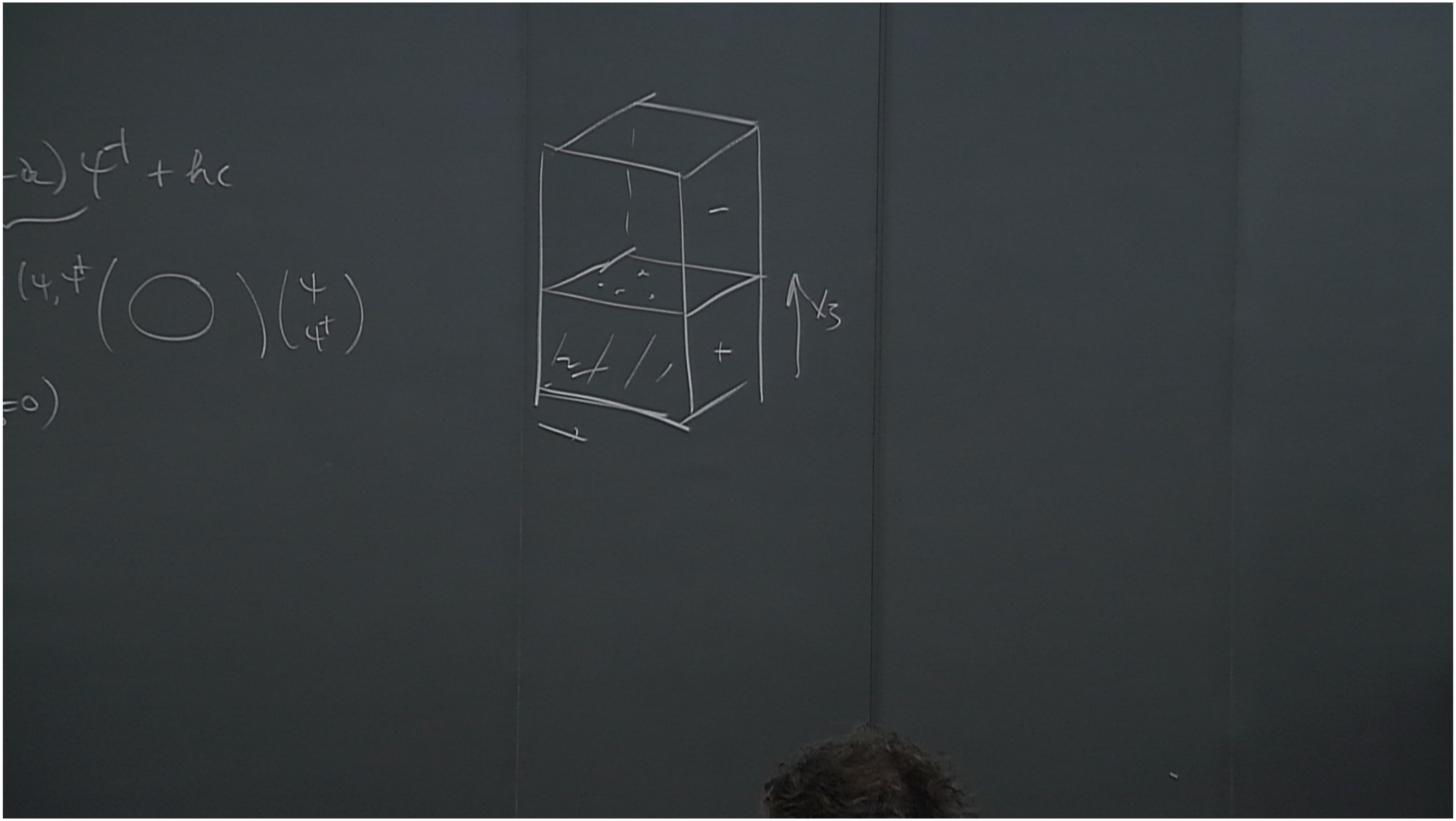
$$S = \int \bar{\psi}\left(\partial_3 - i\partial_1 - i\partial_2 - \mu\right)\psi \quad (\psi, \psi^{\dagger})\begin{pmatrix} \bigcirc \end{pmatrix}\begin{pmatrix} \psi \\ \psi^{\dagger} \end{pmatrix}$$

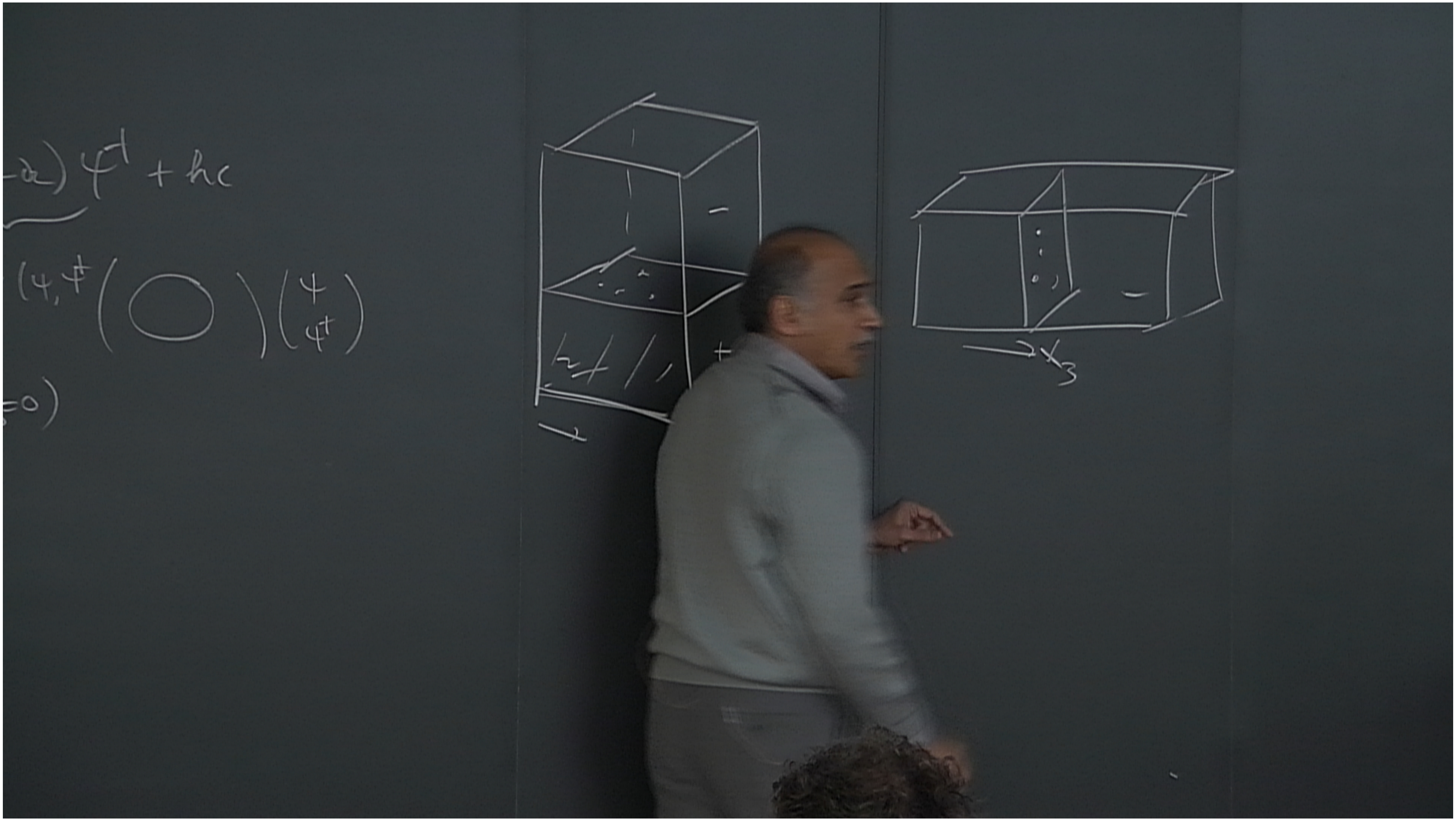
$$= \int \bar{\psi}\left(\partial\!\!\!/ - \mu\right)\psi + \bar{J}\psi$$

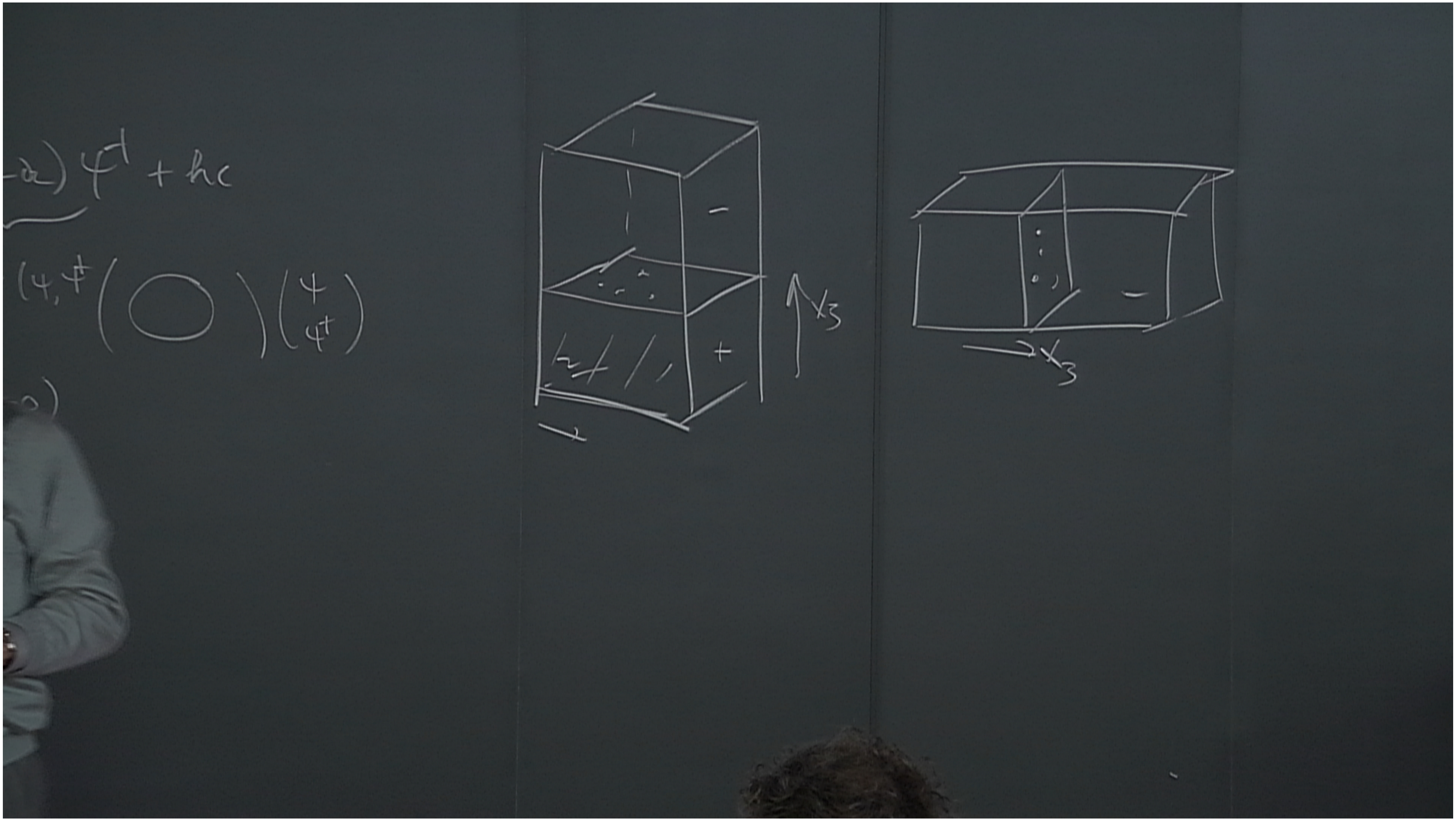


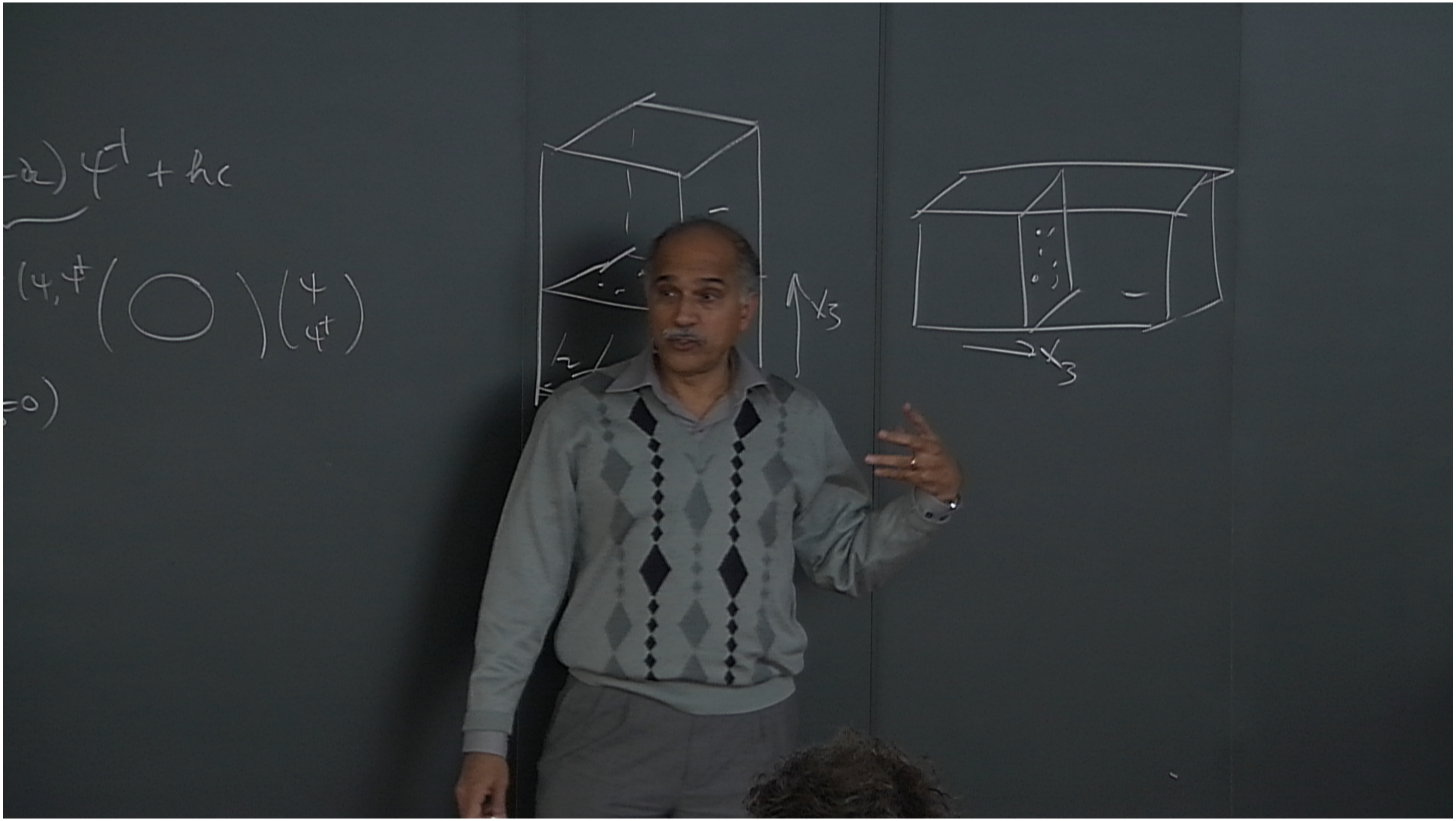


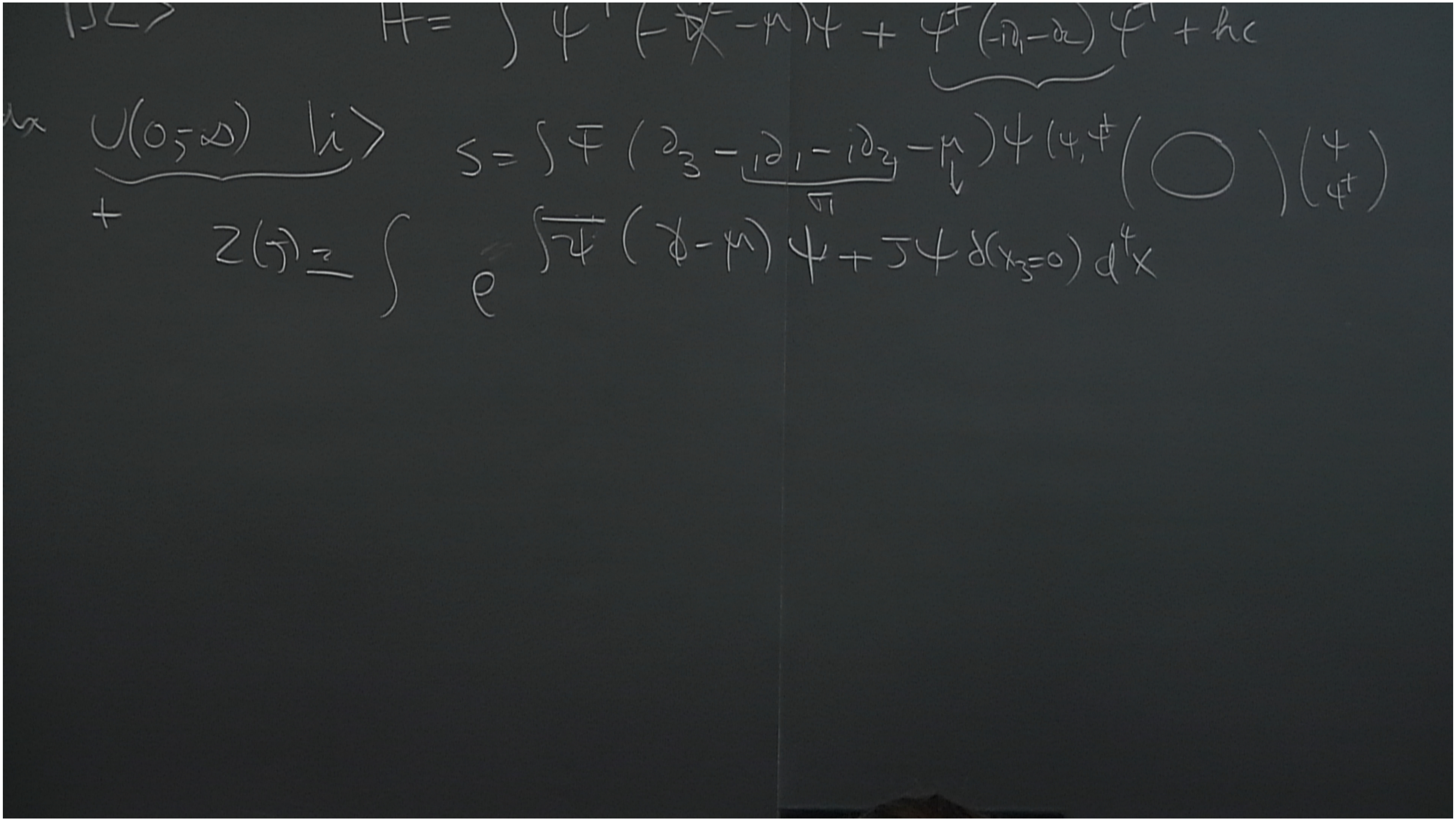

+ hc
x3

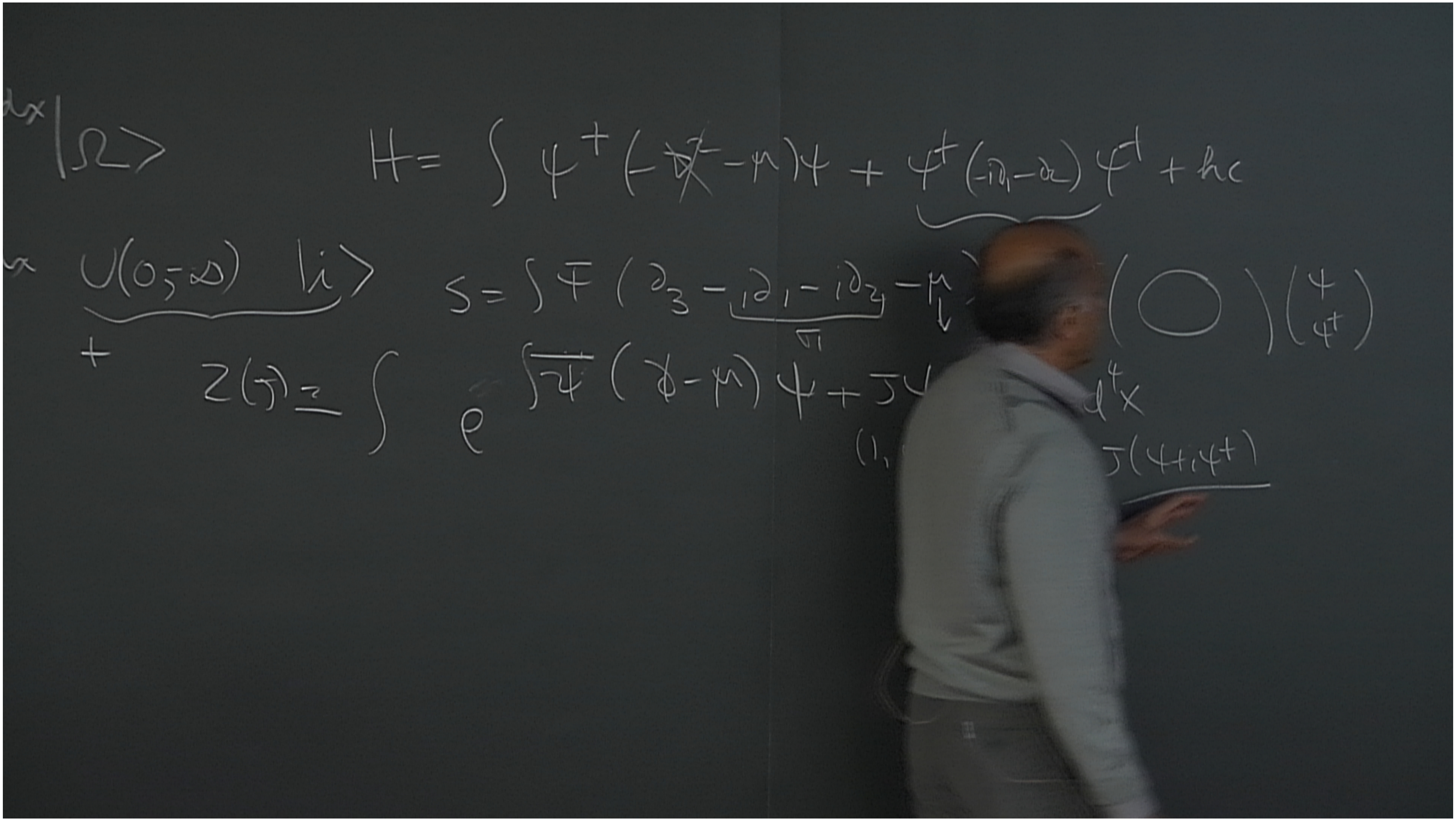

+ hc
−
+
x3

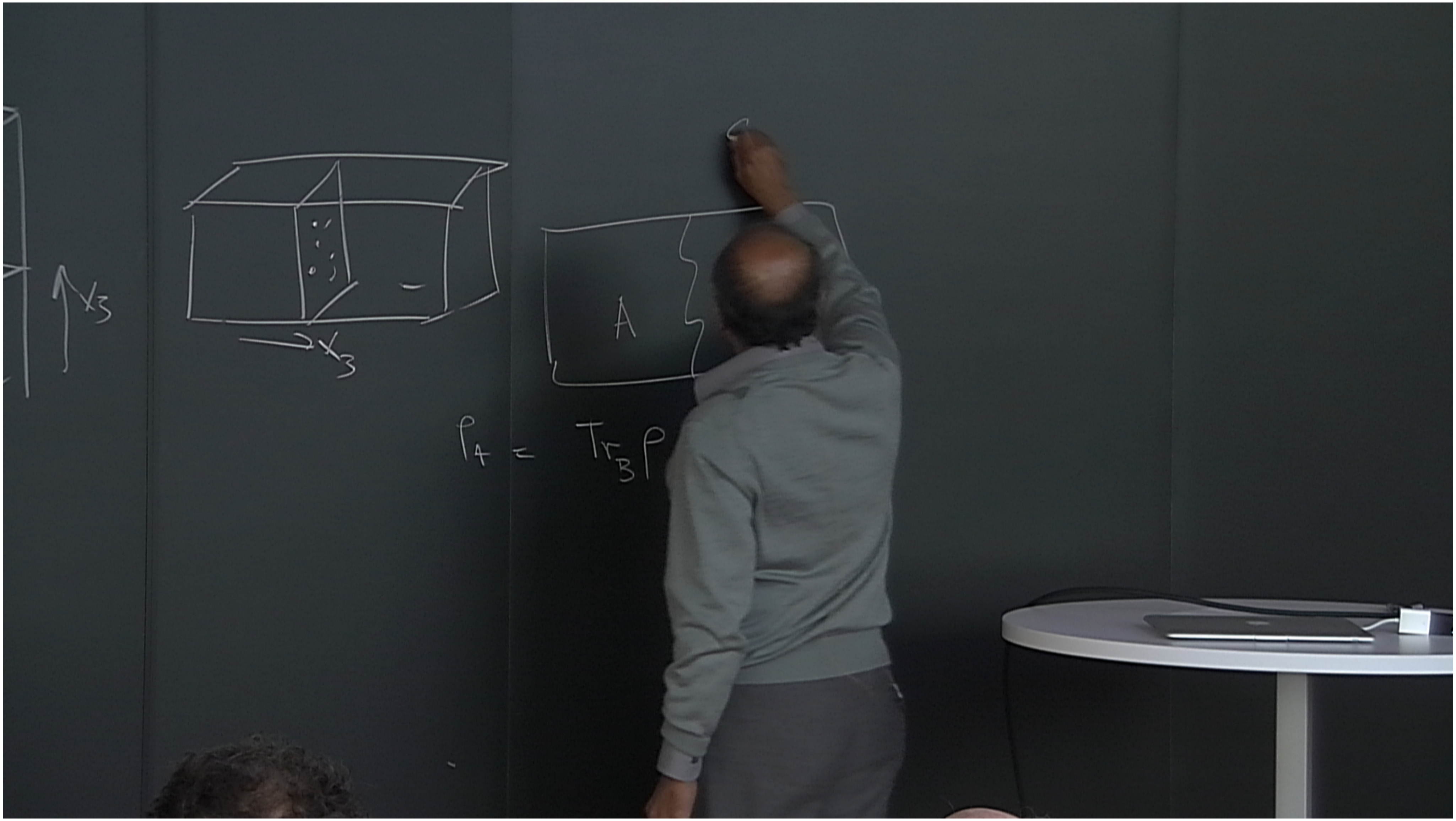

+ hc
x3

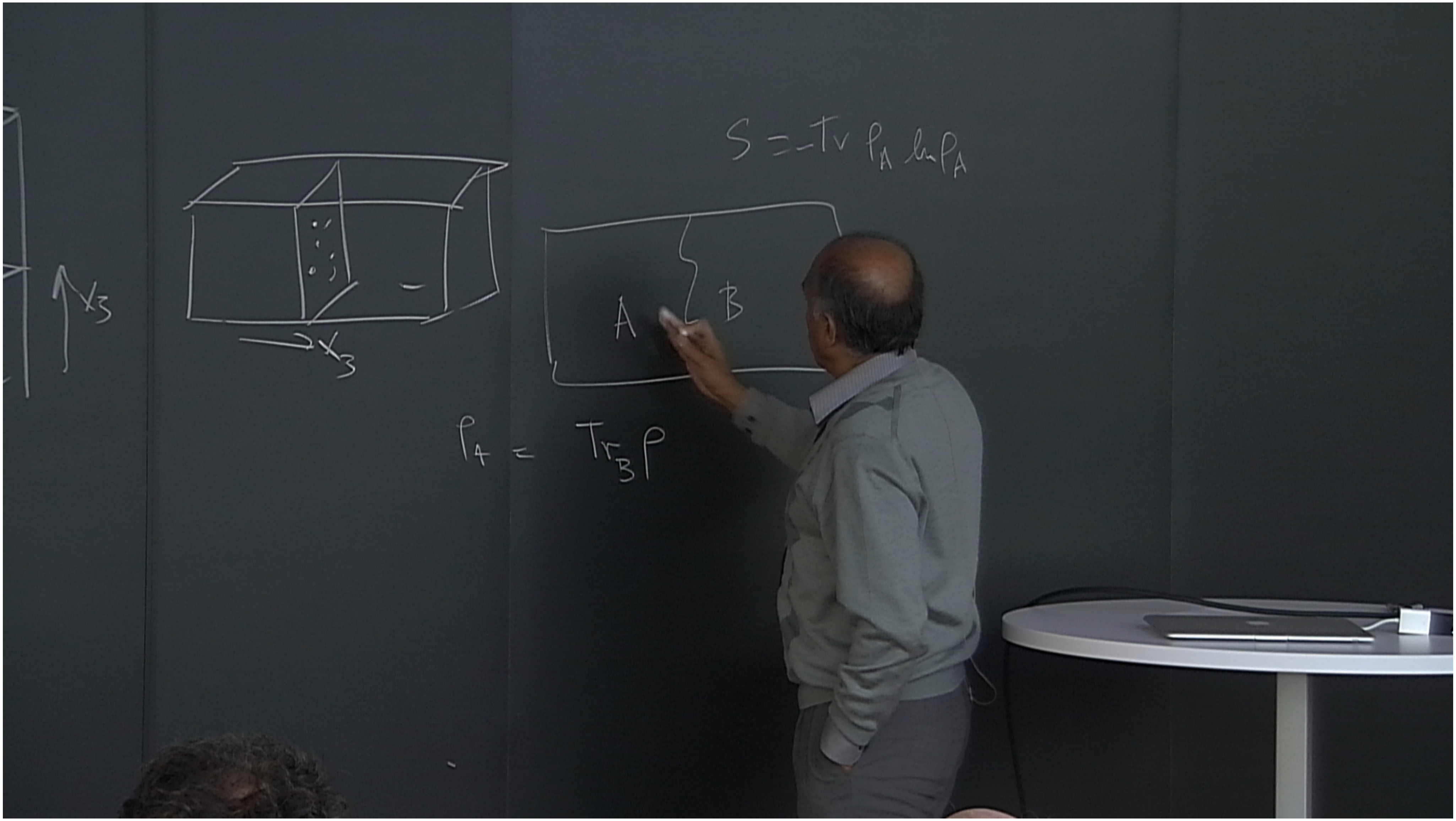

+ hc
x3
x3



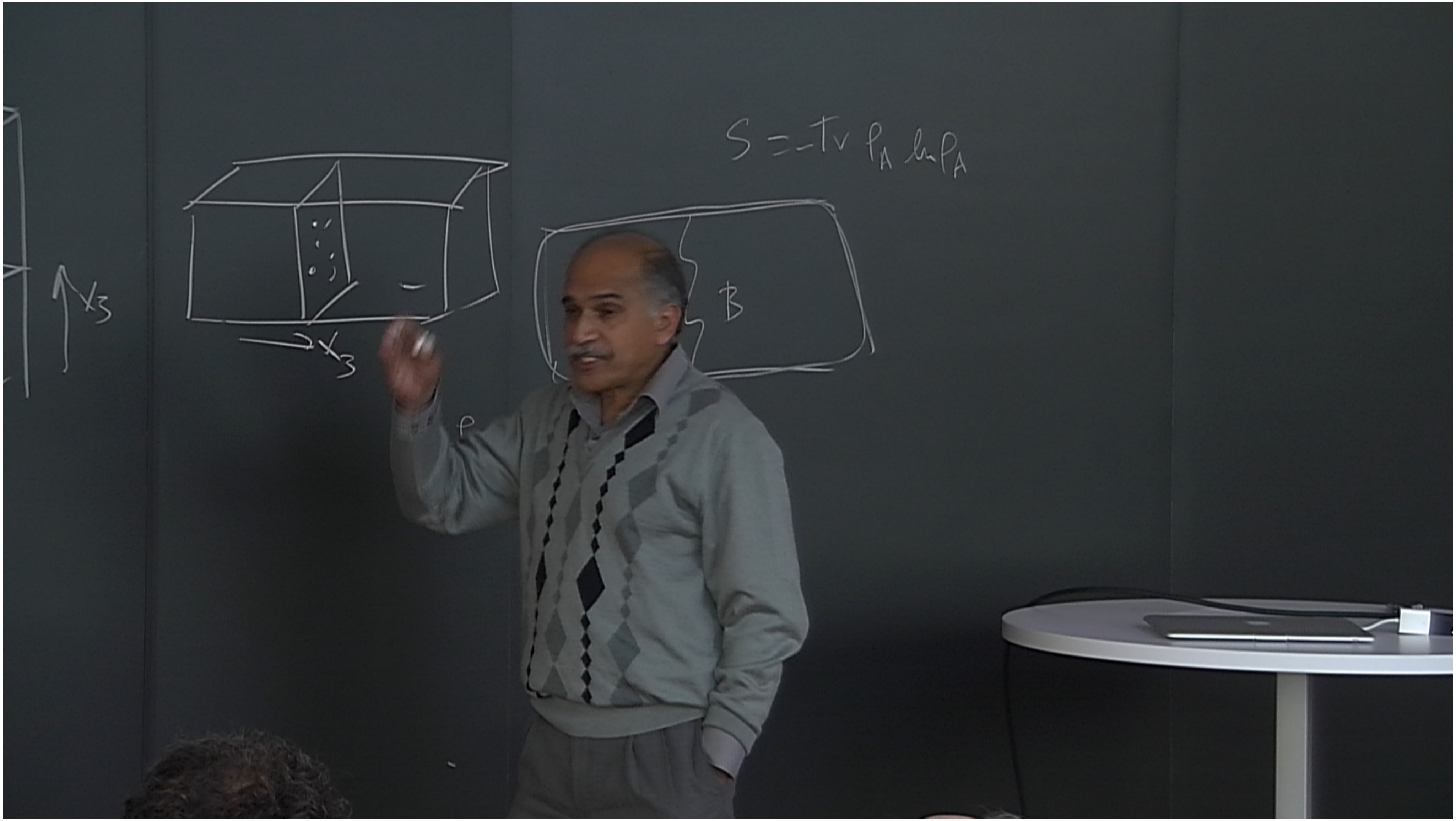




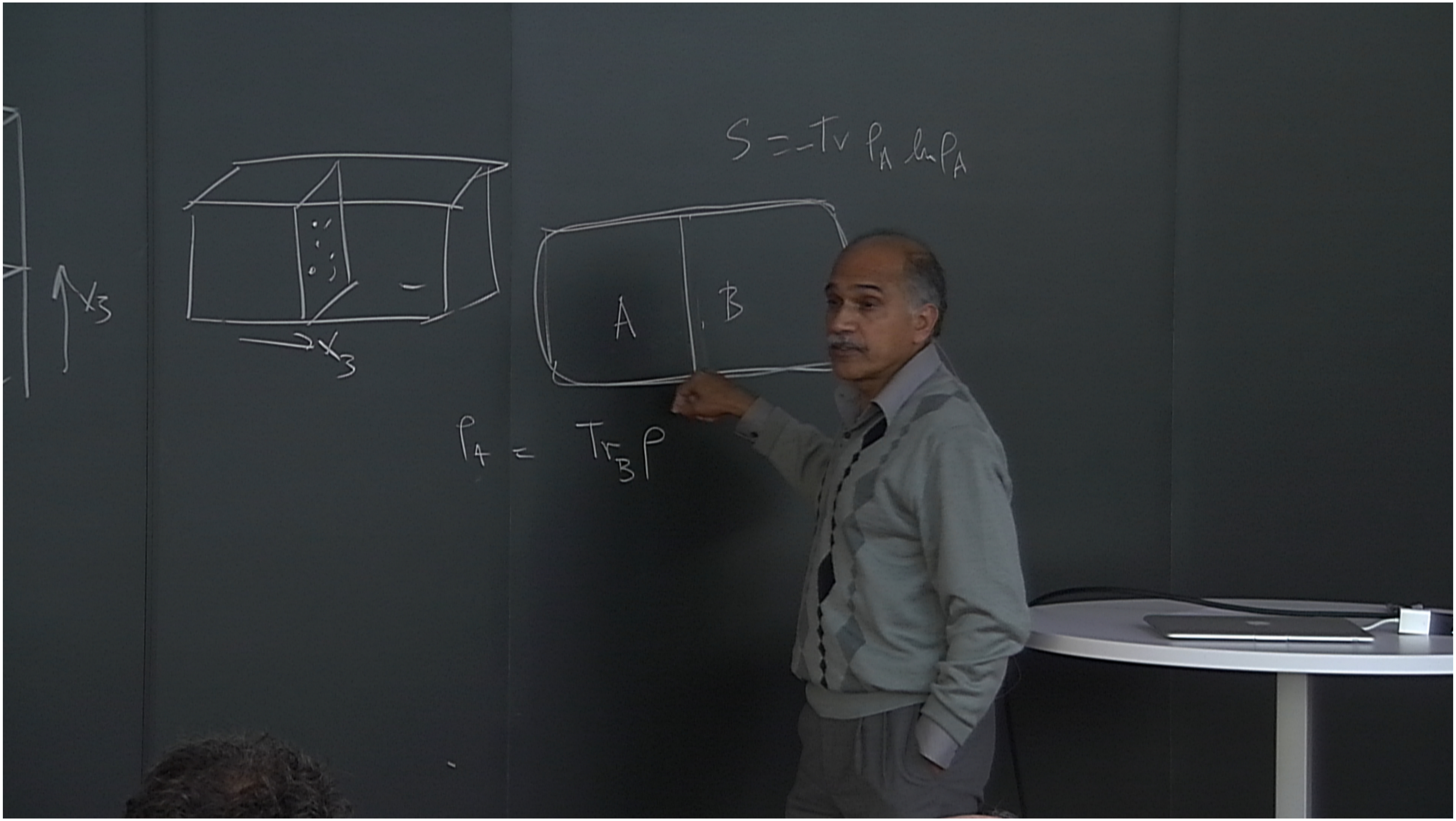

A
x_3
x_3
$\rho_A = \mathrm{Tr}_B\, \rho$



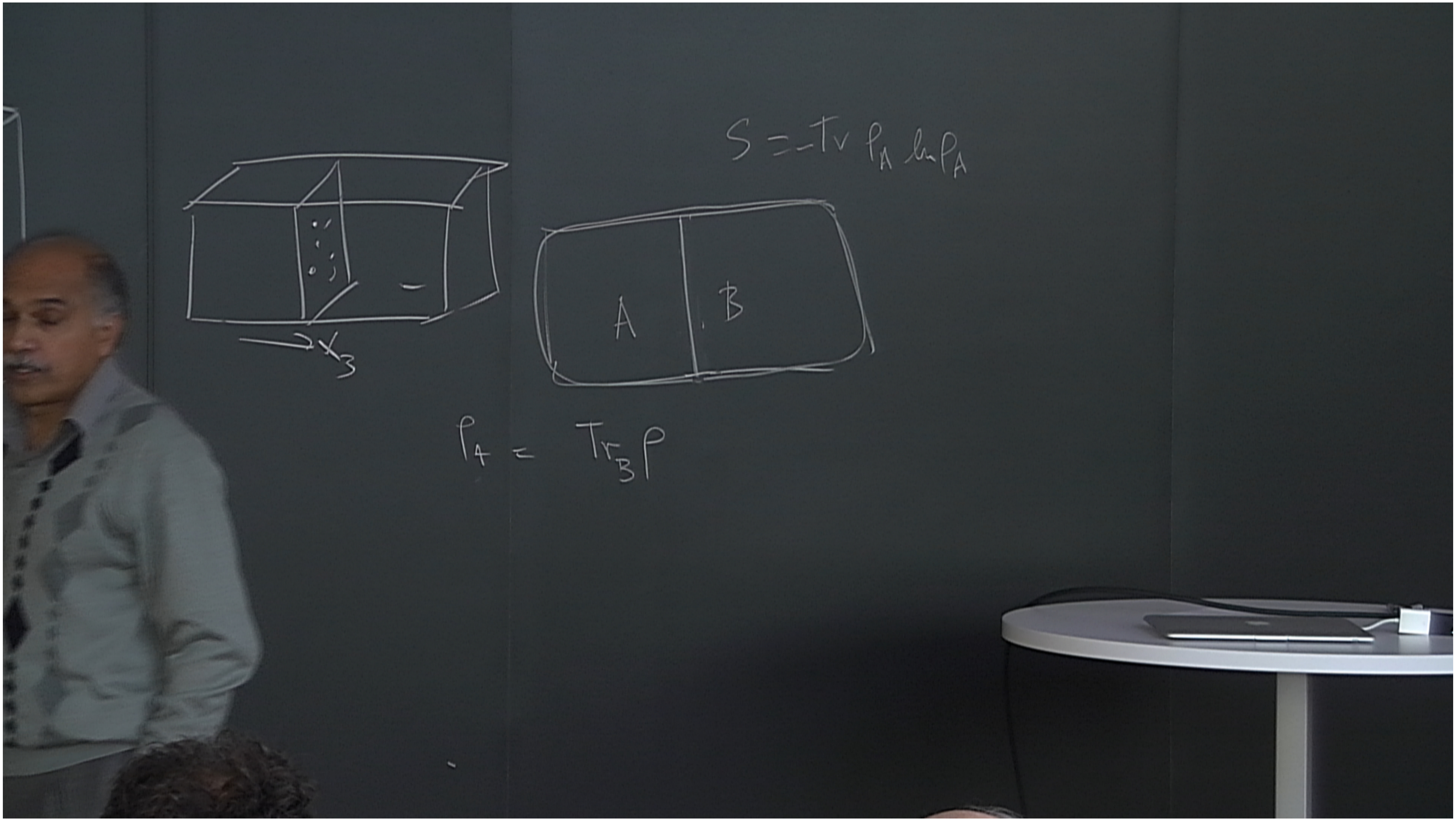
$S = -\mathrm{Tr}\, \rho_A \ln \rho_A$
x_3
x_3
A
B
$\rho_A = \mathrm{Tr}_B\, \rho$



$S = -Tr\,\rho_A \ln \rho_A$
B
x_3
x_3



S = -Tr ρA ln ρA
A
B
ρA = TrB ρ


S = -Tr ρ_A ln ρ_A
A
B
ρ_A = Tr_B ρ
x_3