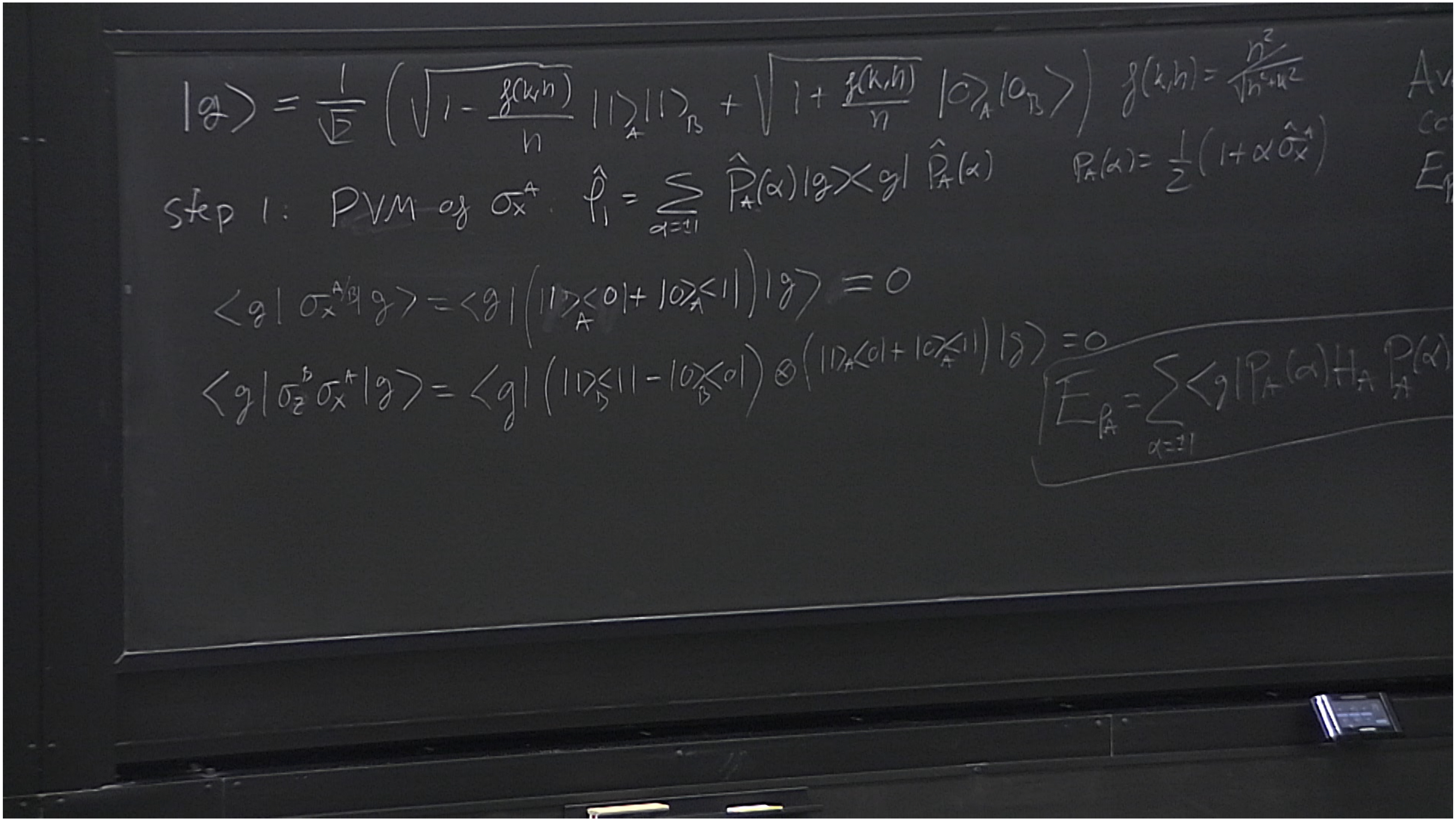
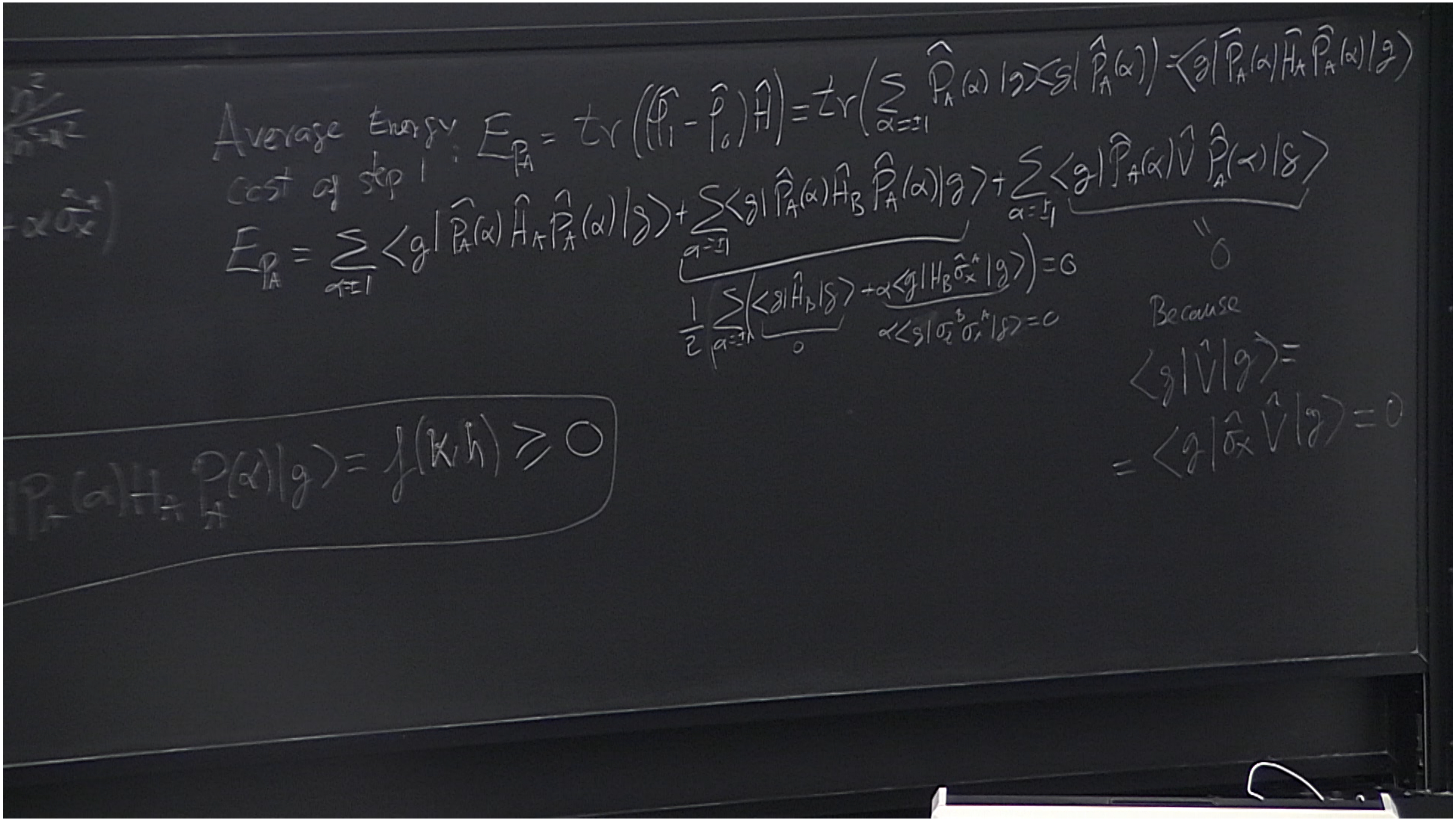
Title: PSI 2017/2018 - Relativistic Quantum Information - Lecture 14

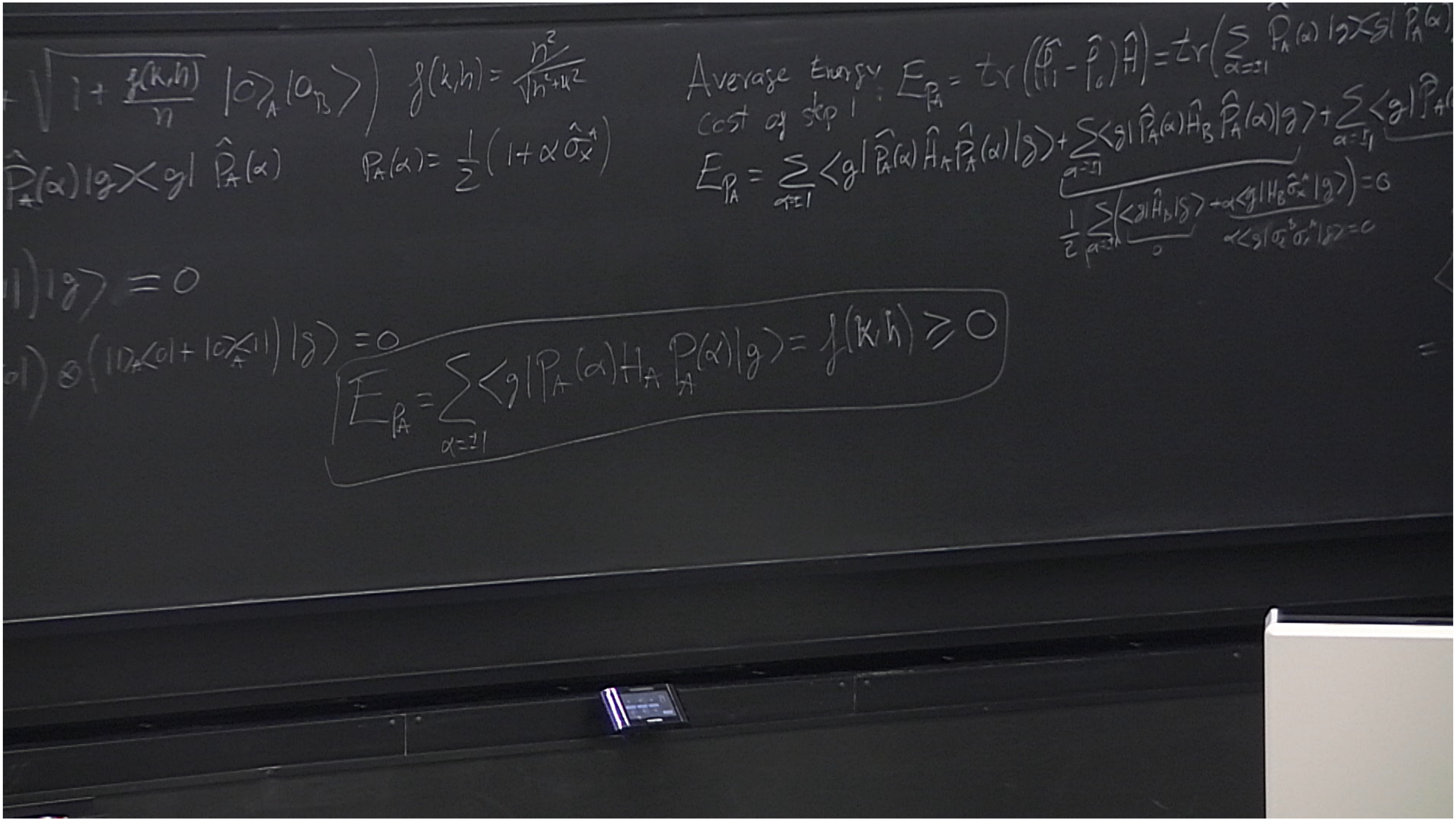
Date: Apr 06, 2018 09:00 AM

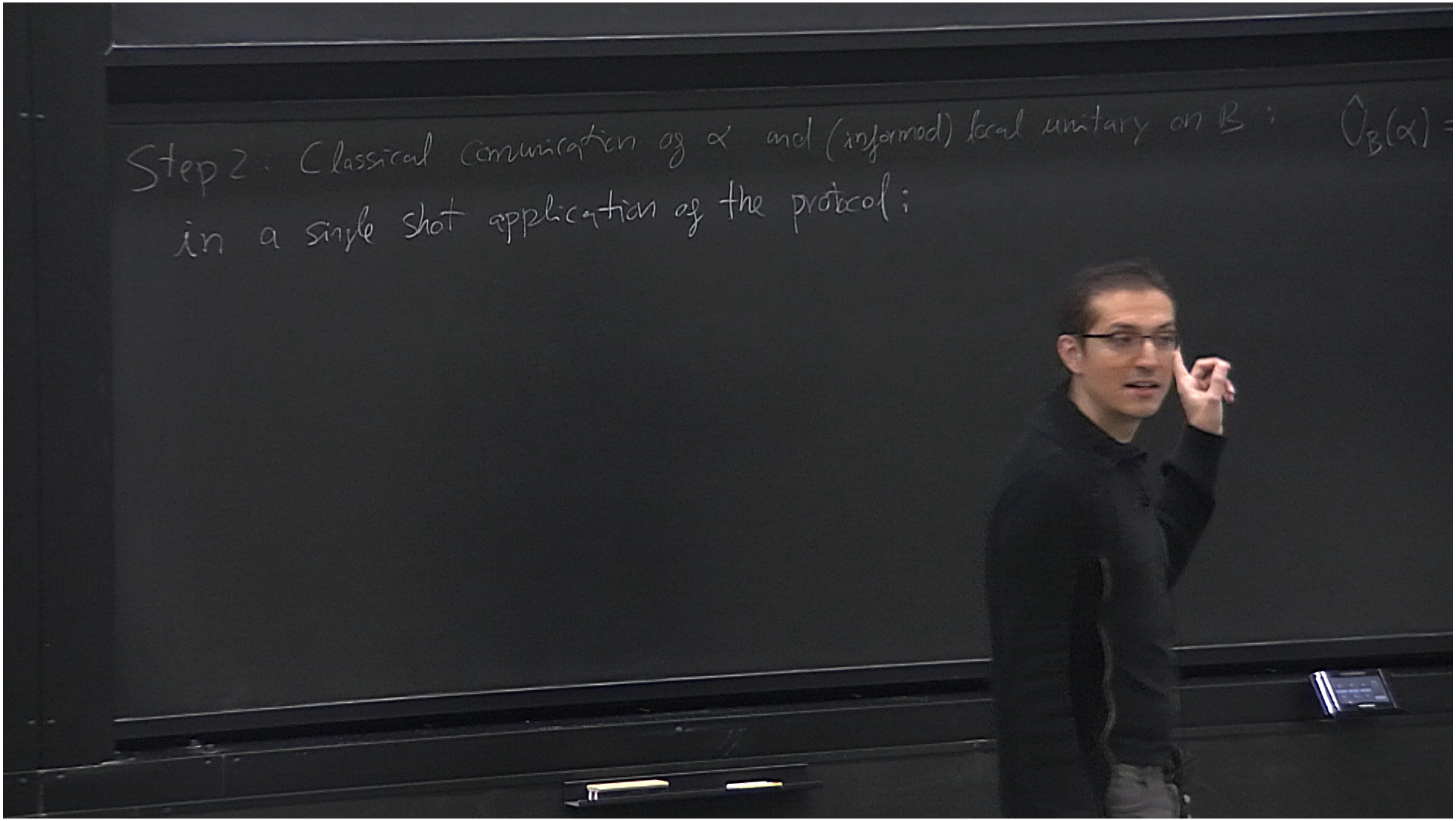
URL: http://pirsa.org/18040007

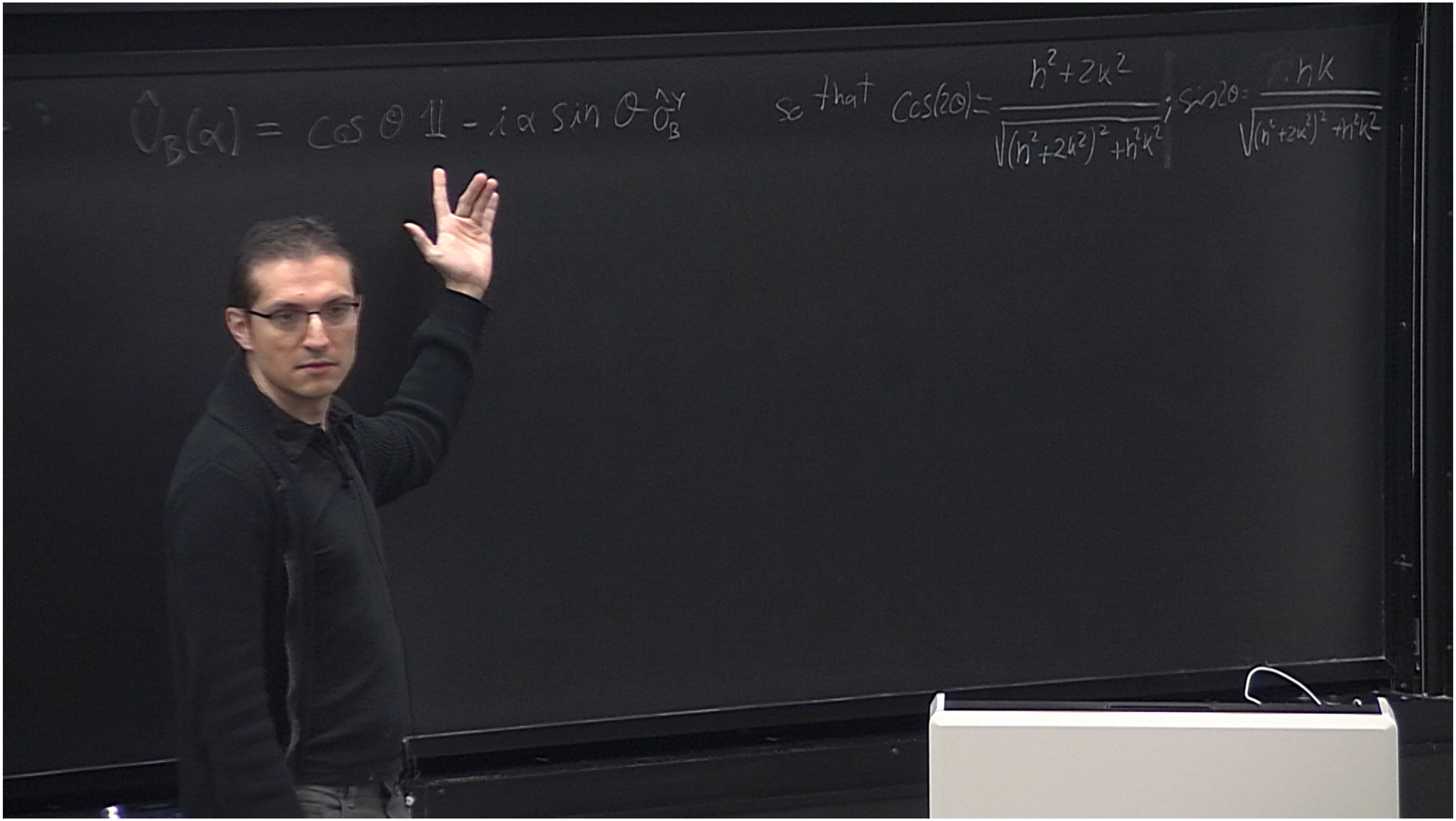
Abstract:


$|g\rangle = \frac{1}{\sqrt{2}}\left(\sqrt{1-\frac{f(k,n)}{n}}\,|1\rangle_A|1\rangle_B + \sqrt{1+\frac{f(k,n)}{n}}\,|0\rangle_A|0_B\rangle\right)$
$f(k,n) = \frac{n^2}{\sqrt{n^2+k^2}}$
$P_A(\alpha) = \frac{1}{2}(1+\alpha\hat{\sigma}_x^A)$
step 1: PVM of σ_x^A. $\hat{\rho}_1 = \sum_{\alpha=\pm1} \hat{P}_A(\alpha)|g\rangle\langle g|\hat{P}_A(\alpha)$
$\langle g|\sigma_x^{A/B}|g\rangle = \langle g|(|1\rangle_A\langle 0| + |0\rangle_A\langle 1|)|g\rangle = 0$
$\langle g|\sigma_z^B\sigma_x^A|g\rangle = \langle g|(|1\rangle_B\langle 1| - |0\rangle_B\langle 0|)\otimes(|1\rangle_A\langle 0| + |0\rangle_A\langle 1|)|g\rangle = 0$
$E_{P_A} = \sum_{\alpha=\pm1}\langle g|P_A(\alpha)H_A P_A(\alpha)$


Average Energy cost of step 1 : $E_{P_A} = tr((\hat{P}_1 - \hat{P}_0)\hat{H}) = tr\left(\sum_{\alpha=\pm1} \hat{P}_A(\alpha)|g\rangle\langle g|\hat{P}_A(\alpha)\right) = \langle g|\hat{P}_A(\alpha)\hat{H}_A\hat{P}_A(\alpha)|g\rangle$
$E_{P_A} = \sum_{\alpha=\pm1}\langle g|\hat{P}_A(\alpha)\hat{H}_A\hat{P}_A(\alpha)|g\rangle + \sum_{\alpha=\pm1}\langle g|\hat{P}_A(\alpha)\hat{H}_B\hat{P}_A(\alpha)|g\rangle + \sum_{\alpha=\pm1}\langle g|\hat{P}_A(\alpha)\hat{V}\hat{P}_A(\alpha)|g\rangle$
$\frac{1}{2}\sum_{\alpha=\pm1}\left(\langle g|\hat{H}_B|g\rangle + \alpha\langle g|H_B\hat{\sigma}_x^A|g\rangle\right) = 0$
$\alpha\langle g|\sigma_z^B\sigma_x^A|g\rangle = 0$
Because
$\langle g|\hat{V}|g\rangle =$
$= \langle g|\hat{\sigma}_x\hat{V}|g\rangle = 0$
$\langle g|\hat{P}_A(\alpha)H_A\hat{P}_A(\alpha)|g\rangle = f(k,h) \geq 0$


Average Energy cost of step 1 :
$E_{P_A} = tr\left(\left(\hat{P}_1 - \hat{P}_0\right)\hat{H}\right)$
$f(k,h) = \frac{h^2}{\sqrt{h^2+k^2}}$
$P_A(\alpha) = \frac{1}{2}\left(1 + \alpha\hat{\sigma}_x^A\right)$
$E_{P_A} = \sum_{\alpha=\pm1} \langle g | P_A(\alpha) H_A P_A(\alpha) | g \rangle = f(k,h) \geq 0$

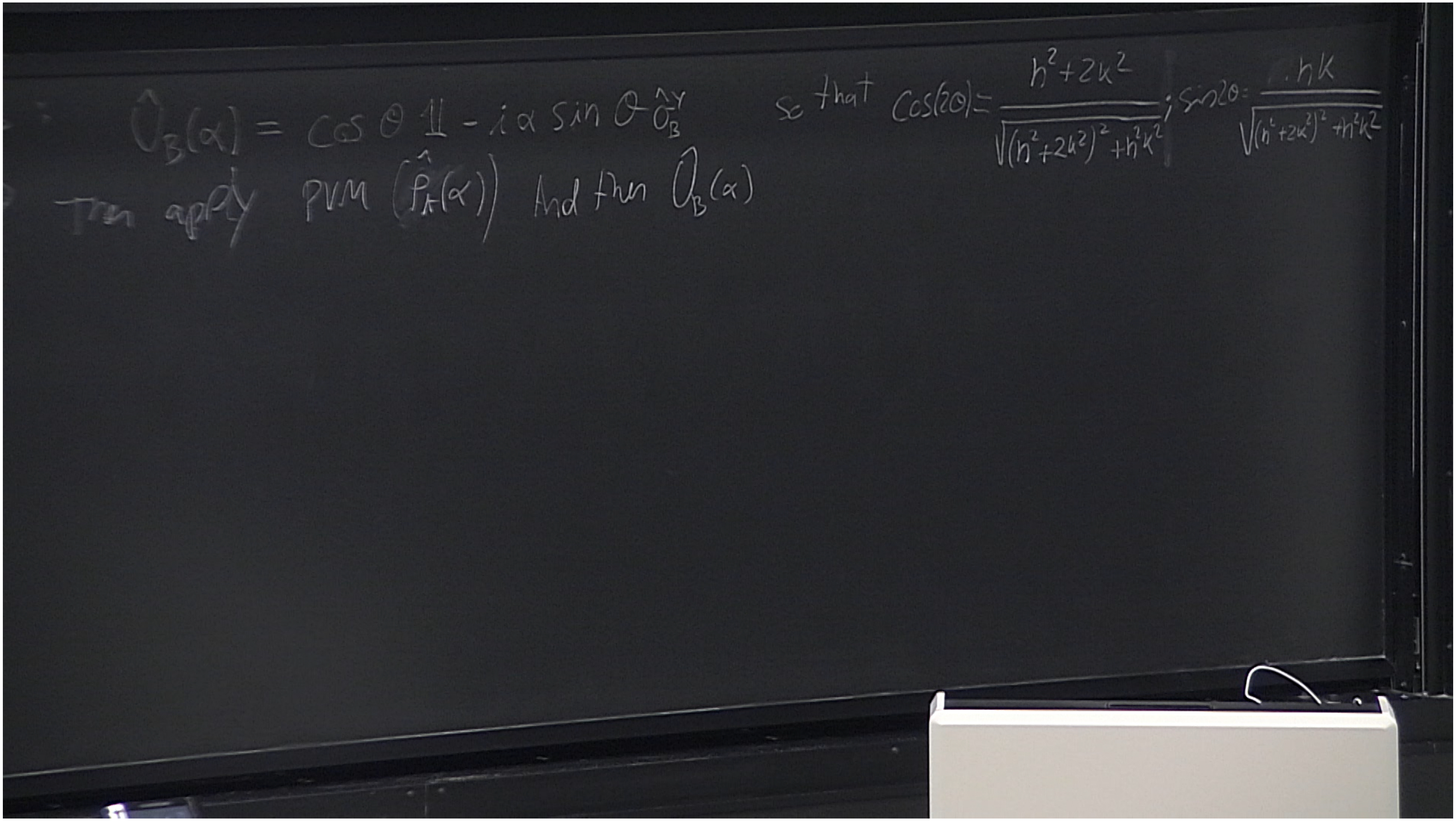

Step 2: Classical communication of α and (informed) local unitary on B: Û_B(α) =
in a single shot application of the protocol;

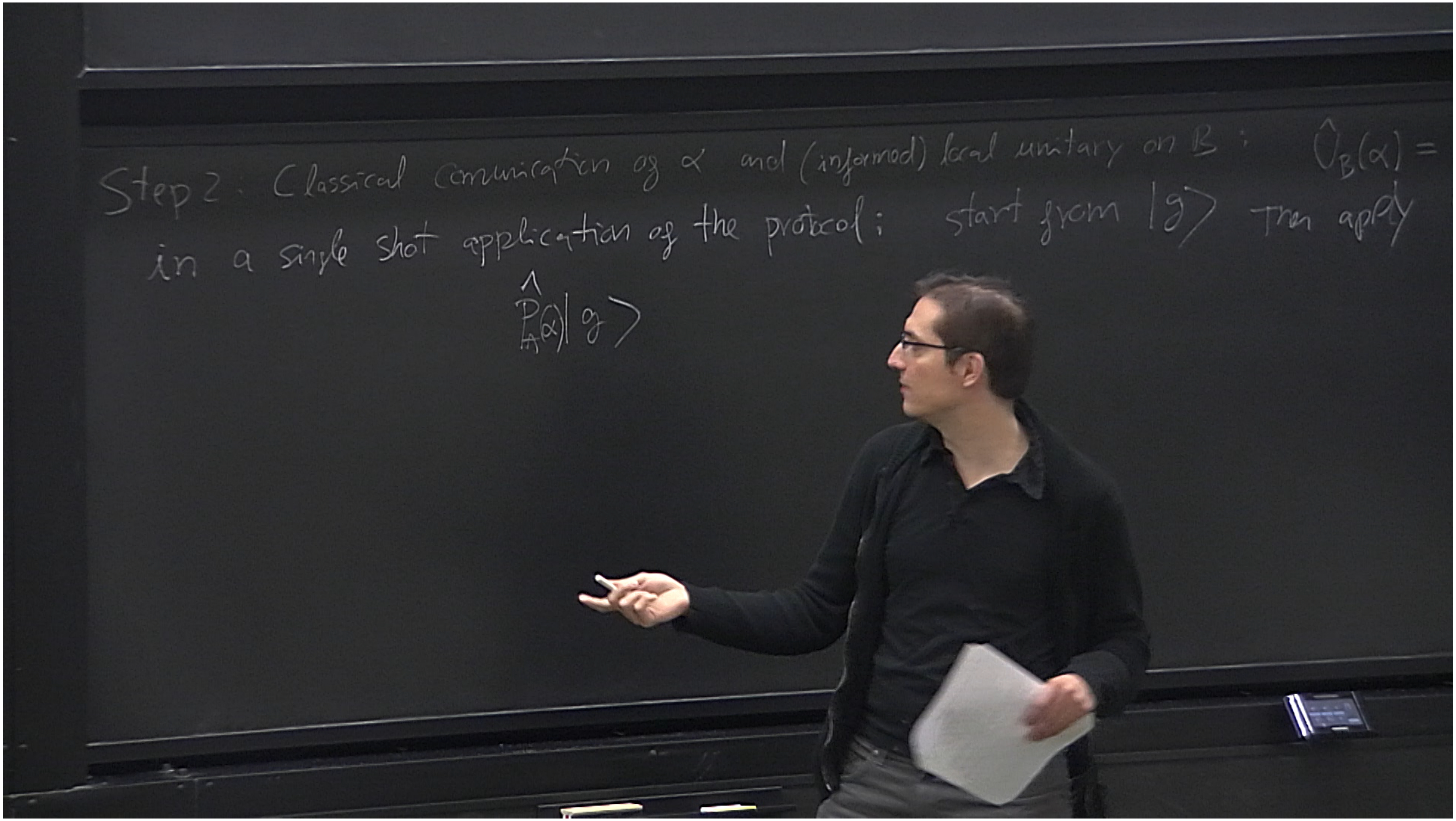

$\hat{U}_B(\alpha) = \cos\theta\, \mathbb{1} - i\alpha \sin\theta\, \hat{\sigma}_B^Y$
so that $\cos(2\theta) = \frac{h^2+2k^2}{\sqrt{(h^2+2k^2)^2+h^2k^2}}$; $\sin 2\theta = \frac{hk}{\sqrt{(h^2+2k^2)^2+h^2k^2}}$

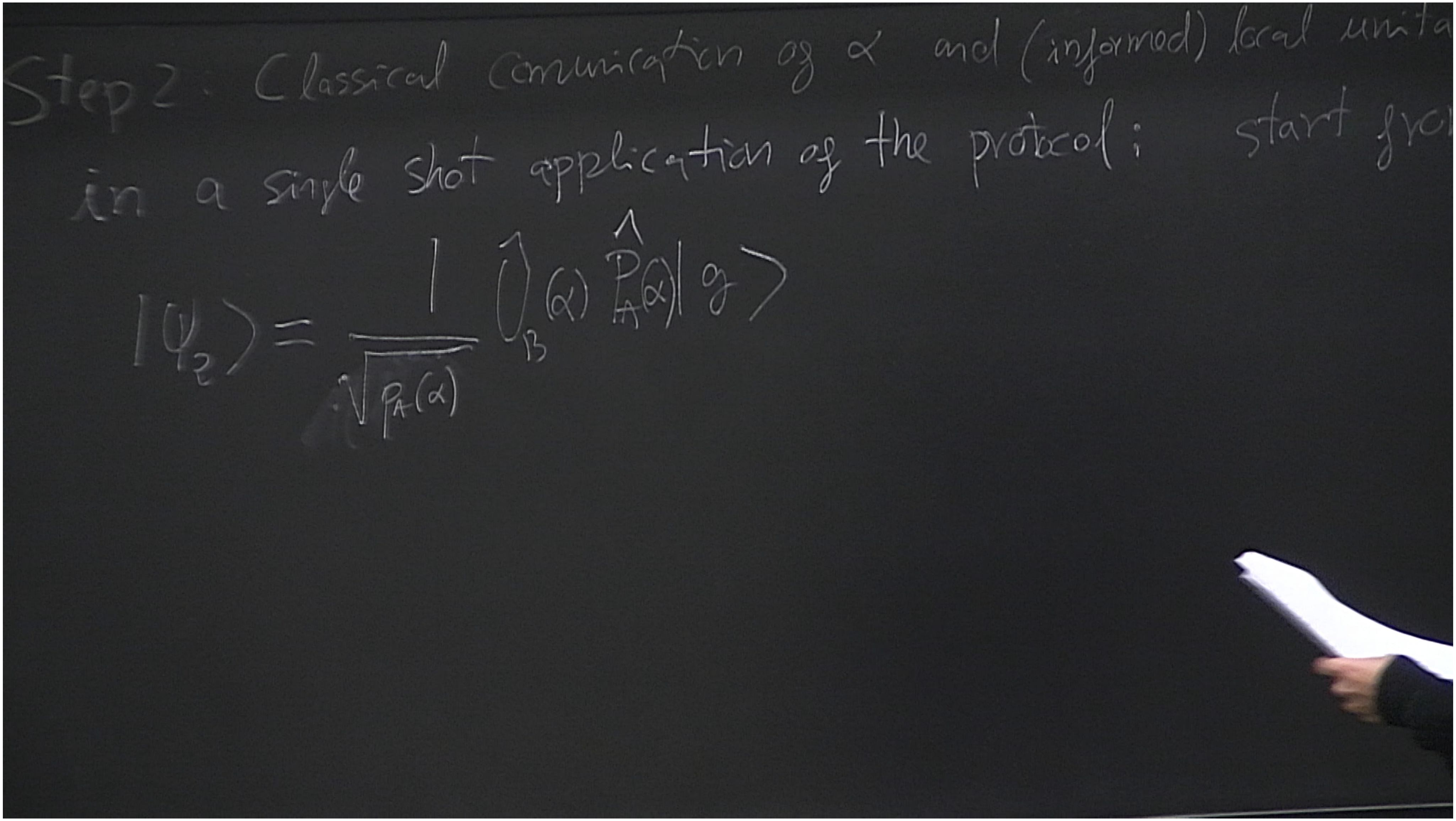
so that $\cos(2\theta) = \dfrac{h^2+2k^2}{\sqrt{(h^2+2k^2)^2+h^2k^2}}$; $\sin 2\theta = \dfrac{2hk}{\sqrt{(h^2+2k^2)^2+h^2k^2}}$

Step 2: Classical communication of α and (informed) local unitary on B: $\hat{U}_B(\alpha) =$

in a single shot application of the protocol: start from $|g\rangle$ Then apply


Û_B(α) = cos θ 𝟙 - iα sin θ σ̂_B^Y
so that cos(2θ) = (h^2+2k^2) / √((h^2+2k^2)^2 + h^2k^2) ; sin 2θ = hk / √((h^2+2k^2)^2 + h^2k^2)
Then apply PVM (P̂_A(α)) And then Û_B(α)

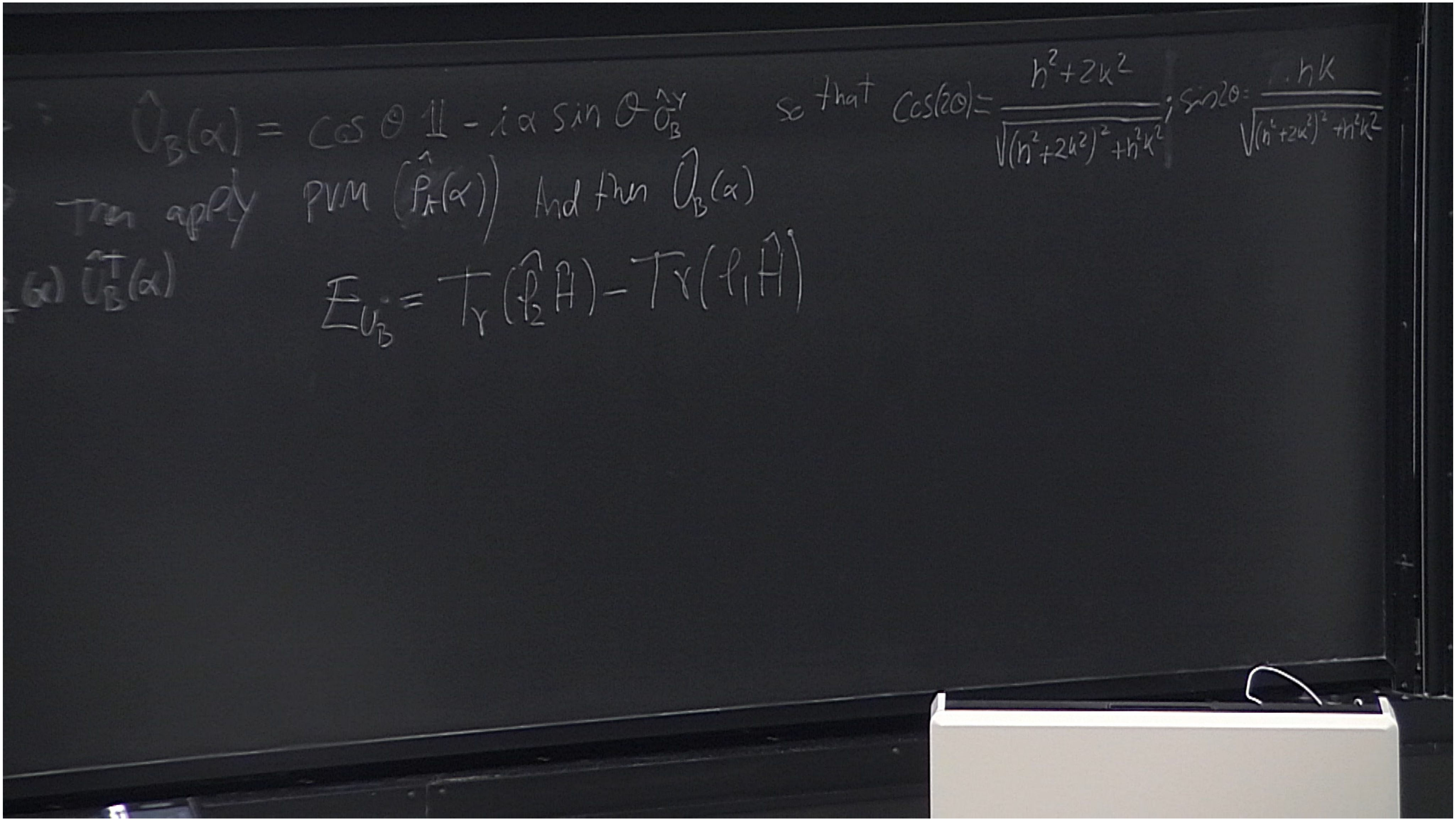

Step 2: Classical communication of α and (informed) local unitary on B : Ô_B(α) =
in a single shot application of the protocol: start from |g> Then apply
P̂_A(α)|g>

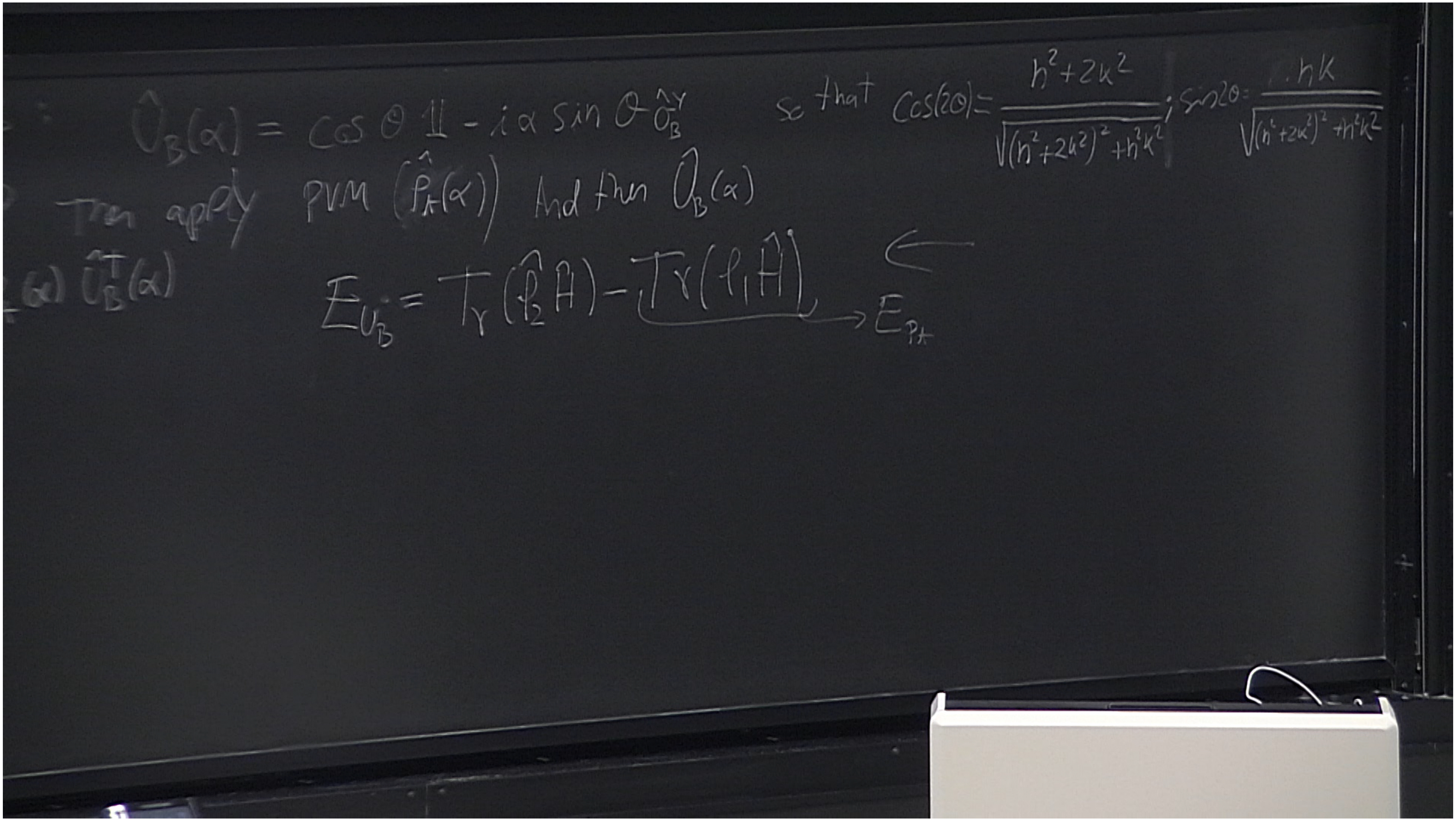

Step 2: Classical communication of α and (informed) local unita
in a single shot application of the protocol: start fro
$|\psi_2\rangle = \frac{1}{\sqrt{p_A(\alpha)}} U_B(\alpha)\,\hat{P}_A(\alpha)|g\rangle$

Step 2: Classical communication of α and (informed) local unitary on B: $\hat{U}_B(\alpha) = C$...

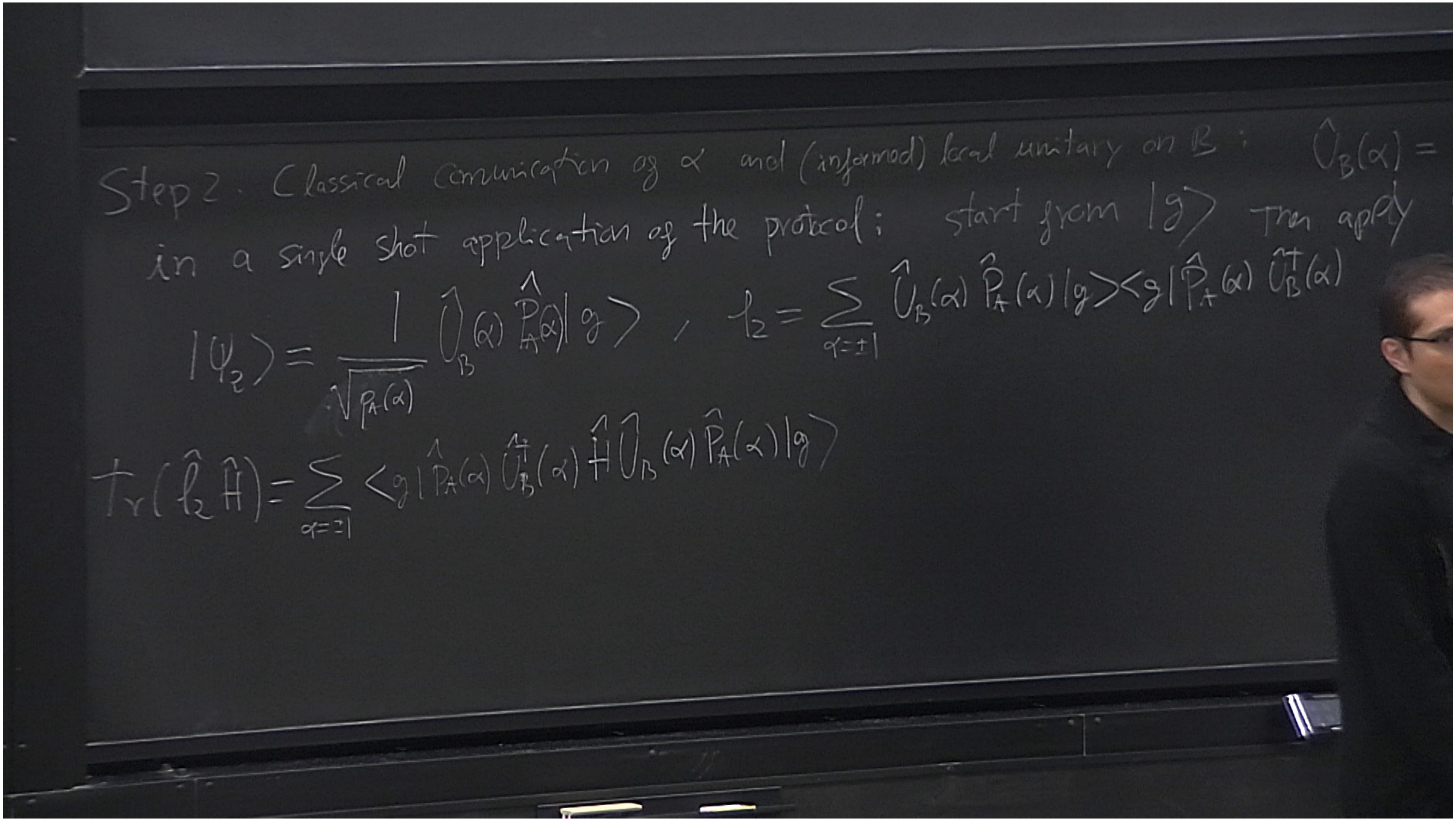
in a single shot application of the protocol: start from $|g\rangle$ Then apply pr...

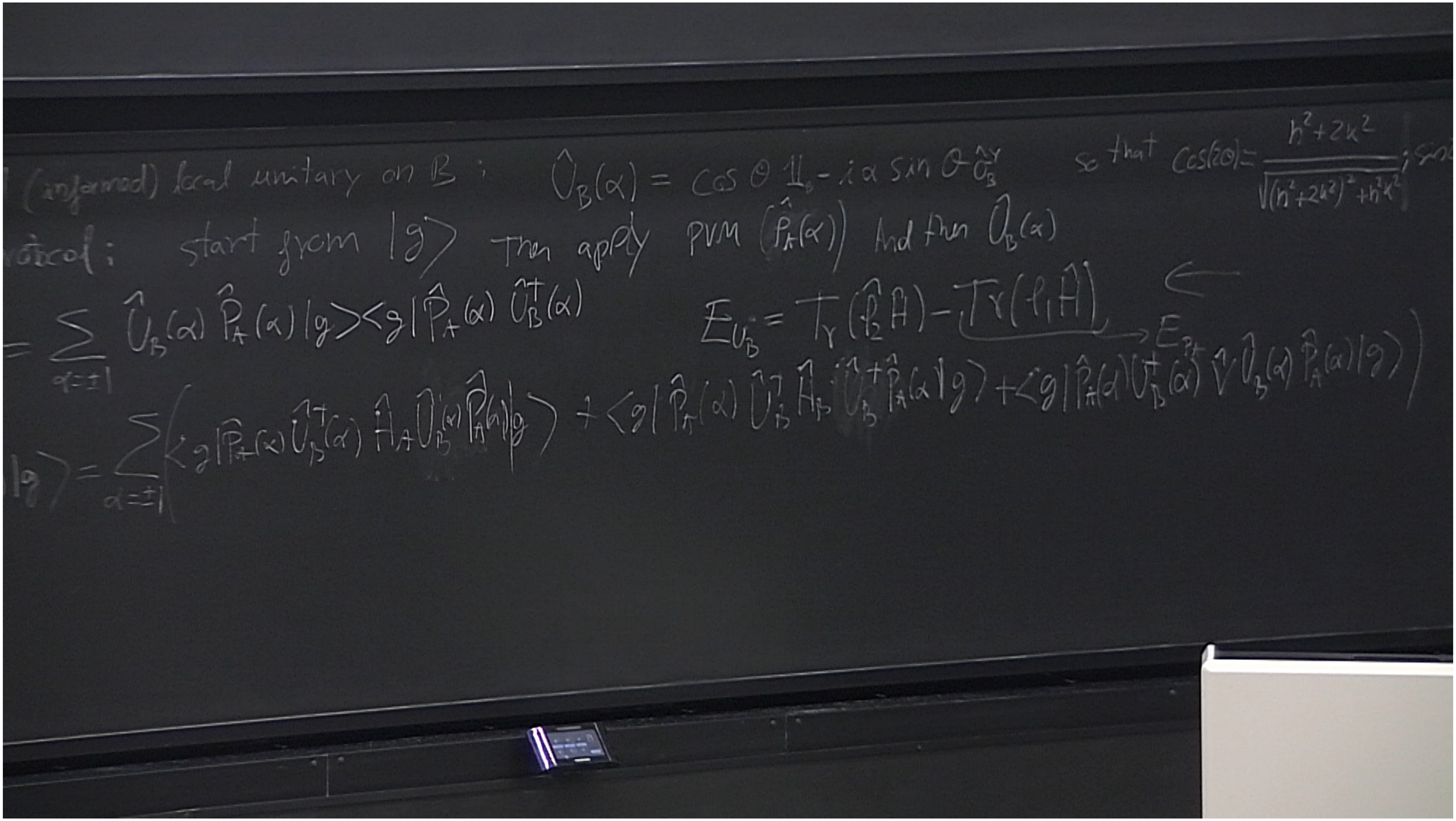
$$|\psi_2\rangle = \frac{1}{\sqrt{p_A(\alpha)}} \hat{U}_B(\alpha) \hat{P}_A(\alpha) |g\rangle \; , \quad \rho_2 = \sum_{\alpha=\pm 1} \hat{U}_B(\alpha) \hat{P}_A(\alpha) |g\rangle\langle g| \hat{P}_A(\alpha) \hat{U}_B^\dagger(\alpha)$$


$\hat{U}_B(\alpha) = \cos\theta\, \mathbb{1} - i\alpha \sin\theta\, \hat{\sigma}_B^y$
so that $\cos(2\theta) = \frac{h^2+2k^2}{\sqrt{(h^2+2k^2)^2+h^2k^2}}$; $\sin 2\theta = \frac{hk}{\sqrt{(h^2+2k^2)^2+h^2k^2}}$
Then apply PVM $(\hat{P}_A(\alpha))$ And then $\hat{U}_B(\alpha)$
$\hat{U}_B^\dagger(\alpha)$
$E_{U_B} = Tr(\hat{P}_2 \hat{H}) - Tr(\hat{P}_1 \hat{H})$



$\hat{O}_B(\alpha) = \cos\theta \, \mathbb{1} - i\alpha \sin\theta \, \hat{\sigma}_B^y$
so that $\cos(2\theta) = \frac{h^2+2k^2}{\sqrt{(h^2+2k^2)^2+h^2k^2}}$; $\sin 2\theta = \frac{hk}{\sqrt{(h^2+2k^2)^2+h^2k^2}}$
Then apply PVM $(\hat{P}_A(\alpha))$ And then $\hat{O}_B(\alpha)$
$\hat{U}_B^{\dagger}(\alpha)$
$E_{U_B} = \mathrm{Tr}(\hat{\rho}_2 \hat{H}) - \mathrm{Tr}(\rho_1 \hat{H})$
$\to E_{P_A}$


Step 2: Classical communication of α and (informed) local unitary on B: $\hat{U}_B(\alpha) =$
in a single shot application of the protocol: start from $|g\rangle$ then apply
$|\psi_2\rangle = \frac{1}{\sqrt{p_A(\alpha)}} \hat{U}_B(\alpha) \hat{P}_A(\alpha)|g\rangle$, $\rho_2 = \sum_{\alpha=\pm1} \hat{U}_B(\alpha) \hat{P}_A(\alpha)|g\rangle\langle g|\hat{P}_A(\alpha) \hat{U}_B^{\dagger}(\alpha)$
$\mathrm{Tr}(\hat{\rho}_2 \hat{H}) = \sum_{\alpha=\pm1} \langle g|\hat{P}_A(\alpha) \hat{U}_B^{\dagger}(\alpha) \hat{H} \hat{U}_B(\alpha) \hat{P}_A(\alpha)|g\rangle$


(informed) local unitary on B : $\hat{U}_B(\alpha) = \cos\theta \, 1\!\!1_B - i\alpha \sin\theta \, \hat{\sigma}_B^y$
so that $\cos(2\theta) = \frac{h^2+2k^2}{\sqrt{(h^2+2k^2)^2+h^2k^2}}$
otocol: start from $|g\rangle$ Then apply PVM $(\hat{P}_A(\alpha))$ And then $\hat{U}_B(\alpha)$
$= \sum_{\alpha=\pm1} \hat{U}_B(\alpha) \hat{P}_A(\alpha) |g\rangle\langle g| \hat{P}_A(\alpha) \hat{U}_B^\dagger(\alpha)$
$E_{U_B} = Tr(\hat{\rho}_2 \hat{H}) - Tr(\rho_1 \hat{H})$ → E_{P_A}
$|g\rangle = \sum_{\alpha=\pm1} \big(\langle g| \hat{P}_A(\alpha) \hat{U}_B^\dagger(\alpha) \hat{H}_A \hat{U}_B(\alpha) \hat{P}_A(\alpha) |g\rangle + \langle g| \hat{P}_A(\alpha) \hat{U}_B^\dagger \hat{H}_B \hat{U}_B^\dagger \hat{P}_A(\alpha) |g\rangle + \langle g| \hat{P}_A(\alpha) \hat{U}_B^\dagger(\alpha) \hat{V} \hat{U}_B(\alpha) \hat{P}_A(\alpha) |g\rangle \big)$

Step 2. Classical communication of α and (informed) local unitary on B: $\hat{O}_B(\alpha) =$

in a single shot application of the protocol: start from $|g\rangle$ then apply

$$|\psi_2\rangle = \frac{1}{\sqrt{p_A(\alpha)}}\hat{O}_B(\alpha)\hat{P}_A(\alpha)|g\rangle, \quad \rho_2 = \sum_{\alpha=\pm1}\hat{O}_B(\alpha)\hat{P}_A(\alpha)|g\rangle\langle g|\hat{P}_A(\alpha)\hat{O}_B^\dagger(\alpha)$$

$$Tr(\hat{\rho}_2\hat{H}) = \sum_{\alpha=\pm1}\langle g|\hat{P}_A(\alpha)\hat{O}_B^\dagger(\alpha)\hat{H}\hat{O}_B(\alpha)\hat{P}_A(\alpha)|g\rangle = \sum_{\alpha=\pm1}\Big(\langle g|\hat{P}_A(\alpha)\hat{O}_B^\dagger(\alpha)\hat{H}_A\hat{O}_B(\alpha)\hat{P}_A(\alpha)|g\rangle + \langle g|\hat{P}_A \ldots$$

Since $[\hat{H}_A, \hat{O}_B] = 0$

Step 2: Classical communication of α and (informed) local unitary on B: $\hat{U}_B(\alpha) =$

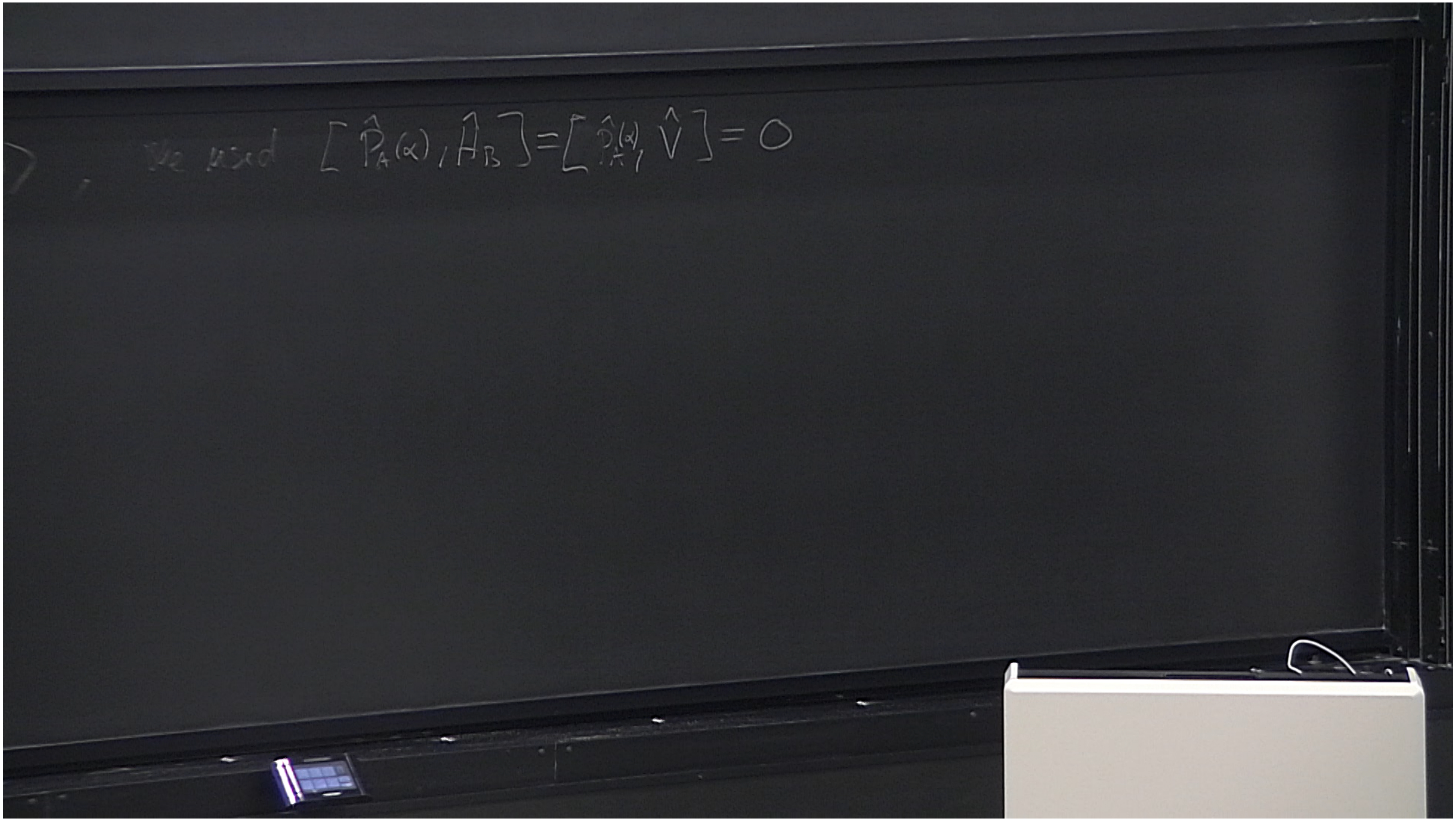
in a single shot application of the protocol: start from $|g\rangle$ Then apply

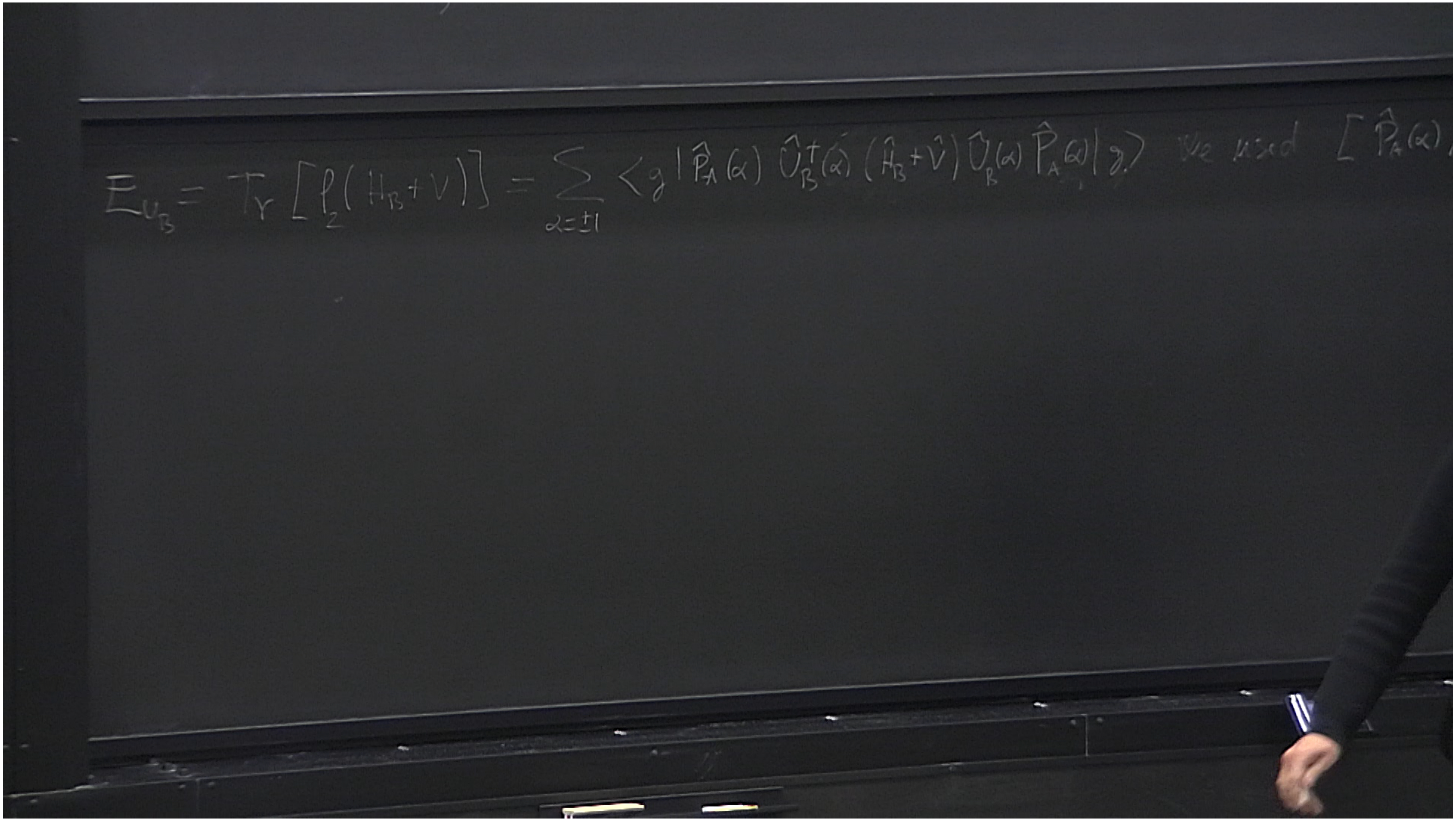
$$|\psi_2\rangle = \frac{1}{\sqrt{p_A(\alpha)}} \hat{U}_B(\alpha) \hat{P}_A(\alpha) |g\rangle \quad , \quad \rho_2 = \sum_{\alpha=\pm 1} \hat{U}_B(\alpha) \hat{P}_A(\alpha) |g\rangle\langle g| \hat{P}_A(\alpha) \hat{U}_B^\dagger(\alpha)$$

$$\mathrm{Tr}(\hat{\rho}_2 \hat{H}) = \sum_{\alpha=\pm 1} \langle g| \hat{P}_A(\alpha) \hat{U}_B^\dagger(\alpha) \hat{H} \hat{U}_B(\alpha) \hat{P}_A(\alpha) |g\rangle = \sum_{\alpha=\pm 1} \underbrace{\Big(\langle g| \hat{P}_A(\alpha) \hat{U}_B^\dagger(\alpha) \hat{H}_A \hat{U}_B(\alpha) \hat{P}_A(\alpha) |g\rangle}_{E_{P_A}} + \langle g| \hat{P}_A \ldots$$

Since $[\hat{H}_A, \hat{U}_B] = 0 \Longrightarrow$

$$E_{U_B} = \mathrm{Tr}\left[\rho_2 (H_B + V)\right] = \sum_{\alpha=\pm 1} \langle g | \hat{P}_A(\alpha)\, \hat{U}_B^{\dagger}(\alpha)\, (\hat{H}_B + \hat{V})\, \hat{U}_B(\alpha) | g \rangle$$


We used $[\hat{P}_A(\alpha), \hat{A}_B] = [\hat{P}_A(\alpha), \hat{V}] = 0$


$E_{U_B} = \mathrm{Tr}\left[\rho_2 (H_B + V)\right] = \sum_{\alpha=\pm 1} \langle g | \hat{P}_A(\alpha)\, \hat{U}_B^\dagger(\alpha)\, (\hat{H}_B + \hat{V})\, \hat{U}_B(\alpha)\, \hat{P}_A(\alpha) | g \rangle$
We used $[\hat{P}_A(\alpha),$

$$E_{U_B} = \mathrm{Tr}\left[\rho_2 (H_B + V)\right] = \sum_{\alpha=\pm1} \langle g | \hat{P}_A(\alpha)\, \hat{U}_B^{\dagger}(\alpha)\, (\hat{H}_B + \hat{V})\, \hat{U}_B(\alpha)\, \hat{P}_A(\alpha) | g \rangle$$

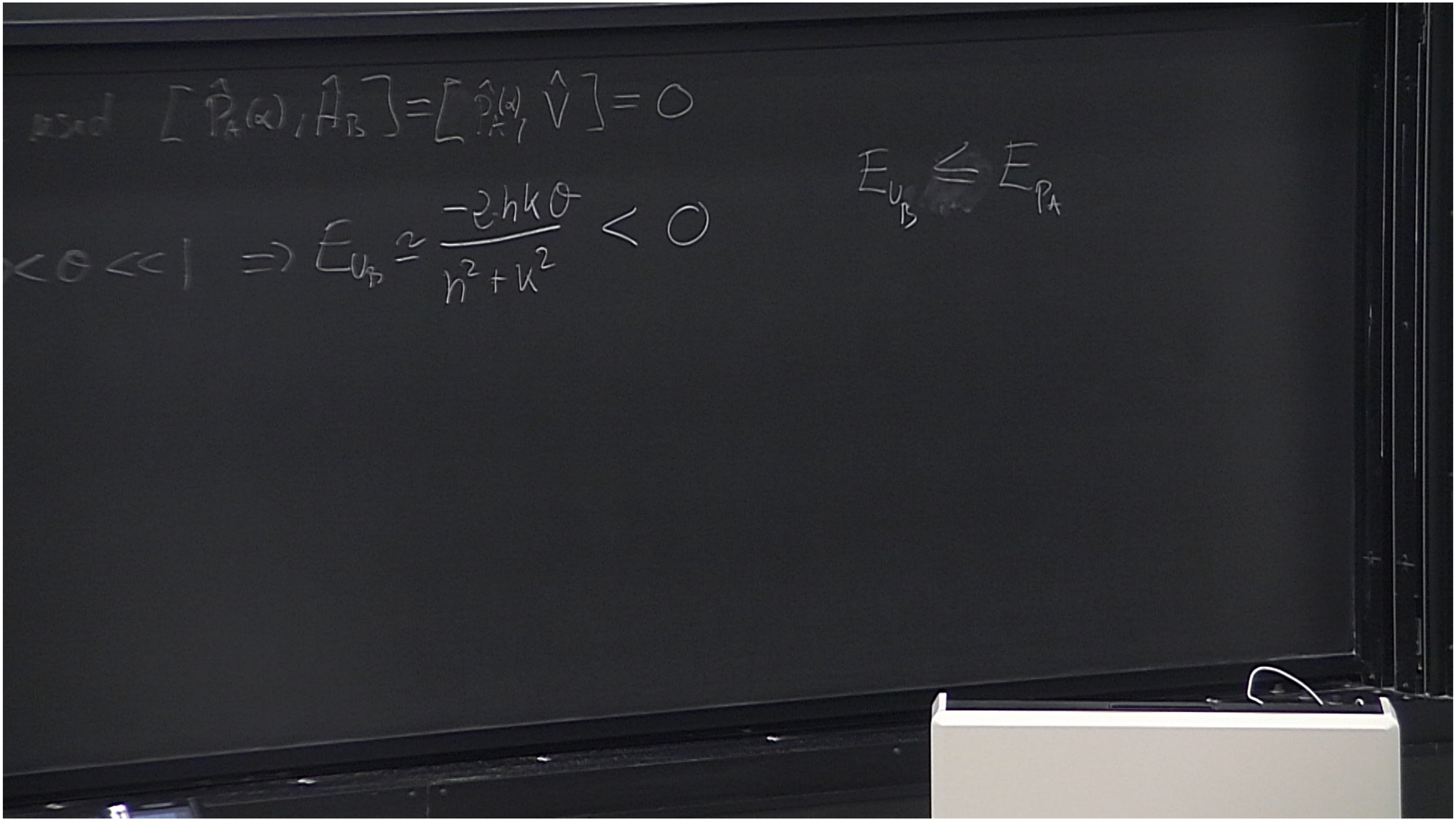
we used $[\hat{P}_A(\alpha),$

$$E_{U_B} = \frac{-1}{h^2+k^2}\left[hk \sin 2\theta - (h^2+2k^2)(1-\cos 2\theta)\right]$$

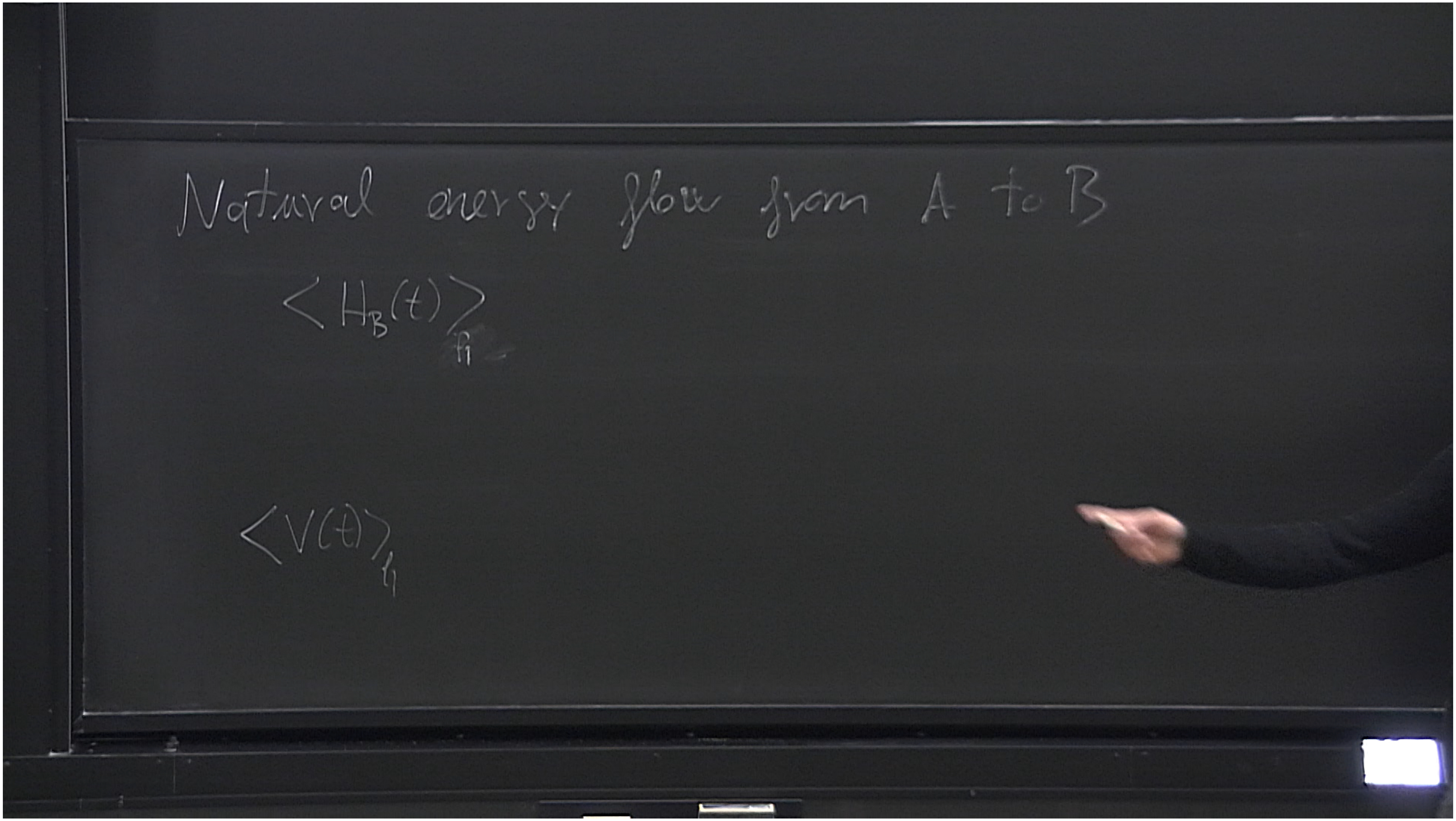
$$\sum_{\alpha=\pm1} \langle g | \hat{P}_A(\alpha)\, \hat{U}_B^\dagger(\alpha)\, (\hat{A}_B + \hat{V})\, \hat{U}_B(\alpha)\, \hat{P}_A(\alpha) | g \rangle$$ we used $[\hat{P}_A(\alpha), \hat{A}_B] = [\hat{P}_A(\alpha), \hat{V}] = 0$

$$\sin 2\alpha - (h^2 + 2k^2)(1 - \cos 2\theta) \Big) \Big]$$

if $0 < \theta \ll 1 \Rightarrow E_{U_B} \simeq \frac{-2hk\theta}{h^2+k^2} < 0$



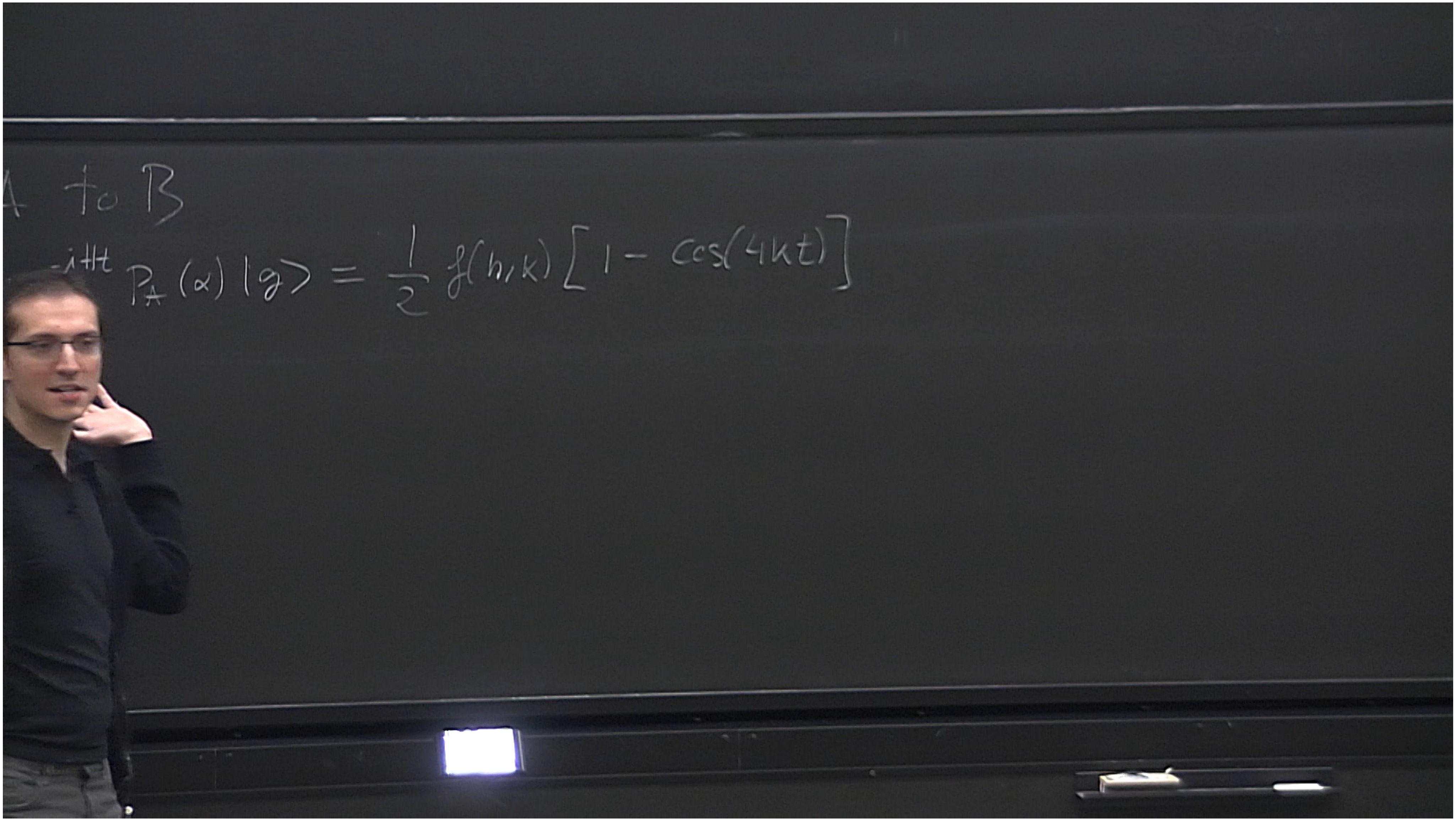
$[\hat{P}_A(\alpha), \hat{A}_B] = [\hat{P}_A(\alpha), \hat{V}] = 0$
$E_{U_B} \leq E_{P_A}$
$< \theta << 1 \Rightarrow E_{U_B} \simeq \frac{-2hk\theta}{h^2+k^2} < 0$

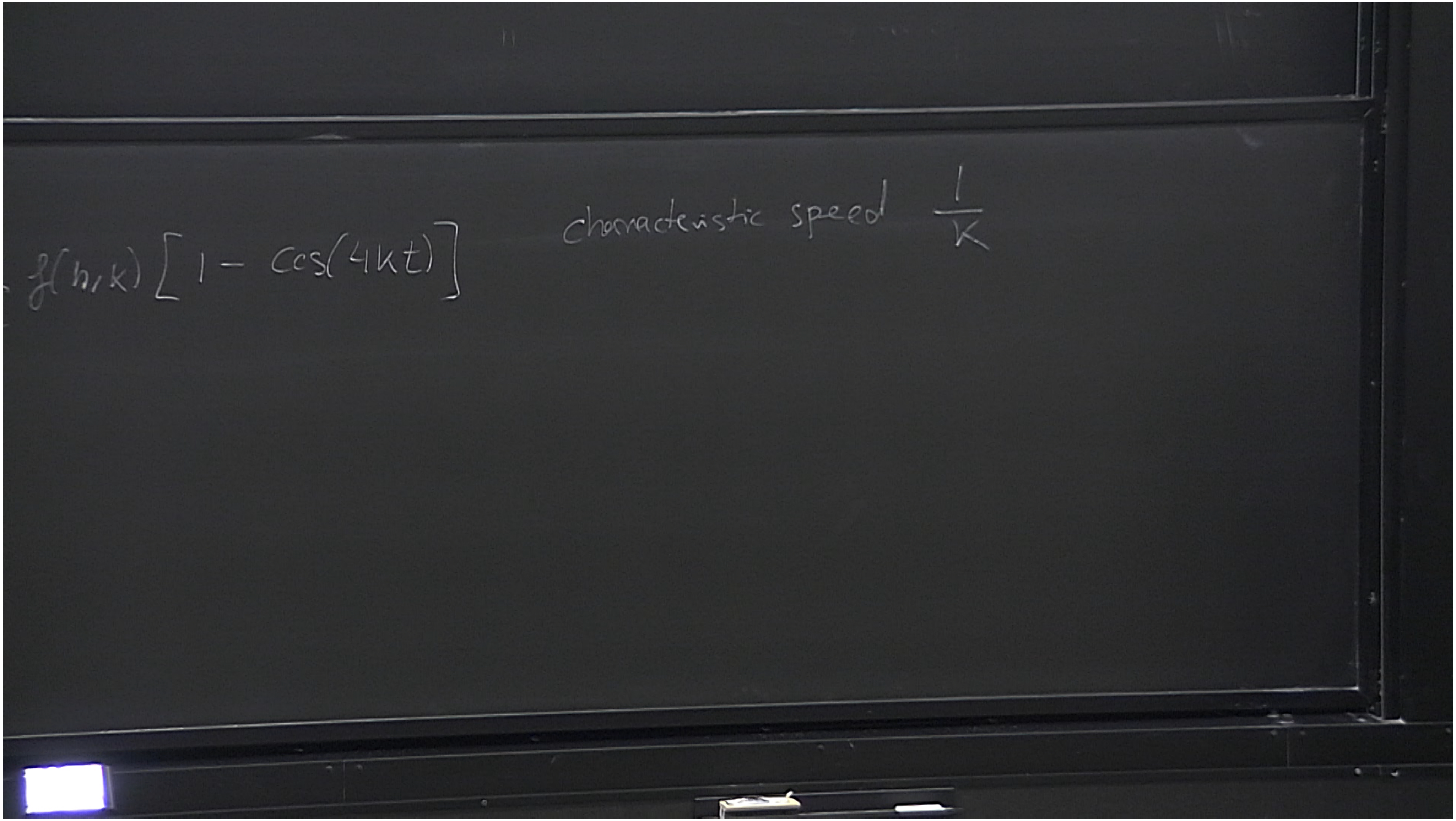

Natural energy flow from A to B
$\langle H_B(t) \rangle_{t_1}$
$\langle V(t) \rangle_{t_1}$

Natural energy flow from A to B

$$\langle H_B(t) \rangle_{P_1} = \sum_{\alpha = \pm 1} \langle g | P_A(\alpha) e^{iHt} H_B e^{-iHt} P_A(\alpha) | g \rangle = \frac{1}{2}$$

$$\langle V(t) \rangle_{P_1}$$

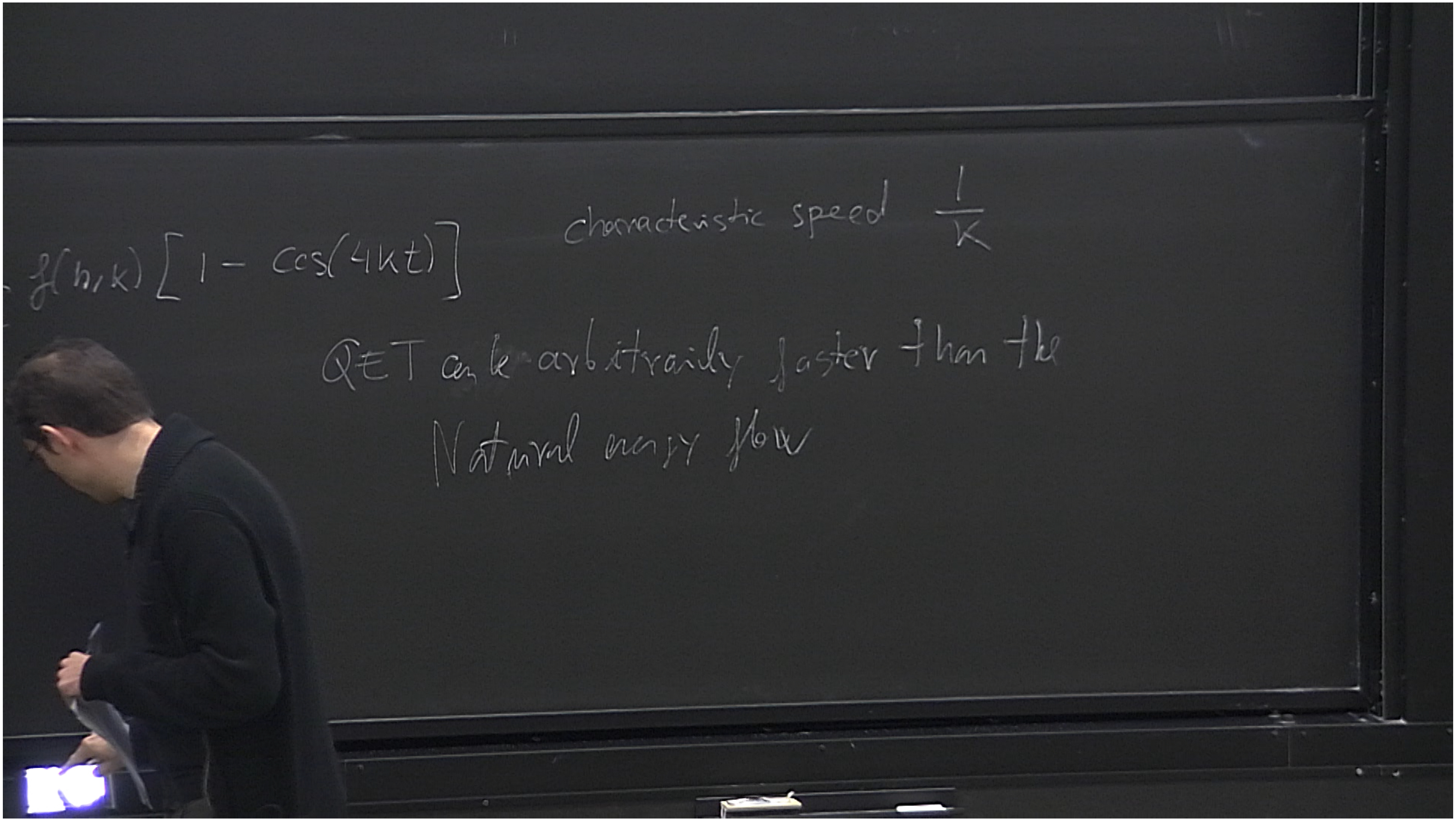

A to B
-iHt PA (α) |g> = 1/2 f(h,k) [1 - cos(4kt)]

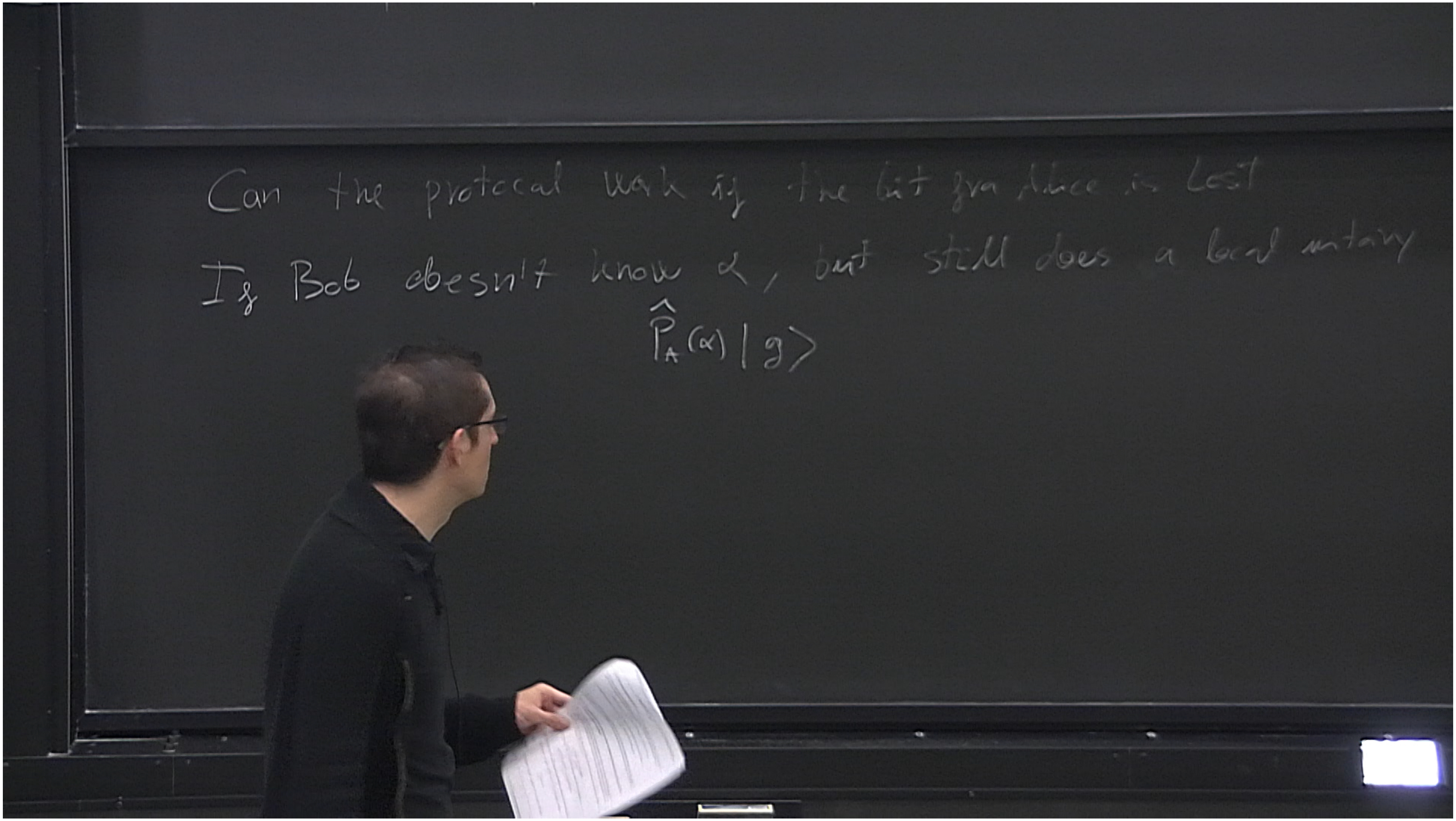

f(n,k) [1 − cos(4kt)]
characteristic speed 1/k

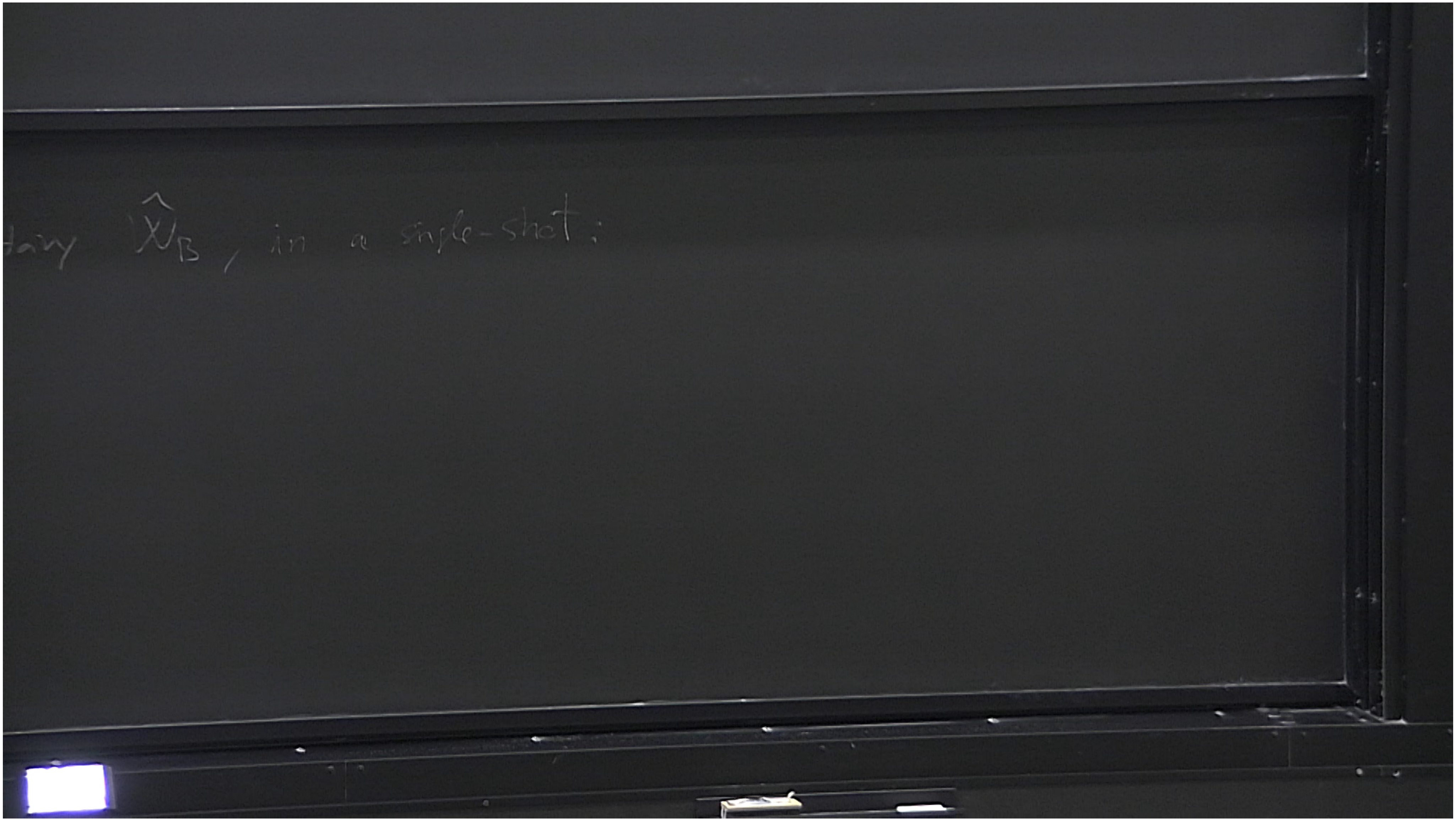
Natural energy flow from A to B

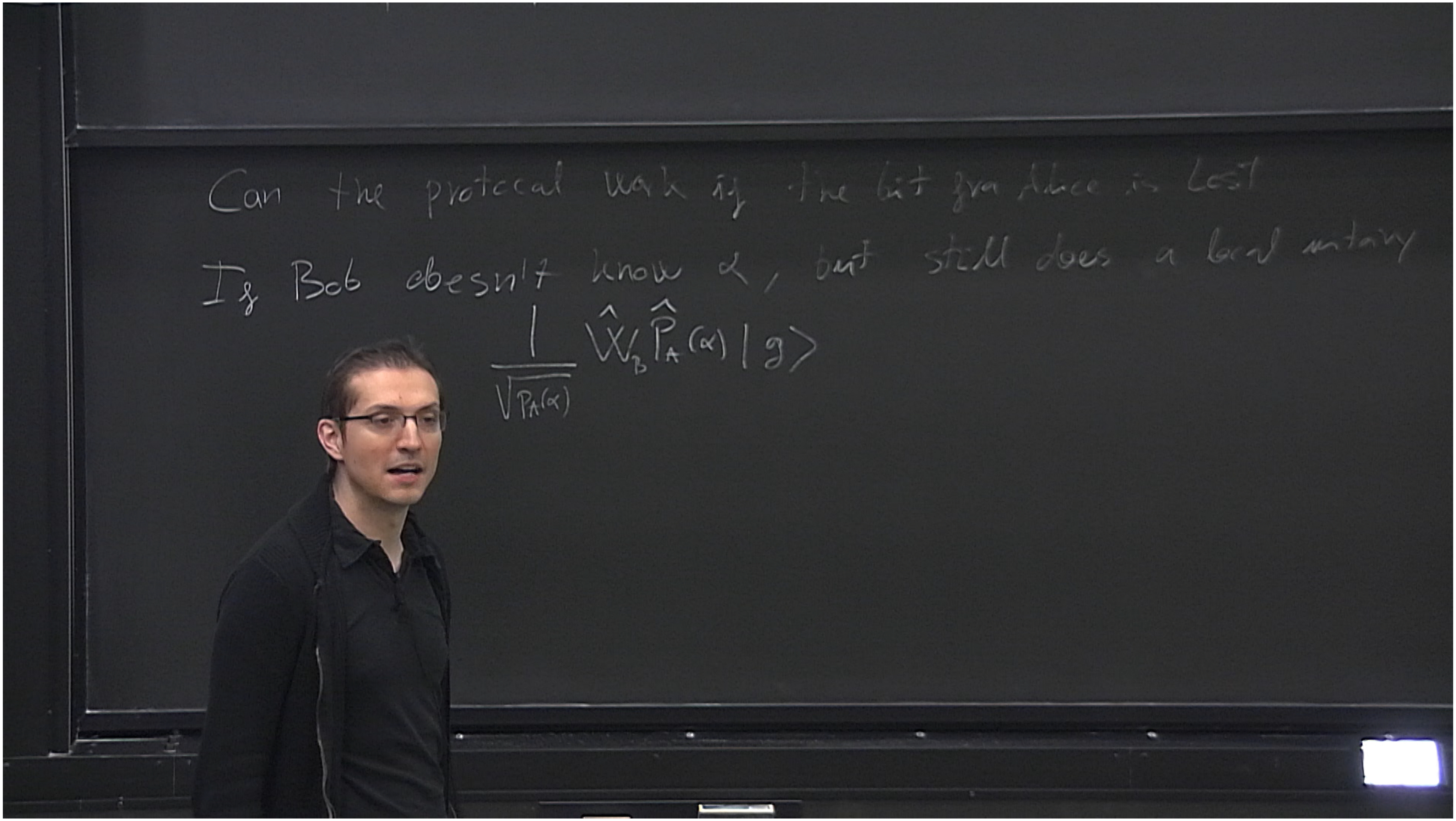
$$\langle H_B(t) \rangle_{P_1} = \sum_{\alpha=\pm 1} \langle g | P_A(\alpha) e^{iHt} H_B e^{-iHt} P_A(\alpha) | g \rangle = \frac{1}{2} f(h, \ldots$$

$$\langle V(t) \rangle_{P_1} = \sum_{\alpha=\pm 1} \langle g | P_A(\alpha) e^{i\hat{H}t} \hat{V} e^{-iHt} (\alpha) | g \rangle = 0$$


f(h,k) [1 − cos(4kt)]
characteristic speed 1/k
QET can be arbitrarily faster than the
Natural energy flow


Can the protocal work if the bit from Alice is lost
If Bob doesn't know α, but still does a local unitary
$\hat{P}_A(\alpha)|g\rangle$

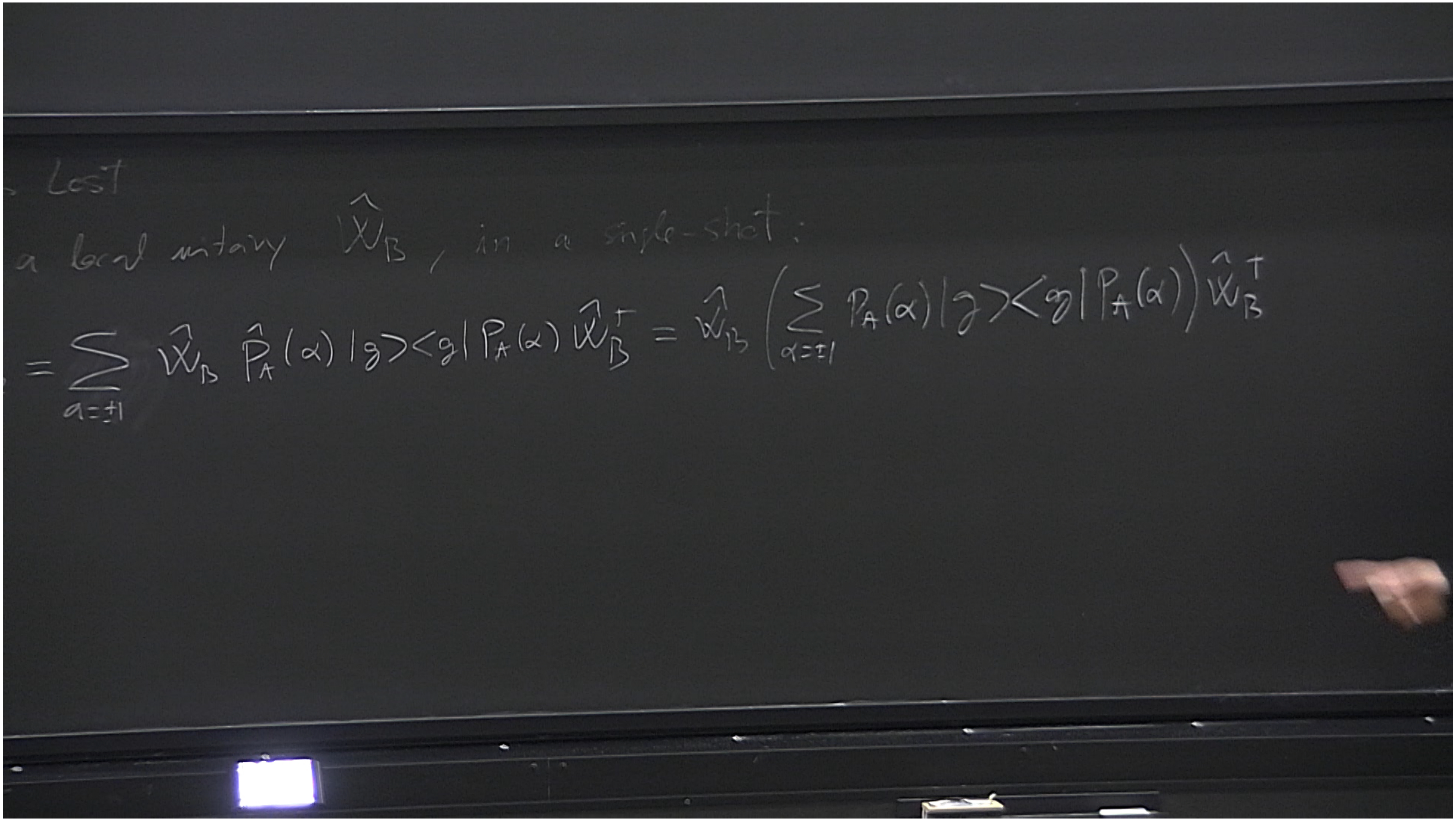

tary $\hat{X}_B$, in a single-shot:


Can the protocol work if the bit from Alice is lost
If Bob doesn't know α, but still does a local unitary
$\frac{1}{\sqrt{P_A(\alpha)}} \hat{W}_B \hat{P}_A(\alpha) |g\rangle$

Can the protocol work if the bit from Alice is lost

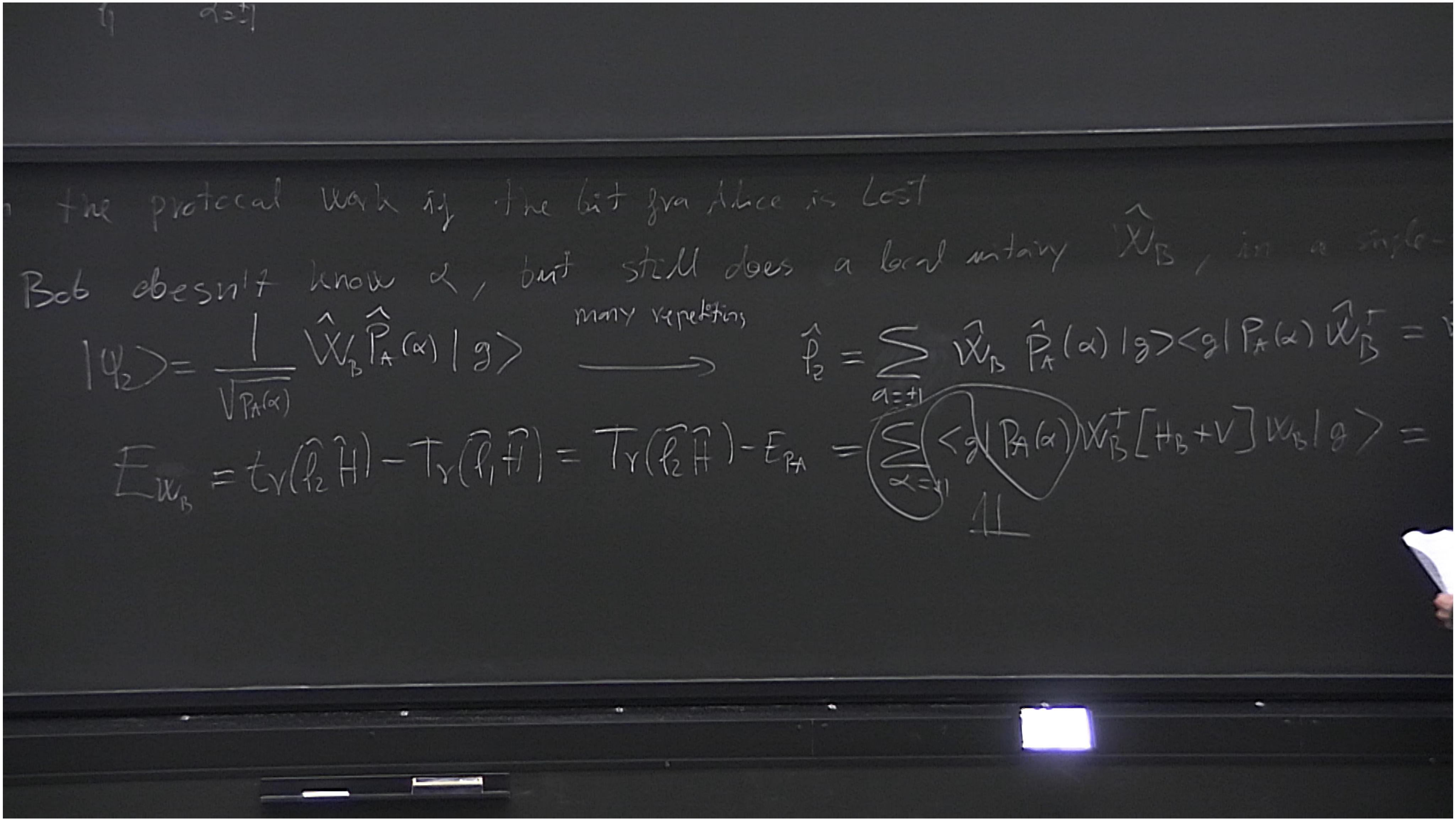
If Bob doesn't know α, but still does a local unitary

$$|\psi_2\rangle = \frac{1}{\sqrt{p_A(\alpha)}} \hat{W}_B \hat{P}_A(\alpha) |g\rangle \xrightarrow{\text{many repetitions}} \hat{\rho}_2 = \sum_{a=\pm 1} \hat{W}_B \hat{P}_A(\alpha$$


Lost
a local unitary $\hat{W}_B$, in a single-shot:
$= \sum_{a=\pm 1} \hat{W}_B \hat{P}_A(\alpha) |g\rangle\langle g| P_A(\alpha) \hat{W}_B^\dagger = \hat{W}_B \left(\sum_{\alpha=\pm 1} P_A(\alpha) |g\rangle\langle g| P_A(\alpha) \right) \hat{W}_B^\dagger$

...tary $\hat{W}_B$, in a single-shot:

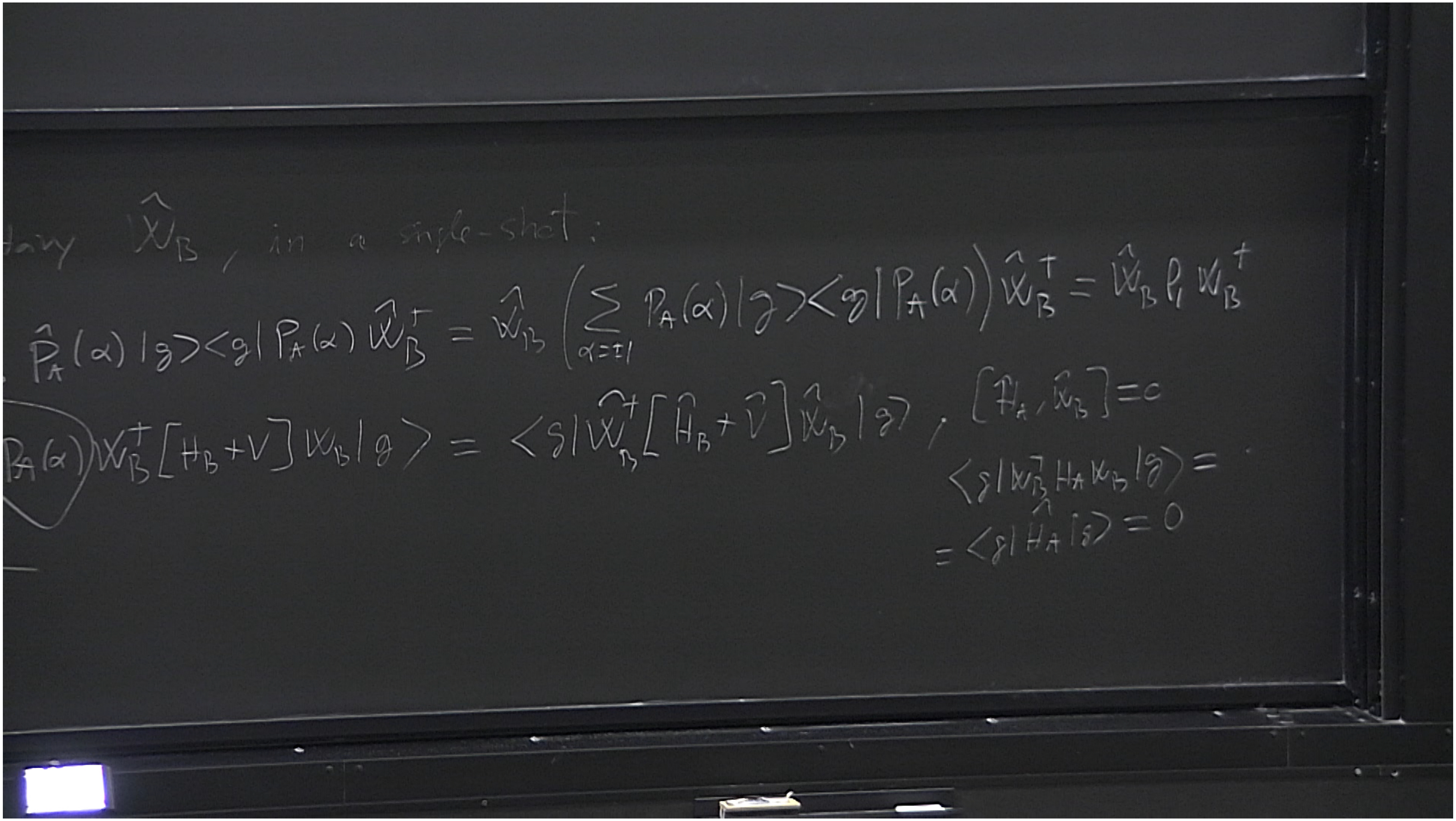
$$\hat{P}_A(\alpha)\,|g\rangle\langle g|\,P_A(\alpha)\,\hat{W}_B^\dagger = \hat{W}_B\left(\sum_{\alpha=\pm1} P_A(\alpha)\,|g\rangle\langle g|\,P_A(\alpha)\right)\hat{W}_B^\dagger = \hat{W}_B\,\rho_1\,W_B^\dagger$$


the protocal work if the bit from Alice is lost
Bob doesn't know α, but still does a local unitary $\hat{W}_B$, in a single-
many repetitions
$|\psi_2\rangle = \frac{1}{\sqrt{P_A(\alpha)}} \hat{W}_B \hat{P}_A(\alpha) |g\rangle \longrightarrow \hat{\rho}_2 = \sum_{\alpha=\pm 1} \hat{W}_B \hat{P}_A(\alpha) |g\rangle\langle g| P_A(\alpha) \hat{W}_B^\dagger =$
$E_{W_B} = tr(\hat{\rho}_2 \hat{H}) - Tr(\hat{\rho}_1 \hat{H}) = Tr(\hat{\rho}_2 \hat{H}) - E_{PA} = \sum_{\alpha=\pm 1} \langle g | P_A(\alpha) W_B^\dagger [H_B + V] W_B | g \rangle =$
$\mathbb{1}$

...tary $\hat{W}_B$, in a single-shot:

$$\hat{P}_A(\alpha)|g\rangle\langle g|P_A(\alpha)\hat{W}_B^\dagger = \hat{W}_B\left(\sum_{\alpha=\pm 1} P_A(\alpha)|g\rangle\langle g|P_A(\alpha)\right)\hat{W}_B^\dagger = \hat{W}_B\,\rho_1\,W_B^\dagger$$

$$P_A(\alpha) W_B^\dagger[H_B+V]W_B|g\rangle = \langle g|\hat{W}_B^\dagger[\hat{H}_B+\hat{V}]\hat{W}_B|g\rangle$$


tary $\hat{W}_B$, in a single-shot:
$\hat{P}_A(\alpha)|g\rangle\langle g|P_A(\alpha)\hat{W}_B^\dagger = \hat{W}_B\left(\sum_{\alpha=\pm1} P_A(\alpha)|g\rangle\langle g|P_A(\alpha)\right)\hat{W}_B^\dagger = \hat{W}_B \rho_1 W_B^\dagger$
$P_A(\alpha)) W_B^\dagger [H_B+V] W_B|g\rangle = \langle g|\hat{W}_B^\dagger [\hat{H}_B+\hat{V}] \hat{W}_B|g\rangle$, $[\hat{H}_A, \hat{W}_B]=0$
$\langle g|W_B^\dagger H_A W_B|g\rangle =$
$= \langle g|\hat{H}_A|g\rangle = 0$

tary $\hat{W}_B$, in a single-shot:

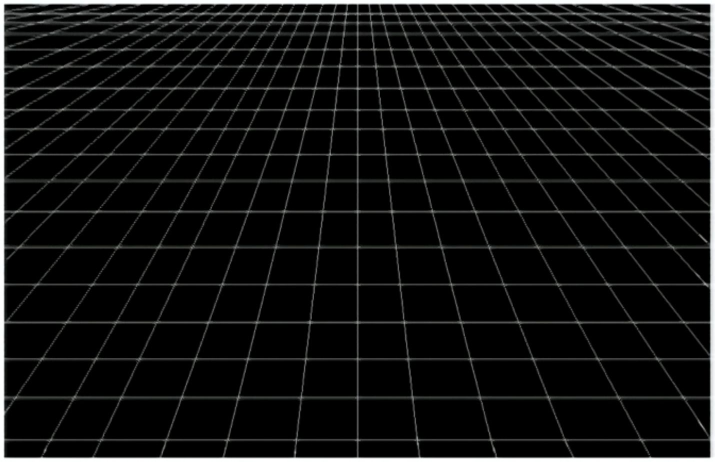
$$\hat{P}_A(\alpha)|g\rangle\langle g|P_A(\alpha)\hat{W}_B^\dagger = \hat{W}_B\left(\sum_{\alpha=\pm1} P_A(\alpha)|g\rangle\langle g|P_A(\alpha)\right)\hat{W}_B^\dagger = \hat{W}_B \rho_1 W_B^\dagger$$

$$P_A(\alpha) W_B^\dagger[H_B+V]W_B|g\rangle = \langle g|\hat{W}_B^\dagger[\hat{H}_B+\hat{V}]\hat{W}_B|g\rangle, \quad [\hat{H}_A,\hat{W}_B]=0$$

$$\langle g|W_B^\dagger H_A W_B|g\rangle = \langle g|\hat{H}_A|g\rangle = 0$$

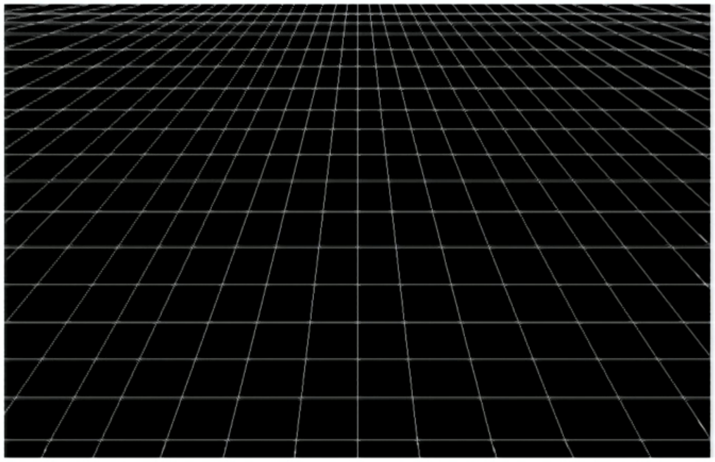
$$E_{W_B} = \langle g|W_B^\dagger[\underbrace{\hat{H}_A+\hat{H}_B+\hat{V}}_{\hat{H}}]\hat{W}_B|g\rangle \geq 0 \Leftarrow$$

Warping the fabric of spacetime



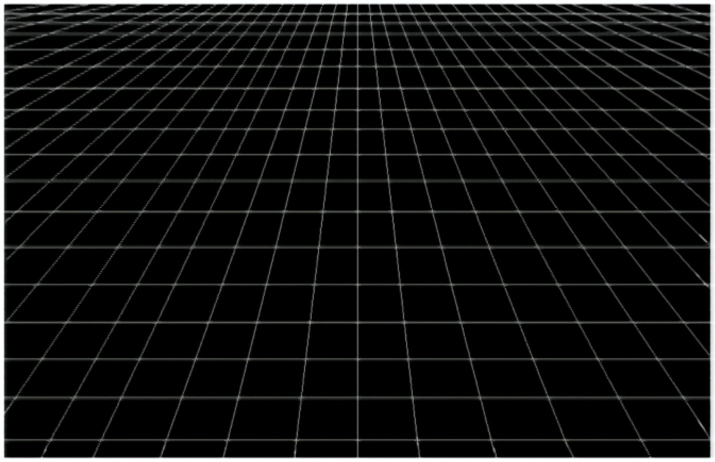
Preparation of states of spacetime

Warping the fabric of spacetime



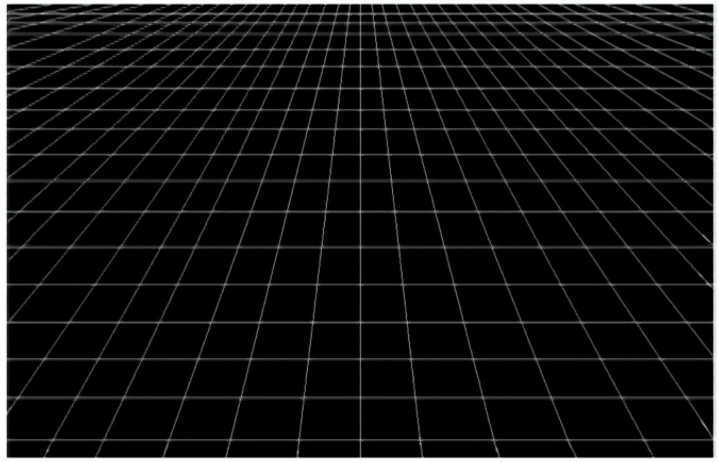
Preparation of states of spacetime

Warping the fabric of spacetime



Preparation of states of spacetime

Warping the fabric of spacetime



Preparation of states of spacetime

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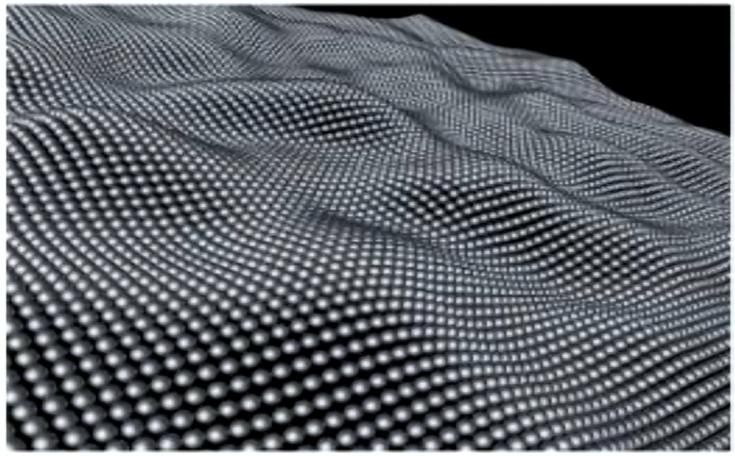


Preparation of states of spacetime

Exotic spacetimes

Einstein Equations: $$\underbrace{R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu}}_{\text{Geometry}} = \underbrace{\frac{8\pi G}{c^4} T_{\mu\nu}}_{\text{Stress-energy}}$$

Weak energy condition: $$T_{\mu\nu}\xi^{\mu}\xi^{\nu} \geq 0.$$

If violated: Exotic solutions:

-Wormholes

-Warp drives

-Anti-gravity / screening

Exotic spacetimes

Quantum Fields violate AWEC:

$$\frac{\tau_0}{\pi}\int_{-\infty}^{\infty}\frac{\langle\hat{T}_{\mu\nu}\xi^{\mu}\xi^{\nu}\rangle}{\tau^2+\tau_0^2}d\tau \geq -\frac{3}{32\pi^2\tau_0^4}.$$

Ford, Pfenning, etc...

Exotic spacetimes

How can we engineer violations of AWEC?

Nature does not have perfect mirrors…

$$\frac{\tau_0}{\pi}\int_{-\infty}^{\infty}\frac{\langle \hat{T}_{\mu\nu}\xi^\mu\xi^\nu\rangle}{\tau^2+\tau_0^2}d\tau \geq -\frac{3}{32\pi^2\tau_0^4}.$$

Breaking Strong Local Passivity
Quantum Energy Teleportation

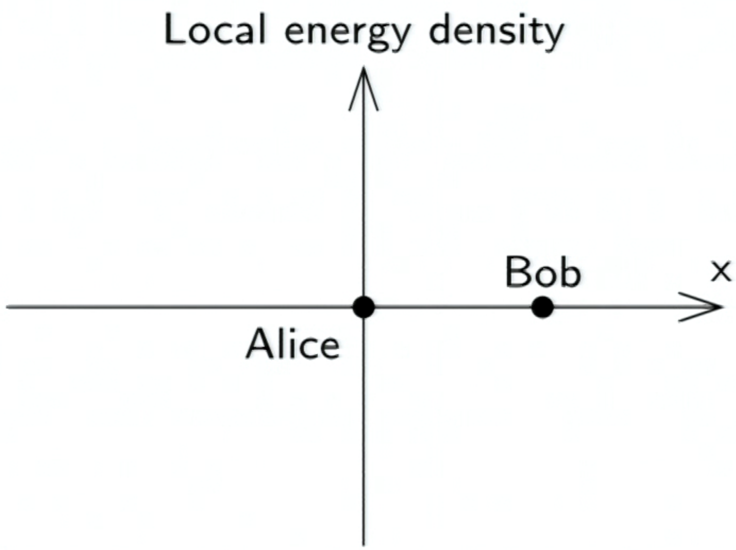
Unexpected result: Unlock zero-point energy
Consuming **entanglement**

What about quantum fields?

Ground state is entangled!

Can we pull the same trick?

Breaking Strong Local Passivity
Quantum Energy Teleportation



[1] Hotta, *Phys. Rev. D.*, 78.045006, Aug 2008

Breaking Strong Local Passivity
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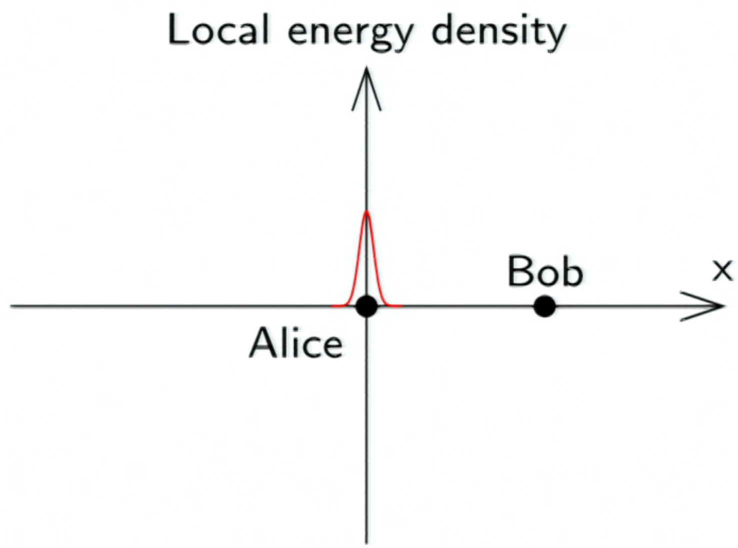

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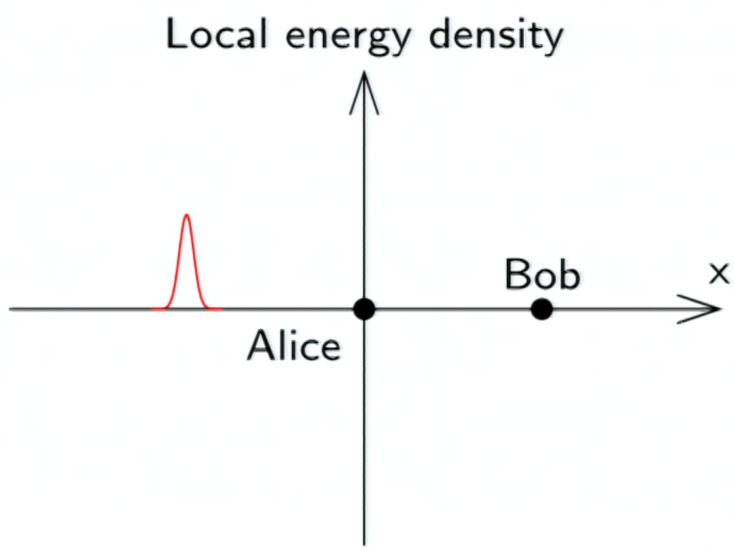

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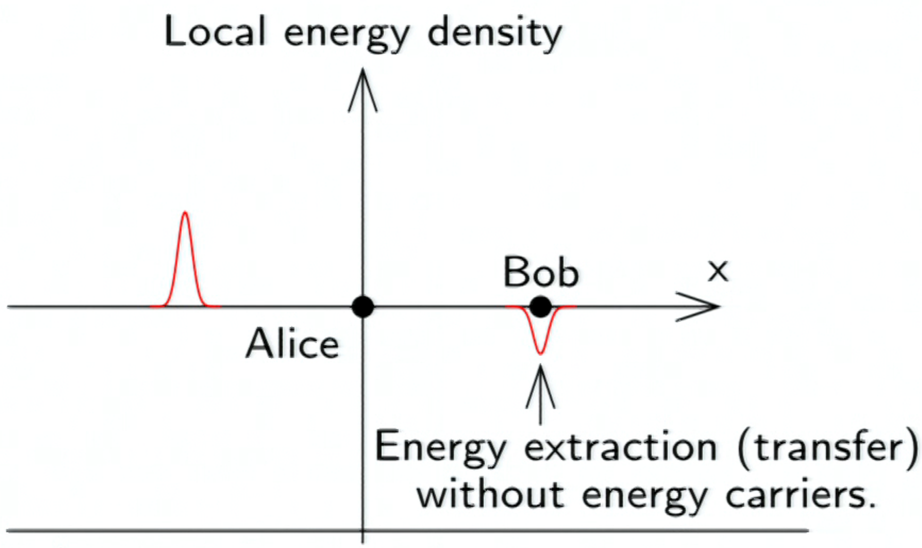

[1] Hotta, *Phys. Rev. D.*, 78.045006, Aug 2008

[2] Hotta, *J. Phys. A: Math. Theor.*, 43,105305 (2010)

Breaking Strong Local Passivity
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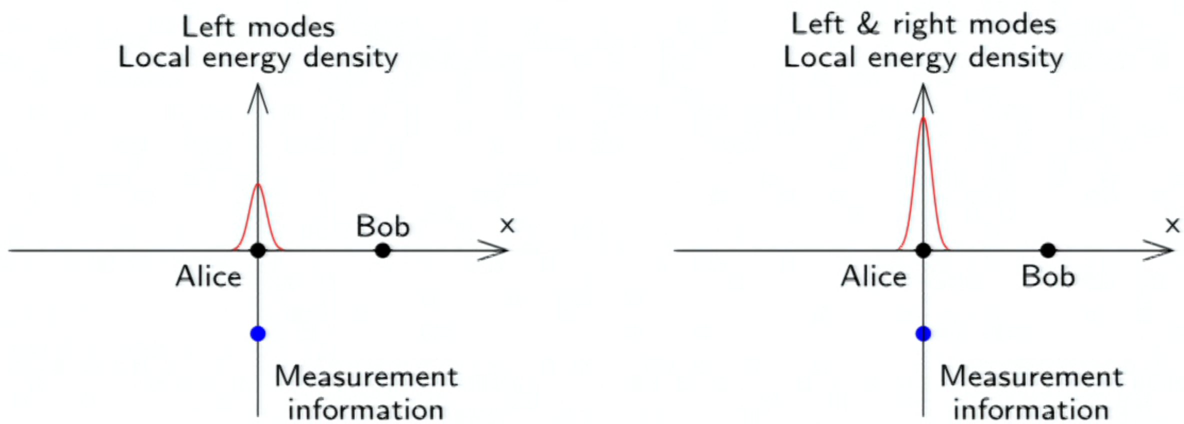

Breaking Strong Local Passivity
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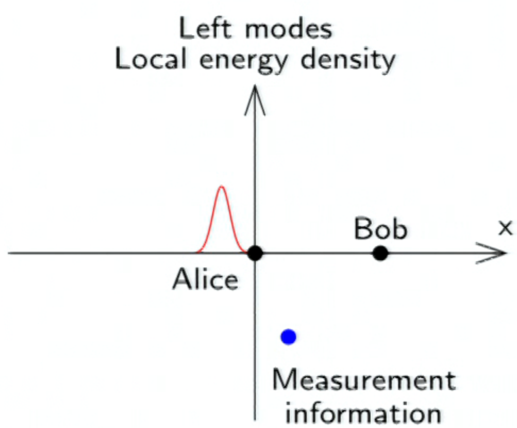

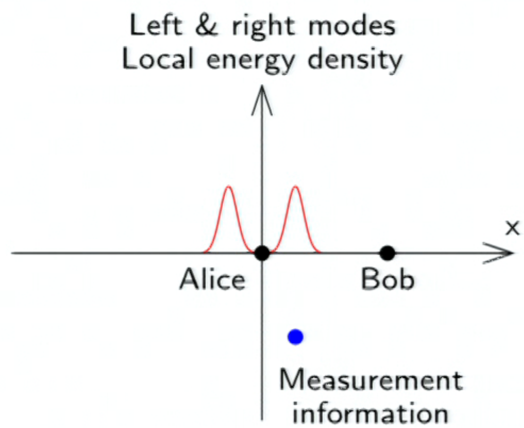

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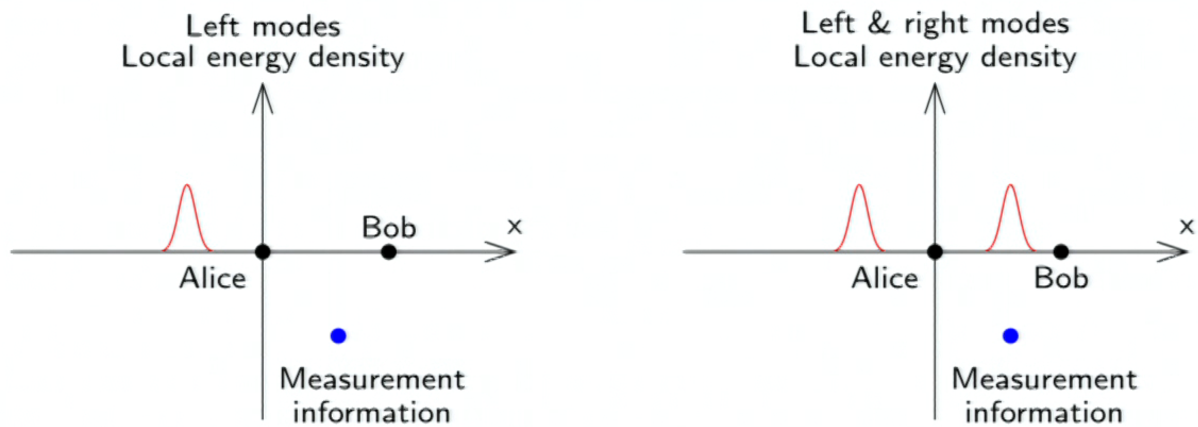

Breaking Strong Local Passivity
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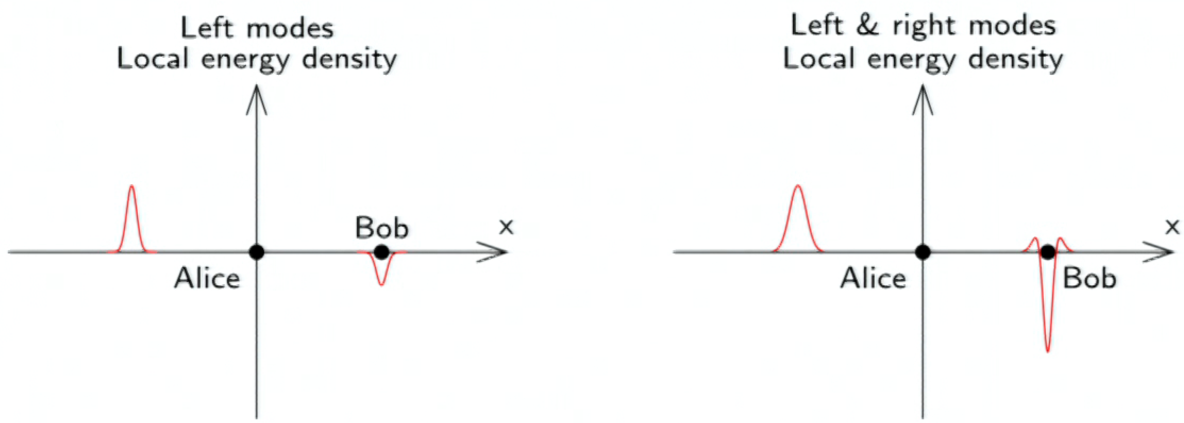

So what's the plan?

What we will do:

1-We will focus on the state of the field

So what's the plan?

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2-We will focus on 3+1D

So what's the plan?

What we will do:

1-We will focus on the state of the field

2-We will focus on 3+1D

3-Protocol made concrete (Using atomic probes, not idealized systems)

Introducing particle detectors

Physics of particle detectors:
Non-relativistic Quantum systems that couple to quantum fields

Think of atoms, nuclei, etc.. coupled to the EM field

Unruh-DeWitt Model

$$H_{\text{UDW}} = \chi(t) \int \mathrm{d}^3\boldsymbol{x}\, \hat{\mu}(\boldsymbol{x} - \boldsymbol{x}_d, t)\, \hat{\phi}(\boldsymbol{x}, t).$$

$$\hat{\phi}(\boldsymbol{x}, t) = \int \frac{\mathrm{d}^3\boldsymbol{k}}{\sqrt{(2\pi)^3 2|\boldsymbol{k}|}} \left[\hat{a}_{\boldsymbol{k}} e^{\mathrm{i}k\cdot x} + \mathrm{H.c.}\right], \quad \hat{\mu}(\boldsymbol{x}, t) = eF(\boldsymbol{x}) \left[\boldsymbol{e}^{\mathrm{i}\Omega t}\hat{\sigma}^+ + e^{-\mathrm{i}\Omega t}\hat{\sigma}^-\right]$$

Mater, Light, Unruh and DeWitt

Is this simplification good at all?

Coupling charges to the EM field

$$H = \frac{\hat{\boldsymbol{p}}^2}{2m} - \frac{e}{2m}\left[\hat{\boldsymbol{p}}\cdot\hat{\boldsymbol{A}}(\boldsymbol{x},t) + \hat{\boldsymbol{A}}(\boldsymbol{x},t)\cdot\hat{\boldsymbol{p}}\right] + \frac{e^2}{2m}\left[\hat{\boldsymbol{A}}(\boldsymbol{x},t)\right]^2 + \hat{V}(\boldsymbol{x},t)$$

Mater, Light, Unruh and DeWitt

Dipolar coupling

$$\hat{\boldsymbol{d}} \cdot \hat{\boldsymbol{E}} = e\,\hat{\boldsymbol{x}} \cdot \hat{\boldsymbol{E}}$$

Reduction to a finite number of levels (say, two-levels separated by an energy gap Ω)

Following: A. Pozas-Kertjens, E. Martin-Martinez. Phys. Rev. D 94, 064074 (2016)

Mater, Light, Unruh and DeWitt

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In the position representation (Inserting $\mathbb{I} = \int \mathrm{d}^3\boldsymbol{x}\, |\boldsymbol{x}\rangle\langle\boldsymbol{x}|$)

$$\hat{\boldsymbol{x}} \cdot \hat{\boldsymbol{E}}(\boldsymbol{x},t) = \int \mathrm{d}^3\boldsymbol{x} \left[\boldsymbol{F}(\boldsymbol{x}) \cdot \hat{\boldsymbol{E}}(\boldsymbol{x},t) e^{\mathrm{i}\Omega t}|e\rangle\langle g| + \boldsymbol{F}^*(\boldsymbol{x}) \cdot \hat{\boldsymbol{E}}(\boldsymbol{x},t) e^{-\mathrm{i}\Omega t}|g\rangle\langle e|\right]$$

$$\boldsymbol{F}(\boldsymbol{x}) = \boldsymbol{x}\langle e|\boldsymbol{x}\rangle\langle\boldsymbol{x}|g\rangle = \psi_e^*(\boldsymbol{x})\boldsymbol{x}\,\psi_g(\boldsymbol{x}).$$

Introducing time dependence in the coupling (switching): $H_{\mathrm{EM}} = e\chi(t)\hat{\boldsymbol{x}} \cdot \hat{\boldsymbol{E}}$

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Mater, Light, Unruh and DeWitt

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Electromagnetic dipole coupling

$$H_{\text{UDW}} = \chi(t) \int \mathrm{d}^3\boldsymbol{x}\, \hat{\mu}(\boldsymbol{x}-\boldsymbol{x}_d, t)\, \hat{\phi}(\boldsymbol{x}, t).$$

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Unruh-DeWitt coupling

Low energy UDW detectors see high-energy physics

The low energy behaviour of particle detectors is sensitive to high-energy effects:

-Lorentz violations:

N. Kajuri, Classical and Quantum Gravity 33, 055007 (2016).

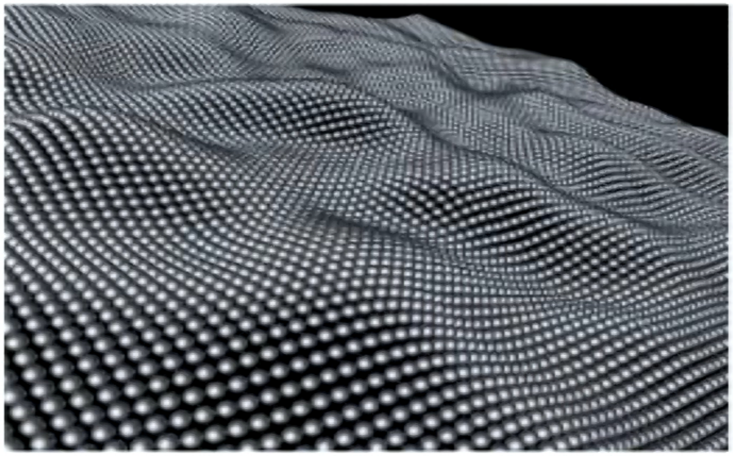
V. Husain and J. Louko, Phys. Rev. Lett. 116, 061301 (2016).

-Lorentz invariant non-local theories (e.g. causal sets)

A. Belenchia, D. M. T. Benincasa, E. Martin-Martinez, M. Saravani Phys. Rev. D 94, 061902(R) (2016)

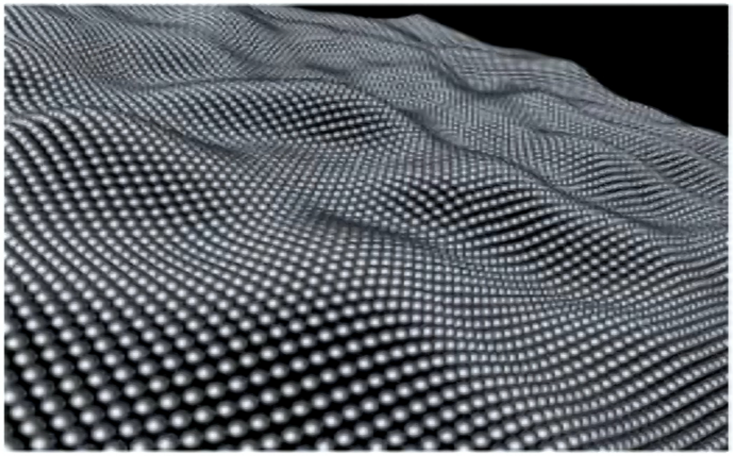
A. Belenchia, D. M. T. Benincasa, S. Liberati, E. Martin-Martinez arXiv:1707.01654 (2017)

Engineering negative energy densities



Preparation of states of spacetime

Engineering negative energy densities



Preparation of states of spacetime

Let's see how effective this protocol is!

Let's try to deliver what I promised. First with a toy model.

A toy first: 1+1D QET stress-energy engineering

The system is initially in a separable state (qubit state $|A_0\rangle$, field vacuum state $|0\rangle$):

$$|\psi(t<0)\rangle = |A_0\rangle \otimes |0\rangle \,.$$

Alice interacts via:

$$\hat{H}_{\text{int}} = \delta(t)\hat{\sigma}_x \otimes \int \mathrm{d}^{n-1}\boldsymbol{r}\, \lambda(\boldsymbol{r})\hat{\pi}(\boldsymbol{r}).$$

Alice teleports her qubit to Bob, interacting via:

$$\hat{H}_{\text{int}} = \delta(t-T)\hat{\sigma}_z \otimes \int \mathrm{d}\boldsymbol{r}\, \mu(\boldsymbol{r})\hat{\phi}(\boldsymbol{r}).$$

LOQC variant of QET Phys. Rev. A 93, 022308 (2016)

Vacuum Entanglement Harvesting

The system is initially in a separable state (qubit state $|A_0\rangle$, field vacuum state $|0\rangle$):

$$|\psi(t<0)\rangle = |A_0\rangle \otimes |0\rangle \,.$$

When $n = 2$ the resulting stress-energy density is given by:

$$\left\langle :\hat{T}_{00}(x,t): \right\rangle = \overbrace{\frac{(\lambda'(x-t))^2}{4} + \frac{(\lambda'(x+t))^2}{4}}^{\text{Alice's energy contribution}} + \overbrace{\frac{(\mu(x-(t-T)))^2}{4} + \frac{(\mu(x+(t-T)))^2}{4}}^{\text{Bob's energy contribution}}$$

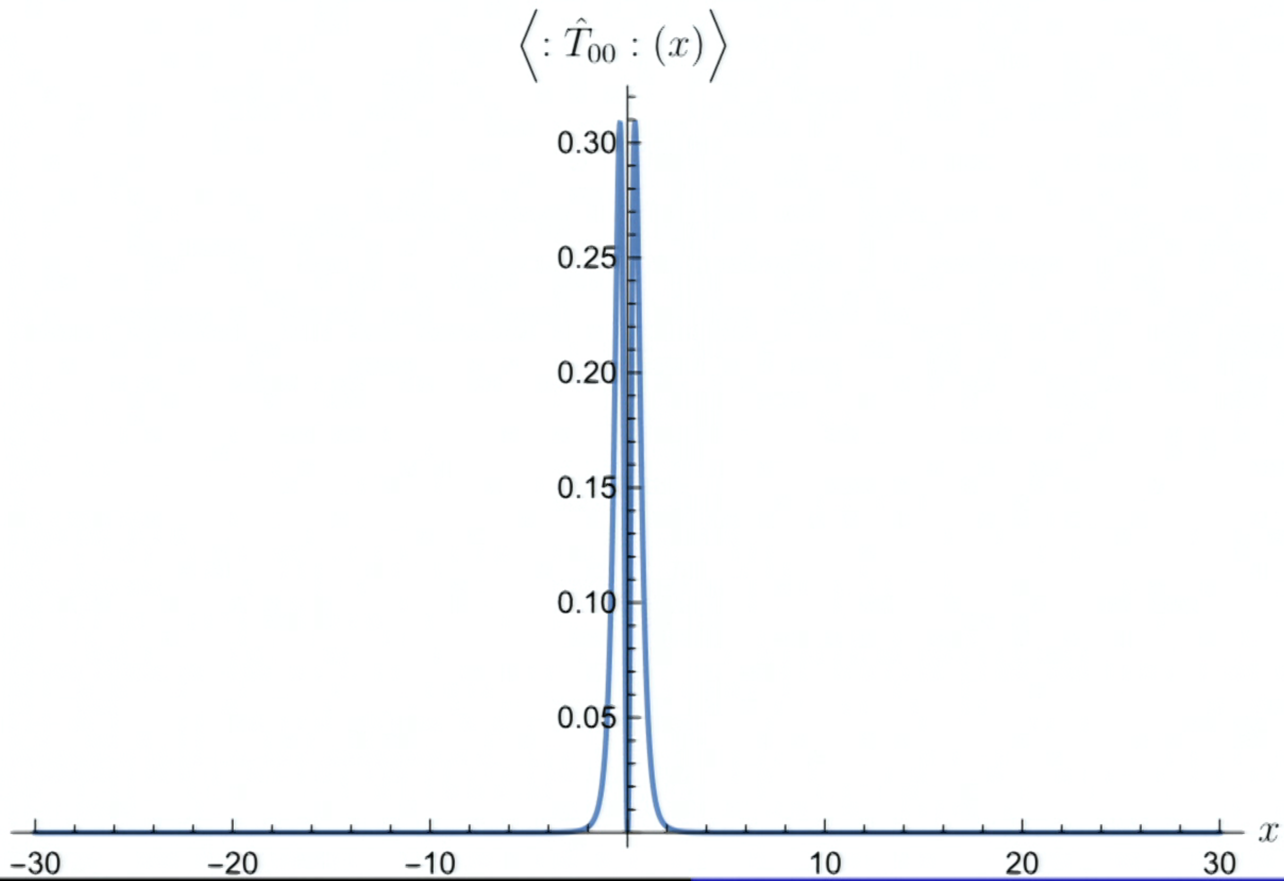
$$+ \underbrace{\frac{e^{-2\|\alpha\|}\langle A_0|\hat{\sigma}_y|A_0\rangle}{2\pi}\mu(x-(t-T))\int dy\lambda'(y)\frac{P.P}{y-x+t}}_{\text{Right moving QET term}}$$

$$+ \underbrace{\frac{e^{-2\|\alpha\|}\langle A_0|\hat{\sigma}_y|A_0\rangle}{2\pi}\mu(x+(t-T))\int dy\lambda'(y)\frac{P.P}{y-x-t}}_{\text{Left moving QET term}} \,.$$

1+1 D QET

Energy density immediately following Alice's interaction.

Lorentzian smearing.



Nicholas Funai Eduardo Martín-Martínez | Using QET to generate exotic spacetime geometries

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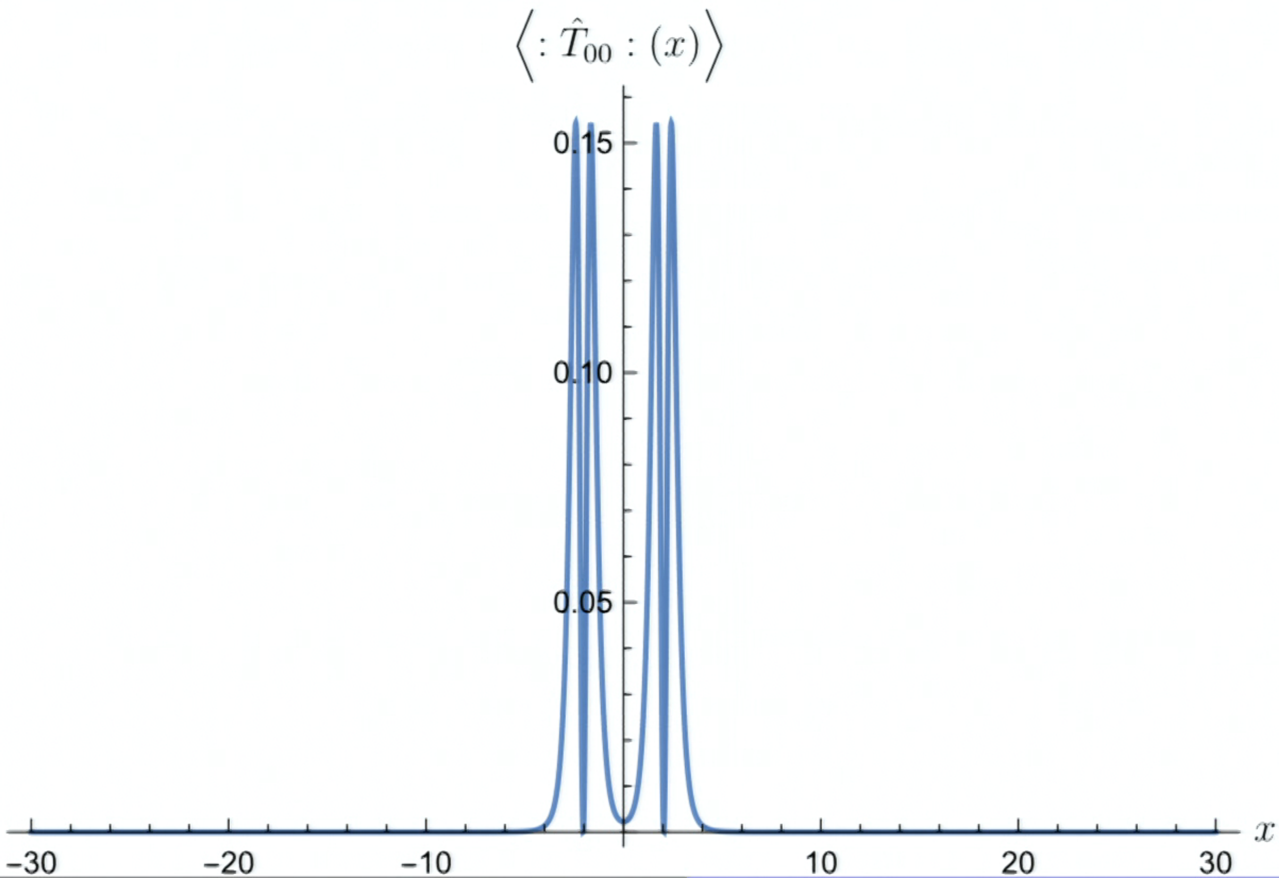

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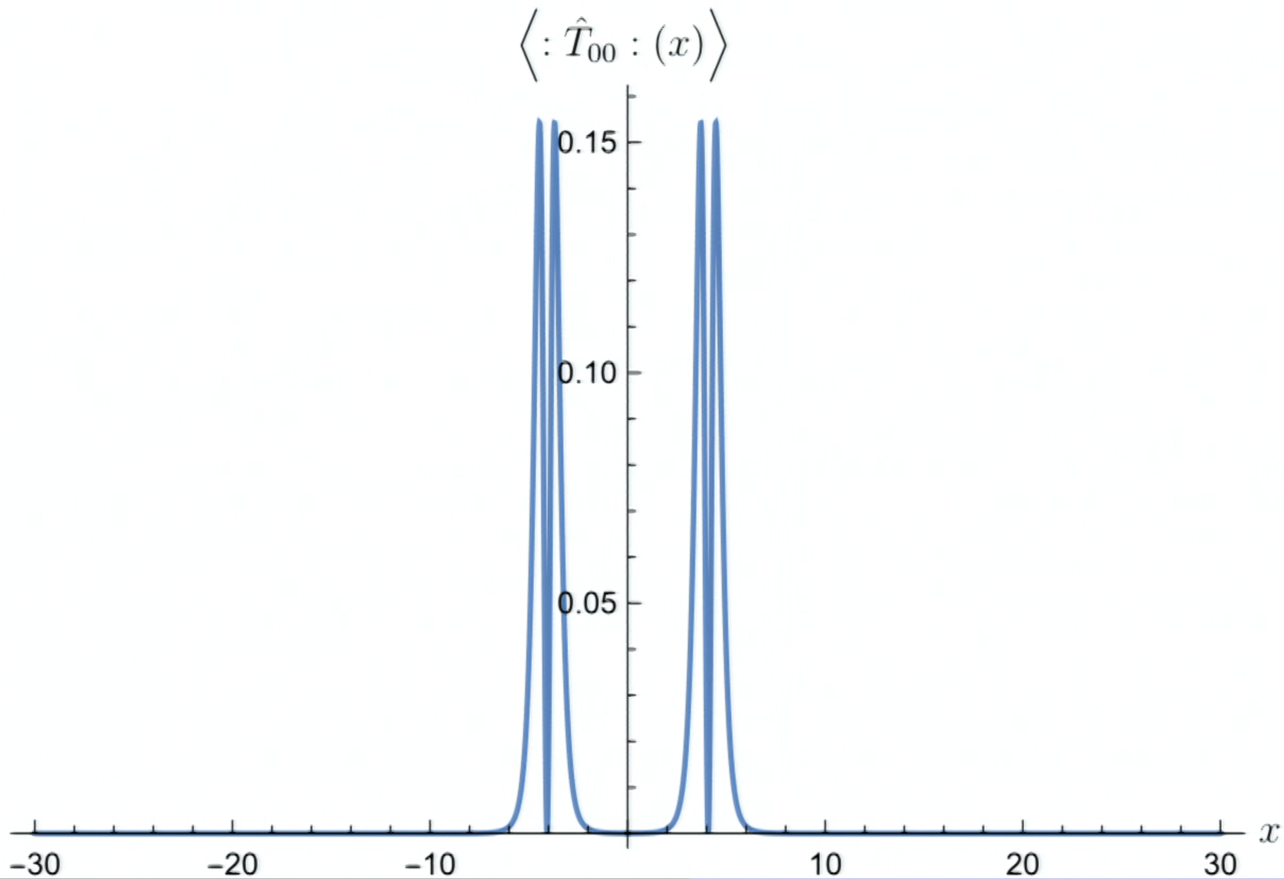

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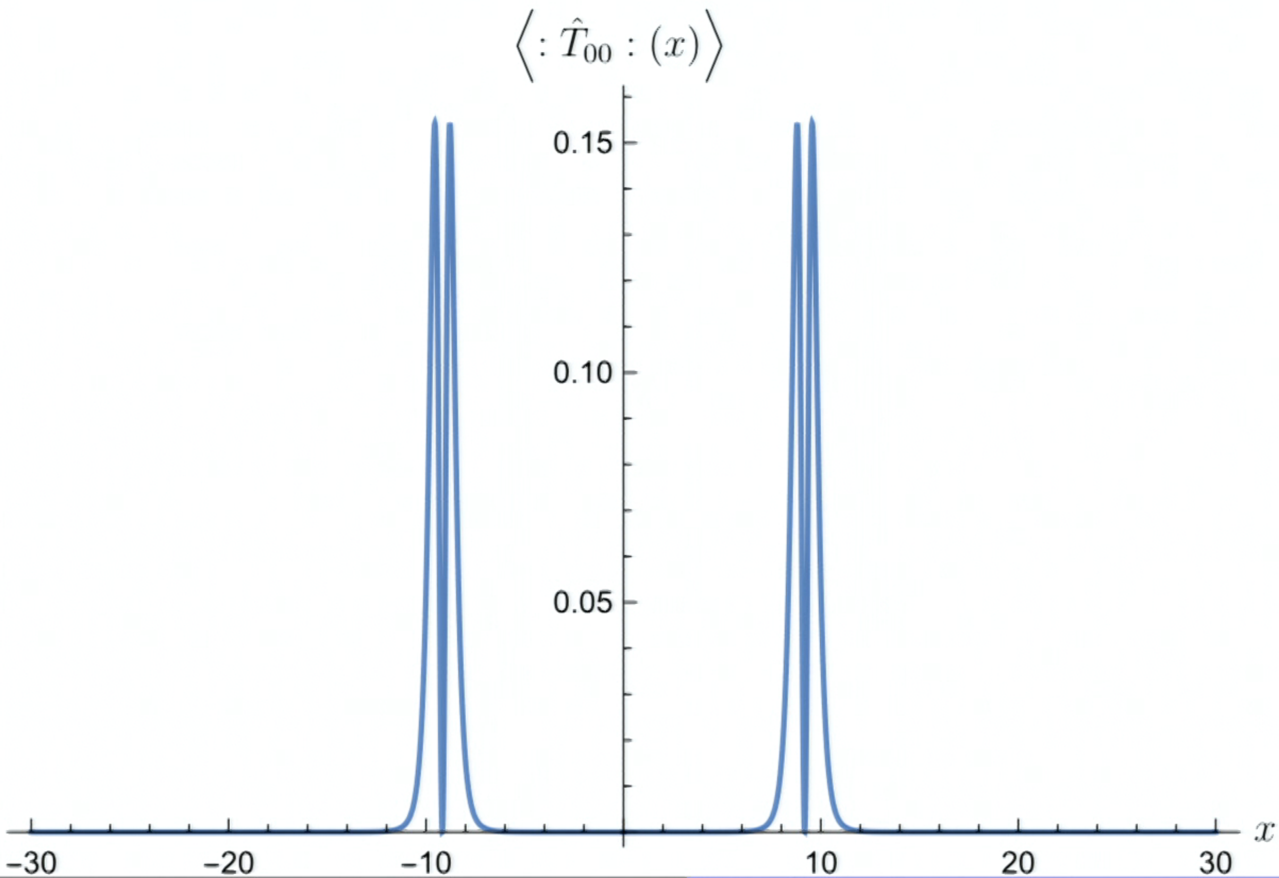
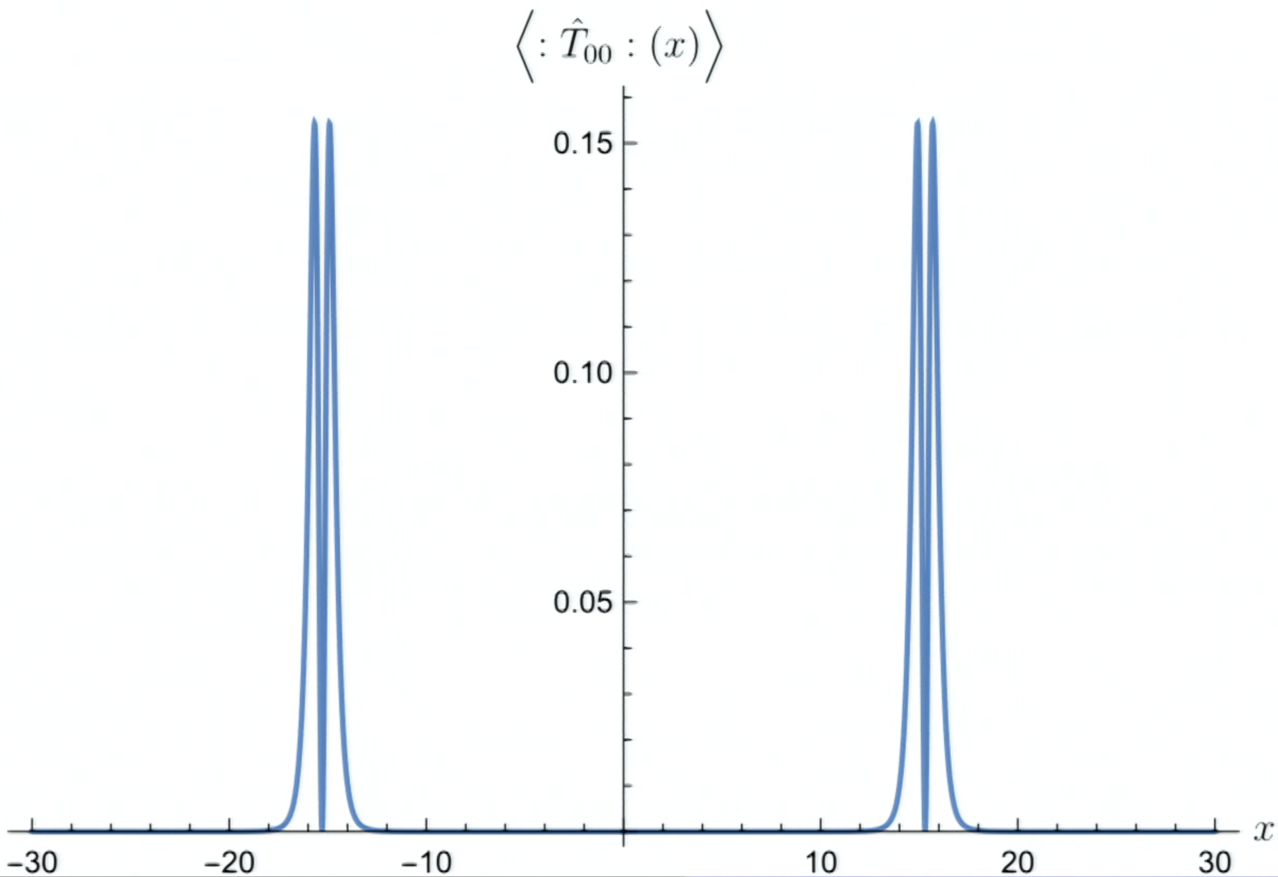


1+1 D QET

Energy density immediately prior to Bob's interaction.

Lorentzian smearing.



1+1 D QET

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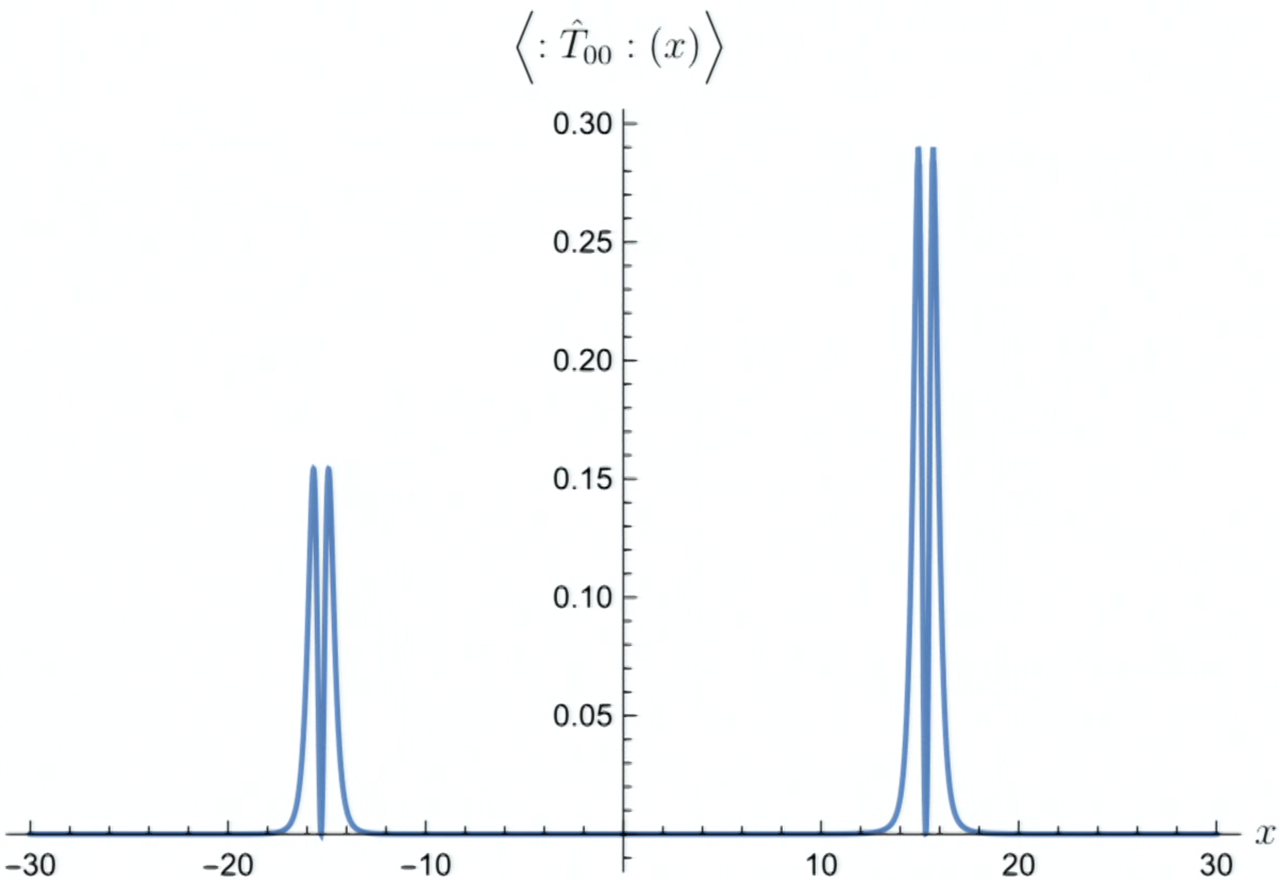

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1+1 D QET

Energy density ΔT after Bob's interaction.

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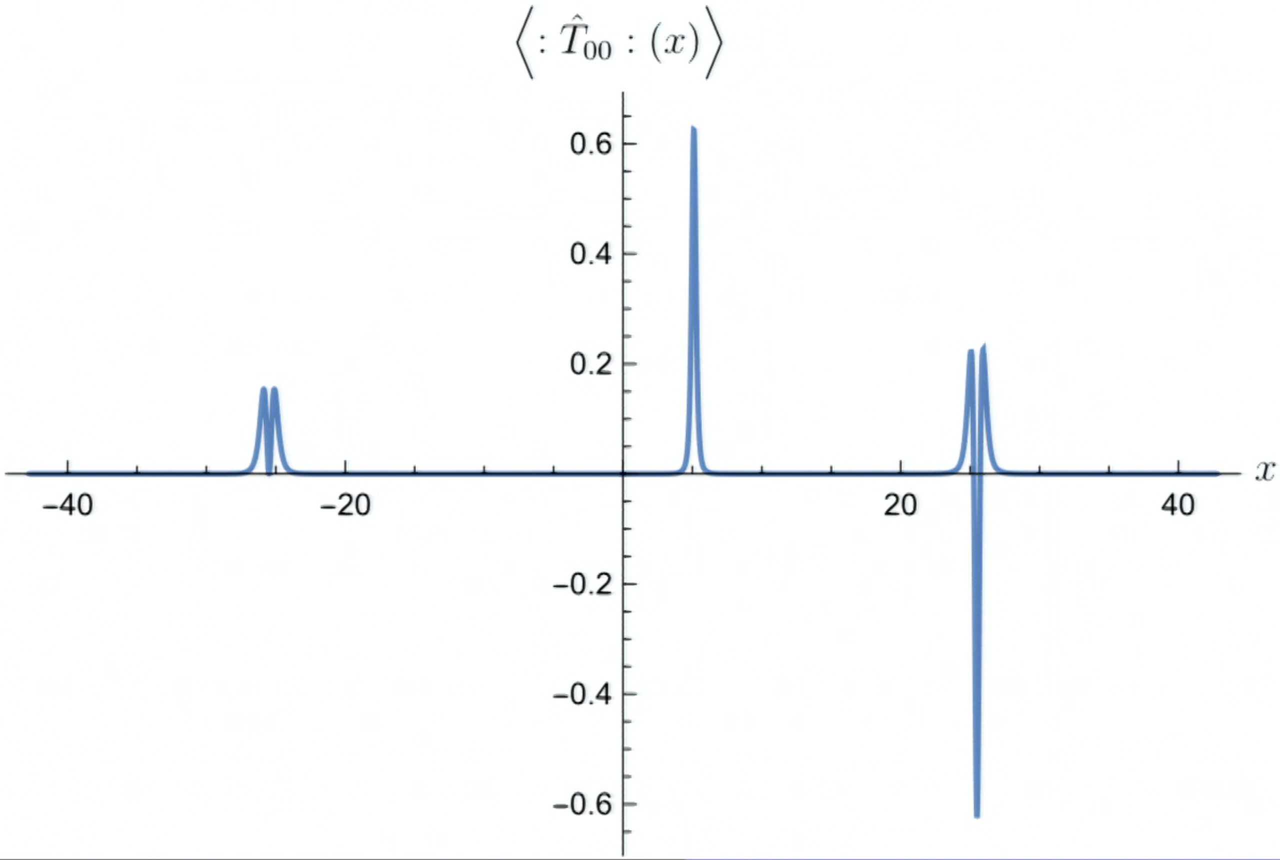

Nicholas Funai Eduardo Martín-Martínez

Using QET to generate exotic spacetime geometries

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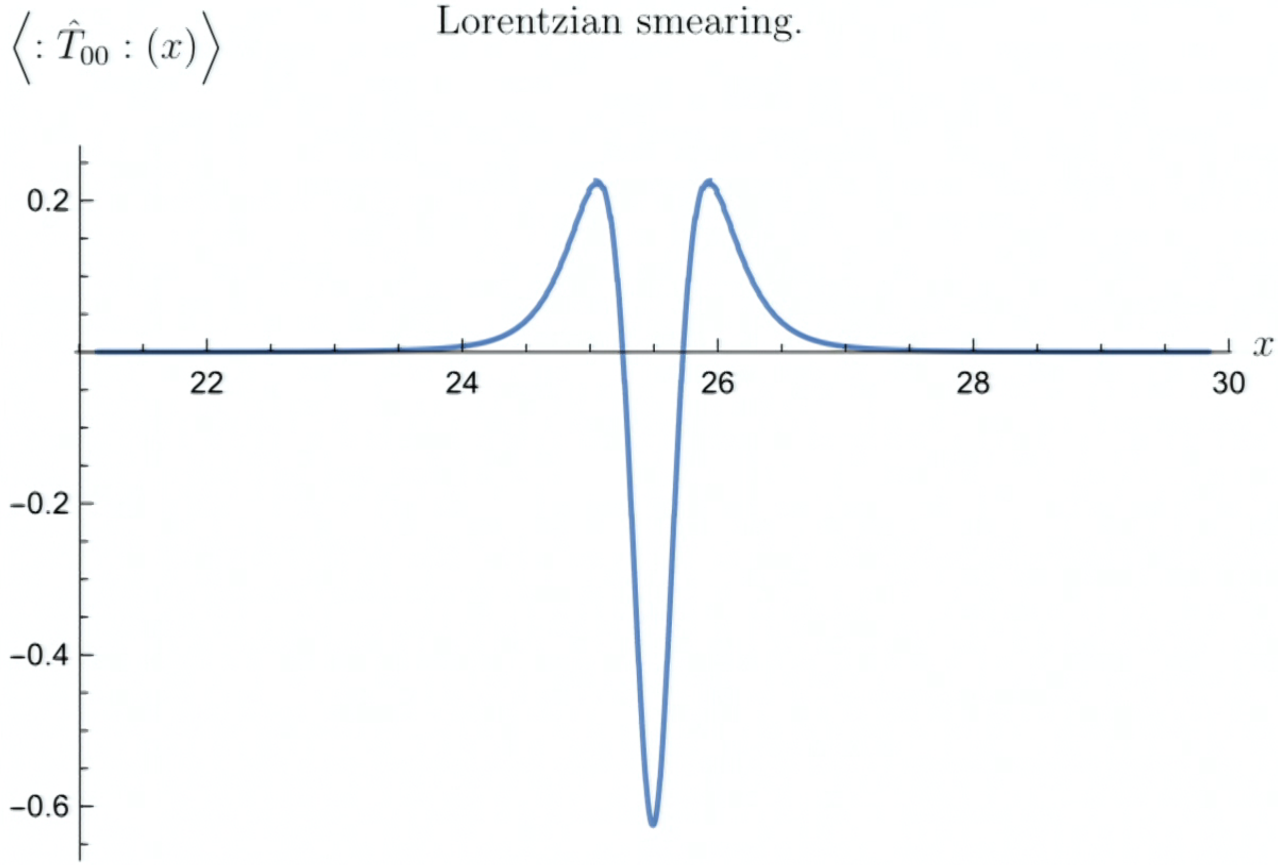


3+1D Case

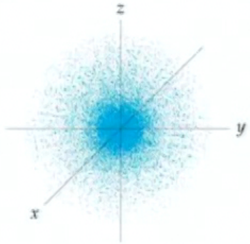
Gravity needs more dimensions….

Several complications

3+1D Case

Gravity needs more dimensions….

We need a distribution of Alices and a distribution of Bobs.



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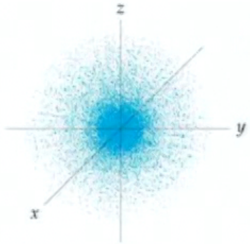

We cannot teleport the state of Alice's detectors to every Bob

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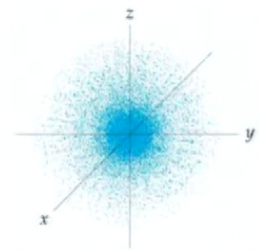
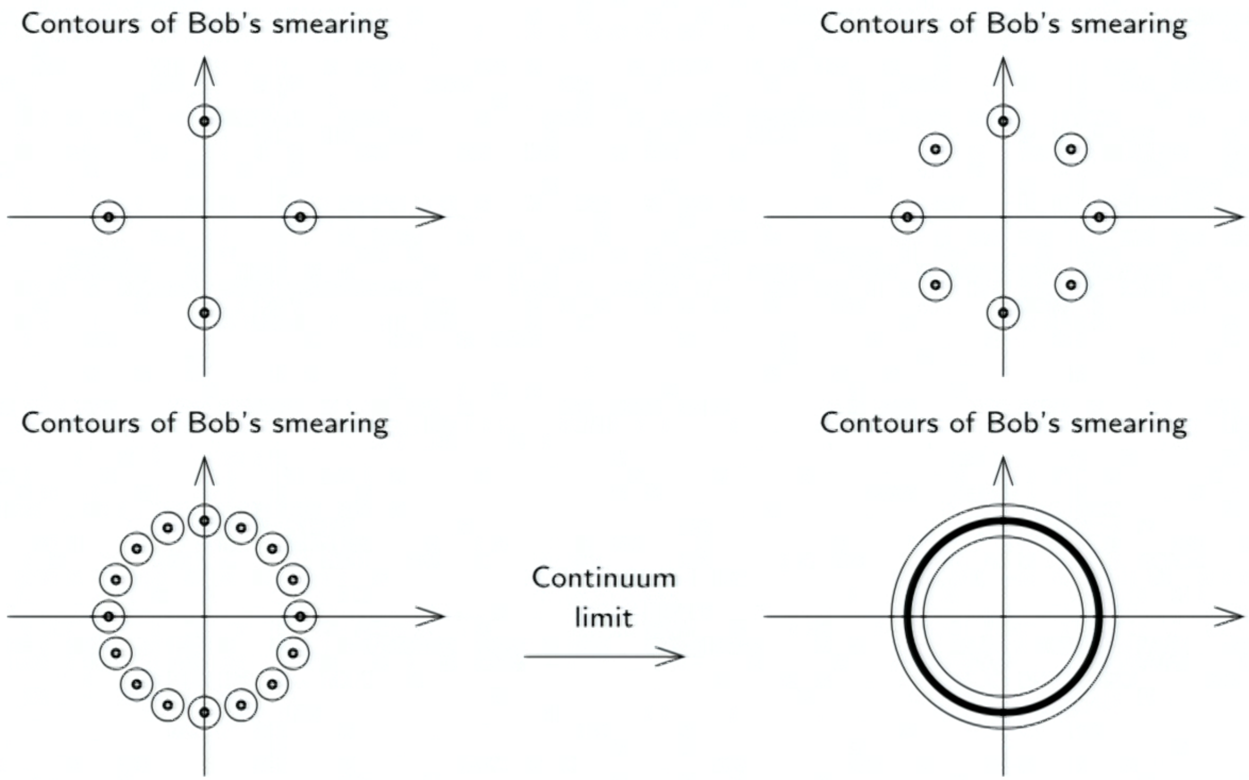


We cannot teleport the state of Alice's detectors to every Bob

Math gets much more complicated…

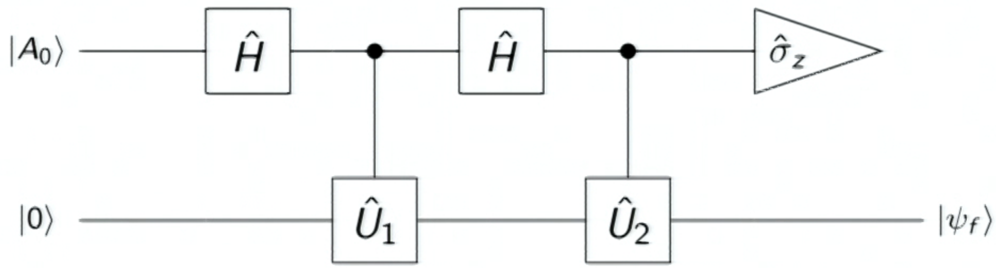
3+1D Case


Contours of Bob's smearing
Contours of Bob's smearing
Contours of Bob's smearing
Continuum
limit
Contours of Bob's smearing

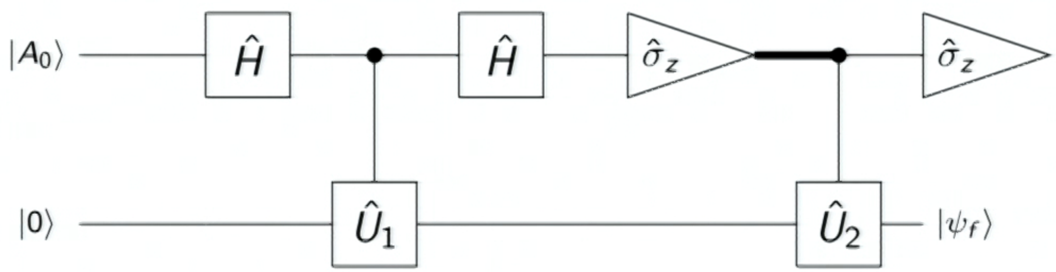
3+1D Case

If $|A_0\rangle$ is an eigenstate of $\hat{\sigma}_y$ then the LOCC protocol gives the same final state ($|\psi_f\rangle$) as LOQC, provided the final measurement $\hat{\sigma}_z$ give the same result.

LOQC



LOCC



3+1D Case

1-Alice measures the field by coupling an atom to it

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3-Alice broadcasts the result of the measurement to an agency of Bob's

4-Bob's agents use that information to prepare atoms and couple to the field

$$\langle\psi(t)|:\hat{T}_{\mu\nu}:(\boldsymbol{x})|\psi(t)\rangle = \Bigg\{ \overbrace{\left(I^1_\mu I^1_\nu - \eta_{\mu\nu}\frac{I^1_\lambda I^{1,\lambda}}{2}\right)}^{\text{Bob's energy contribution}} - \overbrace{\left(I^2_\mu I^2_\nu - \eta_{\mu\nu}\frac{I^2_\lambda I^{2,\lambda}}{2}\right)}^{\text{Alice's energy contribution}}$$

$$\underbrace{- \langle A_0|\hat{\sigma}_y|A_0\rangle e^{-2\|\alpha\|}\left(\left(I^1_\mu I^3_\nu - \eta_{\mu\nu}\frac{I^1_\lambda I^{3,\lambda}}{2}\right) + \left(I^3_\mu I^1_\nu - \eta_{\mu\nu}\frac{I^1_\lambda I^{3,\lambda}}{2}\right)\right)}_{\text{QET term}}\Bigg\}$$

3+1D Case

$$I_\mu^1(\boldsymbol{x}) = \int \mathrm{d}^{n-1}\boldsymbol{y}\mathrm{d}^{n-1}\boldsymbol{k}\hat{k}_\mu e^{-2\varepsilon|\boldsymbol{k}|}(e^{\mathrm{i}\boldsymbol{k}\cdot(\boldsymbol{x}-\boldsymbol{y})} + e^{-\mathrm{i}\boldsymbol{k}\cdot(\boldsymbol{x}-\boldsymbol{y})})\mu(\boldsymbol{y}),$$

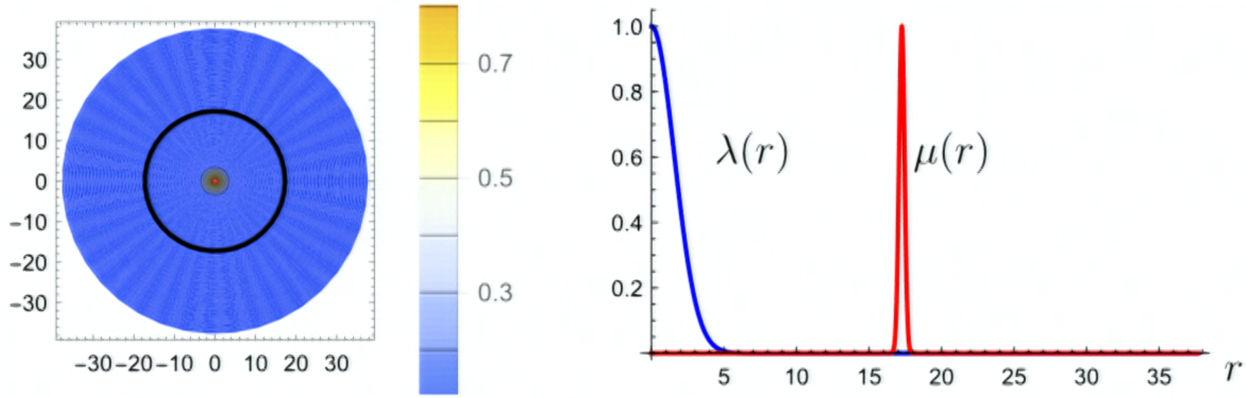
$$I_\mu^2(\boldsymbol{x}) = \int \mathrm{d}^{n-1}\boldsymbol{y}\mathrm{d}^{n-1}\boldsymbol{k}\hat{k}_\mu e^{-2\varepsilon|\boldsymbol{k}|}(e^{\mathrm{i}\boldsymbol{k}\cdot(\boldsymbol{x}-\boldsymbol{y})-\mathrm{i}|\boldsymbol{k}|T} - e^{-\mathrm{i}\boldsymbol{k}\cdot(\boldsymbol{x}-\boldsymbol{y})+\mathrm{i}|\boldsymbol{k}|T})|\boldsymbol{k}|\lambda(\boldsymbol{y}),$$

$$I_\mu^3(\boldsymbol{x}) = \int \mathrm{d}^{n-1}\boldsymbol{y}\mathrm{d}^{n-1}\boldsymbol{k}\hat{k}_\mu e^{-2\varepsilon|\boldsymbol{k}|}(e^{\mathrm{i}\boldsymbol{k}\cdot(\boldsymbol{x}-\boldsymbol{y})-\mathrm{i}|\boldsymbol{k}|T} + e^{-\mathrm{i}\boldsymbol{k}\cdot(\boldsymbol{x}-\boldsymbol{y})+\mathrm{i}|\boldsymbol{k}|T})|\boldsymbol{k}|\lambda(\boldsymbol{y}),$$

$$\|\alpha\| = \frac{1}{2(2\pi)^{n-1}}\int \mathrm{d}^{n-1}\boldsymbol{x}\mathrm{d}^{n-1}\boldsymbol{y}\lambda(\boldsymbol{x})\lambda(\boldsymbol{y})\int \mathrm{d}^{n-1}\boldsymbol{k}|\boldsymbol{k}|e^{-2\varepsilon|\boldsymbol{k}|-\mathrm{i}\boldsymbol{k}\cdot(\boldsymbol{x}-\boldsymbol{y})}.$$

3+1 D QET

Gaussian smearing functions used.

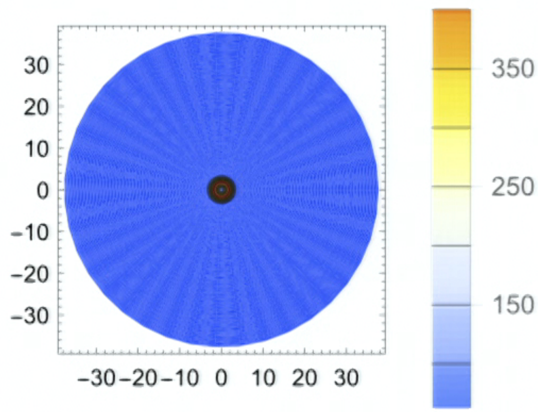


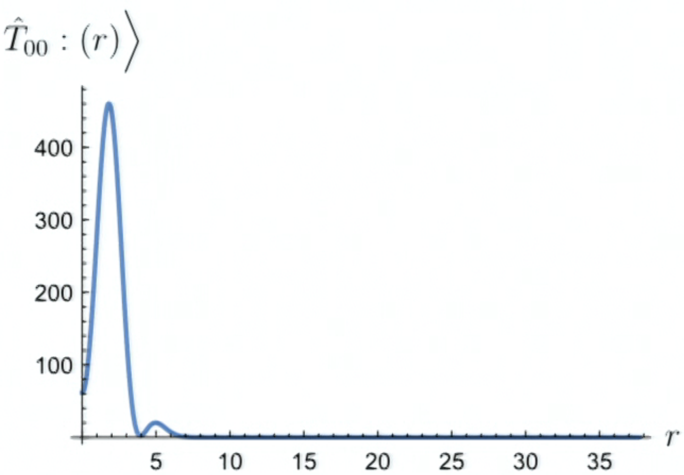
Dynamical picture

3+1 D QET

Energy density after Alice's interaction.

Gaussian smearing.

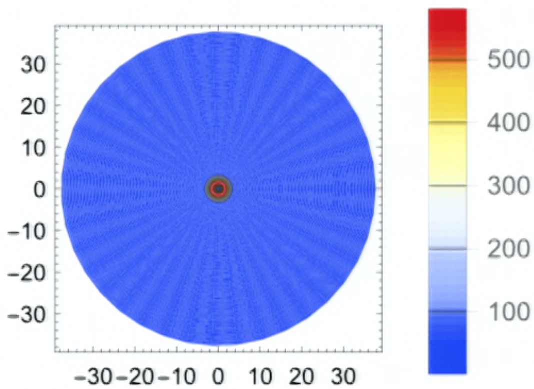


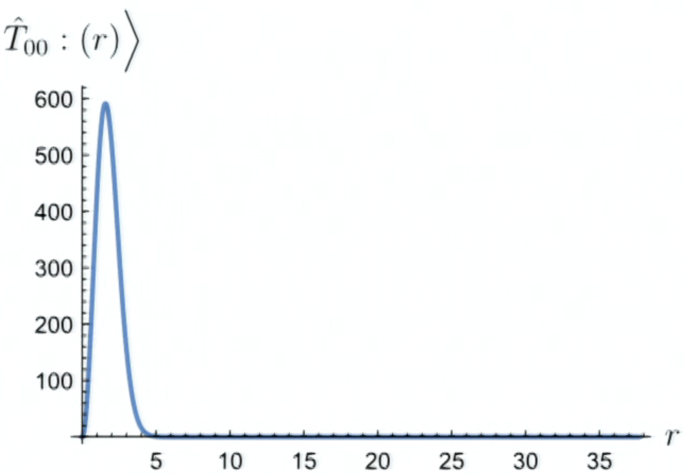


3+1 D QET

Energy density immediately following Alice's interaction.

Gaussian smearing.



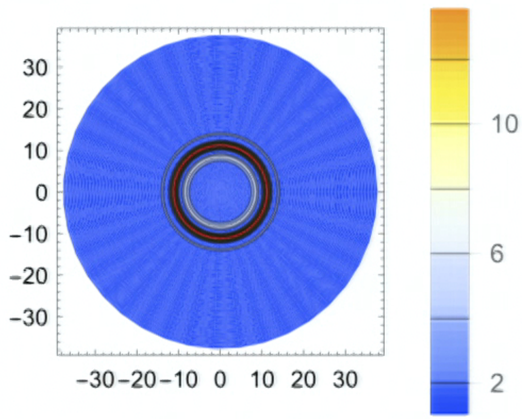


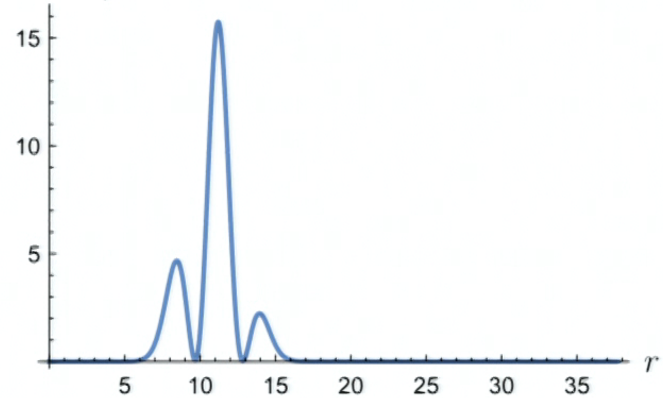
3+1 D QET

Energy density after Alice's interaction.

Gaussian smearing.

$\left\langle : \hat{T}_{00} : (r) \right\rangle$



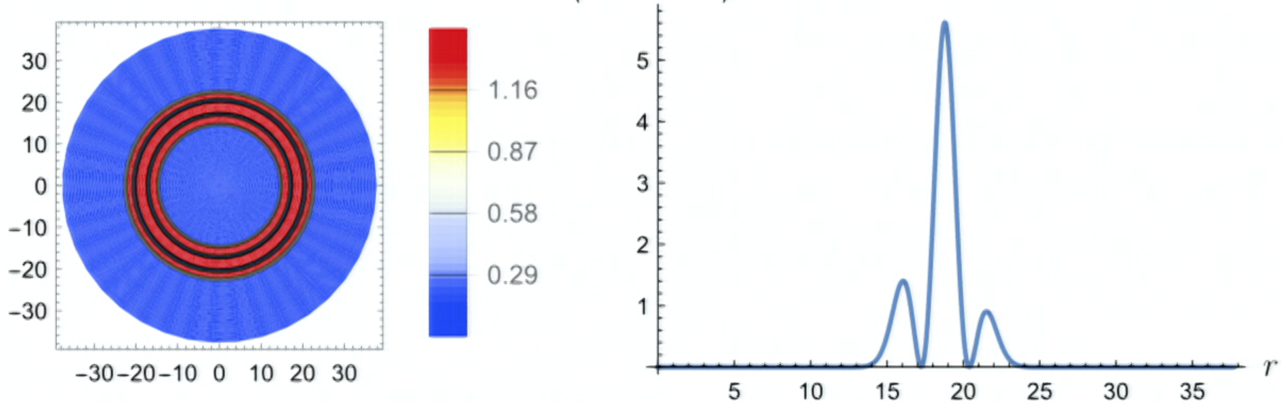


3+1 D QET

Energy density immediately prior to Bob's interaction.

Gaussian smearing.

$$\left\langle : \hat{T}_{00} : (r) \right\rangle$$

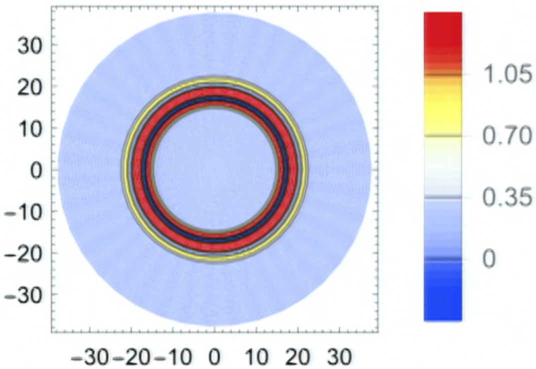


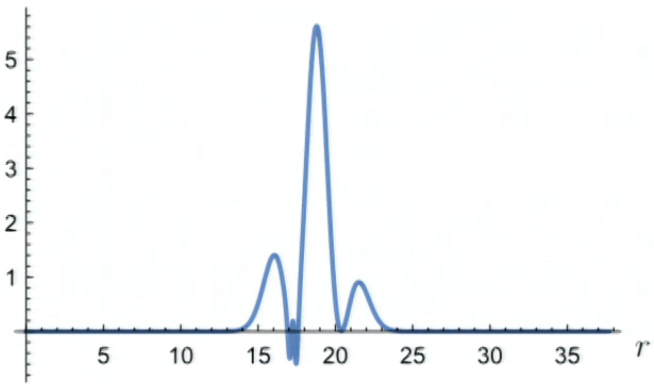
3+1 D QET

Energy density immediately following Bob's interaction.

Gaussian smearing.

$$\left\langle : \hat{T}_{00} : (r) \right\rangle$$



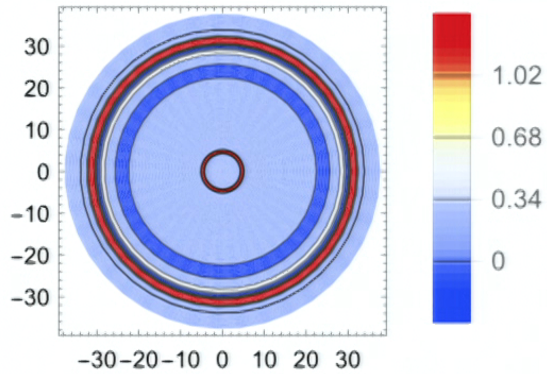


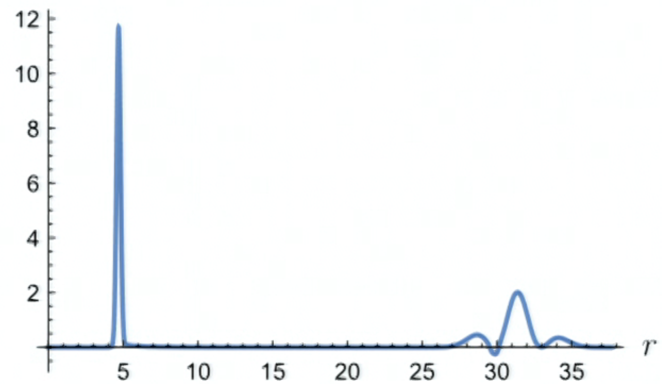
3+1 D QET

Energy density ΔT after to Bob's interaction.

Gaussian smearing.

$$\left\langle : \hat{T}_{00} : (r) \right\rangle$$



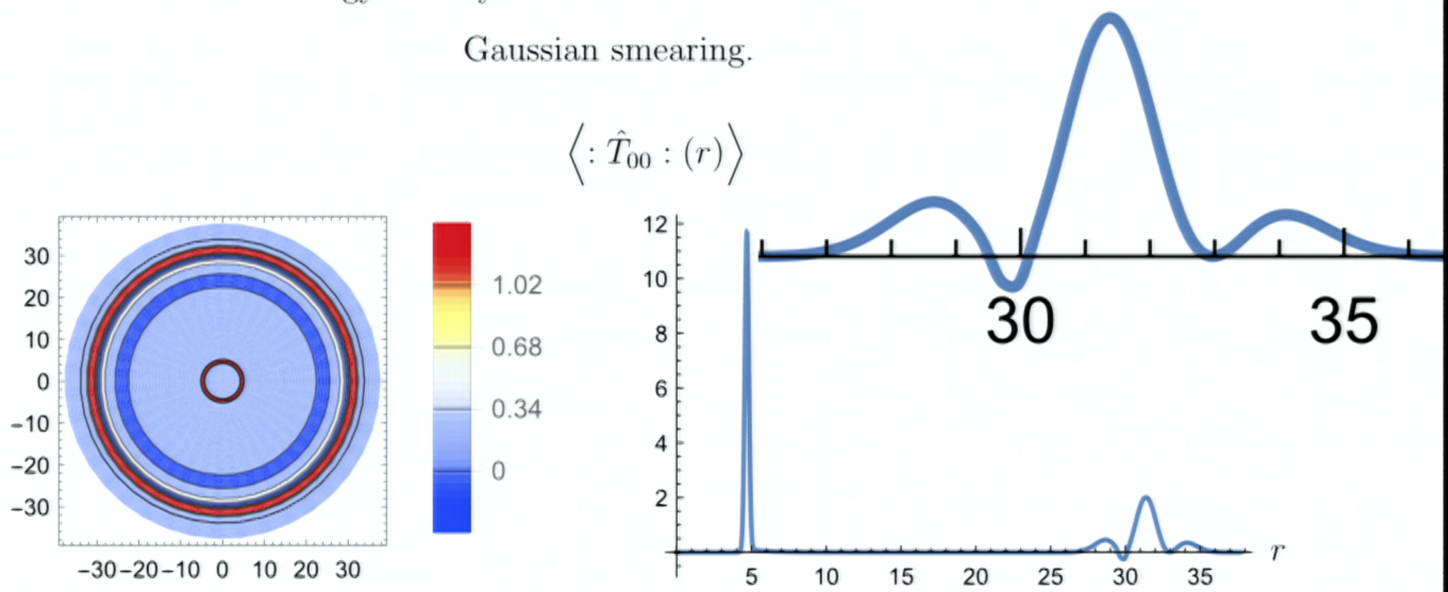


3+1 D QET

Energy density ΔT after to Bob

Gaussian smearing.

$$\left\langle :\hat{T}_{00}:(r)\right\rangle$$



Nicholas Funai Eduardo Martín-Martínez | Using QET to generate exotic spacetime geometries

How much negative energy can we have?

$$\langle\psi(t)|:\hat{T}_{\mu\nu}:(\boldsymbol{x})|\psi(t)\rangle = \Bigg\{ \underbrace{\left(I^1_\mu I^1_\nu - \eta_{\mu\nu}\frac{I^1_\lambda I^{1,\lambda}}{2}\right)}_{\text{Bob's energy contribution}} - \underbrace{\left(I^2_\mu I^2_\nu - \eta_{\mu\nu}\frac{I^2_\lambda I^{2,\lambda}}{2}\right)}_{\text{Alice's energy contribution}}$$

$$\underbrace{- \langle A_0|\hat{\sigma}_y|A_0\rangle e^{-2\|\alpha\|}\left(\left(I^1_\mu I^3_\nu - \eta_{\mu\nu}\frac{I^1_\lambda I^{3,\lambda}}{2}\right) + \left(I^3_\mu I^1_\nu - \eta_{\mu\nu}\frac{I^1_\lambda I^{3,\lambda}}{2}\right)\right)}_{\text{QET term}}\Bigg\}$$

Scaling negative energy (n-dimensions)

$$\langle\psi(t)|:\hat{T}_{\mu\nu}:(\boldsymbol{x})|\psi(t)\rangle = \Bigg\{ \underbrace{\left(I^1_\mu I^1_\nu - \eta_{\mu\nu}\frac{I^1_\lambda I^{1,\lambda}}{2}\right)}_{\text{Bob's energy contribution}} - \underbrace{\left(I^2_\mu I^2_\nu - \eta_{\mu\nu}\frac{I^2_\lambda I^{2,\lambda}}{2}\right)}_{\text{Alice's energy contribution}}$$
$$\underbrace{- \langle A_0|\hat{\sigma}_y|A_0\rangle e^{-2\|\alpha\|}\left(\left(I^1_\mu I^3_\nu - \eta_{\mu\nu}\frac{I^1_\lambda I^{3,\lambda}}{2}\right) + \left(I^3_\mu I^1_\nu - \eta_{\mu\nu}\frac{I^1_\lambda I^{3,\lambda}}{2}\right)\right)}_{\text{QET term}}\Bigg\}$$

$$\|\alpha\| = \frac{1}{2(2\pi)^{n-1}}\int \mathrm{d}^{n-1}\boldsymbol{x}\,\mathrm{d}^{n-1}\boldsymbol{y}\,\lambda(\boldsymbol{x})\lambda(\boldsymbol{y})\int \mathrm{d}^{n-1}\boldsymbol{k}\,|\boldsymbol{k}|\,e^{-\mathrm{i}\boldsymbol{k}\cdot(\boldsymbol{x}-\boldsymbol{y})}$$

If Alice's smearing is scaled $\lambda(\boldsymbol{x}) \to \sigma^{\frac{n-2}{2}}\lambda(\sigma\boldsymbol{x})$ then $\|\alpha\|$ constant.

If additionally $\mu(\boldsymbol{x}) \to \sigma^{\frac{n}{2}}\mu(\sigma\boldsymbol{x})$ then $\left\langle :\hat{T}_{\mu\nu}(\boldsymbol{x},t):\right\rangle \to \sigma^n\left\langle :\hat{T}_{\mu\nu}(\sigma\boldsymbol{x},\sigma t):\right\rangle$

Scaling negative energy

Total amount of negative energy:

$$\Phi_E = \int_{\langle :\hat{T}_{00}(\boldsymbol{x},\tau):\rangle < 0} \langle :\, \hat{T}_{00} :(\boldsymbol{x},\tau)\rangle \, d\tau$$

Scaling negative energy

Total amount of negative energy:

$$\Phi_E = \int_{\langle:\hat{T}_{00}(\boldsymbol{x},\tau):\rangle<0} \langle: \hat{T}_{00} : (\boldsymbol{x},\tau)\rangle \, d\tau$$

$$\lambda(\boldsymbol{x}) \to \sigma^{\frac{n-2}{2}} \lambda(\sigma \boldsymbol{x}),$$
$$\mu(\boldsymbol{x}) \to \sigma^{\frac{n}{2}} \mu(\sigma \boldsymbol{x}),$$
$$\left\langle: \hat{T}_{\mu\nu}(\boldsymbol{x},t) :\right\rangle \to \sigma^{n} \left\langle: \hat{T}_{\mu\nu}(\sigma\boldsymbol{x},\sigma t) :\right\rangle$$
$$\Phi_E \to \sigma^{n-1}\Phi_E.$$

Scaling negative energy

Total amount of negative energy:

$$\Phi_E = \int_{\langle : \hat{T}_{00}(\boldsymbol{x},\tau) : \rangle < 0} \langle : \hat{T}_{00} : (\boldsymbol{x}, \tau) \rangle \, d\tau$$

$$\begin{aligned} \lambda(\boldsymbol{x}) &\to \sigma^{\frac{n-2}{2}} \lambda(\sigma \boldsymbol{x}), \\ \mu(\boldsymbol{x}) &\to \sigma^{\frac{n}{2}} \mu(\sigma \boldsymbol{x}), \\ \left\langle : \hat{T}_{\mu\nu}(\boldsymbol{x}, t) : \right\rangle &\to \sigma^{n} \left\langle : \hat{T}_{\mu\nu}(\sigma \boldsymbol{x}, \sigma t) : \right\rangle \\ \Phi_E &\to \sigma^{n-1} \Phi_E . \end{aligned}$$

Violates quantum inequalities optimally
and saturates QI conjecture

Summary

QET can be used to **operationally** generate **negative energy distributions**.

Does so "**consuming**" space like vacuum entanglement.

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QET protocol scaling saturates the **Quantum Interest Conjecture.**

QET protocol scaling optimally violates **AWEC.**