Title: Lecture - Quantum Foundations, PHYS 639

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Subject: Quantum Foundations

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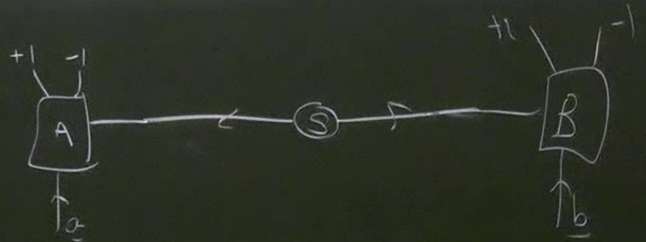


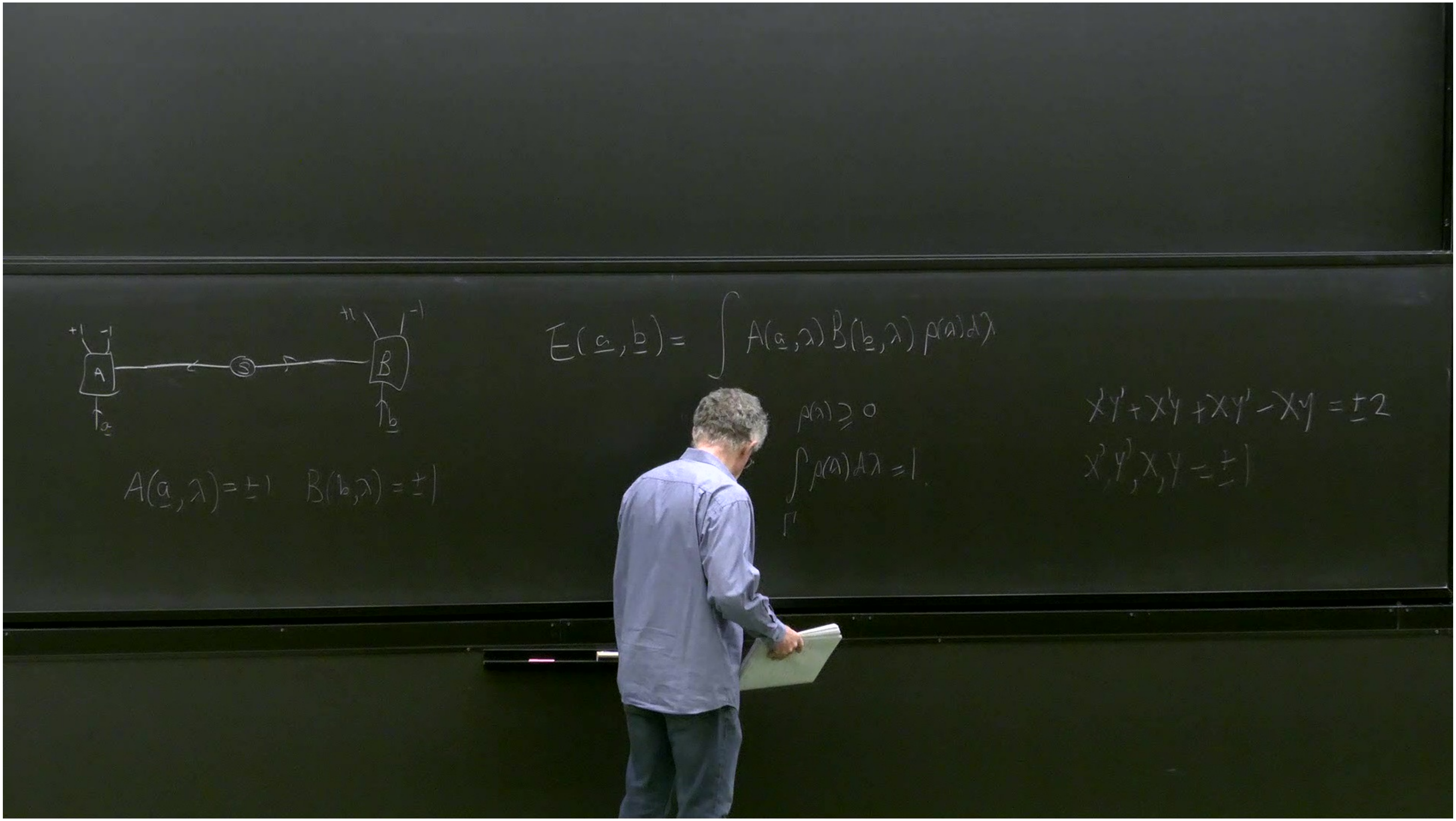
$$E(\underline{a},\underline{b}) = \int_{\Gamma} A(\underline{a},\lambda)\, B(\underline{b},\lambda)\, \rho(\lambda)\, d\lambda$$

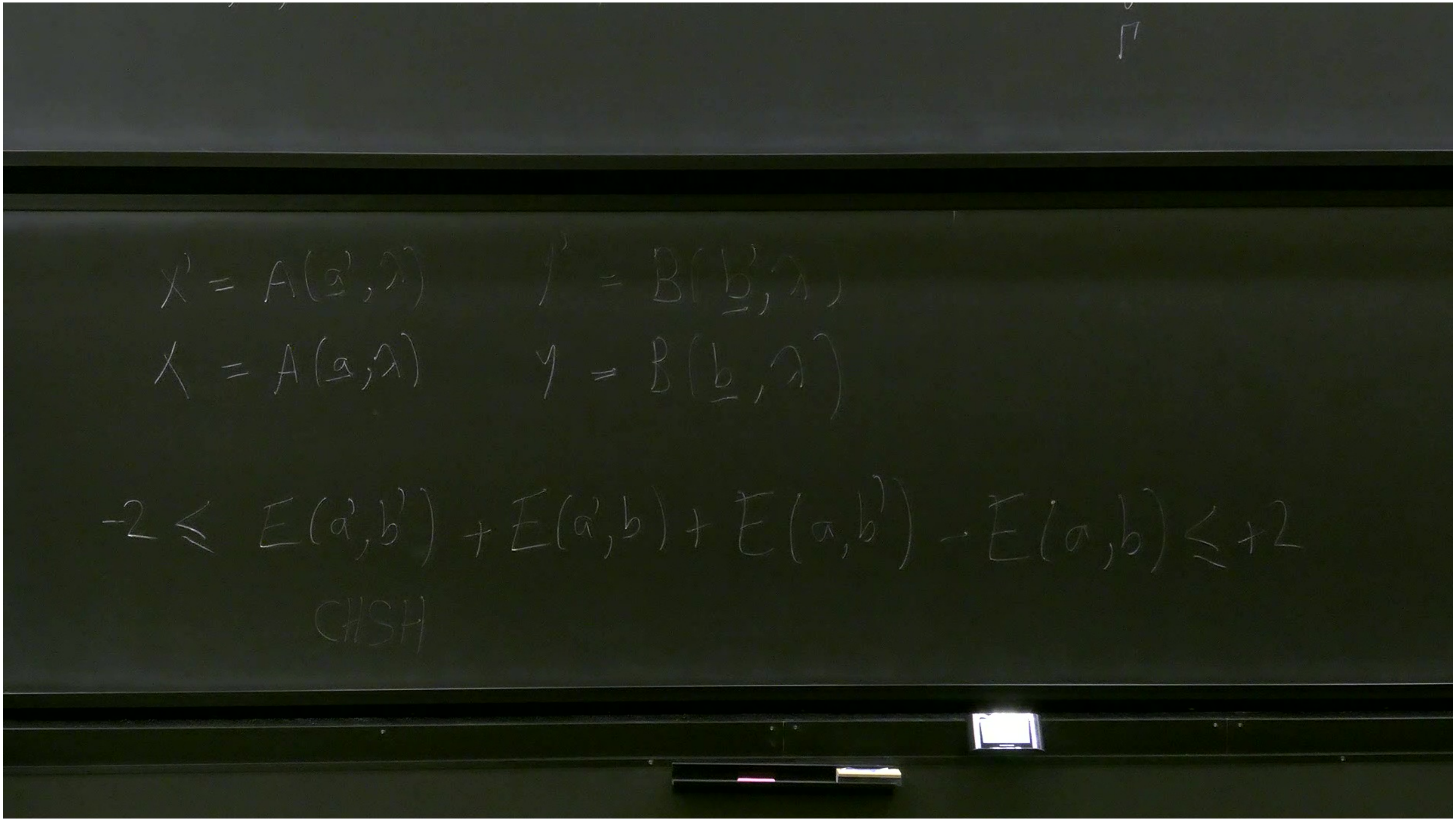
$$\rho(\lambda) \geq 0$$

$$\int_{\Gamma} \rho(\lambda)\, d\lambda = 1.$$

$$A(\underline{a},\lambda) = \pm 1 \qquad B(\underline{b},\lambda) = \pm 1$$

$XY + X$

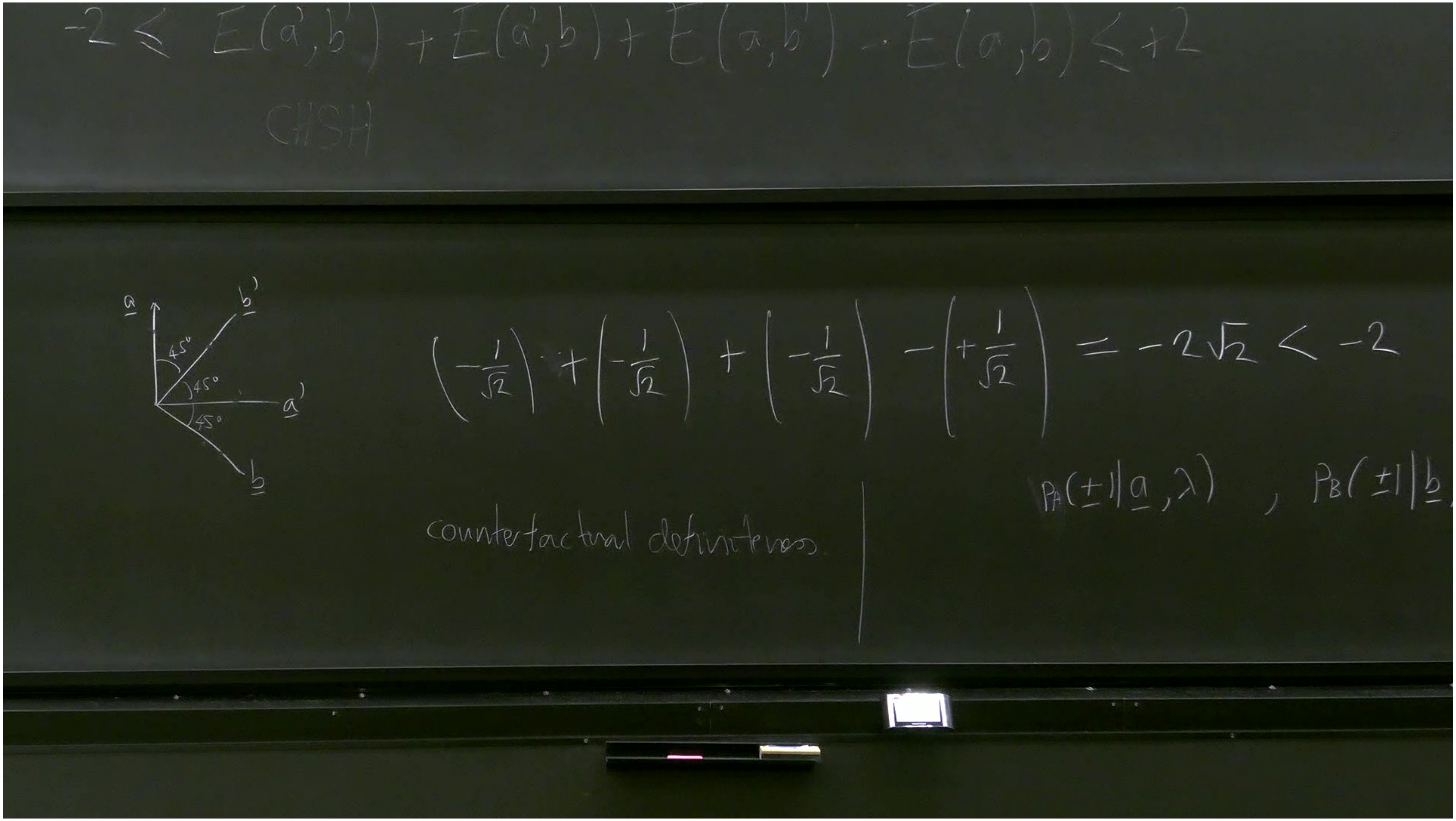

+1 -1
A
S
+1 -1
B
a
b
E(a, b) = ∫ A(a,λ) B(b,λ) ρ(λ) dλ
ρ(λ) ≥ 0
∫ ρ(λ) dλ = 1
Γ
A(a,λ) = ±1
B(b,λ) = ±1
X Y' + X' Y + X Y' − X Y = ±2
X', Y', X, Y = ±1

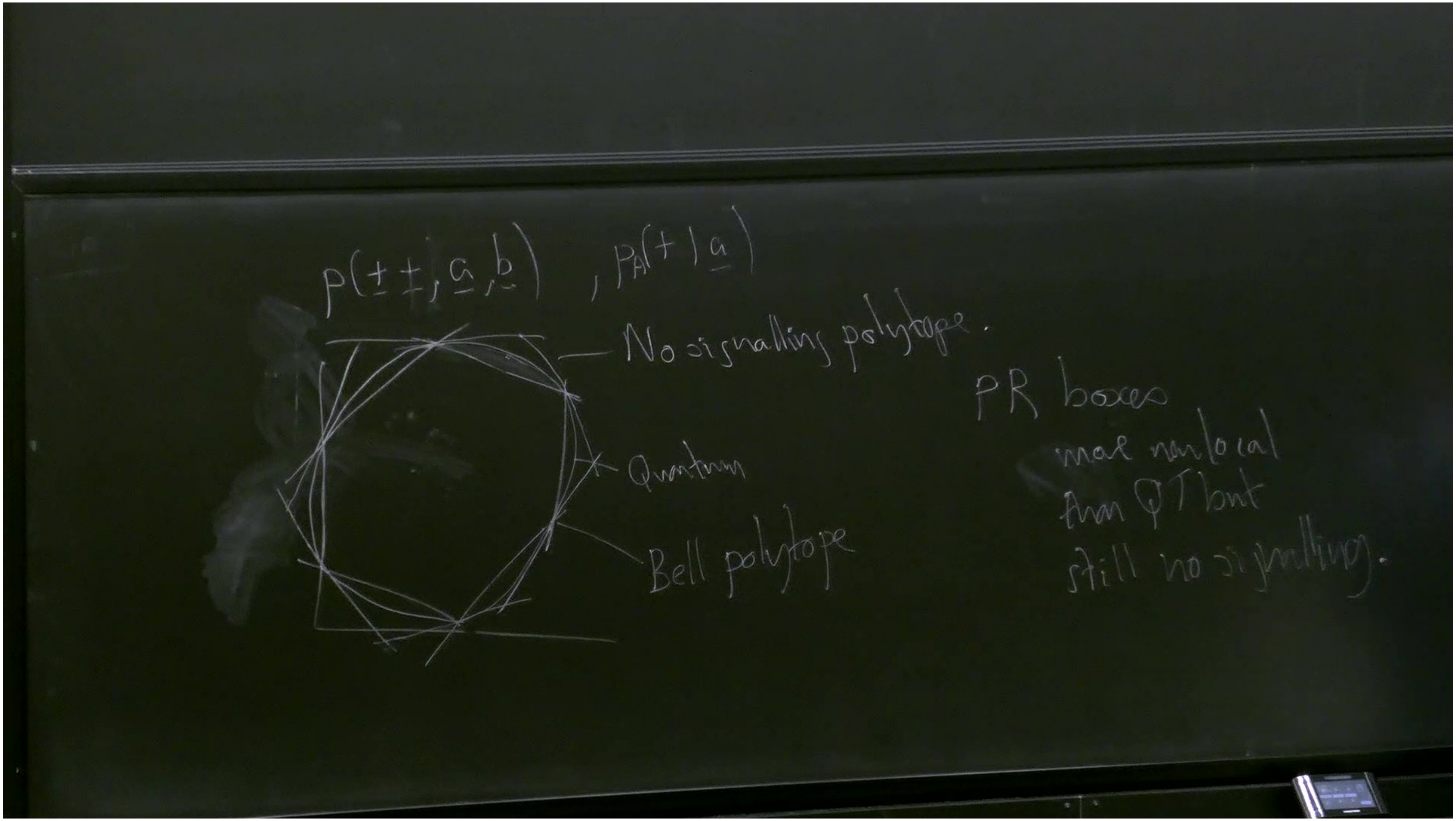

$x' = A(\underline{a}', \lambda)$ $y' = B(\underline{b}', \lambda)$
$x = A(\underline{a}, \lambda)$ $y = B(\underline{b}, \lambda)$
$-2 \leq E(a',b') + E(a',b) + E(a,b') - E(a,b) \leq +2$
CHSH

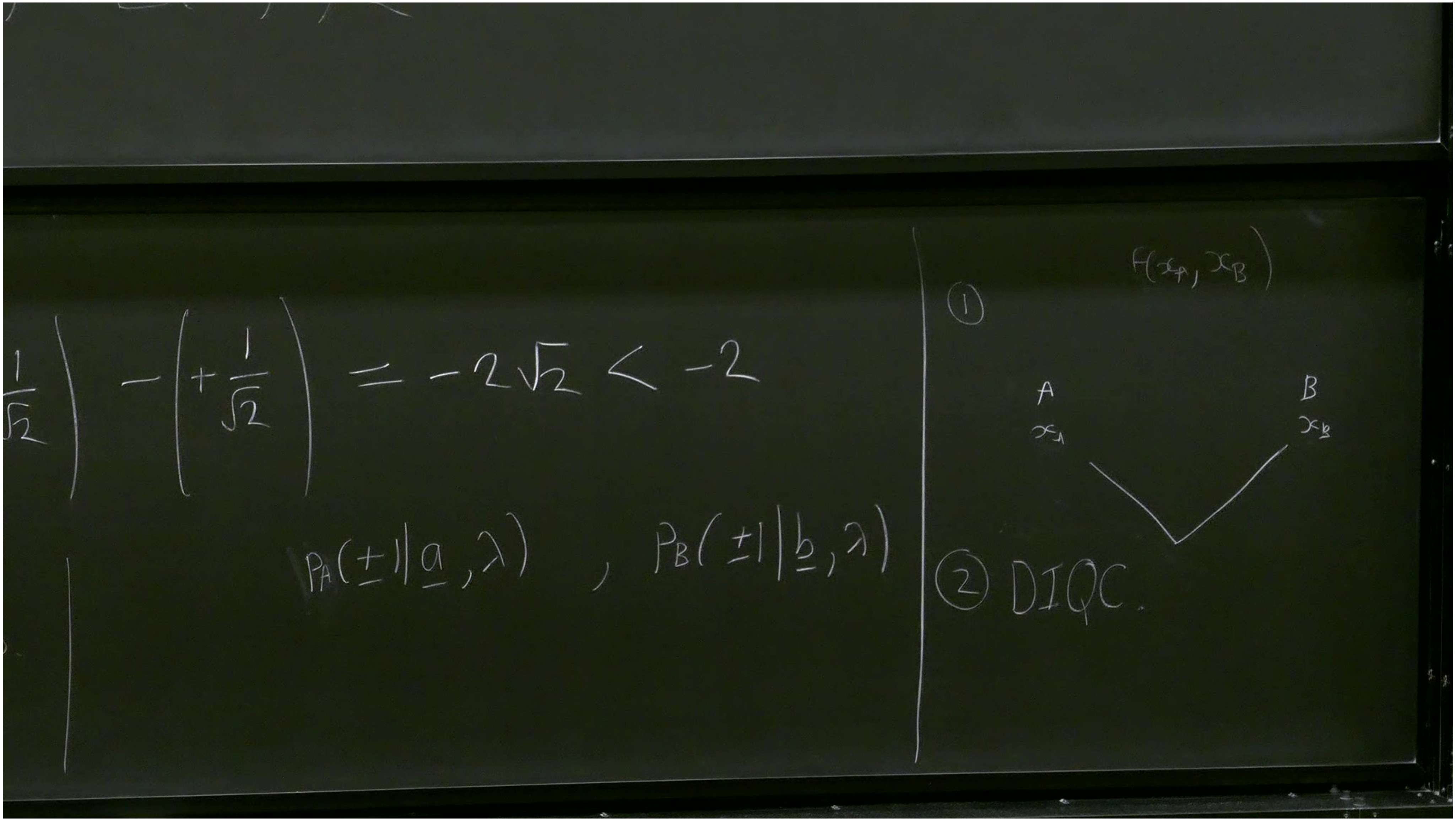
$$|\psi\rangle = \frac{1}{\sqrt{2}}\left(|+\rangle_a|-\rangle_b - |-\rangle_a|+\rangle_b\right)$$

$$E(\underline{a},\underline{b}) = \langle\psi|\hat{\sigma}_{\underline{a}}\otimes\hat{\sigma}_{\underline{b}}|\psi\rangle = -\underline{a}\cdot\underline{b}$$

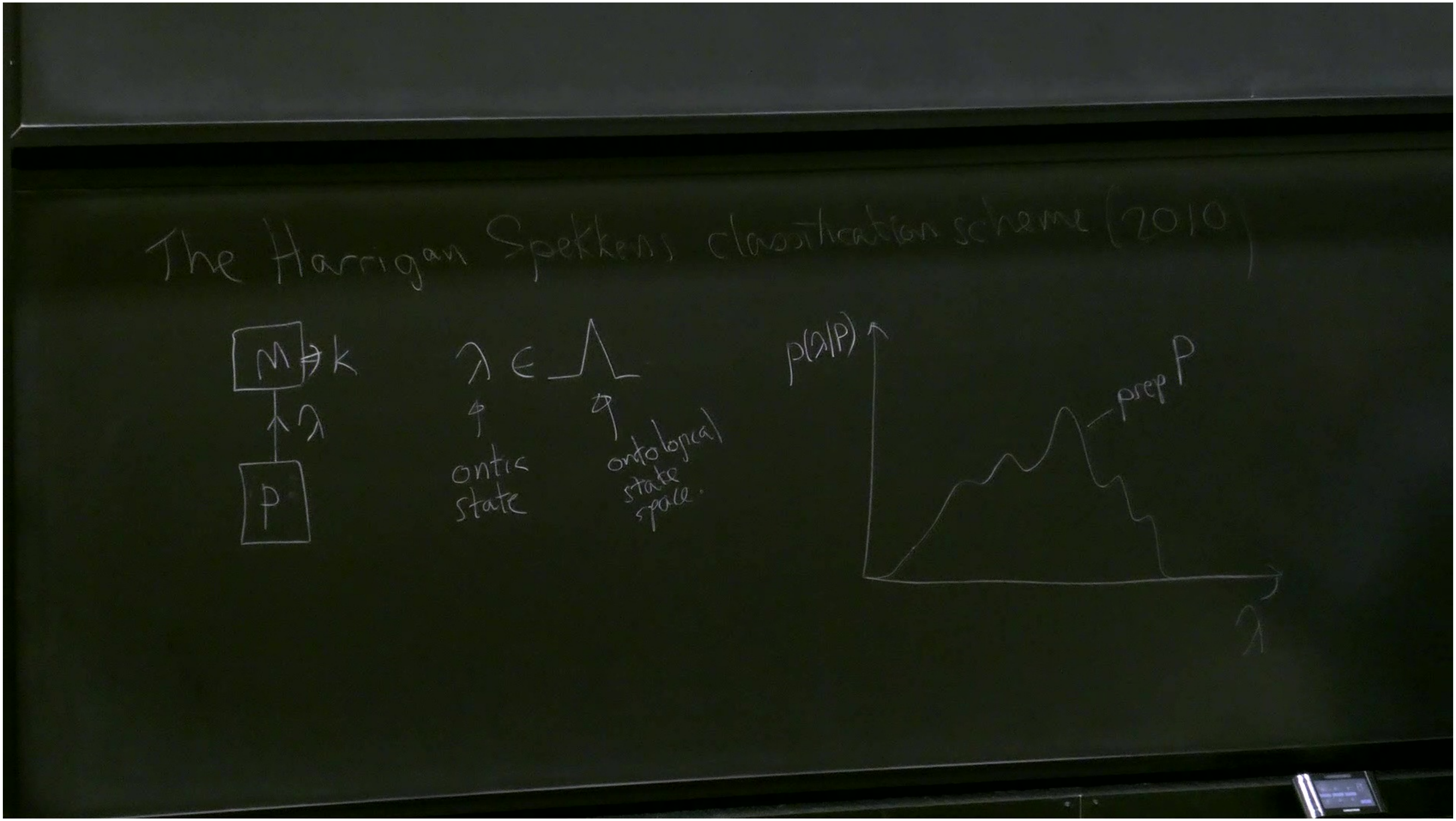
$$) - E(a,b) \leq +2$$

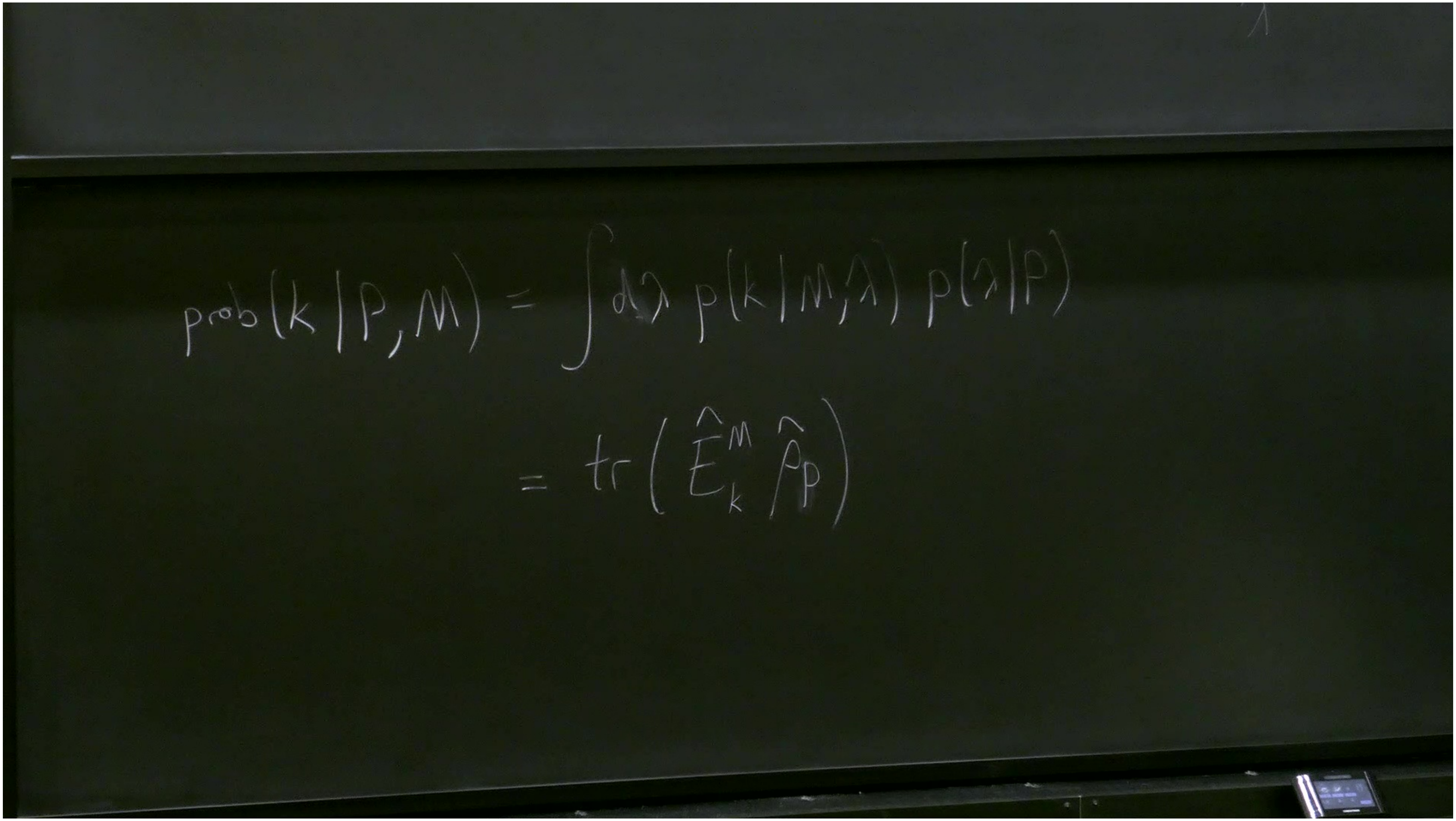

-2 ≤ E(a', b') + E(a', b) + E(a, b') - E(a, b) ≤ +2
CHSH
a
b'
45°
45°
a'
45°
b
(-1/√2) + (-1/√2) + (-1/√2) - (+1/√2) = -2√2 < -2
counterfactual definiteness
P_A(±1|a, λ) , P_B(±1|b,

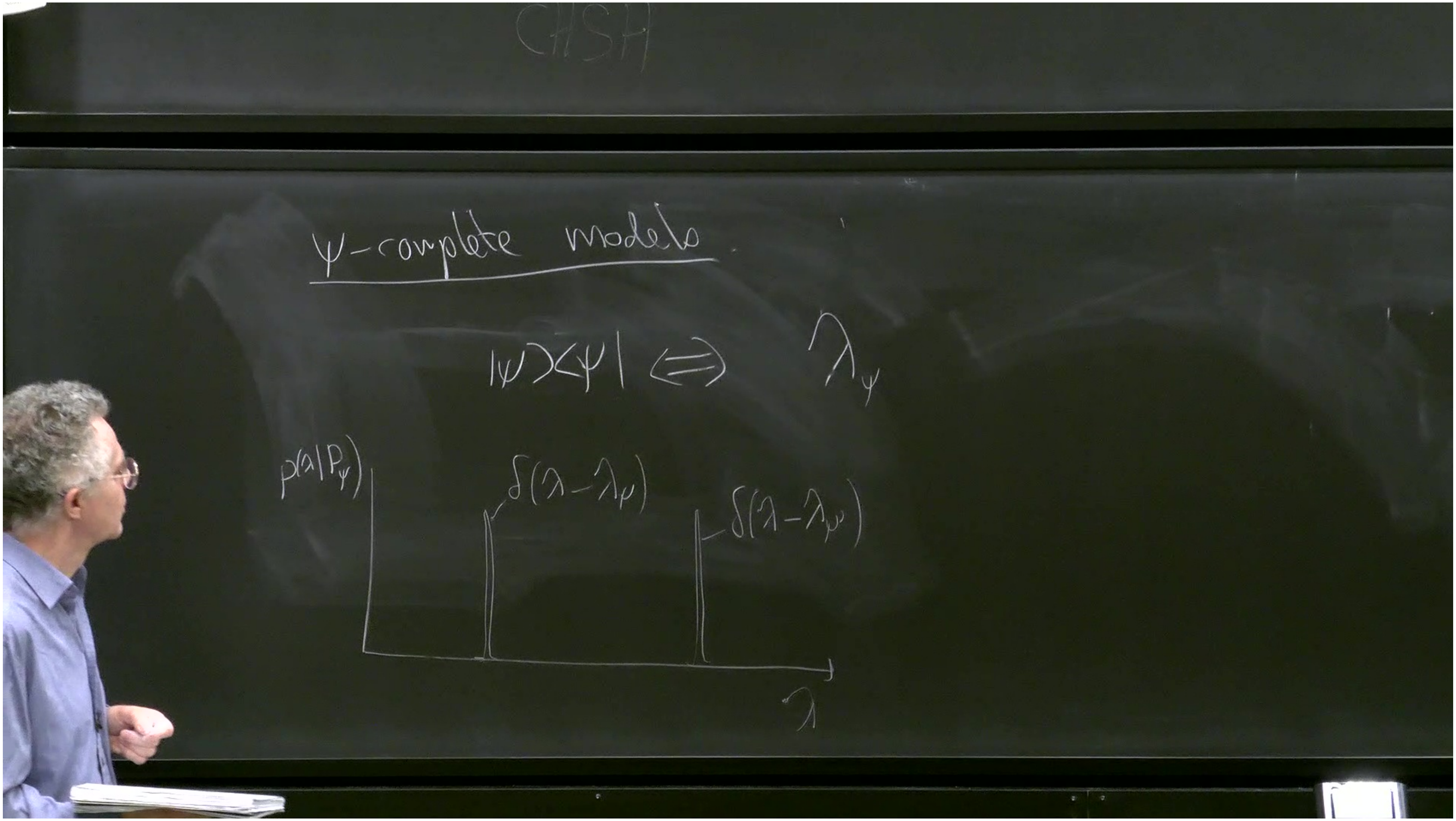

p(± ±, a, b) , P_A(+ | a)
No signalling polytope.
Quantum
Bell polytope
PR boxes
more nonlocal
than QT but
still no signalling.

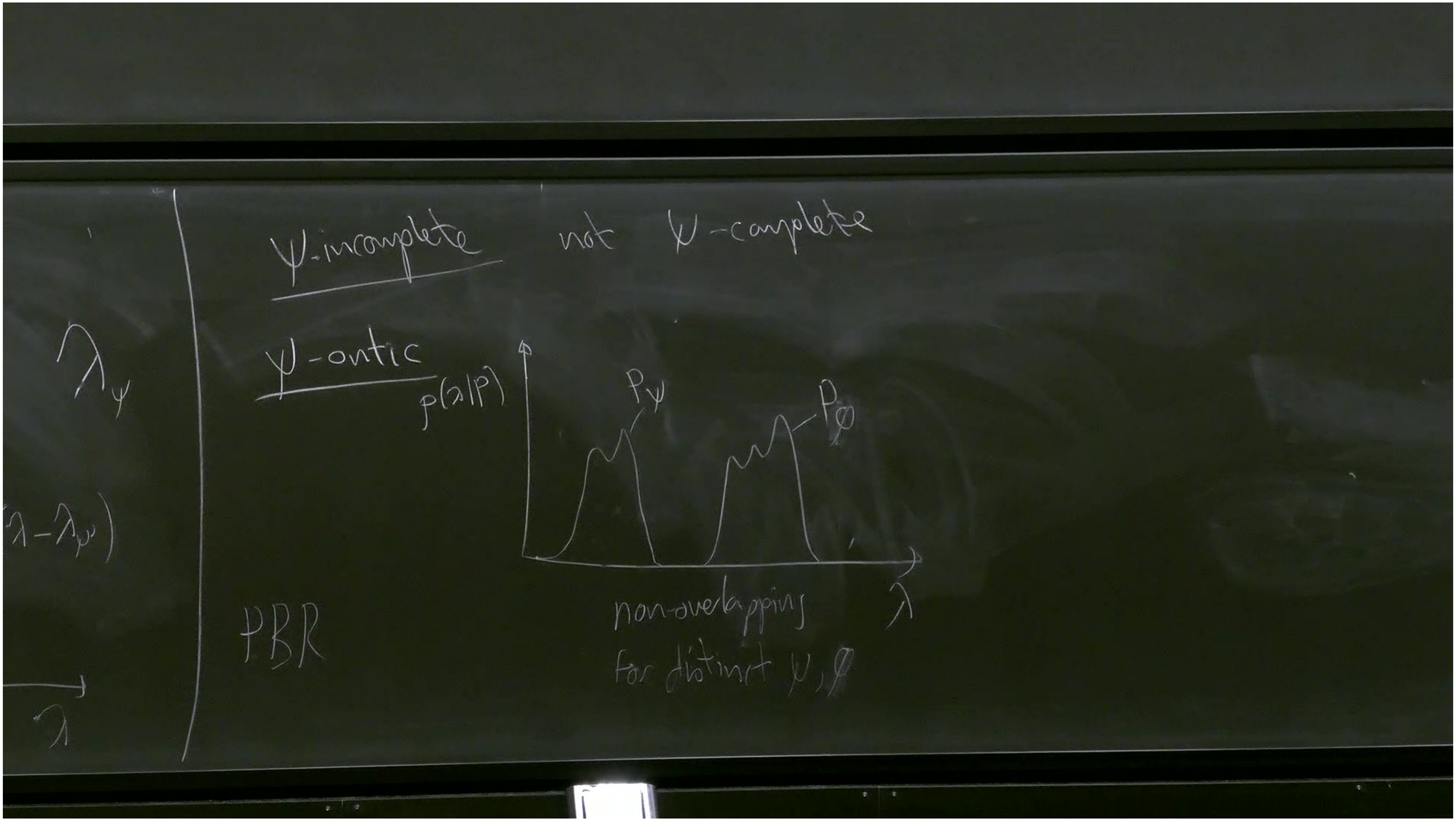


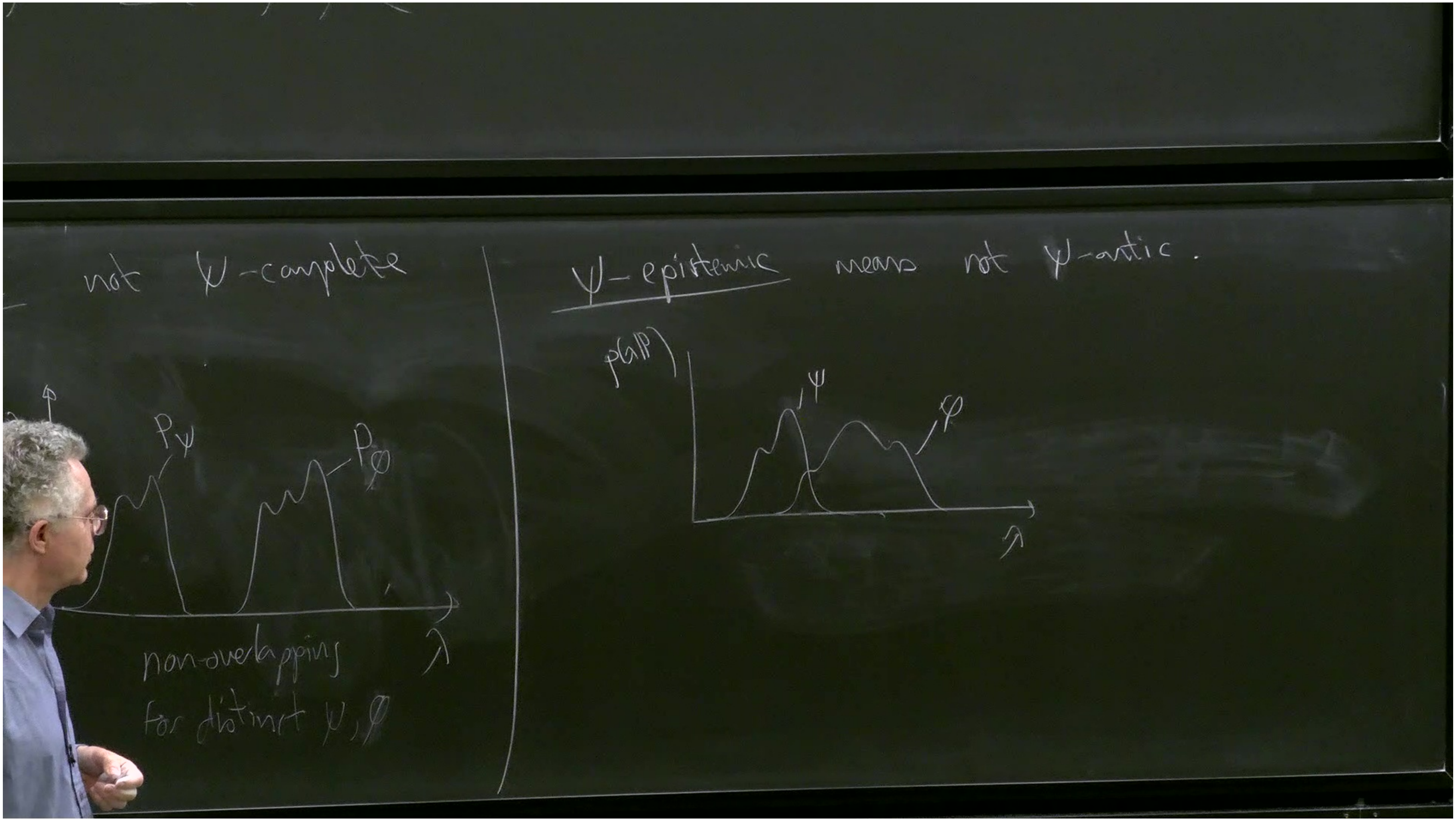
$- \left(+ \frac{1}{\sqrt{2}} \right) = -2\sqrt{2} < -2$
$p_A(\pm 1 | \underline{a}, \lambda)$, $p_B(\pm 1 | \underline{b}, \lambda)$
$f(x_A, x_B)$
①
A
x_A
B
x_B
② DIQC.


The Harrigan Spekkens classification scheme (2010)
M
k
λ
P
λ ∈ Λ
ontic state
ontological state space.
p(λ|P)
prep P
λ

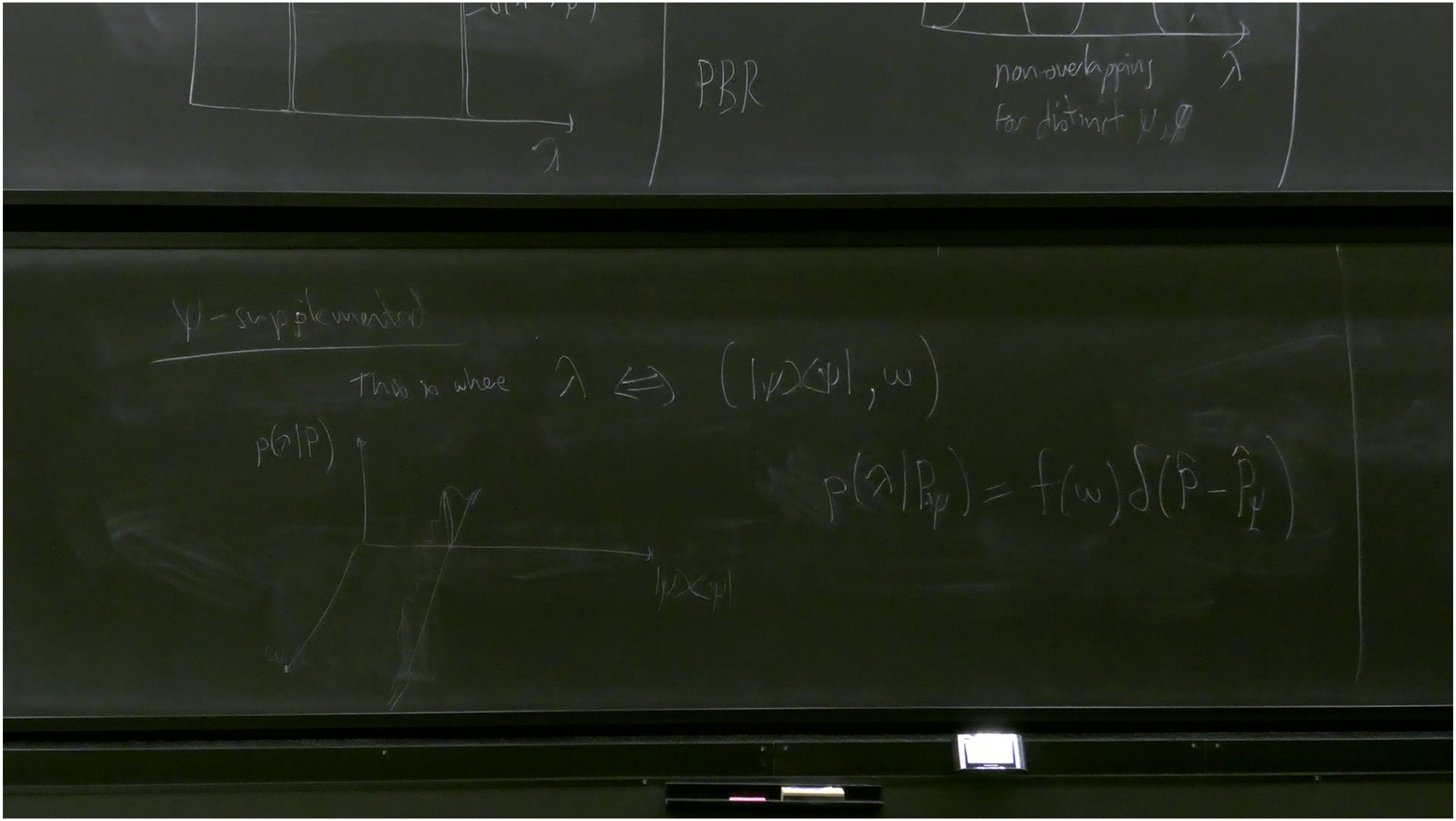

$\mathrm{prob}(k|P,M) = \int d\lambda\, p(k|M,\lambda)\, p(\lambda|P)$
$= \mathrm{tr}(\hat{E}^M_k \hat{\rho}_P)$

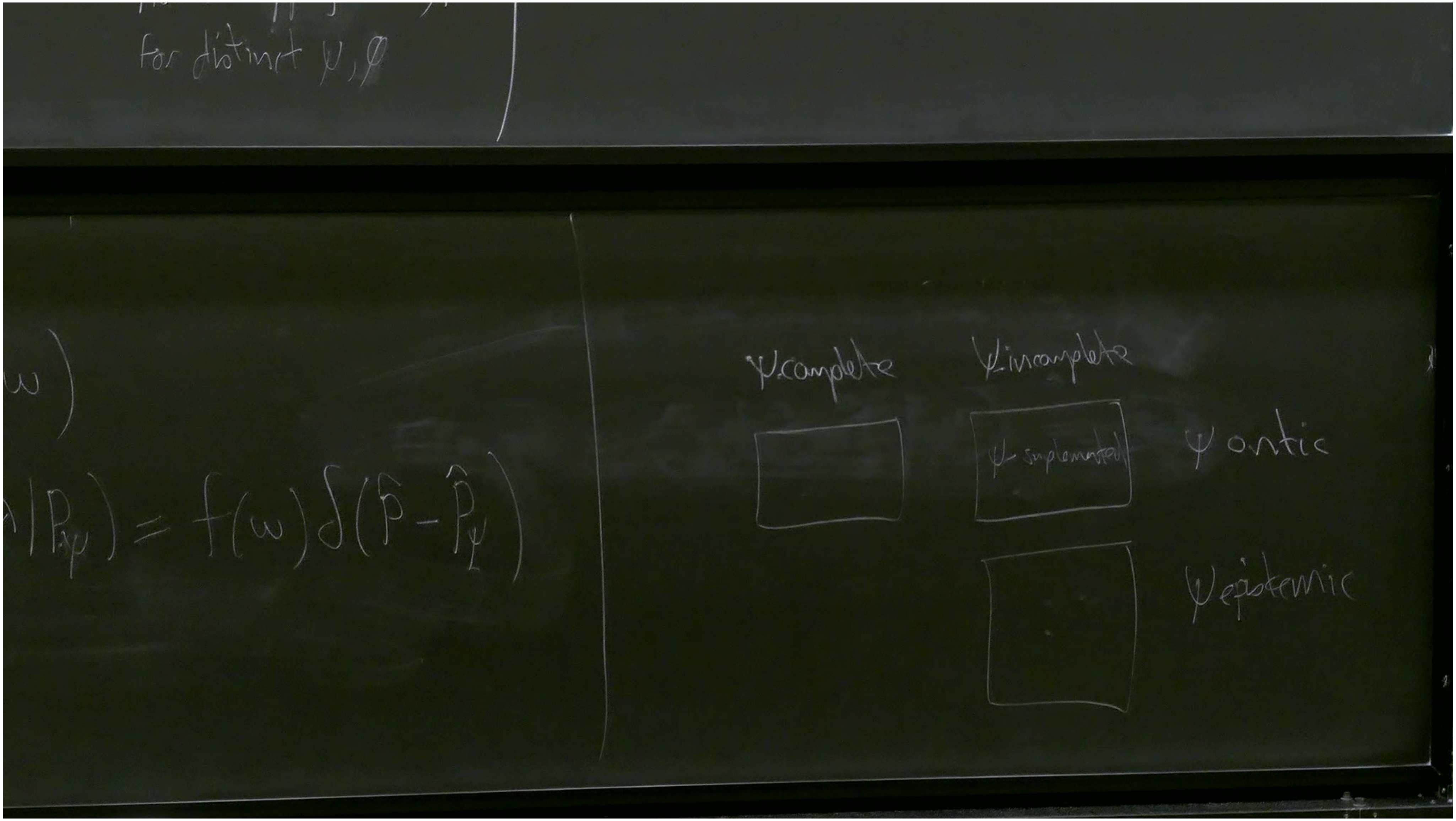

CHSH
ψ-complete models
|ψ⟩⟨ψ| ⟺ λ_ψ
p(λ|P_ψ)
δ(λ−λ_ψ)
δ(λ−λ_ψ')
λ


λψ
λ−λψ')
λ
ψ-incomplete
not ψ-complete
ψ-ontic
p(λ|P)
Pψ
Pφ
λ
non-overlapping
for distinct ψ, φ
PBR



not ψ-complete
P_ψ
P_φ
λ
non-overlapping
for distinct ψ, φ
ψ-epistemic means not ψ-ontic.
p(λ|P)
ψ
φ
λ


λ
PBR
non-overlapping for distinct ψ, ϕ
λ
ψ-supplemented
This is where $\lambda \Leftrightarrow (|\psi\rangle\langle\psi|, \omega)$
$p(\lambda|P)$
$p(\lambda|P_\psi) = f(\omega)\,\delta(\hat{P} - \hat{P}_\psi)$
$|\psi\rangle\langle\psi|$
ω


for distinct ψ, φ
ω)
|P_ψ) = f(ω) δ(P̂ - P̂_ψ)
ψ-complete
ψ-incomplete
ψ-supplemented
ψ-ontic
ψ-epistemic