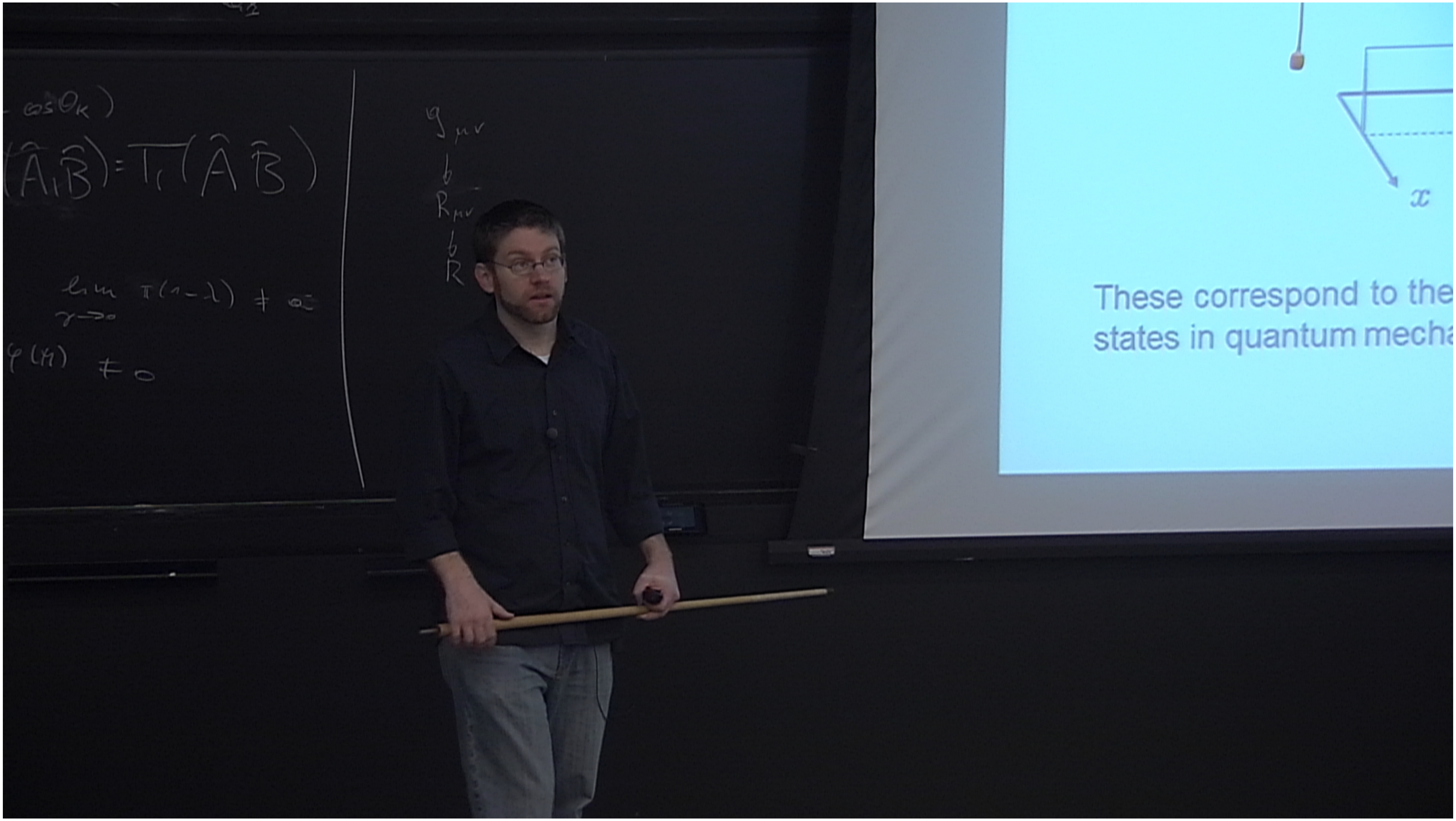
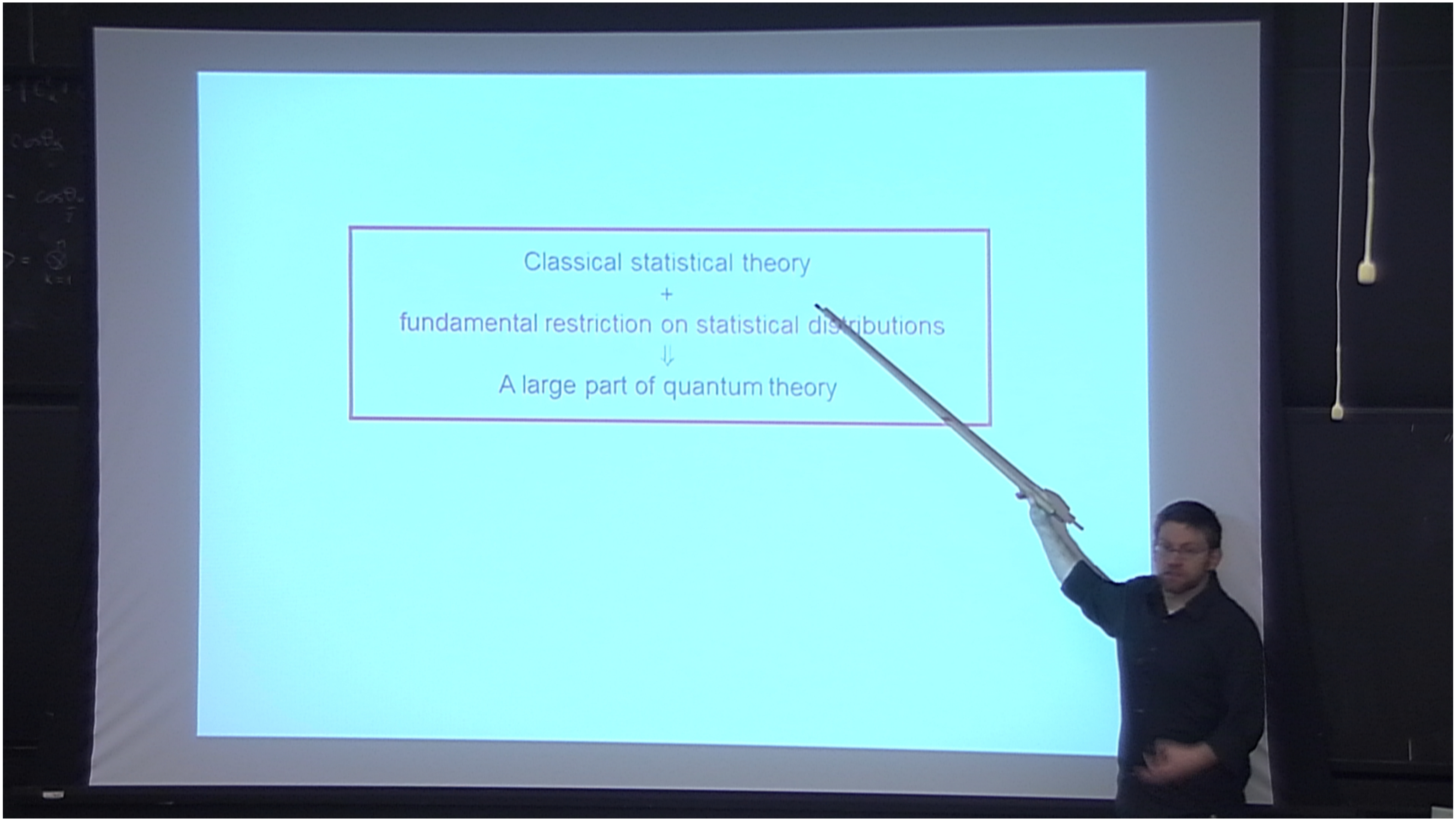
Title: Foundations of Quantum Mechanics - Lecture 7

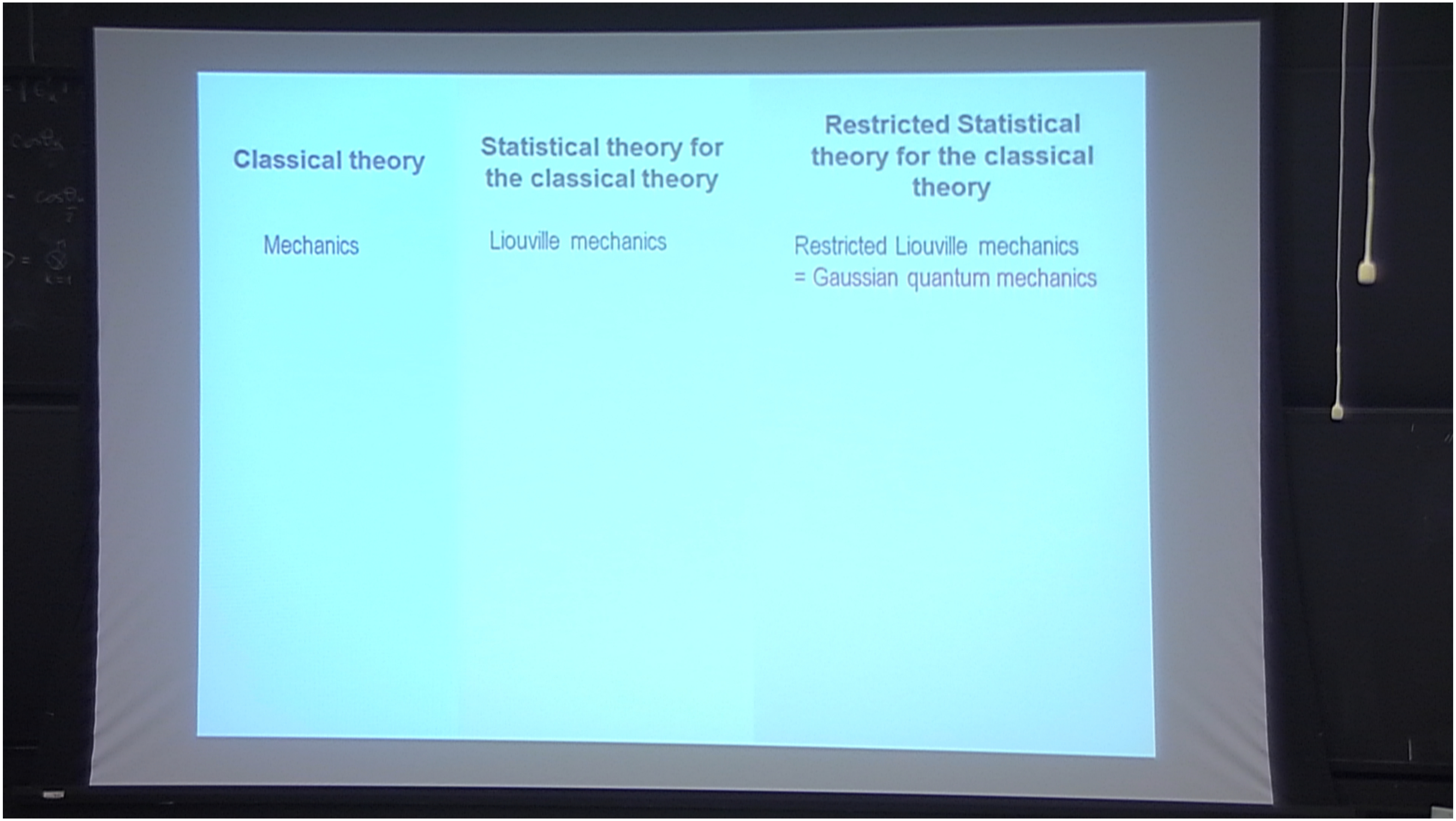
Date: Jan 10, 2012 11:30 AM

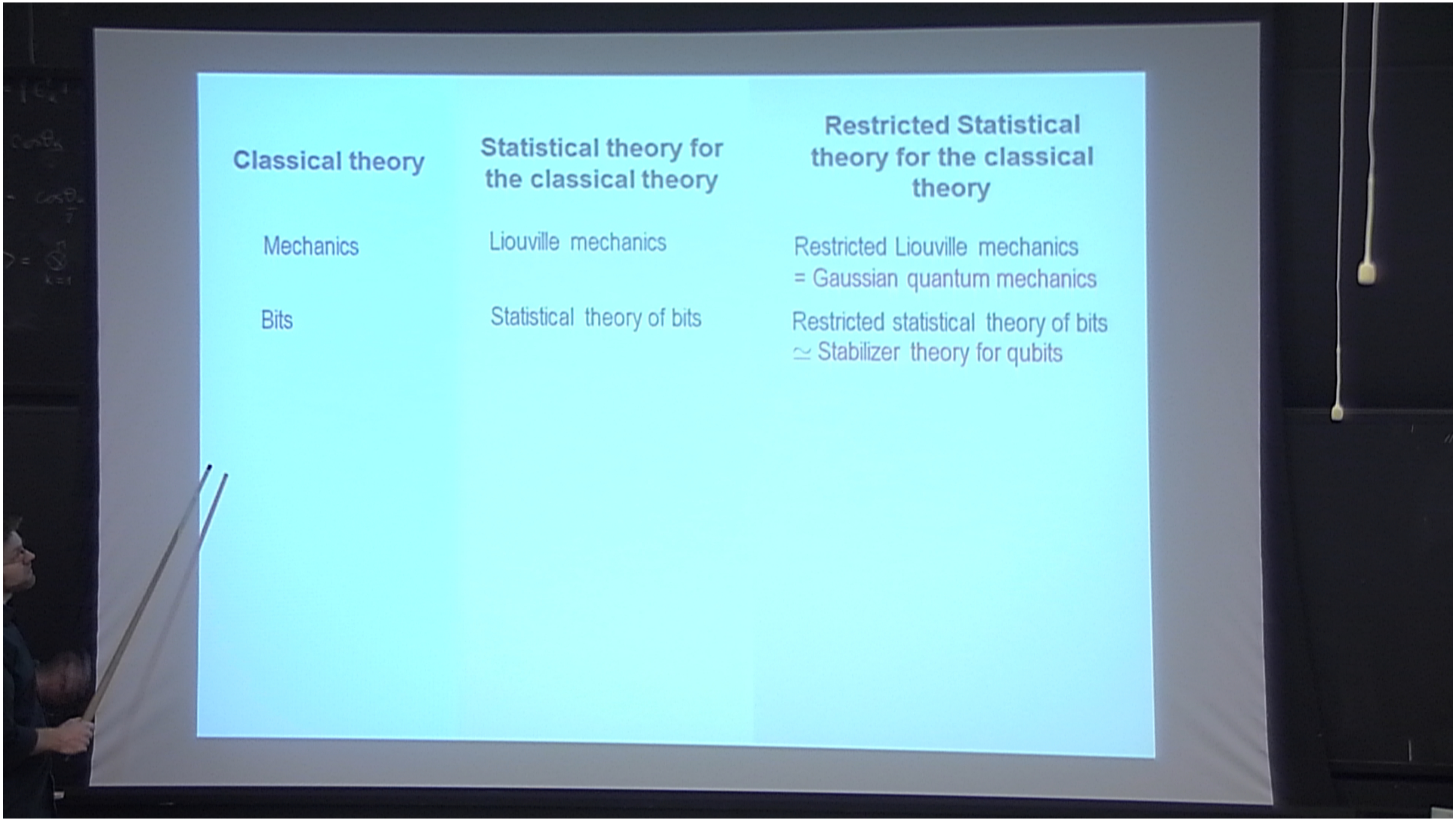
URL: http://pirsa.org/12010046

Abstract:


These correspond to the
states in quantum mecha
x


Classical statistical theory
+
fundamental restriction on statistical distributions
⇓
A large part of quantum theory


Classical theory
Statistical theory for the classical theory
Restricted Statistical theory for the classical theory
Mechanics
Liouville mechanics
Restricted Liouville mechanics
= Gaussian quantum mechanics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Restricted Statistical theory for the classical theory
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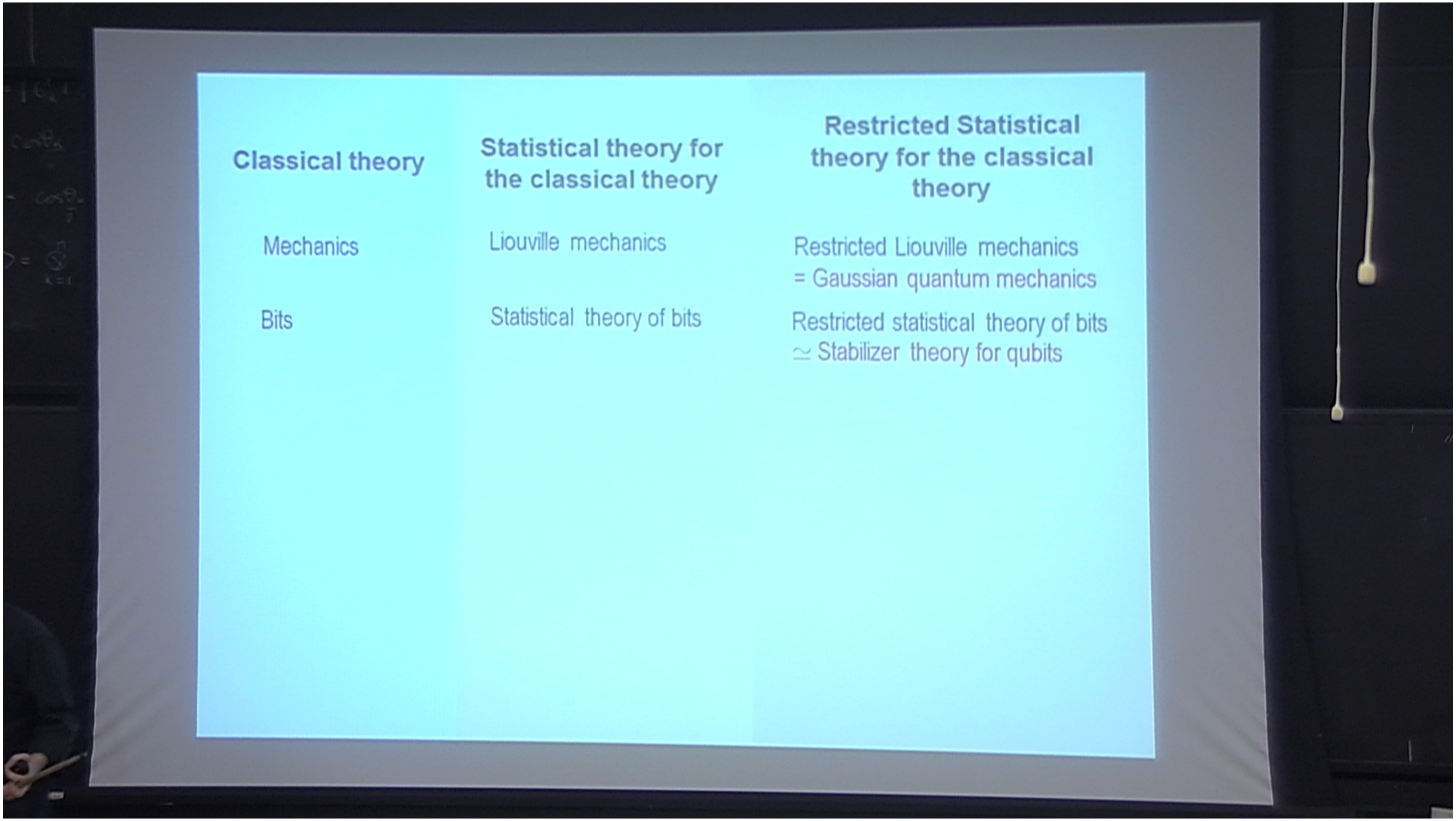
Liouville mechanics
Restricted Liouville mechanics
= Gaussian quantum mechanics
Bits
Statistical theory of bits
Restricted statistical theory of bits
≃ Stabilizer theory for qubits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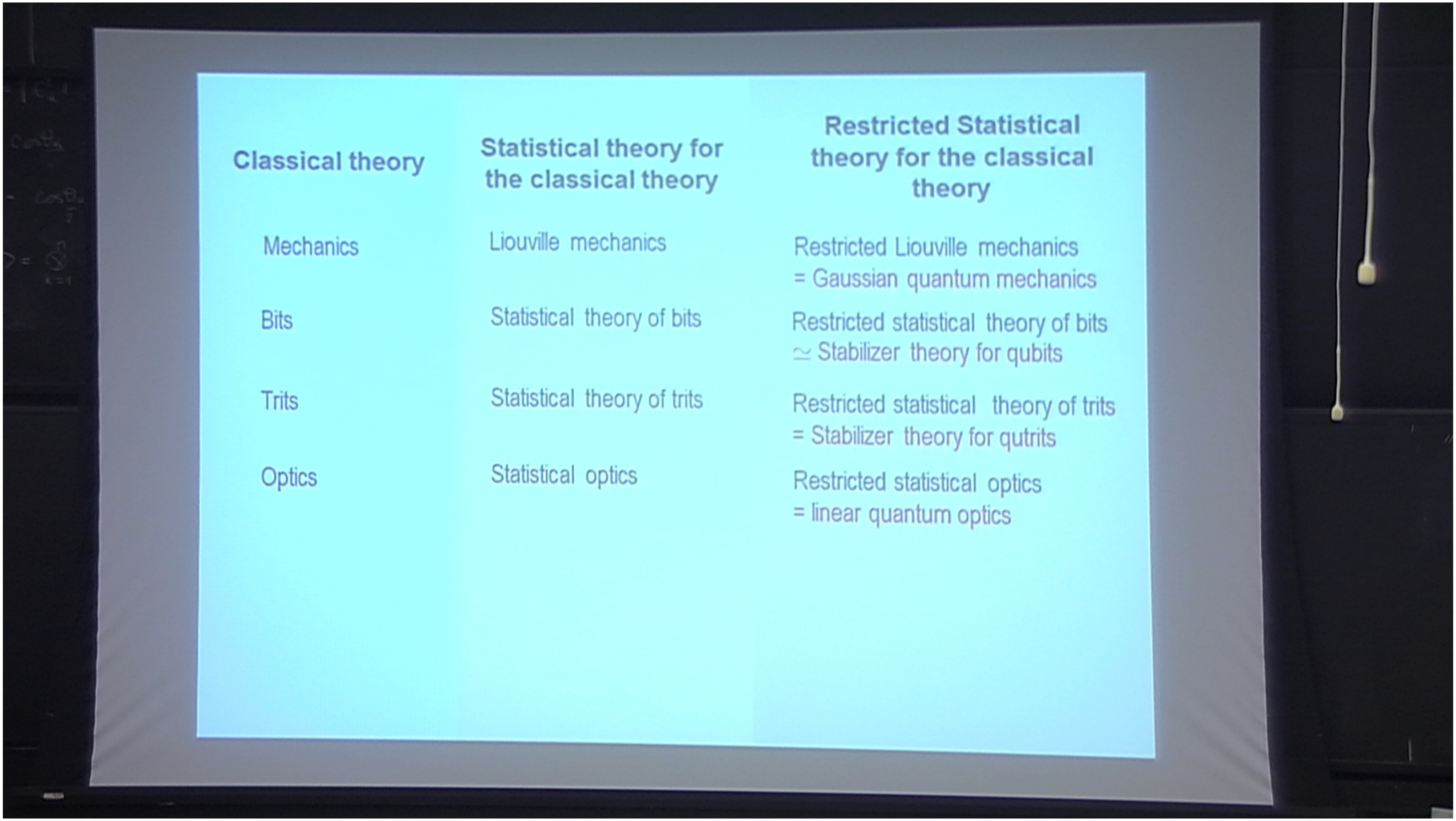
Bits
Statistical theory of bits
Trits
Statistical theory of trits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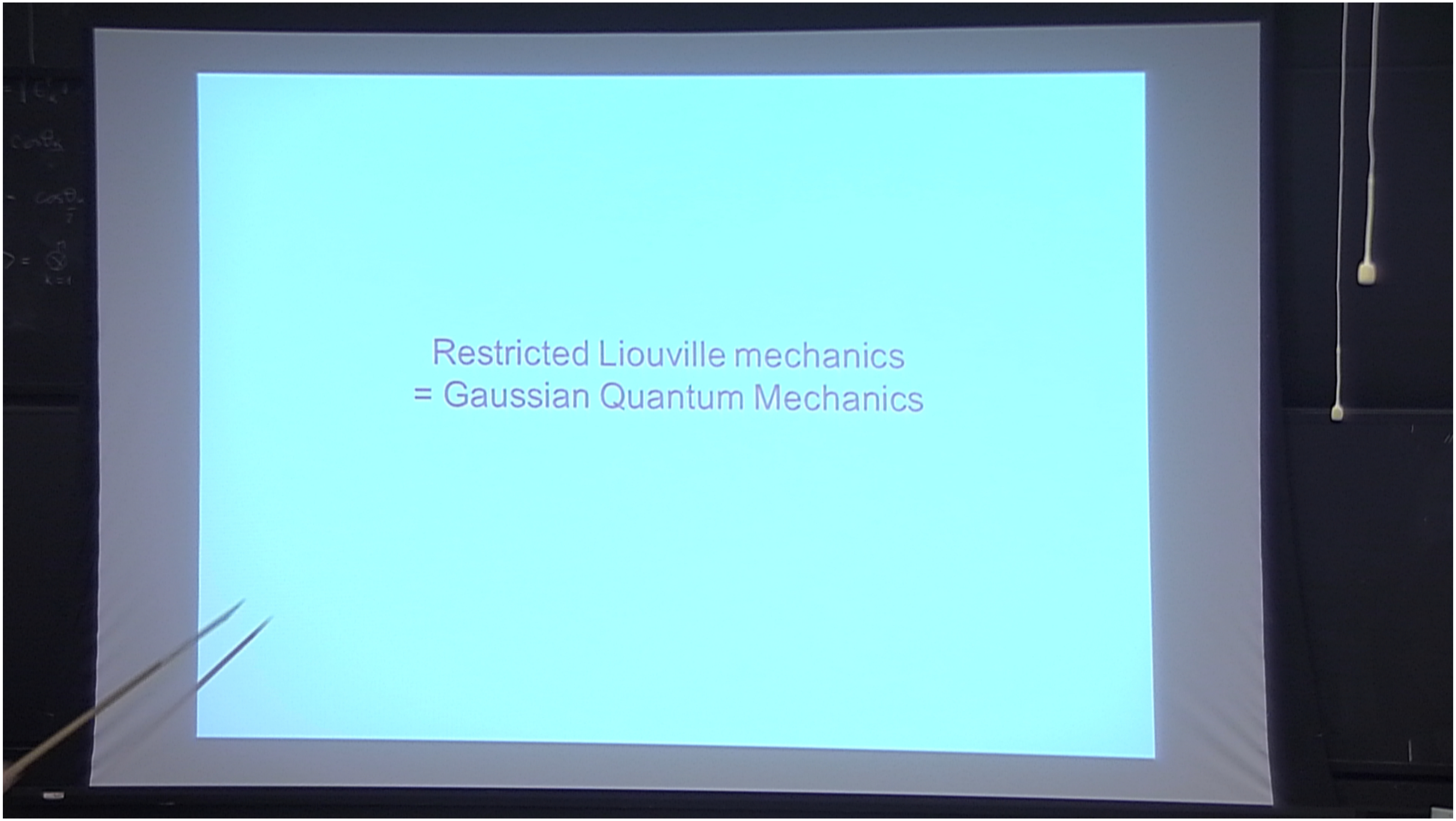
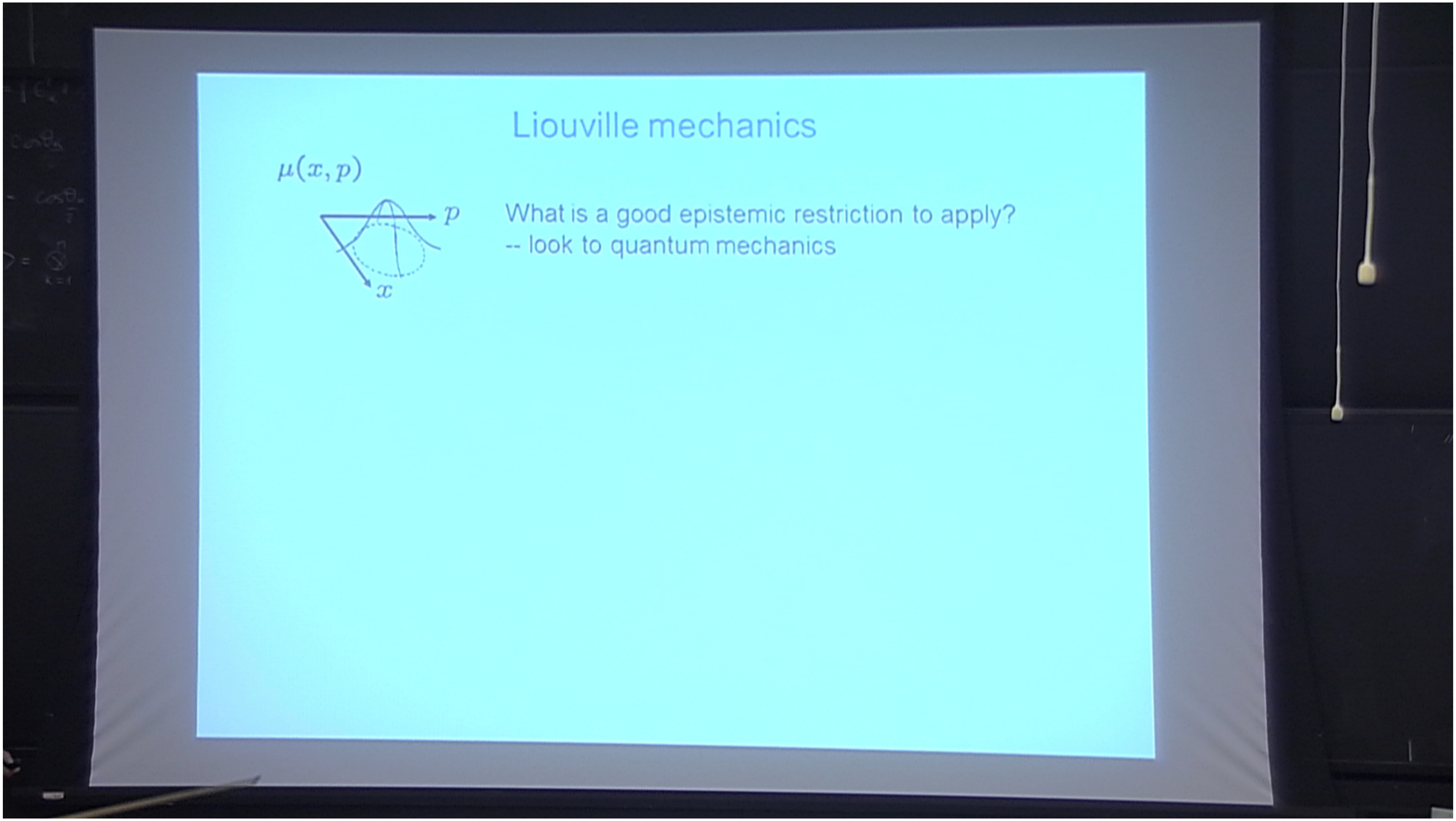
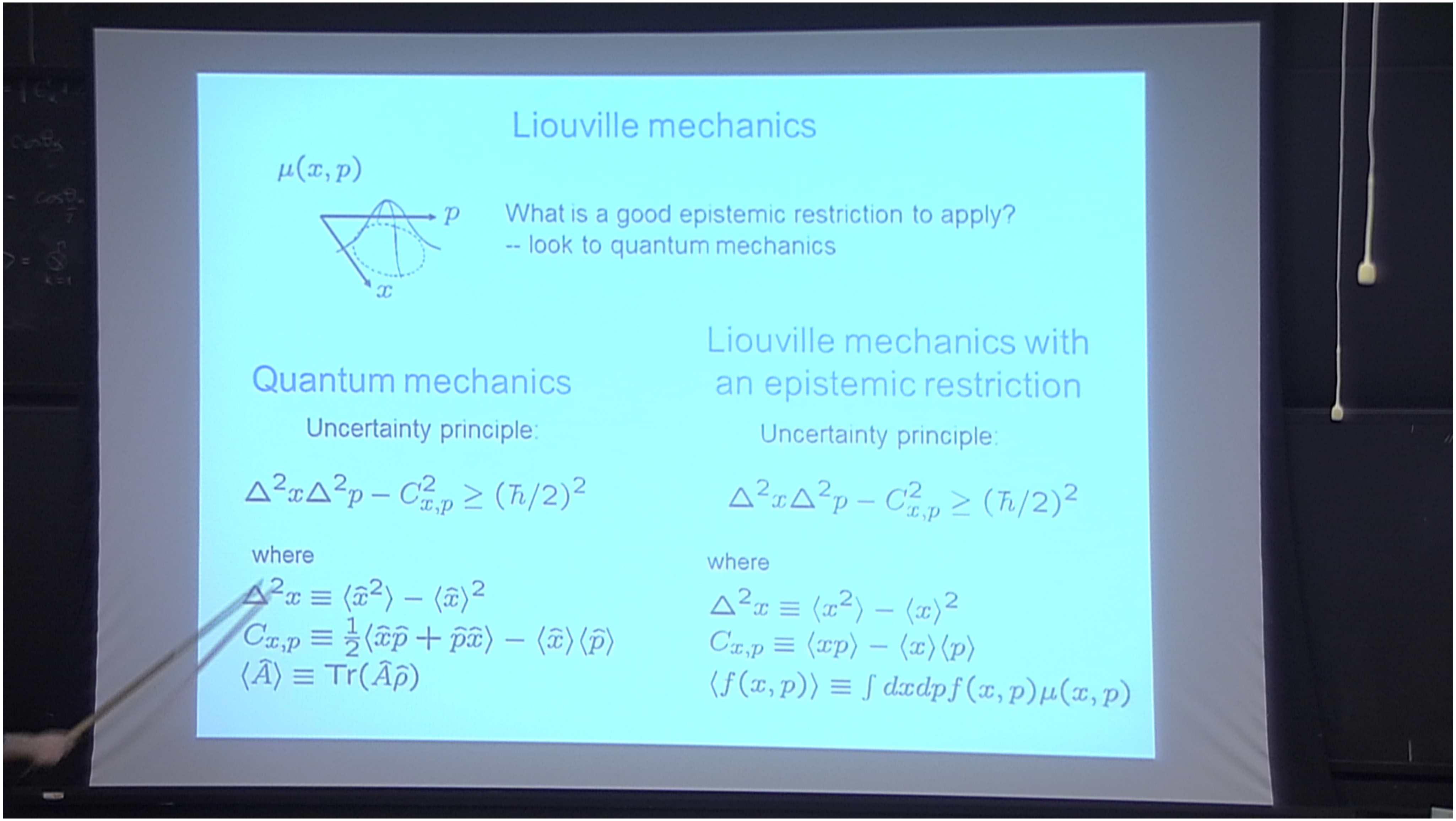
Optics
Statistical optics
Restricted statistical optics = linear quantum optics


Restricted Liouville mechanics
= Gaussian Quantum Mechanics


Liouville mechanics
$\mu(x,p)$
p
x
What is a good epistemic restriction to apply?
-- look to quantum mechanics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Quantum mechanics
Uncertainty principle:
$\Delta^2 x \Delta^2 p - C_{x,p}^2 \geq (\hbar/2)^2$
where
$\Delta^2 x \equiv \langle \hat{x}^2 \rangle - \langle \hat{x} \rangle^2$
$C_{x,p} \equiv \frac{1}{2}\langle \hat{x}\hat{p} + \hat{p}\hat{x} \rangle - \langle \hat{x} \rangle \langle \hat{p} \rangle$
$\langle \hat{A} \rangle \equiv \mathrm{Tr}(\hat{A}\hat{\rho})$
Liouville mechanics with an epistemic restriction
Uncertainty principle:
$\Delta^2 x \Delta^2 p - C_{x,p}^2 \geq (\hbar/2)^2$
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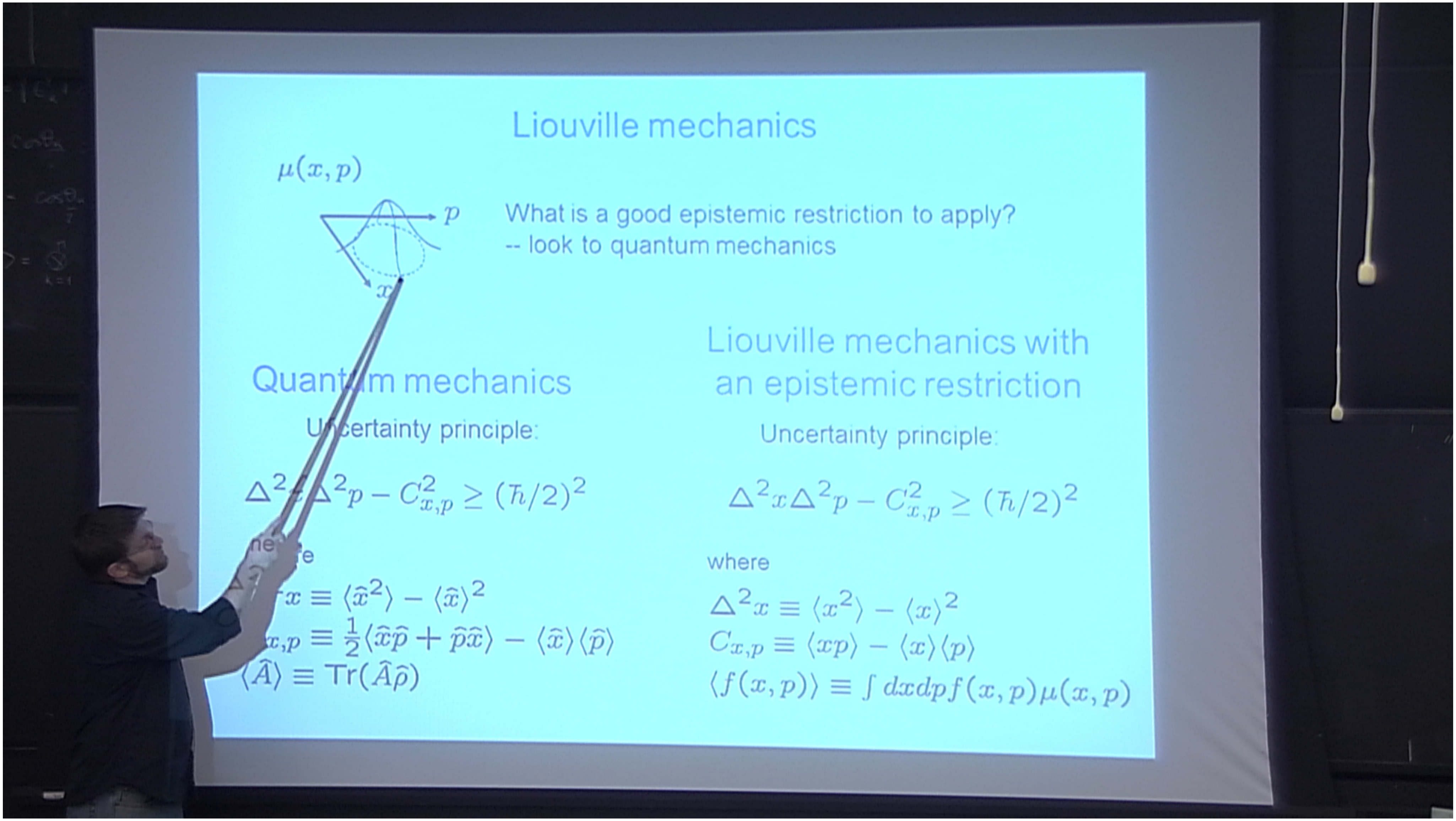
$\Delta^2 x \equiv \langle x^2 \rangle - \langle x \rangle^2$
$C_{x,p} \equiv \langle xp \rangle - \langle x \rangle \langle p \rangle$
$\langle f(x,p) \rangle \equiv \int dx dp f(x,p) \mu(x,p)$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Liouville mechanics with
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$\langle \widehat{A} \rangle \equiv \mathrm{Tr}(\widehat{A}\widehat{\rho})$

Liouville mechanics

$\mu(x,p)$

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Quantum mechanics

Uncertainty principle:

$$\Delta^2 x \Delta^2 p - C_{x,p}^2 \geq (\hbar/2)^2$$

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Liouville mechanics with an epistemic restriction

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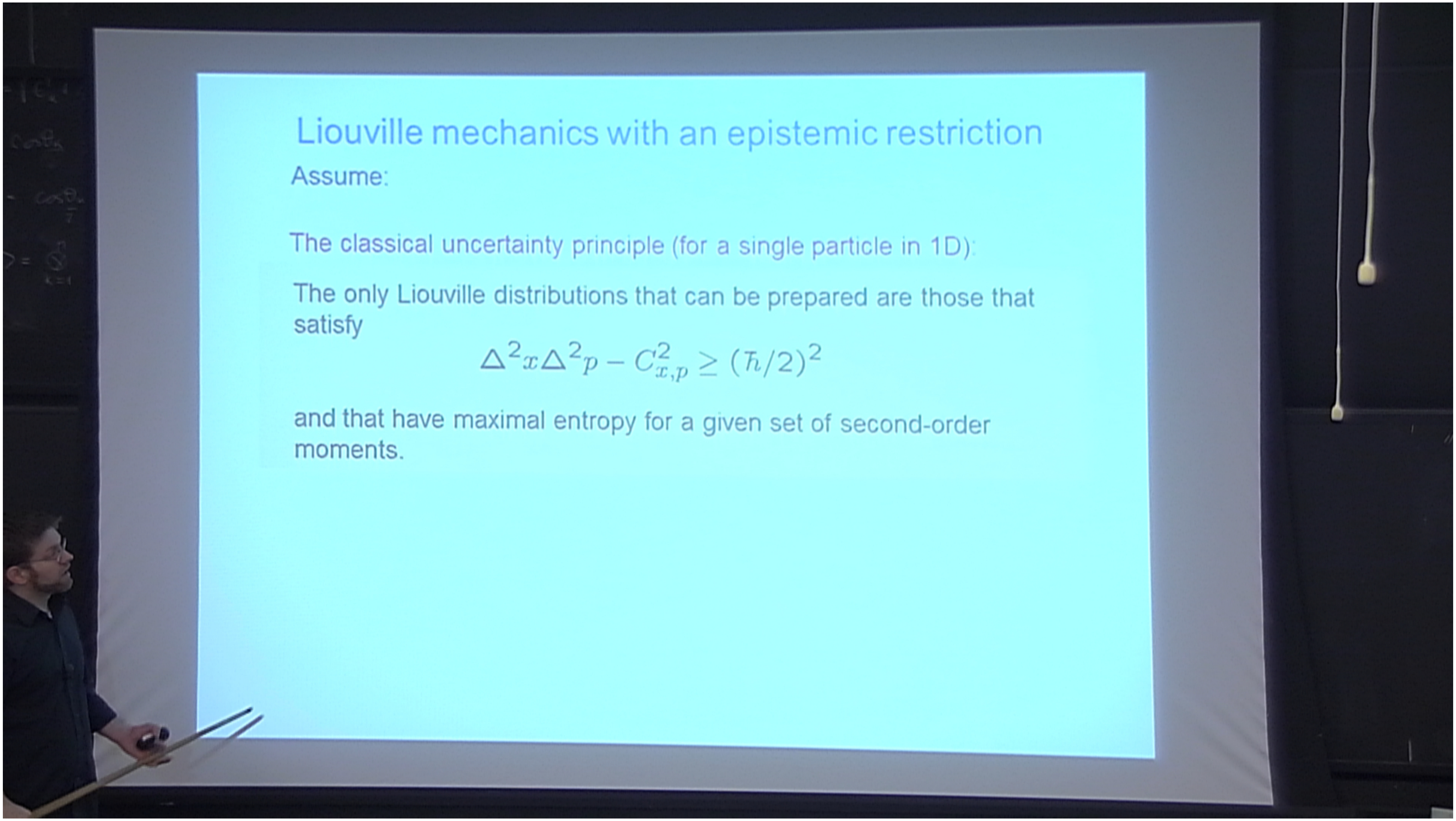
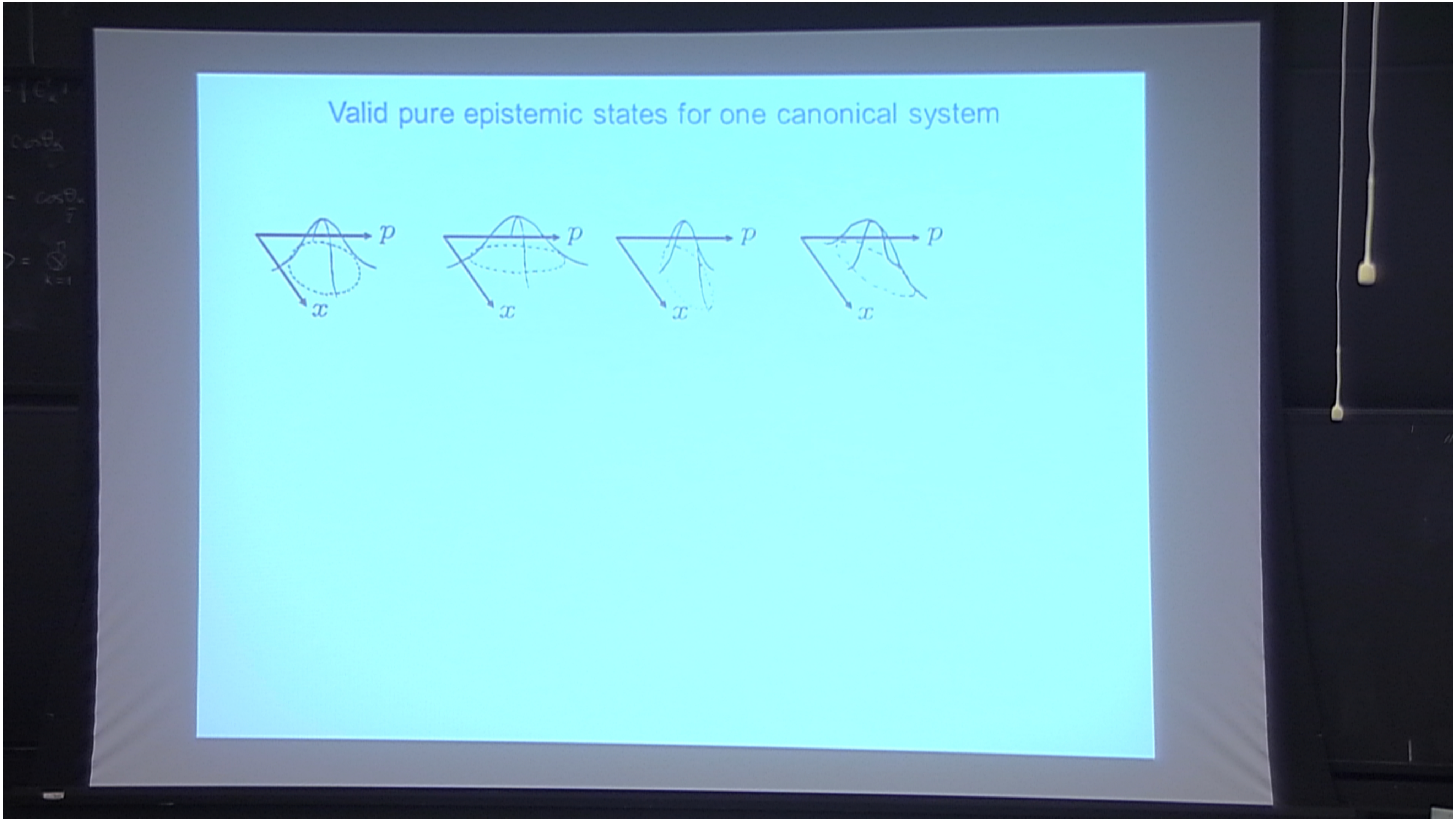
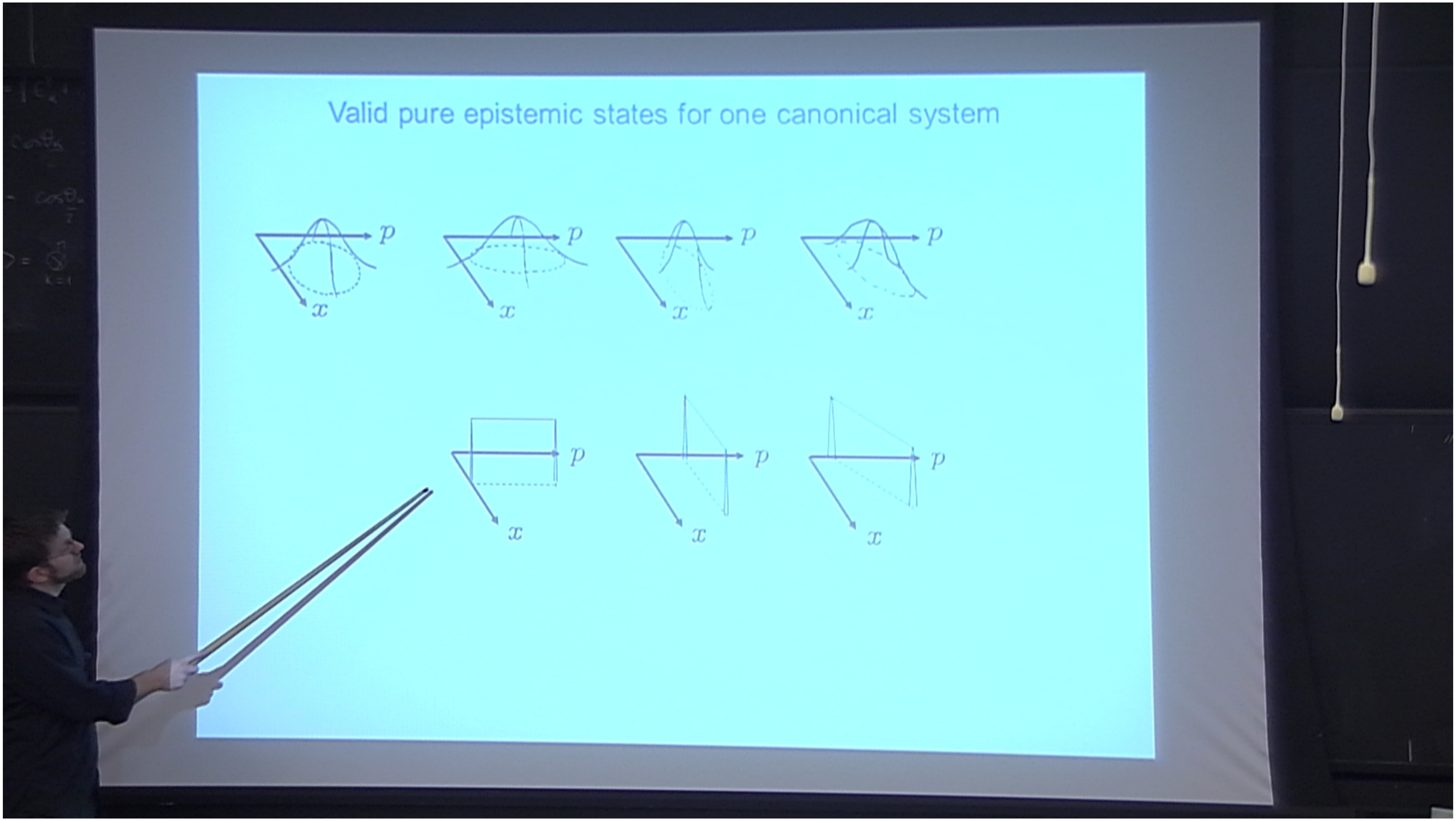

Liouville mechanics with an epistemic restriction
Assume:
The classical uncertainty principle (for a single particle in 1D):
The only Liouville distributions that can be prepared are those that satisfy
$\Delta^2 x \Delta^2 p - C_{x,p}^2 \geq (\hbar/2)^2$
and that have maximal entropy for a given set of second-order moments.


Valid pure epistemic states for one canonical system
p
x
p
x
p
x
p
x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p
x
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x
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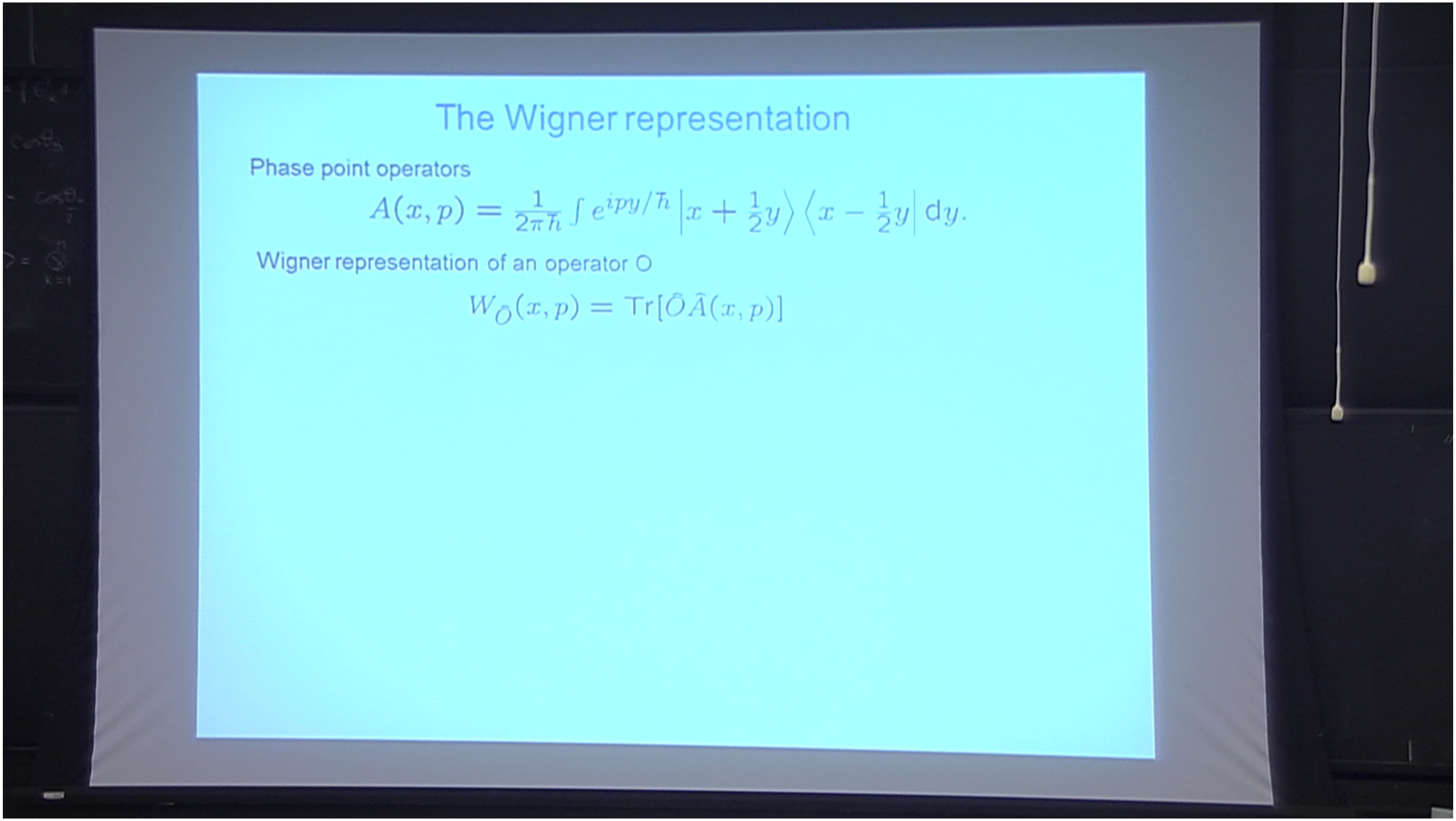
x
p
x
p
x
p
x


The Wigner representation
Phase point operators
$A(x,p) = \frac{1}{2\pi\hbar}\int e^{ipy/\hbar}\left|x+\frac{1}{2}y\right\rangle\left\langle x-\frac{1}{2}y\right|\,\mathrm{d}y.$
Wigner representation of an operator O
$W_{\hat{O}}(x,p) = \mathrm{Tr}[\hat{O}\hat{A}(x,p)]$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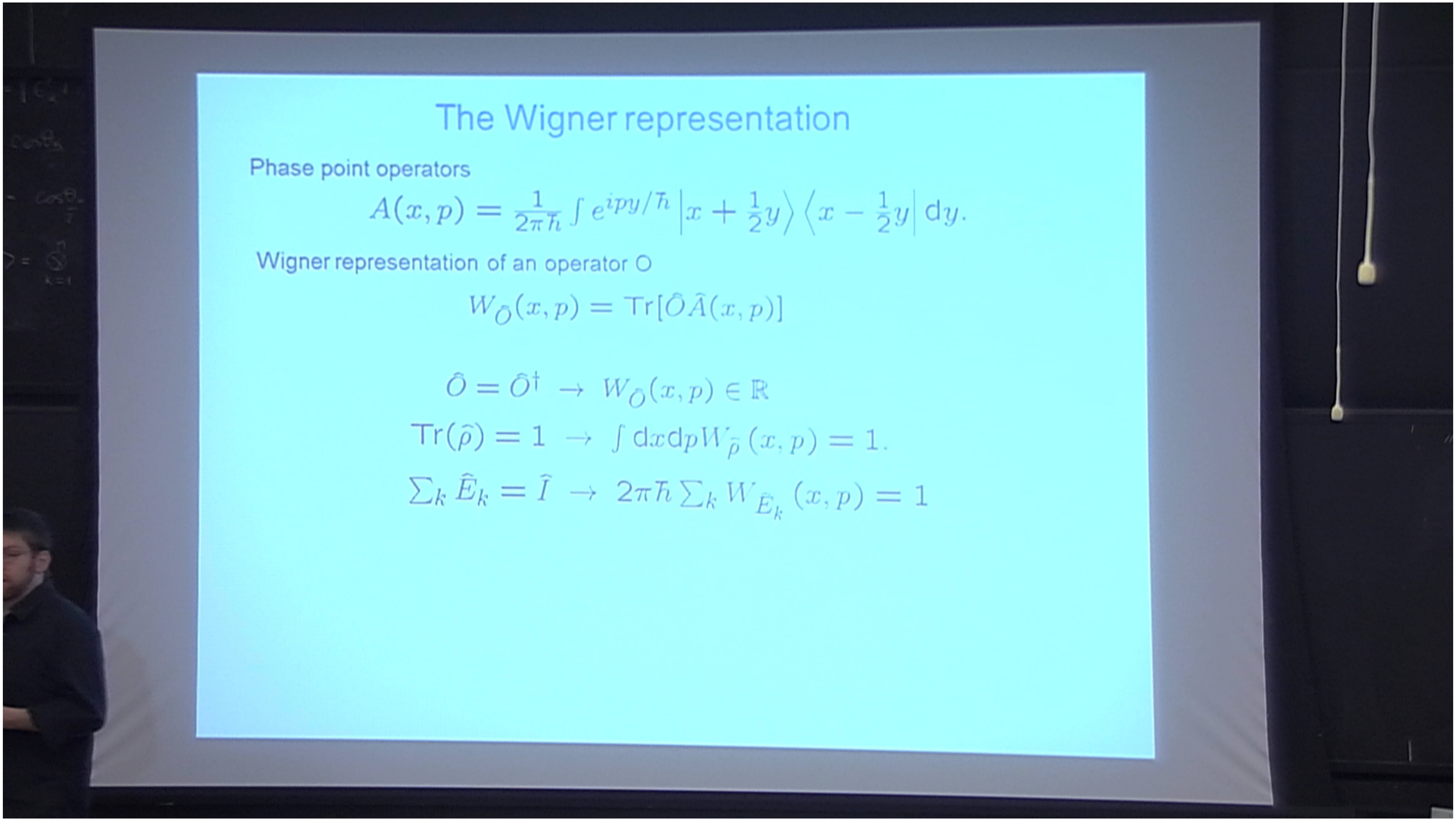
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Wigner representation of an operator O
$W_{\hat{O}}(x,p) = \mathrm{Tr}[\hat{O}\hat{A}(x,p)]$
$\hat{O} = \hat{O}^\dagger \rightarrow W_{\hat{O}}(x,p) \in \mathbb{R}$
$\mathrm{Tr}(\hat{\rho}) = 1 \rightarrow \int \mathrm{d}x\mathrm{d}p W_{\hat{\rho}}(x,p) = 1.$
$\sum_k \hat{E}_k = \hat{I} \rightarrow 2\pi\hbar\sum_k W_{\hat{E}_k}(x,p) = 1$

The Wigner representation

Phase point operators

$$A(x,p) = \frac{1}{2\pi\hbar}\int e^{ipy/\hbar}\left|x+\tfrac{1}{2}y\right\rangle\left\langle x-\tfrac{1}{2}y\right| \mathrm{d}y.$$

Wigner representation of an operator O

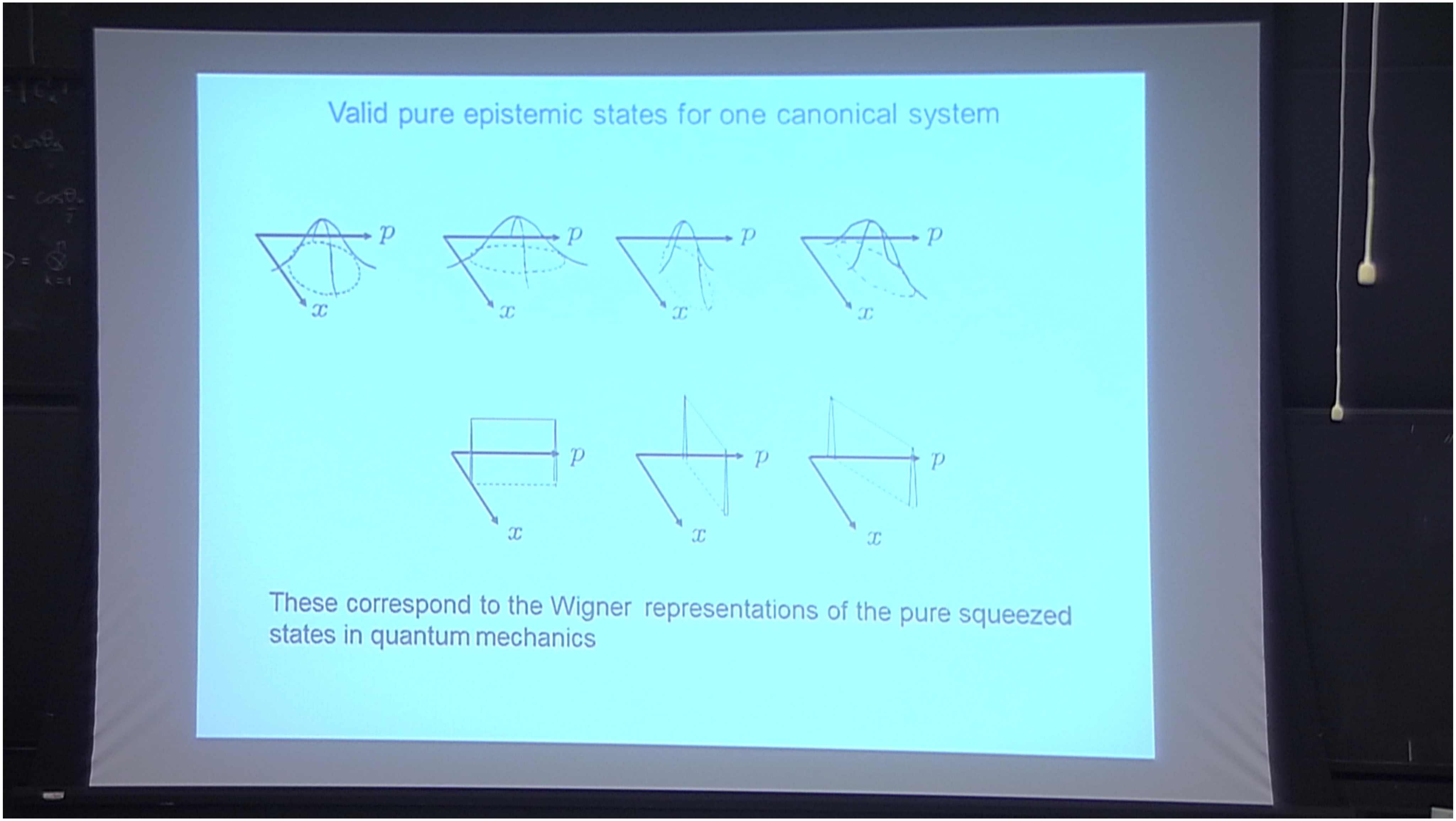
$$W_{\hat{O}}(x,p) = \mathrm{Tr}[\hat{O}\hat{A}(x,p)]$$

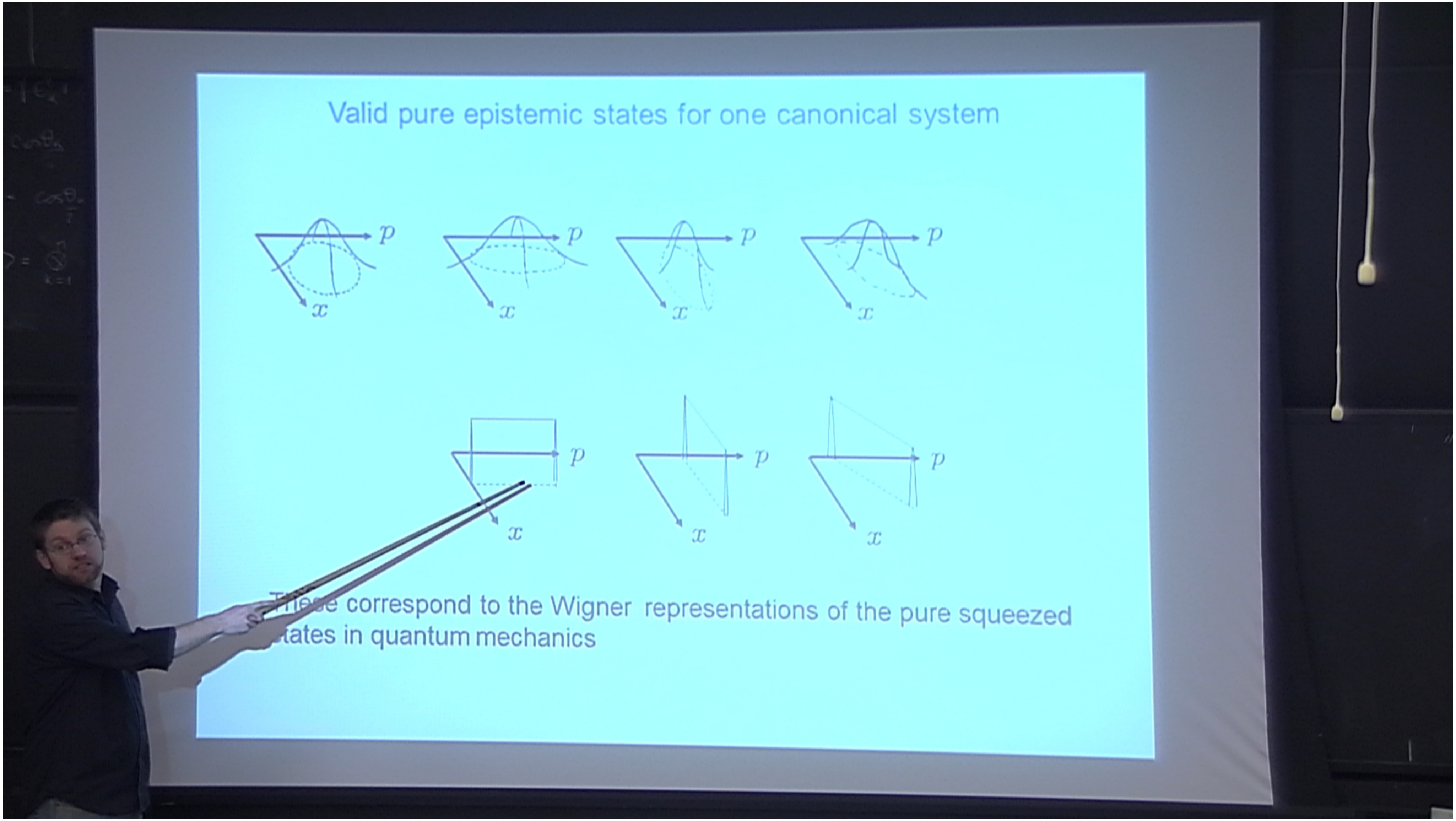
$$\hat{O}=\hat{O}^{\dagger} \rightarrow W_{\hat{O}}(x,p) \in \mathbb{R}$$

$$\mathrm{Tr}(\hat{\rho}) = 1 \rightarrow \int \mathrm{d}x\mathrm{d}p W_{\hat{\rho}}(x,p) = 1.$$

$$\sum_k \hat{E}_k = \hat{I} \rightarrow 2\pi\hbar \sum_k W_{\hat{E}_k}(x,p) = 1$$

and $2\pi\hbar\int \mathrm{d}x\mathrm{d}p W_{\hat{\rho}}(x,p) W_{\hat{E}_k}(x,p) = \mathrm{Tr}[\hat{\rho}\hat{E}_k]$


Valid pure epistemic states for one canonical system
p
x
These correspond to the Wigner representations of the pure squeezed states in quantum mechanics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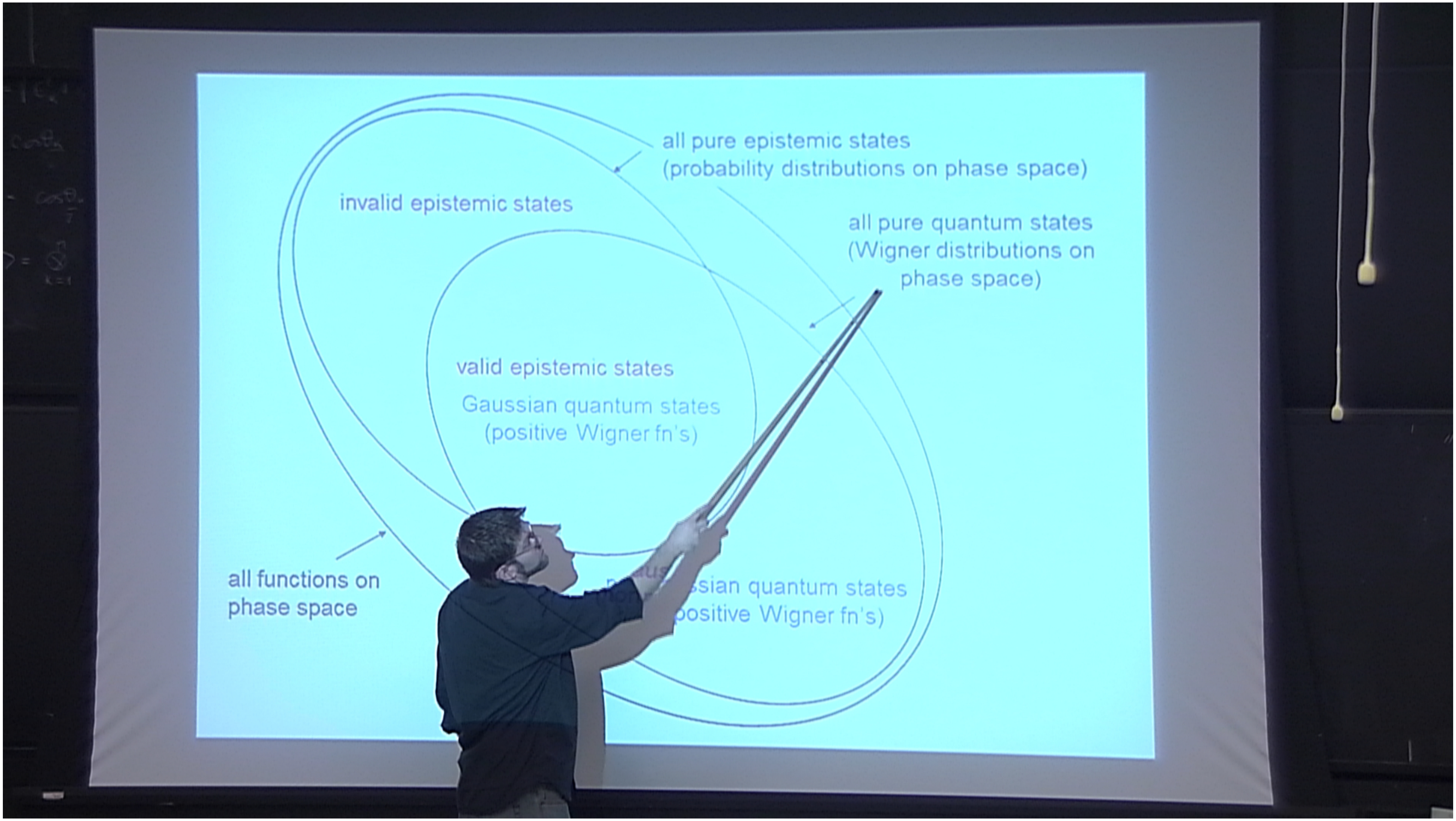
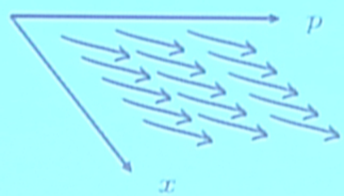
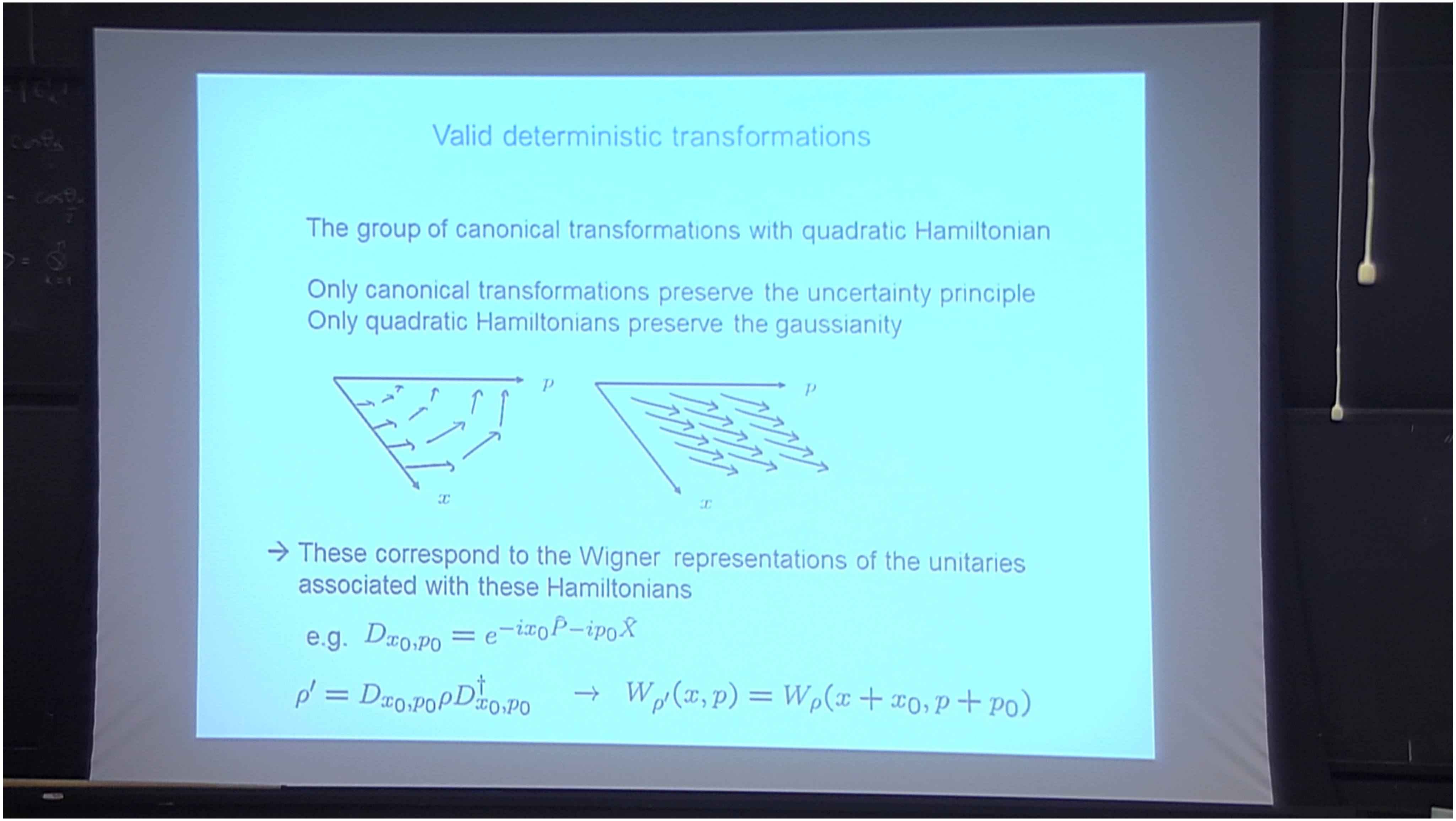

all pure epistemic states
(probability distributions on phase space)
invalid epistemic states
all pure quantum states
(Wigner distributions on
phase space)
valid epistemic states
Gaussian quantum states
(positive Wigner fn's)
all functions on
phase space
ssian quantum states
positive Wigner fn's)

Valid deterministic transformations

The group of canonical transformations with quadratic Hamiltonian

Only canonical transformations preserve the uncertainty principle
Only quadratic Hamiltonians preserve the gaussianity




Valid deterministic transformations
The group of canonical transformations with quadratic Hamiltonian
Only canonical transformations preserve the uncertainty principle
Only quadratic Hamiltonians preserve the gaussianity
p
x
p
x
→ These correspond to the Wigner representations of the unitaries associated with these Hamiltonians
e.g. $D_{x_0,p_0} = e^{-ix_0\hat{P}-ip_0\hat{X}}$
$\rho' = D_{x_0,p_0}\rho D^{\dagger}_{x_0,p_0} \quad \rightarrow \quad W_{\rho'}(x,p) = W_{\rho}(x+x_0, p+p_0)$

Liouville mechanics with an epistemic restriction

Assume:

The classical uncertainty principle (for a single particle in 1D):

The only Liouville distributions that can be prepared are those that satisfy

$$\Delta^2 x \Delta^2 p - C_{x,p}^2 \geq (\hbar/2)^2$$

and that have maximal entropy for a given set of second-order moments.

Among $\mu(x,p)$ with a given set of second-order moments, Gaussian distributions maximize the entropy

Valid deterministic transformations

The group of canonical transformations with quadratic Hamiltonian

Only canonical transformations preserve the uncertainty principle
Only quadratic Hamiltonians preserve the gaussianity

→ These correspond to the Wigner representations of the unitaries associated with these Hamiltonians

e.g. $D_{x_0,p_0} = e^{-ix_0\hat{P}-ip_0\hat{X}}$

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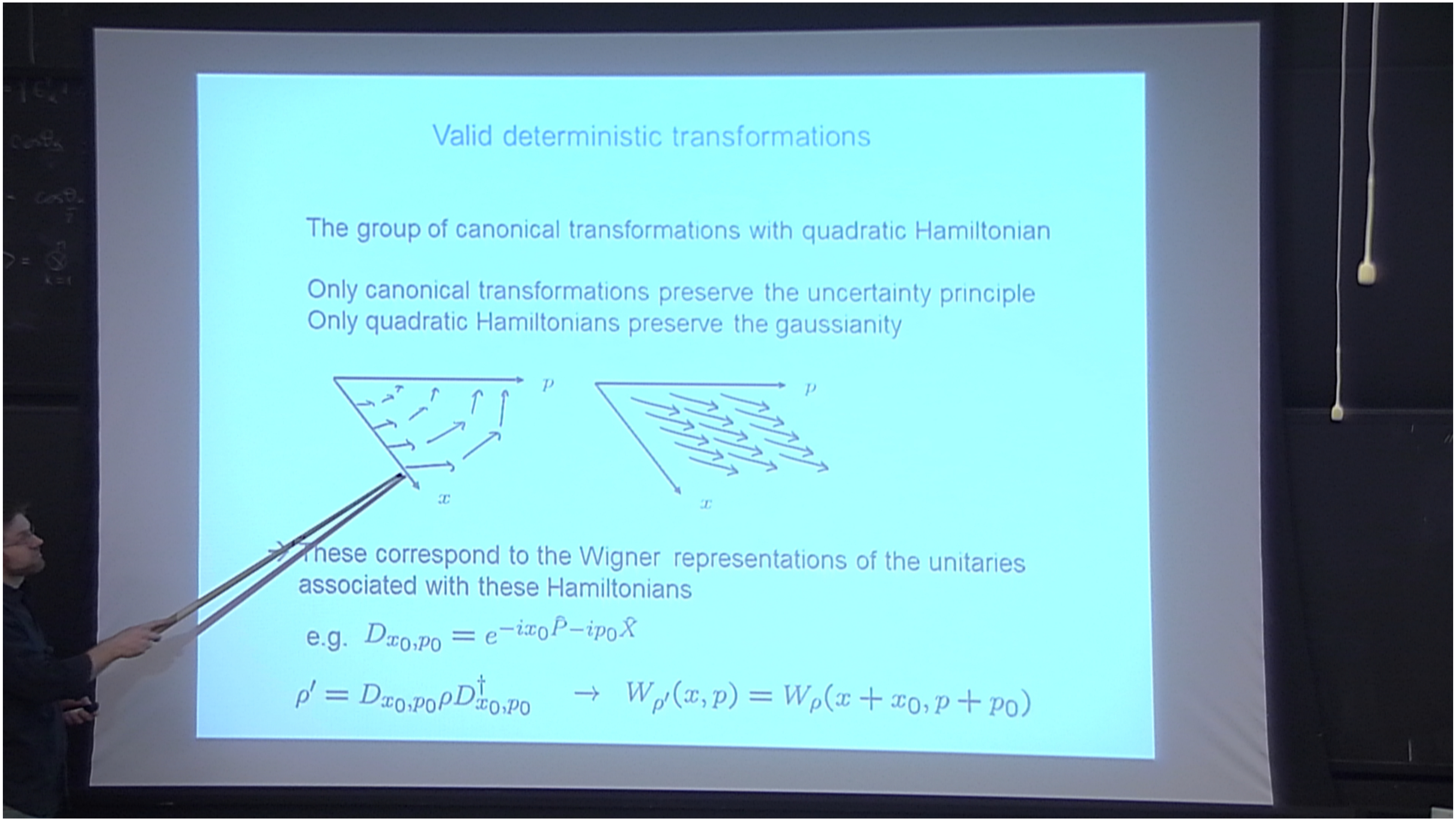
Valid deterministic transformations
The group of canonical transformations with quadratic Hamiltonian
Only canonical transformations preserve the uncertainty principle
Only quadratic Hamiltonians preserve the gaussianity
p
x
p
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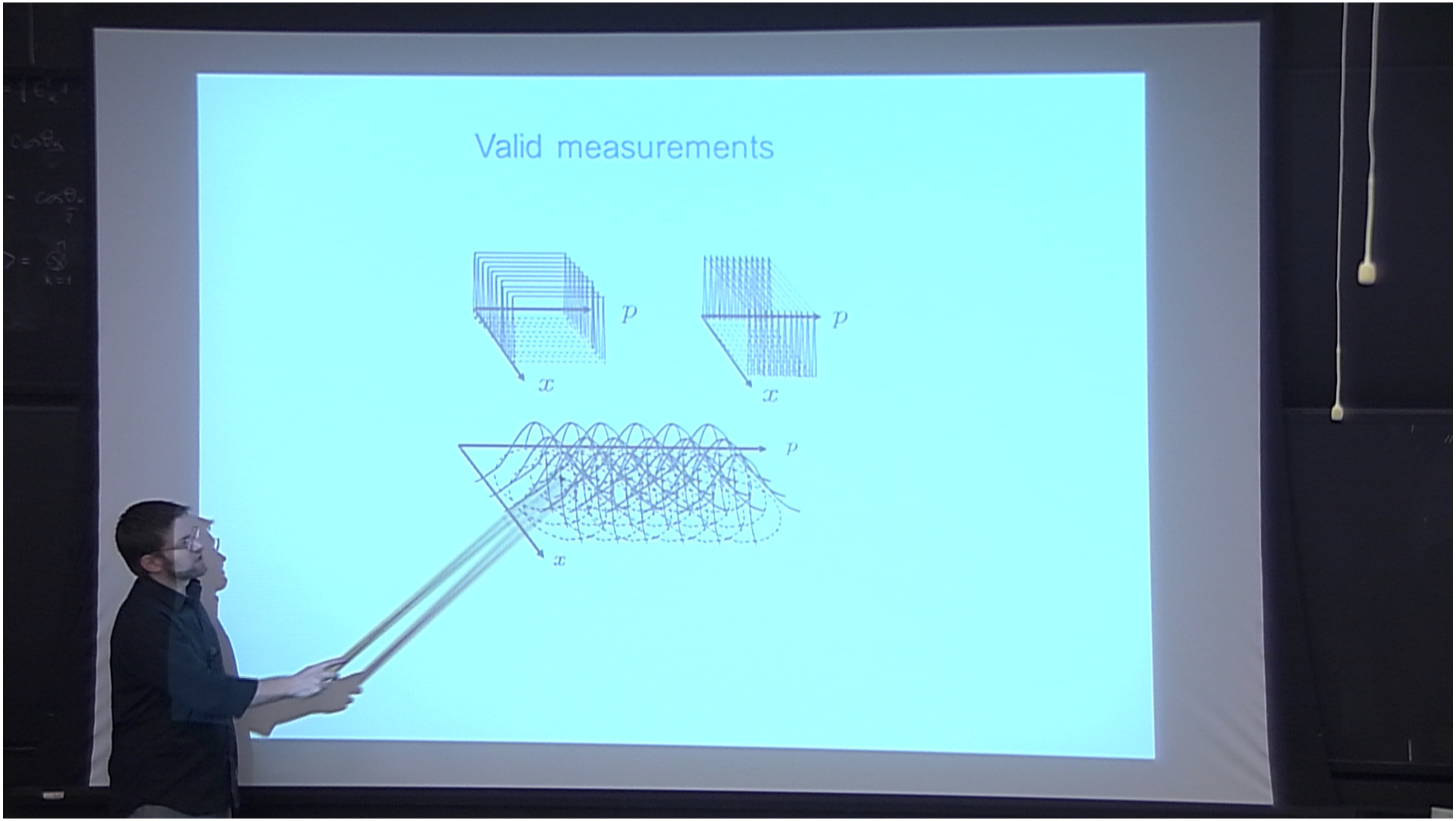
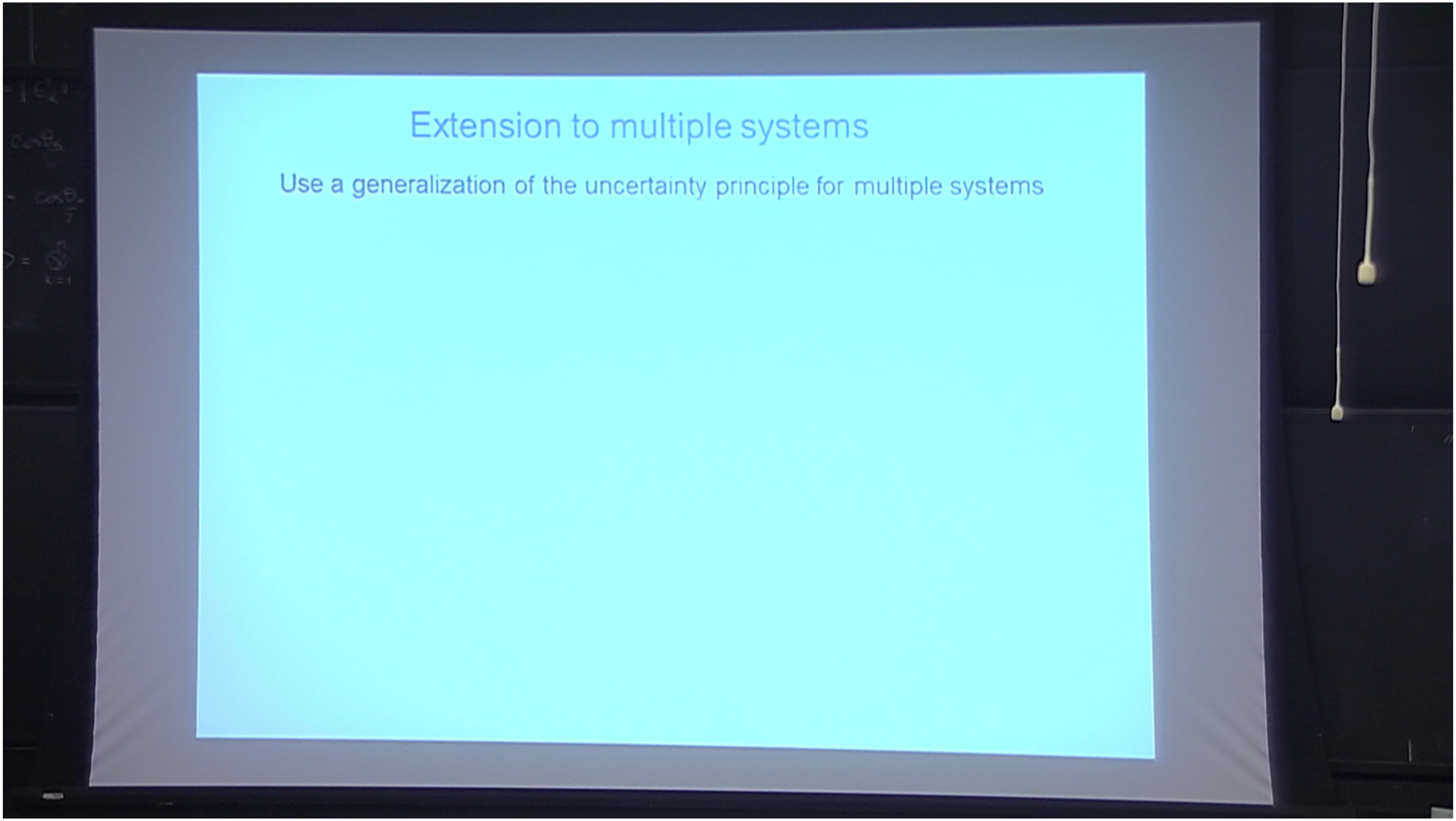
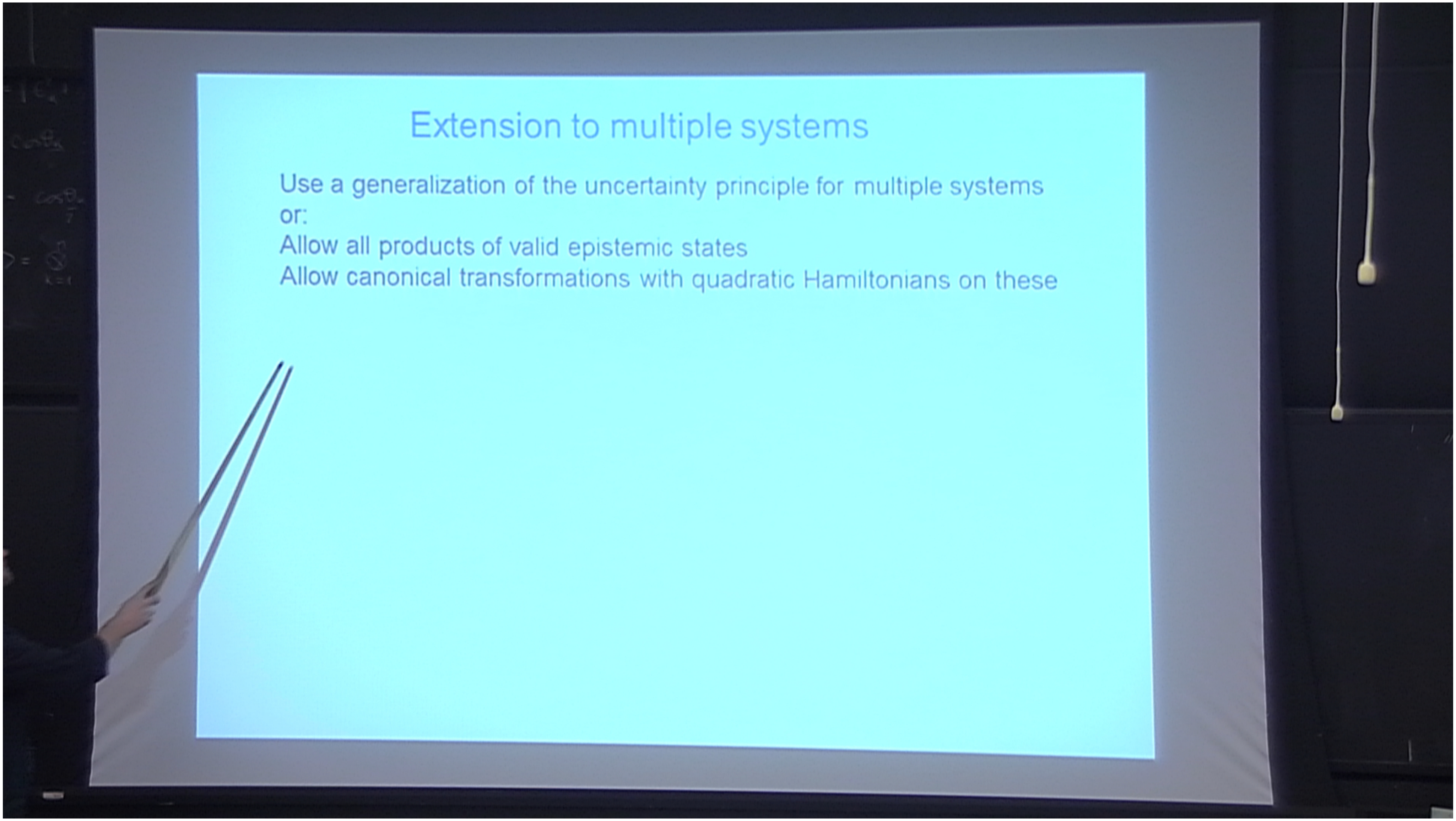
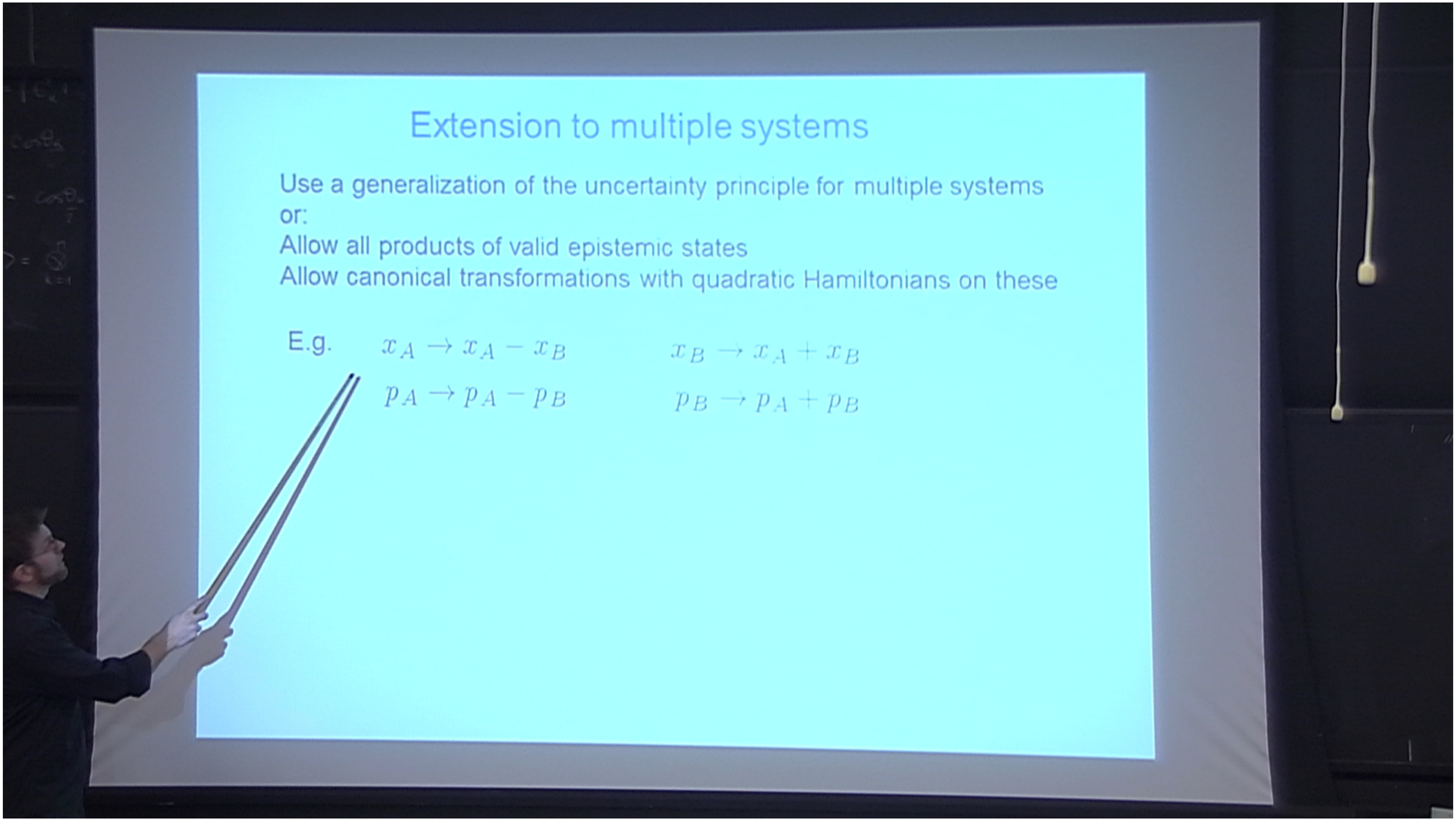

Valid measurements
p
x
p
x
p
x


Extension to multiple systems
Use a generalization of the uncertainty principle for multiple systems


Extension to multiple systems
Use a generalization of the uncertainty principle for multiple systems
or:
Allow all products of valid epistemic states
Allow canonical transformations with quadratic Hamiltonians on these


Extension to multiple systems
Use a generalization of the uncertainty principle for multiple systems
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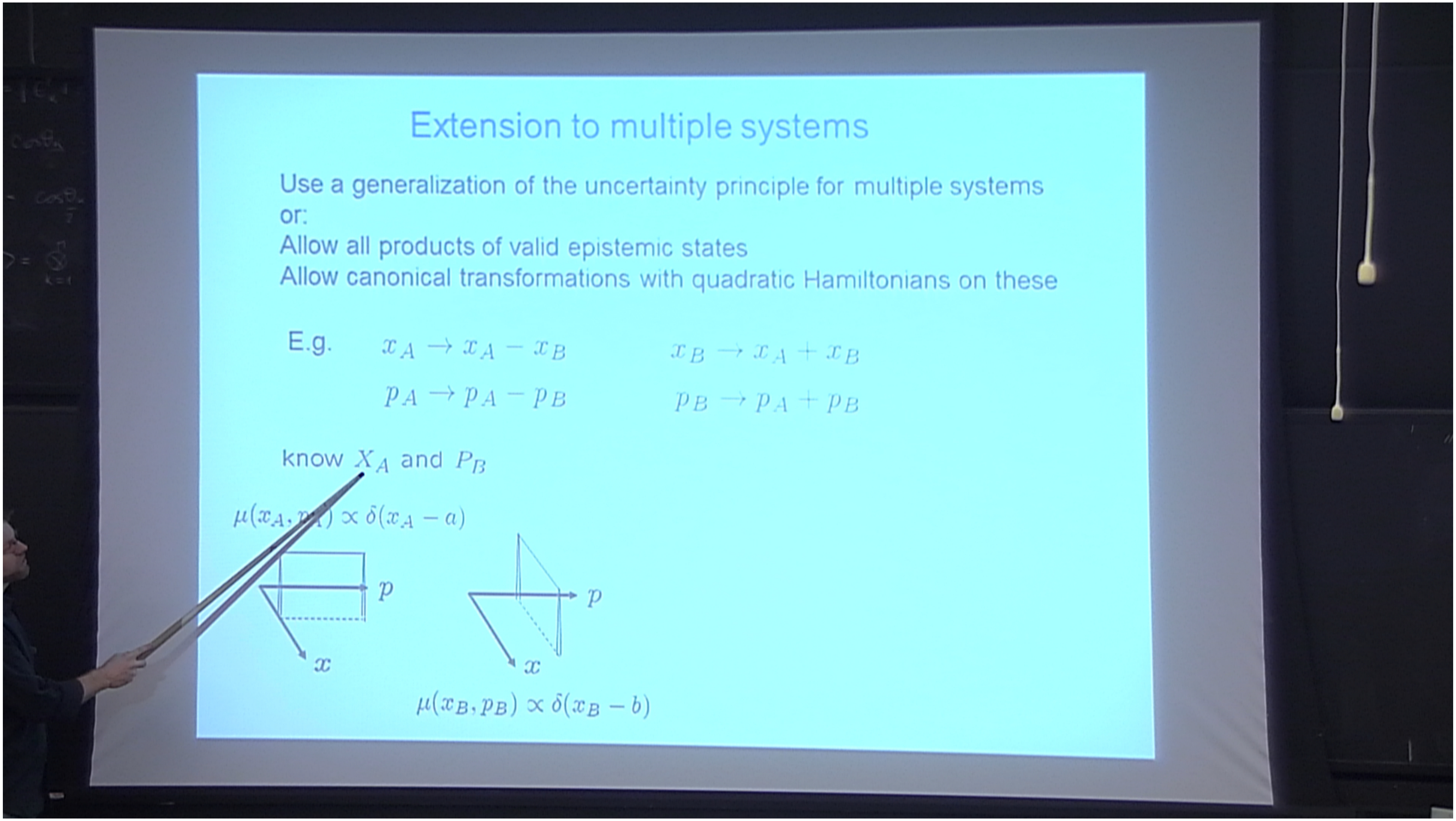
E.g.
$x_A \to x_A - x_B$
$x_B \to x_A + x_B$
$p_A \to p_A - p_B$
$p_B \to p_A + p_B$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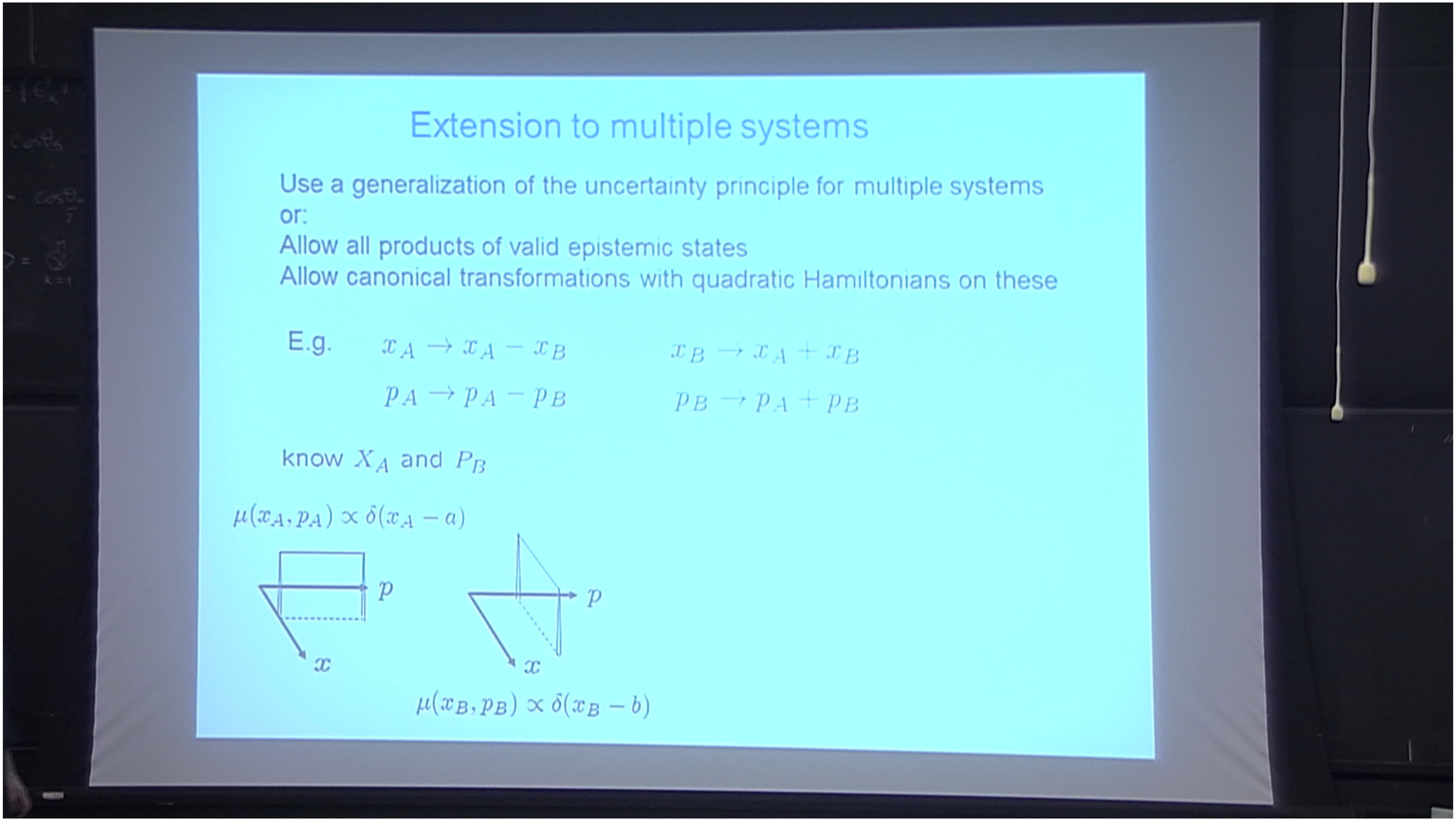
E.g. $x_A \to x_A - x_B$ $x_B \to x_A + x_B$
$p_A \to p_A - p_B$ $p_B \to p_A + p_B$
know X_A and P_B
$\mu(x_A, p_A) \propto \delta(x_A - a)$
p
x
p
x
$\mu(x_B, p_B) \propto \delta(x_B - b)$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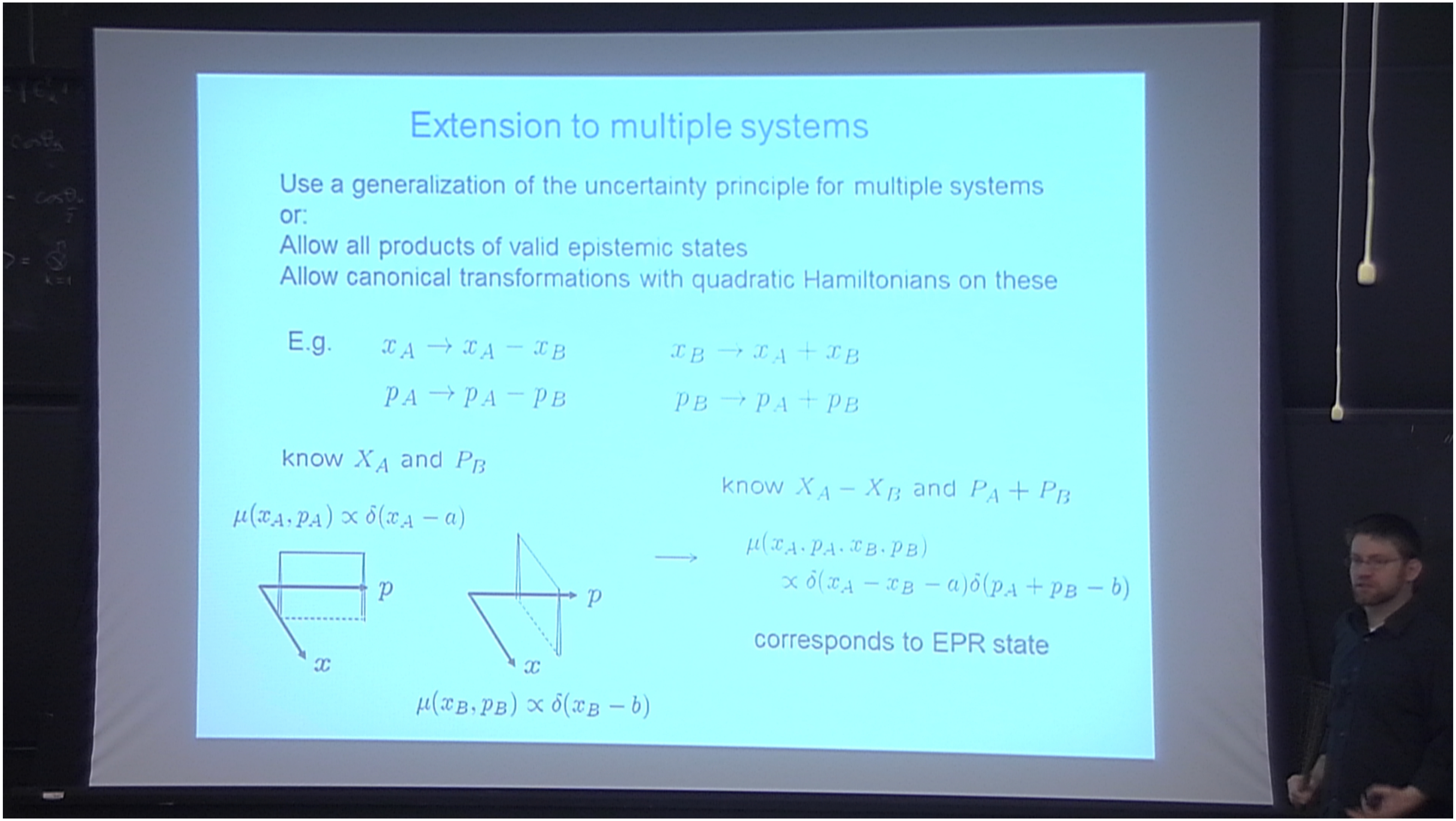
know X_A and P_B
$\mu(x_A, p_A) \propto \delta(x_A - a)$
p
x
p
x
$\mu(x_B, p_B) \propto \delta(x_B - b)$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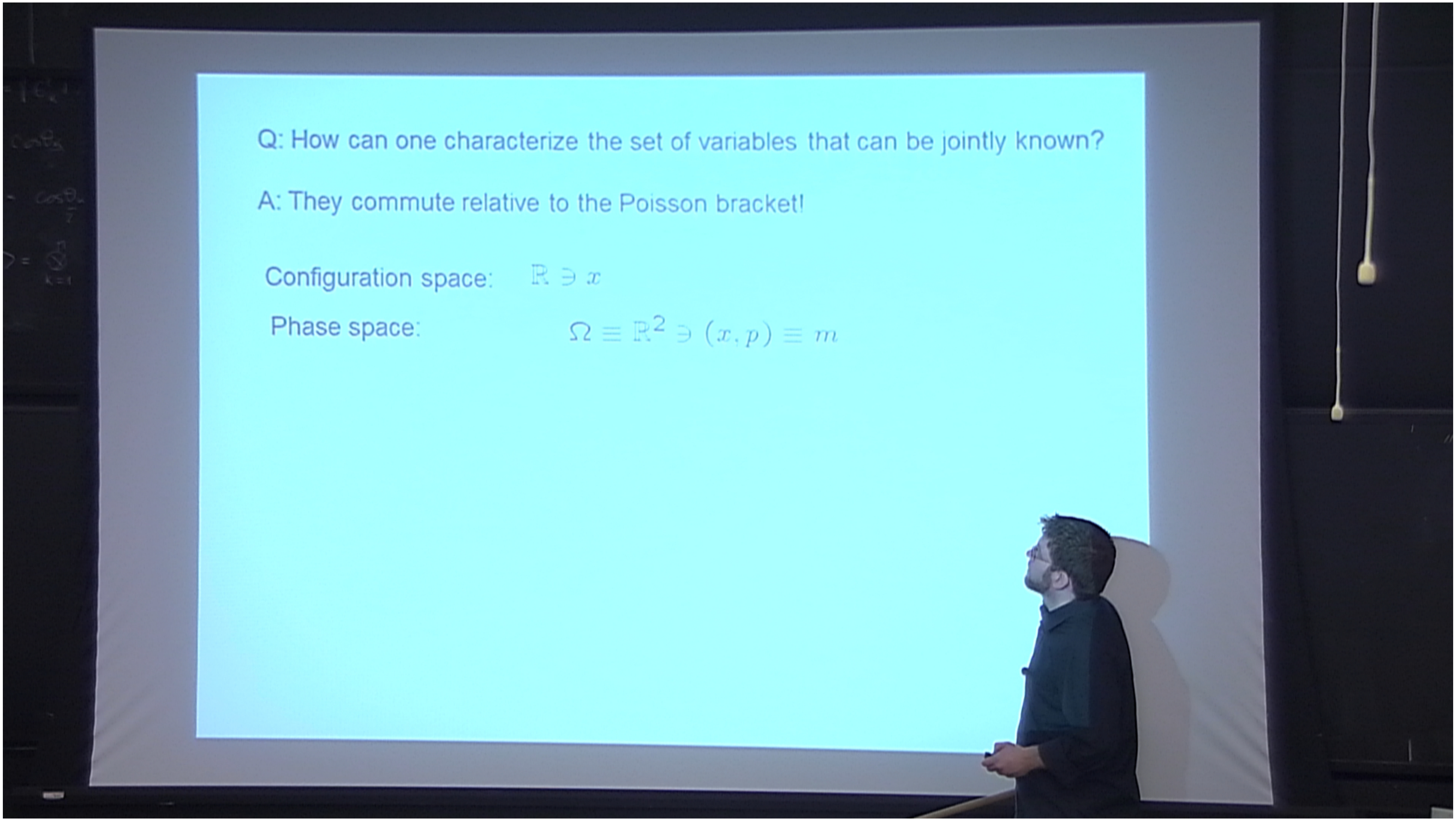
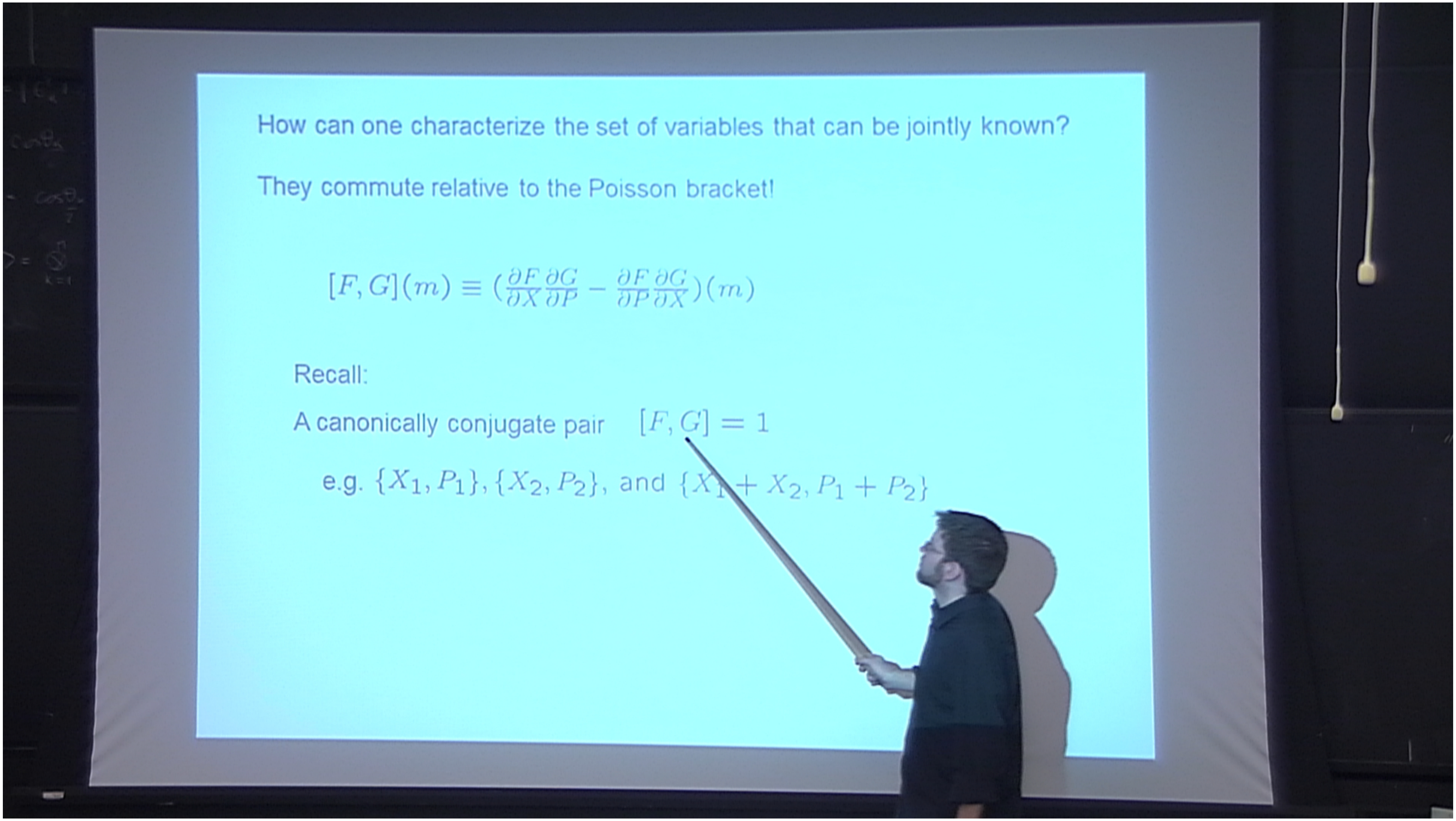
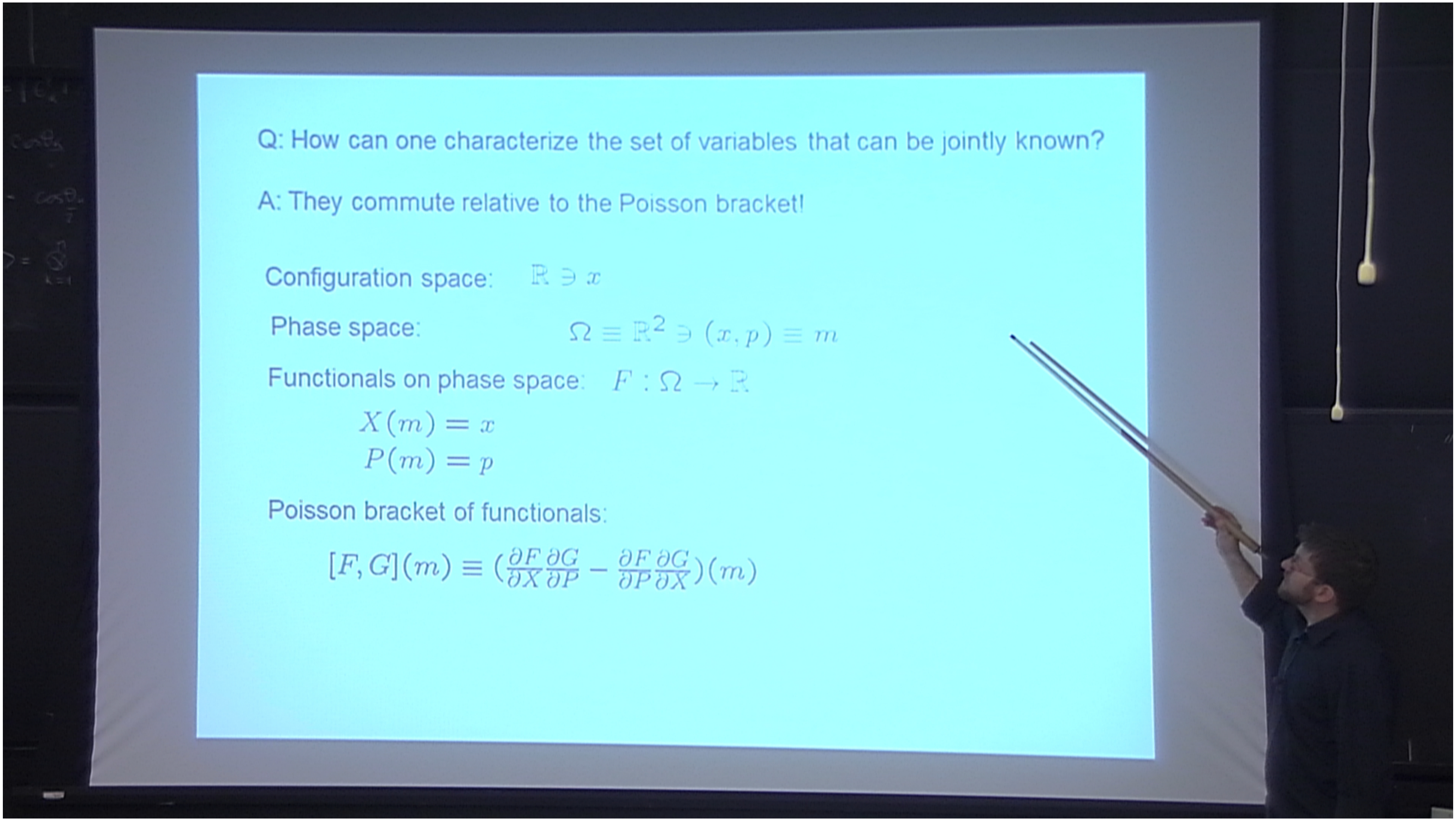
$p_A \to p_A - p_B$ $p_B \to p_A + p_B$
know X_A and P_B
know $X_A - X_B$ and $P_A + P_B$
$\mu(x_A, p_A) \propto \delta(x_A - a)$
p
x
p
x
$\mu(x_B, p_B) \propto \delta(x_B - b)$
$\mu(x_A, p_A, x_B, p_B)$
$\propto \delta(x_A - x_B - a)\delta(p_A + p_B - b)$
corresponds to EPR state


Q: How can one characterize the set of variables that can be jointly known?
A: They commute relative to the Poisson bracket!
Configuration space: $\mathbb{R} \ni x$
Phase space: $\Omega \equiv \mathbb{R}^2 \ni (x, p) \equiv m$


How can one characterize the set of variables that can be jointly known?
They commute relative to the Poisson bracket!
$[F, G](m) \equiv (\frac{\partial F}{\partial X}\frac{\partial G}{\partial P} - \frac{\partial F}{\partial P}\frac{\partial G}{\partial X})(m)$
Recall:
A canonically conjugate pair $[F, G] = 1$
e.g. $\{X_1, P_1\}, \{X_2, P_2\}$, and $\{X_1 + X_2, P_1 + P_2\}$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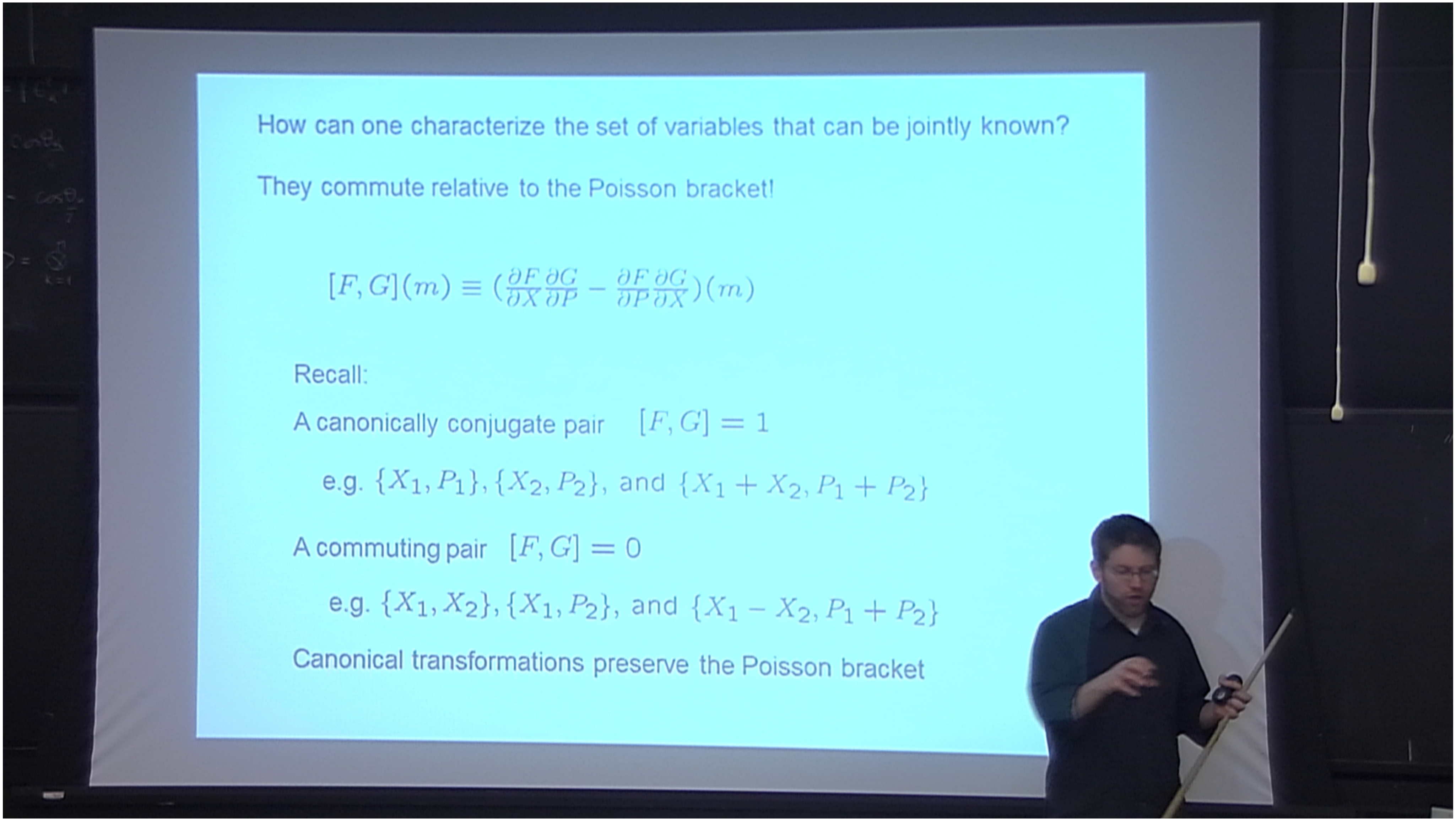
A: They commute relative to the Poisson bracket!
Configuration space: $\mathbb{R} \ni x$
Phase space: $\Omega \equiv \mathbb{R}^2 \ni (x, p) \equiv m$
Functionals on phase space: $F : \Omega \to \mathbb{R}$
$X(m) = x$
$P(m) = p$
Poisson bracket of functionals:
$[F, G](m) \equiv (\frac{\partial F}{\partial X}\frac{\partial G}{\partial P} - \frac{\partial F}{\partial P}\frac{\partial G}{\partial X})(m)$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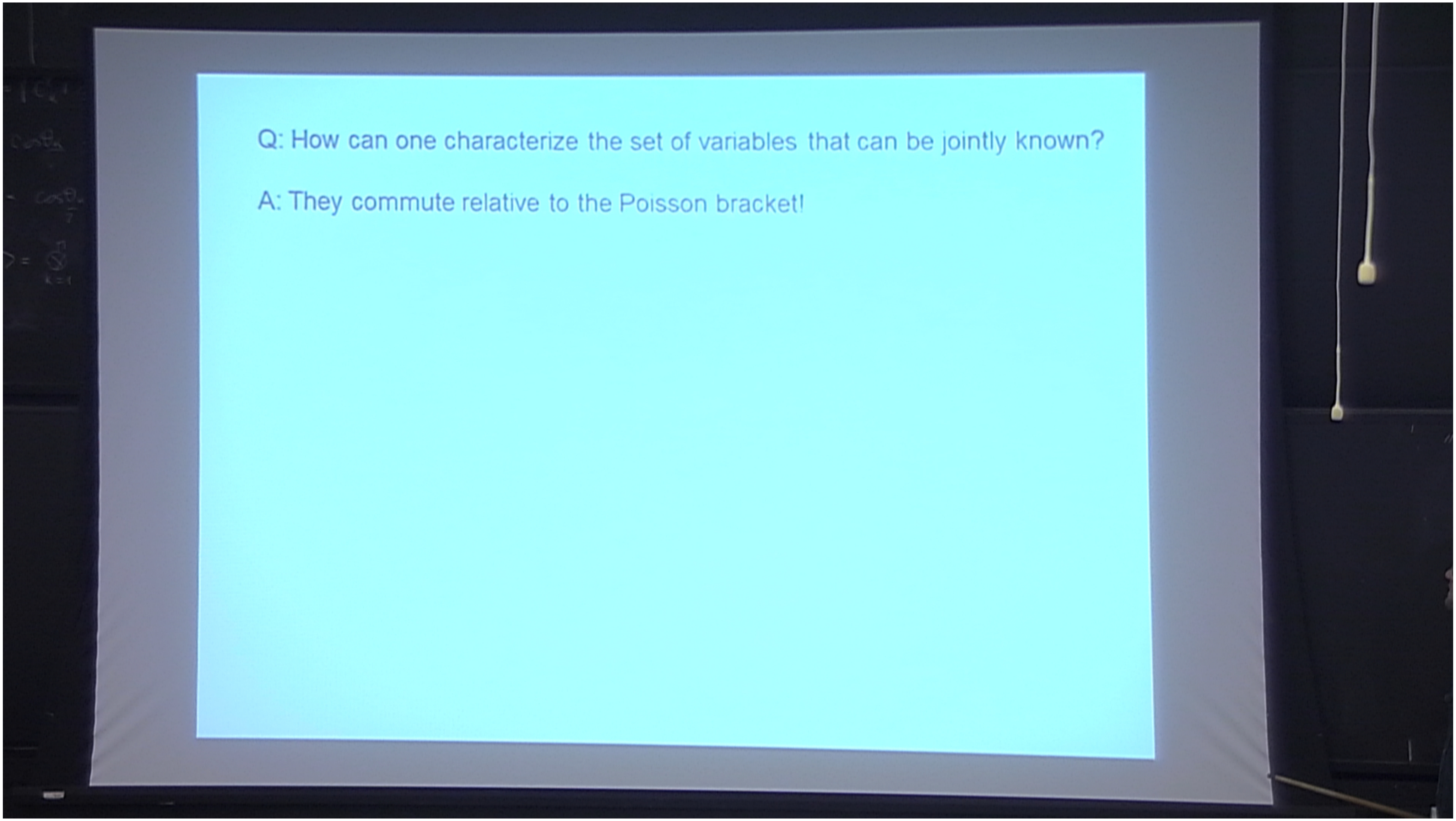
Recall:
A canonically conjugate pair $[F,G]=1$
e.g. $\{X_1,P_1\},\{X_2,P_2\}$, and $\{X_1+X_2,P_1+P_2\}$
A commuting pair $[F,G]=0$
e.g. $\{X_1,X_2\},\{X_1,P_2\}$, and $\{X_1-X_2,P_1+P_2\}$
Canonical transformations preserve the Poisson bracket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How can one characterize the set of variables that can be jointly known?

They commute relative to the Poisson bracket!

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Recall:

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How can one characterize the set of variables that can be jointly known?

They commute relative to the Poisson bracket!

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Recall:

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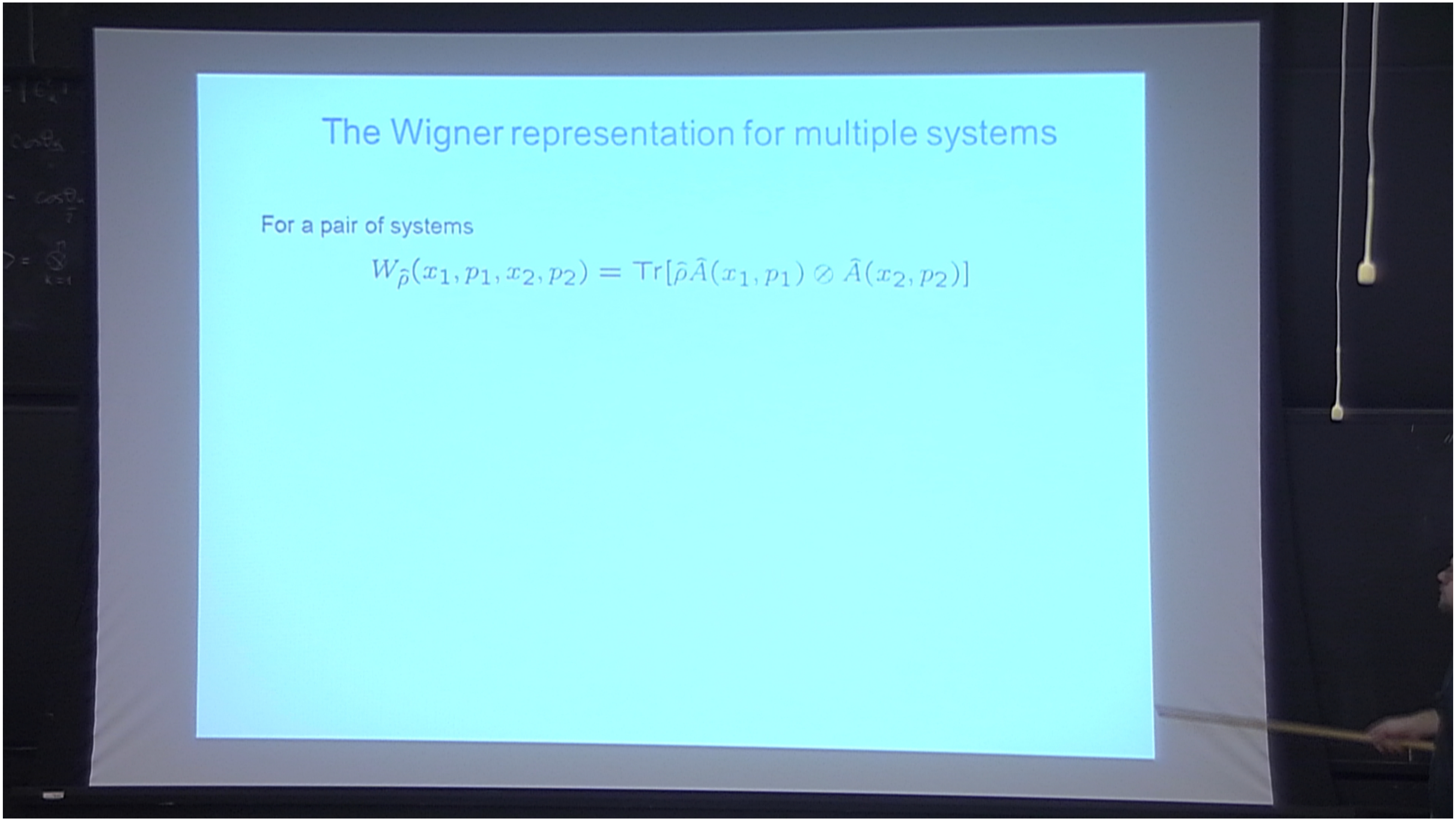
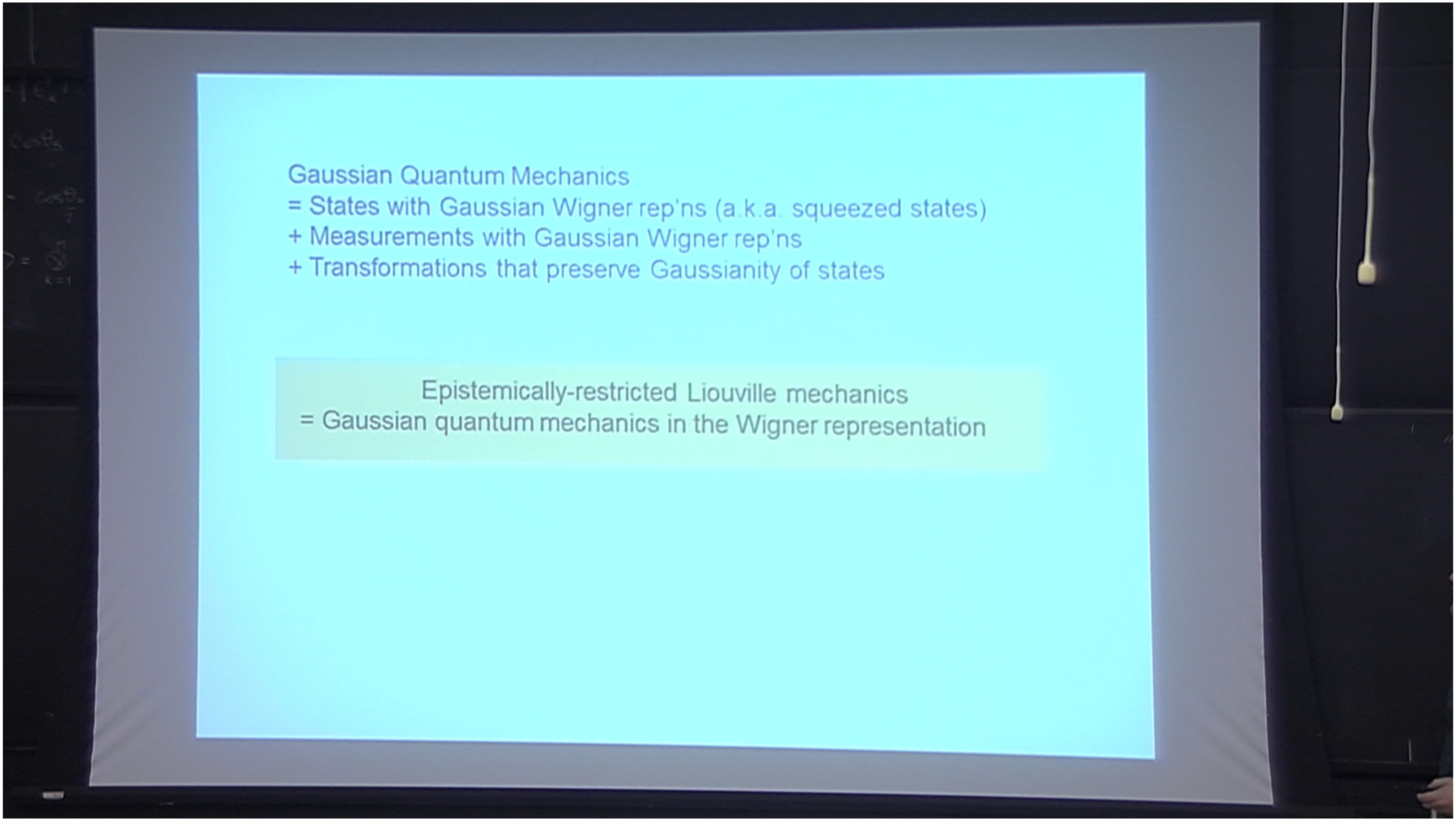
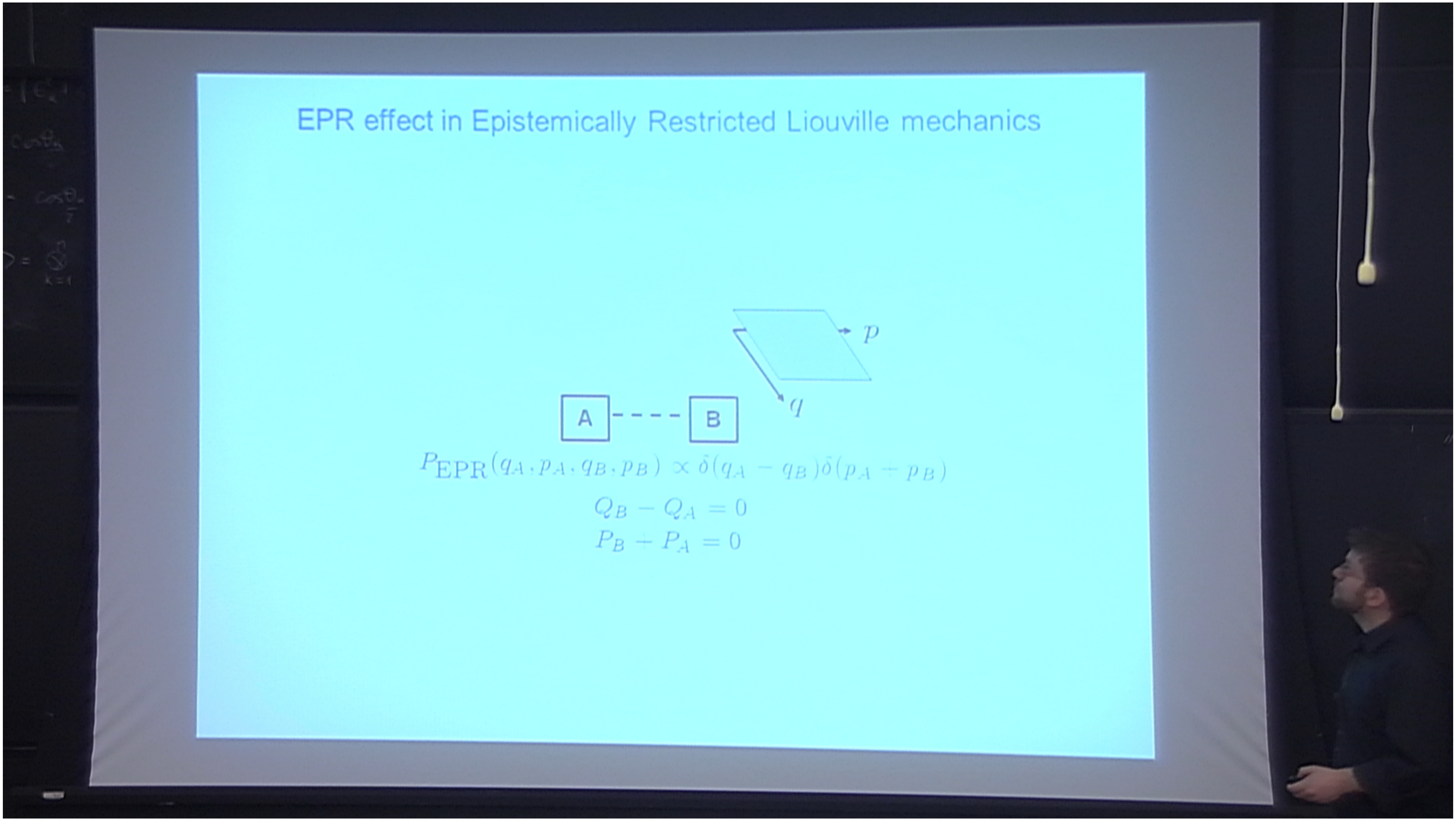
e.g. $\{X_1, P_1\}, \{X_2, P_2\}$, and $\{X_1 + X_2, P_1 + P_2\}$

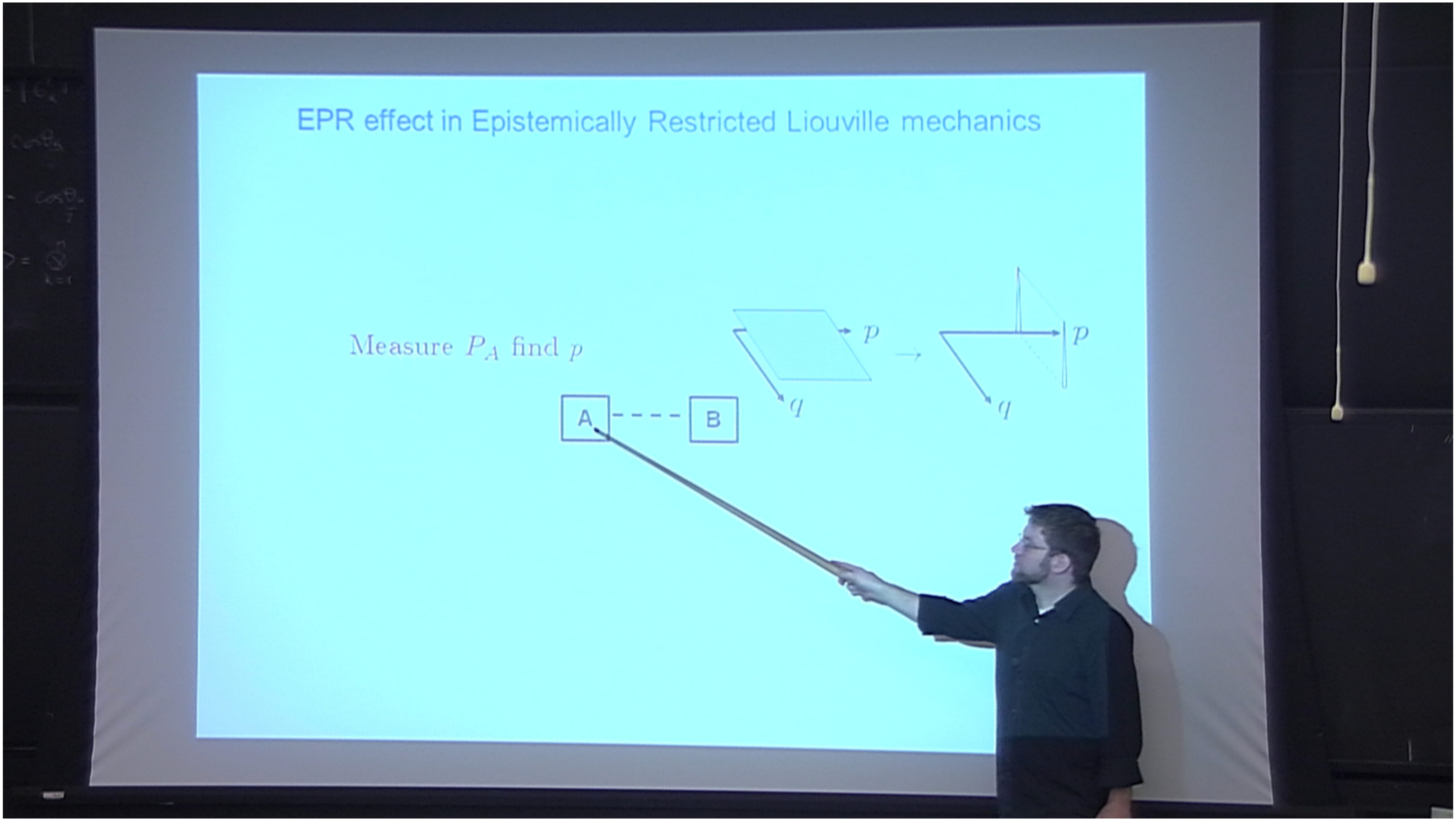
A commuting pair $[F,G] = 0$

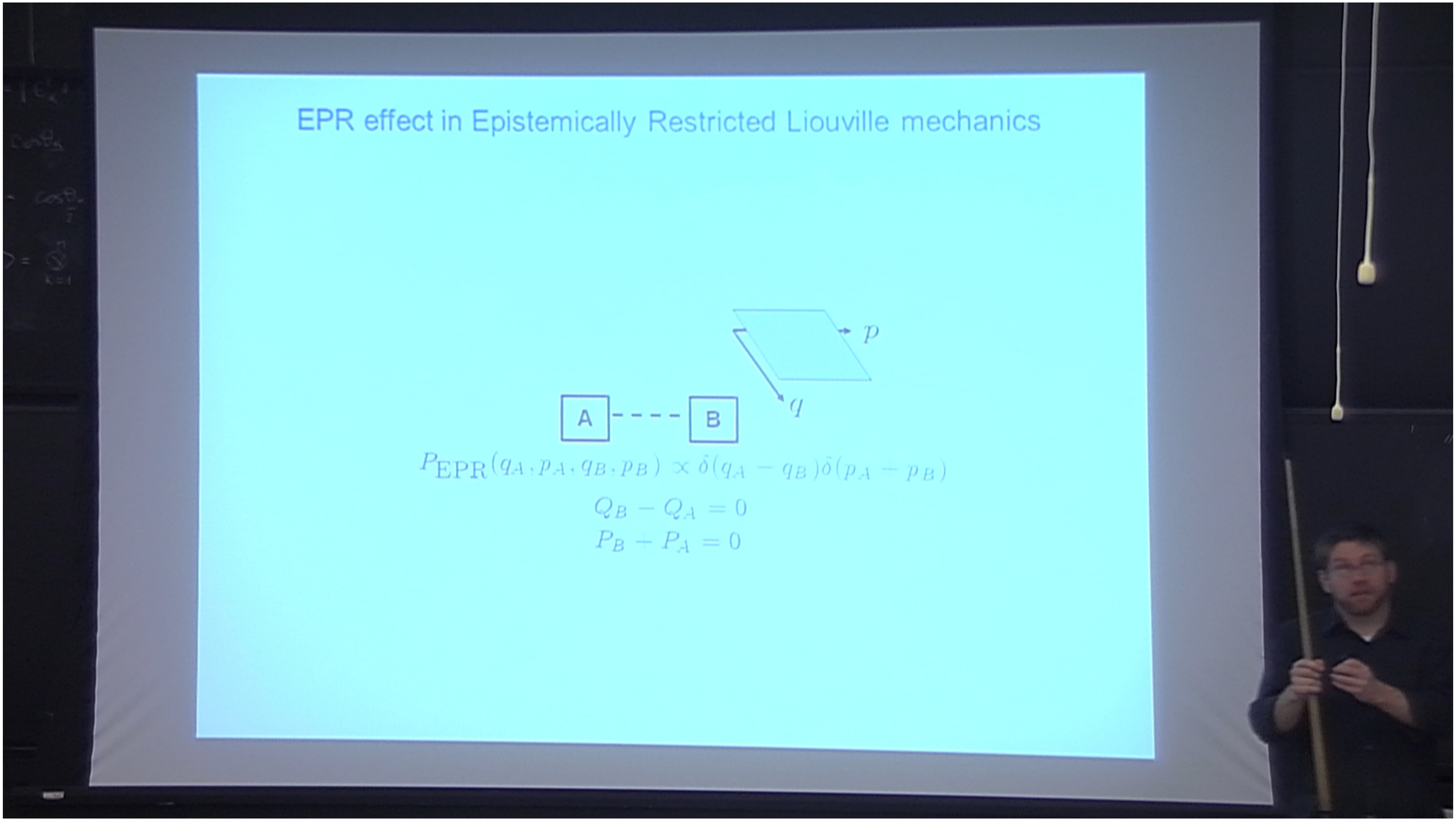
e.g. $\{X_1, X_2\}, \{X_1, P_2\}$, and $\{X_1 - X_2, P_1 + P_2\}$


The Wigner representation for multiple systems
For a pair of systems
$W_{\hat{\rho}}(x_1, p_1, x_2, p_2) = \mathrm{Tr}[\hat{\rho}\hat{A}(x_1, p_1) \otimes \hat{A}(x_2, p_2)]$


Gaussian Quantum Mechanics
= States with Gaussian Wigner rep'ns (a.k.a. squeezed states)
+ Measurements with Gaussian Wigner rep'ns
+ Transformations that preserve Gaussianity of states
Epistemically-restricted Liouville mechanics
= Gaussian quantum mechanics in the Wigner representation


EPR effect in Epistemically Restricted Liouville mechanics
p
q
A
B
$P_{\mathrm{EPR}}(q_A, p_A, q_B, p_B) \propto \delta(q_A - q_B)\delta(p_A + p_B)$
$Q_B - Q_A = 0$
$P_B + P_A = 0$


EPR effect in Epistemically Restricted Liouville mechanics
Measure P_A find p
A
B
p
q
→
p
q


EPR effect in Epistemically Restricted Liouville mechanics
p
q
A
B
$P_{\mathrm{EPR}}(q_A, p_A, q_B, p_B) \propto \delta(q_A - q_B)\delta(p_A - p_B)$
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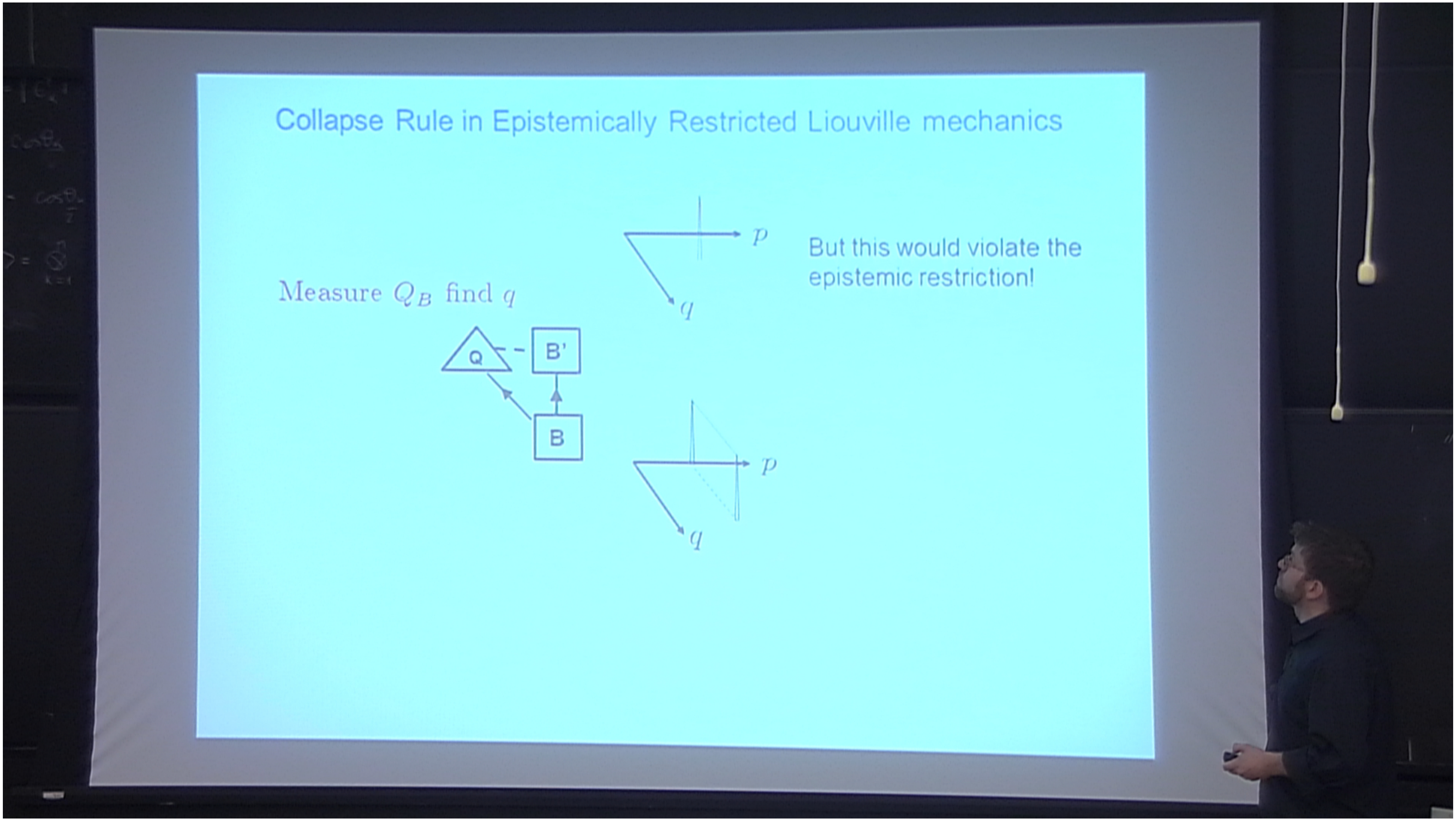
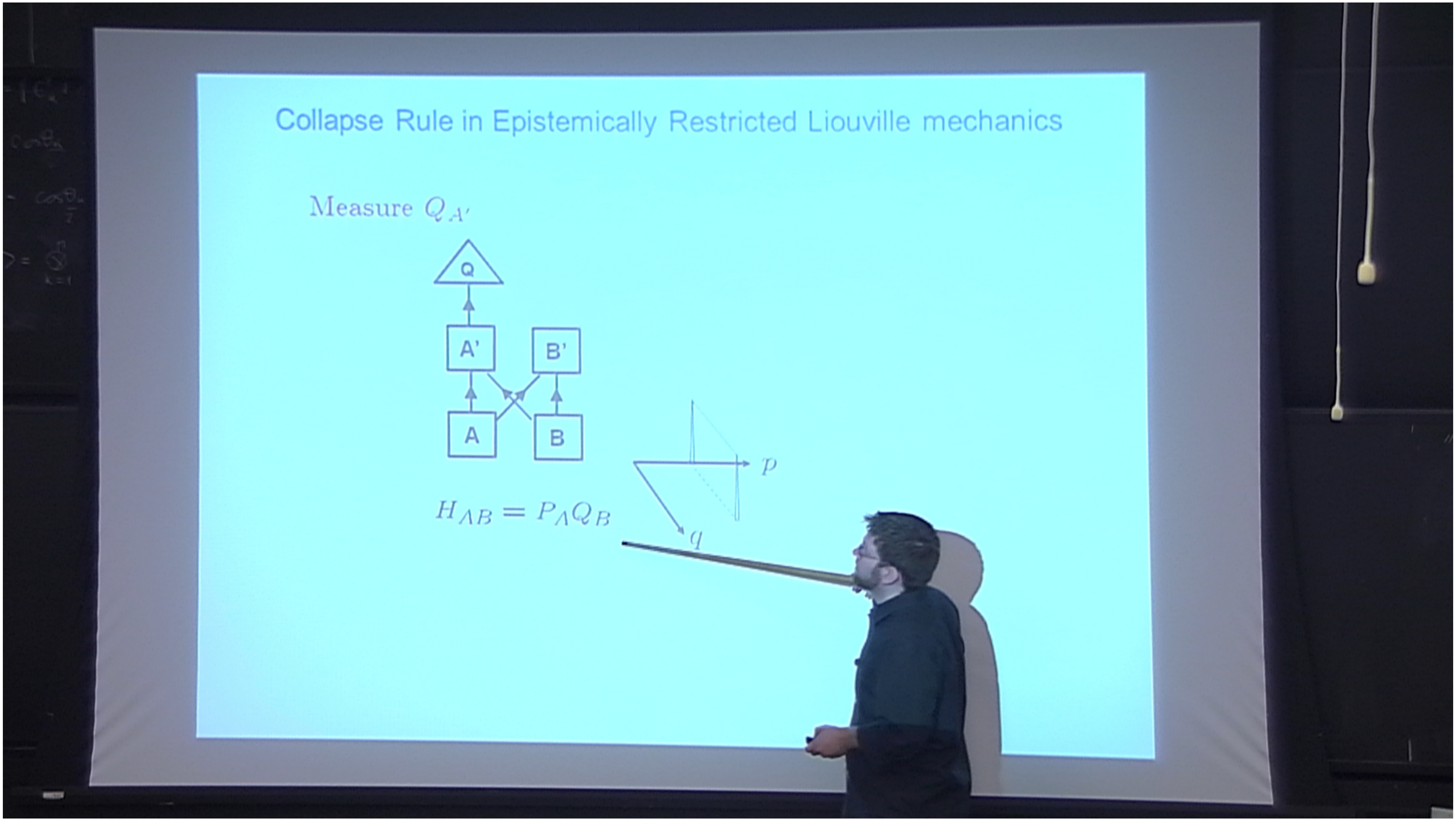
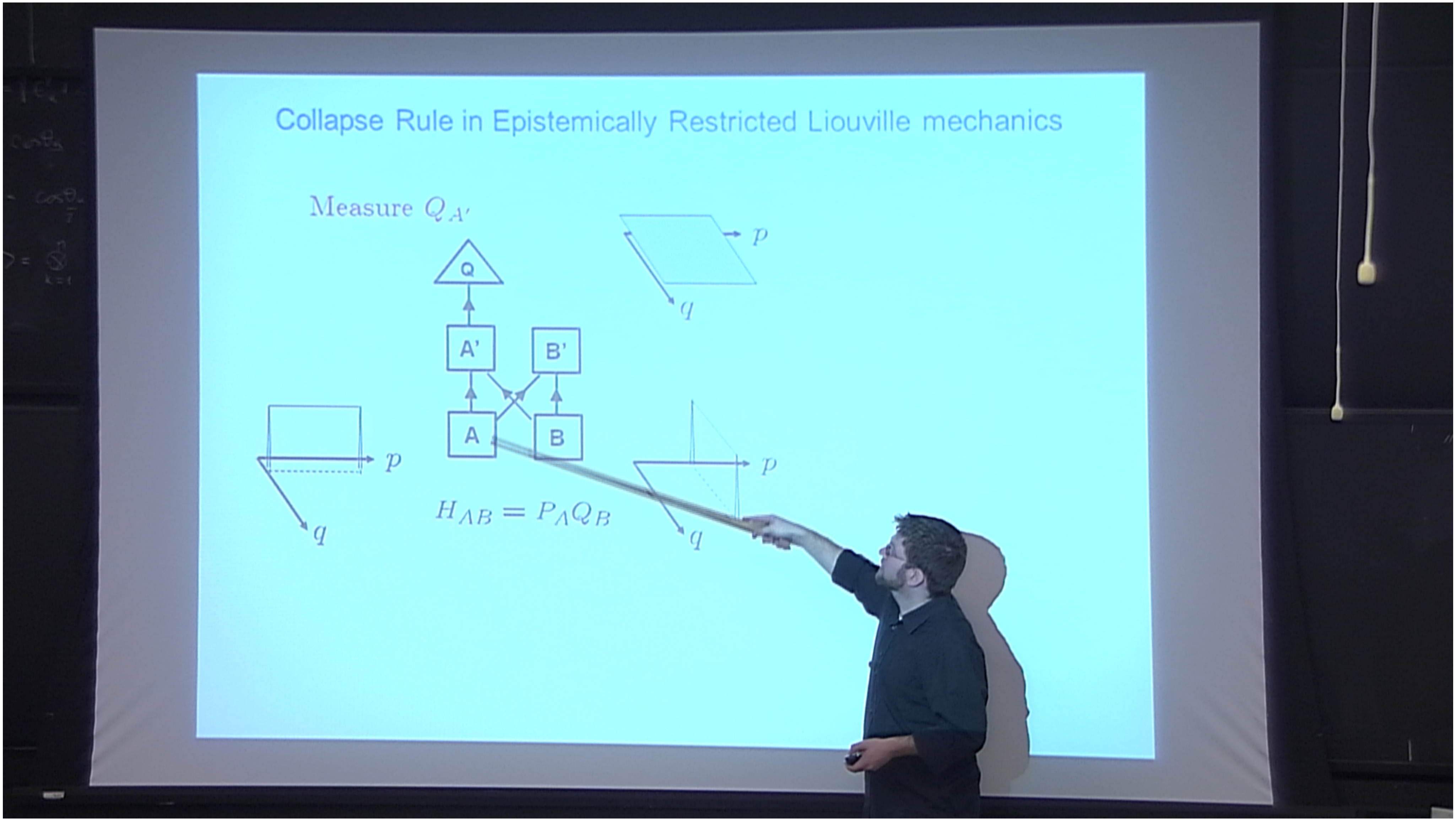
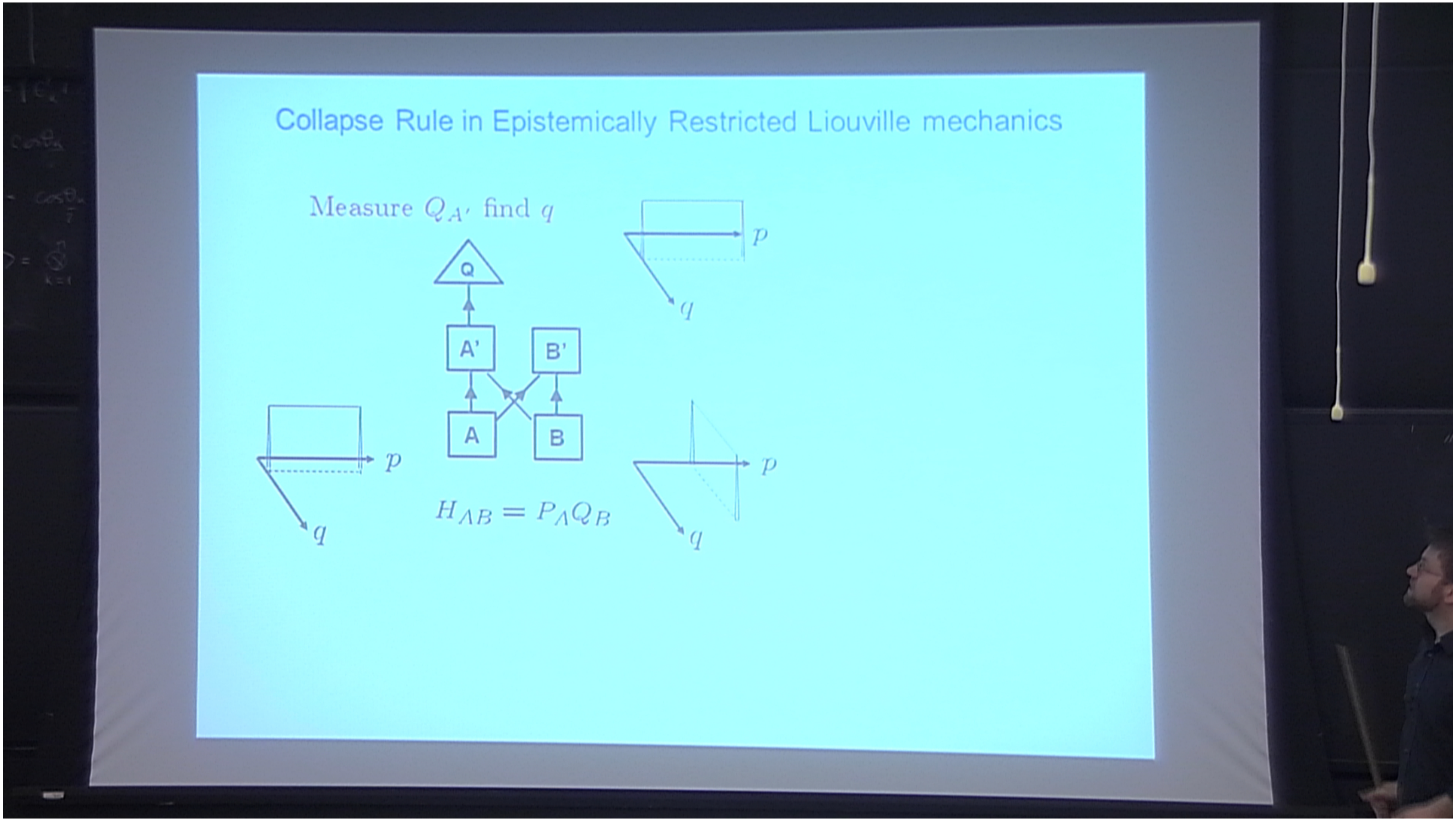
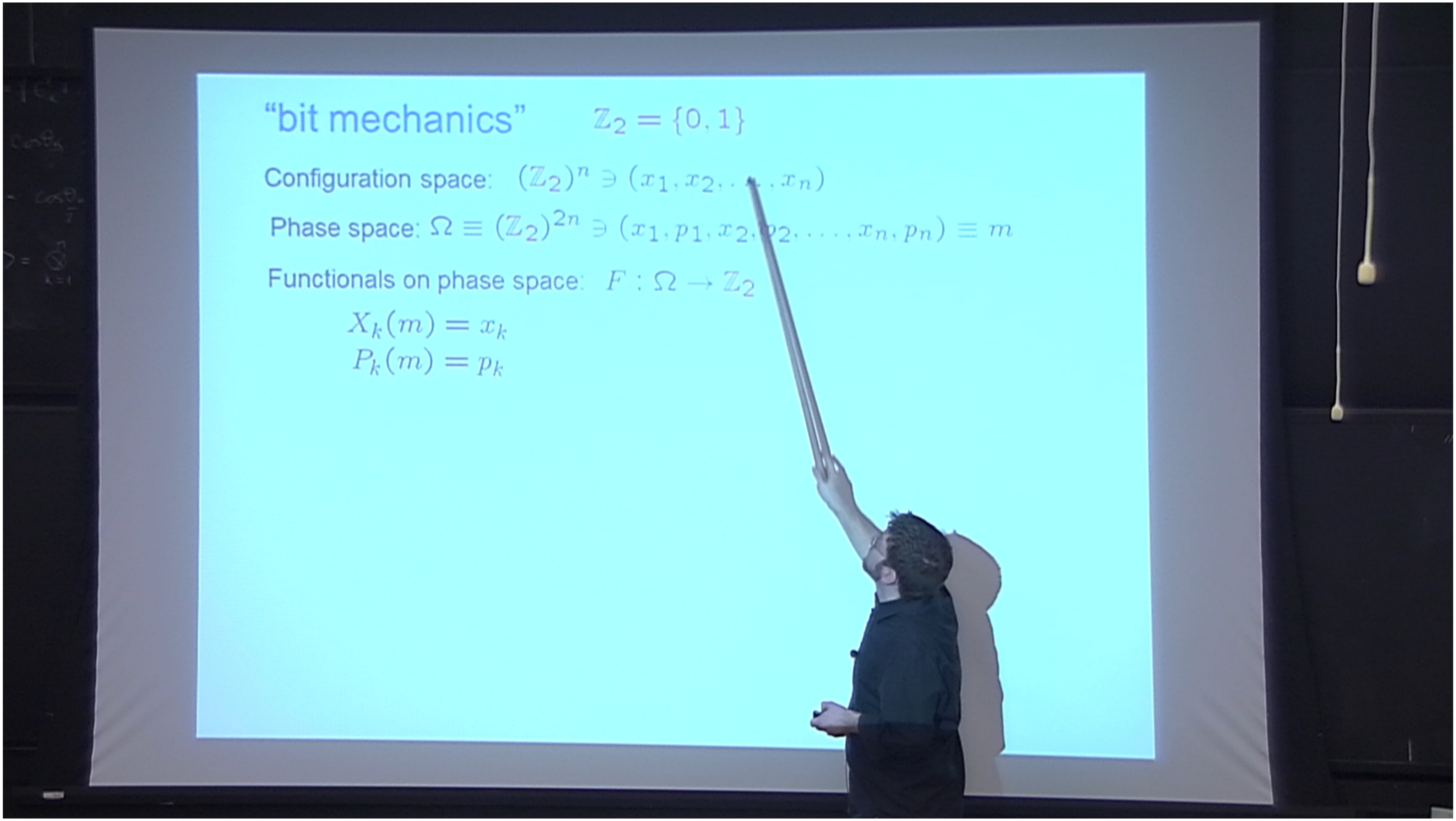

Collapse Rule in Epistemically Restricted Liouville mechanics
Measure Q_B find q
Q
B'
B
p
q
But this would violate the epistemic restriction!
p
q

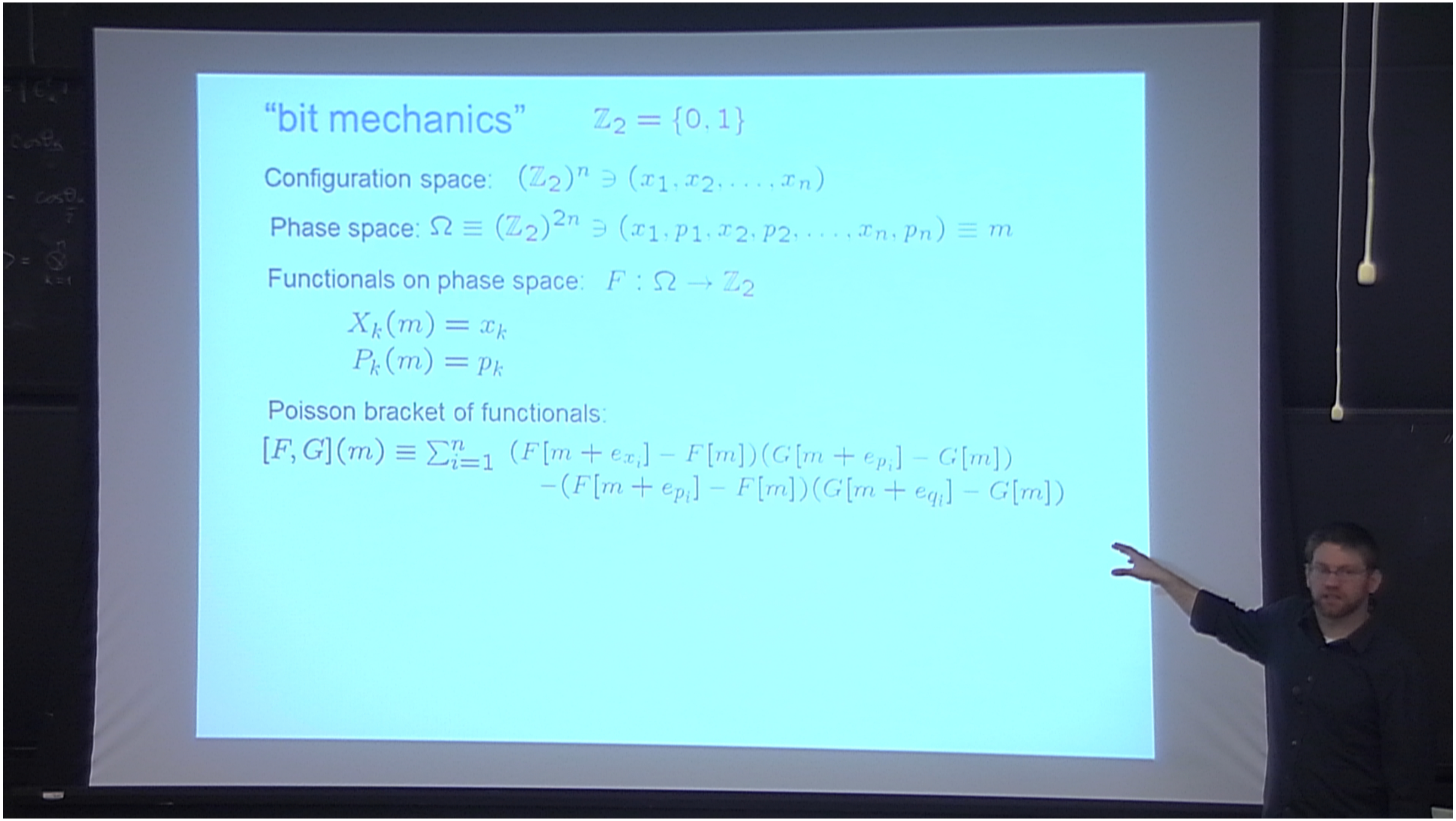

Collapse Rule in Epistemically Restricted Liouville mechanics
Measure $Q_{A'}$
Q
A'
B'
A
B
$H_{AB} = P_A Q_B$
p
q



Collapse Rule in Epistemically Restricted Liouville mechanics
Measure $Q_{A'}$
Q
A'
B'
A
B
p
q
p
q
p
q
$H_{AB} = P_A Q_B$


Collapse Rule in Epistemically Restricted Liouville mechanics
Measure $Q_{A'}$, find q
Q
A'
B'
A
B
p
q
p
q
p
q
$H_{AB} = P_A Q_B$


"bit mechanics" $\mathbb{Z}_2 = \{0, 1\}$
Configuration space: $(\mathbb{Z}_2)^n \ni (x_1, x_2, \ldots, x_n)$
Phase space: $\Omega \equiv (\mathbb{Z}_2)^{2n} \ni (x_1, p_1, x_2, p_2, \ldots, x_n, p_n) \equiv m$
Functionals on phase space: $F : \Omega \to \mathbb{Z}_2$
$X_k(m) = x_k$
$P_k(m) = p_k$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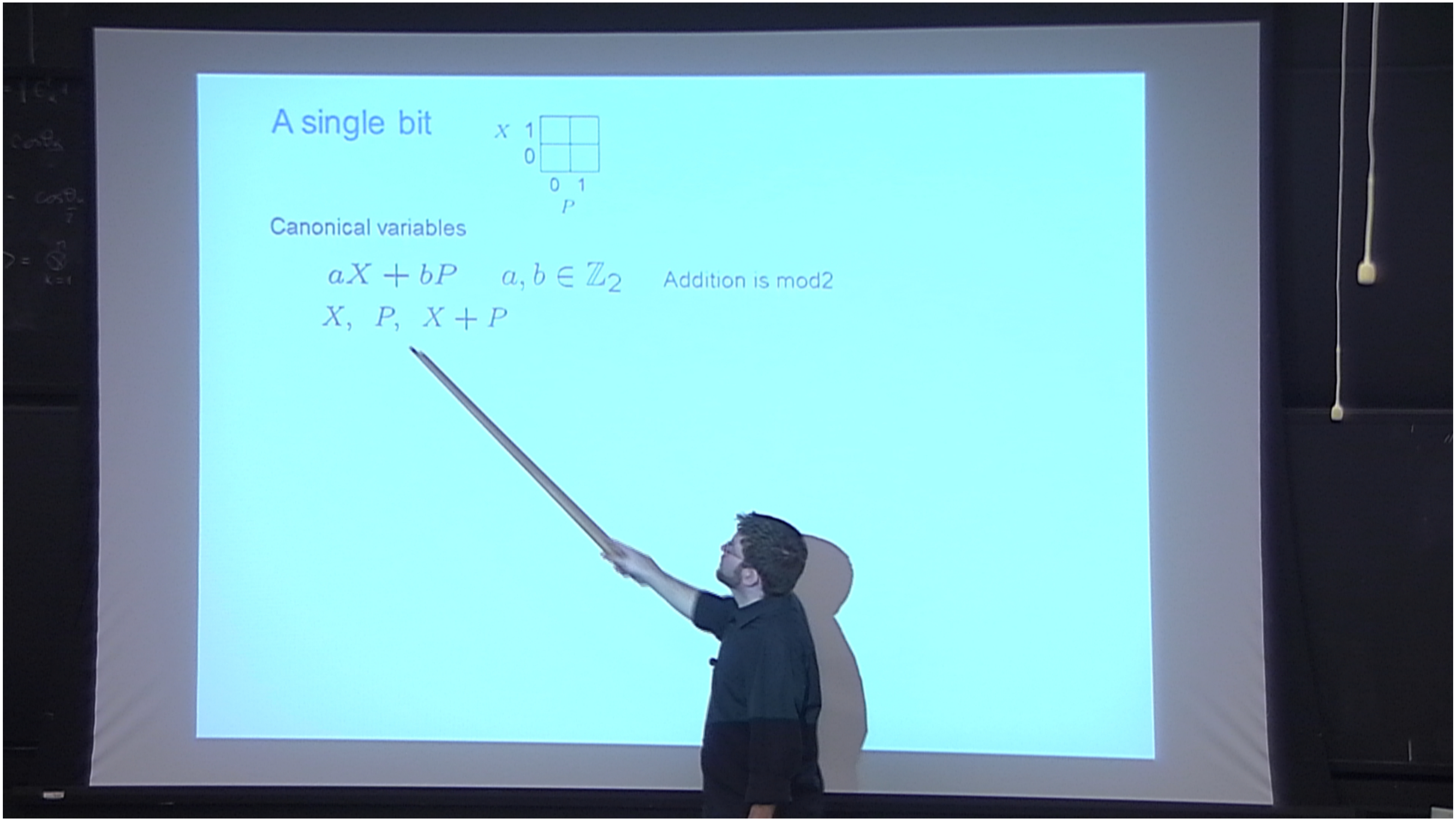
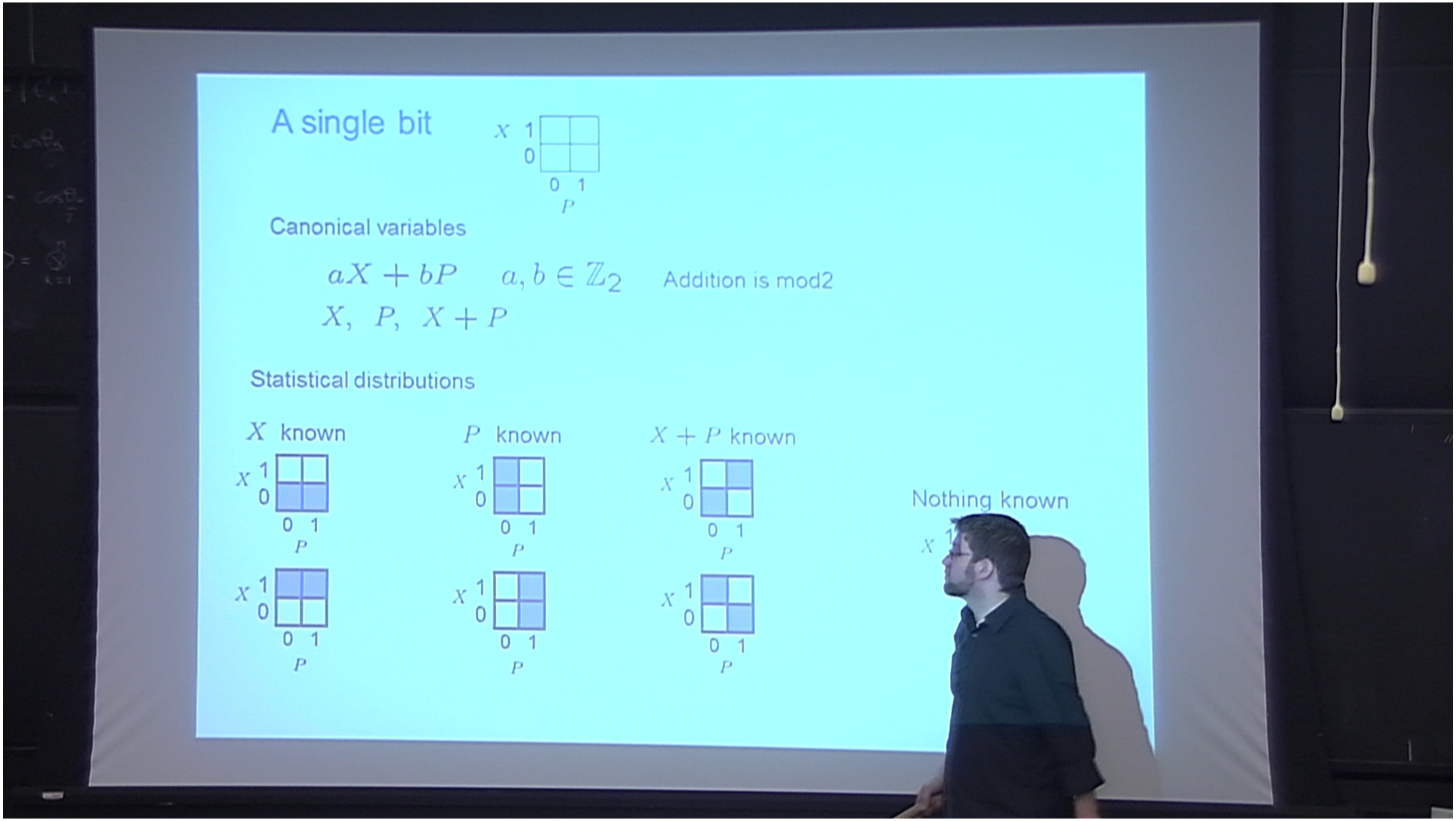
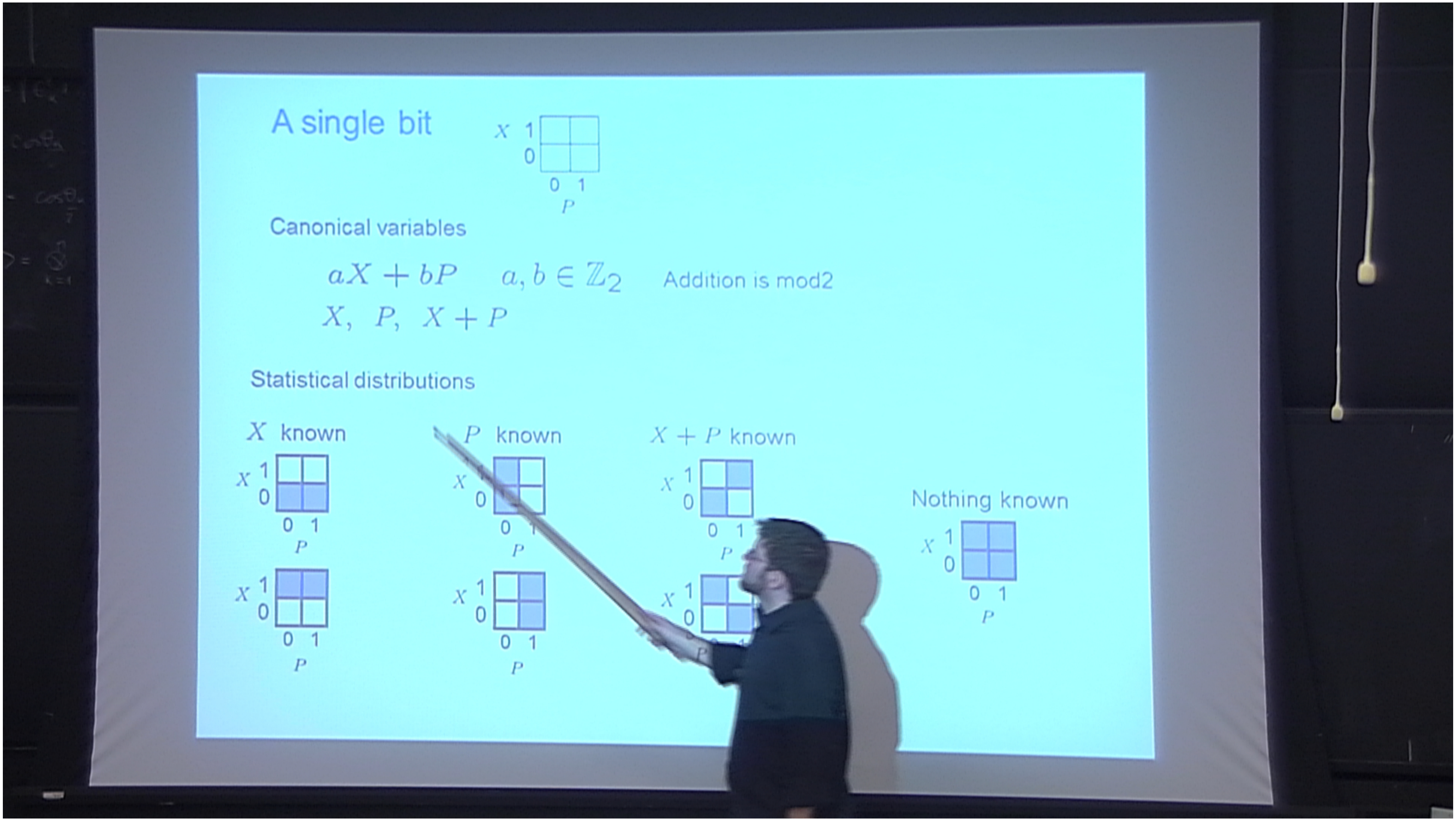
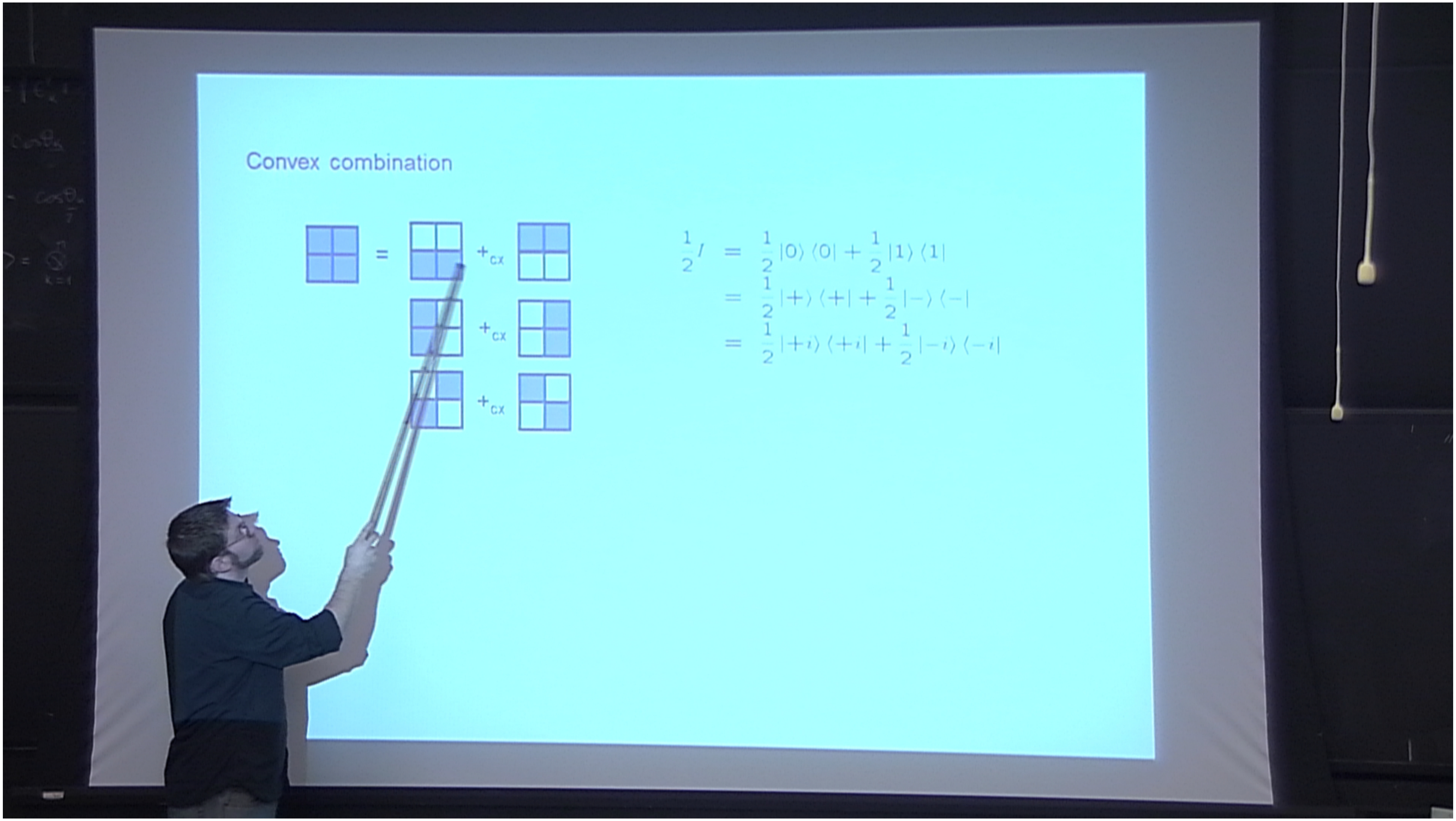
Functionals on phase space: $F : \Omega \to \mathbb{Z}_2$
$X_k(m) = x_k$
$P_k(m) = p_k$
Poisson bracket of functionals:
$[F, G](m) \equiv \sum_{i=1}^{n} (F[m + e_{x_i}] - F[m])(G[m + e_{p_i}] - G[m])$
$-(F[m + e_{p_i}] - F[m])(G[m + e_{q_i}] - G[m])$

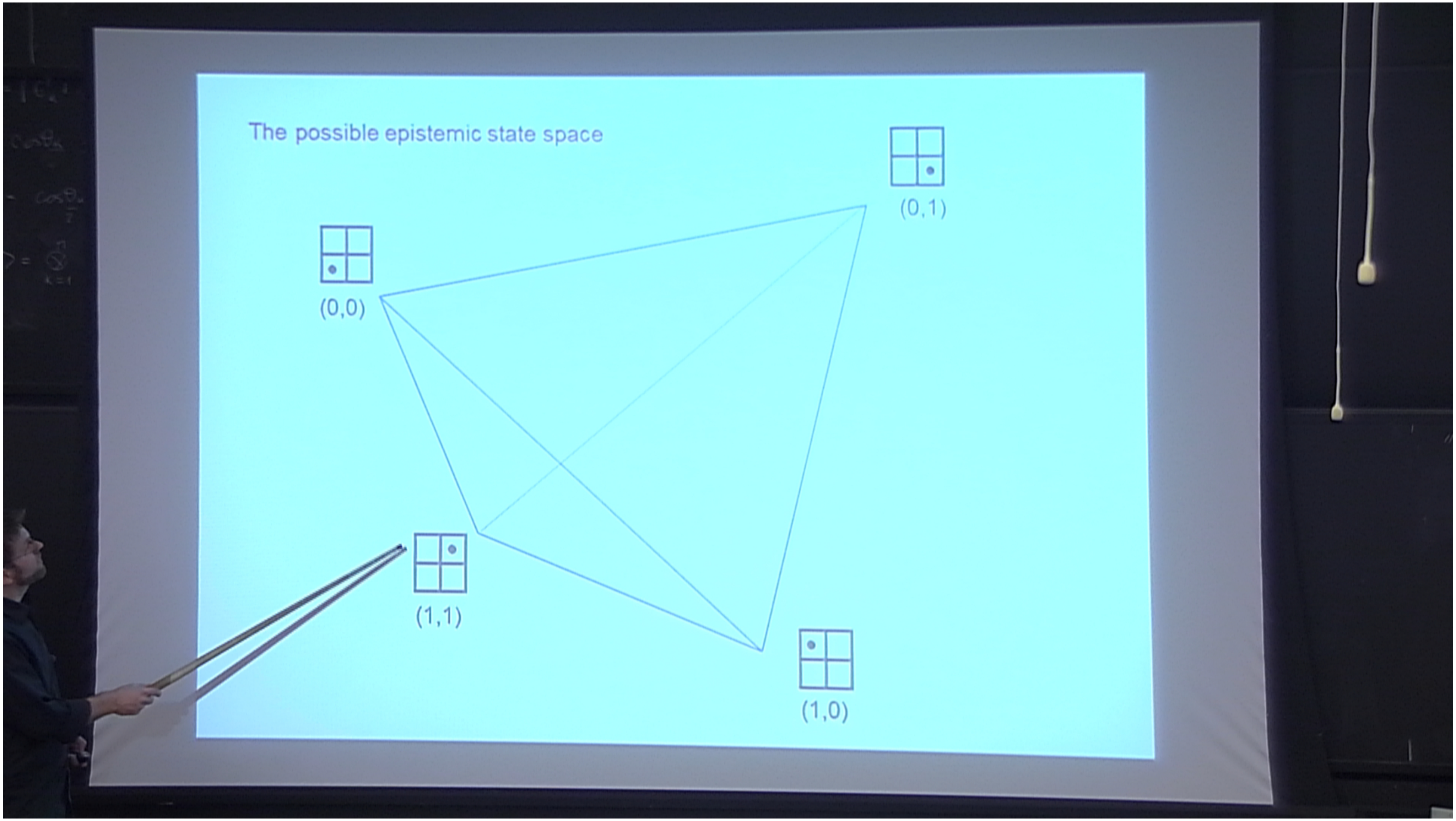

A single bit
X 1
0
0 1
P
Canonical variables
aX + bP   a, b ∈ ℤ2   Addition is mod2
X, P, X + P

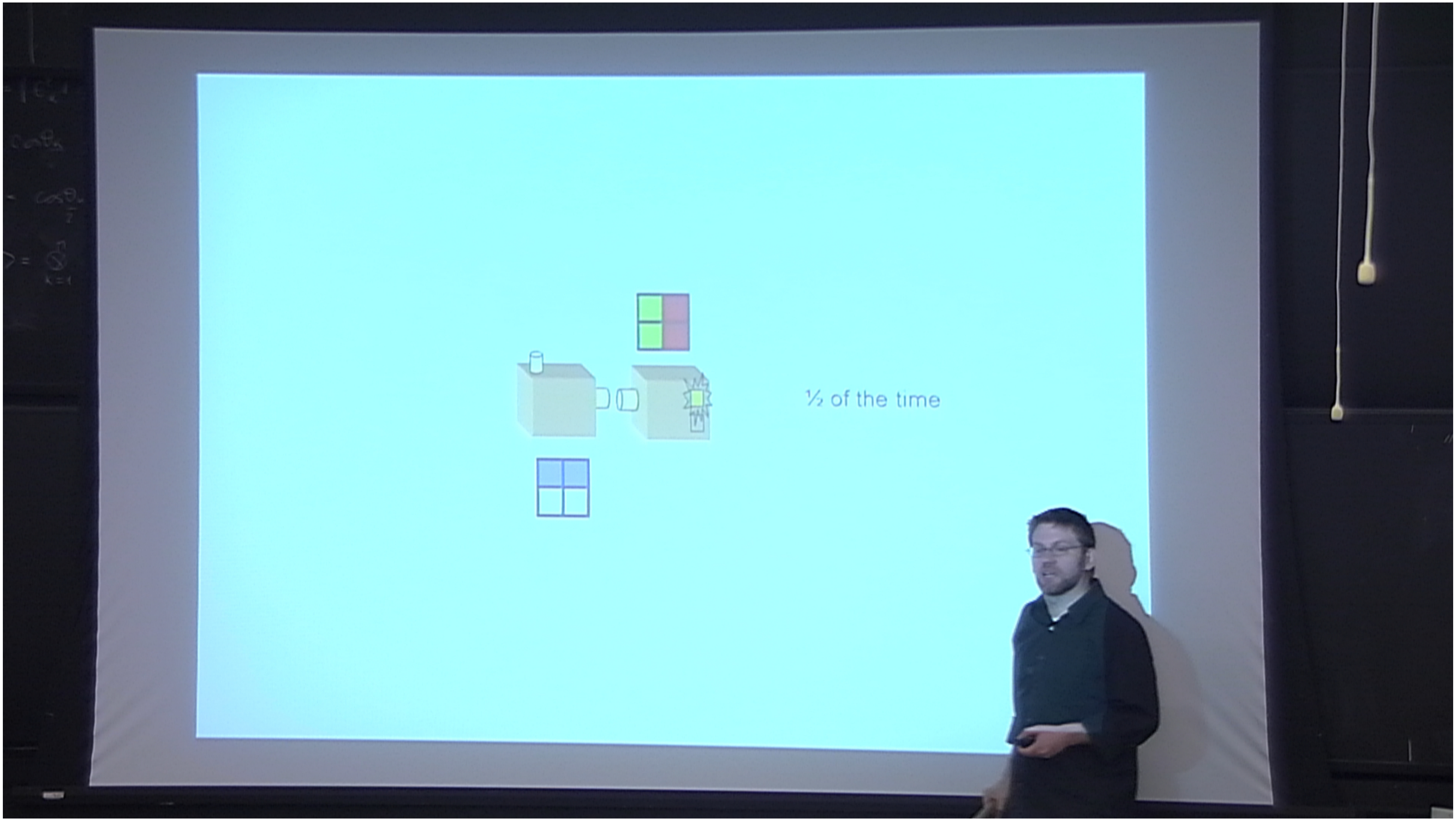


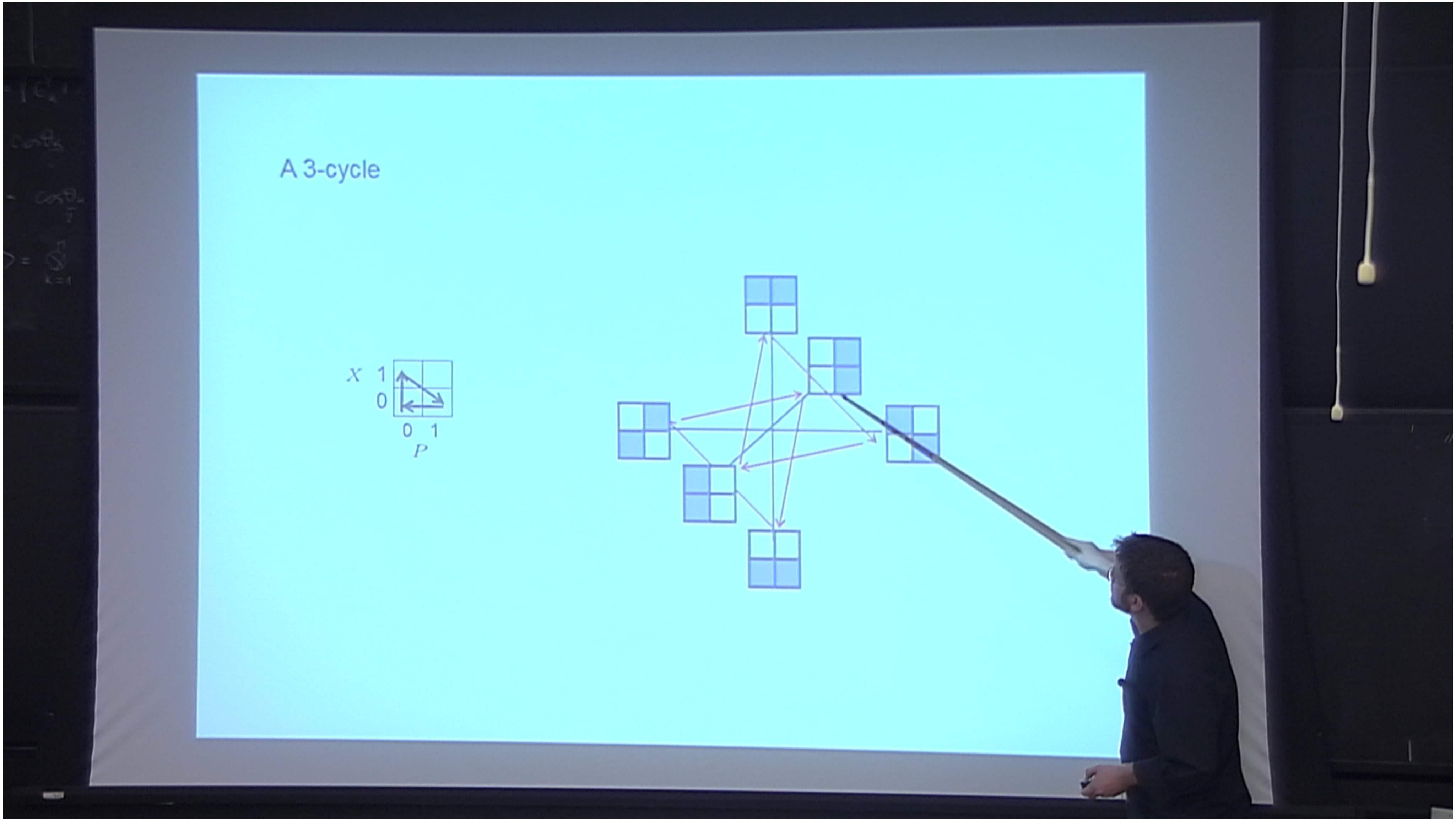
A single bit
Canonical variables
$aX + bP \quad a, b \in \mathbb{Z}_2$
Addition is mod2
$X, \; P, \; X+P$
Statistical distributions
X known
P known
$X+P$ known
Nothing known

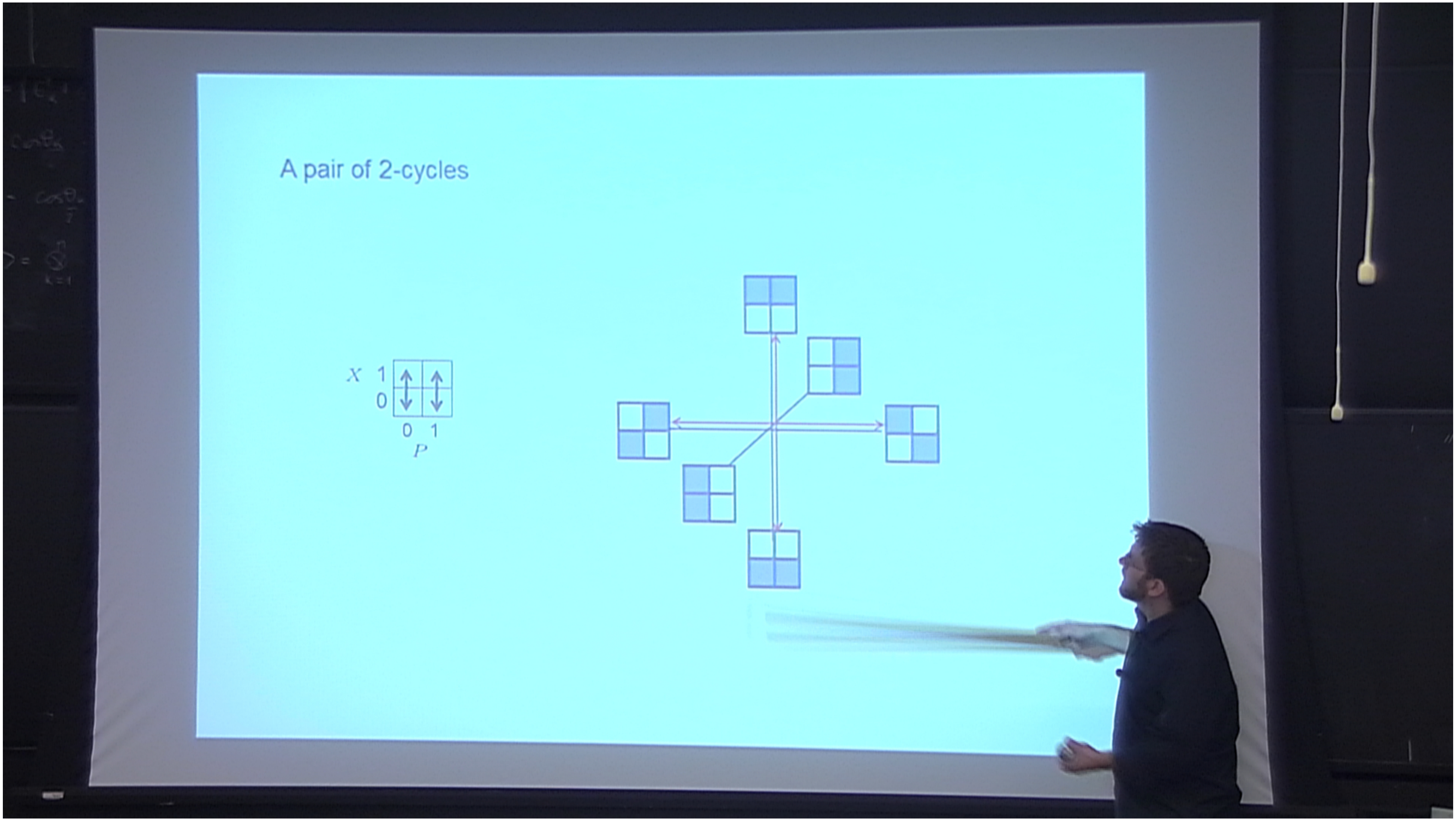

A single bit
Canonical variables
$aX + bP \quad a, b \in \mathbb{Z}_2$
Addition is mod2
$X, \ P, \ X+P$
Statistical distributions
X known
P known
$X + P$ known
Nothing known

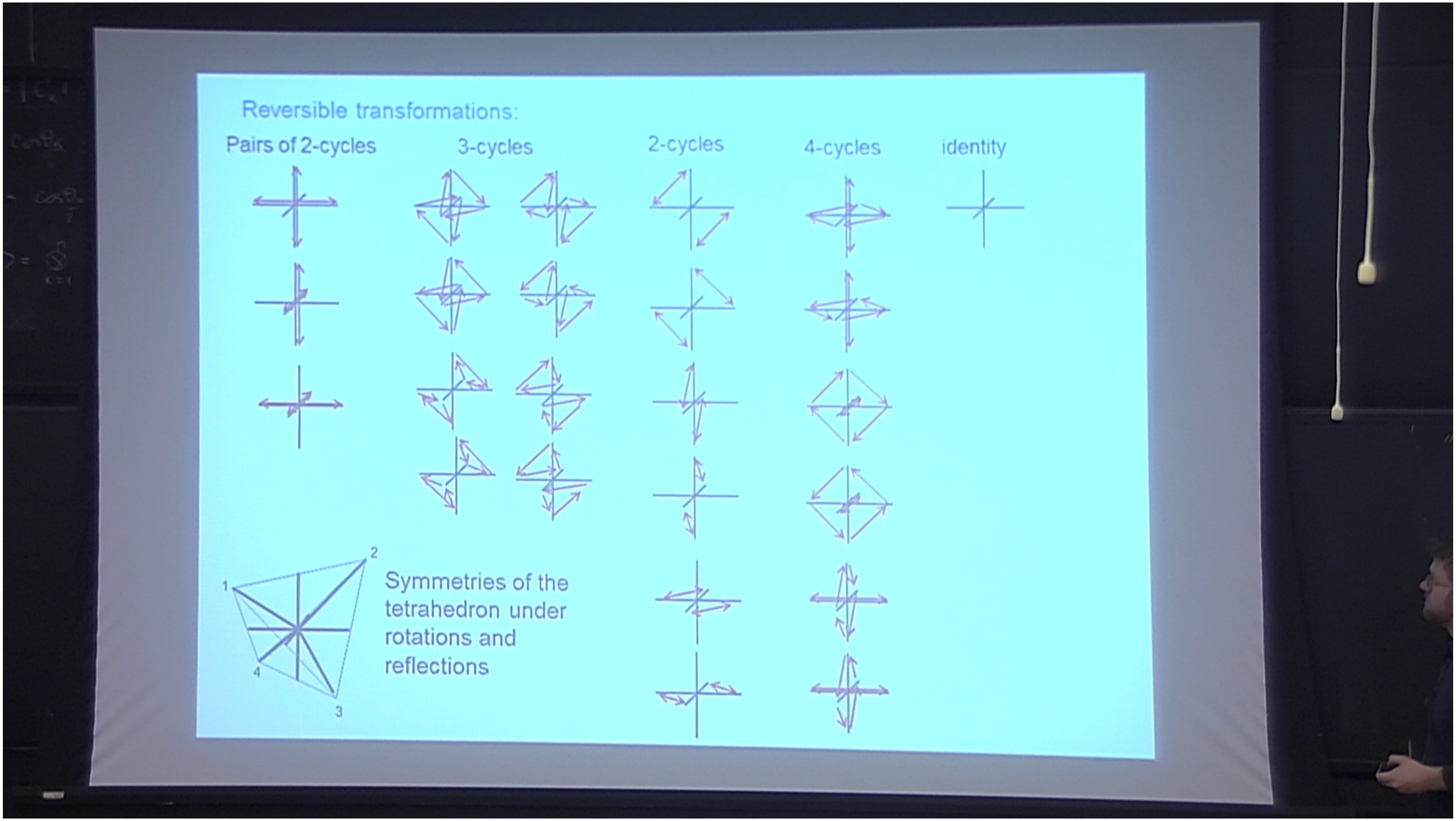

Convex combination
=
+cx
+cx
+cx
$\frac{1}{2}I = \frac{1}{2}|0\rangle\langle 0| + \frac{1}{2}|1\rangle\langle 1|$
$= \frac{1}{2}|+\rangle\langle +| + \frac{1}{2}|-\rangle\langle -|$
$= \frac{1}{2}|+i\rangle\langle +i| + \frac{1}{2}|-i\rangle\langle -i|$

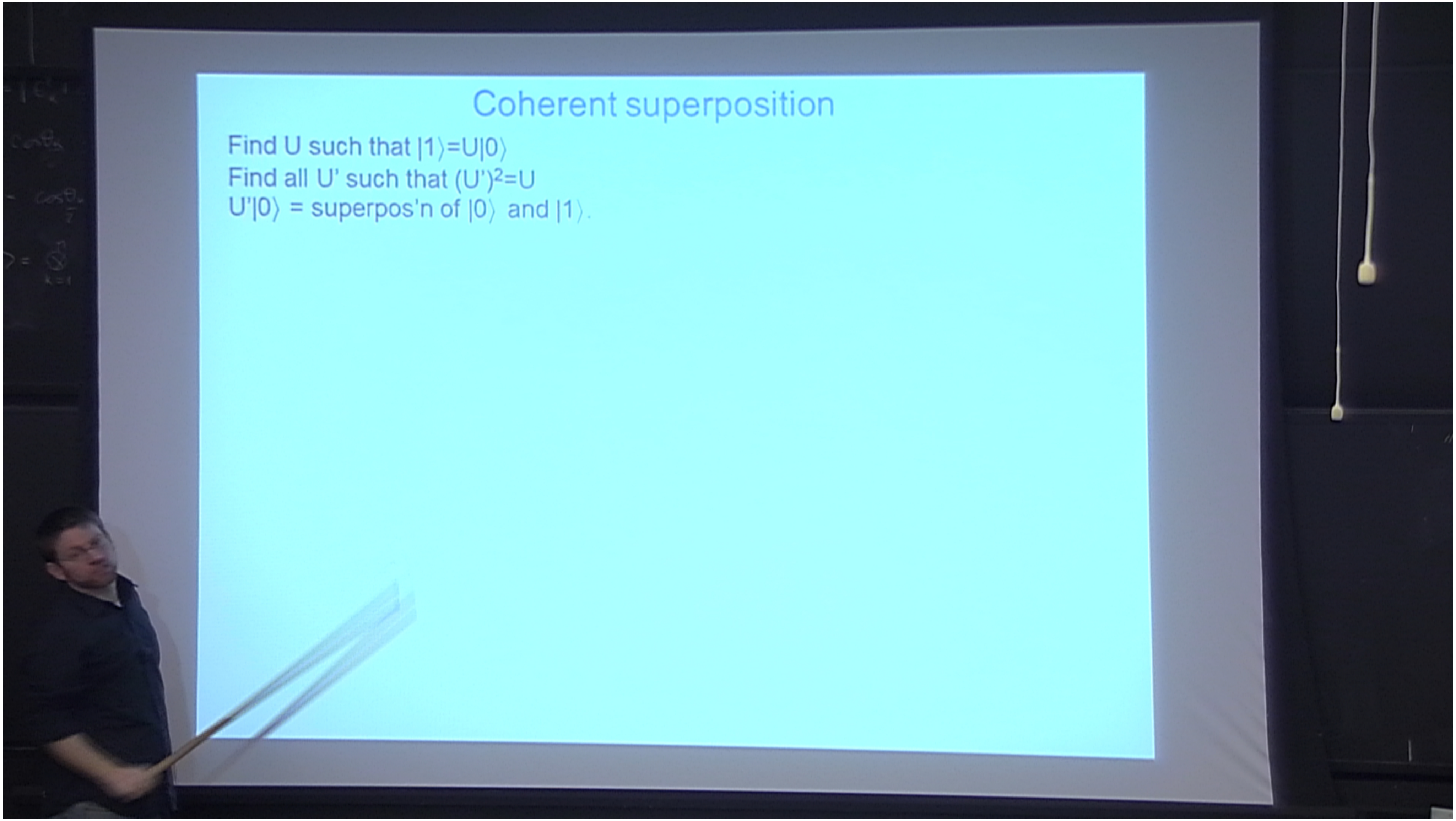

The possible epistemic state space
(0,1)
(0,0)
(1,1)
(1,0)

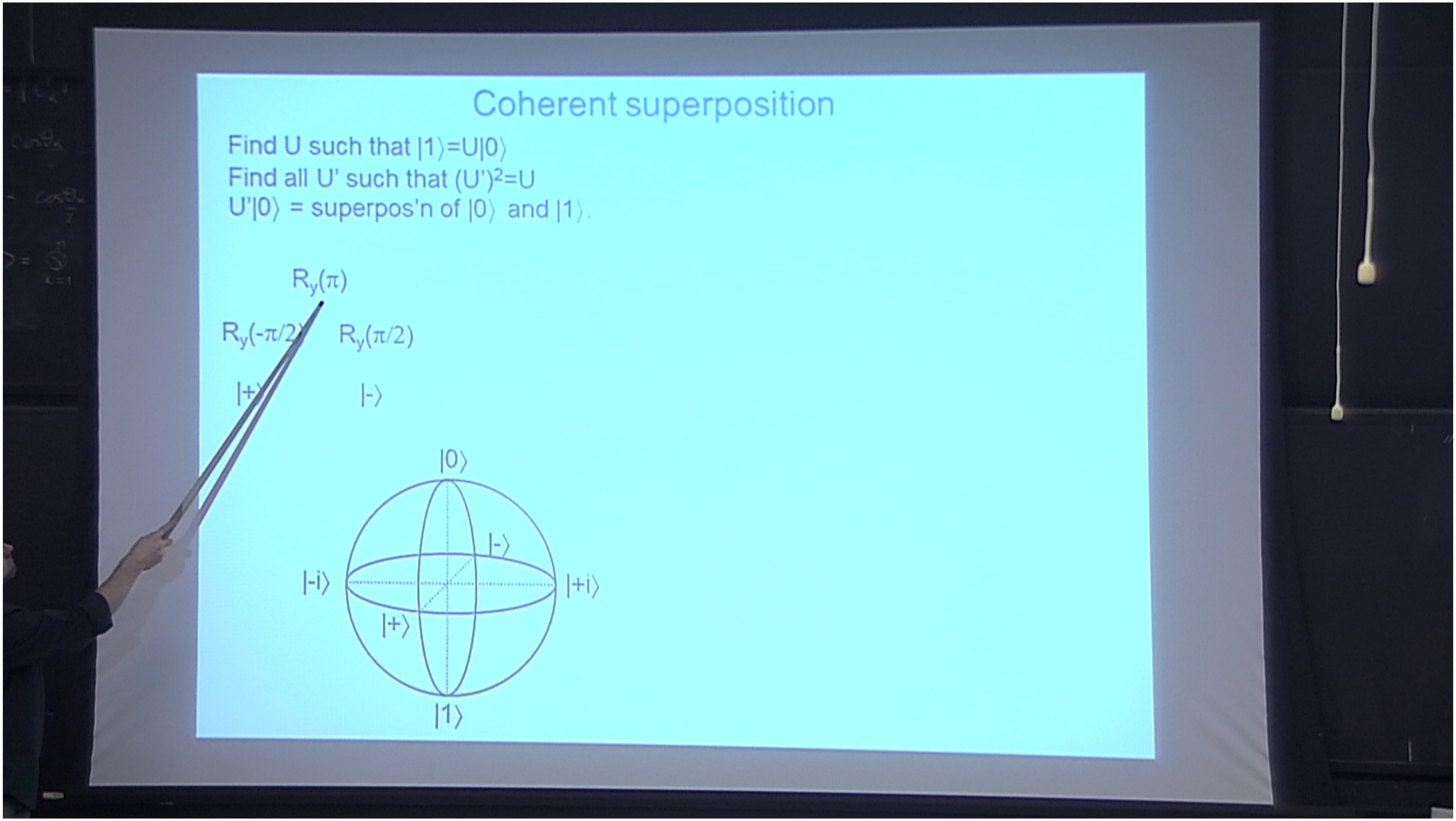

½ of the time

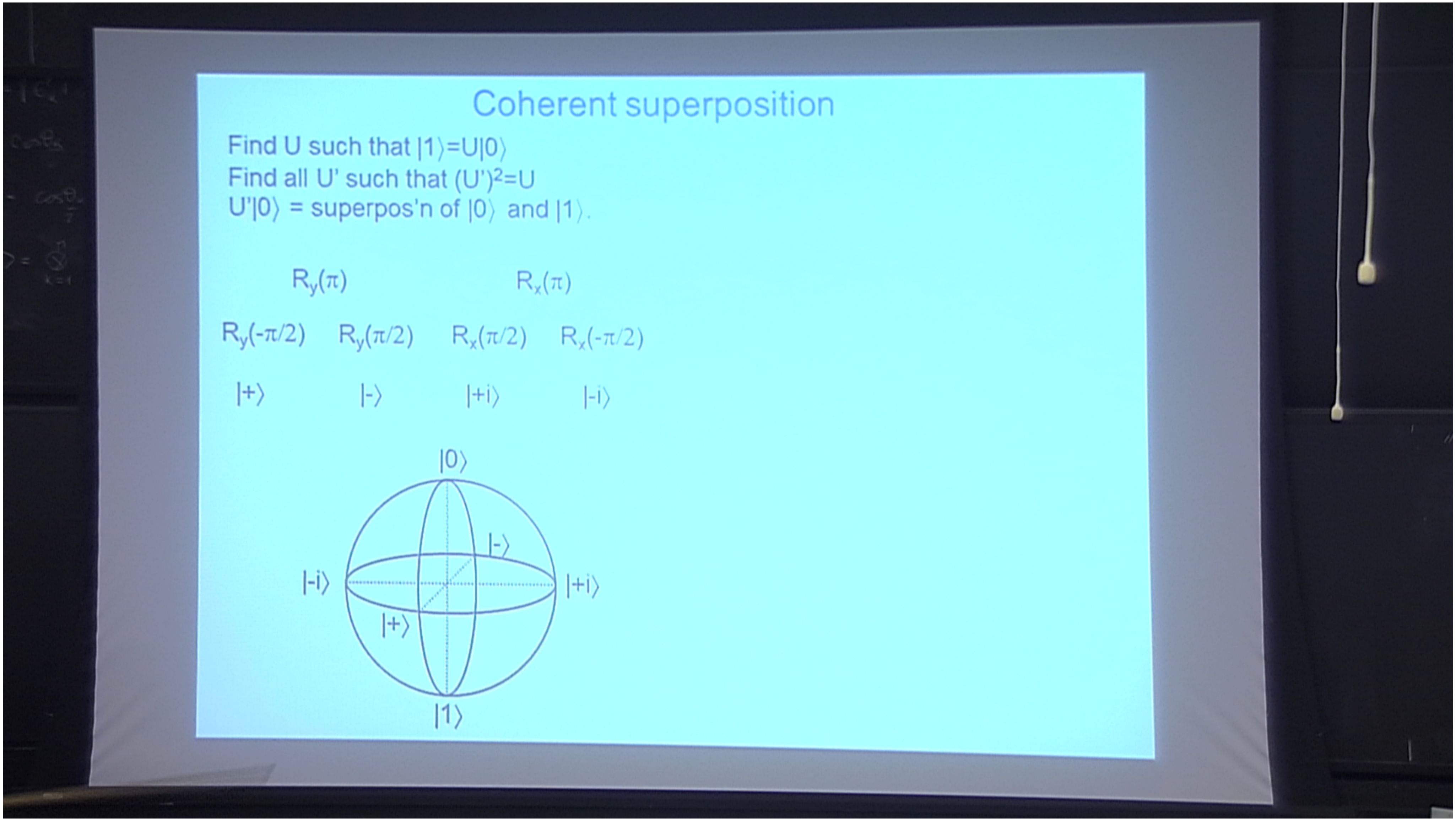

A 3-cycle
X
1
0
0 1
P

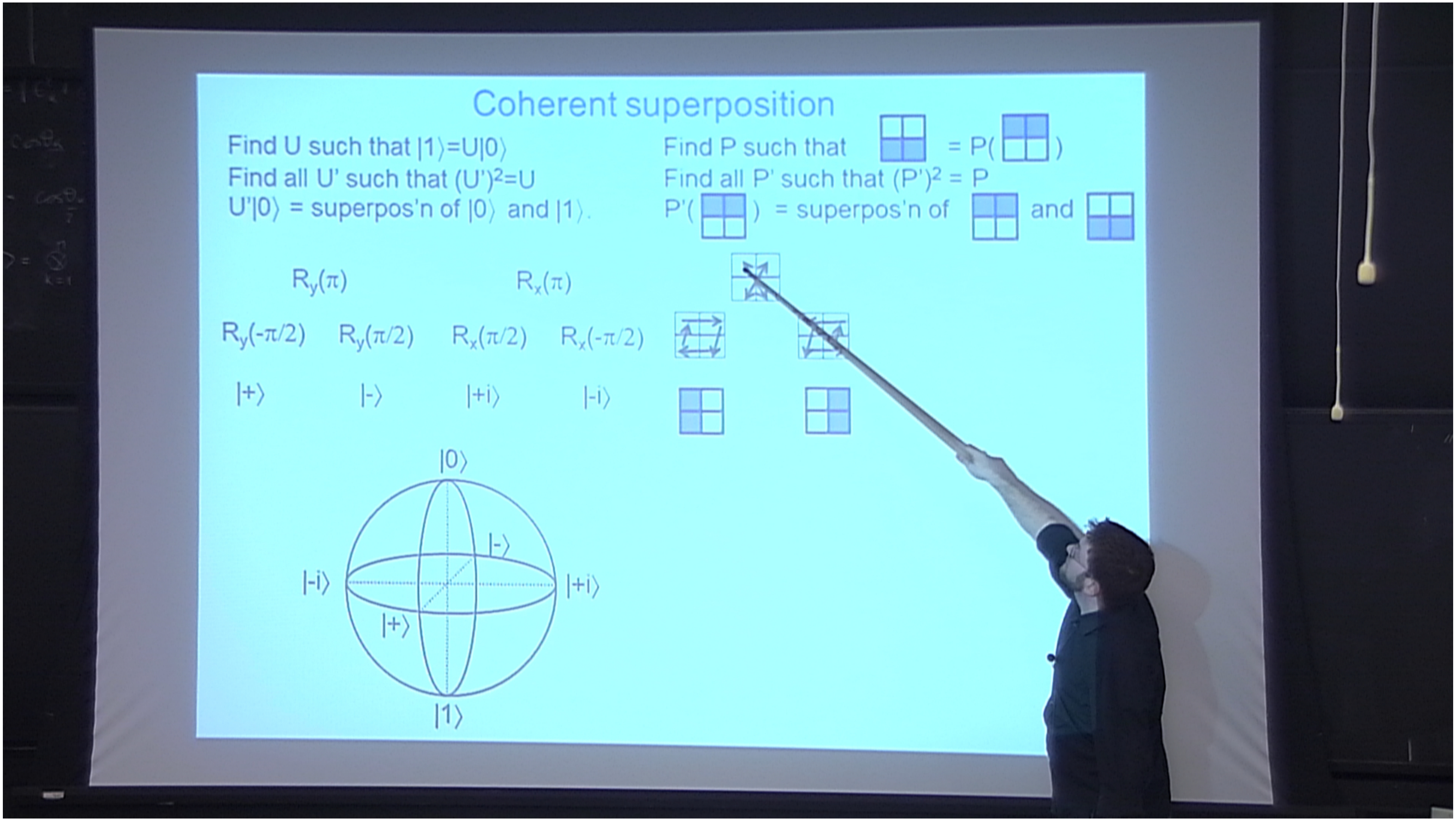

A pair of 2-cycles
X
1
0
0 1
P

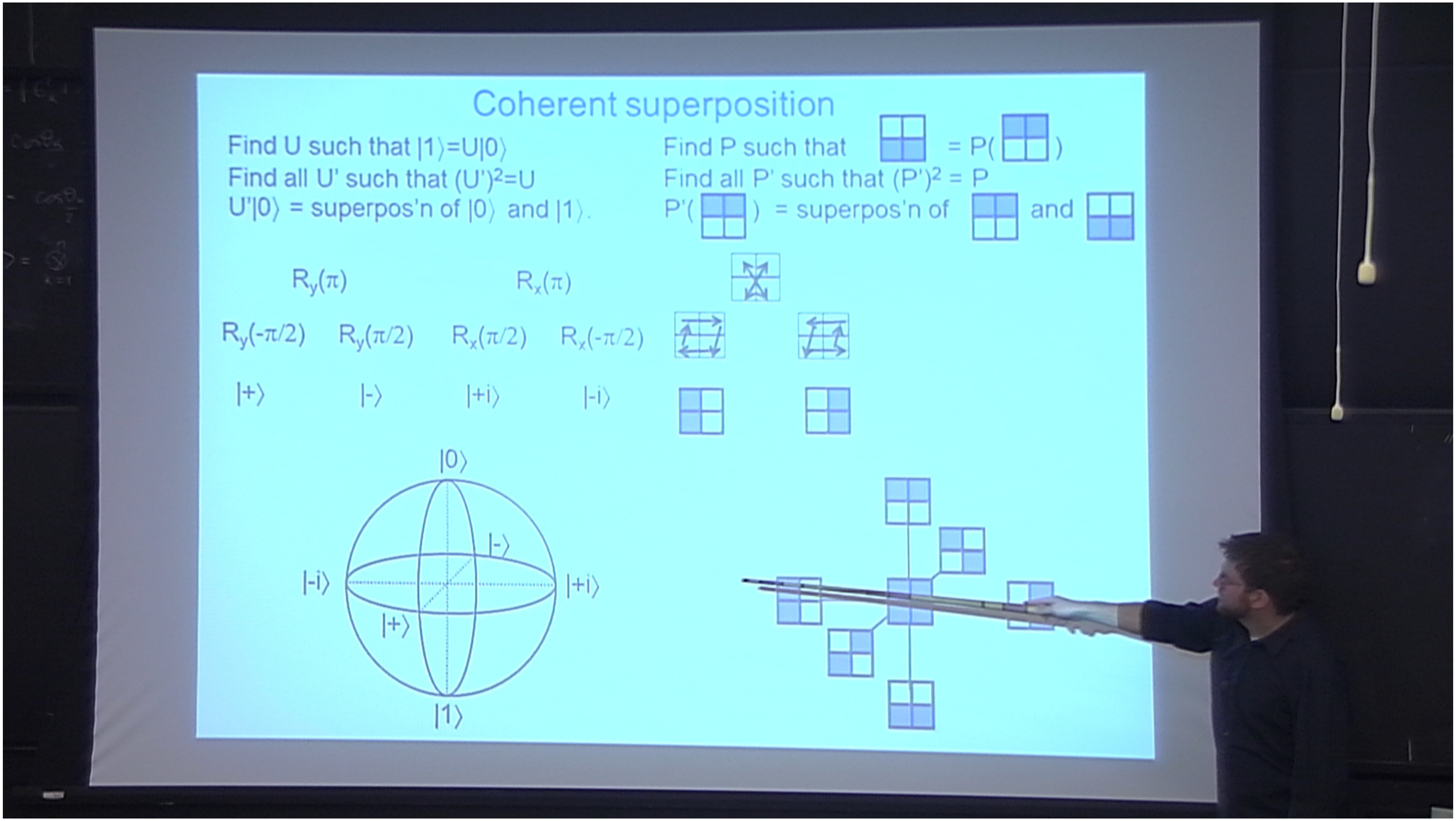

Reversible transformations:
Pairs of 2-cycles
3-cycles
2-cycles
4-cycles
identity
1
2
3
4
Symmetries of the tetrahedron under rotations and reflections


Coherent superposition
Find U such that |1⟩=U|0⟩
Find all U' such that $(U')^2=U$
U'|0⟩ = superpos'n of |0⟩ and |1⟩.


Coherent superposition
Find U such that |1⟩=U|0⟩
Find all U' such that (U')²=U
U'|0⟩ = superpos'n of |0⟩ and |1⟩.
Ry(π)
Ry(-π/2)
Ry(π/2)
|+⟩
|-⟩
|0⟩
|-⟩
|-i⟩
|+i⟩
|+⟩
|1⟩


Coherent superposition
Find U such that |1⟩=U|0⟩
Find all U' such that (U')²=U
U'|0⟩ = superpos'n of |0⟩ and |1⟩.
Rᵧ(π)
Rₓ(π)
Rᵧ(-π/2)
Rᵧ(π/2)
Rₓ(π/2)
Rₓ(-π/2)
|+⟩
|-⟩
|+i⟩
|-i⟩
|0⟩
|-⟩
|-i⟩
|+i⟩
|+⟩
|1⟩


Coherent superposition
Find U such that |1⟩=U|0⟩
Find all U' such that (U')²=U
U'|0⟩ = superpos'n of |0⟩ and |1⟩.
Find P such that = P( )
Find all P' such that (P')² = P
P'( ) = superpos'n of and
Ry(π)
Rx(π)
Ry(-π/2)
Ry(π/2)
Rx(π/2)
Rx(-π/2)
|+⟩
|-⟩
|+i⟩
|-i⟩
|0⟩
|-⟩
|-i⟩
|+i⟩
|+⟩
|1⟩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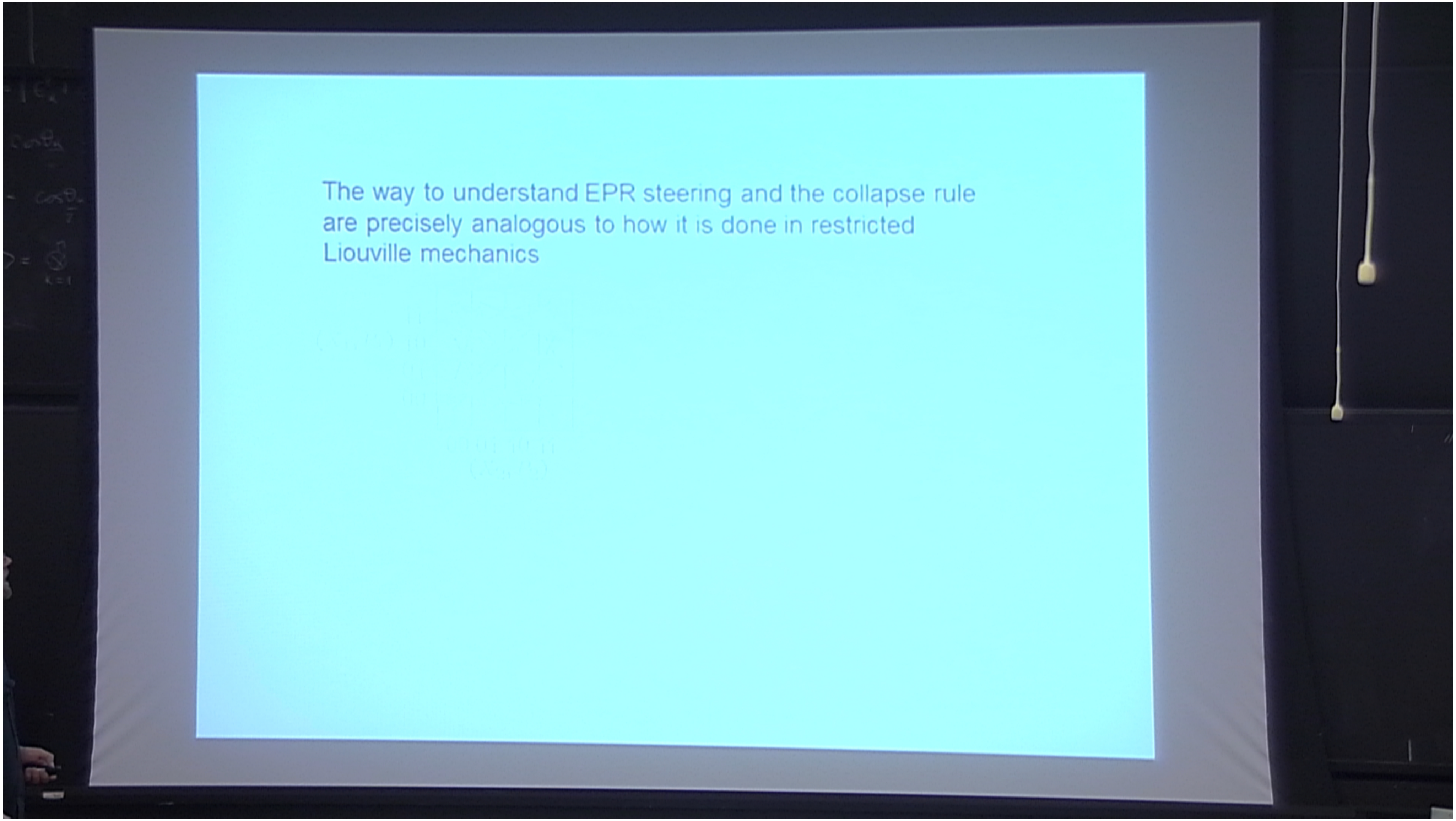
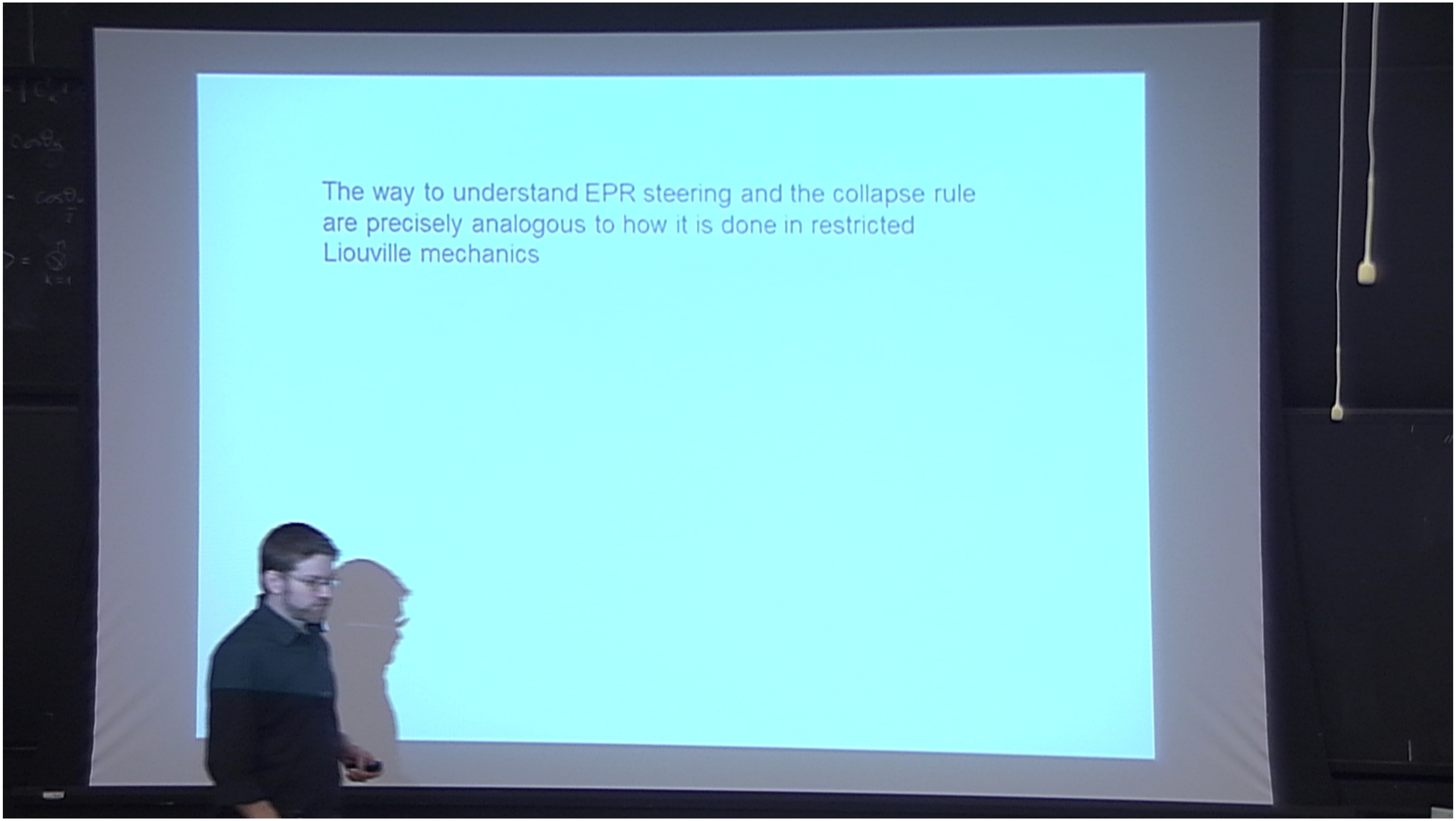
Find all U' such that (U')²=U
U'|0⟩ = superpos'n of |0⟩ and |1⟩.
Find P such that = P( )
Find all P' such that (P')² = P
P'( ) = superpos'n of and
Ry(π)
Rx(π)
Ry(-π/2)
Ry(π/2)
Rx(π/2)
Rx(-π/2)
|+⟩
|-⟩
|+i⟩
|-i⟩
|0⟩
|-⟩
|-i⟩
|+i⟩
|+⟩
|1⟩


The way to understand EPR steering and the collapse rule
are precisely analogous to how it is done in restricted
Liouville mechanics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