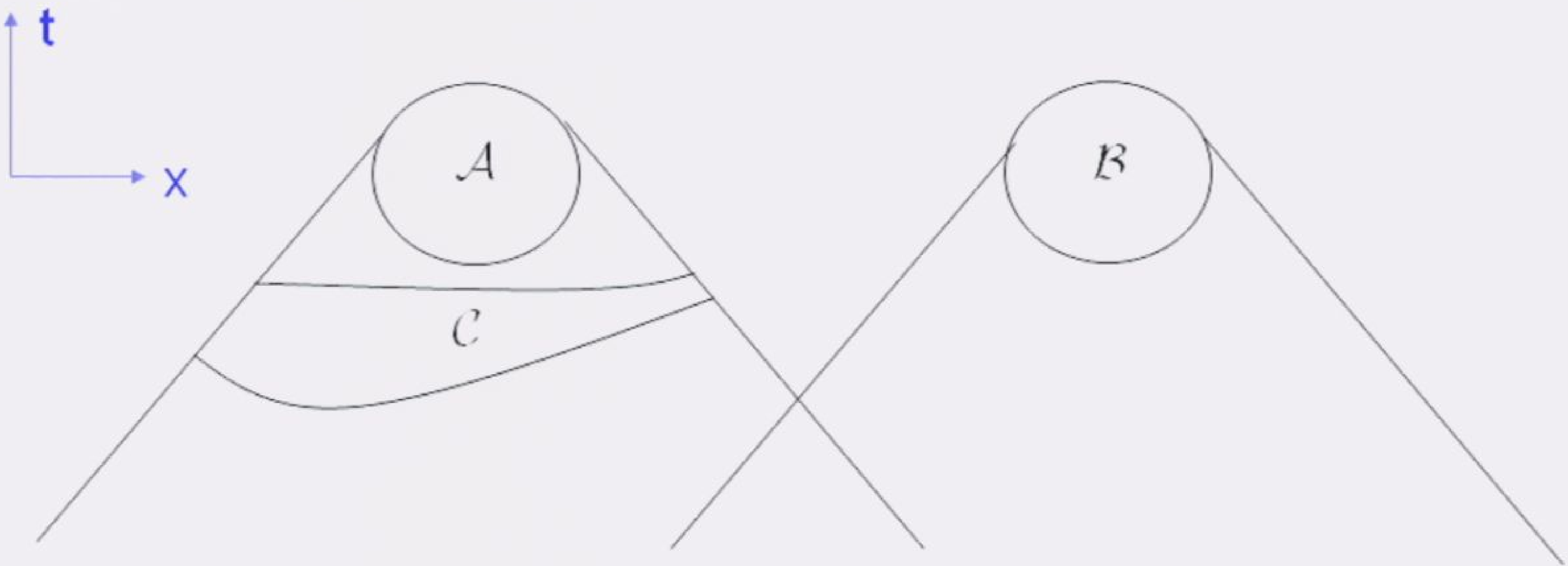
Title: Foundations of Quantum Mech. (PHYS 639) - Lecture 9

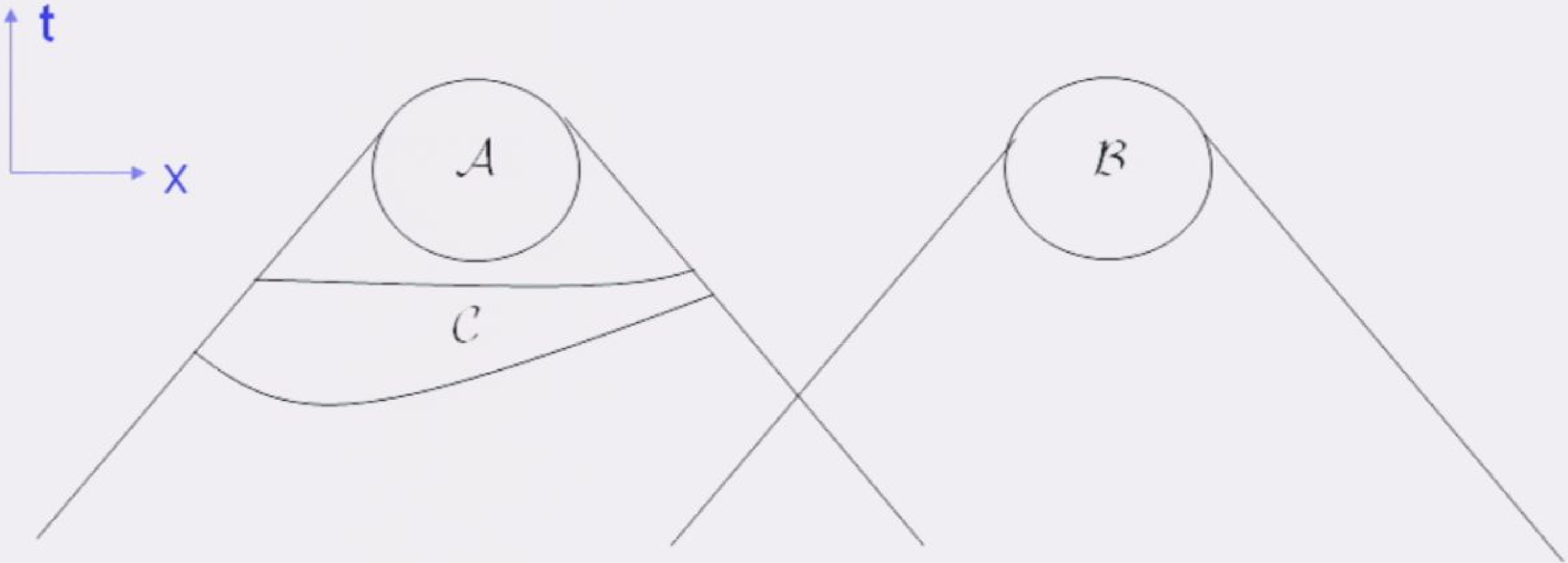
Date: Dec 10, 2009 11:00 AM

URL: http://pirsa.org/09120073

Abstract:



"A theory will be said to be ***locally causal*** if the probabilities for the values of local beables in a space-time region A are unaltered by specification of values of local beables in a space-time region B, when what happens in the backward light cone of A is already sufficiently specified, for example by a full specification of local beables in a space-time region C."
-- J. S. Bell



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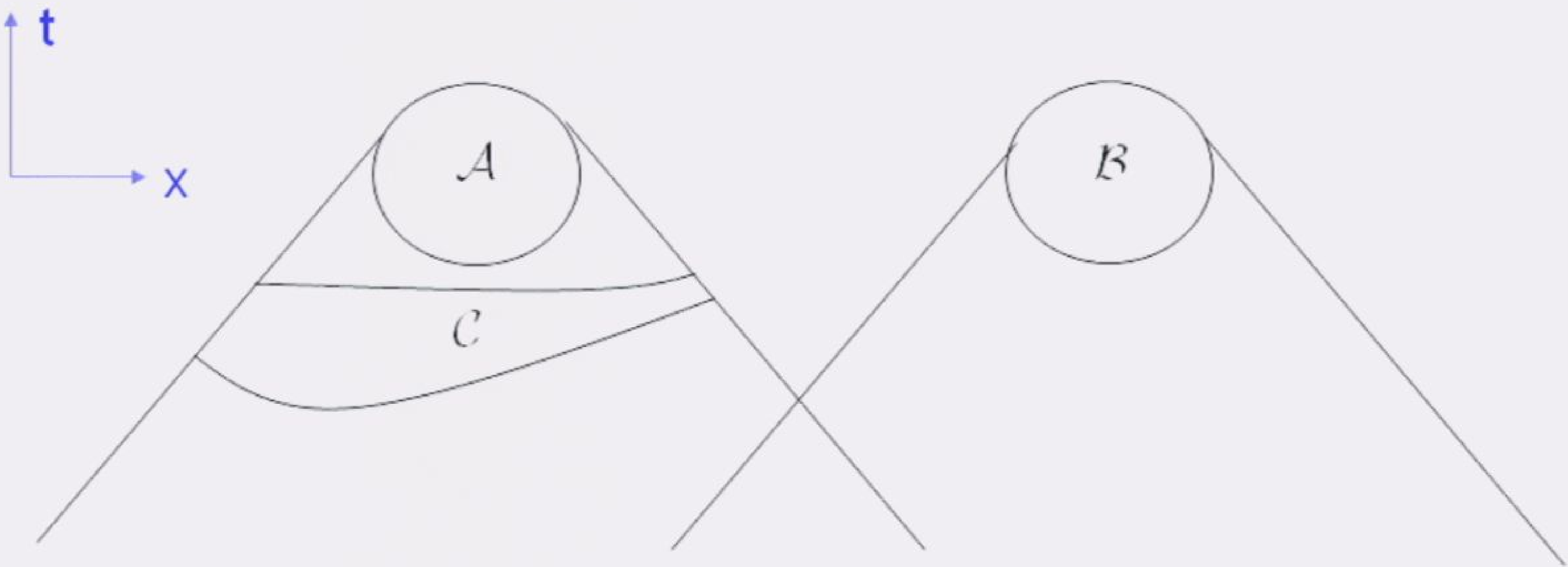

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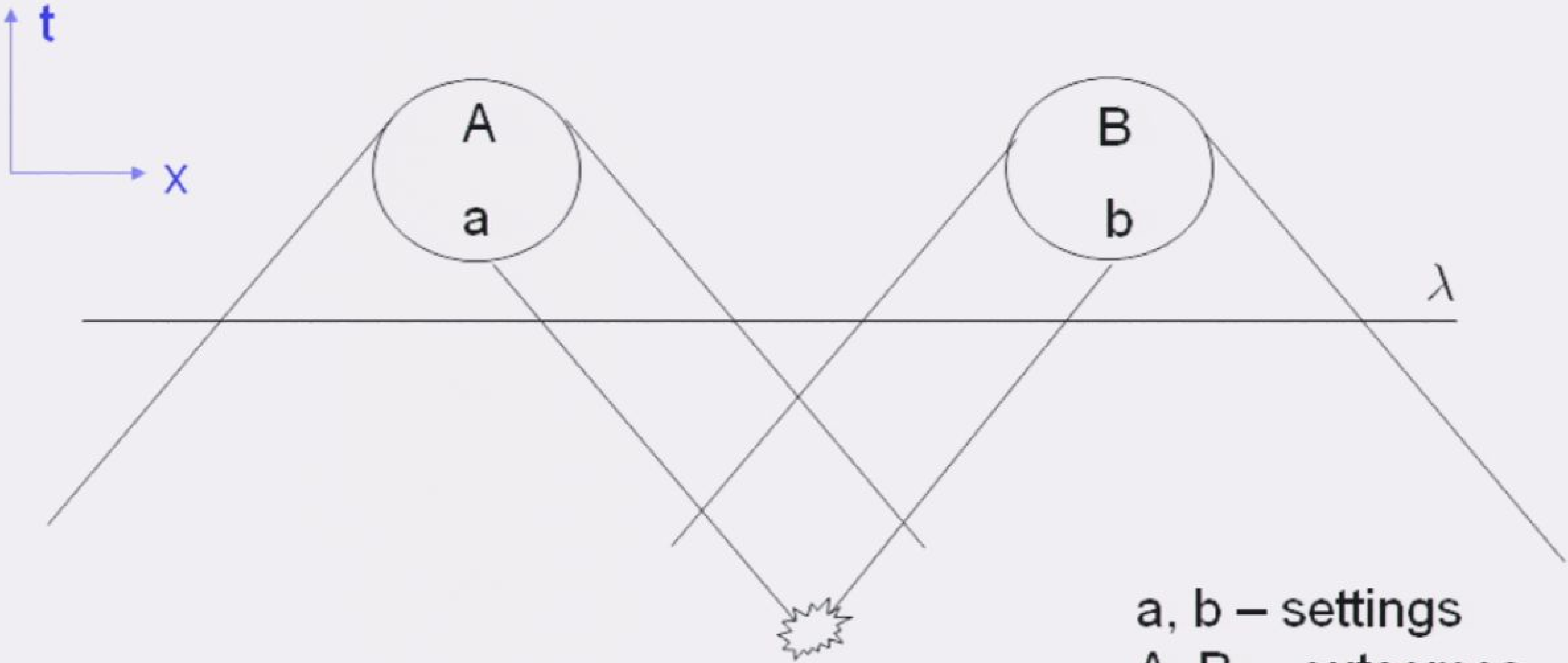
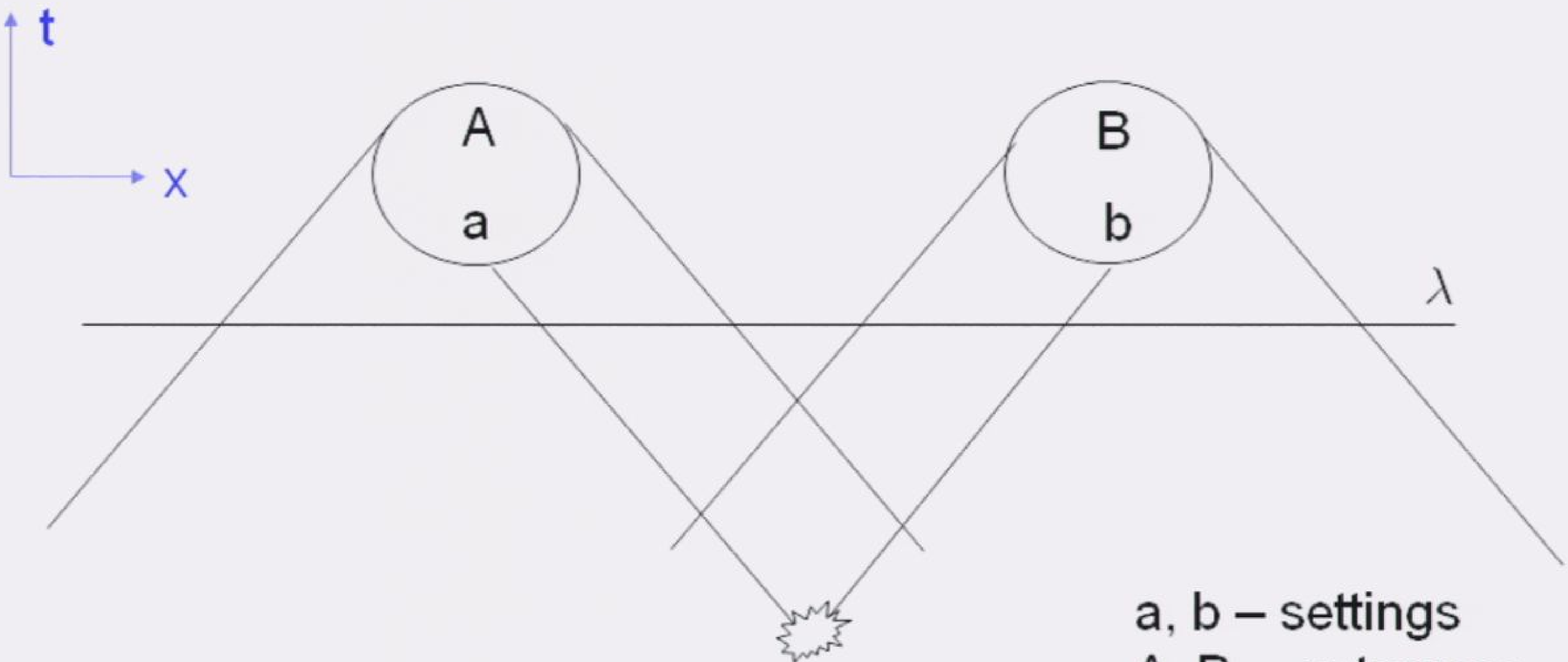
Local causality

$$p(X_A | X_B, \lambda_C) = p(X_A | \lambda_C)$$



a, b – settings
A, B -- outcomes



a, b – settings
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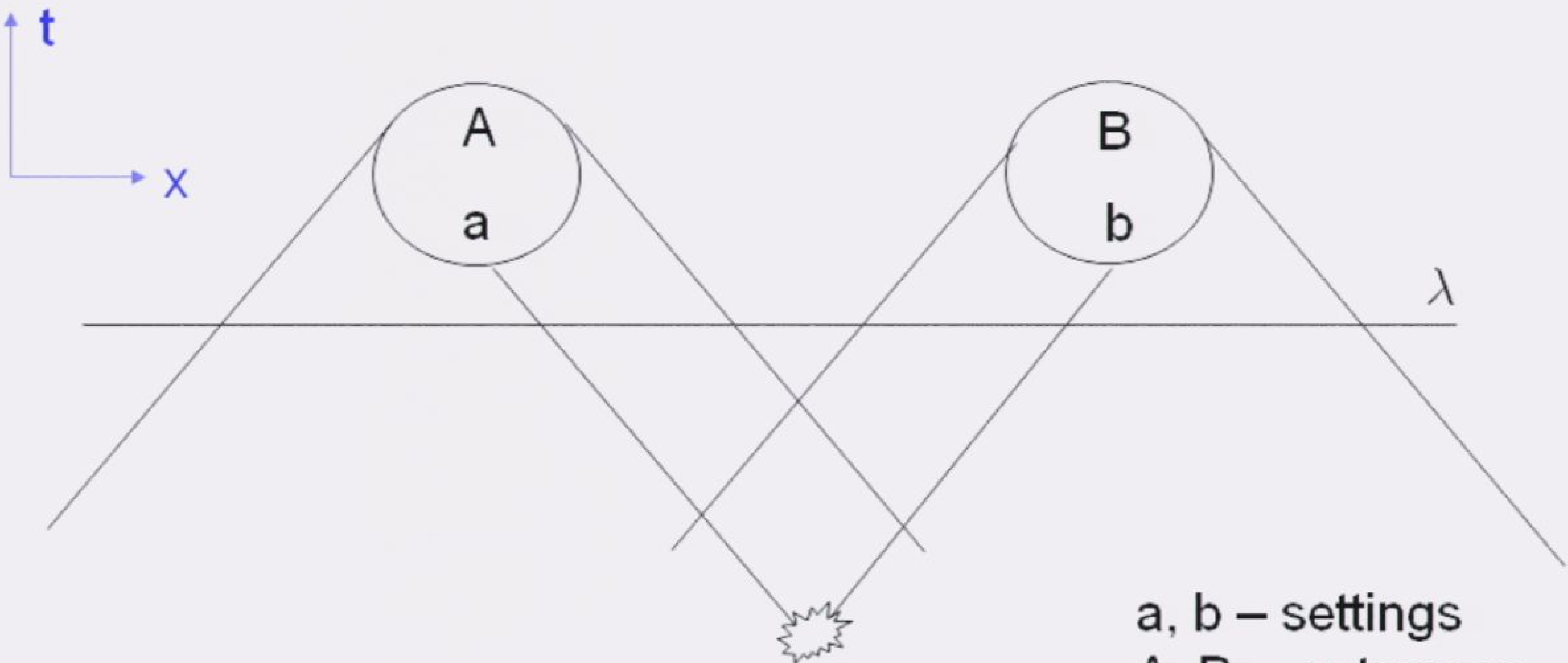
Locality causality implies

$$p(A|a, b, B, \lambda) = p(A|a, \lambda)$$



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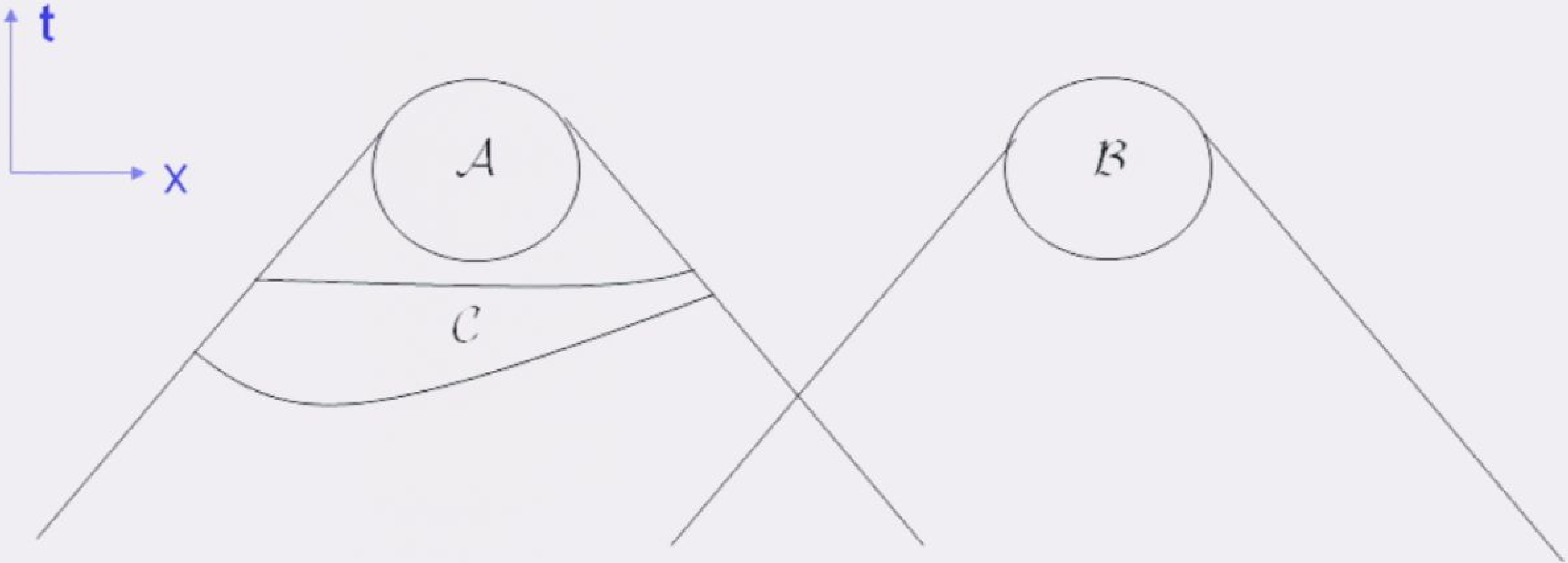

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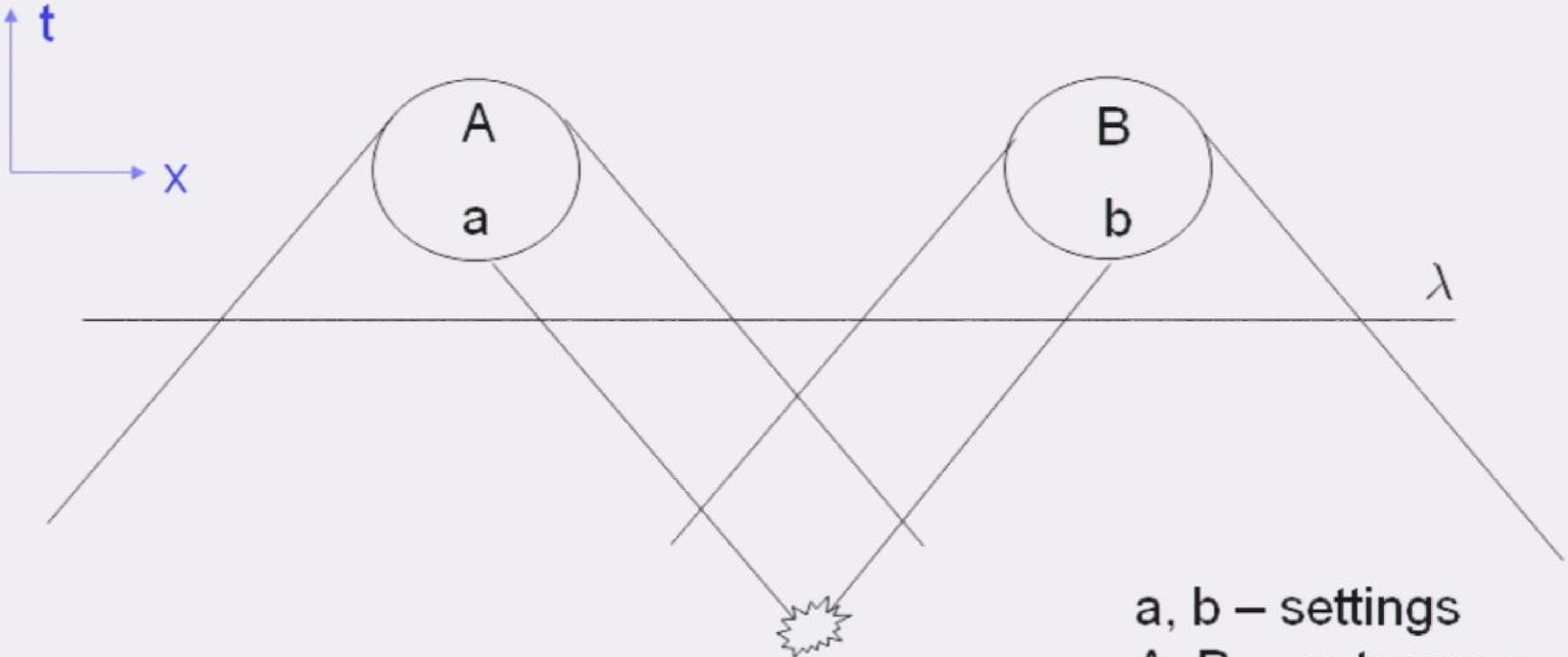

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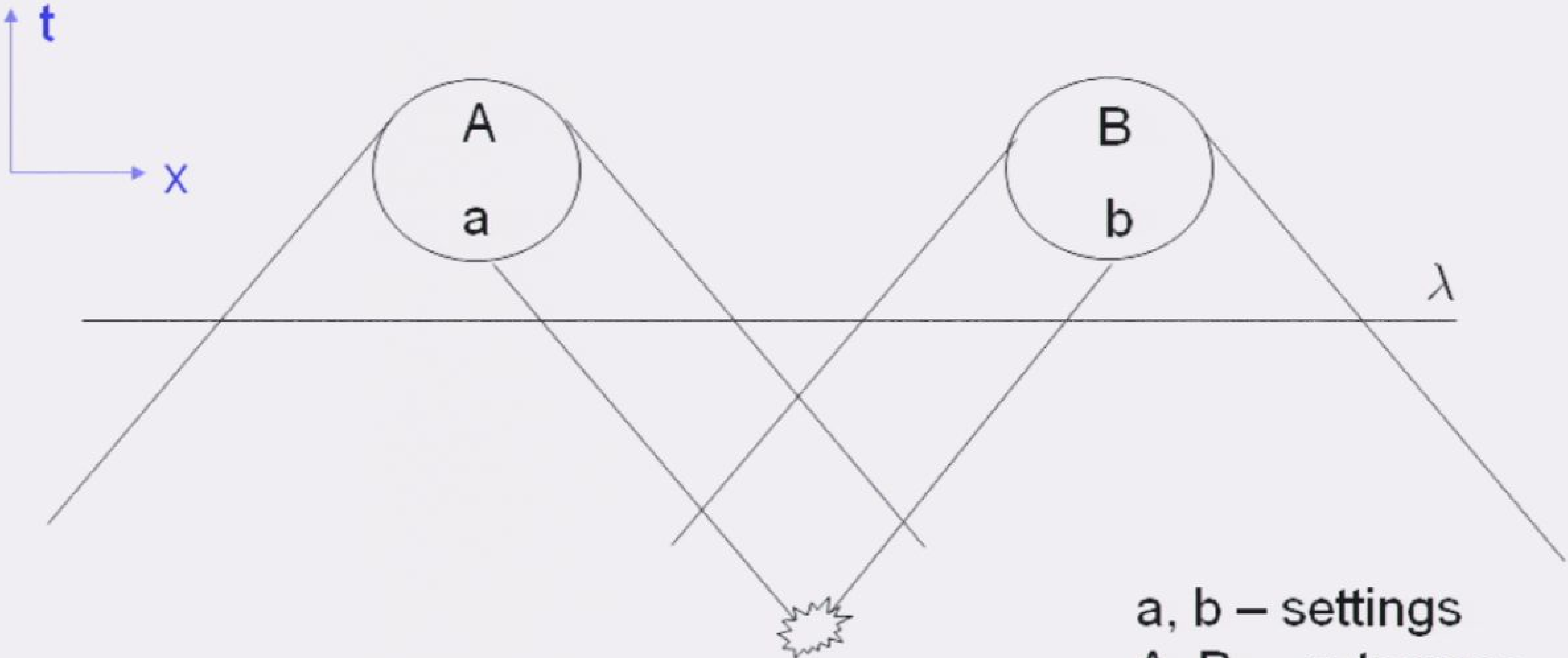

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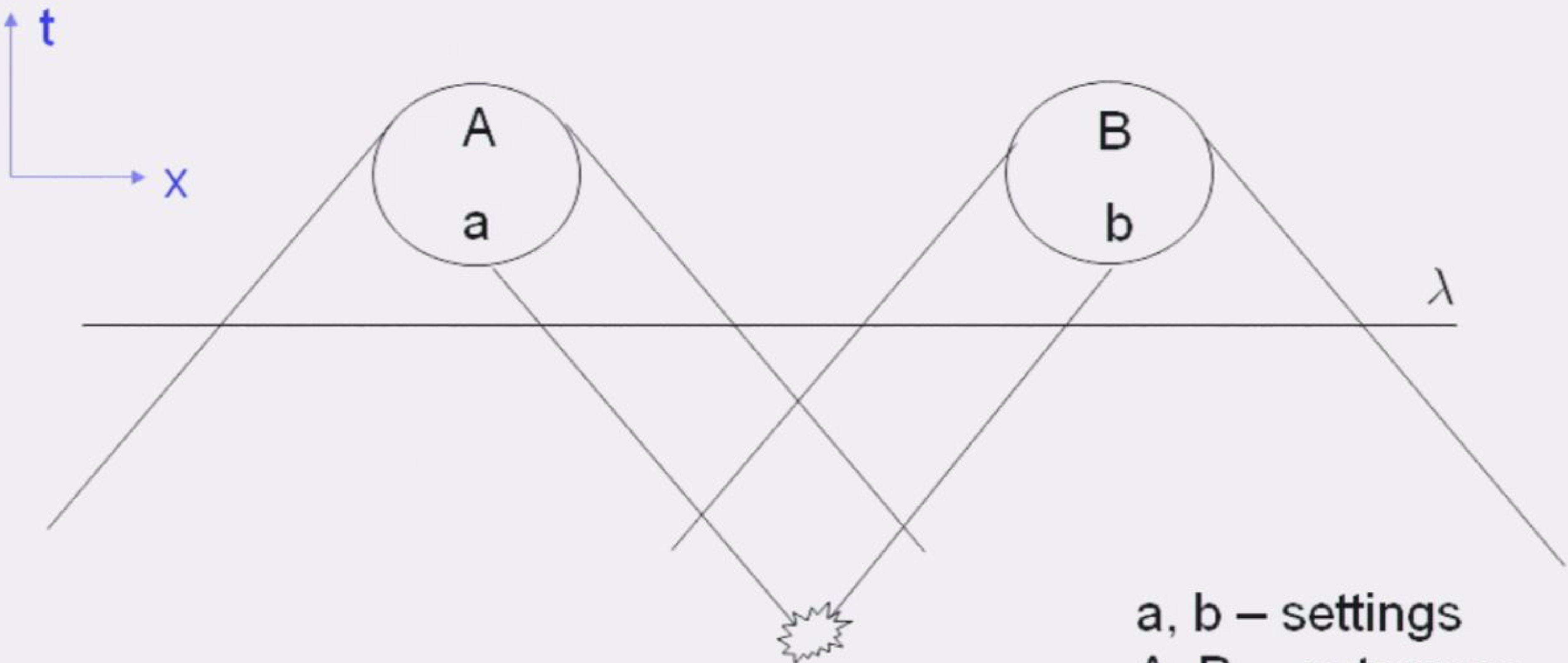

a, b – settings
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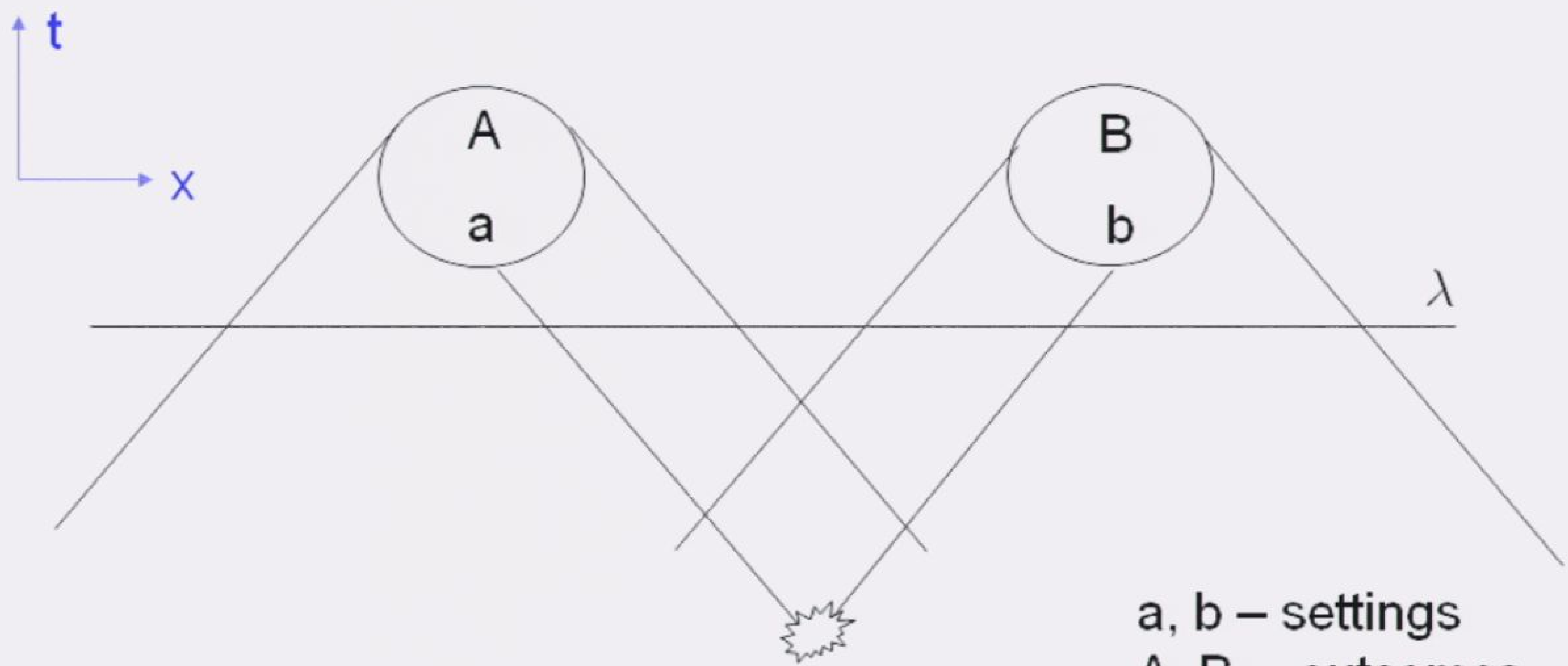
Locality causality implies

$$p(A|a,b,B,\lambda) = p(A|a,\lambda)$$
$$p(B|a,b,A,\lambda) = p(B|b,\lambda)$$

and implies *factorizability*

$$p(A,B|a,b,\lambda) = p(A|a,\lambda)p(B|b,\lambda)$$



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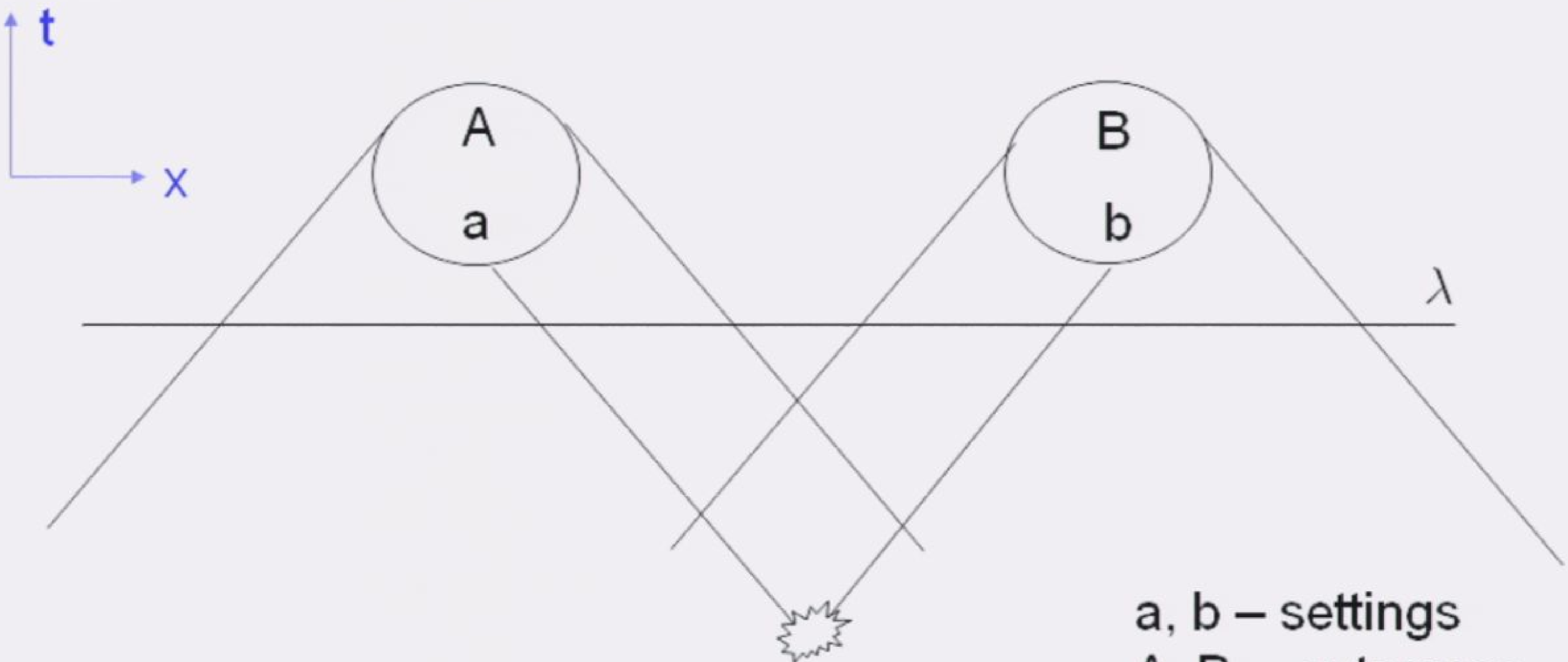

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and implies *factorizability*

$$p(A,B|a,b,\lambda) = p(A|a,\lambda)p(B|b,\lambda)$$

Factorizability from local causality

Recall Bayes' rule

$$p(A, B) = p(A|B)p(B)$$

Factorizability from local causality

Recall Bayes' rule

$$p(A, B) = p(A|B)p(B)$$

$$p(A, B|C) = p(A|B, C)p(B|C)$$

Factorizability from local causality

Recall Bayes' rule

$$p(A, B) = p(A|B)p(B)$$
$$p(A, B|C) = p(A|B, C)p(B|C)$$

therefore

$$p(A, B|a, b, \lambda) = p(A|B, a, b, \lambda)p(B|a, b, \lambda)$$

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By local causality

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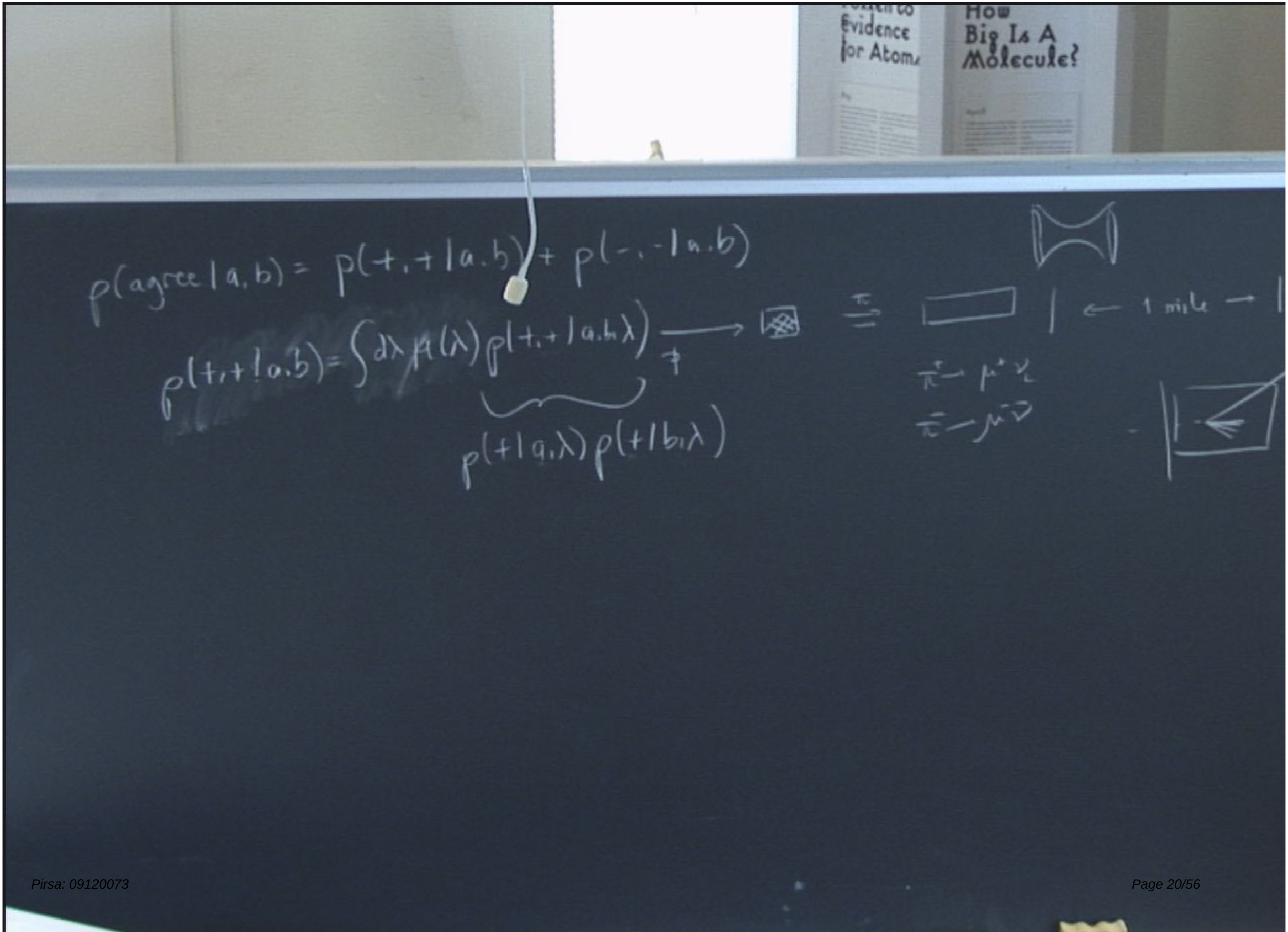
Thus

$$p(A,B|a,b,\lambda) = p(A|a,\lambda)p(B|b,\lambda)$$

$$\frac{1}{4}[\, p(\text{agree}|ab) + p(\text{agree}|ab') + p(\text{agree}|a'b) + p(\text{disagree}|a'b')] \leq 3/4$$


Evidence
for Atoms
How
Big Is A
Molecule?
p(agree | a, b) = p(+,+ | a,b) + p(-,- | a,b)
p(+,+ | a,b) = ∫dλ μ(λ) p(+,+ | a,b,λ)
p(+ | a,λ) p(+ | b,λ)
π
← 1 mile →
π⁺ → μ⁺ ν
π⁻ → μ⁻ ν̄

$$\frac{1}{4}[\ p(\text{agree}|ab) + p(\text{agree}|ab') + p(\text{agree}|a'b) + p(\text{disagree}|a'b')] \leq 3/4$$

Define $C(a,b) = (+1)p(\text{agree}|ab) + (-1)p(\text{disagree}|ab)]$

$$|C(a,b) + C(a',b) + C(a,b') - C(a',b')| \leq 2$$

The Clauser-Horn-Shimony-Holt (CHSH) inequality

$$\tfrac{1}{4}[\ p(\text{agree}|ab) + p(\text{agree}|ab') + p(\text{agree}|a'b) + p(\text{disagree}|a'b')] \leq 3/4$$

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Responses to Bell's theorem

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- Experimental loopholes

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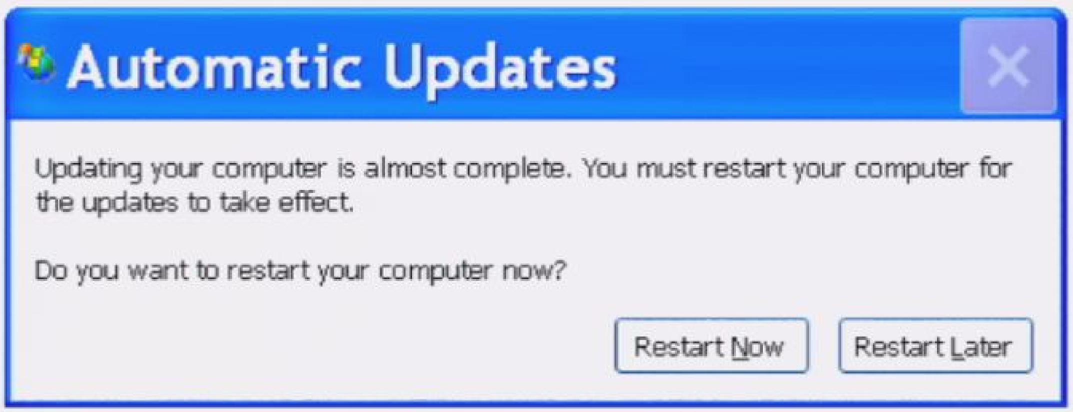

Responses to Bell's theorem

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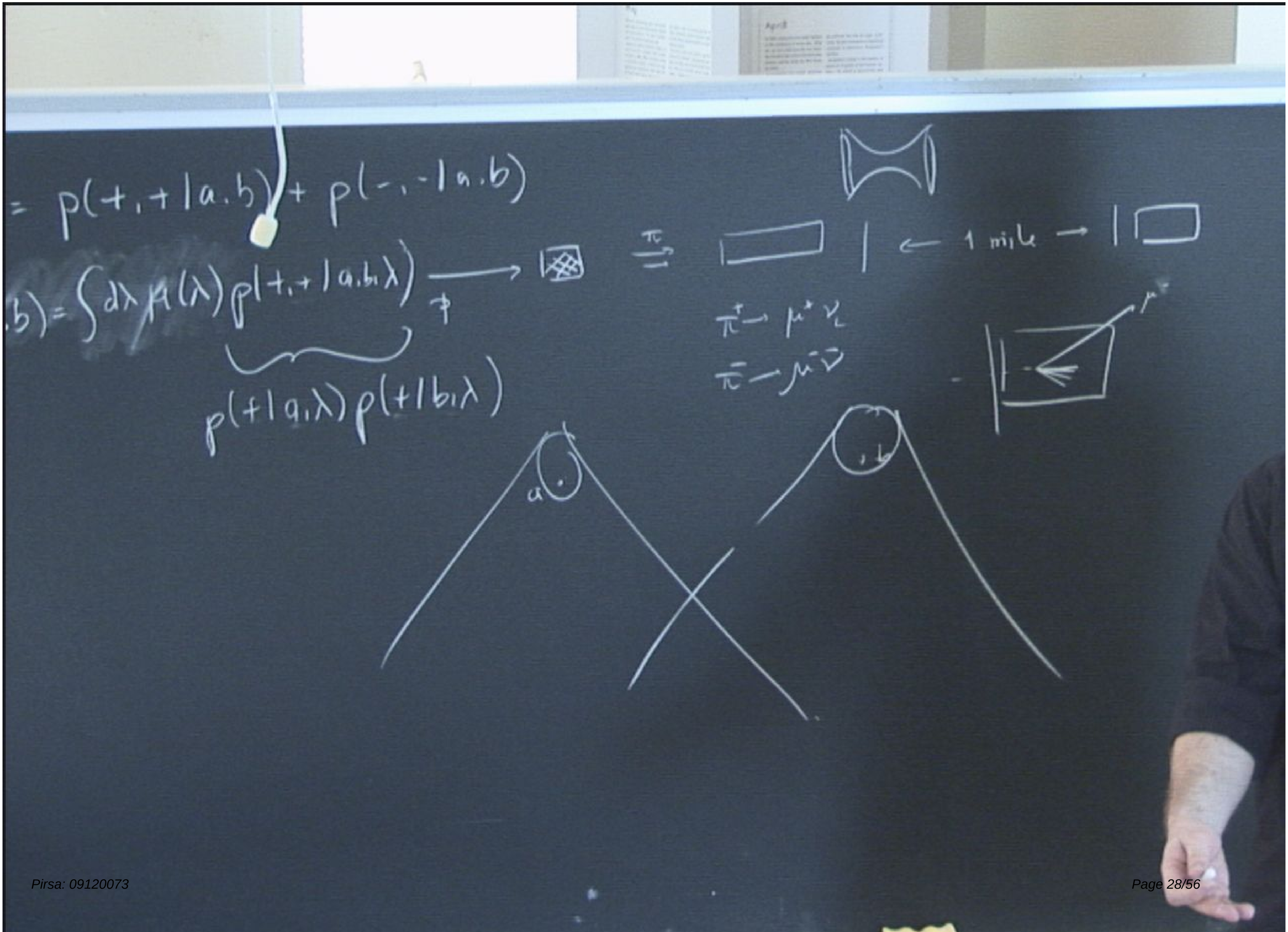
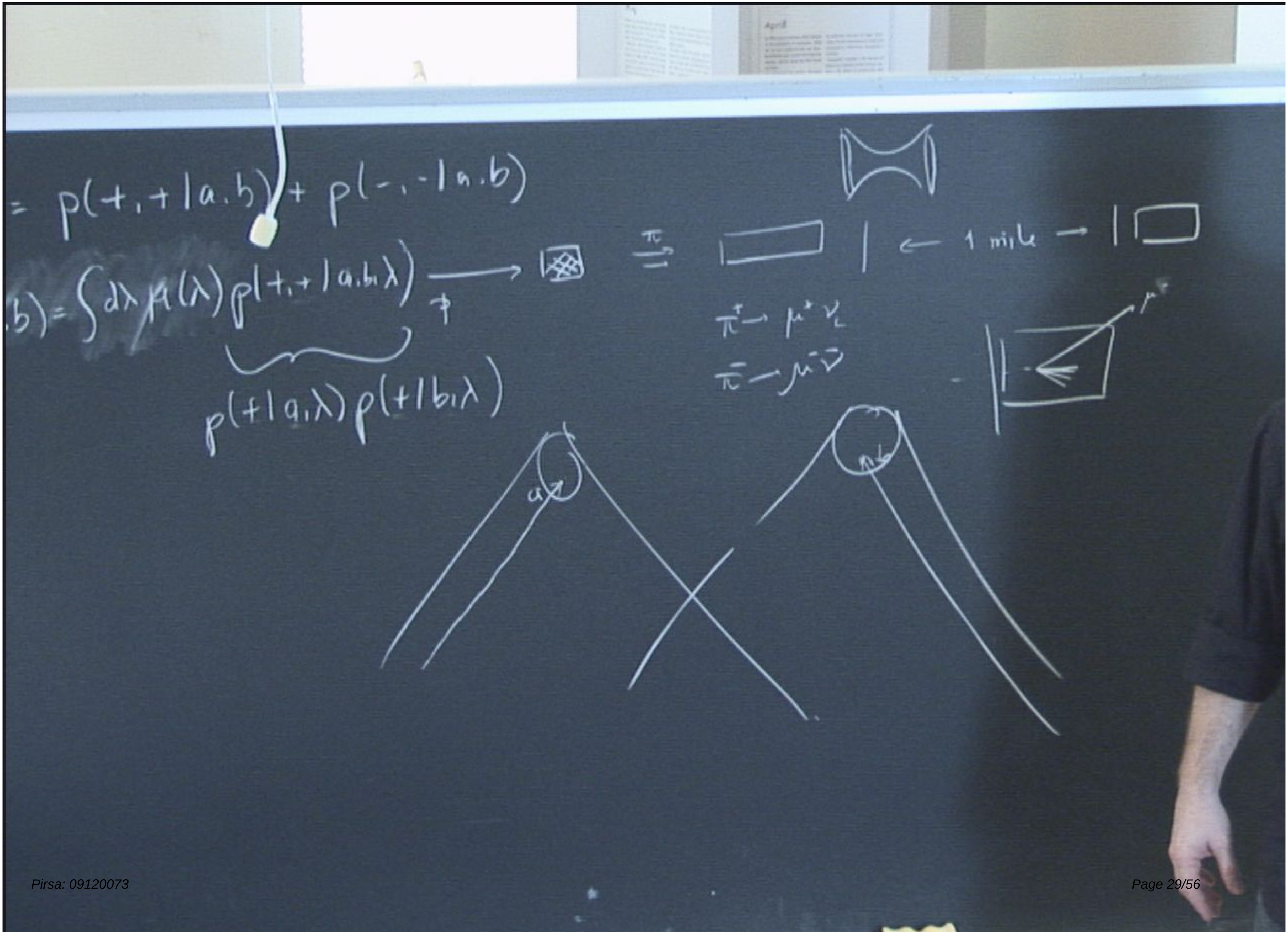
- Superdeterminism $p(a, b, \lambda) \neq p(a)p(b)p(\lambda)$
  free will
  complexity
  causal connection in the past


= p(+,+|a,b) + p(-,-|a,b)
b) = ∫dλ μ(λ) p(+,+|a,b,λ)
p(+|a,λ) p(+|b,λ)
← 1 mile →
π+ → μ+ νL
π- → μ- ν̄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p(+|a,λ) p(+|b,λ)
1 mile
a

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- Retrocausation $p(\lambda|a, b) \neq p(\lambda)$

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  - free will
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- Retrocausa

Automatic Updates

Updating your computer is almost complete. You must restart your computer for the updates to take effect.

Do you want to restart your computer now?

Restart Now | Restart Later

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  - probably amounts to a failure of separability

- Failure of separability
  - how to recover *macroscopic* separability?

History of nonlocality in realist theories

Einstein's Solvay argument, 1927
Einstein, Podolsky and Rosen, 1935

ψ-completeness + Q Statistics + local causality $\rightarrow$ contradiction

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John Bell, 1964

Q Statistics + local causality $\rightarrow$ Contradiction!

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John Bell, 1964

Q Statistics + local causality $\rightarrow$ Contradiction!

So locality can't be achieved for *any* of the alternatives!

Locality offers no verdict on ψ-complete vs. ψ-incomplete

When seeking a realist explanation of Bell's theorem, there is a tension between:

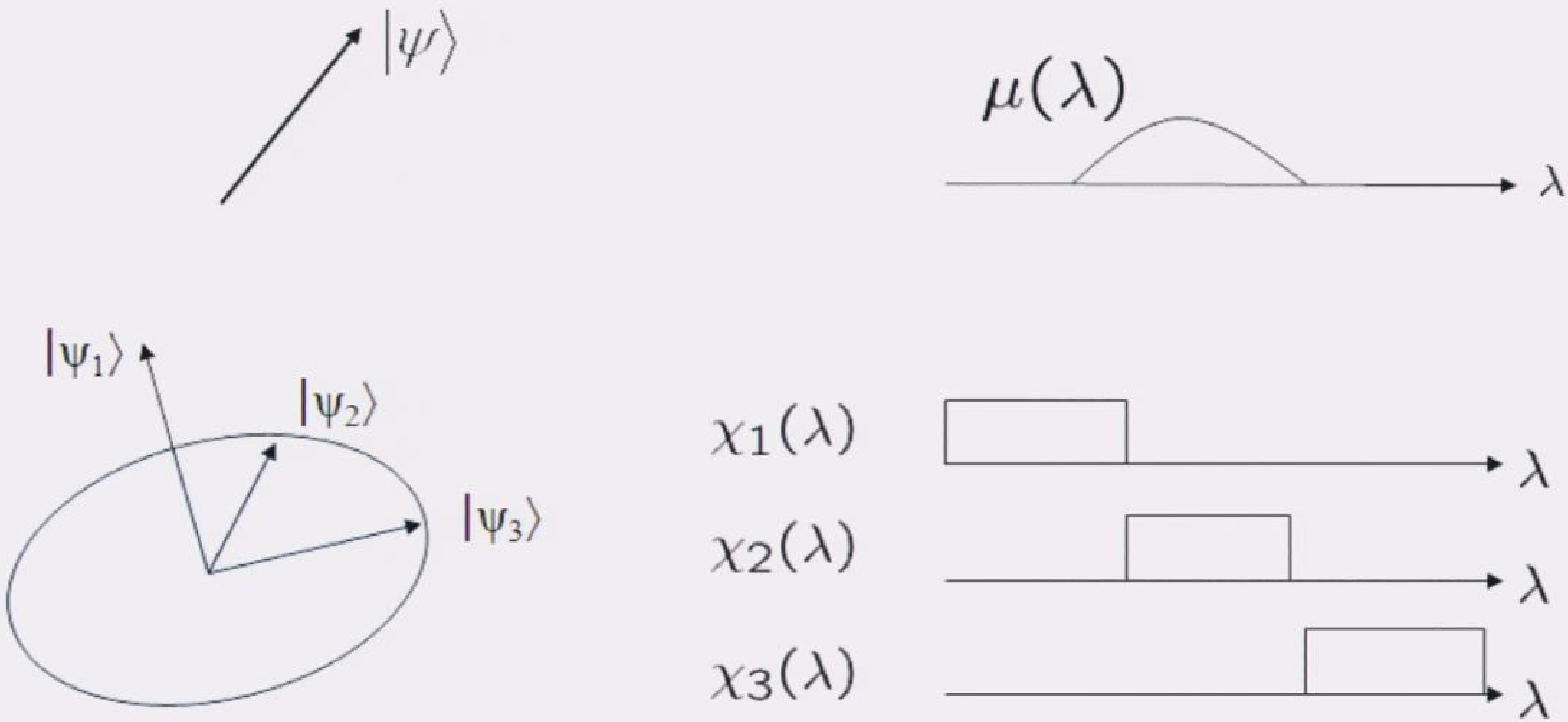
1) No superluminal signalling (independence of statistics at one wing on choice of measurement at the other)

2) The necessity of superluminal causation (dependence of particular outcomes at one wing on choice of measurement at the other)

Contextuality

The traditional notion

Deterministic hidden variable models

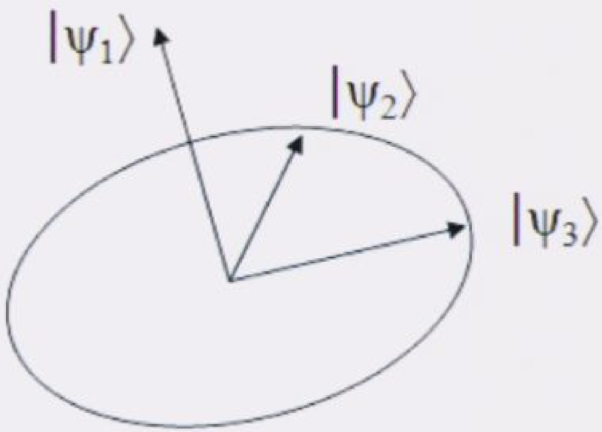


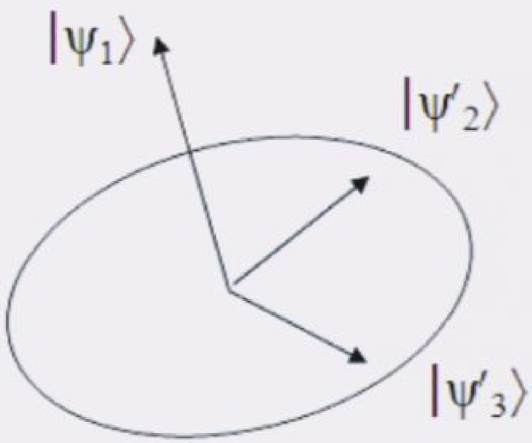
It is assumed that the outcomes are deterministic given

$$|\langle\psi|\chi_k\rangle|^2 = \int d\lambda \mu(\lambda)\chi_k(\lambda)$$

Traditional notion of noncontextuality

A given projector may appear in many different measurements





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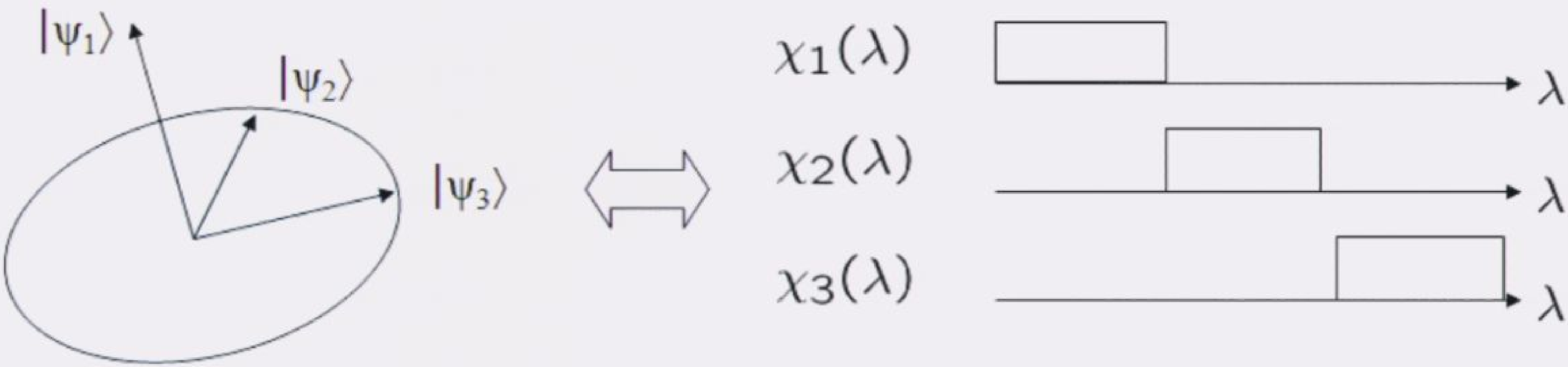
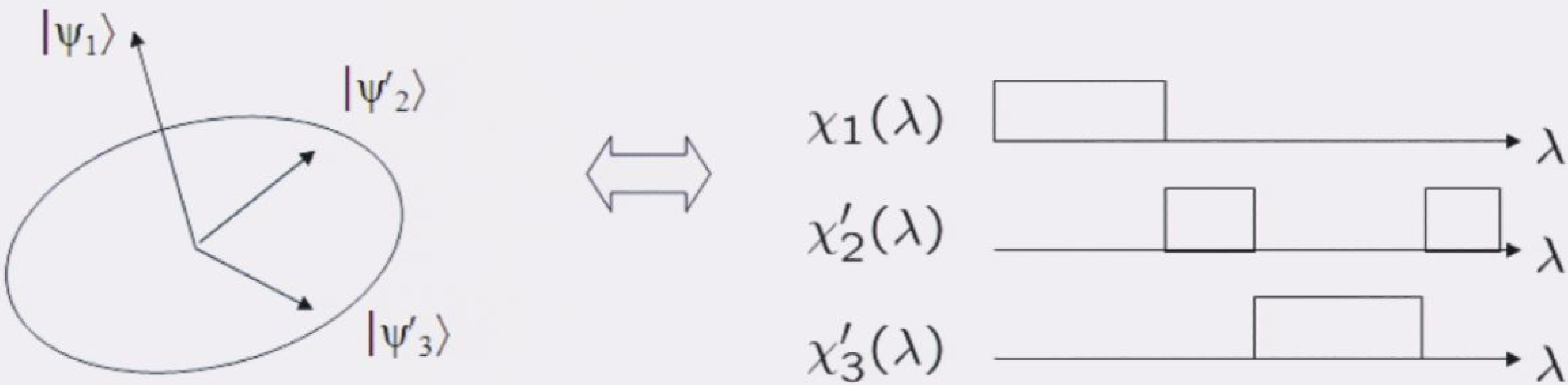


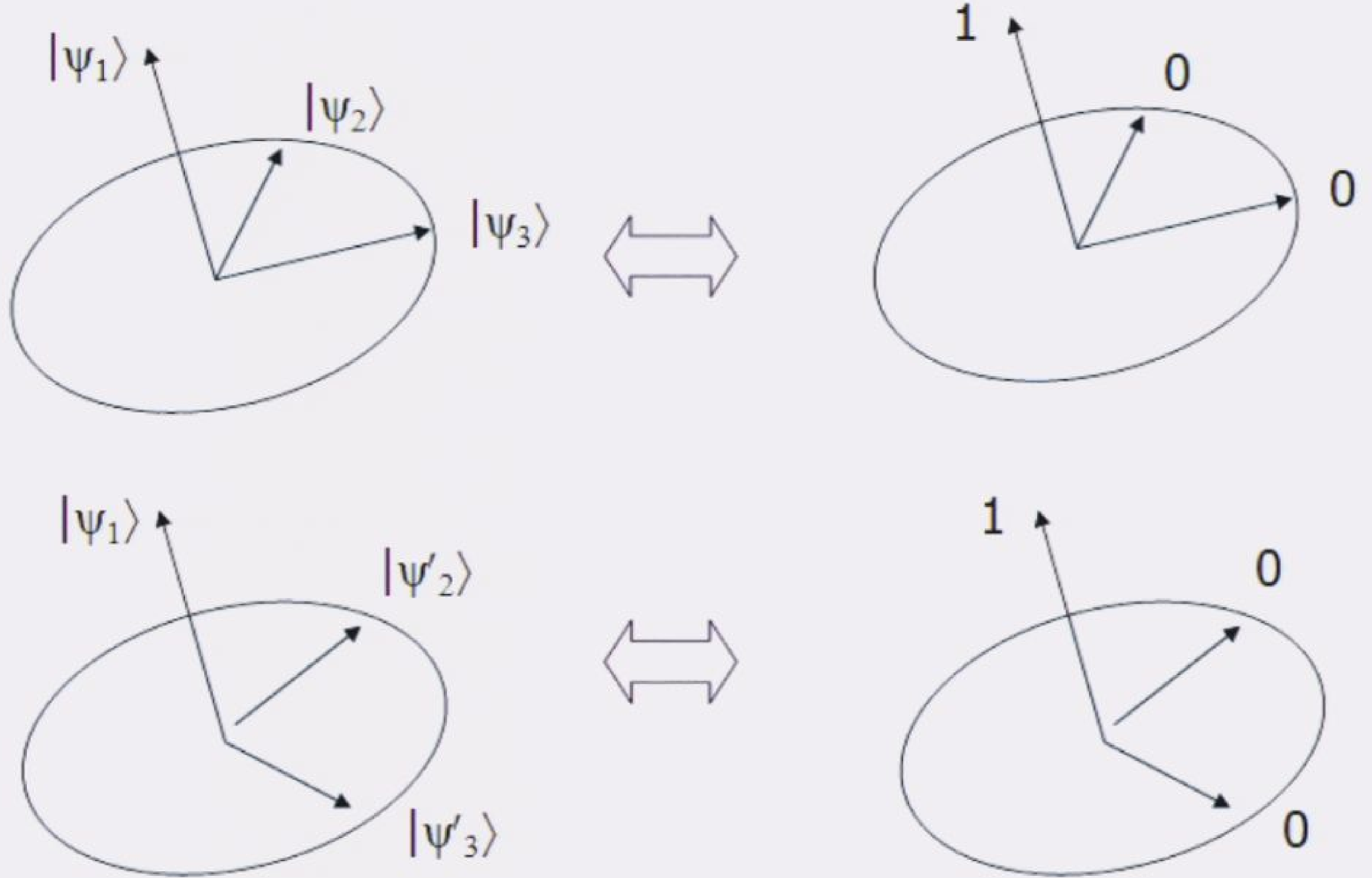


The traditional notion of noncontextuality:

Every projector P is associated with the same $\chi(\lambda)$

Alternatively,

$$\chi_\psi(\lambda) = 0 \text{ or } 1$$
$$\sum_k \chi_{\psi_k}(\lambda) = 1$$



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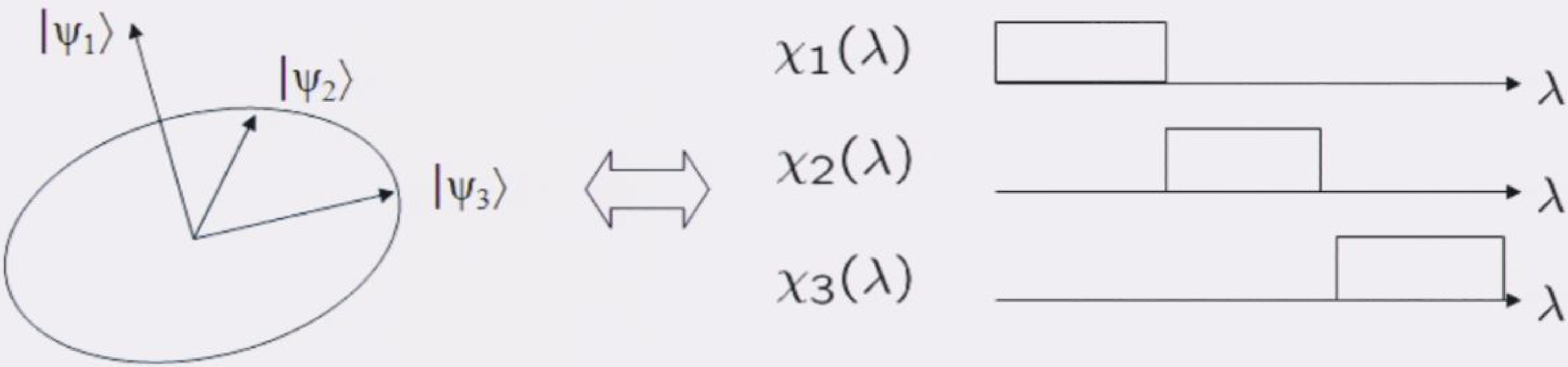

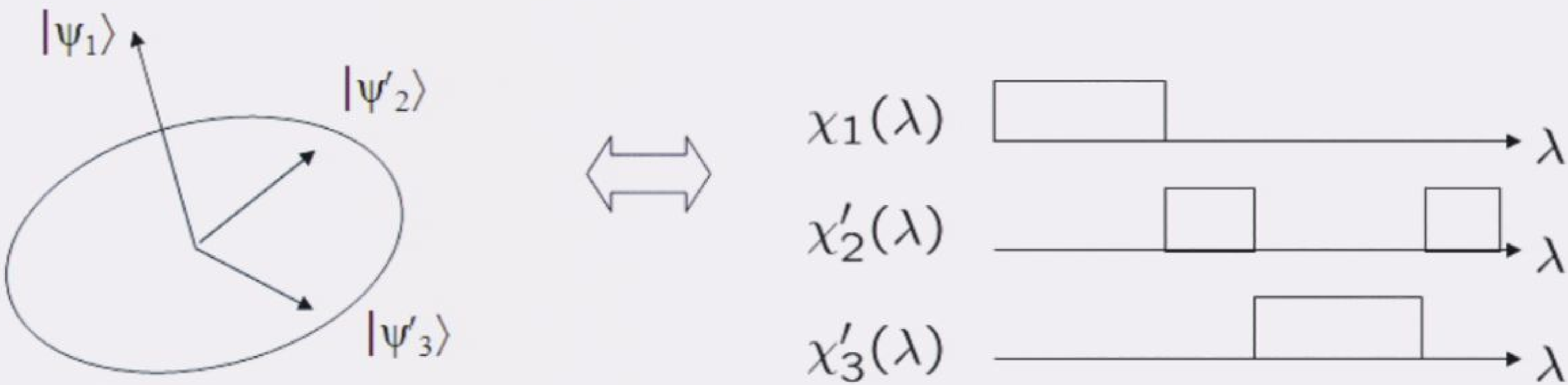

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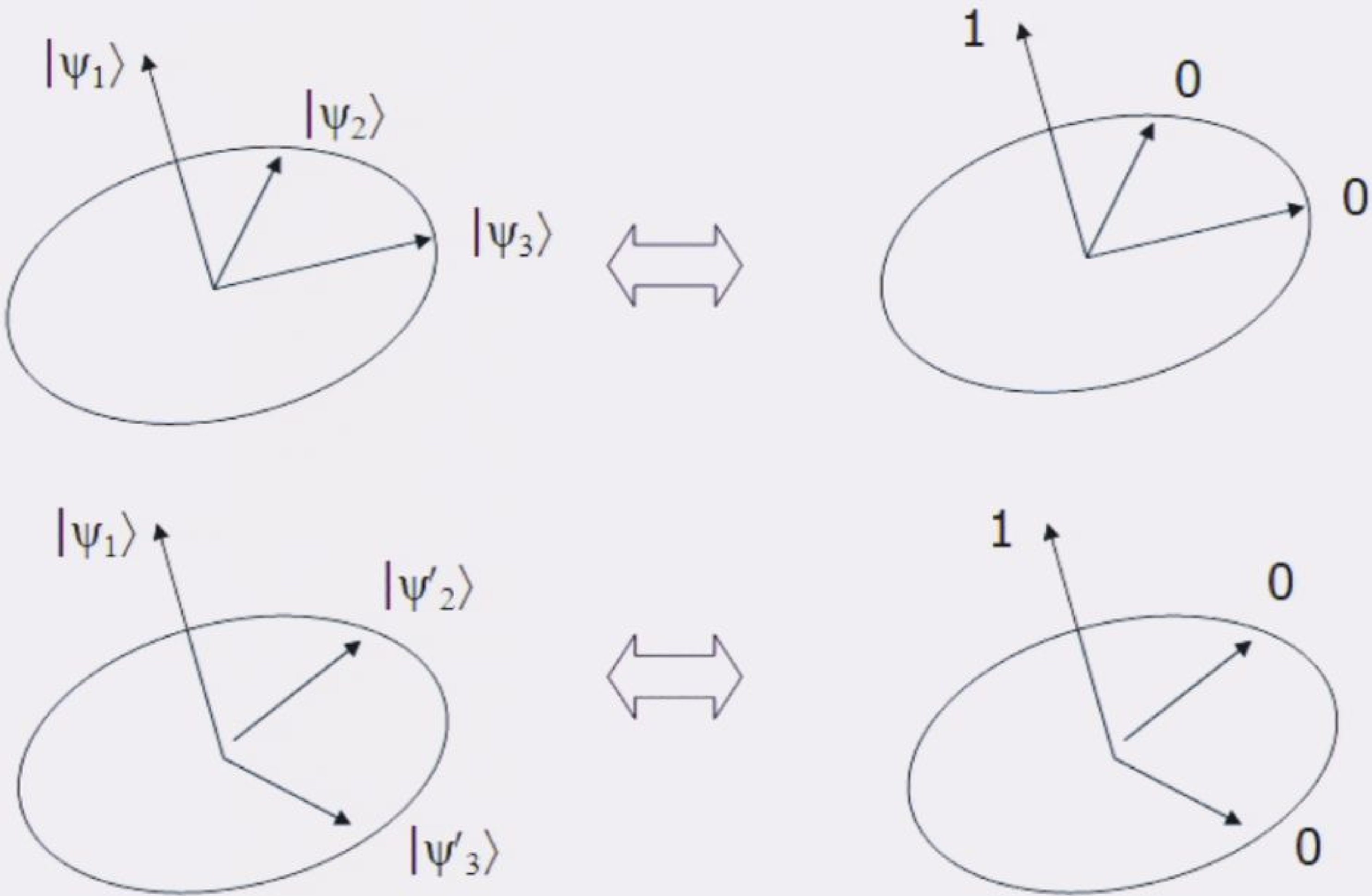

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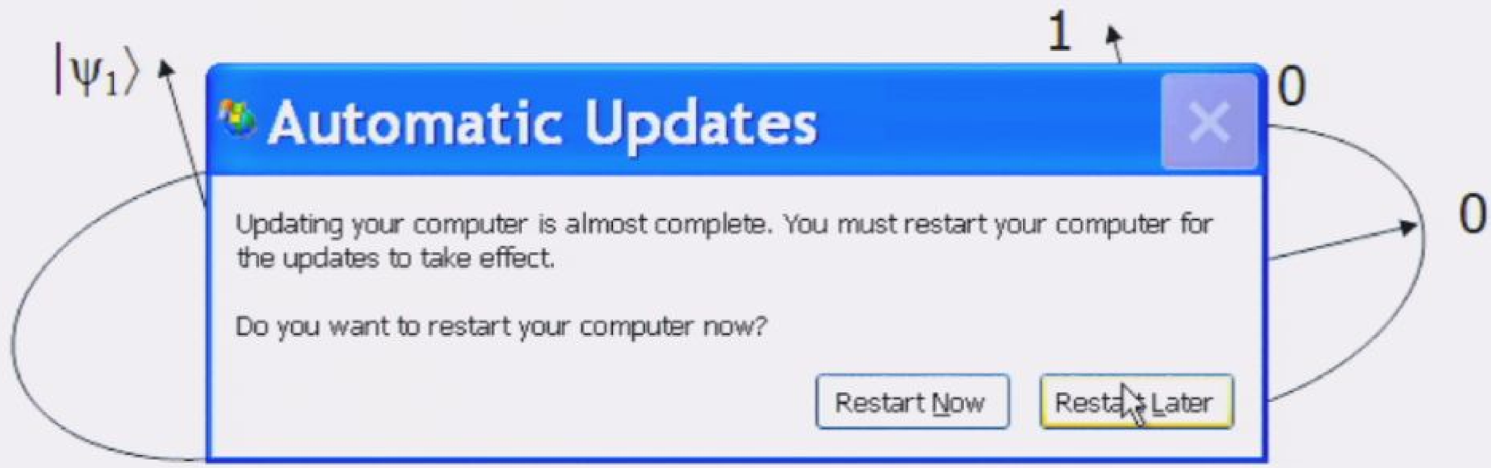

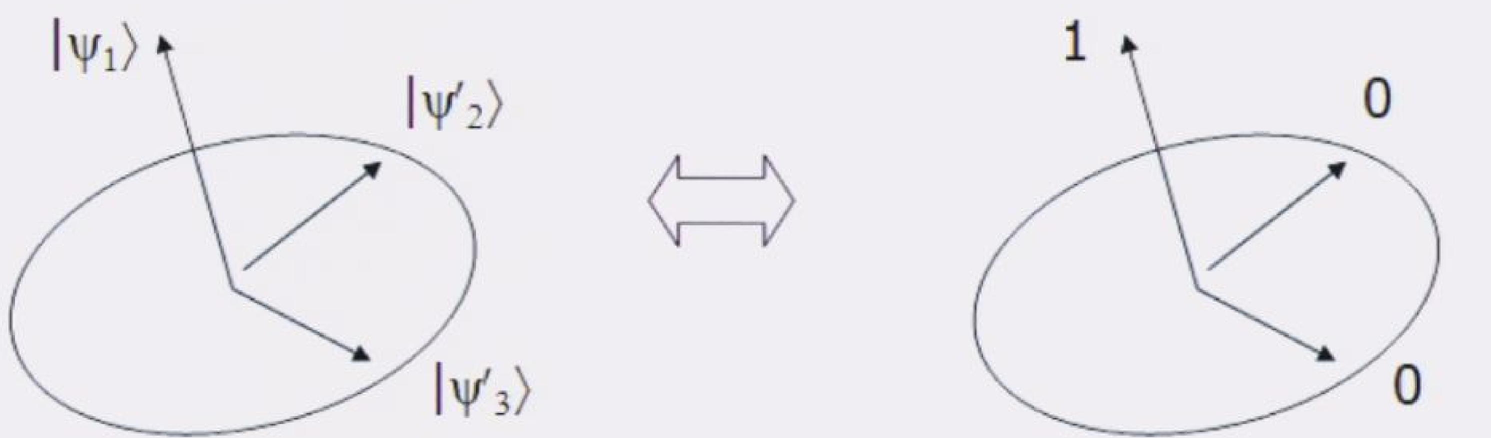

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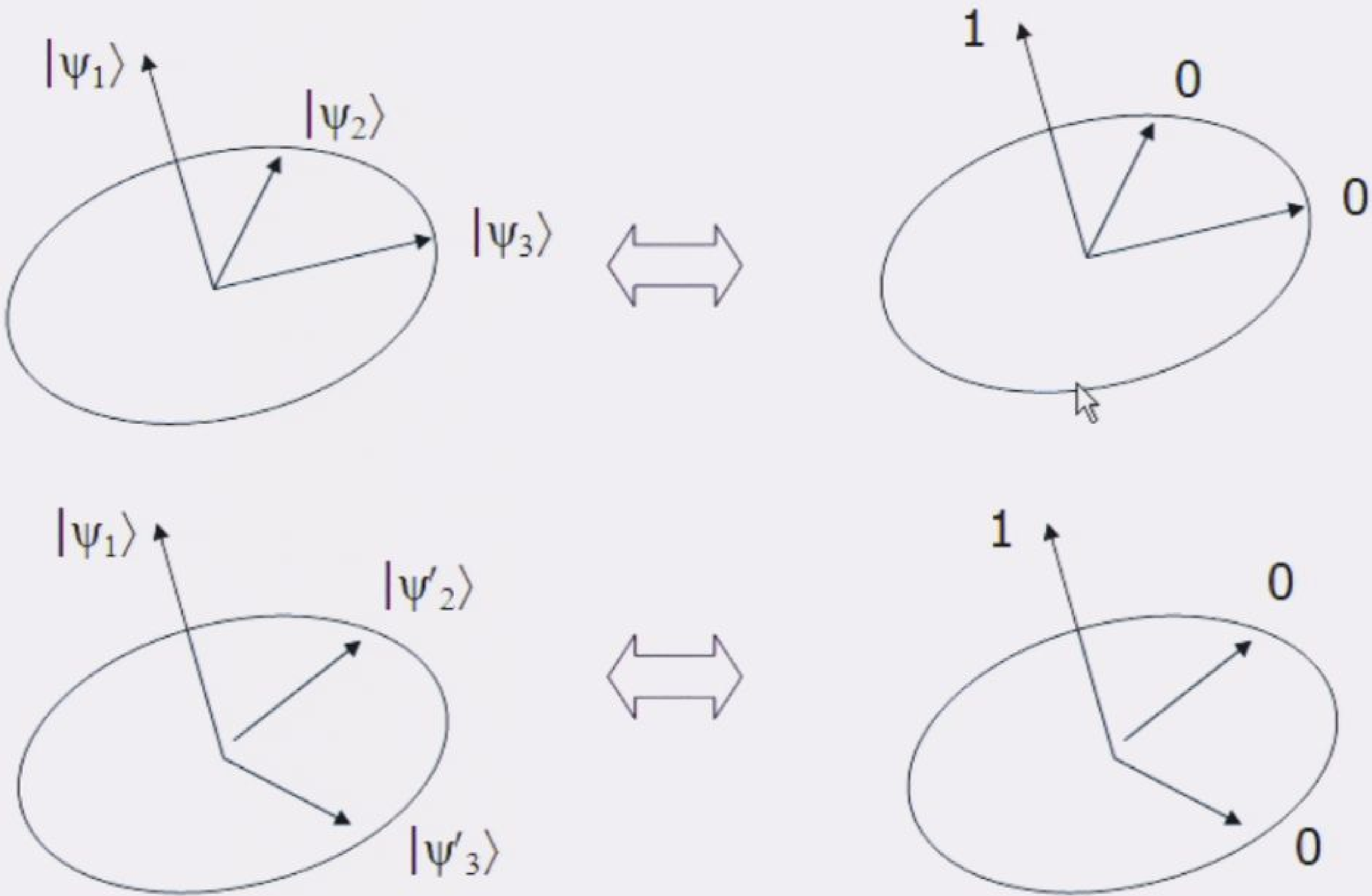


John S. Bell

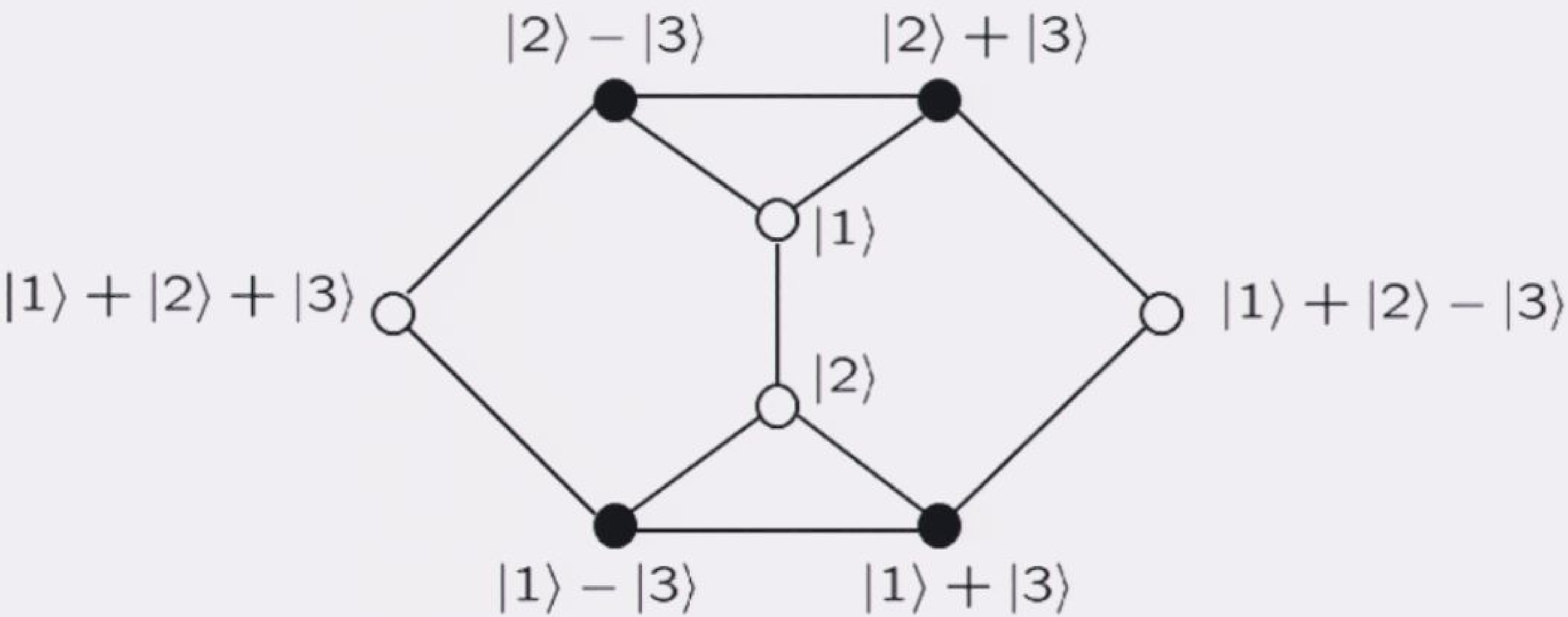
Ernst Specker (with son) and
Simon Kochen

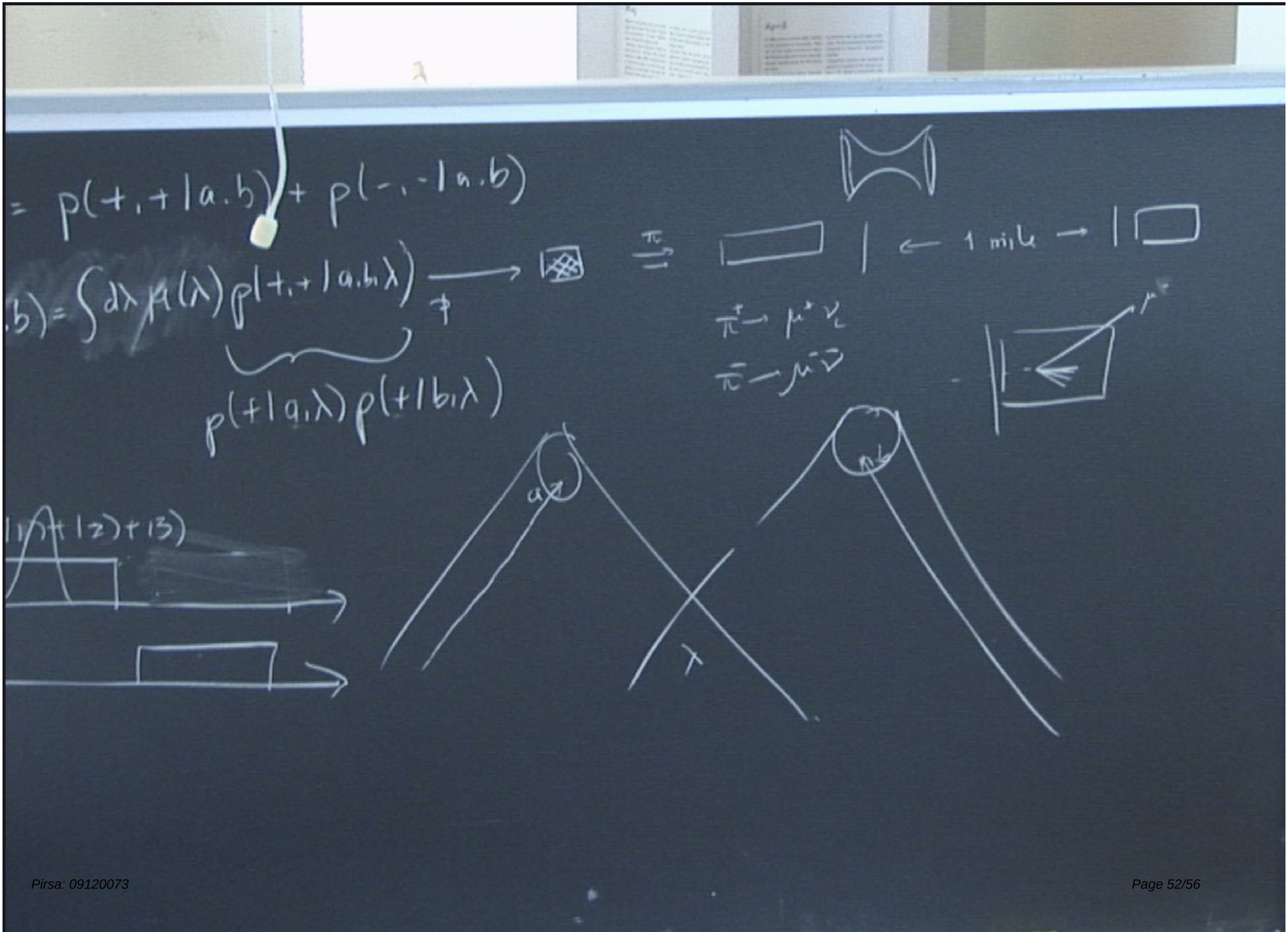
Bell-Kochen-Specker theorem: A noncontextual hidden variable model of quantum theory for Hilbert spaces of dimension 3 or greater is impossible.

Example (Clifton's statistical 8 ray proof in 3d):

$|\psi\rangle$ ○ $\longrightarrow \chi_{|\psi\rangle}(\lambda) = 1$

$|\psi\rangle$ ● $\longrightarrow \chi_{|\psi\rangle}(\lambda) = 0$

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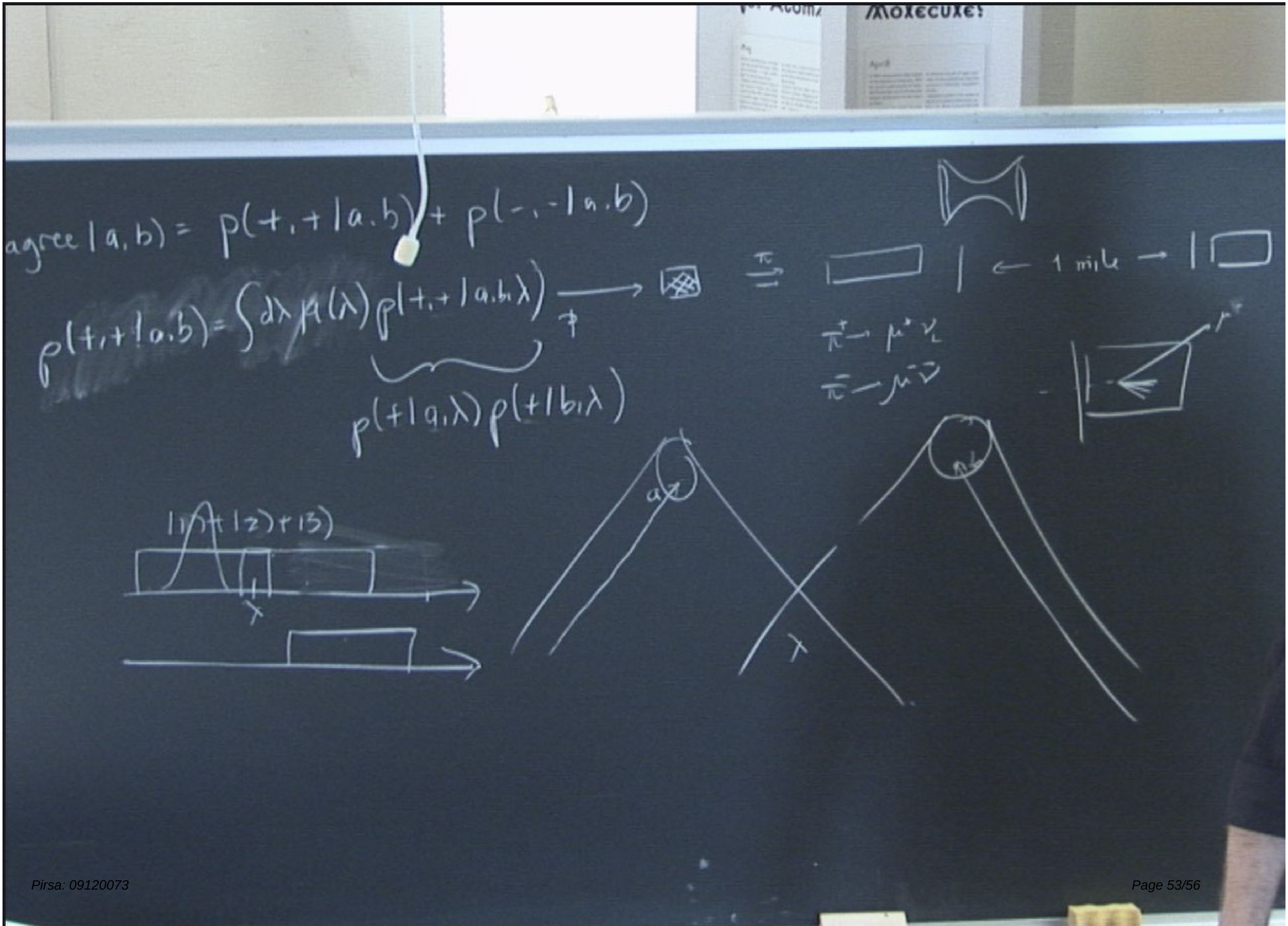
p(+|a,λ) p(+|b,λ)
← 1 mile →


agree | a, b) = p(+,+ | a.b) + p(-,- | a.b)
p(+,+ | a.b) = ∫dλ μ(λ) p(+,+ | a.b,λ)
p(+ | a,λ) p(+ | b,λ)
1 mile

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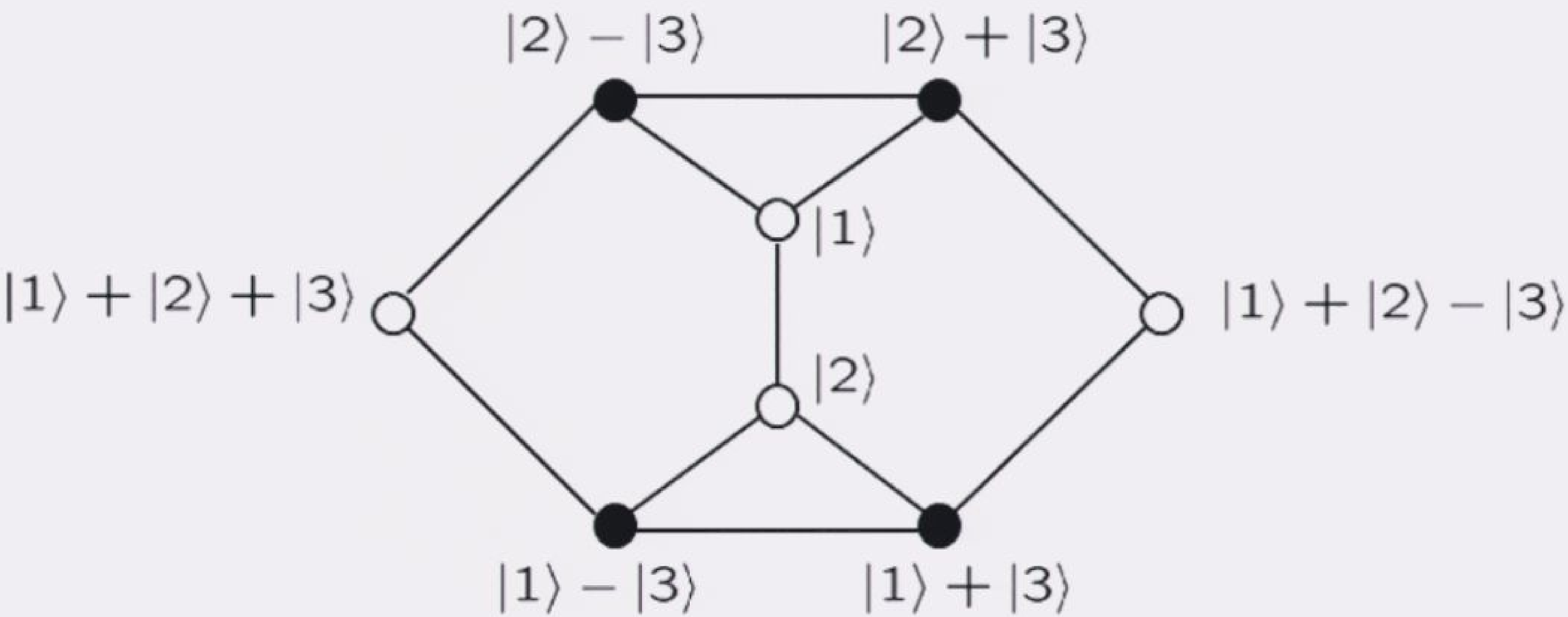

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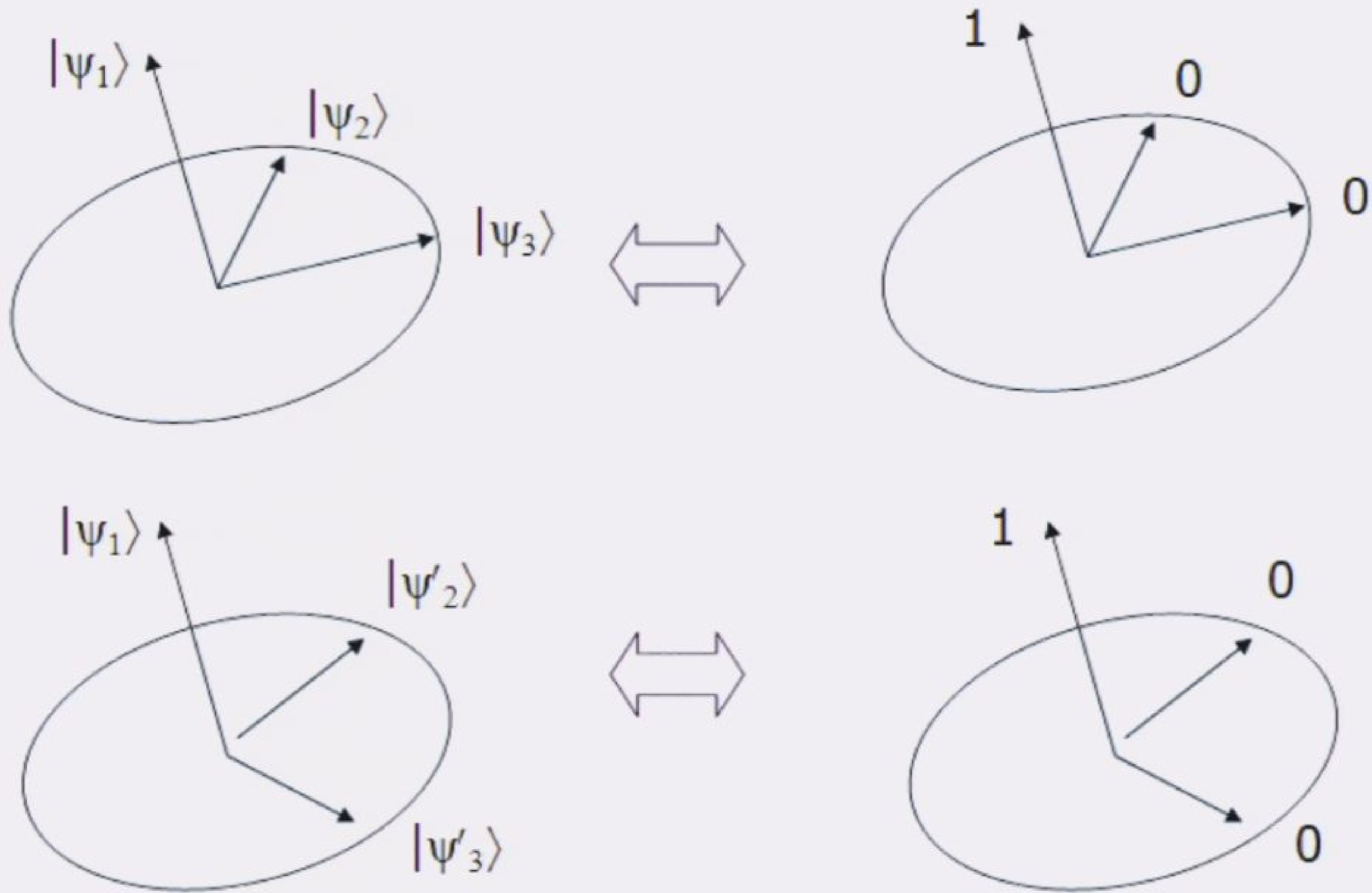

Traditional notion of noncontextuality

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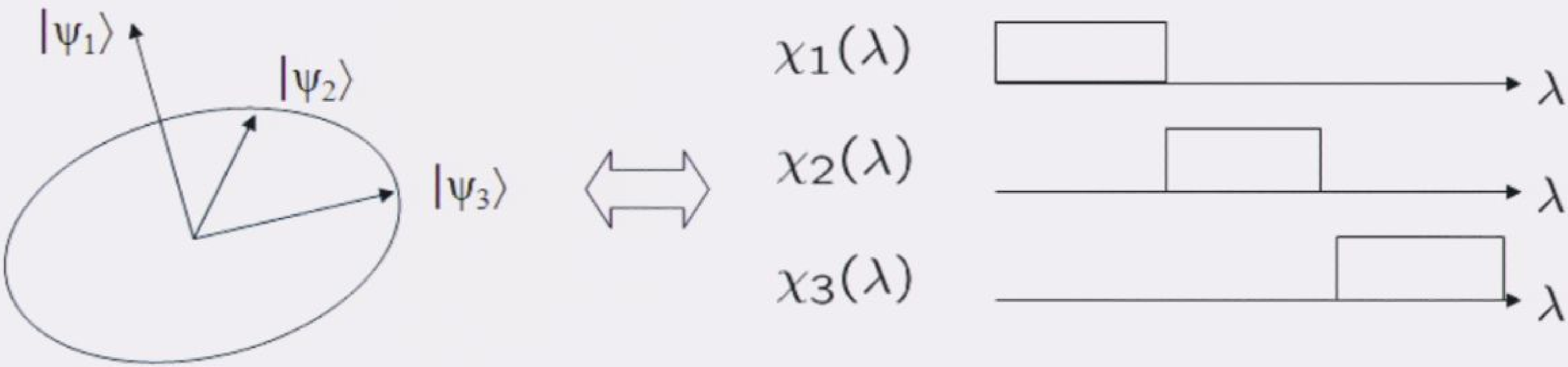

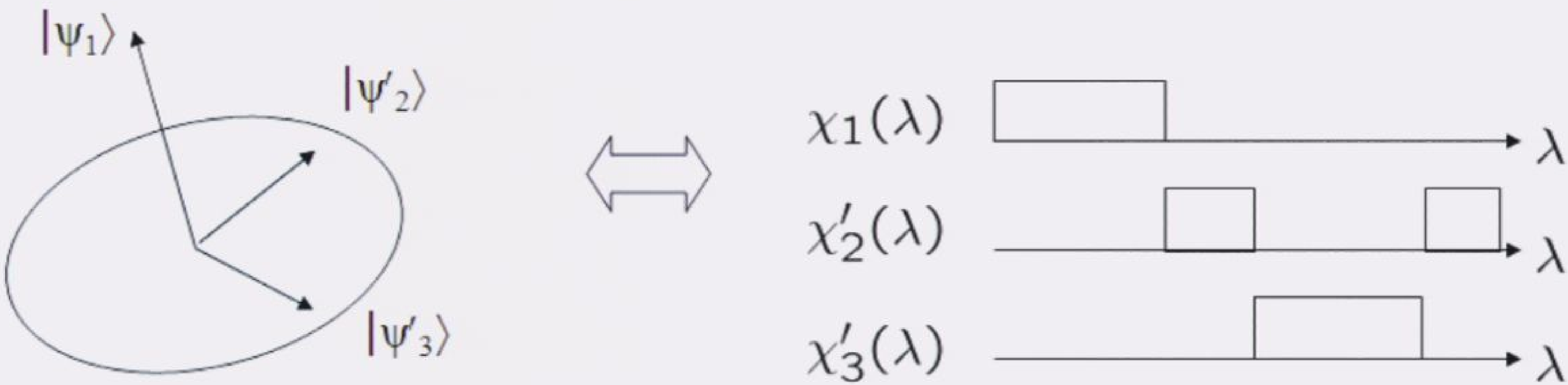

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