Title: Quantum Nonlocality Based on Finite-speed Causal Influences Leads to Superluminal Signalling

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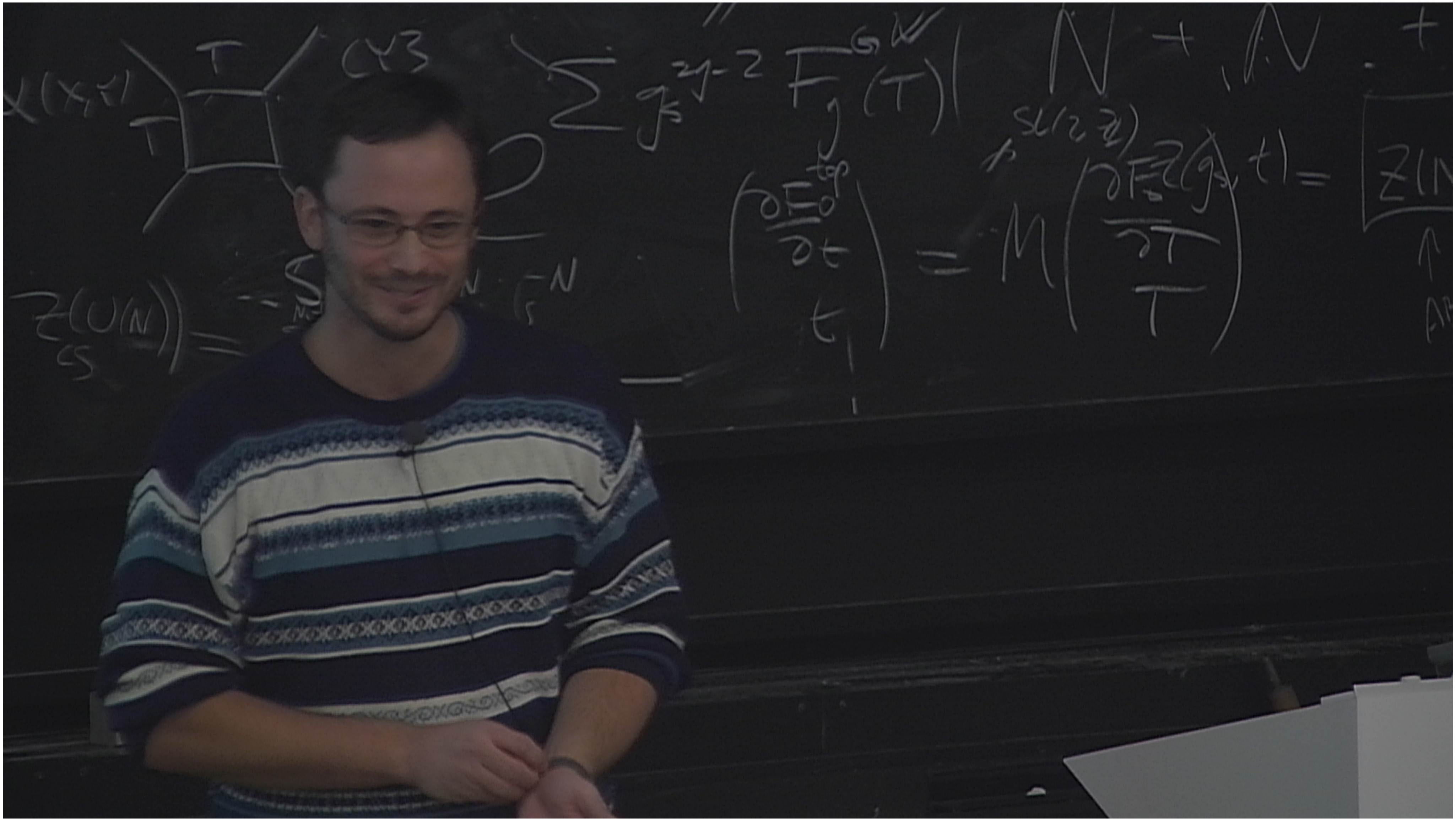
Abstract: The experimental violation of Bell inequalities using spacelike separated measurements precludes the explanation of quantum correlations through causal influences propagating at subluminal speed. Yet, it is always possible, in principle, to explain such experimental violations through models based on hidden influences propagating at a finite speed v>c, provided v is large enough. Here, we show that for any finite speed v>c, such models predict correlations that can be exploited for faster-than-light communication. This superluminal communication does not require access to any hidden physical quantities, but only the manipulation of measurement devices at the level of our present-day description of quantum experiments. Hence, assuming the impossibility of using quantum non-locality for superluminal communication, we exclude any possible explanation of quantum correlations in term of finite-speed influences.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QUANTUM NONLOCALITY BASED ON FINITE-SPEED CAUSAL INFLUENCES LEADS TO SUPERLUMINAL SIGNALING

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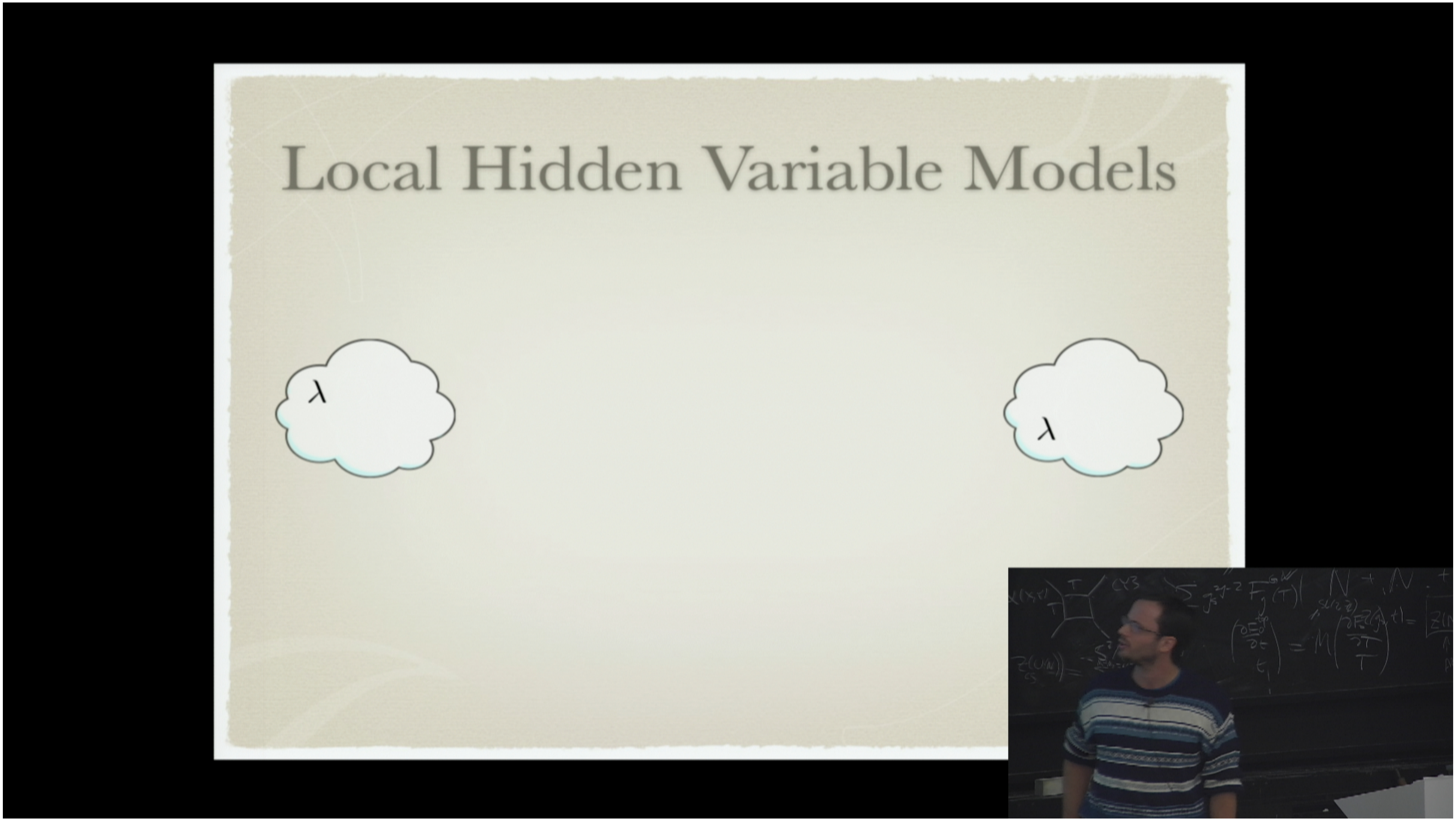
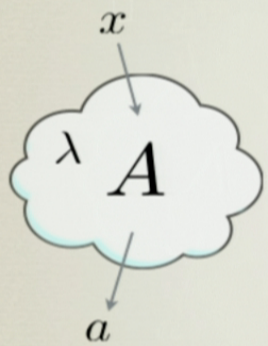
arXiv:1110.3795

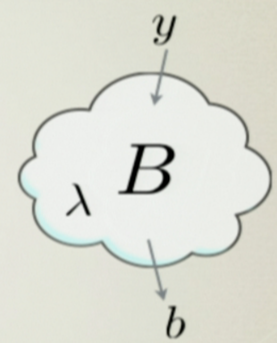

Local Hidden Variable Models
λ
λ

Local Hidden Variable Models

Local Hidden Variable Models

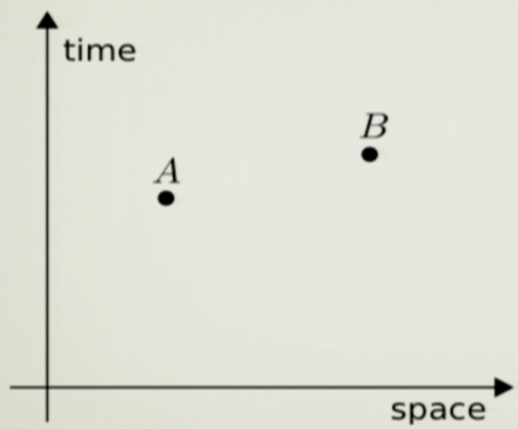


$$P(ab|xy) = \sum_{\lambda} q(\lambda) P(a|x\lambda) P(b|y\lambda)$$

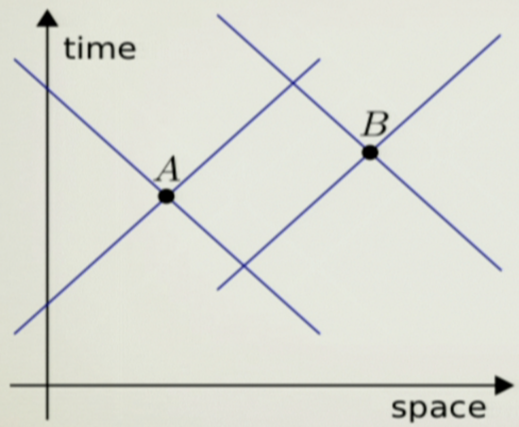


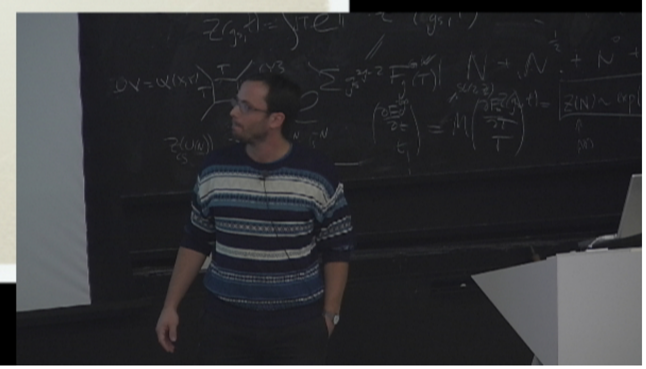
Separability condition => Bell inequalities

Experiment in space-time

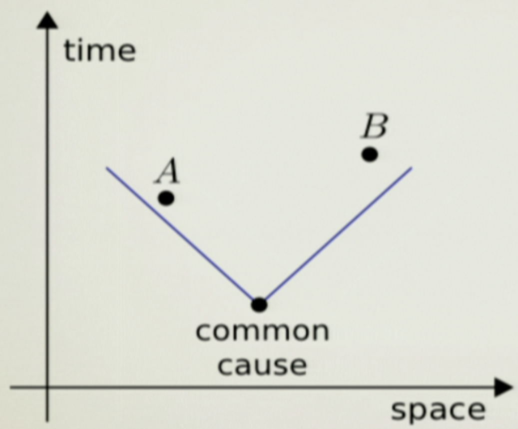


Experiment in space-time



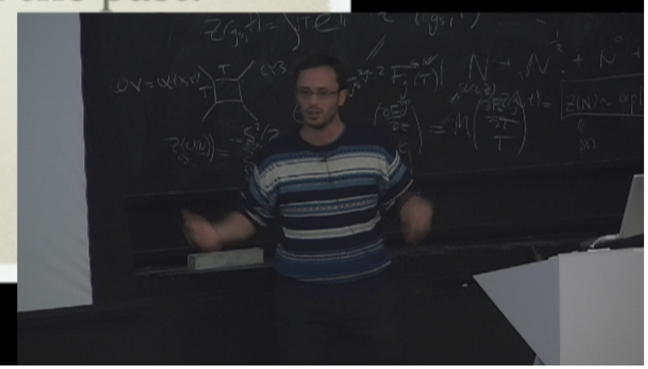


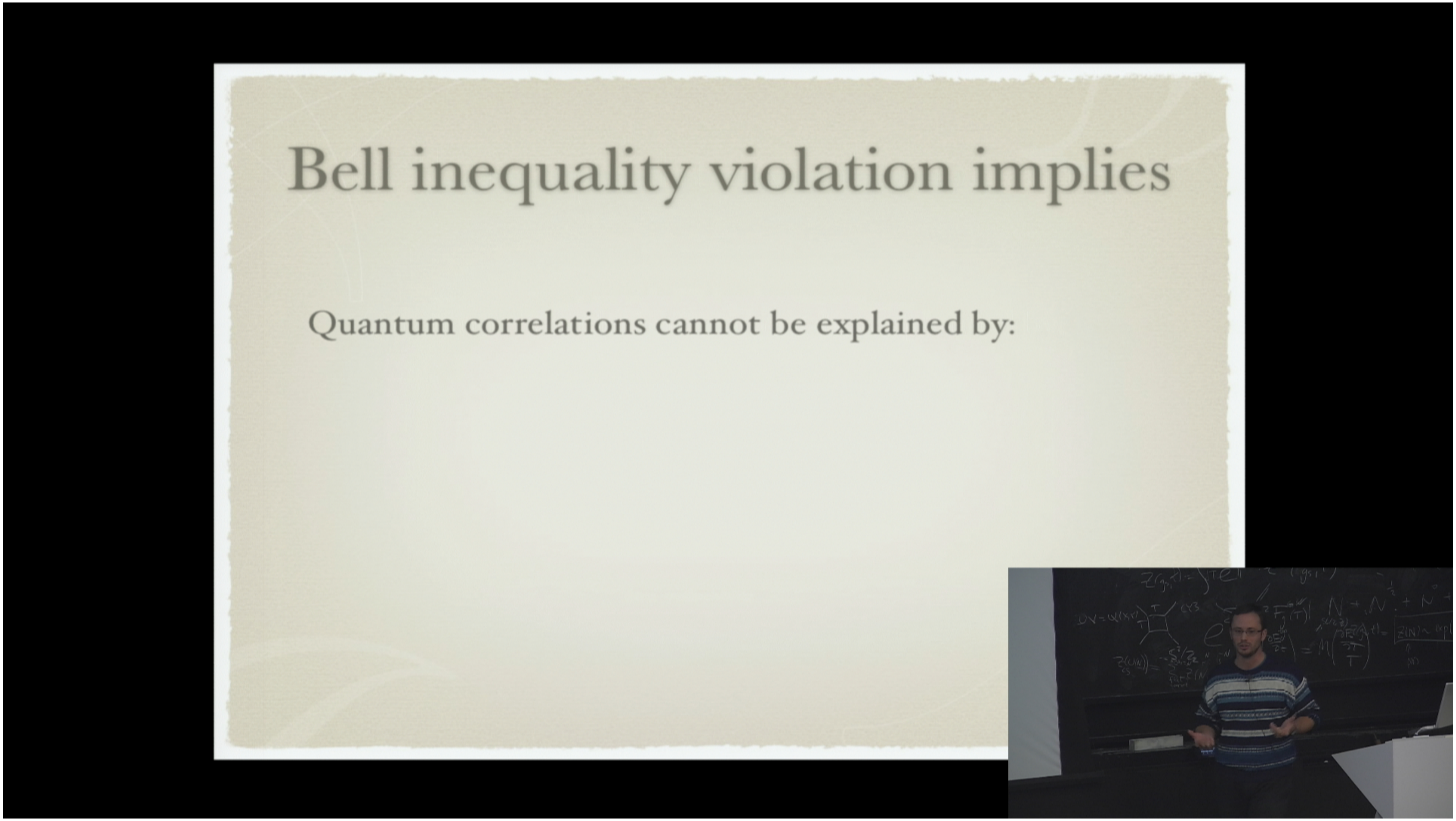
Experiment in space-time



Intuition:

If no information can be exchanged between A and B, correlations must have been prepared in the past.

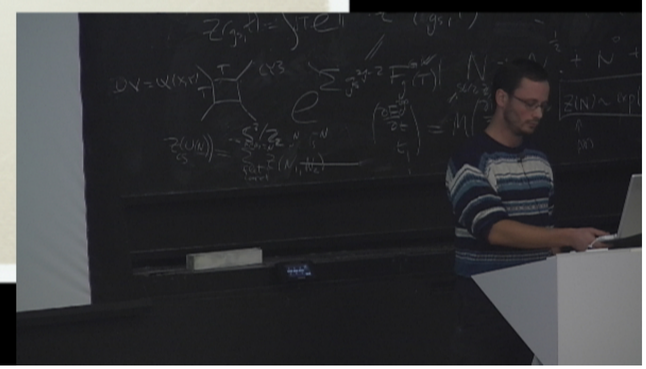



Bell inequality violation implies
Quantum correlations cannot be explained by:

Bell inequality violation implies

Quantum correlations cannot be explained by:

* Common causes
* Influences propagating slower than light



Bell inequality violation implies

Quantum correlations cannot be explained by:

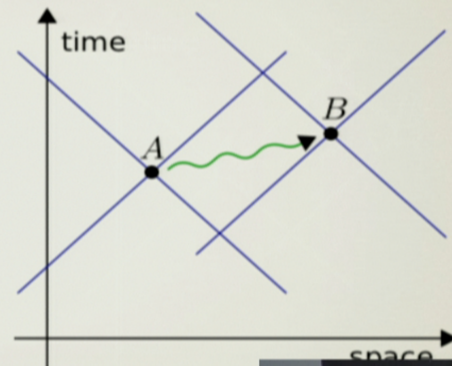
* Common causes
* Influences propagating slower than light

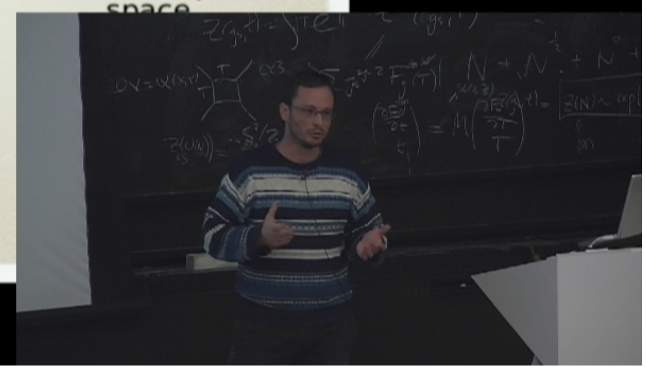
How should we understand the emergence of nonlocal correlations?

Superluminal influences

- Can explain all experimental results with v large enough
- Formalizable in a preferred reference frame
- Need not violate the no-signaling conditions:

$$\sum_b P(ab|xy) = P(a|x) \; \forall y$$



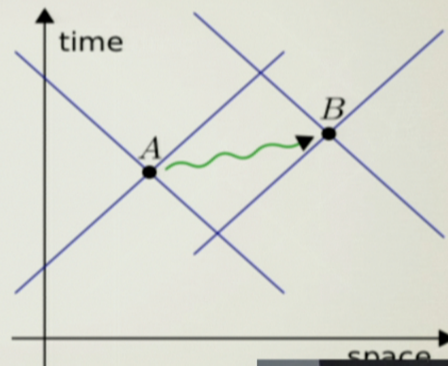


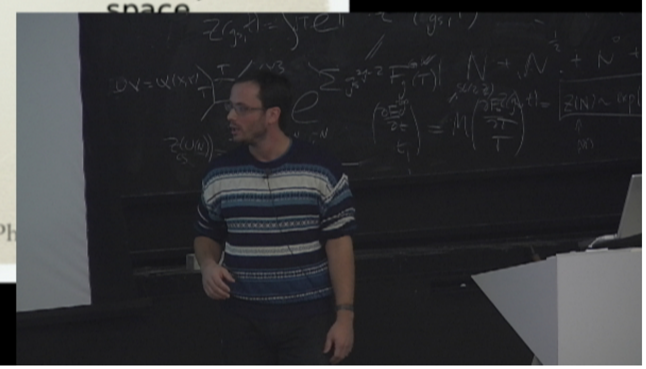
Superluminal influences

* Can explain all experimental results with v large enough
* Formalizable in a preferred reference frame
* Need not violate the no-signaling conditions:

$$\sum_b P(ab|xy) = P(a|x)\ \forall y$$

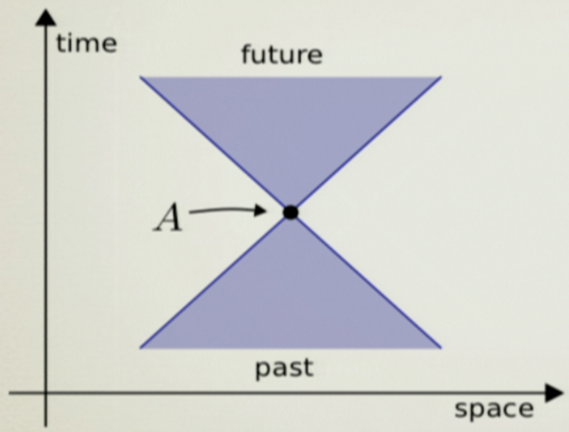
* Experiments* imply v > 10'000 c

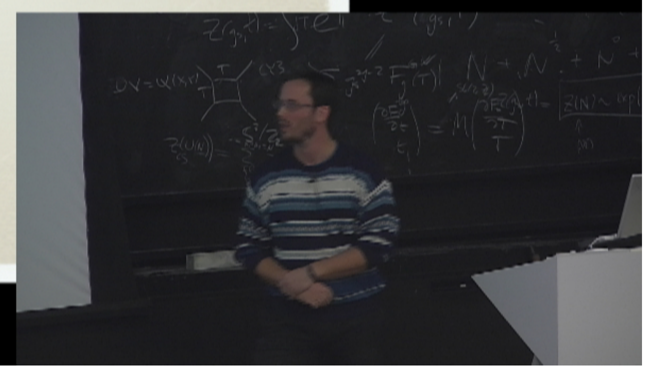




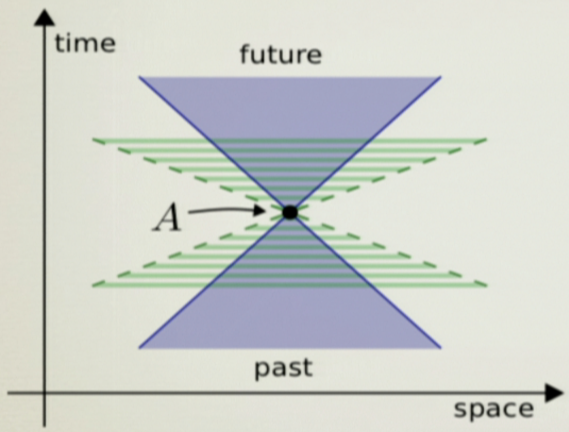
* D. Salart, et al, Nature 454, 861 (2008) and B. Cocciaro et al, Ph

v-Causal Model



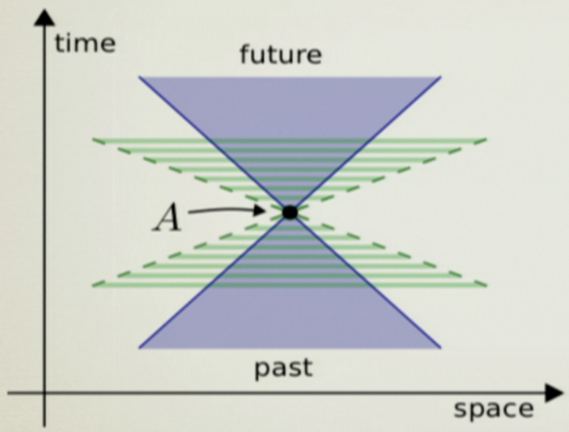


v-Causal Model



* **v-cones** define possible zones of influence

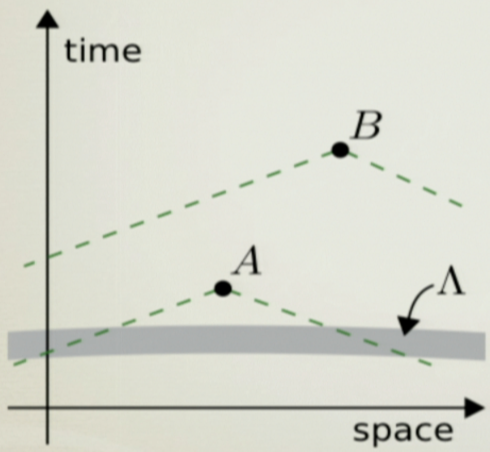
v-Causal Model

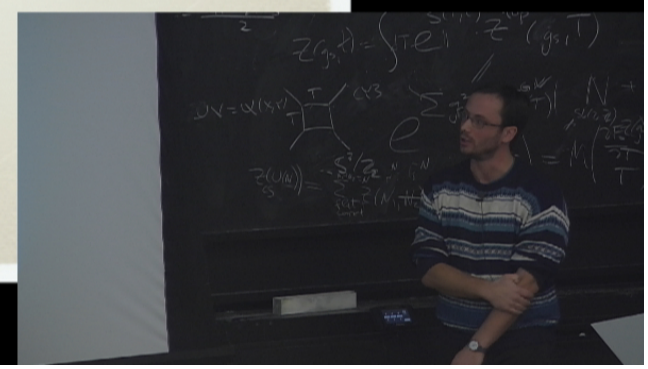


- v-cones define possible zones of influence
- Model involves finite-speed influences
- An event can only depend on the content of its past v-cone

v-Causal Model

A < B :





v-Causal Model

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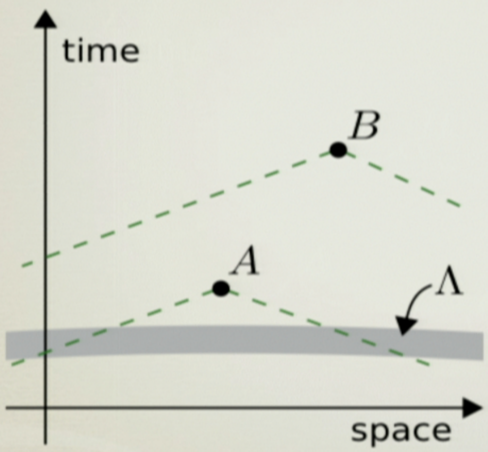
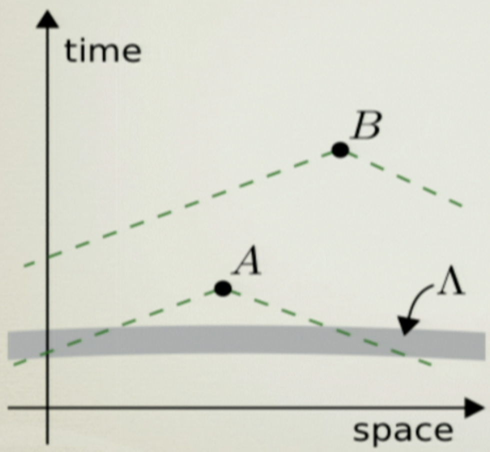


$$P(ab|xy) = \sum_\lambda q(\lambda)P(ab|xy\lambda)$$
$$= \sum_\lambda q(\lambda)P(a|x,y\lambda)P(b|y,ax\lambda)$$
$$= \sum_\lambda q(\lambda)P(a|x\lambda)P(b|y,ax\lambda)$$

v-Causal Model

A < B :

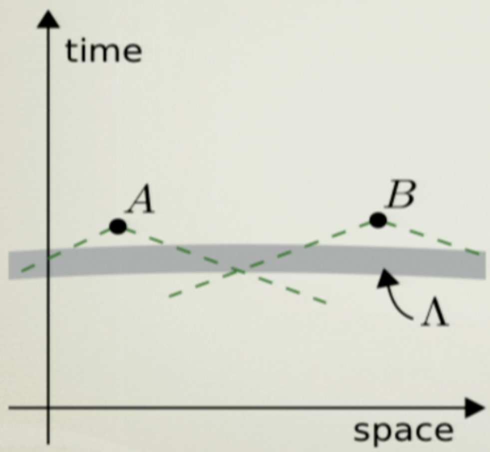


$$
\begin{aligned}
P(ab|xy) &= \sum_\lambda q(\lambda) P(ab|xy\lambda) \\
&= \sum_\lambda q(\lambda) P(a|x, y\lambda) P(b|y, ax\lambda) \\
&= \sum_\lambda q(\lambda) P(a|x\lambda) P(b|y, ax\lambda)
\end{aligned}
$$

Any no-signaling correlation can be reproduced in this way

v-Causal Model

A ~ B :



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$$= \sum_\lambda q(\lambda) P(a|x\lambda) P(b|y\lambda)$$

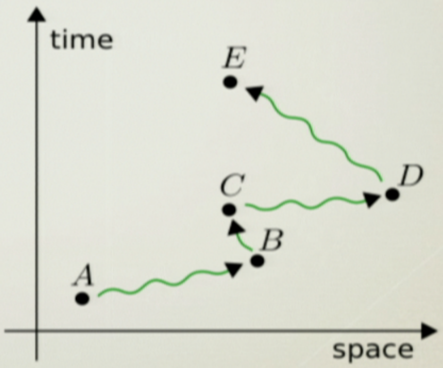
Separability condition
=> local correlations

v-Causal Model for Quantum Correlations

* When a chain of influence goes through all parties, the model reproduces the expected correlations:

$$T = (A < B < C < D < E)$$

$$\Rightarrow \; P_T = P_Q$$



v-Causal Model for Quantum Correlations

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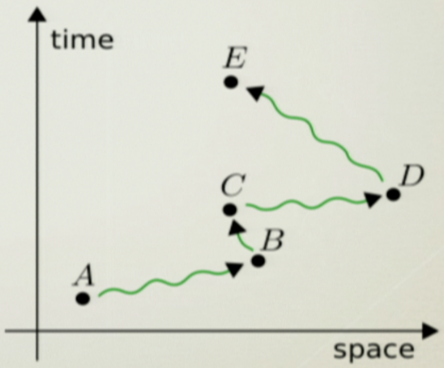
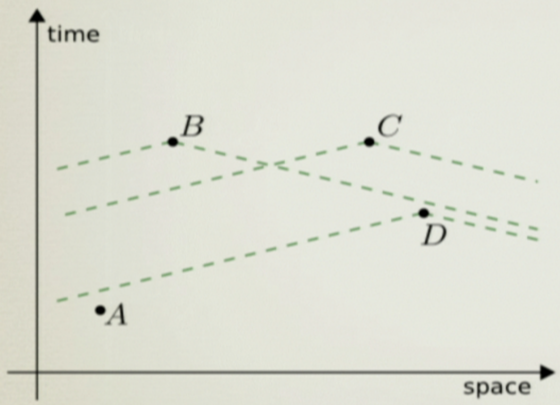
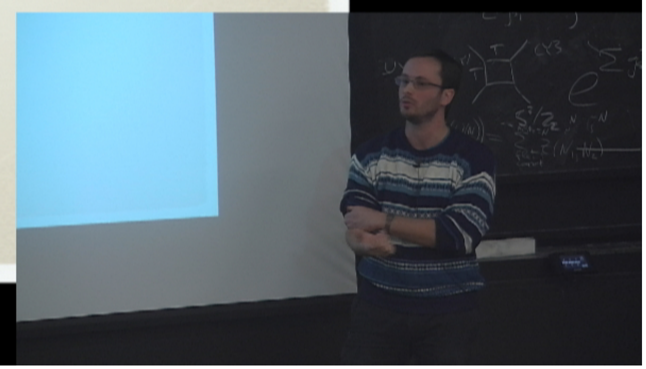


* Otherwise, the model needs not reproduce the expected correlations.

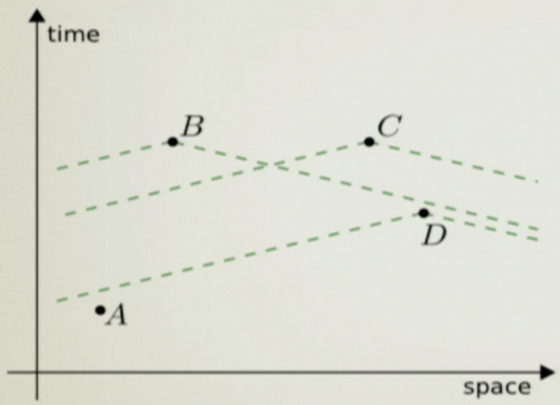
A Particular Scenario



* 4-partite experiment
* $R = (A < D < (B \sim C))$

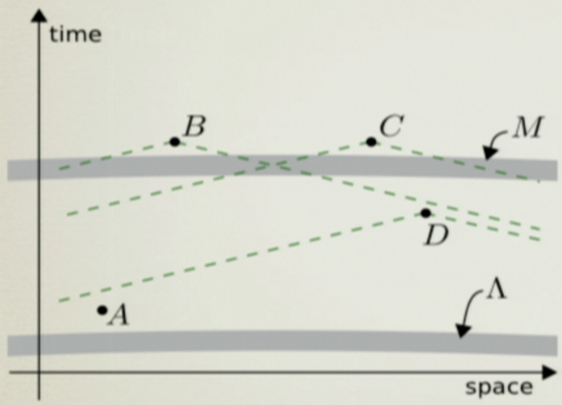


A Particular Scenario



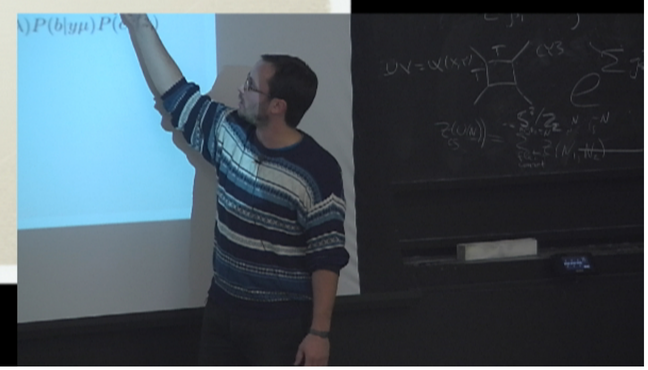
* 4-partite experiment
* $R = (A < D < (B \sim C))$
* We will show that:
  - $BC|AD$ is local
  - the ABD and ACD marginals are quantum

A Particular Scenario

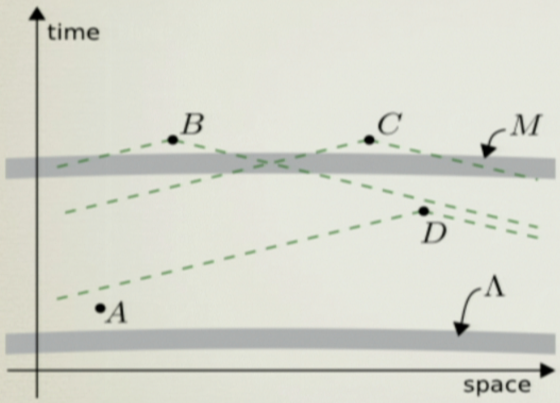


General correlation:

$$P_R(abcd|xyzw)$$
$$= \sum_\lambda q(\lambda)P(a|x\lambda)P(d|w\lambda, ax)$$
$$\times \sum_\mu q(\mu|axdw\lambda)P(b|y\mu)P(c|z\mu)$$



A Particular Scenario



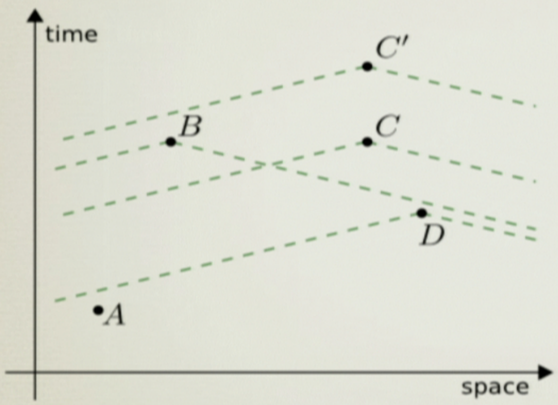
General correlation:

$$P_R(abcd|xyzw) = \sum_\lambda q(\lambda) P(a|x\lambda) P(d|w\lambda, ax) \times \sum_\mu q(\mu|axdw\lambda) P(b|y\mu) P(c|z\mu)$$

$BC|AD$ is local:

$$P_R(bc|yz, axdw) = \frac{P_R(abcd|xyzw)}{P_R(ad|xw)} = \sum_\mu \tilde{q}(\mu|axdw) P(b|y\mu) P(c|z\mu)$$

A Particular Scenario

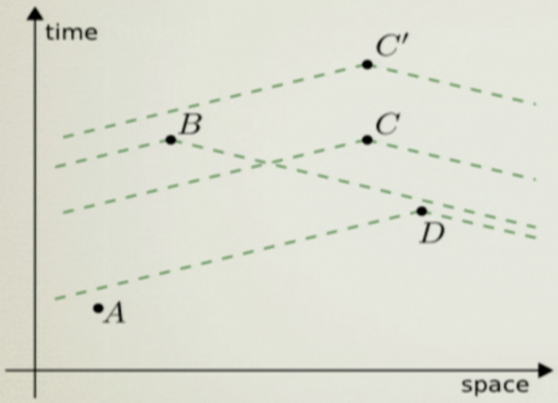


The ABD marginal is quantum:

$$T = (A < D < B < C')$$

$$P_T = P_Q$$

A Particular Scenario



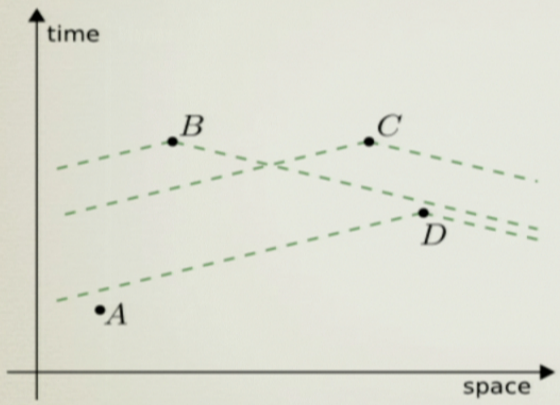
The ABD marginal is quantum:

$$T = (A < D < B < C')$$

$$P_T = P_Q$$

$$P_R^{ABD} = P_T^{ABD}$$

A Particular Scenario



In this situation, any v-causal model for quantum correlations satisfies:

- $BC|AD$ is local
- the ABD and ACD marginals are quantum

Lemma

In a 4-partite scenario with binary inputs and outputs, if

- The conditional $BC|AD$ marginal $P(bc|yz, axdw)$ is local
- The correlations satisfy the no-signaling conditions

The inequality $\langle S \rangle \leq 7$ holds for

$$
\begin{aligned}
S = & - 3A_0 - B_0 - B_1 - C_0 - 3D_0 - A_1B_0 - A_1B_1 + A_0C_0 \\
& + 2A_1C_0 + A_0D_0 + B_0D_1 - B_1D_1 - C_0D_0 - 2C_1D_1 \\
& + A_0B_0D_0 + A_0B_0D_1 + A_0B_1D_0 - A_0B_1D_1 - A_1B_0D_0 \\
& - A_1B_1D_0 + A_0C_0D_0 + 2A_1C_0D_0 - 2A_0C_1D_1
\end{aligned}
$$

Sketch of the Proof

By no-signaling we have:

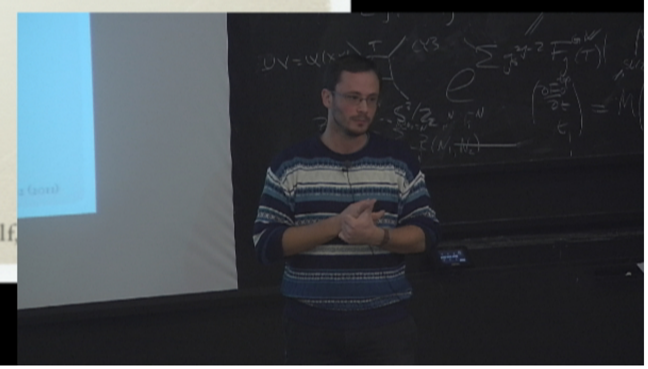
$$\begin{aligned}\frac{7-\langle S\rangle}{8} &= P(1000|0000) + P(0001|0010) + P(0011|0011)\\ &+ P(0100|0011) + P(1000|0100) + P(0011|0110)\\ &+ P(0000|0111) + P(0111|0111) + P(0010|1000)\\ &+ P(1100|1000) + P(0010|1100) + P(1100|1100)\\ &+ P_{BC|AD}(11|00,0000) + P_{BC|AD}(00|01,0000)\\ &+ P_{BC|AD}(00|10,0000) - P_{BC|AD}(00|11,0000) \geq 0\end{aligned}$$

Quantum violation

* The value $\langle S \rangle \simeq 7.3$ can be achieved by measuring a 4-qubit state
* One of the hypotheses of the lemma must be wrong:

$BC|AD$ is nonlocal

See also S. Coretti, E. Hänggi, S. Wolf



Quantum violation

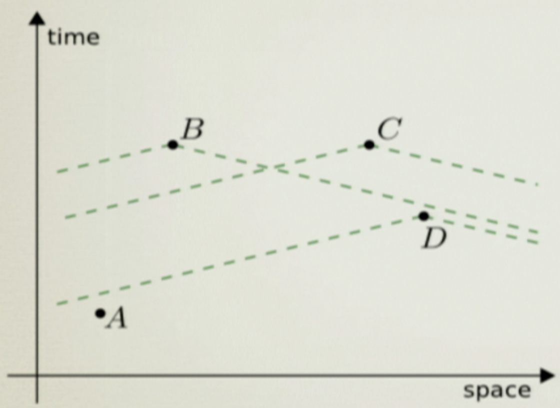
* The value $\langle S \rangle \simeq 7.3$ can be achieved by measuring a 4-qubit state
* One of the hypotheses of the lemma must be wrong:

$BC|AD$ is nonlocal | $P(abcd|xyzw)$ is signaling

* S only involves ABD and ACD marginals

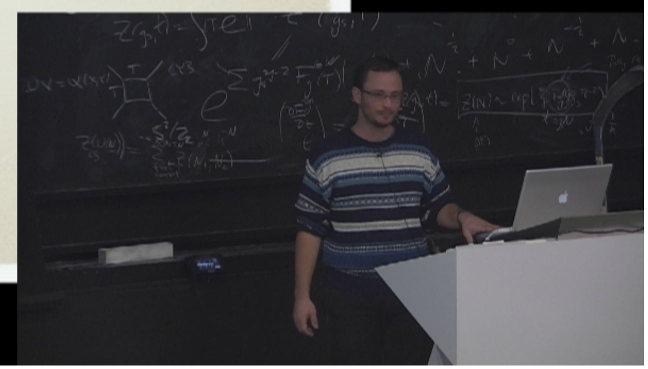
See also S. Coretti, E. Hänggi, S. Wolf, PRL 107, 100402 (2011)

Where is the signaling?

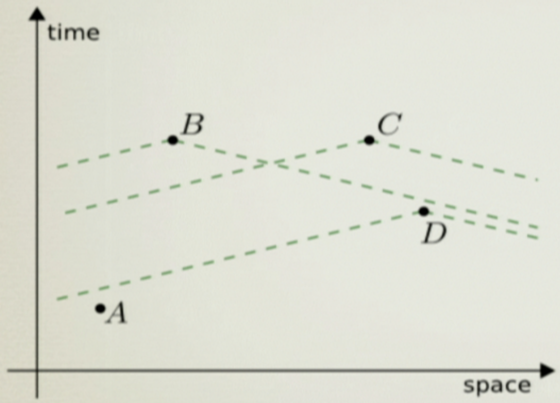


* No-signaling conditions:

$$\sum_d P(abcd|xyzw) = P(abc|xyz)$$



Where is the signaling?

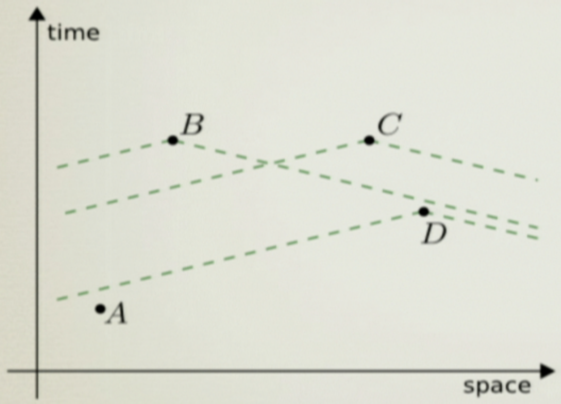


* No-signaling conditions:

$$\sum_d P(abcd|xyzw) = P(abc|xyz)$$

* ABD and ACD defined independently of z and y.

Where is the signaling?



* No-signaling conditions:

  $\sum_d P(abcd|xyzw) = P(abc|xyz)$

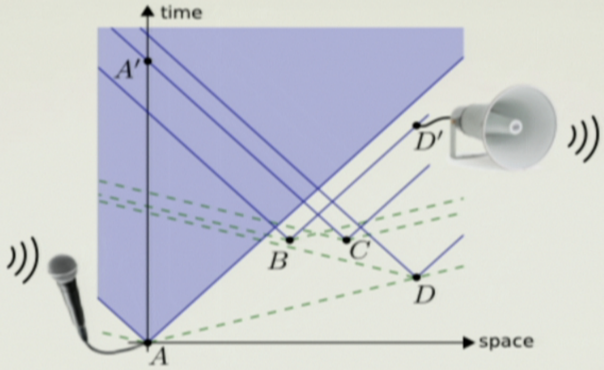
* ABD and ACD defined independently of z and y.

* One of the two:

  $A \to BCD$

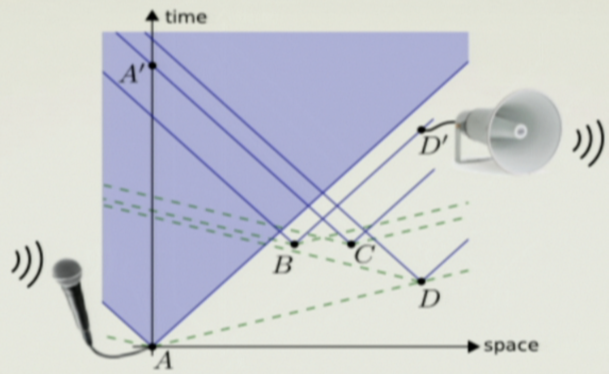
  $D \to ABC$

Detecting signaling



With light-speed communication, the signaling marginal can be evaluated outside of the fourth party's lightcone.

Detecting signaling



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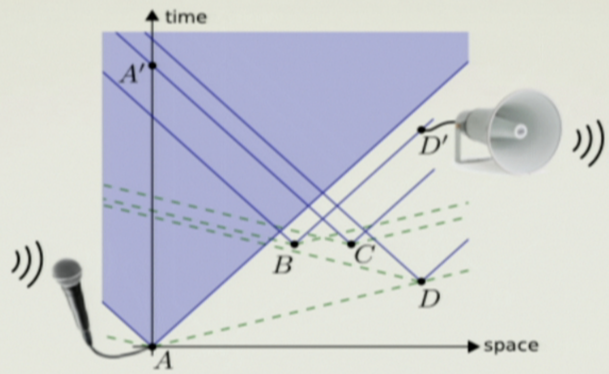
Detecting signaling



With light-speed communication, the signaling marginal can be evaluated outside of the fourth party's lightcone.

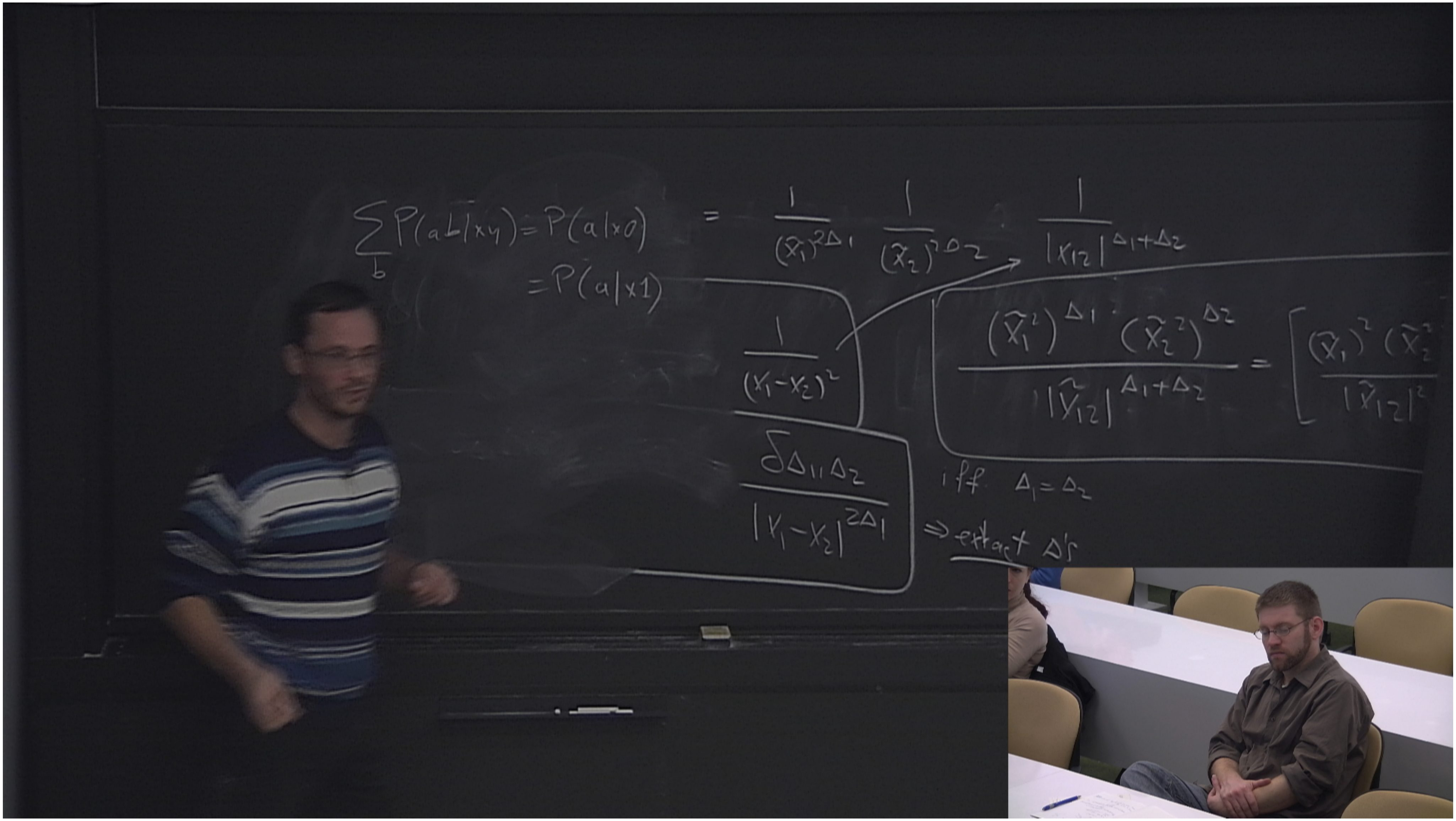
Finite-speed influences lead to signaling.

Conclusion

Quantum nonlocality
+
No-signaling

→

Infinite-speed
influences


iff $\Delta_1 = \Delta_2$
⇒ extract Δ's