



# Quantum correlations in Newtonian Space-time: faster than light communication or nonlocality

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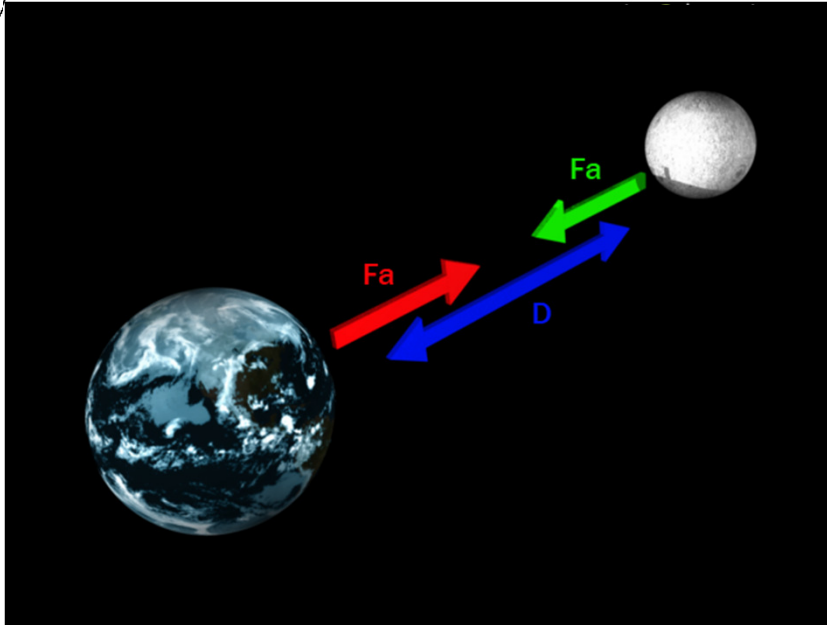
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- The violation of a Bell inequality presents us with a tremendous challenge to tell stories about how things happen in nature.
- It make sense to look for a universal privileged reference frame in which the story would be as in a Newtonian space-time.
- Quantum nonlocality based on finite-speed causal influences leads to superluminal communication.

**Nature Physics 8, 867-70, 2012; see also quant-**



# Newton's Nonlocality

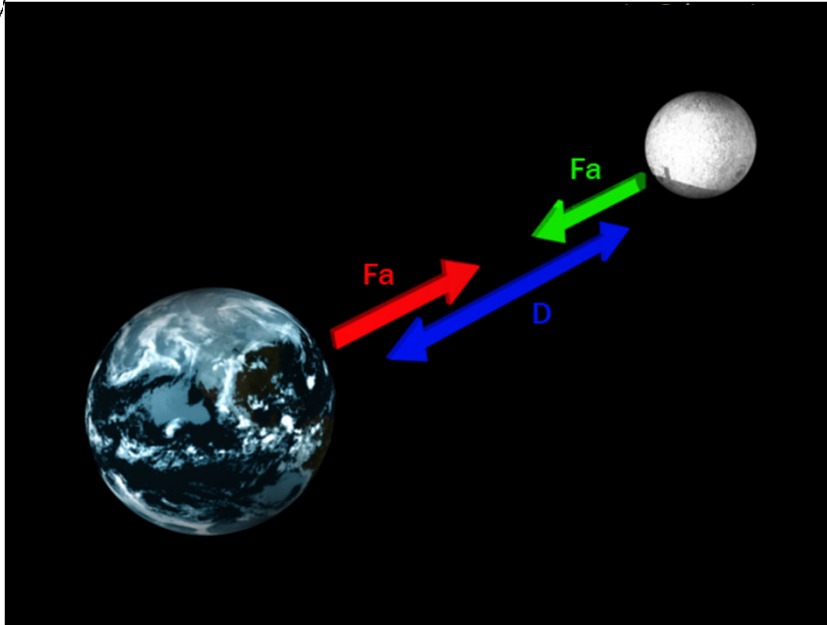


A stone moved on the moon would **immediately** affect the gravitational field on earth.

How can these two locations out there in space-time know about each other ?



# Newton's Nonlocality



A stone moved on the moon would **immediately** affect the gravitational field on earth.

Had someone tested this prediction, he would:

1. have falsified Newton's theory, and
2. have found that gravity propagates at the speed of light.



## Let's read Newton's words:



That Gravity should be innate, inherent and essential to Matter, so that one Body may act upon another at a Distance thro' a Vacuum, without the mediation of any thing else, by and through which their Action and Force may be conveyed from one to another, is to me so great an Absurdity, that I believe no Man who has in philosophical Matters a competent Faculty of thinking, can ever fall into it. Gravity must be caused by an Agent acting constantly according to certain Laws, but whether this Agent be material or immaterial, I have left to the Consideration of my Readers.

Isaac Newton

Papers & Letters on Natural Philosophy and related documents

Edited by Bernard Cohen, assisted by Robert E. Schofield

Harvard University Press, Cambridge, Massachusetts, 1958



# Signalling = non-physical communication

- To send information one has to encode it into a physical support and send this support to the receiver.  
Landauer: Information is physical.
- Any other way of communicating would be signalling; it would be non-physical communication.
- Moreover, signalling would allow faster-than-light communication. But no-signalling is even more fundamental than relativity.

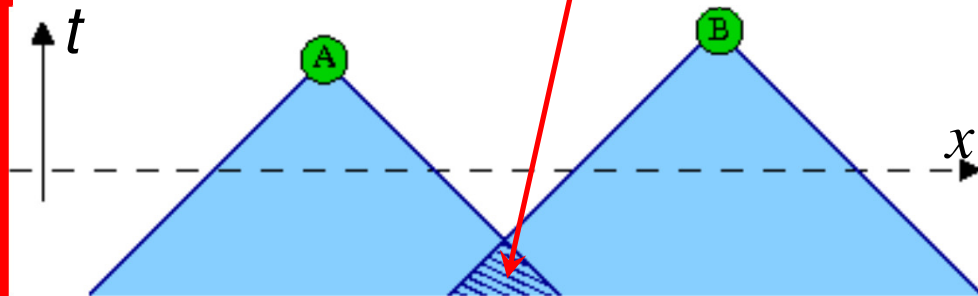


# Principle of Continuity

- Everything (mass, energy and information) propagates gradually and continuously (contiguously) through space as time passes.
- Nothing jumps instantaneously from here to there (no instantaneous teleportation).

⇒ Correlations can have only two types of explanations.

Either common local cause or influences at finite speed





<b>Principle of Continuity</b> <div> <span>Common Cause</span> <span>Direct Cause</span> </div>	
<b>Explanations of correlations by local common causes</b>	<b>Explanations of correlations by an event influencing another one</b>
<b>Variables</b>	<b>Influences</b>
<b>(hidden)</b>	<b><u>hidden</u></b>
<b><u>Local</u></b>	<b>Finite speed</b>
<b>Bell's theorem</b>	<b>This talk</b>
<b>Contradiction with quantum predictions</b>	
<b>Falsified explanation</b>	



Assume a real influence propagates  
From A to B, but with finite speed







Assume a real influence propagating faster than light but with finite speed

$$p(a,b|x,y,\lambda) = p(a|x,\lambda) \cdot p(b|y,\lambda)$$





Assume a real influence propagating faster than light but with finite speed

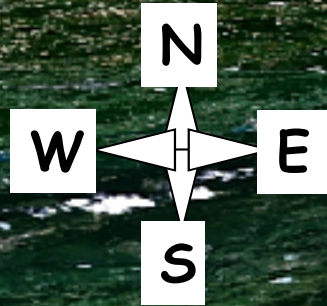
$$p(a,b|x,y,\lambda) = p(a|x,\lambda) \cdot p(b|y,\lambda)$$



Faster than light influences defined in a universal privileged frame,  
e.g. the one in which the cosmic background microwave radiation is isotropic.

No grand-father paradox.

# Satigny – Geneva – Jussy



Satigny

18.0 km

Jussy

Geneva

Salart et al., Nature 454, 861, 2008  
Cocciaro et al., PLA 375, 379, 2011  
J-W Pan's group, PRL 110, 260407, 2013

**Experimental lower bound  $v \geq 10^4 c$  on the speed of hidden influence**





## And so ?

- The influence may merely propagate faster,
- or may not exist at all.
- 2-party experiments will never be able to exclude hidden influences, only set lower bounds on its speed.
- **With only 2 parties, the hypothetical hidden influence could remain hidden for ever.**



# Bell, Bohm and others

- Correlation between distant events strongly suggest that “something is going on behind the scene”, as John Bell advocated.
- David Bohm and Basil Hiley: “it is quite possible that quantum nonlocal connections might be propagated, not at infinite speeds, but at speeds very much greater than that of light. In this case, we could expect observable deviations from the predictions of current quantum theory” [The Undivided Universe, Routledge, London and NY 1993].
- Most (non relativistic) text books tell a story like “a first measurement collapses the entire wavefunction, hence changes (influences) the state of all systems entangled with the measured system”.



# $v$ -causality

- Assume that a hidden influence propagates at speed  $v < \infty$ .
- $v$  can be larger than  $c$  (defined in a universal privileged frame).
- Whenever an event happens, the rest of the universe is informed at speed  $v$ .
- Whenever the hidden influence arrives on time, future events are correlated as predicted by QM.
- Whenever the hidden influence doesn't arrive on time, events can only be Bell-local correlated (i.e. correlated by local variables).

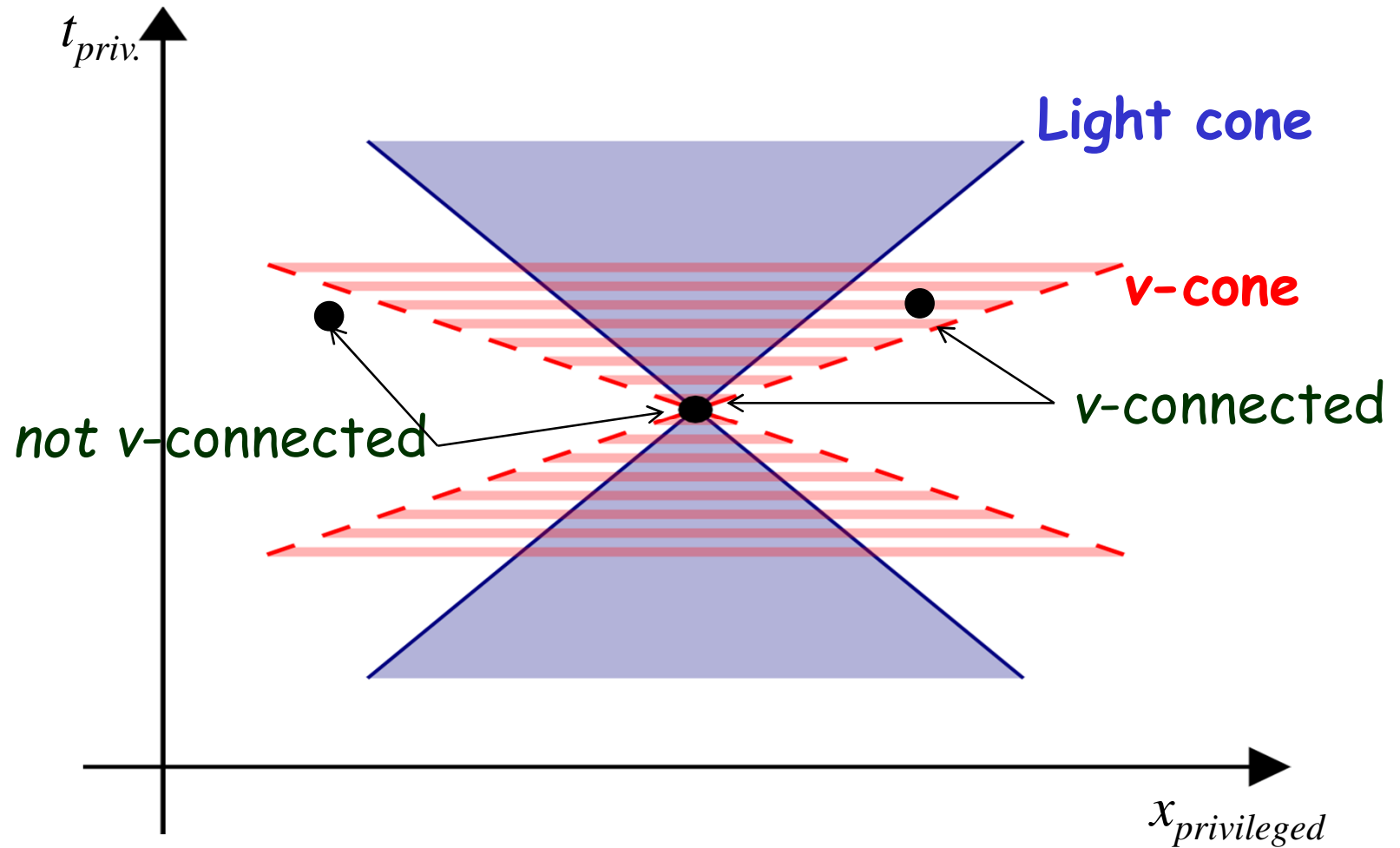
⇒  $v$ -causal predictions may differ from quantum theory

≠ Bohm

**We shall see that hidden influence at finite speed leads to signalling at the macroscopic level, i.e. hidden influences at finite speed can't remain hidden**



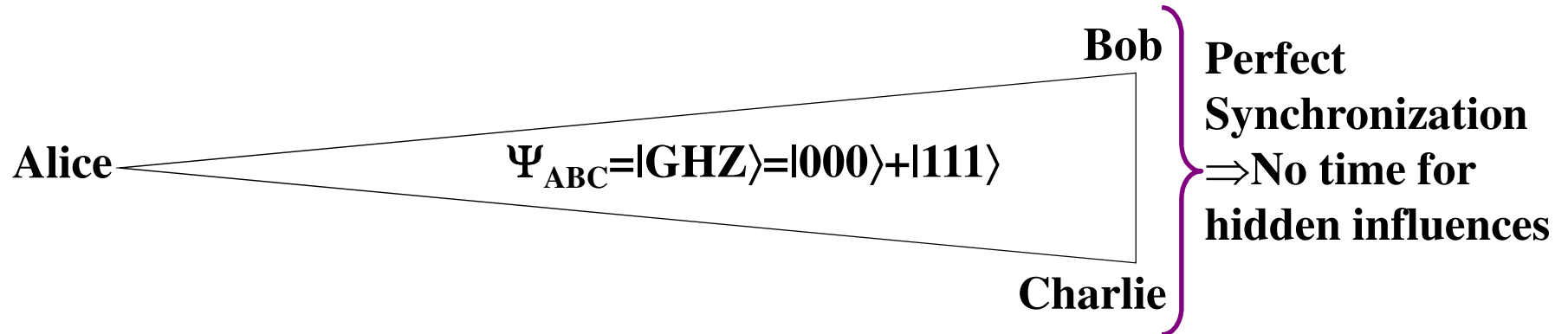
# $v$ -causality





# Hidden influences alone would allow faster-than-light communication

V. Scarani, W. Tittel, H. Zbinden and N. Gisin, Phys.Lett. A 276, 1-7 (2000)  
V. Scarani & NG, Brazilian J. of Physics 35, 328-332 (2005), quant-ph/0410025  
L.C. Ryff, arXiv:0903.1076



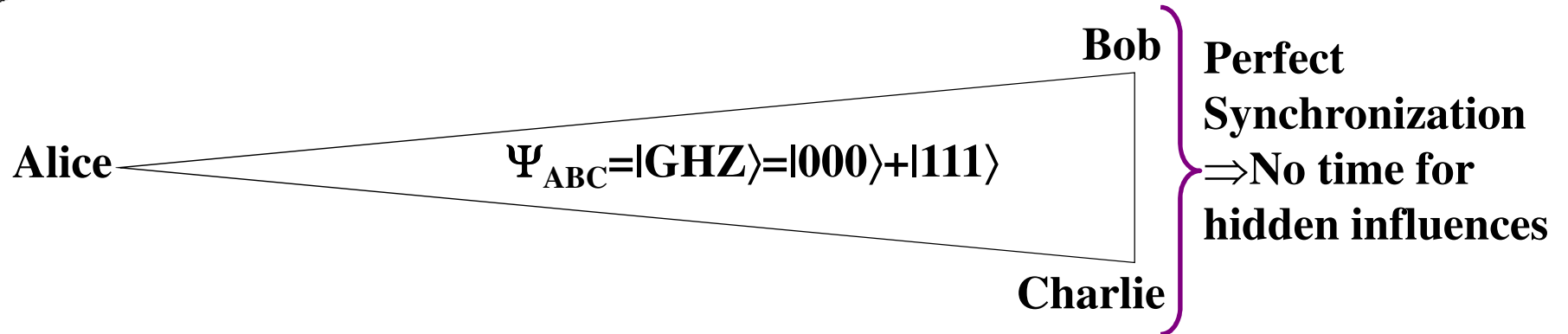
If Alice doesn't measure, then Bob & Charlie's outcomes are independent.

If Alice first measures  $\sigma_z$  and Bob & Charlie later also measure  $\sigma_z$ ,  
then Bob & Charlie's outcomes are always the same.





# Hidden influences would allow signalling, i.e. communication without transmission

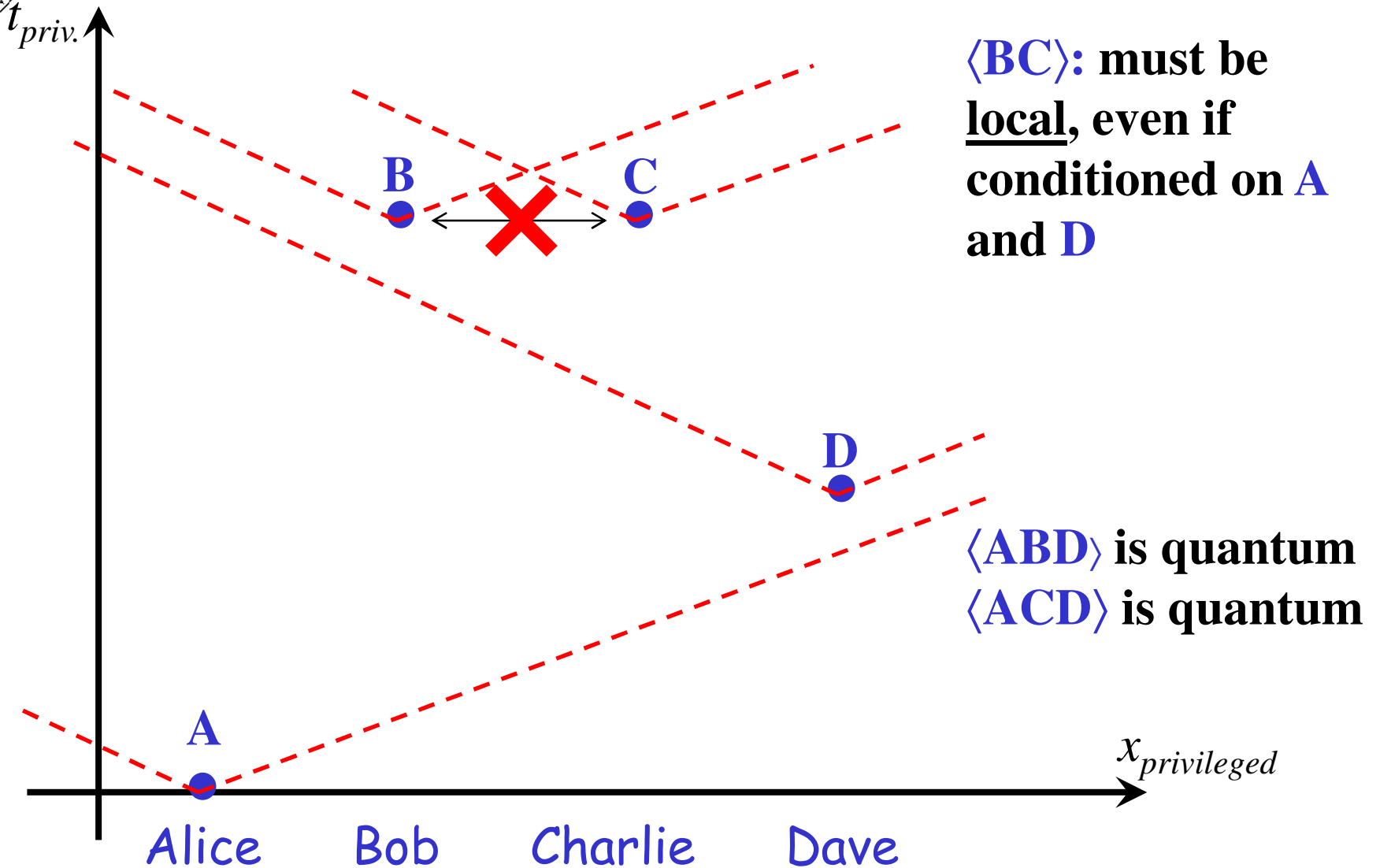


**An immediate objection is that whenever the hidden influence doesn't arrive on time, the outcome could be determined by local (hidden) variables.**

**This corresponds to an explanation combining local variables and finite-speed influences.**

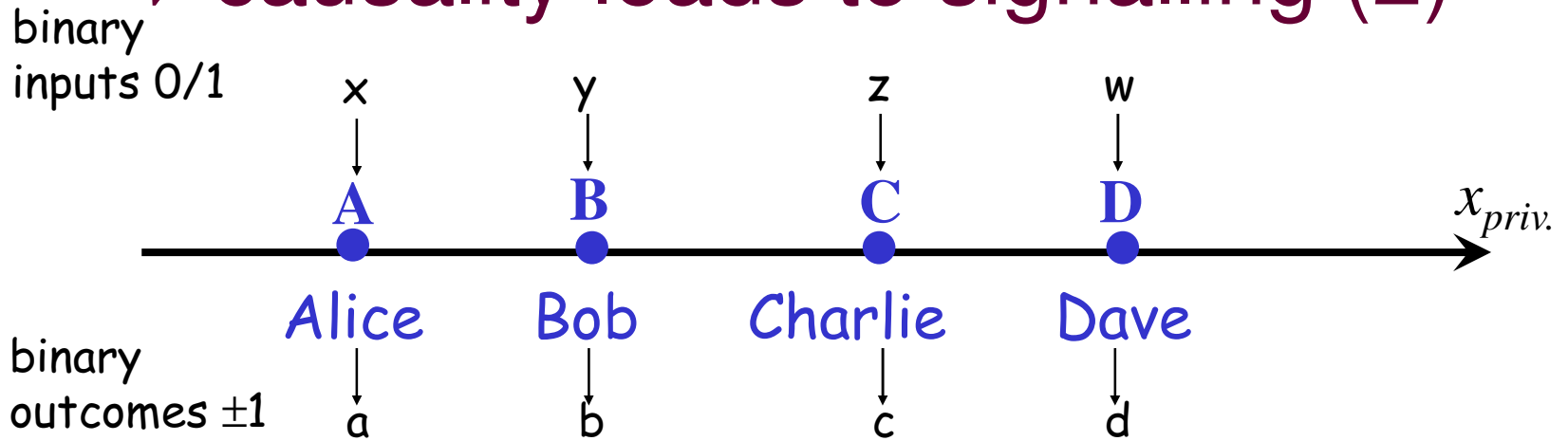


# $\nu$ -causality leads to signalling (1)





## $\nu$ -causality leads to signalling (2)



Theorem: If  $p(a,b,c,d|x,y,z,w)$  is formally non-signalling and  $p(b,c|y,z, a,x,d,w)$  is local for all  $a,x,d,w$ , then

$$J \leq 7$$

NO BC

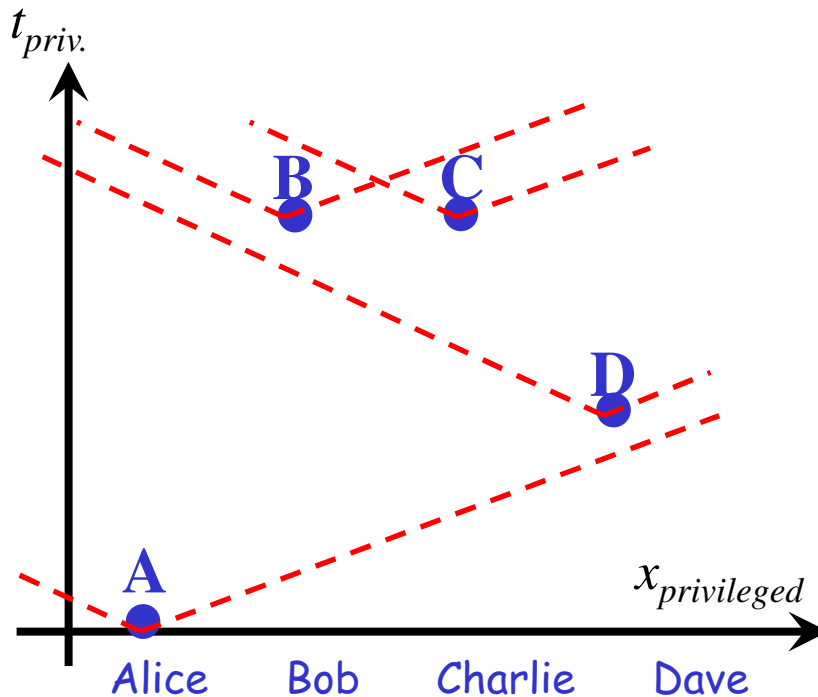
Where  $J = -3\langle A_1 \rangle - \langle B_0 \rangle - \langle B_1 \rangle - \langle C_0 \rangle - 3\langle D_0 \rangle - \langle A_1 B_0 \rangle - \langle A_1 B_1 \rangle + \langle A_0 C_0 \rangle$   
 $+ 2\langle A_1 C_0 \rangle + \langle A_0 D_0 \rangle + \langle B_0 D_1 \rangle - \langle B_1 D_1 \rangle - \langle C_0 D_0 \rangle - 2\langle C_1 D_1 \rangle$   
 $+ \langle A_0 B_0 D_0 \rangle + \langle A_0 B_0 D_1 \rangle + \langle A_0 B_1 D_0 \rangle - \langle A_0 B_1 D_1 \rangle - \langle A_1 B_0 D_0 \rangle$   
 $- \langle A_1 B_1 D_0 \rangle + \langle A_0 C_0 D_0 \rangle + 2\langle A_1 C_0 D_0 \rangle + 2\langle A_0 C_1 D_1 \rangle$



$$\begin{aligned}
 J = & -3\langle A_0 \rangle - \langle B_0 \rangle - \langle B_1 \rangle - \langle C_0 \rangle - 3\langle D_0 \rangle - \langle A_1 B_0 \rangle - \langle A_1 B_1 \rangle + \langle A_0 C_0 \rangle \\
 & + 2\langle A_1 C_0 \rangle + \langle A_0 D_0 \rangle + \langle B_0 D_1 \rangle - \langle B_1 D_1 \rangle - \langle C_0 D_0 \rangle - 2\langle C_1 D_1 \rangle \\
 & + \langle A_0 B_0 D_0 \rangle + \langle A_0 B_0 D_1 \rangle + \langle A_0 B_1 D_0 \rangle - \langle A_0 B_1 D_1 \rangle - \langle A_1 B_0 D_0 \rangle \\
 & - \langle A_1 B_1 D_0 \rangle + \langle A_0 C_0 D_0 \rangle + 2\langle A_1 C_0 D_0 \rangle + 2\langle A_0 C_1 D_1 \rangle
 \end{aligned}$$

NO BC

Any v-causal model predicts the same value for J as QM



*v-causal predictions differ from Q theory, but since J doesn't contain any term involving B and C, the v-causal prediction for J is merely the Q value.*

Moreover, in an experiment B and C do not need to be measured in the same run.  
 $\Rightarrow$  No B-C timing issue !



## $\nu$ -causality leads to signalling (3)

Fact: there are quantum states and measurements predicting  $J > 7$

Theorem: If  $p(a,b,c,d|x,y,z,w)$  is formally non-signalling  
and  $p(b,c|y,z, a,x,d,w)$  is local for all  $a,x,d,w$ ,  
then

$$J \leq 7$$

Consequence: Since any  $\nu$ -causal model predicts that  
 $p(b,c|y,z, a,x,d,w)$  is local,  
 $p(a,b,c,d|x,y,z,w)$  must be formally signalling.

Note: in  $\nu$ -causal models, the hidden influence is carrying the  
information; hence – here – signalling is not  
“non-physical communication”.

A similar inequality involving only 3 parties: T. Barnea et al., PRA 88, 022123 (2013)



## *A side remark*

Theorem: If  $p(a,b,c,d|x,y,z,w)$  is formally non-signalling  
and  $p(b,c|y,z, a,x,d,w)$  is local for all  $a,x,d,w$ ,  
then

$$J \leq 7$$

Assuming no-signalling: If  $J > 7$ , one can infer that B-C share  
non-local correlations without ever measuring  
B and C jointly !

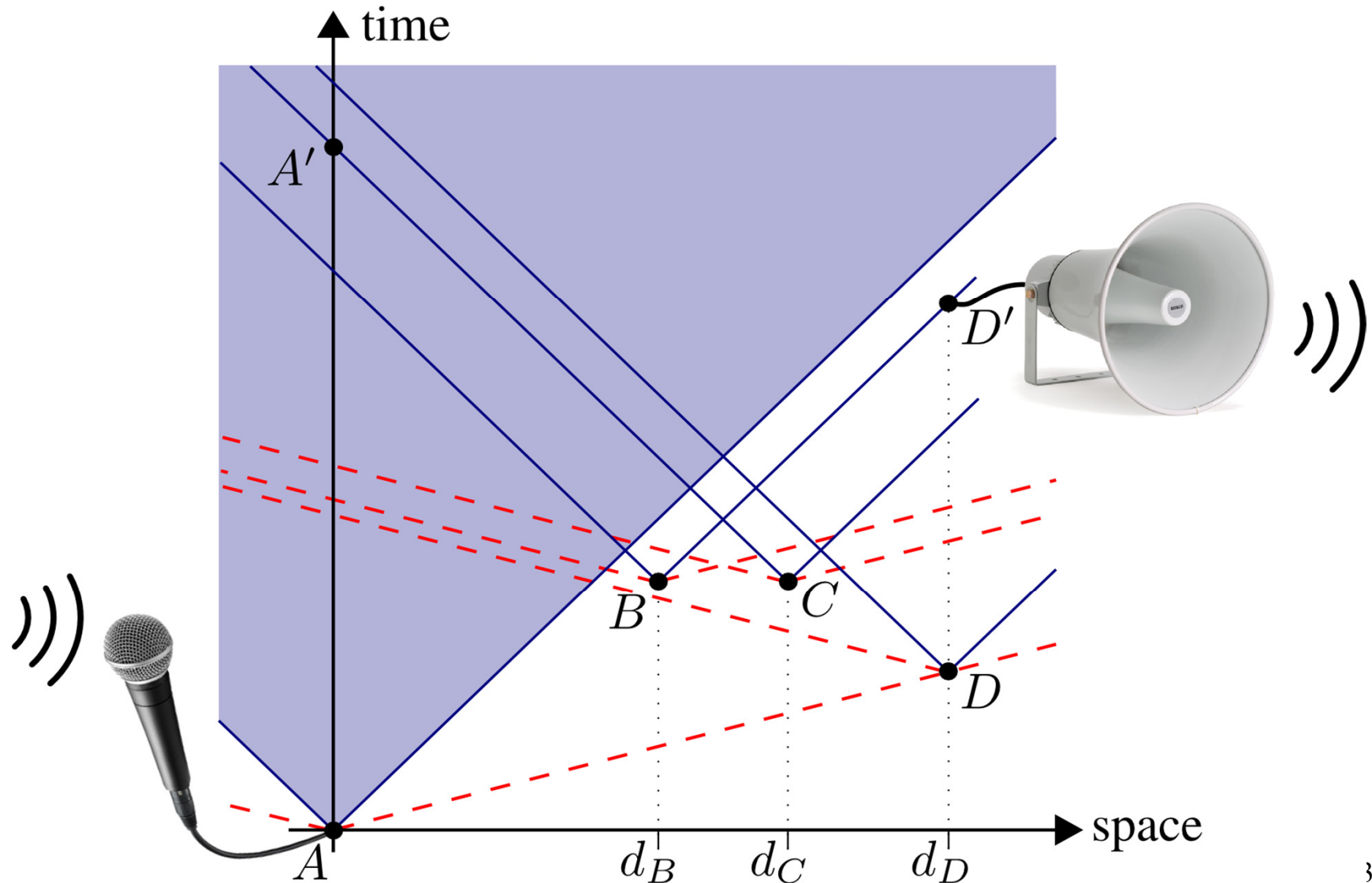
Nature Physics **8**, 867-70, 2012; arXiv:1210.7308

A similar inequality involving only 3 parties: T. Barnea et al., PRA 88, 022123 (2013)



# $v$ -causality leads to supraluminal communication

at the level of classical inputs and outputs





Principle of Continuity	
<i>Common Cause</i>	<i>Direct Cause</i>
<b>Explications of correlations by local common causes</b>	<b>Explications of correlations by an event influencing another</b>
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<b>Contradiction with quantum predictions</b>	<b>Contradiction with no faster than light communication</b>
<b>Falsified explanation</b>	<b>Falsified explanation</b>
<b>Nature doesn't satisfy the principle of continuity</b>	
<b>Nature is nonlocal</b>	





## Open questions

- How does an event  $A$  know that it is nonlocally correlated to another event  $B$  ?
- Who keeps track of who is entangled with whom ?
- Multipartite nonlocality: is "non signalling-Svetlichny" the relevant concept? [arXiv:1112.2626](#), [PRA A 88, 014102, 2013](#).



# Conclusion

A violation of the inequality  $S \leq 7$  implies either a violation of the principle of continuity, or the possibility of faster than light communication at the level of the classical measurement settings and results.

Both alternatives are about equally hard to swallow.

Let's assume there is no faster than light communication.

Though faster than light communication in one universal privileged frame doesn't allow one to communicate to one's past: No grand father paradox.



# Open questions

- How to tell a consistent story about quantum nonlocality?
- Somehow one has to tell stories using «nonlocal concepts», like nonlocal randomness: a random event that can manifest itself at several locations.

