Title: Simulating quantum correlations with and without communication

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Abstract:

Simulating Quantum Correlations with and without Communication

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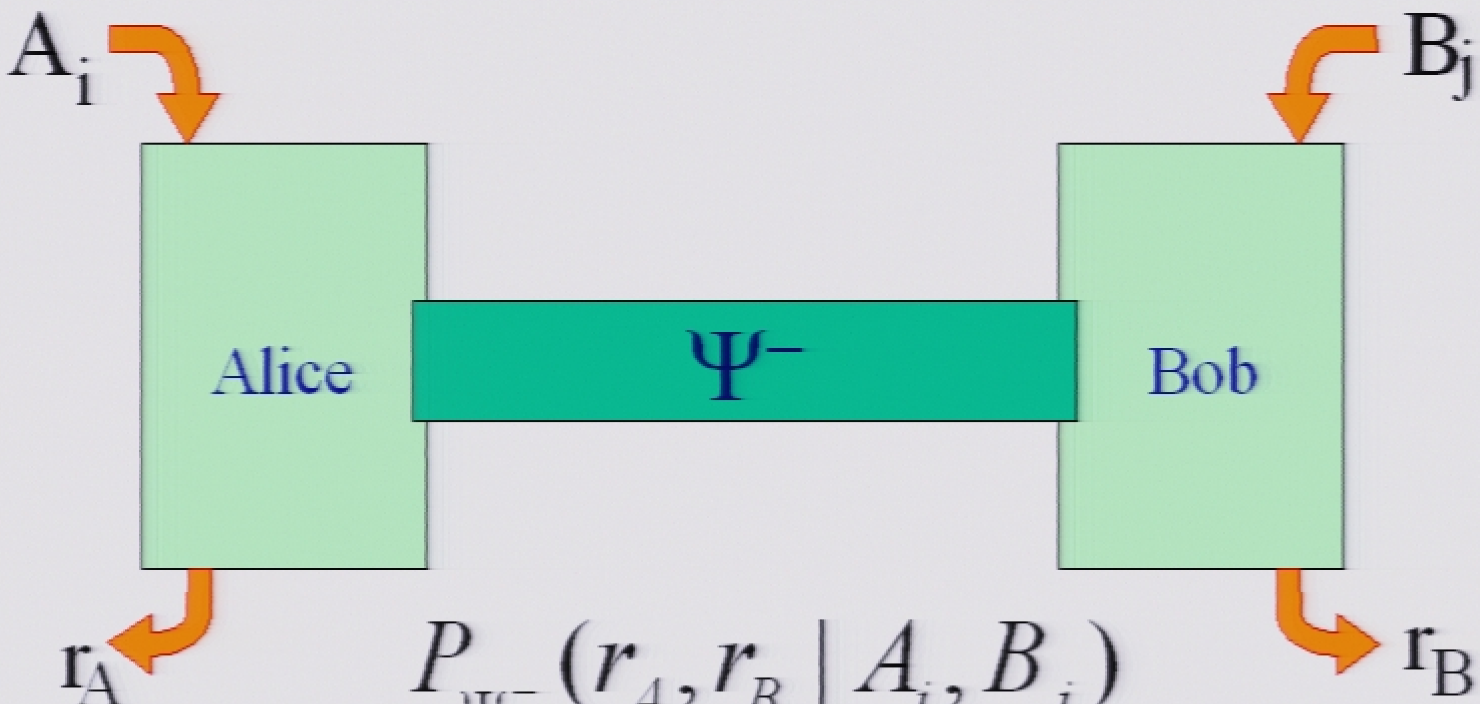
The Ψ^- Channel



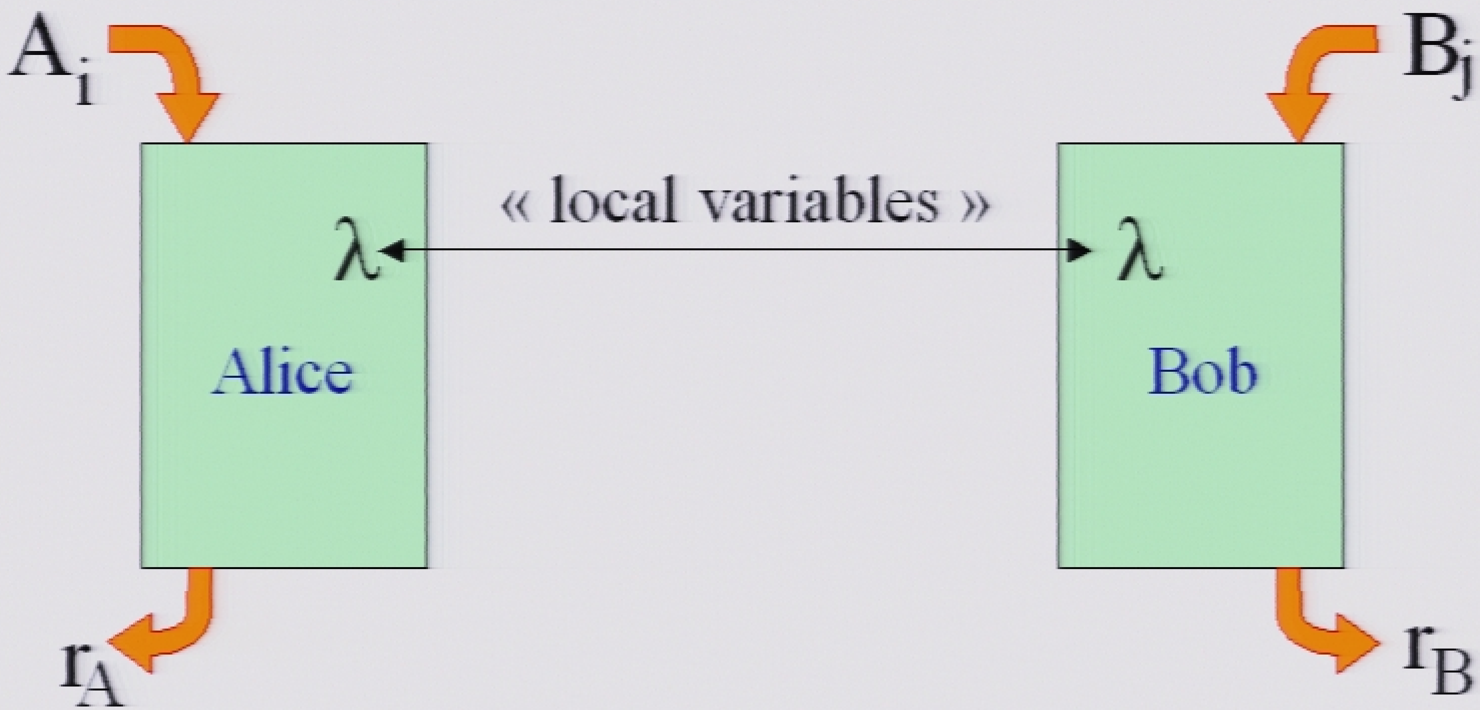
$$P_{\Psi^-}(r_A, r_B \mid A_i, B_j)$$

There exists in Nature a channel which allows to distribute some correlations at any distance, without signaling:

$$\sum_{r_B} P_{\Psi^-}(r_A, r_B \mid A_i, B_j) = P_{\Psi^-}(r_A \mid A_i, \not{B}_j)$$

How can we possibly describe it?

Bell's Theorem



$$r_A = r_A(A_i, \lambda) \qquad\qquad r_B = r_B(B_j, \lambda)$$

$$P_\lambda(r_A, r_B \mid A_i, B_j) \not\leftrightarrow P_{\Psi^-}(r_A, r_B \mid A_i, B_j)$$

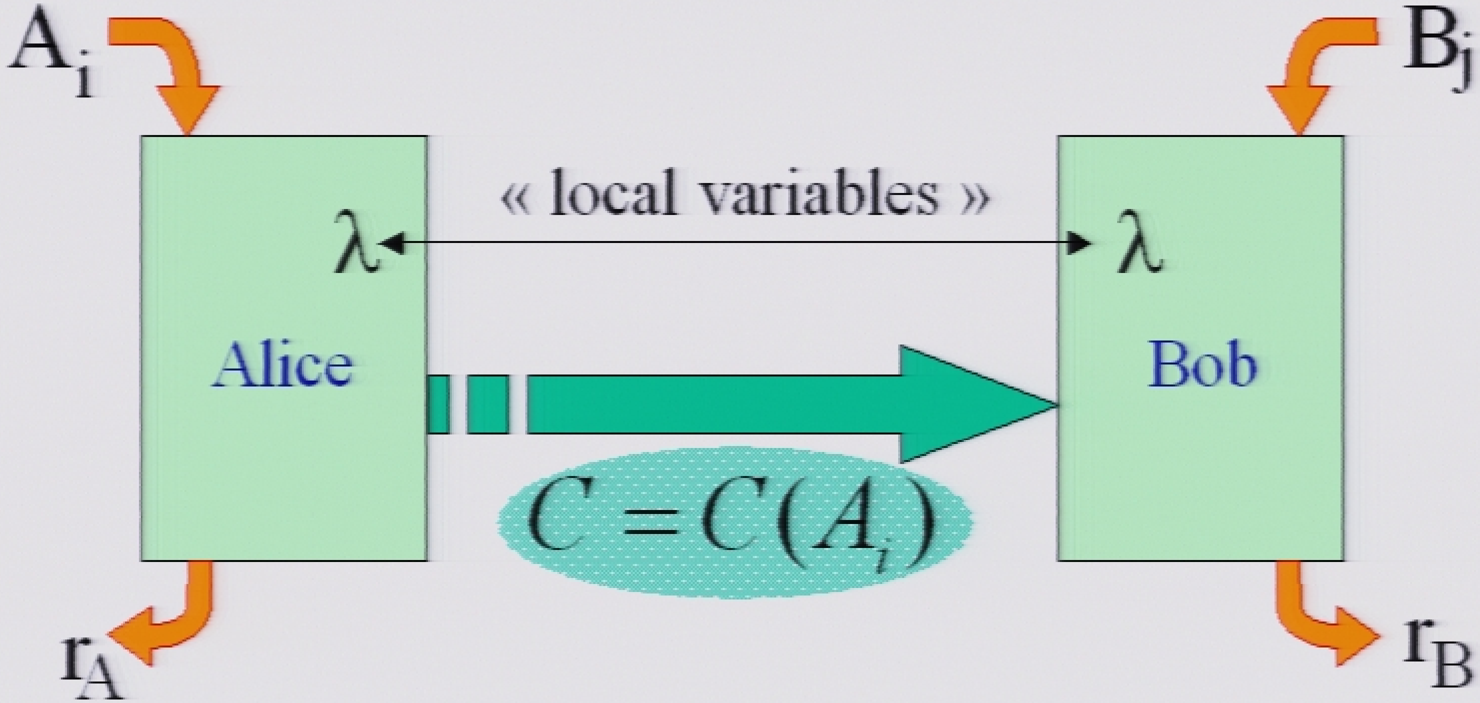
Plan of the talk

Some resources must be added to LV in order to simulate entanglement

- Resource #1: Communication
  - Amount of Communication for the Singlet
  - Experimental Lower Bound on its Speed
  - Danger: Signaling
- Resource #2: Non-local machine
  - Definition and nice features
  - Simulation of non-max entg states of two qubits
- Conclusions

Resource #1
Communication

Adding a Resource: Communication



$$r_A = r_A(A_i, \lambda) \qquad r_B = r_B(B_j, \lambda, C)$$

$$P_{\lambda + C}(r_A, r_B \mid A_i, B_j) \leftrightarrow P_{\Psi^-}(r_A, r_B \mid A_i, B_j)$$

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- Pioneering work: Tapp et al., PRL 1999
  - C=8 bits to simulate the singlet.
- Refinements: Gisin-Gisin 1999; Steiner 2000.
- Main reference: B. Toner, D. Bacon, PRL 2003
  - The singlet can be exactly simulated using C=1 bit of communication (explicit model);
  - For non-maximally entangled states: C=2 bits is enough, but « not necessarily optimal ».

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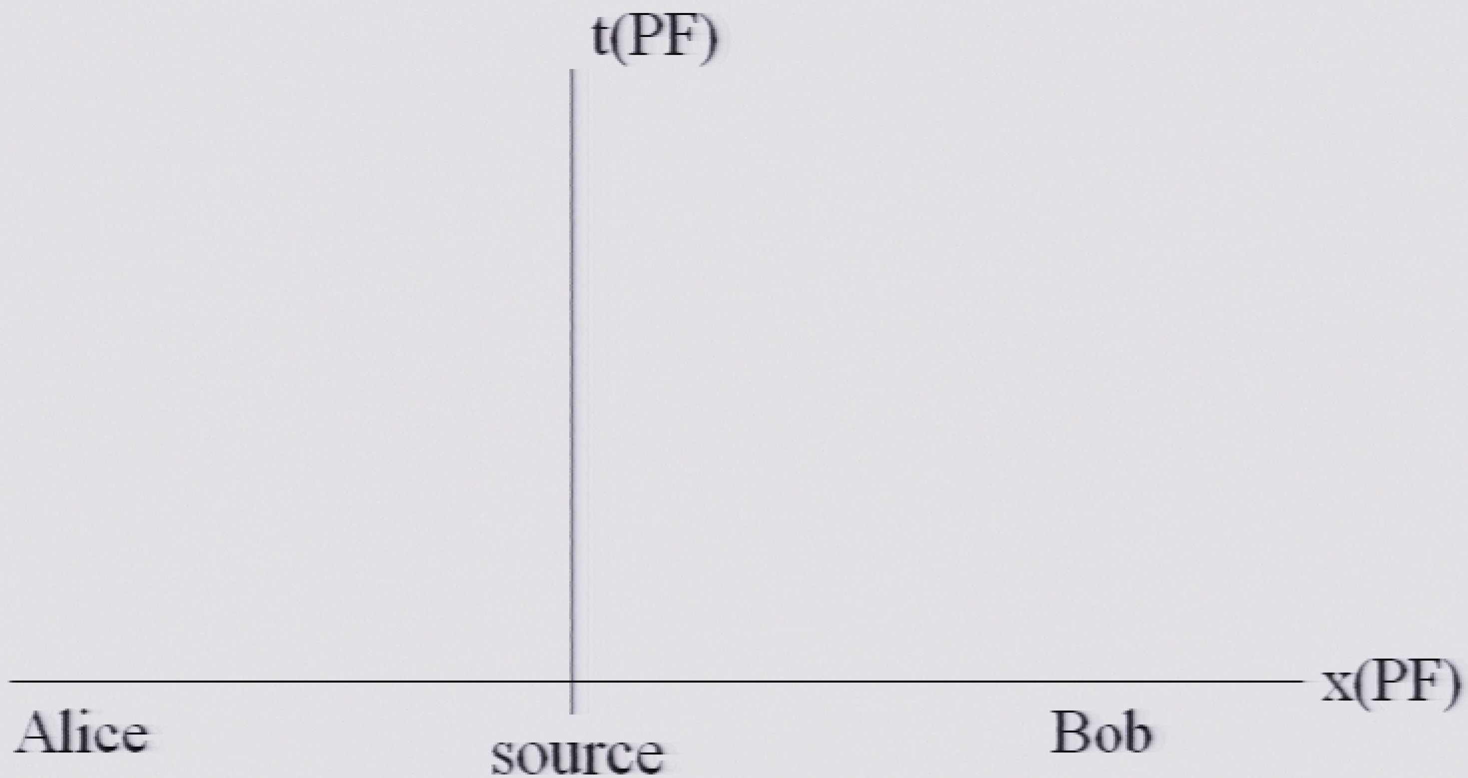
- It must be faster than light (how much?)
- ➔ Answer: many orders of magnitude (see next)
- Communication means signaling: if Nature really uses it, why is it hidden for us?
- ➔ Good question ☺
- Is it easy to build a model of communication which does not allow signaling?

Bounds for the Speed (Preferred Frame)



Bounds: PF = rest frame of the lab

$$D_{Lab}(A,B) = 10.6km$$

$$c\tau_{Lab} = \left| D(A,S) - D(B,S) \right| \leq 10mm$$

$$c\tau_{coh} = 1.5mm \quad (\tau_{coh} = 5ps)$$

Correlations observed

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Photons @ telecom wavelengths

$$v_{Lab} \geq 10^6 c$$

Non-trivial!

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These parameters + Lorentz ⇒ **v** in any frame:

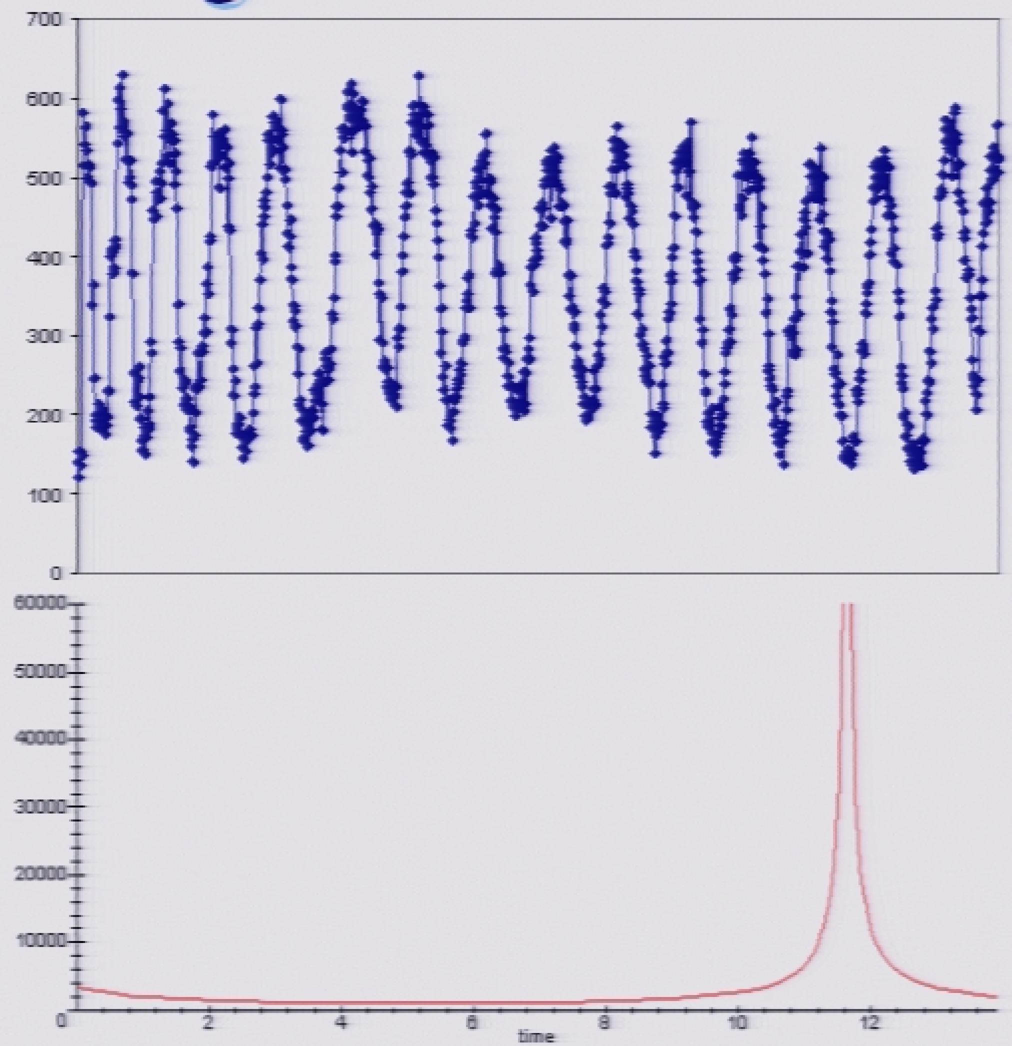
$$|v(\beta)| = c\frac{1 - r\beta}{r - \beta} \quad \text{with} \quad \beta = \frac{\hat{D}\cdot\vec{u}_{PF|Lab}}{c},\ r = \frac{D_{Lab}}{c\tau_{Lab}} = \frac{v_{Lab}}{c}$$

Application: frame of the cosmic background radiation

Bounds: PF = Cosmic Microwave Background

- Defined by absence of dipole of the radiation
- Speed: 369 km/s with respect to the Sun
- Earth rotation: β varies along the day.

$$|v(t)| = c\frac{1 - r\beta(t)}{r - \beta(t)}$$



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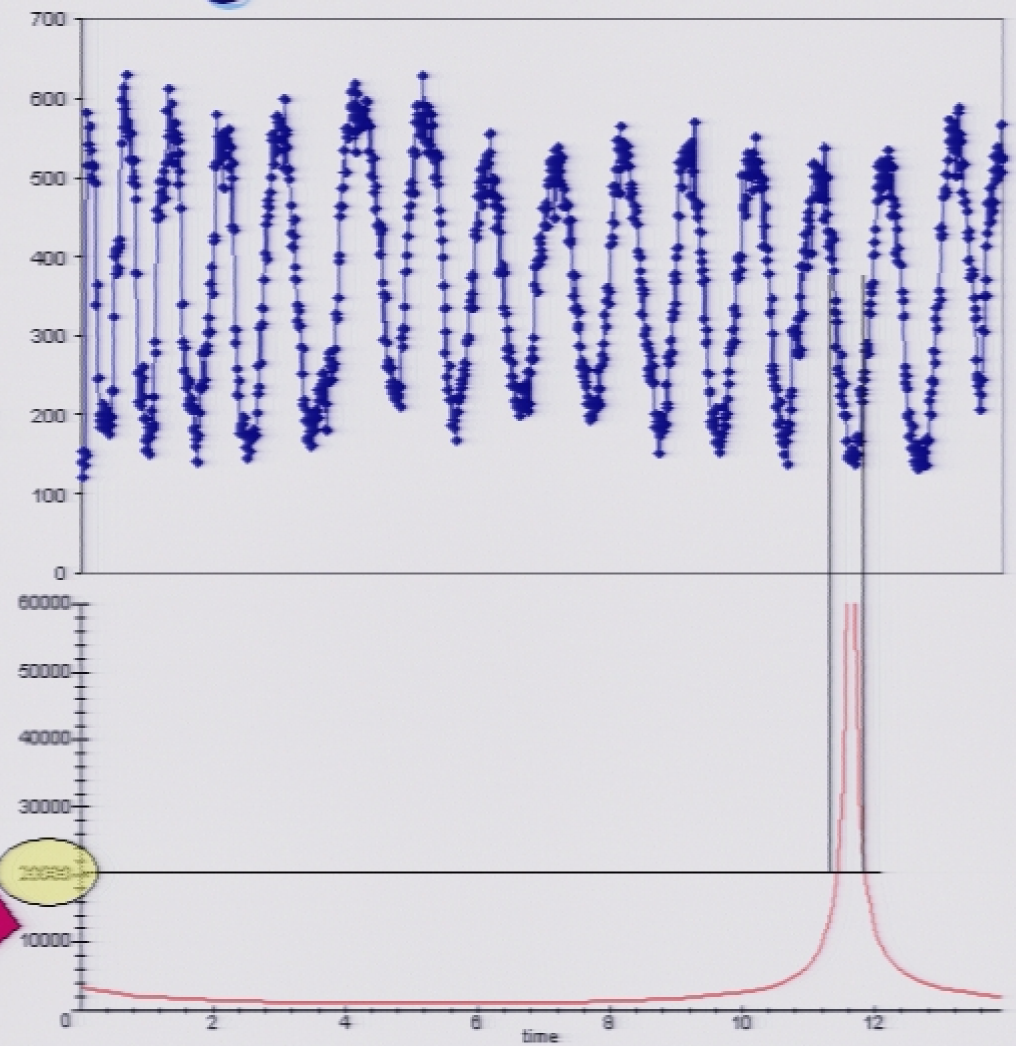
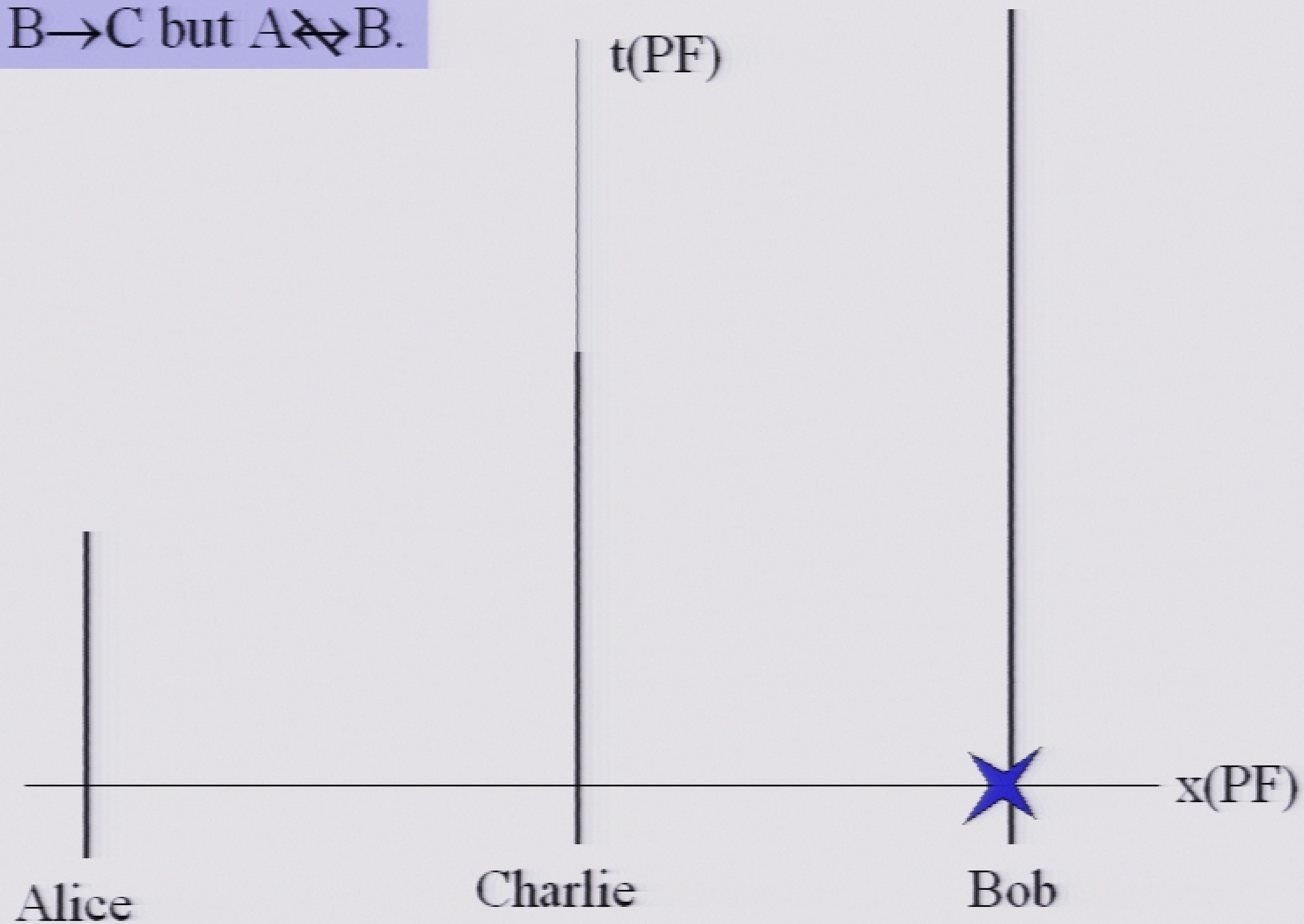


$$|v(t)| = c\,\frac{1 - r\beta(t)}{r - \beta(t)}$$

$$v_{CMB} \geq 2 \times 10^4\, c$$

What Happens to 3 Particles if $\mathbf{v}<\infty$

$A \to C$, $B \to C$ but $A \not\to B$.



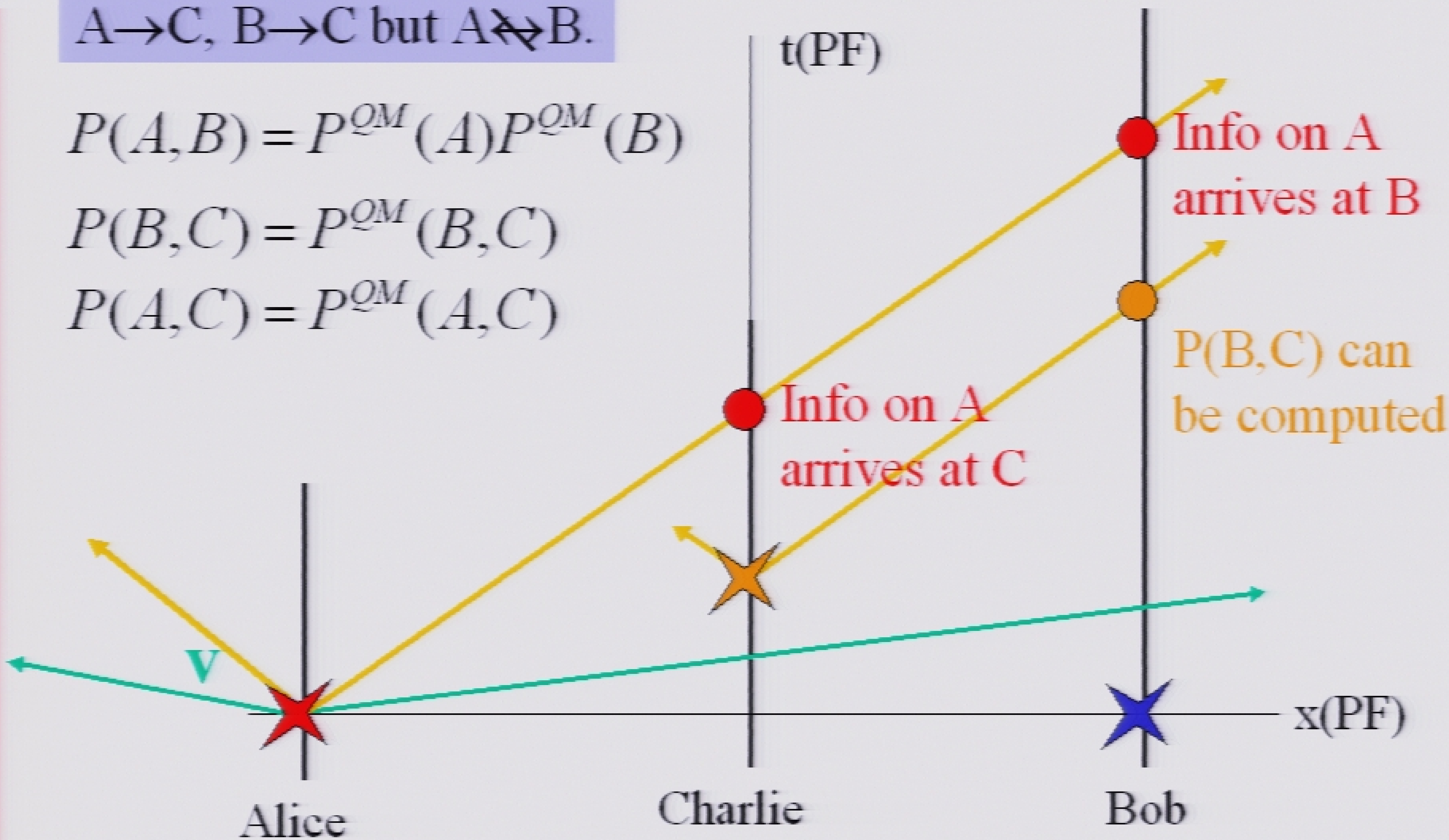
What Happens to 3 Particles if **v**<∞

A→C, B→C but A↛B.

$$P(A,B) = P^{QM}(A)P^{QM}(B)$$

$$P(B,C) = P^{QM}(B,C)$$

$$P(A,C) = P^{QM}(A,C)$$



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- Under the assumption of no local variables,

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- Consider now the GHZ state measured in the Z basis:

$$\left. \begin{array}{l} P^{QM}(A=C)=1 \\ P^{QM}(B=C)=1 \end{array} \right\} \text{necessarily} \quad P(A=B)=1$$

correlation A-B

- Same contradiction exists under relaxed assumptions (allowing for a large family of hidden variables).

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- One bit is enough to simulate the singlet.
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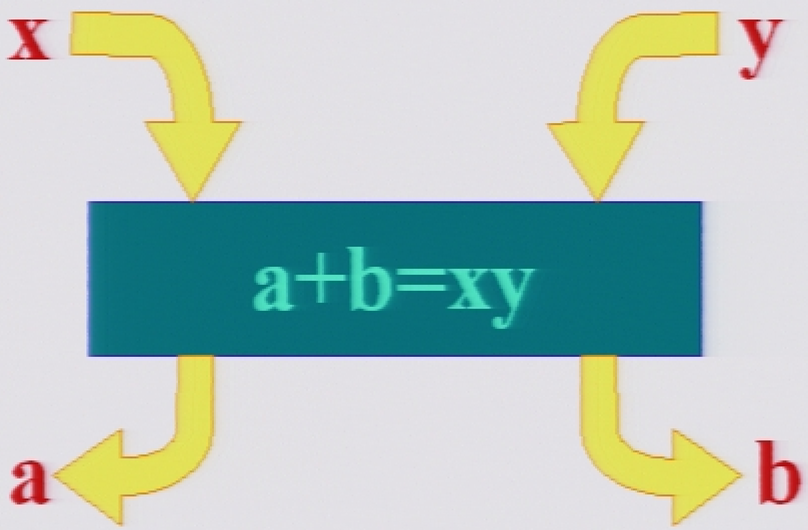
- Not mentioned: experiments confirm QM against theories with Communication without PF.
  - H.Zbinden et al., PRA 2001; A. Stefanov et al., PRL 2002

Resource #2
Non-Local Machines

A Non-local, No-signaling Resource

Communication is a form of signaling. If quantum systems signal among them, why has Nature conspired to hide it? More natural to work with a non-local resource which has no-signaling embedded in it: the Non-Local Machine (NLM)



Popescu, Rohrlich, q-ph/9709026

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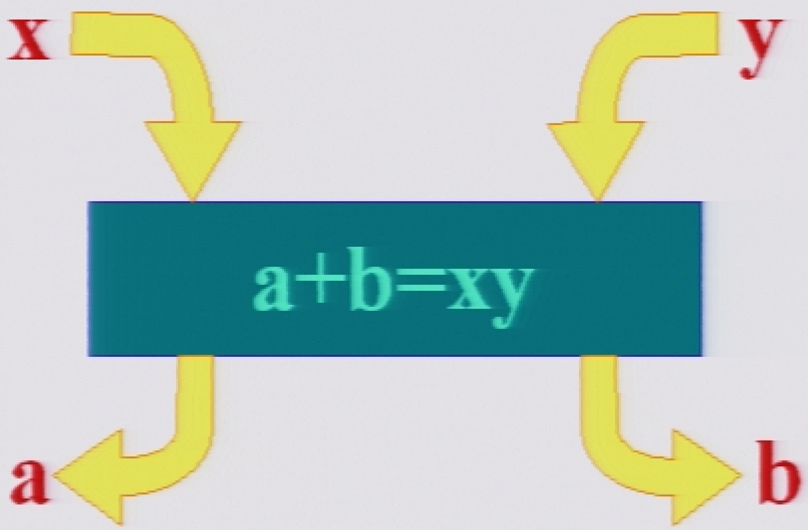

x	y	(a,b)
0	0	$a = b : \begin{cases}(0,0)\\(1,1)\end{cases}$
0	1	$a = b : \begin{cases}(0,0)\\(1,1)\end{cases}$
1	0	$a = b : \begin{cases}(0,0)\\(1,1)\end{cases}$
1	1	$a \neq b : \begin{cases}(0,1)\\(1,0)\end{cases}$

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CHSH with the NLM

Local variables: $S \leq 2$

QM (Cirel'son bound): $S \leq 2\sqrt{2}$

where

$$S = E(A_0, B_0) + E(A_1, B_0) + E(A_0, B_1) - E(A_1, B_1)$$

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NLM:

Input	$x=0, y=0$	$x=1, y=0$	$x=0, y=1$	$x=1, y=1$
Output	$a=b$	$a=b$	$a=b$	$a \neq b$
	$E=+1$	$E=+1$	$E=+1$	$E=-1$

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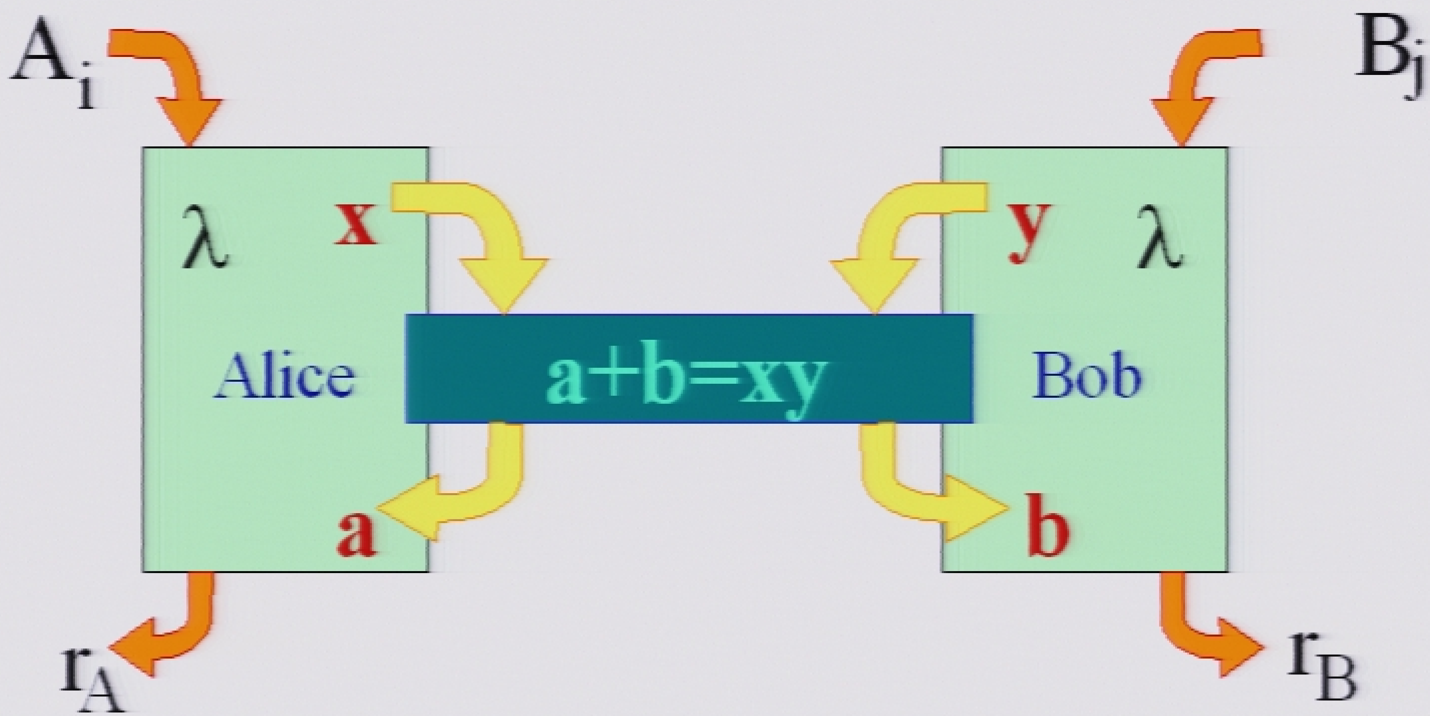
$$\Rightarrow \boxed{S=4}$$

Simulating Entanglement with the NLM



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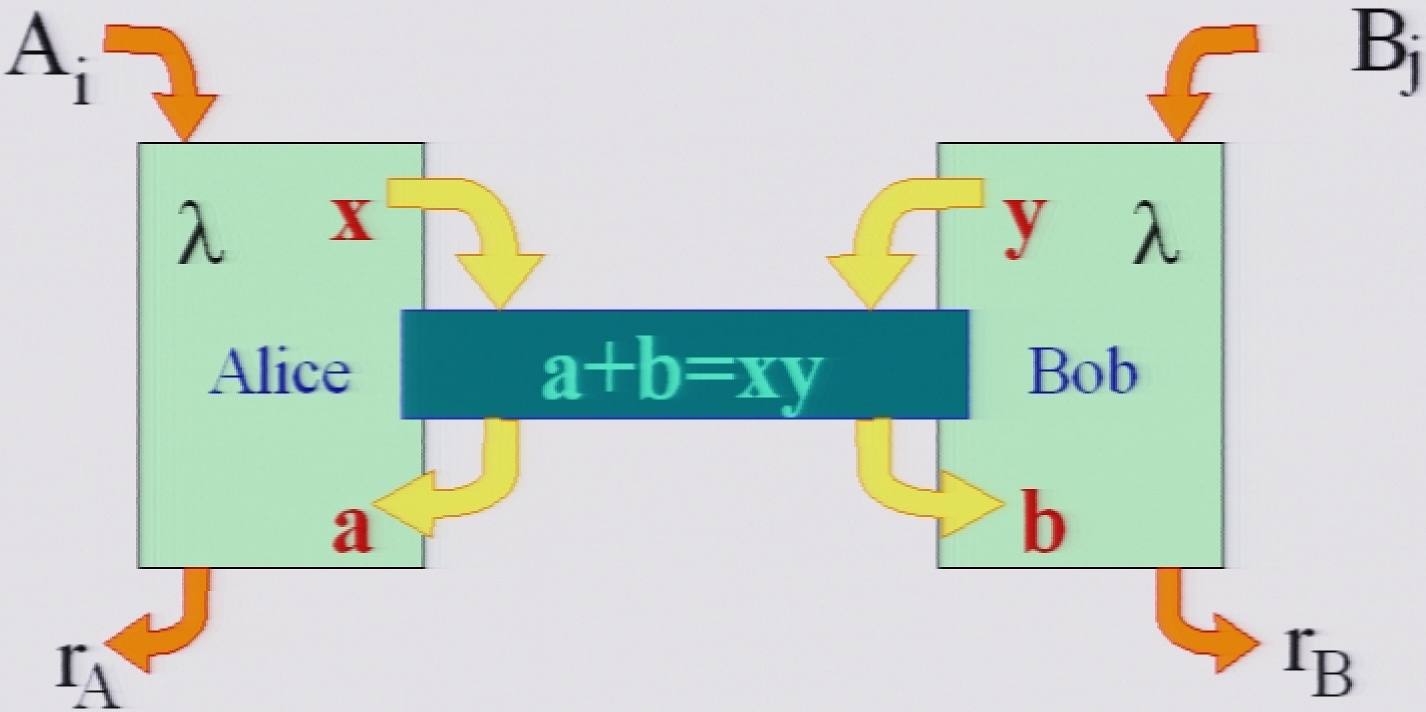

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→ The singlet can be simulated with a single use of the NLM (N.Cerf, N.Gisin, S.Massar, S. Popescu, q-ph/0410027)

Non-Max. Entg States: More Non-Local

To simulate the correlations created by states of the form

$$\Psi(\theta) = \cos\theta|00\rangle + \sin\theta|11\rangle$$

with $0<\theta<\pi/7.8$, strictly more than one use of the NLM is required. N. Brunner, N. Gisin, V.S., New. J. Phys. **7**, 88 (2005)

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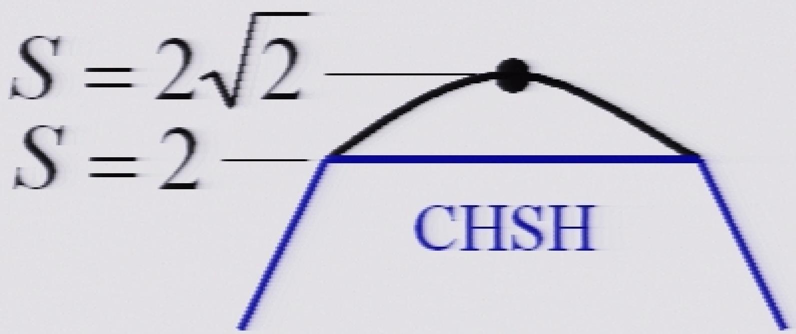
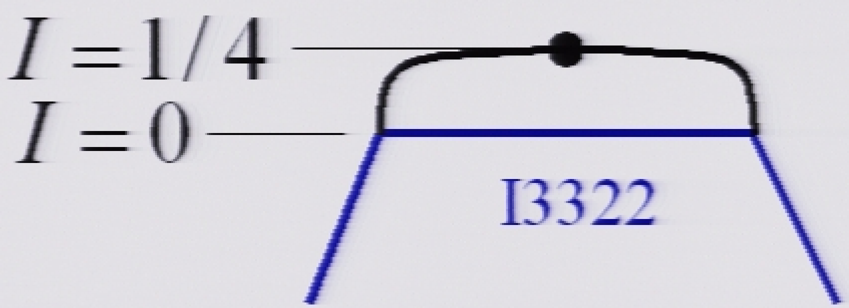
- ➔ In the region $\pi/7.8<\theta<\pi/4$, nothing is known yet.

Proof: 3 Settings, 2 Outcomes

There are just two Bell inequalities (D.Collins, N.Gisin JPA 2004):





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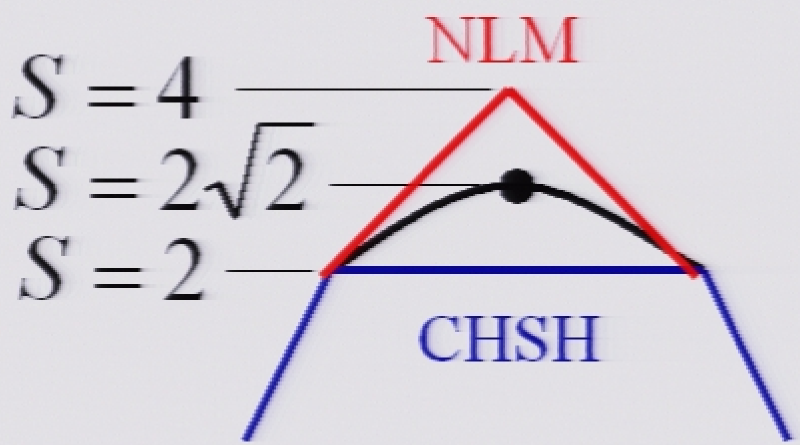
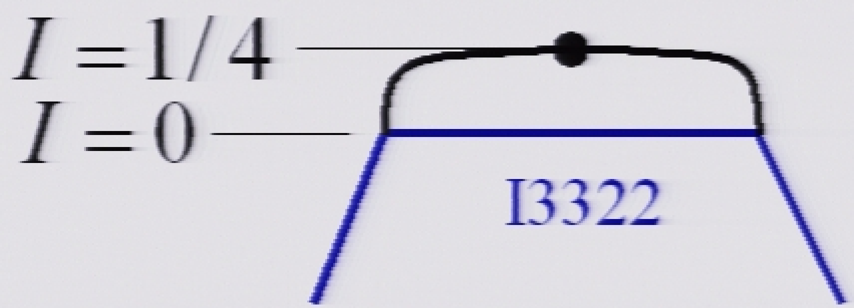


- A single NLM point
- QM within NLM



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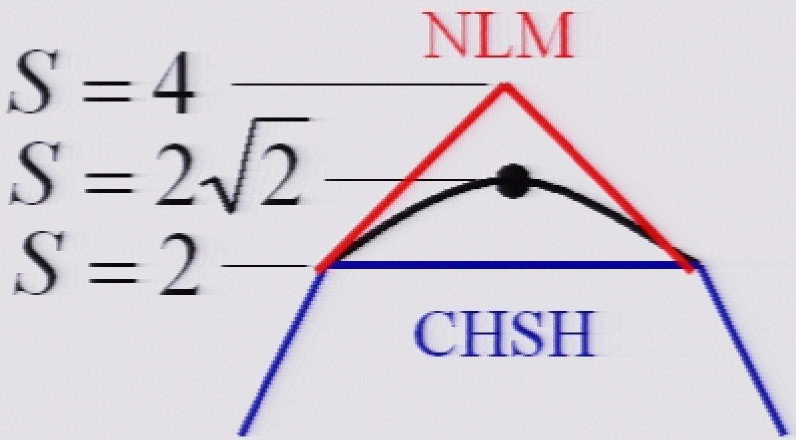

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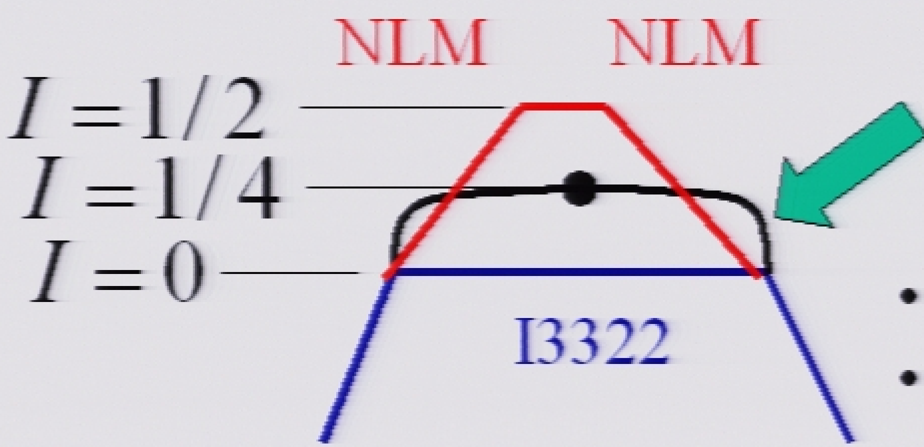

- 28 NLM points
- QM outside NLM

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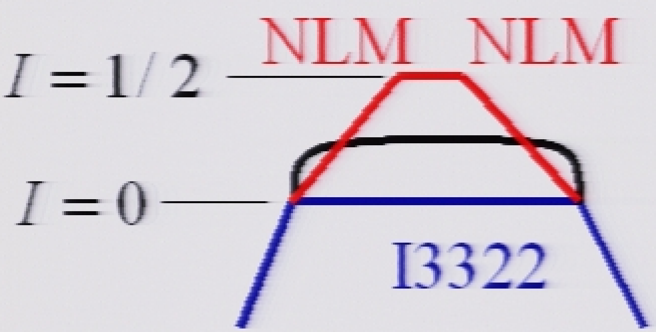

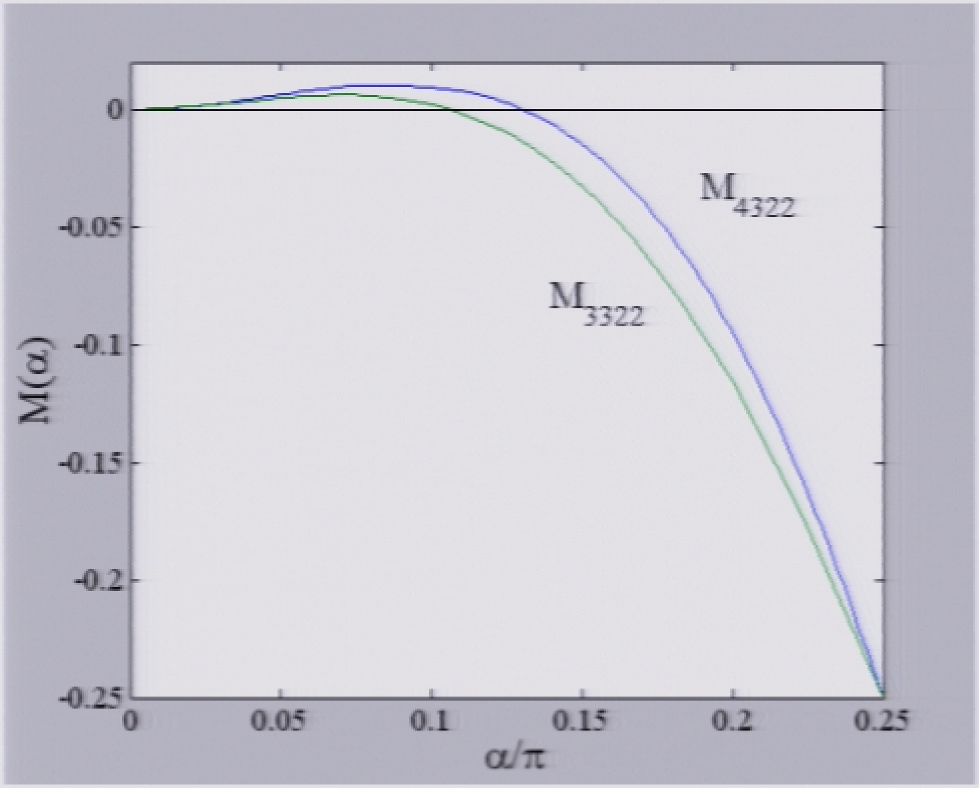

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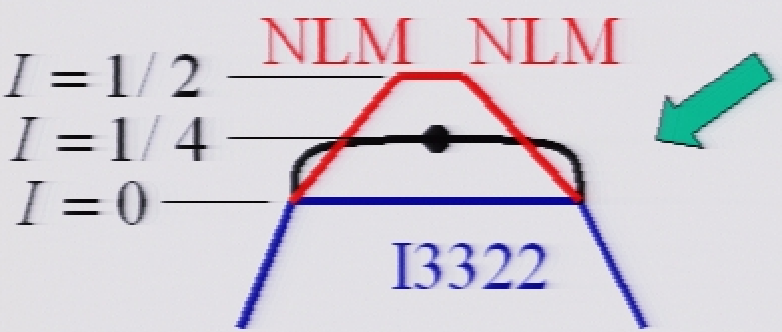
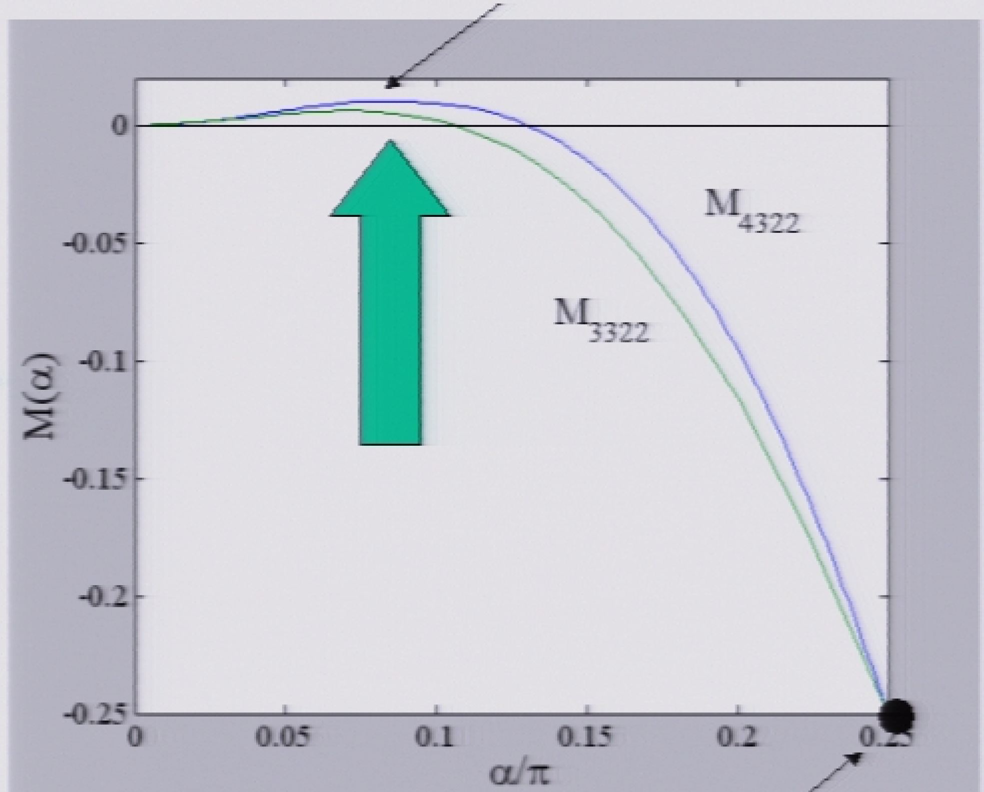
Maximal violation: 0.0102





Singlet at $-1/4=1/4-1/2$

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- For non-maximally entangled states, more resources are required.
  - N. Brunner, N. Gisin, V.S., New J. Phys. 7, 88 (2005)
  - Communication: analog result not known yet.

Conclusions

- Try to simulate entanglement with other resources
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- Example #1: Communication
  - Familiar resource, but very problematic
    - Faster-than-light, why no signaling?
    - Asymmetry sender-receiver
- Example #2: Non-Local Machines
  - More suited, easier to work with
  - Unknown whether all of entanglement can be simulated with it.