The Quantum Measurement Problem & Quantum Nonlocality: How does Nature do it?

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- What is Physics and what are the problems of quantum theory.
- Experiments (and some theory) inspired by the question: "How Does Nature produce Nonlocal Correlations?"
- Experiments involving the question "What is a quantum measurement and when/where does it occur?"
- Experiments inspired by the Measurement Problem: Large Entanglement.

Quantum Physics

- **Quantum theory is a beautiful and fascinating theory:**
  By "brute mental force" one can understand the strange and marvelous world of atoms and photons !
- **Quantum theory is amazingly consistent:**
  How could the father develop such a consistent theory based on the little experimental evidence they had?
- **One can't add a bit of (deterministic) nonlinearity without activating nonlocality (NG, Helv.Phys.Acta 1989).**

The Measurement Problem and Non-Locality

- **Both are real physics problems:**
  The next theories will show us that they are both the seeds of conceptual revolutions.
- **Likewise the concept of "massive point particle" is a real physics problem for classical mechanics:**
  How could there be mass in zero volume? And if zero volume is only an approximation, why could one not break it in two pieces?
- **But it is exceedingly difficult to find these next theories by merely studying these two problems:**
  However, by thinking about these problems one gets inspiration to design experiments that may, some day, lead to new theories.

The Measurement Problem

- **Measurement Problem = Which configurations of atoms and photons characterize measurement setups?**
- **Hypothesis: None!**

  This leads straight to some many-worlds "interpretation".
- **A Physics Theory must tell us what is measurable and how one can measure it:**

  Hence many-worlds is not a physics theory, but rather an uninteresting sort of tautology, a bit like solipsism.
- **Physics is all about extracting information about How Nature Does it**

  and for physicists "extracting information" means performing measurements.

Quantum Non-Locality (QNL) = violation of some Bell inequality

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- **QNL doesn't tell us how Nature is,**
  it tells us that Nature can't be described using only local variables that propagate gradually and continuously through space.
- **A better terminology could be "Discontinuity":**
  non-contiguous regions of space are somehow connected or able to coordinate.
- **40 years ago QNL was an open question, but today it is save to assume that Nature is indeed NL (though there is still a stringent need for loophole free Bell test).**
- **The real question is: How does Nature do it?**
  Some don't care, claiming that physics is only about making predictions. But usually the same persons are also not interested in how one can check these predictions, i.e. perform measurements.

Science is also about telling stories about How Nature Does It

- **F=-G*m*M/d^2 is not an explanation of the ties.**

  A story like "the moon attracts the water in the ocean and hence produces ties" is much less predictive, but has a much larger explanatory power.

- **Let's try to understand How Nature produces Non-Local Correlations**

  and

- **How Large entangled object can be (i.e. "Large Entanglement").**

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 at a **distance** 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.

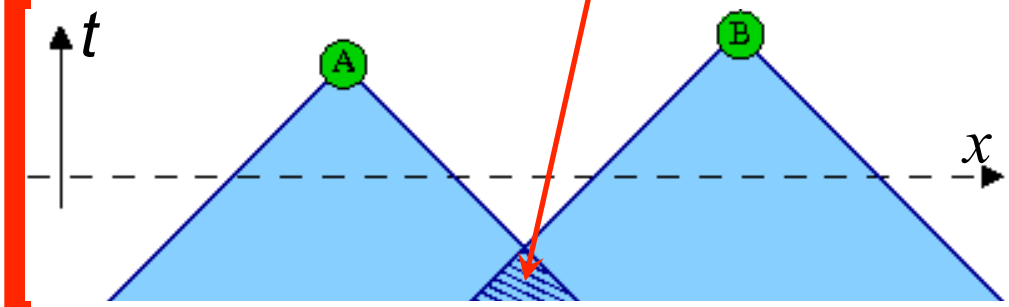
- Moreover, signalling would allow faster-than-light communication. But no-signalling is even more fundamental than relativity.

Principle of Continuity

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

Þ Correlations can have only two types of explanations.

Either common local cause or influences at finite speed



Principle of Continuity

Common Cause	Direct Cause
Explanations of correlations by local common causes	Explanations of correlations by an event influencing another one
Variables	Influences
(hidden)	hidden
Local	Finite speed
Bell's theorem	This talk
Contradiction with quantum predictions	
Falsified explanation	

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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".

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

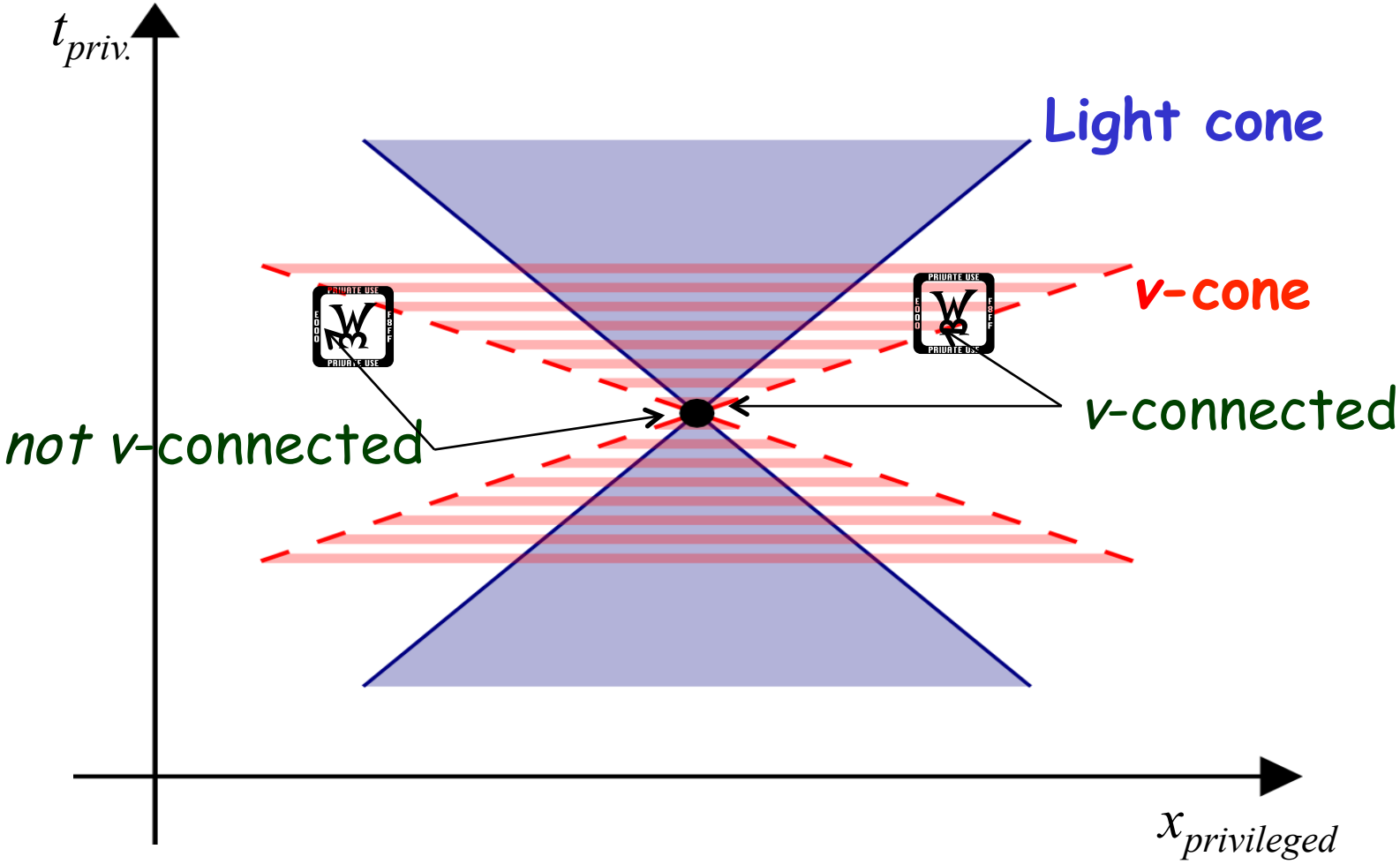
$$p(a,b|x,y,\lambda) = p(a|x,\lambda)\,\lambda\,p(b|y,\lambda)$$

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

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

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

-causality



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

In which frame should the events be simultaneous ?

Let's test these hypothetical preferred reference frame

Alice and Bob,
east-west orientation,
perfect synchronization
with respect to earth

- perfect synchronization w.r to any frame moving perpendicular to the A-B axis
- in 12 hours all hypothetical privileged frame are scanned.

Ph. Eberhard, private communication

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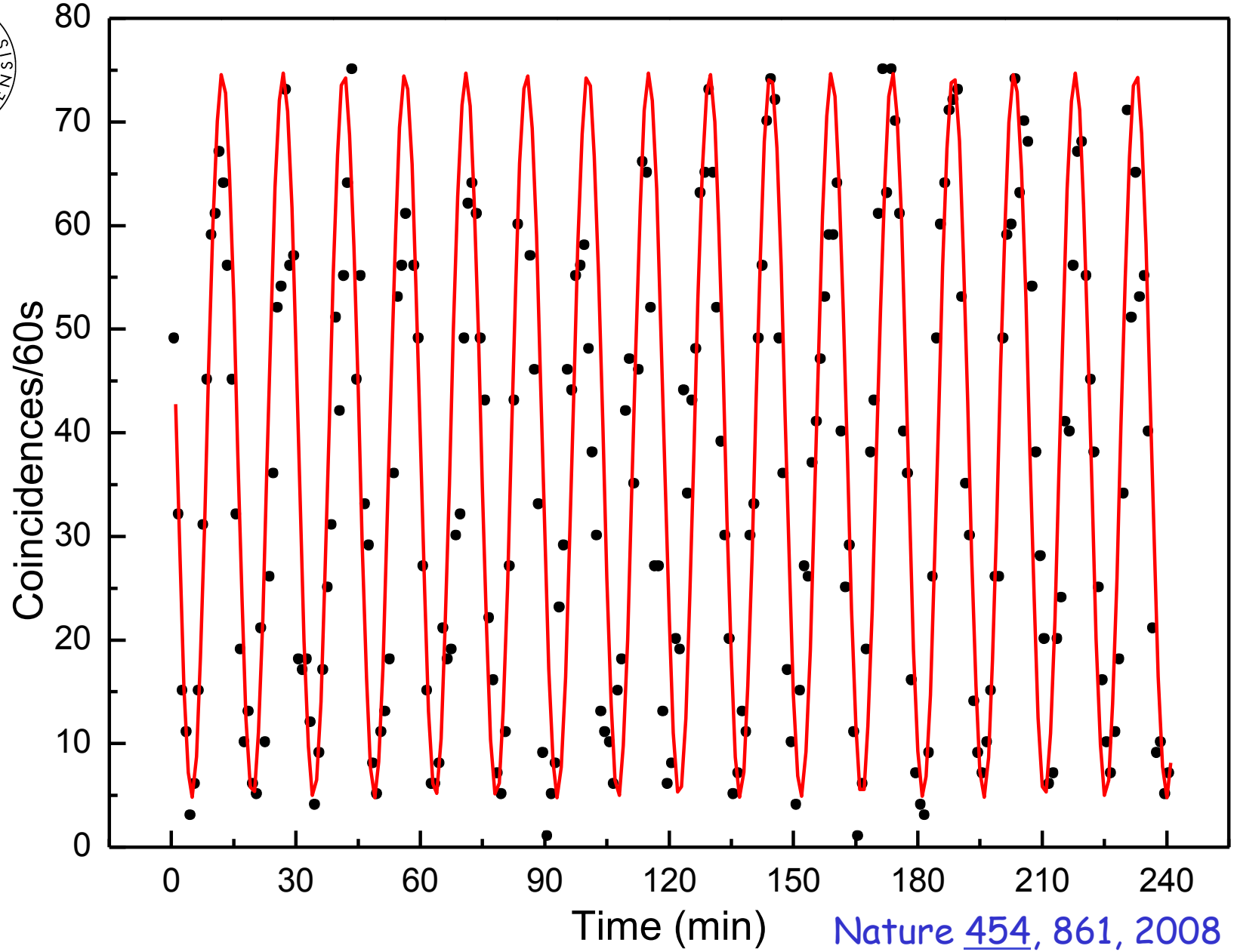

Nature 454, 861, 2008

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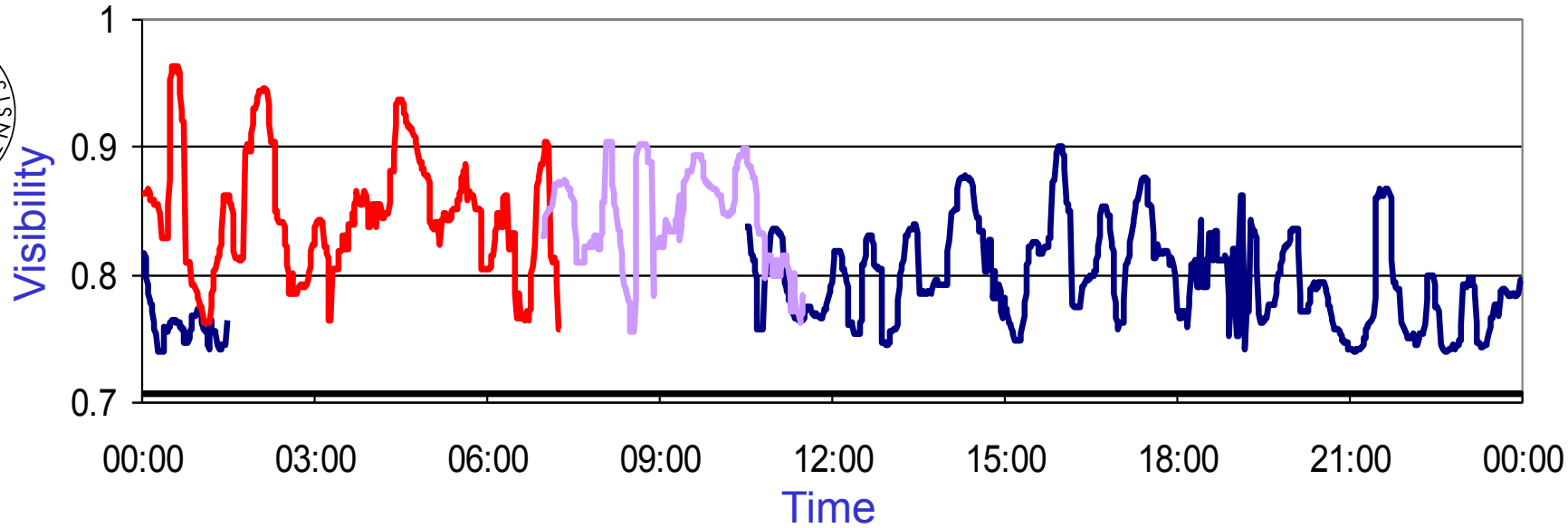
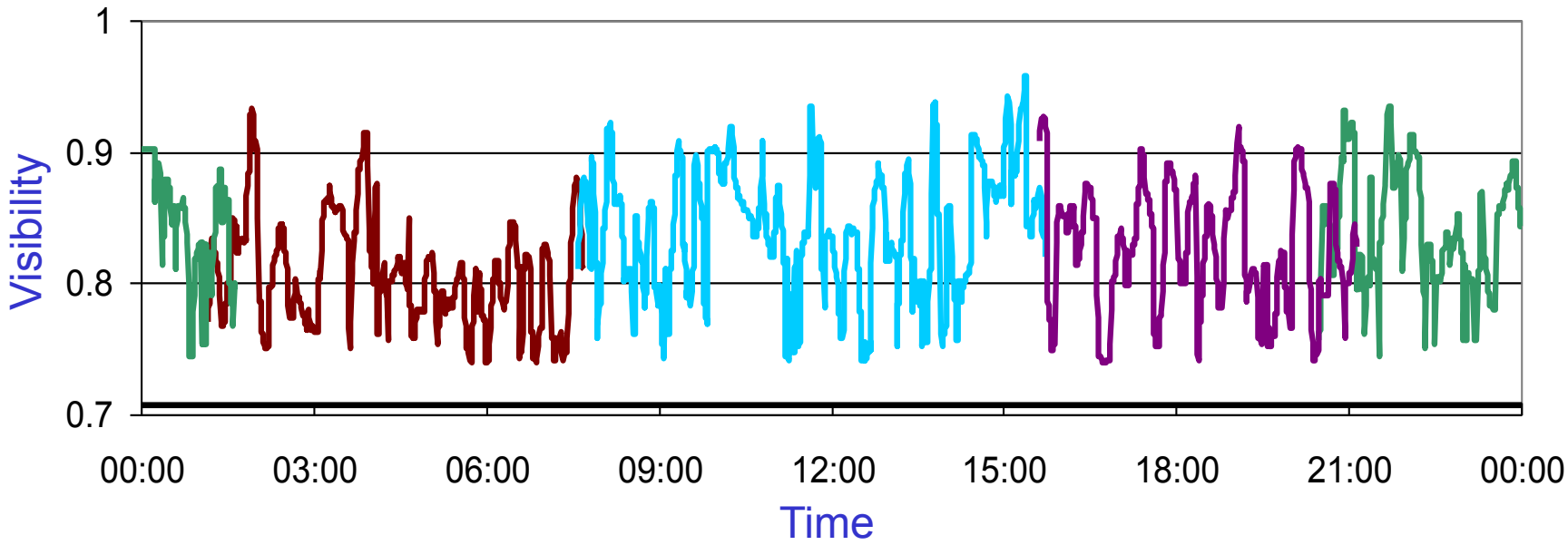




Nature 454, 861, 2008

Finite precision

- The «*Speed of Quantum Information*» V_{QI} is $V_{QI} \geq \dfrac{\left\|\vec{r}_B^{\,'} - \vec{r}_A^{\,'}\right\|}{\left|t_B^{\,'} - t_A^{\,'}\right|}$

- After a Lorentz transformation, one finds

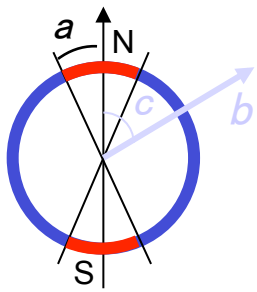
$$\left(\frac{V_{QI}}{c}\right)^2 \geq 1 + \frac{\left(1-\beta^2\right)\left(1-\rho^2\right)}{\left(\rho+\beta_{\|}\right)^2} \underset{\text{if } |\rho| \leq \bar{\rho}}{\geq} 1 + \frac{\left(1-\beta^2\right)\left(1-\bar{\rho}^2\right)}{\left(\bar{\rho}+\left|\beta_{\|}\right|\right)^2}$$

$b = v/c$ is the relative speed of the Earth frame in the privileged frame,

$r = ct_{AB}/r_{AB}$ defines the alignment of the 2 detections in the Earth frame

T = 360 seconds $\bar{\rho}$ **5.4 10^{-6}** $\bar{\rho}$ **5.8^{o}**

time T, during which $|b_{||}(t)|$ is upper-bounded by:



- $\tan\chi > \tan\alpha \Rightarrow \left|\beta_{\|}(t)\right| \leq |\beta| \sqrt{\sin^2\chi\cos^2\alpha - \cos^2\chi\sin^2\alpha}\ \dfrac{\omega T}{2}$
- $\tan\chi < \tan\alpha \Rightarrow \left|\beta_{\|}(t)\right| \leq |\beta| \left(\left|\cos\chi\sin\alpha\right| - \left|\sin\chi\cos\alpha\right|\cos\dfrac{\omega T}{2}\right.$

Nature 454, 861, 2008

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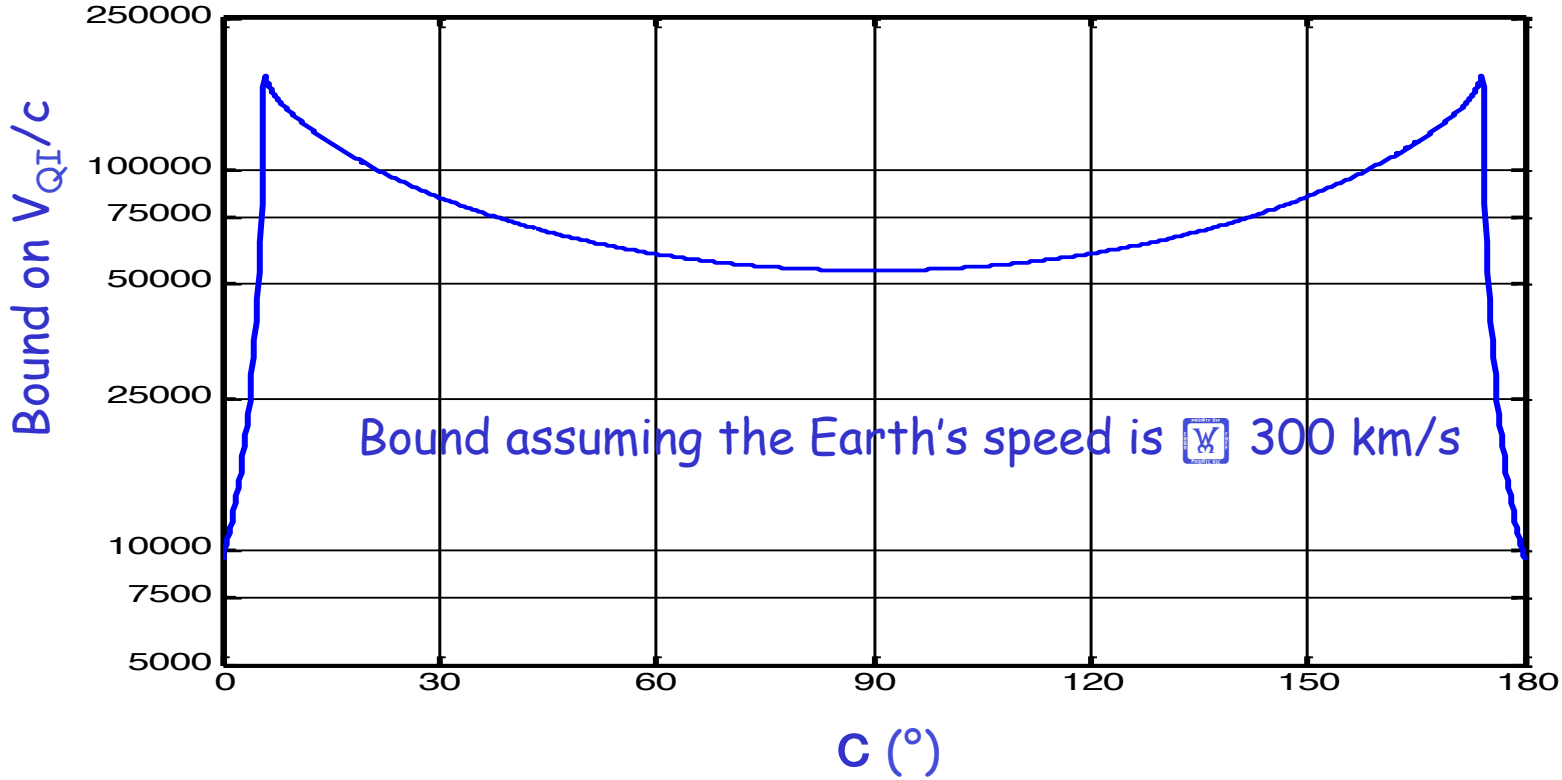

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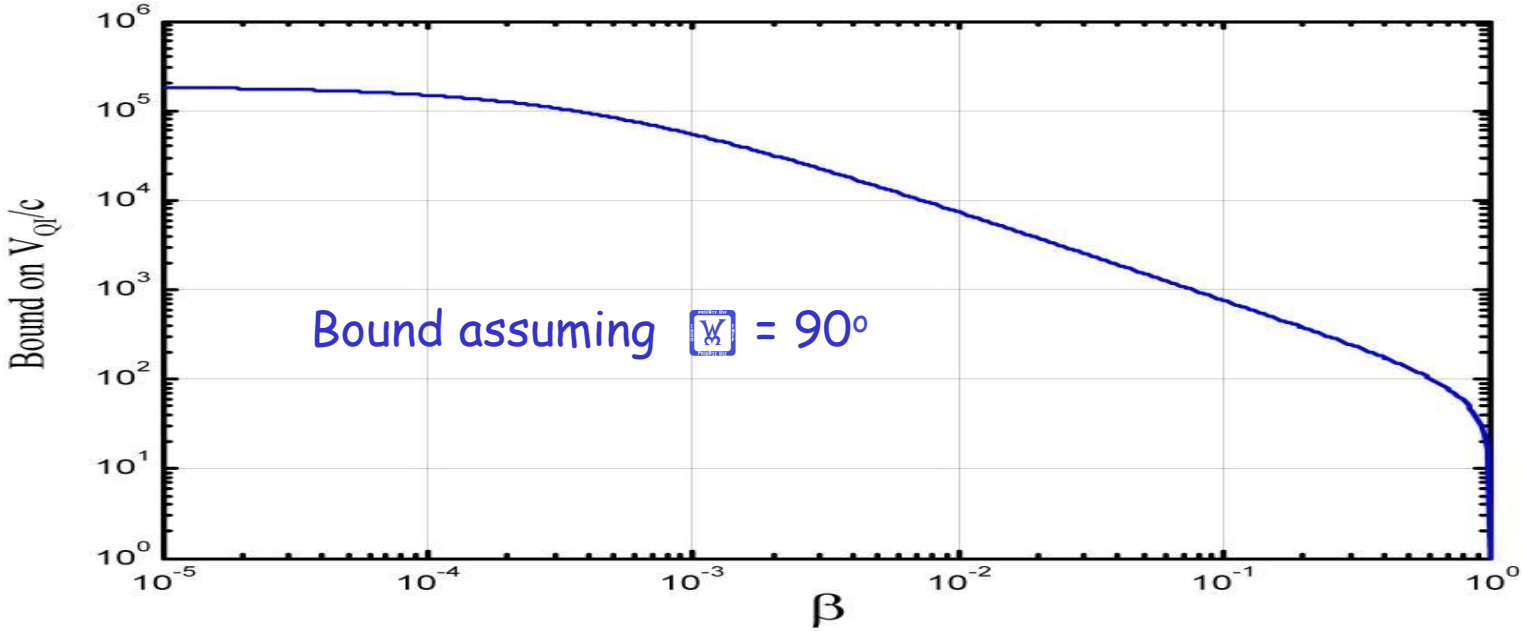
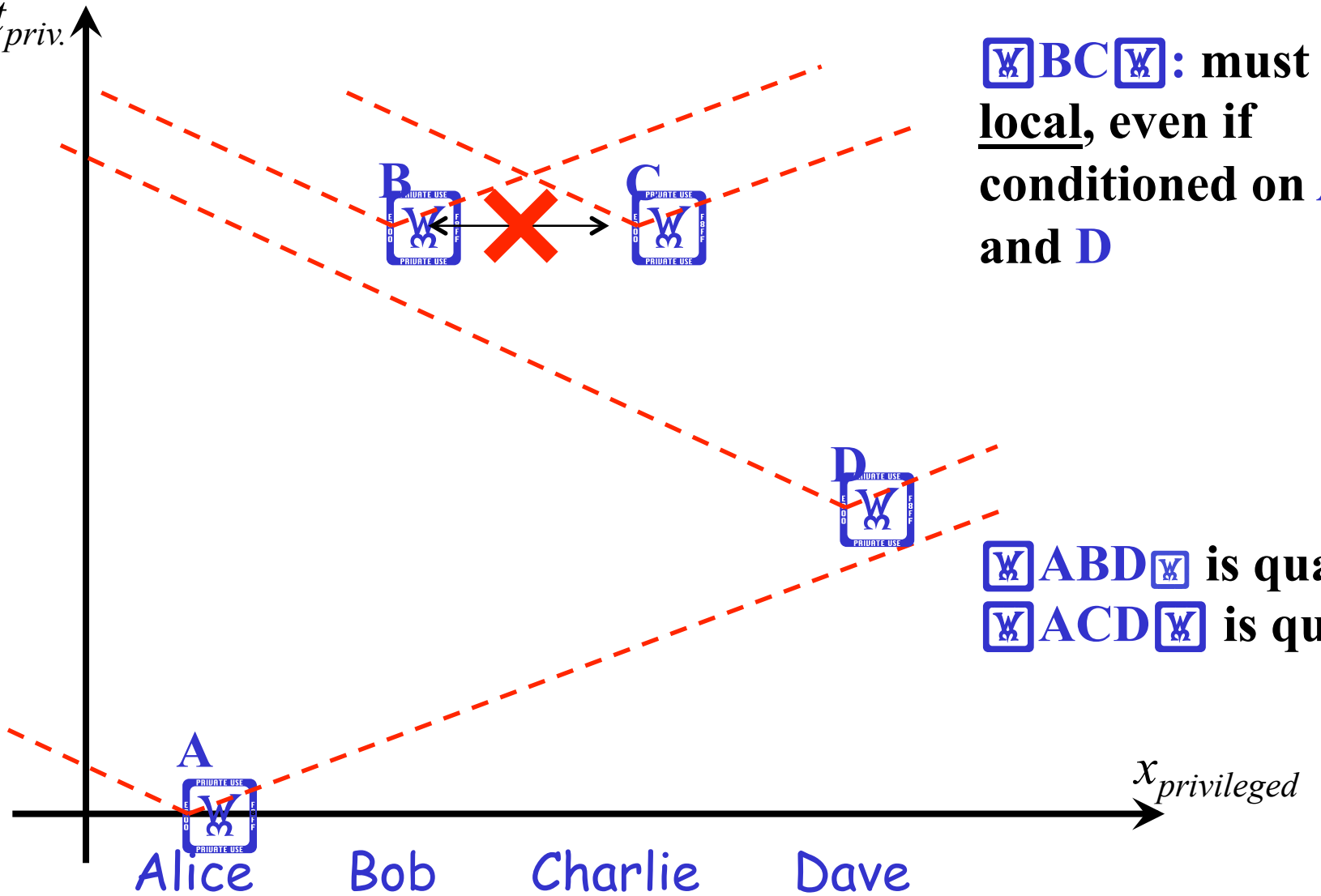


And so ?

- 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.**

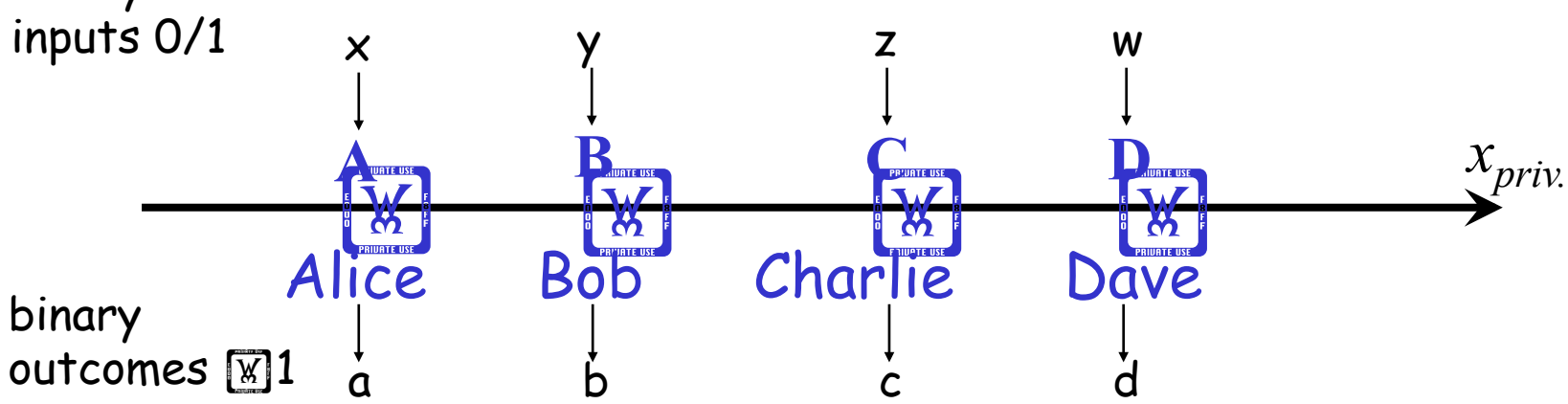
W-causality leads to signalling (1)



W BC W: must be <u>local</u>, even if conditioned on A and D

W ABD W is quantu
W ACD W is quantu

[W]-causality leads to signalling (2)



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

J [W] 7

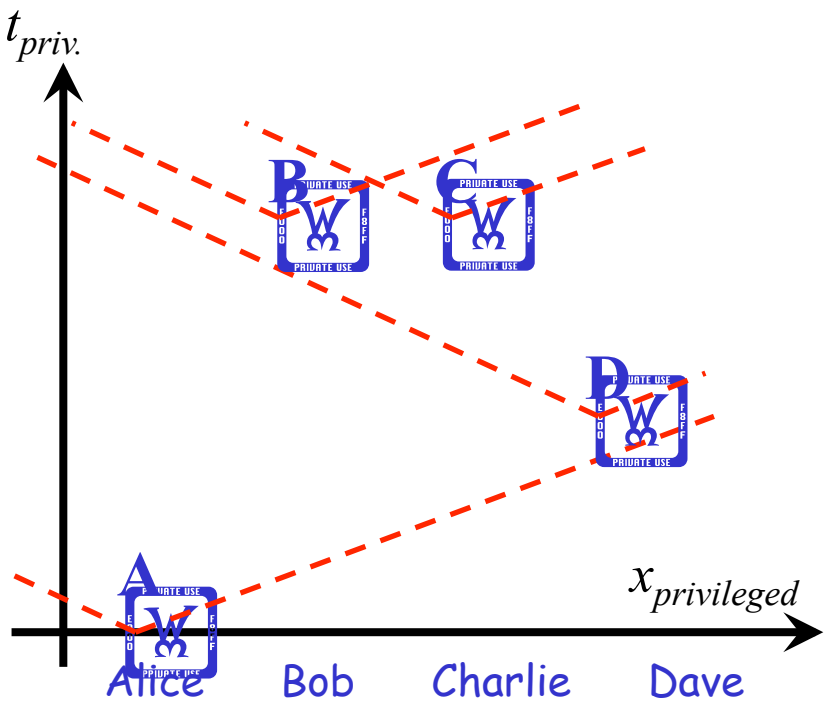
NO BC

Where J = -3[W]A1[W] - [W]B0[W] - [W]B1[W] - [W]C0[W] - 3[W]D0[W] - [W]A1B0[W] - [W]
+ 2[W]A1C0[W] + [W]A0D0[W] + [W]B0D1[W] - [W]B1D1[W] - [W]C0D0[W] - 2[W
+ [W]A0B0D0[W] + [W]A0B0D1[W] + [W]A0B1D0[W] - [W]A0B1D1[W] - [W]A1B
- [W]A1B1D0[W] + [W]A0C0D0[W] + 2[W]A1C0D0[W] + 2[W]A0C1D1[W]

$$J = -3\,W A_0 W - W B_0 W - W B_1 W - W C_0 W - 3\,W D_0 W - W A_1 B_0 W - [$$
$$+ 2\,W A_1 C_0 W + W A_0 D_0 W + W B_0 D_1 W - W B_1 D_1 W - W C_0 D_0 W - 2$$
$$+ W A_0 B_0 D_0 W + W A_0 B_0 D_1 W + W A_0 B_1 D_0 W - W A_0 B_1 D_1 W - W A$$
$$- W A_1 B_1 D_0 W + W A_0 C_0 D_0 W + 2\,W A_1 C_0 D_0 W + 2\,W A_0 C_1 D_1 W$$

NO BC

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



W-causal predictions differ from Q theory, but since J doesn't contain any term involving B and C, the W-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.

W <u>No B-C timing issue</u> !

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

$\mathcal{W}$-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 non-signalling
and p(b,c|y,z, a,x,d,w) is local for all a,x,d,w,
then

$$J \mathrel{\underset{\mathcal{W}}{\leq}} 7$$

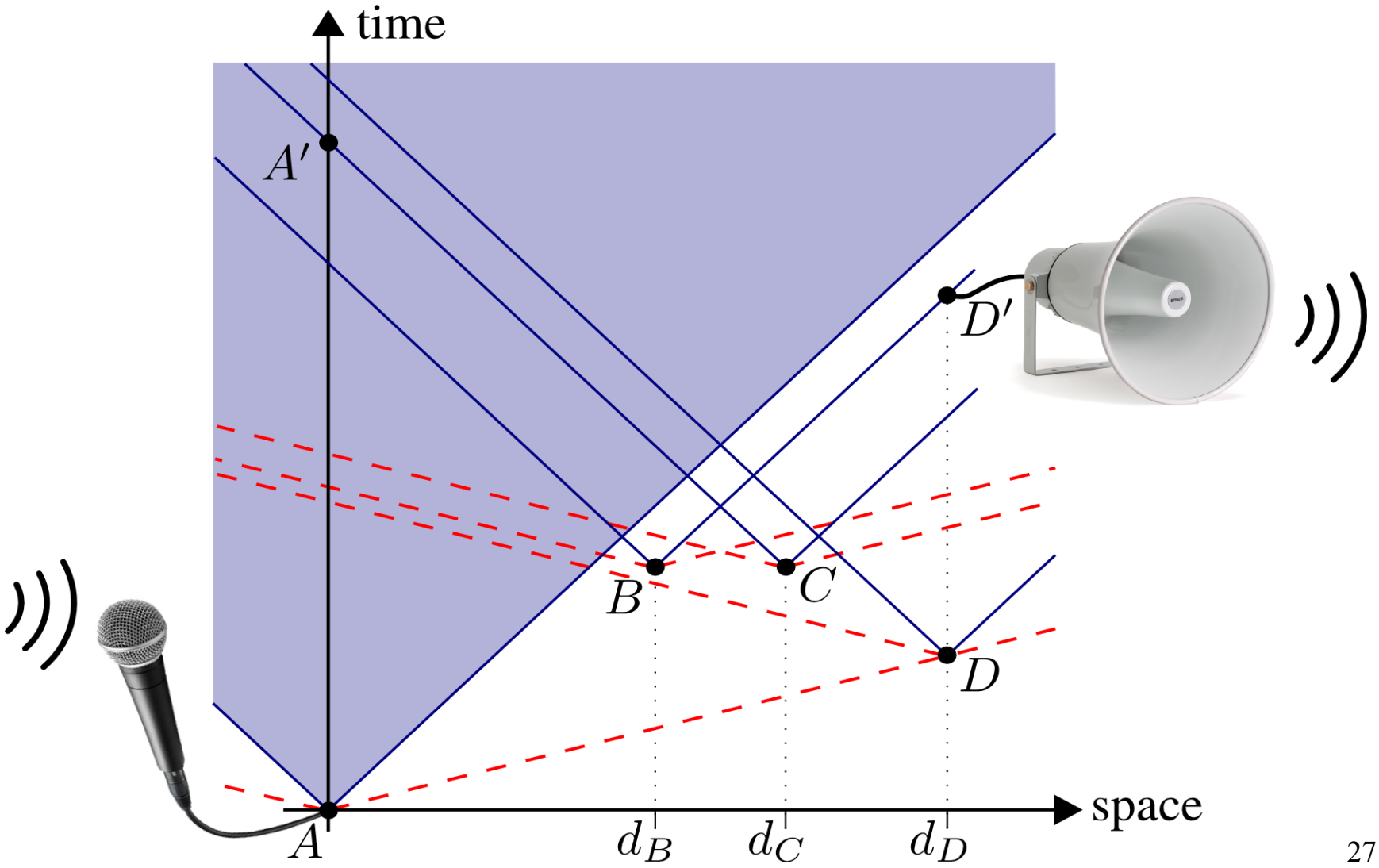
Consequence: Since any *v*-causal model predicts that
p(b,c|y,z, a,x,d,w) is local,
p(a,b,c,d|x,y,z,w) must be signalling.

Note: in *v*-causal models, the hidden influence is carrying the information; hence – here – signalling is not "non-physical communication", but "faster than light comm."

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

W-causality leads to supraluminal communication

at the level of classical inputs and outputs



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Principle of Continuity	
Common Cause	Direct Cause
Explications of correlations by local common causes	Explications of correlations by an event influencing another
Variables	Influences
(hidden)	hidden
Local	Finite speed
Bell's theorem	This talk
Contradiction with quantum predictions	Contradiction with no faster than light communication
Falsified explanation	Falsified explanation
Nature doesn't satisfy the principle of continuity	
Nature is nonlocal	

Conclusion

A violation of the inequality S[illegible]7 implies

<u>either</u> a violation of the principle of continuity,

<u>or</u> the possibility of faster than light communication at the level of the classical

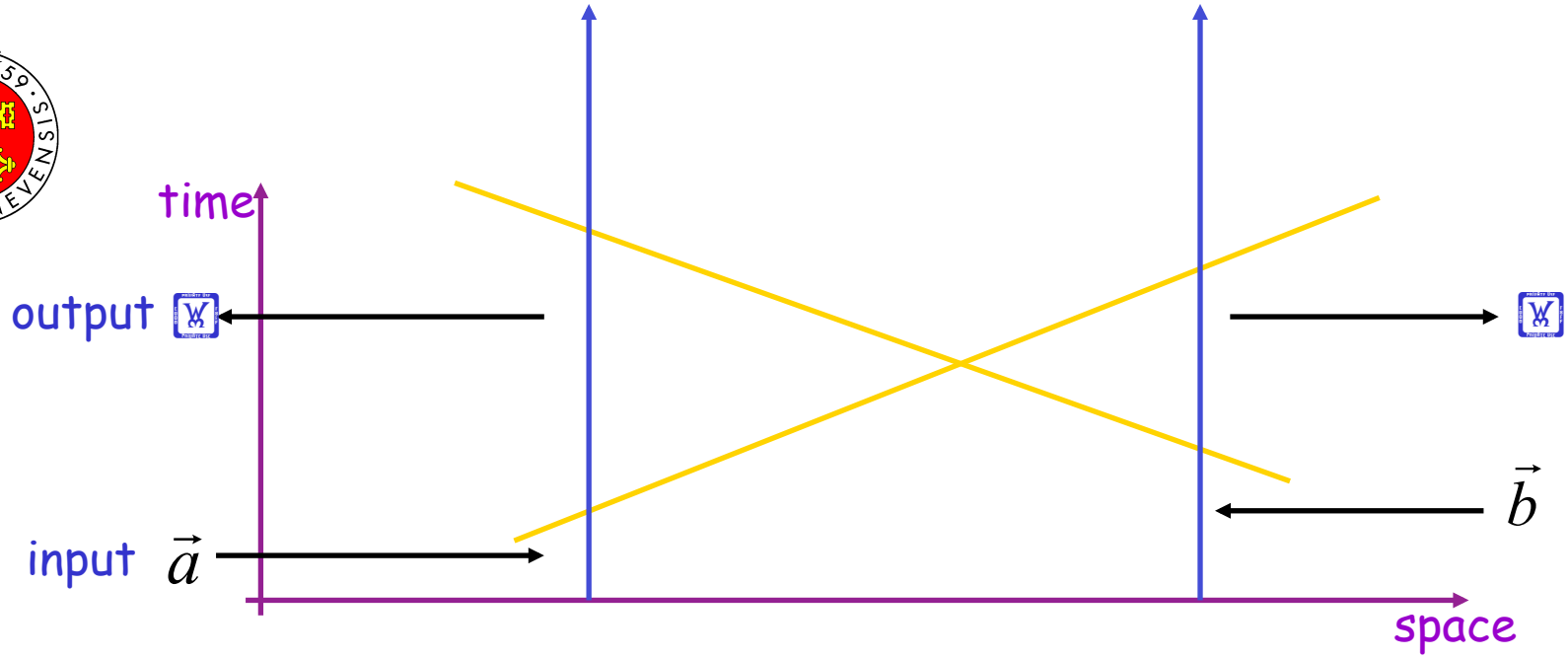
Conclusion:
One should improve the Salart experiment.

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.

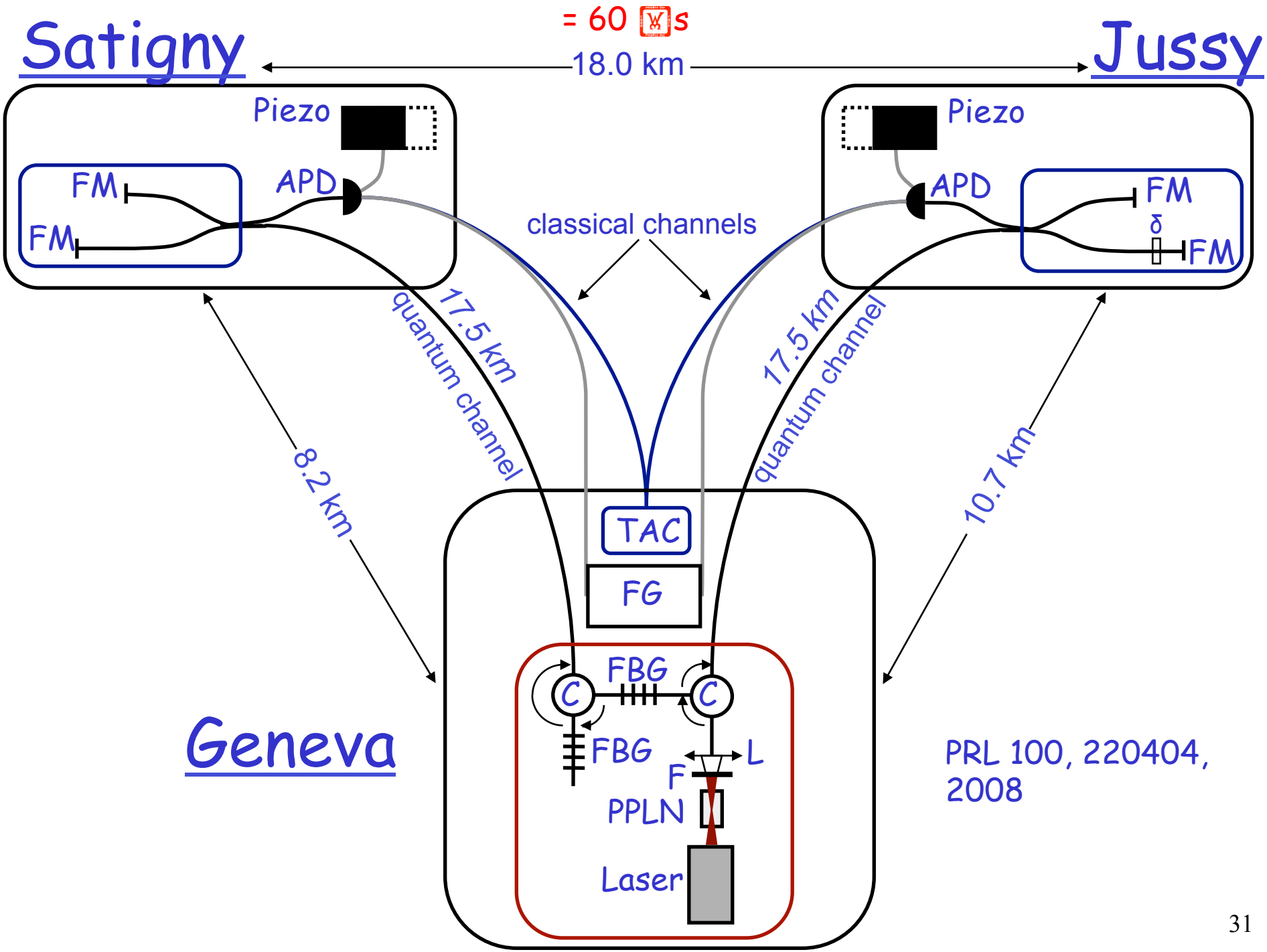
Nature Physics 8, 867-70, 2012; arXiv:1210.7308



- **When is a quantum measurement finished ?**
- Possibly only once a macroscopic mass has significantly moved, as advocated e.g. by Diosi and Penrose.
- In usual Bell tests, detection events only trigger the motion of electrons of insufficient mass to finish the measurement process.

Adrian Kent noticed that according to this plausible assumption, no Bell test so far ensured space-like separation !

A. Kent, arXiv:gr-qc/0507045



PRL 100, 220404, 2008

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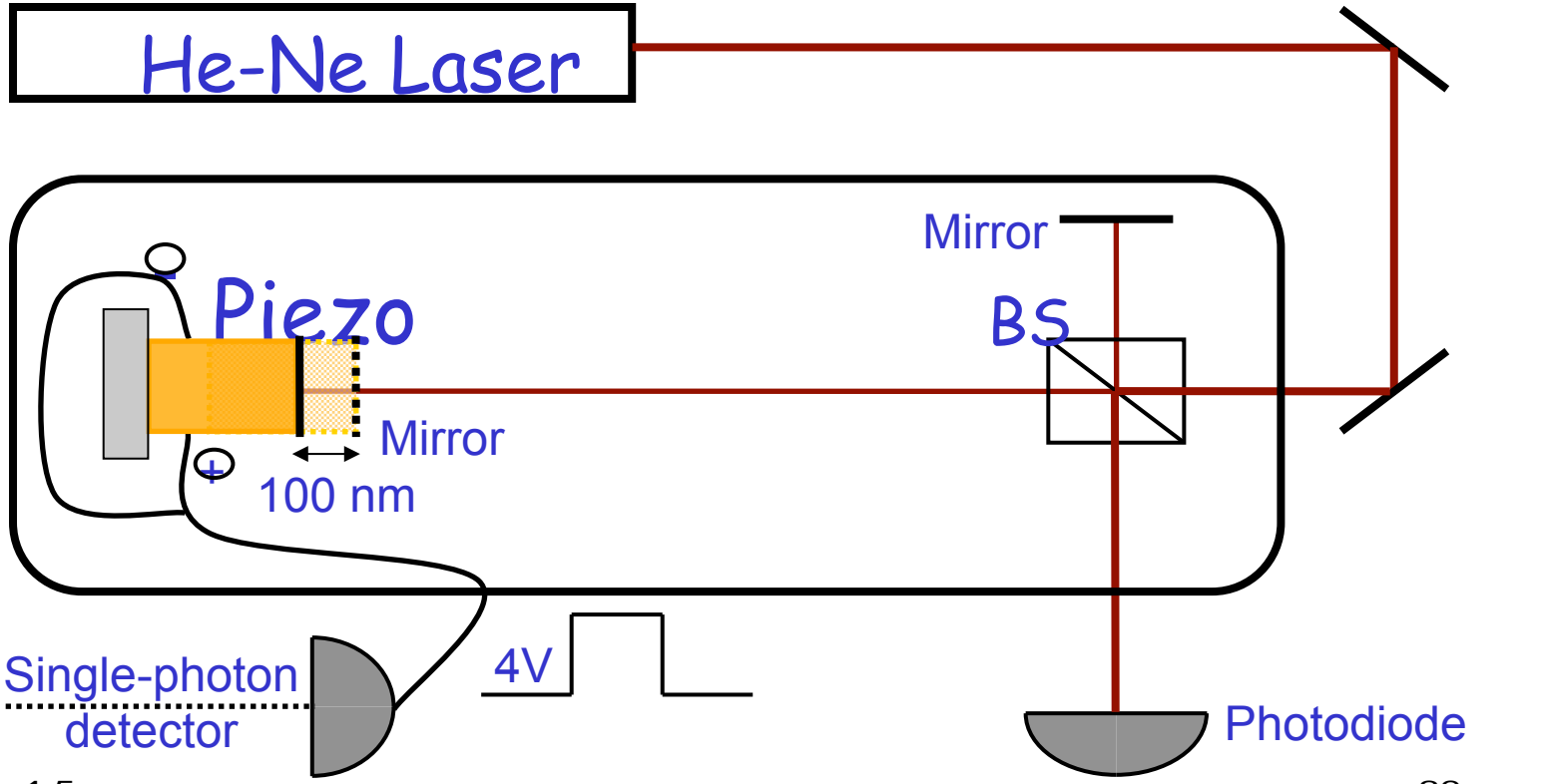
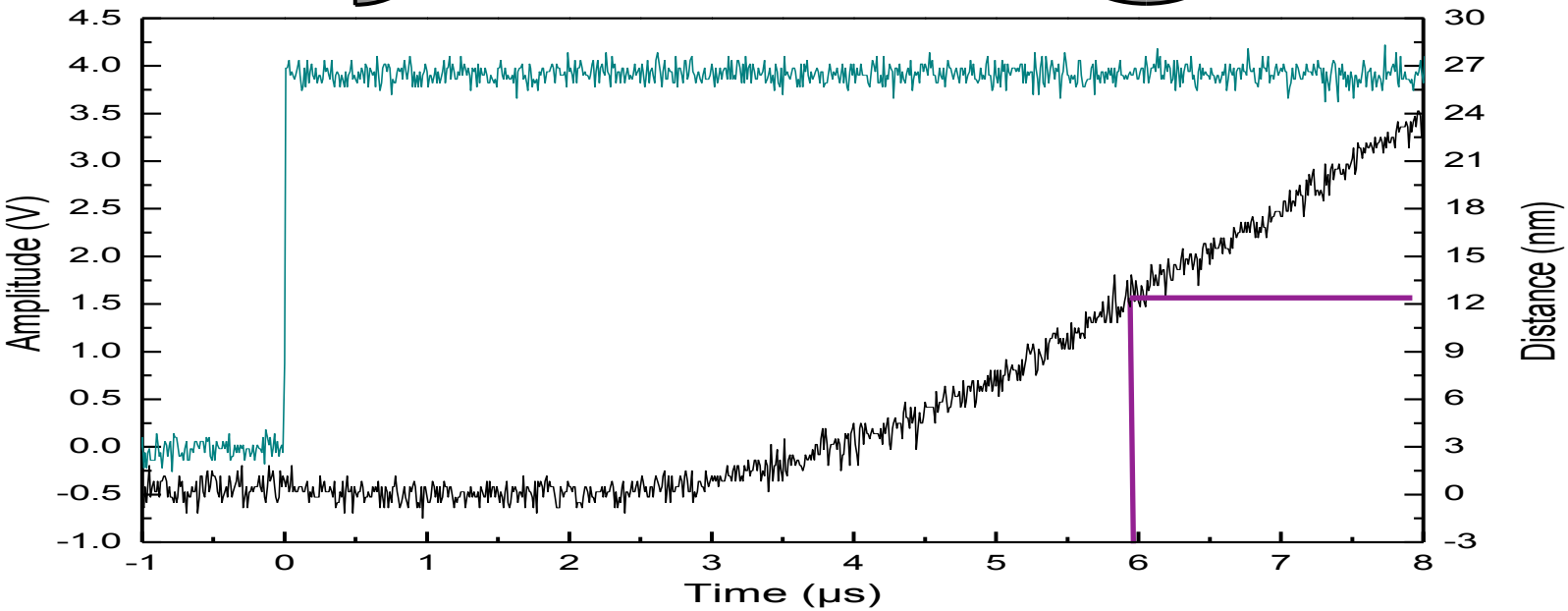




Diosi-Penrose formula for collapse time of the superposition: $\Psi_1 + \Psi_2$

- Diósi's equation

$$\tau_d^{-1} = \frac{Gm^2}{2\hbar} \iint d^3r\, d^3r' \frac{\left(|\psi_1(r)|^2 - |\psi_2(r)|^2\right)\left(|\psi_1(r')|^2 - |\psi_2(r')|^2\right)}{|r - r'|}$$

- For a parallelepiped mirror

$$\tau_d = \frac{3\hbar V}{2\pi G m^2 d^2}$$

- Numerical application in our case

$$\tau_d = 1\mu s$$

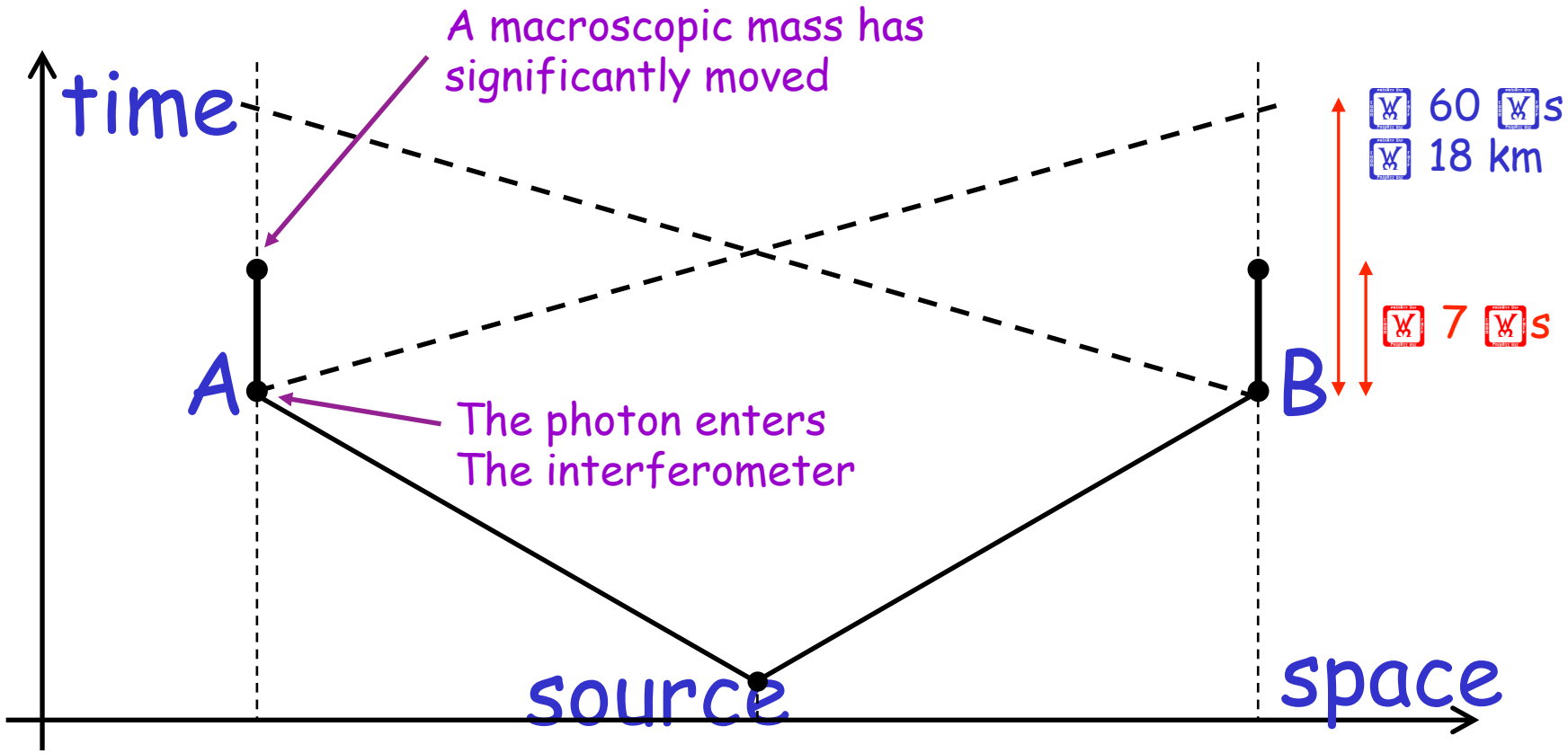
$m = 2 \cdot 10^{-6}\, kg$

$d = 12.6\, nm$

$V = 3\, mm \times 2\, mm \times 0.15\, mm = 9 \cdot 10^{-10}\, m^3$

S. Adler, J.Phys. A40, 755 (2007)

Bell test with true space-like separation



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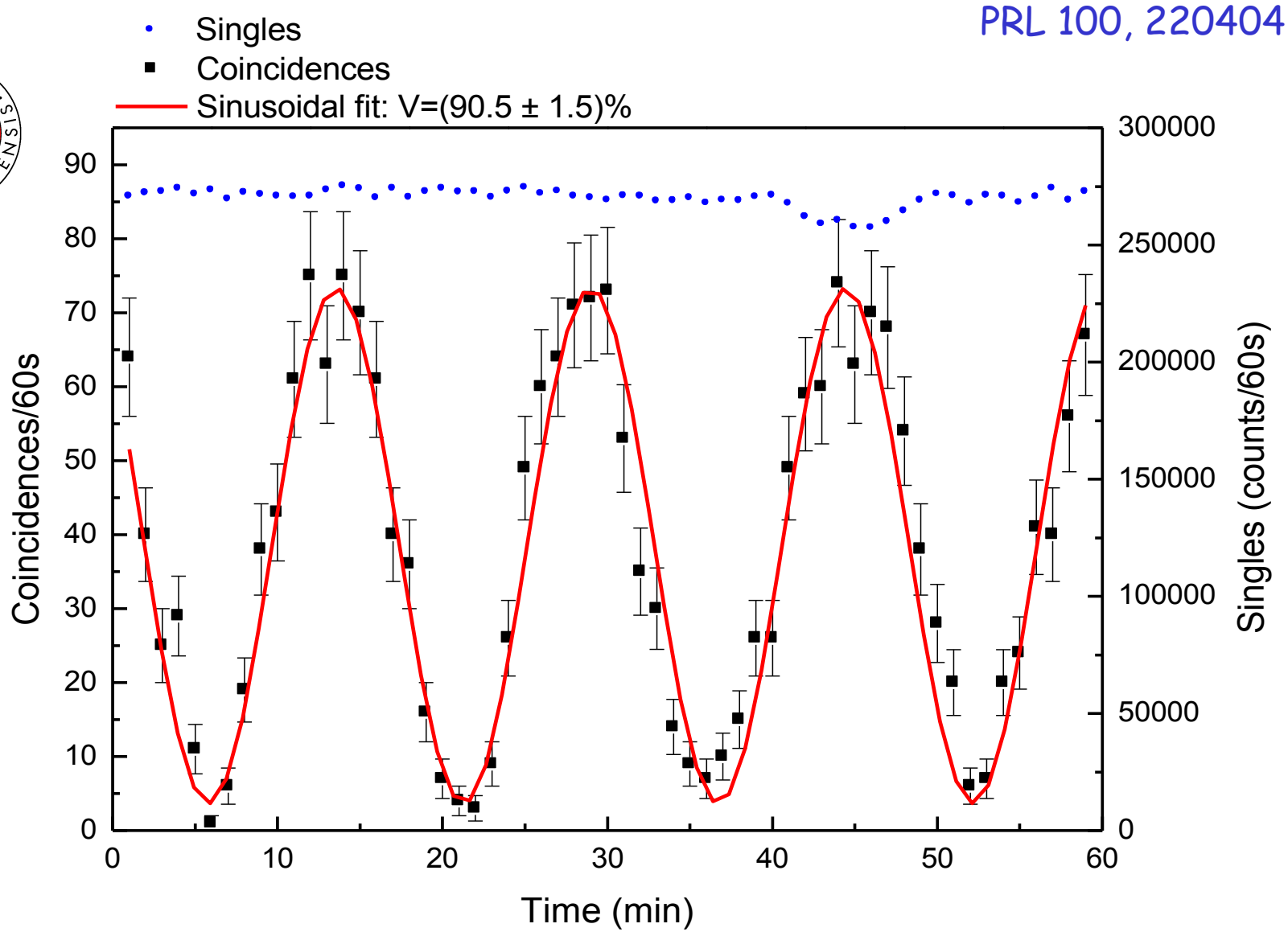
quant-ph/0803.2425
PRL 100, 220404, 2008

PRL 100, 220404, 2008



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Visibility > 90% ⇒ nonlocal correlations between truly space-like separated events.

Assume the frames are determined locally by the massive choice devices

- **<u>Intuition</u>: locally, choices are made by Nature taking into account all events in the past relative to the inertial frame of the choice device**

¨Two choice devices can be in relative motion such that each

detects a particle from an entangled pair

<u>before the other</u> !?!?

- Possibility to perform a different kind of test !!!

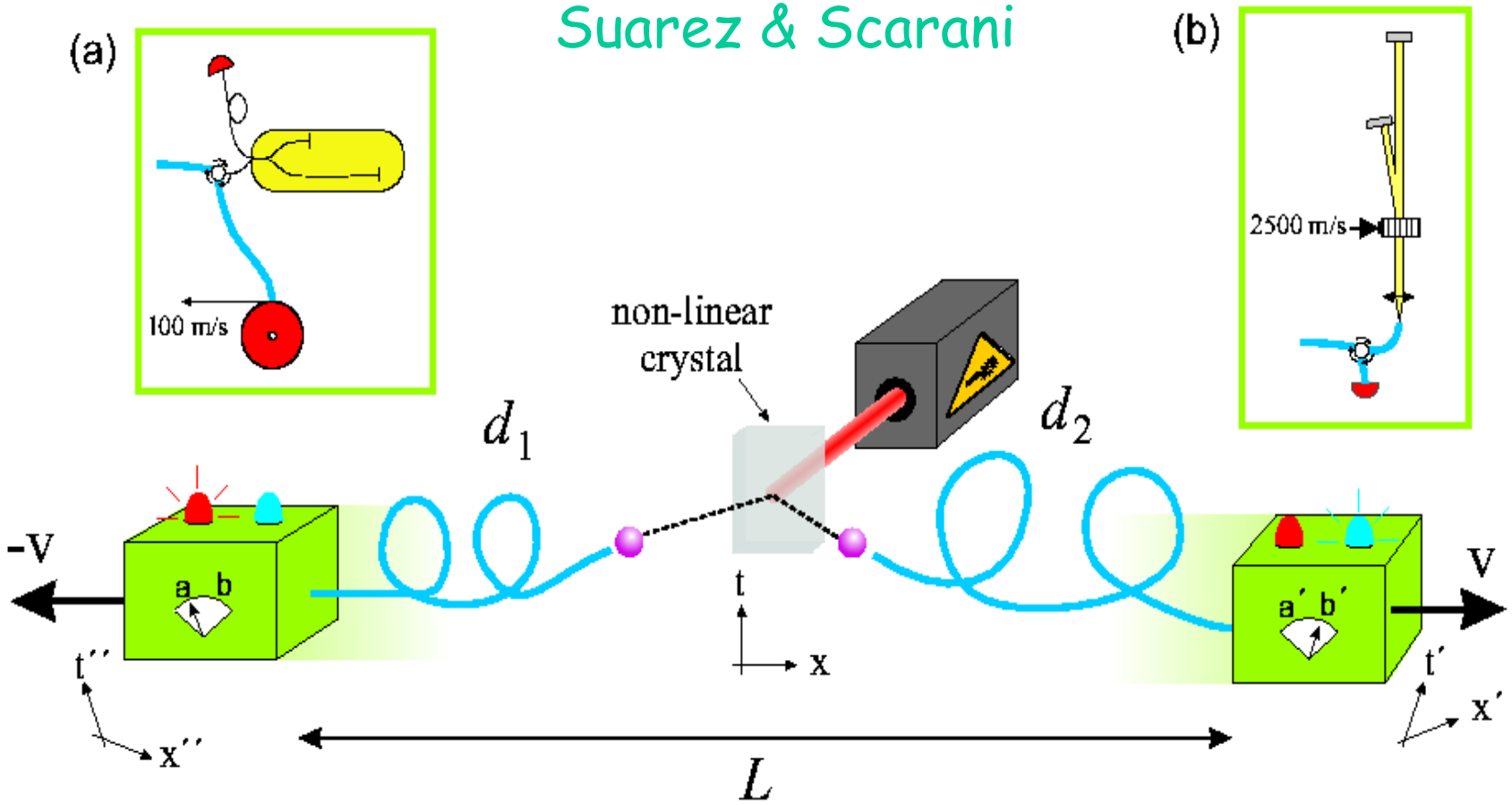
- In a before-before experiment, both particles make independent random choices,
  - the correlation should disappear.

A. Suarez and V. Scarani, Phys. Lett. A <u>232</u>, 9, 1997

Further experiments: before-before configurations

NG, Sundays in a quantum engineer's life, quant-ph/0104140
in *Quantum [Un]speakable*, pp 199-208, ed. R.A. Bertlmann and A. Zeilinger, Springer 200

Suarez & Scarani



PRL 88,120404,2002; J.Phys.A 34,7103,2001; Phys.Lett.A 276,1,2000

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Experimental Conclusion

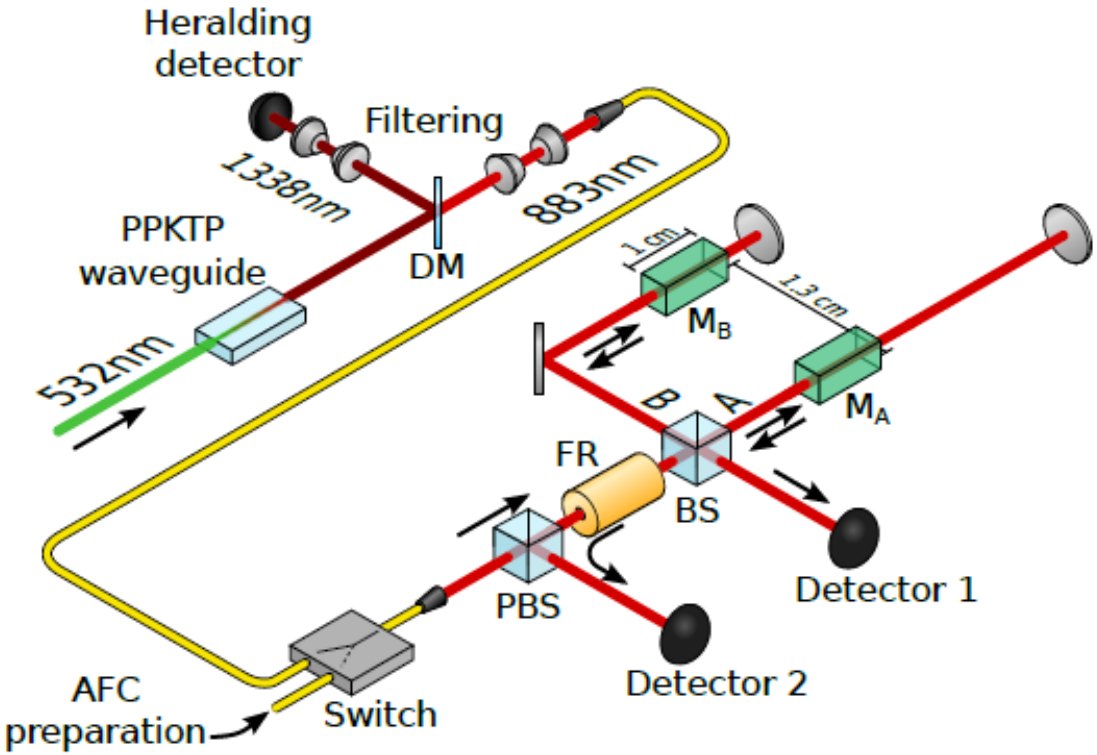
From all the performed experiments one has to conclude that quantum correlations can't be explained as time-ordered events.

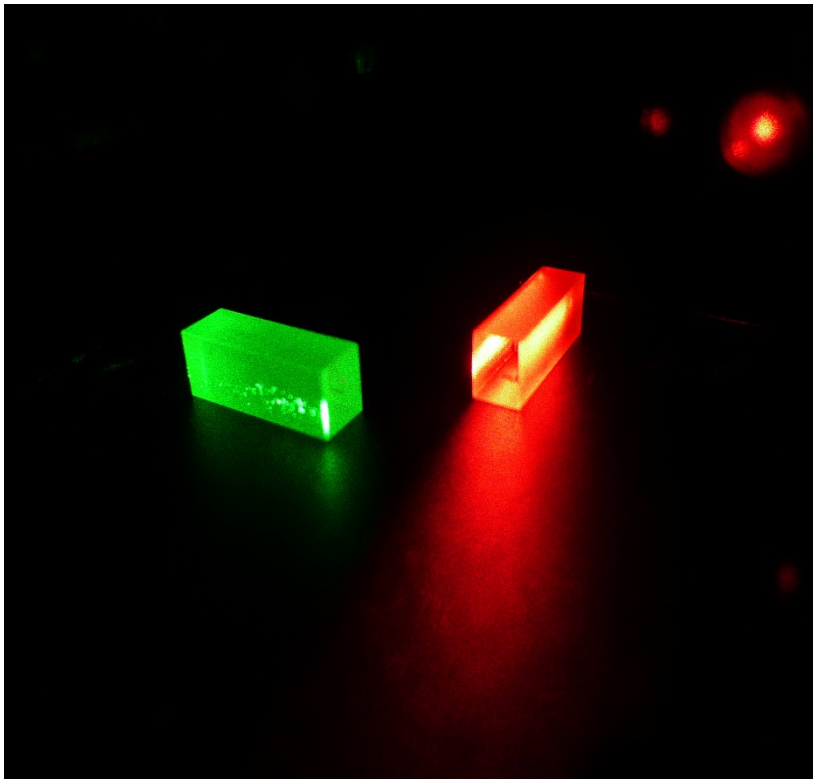
- There is no spooky action at a distance: there is not a first event that influences a second event.
- Quantum correlation just happen, somehow from outside space-time :
  there is no story in space-time that tell us how it happens !
- Or one needs to enlarge our story-toolbox with something like: one random event may manifest itself at several locations

… or … the influences propagate at surprisingly large speeds

Can the entangled crystals be seen as macroscopic entanglement ?

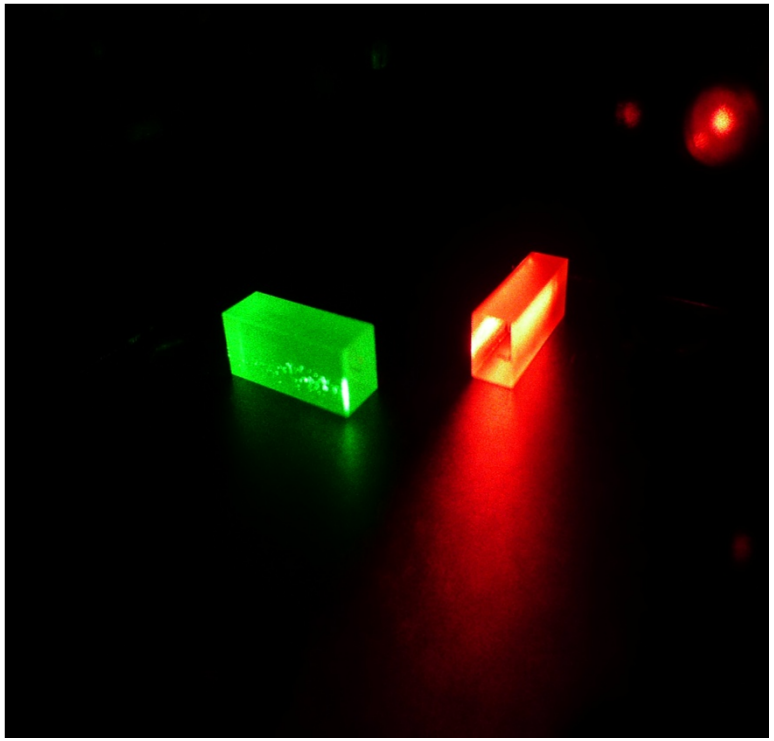
Nature Photonics
6, 234-7, 2012





What is macroscopic ?
What is quantum ?

- Quantum = entanglement.
- Do these 2 crystals count as large entanglement? No !
- Billions of ions in a macroscopic object, but “only” one - delocalized - excitation



Nature Photonics 6, 234-7, 2012

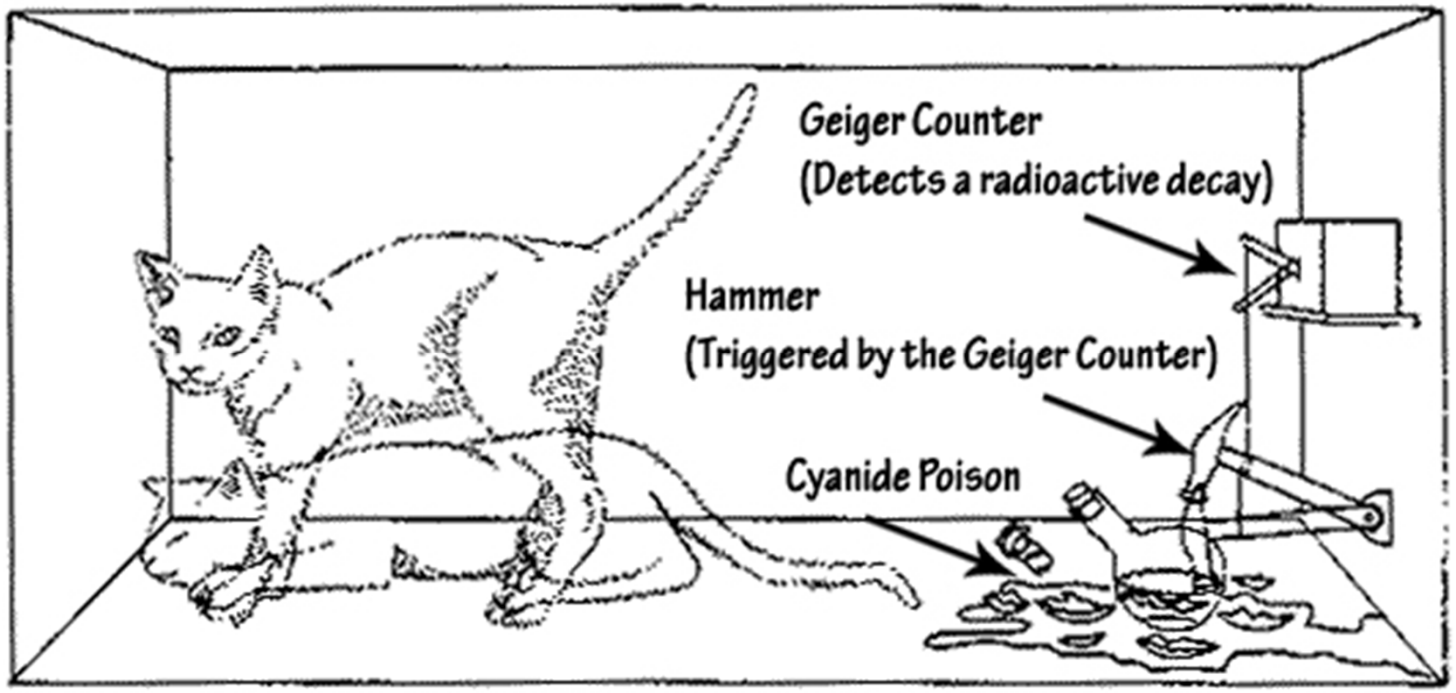
What is Large Entanglement

- Many e-bits (=bits of entanglement).
- Large distance (but this is not the topic I like to discuss today).
- Large mass and/or large number of particles.
- Large number of excitations.
- Large number of parties.
- Sensitive to some form of decoherence

$\Rightarrow$ Large Entanglement has many facets

How difficult is it to prove quantumness of macroscopic states,
P. Sekatski, N. Gisin and N. Sangouard, PRL 113, 090403 (2014)
The size of quantum superposition as measured with "classical" detectors,
P. Sekatski, N. Sangouard and N. Gisin, PRA 89, 012116 (2014)

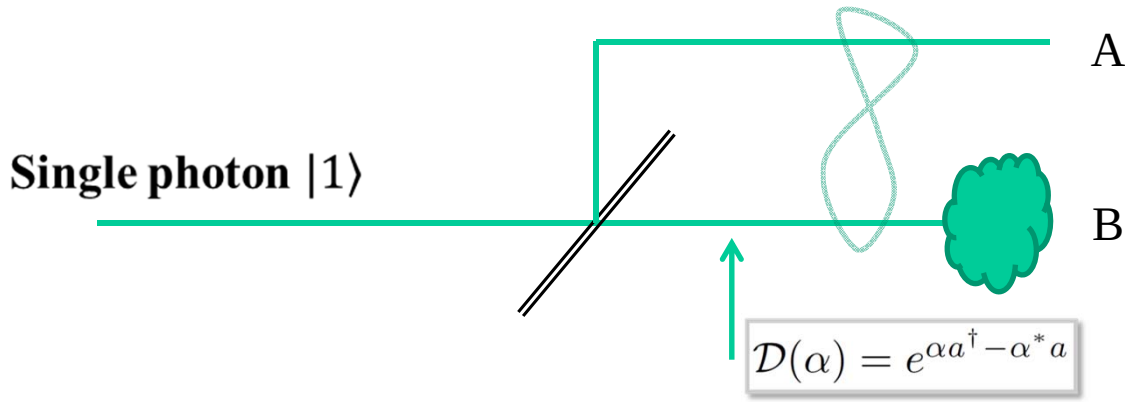
Large Entanglement is *not* invariant under local unitaries



$$\frac{1}{\sqrt{2}}\left(|0\rangle|1\rangle - |1\rangle|0\rangle\right) \xrightarrow[\text{evolution}]{\text{Local}} \frac{1}{\sqrt{2}}\left(|0\rangle|dead\rangle - |1\rangle|alive\rangle\right)$$

The notion of large entanglement is a local property and cannot be invariant under Local Unitaries, contrary to entanglement!

Example: displaced single photon



Displaced single photon entanglement: $|1\rangle_A \underbrace{|\alpha\rangle_B}_{|\Psi_0\rangle} + |0\rangle_A \underbrace{\mathcal{D}(\alpha)|1\rangle_B}_{|\Psi_1\rangle}$

P. Sekatski et al., Phys. Rev. A 86, 060301 (2012)

N.Bruno et al._, arXiv:1212.3710
Nature Physics 9,545 (2013)

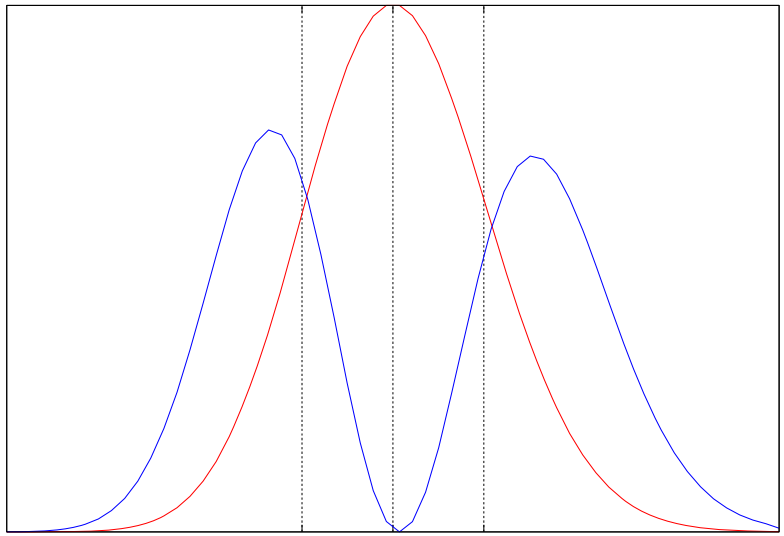
A.I. Lvovski et al., arXiv:1212.3713
Nature Physics 9, 541 (2013)

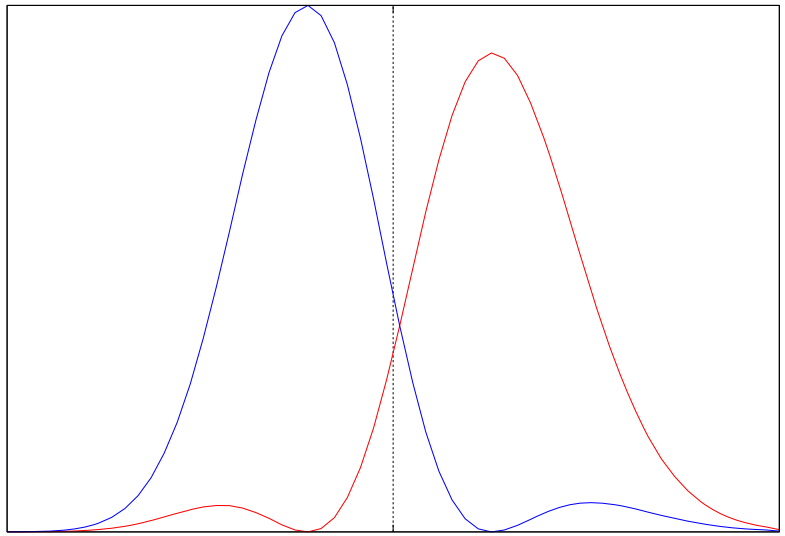
Distinguishability with a classical detector

$$|0\rangle \otimes D(\alpha)|1\rangle + |1\rangle \otimes |\alpha\rangle = |+\rangle \otimes \Psi_- + |-\rangle \otimes \Psi_+$$

Where $\Psi_\pm = D(\alpha)|1\rangle \pm |\alpha\rangle$

Photon number distribution



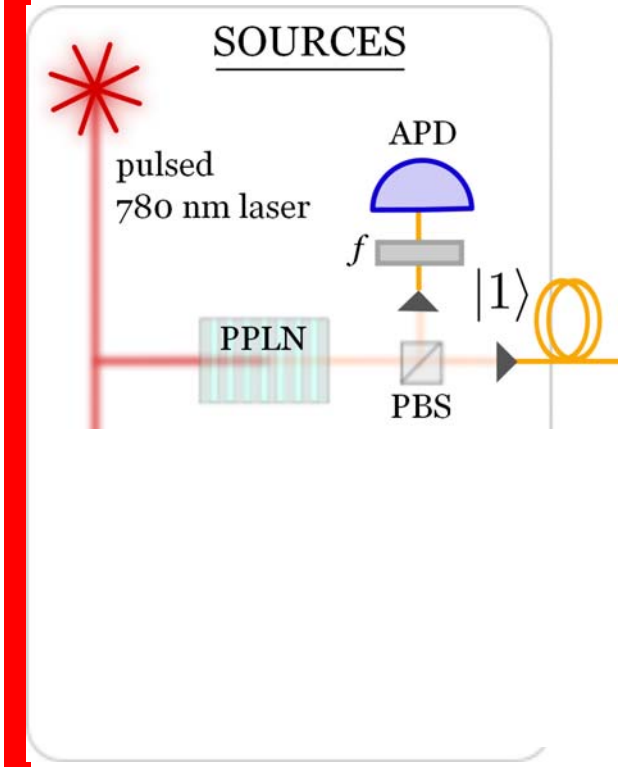


For $|\alpha|^2 >> \Delta$, Pguess $\cong 74\%$ For $|\alpha|^2 >> \Delta$, Pguess $\cong 89\%$

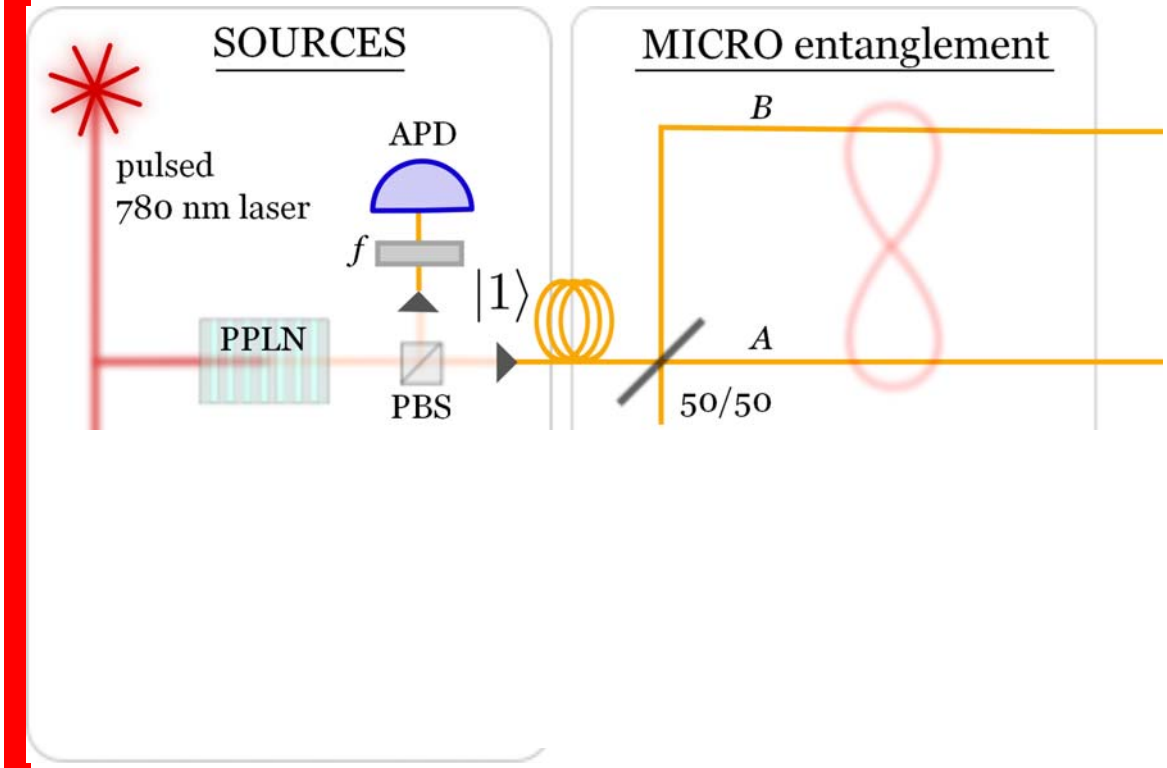
P. Sekatski et al., Phys. Rev. A 86, 060301 (2012)

N.Bruno et al._, arXiv:1212.3710, Nature Physics 9, 545 (2013)

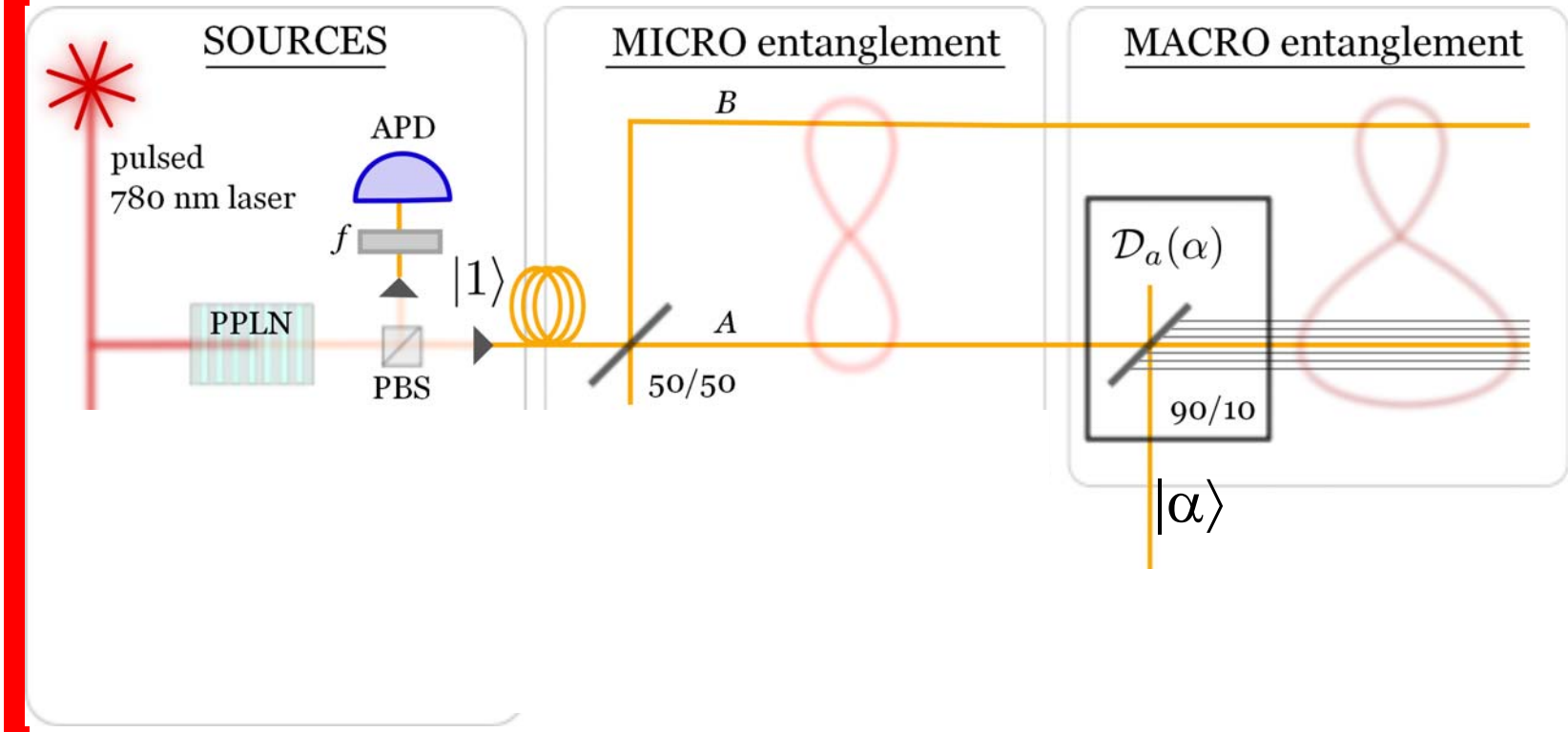
Experiment: sources



Experiment: 1-ν entanglement

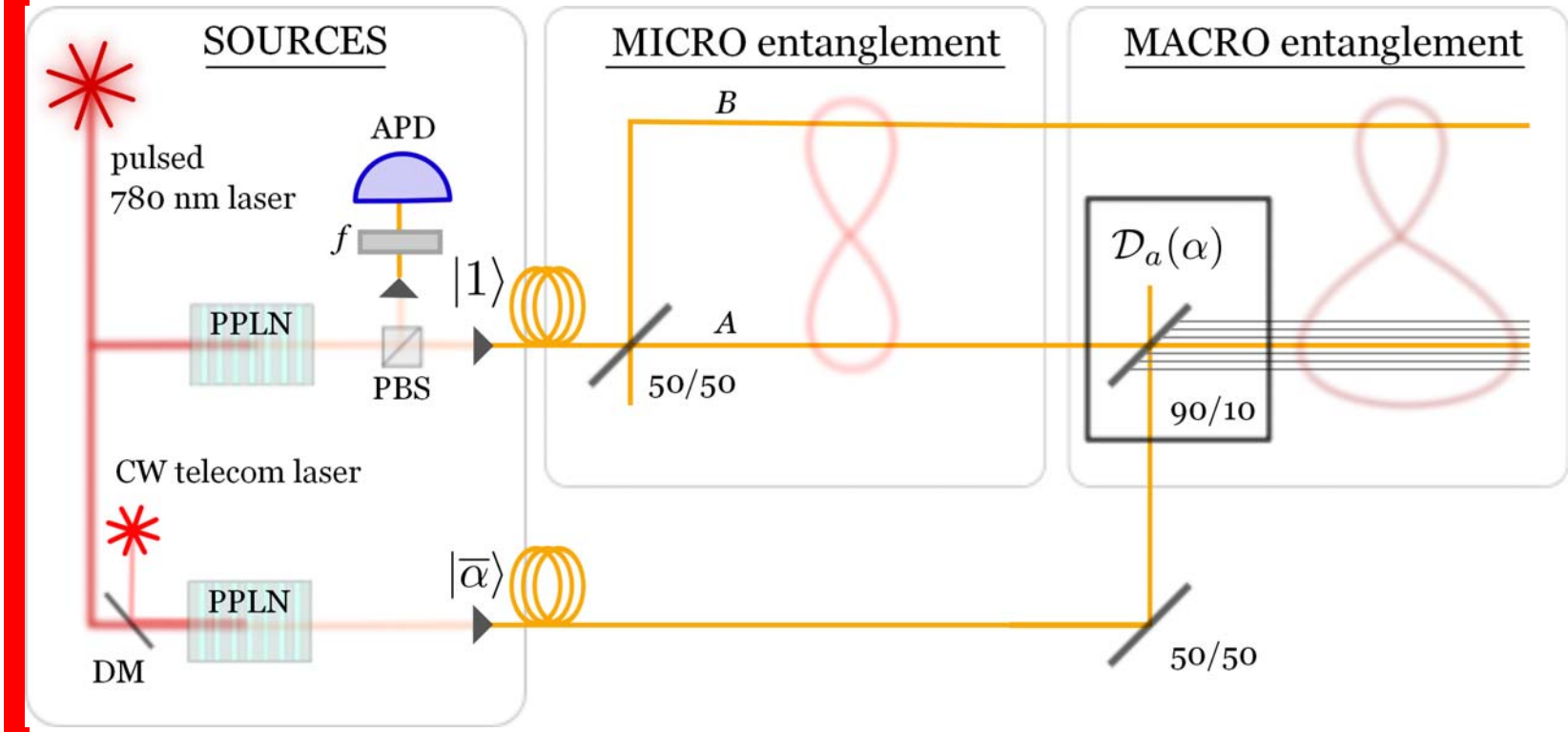


Experiment: Large Entanglement



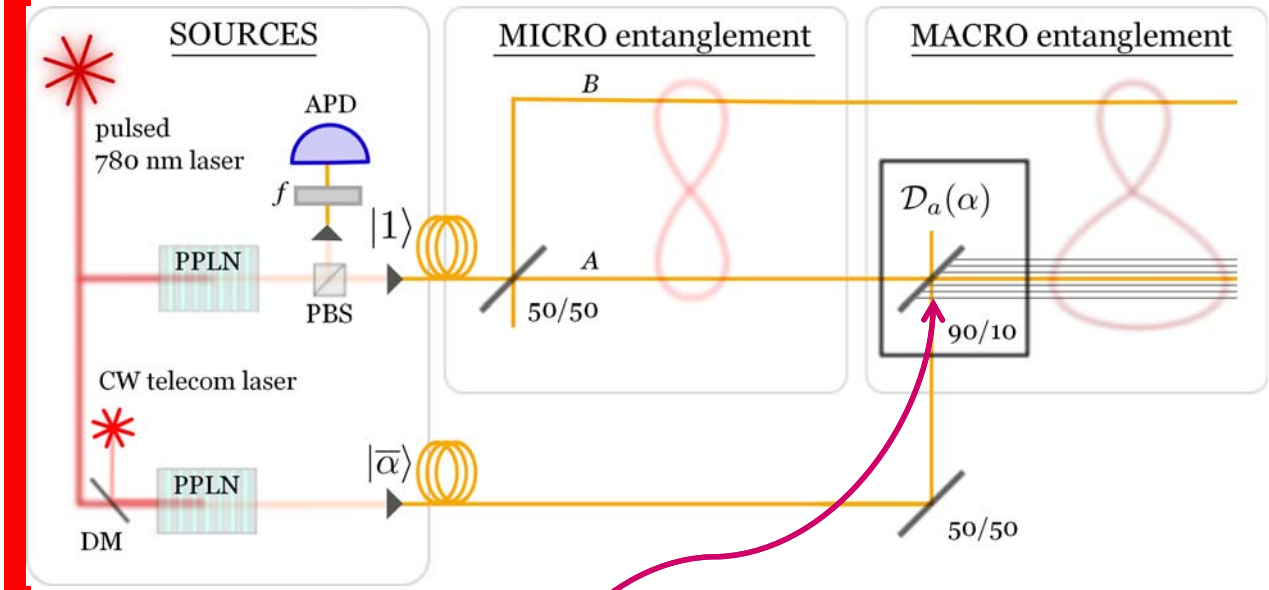
Need to check that we didn't merely put an elephant next to a singlet

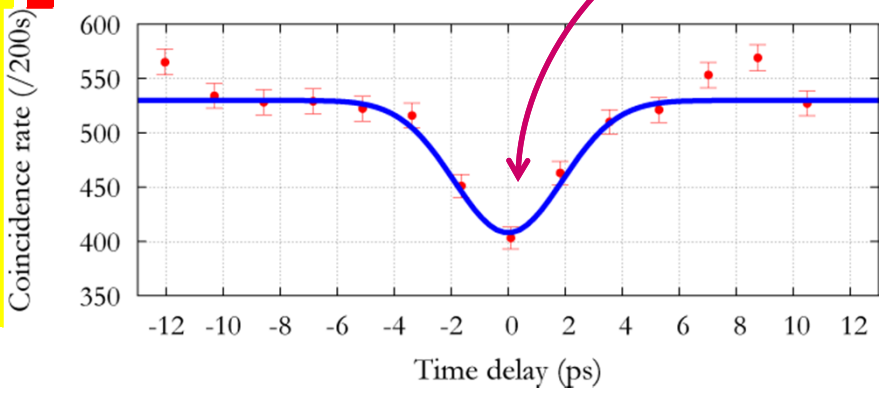
Experiment: Large Entanglement



Need to check that we didn't merely put an elephant next to a singlet

More than merely an elephant next to a singlet



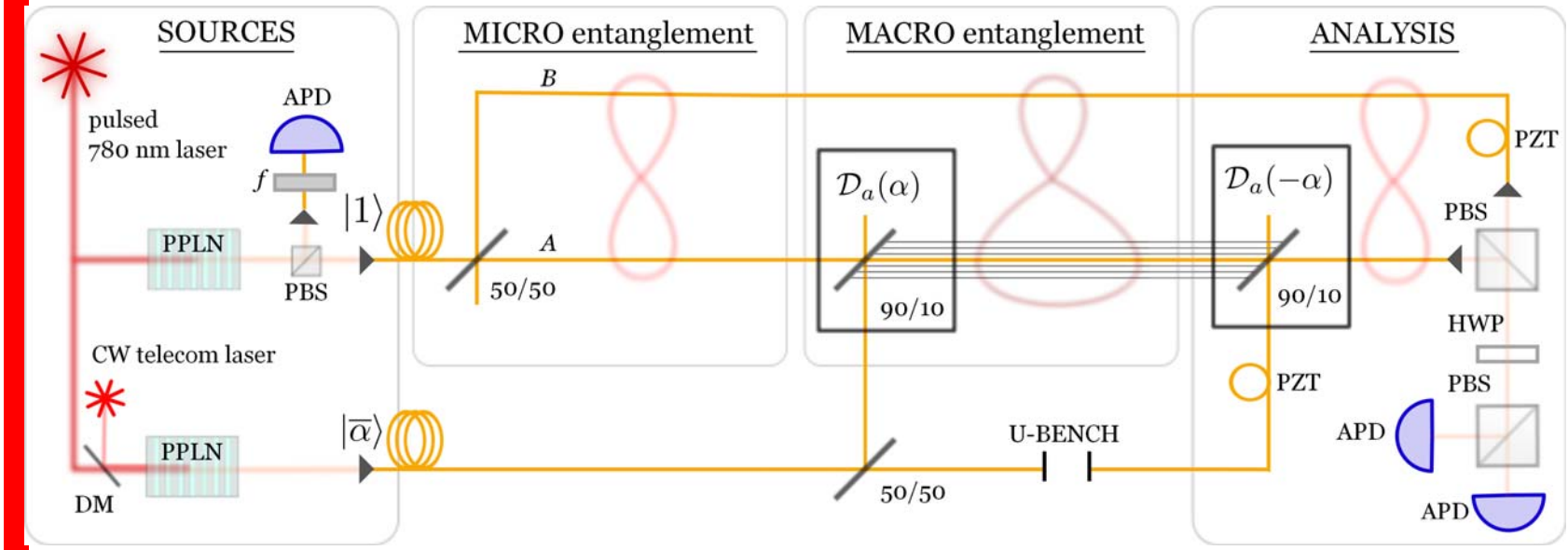


$V_{exp} = 0.23 \pm 0.04$

Mainly limited by 90/10 coupler

N.Bruno et al., *arXiv:1212.3710*, *Nature Physics* 9, 545 (2013)

Experiment: demonstrate Large Entanglement

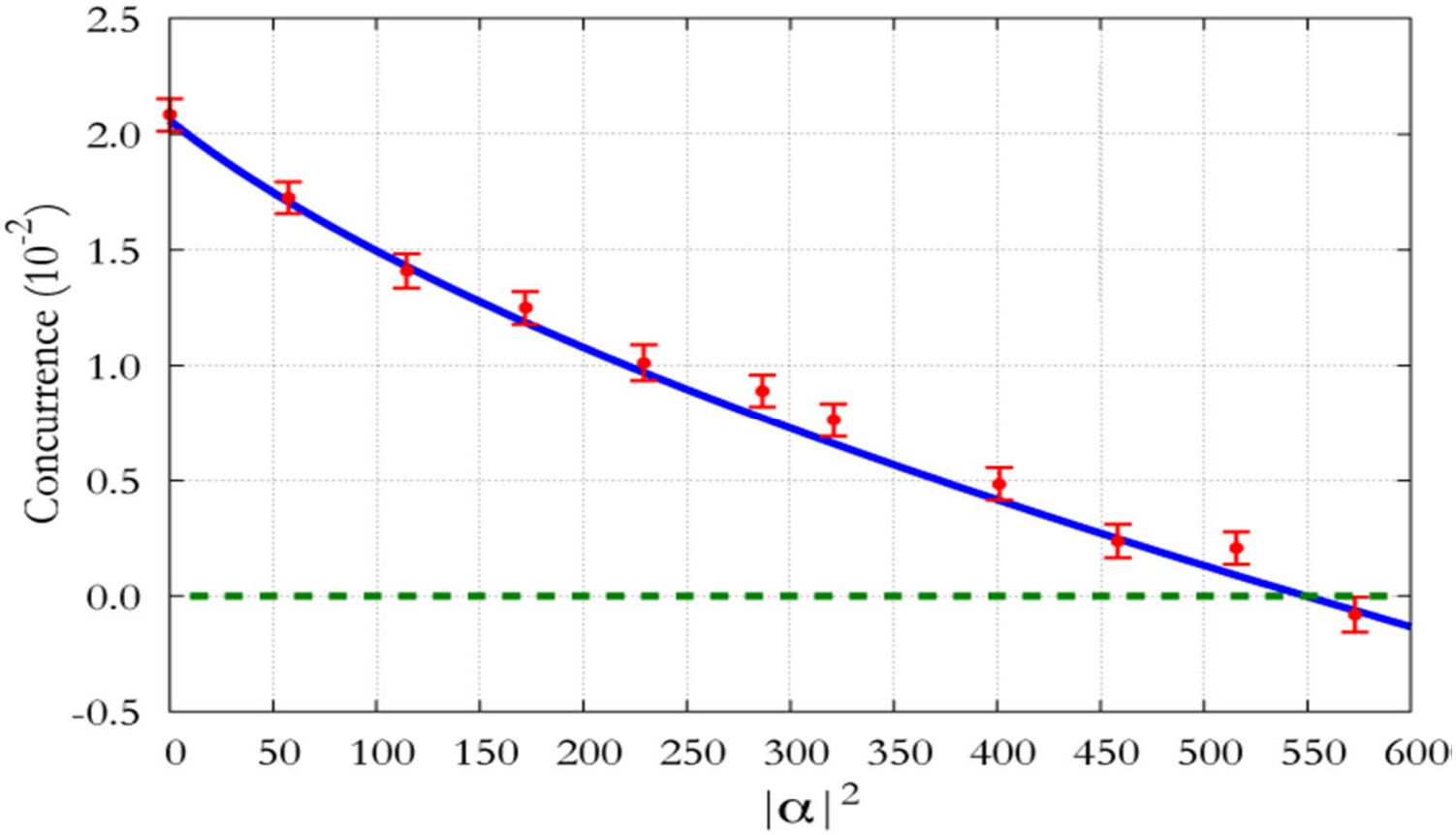


GAP Optique Geneva University

Experiment: Result

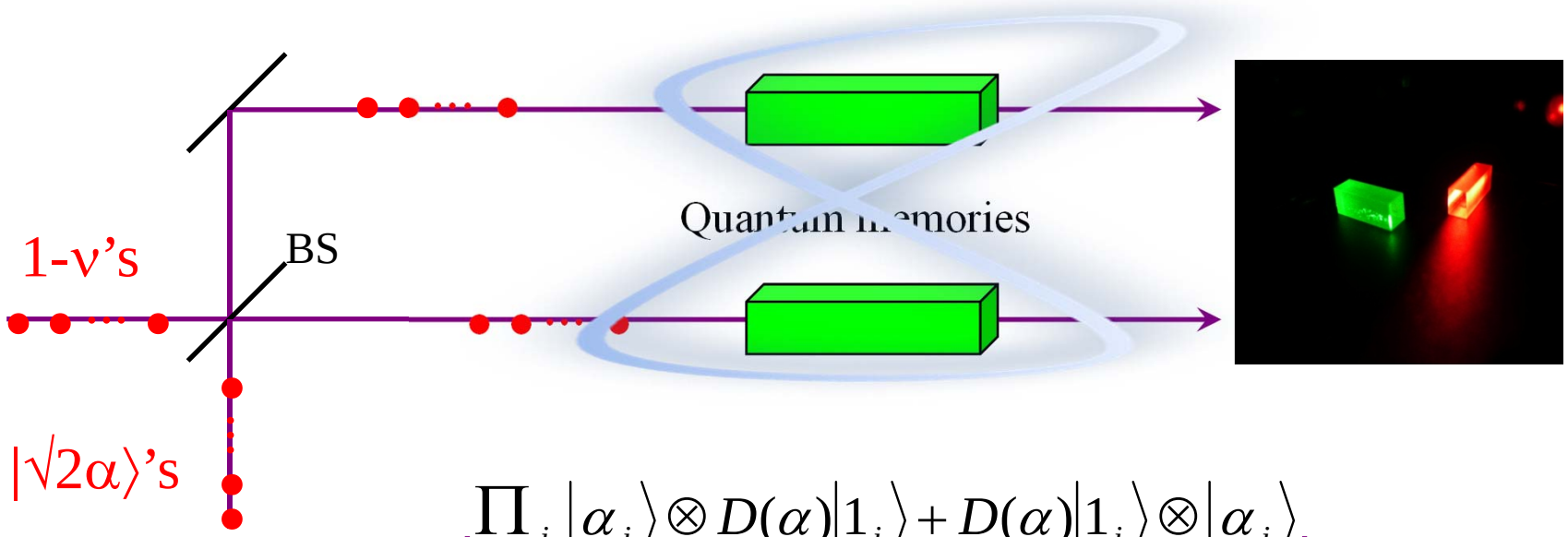
We measured the concurrence C (a measure of entanglement):

$$C \geq V(p_{10} + p_{01}) - 2\sqrt{p_{00}p_{11}}$$



N.Bruno et al., *arXiv:1212.3710*, *Nature Physics* 9, 545 (2013)

Toward truly Large Entanglement



$$\underbrace{\Pi_j \left|\alpha_j\right\rangle \otimes D(\alpha)\left|1_j\right\rangle + D(\alpha)\left|1_j\right\rangle \otimes \left|\alpha_j\right\rangle}$$

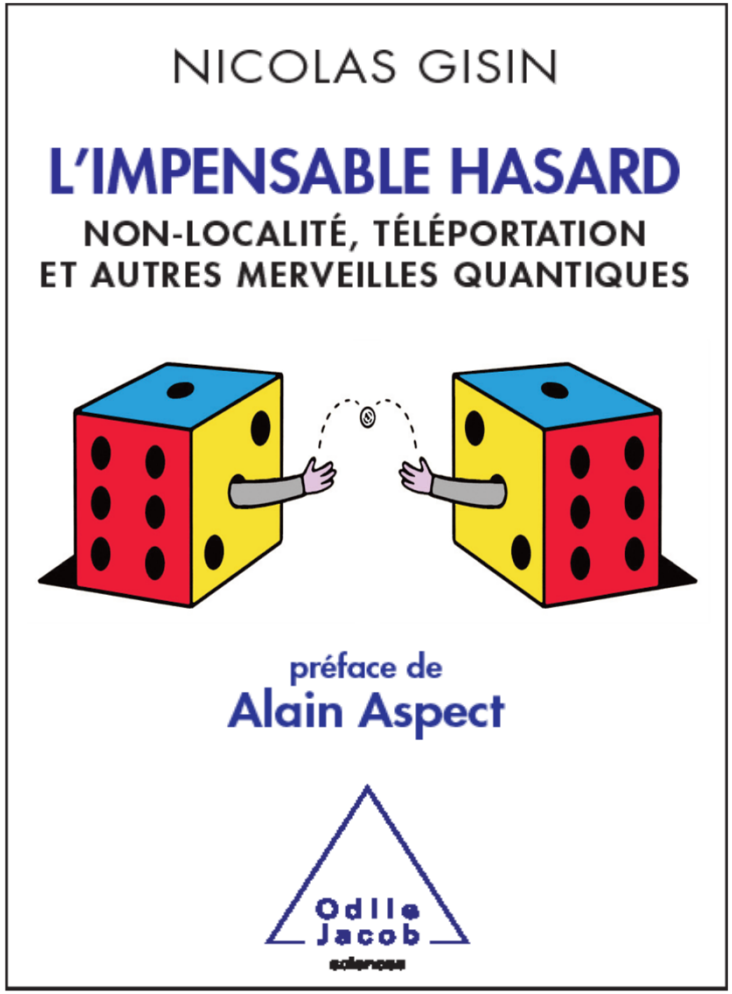
Inside the crystal, no longer a product state, but a complex sort of Dicke state with involved phase relations.

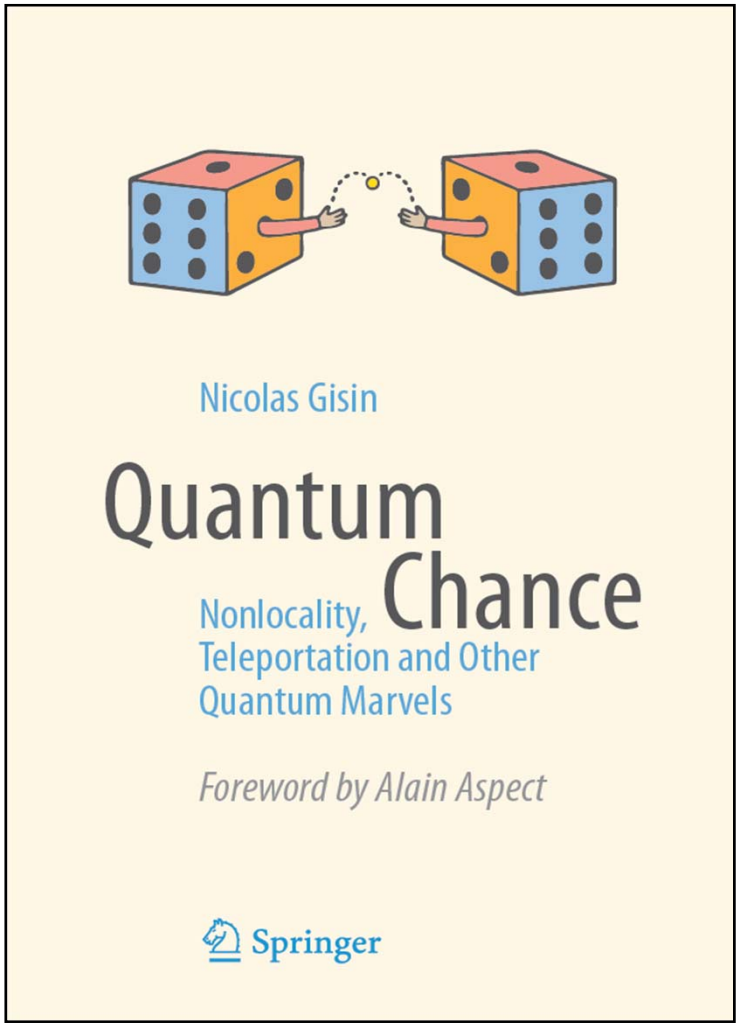
billions of atoms
thousands of excitations
hundreds of e-bits

Conclusion

- Quantum theory is beautiful and terribly self-consistent.
- However, it is plagued with two main problems: the measurement problem and quantum non-locality.
- Staring at these problems may not help is solving them, i.e. in finding the next theory.
- However, they can inspire experiments that may, some day, lead to find the limit of quantum theory.
- The last two decades saw tremendous progress in our understanding of non-locality and our ability to play with it.
- Today's technology makes it likely that the same will happen for "Large Entanglement" and the measurement problem over the next two decades.

Further reading





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 ?

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).

$\Rightarrow$ **v-causal predictions may differ from quantum theory**

$\neq$ Bohm