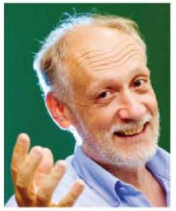


Quantum nonlocality: How does Nature do it? And what can we do with it?

Nicolas Gisin

Group of Applied Physics, Université de Genève, Switzerland

Wednesday, 4 May – 4:30 p.m.

Since our early childhood we know in our bones that in order to interact with an object we have either to go to it or to throw something at it. Yet, contrary to all our daily experience, Nature is nonlocal: there are spatially separated systems that exhibit nonlocal correlations. In recent years this led to new experiments, deeper understanding of the tension between quantum physics and relativity [1] and to proposals for disruptive technologies [2].

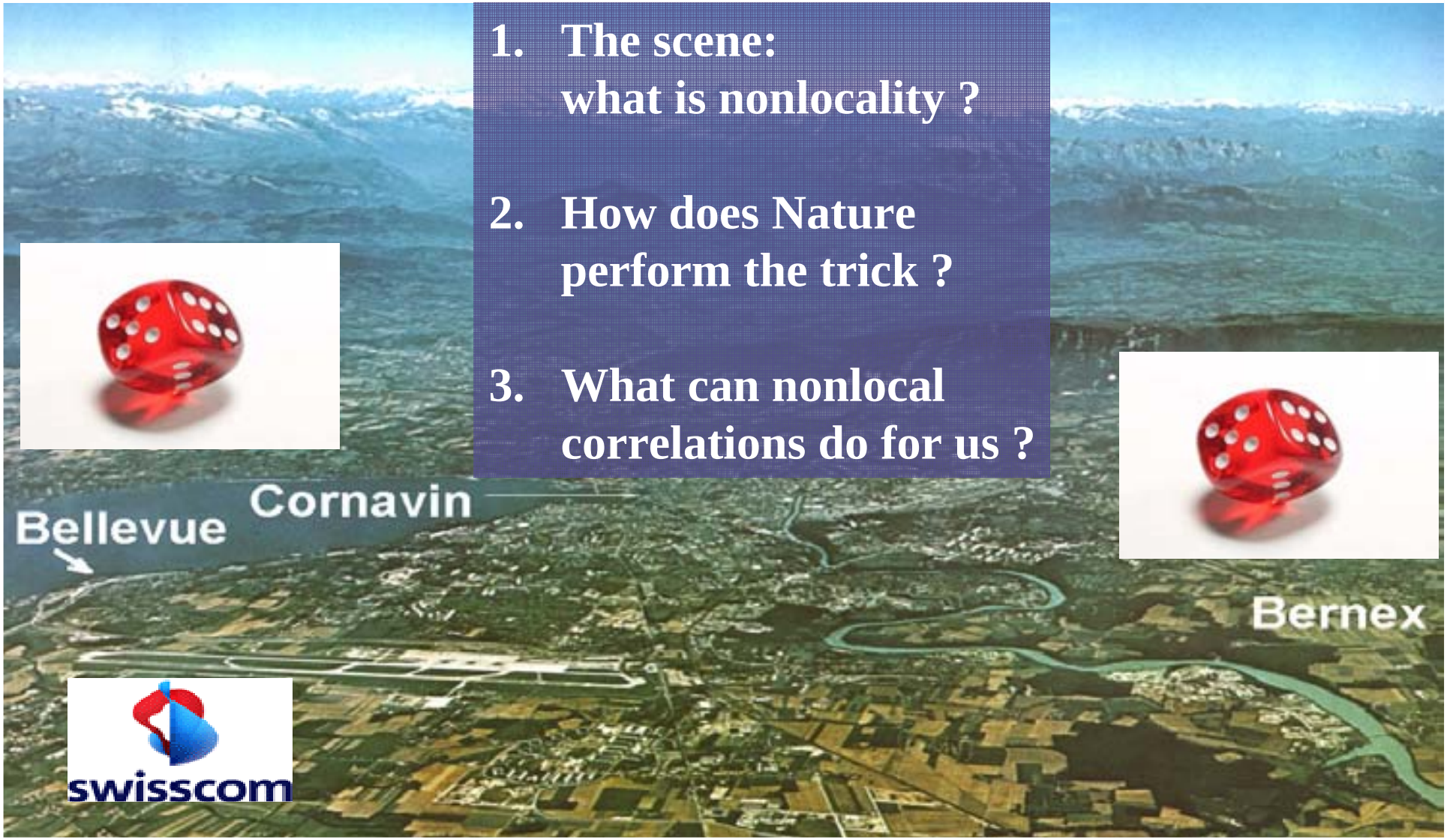
After an introduction to the modern view of the subject, I'll present recent experiments that test John Bell's intuition that 'there is something going on behind the scene' [3]. These experiments put stringent lower bounds on any hypothetical influence (e.g. spooky action at a distance in Einstein's terminology) propagating at speeds faster than light defined in a universal preferred reference frame [4,5]. Finally, I introduce the concept of 'Device-Independent Quantum Key Distribution', a sort of self-testing quantum device that exploits nonlocality [6]. An experimental proposal for DI-QKD will also be sketched [7].

[1] N. Gisin, *Science* 326, 1357 (2009)
[2] N. Gisin and R. Thew, *Electronics Lett.* 46, 965 (2010)
[3] J. S. Bell in *The Ghost in the Atom*, eds P. C. W. Davies and J. R. Brown, Cambridge University Press, pp 45-57 (1993)
[4] D. Salart et al., *Nature* 454, 861 (2008)
[5] B. Cocciaro, S. Faetti and L. Fronzoni, arXiv: 1006.2697
[6] A. Acin, N. Gisin and L. Masanes, *Phys. Rev. Lett.* 97, 120405 (2006)
[7] N. Gisin, S. Pironio and N. Sangouard, *Phys. Rev. Lett.* 105, 070501 (2010)

Quantum Nonlocality:

How does Nature do it? And what can we do with it?

Nicolas Gisin GAP, University of Geneva, Switzerland



Teleportation

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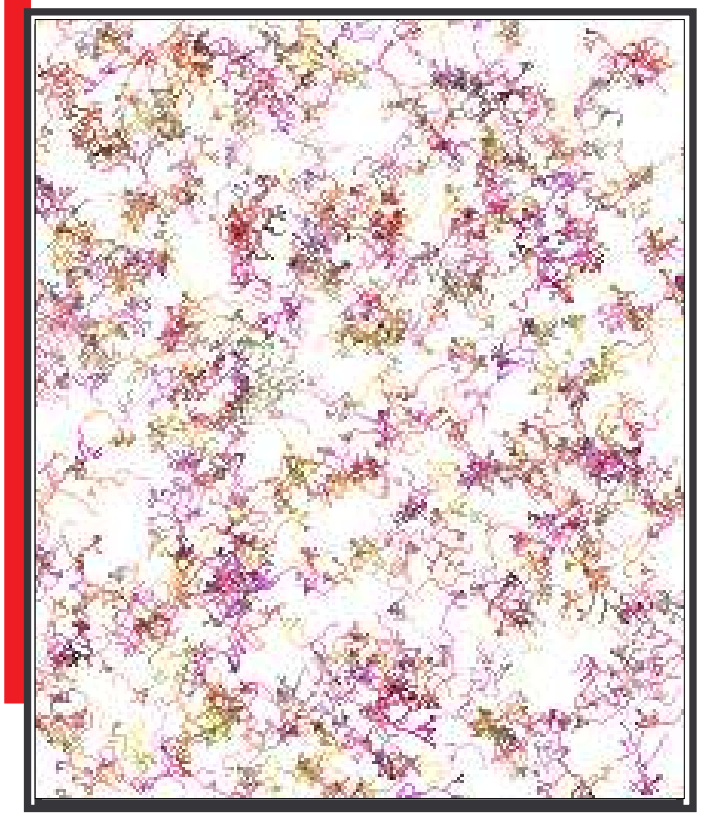
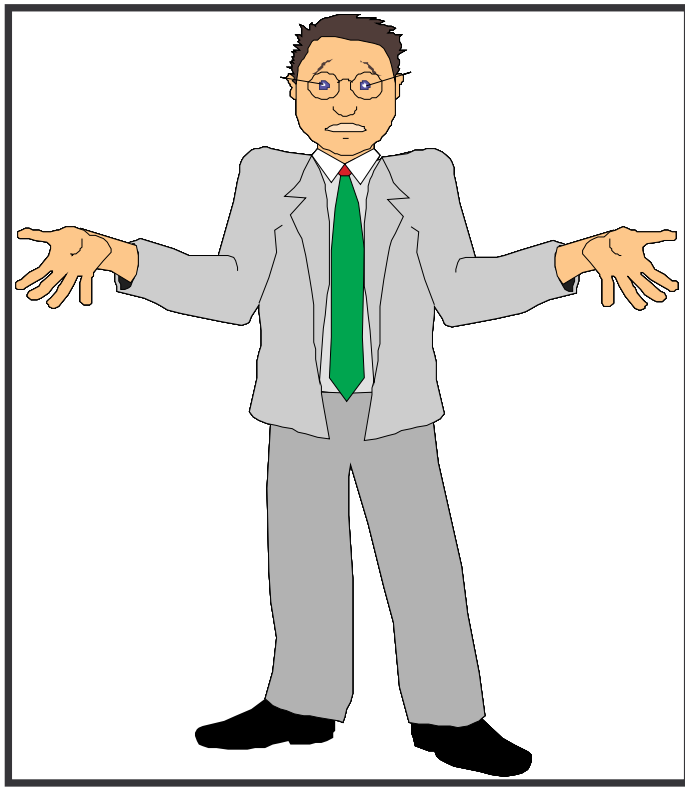
The science-fiction

Transmitter



Receiver



Quantum Teleportation

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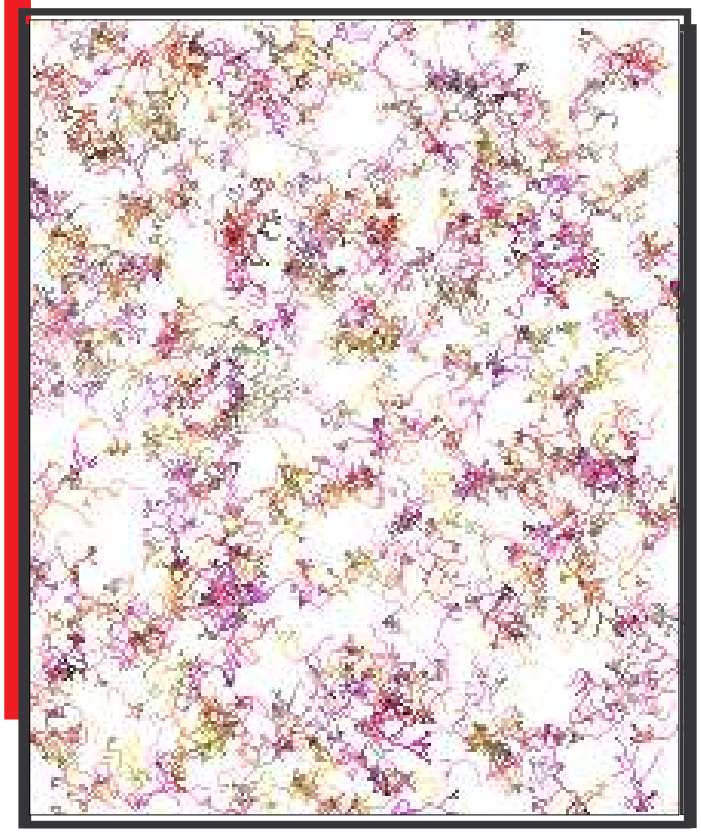
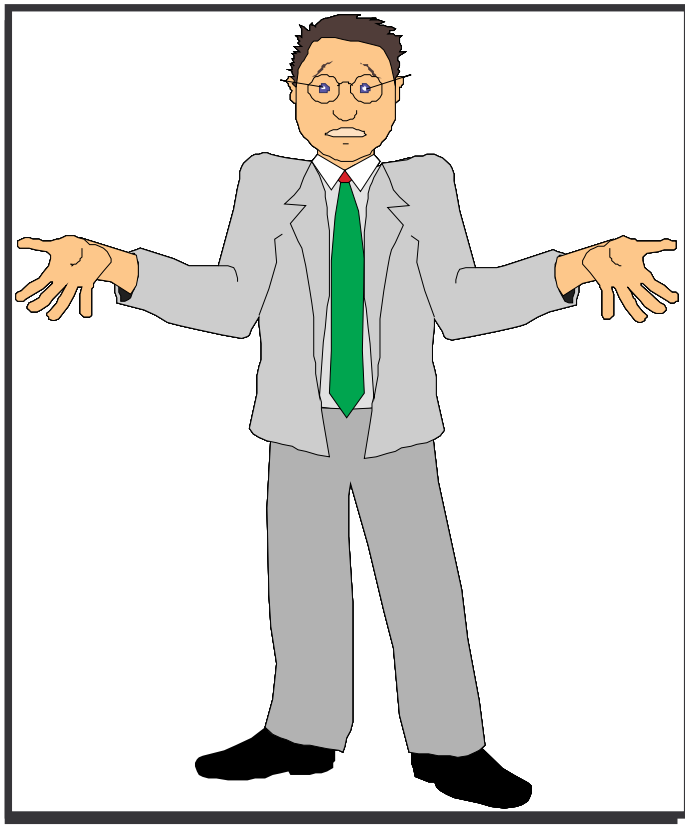
Transmitter



Receiver

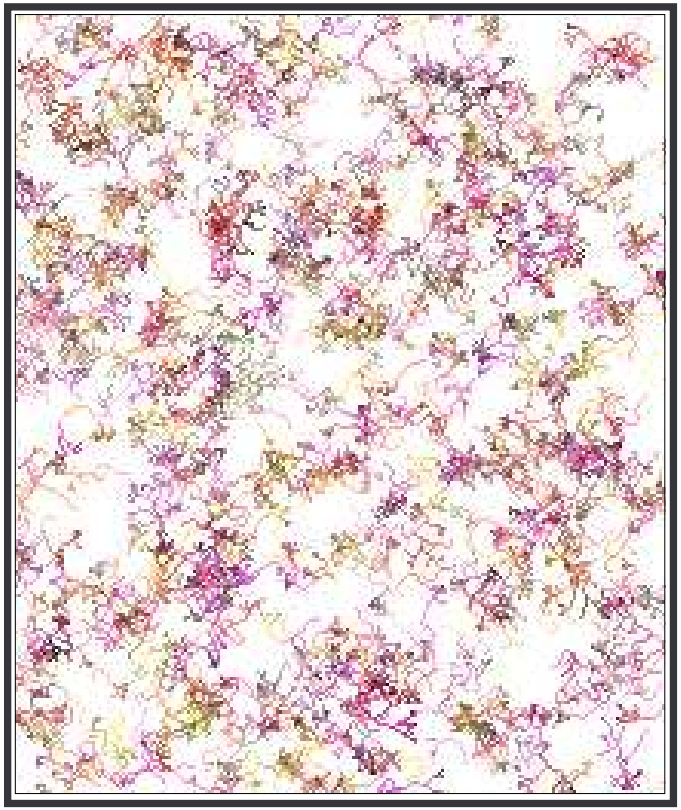


Teleportation

GAP Optique Geneva University

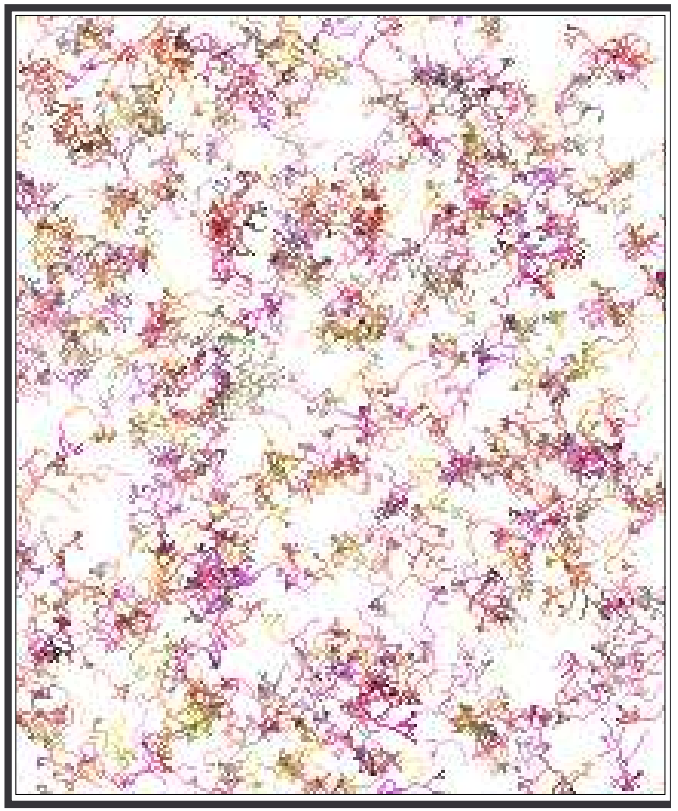
The science

Transmitter

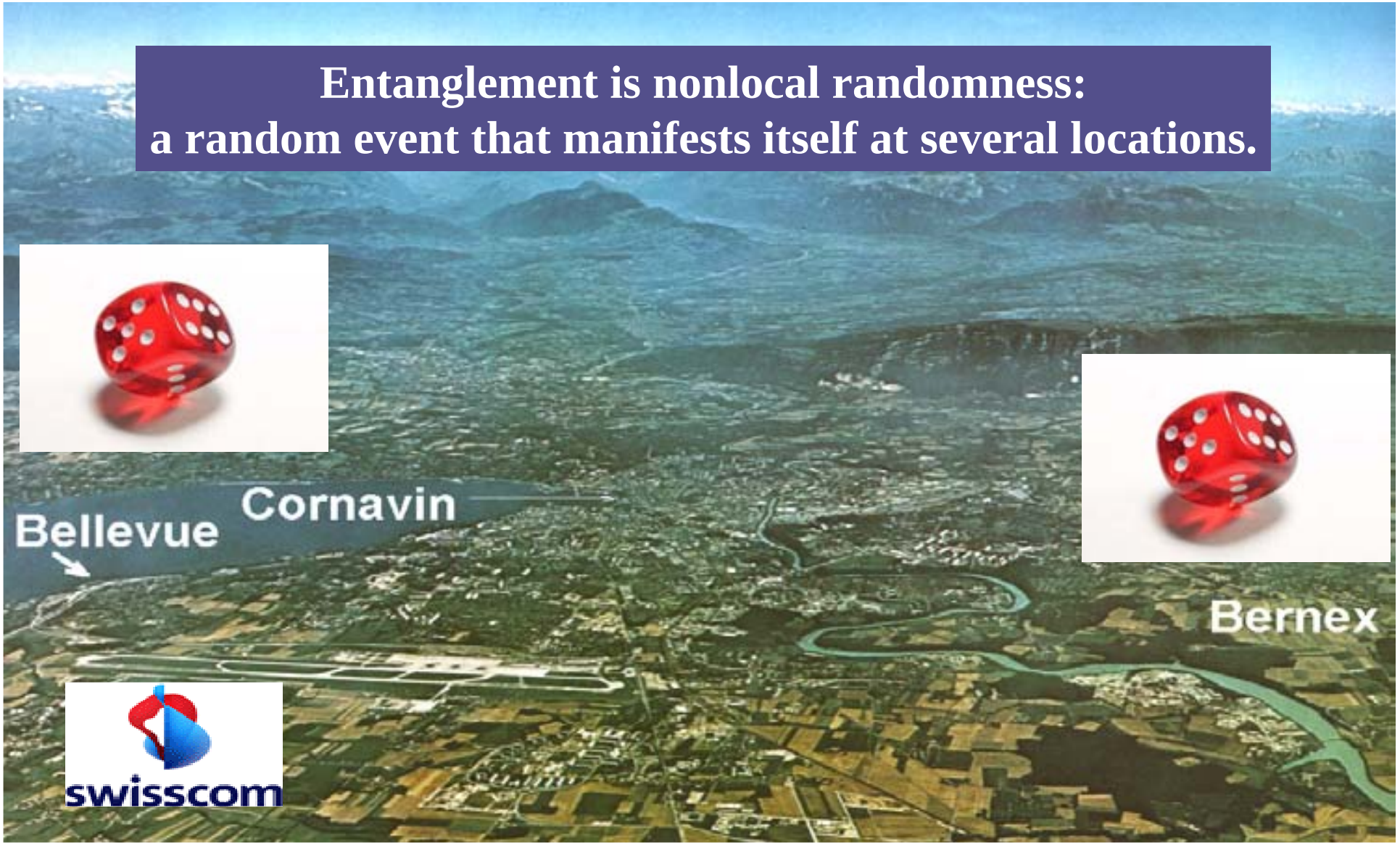


The teleportation channel consists in entangled particles

Receiver



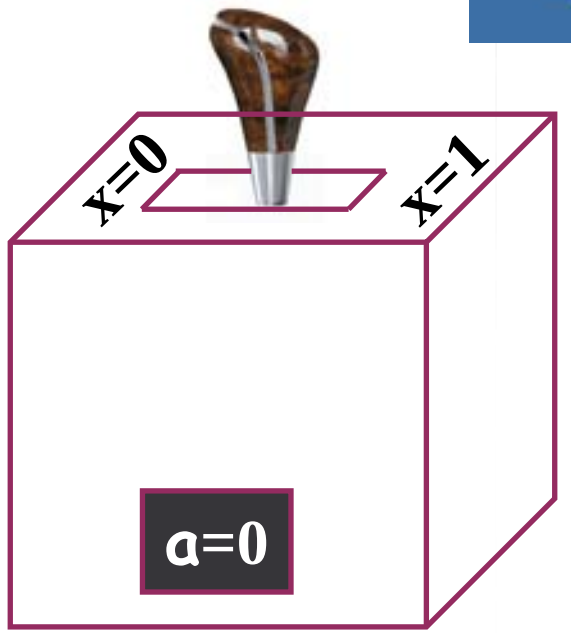
Quantum Nonlocality and Entanglement



The Bell Game

Alice

Heure	x	a
9h00	0	0
9h01	0	1
9h02	1	1
9h03	0	1
9h04	1	0
9h05	1	0
9h06 ...		



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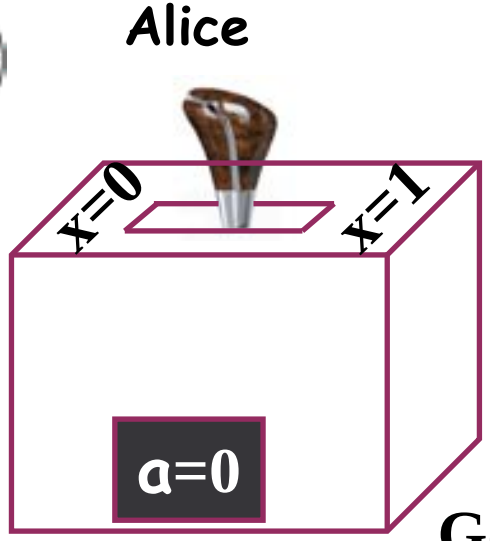
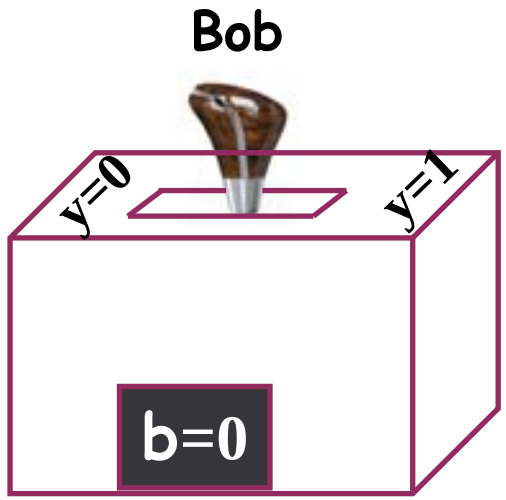
The Bell Game





Goal of the game:

1. **Whenever x=0 or y=0, a=b**
2. **Whenever x=1 and y=1, $a \neq$b**

Note: only the correlation between the outcomes *a* and b is important, the individual values of *a* and of b are irrelevant.

$\Rightarrow$ **Only by comparing *a* and b can Alice and Bob know whether they achieved the goal or not.**

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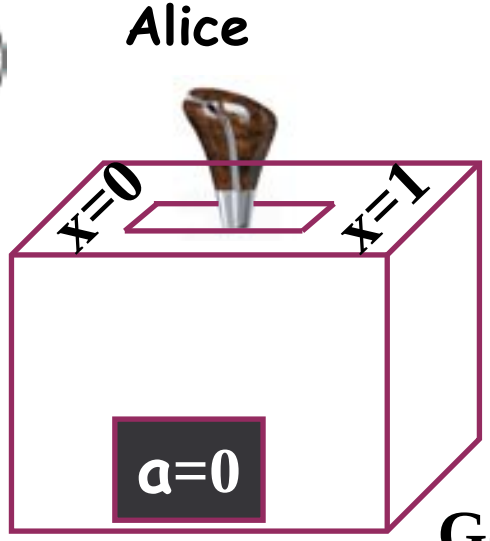
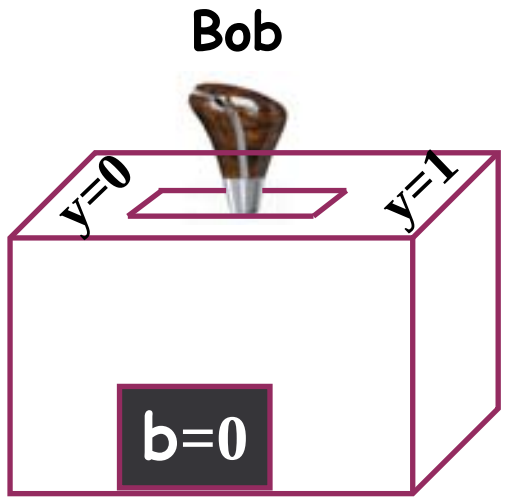
The Bell Game





Goal of the game:

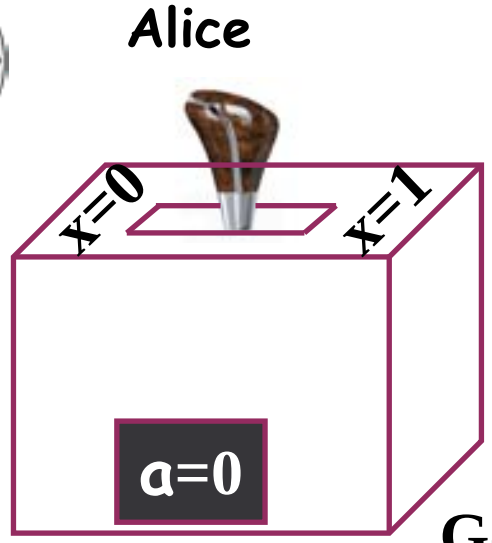
1. **Whenever x=0 or y=0, a=b**
2. **Whenever x=1 and y=1, $a \neq$b**

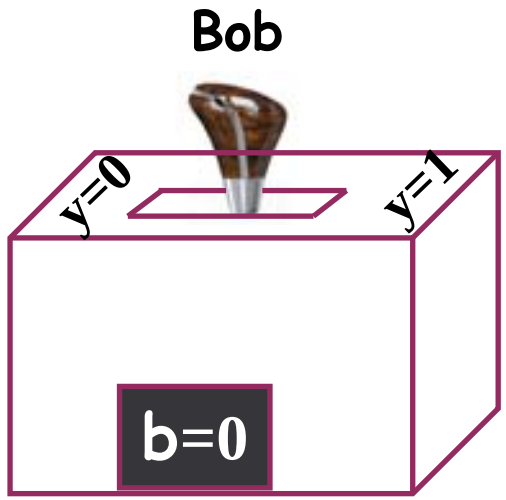
Note: The goal of the game can be sumaries in an equation:

$$a + b = x \cdot y \quad \text{(modulo 2)}$$

$\Rightarrow$ **The mathematics of the Bell game is trivial.**

The Bell Game





Goal of the game:

1. **Whenever x=0 or y=0, a=b**
2. **Whenever x=1 and y=1, $a \neq$b**

Score:

- **Repeat the game very often choosing the x,y at random.**
- **Come together and compare the results.**
- **For all combinations of choices (x,y) compute the rate of success**
- **Add the 4 rates.**

$$\Rightarrow \; 0 \leq S = \langle a+b=x \cdot y \rangle \leq 4$$

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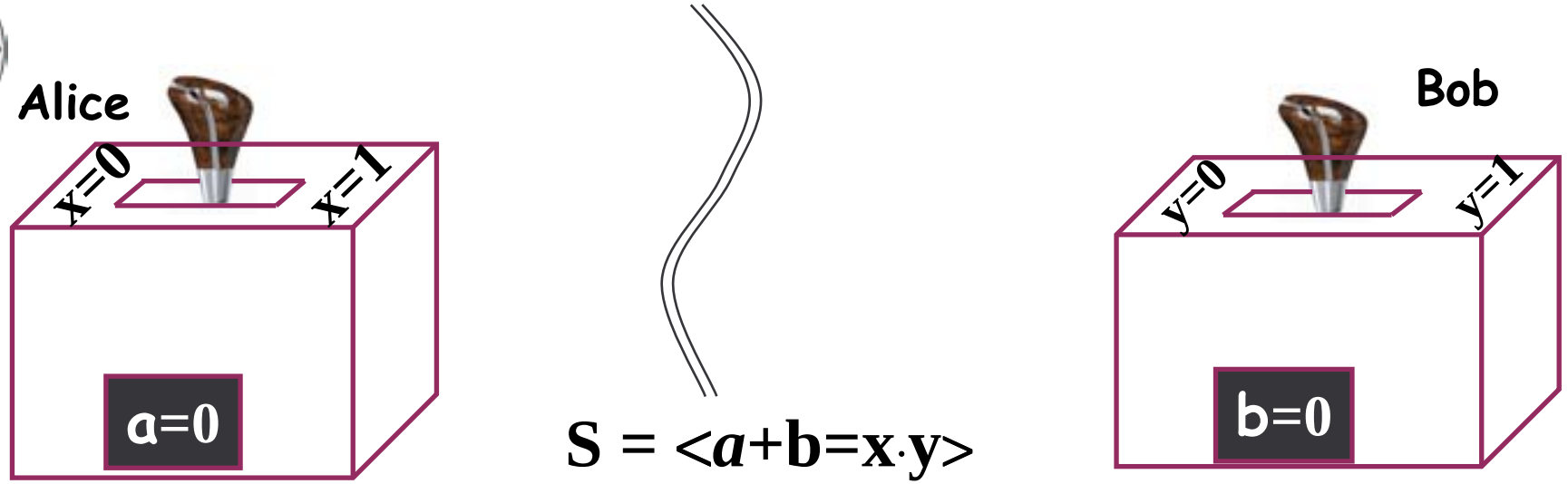
How to win the Bell Game



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1. ~~Communication from Alice to Bob and/or from Bob to Alice.~~

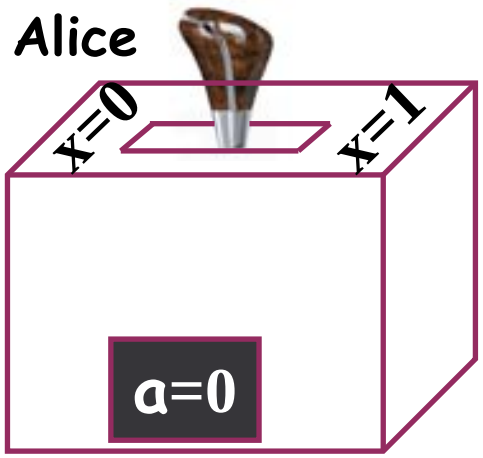
2. Agree in advance on some strategy.
   An example of a simple strategy is to decide to always produce the outcome 0. In this way S=3

   Another example is that Alice always produces *a*=0, while Bob b=y.

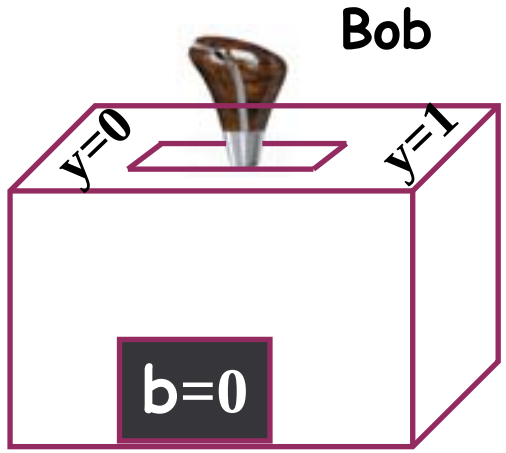
$\Rightarrow$ (x,y)=(0,0) ok, (x,y)=(0,1) no!, (x,y)=(1,0) ok, (x,y)=(1,1) ok

$\Rightarrow$ S =3

How to win the Bell Game



$S = \langle a+b=xy \rangle$



Alice has only 4 possible strategies (2 inputs & 2 outcomes: $2^2=4$):

1: $a = 0$
2: $a = 1$
3: $a = x$
4: $a = 1-x$

The strategy may change from minute to minute, but at each minute Alice uses one strategy.

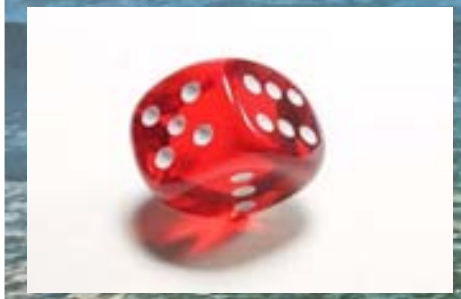
Bob has also only 4 possible strategies. Hence, together they have 4×4=16 combinations of strategies. All combinations give S=1 or S=3. $\Rightarrow$ $S \leq 3$ Bell inequality

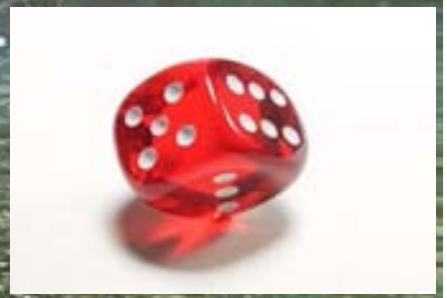
Quantum entanglement allows one to win the Bell game with a score of 3.41

Entanglement is nonlocal randomness:
a random event that manifests itself at several locations.

$S = 2+\sqrt{2} \approx 3.41$

Violation of Bell inequality
$\Rightarrow$ Quantum correlations
can be nonlocal !





During my early carrier as a physicist... when I was about 6 months old… I learned the hard way that in order to «interact» with an object I had either to crawl to it or to throw something at it.

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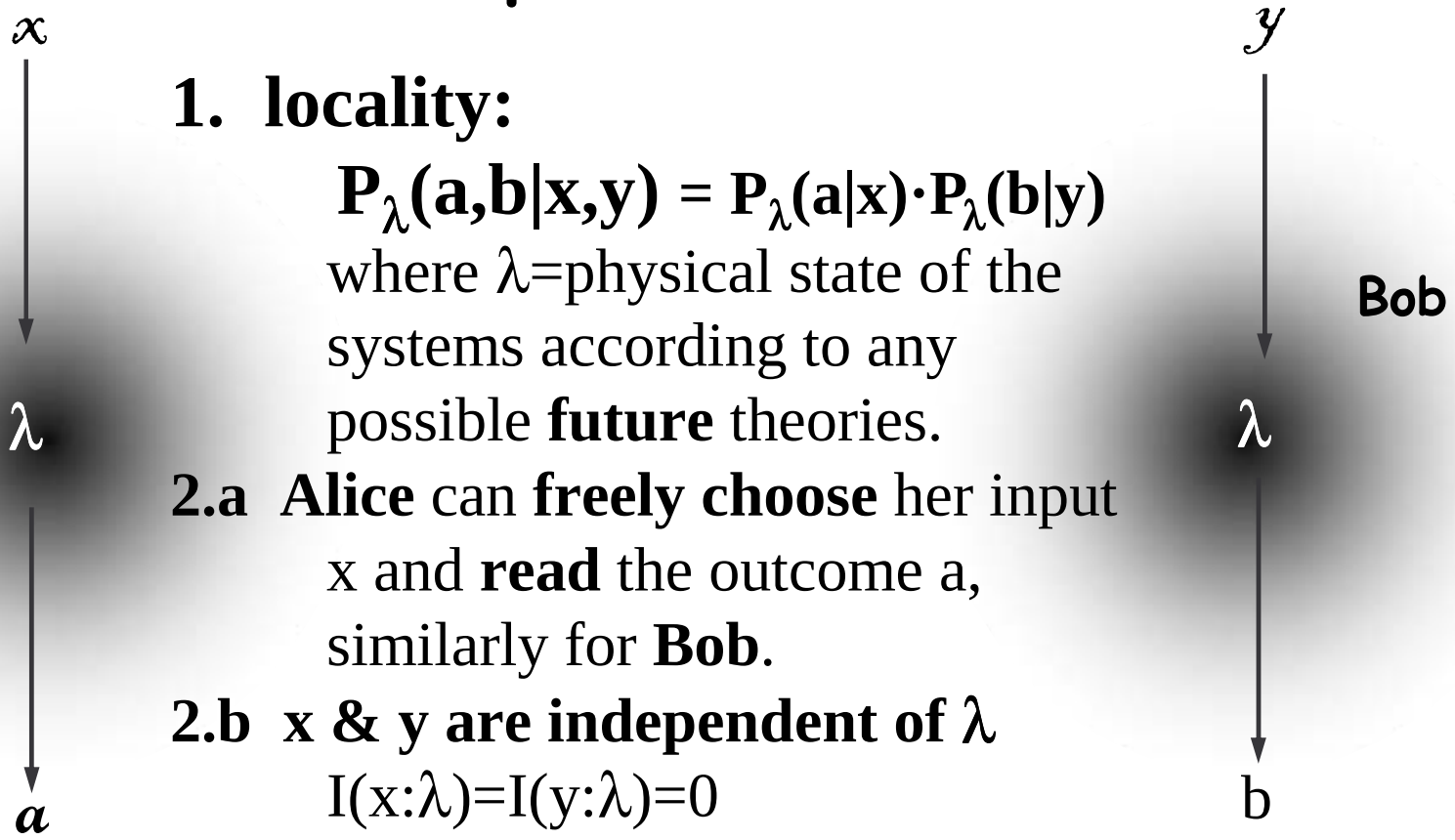
Assumptions:



1. **locality:**

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

   where λ=physical state of the systems according to any possible **future** theories.

2.a **Alice** can **freely choose** her input x and **read** the outcome a, similarly for **Bob**.

2.b **x & y are independent of λ**

   I(x:λ)=I(y:λ)=0

3. ***a* and b are classical variables**

Conclusion: Bell inequalities

N. Gisin, Non-realism : deep thought or a soft option ? quant-ph/0901.4255, Found. Phys. 2010, DOI 10.1007/s10701-010-9508-1

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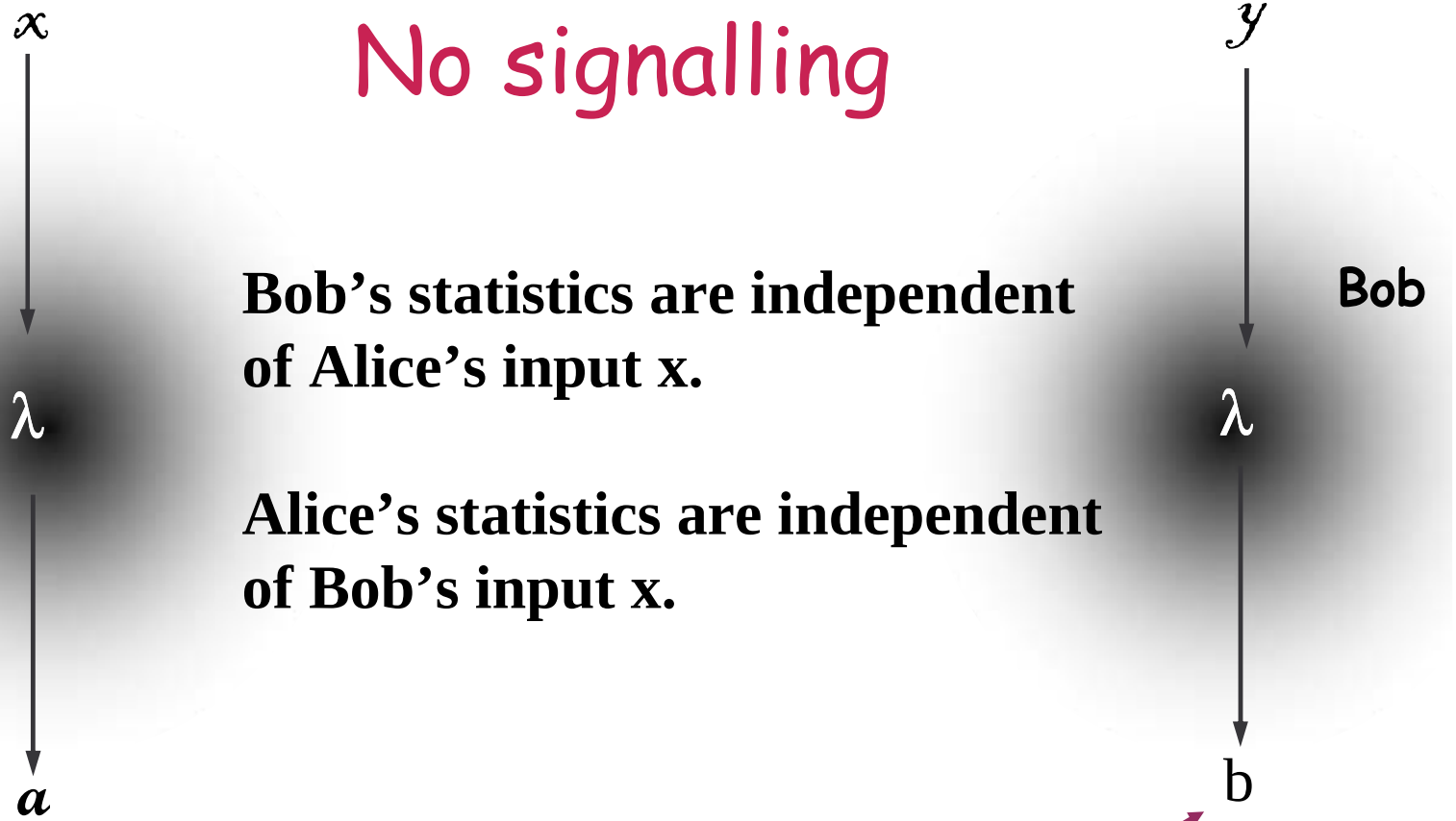
No signalling



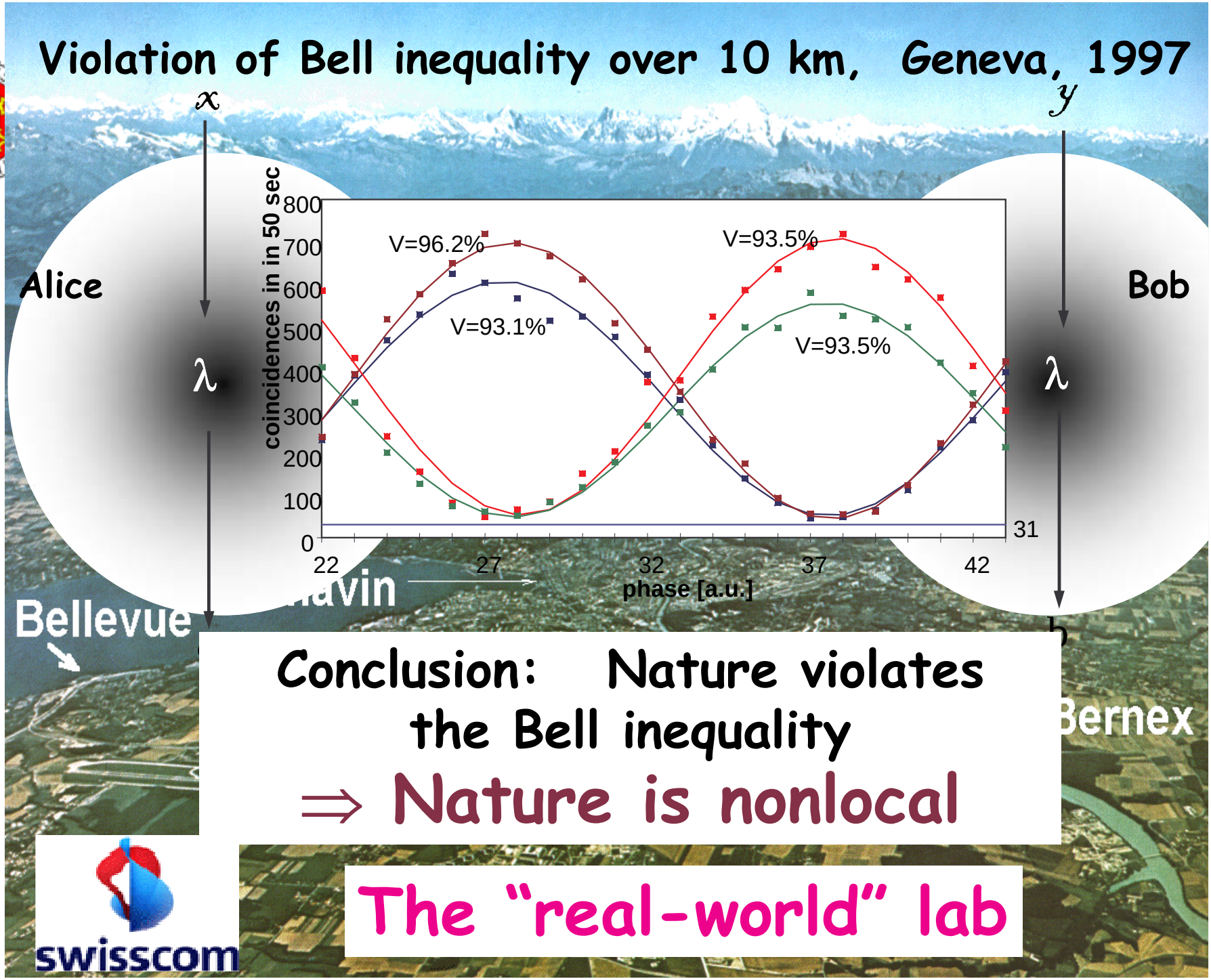
Bob's statistics are independent of Alice's input x.

Alice's statistics are independent of Bob's input x.

$$\sum_a P_\lambda(a,b \mid x,y) = P_\lambda(b \mid y)$$

N. Gisin, Non-realism : deep thought or a soft option ? quant-ph/0901.4255, Found. Phys. 2010, DOI 10.1007/s10701-010-9508-1

Violation of Bell inequality over 10 km, Geneva, 1997



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Conclusion: Nature violates the Bell inequality

⇒ Nature is nonlocal

swisscom

The "real-world" lab

How does Nature perform the trick ?

- How can these two locations out there in space-time know about each other ?
- How does an event A know that it is nonlocally correlated to another event B ?
- Who keeps track of who is entangled with whom ?

NG, Quantum nonlocality : how does nature do it ?
Science, 326, 1357, 2009; arXiv:0912.1475

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How does Nature perform the trick ?

- $P(a,b|x,y) \neq P(a|x) \cdot P(b|y)$ strongly suggests that Alice influences Bob or vice-versa (as in most text books).
- This influence was termed by Einstein: "spooky action at a distance".
- Toner and Bacon showed that a single bit of "influence" would suffice, **PRL 91, 187904 (2003).**

⇒ Let's consider this hypothetical influence seriously.

⇒ Let's test this hypothetical influence, assuming it propagates at finite speed.

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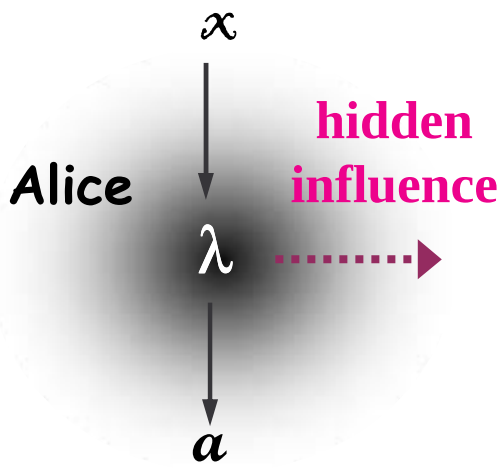
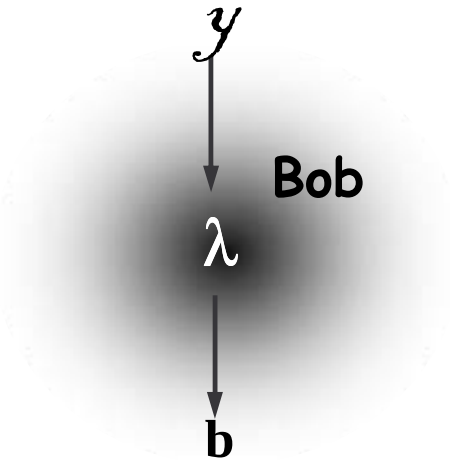
Assume a real influence propagating faster than light but with finite speed





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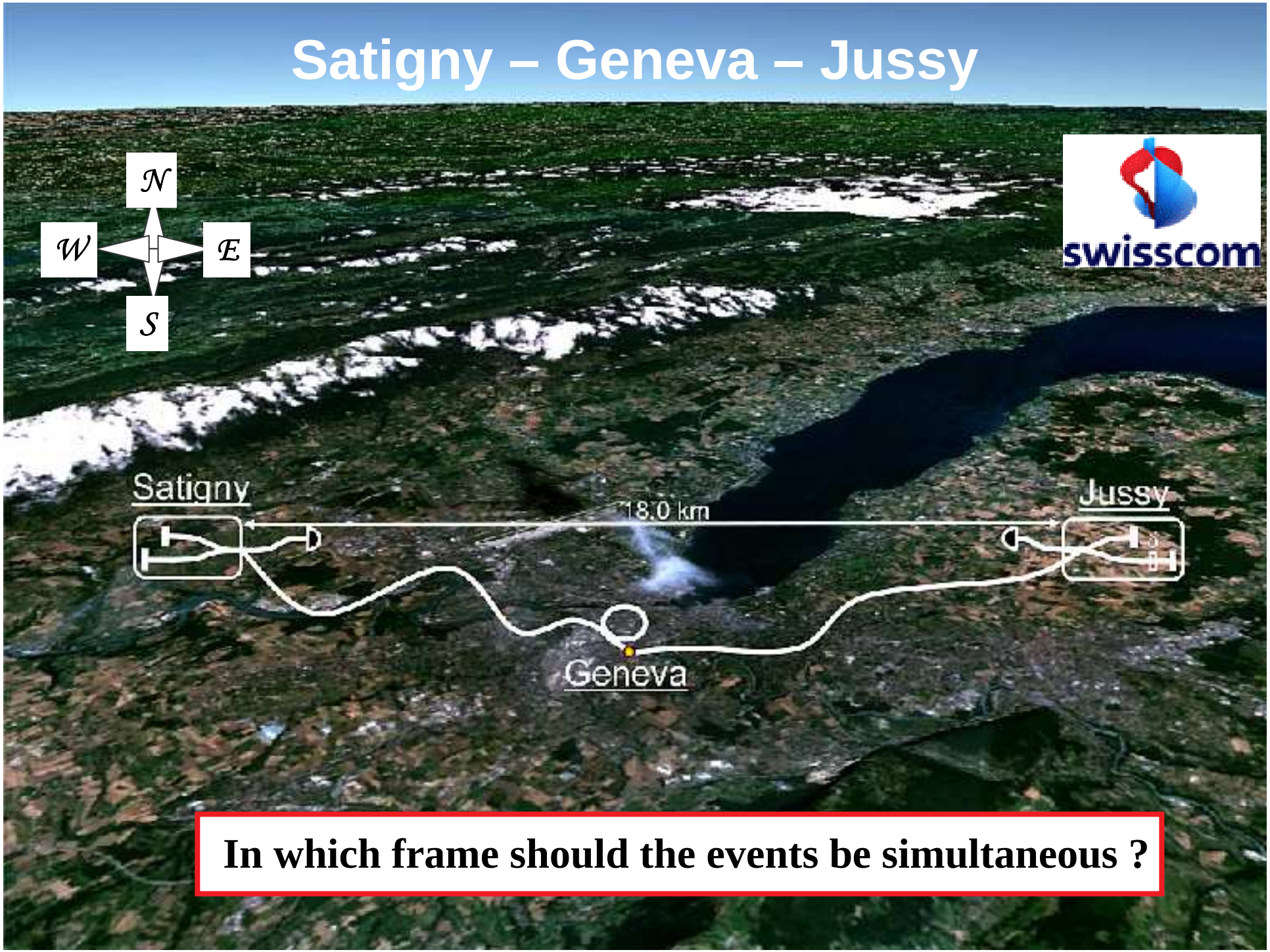
Assume a real influence propagating faster than light but with finite speed

Satigny – Geneva – Jussy



In which frame should the events be simultaneous ?

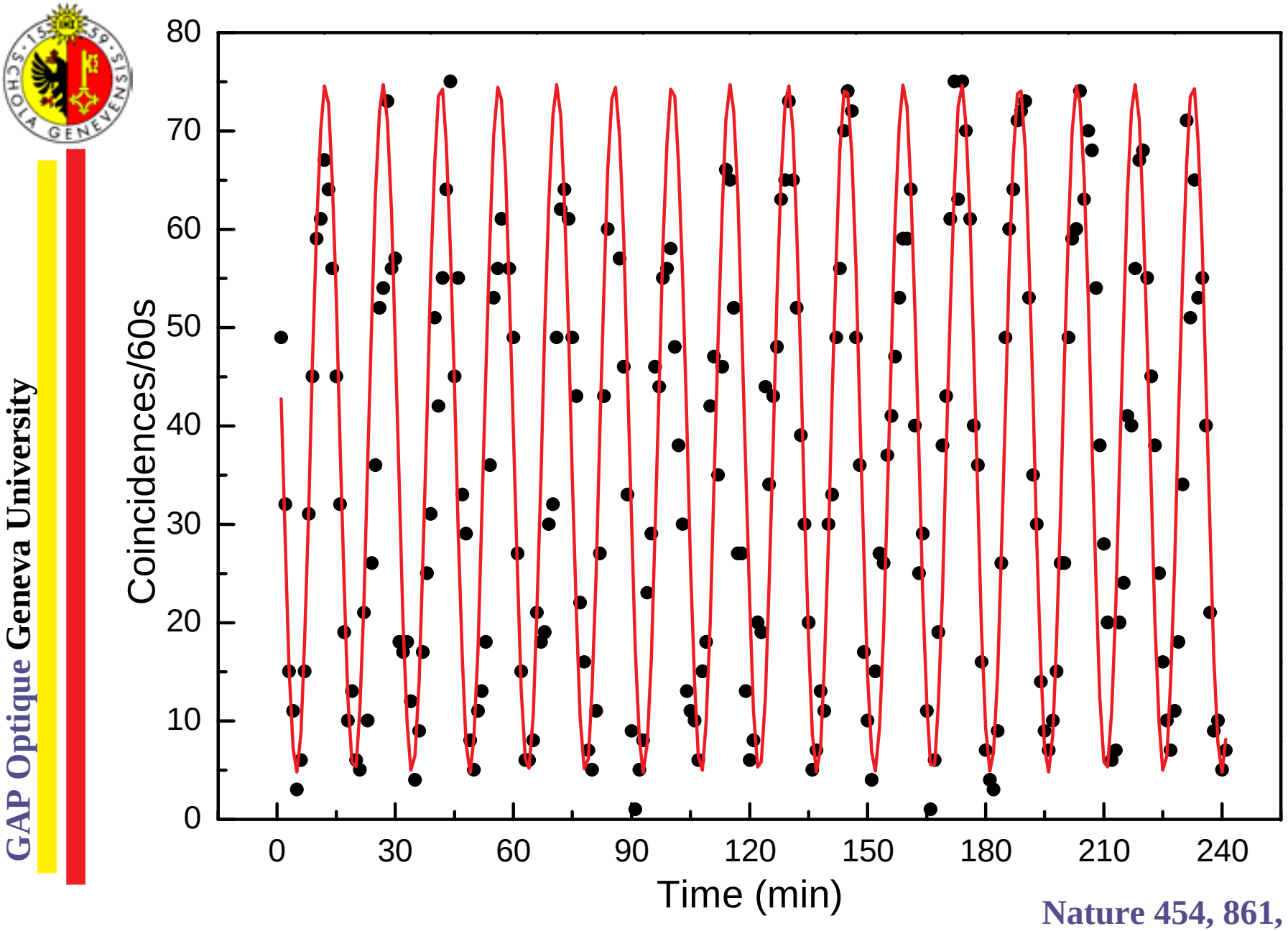
Let's test this hypothetical preferred reference frame

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

⇒ perfect synchronization w.r.t any frame moving perpendicular to the A-B axis

⇒ in 12 hours all hypothetical privileged frames are scanned.

Ph. Eberhard, private communication



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Nature 454, 861, 2008

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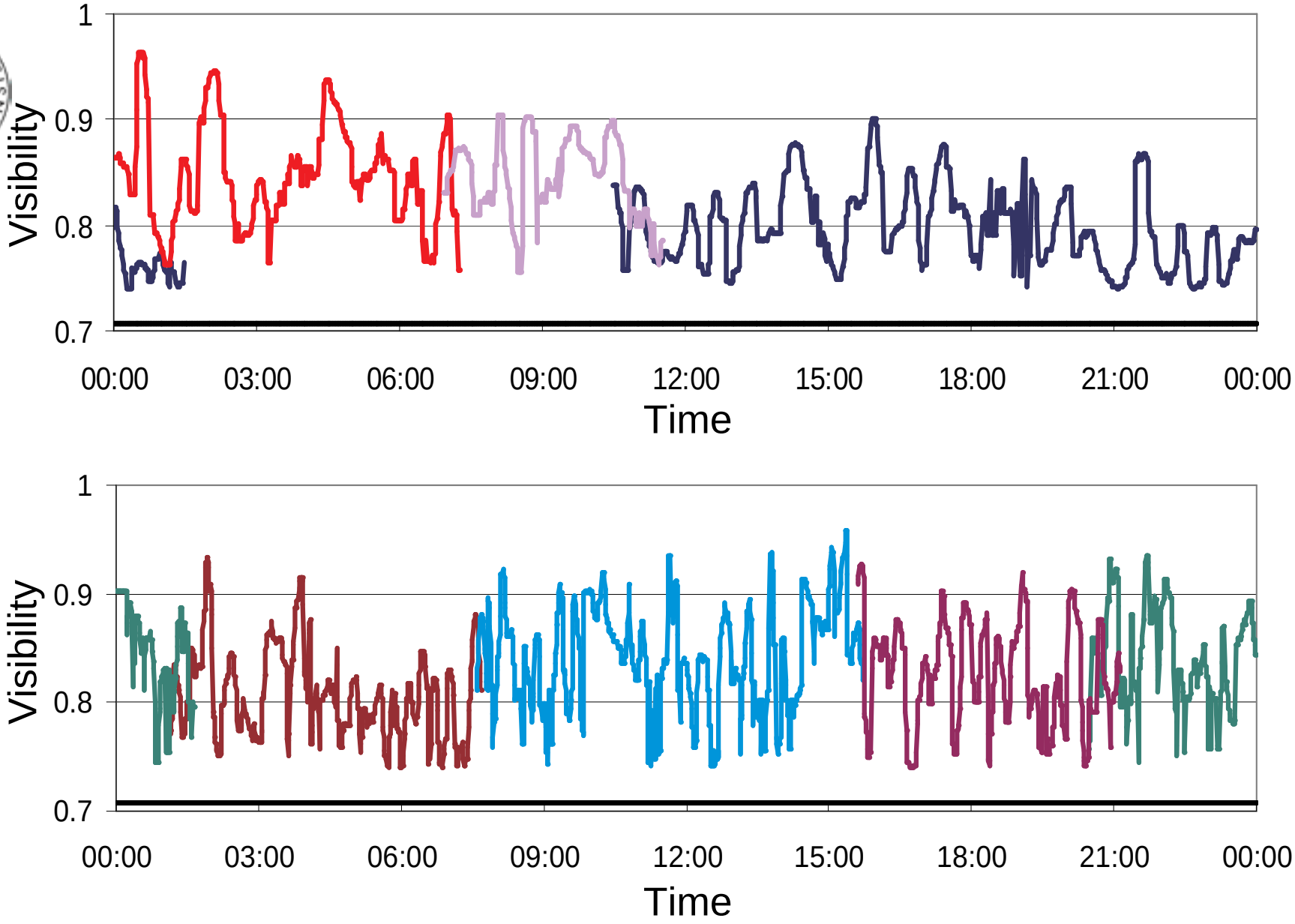


Nature 454, 861, 2008

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

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

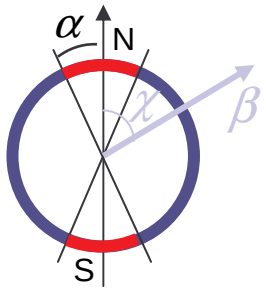
if $|\rho| \leq \bar{\rho}$

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

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

T = 360 seconds $\qquad \bar{\delta} \cong 5.4\ 10^{-6} \qquad \alpha \cong 5.8^{o}$

time T, during which $|\beta_{\|}(t)|$ 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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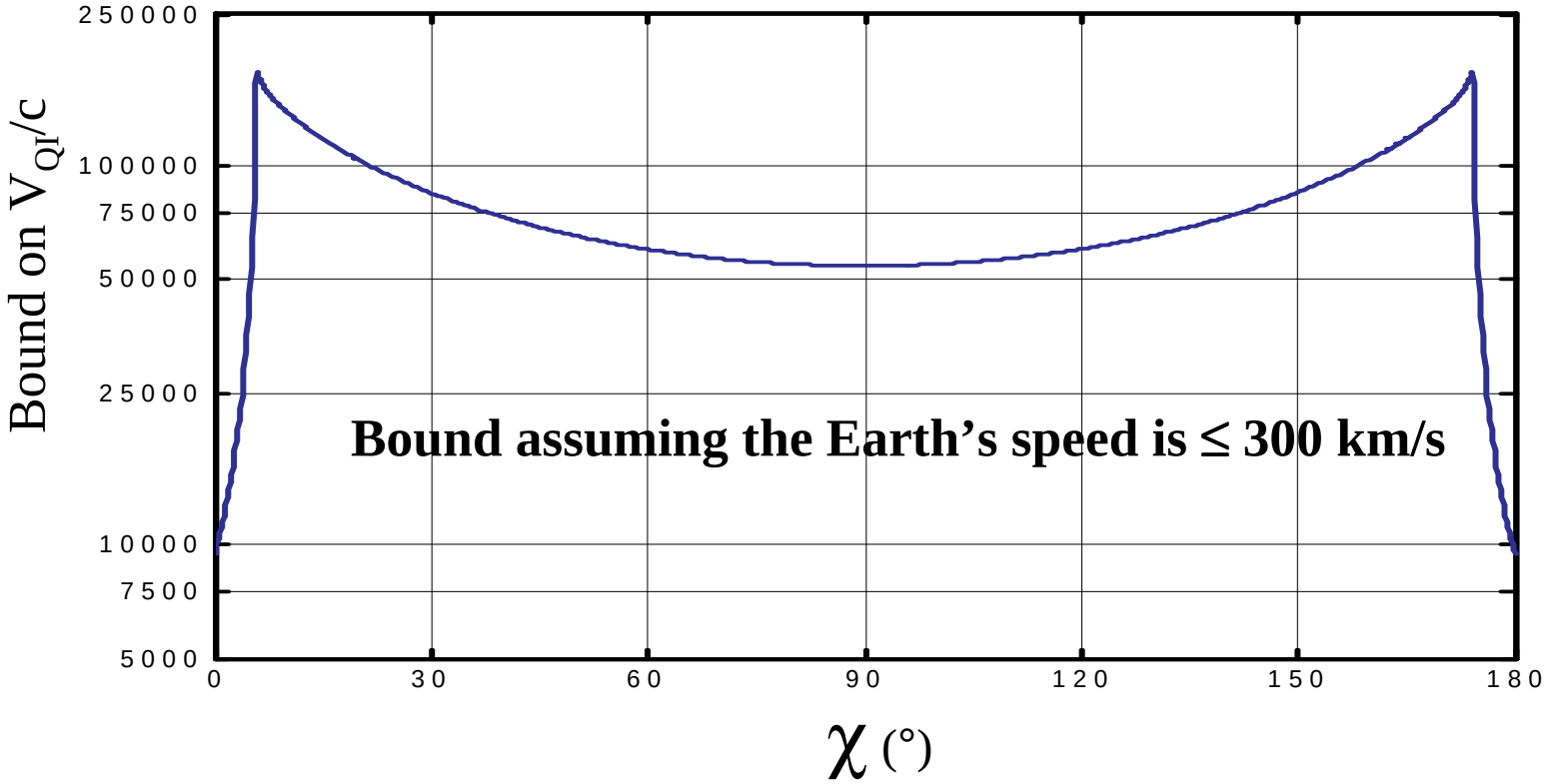

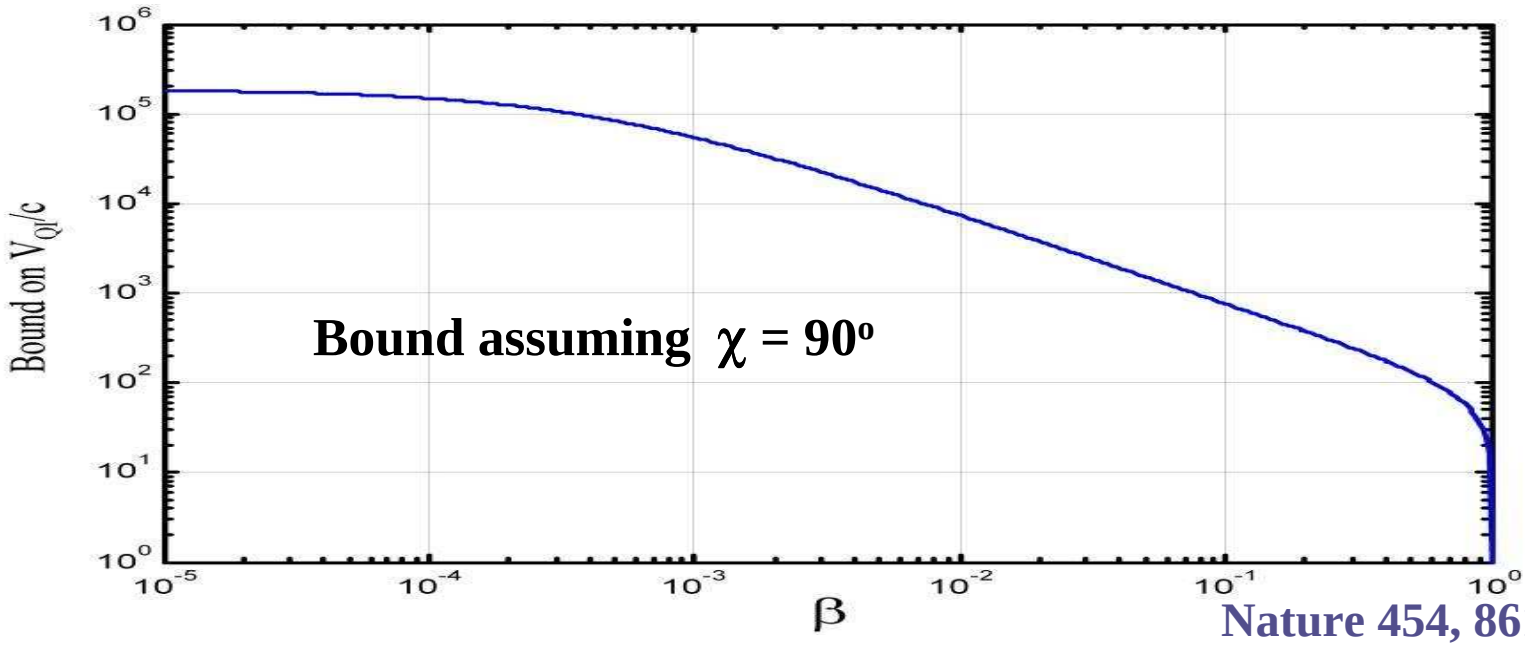

Nature 454, 861, 2008

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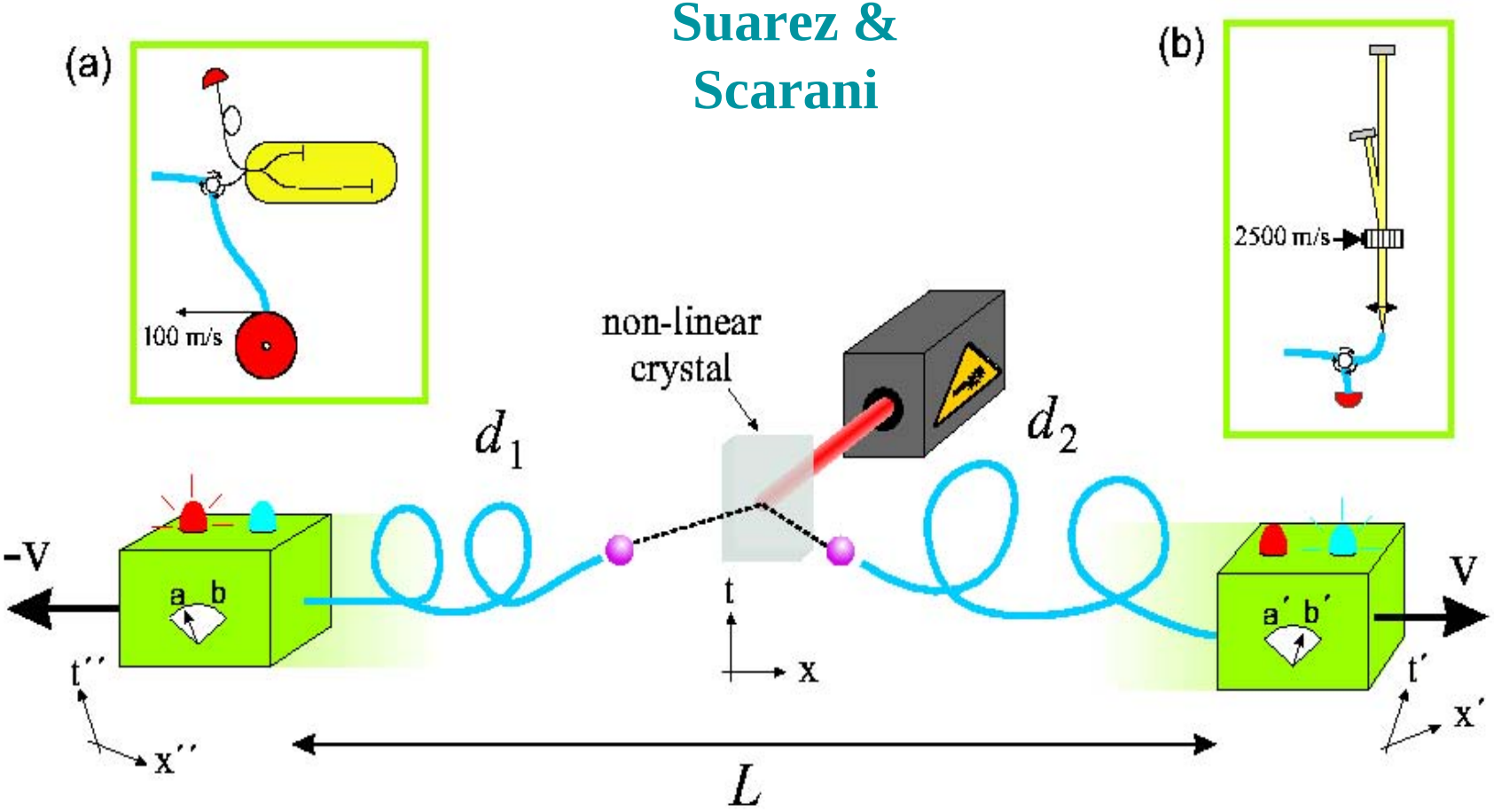
Further experiments: before-before configurations

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 2002

Suarez & Scarani



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

Mid-Conclusion

⇒ There is no spooky action at a distance: there is not a first event that influences a second event.

⇒ Quantum correlation just happen, without any time-ordering, somehow from outside space-time !

(there is no story in space-time that tells us how it happens)

… or … the influences propagate at surprisingly large speeds

Nonlocality in Newton's gravitation

Signalling: A stone moved on the moon would immediately affect our weight here on earth.

Physics presented a nonlocal view of nature during all its history since Newton until today, except bw 1917-1927 !

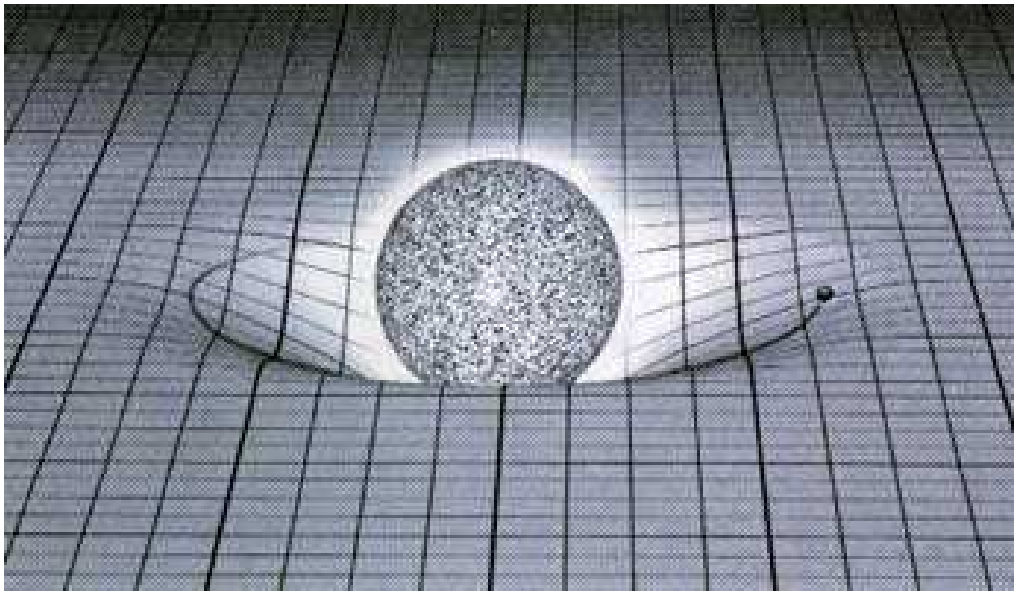
Let's read Newton's words:

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

Einstein, the greatest mechanical engineer

- Today, thanks to Einstein, gravitation is no longer considered as a kind of action at a distance. A moon-quake triggers a bunch of gravitons that propagate through space and « informs » Earth. The propagation is very fast, but at finite speed, the speed of light, i.e. about 1 second from the moon to our Earth.



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Is Quantum Nonlocality waiting for its Einstein ?

- Most probably : NO !
  If the experiments are correct, then no futur « Einstein » could ever restore locality in quantum correlations.

- So, how does Nature perform the trick ?!?

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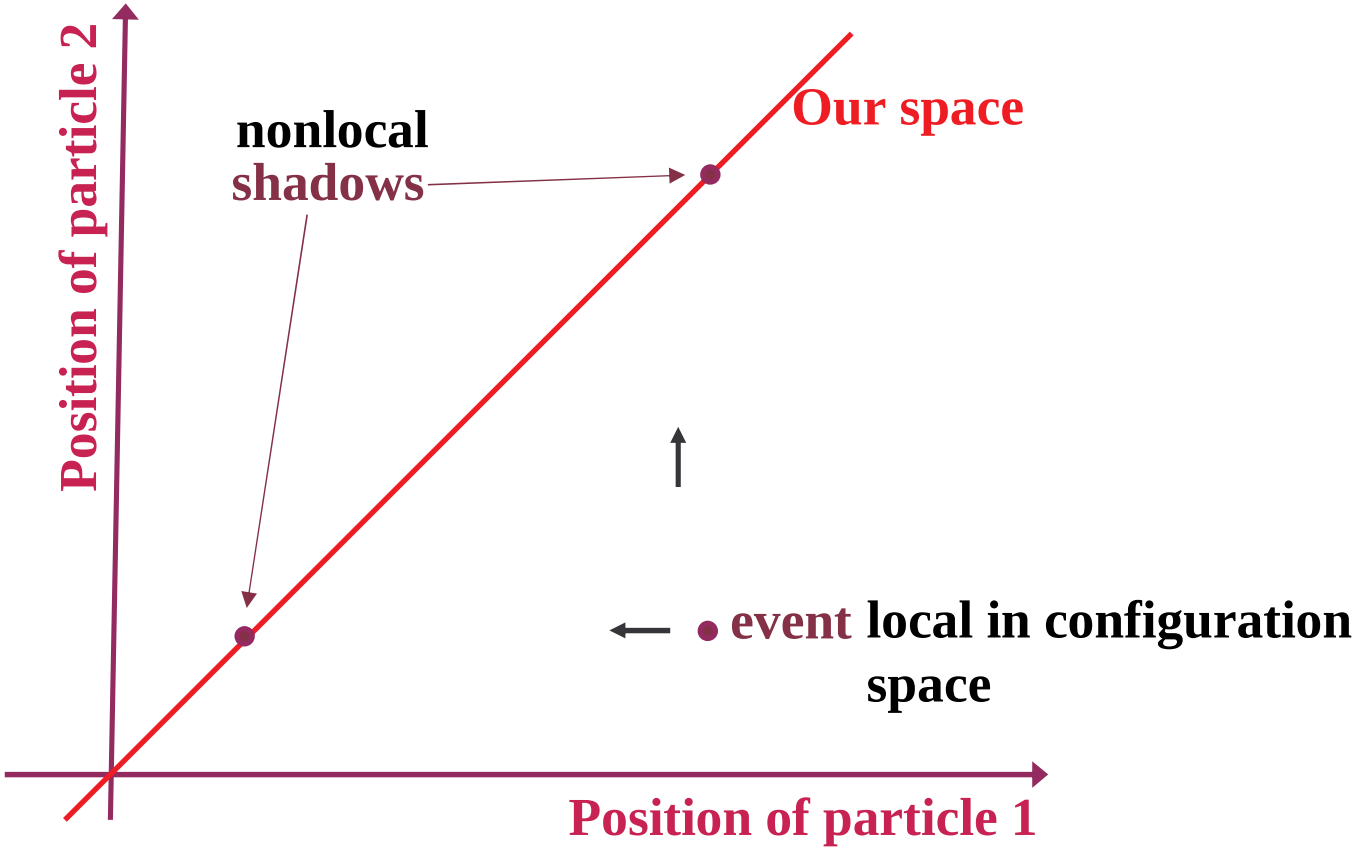
From outside space-time

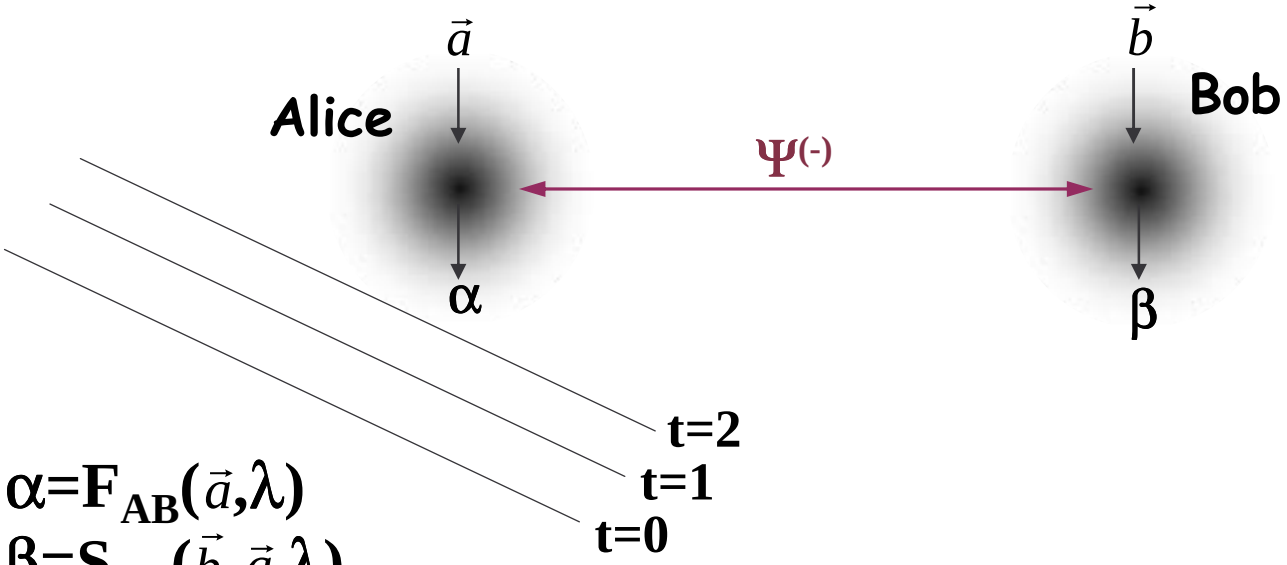
The real stuff happens in configuration space where the wavefunction propagates.

In our space we see only the shadows.



Deterministic nonlocal hidden variables

Let's try to add randomness, given from the beginning, to turn stochastic events into deterministic ones: $\lambda=\{\Psi,r_a,r_b\}$.



$\alpha=F_{AB}(\vec{a},\lambda)$

$\beta=S_{AB}(\vec{b},\vec{a},\lambda)$

$$F_{AB}(\vec{a},\lambda)=\begin{cases}+1 & if\ r_a\le 1/2\\ -1 & if\ r_a>1/2\end{cases}$$

$$S_{AB}(\vec{b},\vec{a},\lambda)=\begin{cases}+1 & if\ r_a\le\frac{1}{2}\ \&\ r_b\le\frac{1-\vec{a}\cdot\vec{b}}{2}\\ & or\ r_a>\frac{1}{2}\ \&\ r_b>\frac{1+\vec{a}\cdot\vec{b}}{2}\\ -1 & else\end{cases}$$

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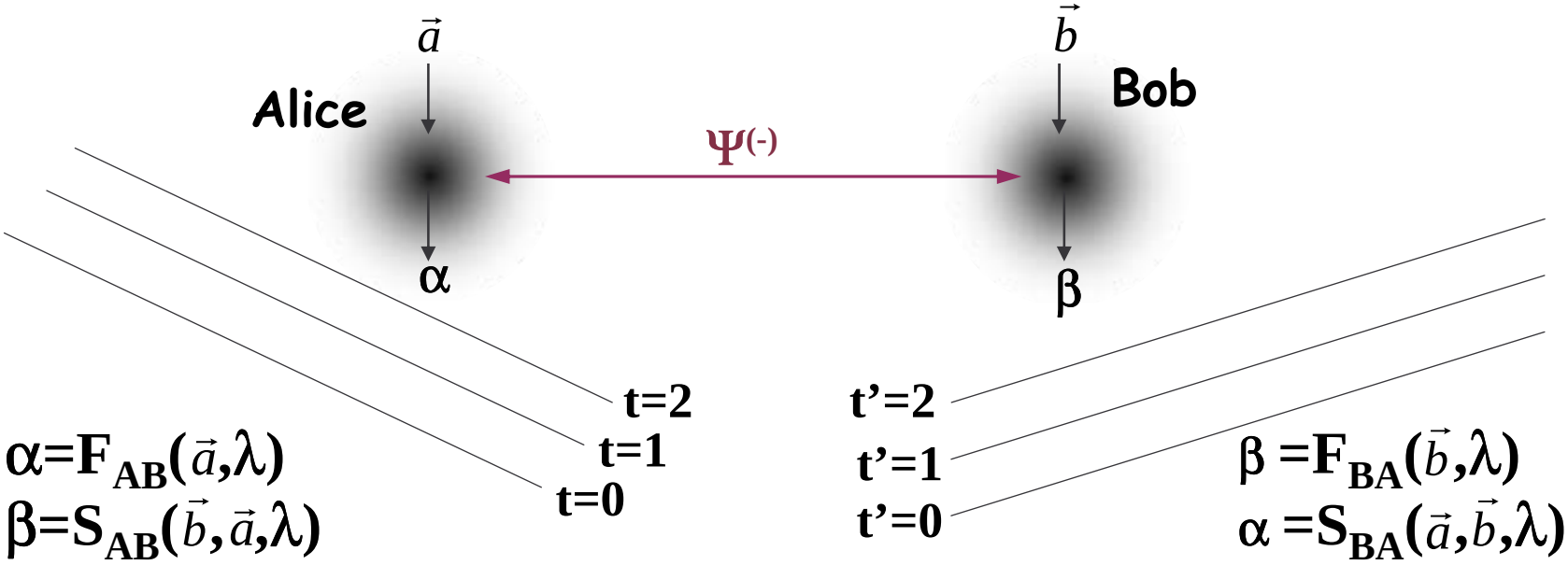
Deterministic nonlocal hidden variables

Let's try to add randomness, given from the beginning, to turn stochastic events into deterministic ones: $\lambda=\{\Psi,r_a,r_b\}$.



$\alpha=F_{AB}(\vec{a},\lambda)$
$\beta=S_{AB}(\vec{b},\vec{a},\lambda)$

$\beta=F_{BA}(\vec{b},\lambda)$
$\alpha=S_{BA}(\vec{a},\vec{b},\lambda)$

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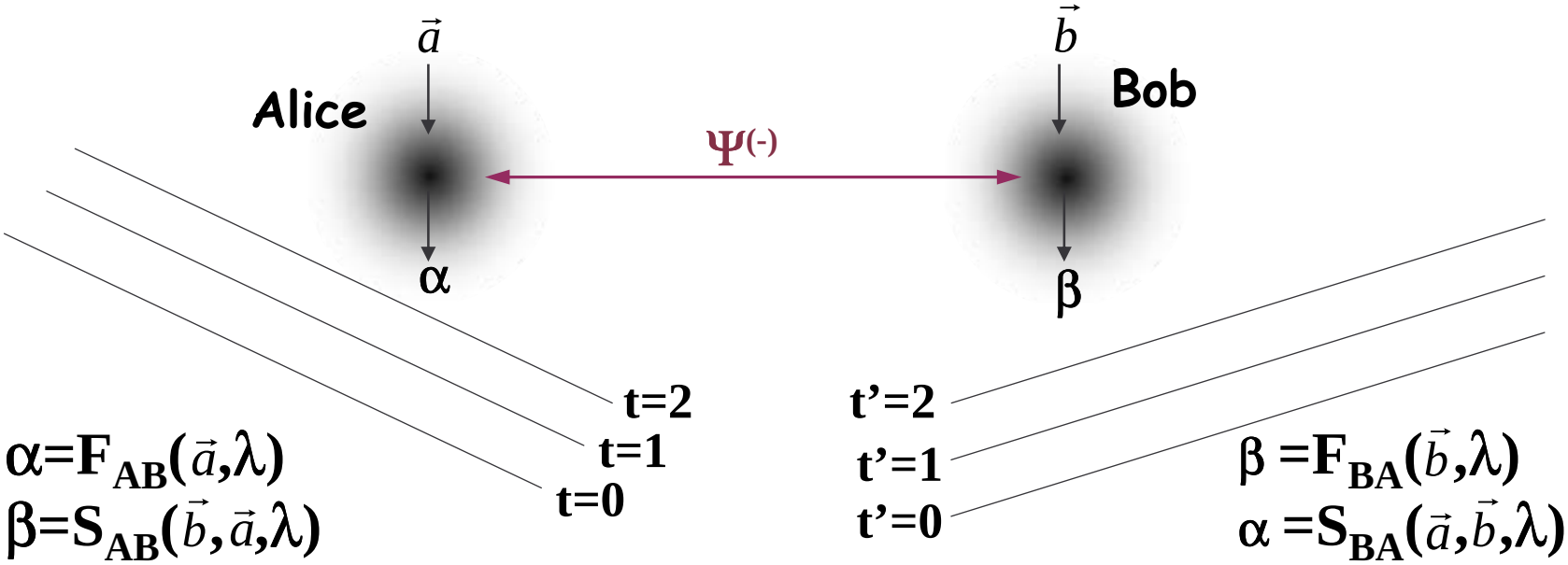


Could there be λ, F_{AB}, S_{AB}, F_{BA} and S_{BA} s.t.

$$F_{AB}(\vec{a},\lambda) = S_{BA}(\vec{a},\vec{b},\lambda) \ ?$$

Theorem: NO !

Proof: S_{BA} would be independent of $\vec{b}$

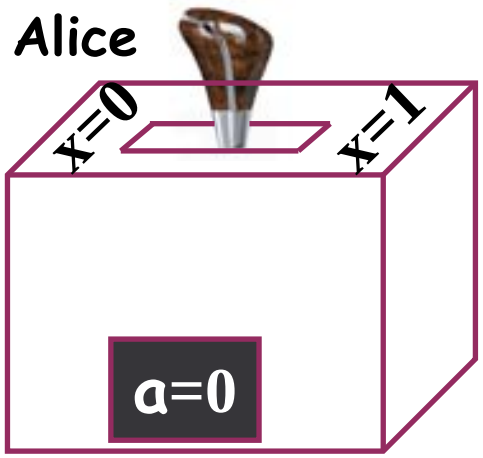
$\Rightarrow$ locality $\Rightarrow$ Bell inequality.

Impossibility of covariant deterministic nonlocal hidden-variable extensions of quantum theory

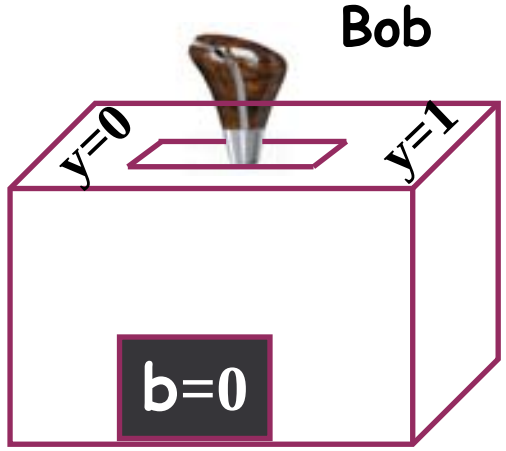
NG, PRA 83, 020102, 2011

Quantum correlations can't be described with local variables, nor can they be described with deterministic nonlocal variables.

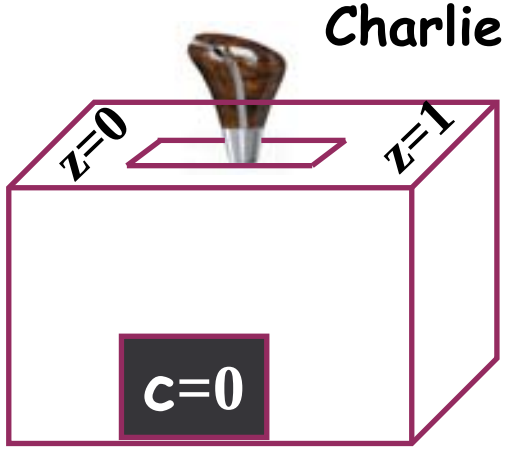
Can one clone Bob's Q system ?



$S_{AB} = \langle a+b=x\cdot y \rangle$



$S_{AC} = \langle a+c=x\cdot z \rangle$



$S_{AB}+S_{AC} = a+b+a+c$

$= b+c = x\cdot(y+z)$

⇒ **If Bob and Charlie chose y=1, z=0, then they can deduce Alice's choice x from their outcomes b+c.**

⇒ **Signalling !!!**

No signalling ⇒ no cloning

Optimal Quantum Cloning is at the limit of no-signalling !

NG, Phys. Lett. A 242, 1 (1998)

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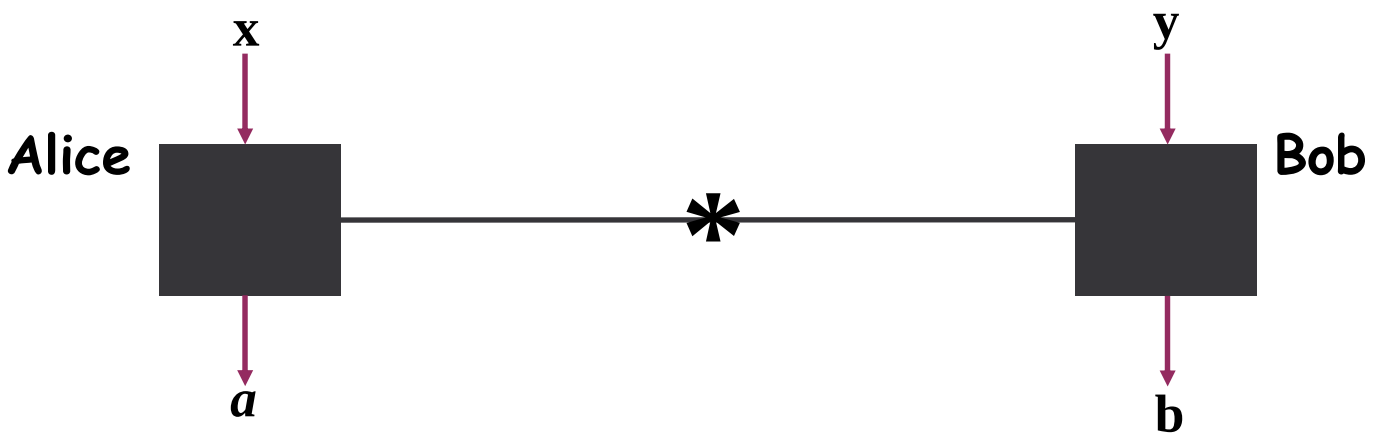
What can nonlocal correlations do for us ?

Entanglement Based Quantum Crypto

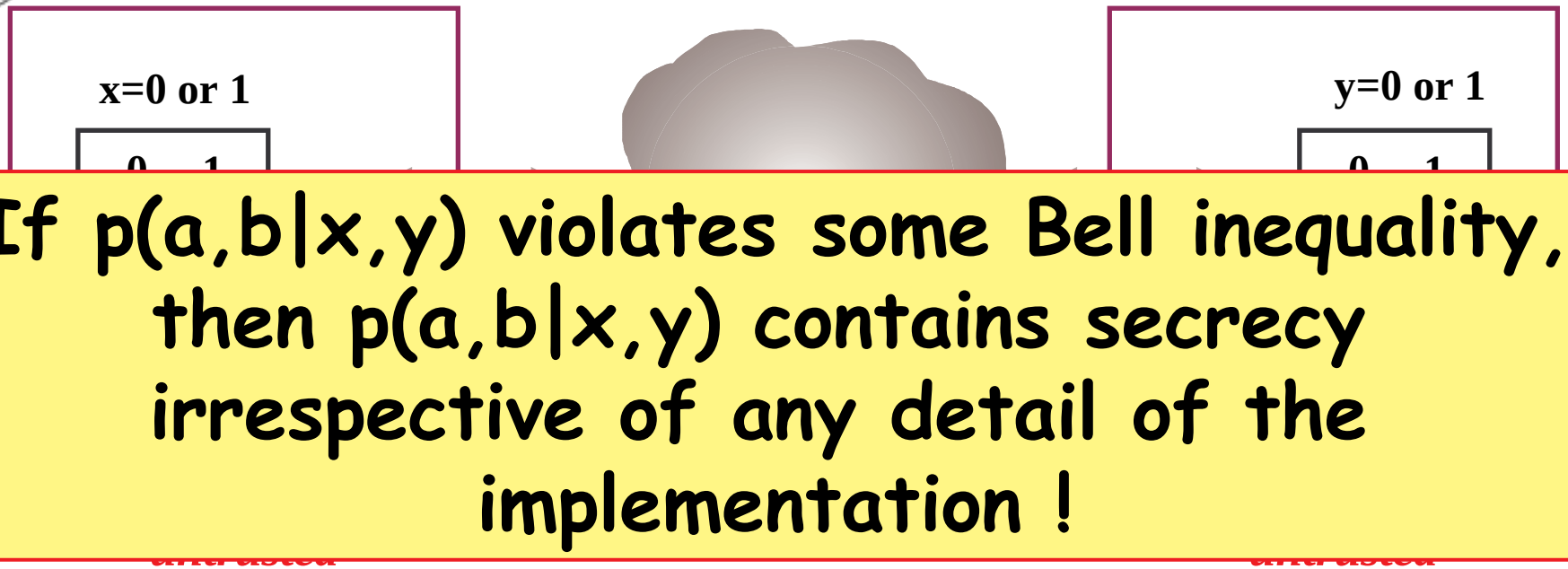
Ekert's intuition, PRL 67, 661 (1991)



If the entanglement is large enough to violate Bell, then *a* & b are random and secret w.r. to any adversary

Exploit quantum nonlocality for cryptography

Alice **Bob**



If p(a,b|x,y) violates some Bell inequality, then p(a,b|x,y) contains secrecy irrespective of any detail of the implementation !

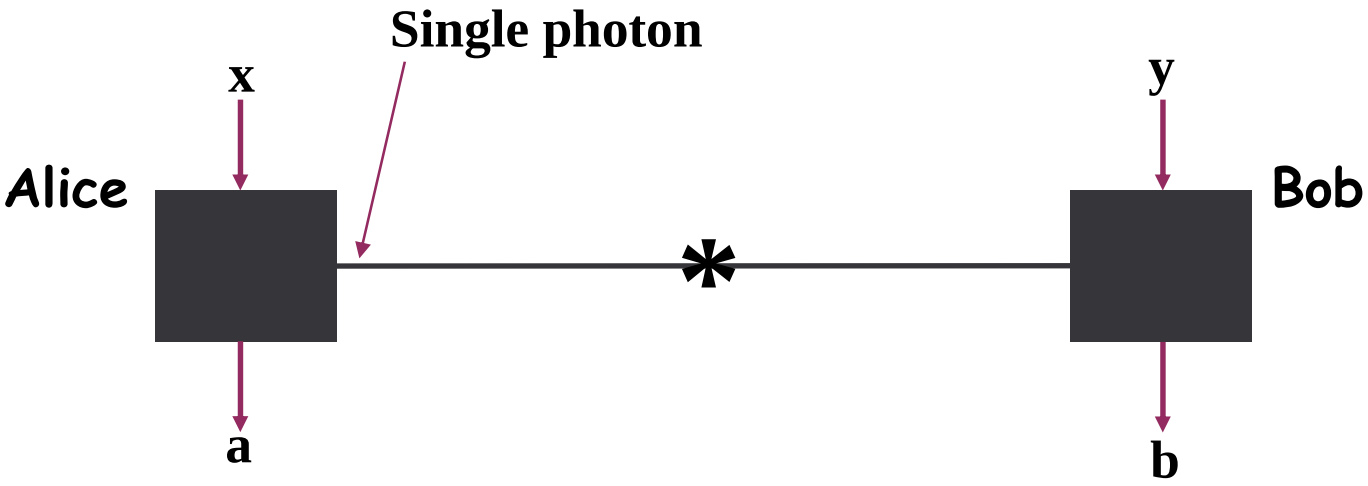
After publicly announcing a fair sample of their data, Alice and Bob's information is entirely contained in the conditional probability

p(a,b|x,y)

PRL 98, 230501, 2007; PRL 97, 120405, 2006; NJP 11, 1, 2009

Applied Physics

Bennett & Brassard (1984)



Applied physics = the art of understanding physics well enough to simplify the implementation of a physical process until it is practical without loosing the essence.

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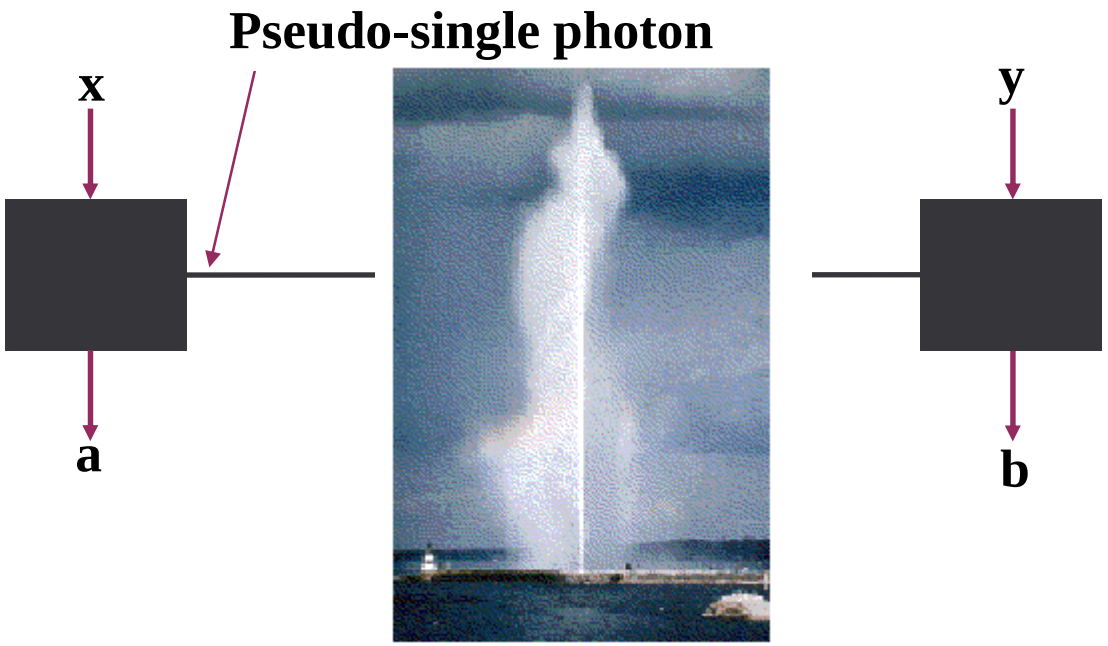
Weak pulse Quantum Crypto



Quantum Cryptography under Lake Geneva,
Nature 378, 449 (1995)
EPL 33, 335 (1996)

Spin-off from the University of Geneva, 2001

id Quantique

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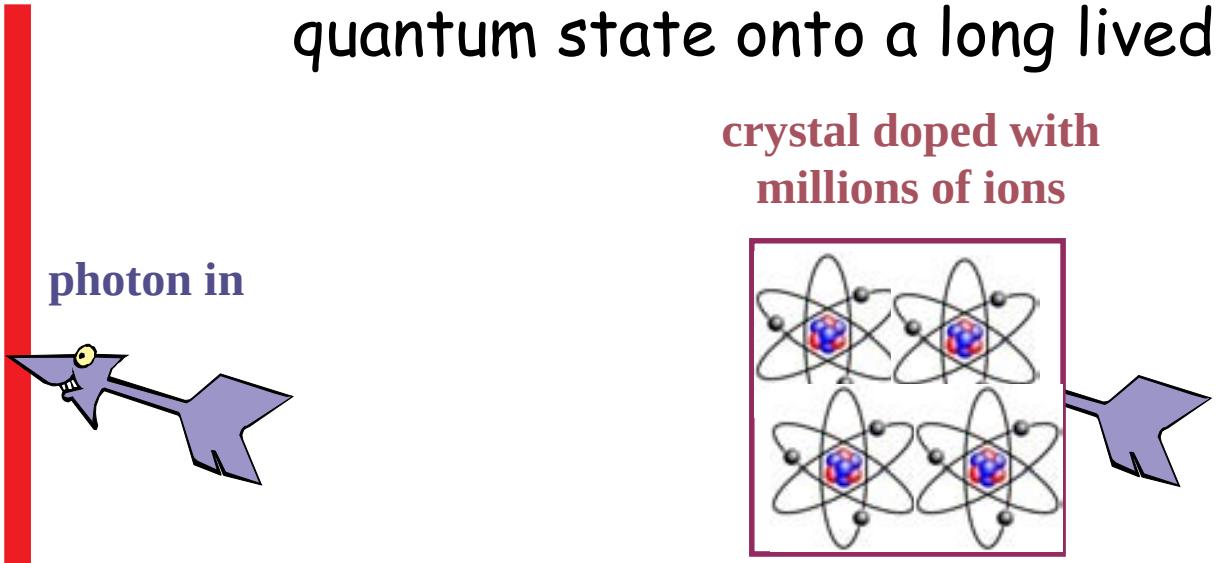
Used daily by some Swiss banks

Quantum memory

Goal: controlled and reversible mapping of a photonic quantum state onto a long lived atomic ensemble.



The quantum state of the photon is now coded in a huge entangled states of millions of « atoms »

Nature 456, 773, 2008

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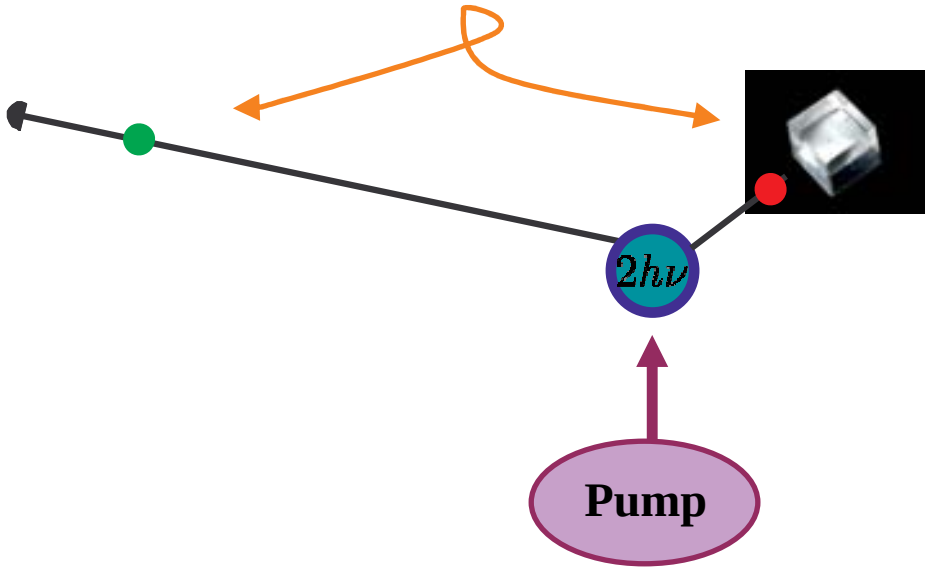
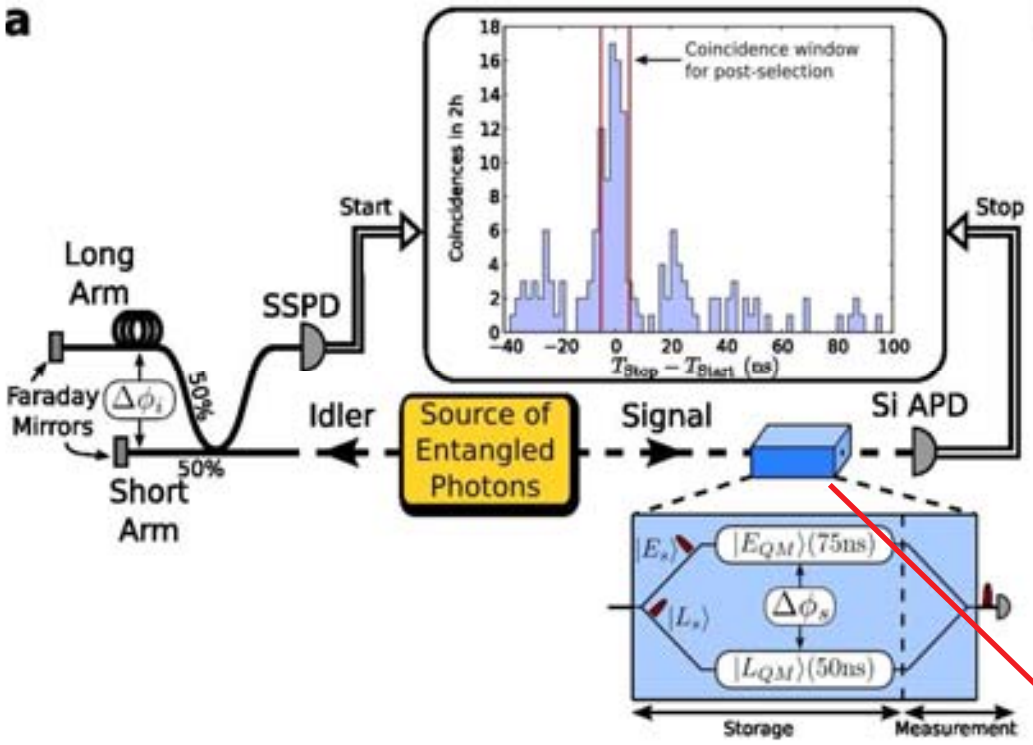
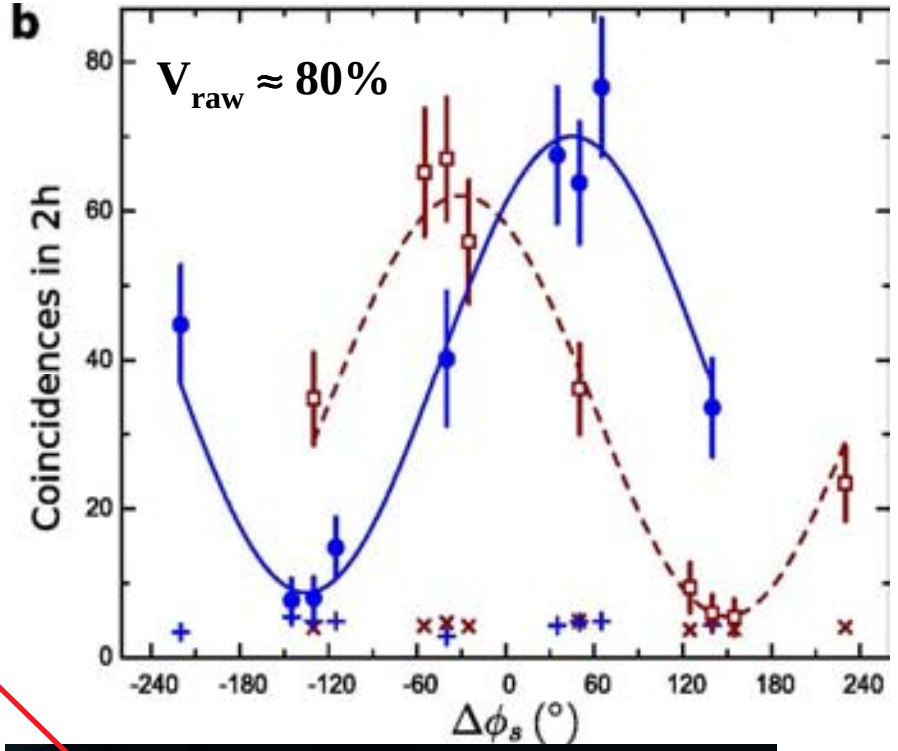
Demonstration of entanglement between a telecom photon and an excitation stored in a crystal

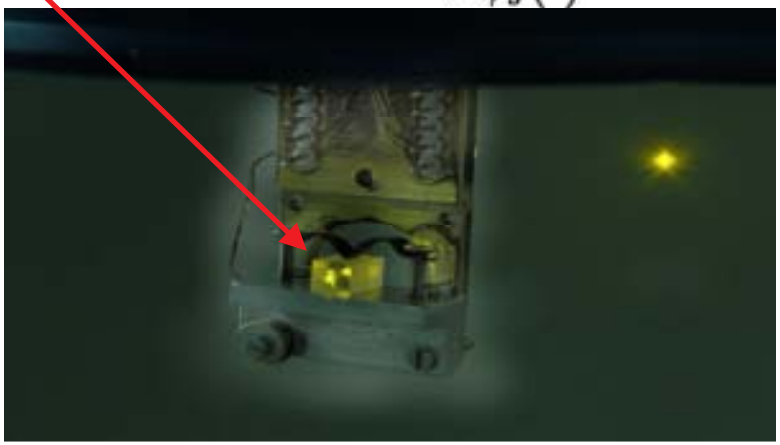


Photon-Crystal 2-qubit interference

Clausen, Usmani et al, Nature 469, 508-511, 2011





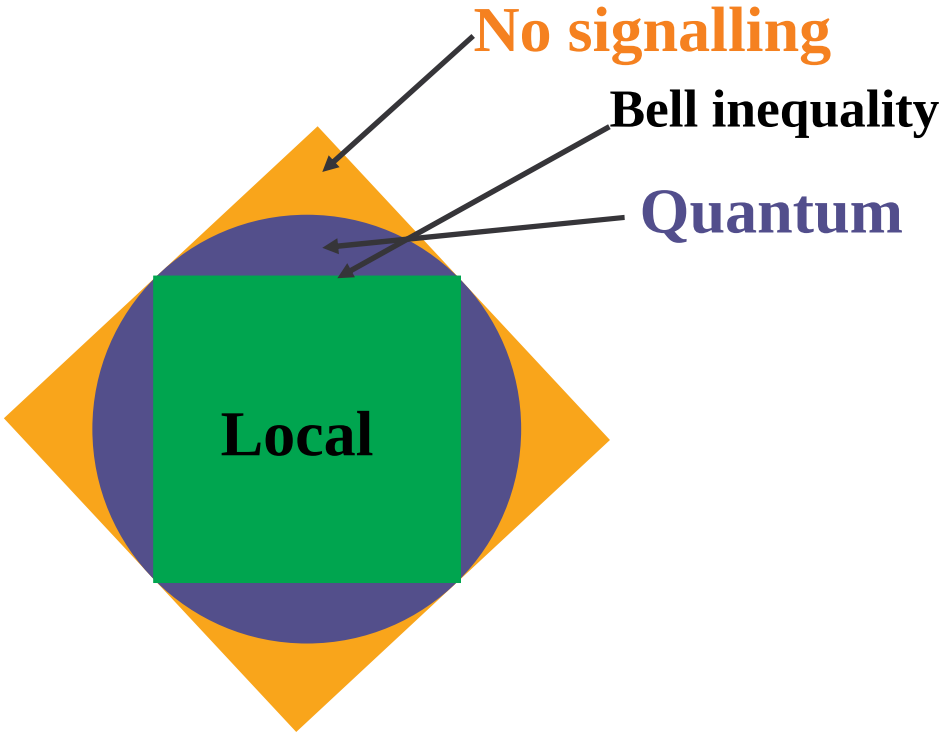


Photon-Crystal entanglement with a violation of the CHSH-Bell inequality: S ≈ 3.3 > 3

Studying nonlocal correlations from outside the Hilbert space

P(a,b|x,y) can be considered as a vector and represented as a point in a vector space:

<u>New question</u>:
why are quantum correlations not more nonlocal ?



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Conclusions

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Photonics

QuReP

FET-IP

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quantum qp photonics
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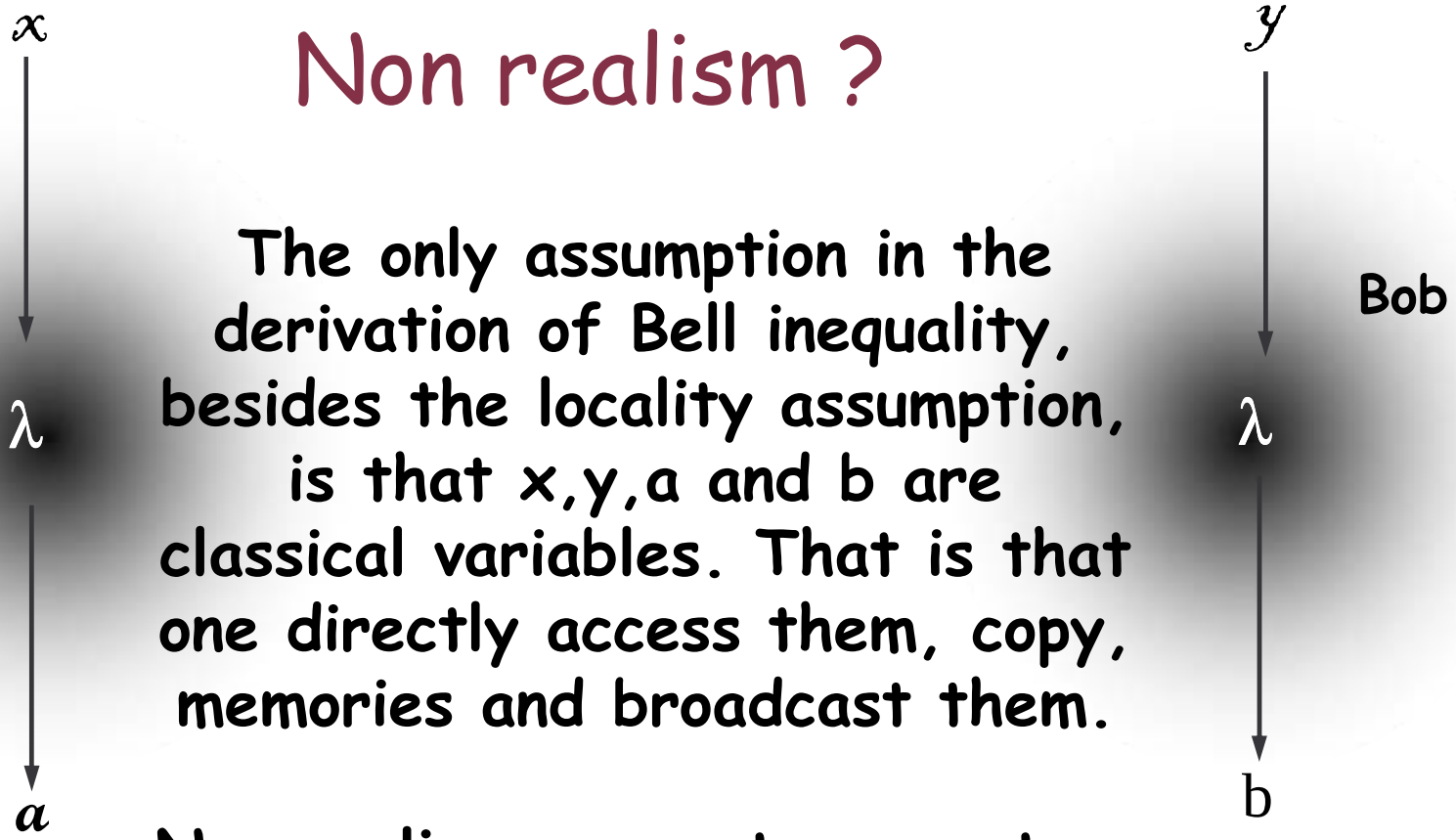
Non realism ?



The only assumption in the derivation of Bell inequality, besides the locality assumption, is that x,y,a and b are classical variables. That is that one directly access them, copy, memories and broadcast them.

Non realism seems to me not an alternative to nonlocality. And what could "local non realism" mean ?!?

N. Gisin, Non-realism : deep thought or a soft option ? quant-ph/0901.4255, Found. Phys. 2010, DOI 10.1007/s10701-010-9508-1