Quantum Entanglement: Fundamental and Applied Physics

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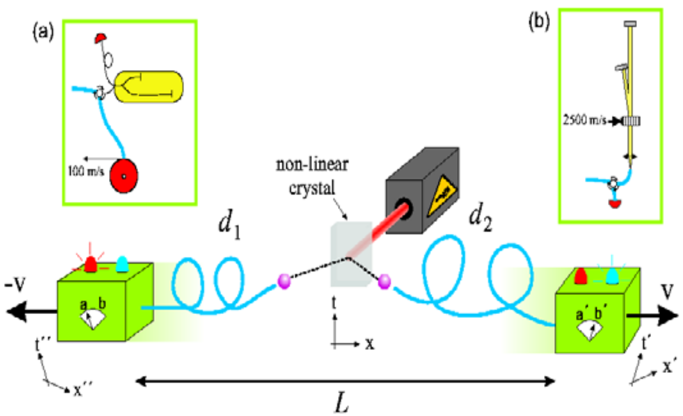
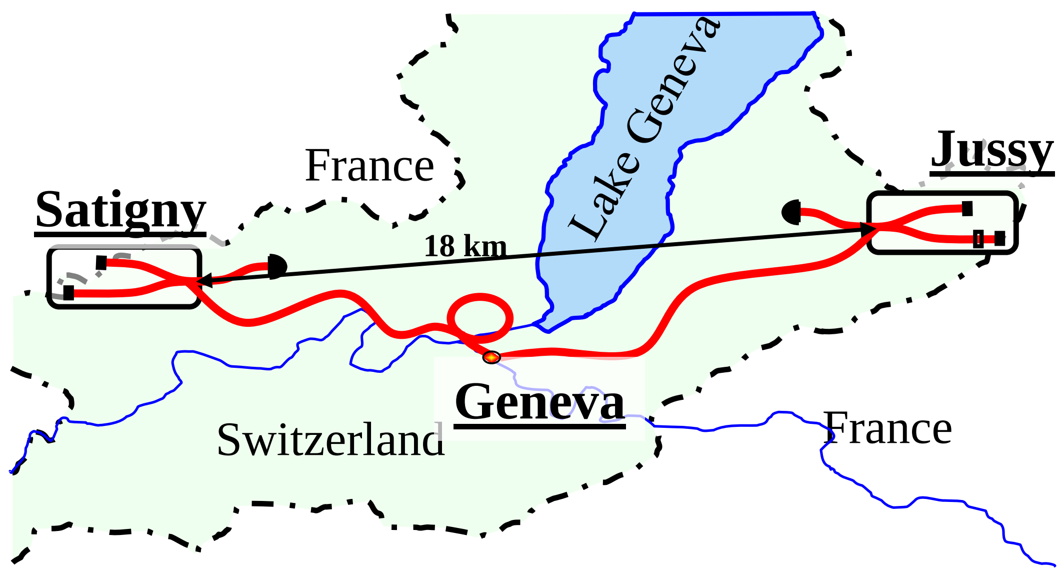




x Alice Bob y

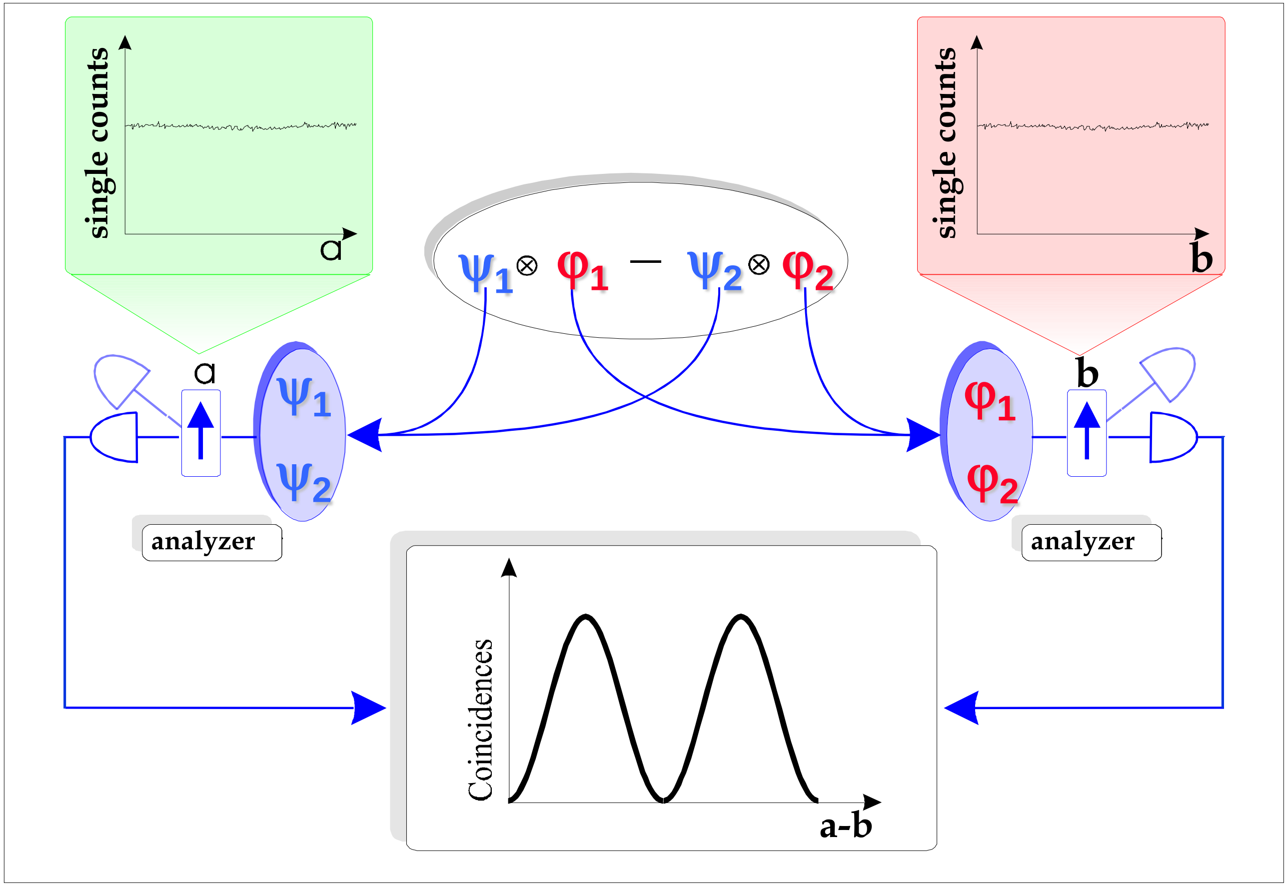
$$\boxed{a + b = x.y}$$

a b

Quantum non locality

Alice

Bob



- **the statistics of the correlations can't be described by local variables ➡ Quantum non locality**

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x y

$$P_\Psi(a,b|x,y) \neq P_\Psi(a|x)\cdot P_\Psi(b|y)$$

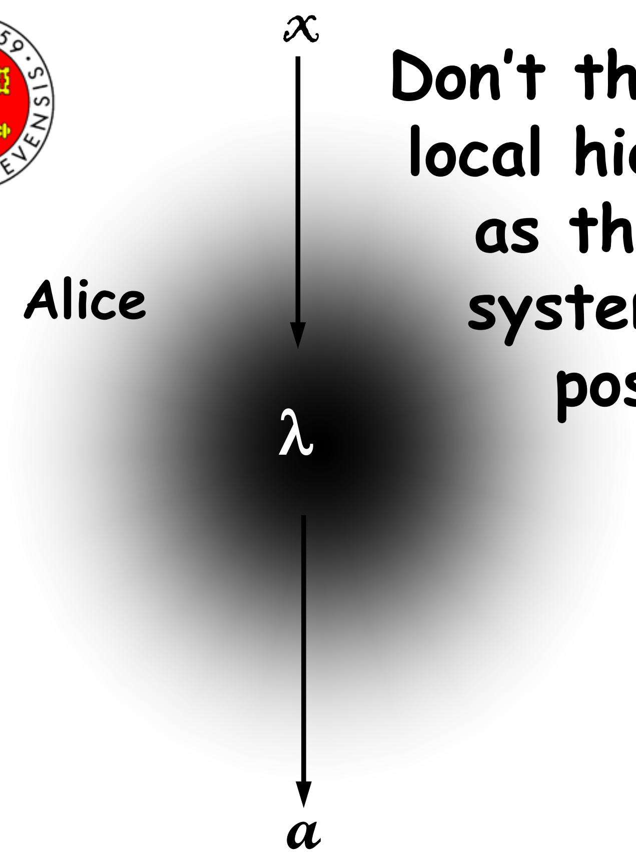
Alice Bob

Ψ Ψ

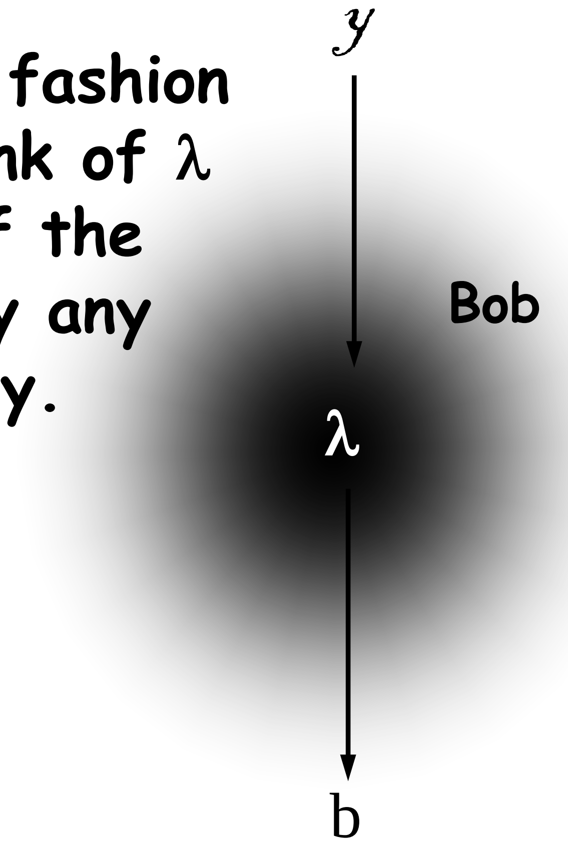
The events at Alice and Bob's sides are not independent !
It seems that somehow the two sides are coordinated or "interact" !?!
(but without signaling)

a b

Spatially separated systems are not logically separated.



Don't think of λ as an old fashion local hidden variable. Think of λ as the physical state of the systems as described by any possible future theory.



NG, Quantum Nonlocality: How Does Nature do it? Science 326, 1357 (2009)

Assumptions:

x Alice λ a

y Bob λ b

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**.

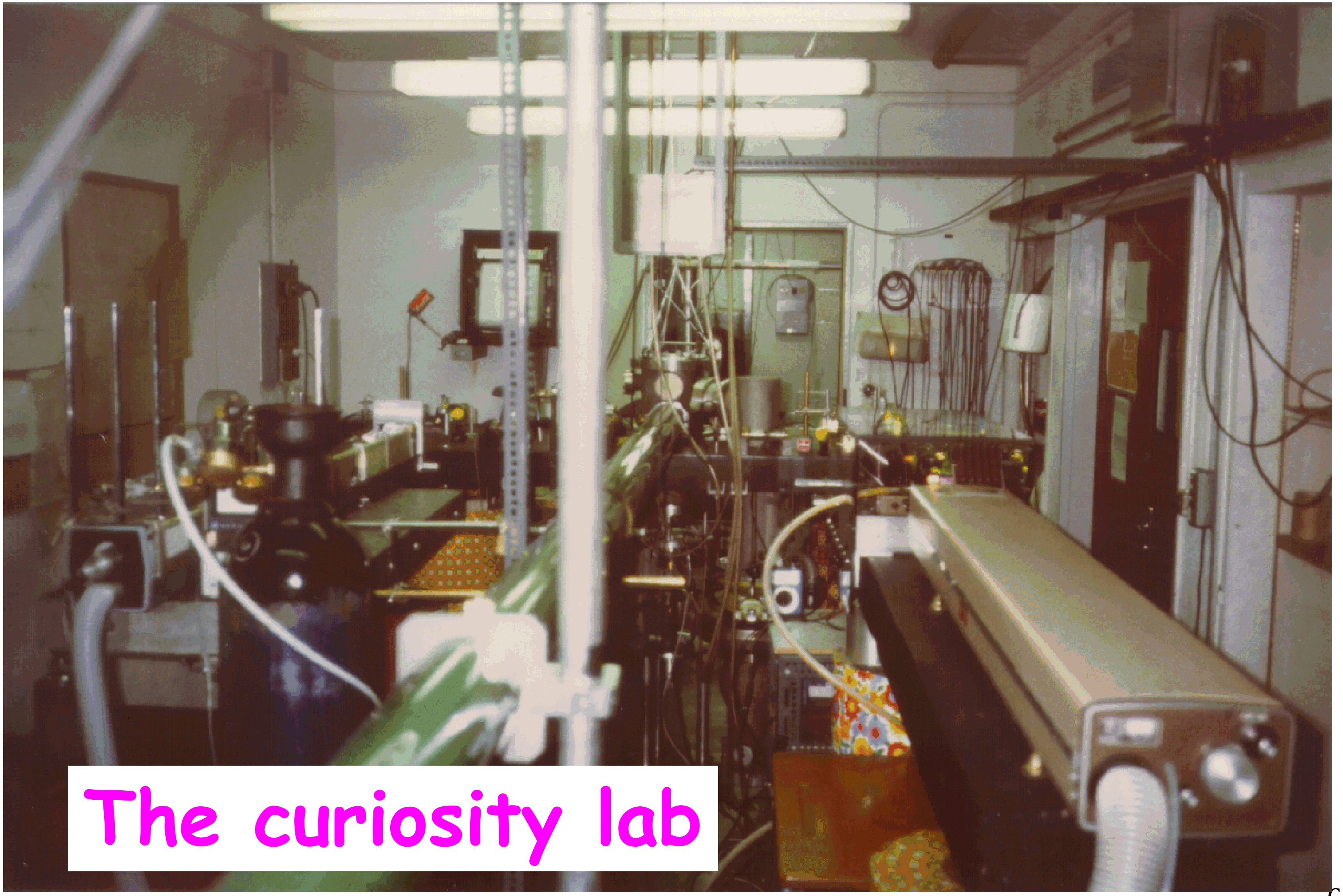
2.b x & y are independent of λ

$I(x:\lambda)=I(y:\lambda)=0$

Conclusion: Bell inequalities

NG, Quantum Nonlocality: How Does Nature do it? Science 326, 1357 (2009)

Tests of Bell's inequality: Aspect's 1982 experiment



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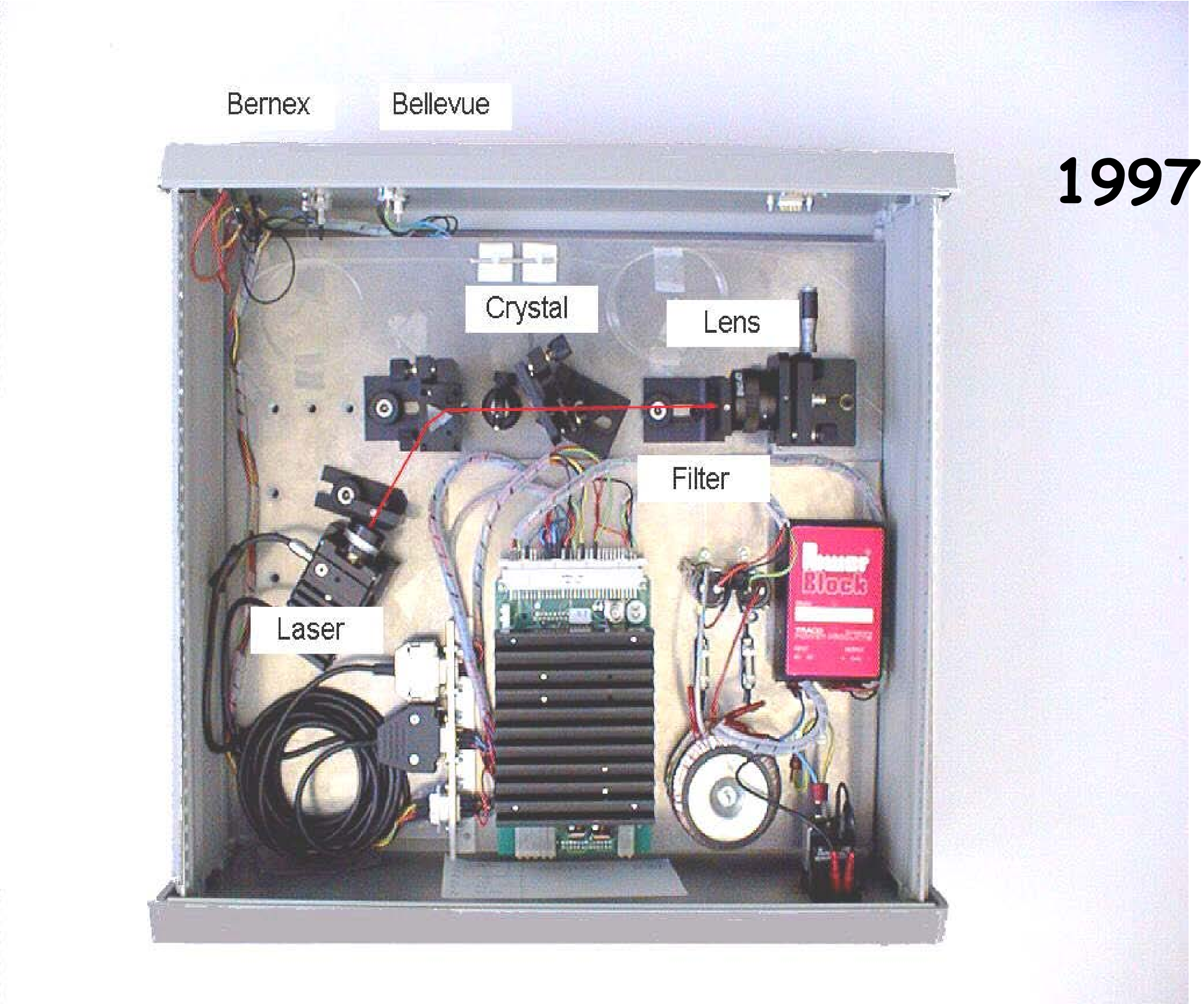
Violation of Bell inequality over 10 km



1997

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Violation of Bell inequality over 10 km, Geneva, 1997

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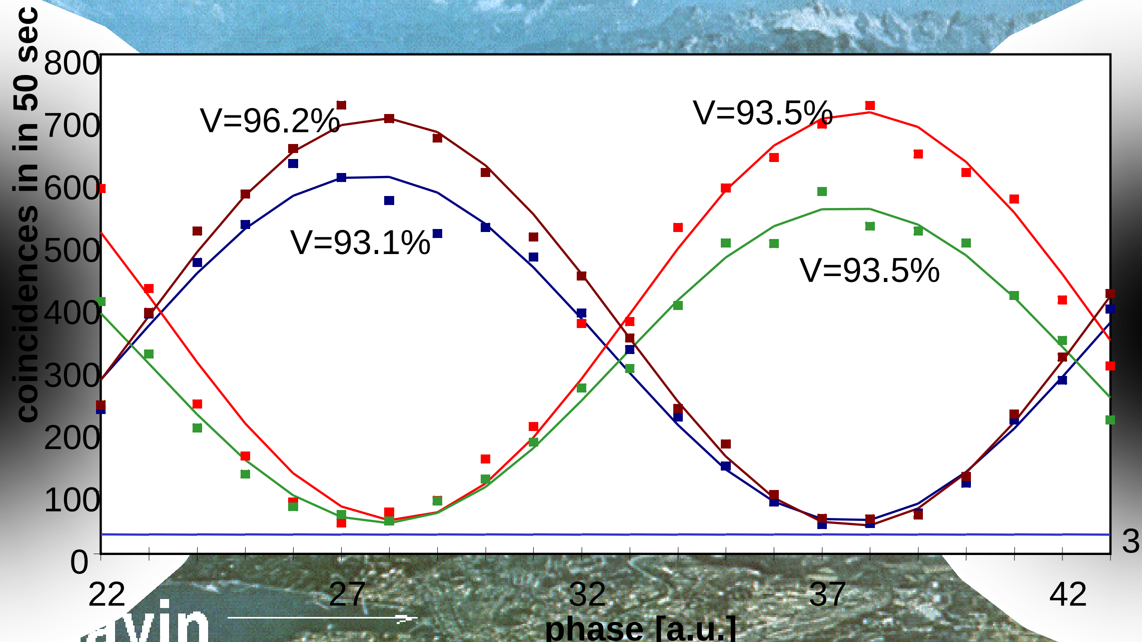
experimental result

x y

Alice Bob

λ λ



Bellevue

Bernex

Conclusion: Nature violates the Bell inequality

⇒ Nature is nonlocal

swisscom

PRL 81, 3563, 1998 ; PRA A, 59, 4150-4163, 1999

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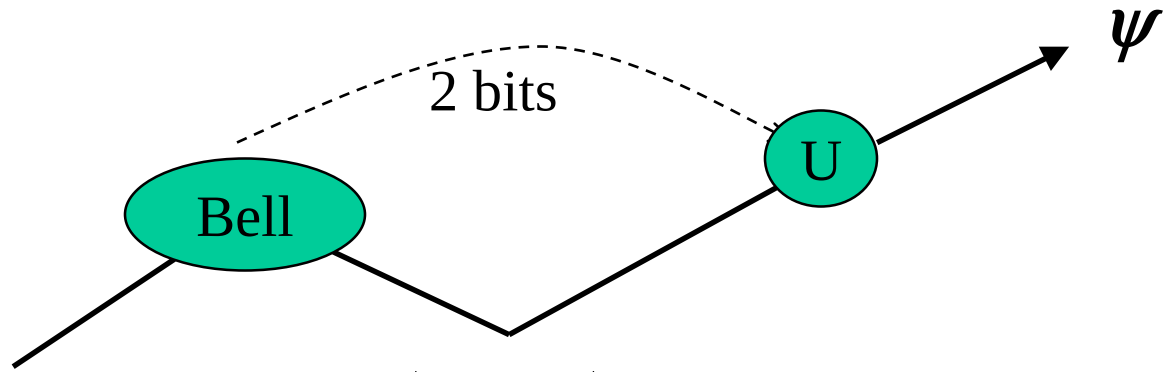
Quantum teleportation: formal description



$$\psi \quad \otimes \quad |EPR\rangle \quad =$$

$$(c_0|0\rangle + c_1|1\rangle) \otimes (|0,0\rangle + |1,1\rangle)/\sqrt{2}$$

$$= \frac{1}{2\sqrt{2}}(|0,0\rangle + |1,1\rangle) \otimes \underbrace{(c_0|0\rangle + c_1|1\rangle)}_{\to\ \Psi}$$

$$+ \frac{1}{2\sqrt{2}}(|0,0\rangle - |1,1\rangle) \otimes \underbrace{(c_0|0\rangle - c_1|1\rangle)}_{\to\ \sigma_z\Psi}$$

$$+ \frac{1}{2\sqrt{2}}(|0,1\rangle + |1,0\rangle) \otimes \underbrace{(c_1|0\rangle + c_0|1\rangle)}_{\to\ \sigma_x\Psi}$$

$$+ \frac{1}{2\sqrt{2}}(|0,1\rangle - |1,0\rangle) \otimes \underbrace{(c_1|0\rangle - c_0|1\rangle)}_{\to\ \sigma_y\Psi}$$

PR-box: E(0,0) + E(0,1) + E(1,0) - E(1,1) = 4

Alice

Bob

$x \in \{0,1\}$

$y \in \{0,1\}$

modulo 2

$a + b = x.y$

$a \in \{0,1\}$

$b \in \{0,1\}$

Prob($a=1|x,y$) = ½, independent of $y \Rightarrow$ no signaling

Found.Phys. 24, 379, 1994

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Non local Randomness

- Assume that distances really exist.
- Assume there is no super-determinism conspiracy.

x_i

Promise: $a \oplus b = x \cdot y$

y_i

distance

a_i

b_i

P(a,b|x,y)

		x=0		x=1	
		a=0	a=1	a=0	a=1
y=0	b=0				
	b=1				
y=1	b=0				
	b=1				

Non local Randomness

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- Assume that distances really exist.
- Assume there is no hyper-determinism conspiracy.

Promise: $a \oplus b = x \cdot y$

x_i

a_i

distance

y_i

b_i

P(a,b|x,y)

		x=0, a=0	x=0, a=1	x=1, a=0	x=1, a=1
y=0	b=0	p	0	p	0
y=0	b=1	0	p	0	
y=1	b=0		0	0	
y=1	b=1	0	p	p	0

Normalization: 2p=1

Non local Randomness

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- Assume that distances really exist.
- Assume there is no hyper-determinism conspiracy.

Promise: $a \oplus b = x \cdot y$

x_i

a_i

distance

y_i

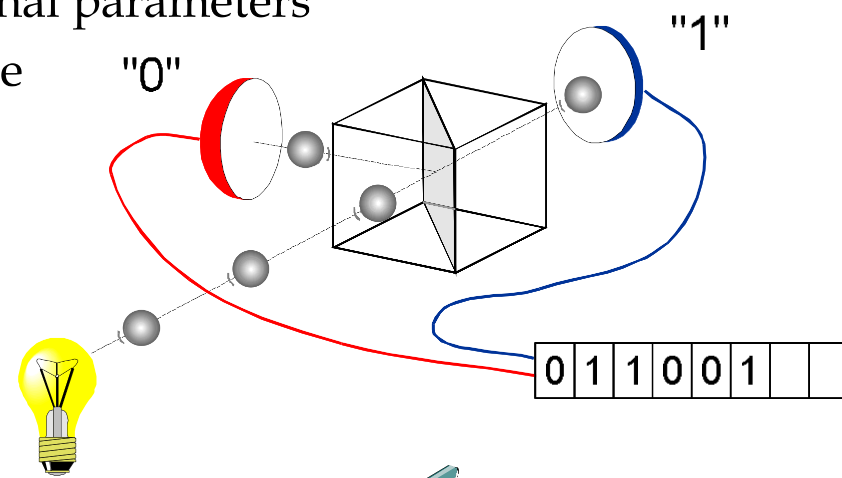
b_i

P(a,b|x,y)

		x=0		x=1	
		a=0	a=1	a=0	a=1
y=0	b=0	1/2	0	1/2	0
	b=1	0	1/2	0	1/2
y=1	b=0	1/2	0	0	1/2
	b=1	0	1/2	1/2	0

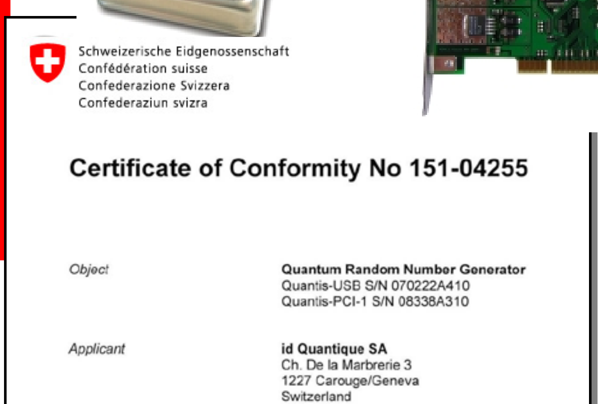
Quantum physical RNG

- Quantum physics is fundamentally random
  - Cannot be influenced by any external parameters
  - Output is completely unpredictable
- High bit rate
  - 4 or 16 Mbits/s
- Markets
  - Cryptography
  - Gaming and Lotteries
  - Scientific



Key generation

NEW


Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra

Certificate of Conformity No 151-04255

Object	**Quantum Random Number Generator** Quantis-USB S/N 070222A410 Quantis-PCI-1 S/N 08338A310
Applicant	**id Quantique SA** Ch. De la Marbrerie 3 1227 Carouge/Geneva Switzerland


CTL
COMPLIANCE TESTING LABORATORY

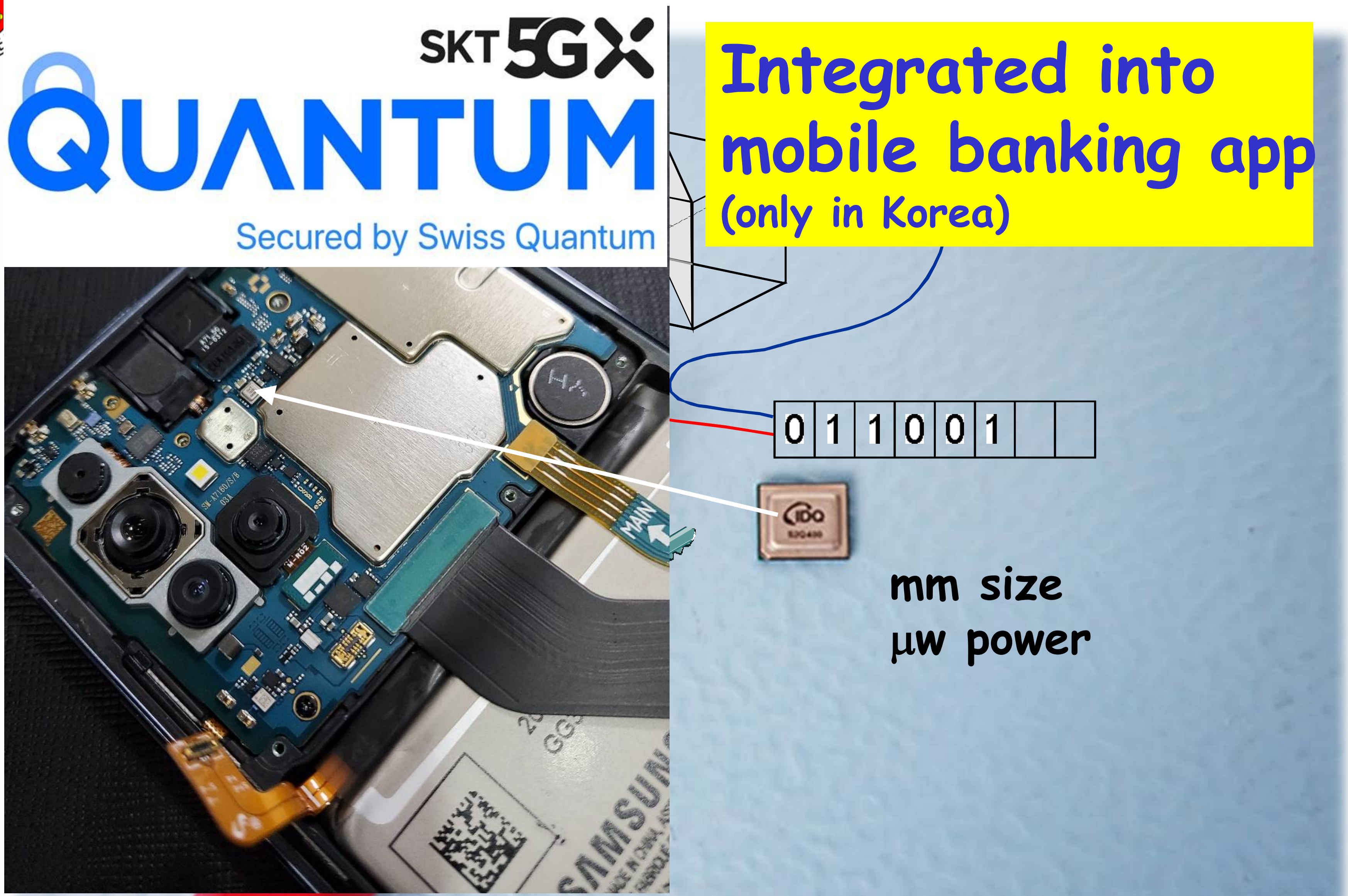
Certificate of Compliance

This is to certify that the Random Number Generator

Quantis-v10.10.08

by

Quantum Random Number Generator



Integrated into mobile banking app
(only in Korea)

mm size
µw power

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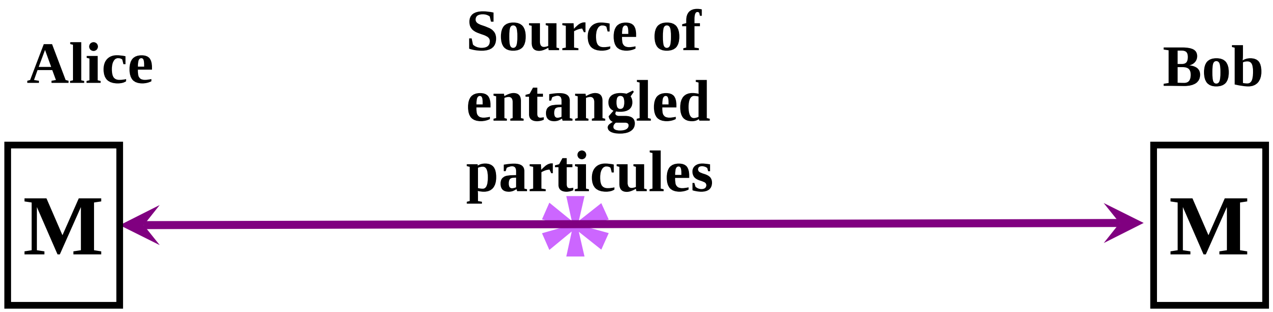
No-cloning and no-signaling

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

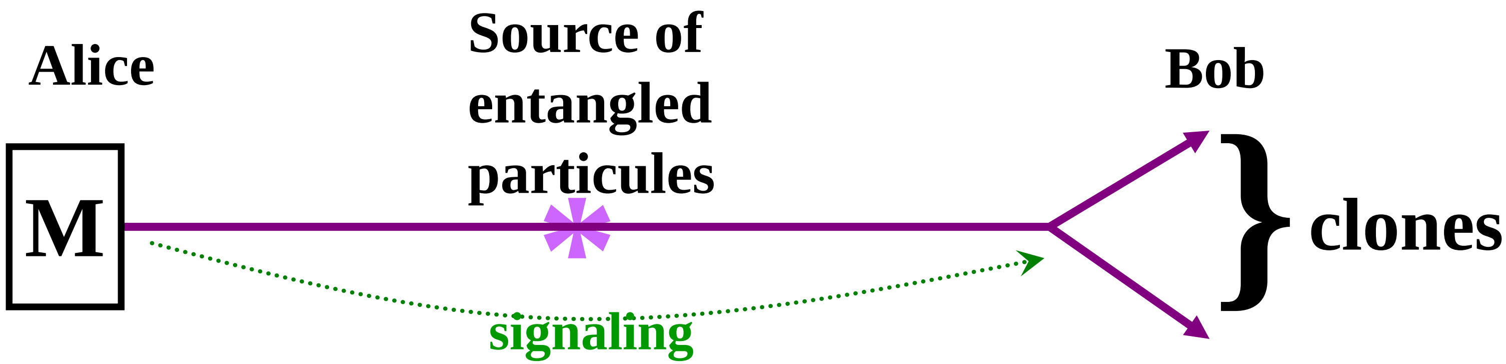


$\uparrow$ or $\downarrow$ = $\rightarrow$ or $\leftarrow$

$\Rightarrow$ Entanglement doesn’t allow for signaling

No-cloning and no-signaling

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



$\uparrow$ **or** $\downarrow$ = $\rightarrow$ **or** $\leftarrow$

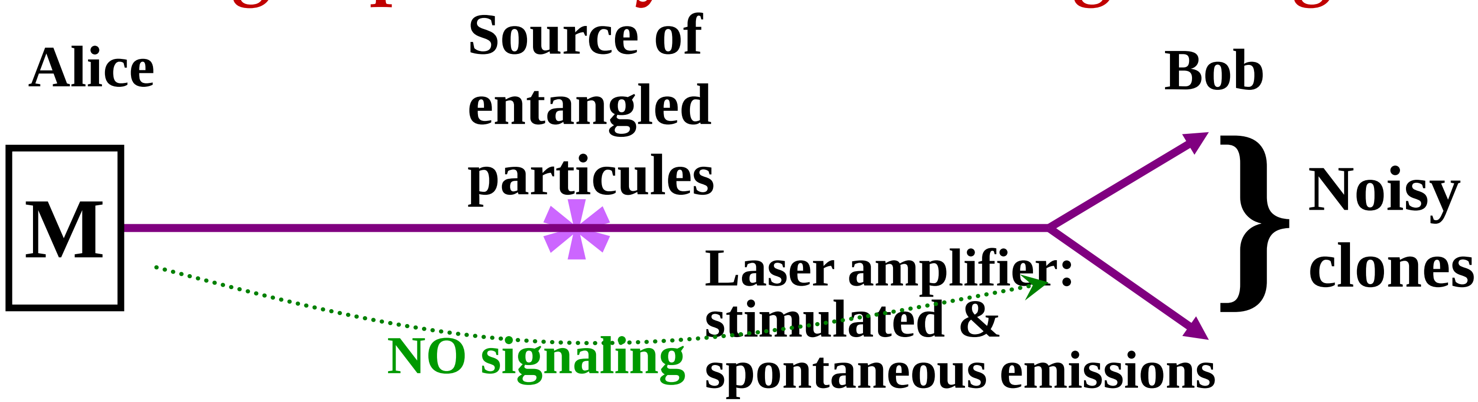
$\uparrow\uparrow$ **or** $\downarrow\downarrow$ $\neq$ $\rightarrow\rightarrow$ **or** $\leftarrow\leftarrow$

$\Rightarrow$ Perfect cloning would allow one to exploit entanglement for signaling !

No-cloning and no-signaling

NG, Phys. Lett. A <u>242</u>, 1 (1998)

- **Interestingly, optimal-but-imperfect quantum cloning is precisely at the no-signaling limit !**



$$F=\frac{2\cdot 1+1\cdot \frac{1}{2}}{2+1}=\frac{5}{6}$$

$$a^{+}|1\rangle=\sqrt{2}|2\rangle$$
$$a^{+}|0\rangle=1|1\rangle$$

Exploit quantum nonlocality for cryptography

Alice **Bob**

x=0 or 1 **y=0 or 1**

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 !

Non-local quantum correlations are cryptographic keys

in the conditional probability

p(a,b|x,y)

PRL 98, 230501, 2007; PRL 97, 120405, 2006; NJP 11, 1, 200

Spin-off from the University of Geneva, 2001

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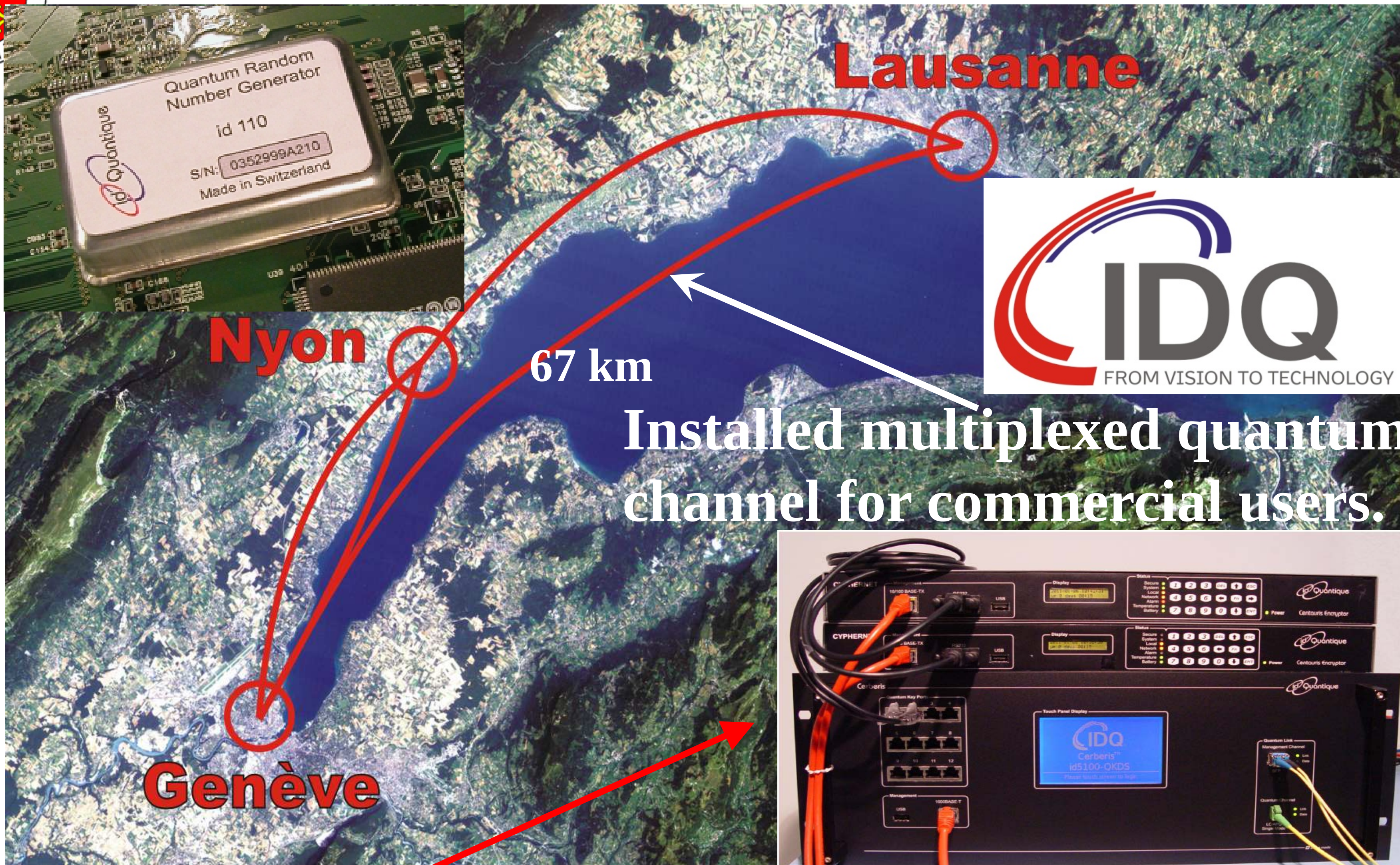
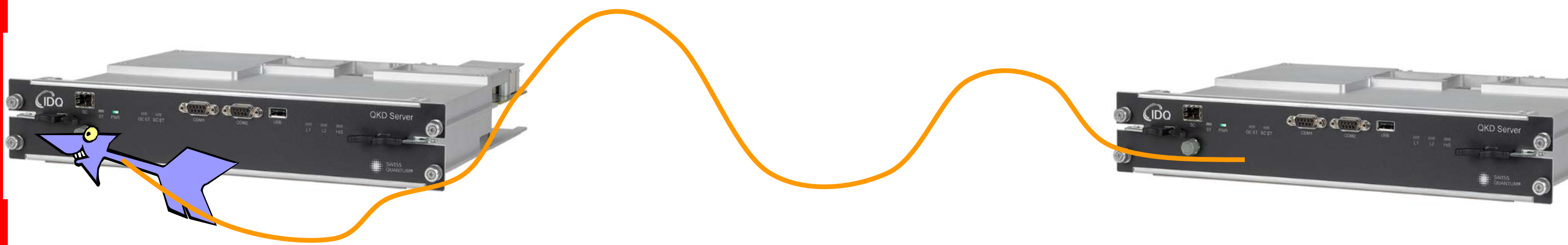


Installed multiplexed quantum channel for commercial users.

Used daily by some commercial customers

Quantum Key Distribution

- Encode a quantum state into a photon and send the latter from Alice to Bob:



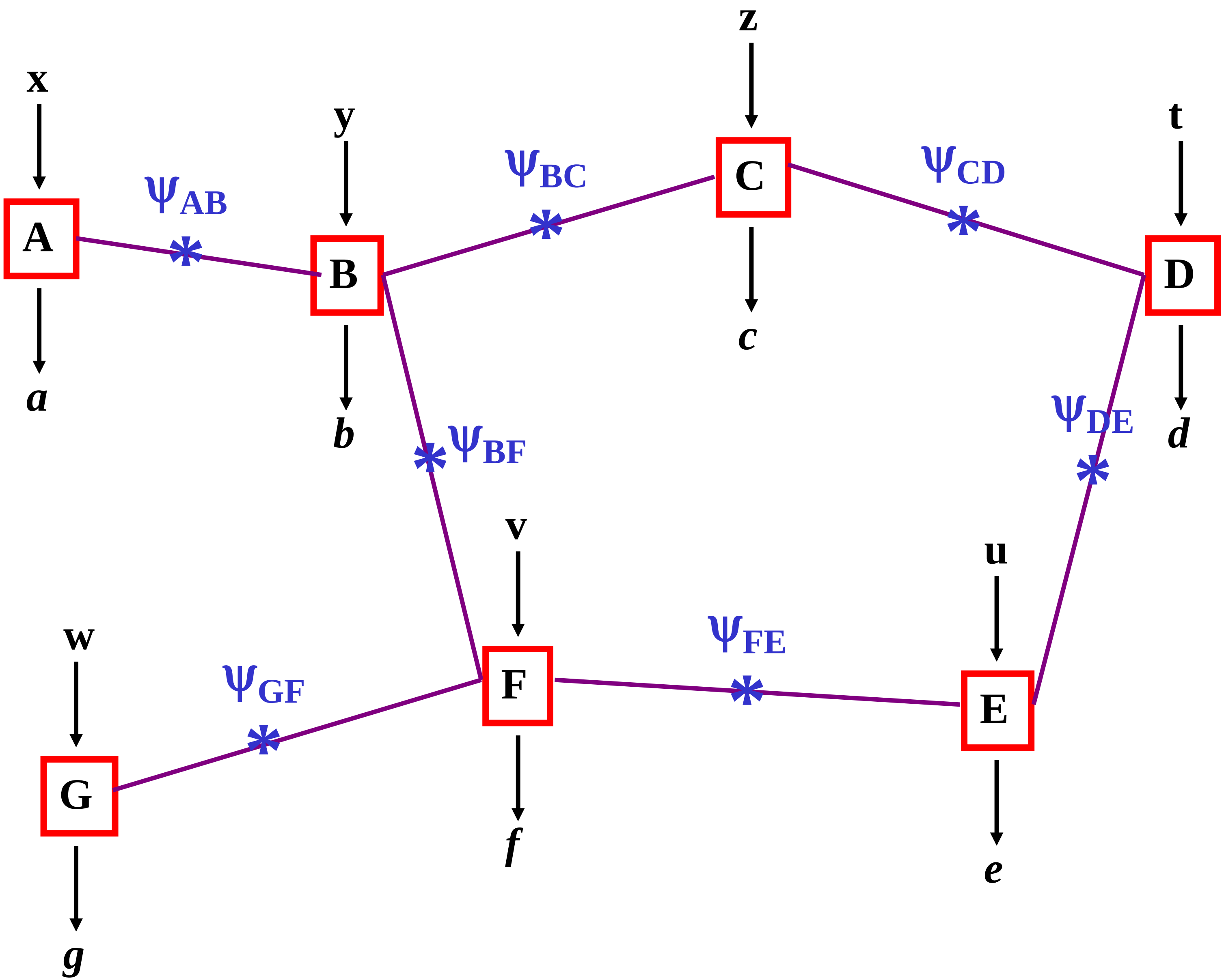
- This is pretty simple and well mastered by id Quantique SA. This is how all commercial Quantum Cryptography works already todays.

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 ?

How does nature do it ?, Science, 326, 1357, 2009

N independent sources: product state $\psi^{\otimes N}$



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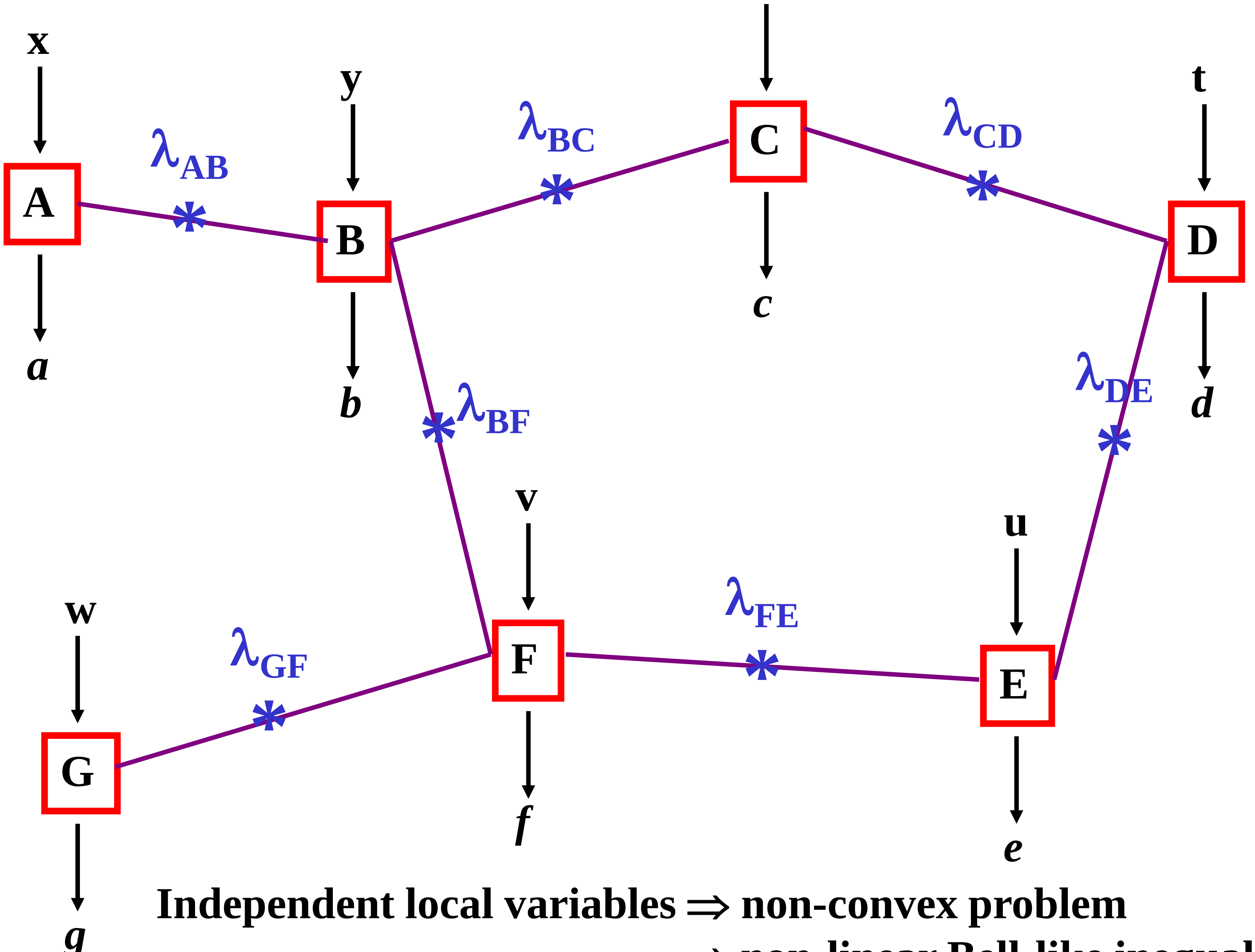
⇒ N independent local variables



Independent local variables ⇒ non-convex problem

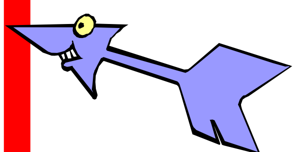
⇒ non-linear Bell-like inequalities.

Quantum memory & Q-internet

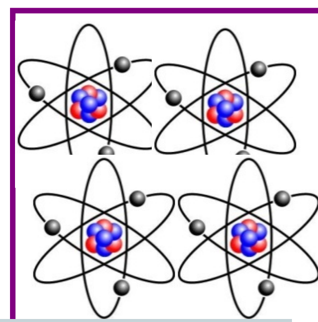
University

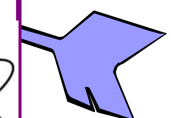
Goal: controlled and reversible mapping of a photonic quantum state onto a long lived atomic ensemb

photon in

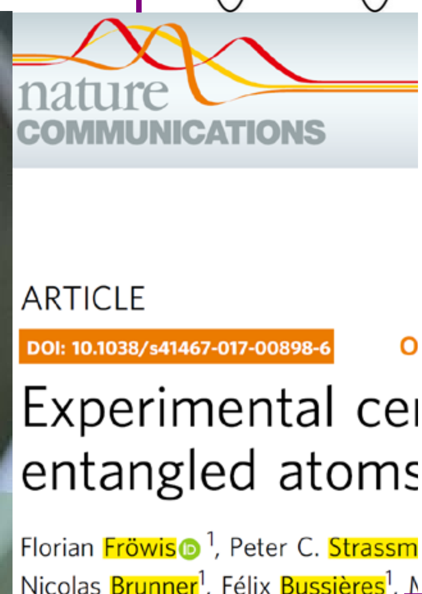


crystal doped with billions of ions





photon out at desired time in same Q state

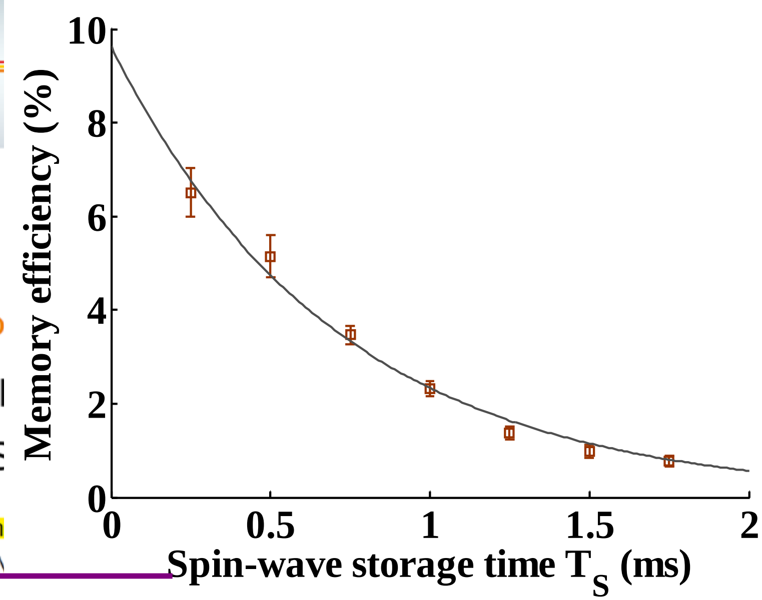

nature COMMUNICATIONS

ARTICLE

DOI: 10.1038/s41467-017-00898-6

Experimental ce
entangled atoms

Florian Fröwis[1], Peter C. Strassm
Nicolas Brunner[1], Félix Bussières[1],



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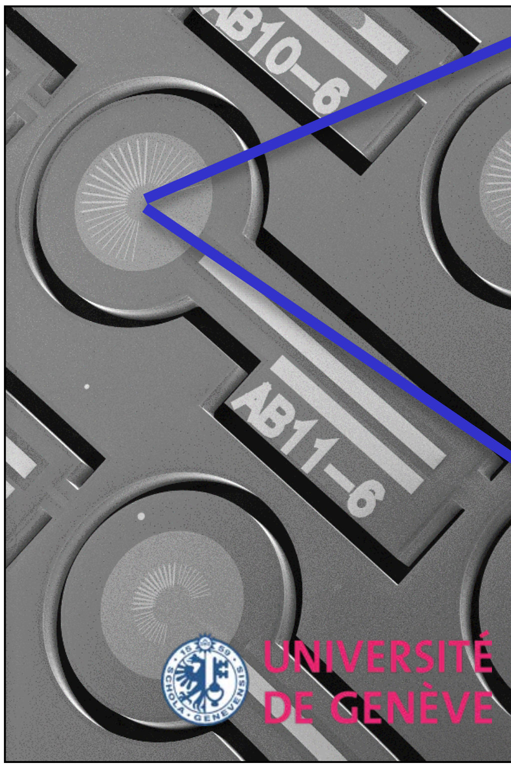
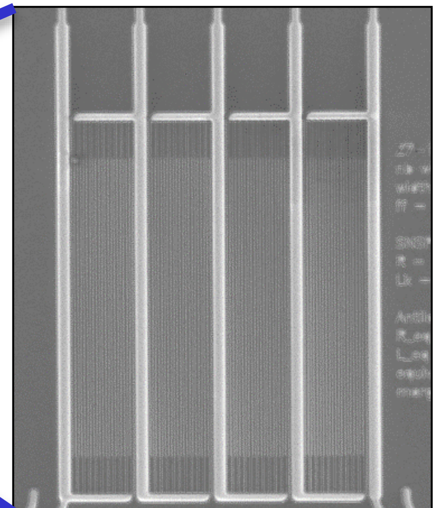
Superconducting nanowire single photon detection systems

- **Faster and smarter detectors**

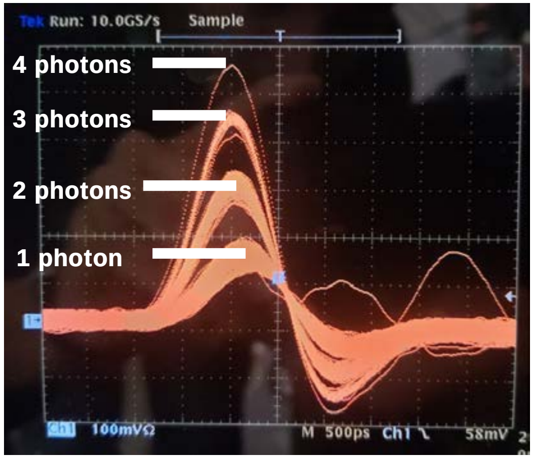




Fastest SNSPD detectors with PNR enabled
Joint development with the University of Geneva
Commercially available at IDQ

Parallelly-connected SNSPDs lead to

- **Counting rates as high as 200 MHz**
- >70% nominal efficiency



Prof. Hugo Zbinden

Physics of SNSPD is amazingly poorly understood

Application of superconducting single-photon detectors to …

Rockets

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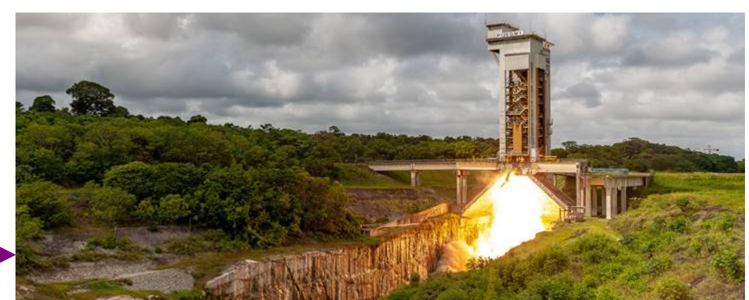
- Ariane 6 will the first space launcher ever using **<u>Opto-Pyrotechnics</u>** instead of conventional electro-pyrotechnics
- **ArianeGroup worked with IDQ to design a fiber optic integrity and performance monitoring for entire Opto-Pyro control system**
- First real-life test: last week

Pyrotechnic sub-systems: vital part of the avionics system – responsible for ignition, separation, passivation and neutralization



Conclusion

- Quantum Entanglement is a marvellous playing ground from Fundamental physics to Applications and back.

1. **The Age of Entanglement, par Louisa Gilder, Ed. Knopf 2008.**
2. ***Initiation à la Physique Quantique, par Valerio Scarani, Edition Vuibert, 2003.***
3. **L'Impensable Hasard, par Nicolas Gisin, Ed. Odile Jacob 2012.**