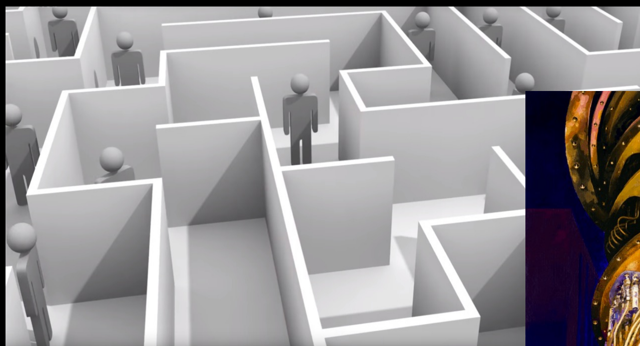
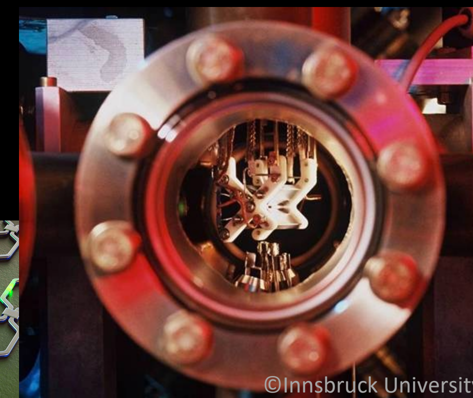
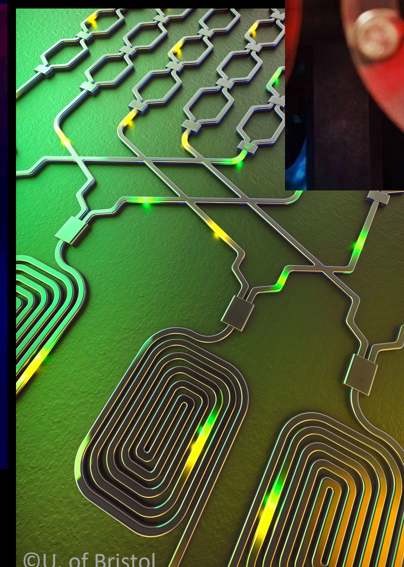
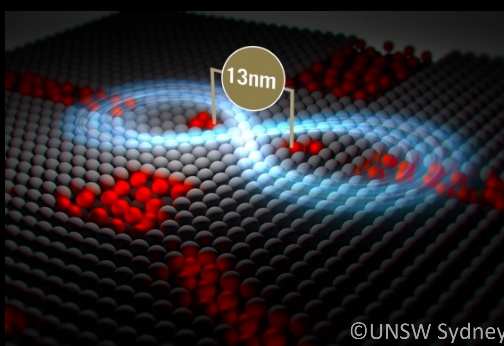
Une seconde révolution quantique

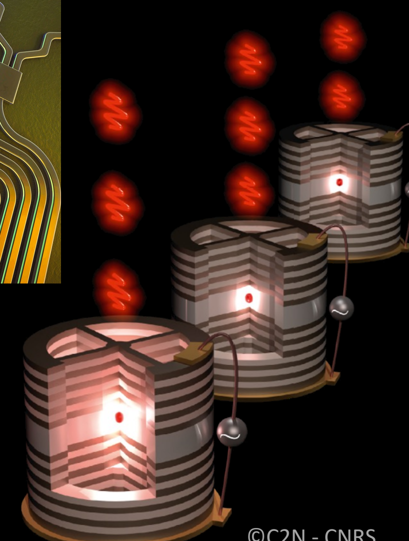
Fondements, applications











Pascale Senellart

Center for Nanoscience and Nanotechnology
CNRS – Paris Sud University – Paris Saclay University

Un sujet d’actualité scientifique

China’s quantum satellite achieves ‘spooky action’ at record distance

By **Gabriel Popkin** | Jun. 15, 2017 , 2:00 PM

June 2017

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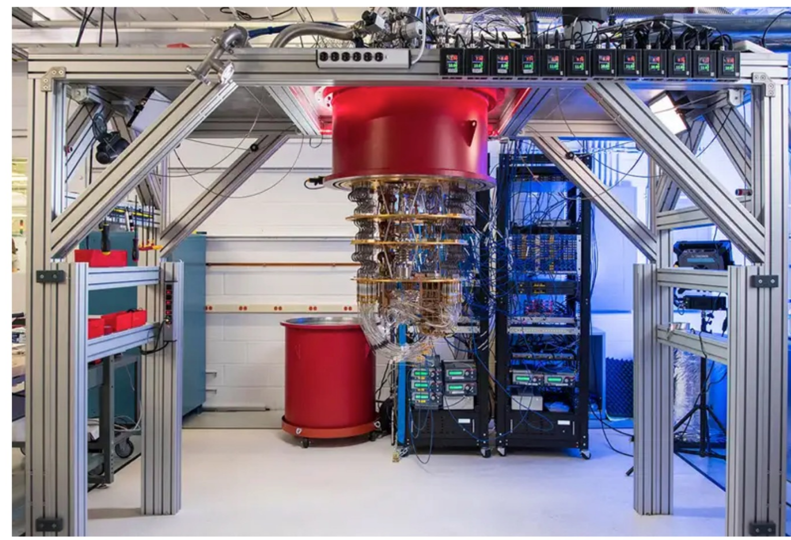
It’s official: Google has achieved quantum supremacy

PHYSICS 23 October 2019

By Daniel Cossins



Google’s quantum computer is a record-breaker
HANNAH BENET/Google

Octobre 2019

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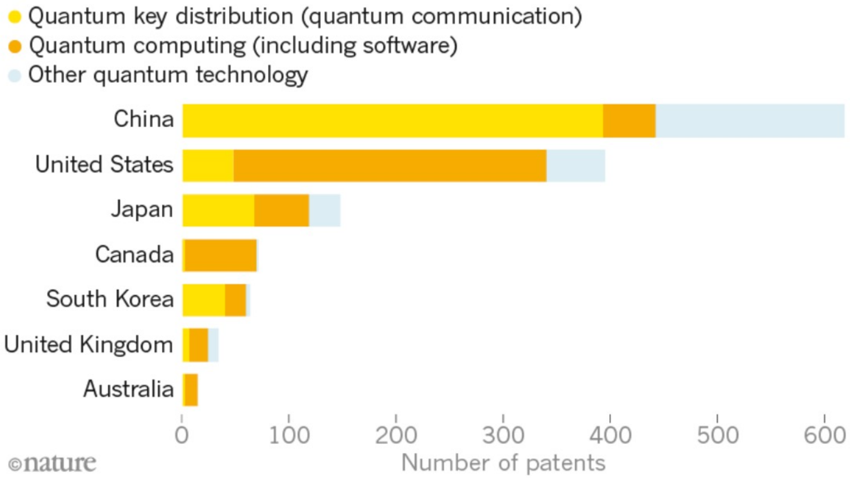
Quantum gold rush: the private funding pouring into quantum start-ups

A *Nature* analysis explores the investors betting on quantu

Quantum patents

An analysis of global patents in quantum technology since 2012 shows China dominating quantum communication, but North America ahead on quantum computing.



Source: Martino Travagnin/EC Joint Research Centre

Un sujet d'actualité politique

The Guardian view on quantum computing: the new space race
Editorial

The main use of quantum technology might not be to hack existing systems but to create unhackable communication networks of the future

Dec 2017

China will open a $10 billion quantum computer center and others also investing in quantum computing

Oct 2017

Brian Wang | October 10, 2017

MIT Technology Review

Dec 2018

Computing Dec 22, 2018

President Trump has signed a $1.2 billion law to boost US quantum tech

Quantum USA Vs. Quantum China: The World's Most Important Technology Race

Moor Insights and Strategy Contributor
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Straight talk from Moor Insights & Strategy tech industry analysts

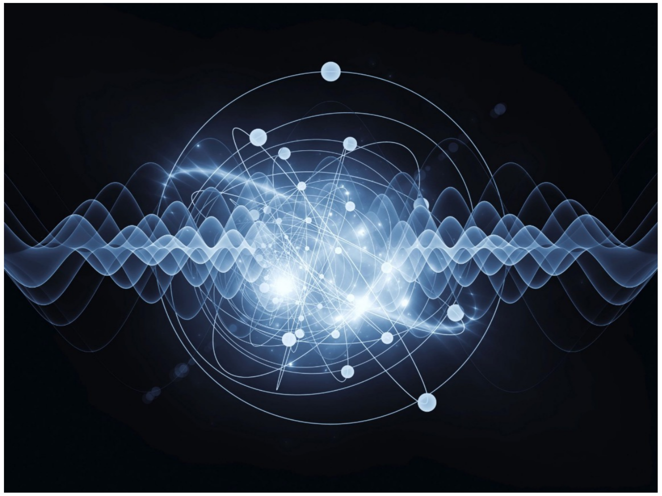
Forbes Oct 2019

Plans quantiques européens et Français

January 2018

Quantum Technologies Flagship

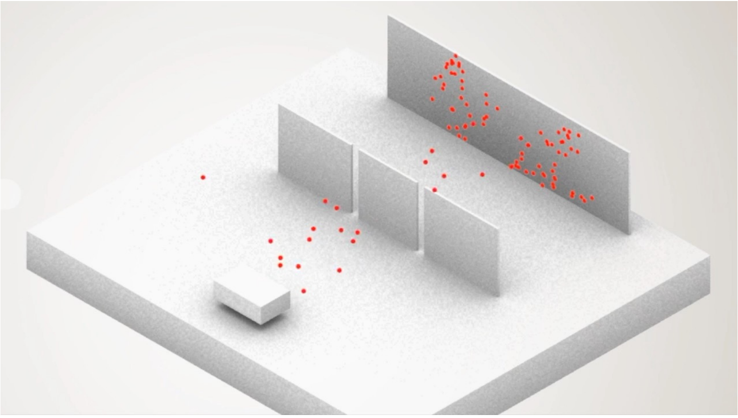
The Quantum Technologies Flagship aims to place Europe at the forefront of the second quantum revolution, bringing transformative advances to science, industry and society.

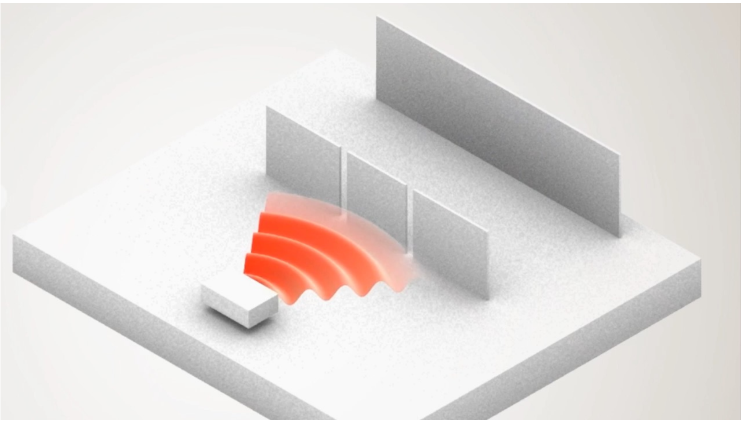


January 2021

Physique quantique et révolutions technologiques

Wave particle duality

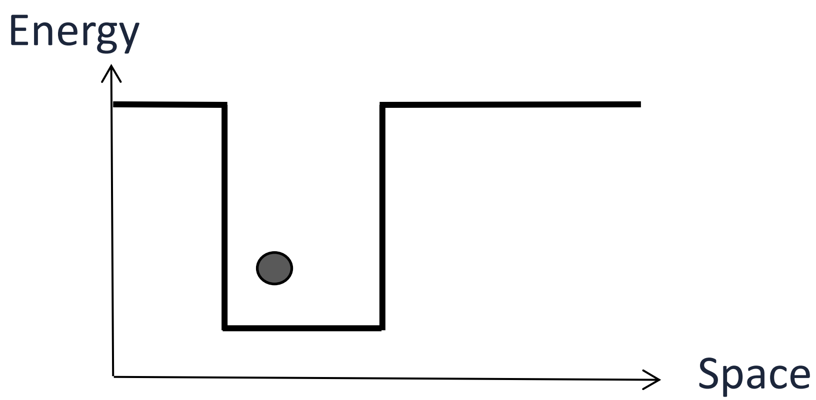


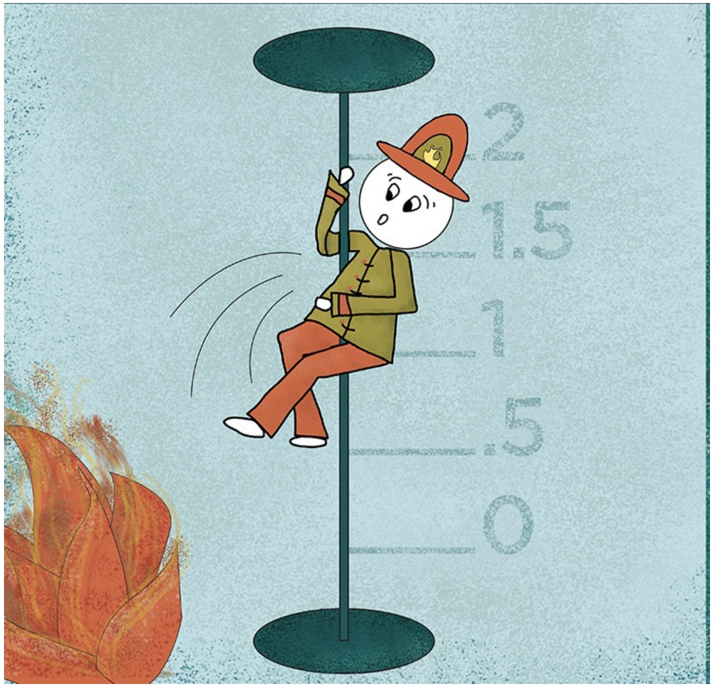


Wave particule duality – J. Bobroff -©vulgarisation.fr

Basics of quantum revolutions

Quantized energy levels

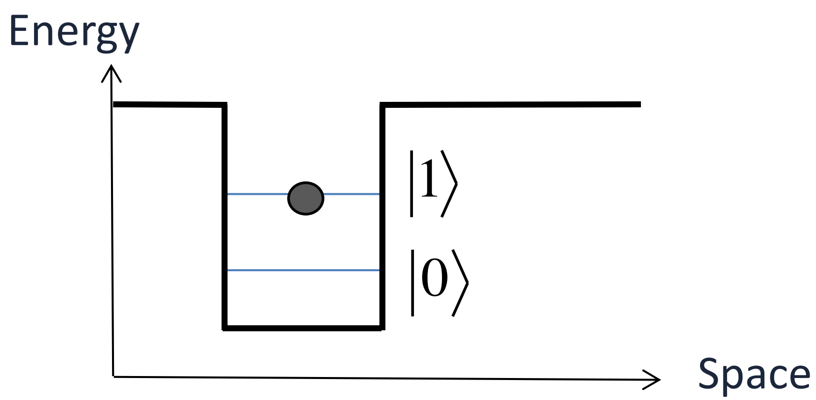




Credit: N. Hanacek/NIST

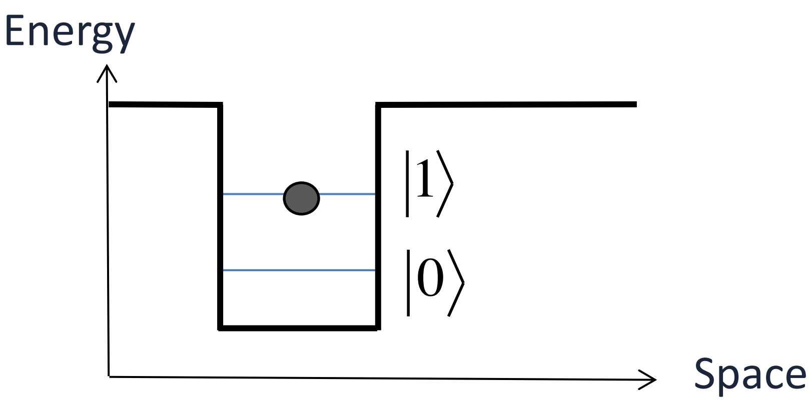
Basics of quantum revolutions

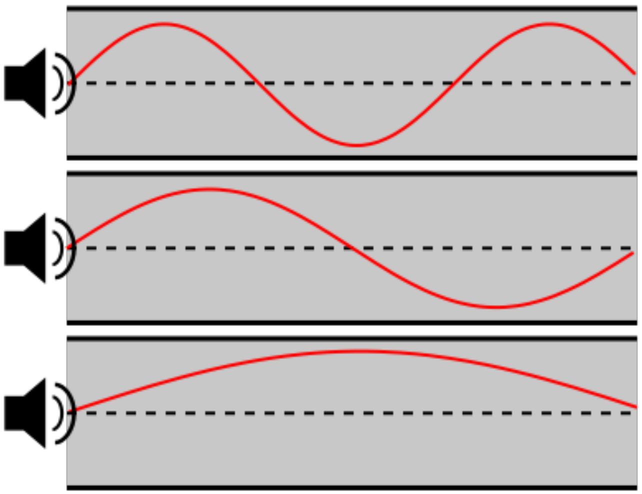
Quantized energy levels

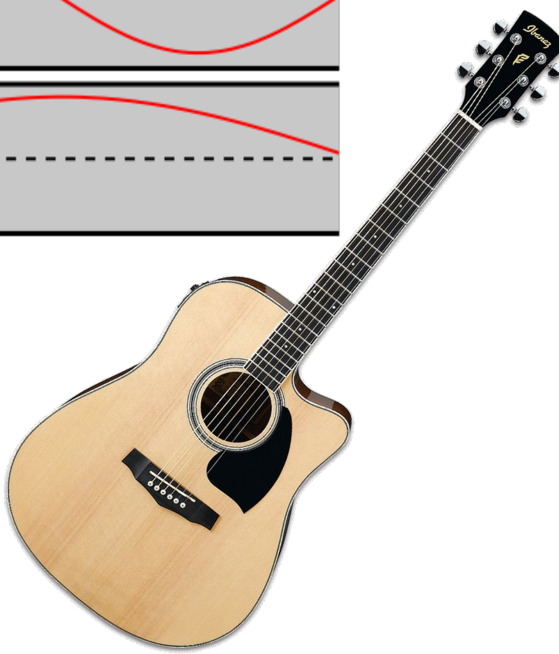


Credit: N. Hanacek/NIST

Quantized energy levels



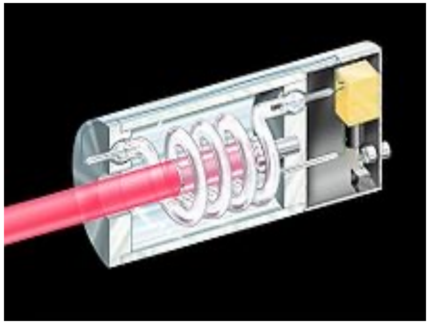




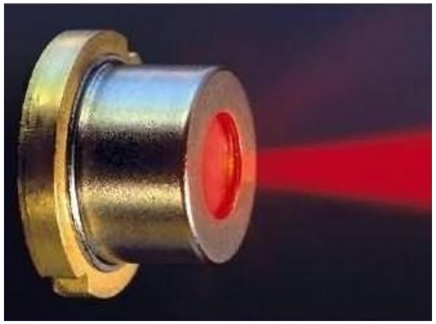
$$i\hbar\frac{\mathrm{d}}{\mathrm{d}t}|\Psi(t)\rangle = \hat{H}|\Psi(t)\rangle$$

Première révolution quantique

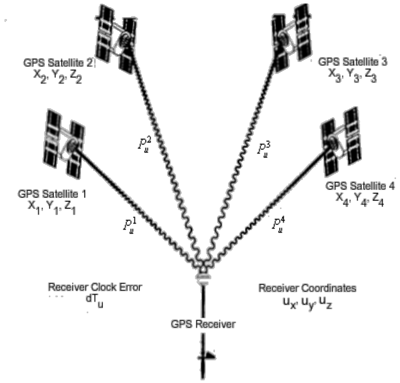
Transistor
1947



Ruby laser
1960



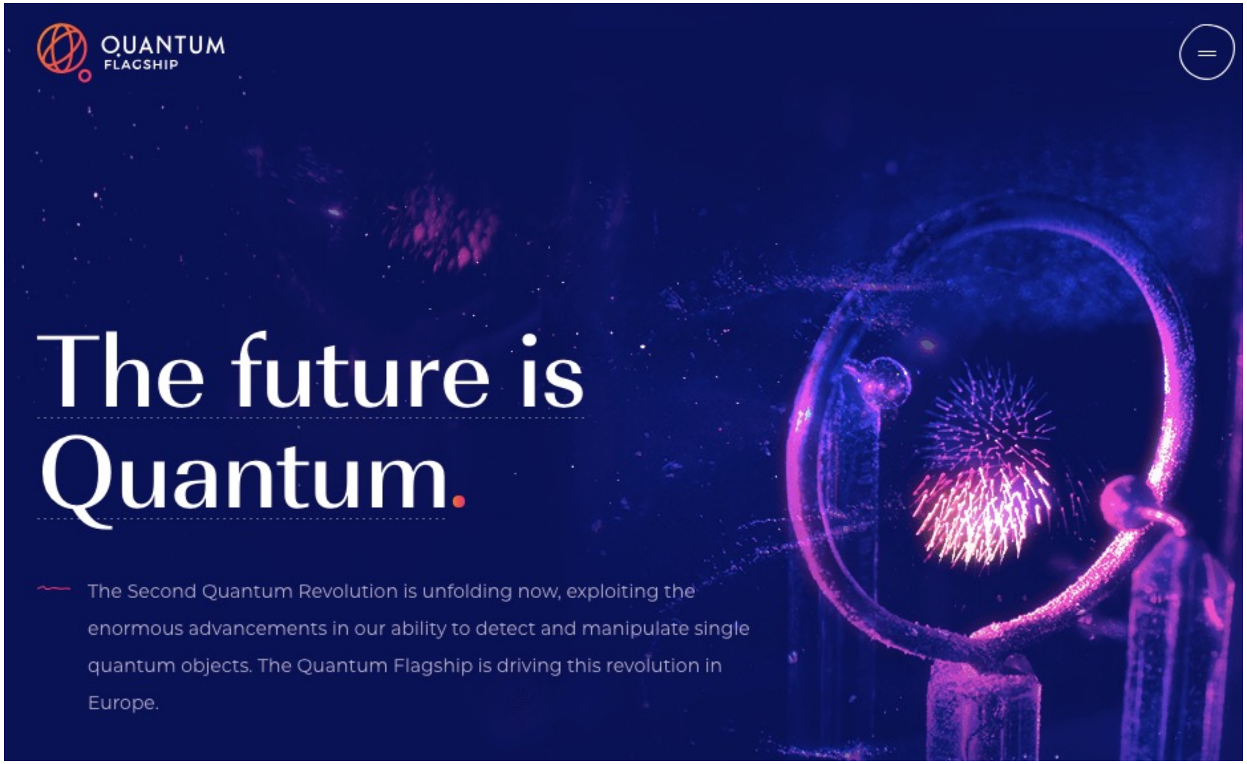
Laser diode
1962



GPS
1995

Connaissance précise et ingénierie des niveaux d’énergie

Vers une seconde révolution technologique

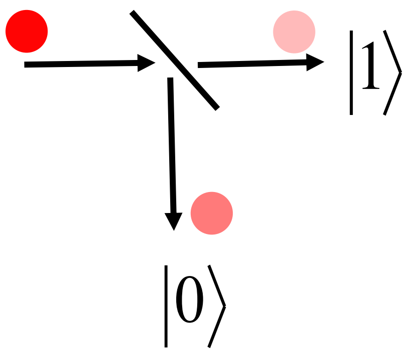


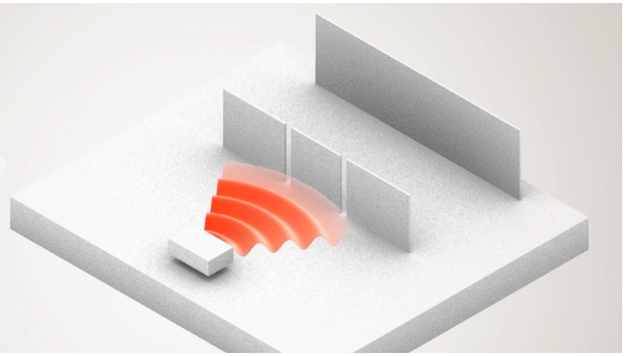
See website for the European Flagship on Quantum Technologies www.qt.eu

Exploiter la superposition quantique et l'intrication

Bases de la 2nde révolution quantique

Superposition cohérence

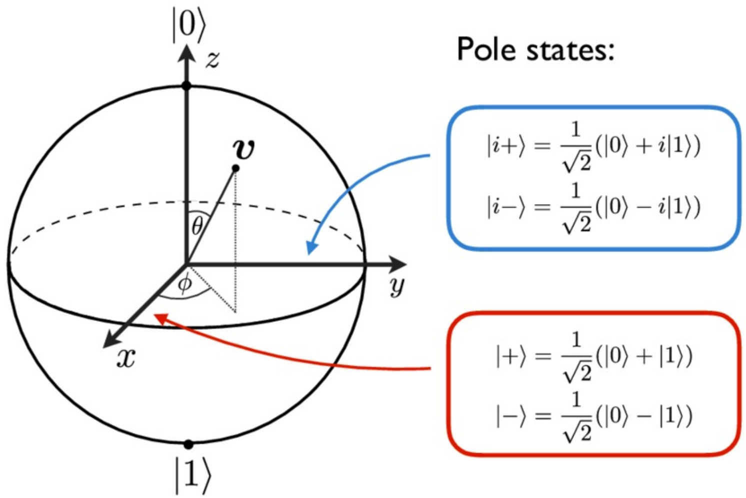




Du bit d'information classique   0 ou 1

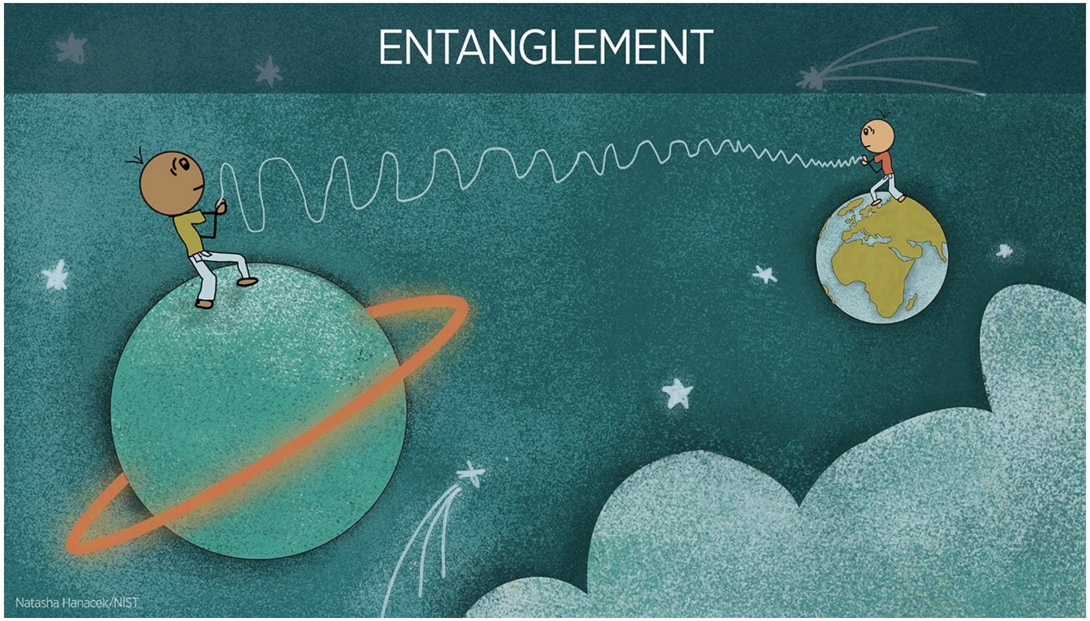
Au bit d'information quantique $\alpha|0\rangle + \beta|1\rangle$

$$|\alpha|^2 + |\beta|^2 = 1, \qquad \alpha, \beta \in \mathbb{C}$$



Bases de la 2nde révolution quantique

2nd ingrédient: intrication



Credit: N. Hanacek/NIST

Bases de la 2^nde révolution quantique

2^nd ingredient: intrication

Etat intriqué à deux. particules A et B

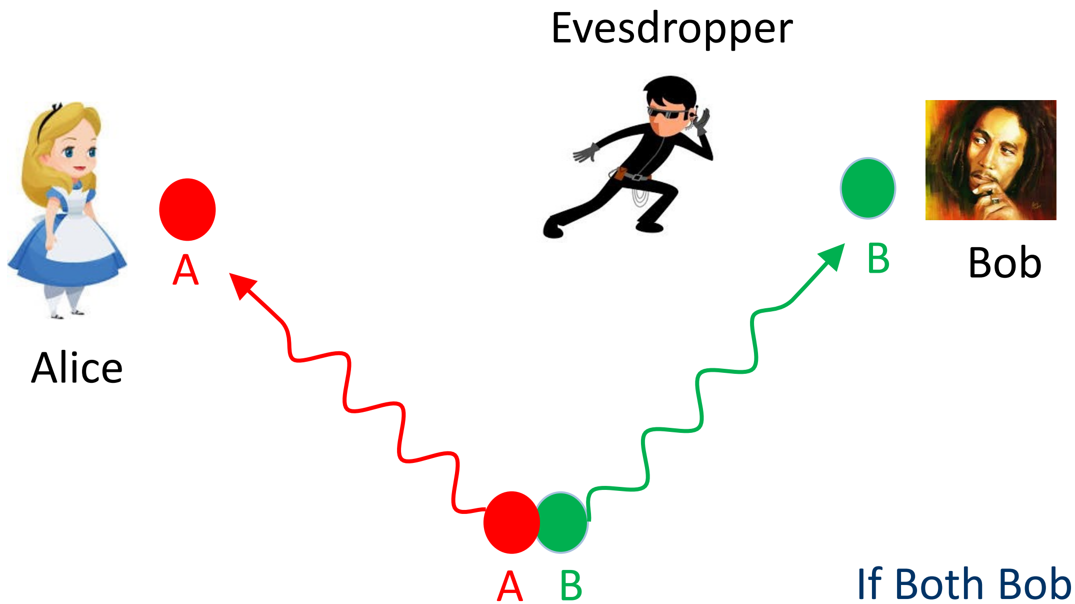
$$\frac{|0_A,0_B\rangle + |1_A,1_B\rangle}{\sqrt{2}}$$

Si A est mesurée dans l'état 0, alors B est dans l'état 0

Si A est mesurée dans l'état 1, alors B est dans l'état 1

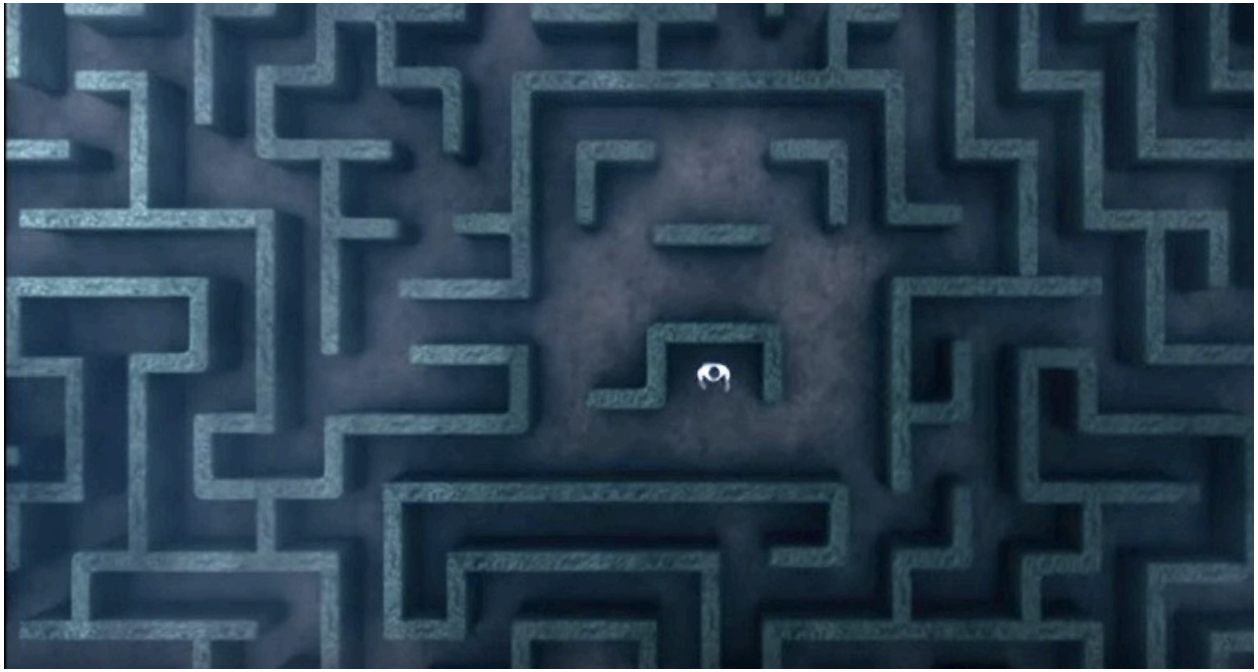
Deux particules avec un destin aléatoire commun

Intrication et communications sécurisées



If Both Bob and Alice measure a photon,
they share the same information

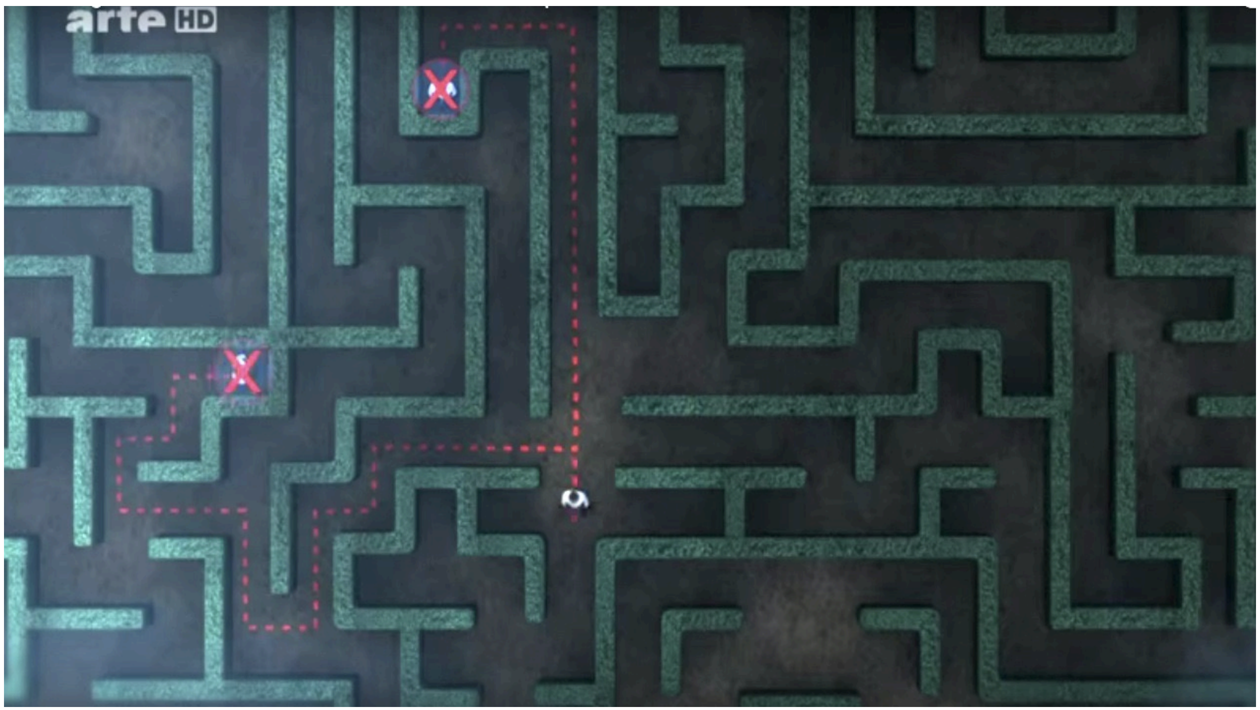
Superposition quantique – parallélisme et étrangeté

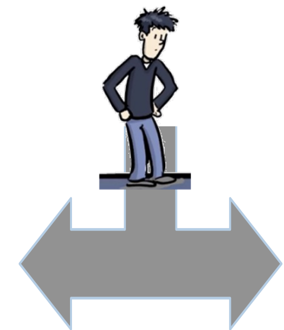


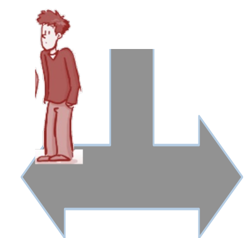
Credit: The Fabric of The Cosmos: Quantum Leap

Cas classique

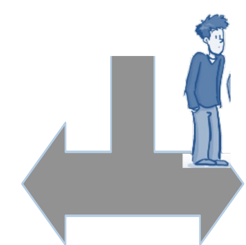
$$\boxed{|0\rangle = |left\rangle \qquad |1\rangle = |right\rangle}$$







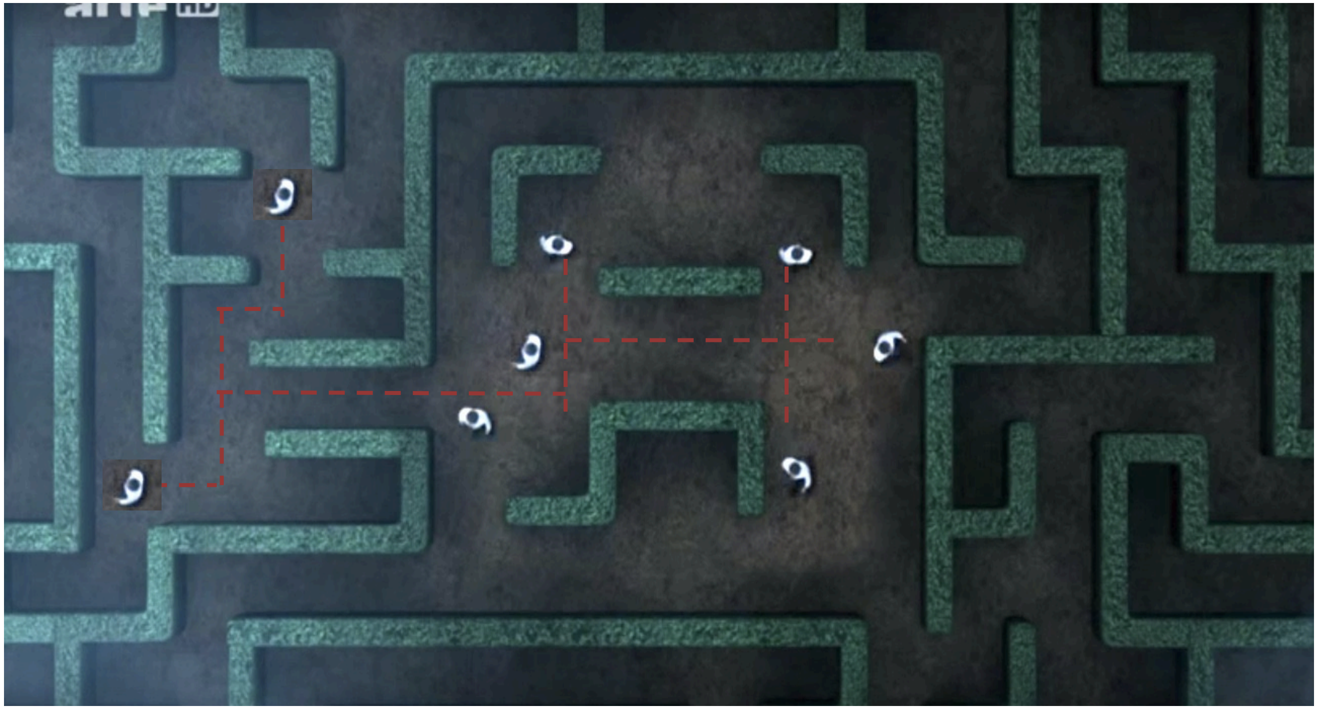
ou

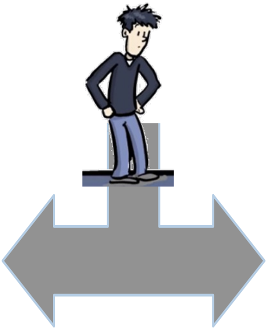


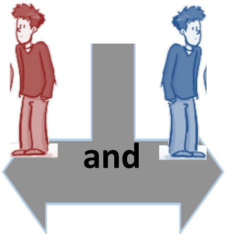
Credit: The Fabric of The Cosmos: Quantum Leap

Superposition quantique – parallélisme et étrangeté

$$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$$

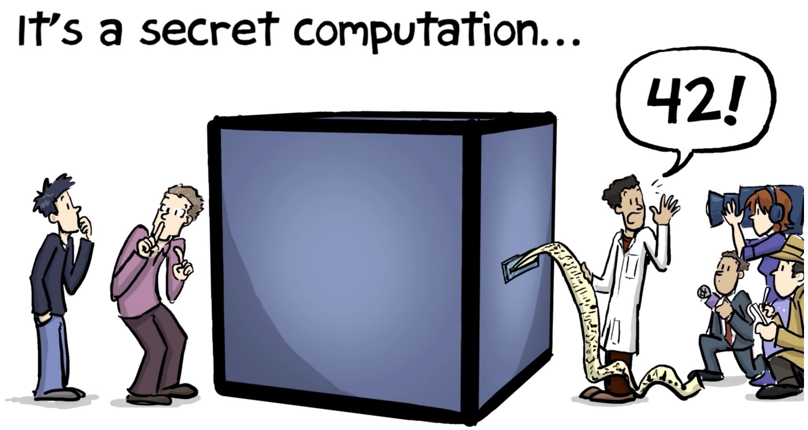


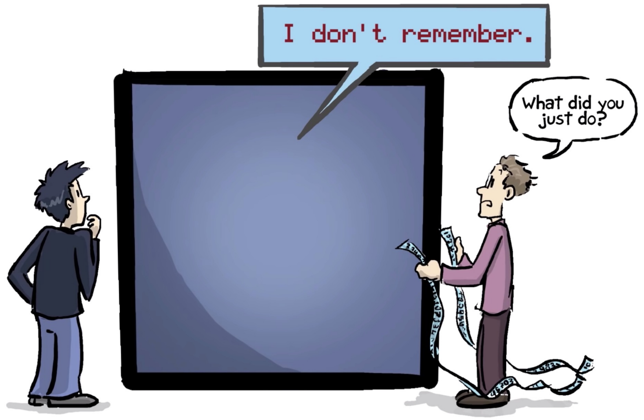




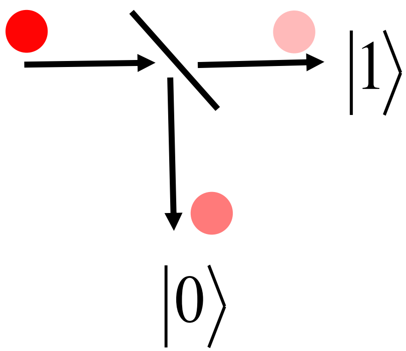
Credit: The Fabric of The Cosmos: Quantum Leap

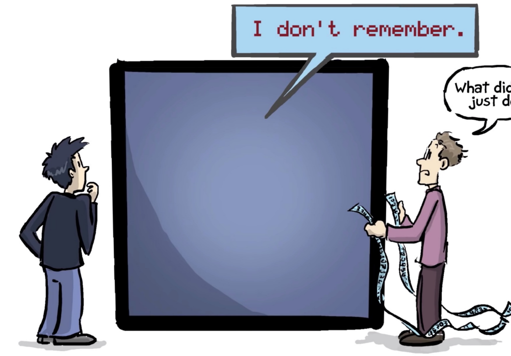
Superposition quantique – parallélisme et étrangeté





superposition & mesure





bit quantique $\alpha|0\rangle + \beta|1\rangle$ avec $|\alpha|^2 + |\beta|^2 = 1$

Measurement:

- Probability $|\alpha|^2$ to measure the qubit in the state $|0\rangle$

  $\Rightarrow$ After measurement qubit state = $|0\rangle$

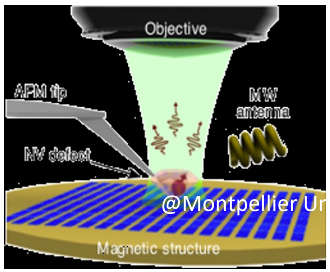
- Probability $|\beta|^2$ to measure the qubit in the state $|1\rangle$

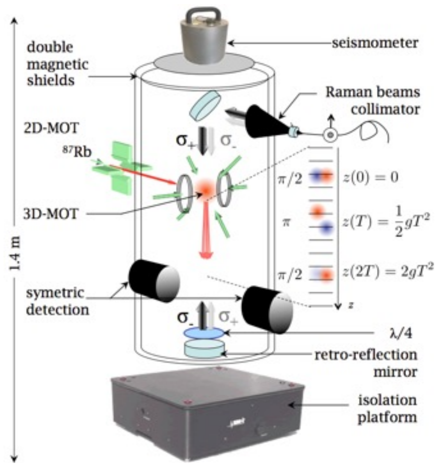
  => After measurement qubit state = $|1\rangle$

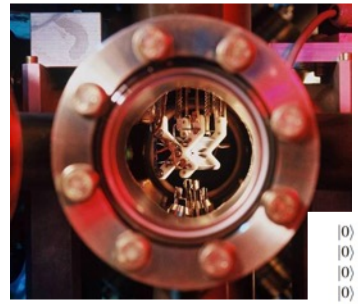
Applications envisagées de la 2nde révolution quantique

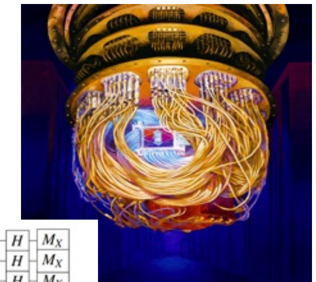
Calcul quantique digital

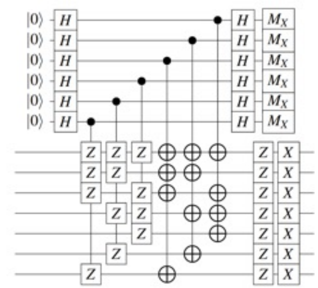
Capteurs quantiques





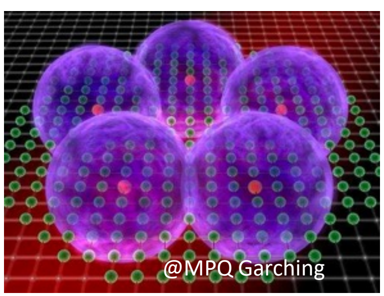


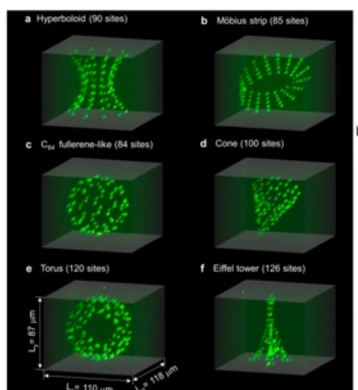


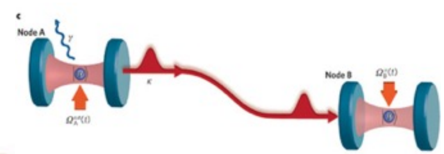


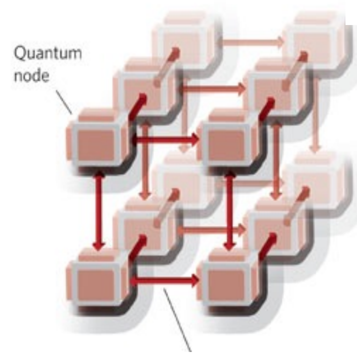
Communications quantiques

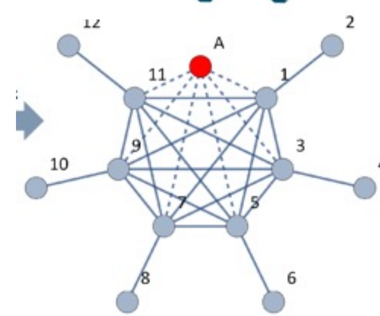
Calcul quantique analogique





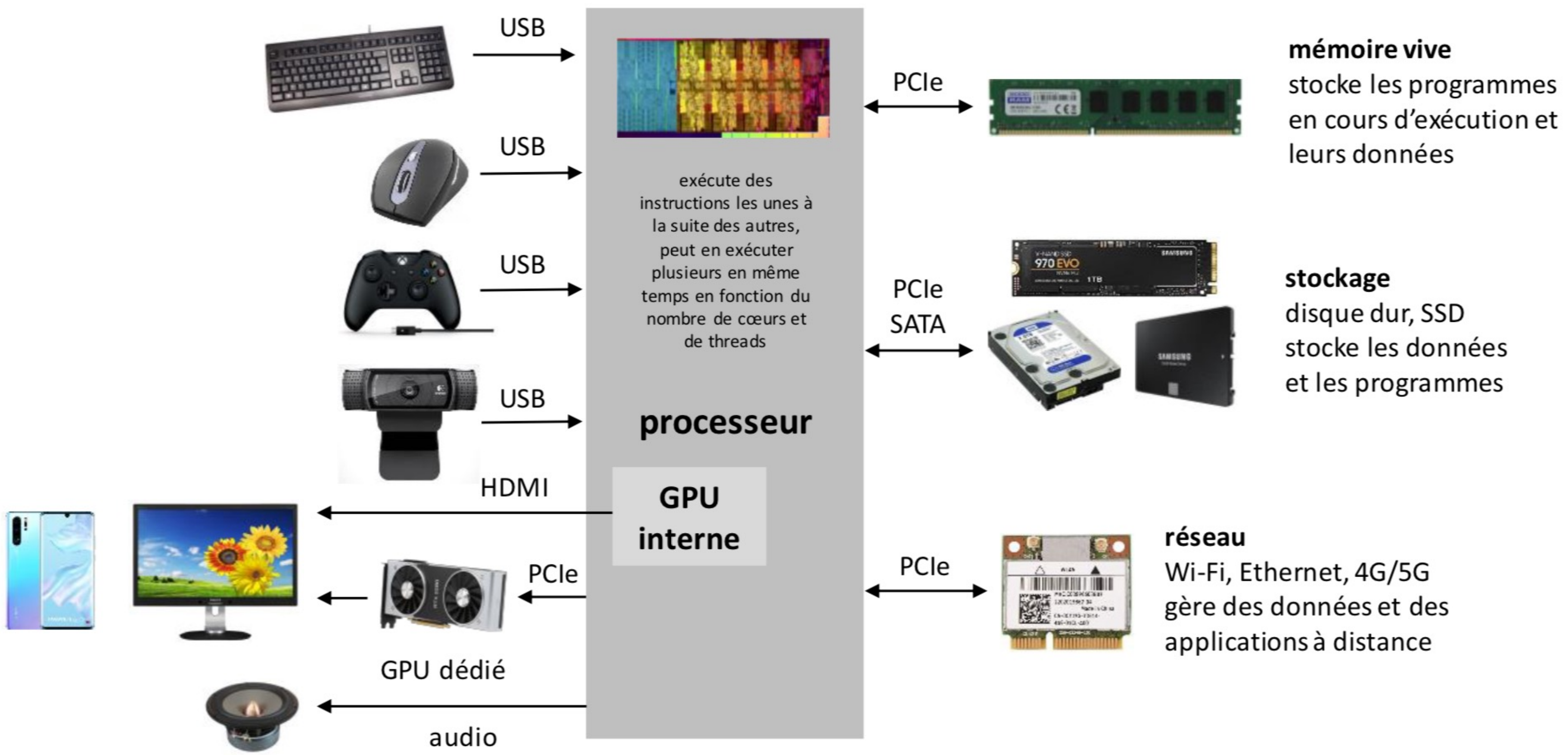




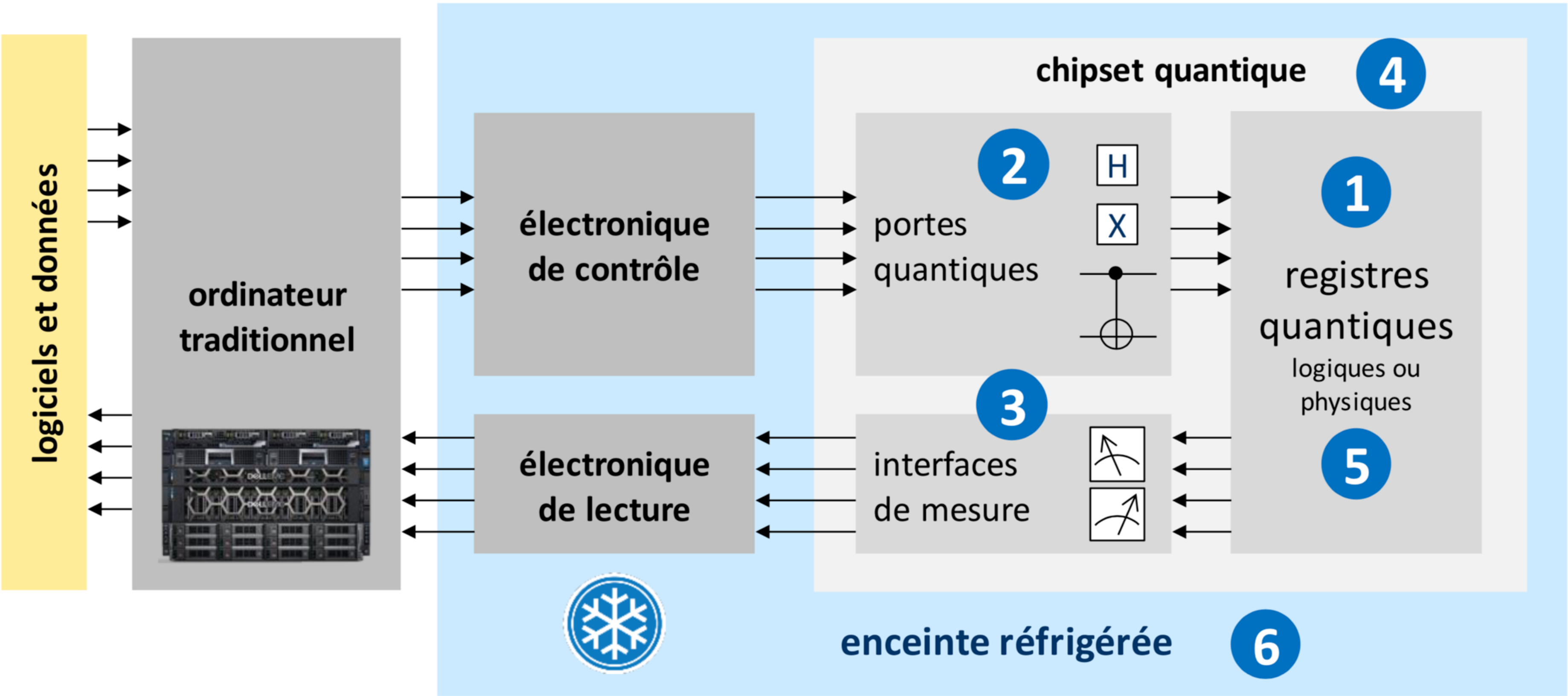


Ordinateur quantique : les bases

Architecture ordinateur classique



Architecture ordinateur quantique



Quantum computer ingredients
(Di Vicenzo's criteria)

David Di Vicenzo @ IBM

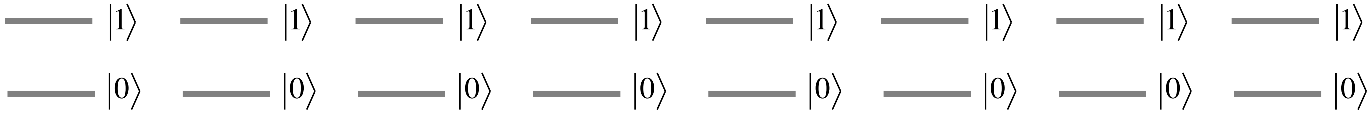
- A scalable physical system with well characterized qubits
- The ability to initialize the state of the qubits
- A qubit-specific measurement capability
- A "universal" set of quantum gates
- Long decoherence times

DiVincenzo, David P. (2000-04-13). "The Physical Implementation of Quantum Computation". Fortschritte der Physik. 48 (9–11): 771–783.

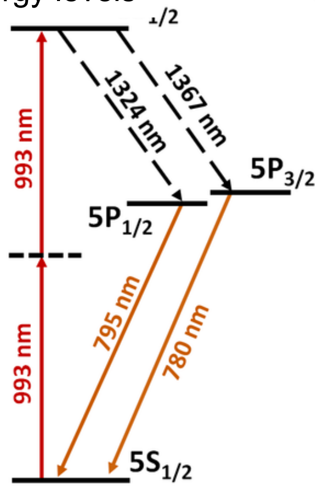
Quantum computer ingredients

(Di Vicenzo's criteria)

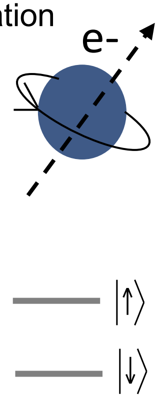
- A scalable physical system with well characterized qubits

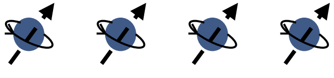


Atom energy levels

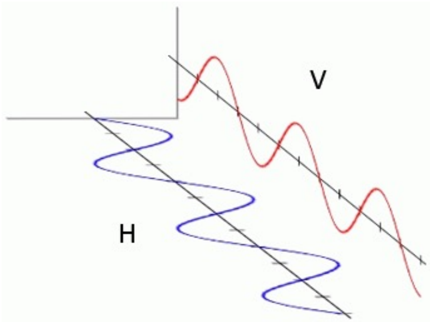


Spin orientation





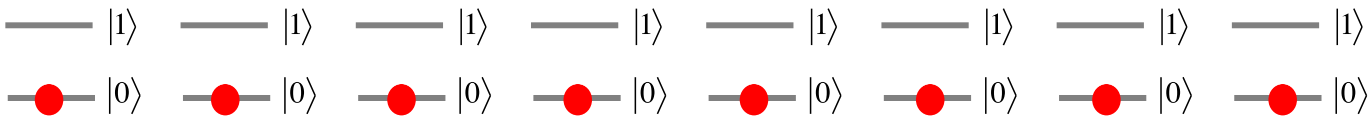
Photon polarization



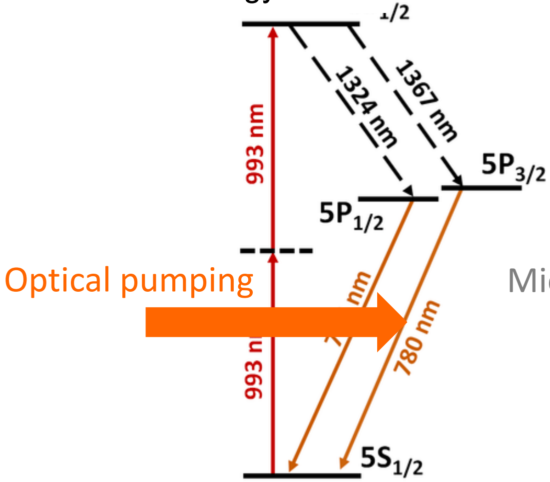
Quantum computer ingredients

(Di Vicenzo's criteria)

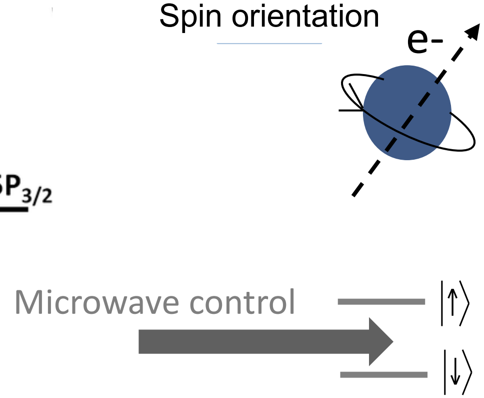
- The ability to initialize the state of the qubits



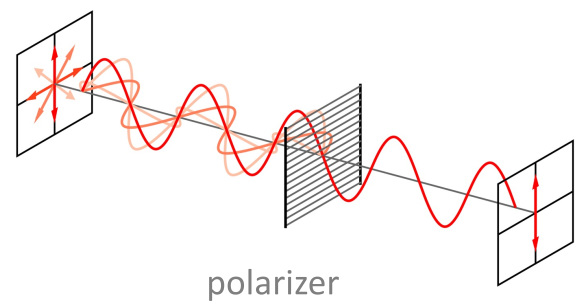
Atom energy levels



Spin orientation



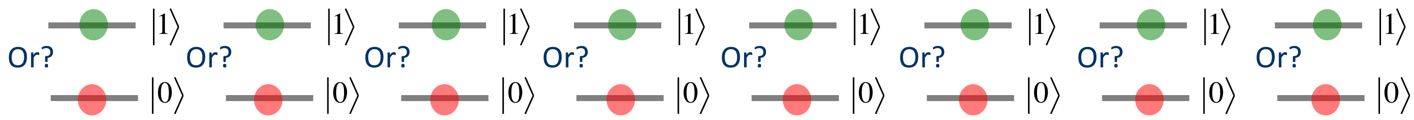
Photon polarization

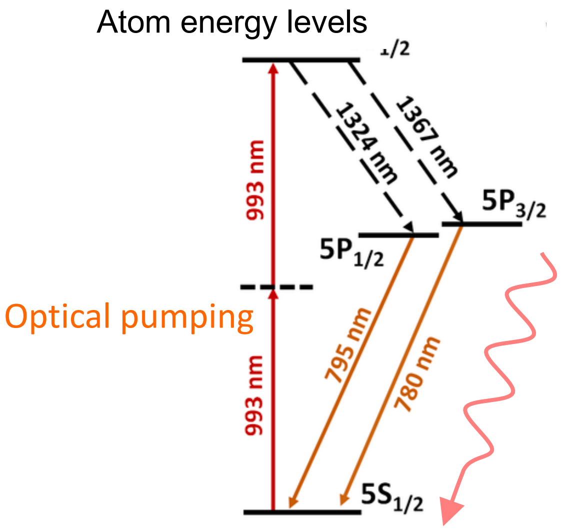


Quantum computer ingredients

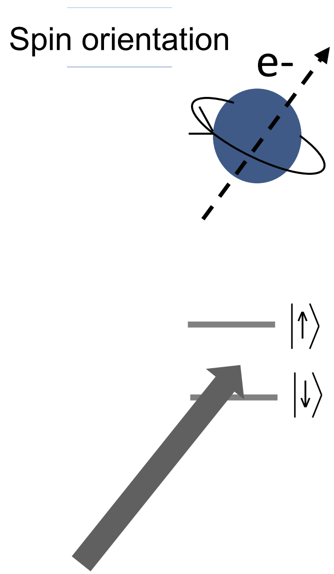
(Di Vicenzo's criteria)

- A qubit-specific measurement capability

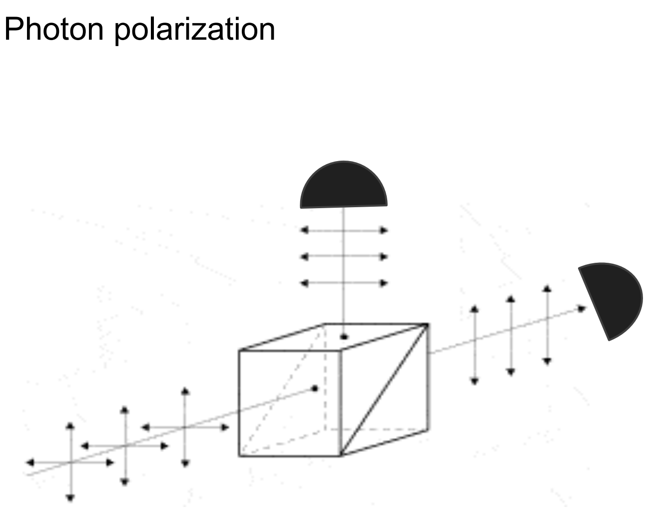




Fluorescence



Microwave readout



Polarizer + single photon detectors

Quantum computer ingredients

(Di Vicenzo's criteria)

- A "universal" set of quantum gates :

- Single qubit gates

$$\longrightarrow \alpha|0\rangle + \beta|1\rangle$$

Pauli-X (X)	$\boxed{\mathbf{X}}$ $\oplus$	$\begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}$	$\alpha|0\rangle + \beta|1\rangle \longrightarrow \beta|0\rangle + \alpha|1\rangle$
Pauli-Y (Y)	$\boxed{\mathbf{Y}}$	$\begin{bmatrix} 0 & -i \\ i & 0 \end{bmatrix}$	
Pauli-Z (Z)	$\boxed{\mathbf{Z}}$	$\begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix}$	
Hadamard (H)	$\boxed{\mathbf{H}}$	$\frac{1}{\sqrt{2}}\begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}$	$|0\rangle \longrightarrow \frac{|0\rangle + |1\rangle}{\sqrt{2}}$

DiVincenzo, David P. (2000-04-13). "The Physical Implementation of Quantum Computation". Fortschritte der Physik. 48 (9–11): 771–783.

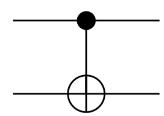
Quantum computer ingredients

(Di Vicenzo's criteria)

- A "universal" set of quantum gates :

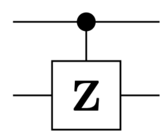
- Two qubit gates

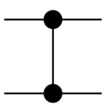
Controlled Not (CNOT, CX)



$$\begin{bmatrix}1 & 0 & 0 & 0\\0 & 1 & 0 & 0\\0 & 0 & 0 & 1\\0 & 0 & 1 & 0\end{bmatrix}$$

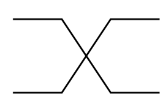
Controlled Z (CZ)

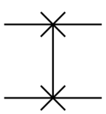




$$\begin{bmatrix}1 & 0 & 0 & 0\\0 & 1 & 0 & 0\\0 & 0 & 1 & 0\\0 & 0 & 0 & -1\end{bmatrix}$$

SWAP



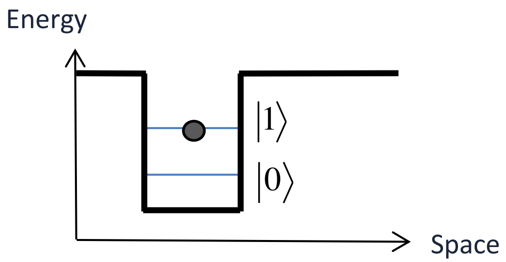


$$\begin{bmatrix}1 & 0 & 0 & 0\\0 & 0 & 1 & 0\\0 & 1 & 0 & 0\\0 & 0 & 0 & 1\end{bmatrix}$$

DiVincenzo, David P. (2000-04-13). "The Physical Implementation of Quantum Computation". Fortschritte der Physik. 48 (9–11): 771–783.

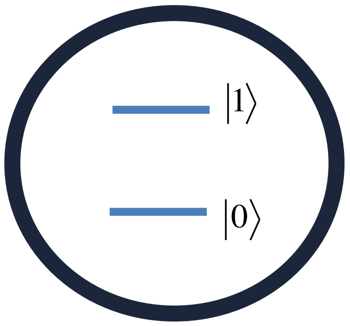
The enemy : decoherence

- Long decoherence times



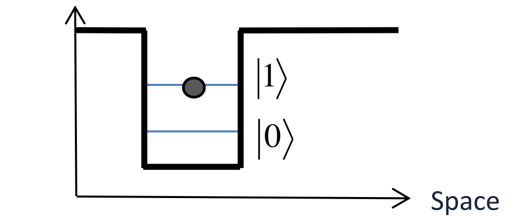
quantum bit $\alpha|0\rangle + \beta|1\rangle$ with $|\alpha|^2 + |\beta|^2 = 1$

Isolated quantum bit



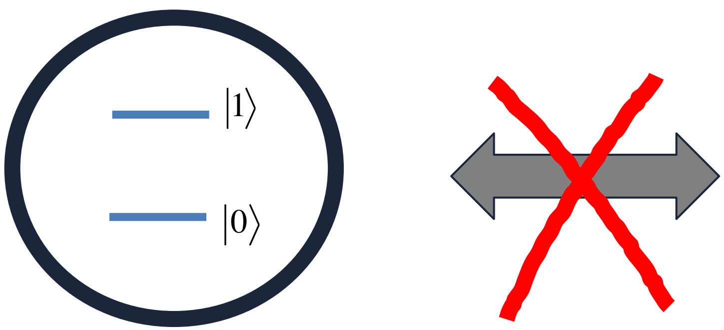
The enemy : decoherence

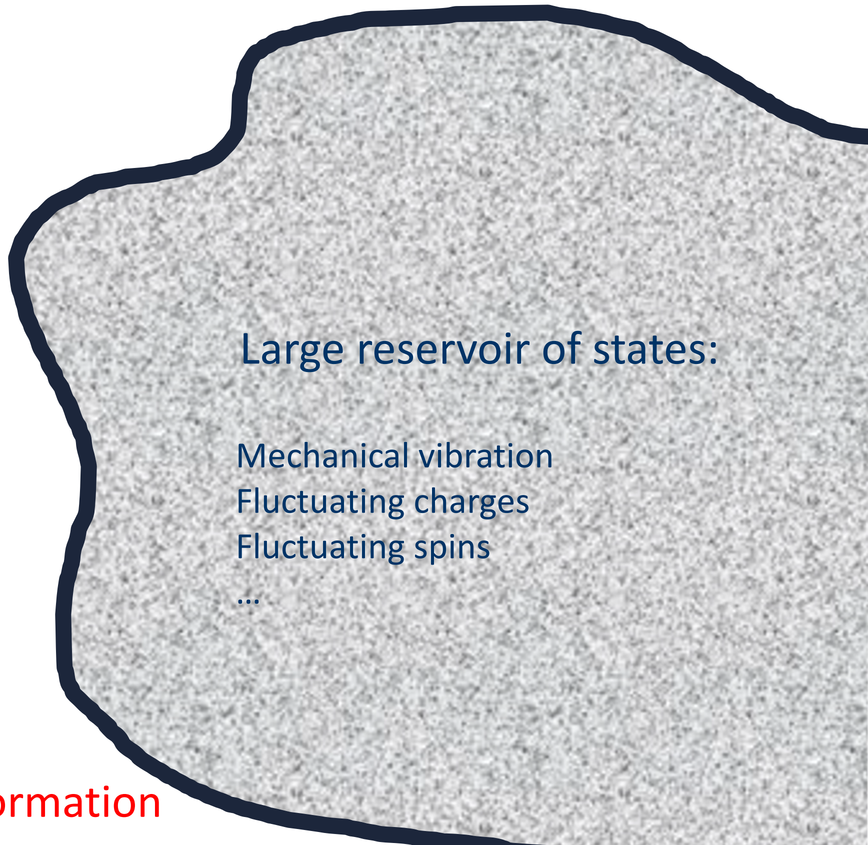
- Long decoherence times



quantum bit $\alpha|0\rangle + \beta|1\rangle$ with $|\alpha|^2 + |\beta|^2 = 1$

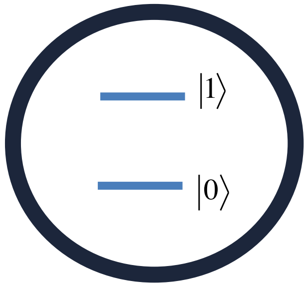
Isolated quantum bit





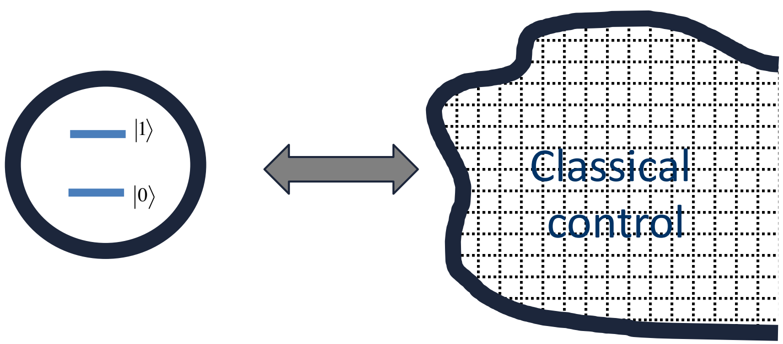
Irreversible loss of energy and/or information

Necessary compromises

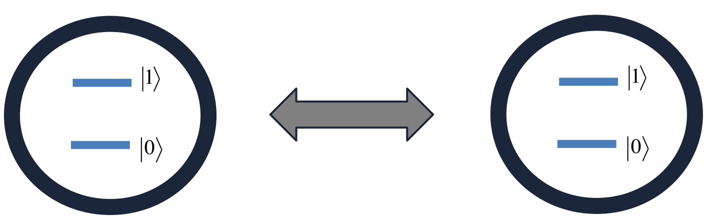


No decoherence ➡ Isolated quantum bit

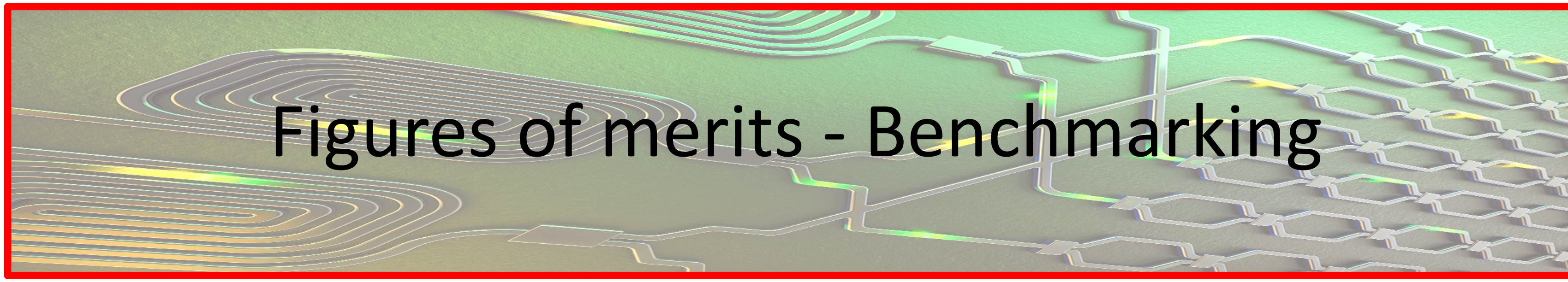
But coupling to the outside world necessary



To manipulate the quantum bit



To implement 2 quantum bit gates



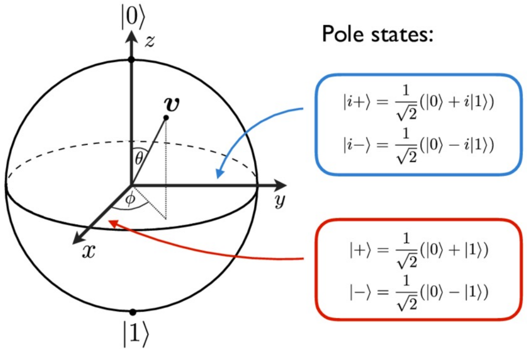
Figures of merits - Benchmarking

Figures of merit

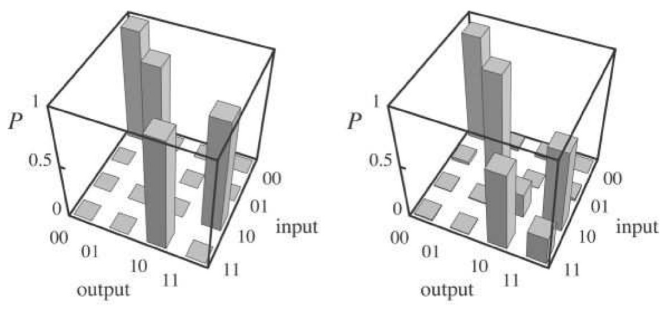
Number of qubits

Fabricated versus measured Number of quantum bits

Single qubit gate errors

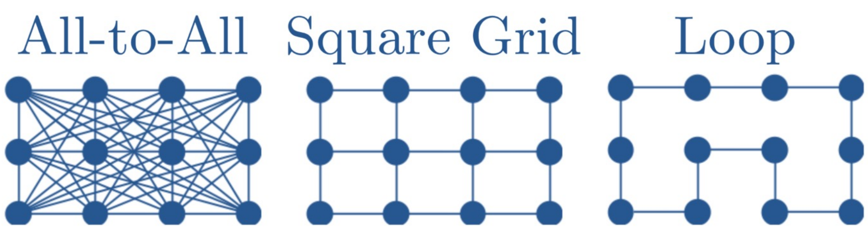


Two-qubit gate errors

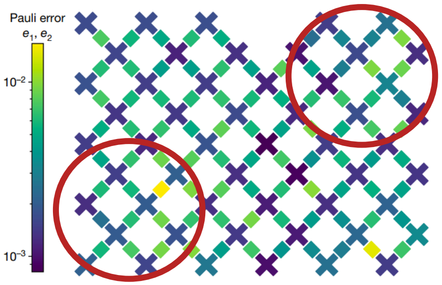


Nature 426, 264 (2003)

Connectivity



Parallelisation capabilities



Google sycomore

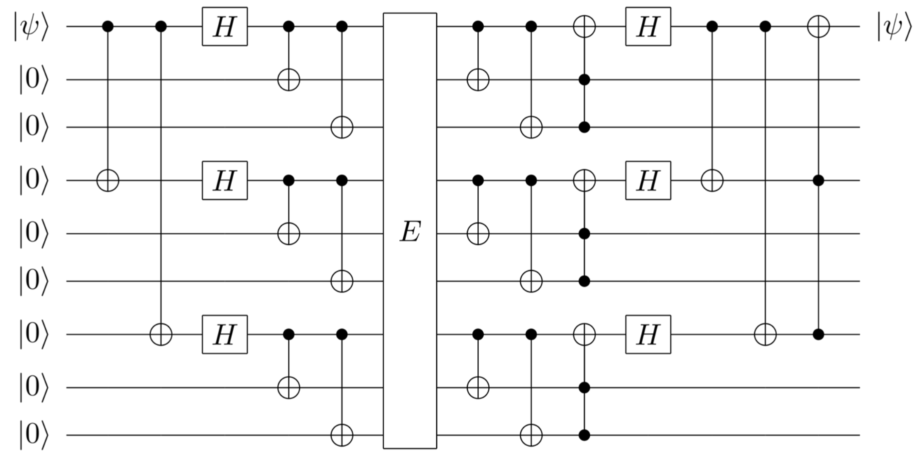
Quantum depth

Ratio between coherence time and gate time

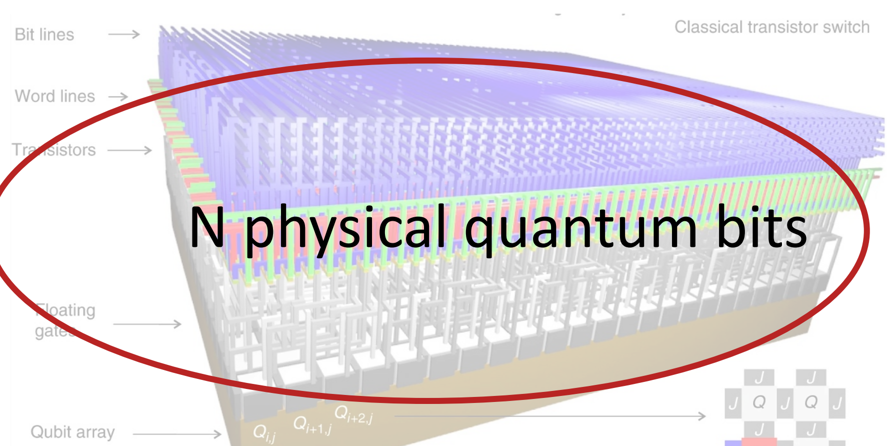
time

Physical versus logical quantum bits

Shor code for arbitrary single-qubit error correction.



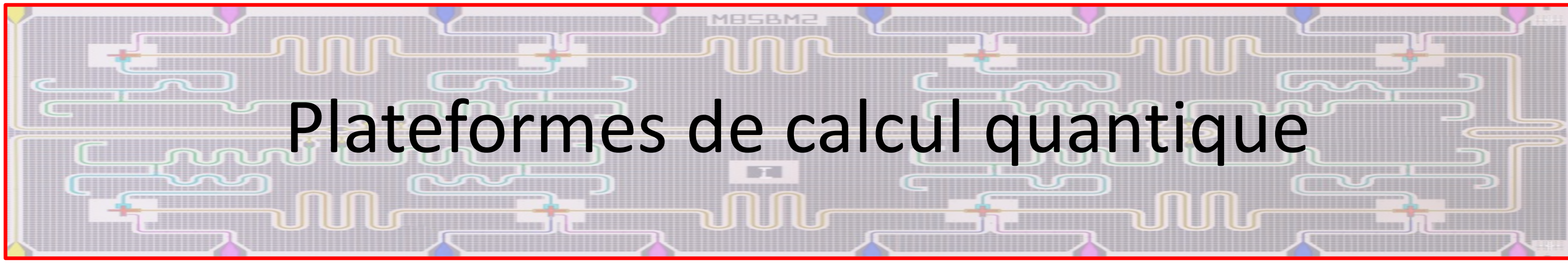
Error correction:
- Additional quantum bits
- Additional gates



N physical quantum bits

Nature Communications 8, Article 1766 (2017)

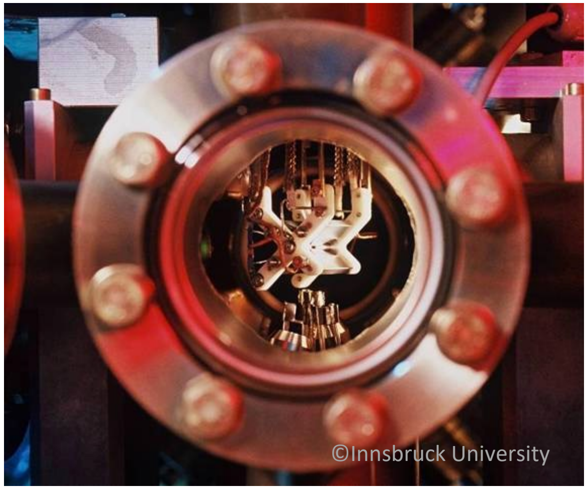
1 logical quantum bit



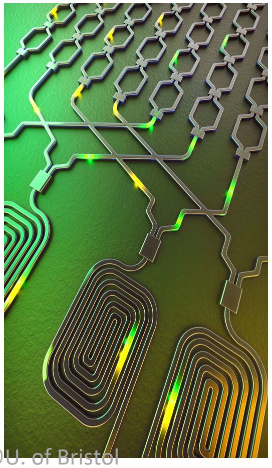
Plateformes de calcul quantique

Leading platforms

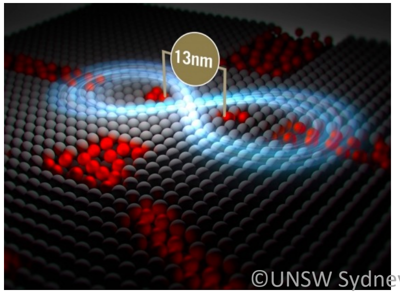
Superconducting qubits



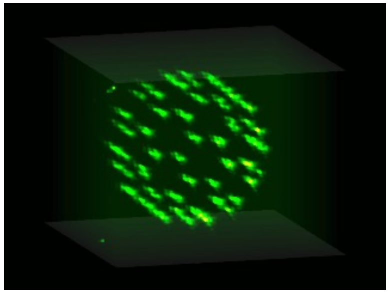
Trapped ions



Photons



Silicon qubits

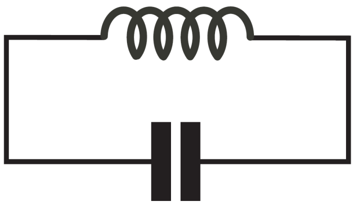


Neutral atoms

Boston Consulting Group – Nov 2018

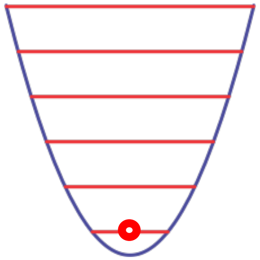
Superconducting circuits

LC circuit



$$\omega_0 = \frac{1}{\sqrt{LC}} \sim \text{GHz}$$

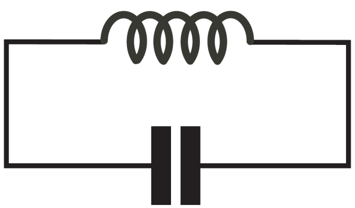
Harmonic oscillator



Equidistant energy levels
No quantum bit

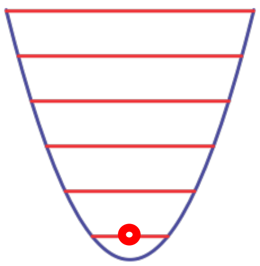
Superconducting circuits

LC circuit



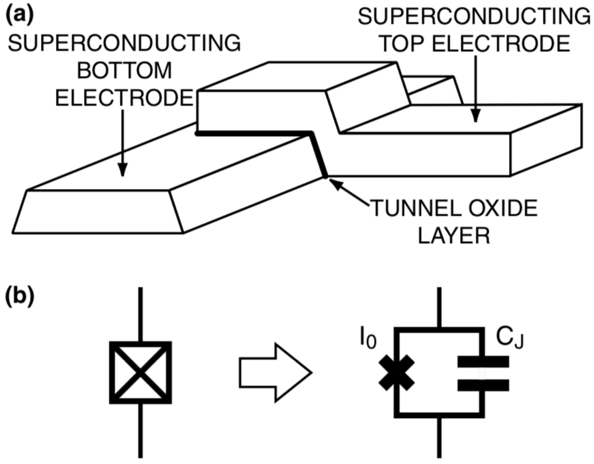
$$\omega_0 = \frac{1}{\sqrt{LC}} \sim \text{GHz}$$

Harmonic oscillator

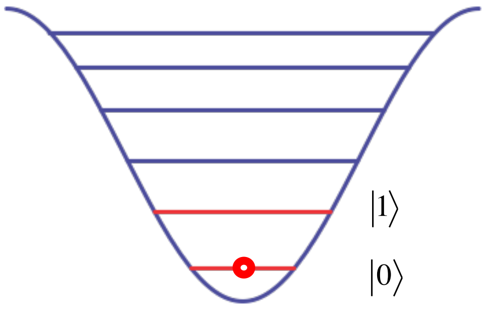


Equidistant energy levels
No quantum bit

Non linear component



Josephson junction



$$\boxed{T = 50\ \text{mK} < \hbar\omega_0/k_B \approx 250\ \text{mK}}$$

To know more : Devoret and Martinis - Quantum Information Processing, Vol. 3, Nos. 1–5, October 2004 (© 2004)

Some chip example

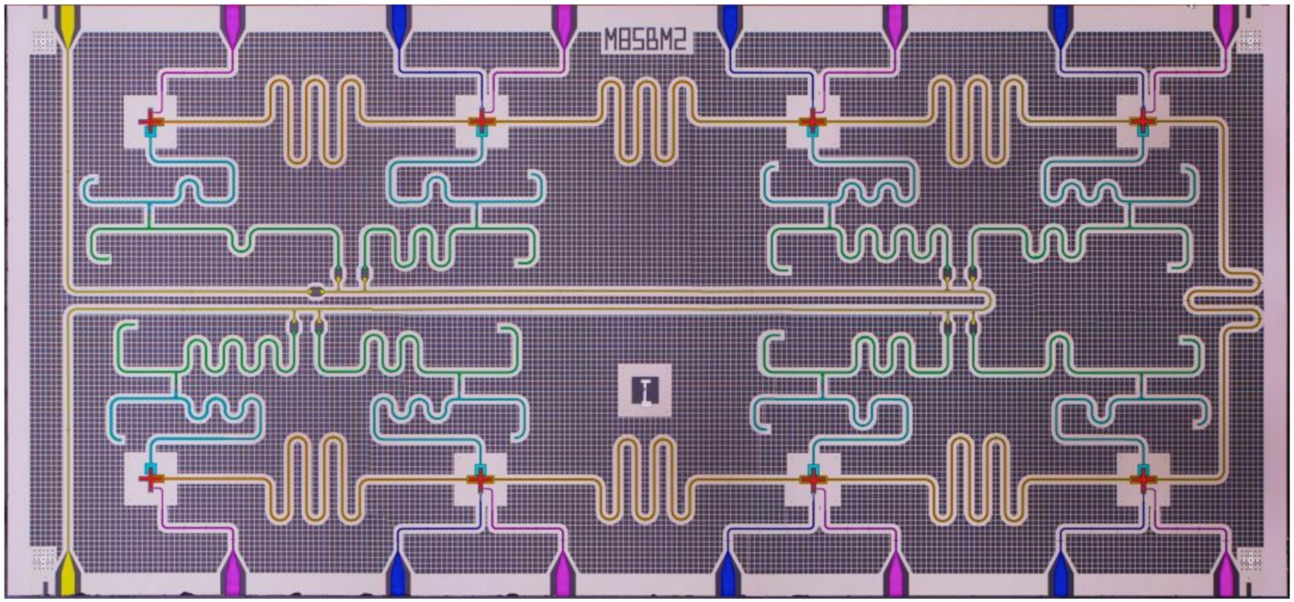


Figure 3: False-coloured image of an 8-qubit superconducting quantum processor fabricated at ETH Zurich. All eight qubits (red) are measured using a common readout line (yellow), by coupling each qubit (red) to a pair of readout resonator (cyan) and Purcell filter (green). Qubit control is enabled by individual charge lines (purple) and flux lines (blue). Coupling between nearest neighbour qubits is mediated by bus resonators (orange).

arXiv 1712.03773

Superconducting circuits

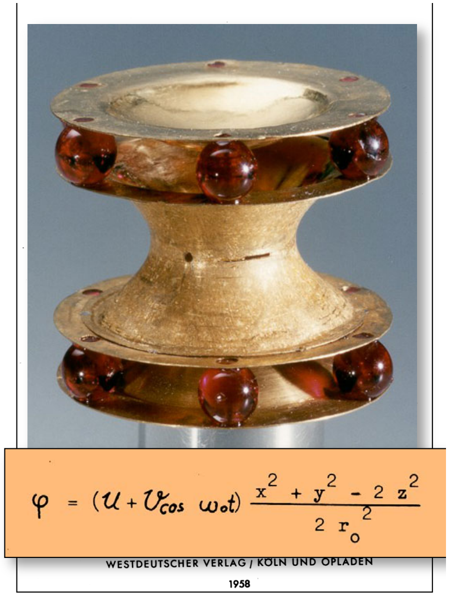
Assests:

- Electronic based technology
- On chip – scalable
- Many degrees of freedom
- Only electronics – very flexible

Some challenges:

- Wiring
- Cooling down
- Noise: charges, magnetic fluctuations

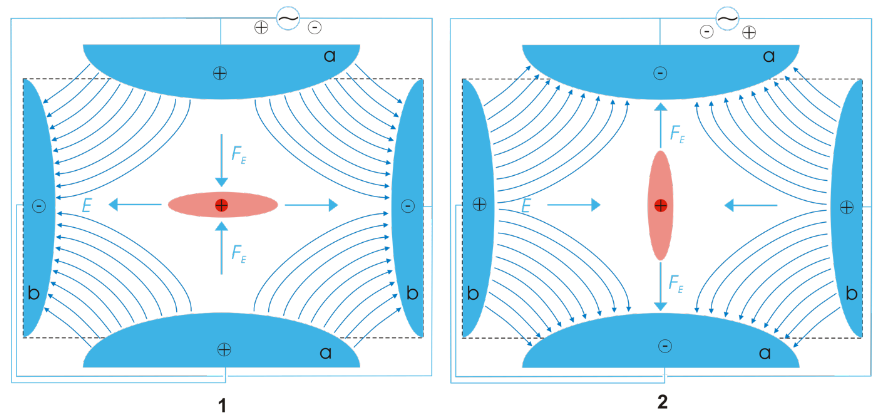
Trapped ions



1989 Nobel prize

Hans G. Dehmelt and Wolfgang Paul
"for the development of the ion trap technique."

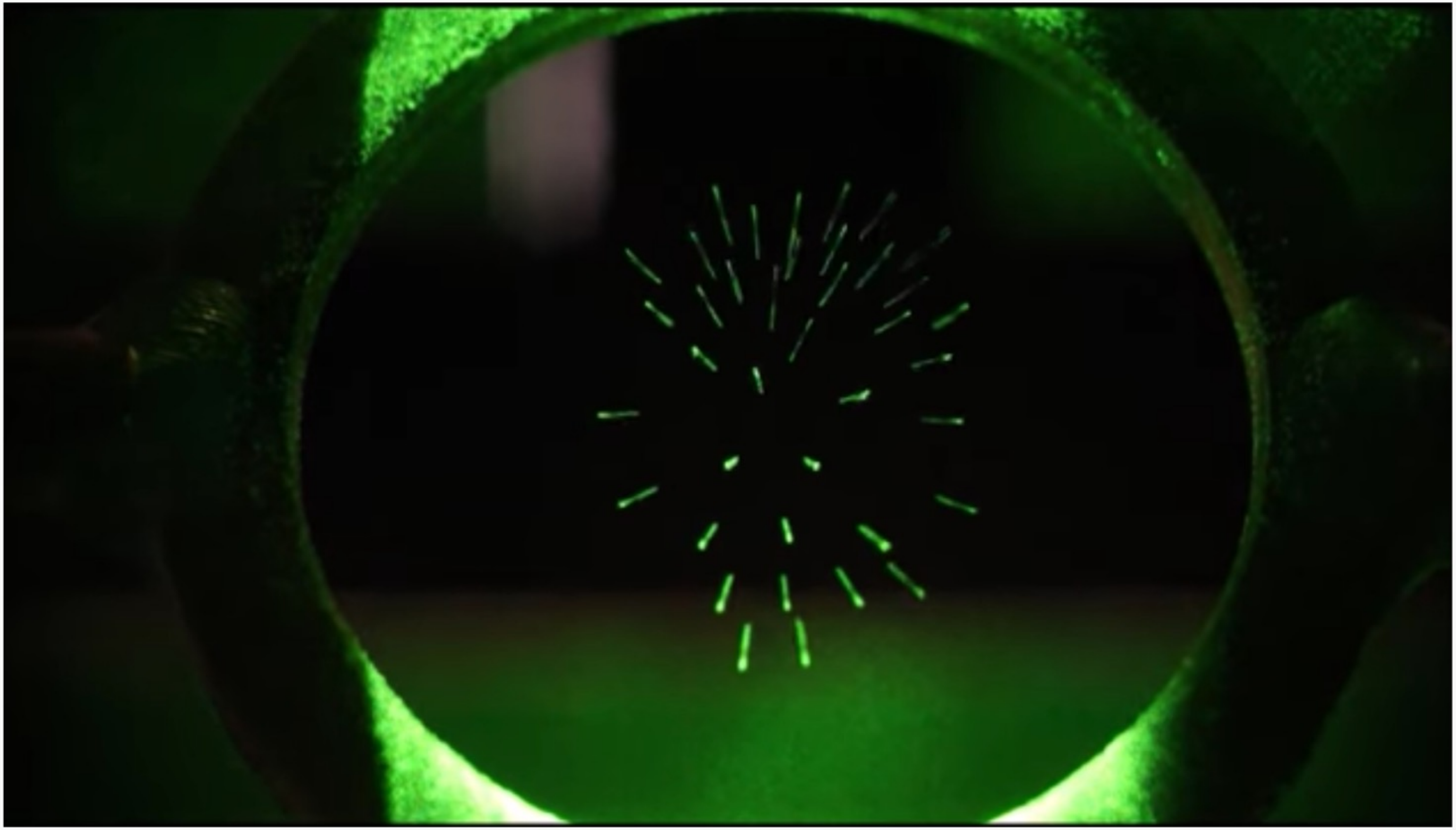
Quadrupolar trap for charged particle



To know more : Séminaire au Collège de France – Professeur Rainer Blatt – Insbruck University- 10 mars 2015

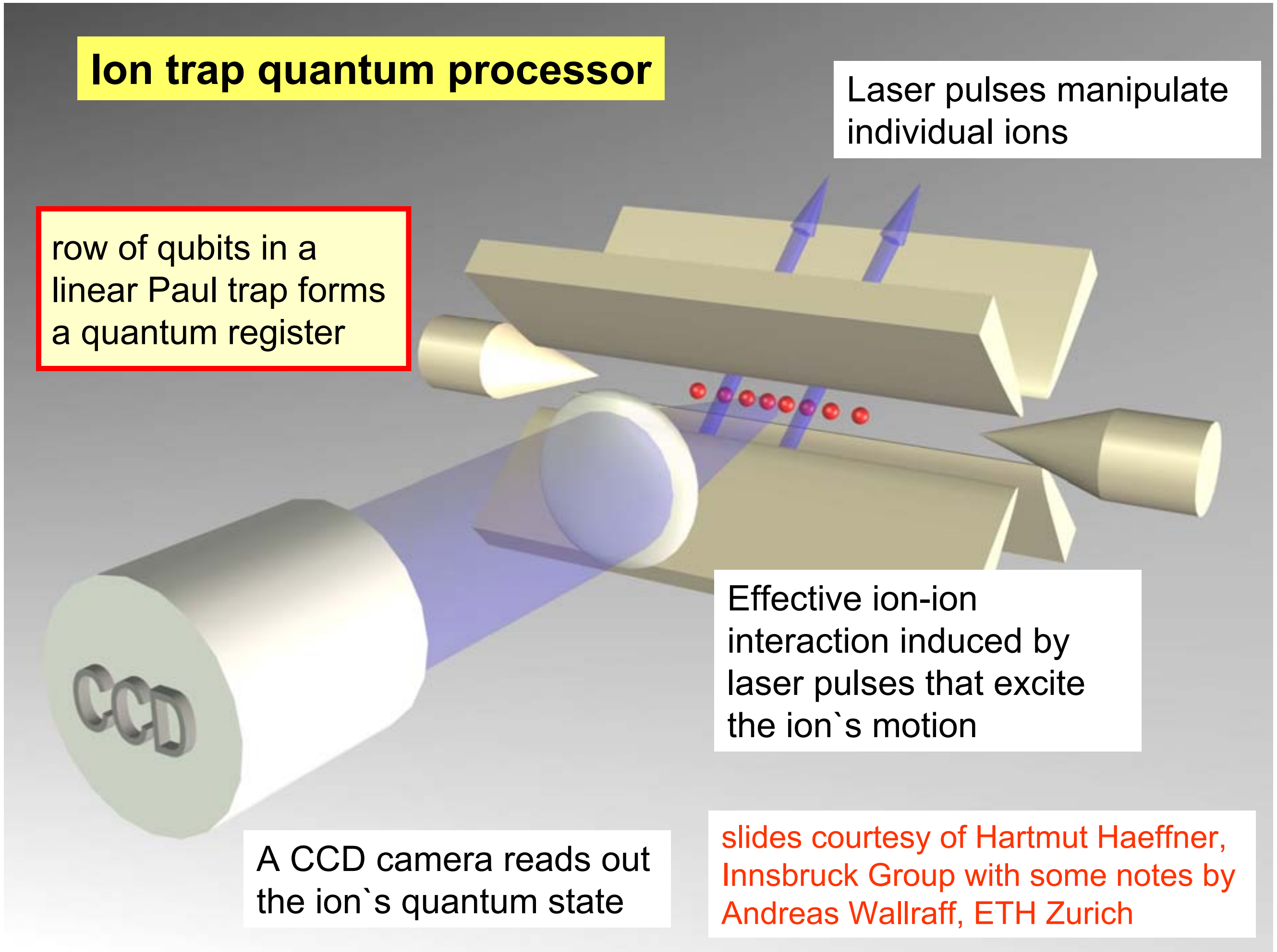
Vidéo et transparents en ligne: https://www.college-de-france.fr/site/serge-haroche/seminar-2015-03-10-11h00.htm

PIÈGE DE PAUL

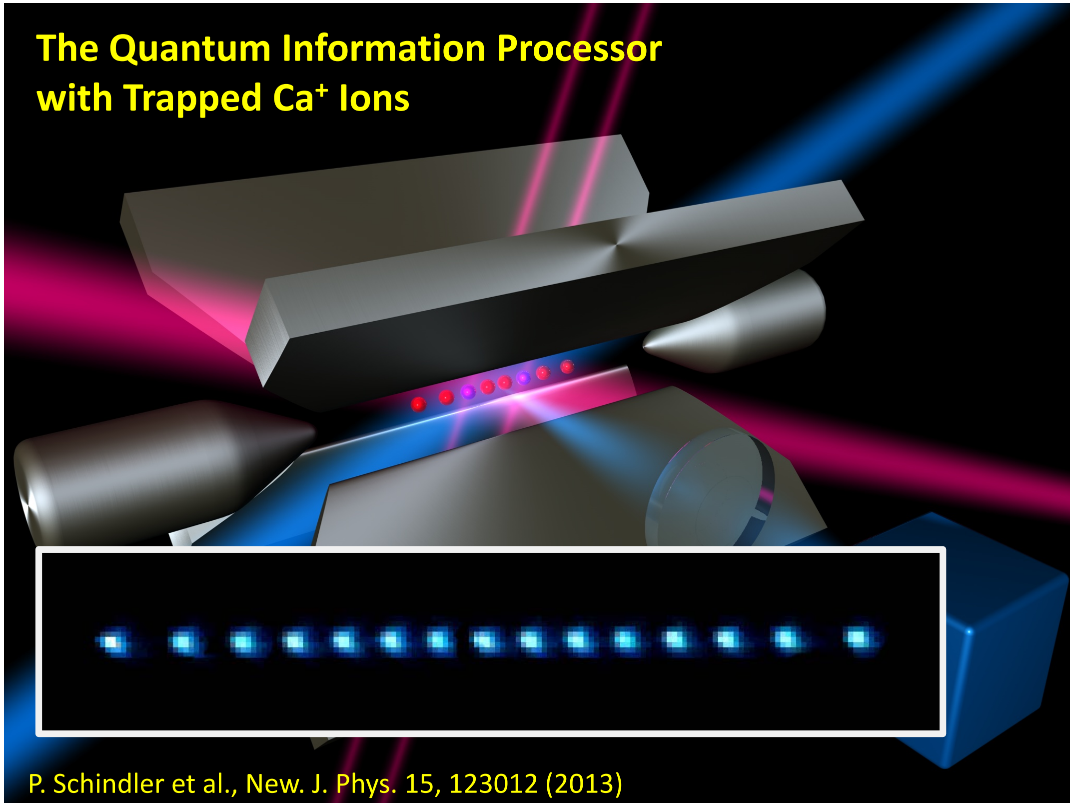


https://www.youtube.com/watch?v=a5v-W_pAqIs

Trapped ions



Trapped ions



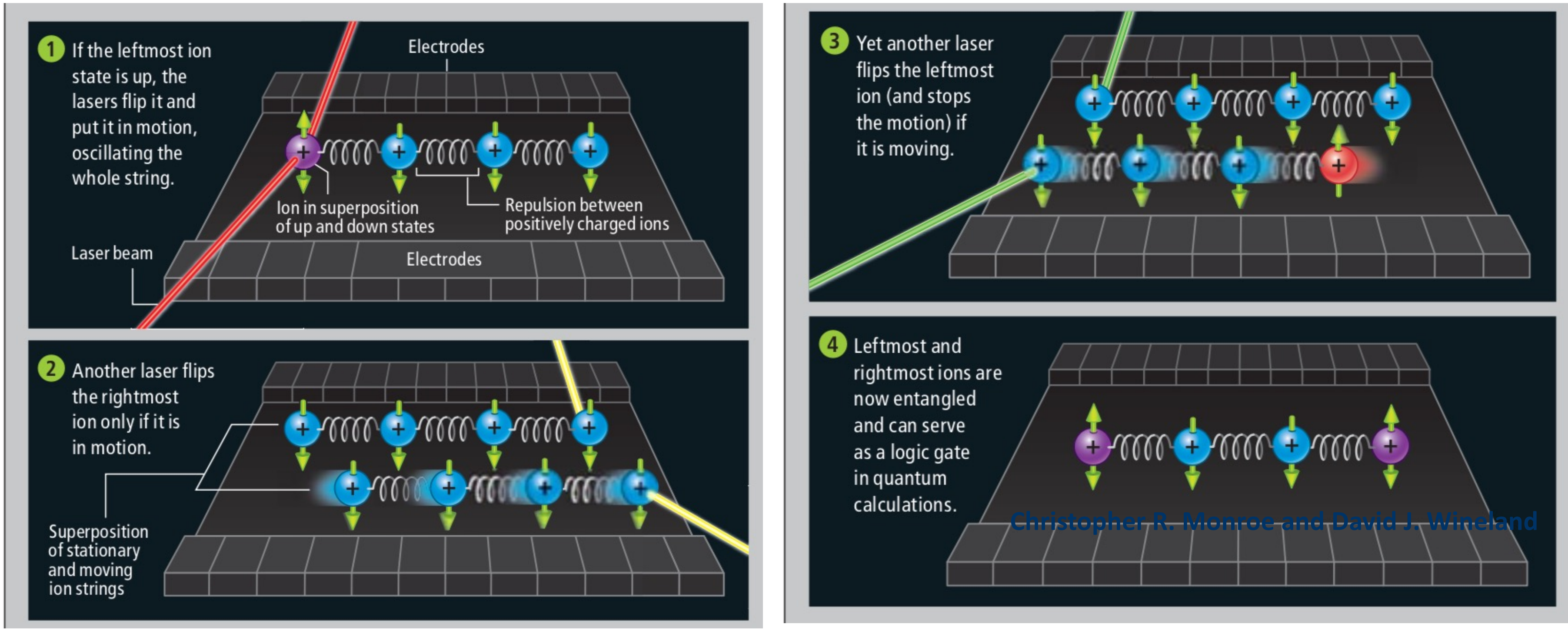
Trapped ions

Two-qubit gates

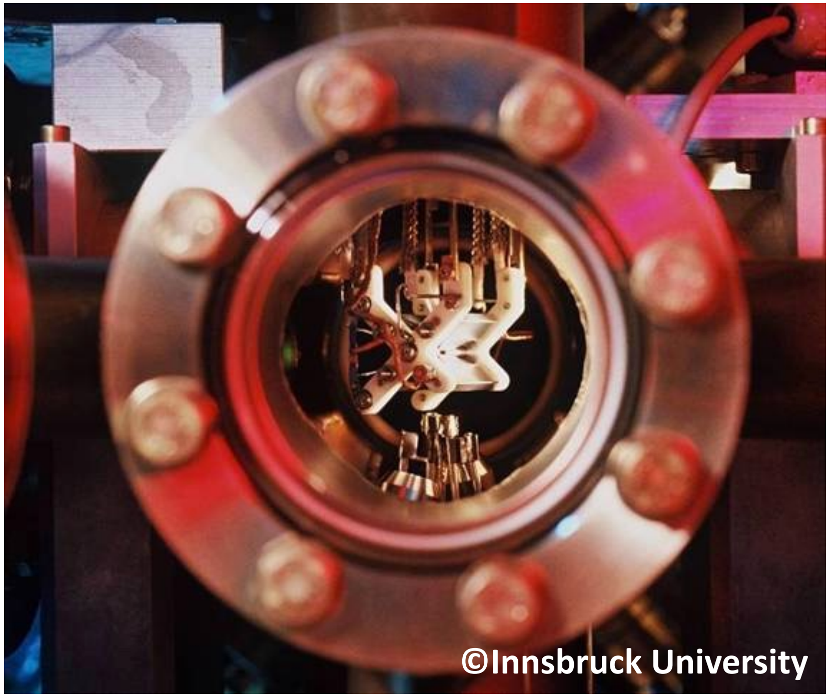
VOLUME 74, NUMBER 20 PHYSICAL REVIEW LETTERS 15 MAY 1995

Quantum Computations with Cold Trapped Ions

J. I. Cirac and P. Zoller*
Institut für Theoretische Physik, Universiät Innsbruck, Technikerstrasse 25, A-6020 Innsbruck, Austria



Trapped ions



Assests:

- Low decoherence
- Excellent connectivity
- Room temperature (except for vacuum)

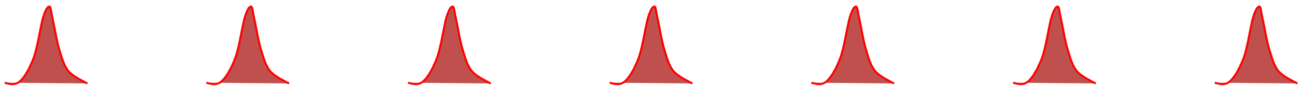
Some challenges:

- Miniaturizarion
- Increasing the qubit number

Photons

Single photon qubit

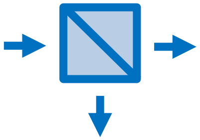
On demand deterministic single photon source



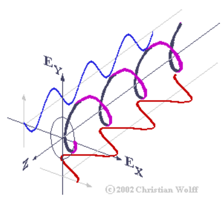
$|1\rangle \quad |1\rangle \quad |1\rangle \quad |1\rangle \quad |1\rangle \quad |1\rangle \quad |1\rangle$

Many degrees of freedom - Hyperencoding

- ✓ **Path**

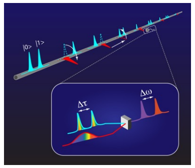


- ✓ **Polarization**

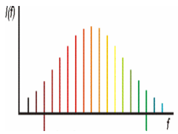


- ✓ **OAM**

- ✓ **Time**

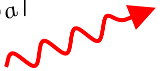


- ✓ **Energy**



- ✓ **Photon number**

$\sqrt{p_0}|0_a\rangle + \sqrt{p_1}e^{i\alpha_1}|1_a\rangle$



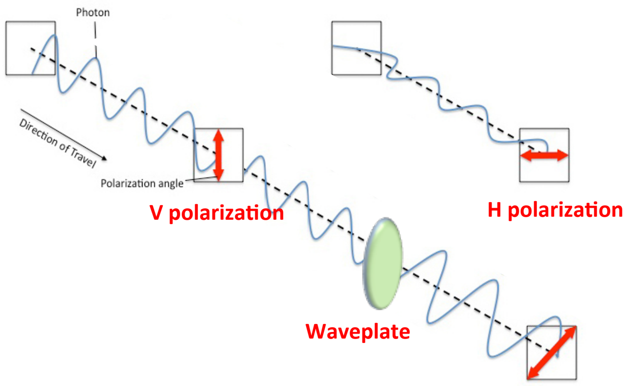
Photons

No decoherence

Photons are non-interacting particles in vacuum

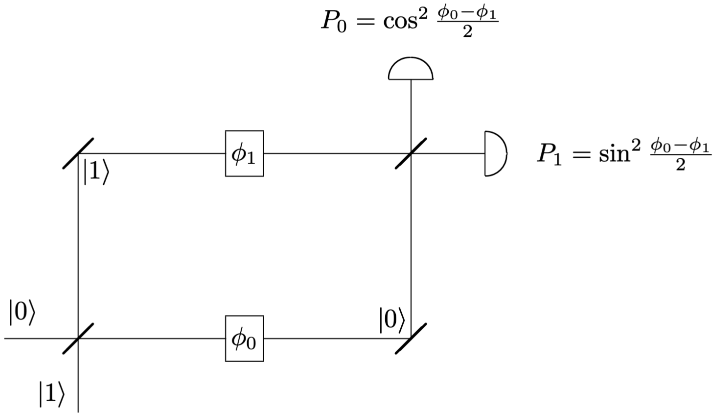
Single qubit gates

Polarization encoding



$$\boxed{|\Psi\rangle = \alpha|H\rangle + \beta e^{i\varphi}|V\rangle}$$

Path encoding



$$\boxed{|\Psi\rangle = \alpha|a\rangle + \beta e^{i\varphi}|b\rangle}$$

Two quantum bit gates ?? (the great challenge)

A scheme for efficient quantum computation with linear optics

E. Knill*, R. Laflamme* & G. J. Milburn†

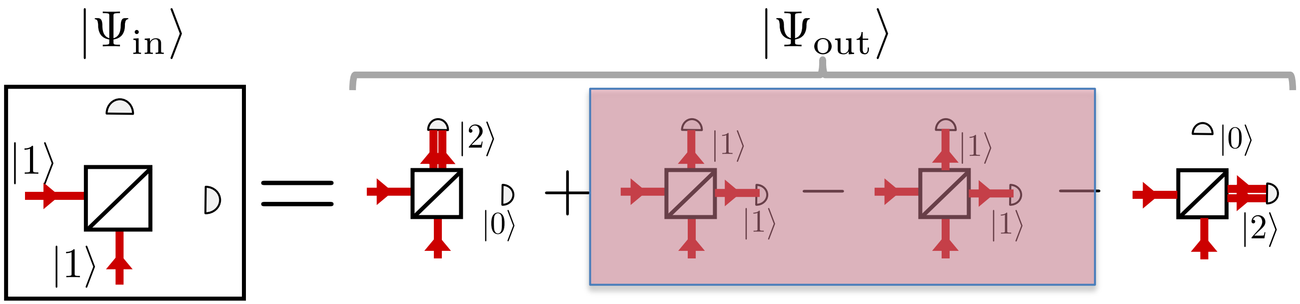
* *Los Alamos National Laboratory, MS B265, Los Alamos, New Mexico 87545, USA*
† *Centre for Quantum Computer Technology, University of Queensland, St. Lucia, Australia*

Quantum computers promise to increase greatly the efficiency of solving problems such as factoring large integers, combinatorial optimization and quantum physics simulation. One of the greatest challenges now is to implement the basic quantum-computational elements in a physical system and to demonstrate that they can be reliably and scalably controlled. One of the earliest proposals for quantum computation is based on implementing a quantum bit with two optical modes containing one photon. The proposal is appealing because of the ease with which photon interference can be observed. Until now, it suffered from the requirement for non-linear couplings between optical modes containing few photons. Here we show that efficient quantum computation is possible using only beam splitters, phase shifters, single photon sources and photo-detectors. Our methods exploit feedback from photo-detectors and are robust against errors from photon loss and detector inefficiency. The basic elements are accessible to experimental investigation with current technology.

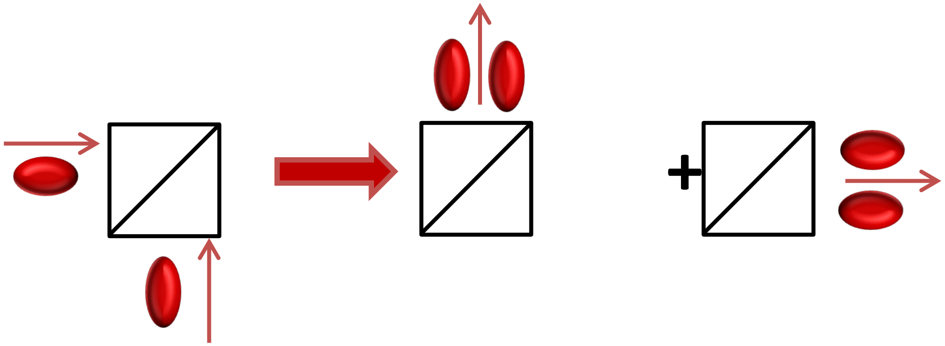
Knill, E.; Laflamme, R.; Milburn, G. J. Nature (2001)

Linear optical quantum computing

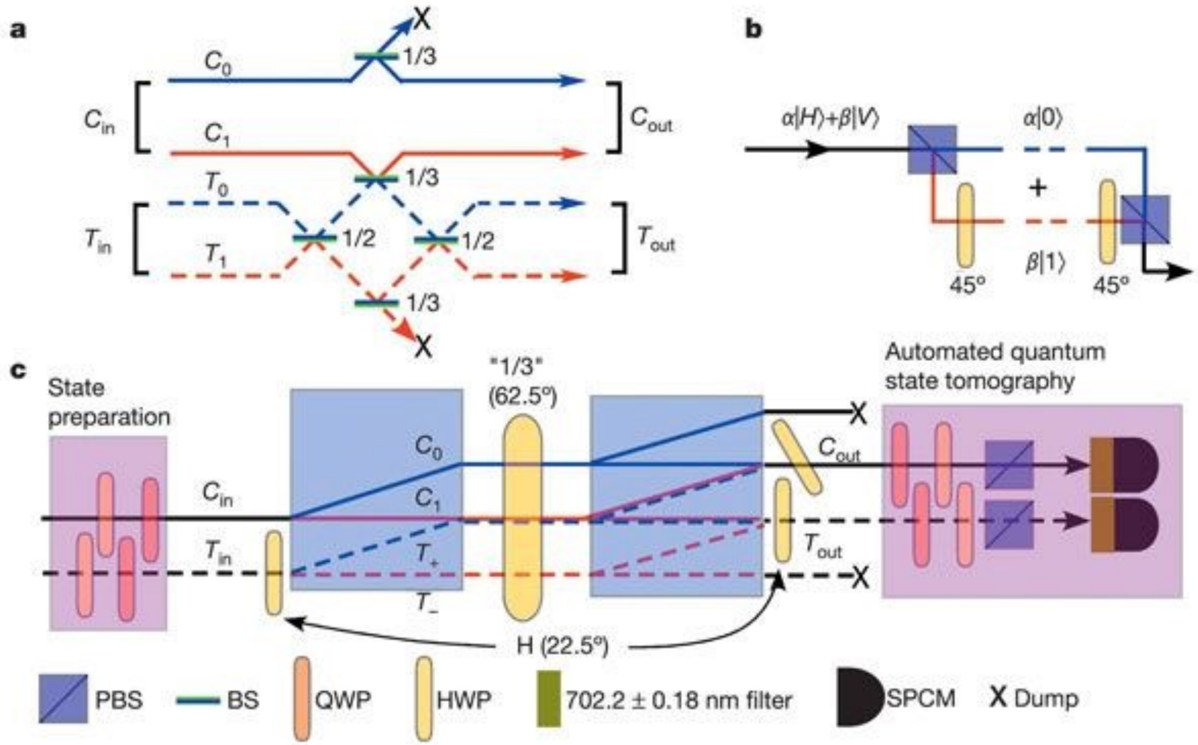
Exploit the quantum interference



$$|\Psi_{\text{in}}\rangle = |1_a, 1_b\rangle \Rightarrow |\Psi_{\text{out}}\rangle = \frac{1}{\sqrt{2}}\left(|2_c, 0_d\rangle - |0_c, 2_d\rangle\right)$$



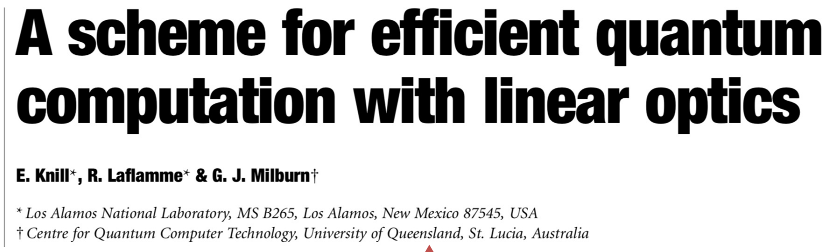
Example of 2-photon CNOT gate

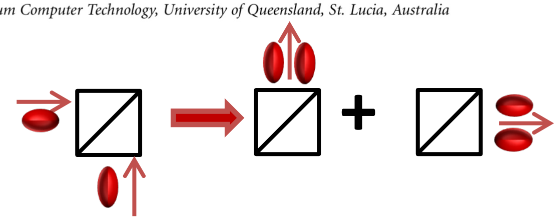


Nature volume 426, 264 (2003)

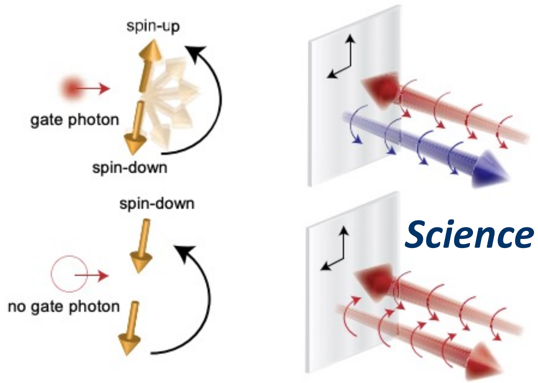
Calcul quantique optique : roadmap

NISQ: calcul linéaire





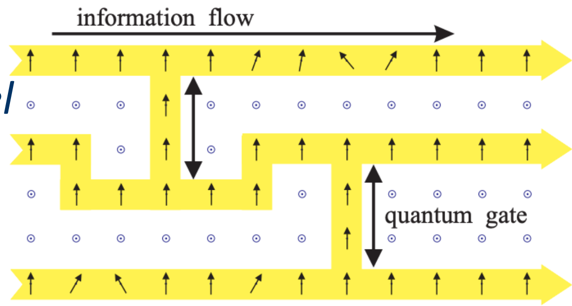
Calcul non linéaire

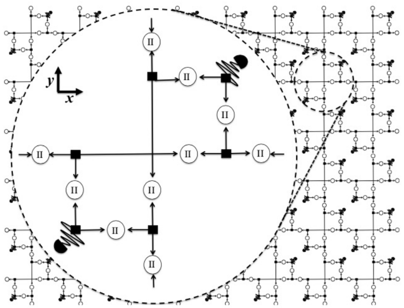


S. Sun et al.,
Science 361, 57 (2018)

Calcul basé sur la mesure

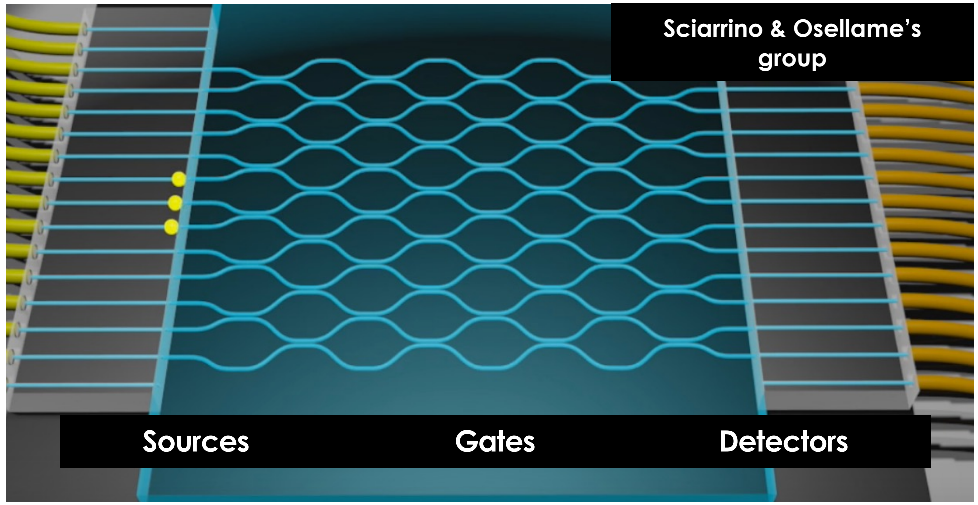
R. Raussendorf, D.E. Browne, H.J. Briegel
Phys. Rev. A 68, 022312 (2003)





APL Photonics 2, 030901 (2017)
Terry Rudolph

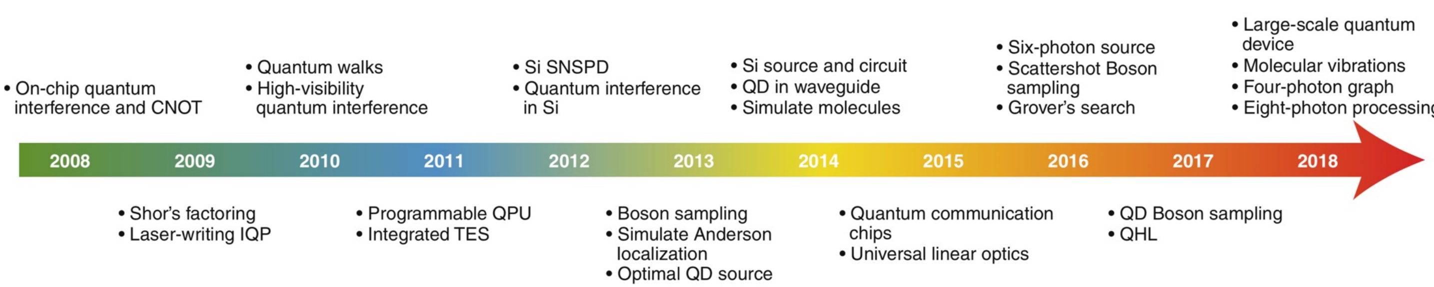
Optical Quantum computer architecture



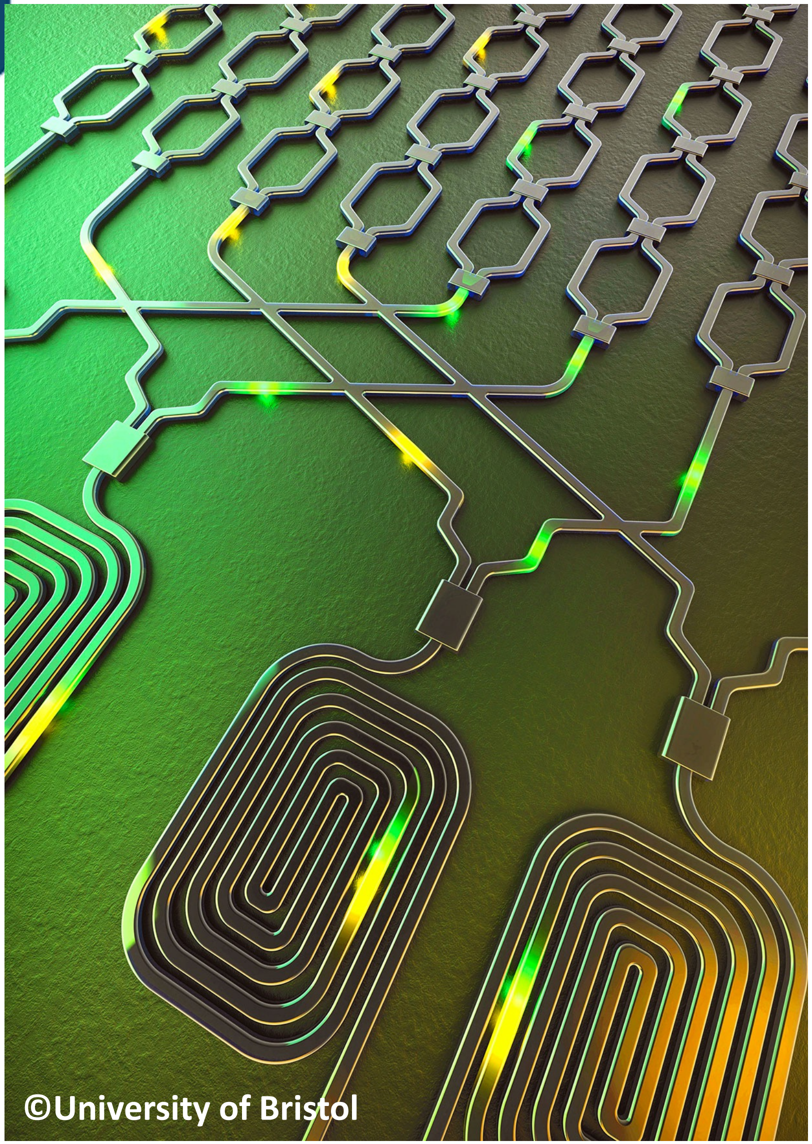
nature photonics
REVIEW ARTICLE
https://doi.org/10.1038/s41566-019-0532-1

Integrated photonic quantum technologies

Jianwei Wang[1], Fabio Sciarrino[2], Anthony Laing[3] and Mark G. Thompson[3*]



Photons



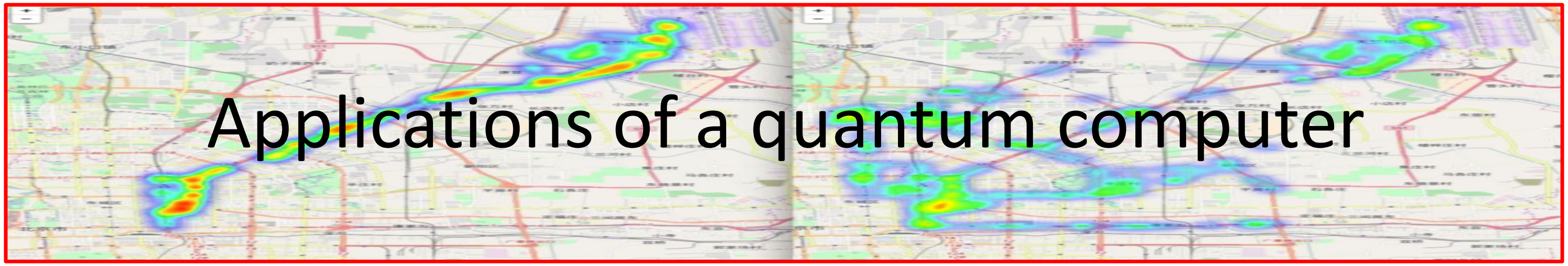
Assests:

- No decoherence
- Good connectivity
- Room temperature processing
- Naturally connect to a quantum network

Some challenges:

- Very inefficient 2-qubit gates
- Efficient light sources

Applications of a quantum computer



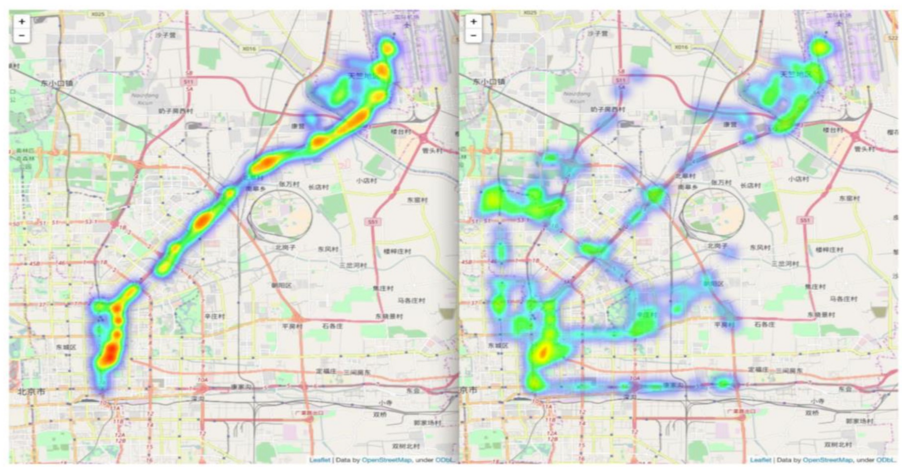
Applications of a universal quantum computer

Where High Power Computation (HPC) is needed:

- Machine learning, Big data
- Optimisation problems (traffic, energy)
- Quantum and physics simulations (new materials, new molecules)
- Cybersecurity
- Finances…

..an ever growing lists as industrials gets involved

Dwave quantum annealing computer (since 2010)

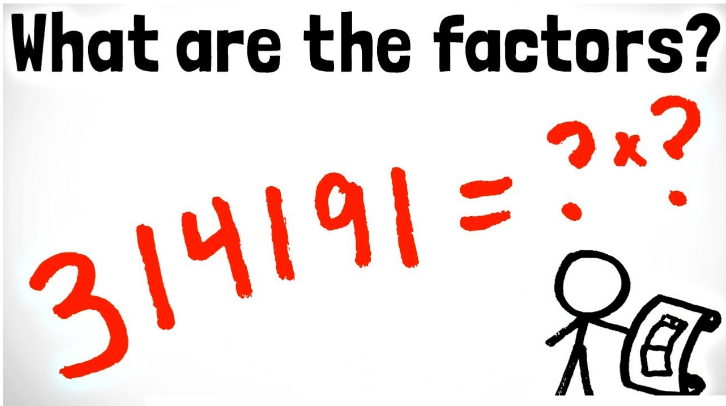


27.09.2017 K-SI/LD | Dr. Gabriele Compostella

arXiv:1708.01625

Quadratic Unconstraint Binary Optimisation

Decipher today's cryptography



Public-key cryptography:

hardness of factorizing prime numbers

SIAM J. COMPUT.
Vol. 26, No. 5, pp. 1484–1509, October 1997

POLYNOMIAL-TIME ALGORITHMS FOR PRIME FACTORIZATION AND DISCRETE LOGARITHMS ON A QUANTUM COMPUTER*

PETER W. SHOR†

Abstract. A digital computer is generally believed to be an efficient universal computing device; that is, it is believed able to simulate any physical computing device with an increase in computation time by at most a polynomial factor. This may not be true when quantum mechanics is taken into consideration. This paper considers factoring integers and finding discrete logarithms, two problems which are generally thought to be hard on a classical computer and which have been used as the basis of several proposed cryptosystems. Efficient randomized algorithms are given for these two problems on a hypothetical quantum computer. These algorithms take a number of steps polynomial in the input size, e.g., the number of digits of the integer to be factored.

Requires tens of millions of excellent quantum bits and gates

(error <0.1%)

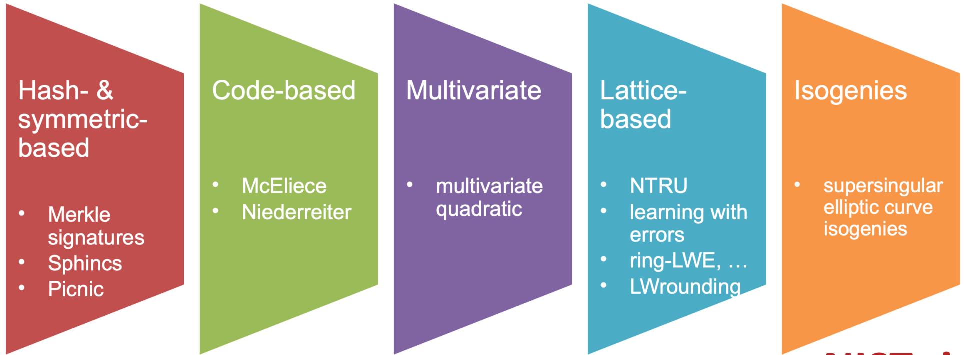
Shor's algorithm threat

Computational response: Post-quantum cryptography

Principe: Develop cryptography protocols that resist quantum computational power

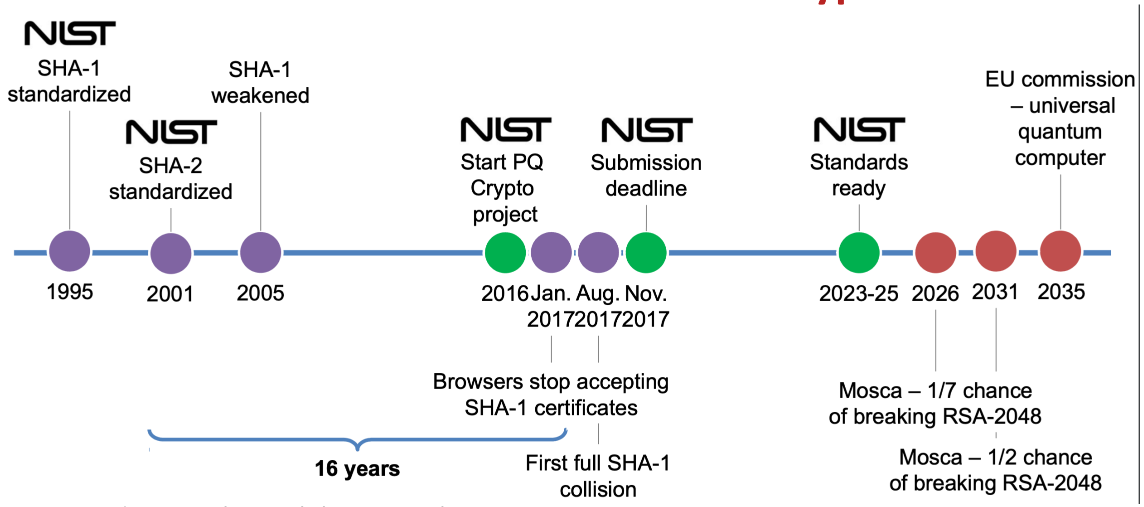
Post-quantum crypto

Classical crypto with no known exponential quantum speedup



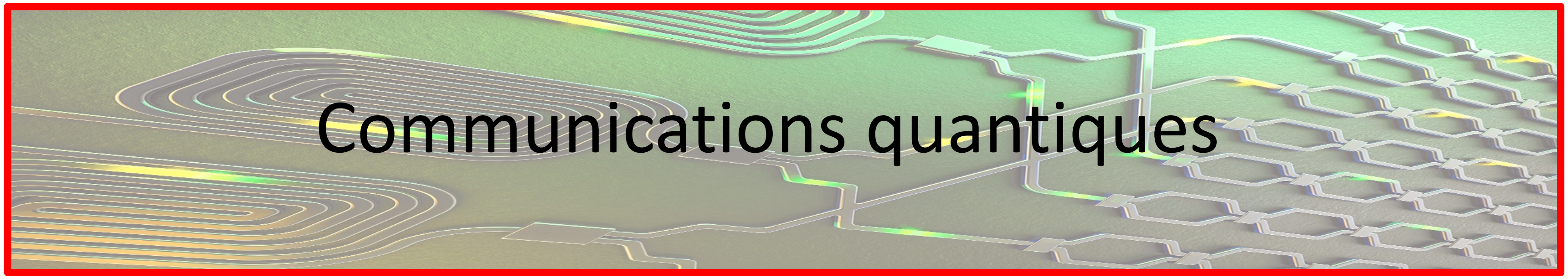
Credit: Douglas Stebila - Waterloo

NIST time line to define new encryption standards

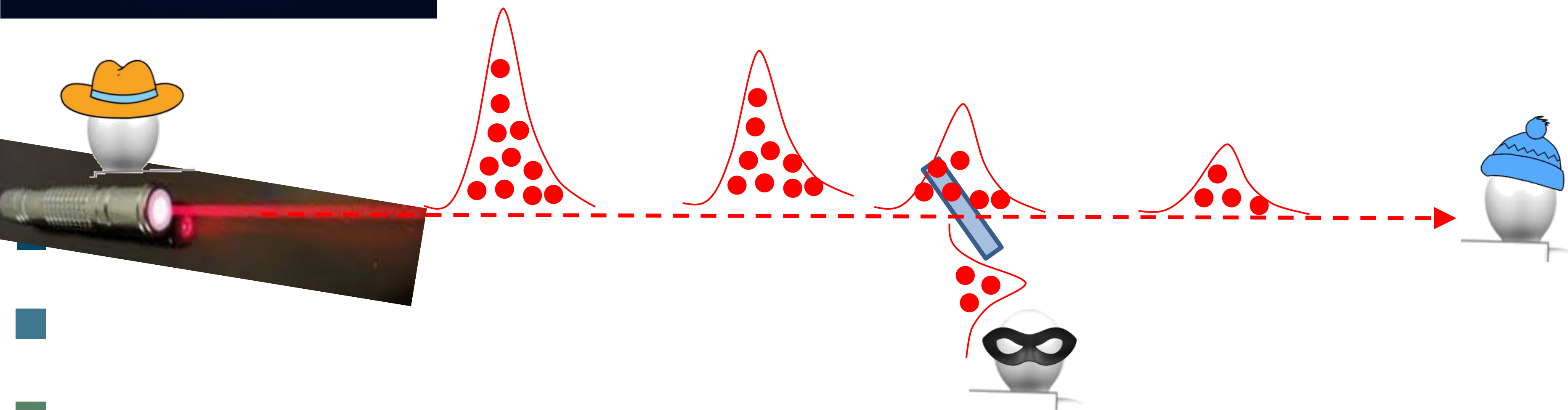


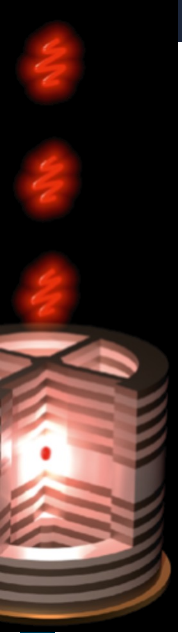
Credit: Douglas Stebila - Waterloo

Communications quantiques

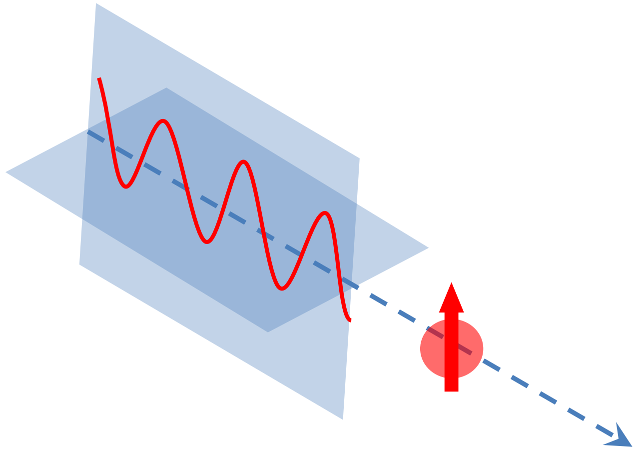


Classical communication

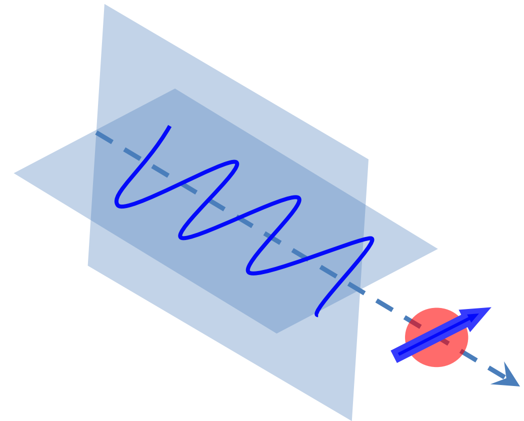




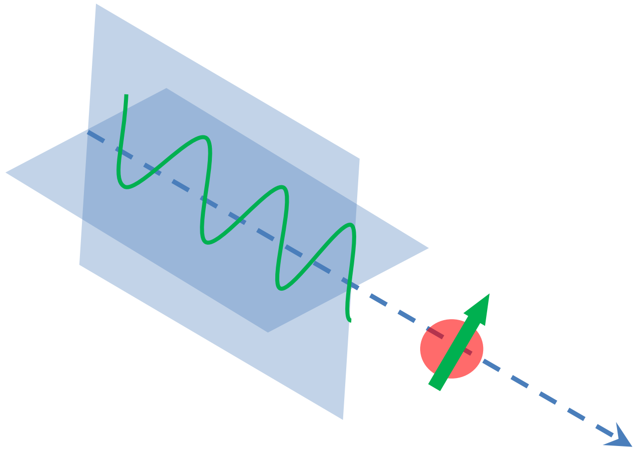
Encoding information on a single photon



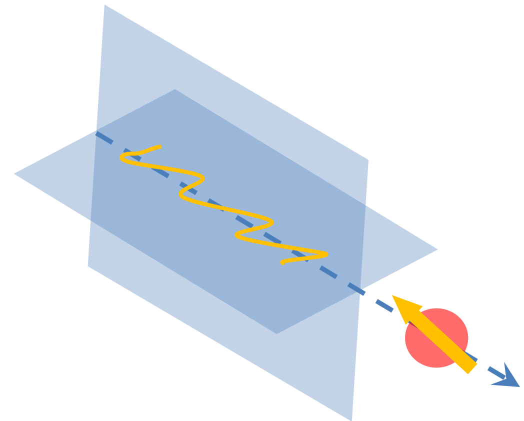
$|0\rangle$



$|1\rangle$

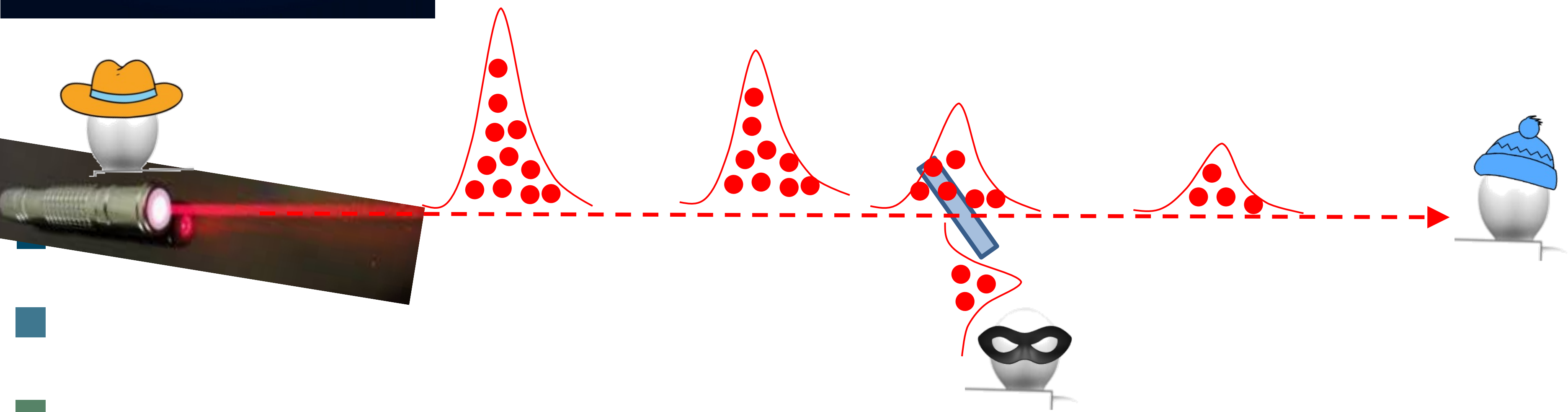


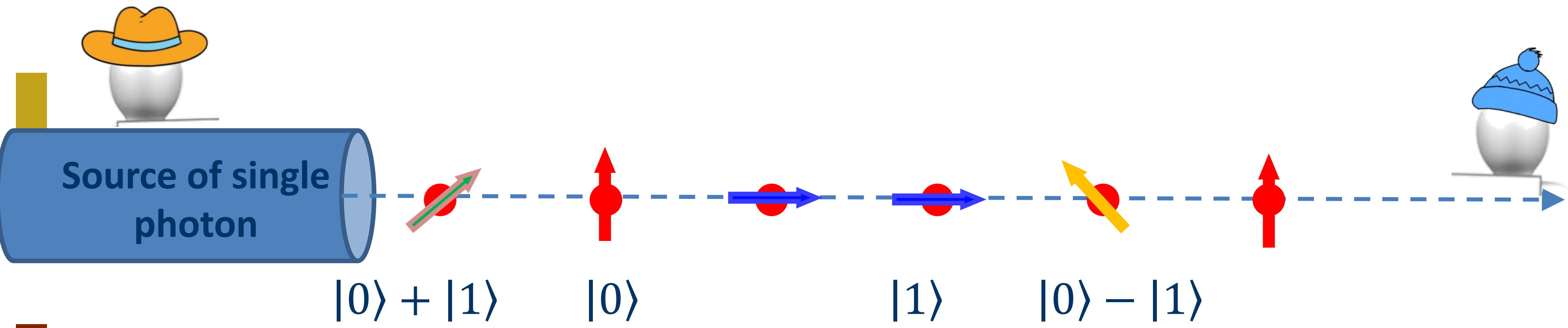
$|0\rangle + |1\rangle$



$|0\rangle - |1\rangle$

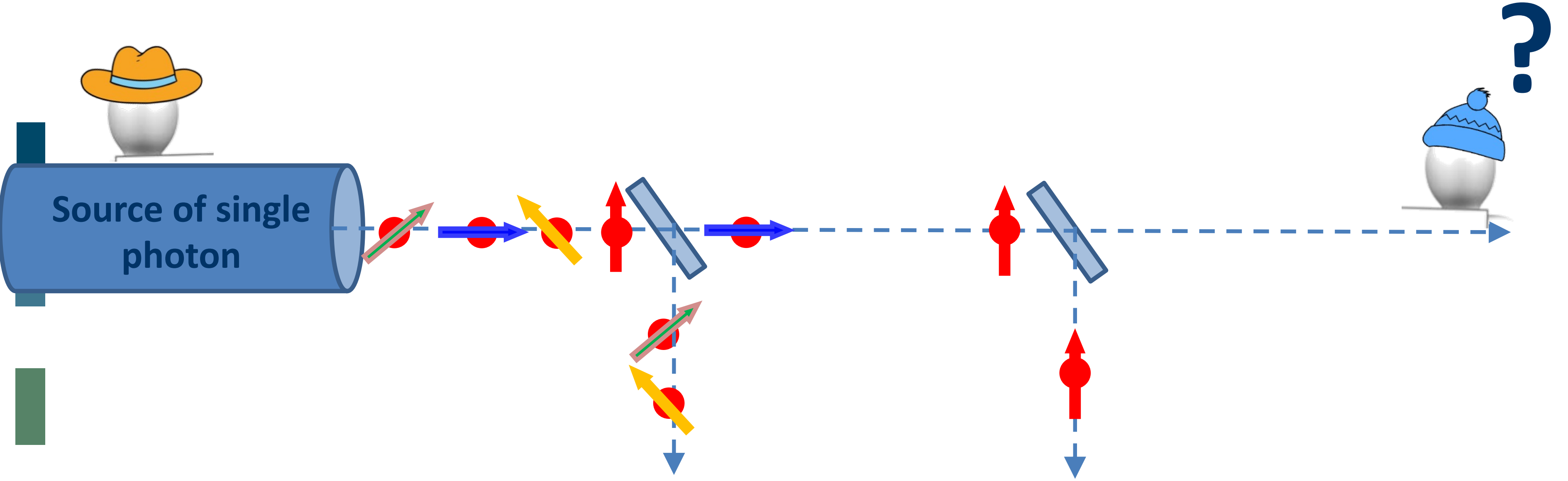
Secret communication



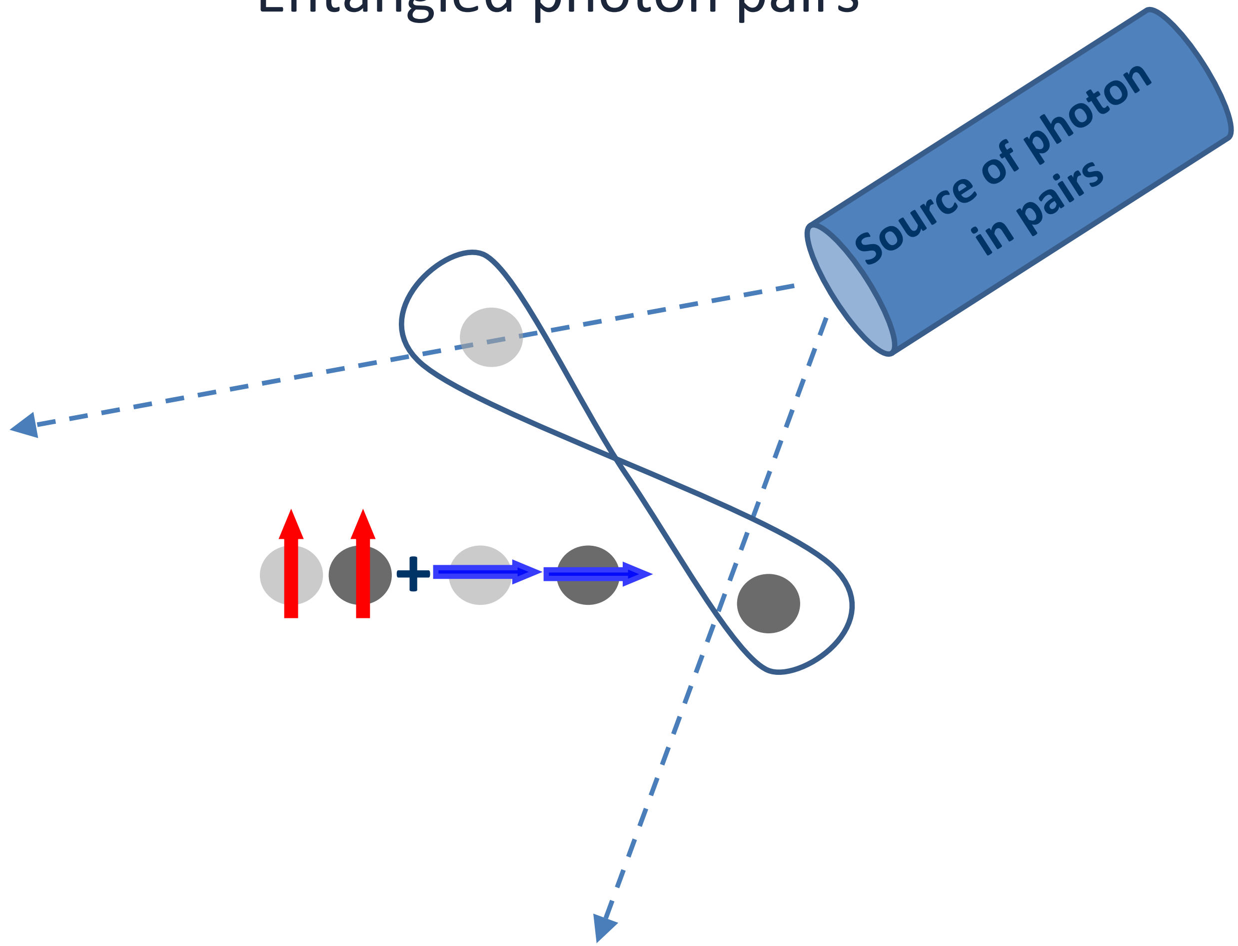


Secret communication

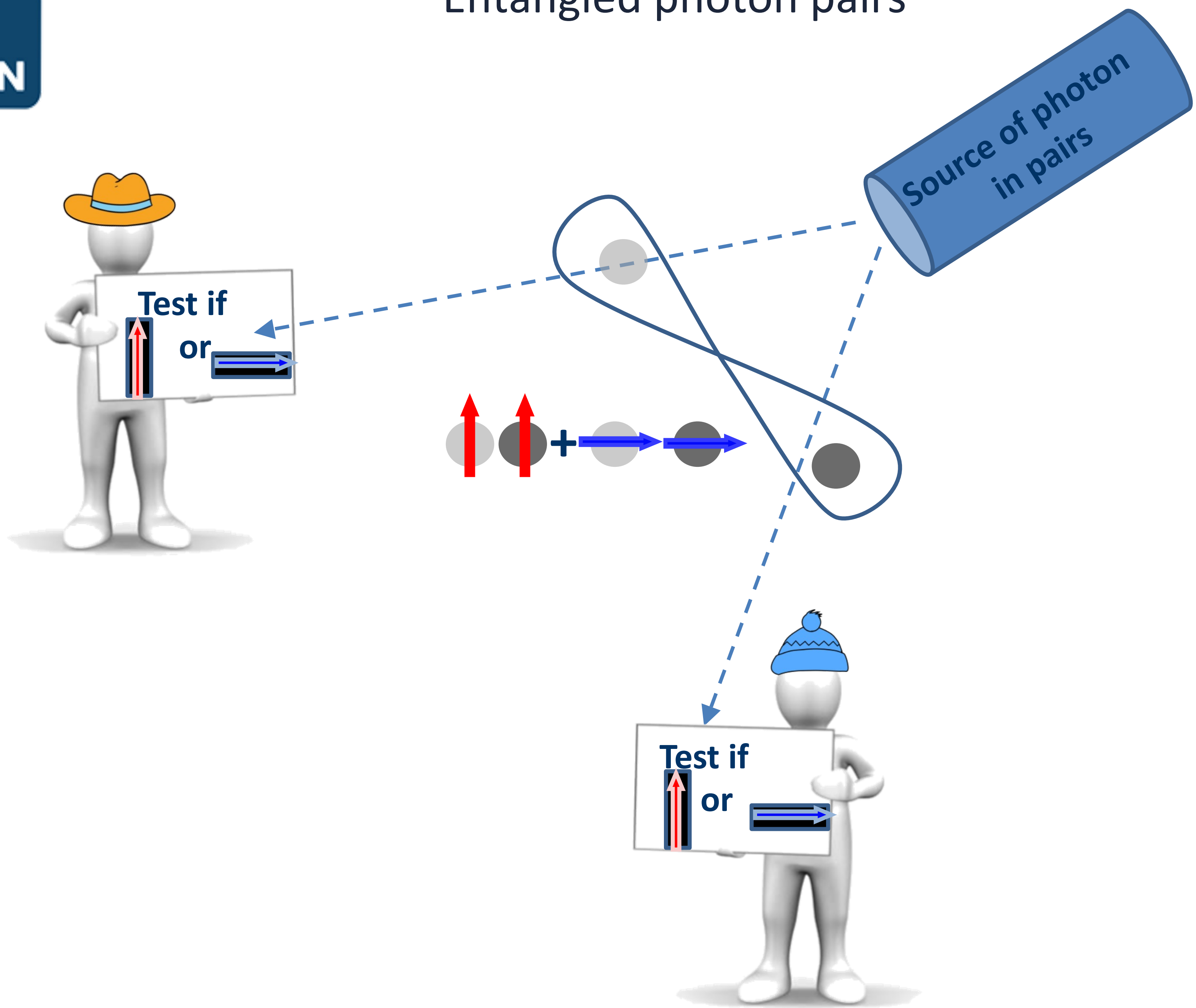
But losses...



Entangled photon pairs



Entangled photon pairs



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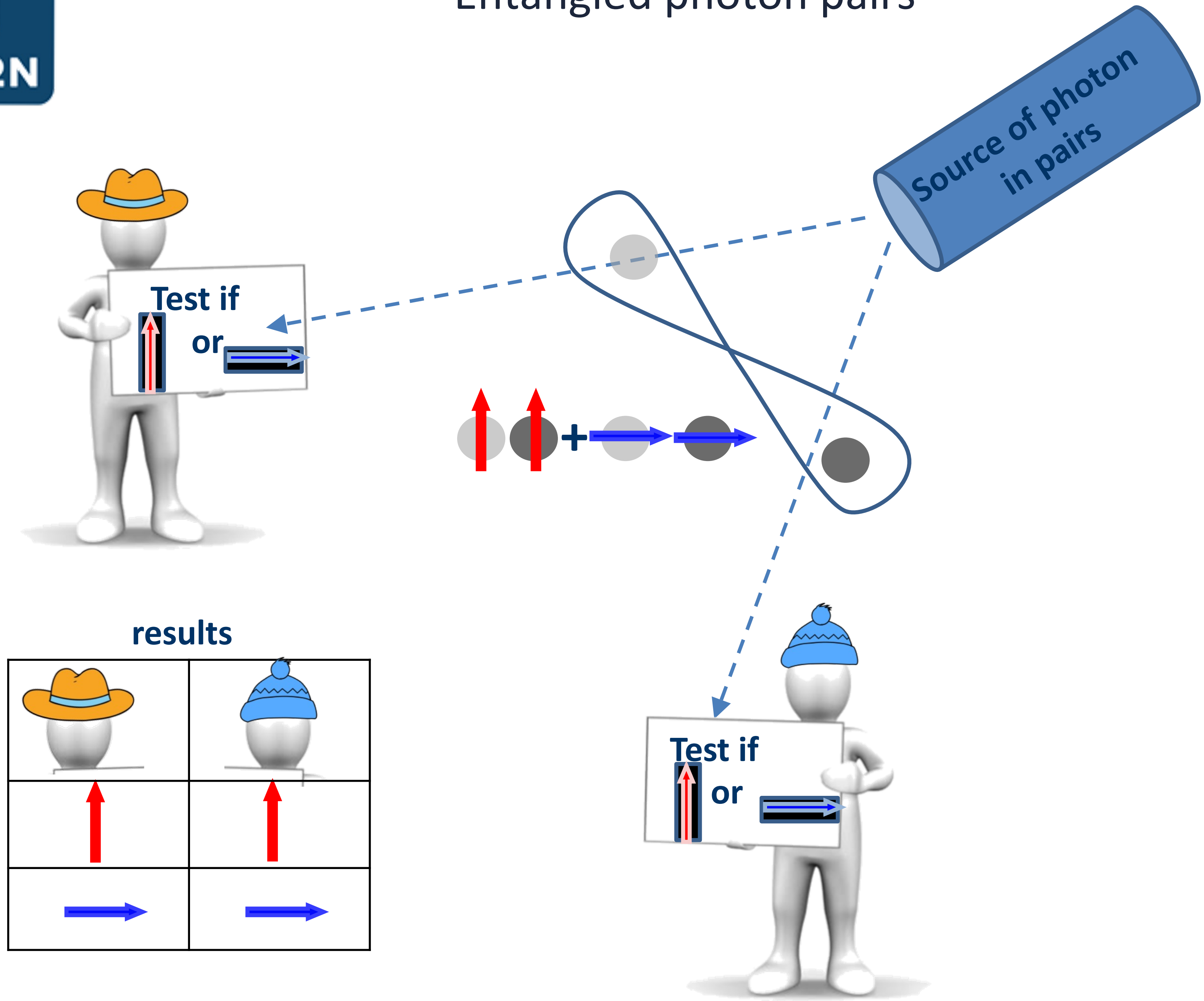

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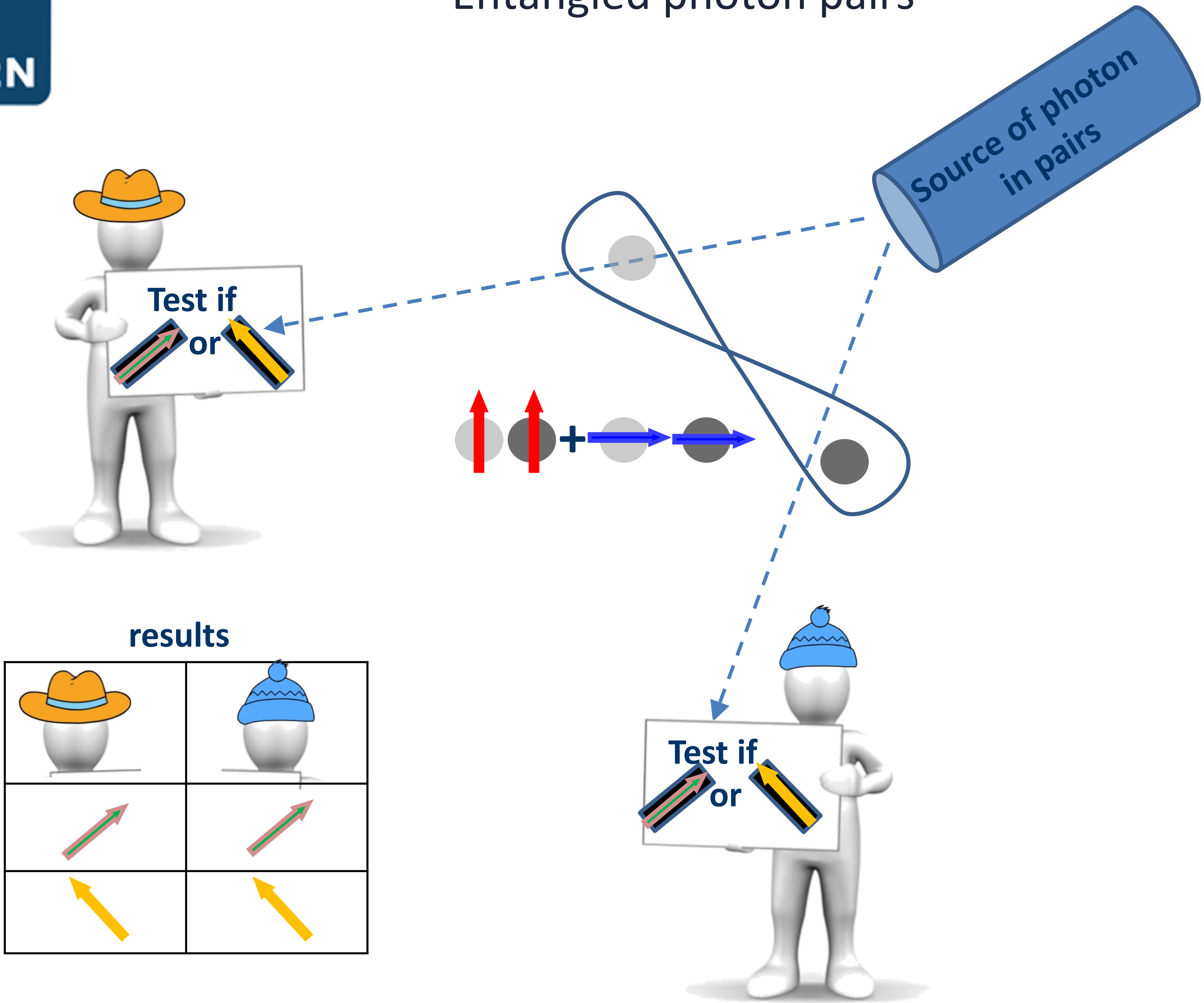

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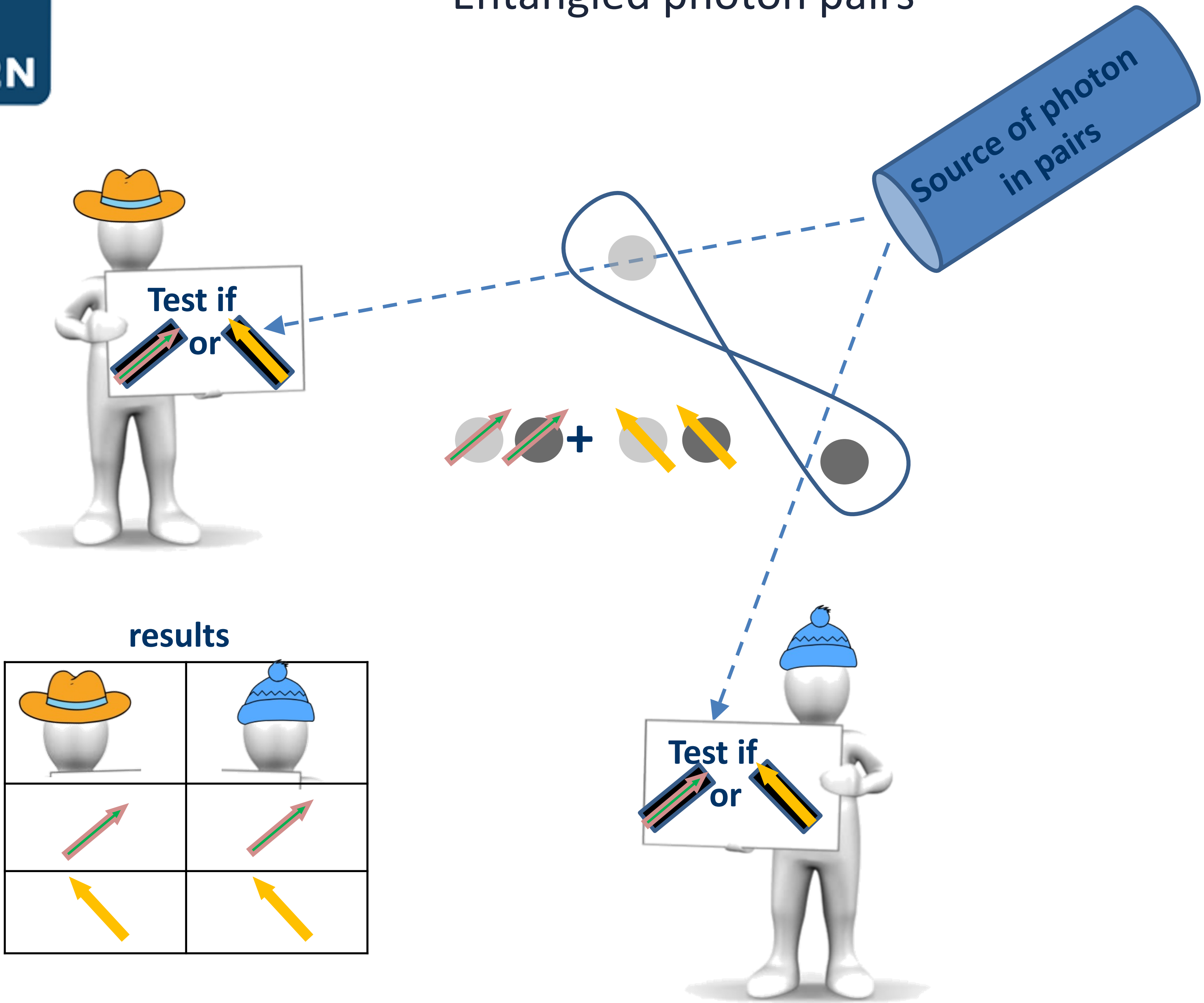
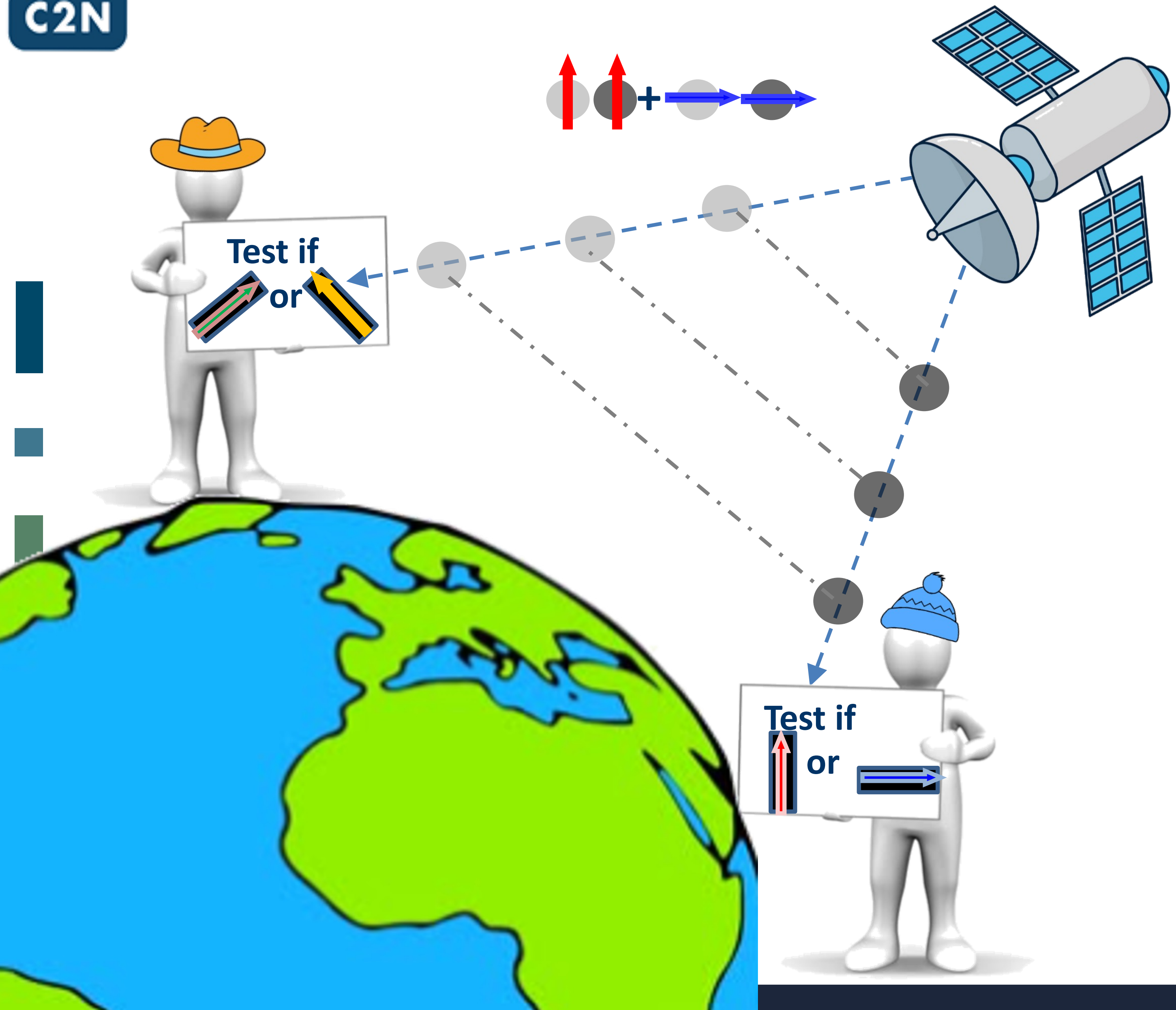
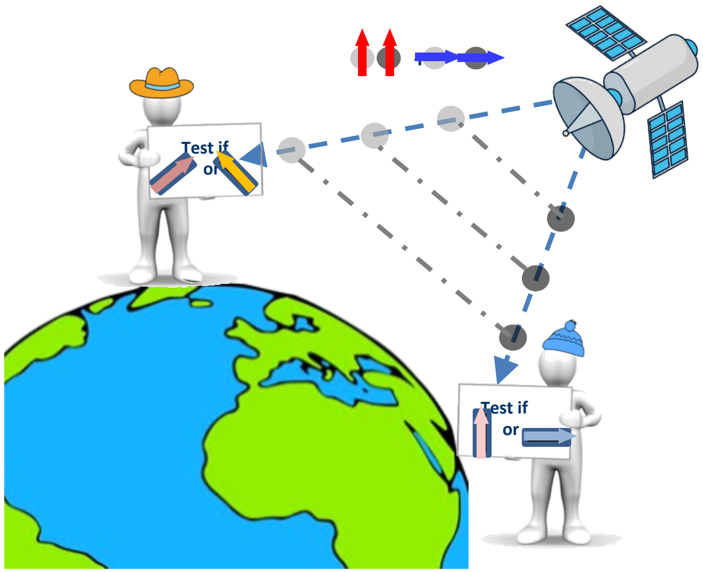


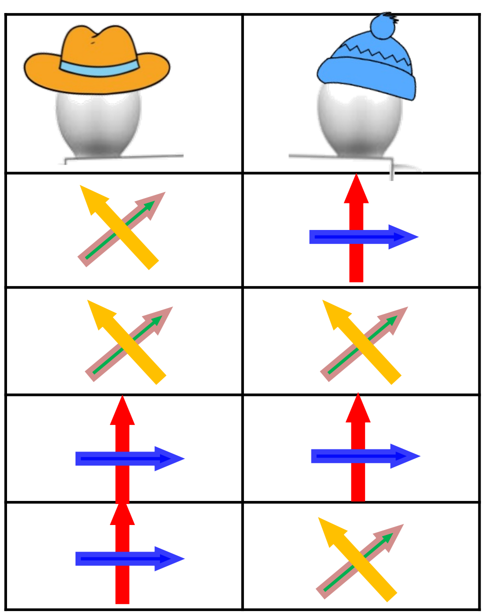
Secret communication & entanglement



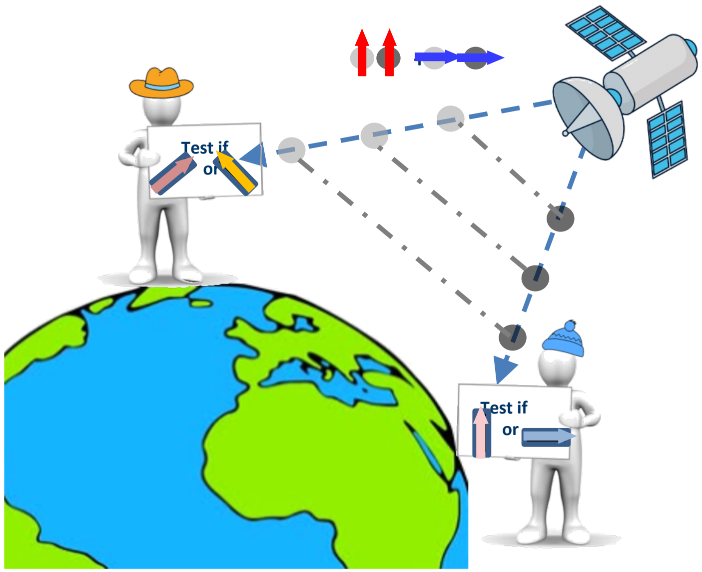
Secret communication & entanglement



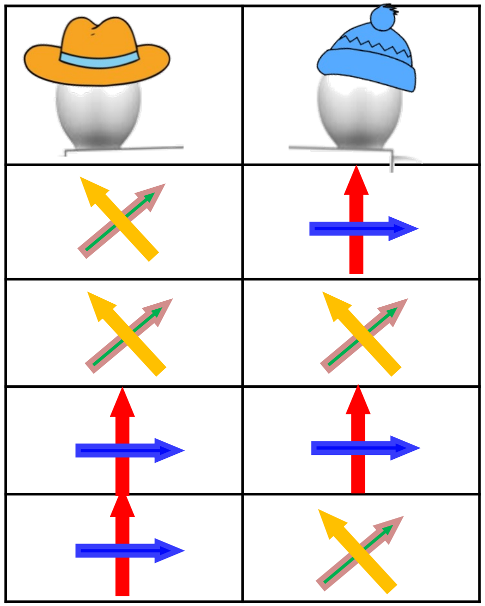
Test direction



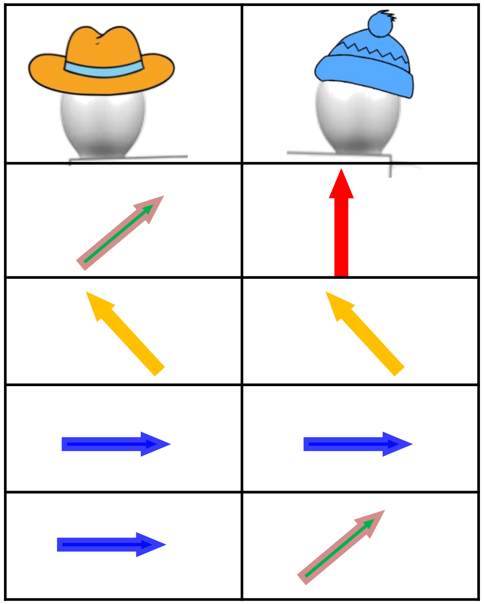
Secret communication & entanglement



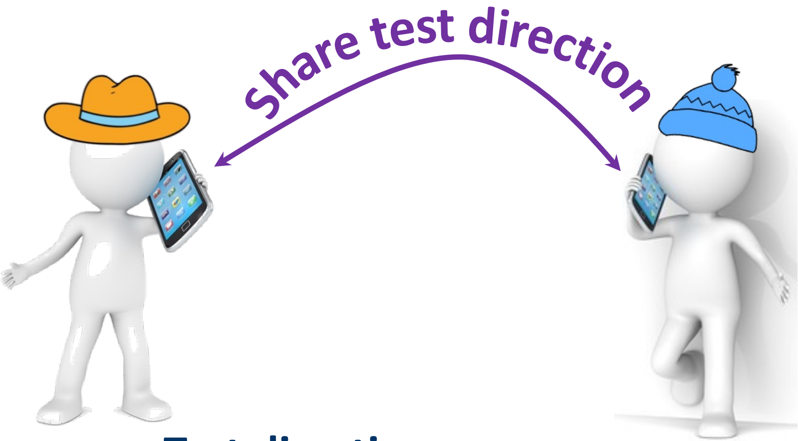
Test direction

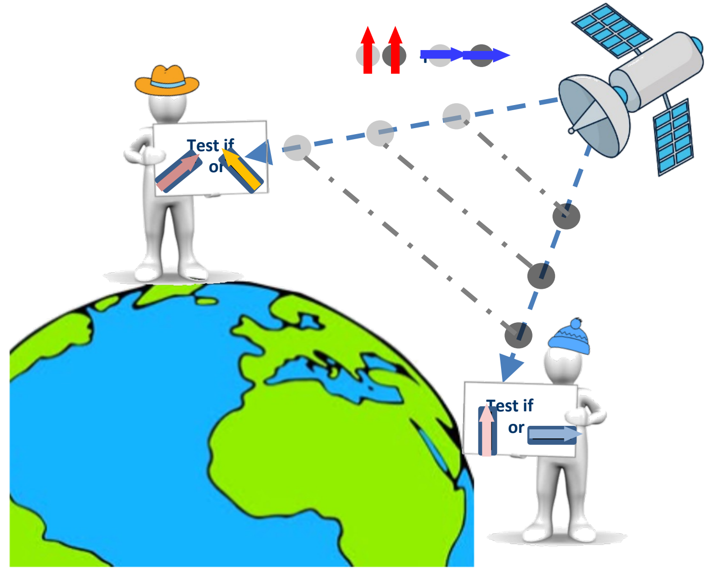


result



Secret communication & entanglement





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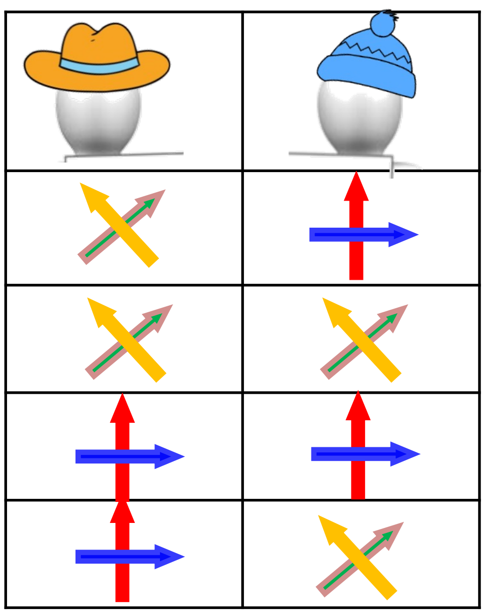

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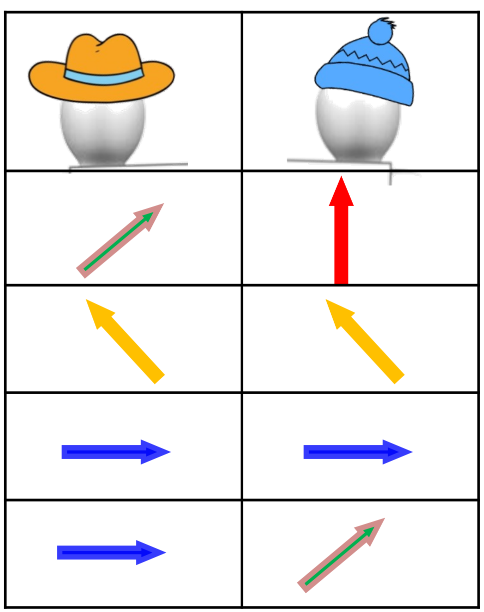
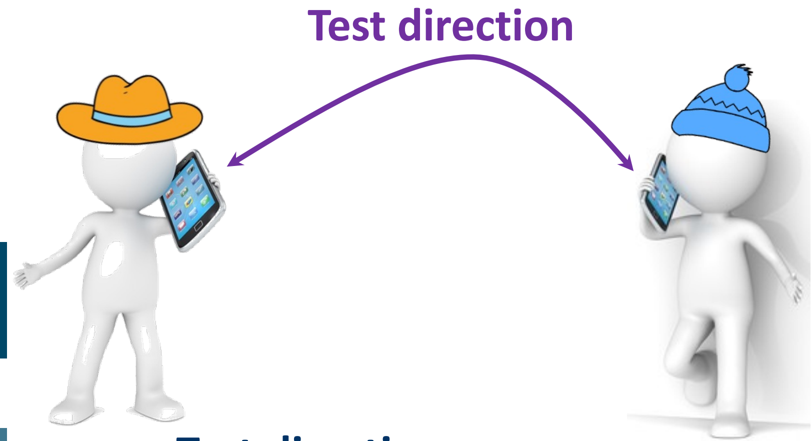
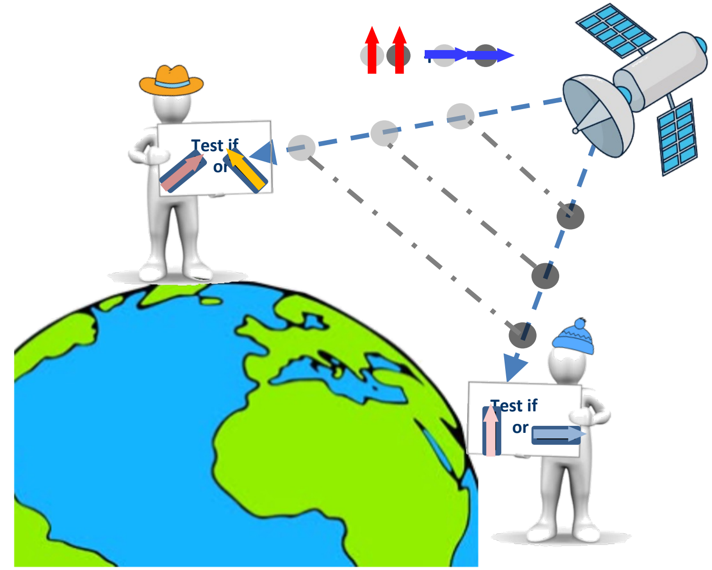


Secret communication & entanglement





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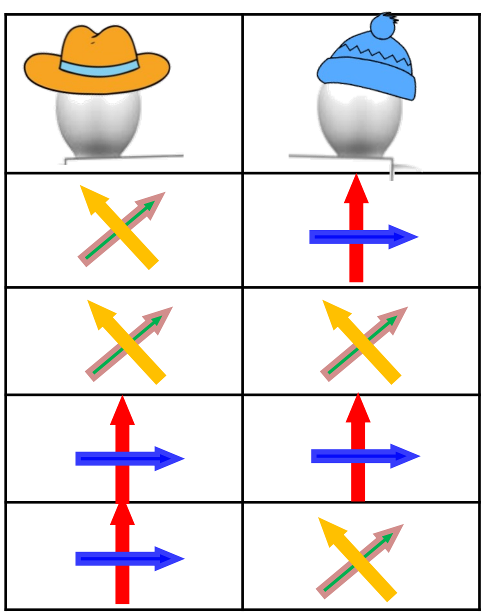
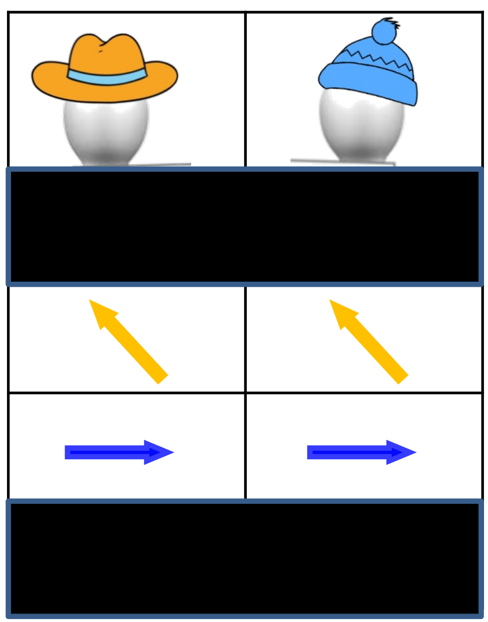
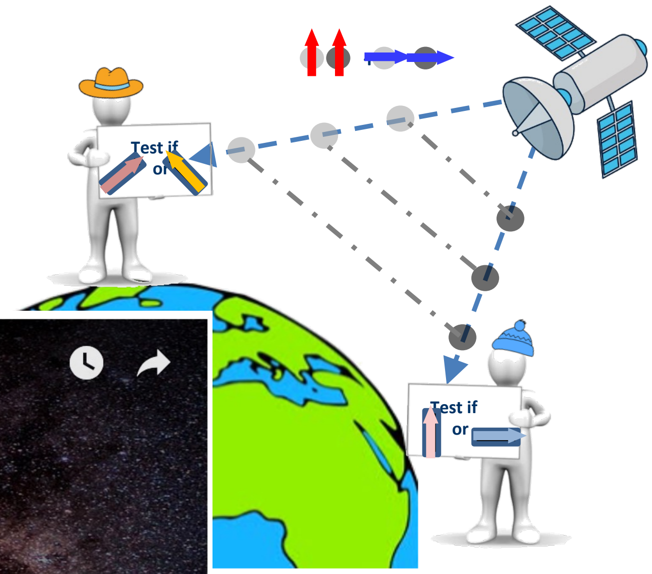
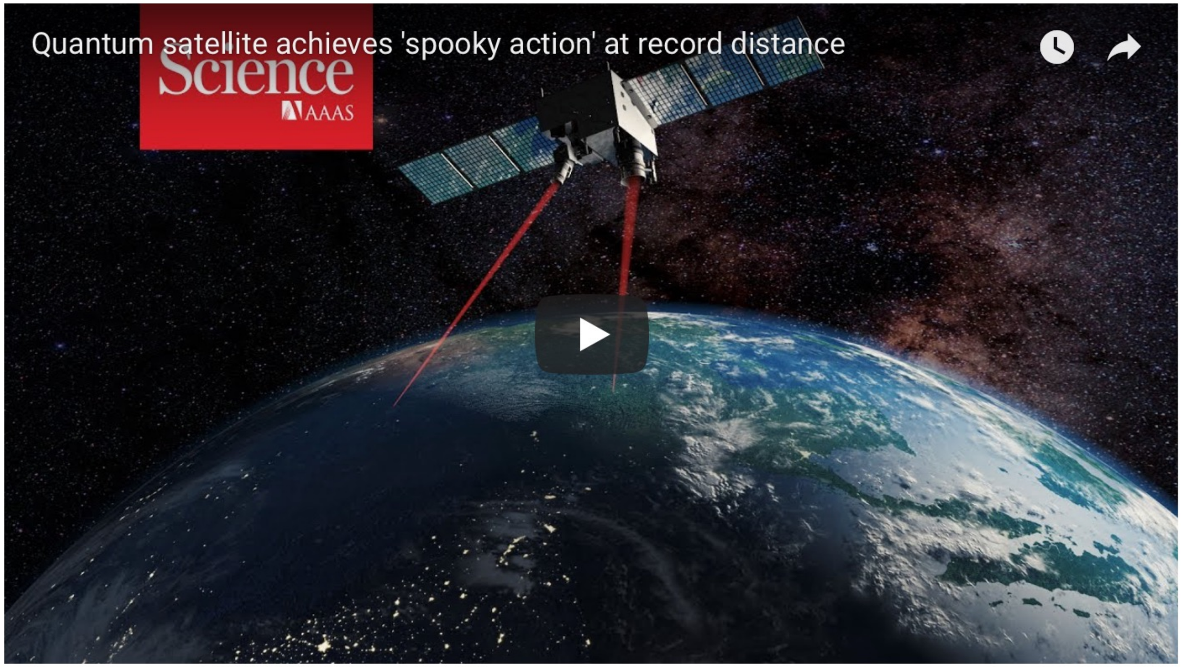


result



Secret communication & entanglement



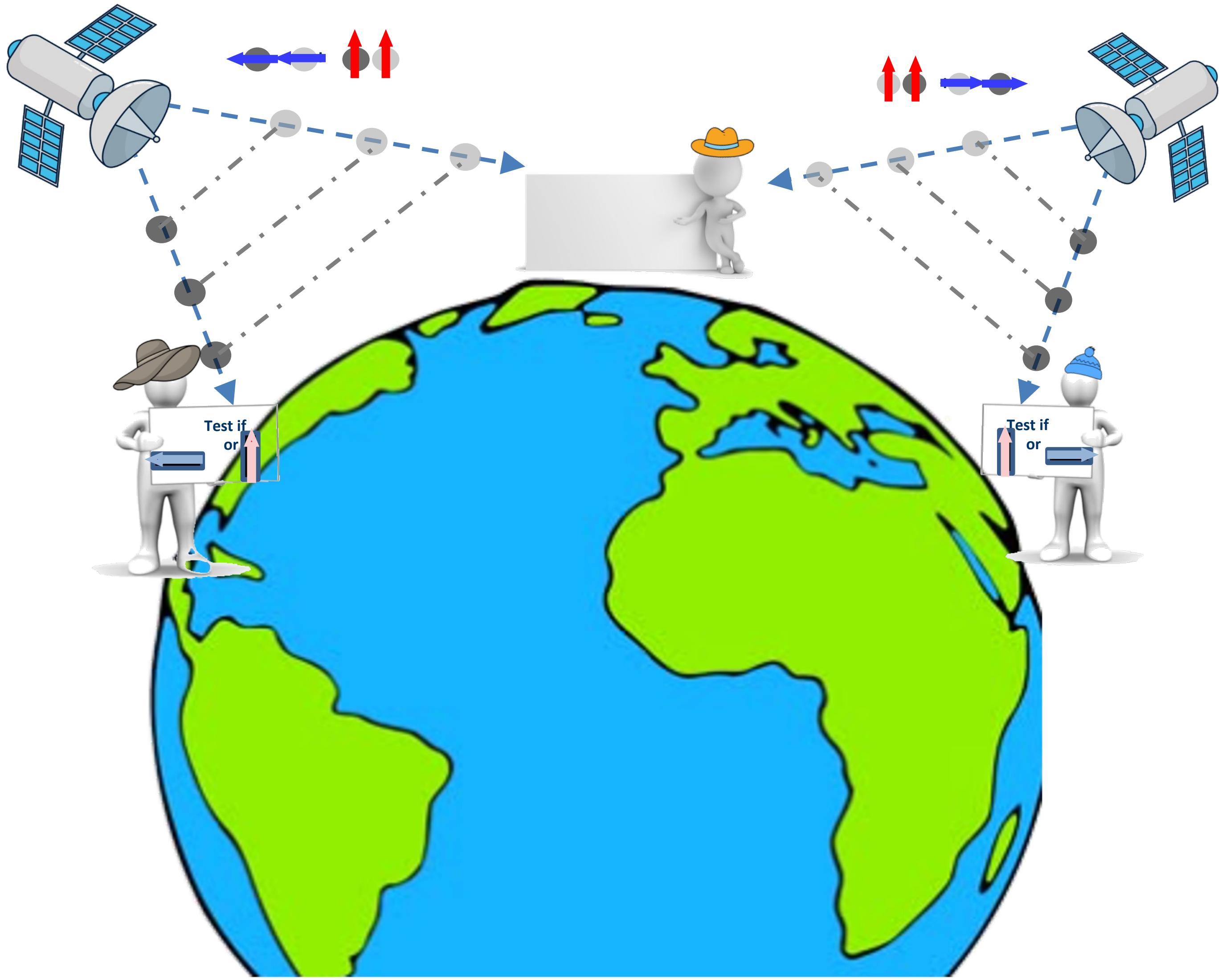


China's quantum satellite achieves 'spooky action' at record distance

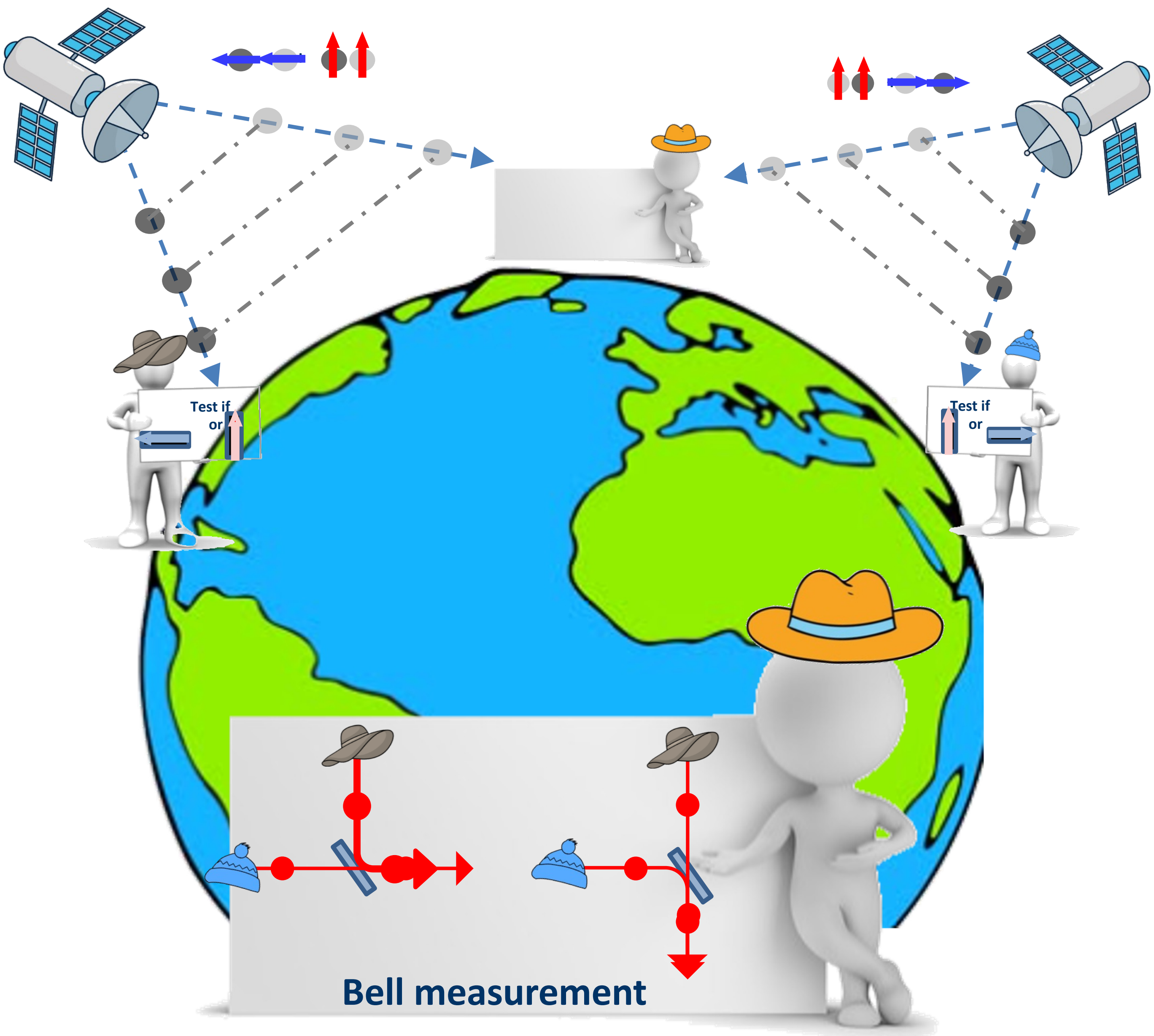
By **Gabriel Popkin** | Jun. 15, 2017 , 2:00 PM

June 2017

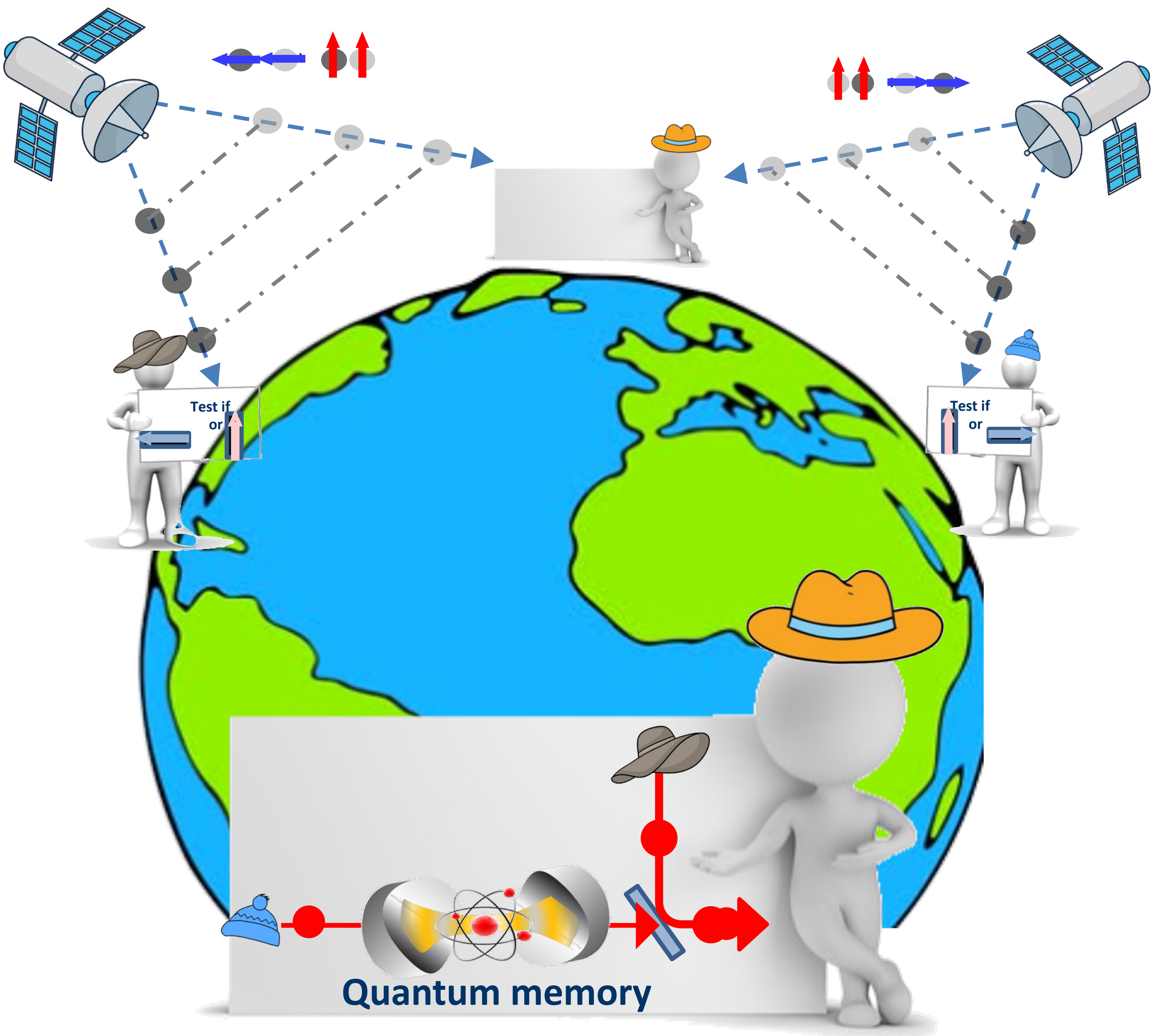
Quantum networks



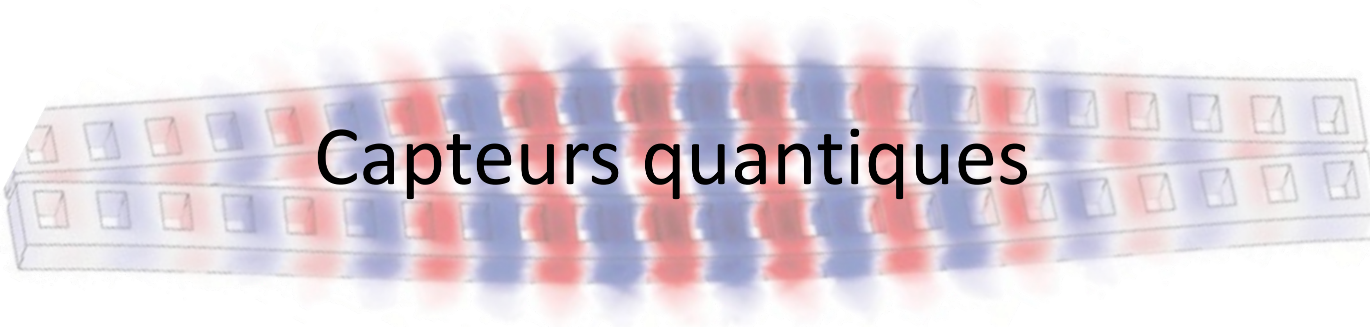
Quantum networks



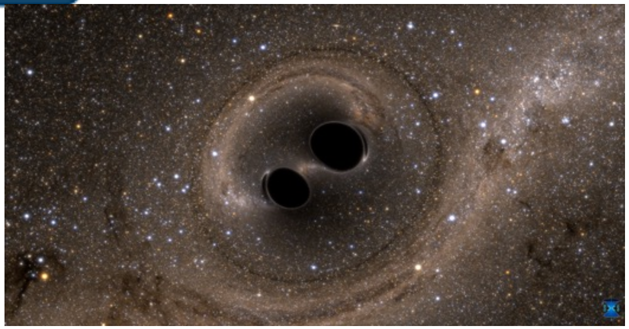
Quantum networks

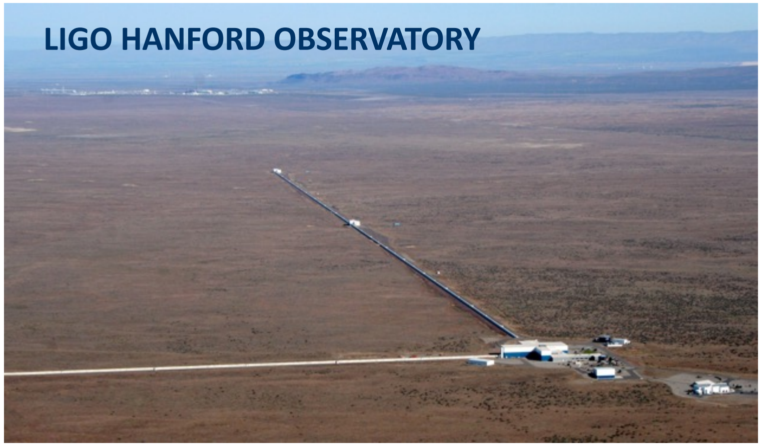


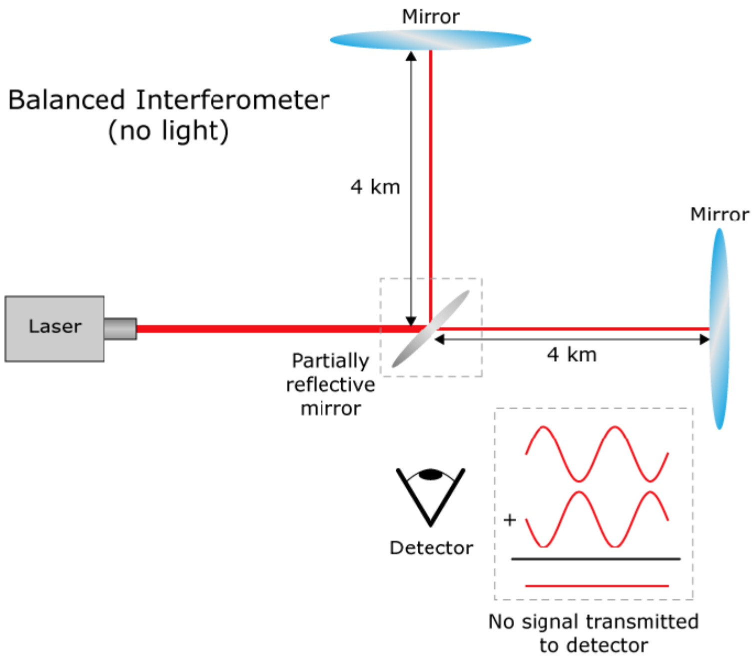
Capteurs quantiques



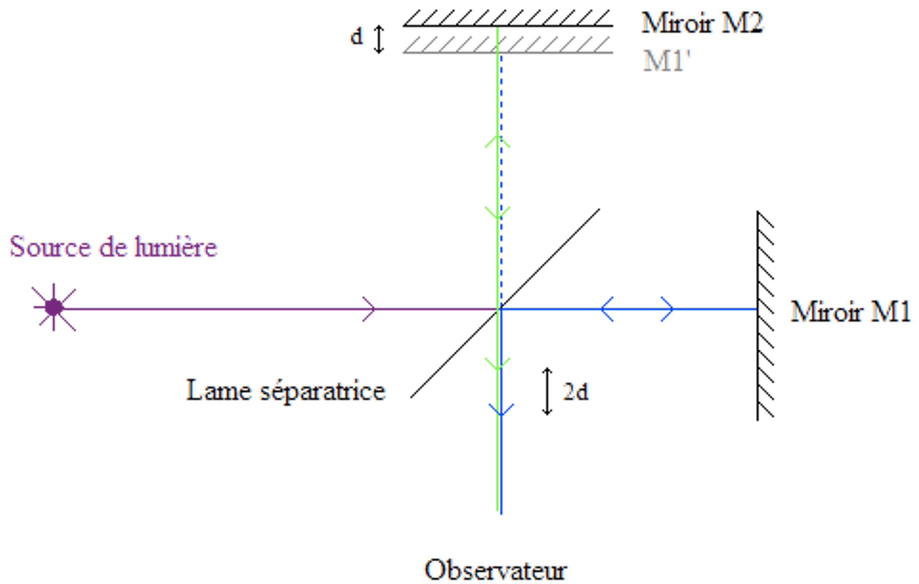
Détection d’ondes gravitationnelles:

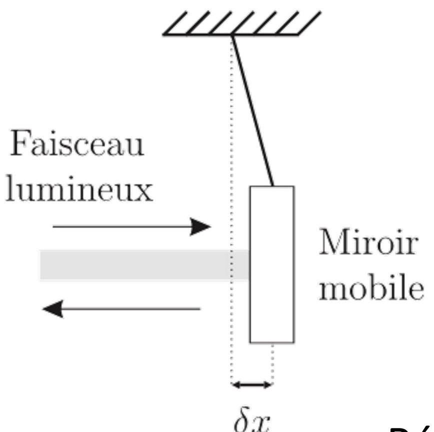






Force de pression de radiation



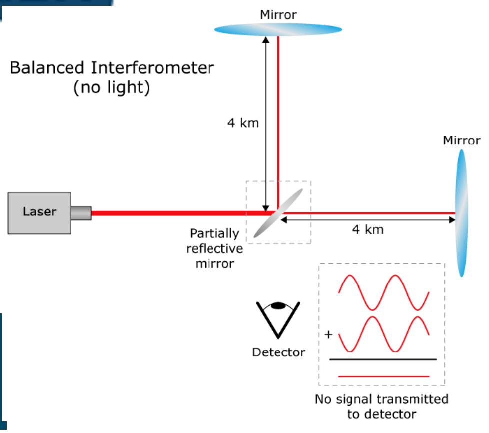


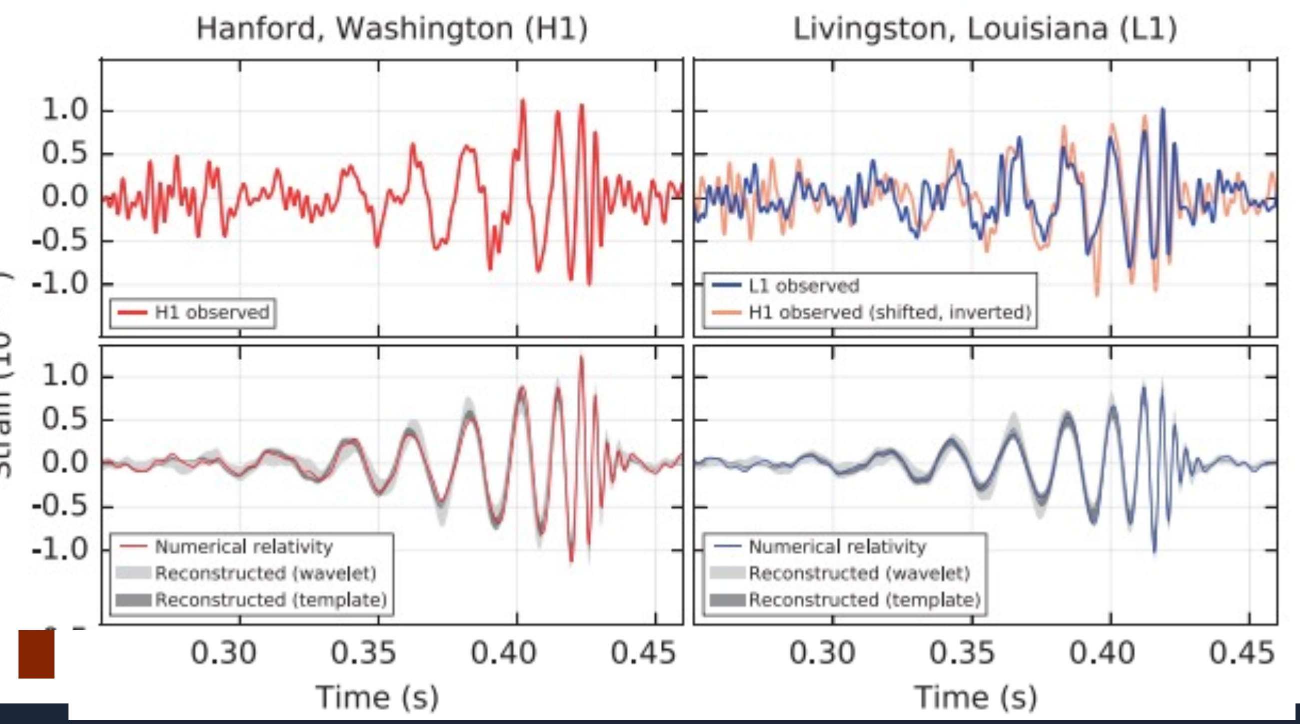
$$\delta\varphi = 4\pi\frac{\delta x}{\lambda}$$

Rétro-action du miroir sur la lumière

=> interférences sur le faisceau réfléchis dépendant du mouvement du miroir

Détection d’ondes gravitationnelles:





Détection d’ondes gravitationnelles: Utilisation d’états de la lumière comprimés

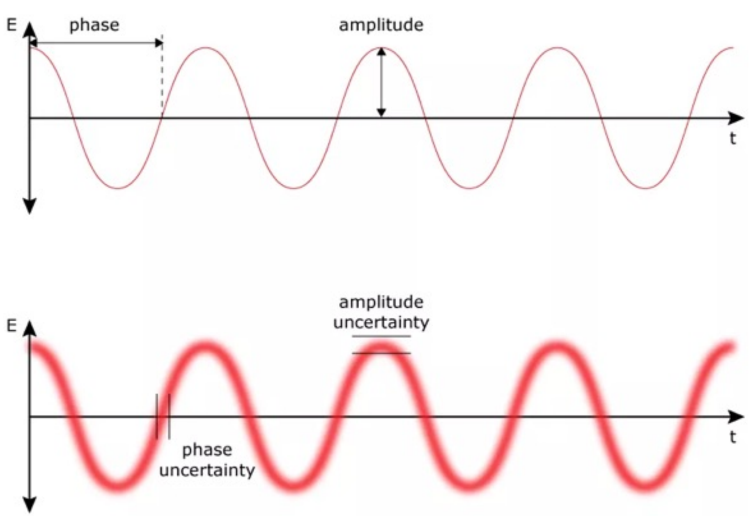
nature photonics

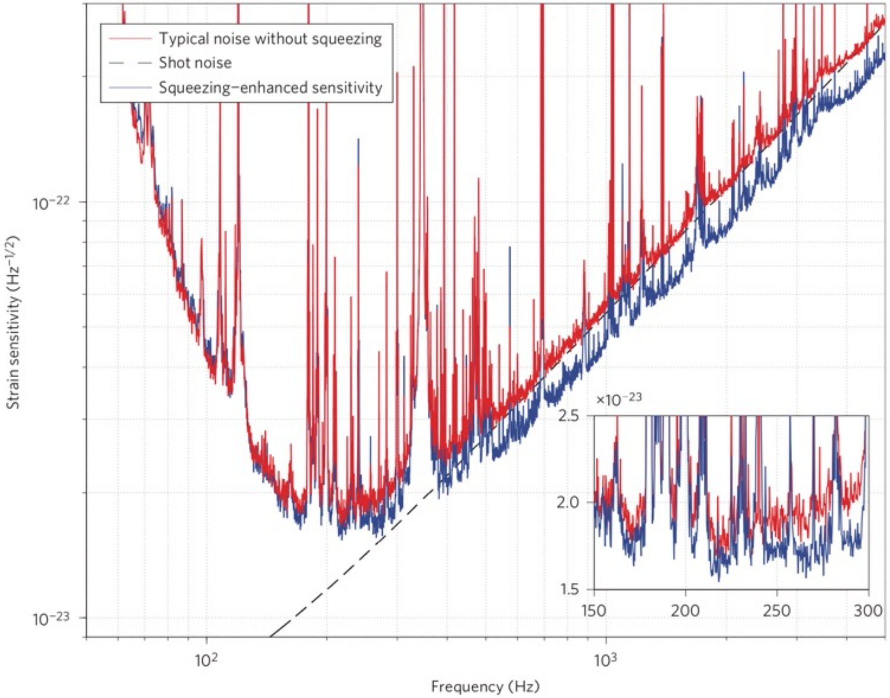
LETTERS

PUBLISHED ONLINE: 21 JULY 2013 | DOI: 10.1038/NPHOTON.2013.177

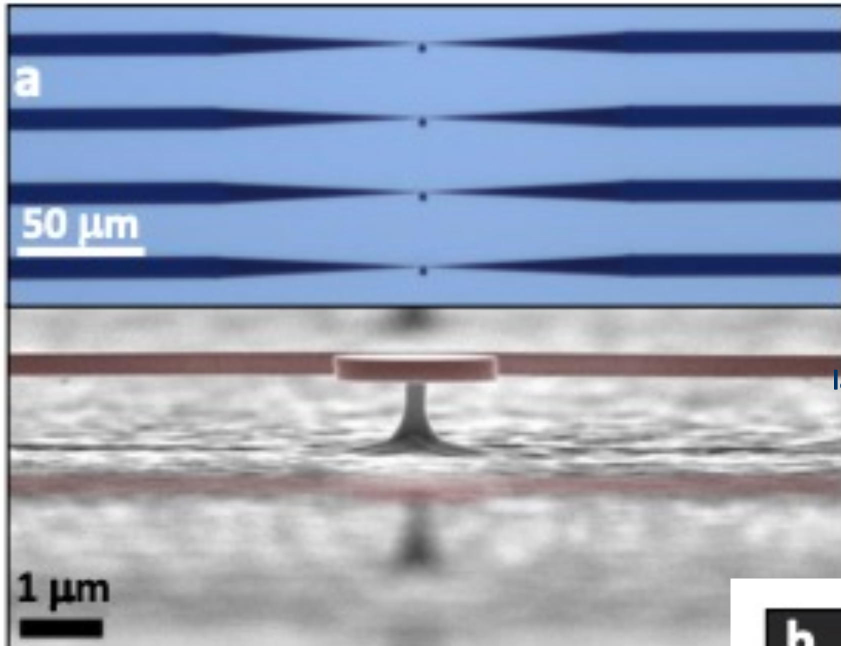
Enhanced sensitivity of the LIGO gravitational wave detector by using squeezed states of light

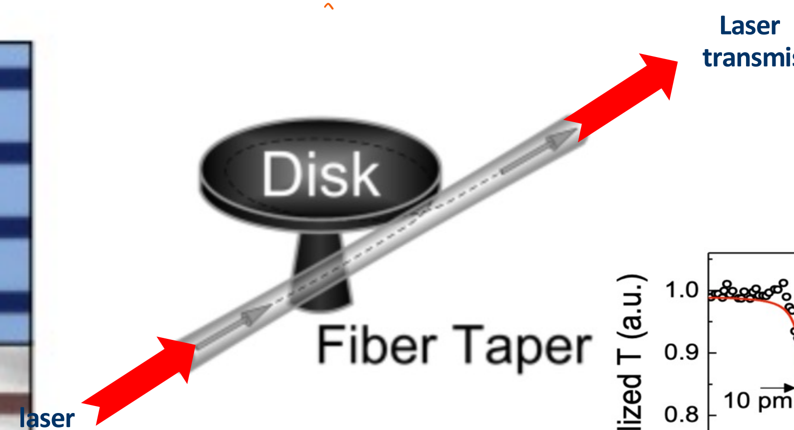
The LIGO Scientific Collaboration*

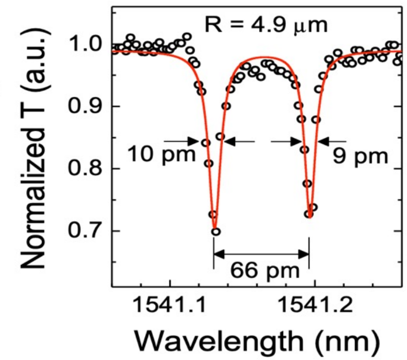


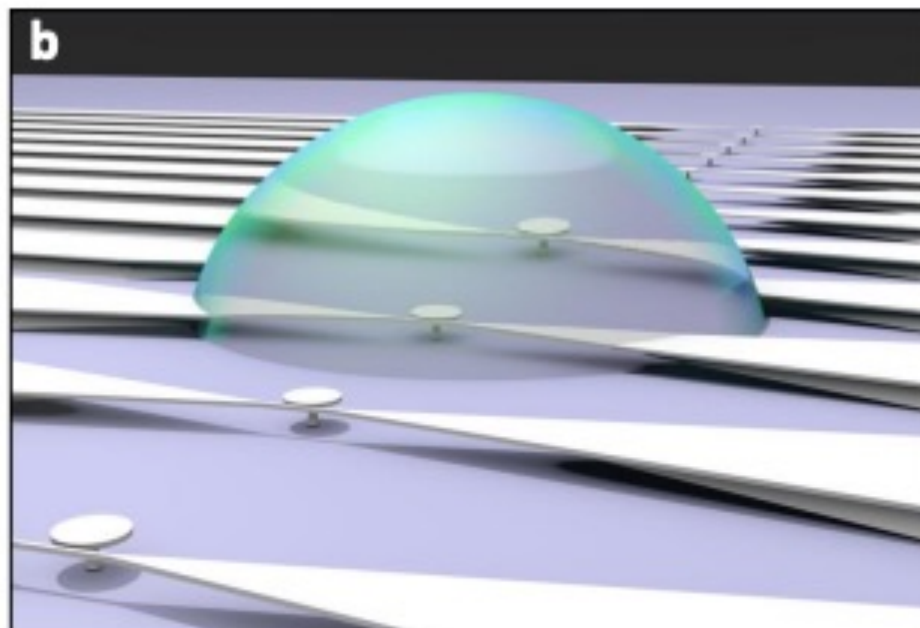


Lumière et capteurs quantiques









Nature Nanotechnology 10, 810 (2015)

Second quantum revolution?

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