De la physique quantique à l'informatique quantique

SORBONNE UNIVERSITÉ

Quantum Information Center
ALLIANCE SORBONNE UNIVERSITÉ

Nicolas Treps

Laboratoire Kastler Brossel
Physique quantique et applications

COLLÈGE DE FRANCE 1530

ENS

cnrs
dépasser les frontières

LES RÉVOLUTIONS QUANTIQUES

GPS

Théories des Quantas - Planck — transistor — Disque dur — laser — IRM

Début du 20ème siècle — 1947 — 1954 — 1960 — 1973

Albert Einstein (1879-1955)

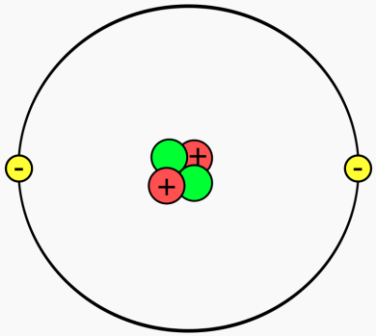
Werner Heisenberg (1901-1976)

Erwin Schrödinger (1887-1961)

F. Bloch

E.M. Purcell

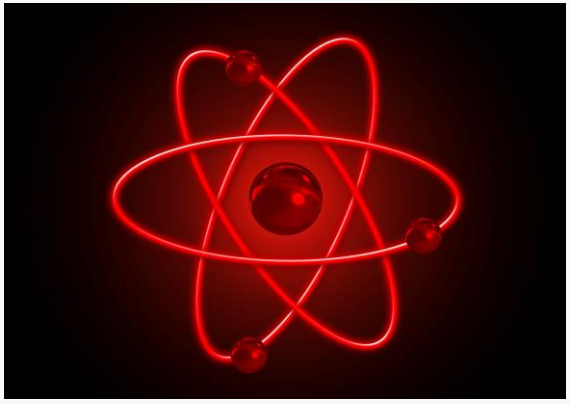
La première révolution quantique



La stabilité de la matière, la taille des objets
La physique nucléaire
etc…

Pourquoi la physique quantique ?

Prenons un atome :



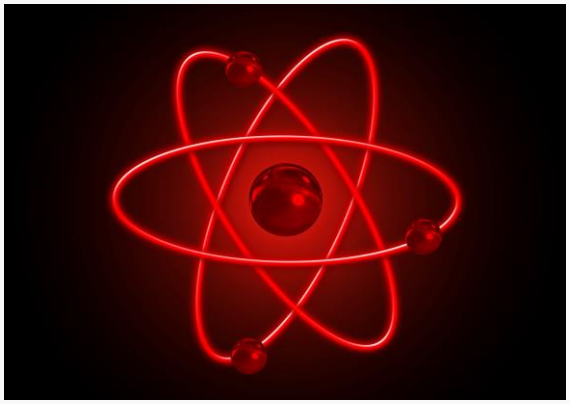
Taille de l'atome : ~1Å = 10^{-10}m

Mesure du rayon du proton :
0,8418 femtomètre en utilisant des muons (à +/- 0,0007), au lieu de 0,877 femtomètre pour les mesures utilisant des électrons.
(@LKB 2010)

Taille du proton: ~ 10^{-15}m

La matière classique, pourquoi ça ne devrait pas se tenir…

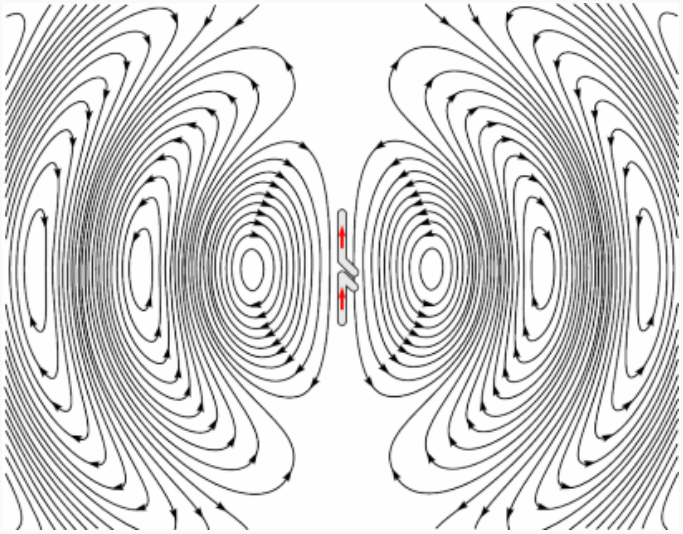
Un électron qui oscille autour du proton = une antenne



Taille de l'atome : ~1Å = 10^{-10}m

Une antenne : ça rayonne de l'énergie
-> l'atome n'est pas stable

Un atome, c'est pas « crochu »
Un atome, c'est du vide

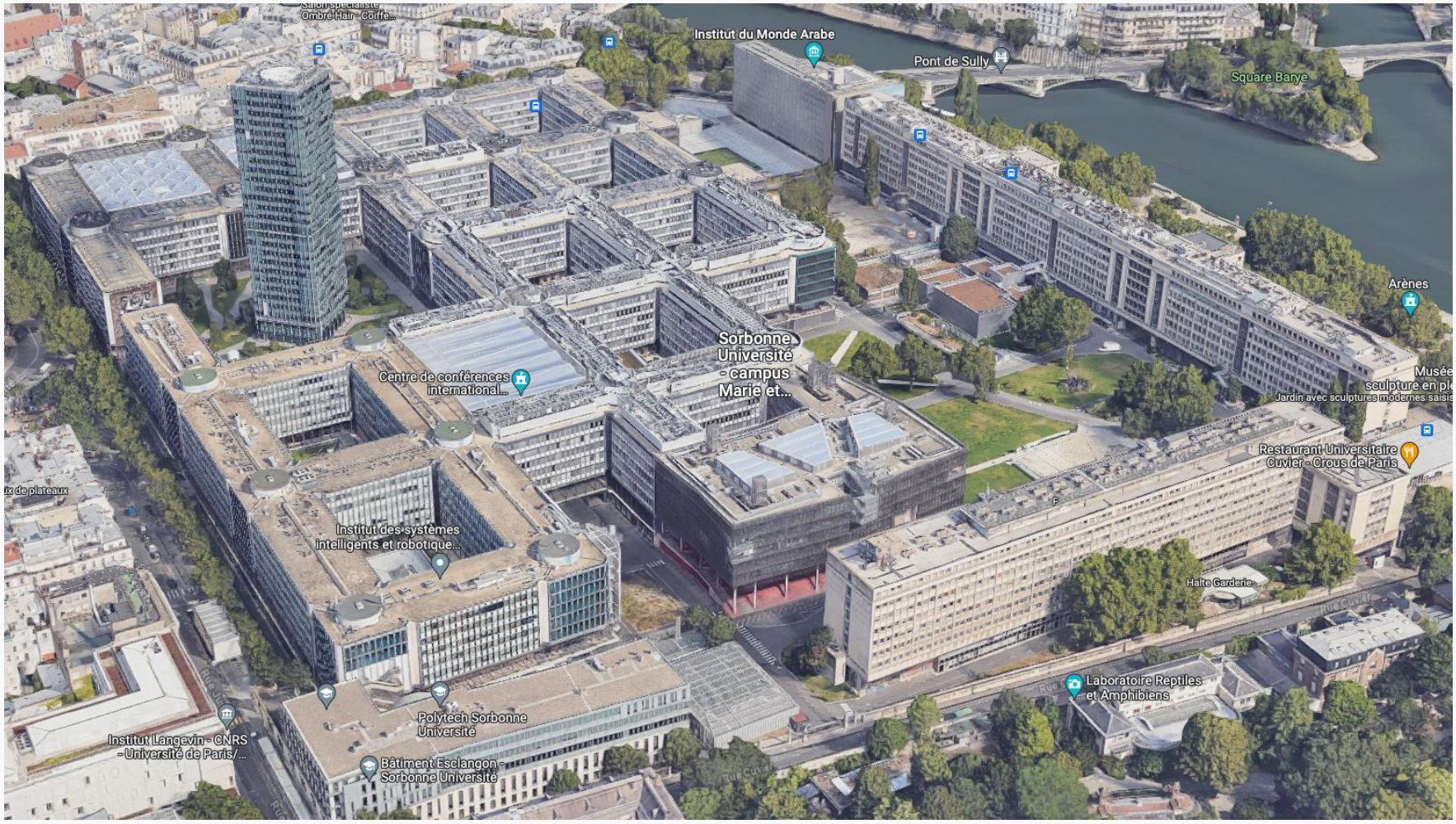


Taille du proton: ~ 10^{-15}m

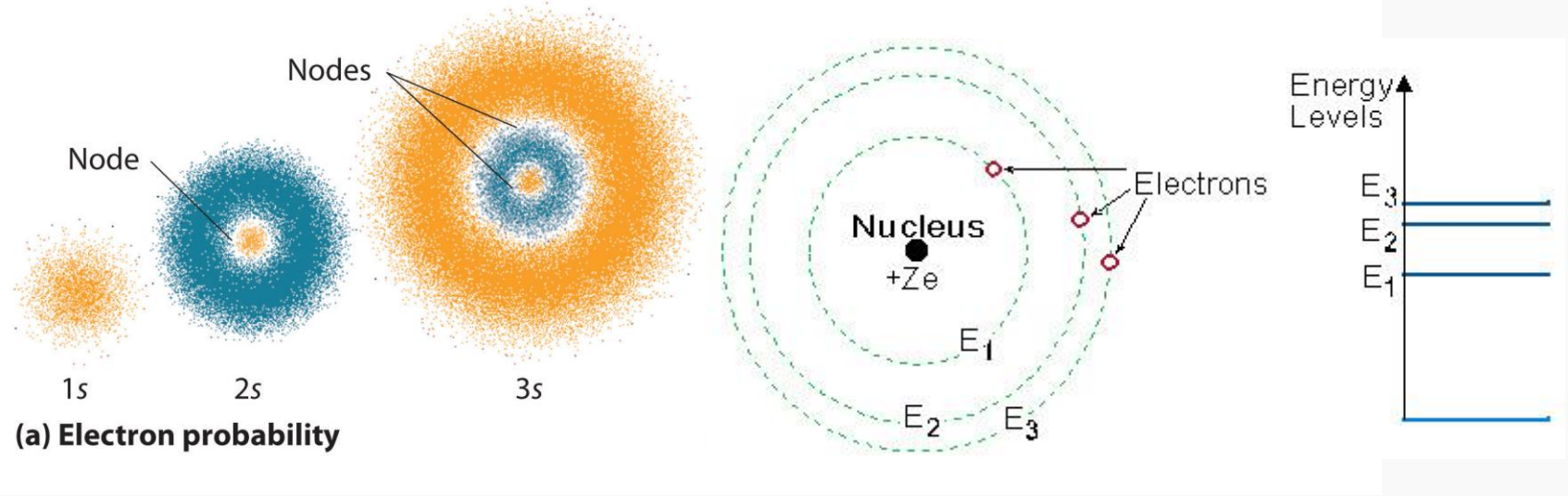
La matière c’est du vide !

Si l’atome avait la taille de Jussieu

-> le noyau aurait celle d’un grain de poivre !



C’est quoi l’atome, le vrai ?



- Probabilité de présence
- Non-localité
- Principe de superposition
- Complémentarité

(donne la taille caractéristique de la matière)

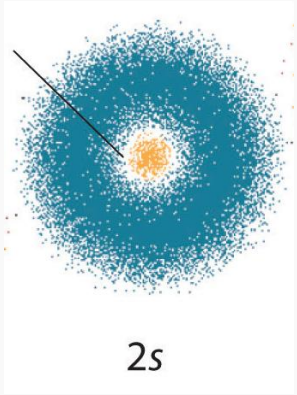
$$\hbar$$

https://chem.libretexts.org/Bookshelves/Organic_Chemistry/ CC BY-NC-SA 4.0

LA SUPERPOSITION QUANTIQUE

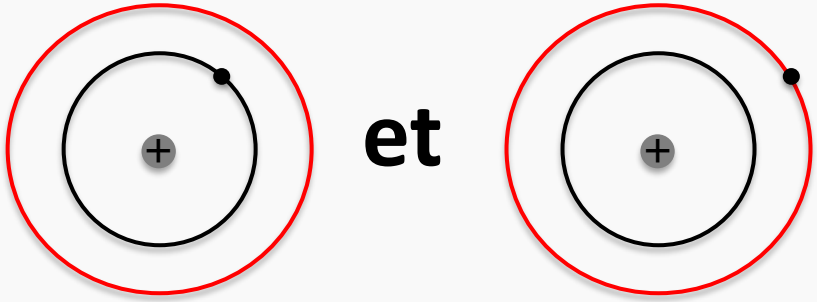
Un atome peut être dans 2 états à la fois:

et



LA SUPERPOSITION QUANTIQUE

Un atome peut être dans 2 états à la fois:



Un chat peut être mort et vivant…

LES RÉVOLUTIONS QUANTIQUES

Richard Feynman

Serge Haroche

Alain Aspect

et aussi Charles Bennett, Gilles Brassard, Artur Ekert, Peter Shor…

Théories des Quantas - Planck

Début du 20ème siècle

fin 20ème/ début 21ème

Mise en évidence des principes fondamentaux sur des particules individuelles
Premiers algorithmes quantiques

La deuxième révolution quantique

Manipulation de particules individuelles, lois de la physique quantiques appliquées à des systèmes multi-particules, interactions, **applications**

LES RÉVOLUTIONS QUANTIQUES

The Nobel Prize in Physics 2012 was awarded jointly to Serge Haroche and David J. Wineland "for ground-breaking experimental methods that enable measuring and manipulation of individual quantum systems"

Aspect

Vol 446|15 March 2007|doi:10.1038/nature05589 nature

LETTERS

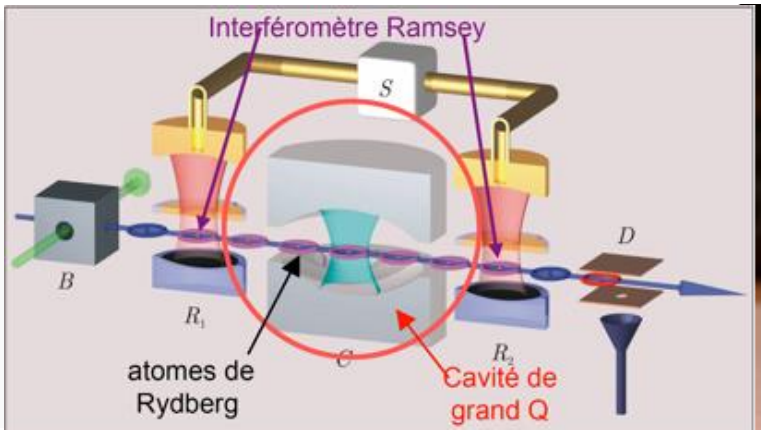
ter Shor…

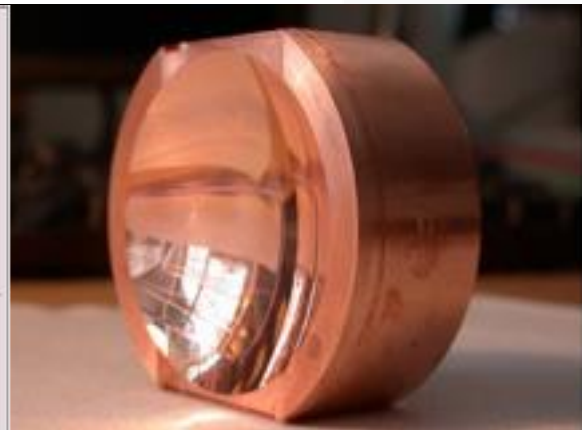
ébut 21ème

ntaux sur

Quantum jumps of light recording the birth and death of a photon in a cavity

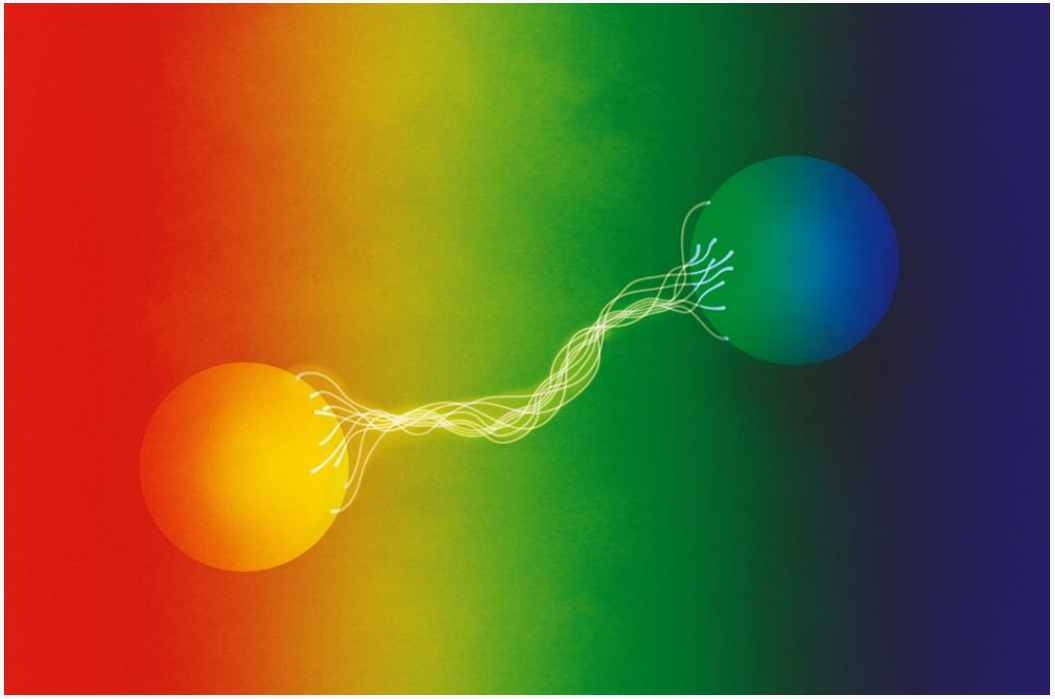
Sébastien Gleyzes[1], Stefan Kuhr[1]†, Christine Guerlin[1], Julien Bernu[1], Samuel Deléglise[1], Ulrich Busk Hoff[1], Michel Brune[1], Jean-Michel Raimond[1] & Serge Haroche[1,2]





L'INTRICATION QUANTIQUE – LA NON LOCALITÉ

$$\frac{|01\rangle + |10\rangle}{\sqrt{2}}$$



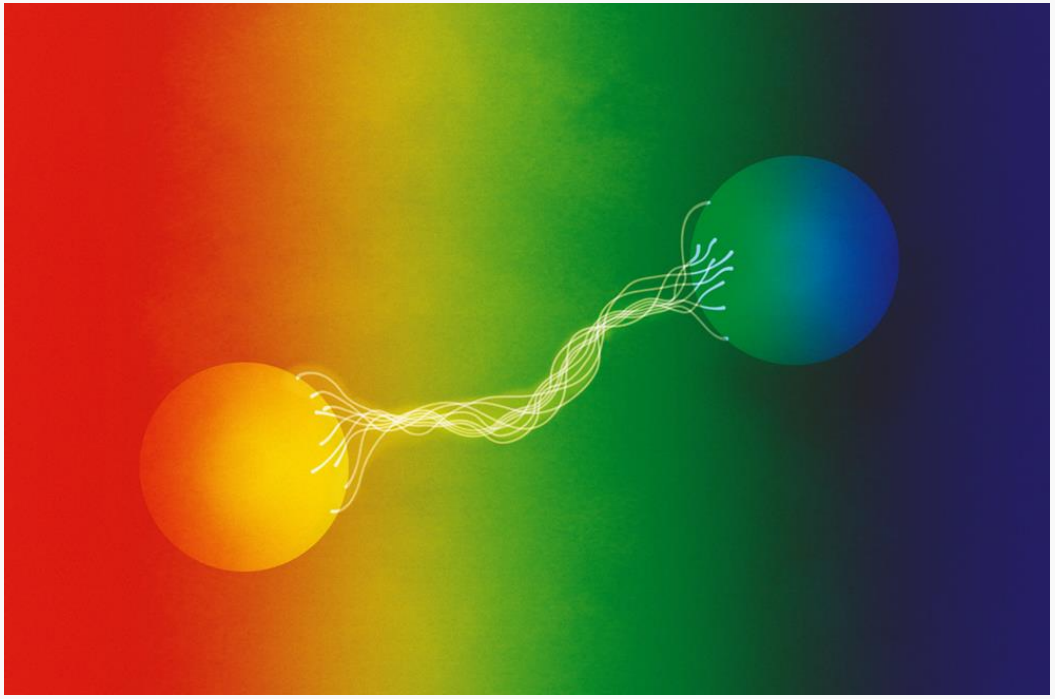
Prix Nobel de Physique 2022 :
Alain Aspect, John Clauser and Anton Zeilinger have each conducted groundbreaking experiments using entangled quantum states, where two particles behave like a single unit even when they are separated. Their results have cleared the way for new technology based upon quantum information.

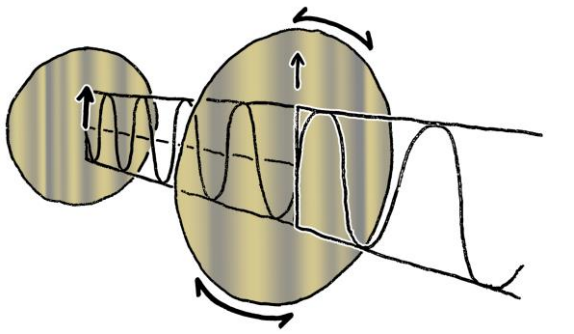
Preuve que la réalité physique est non-locale, et que l'aléatoire est inhérent à la physique quantique

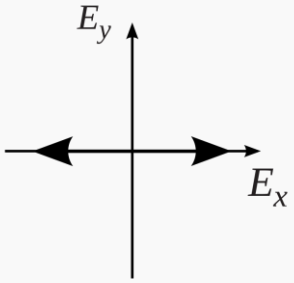
Qu’est-ce que l’intrication ?

Avec des photons

$$\frac{|01\rangle + |10\rangle}{\sqrt{2}}$$







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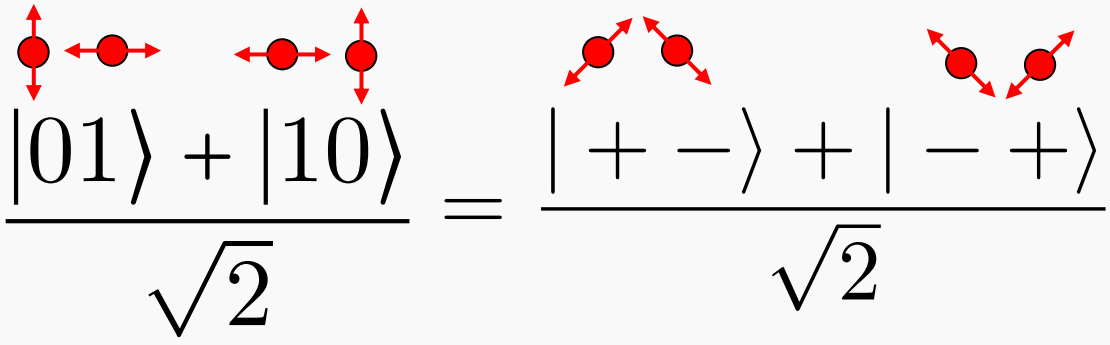
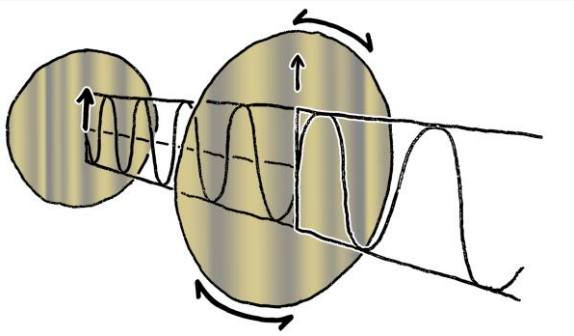
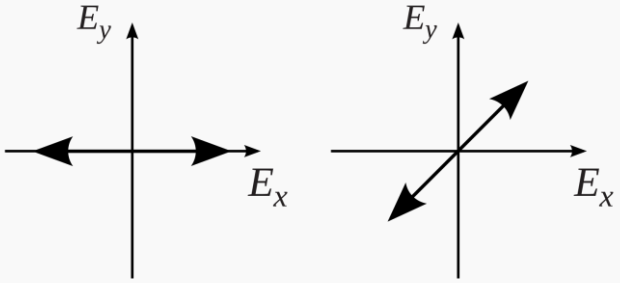


$$\frac{|01\rangle + |10\rangle}{\sqrt{2}} = \frac{|+-\rangle + |-+\rangle}{\sqrt{2}}$$

$$|+\rangle = \frac{|0\rangle + |1\rangle}{\sqrt{2}} \qquad |-\rangle = \frac{|0\rangle - |1\rangle}{\sqrt{2}}$$





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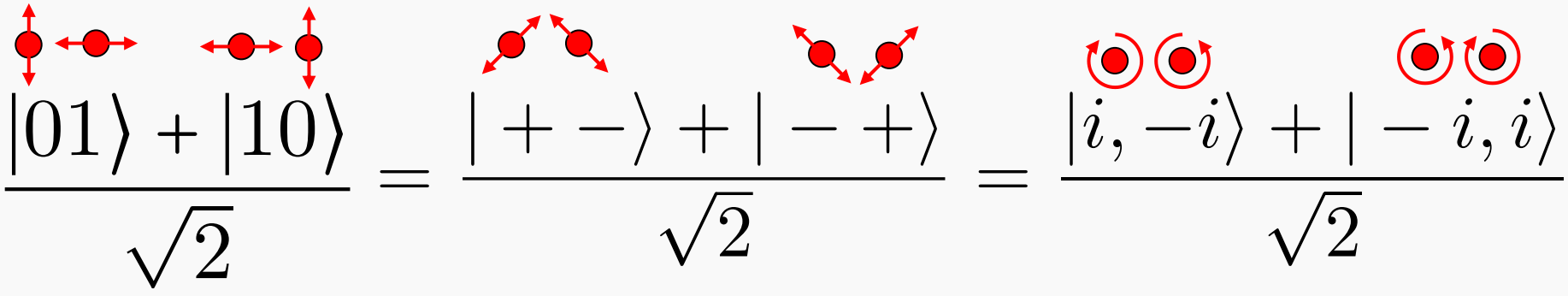
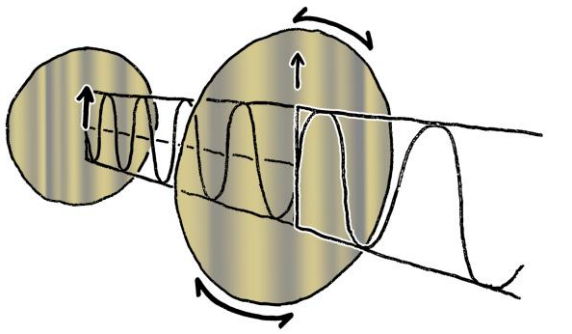
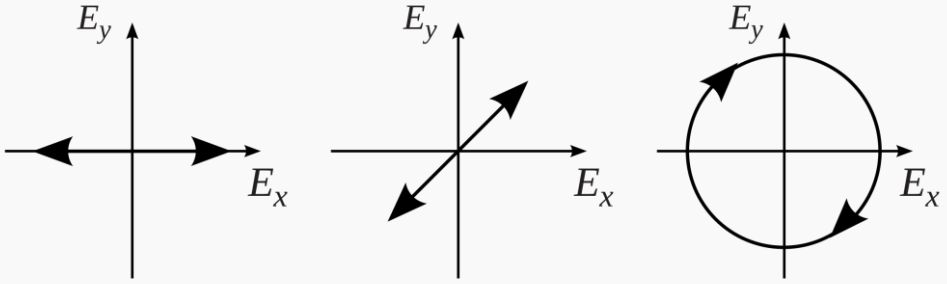


$$|+\rangle = \frac{|0\rangle + |1\rangle}{\sqrt{2}} \qquad |-\rangle = \frac{|0\rangle - |1\rangle}{\sqrt{2}}$$



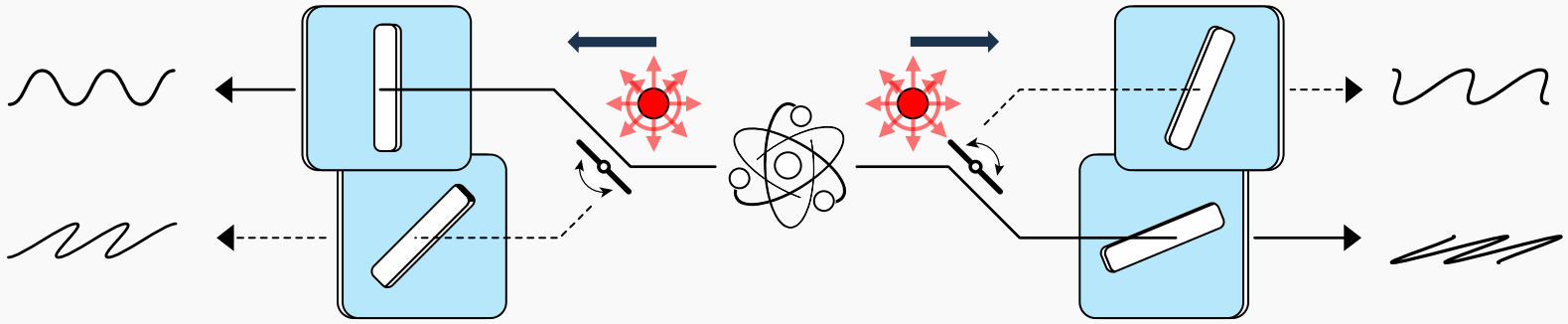


Qu’est-ce que l’intrication ?

Avec des photons

$$\frac{|01\rangle + |10\rangle}{\sqrt{2}} = \frac{|+-\rangle + |-+\rangle}{\sqrt{2}} = \frac{|i,-i\rangle + |-i,i\rangle}{\sqrt{2}}$$

$$|+\rangle = \frac{|0\rangle + |1\rangle}{\sqrt{2}} \qquad |-\rangle = \frac{|0\rangle - |1\rangle}{\sqrt{2}}$$



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Qu'est-ce que l'intrication ?

VOLUME 47, NUMBER 7 PHYSICAL REVIEW LETTERS 17 AUGUST 1981

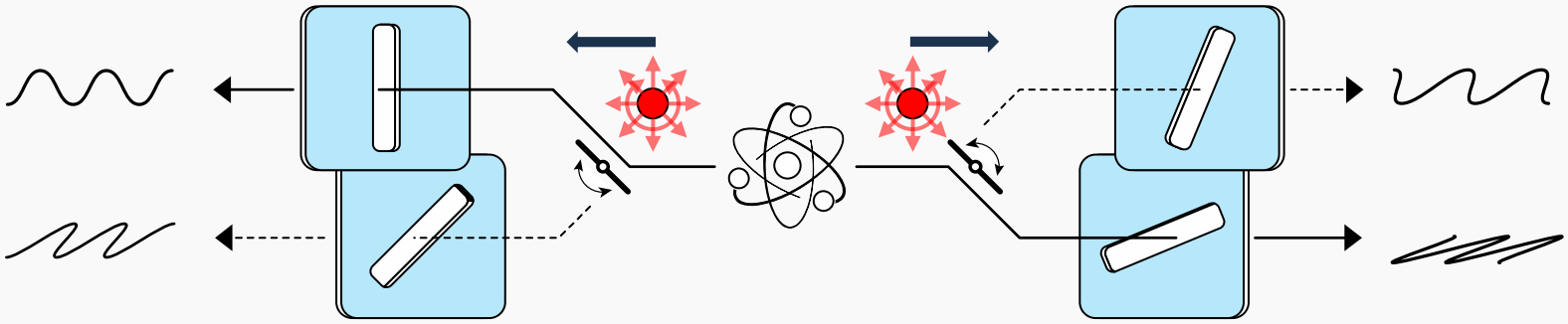
Experimental Tests of Realistic Local Theories via Bell's Theorem

Alain Aspect, Philippe Grangier, and Gérard Roger
Institut d'Optique Théorique et Appliquée, Université Paris-Sud, F-91406 Orsay, France

$$S_{\text{exp}} = 0.126 \pm 0.014, \qquad (5)$$

violating inequality (1) by 9 standard deviations

Display statistics that cannot be mimicked by a classical system



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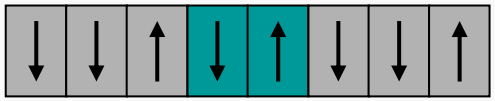
UN AVANTAGE POUR LE CALCUL

Information binaire classique



Aimantation

↓ = 0

↑ = 1

bit classique

N bit classiques : 1 nombre entre 0 et 2^N

Information binaire quantique

$|1\rangle$

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

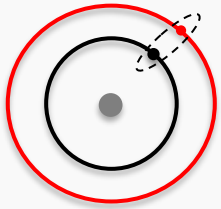
$|0\rangle$

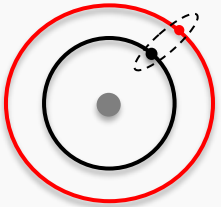
= bit quantique
qubit

Atome

photons, circuits supraconducteurs, ions, atomes, spins semiconducteurs, etc.

2 qubit :





$\alpha_1|00\rangle+\alpha_2|01\rangle+\alpha_3|10\rangle+\alpha_4|11\rangle$

N qubits -> 2^N nombres

LES ALGORITHMES QUANTIQUES

L'algorithme de Shor (Peter Shor, 1994)

Factoriser un entier *N* en nombres premiers

Un « ordinateur quantique » est capable de factoriser le produit de deux Nombres premiers en un temps polynomial ! **Grand retentissement**

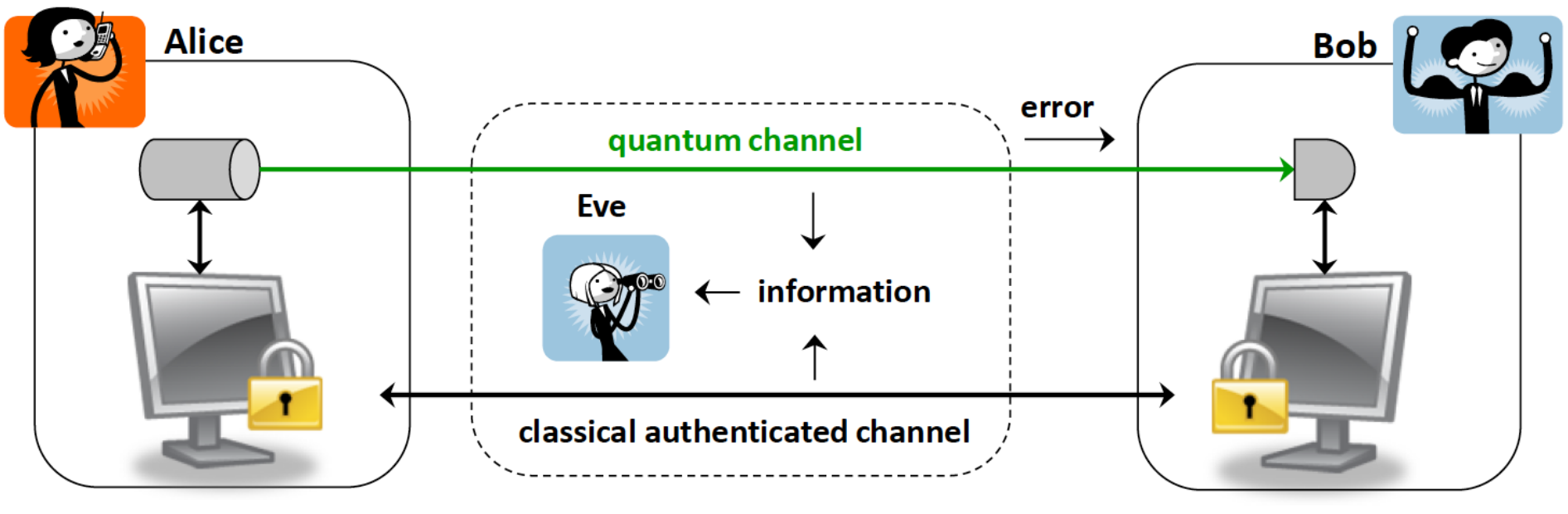
Ordinateur classique : **$Tcl[2^{1024}] / Tcl[2^{512}] = 6.2\ 10^6$**

Algorithme de Shor : **$Tshor[2^{1024}] / Tshor[2^{512}] = 8$**

CASSER les codes de cryptographie type RSA

La cryptographie quantique

La QKD permet l'échange de messages secrets avec une sécurité de l'information garantie par la théorie contre une écoute indiscrète toute-puissante



Les informations sur les clés sont codées dans des supports photoniques
L'analyse des erreurs dues aux mesures d'Eve conduit à une clé secrète

Merci à Eleni Diamanti pour les diapos !!

LES ALGORITHMES QUANTIQUES

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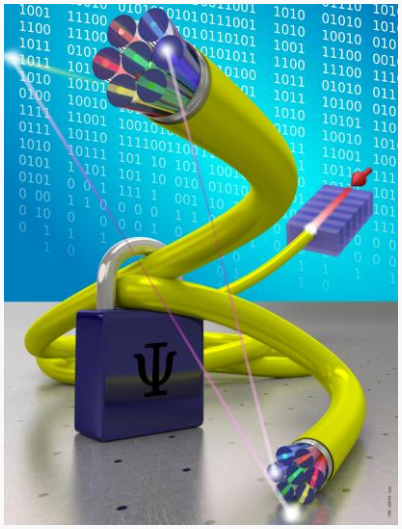
MAIS : le problème des erreurs

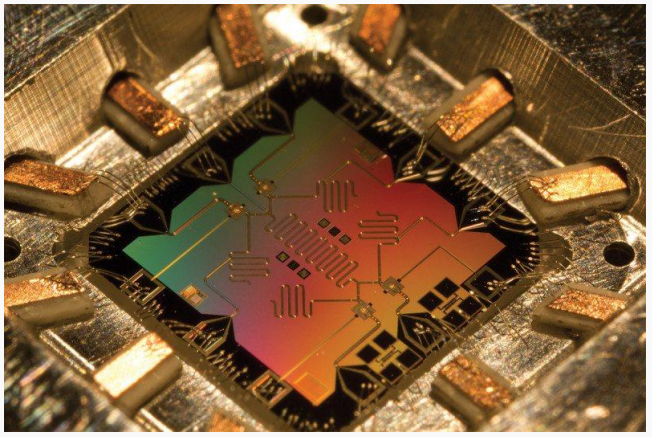
-> Milliers de qubits par qubit logic pour erreurs expérimentales réalistes...

LES TECHNOLOGIES QUANTIQUES

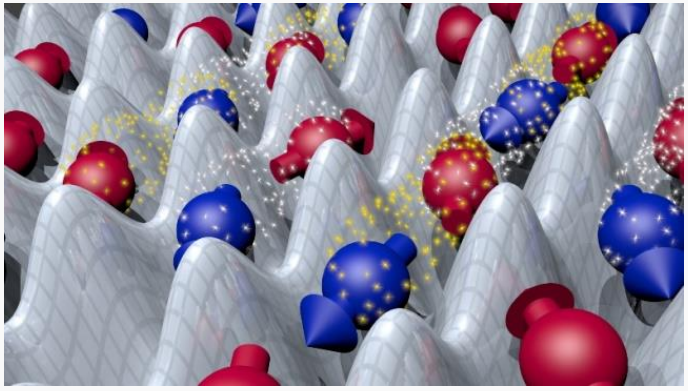
Communication sécurisées



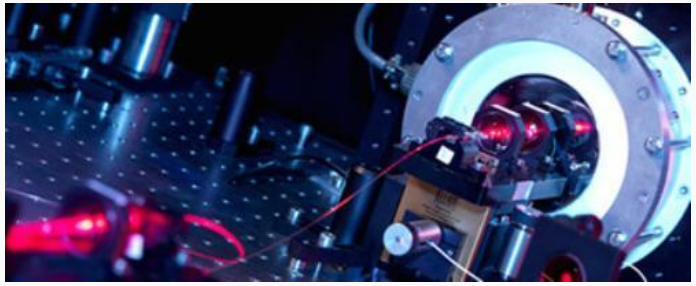
Puissance de calcul décuplée



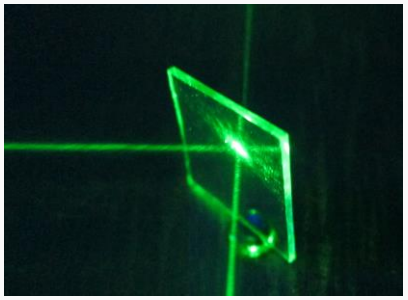
Simulation de systèmes complexes



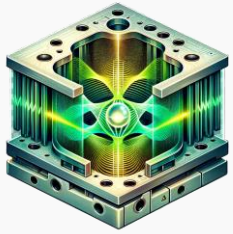
Mesure et capteurs avec des sensibilités sans précédent

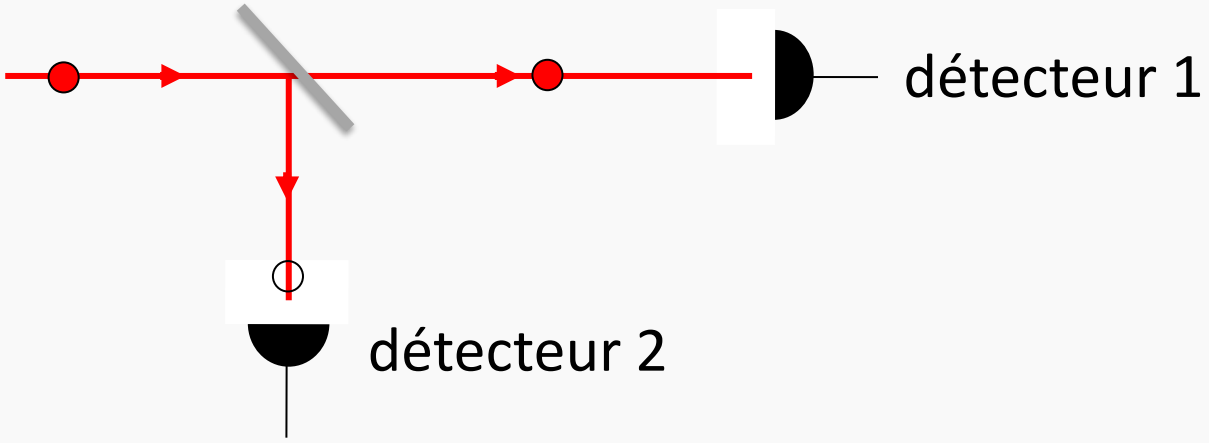


L’information quantique avec des photons



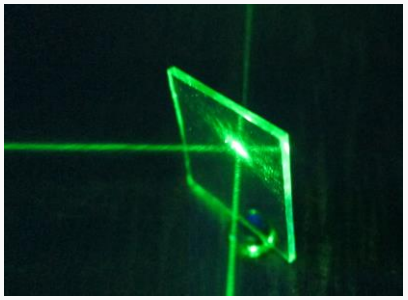
1 photon





JAMAIS 2 « clics » à la fois $\Rightarrow$ réfléchi **OU** transmis

L’information quantique avec des photons



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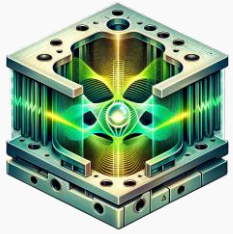

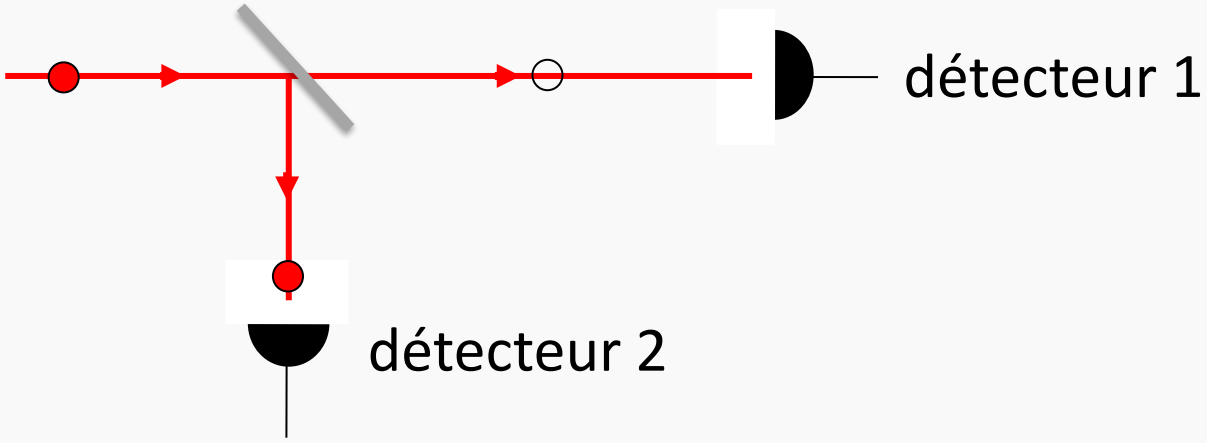

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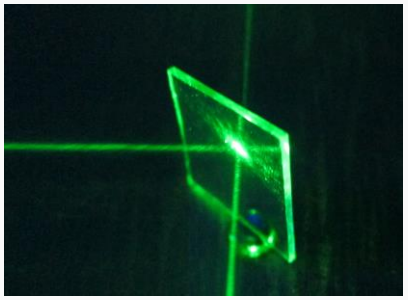
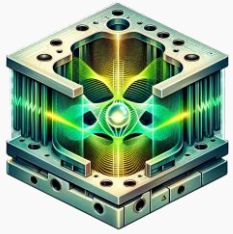
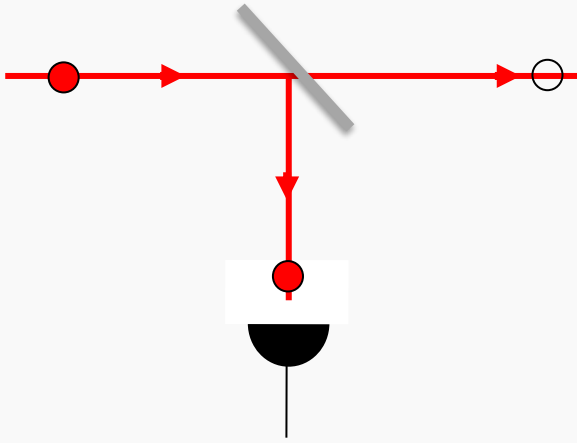
L’information quantique avec des photons



1 photon



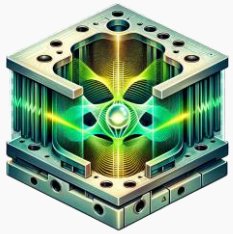


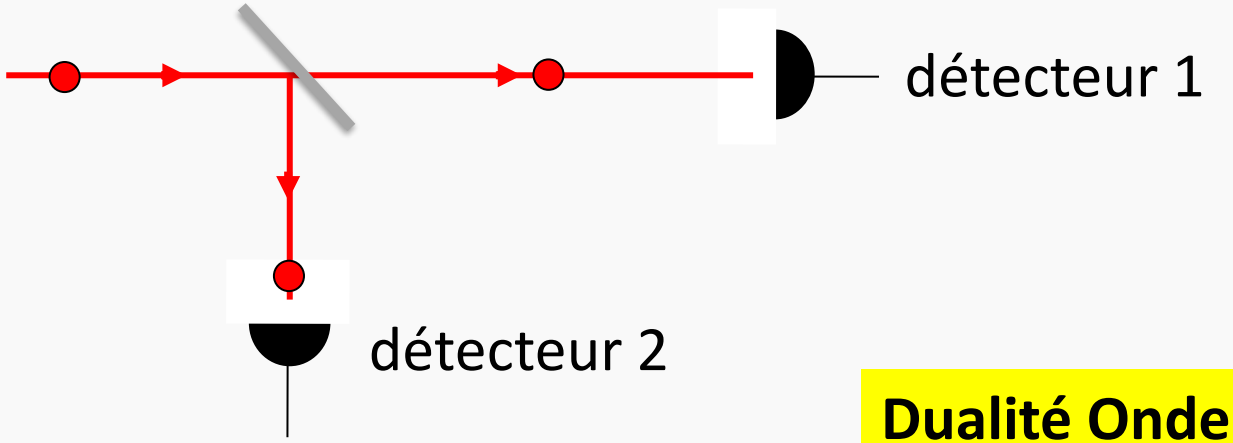
Une application : générateur de nombre aléatoires

-> Loterie (…), centres de calcul

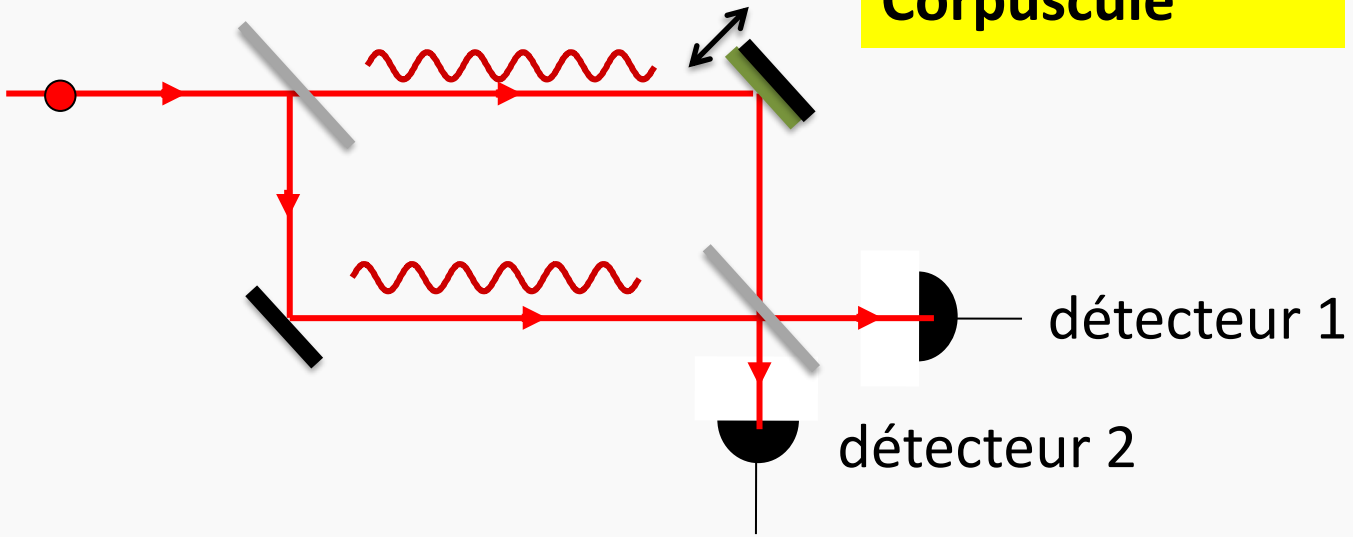
Faire du calcul quantique avec ça ?

1 photon





Dualité Onde - Corpuscule

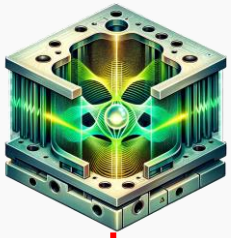


->probabilité proportionnelle à la figure d'interférences classique

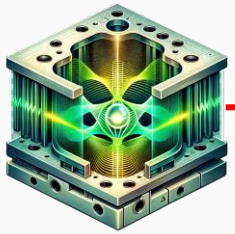
« Facile » à calculer avec un ordinateur classique

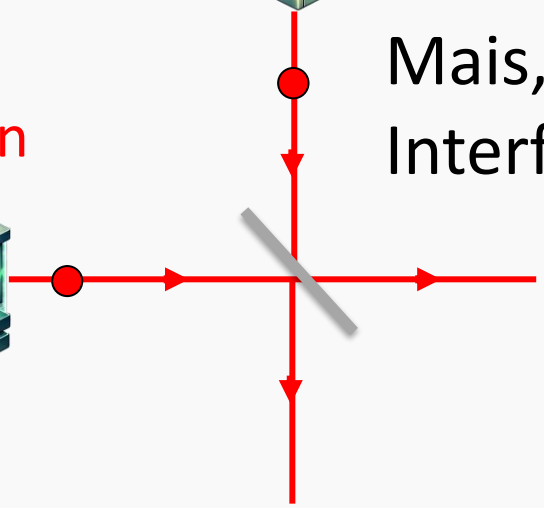
Et si on utilise 2 photons

1 photon



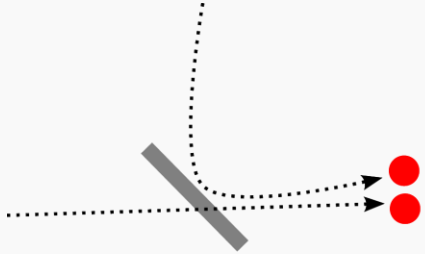
1 photon

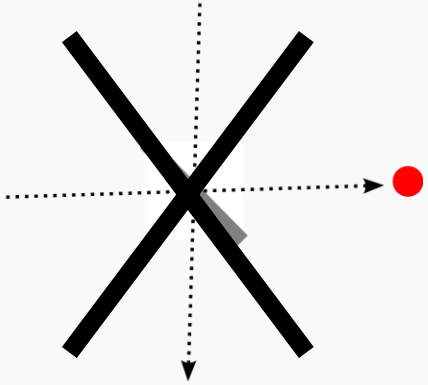


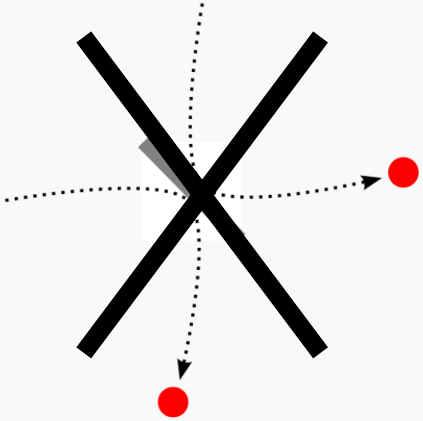


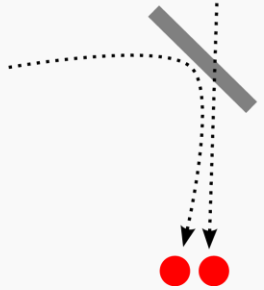
Mais,
Interférences quantiques

4 possibilités :







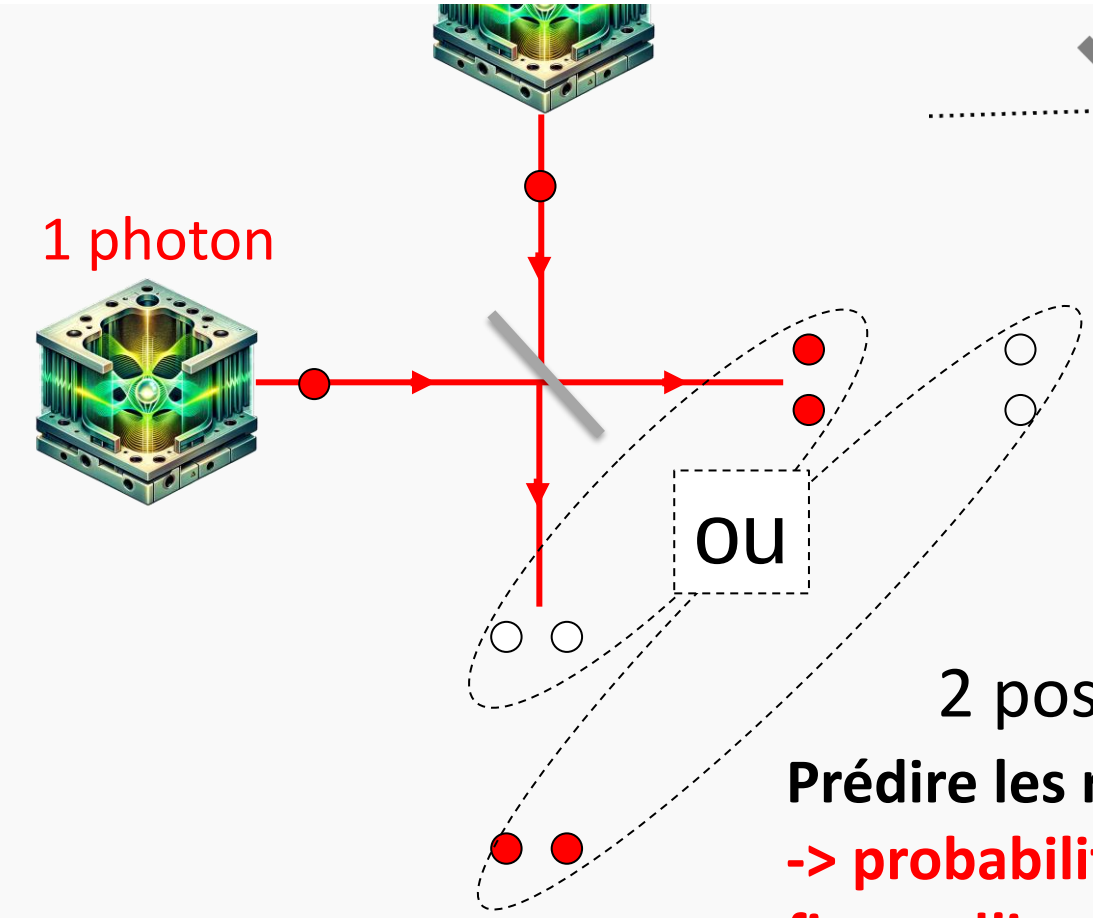


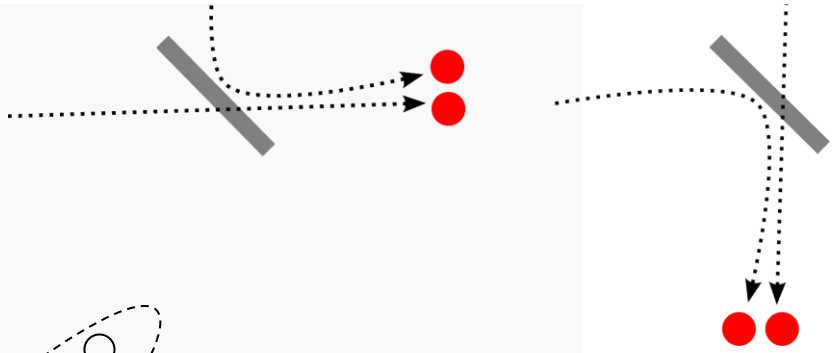
Et si on utilise 2 photons

VOLUME 59, NUMBER 18 PHYSICAL REVIEW LETTERS 2 NOVEMBER 1987

Measurement of Subpicosecond Time Intervals between Two Photons by Interference

C. K. Hong, Z. Y. Ou, and L. Mandel
Department of Physics and Astronomy, University of Rochester, Rochester, New York 14627
(Received 10 July 1987)





2 possibilités :

Prédire les résultats de mesure :

-> probabilité N'EST PLUS déductible de la figure d'interférences classique

L'avantage quantique

Idée :

Utiliser ces probabilités « non-classiques » pour effectuer une opération inaccessible à un ordinateur usuel

Les statistiques des mesures sont liées au permanent d'une matrice, problème exponentiellement complexe pour un ordinateur classique

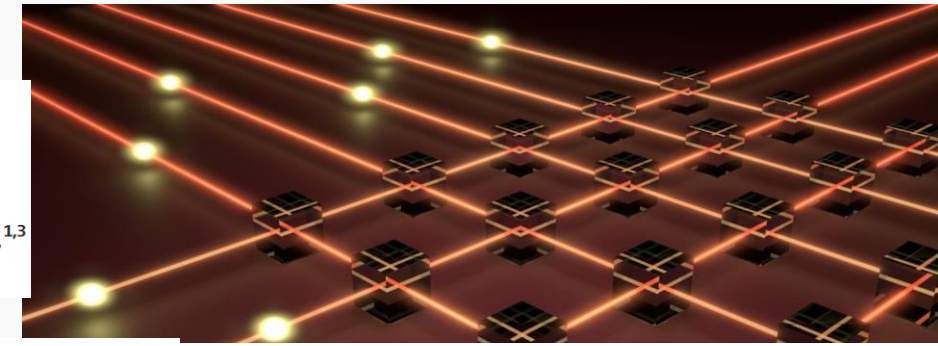
https://youtu.be/jiodj5b8Z1E

L'avantage quantique

15 FEBRUARY 2013 VOL 339 SCIENCE

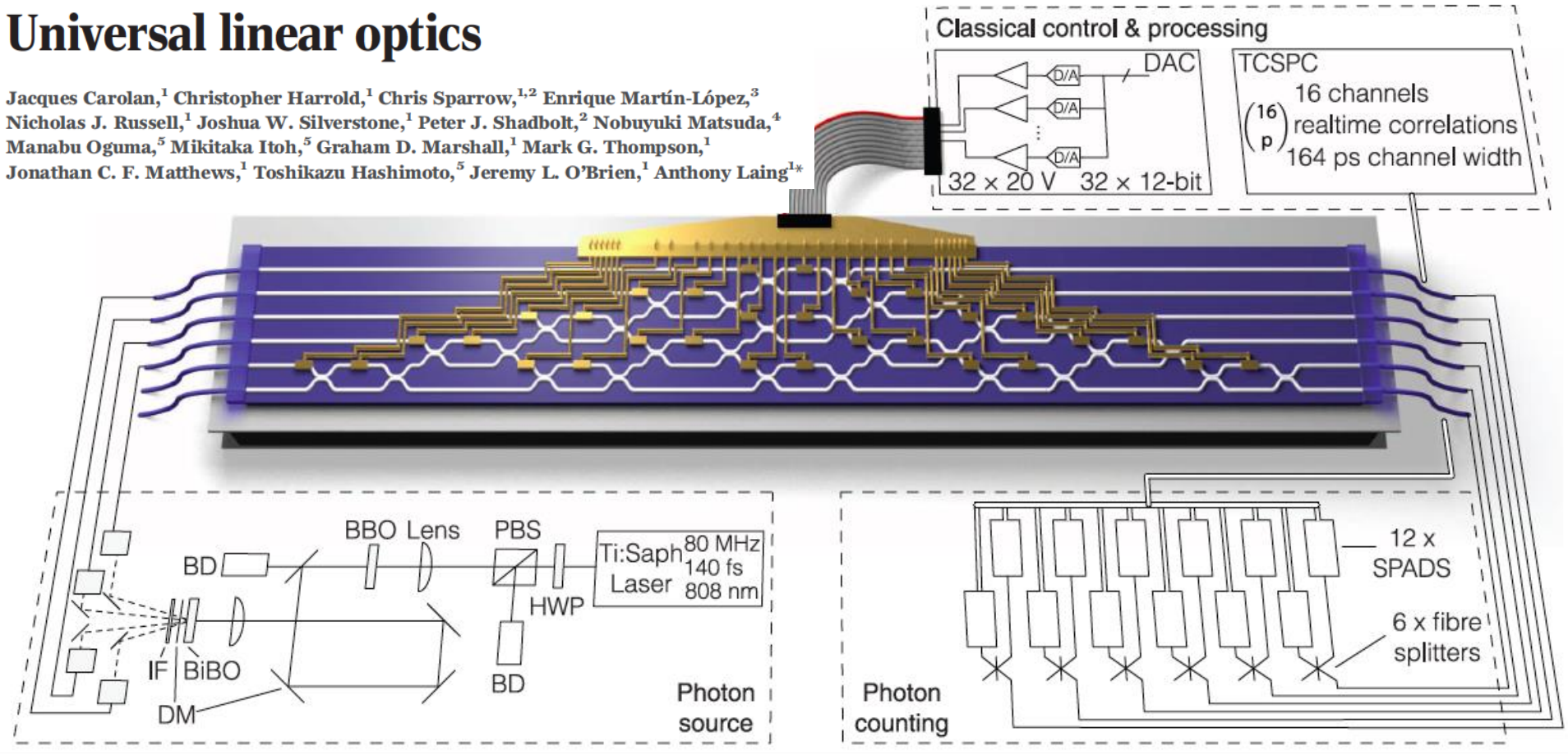
Boson Sampling on a Photonic Chip

Justin B. Spring,[1]* Benjamin J. Metcalf,[1] Peter C. Humphreys,[1] W. Steven Kolthammer,[1] Xian-Min Jin,[1,2] Marco Barbieri,[1] Animesh Datta,[1] Nicholas Thomas-Peter,[1] Nathan K. Langford,[1,3] Dmytro Kundys,[4] James C. Gates,[4] Brian J. Smith,[1] Peter G. R. Smith,[4] Ian A. Walmsley[1]*



Universal linear optics

Jacques Carolan,[1] Christopher Harrold,[1] Chris Sparrow,[1,2] Enrique Martín-López,[3] Nicholas J. Russell,[1] Joshua W. Silverstone,[1] Peter J. Shadbolt,[2] Nobuyuki Matsuda,[4] Manabu Oguma,[5] Mikitaka Itoh,[5] Graham D. Marshall,[1] Mark G. Thompson,[1] Jonathan C. F. Matthews,[1] Toshikazu Hashimoto,[5] Jeremy L. O'Brien,[1] Anthony Laing[1]*



L’avantage quantique

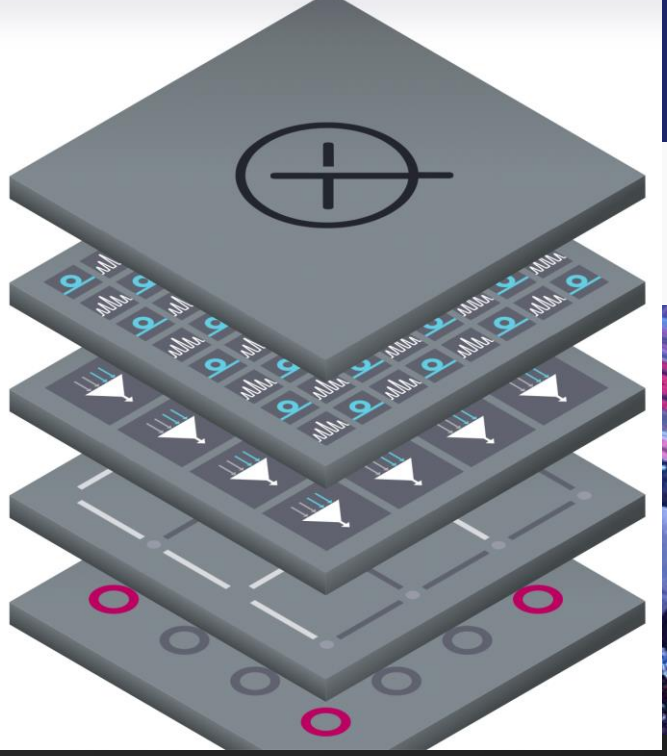
QUANTUM COMPUTING

Quantum computational advantage using photons

Han-Sen Zhong[1,2]*, Hui Wang[1,2]*, Yu-Hao Deng[1,2]*, Ming-Cheng Chen[1,2]*, Li-Chao Peng[1,2], Yi-Han Luo[1,2], Jian Qin[1,2], Dian Wu[1,2], Xing Ding[1,2], Yi Hu[1,2], Peng Hu[3], Xiao-Yan Yang[3], Wei-Jun Zhang[3], Hao Li[3], Yuxuan Li[4], Xiao Jiang[1,2], Lin Gan[4], Guangwen Yang[4], Lixing You[3], Zhen Wang[3], Li Li[1,2], Nai-Le Liu[1,2], Chao-Yang Lu[1,2]†, Jian-Wei Pan[1,2]†

XANADU

Quantum computational advantage with a programmable photonic processor



QUANDELA

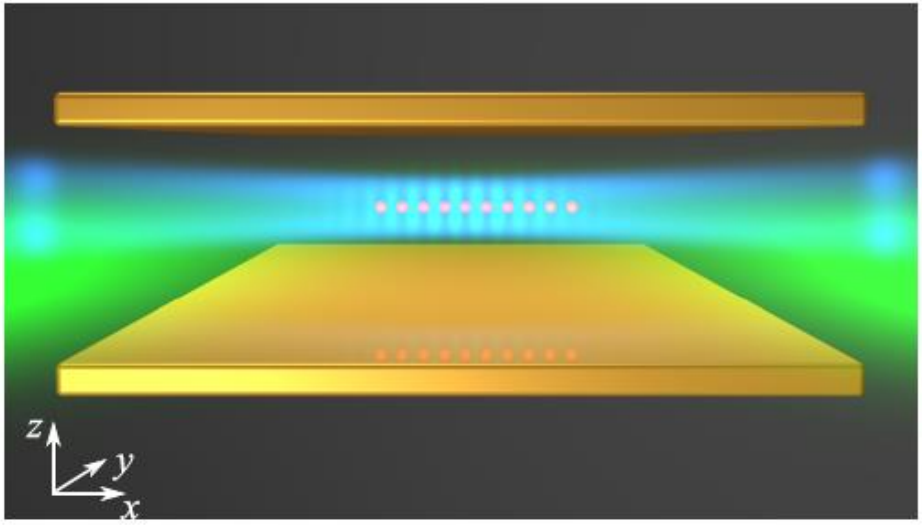
DISCOVER OUR QUANTUM COMPUTING PLATFORM

Discover MOSAIQ, our modular, reconfigurable, interconnected and scalable quantum computing platform.It is photonically universal, and supports prototyping, testing and development of algorithms that will change the way your industry computes.

LEARN MORE >

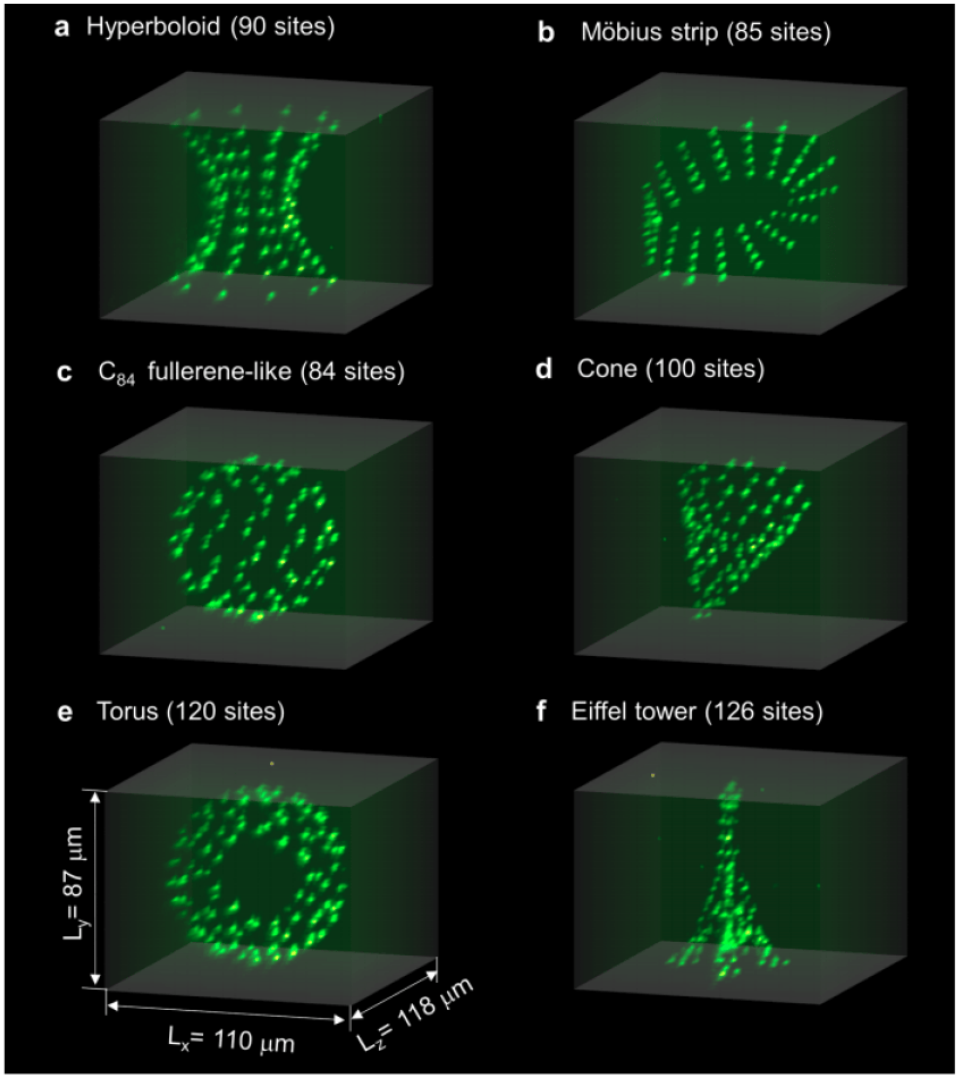
Quelques plateformes technologiques

Ions and Atoms



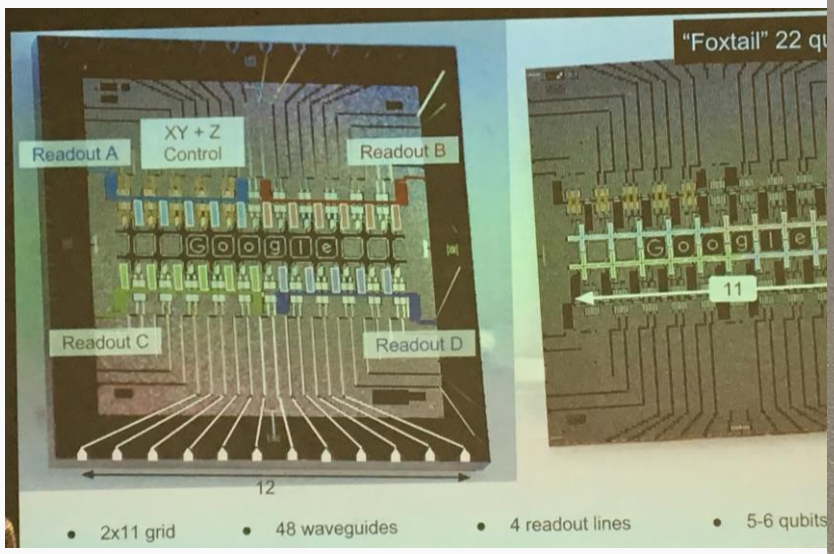
Groupe de Michel Brune, LKB

Groupe d'Antoine Browaeys, LCFIO, Pasqal

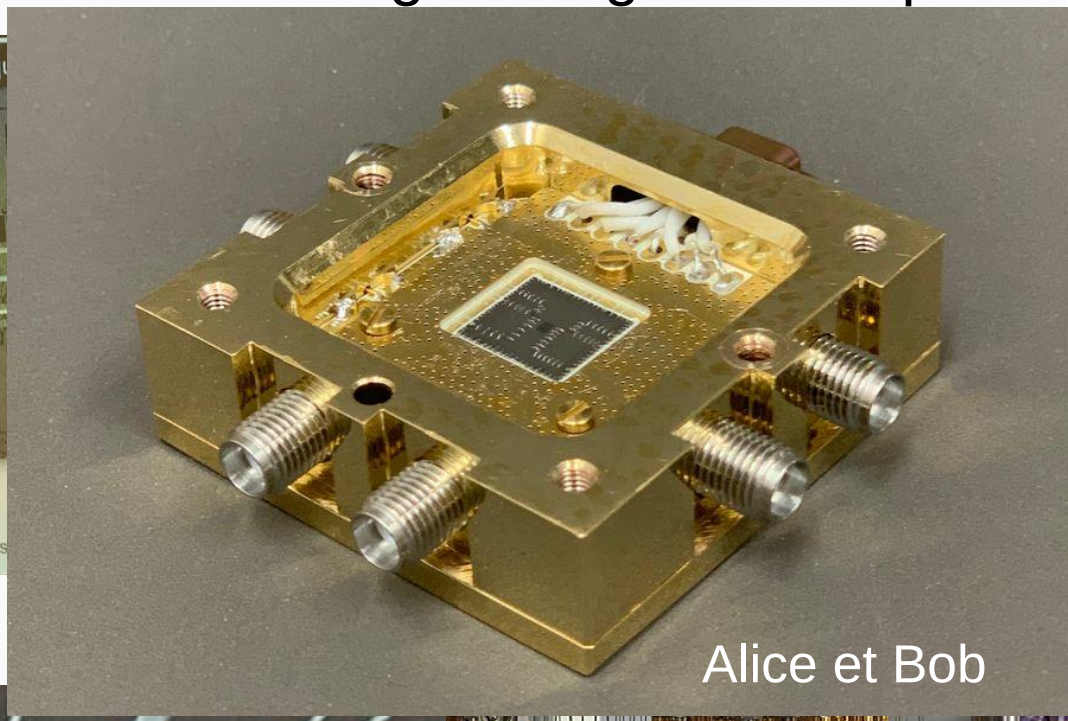


Quelques plateformes technologiques

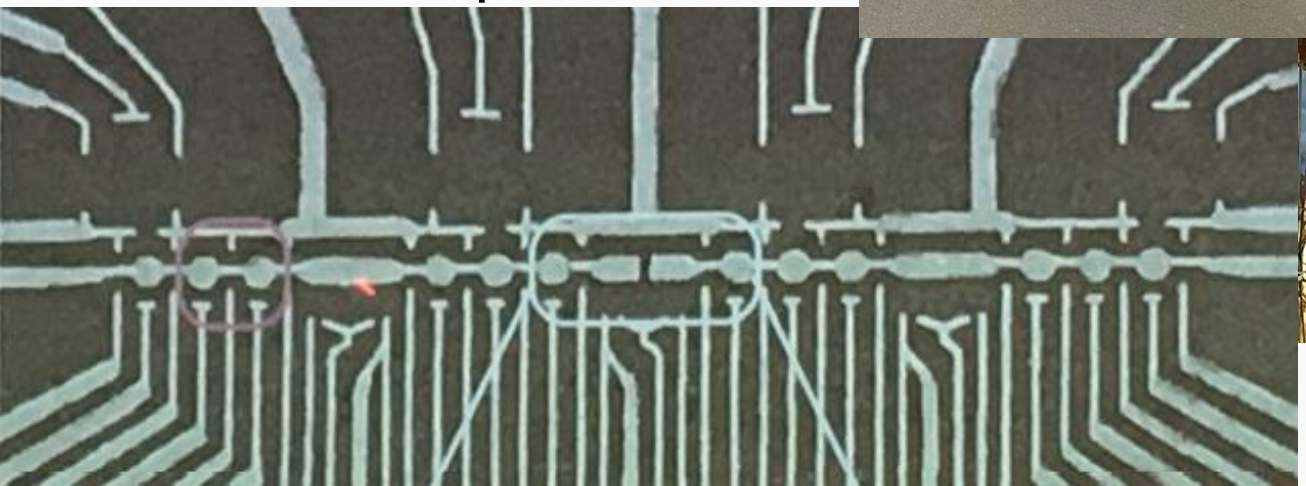
Superconducting qubits



Challenge: Integrate 10^6 qubits

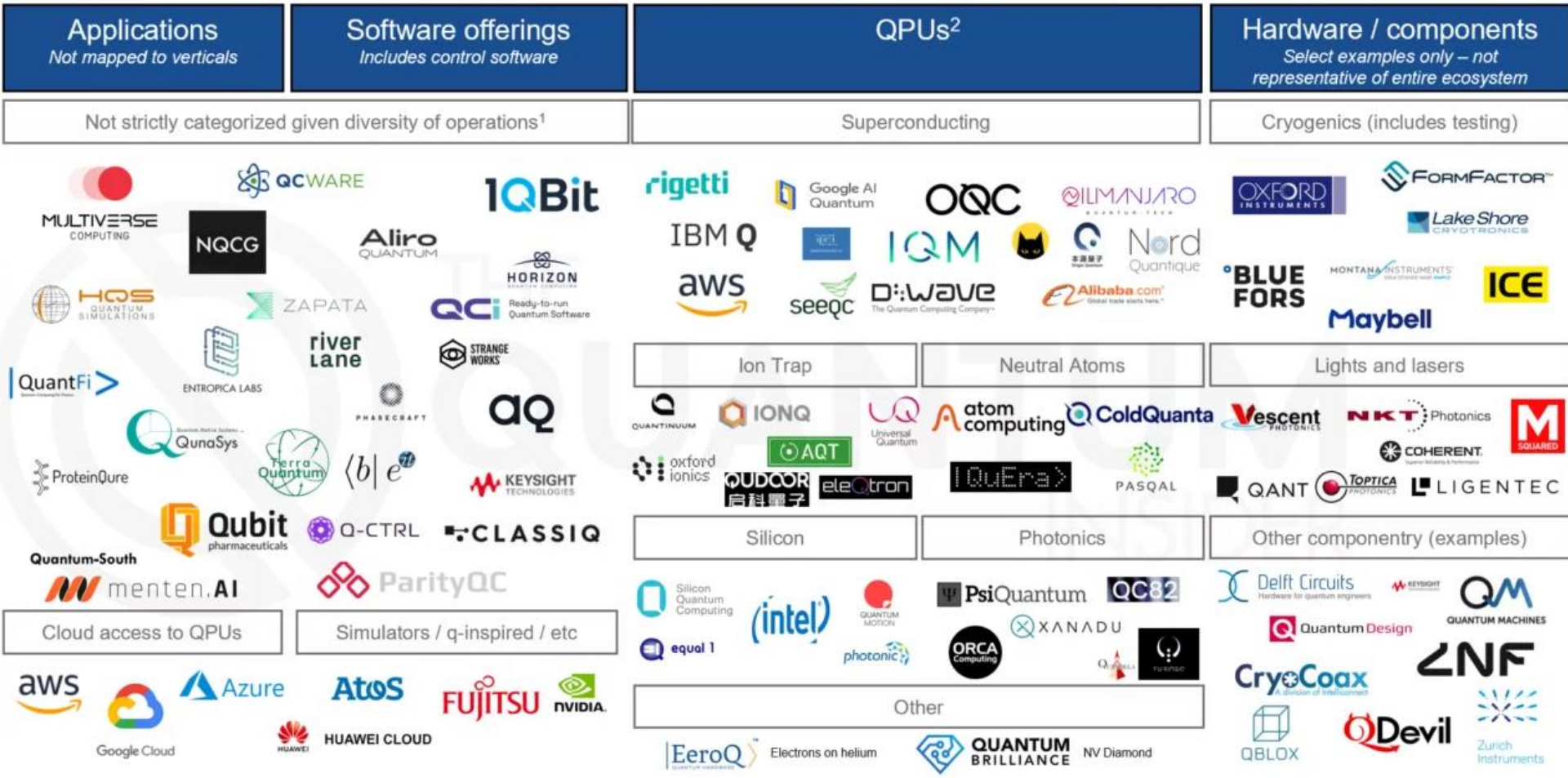


semiconductor quantum dots



Marcus group, Copenhagen

Quelques entreprises !



Financement des start-up

	Qubit technology	Total funding	Creation date
PsiQuantum	Photon	$665M	2015
IONQ	Ion traps	$657M	2015
D-Wave The Quantum Computing Company	Annealing	$305M	1999
rigetti	Superconducting	$300M	2013
XANADU	Photons	$262M	2016
Infleqtion	Neutral Atoms	$189M	2007
photonic	Silicon	$140M	2016

	Qubit technology	Total funding	Creation date
IQM	Superconducting	$295M	2018
OQC	Superconducting	$151M	2017
PASQAL	Neutral atoms	$139M	2019
QUANDELA	Photons	$71M	2017
QUANTUM MOTION	Silicon	$60M	2017
eleQtron	Ion traps	$53M	2020

+ other Quantum Computing companies that have raised 50 M€ or less (Orca Computing, Alice&Bob, Oxford Ionics, Quobly,...)

Financement des start-up

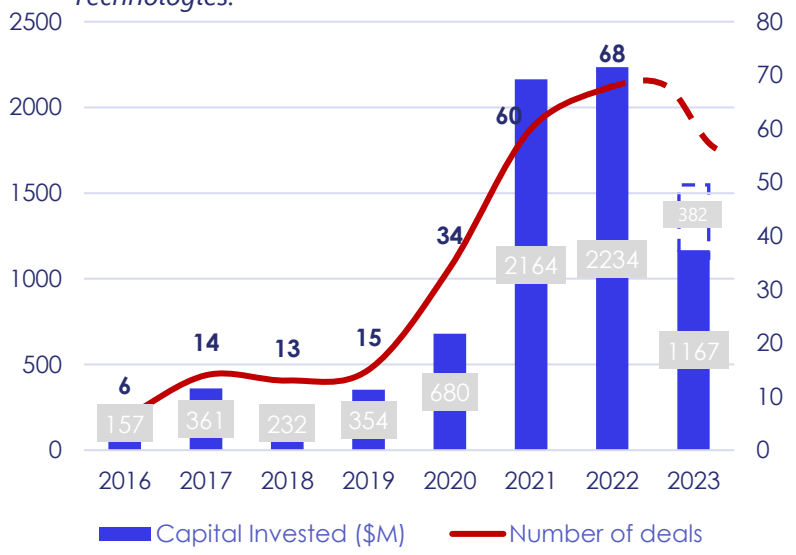
Sector dynamism

Consistent growth for 4 consecutive years until 2023
In 2021, quantum startups accounted for **3 of the 22 largest deep-tech deals**.

2023 sector momentum

More than **$1B** raised already mid-2023, with projections **>** **$1.5B** by year end.
While rounds were slower to materialize early 2023, **the sector has been very active in the second semester**
Over 30 new private funding rounds disclosed in Q1 '23 only

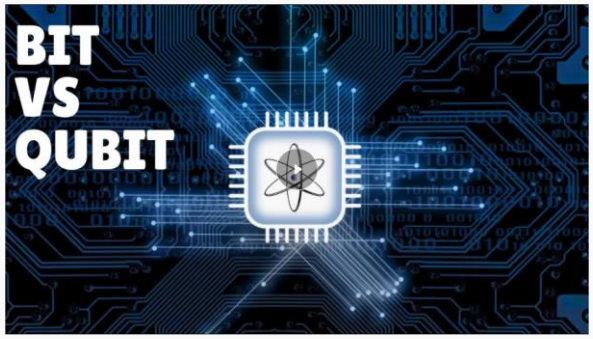
Total capital invested and # of deals in Quantum Technologies.



Source: BCG

Pour aller plus loin

https://qics.sorbonne-universite.fr/formation/formation-la-mediation-scientifique



https://www.youtube.com/watch?v=URo686ESEFg

Quantum Information Center
ALLIANCE SORBONNE UNIVERSITÉ

Paris Centre for Quantum Technologies

Paris Centre for Quantum Technologies

QuanTiP
Domaine de Recherche et d'Innovation Majeur

Quantum Technologies in Paris Region

Il reste beaucoup de choses à découvrir

Merci à
Eleni Diamanti, Valentina Parigi, Mattia Walschaers, Frédéric Grosshans