

COLLÈGE
DE FRANCE

— 1530 —

Leçon inaugurale - 11 décembre 2025

Pascale SENELLART

*Les débuts d'une seconde
révolution quantique*

CHAIRE ANNUELLE INNOVATION TECHNOLOGIQUE LILIANE BETTENCOURT

Avec le soutien de la Fondation Bettencourt Schueller

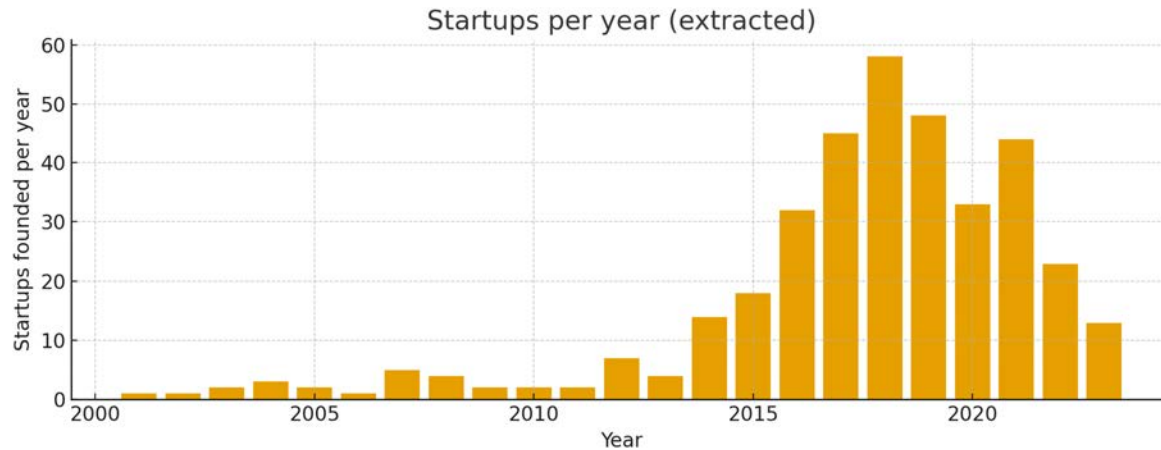
After 100 years of the initial development of quantum mechanics, our journey of exploring its impact on human society has just begun. Quantum science and technology (QST) is advancing at an unprecedented pace.



INTERNATIONAL YEAR OF Quantum Science and Technology

« Cent ans après les premiers développements de la mécanique quantique, notre exploration de son impact sur la société humaine ne fait que commencer. Les sciences et technologies quantiques progressent à un rythme sans précédent. »

Une nouvelle phase d'innovation intense



Extrait de
<https://www.mckinsey.com/~media/mckinsey/business%20functions/mckinsey%20digital/our%20insights/steady%20progress%20in%20approaching%20the%20quantum%20advantage/quantum-technology-monitor-april-2024.pdf>



Source O. Ezratty

CHAIRE ANNUELLE

Chaire annuelle Innovation technologique Liliane Bettencourt

2006 - aujourd'hui

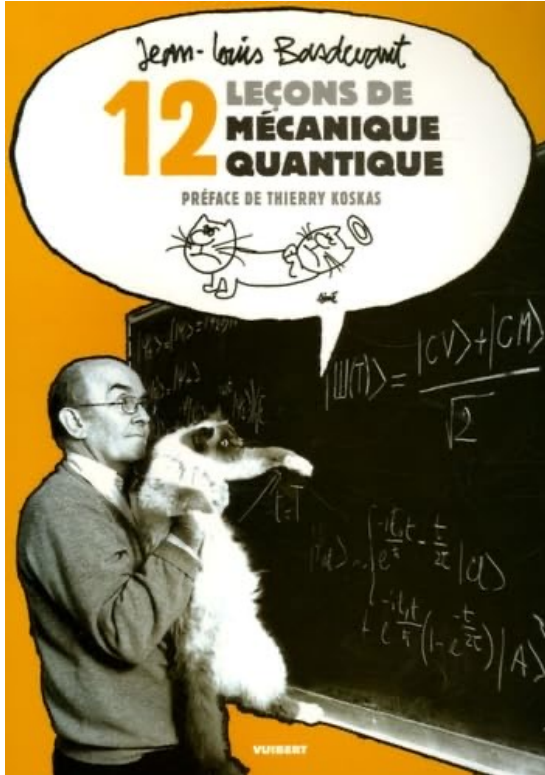


Fondation
Bettencourt
Schueller

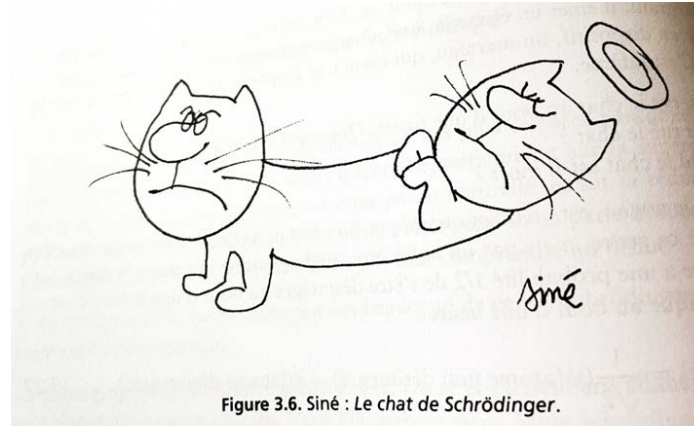
Reconnue d'utilité publique depuis 1987



« Personne ne comprend la mécanique quantique »

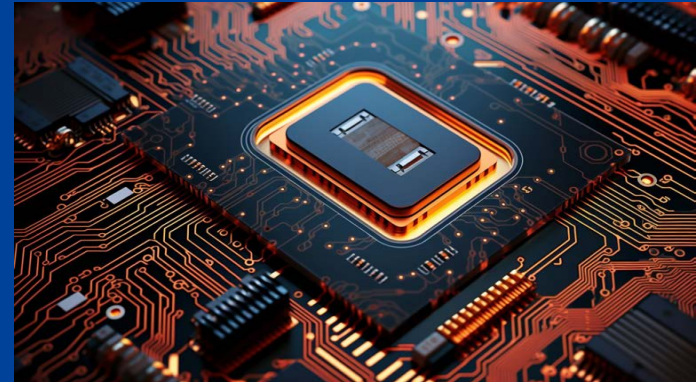
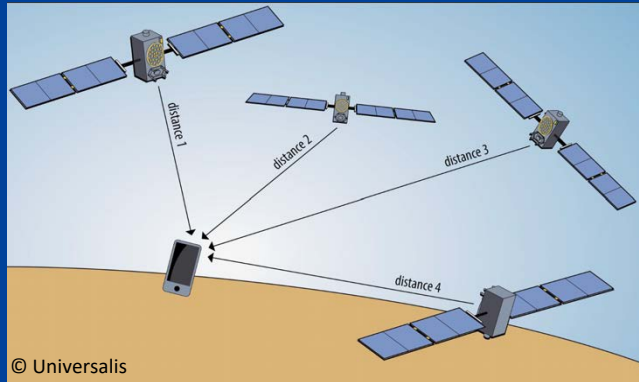


« I think I can safely say that *nobody* understands quantum mechanics. »
Richard Feynman 1965



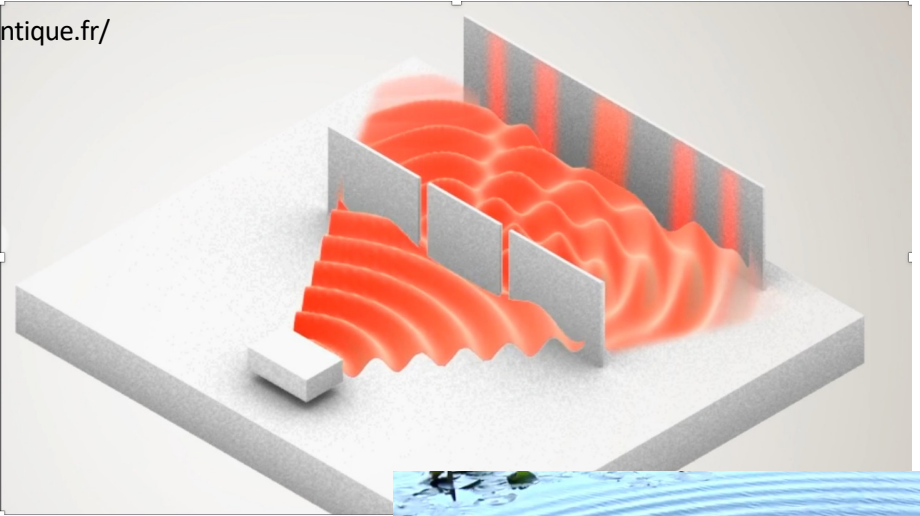
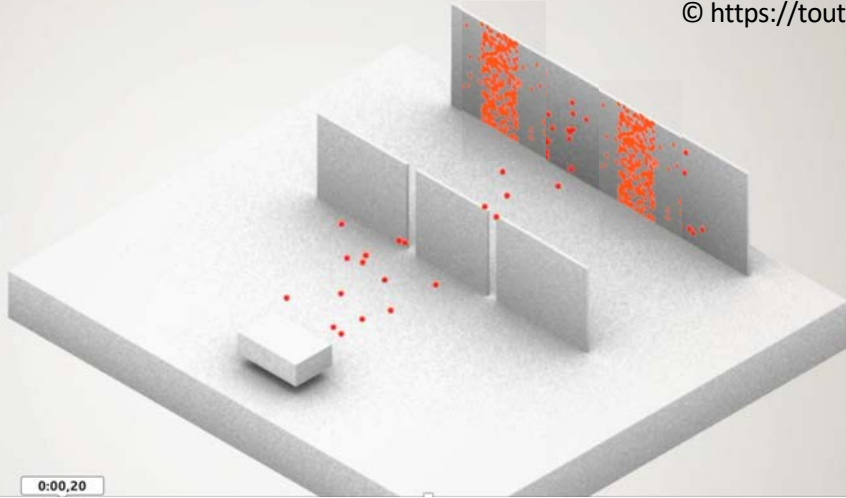


Mécanique quantique et révolution technologique au 20^{ème} siècle



Dualité onde-corpuscule

© <https://toutestquantique.fr/>



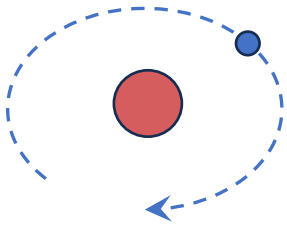
Rayonnement du corps noir, Planck 1900

Effet photoélectrique, Einstein 1905

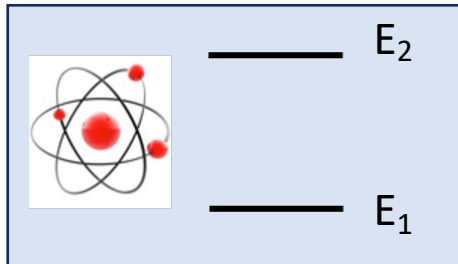
De Broglie 1924 : dualité onde-particule



Atome d'hydrogène
Bohr 1922

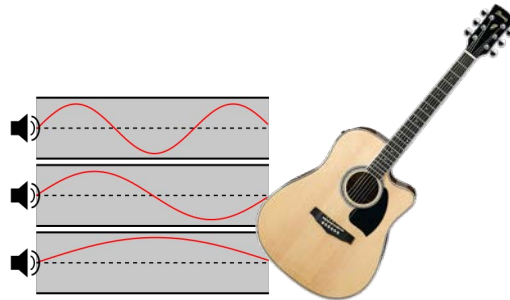


Bohr, Leçon Nobel 1922

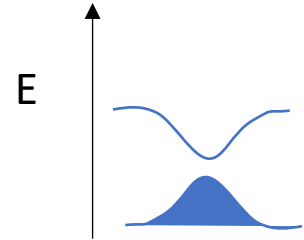
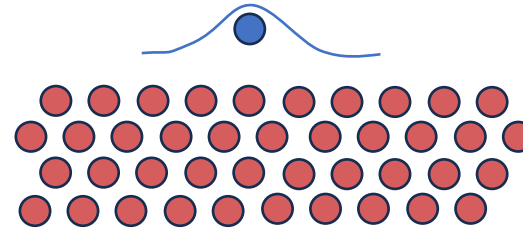


Equation de Schrödinger
1926

$$i\hbar \frac{d\psi(t)}{dt} = \hat{H}\psi(t)$$



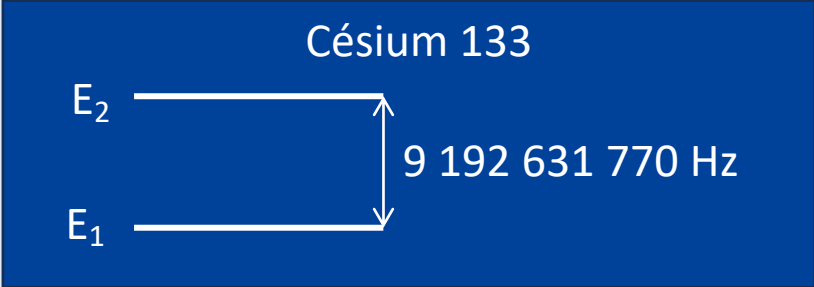
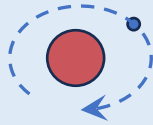
Solides
Bloch 1929



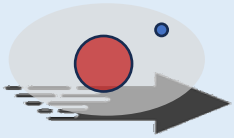
Zeitschrift für Physik,
52, 555. (1929)

Connaissance et contrôle des niveaux atomiques

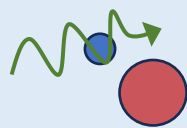
Physique
atomique



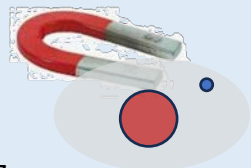
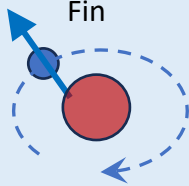
Doppler



Lumière

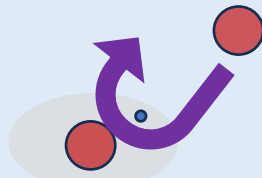


Fin

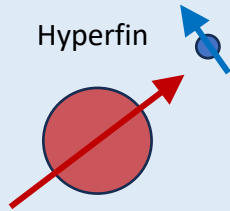


Zeeman

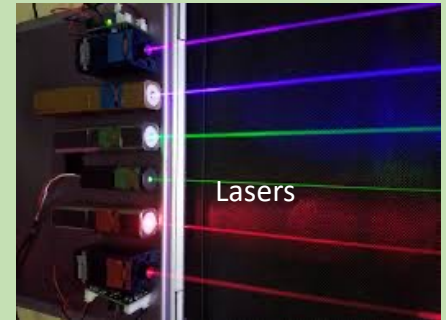
Collisions



Hyperfin



Technologies



Vide



Electronique



Première révolution technologique

Connaissance des niveaux d'énergie dans les atomes

Horloge atomique 1955

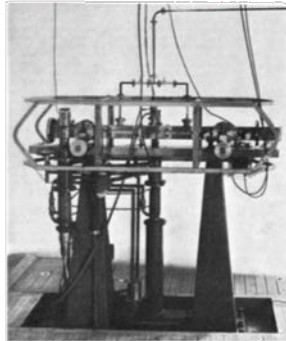


Fig. 1. The atomic beam absorption experiment of the apparatus, the cell of different lengths, the cell and the detector are shown for the case of the atomic beam. The distance between the cell and the detector is the same as the distance between the cell and the detector.

Nature 176,280 (1955)

Laser 1960

(b)

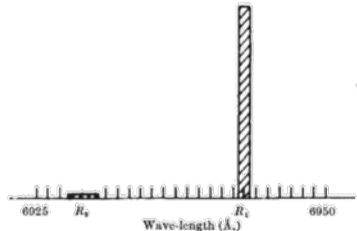
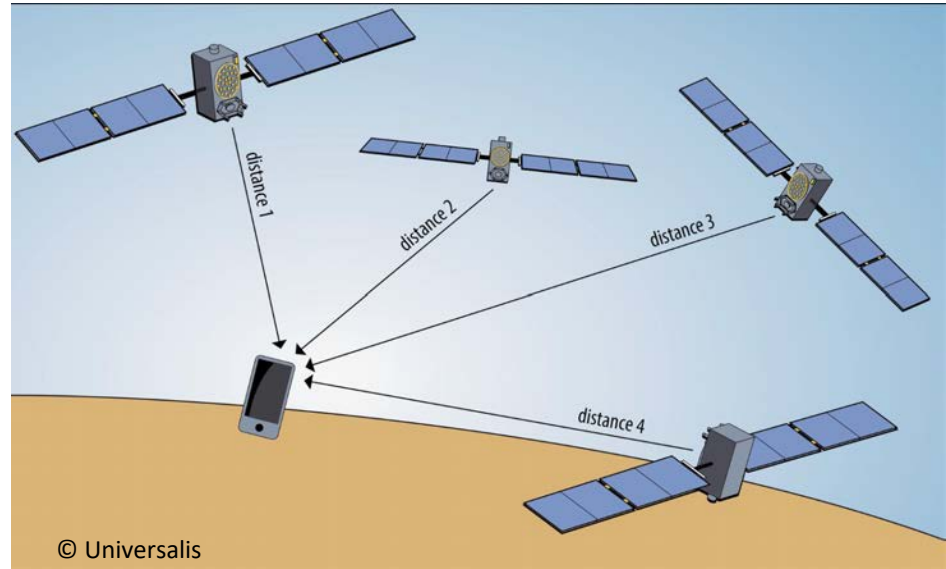


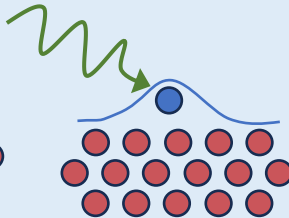
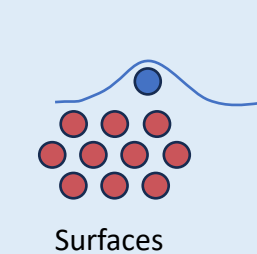
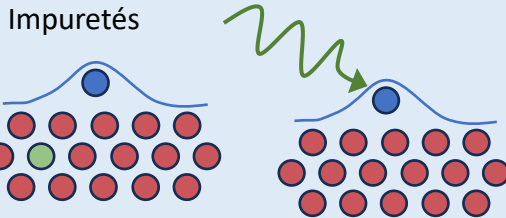
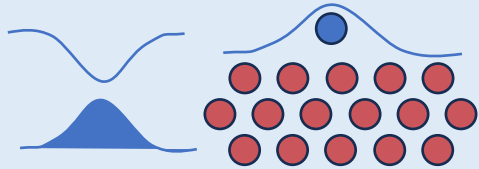
Fig. 2. Emission spectrum of ruby: a, low-power excitation; b, high-power excitation.

Nature 187,493 (1960)

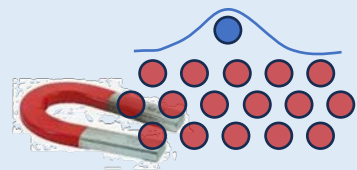


© Universalis

Physique du solide

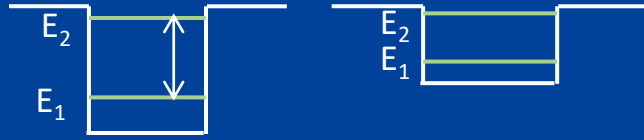


Lumière

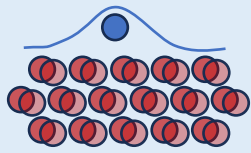


Zeeman

Electrons dans les solides



Vibrations

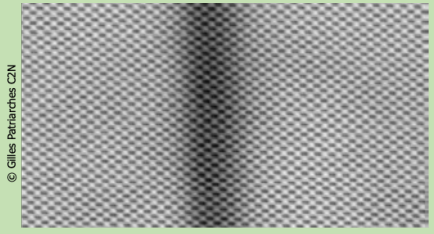


Microscopie électronique



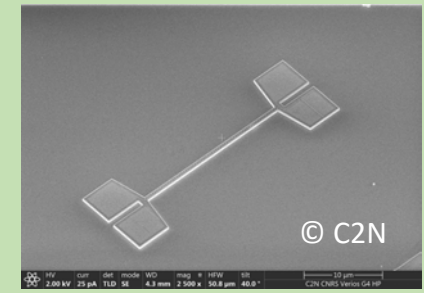
Technologies

Elaboration des matériaux



© Gilles Perbarthes C2N

Micro et Nano technologies



© C2N

Ingénierie des niveaux d'énergie dans des solides

Transistor 1948

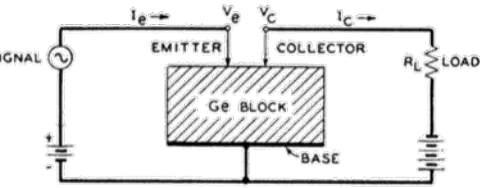


FIG. 1. Schematic of semi-conductor triode.

Laser semiconductor 1962

Phys. Rev.74, 230 (1948)

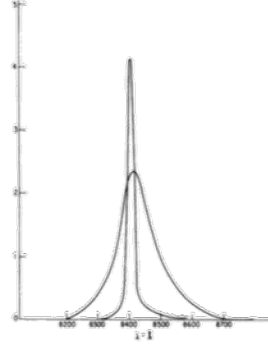
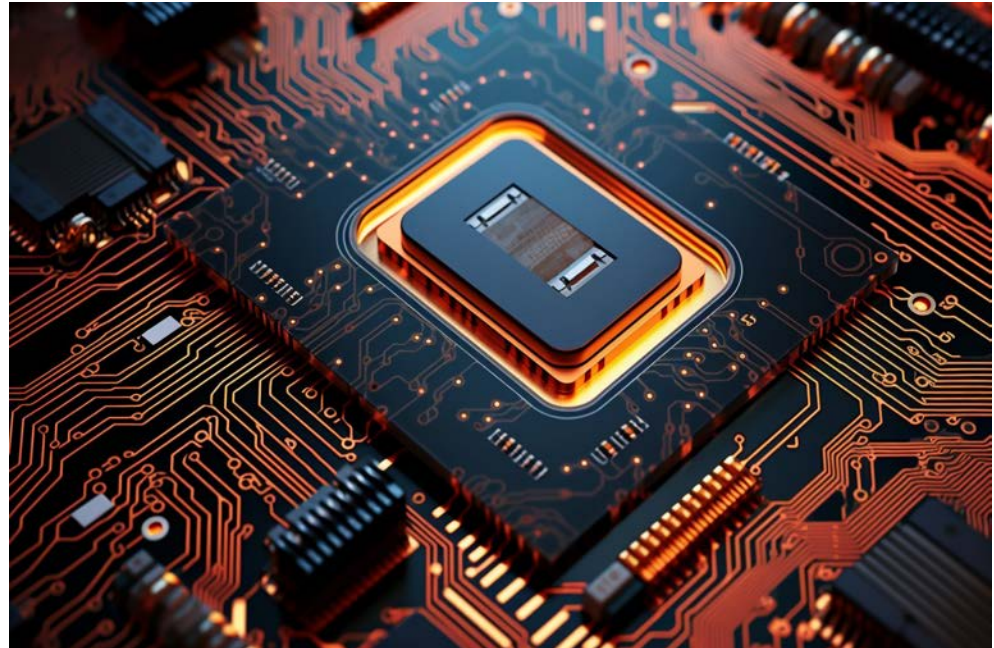
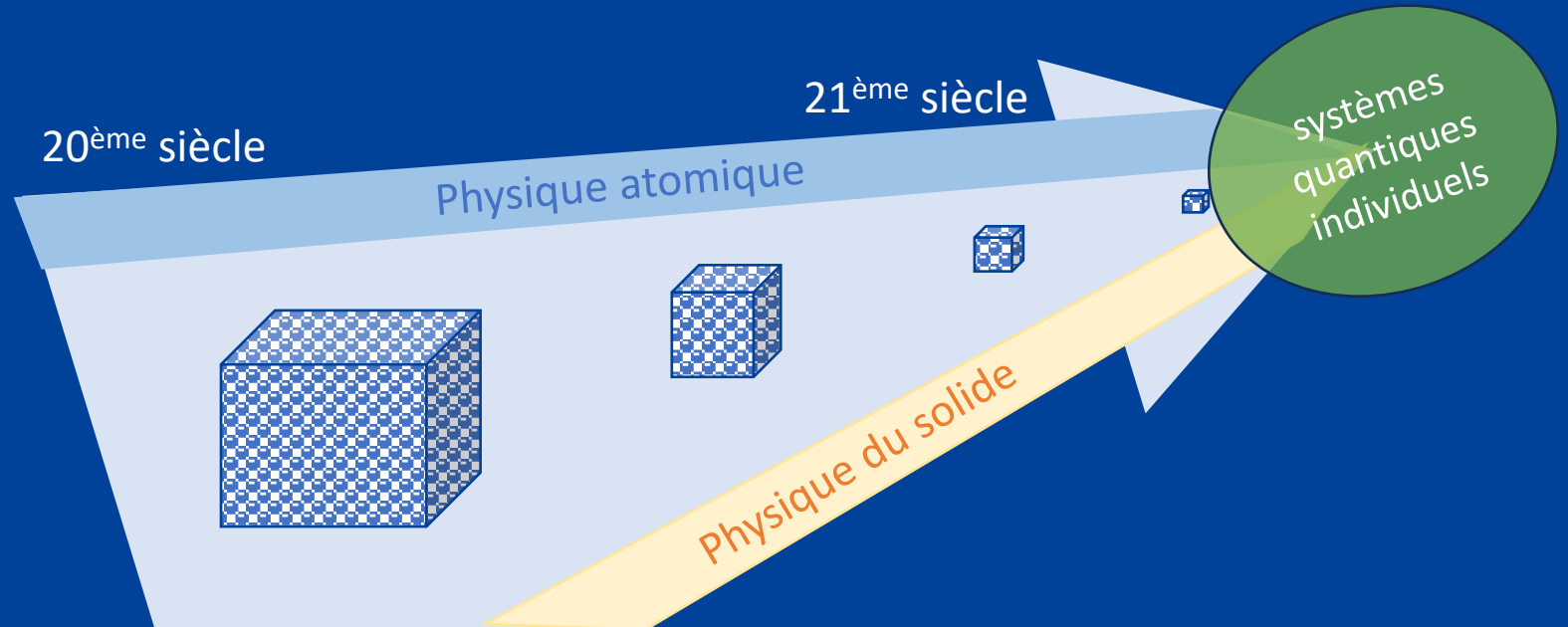


FIG. 2. Spectral distributions from diode L-69 below and above threshold. Different vertical scales.

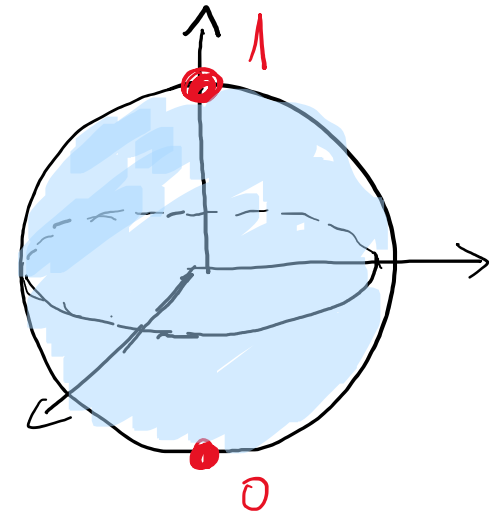
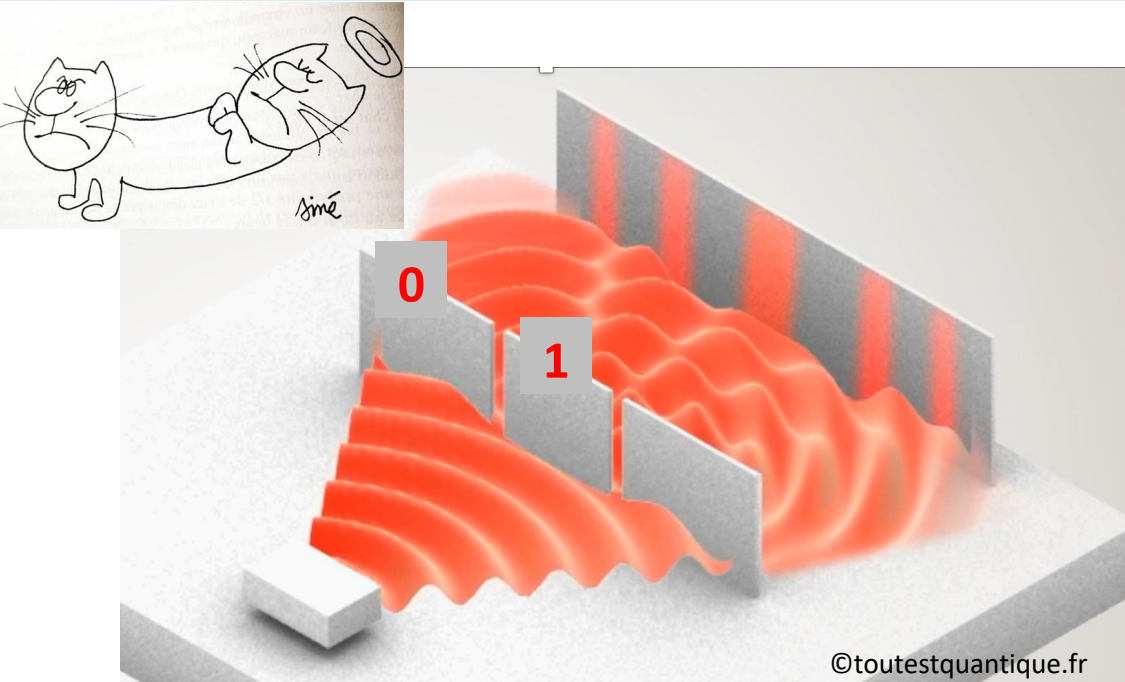
Phys. Rev. Lett. 9, 366 (1962)



Vers l'observation de concepts avancés



Superposition quantique



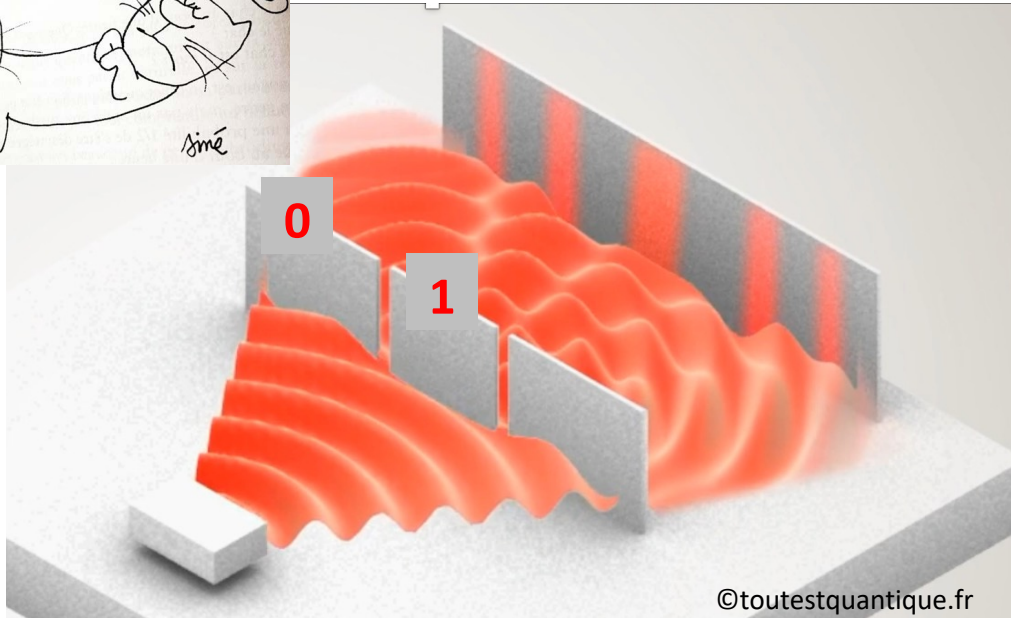
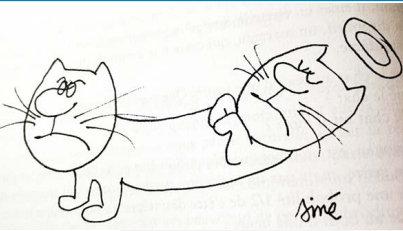
Bit d'information
classique 0 ou 1



Bit d'information
quantique

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

Superposition quantique



16 qubits

256x256 pixels
en couleurs



16 bits

4x4 pixels
noirs *ou* blancs



Bit d'information
classique 0 ou 1



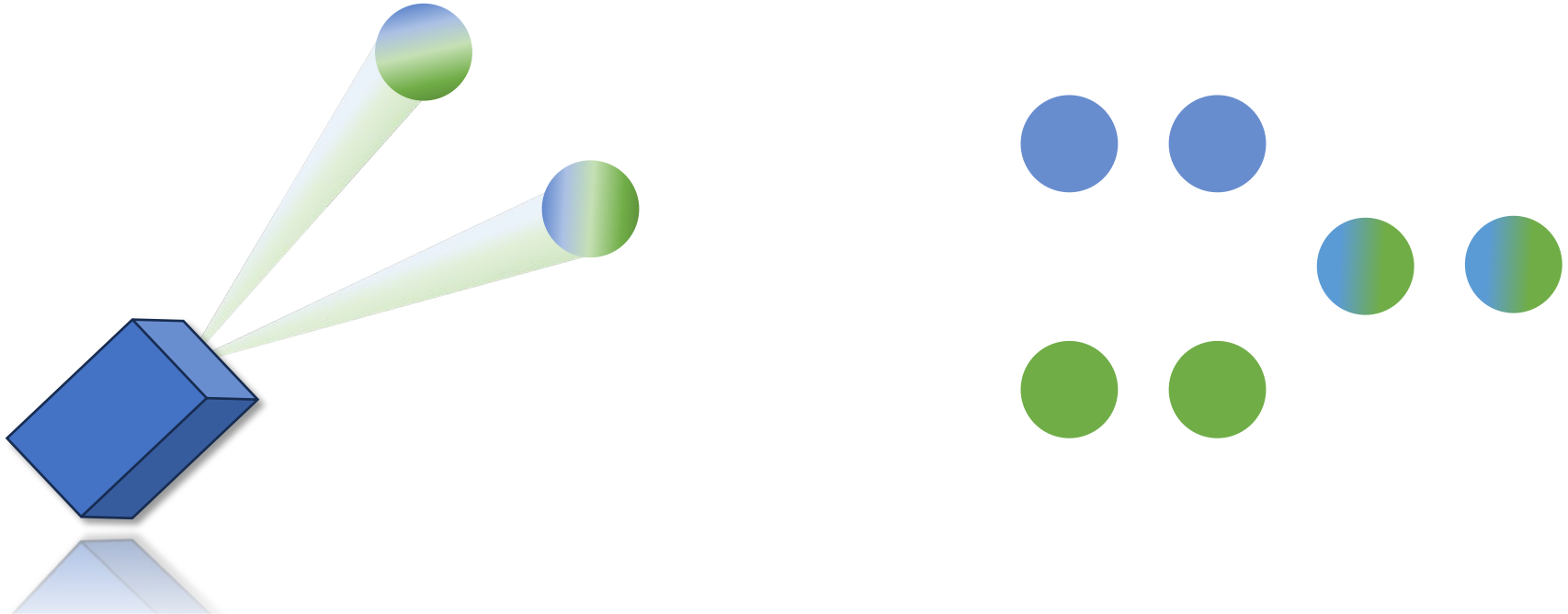
Bit d'information
quantique

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

Deux particules avec un destin aléatoire commun



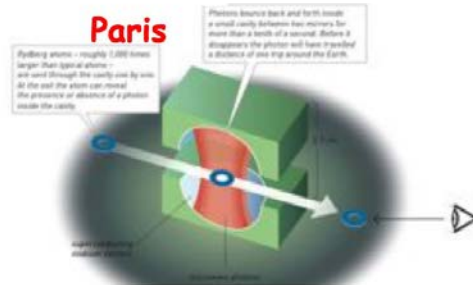
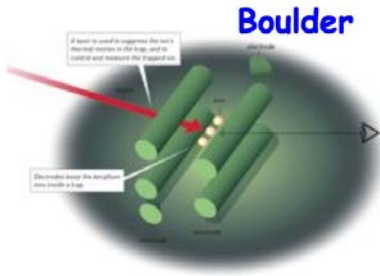
Deux photons avec un destin
aléatoire commun



Contrôle de systèmes quantiques individuels



Nobel de Physique 2012
S. Haroche, D. Wineland

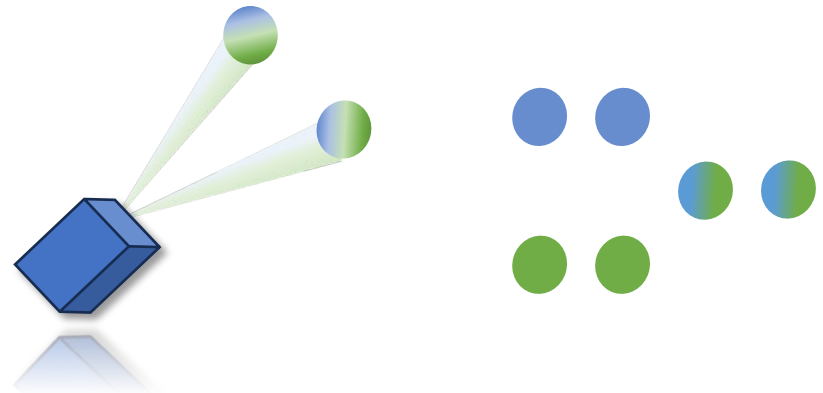


Two sides of the same coin: manipulating non destructively single atom with photons or single photon with atoms

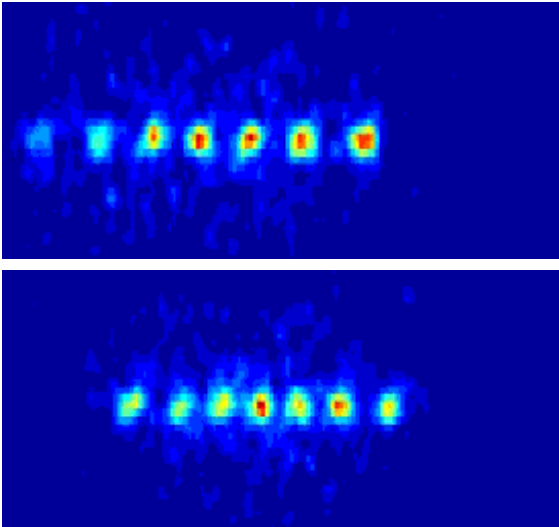
Intrication et absence de variables cachées



Nobel de Physique 2022
A. Aspect, J. Clauser & A. Zeilinger

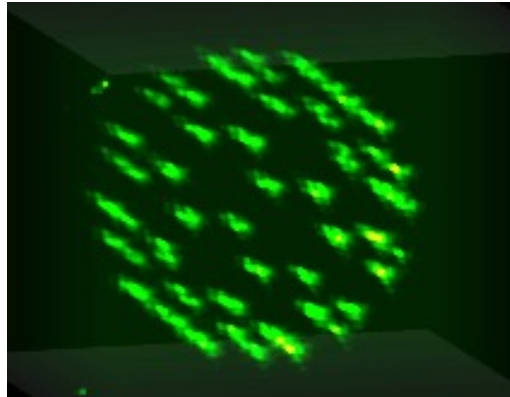


ions



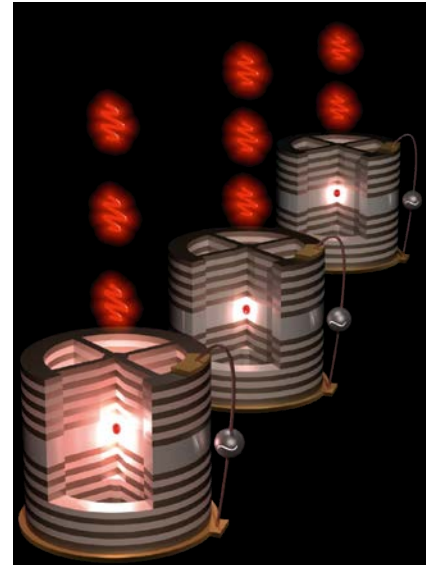
R. Blatt, Innsbruck

atomes



A. Browaeys, Palaiseau

photons



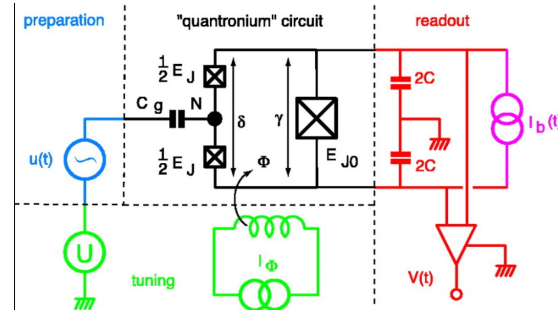
P. Senellart, Palaiseau

Comportement quantique de systèmes artificiels

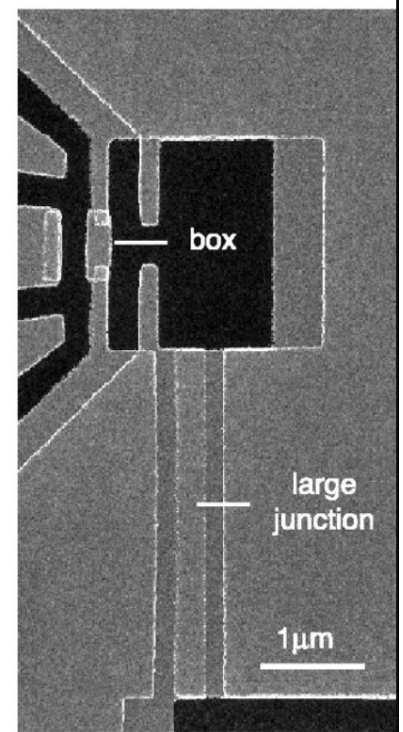


Nobel de Physique 2025
J. Clarke, M. H. Devoret, J. M. Martinis

"for the discovery of macroscopic quantum mechanical tunnelling and energy quantisation in an electric circuit"



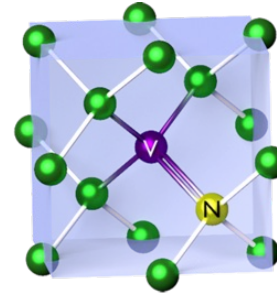
Science 296, 5569 (2002)



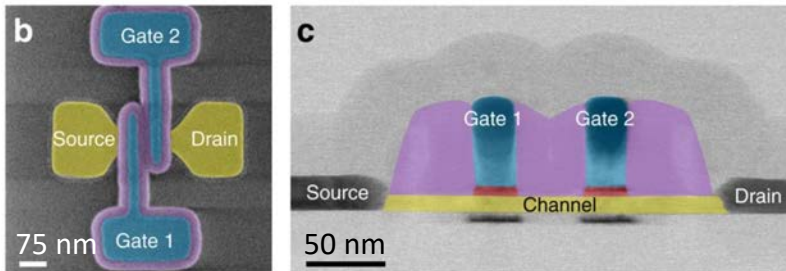
Contrôle de systèmes quantiques artificiels



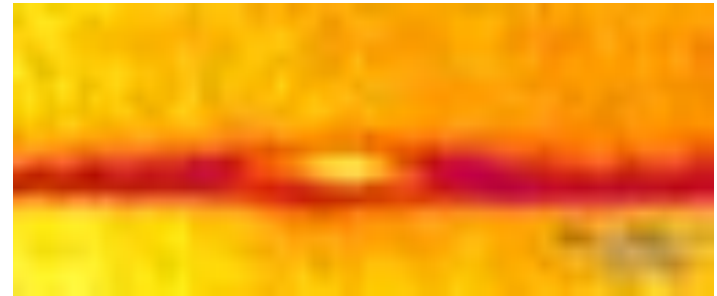
<https://images.cnrs.fr/video/2061>



© wikipedia

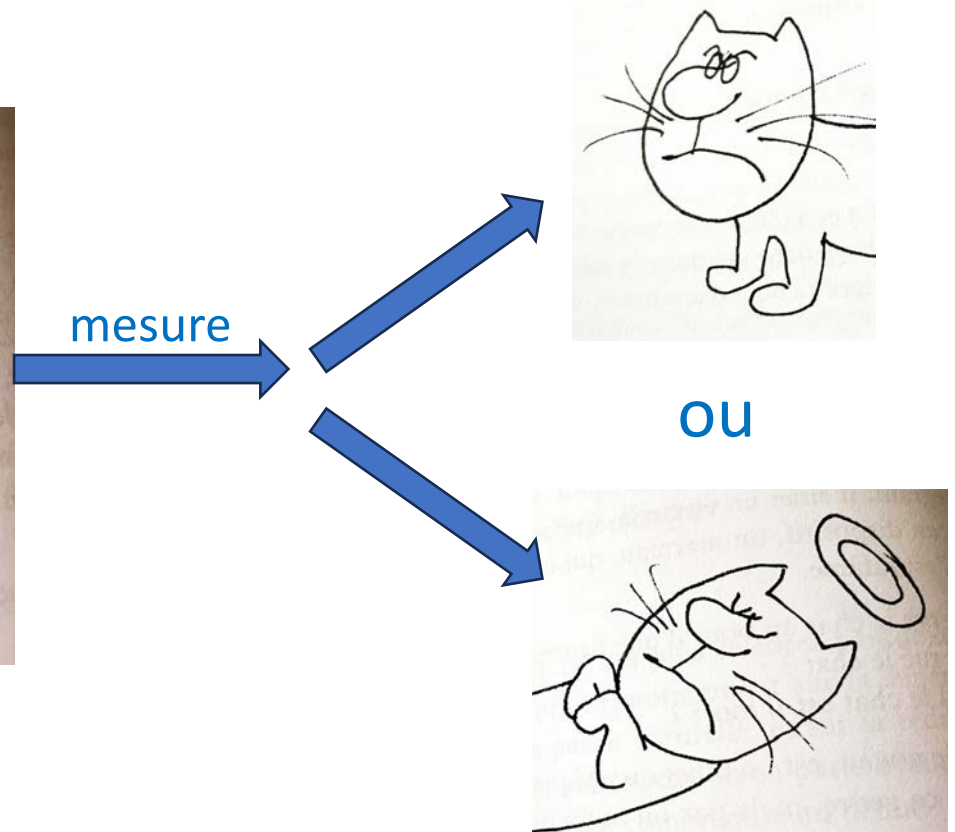
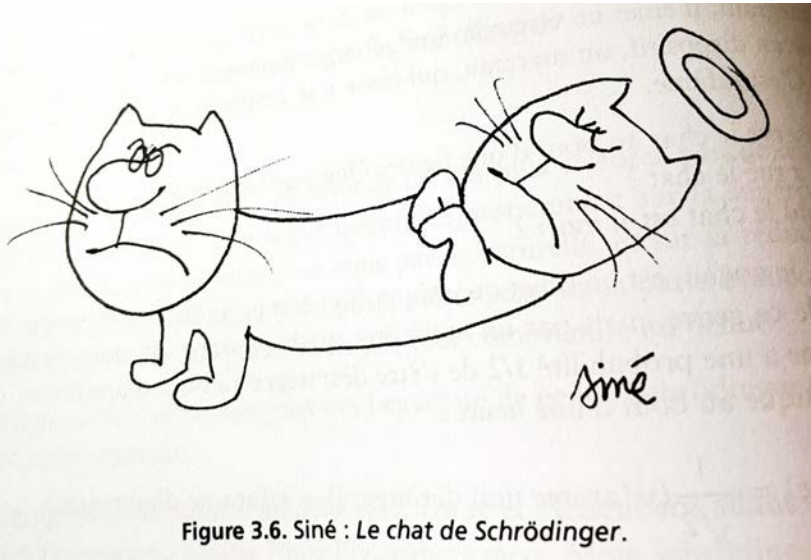


doi: 10.1109/ESSCIRC55480.2022.9911381



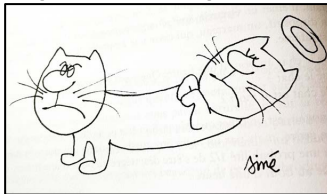
© Centre de nanosciences et nanotechnologies

Fragilité de la superposition quantique

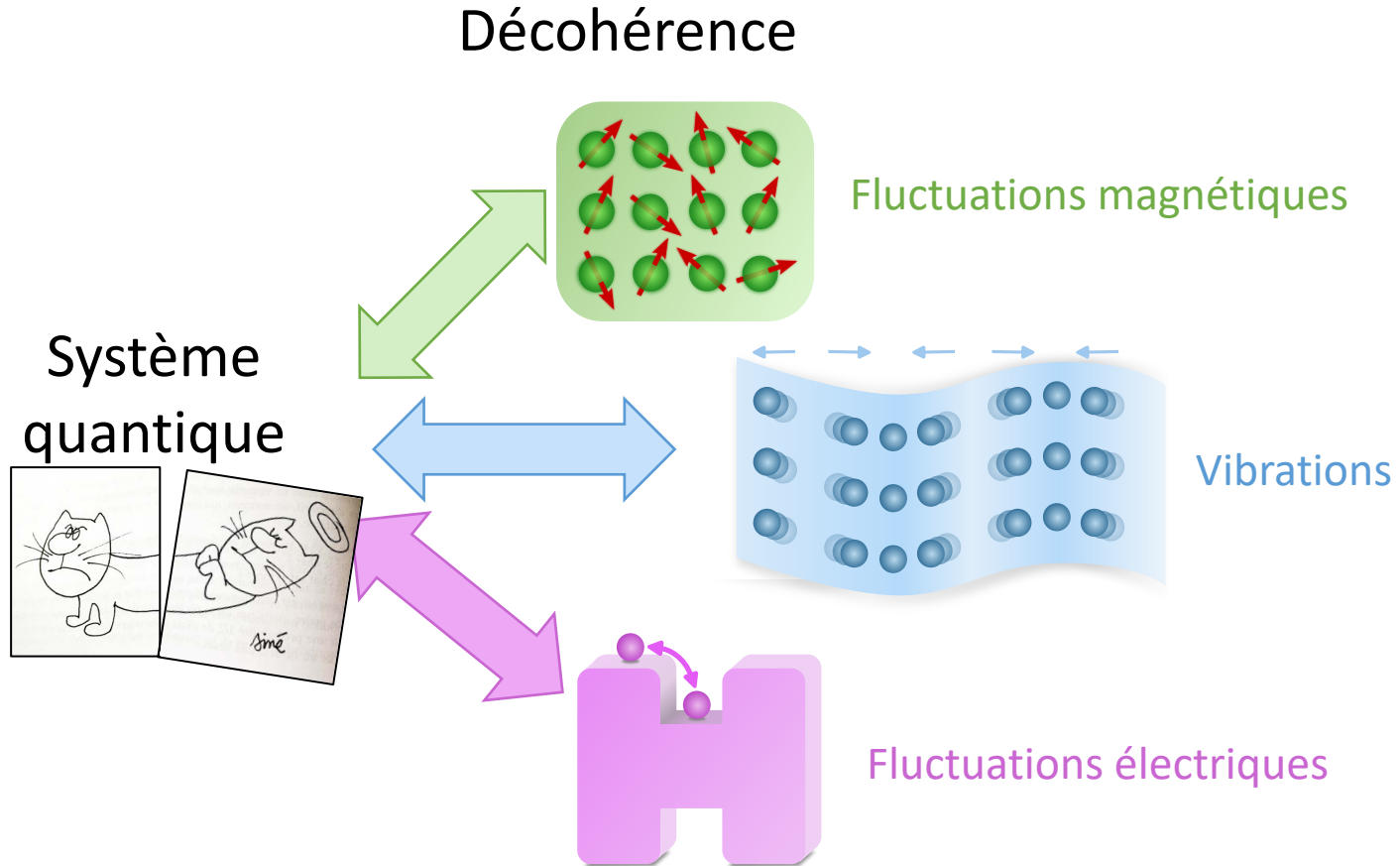


Décohérence

Systeme
quantique

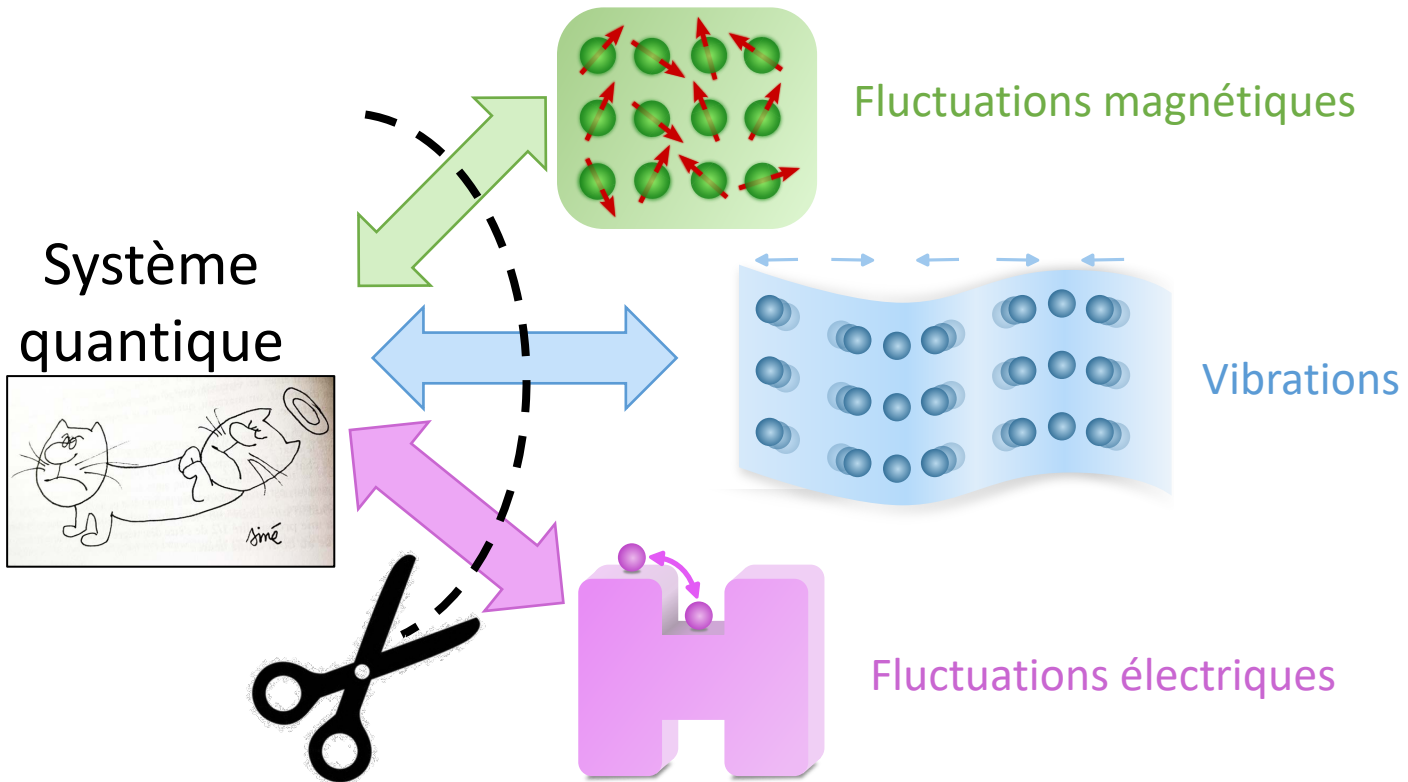


Fragilité de la superposition quantique



Fragilité de la superposition quantique

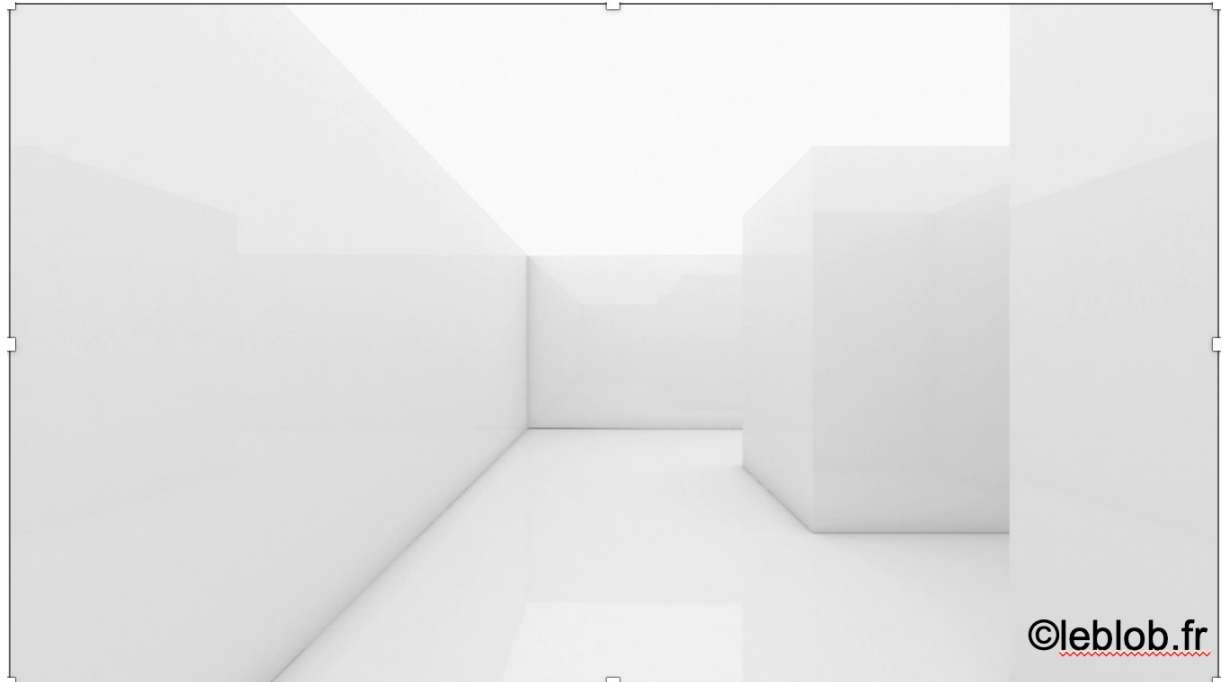
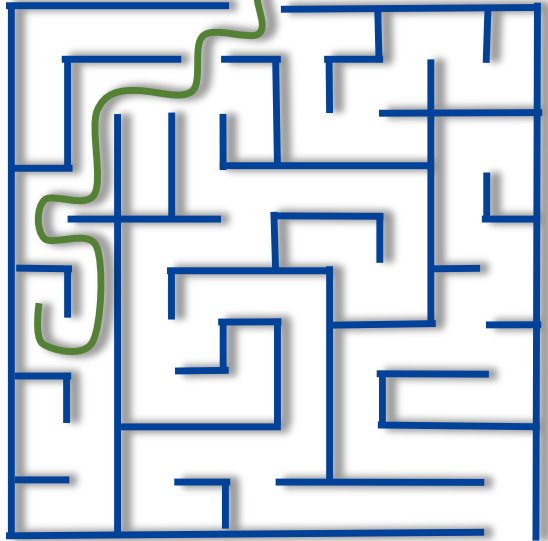
Décohérence



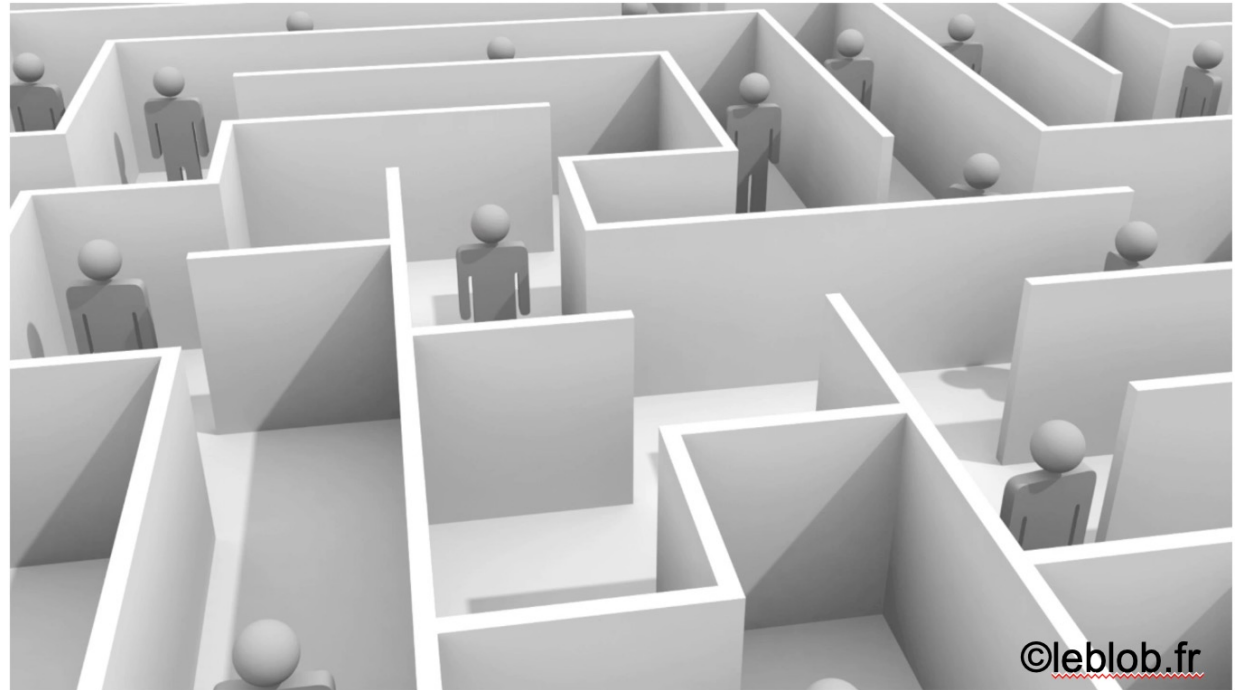
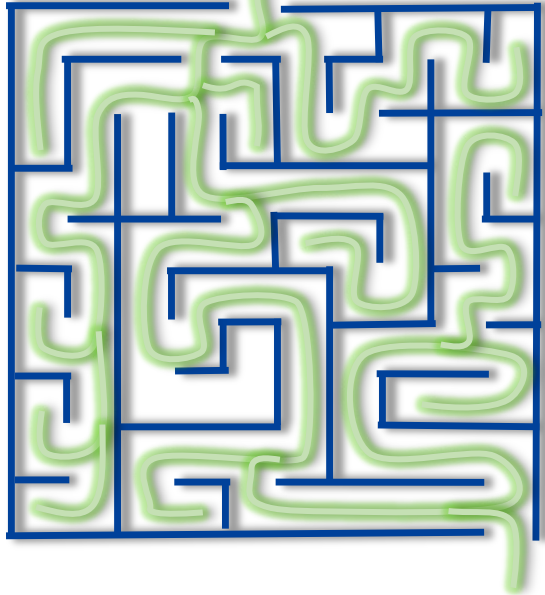
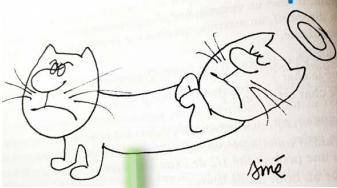
Début d'une seconde révolution technologique



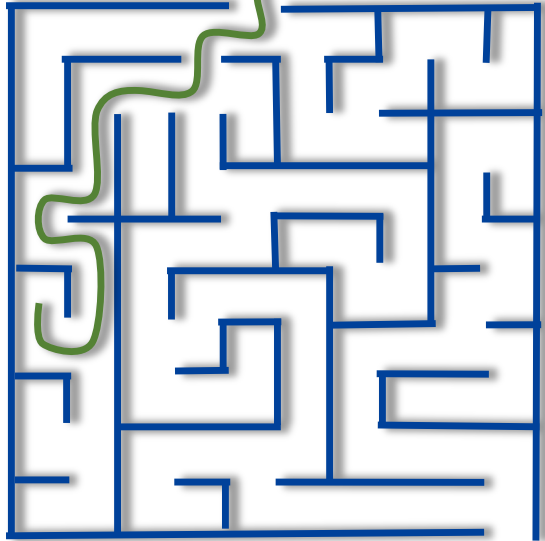
Bit d'information classique 0 ou 1



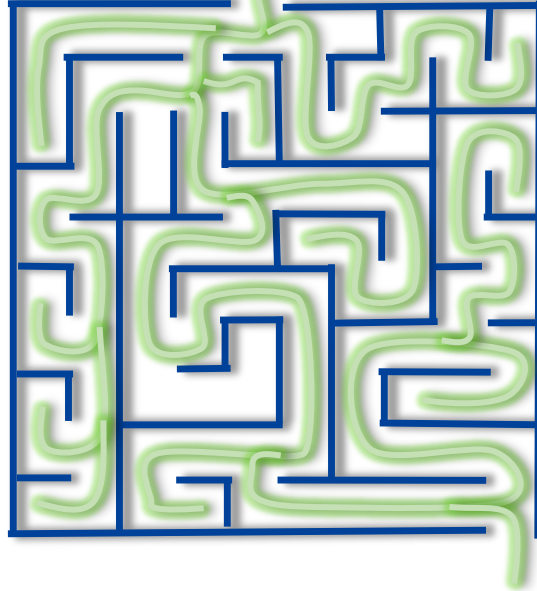
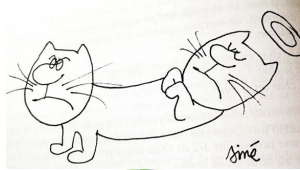
Bit d'information quantique 0 et 1



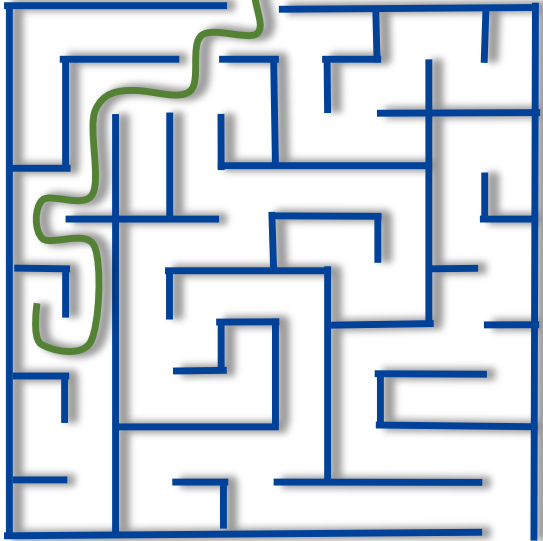
classique



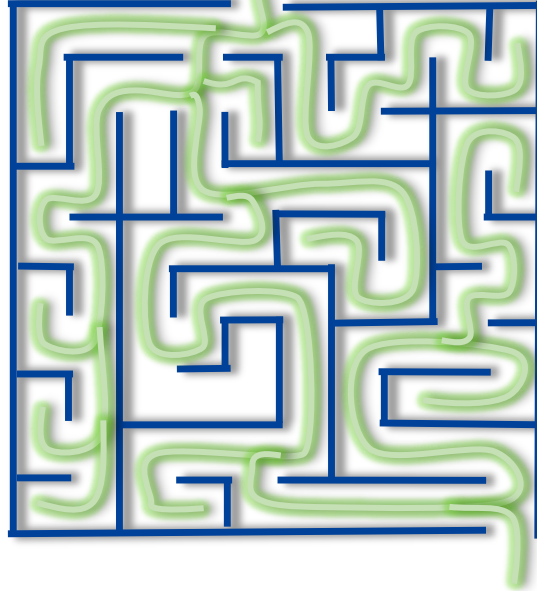
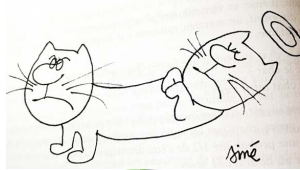
superposition



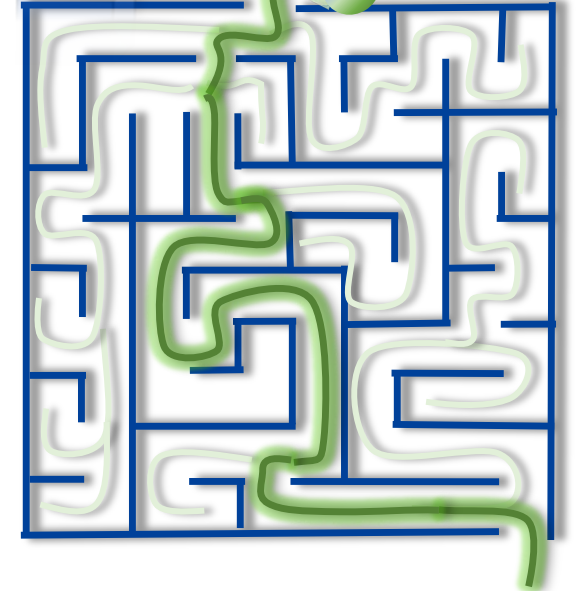
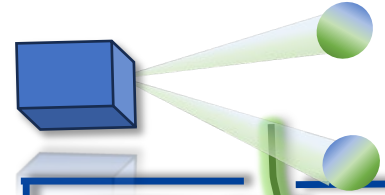
classique



superposition



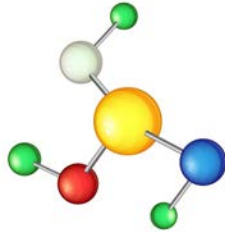
intrication



Applications du calcul quantique : calcul intensif



Logistique



Nouveaux matériaux

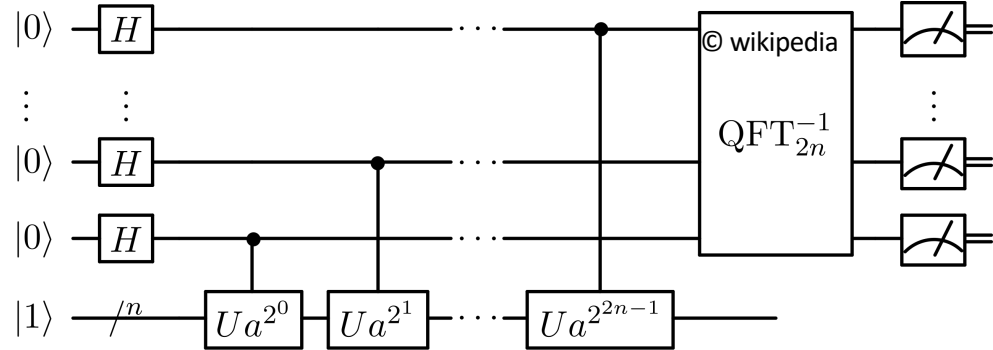


Intelligence artificielle



Optimisations de flux

Algorithmes quantiques



Algorithme de Shor

568826753508405557=1204036733 x 47236729

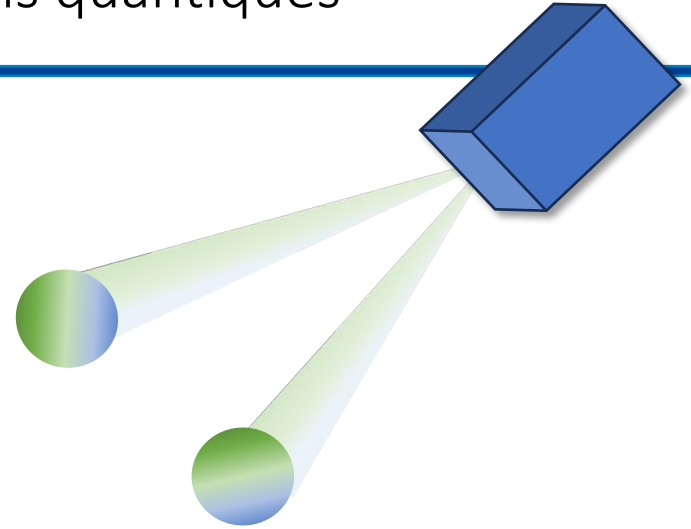


China's quantum satellite achieves 'spooky action' at record distance *Science* 356, 1140–1144 (2017)

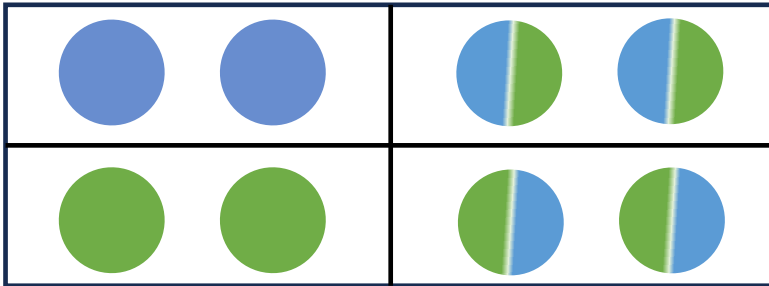
By Gabriel Popkin | Jun. 15, 2017, 2:00 PM

June 2017

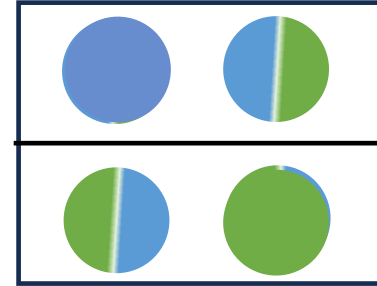
Echanges de clés cryptographiques



Résultats possibles



Résultats impossibles



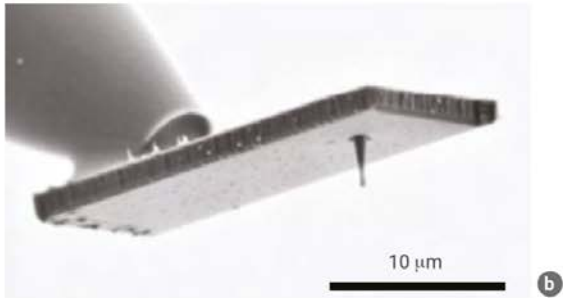
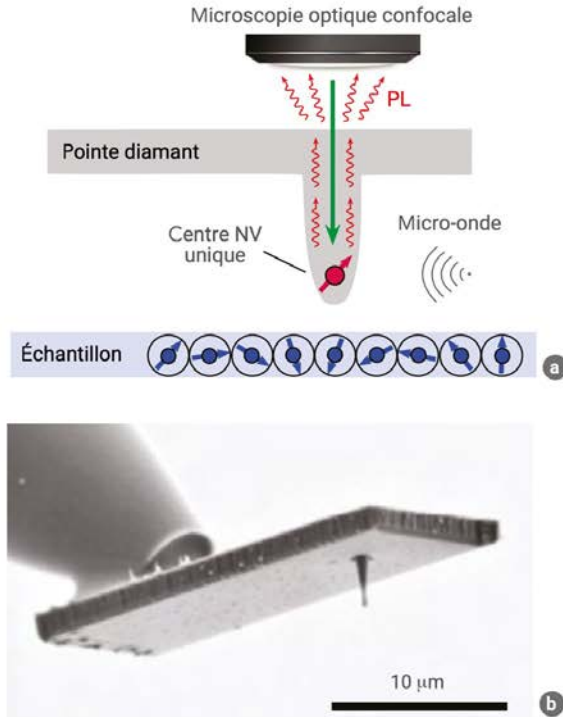
Communications quantiques



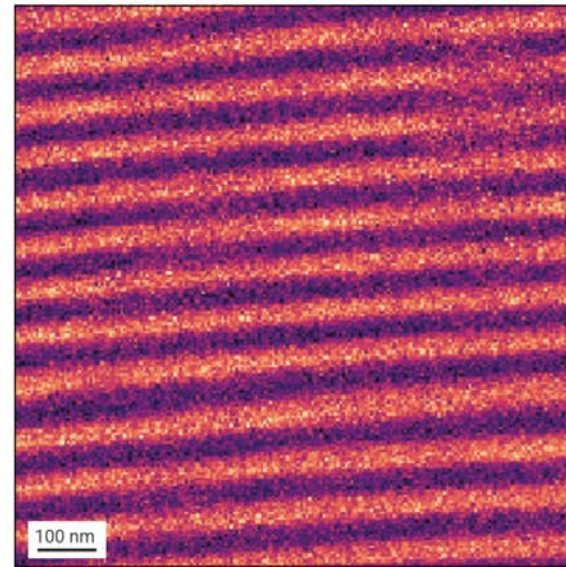
npj Quantum Information 11, 137 (2025)



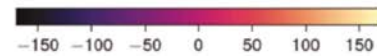
Capteurs quantiques à base de diamant



Cycloïde antiferromagnétique dans BiFeO_3

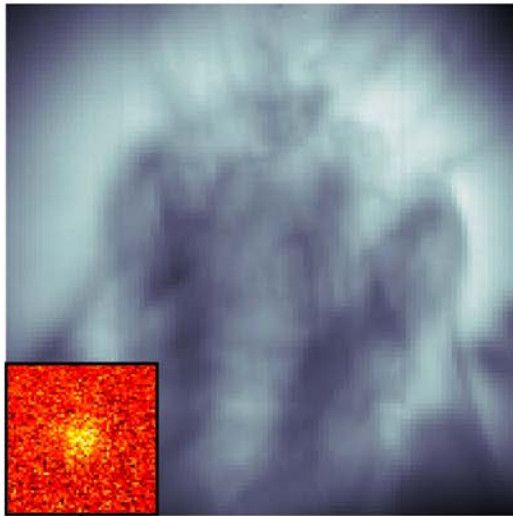


c



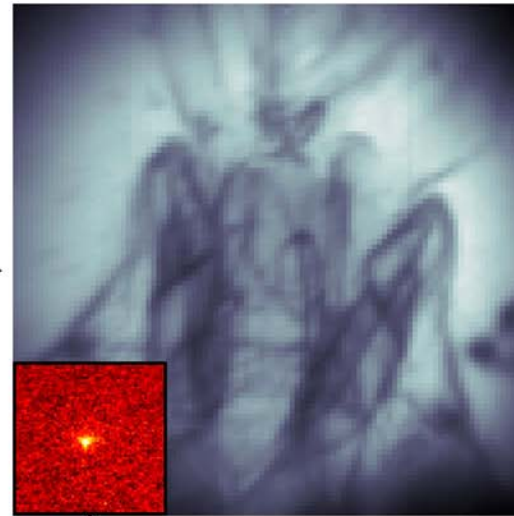
$B_{\text{NV}} (\mu\text{T})$

Image d'intensité
floue



Mesure des corrélations
entre photons

Image d'intensité
après correction

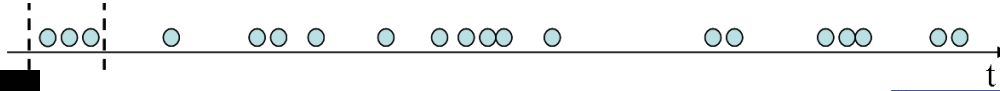


Corrélations renforcées

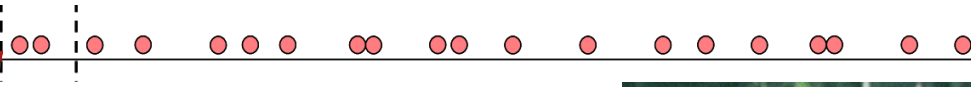
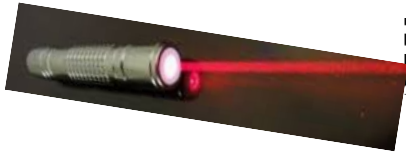
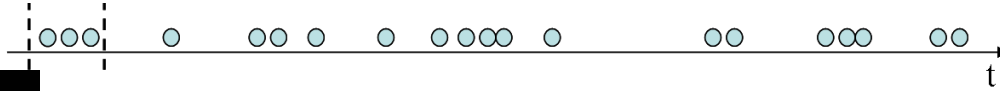
Des photons pour les technologies quantiques



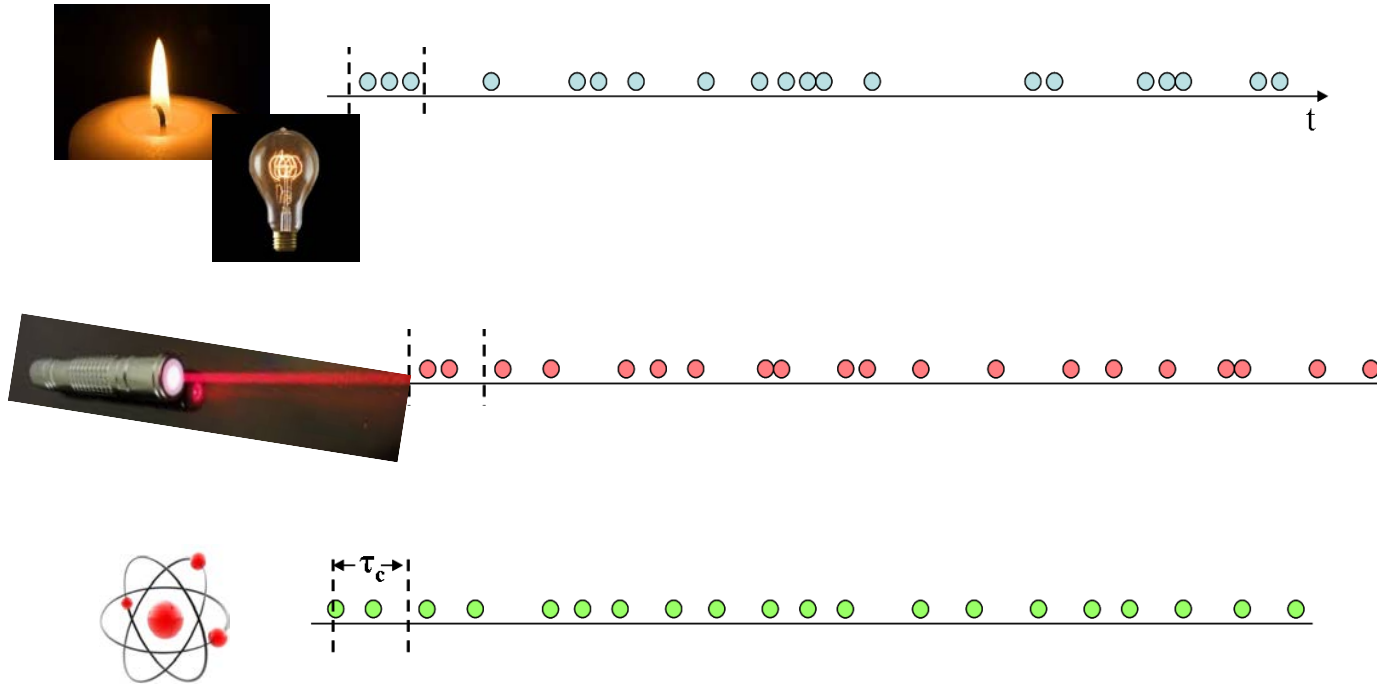
Sources de lumière



Sources de lumière



Sources de lumière



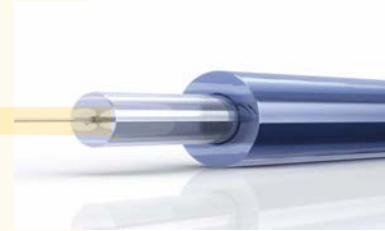
Phys. Rev. Lett. **39**, 691 (1977)
Euro. Phys. Lett. **1**, 173 (1986)

Des sources de photons uniques



Des sources de photons uniques

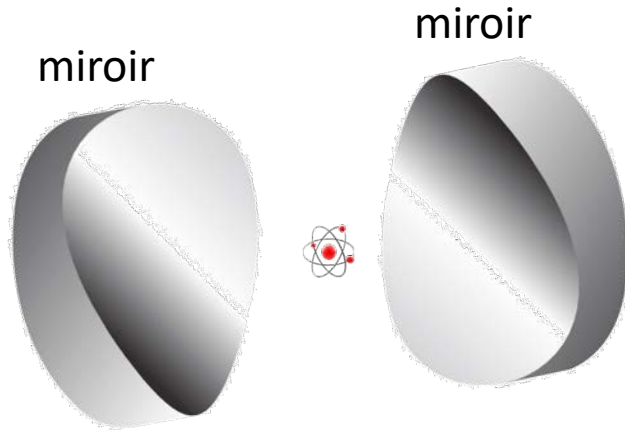
atome



Fibre optique

Source très inefficace

Contrôler l'émission de lumière d'un atome

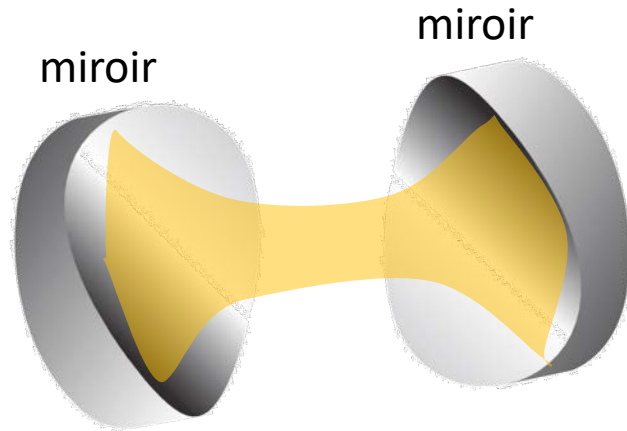


B10. Spontaneous Emission Probabilities at Radio Frequencies. E. M. PURCELL, *Harvard University*.—For nuclear magnetic moment transitions at radio frequencies the probability of spontaneous emission, computed from

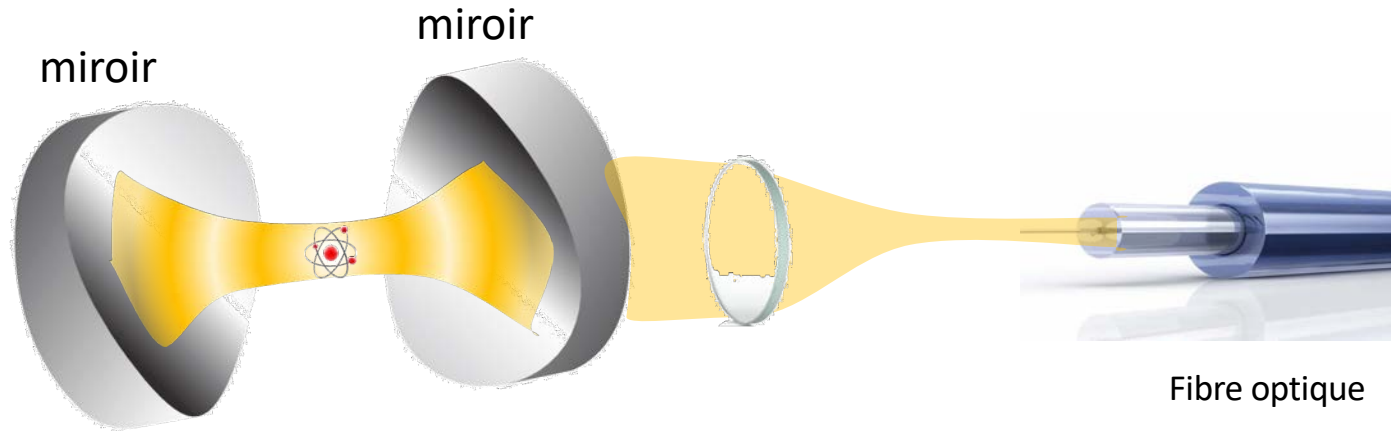
$$A_{\nu} = (8\pi\nu^2/c^3)\hbar\nu(8\pi^3\mu^2/3h^2) \text{ sec.}^{-1},$$

is so small that this process is not effective in bringing a spin system into thermal equilibrium with its surroundings. At 300°K, for $\nu = 10^7 \text{ sec.}^{-1}$, $\mu = 1$ nuclear magneton, the corresponding relaxation time would be 5×10^{21} seconds! However, for a system coupled to a resonant electrical circuit, the factor $8\pi\nu^2/c^3$ no longer gives correctly the number of radiation oscillators per unit volume, in unit frequency range, there being now *one* oscillator in the frequency range ν/Q associated with the circuit. The spontaneous emission probability is thereby increased, and the relaxation time reduced, by a factor $f = 3Q\lambda^3/4\pi^2V$, where V is the volume of the resonator. If a is a dimension characteristic of the circuit so that $V \sim a^3$, and if δ is the skin-depth at frequency ν , $f \sim \lambda^3/a^2\delta$. For a non-resonant circuit $f \sim \lambda^3/a^3$, and for $a < \delta$ it can be shown that $f \sim \lambda^3/a\delta^2$. If small metallic particles, of diameter 10^{-3} cm are mixed with a nuclear-magnetic medium at room temperature, spontaneous emission should establish thermal equilibrium in a time of the order of minutes, for $\nu = 10^7 \text{ sec.}^{-1}$.

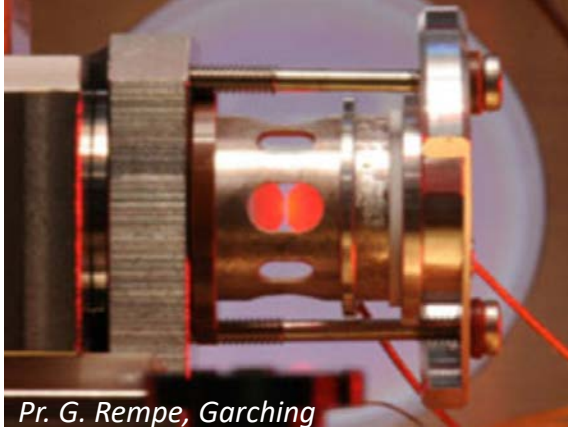
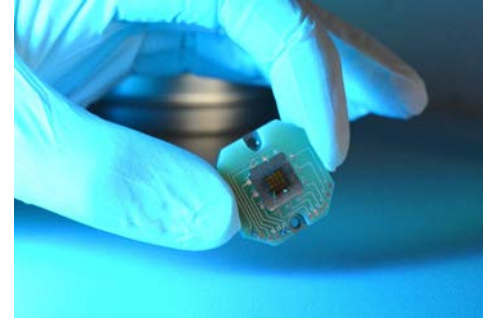
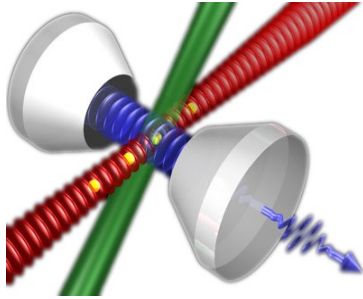
Caisse de résonance pour la lumière



Contrôler l'émission de lumière d'un atome

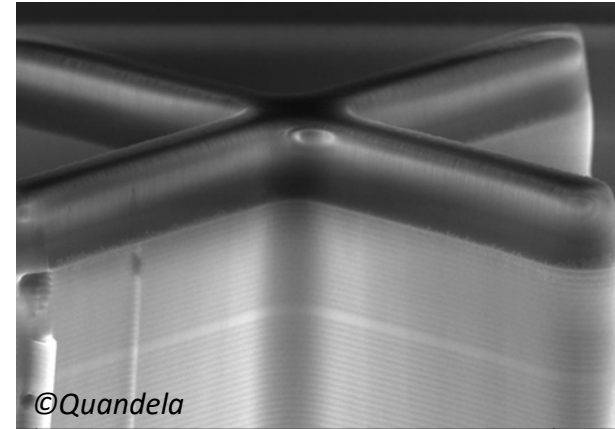


Atomes et atomes artificiels



Pr. G. Rempe, Garching

cm



©Quandela

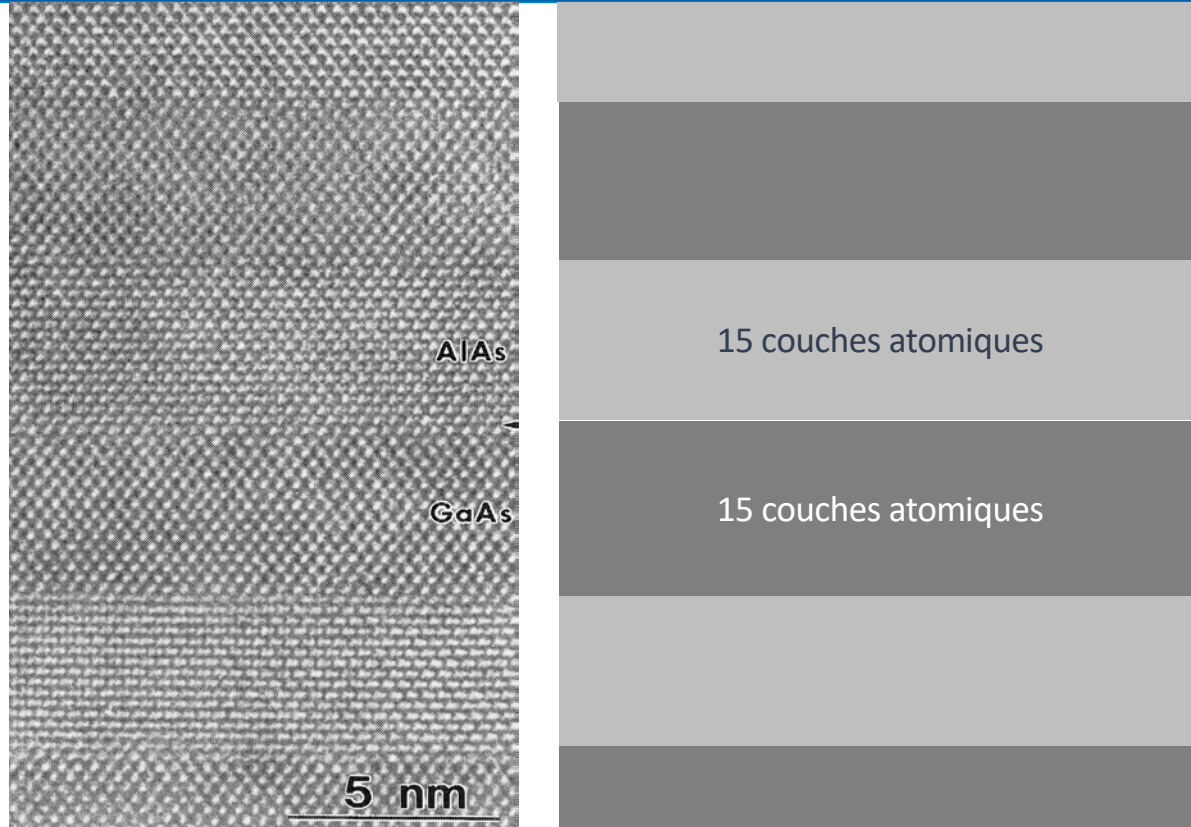
25 μm

Atomes artificiels semiconducteurs

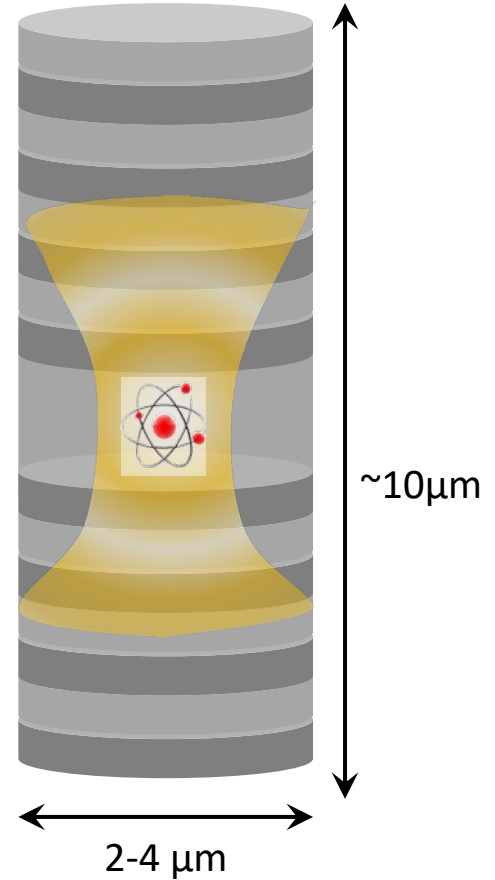
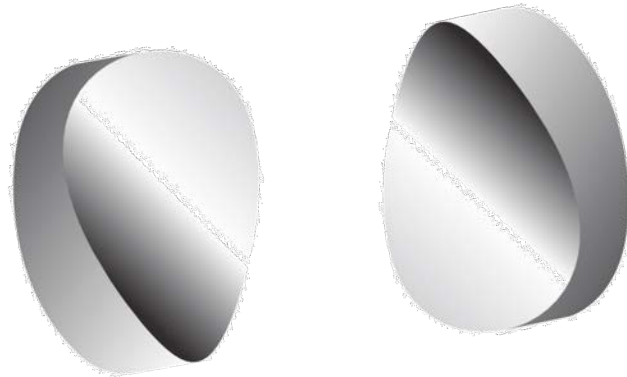
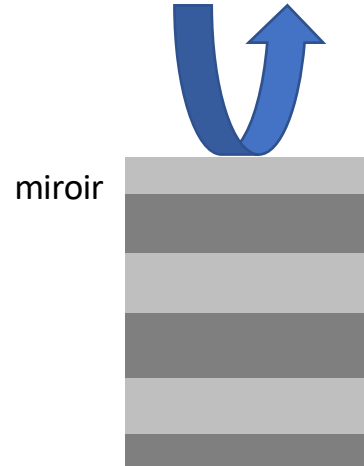
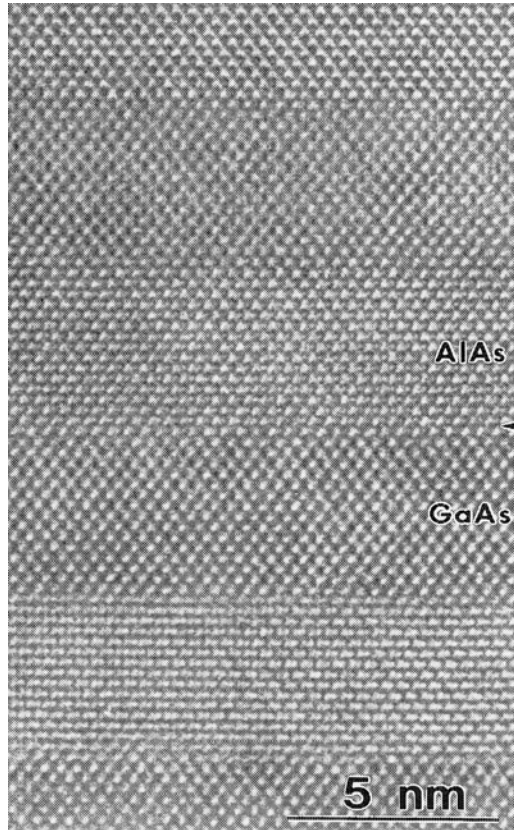


Sculpter la matière à l'échelle micro et nanométrique

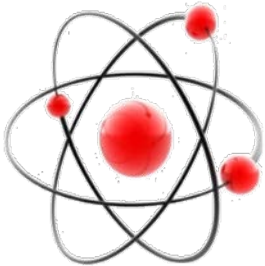
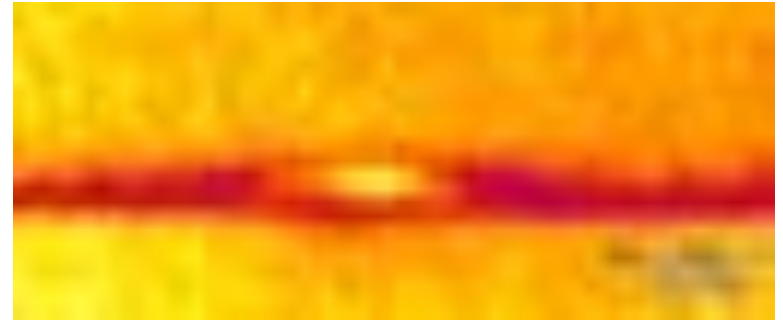
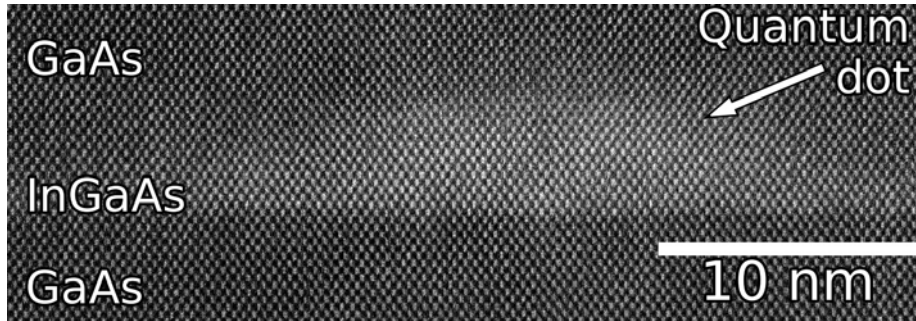
Synthèse de miroirs



Synthèse de miroirs



Boîtes quantiques – atomes artificiels



Growth by molecular beam epitaxy and characterization of InAs/GaAs strained-layer superlattices

L. Goldstein, F. Glas, J. Y. Marzin, M. N. Charasse, and G. Le Roux
Centre National d'Etudes des Telecommunications, 196 rue de Paris, 92220 France

(Received 26 July 1985; accepted for publication 4 September 1985)

1985

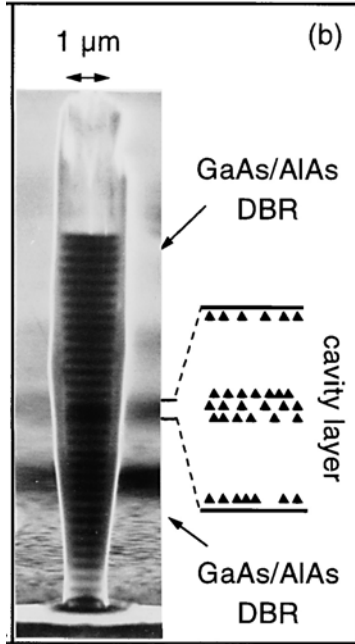
InAs/GaAs superlattices with ultra-thin InAs (few monolayer) were grown on GaAs substrates. Nucleation of InAs occurs in a two-dimensional or a three-dimensional way depending on the growth conditions. The physical properties: x ray, transmission electron microscopy, and photoluminescence were used to characterize the different growth processes.

Appl. Phys. Lett. 47, 1099 (1985)

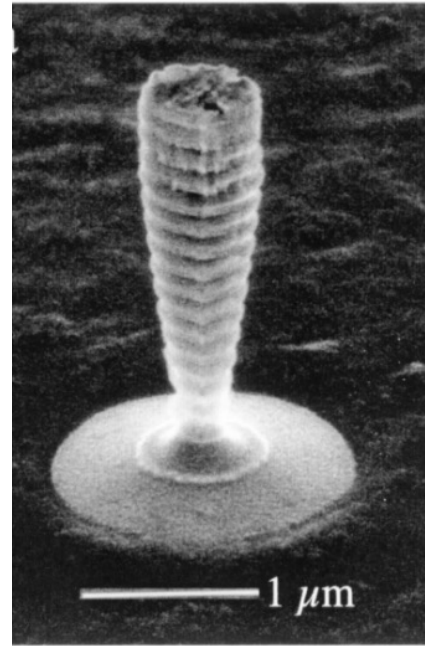
Phys. Rev. Lett. 73, 716 (1994)

Science 290, 2822 (2000)

Premières observations

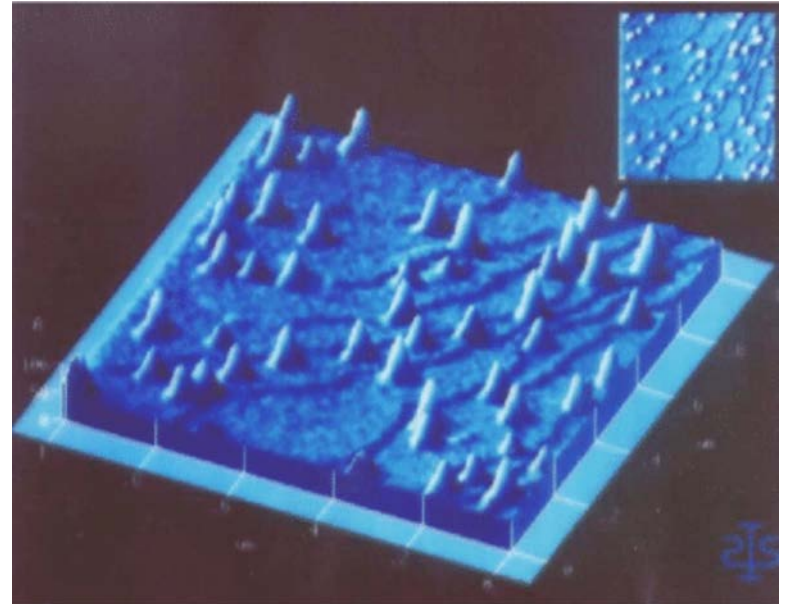


J. M. Gerard, et al.
Phys. Rev. Lett., 81, 1110 (1998)

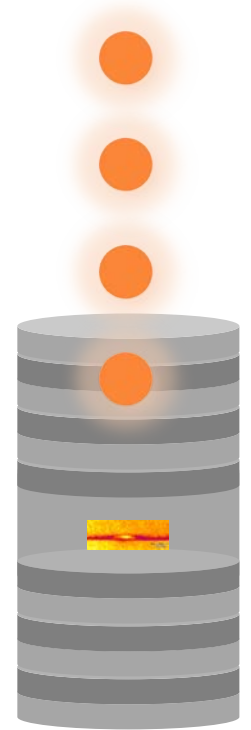
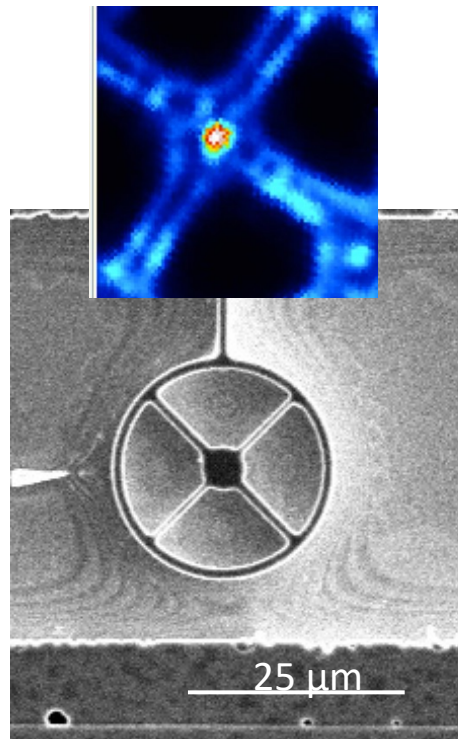
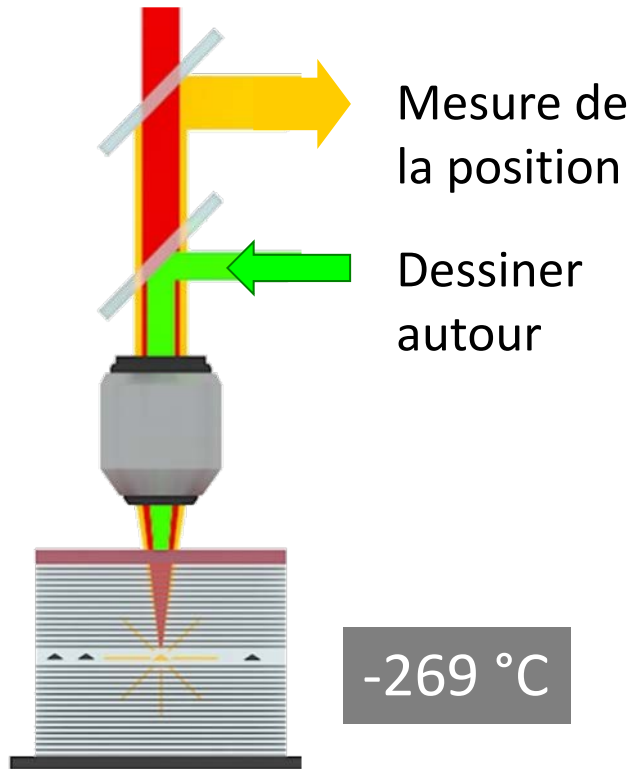


G. S. Solomon et al.,
Phys. Rev. Lett. 86, 3903 (2001)

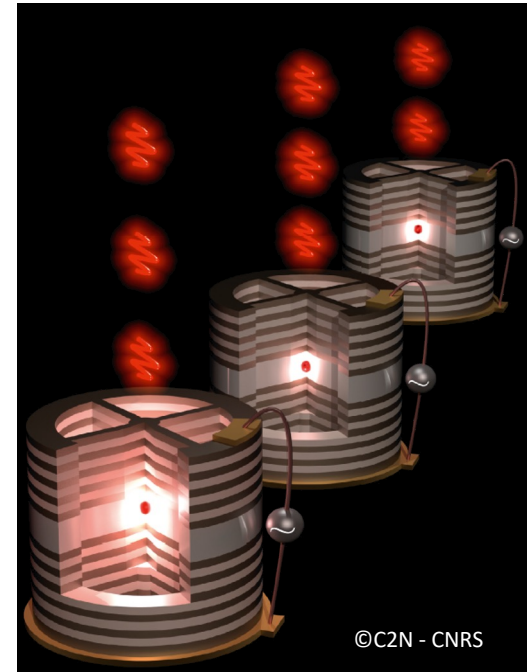
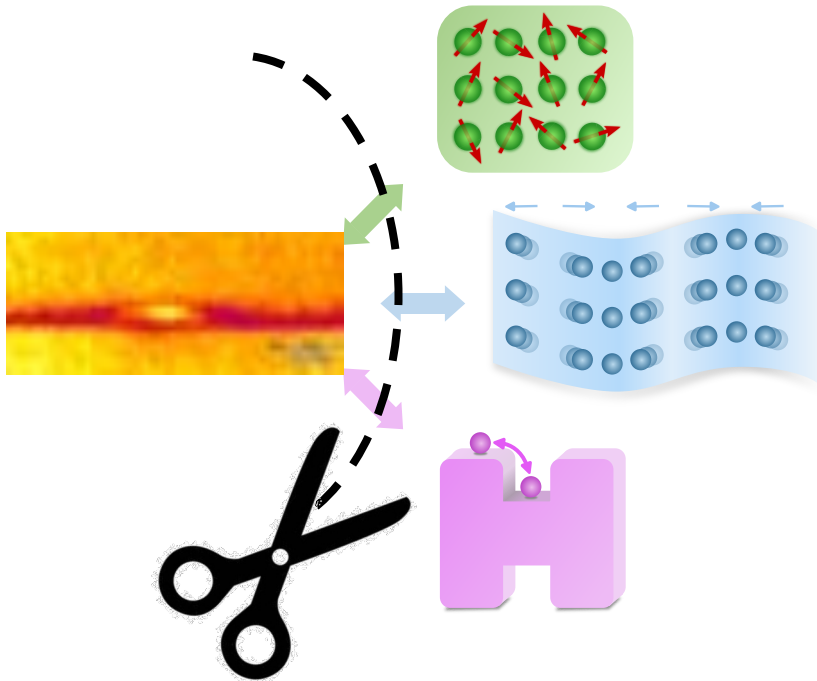
Défi technologique



Levée d'un verrou technologique



Réduction de la décohérence



*Somaschi, Giesz, De Santis et al.
Nature Photonics 10, 340 (2016)*

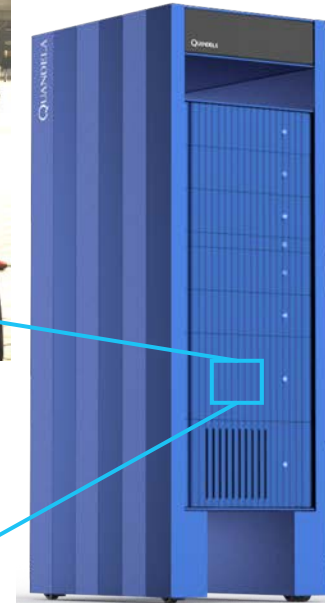
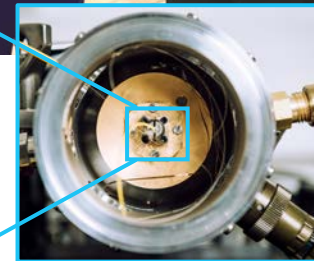
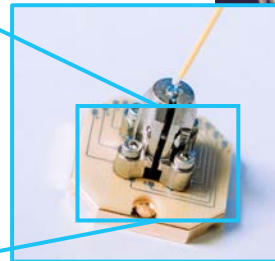
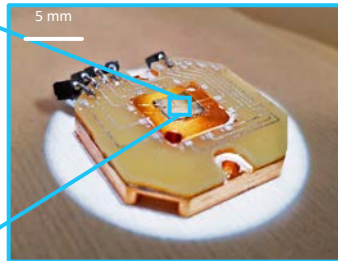
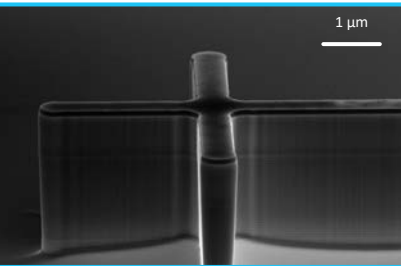
Sources de photons identiques depuis 2016

Création Quandela 2017

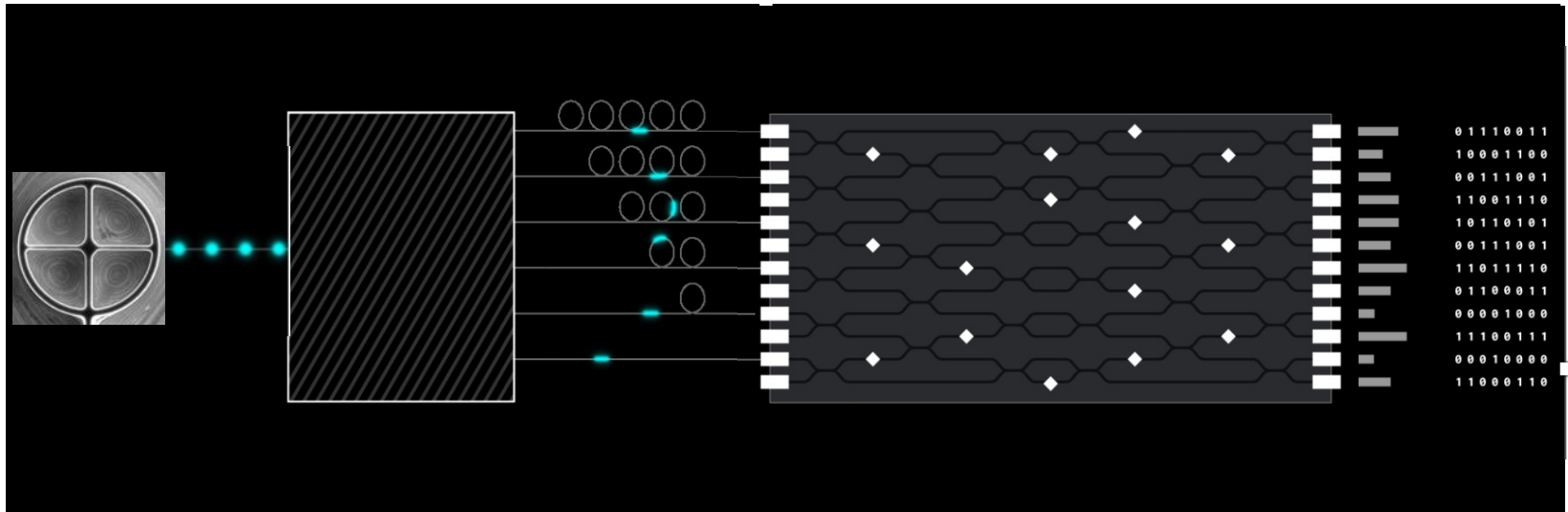
Mettre les sources de photons à la disposition de la communauté scientifique

Valérien Giesz

Niccolo Somaschi



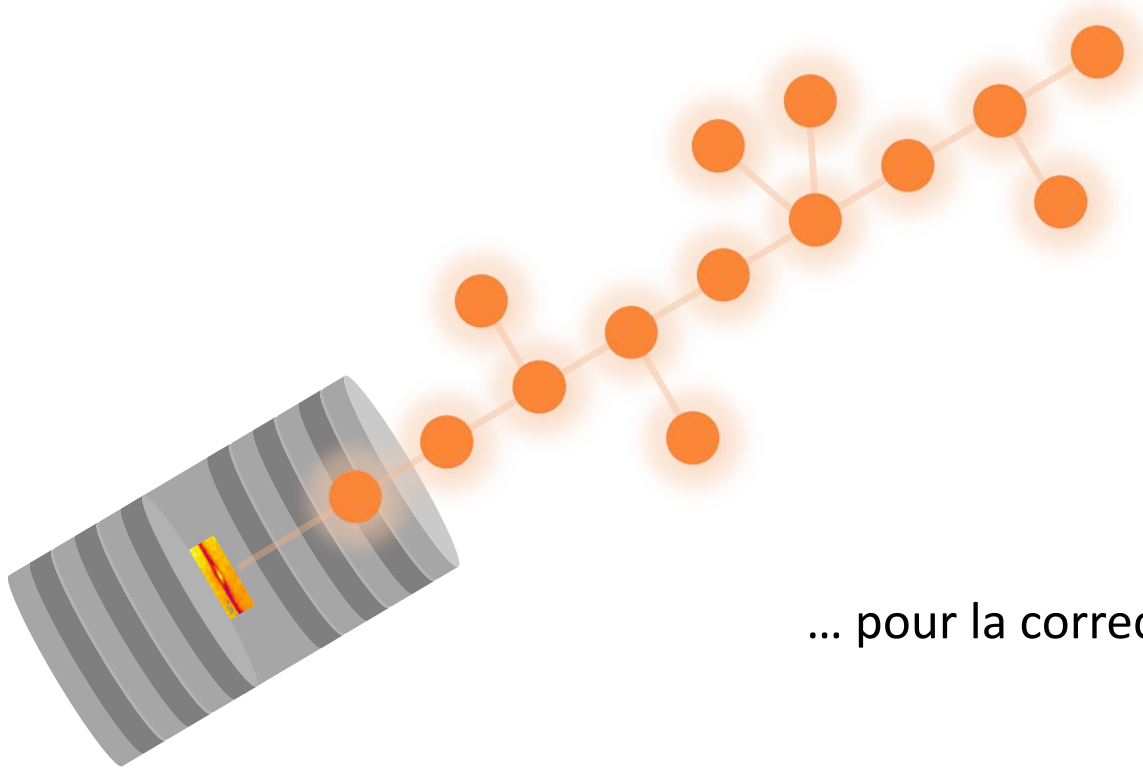
Ordinateur quantique photonique



Lucy – machine installée au CEA - TGCC

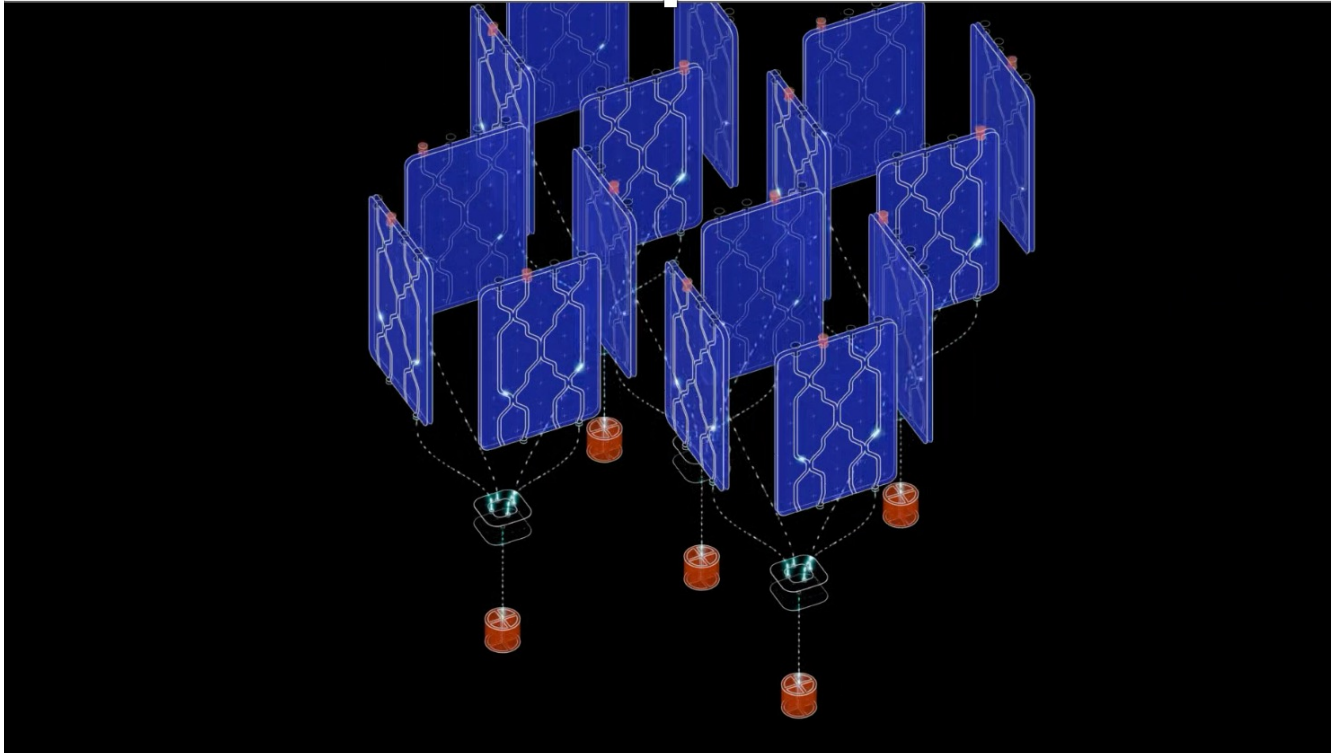


Des guirlandes de photons...



... pour la correction d'erreurs

Vers l'ordinateur universel



Une aventure collective



De l'improbable, sans variables cachées



**Arrêté du 12 février 1987 relatif à la bourse
de la vocation scientifique et technique des femmes**

NOR : ASEK8703108A

Le ministre des affaires sociales et de l'emploi,

Vu le décret n° 86-695 du 4 avril 1986 relatif aux attributions du ministre des affaires sociales et de l'emploi ;

Vu le décret n° 86-729 du 2 mai 1986 relatif à la déléguée à la condition féminine,

Arrête :

Art. 1^{er}. - La bourse de la vocation scientifique et technique des femmes doit apporter une aide financière à des jeunes filles qui désirent suivre une formation scientifique et technique dans une grande école ou un établissement d'enseignement supérieur public en vue d'obtenir une qualification d'ingénieur ou une qualification d'un niveau équivalent et que la situation économique de leur famille pourrait détourner de ces filières de formation. Cette aide leur est apportée pendant les quatre premières années de leurs études.

Art. 2. - Cette bourse est attribuée chaque année à cinquante jeunes filles à la suite d'un concours national. Un arrêté du ministre des affaires sociales et de l'emploi en fixe le montant.

Regard sur le passé – Pensées pour le futur



IBM

Seite 01 von 1
 Program: **SELEKTION UND DRUCK PRG.** Programmierer: **A. REISE** Problem: Datum: **30.05.68**

Zeile	Markiert	Operation	Operand und Bemerkungen
1	2	3	4
0.1		OFF	
0.2		CTL	6601
0.3	ABF	SQL	001
0.4		DRG	101
0.5	DRUCKB	DA	1X&0
0.6		DRG	400
0.7	START	R	
0.8		HLC	ARF+4,FELD+5
0.9	EINSPR	HLC	SCHLUS
1.0		R	
1.1		C	ARF+4,FELD
1.2		BU	EINSPR
1.3		HLC	ARF+3,DRUCKB+29
1.4		W	
1.5		R	EINSPR
1.6	SCHLUS	H	
1.7		END	START
1.8			
1.9			

IBM 1440 Autocoder

