Quantum entanglement

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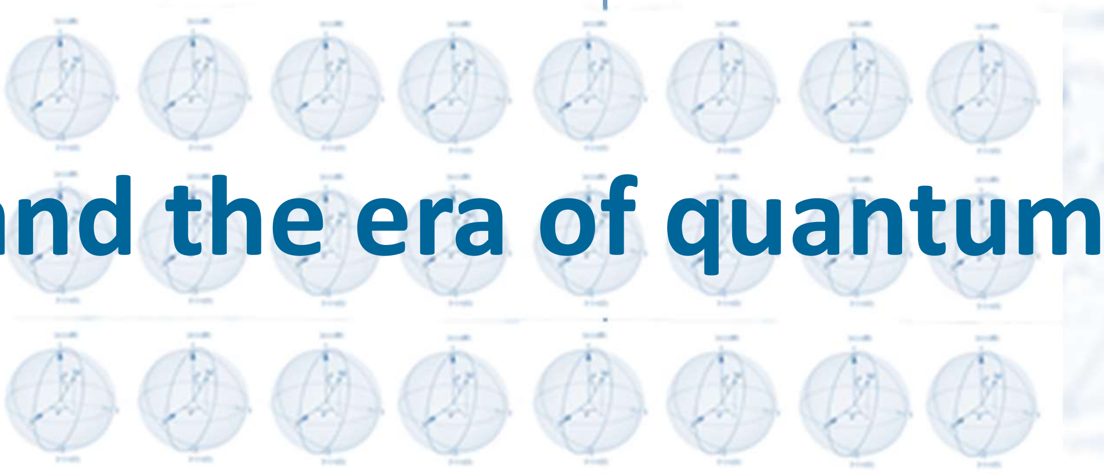

and the era of quantum technologies

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Optics & its applications 2022

Key distinctions between quantum and classical mechanics

1. **The quantum superposition principle:**

   Single quantum system

2. **Entanglement:** Composite quantum system.

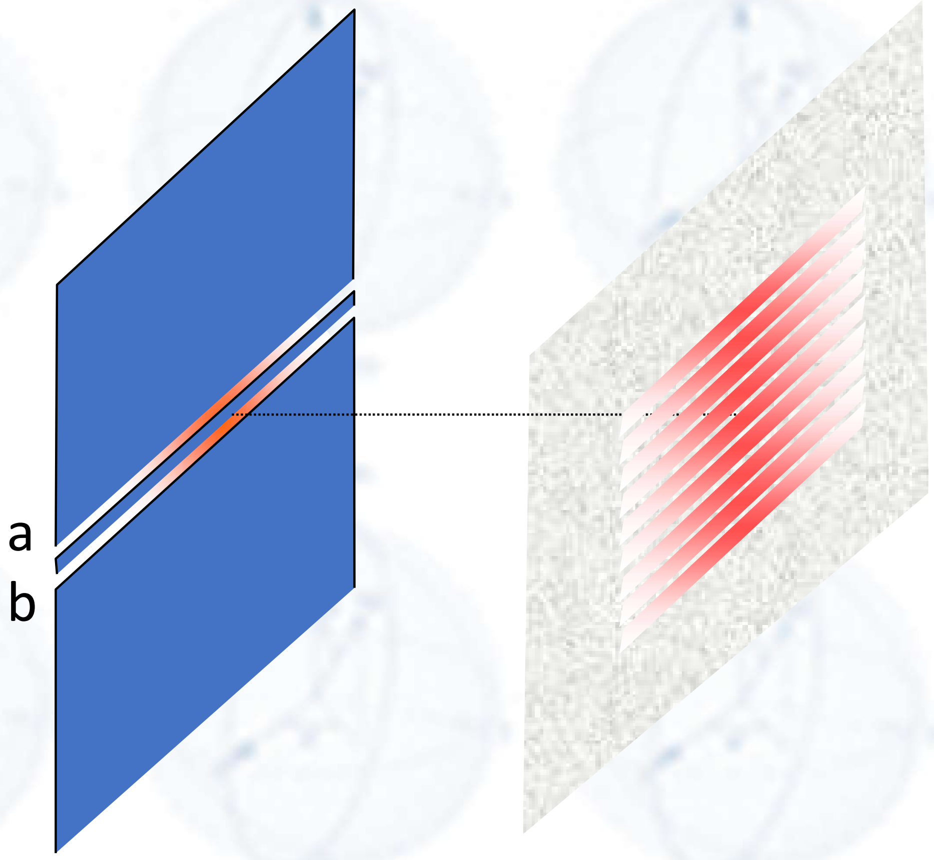
The state of parts of a quantum system, keep correlated even after spatial separation. The quantum world is nonlocal.

They challenge our binary logics and the intuitive concepts of reality and locality. But experimental observations on isolated quantum systems, have ruled in favor of QM.

Coherent quantum superposition

Feynman (Lectures, 1965) :

Young's experiment of double slits "has in it the heart of quantum mechanics"



$$|\Psi\rangle = \frac{1}{\sqrt{2}}\left(|\Psi_a\rangle + |\Psi_b\rangle\right)$$

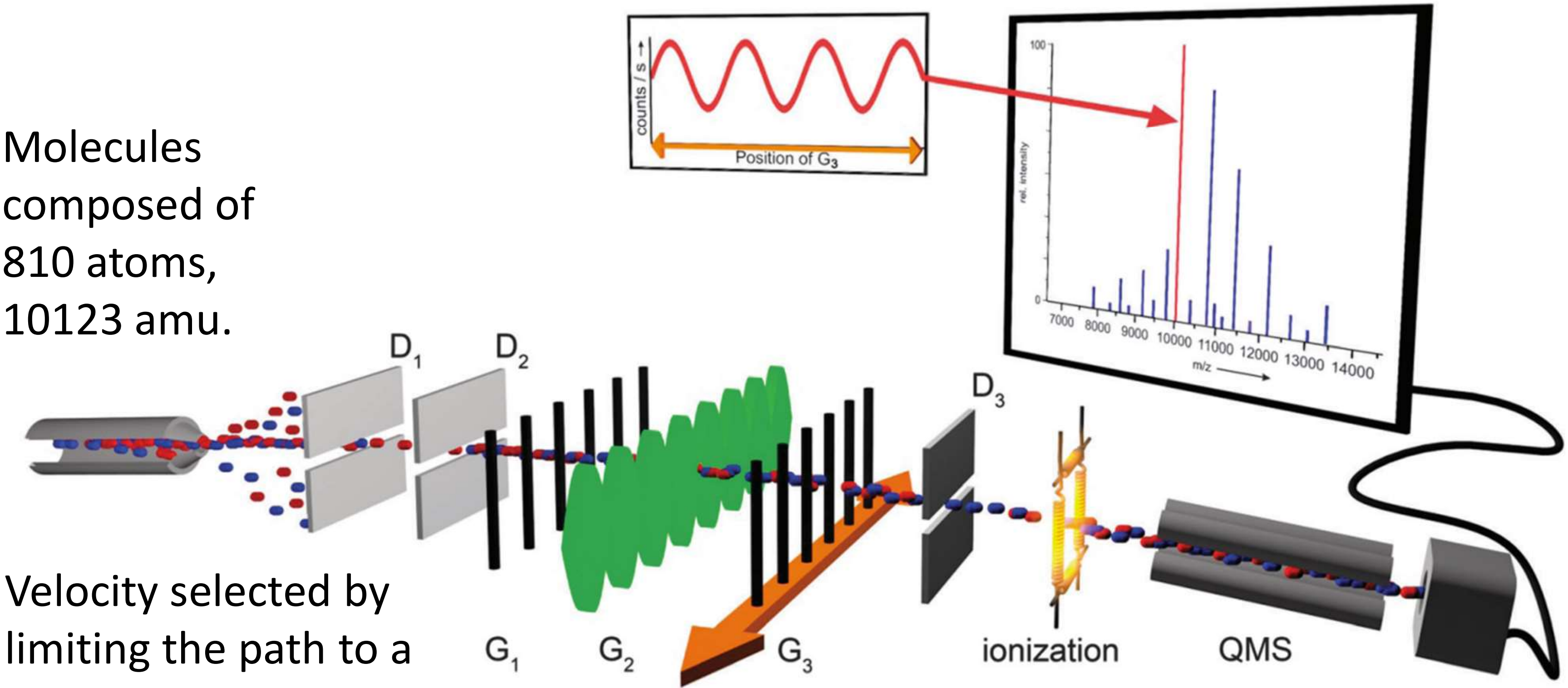
- Photons
- Electrons
- Neutrons
- Atoms
- Molecules (C^{60})
- Supramolecules

Matter-wave interference with $C_{284}H_{190}F_{320}N_4S_{12}$

S. Eibenberger et al., Phys. Chem. Chem. Phys., 2013, **15**, 14696

Kapitza–Dirac– Talbot–Lau interferometer (KDTLI)

Molecules composed of 810 atoms, 10123 amu.



Velocity selected by limiting the path to a free flight parabola

$$v = 85\, m/s$$

$$\lambda_{DB} = 500\, fm$$

Diffraction of matter–waves at an optical phase grating

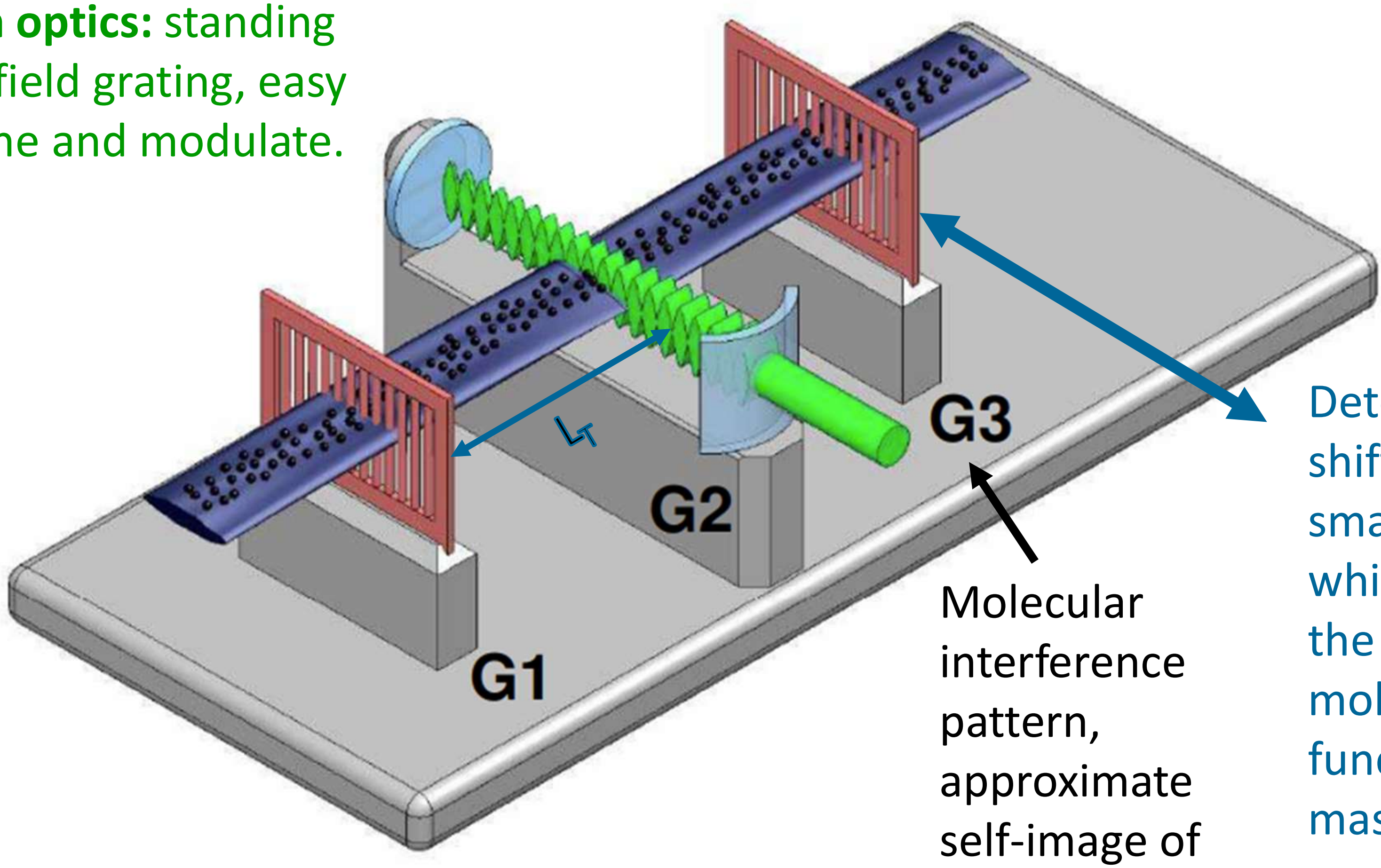
Quadrupole mass spectrometer

Kapitza–Dirac– Talbot–Lau interferometer (KDTLI)

Near field interferometry

$$d = \lambda_L/2$$

Atom optics: standing light field grating, easy to tune and modulate.



Molecular interference pattern, approximate self-image of G2 at G3

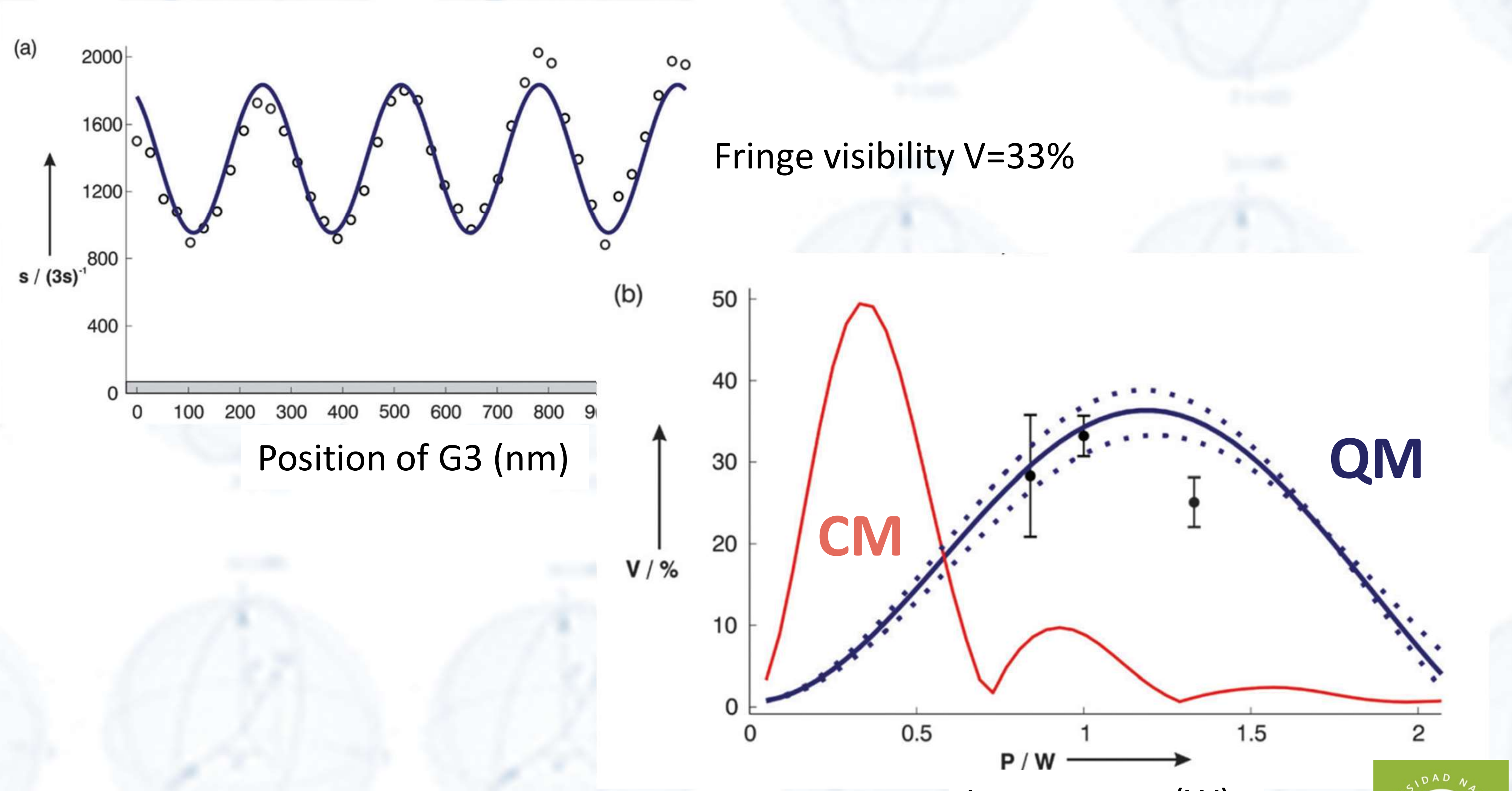
Detection by shifting G3 in small steps while counting the transmitted molecules as a function of the mask position

$$L_T = d^2/\lambda_{DB}$$

$$\lambda_{DB} = h/mv$$

Matter-wave interference with $C_{284}H_{190}F_{320}N_4S_{12}$

S. Eibenberger et al. Phys. Chem. Chem. Phys., 2013, **15**, 14696



Position of G3 (nm)

Fringe visibility V=33%

Laser power (W)

Composite quantum systems

When the superposition principle is applied to **composite systems**, it leads to the essential concept of **entanglement**.

Einstein, Podolski and Rosen (EPR) (1935).

Quantum mechanics is incomplete

Criterion of reality

"If, without in any way disturbing a system, we can predict with certainty the value of a physical quantity, then there exists an element of physical reality corresponding to this physical quantity. "

Locality

Two systems interact, and a measurement is done when they *cease* to interact. Therefore, “no real change can take place in the second system in consequence of anything that may be done to the first system”.

Einstein, A., B. Podolsky, and N. Rosen, 1935, Phys. Rev. 47, 777.

EPR

March 25

1935

Bohr

July 13

Can Quantum-Mechanical Description of Physical Reality Be Considered Complete?

Niels Bohr

Two particles in the EPR case are always parts of one quantum system and thus measurement on one particle changes the possible predictions that can be made for the whole system and therefore for the other particle.

1935

EPR
March 25

Bohr
July 13

Schrödinger
Nov 20, Dec 6, Dec 13

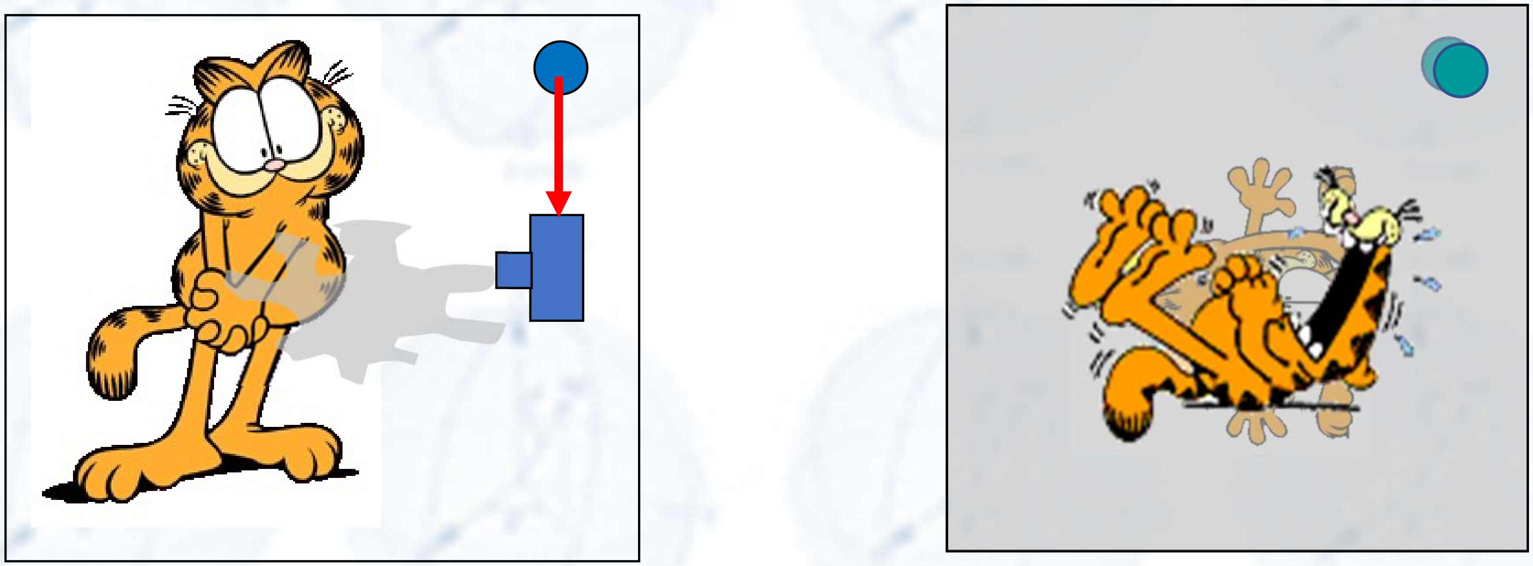
The present situation in quantum mechanics, I, II, III

You can also construct quite burlesque cases. **A cat is placed in a vault locked, along with following hell machine**: in a Geiger counter there is a tiny amount of radioactive substance, so little, that in the course of an hour perhaps one of the atoms decays, likewise but probably none; when it happens, the counter actuates through a relay a little hammer that shatters a little flask containing prussic acid. Leaving alone the system for an hour, one will think that the cat is still alive, when no atom has decayed in the meantime. The first atomic decay would have poisoned the cat.

The wave function of the whole system would be expressed as having the living and the dead cat mixed in equal parts.

The Schrödinger cat

Imaginary (Gedanken) experiment



$$|\Psi\rangle = |A, alive\rangle + |B, dead\rangle$$

Only when the box is opened (measurement of the quantum state of the cat) the wave packet "collapses" or is reduced into one of the states:

$|A, alive\rangle$ or $|B, dead\rangle$

E. Schrödinger, *Naturwissenschaften* **23** (48): 807–812.

- **1935**

EPR

Bohr

Schrödinger

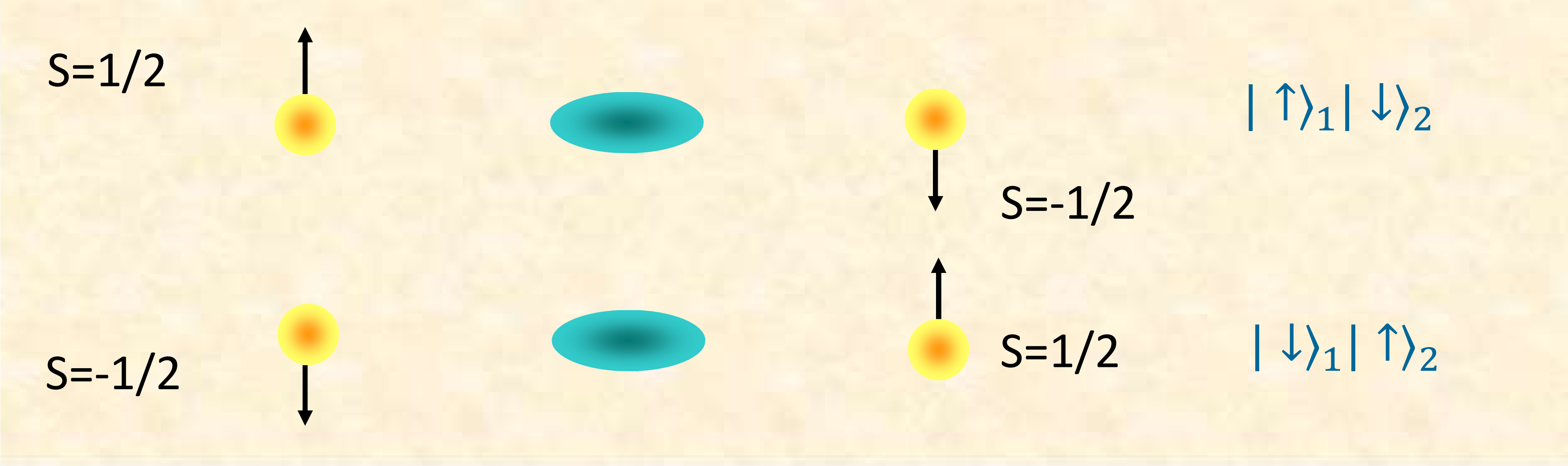
Bohm

- **1951**

Proposed experiment with diatomic molecule of total spin zero. The two atoms are separated by a method that does not influence the total spin.

D. Bohm, Quantum Theory (Prentice-Hall, Inc., New York, 1951)

Composite quantum system



Emergent quantum state of the system:

$$|\Psi\rangle_{12} = \frac{1}{\sqrt{2}}(|\uparrow\rangle_1|\downarrow\rangle_2 - |\downarrow\rangle_1|\uparrow\rangle_2)$$

Entangled!

Entangled states

$$|\Psi\rangle = \frac{1}{\sqrt{2}}\left(|\uparrow\rangle_1|\downarrow\rangle_2 - |\downarrow\rangle_1|\uparrow\rangle_2\right)$$

$|\uparrow\rangle_1|\downarrow\rangle_2$ **Measurement of spin 1: “up”**

$\Rightarrow$ **spin 2: “down”**

- Independent of the separation of the spins
- Independent of the orientation of the measurement

Hidden variables, the specification of which would predetermine the result of measuring any observable of the system.

- **1935**

EPR

Bohr

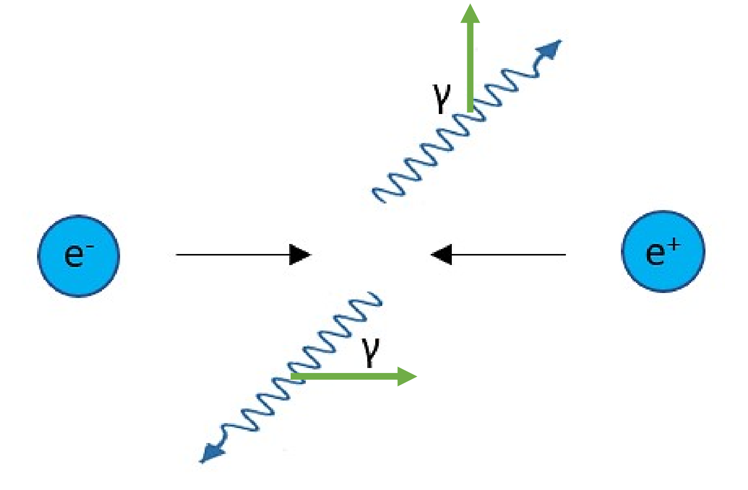
Schrödinger

Bohm

- **1951**

Bohm & Aharanov

- **1957**



Correlated photons produced in the annihilation radiation of a positron-electron pair: Two photons are emitted in opposite directions with orthogonal polarizations.

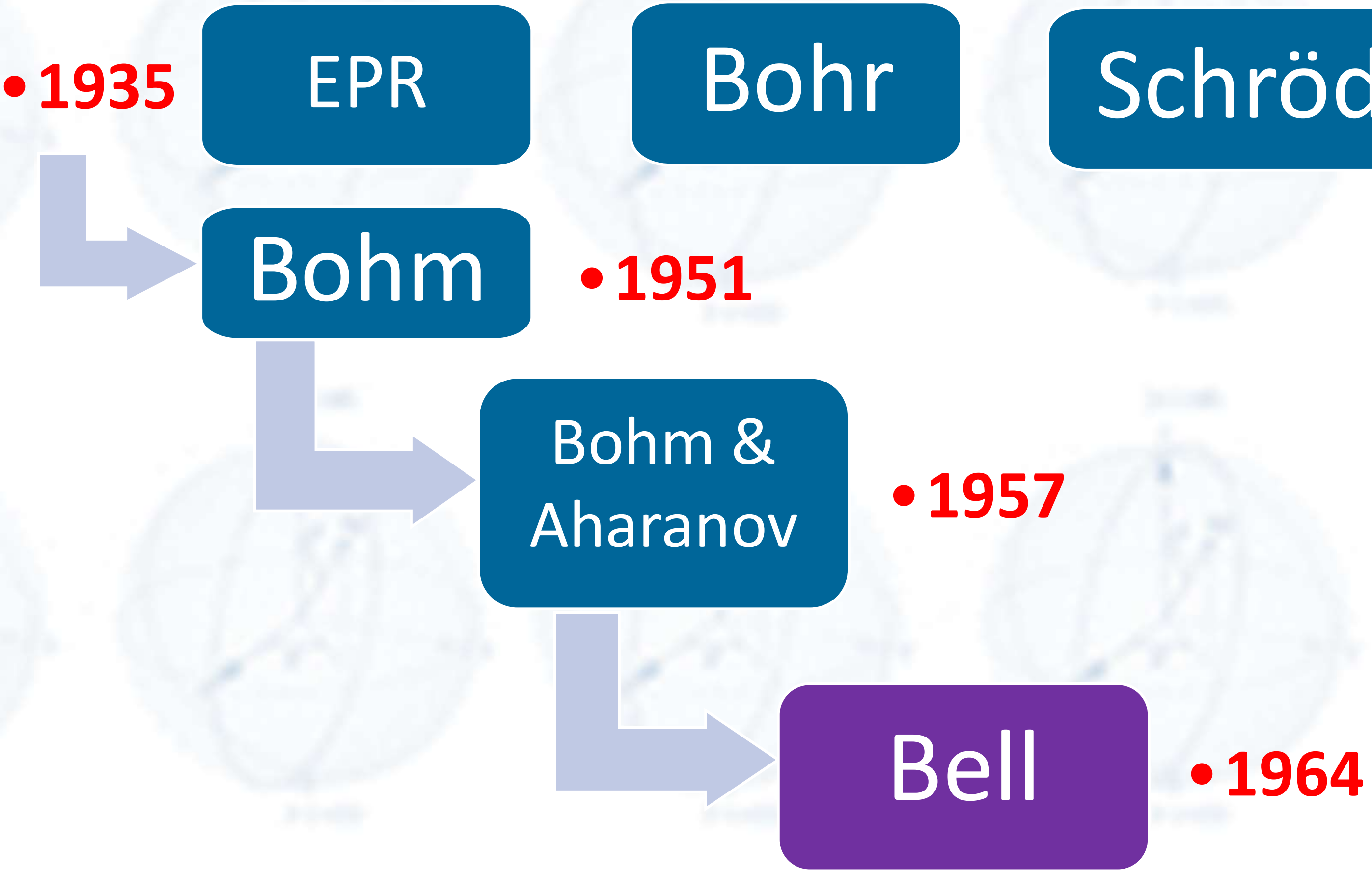
D. Bohm and Y. Aharonov, Phys. Rev. 108, 1070 (1957)

LRT

- The physical state of the emitted photons should be described completely by hidden variables (λ). A source subjected to fluctuations will produce photons with different λ.
- The values measured by two observers are only dependent on their own measurement device (locality).
- The result of the measurements is determined *a priori* by the value of λ (reality).

The results obtained by ***one*** observer must be independent of the direction of polarization selected by the ***other*** observer to do his/her measurement.

Contradiction with the predictions of quantum mechanics for entangled states.



- 1935

EPR

Bohr

Schrödinger

Bohm

- 1951

Bohm &
Aharanov

- 1957

Bell

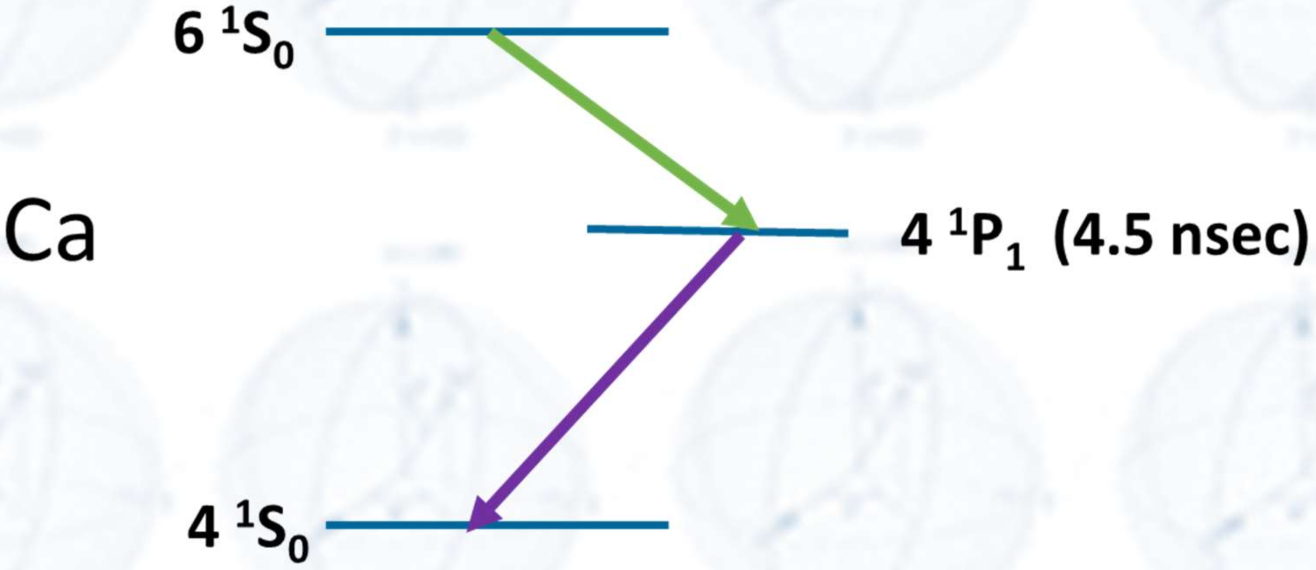
- 1964

Bell inequalities: **decisive experimental test** of the entire family of local hidden-variable theories (HV LRT)

J. S. Bell, Physics Vol. 1, No. 3, pp. 195—200, 1964

- 1935 **EPR** **Bohr** **Schrödinger**
  - **Bohm** 1951
    - **Bell** 1964
      - **Clauser et al.** 1969

Proposal: Generalization of Bell's theorem to realizable experiments



J. F. Clauser, M.A. Horne, A. Shimony and R. A. Holt, PRL 23, 880 (1969)

Bell inequalities: experiments

Polarization correlation of a pair of optical photons

- A source of correlated pair of photons that are emitted in different directions

- Each photon enters a device that determines the orientation of the polarizers and detects a photon after the polarizer.

- The information about location and time of a detection event is sent to a coincidence circuit that measures the number of events temporally correlated.

- **Trick**: to chose a linear combination of correlation functions whose value can be estimated and that allows to distinguish experimentally between LRHVT and QM.

Experimental realizations of the Einstein-Podolsky-Rosen-Bohm *Gedankenexperiment*:

Violation of Bell's Inequalities

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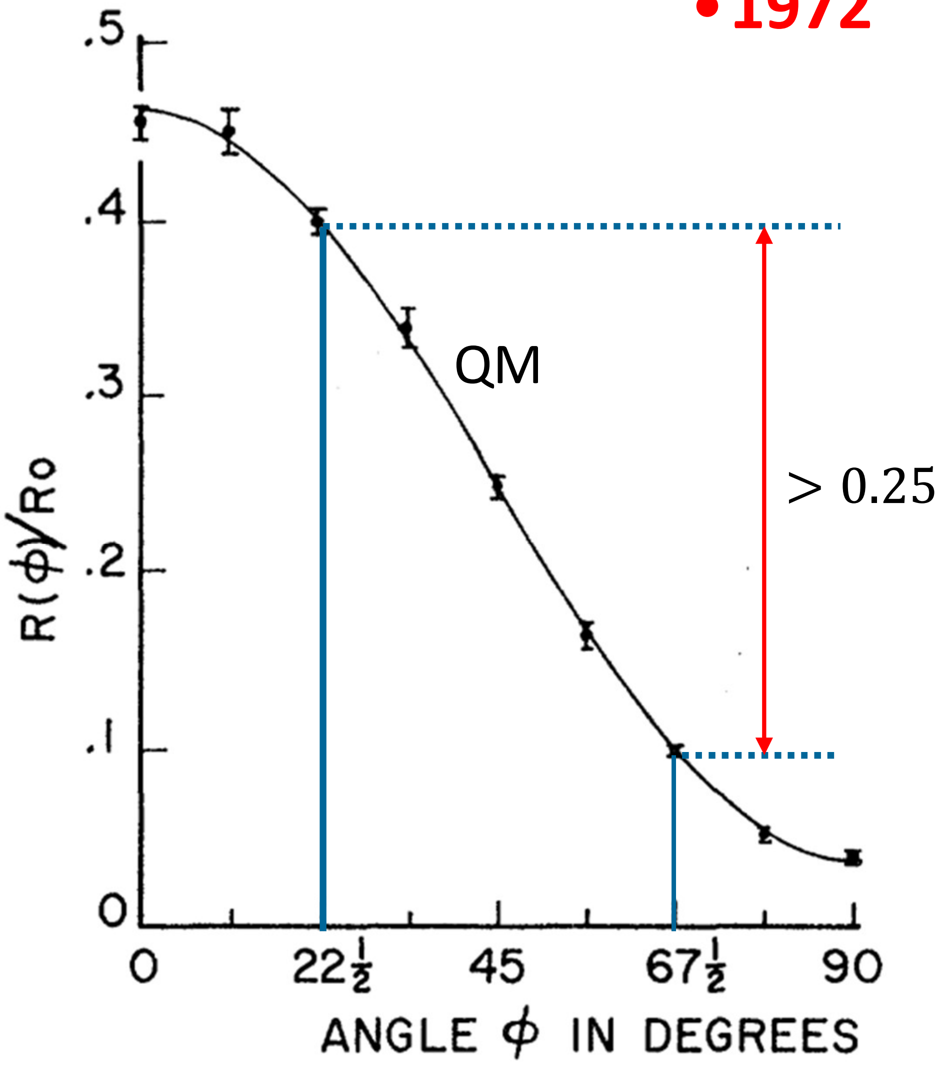
Entangled states – from theory to technology

Freeman & Clauser

- **1972**



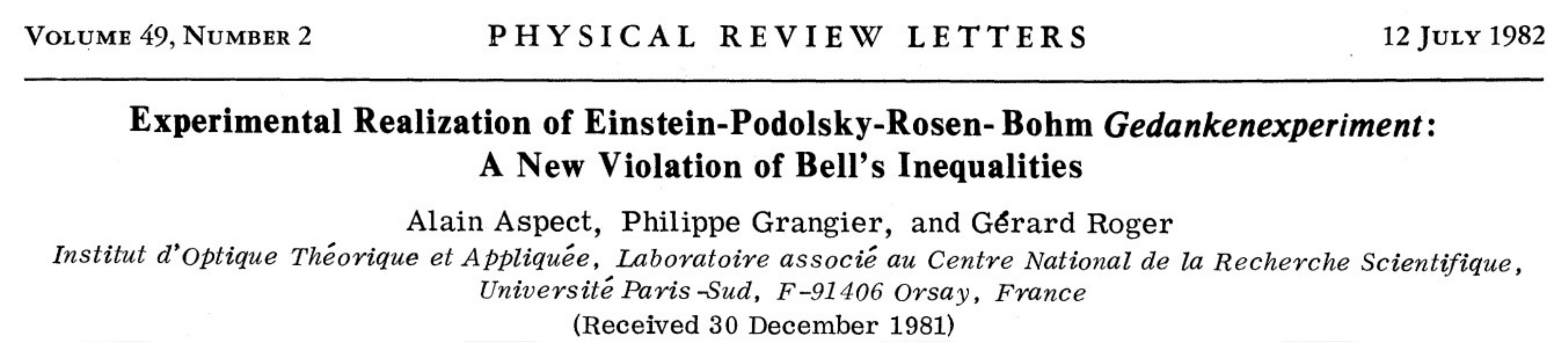
HVT

$$|R(22.5)/R_0 - R(67.5)/R_0| \leq 0.25$$

- R(ϕ): coincidence rate for two photon detection, as a function of the angle ϕ between the planes of linear polarization defined by the orientation of the inserted polarizers.
- R_o : coincidence rate with both polarizers removed.

S. J. Freedman and J. F. Clauser, PRL 28, 938 (1972)

- **1982**

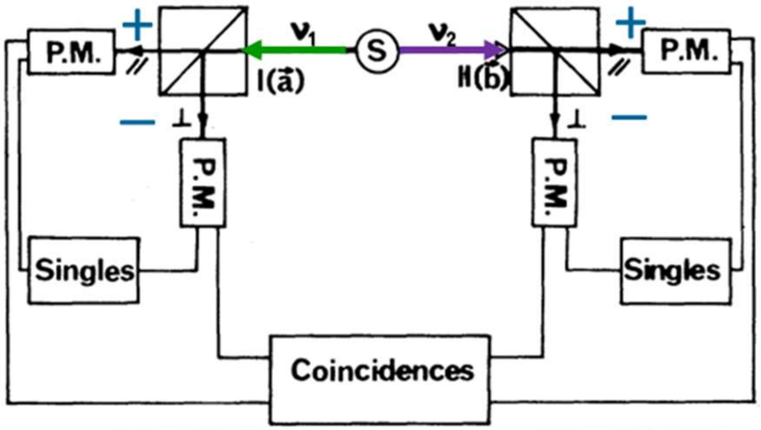


Volume 49, Number 2 PHYSICAL REVIEW LETTERS 12 July 1982

Experimental Realization of Einstein-Podolsky-Rosen-Bohm *Gedankenexperiment*: A New Violation of Bell's Inequalities

Alain Aspect, Philippe Grangier, and Gérard Roger
Institut d'Optique Théorique et Appliquée, Laboratoire associé au Centre National de la Recherche Scientifique, Université Paris-Sud, F-91406 Orsay, France

(Received 30 December 1981)



$$S = E\left(\vec{a},\vec{b}\right) - E\left(\vec{a},\vec{b'}\right) + E\left(\vec{a'},\vec{b}\right) + E\left(\vec{a'},\vec{b'}\right)$$

Bell's inequality: $-2 \leq S \leq 2$ **for LRHVT**

$$E\left(\vec{a},\vec{b}\right) = \frac{R_{++}\left(\vec{a},\vec{b}\right) + R_{--}\left(\vec{a},\vec{b}\right) - R_{+-}\left(\vec{a},\vec{b}\right) - R_{-+}\left(\vec{a},\vec{b}\right)}{R_{++}\left(\vec{a},\vec{b}\right) + R_{--}\left(\vec{a},\vec{b}\right) + R_{+-}\left(\vec{a},\vec{b}\right) + R_{-+}\left(\vec{a},\vec{b}\right)}$$

$$\left(\vec{a},\vec{b}\right) = \left(\vec{b},\vec{a'}\right) = \left(\vec{a'},\vec{b'}\right) = 22.5^o$$

$$(\vec{a},\vec{b}') = 67.5^o$$

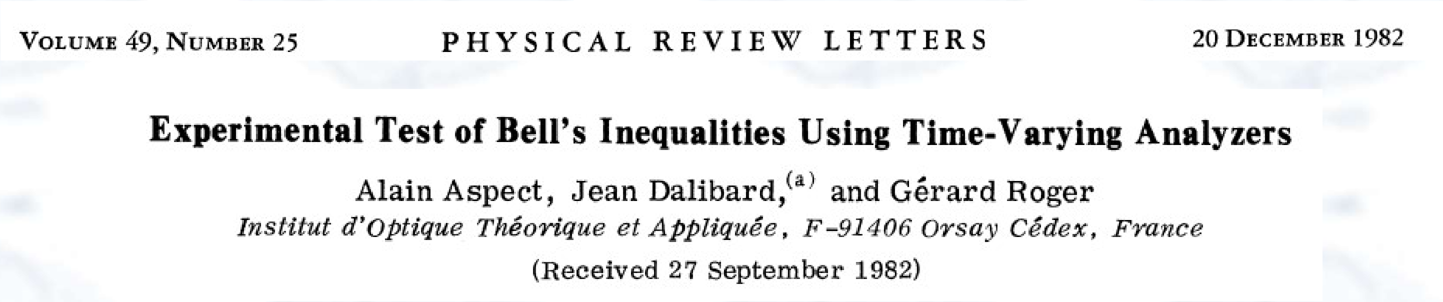
$$S_{QM} = \pm 2\sqrt{2}$$

$$S_{QM-exp} = 2{,}70 \pm 0.05$$

$$S_{exp} = 2{,}697 \pm 0.015$$

- **1982**

“We are thus led to the rejection of realistic local theories …. the static character of all previous experiments, could be ruled out by a "timing experiment" with variable analyzers”

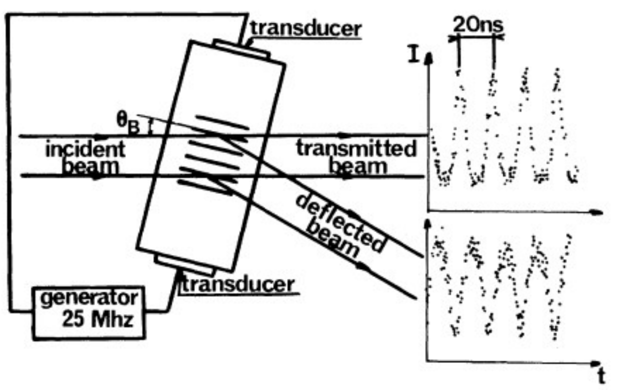


VOLUME 49, NUMBER 25 PHYSICAL REVIEW LETTERS 20 DECEMBER 1982

Experimental Test of Bell’s Inequalities Using Time-Varying Analyzers

Alain Aspect, Jean Dalibard,(a) and Gérard Roger
Institut d’Optique Théorique et Appliquée, F-91406 Orsay Cédex, France

(Received 27 September 1982)



Two switching devices followed by two polarizers in two different orientations. Each combination is equivalent to a polarizer switched fast between two orientations in a time short compared with the transit time of the photon

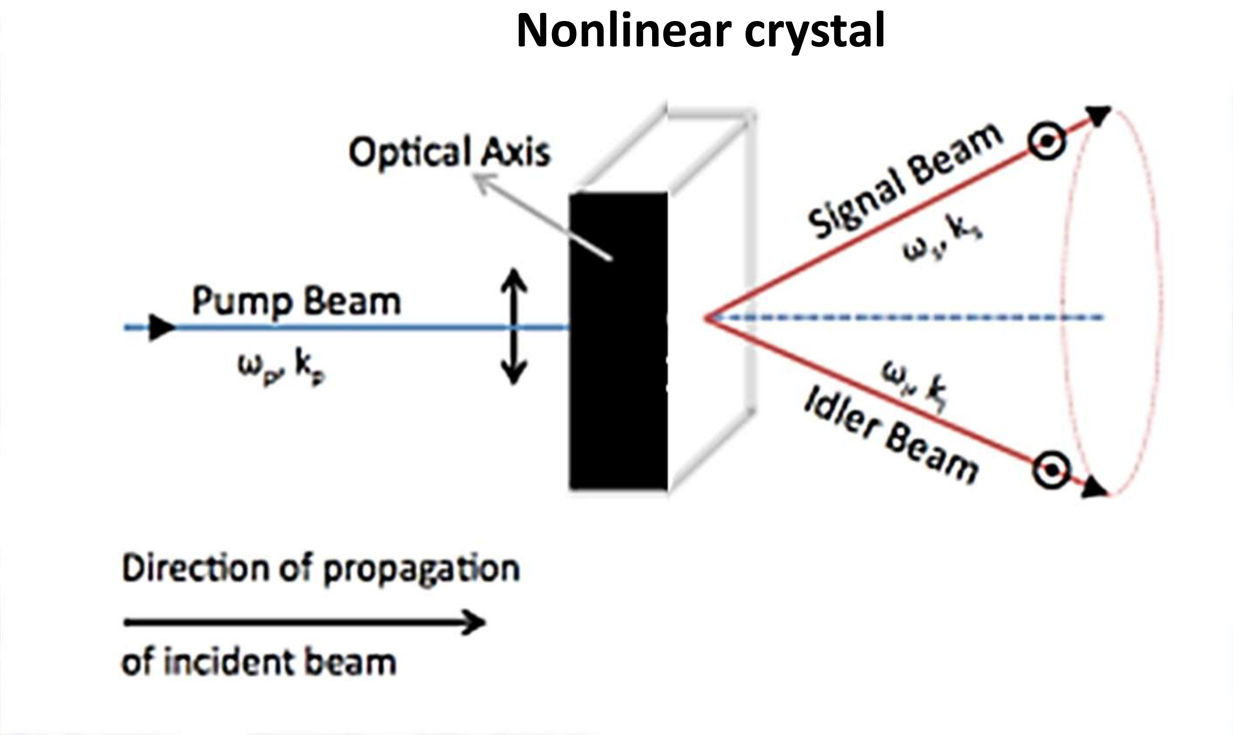
Bell’s inequality $-1 \leq S \leq 0$ $S_{QM} = 0.112$ $S_{\text{exp}} = 0.101 \pm 0.020$

5 standard deviations!

But the polarizer separation (12 m) was too small to allow for a truly random resetting of the polarizers.

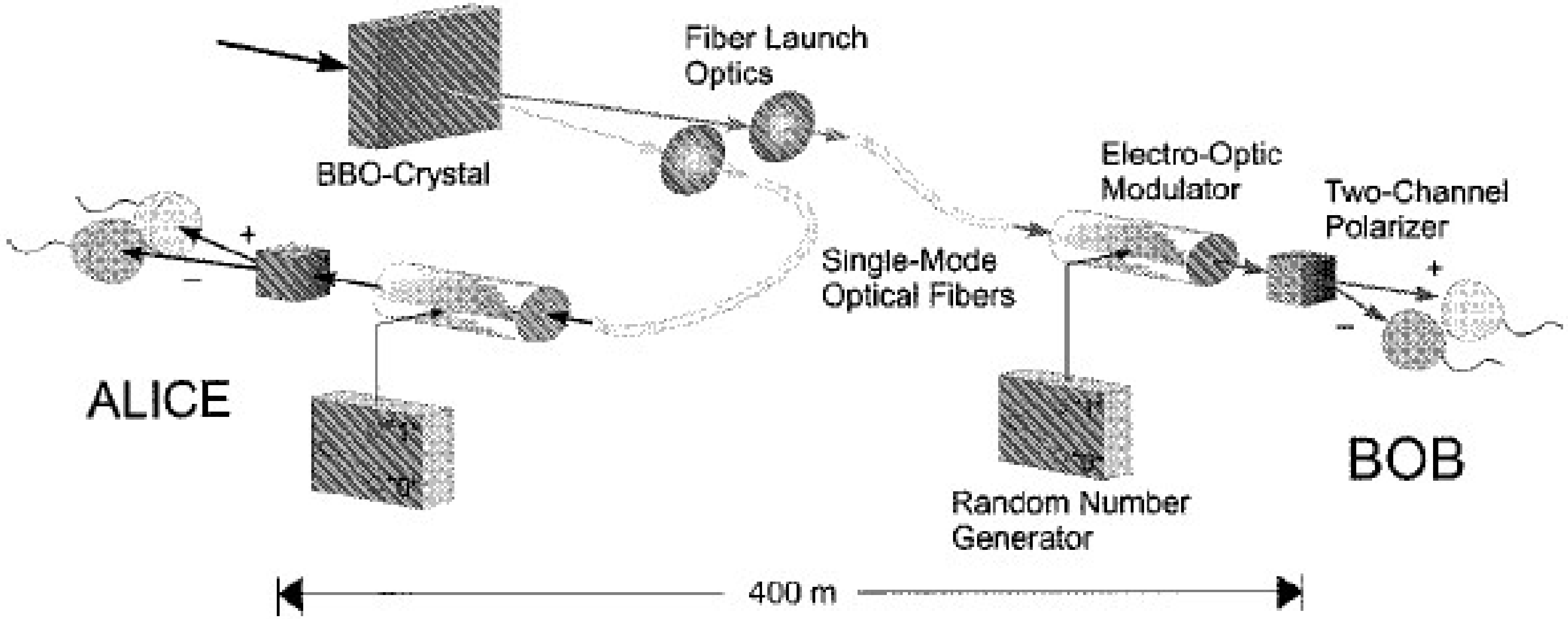
- **1988**

New generation of experiments with photon pairs using optical PDC



Y. H. Shih and C. O. Alley, Phys. Rev. Lett. 61, 2921 (1988)

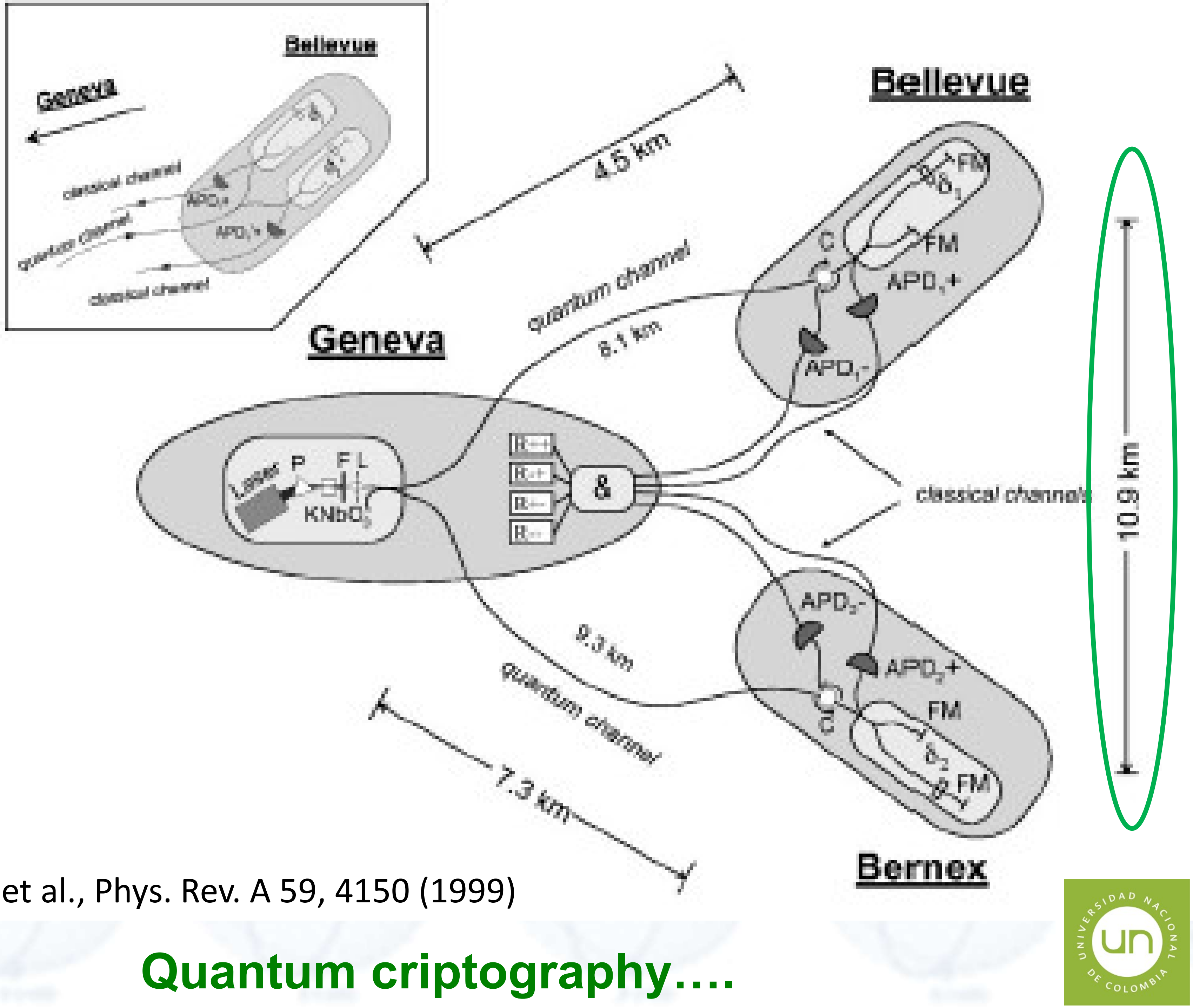
- **1998** **Long distance;** Weihs, G., Jennewein, T., Simon, C., Weinfurter, H. & **Zeilinger, A.** Phys. Rev. Lett. 81, 5039–5043 (1998).



Independent observers

Random number generators decide the direction for the polarization measurement when the photon is already on flight.

- 1999



W. Tittel et al., Phys. Rev. A 59, 4150 (1999)

Quantum criptography….

“It is still not obvious to me that there is not a real problem…. I have been always entertained by squeezing the difficulties of quantum mechanics into a smaller corner each time, so that I am worried with this issue in particular. It seems almost ridiculous that the discussion might be reduced to the numerical problem of one thing being larger than other. But there we have it — it is larger...”.

Richard Feynman.

“Yes, it is larger by 30 standard deviations”.

A. Aspect

Conclusion?

- **1999**

“The experimental violation of Bell’s inequalities confirms that a pair of entangled photons separated by hundreds of metres must be considered a single non-separable object — it is impossible to assign local physical reality to each photon. In some sense, both photons keep in contact through space and time.”

The non separability does not imply the possibility of communication at velocity higher than that of light. In Weihs experiment the correlation changes the results immediately when the direction of one of the polarizers is changed. There is no time for signal propagation.

NO quantum separability

Alain Aspect, *Nature* **volume 398**, pages189–190 (1999)

What is “entanglement”?

J. Bell: ….a correlation stronger that any classical correlation.

D. Mermin ….a correlation that contradicts the theory of elements of reality.

A. Peres “ …a magic trick that the quantum magicians use to produce phenomena that can not be imitated by the classical magicians.”

C. Bennett … a means for quantum **teletransportation**.

P. Shor … a global structure of the wave function that allows the creation of faster **algorithms**.

A. Ekert … a tool for **secure telecommunication**

The era of quantum technology

- Quantum computing
- Quantum communication
- Quantum teleportation
- Quantum sensing

The US National Quantum Initiative

Quantum Information Science and Technology

Signed on December 21 of 2018

- **Quantum communication:** security of data transported in information networks.
- **Quantum sensors**: acceleration, rotation, gravitational and EM fields. Applications in biomedicine, GPS, mineral prospecting and buried structures.
- **Quantum computing**: solve intractable problems with the best conventional supercomputers. Applications: Crack encryption codes by prime factorization, simulate structures of complex molecules or materials to accelerate new drug discovery, improve solar collectors, and optimize complex logistics, finance, and pattern recognition models.

The quantum computer

Feynman (1985)

“It seems that the laws of physics present no barrier to reducing the size of computers until the bits are the size of the atoms, and quantum behavior holds dominant sway.”

“Nature isn’t classical dammit, and if you want to make a simulation of Nature you better make it quantum mechanical, and by golly it’s a problem because it doesn’t look so easy.”

The quantum computer should solve quantum problems in physics and chemistry, hard to solve with classical computers.

The quantum computer

Sebastian Blatt,
technical director of planqc

“Systems with many quantum particles cannot be simulated on classical computers. Even the best supercomputers in the world can manage maybe 30 or 40 particles.” How can this problem be avoided?
"You simply recreate the quantum systems in analog simulations, which themselves consist of many quantum particles, and observe what happens."

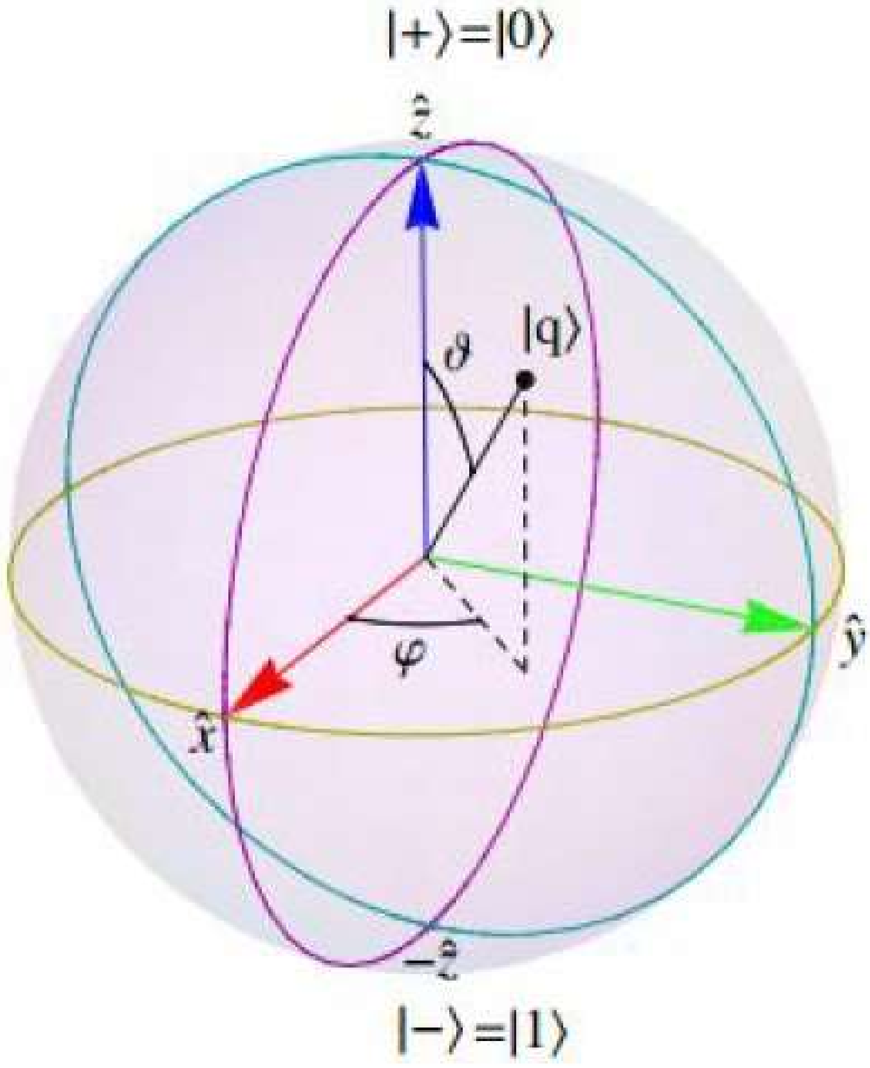
Bits: “0” & “1”

↓

Qubit

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

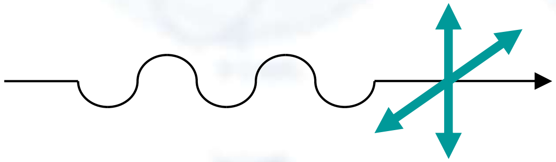
$$|\alpha|^2 + |\beta|^2 = 1$$



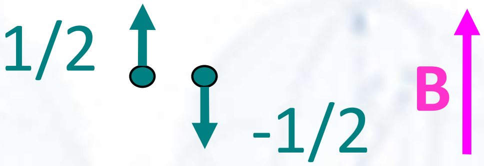
Qubits

Quantum two-level systems

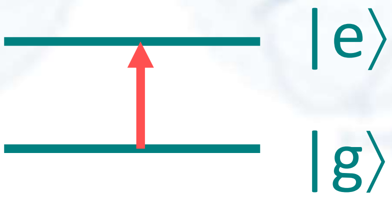
- Polarization of a photon



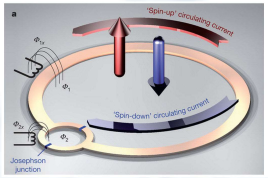
- Particle with Spin 1/2



- Two-level atoms

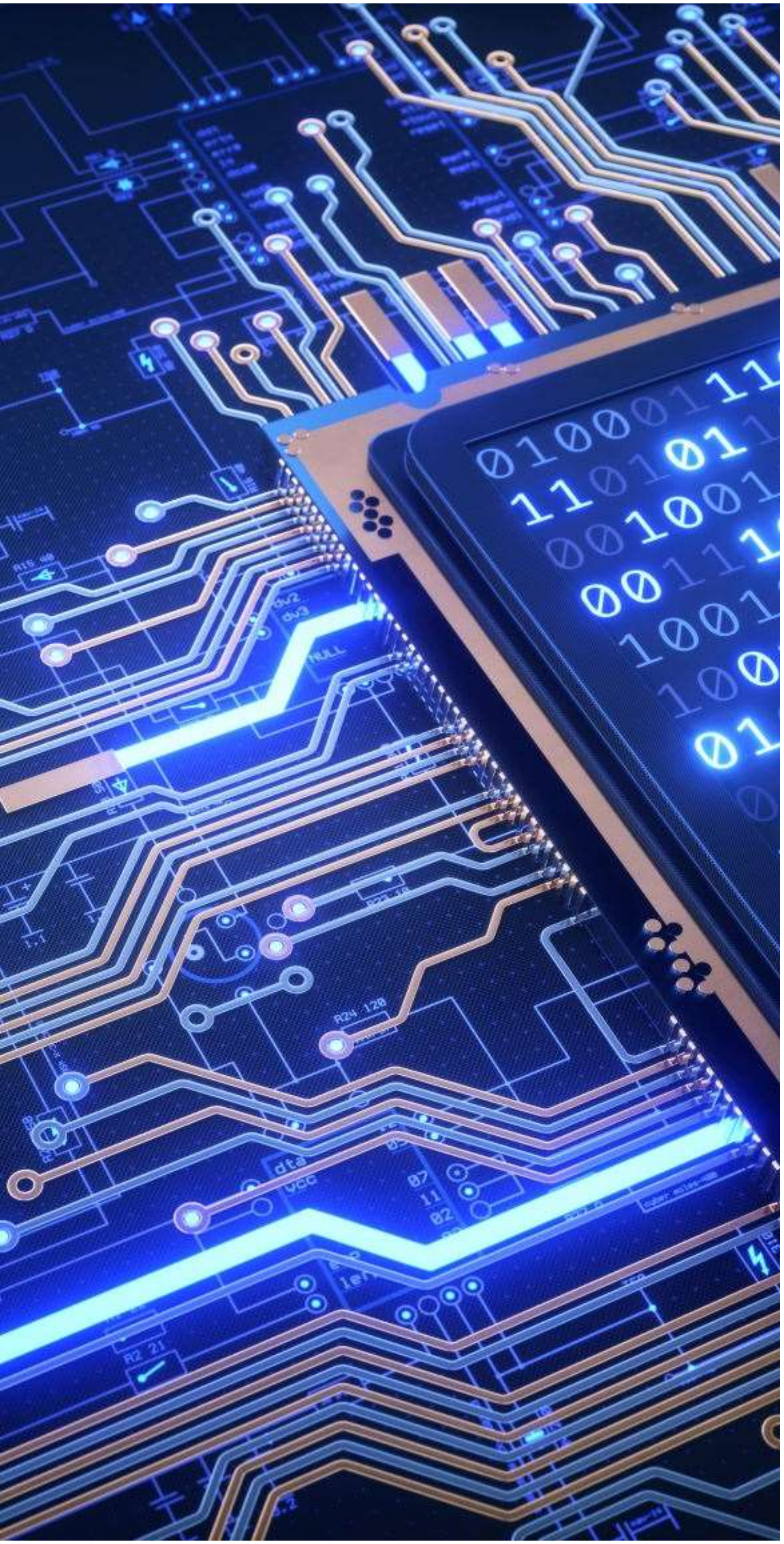


- Josephson junction: qubit of flux



Credit D-Wave

- Molecular nanomagnets, supramolecular assemblies and biomolecules



Di Vincenzo’s criteria of viability for a quantum computer (2000)

- A **scalable physical system** with well-characterized qubits.
- The ability to **initialize** the state of the qubits to a simple fiducial **state**.
- **Long (relative) decoherence times** much longer than the gate-operation time.
- A **universal set of quantum gates**.
- A **qubit-specific measurement capability.**

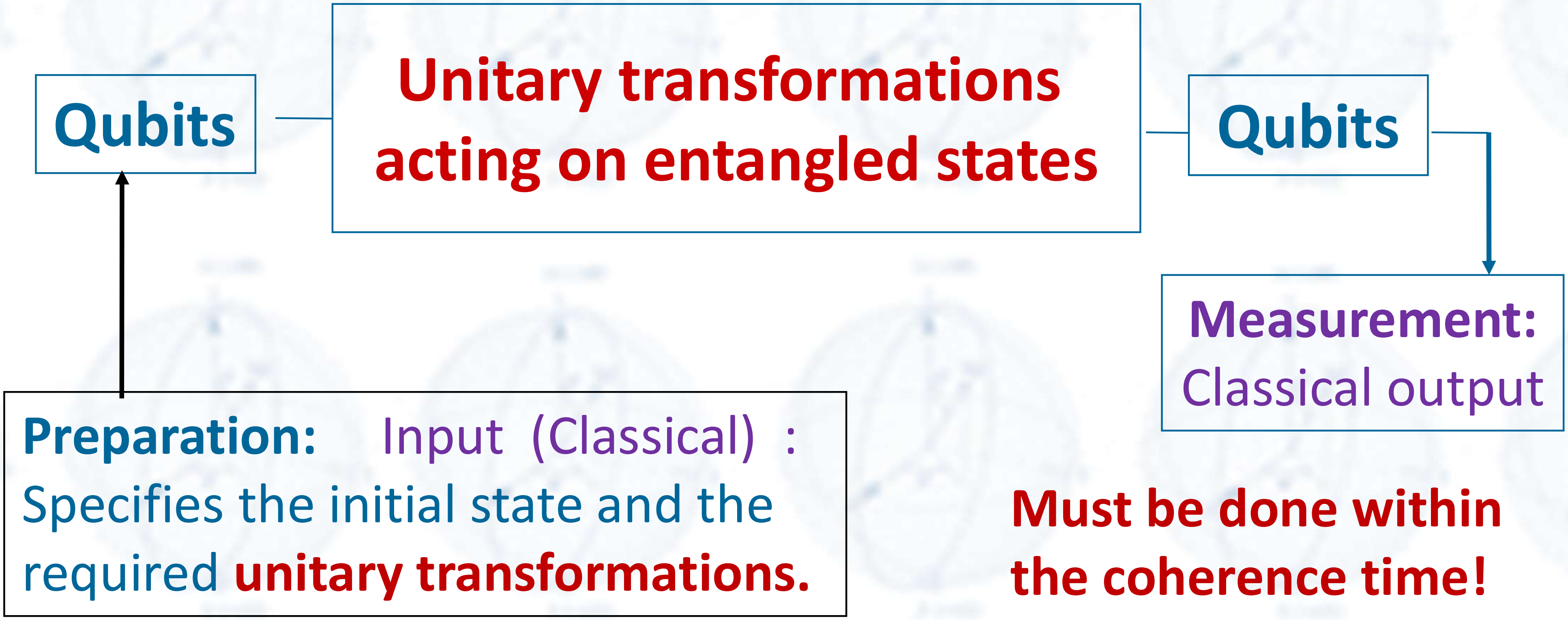
CLASSICAL COMPUTING

Bits

Boolean operations

Bits

QUANTUM COMPUTING



Qubits

Unitary transformations acting on entangled states

Qubits

Measurement: Classical output

Preparation: Input (Classical) : Specifies the initial state and the required **unitary transformations.**

Must be done within the coherence time!

Unitary transformations

N-qubit states

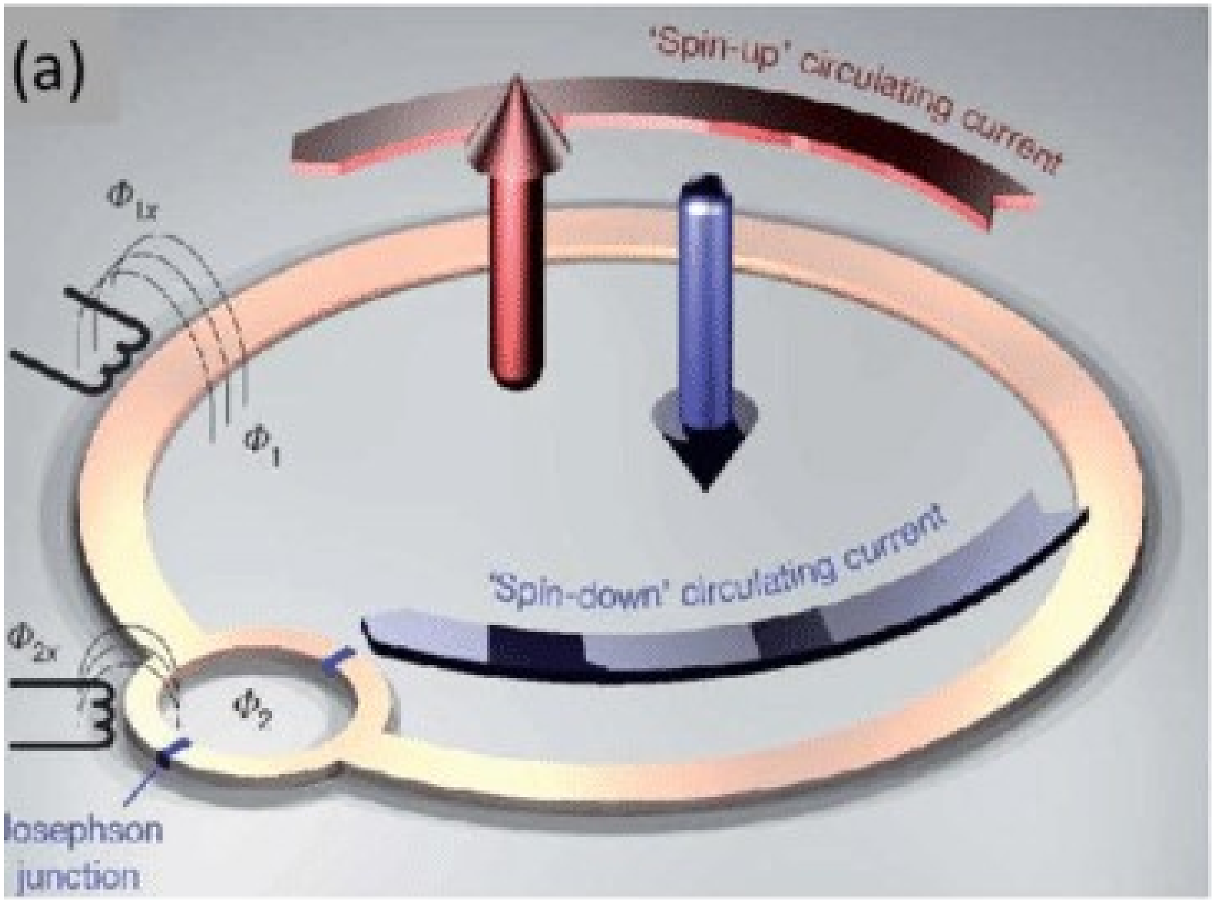
A N-qubit quantum state, where each qubit has two posible states $|0\rangle$, $|1\rangle$ results in **2^N different quantum states of the system**

$$|\psi\rangle = a\,|011100101...\rangle + b\,|111010001...\rangle + ...$$

$$U|\psi\rangle = U\,a\,|011100101...\rangle + U\,b\,|111010001...\rangle + ...$$

Each term makes its own calculation in parallel

Measurement



Superconducting qubits

IBM

Google

Rigetti

D-Wave

Quantum circuits

Quantum Summit 2022:

- **IBM OSPREY Processor: 433 qubits**
- 2023: Condor processor 1121 qubits
- 2025: 4000 qubits

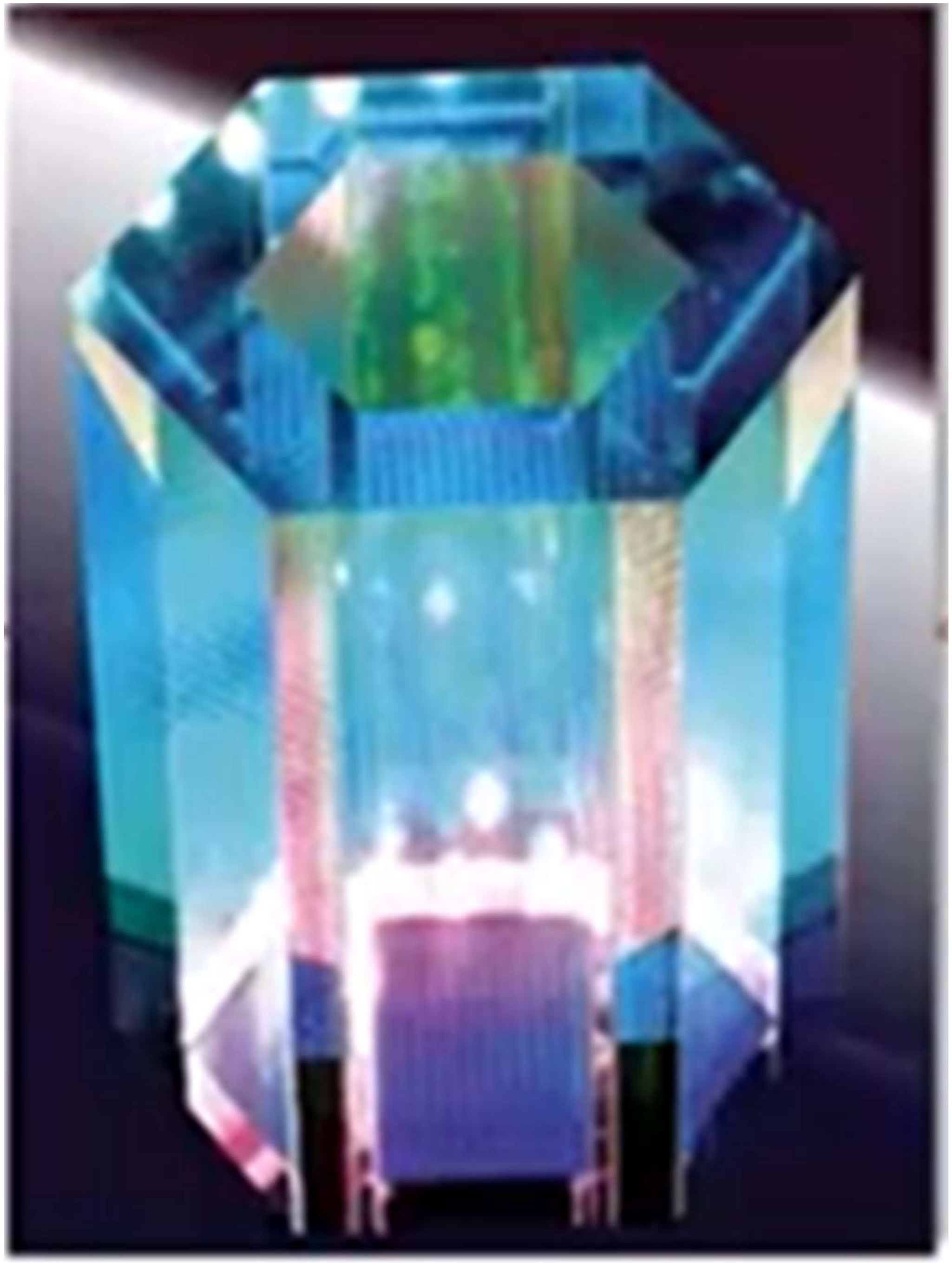
Cold atom qubits

ColdQuanta

QuEra

Planqc

Atom computing



Cold neutral atoms

Optical lattices

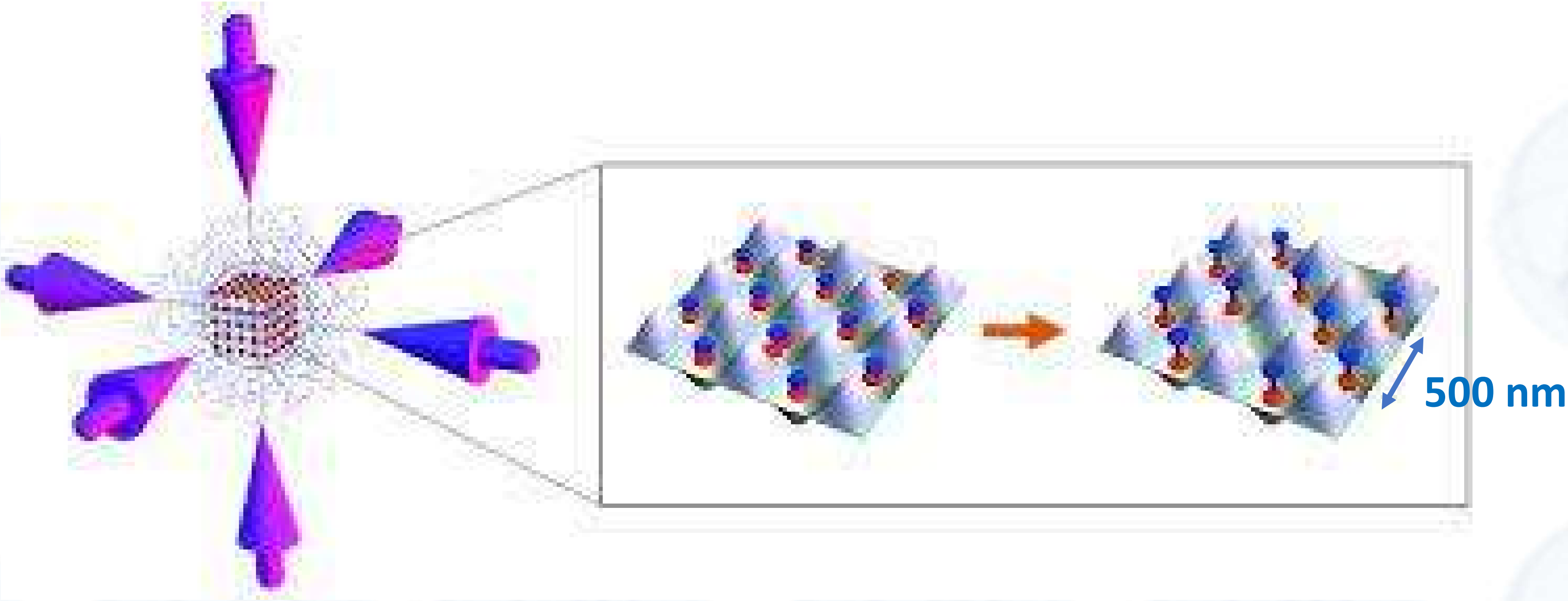
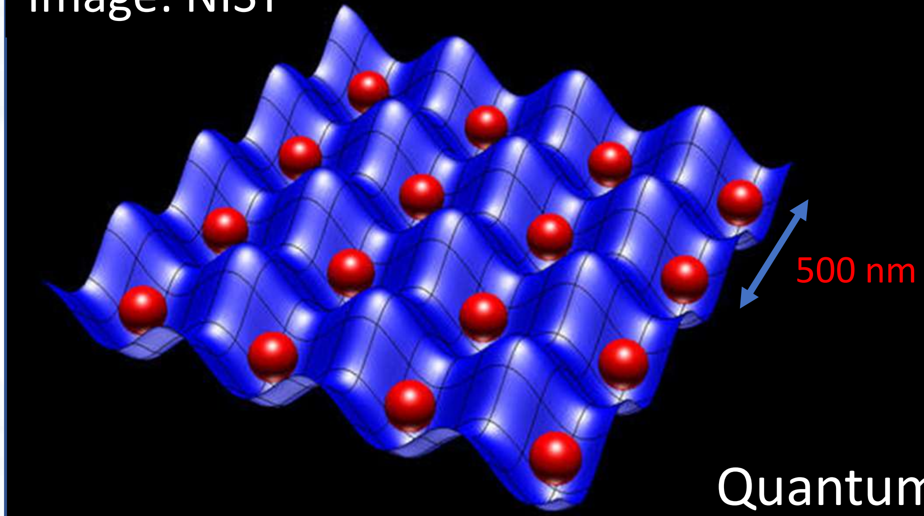
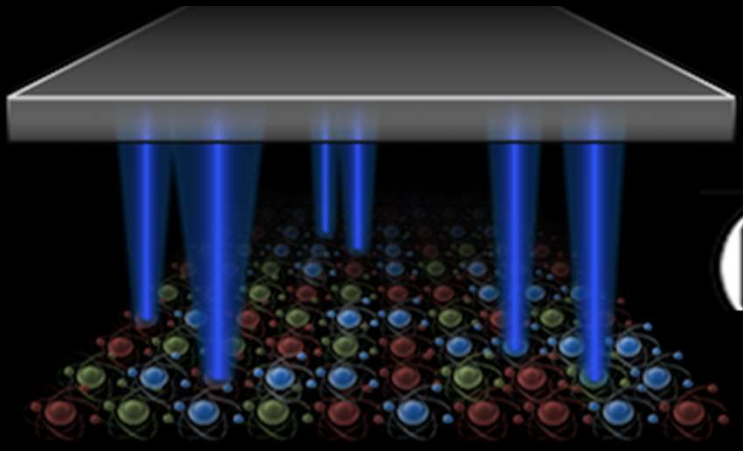


Image: NIST

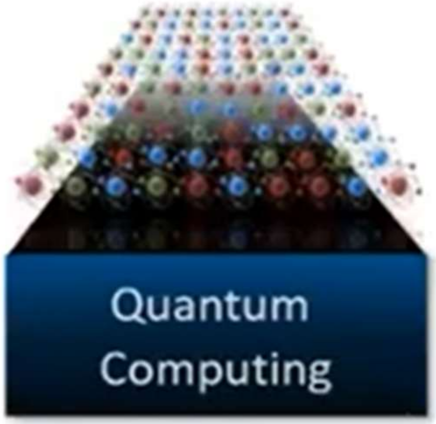


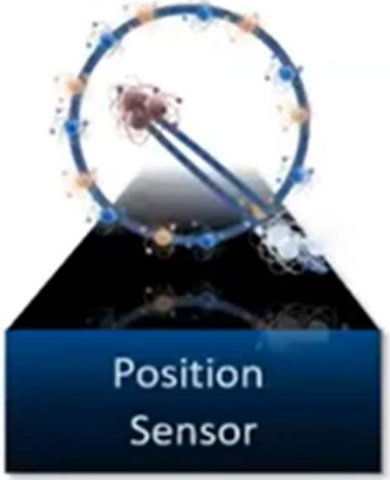
Quantum computer with cold atoms and light circuits



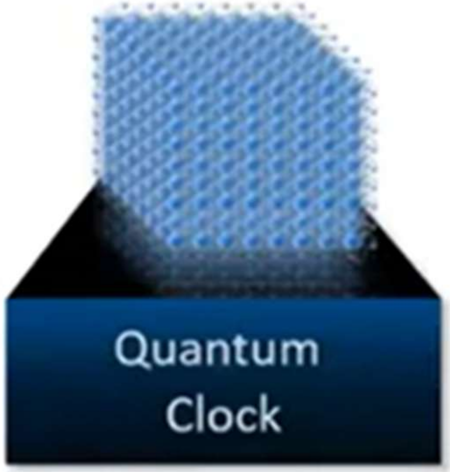
ColdQuanta
The Quantum Atomics Company

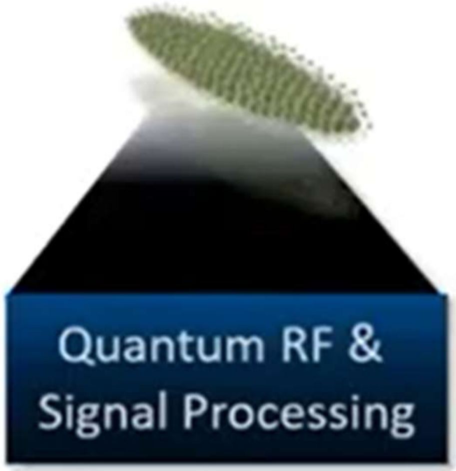
ColdQuanta
The Quantum Atomics Company



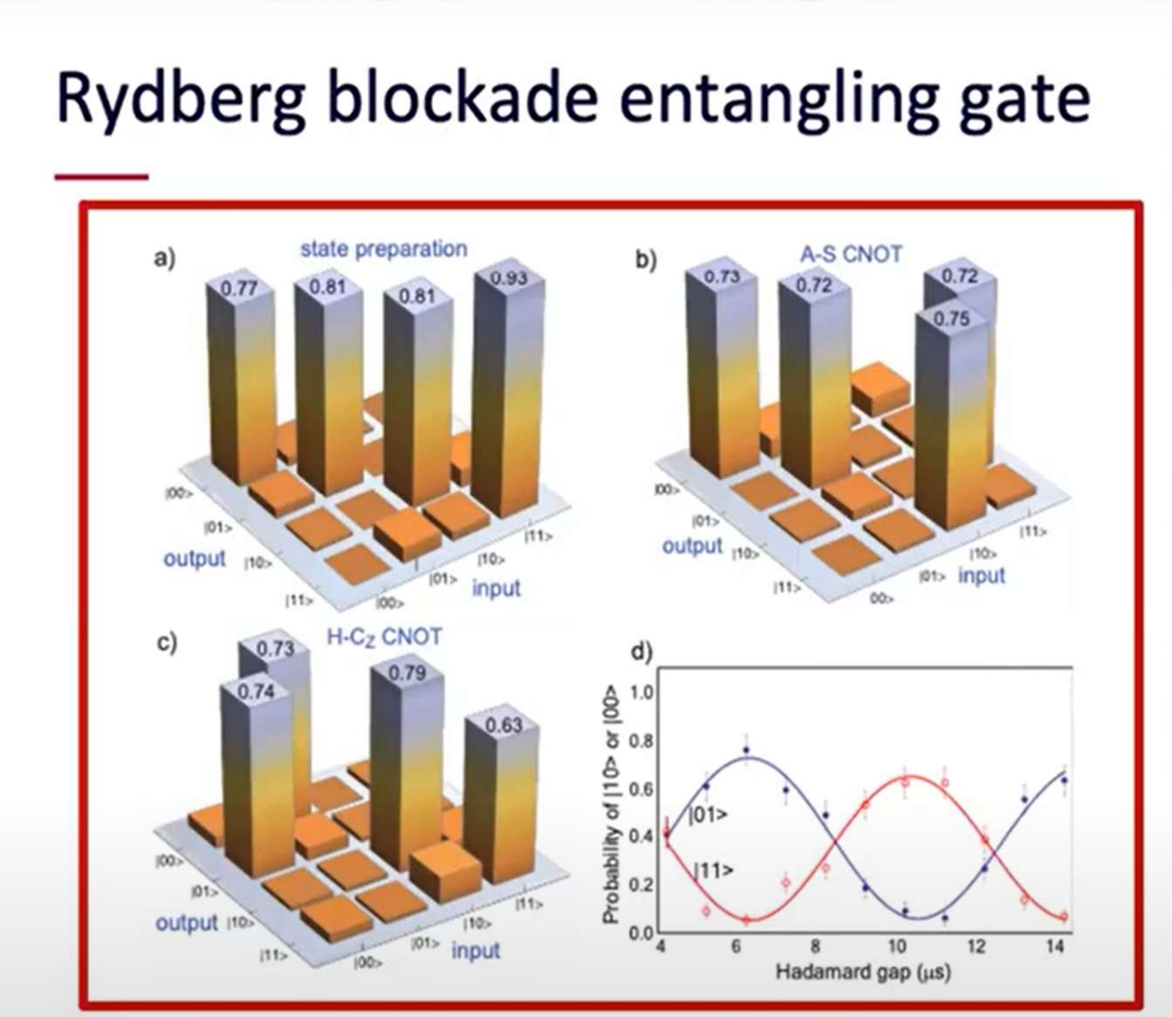


Accelerometers
& gyroscopes

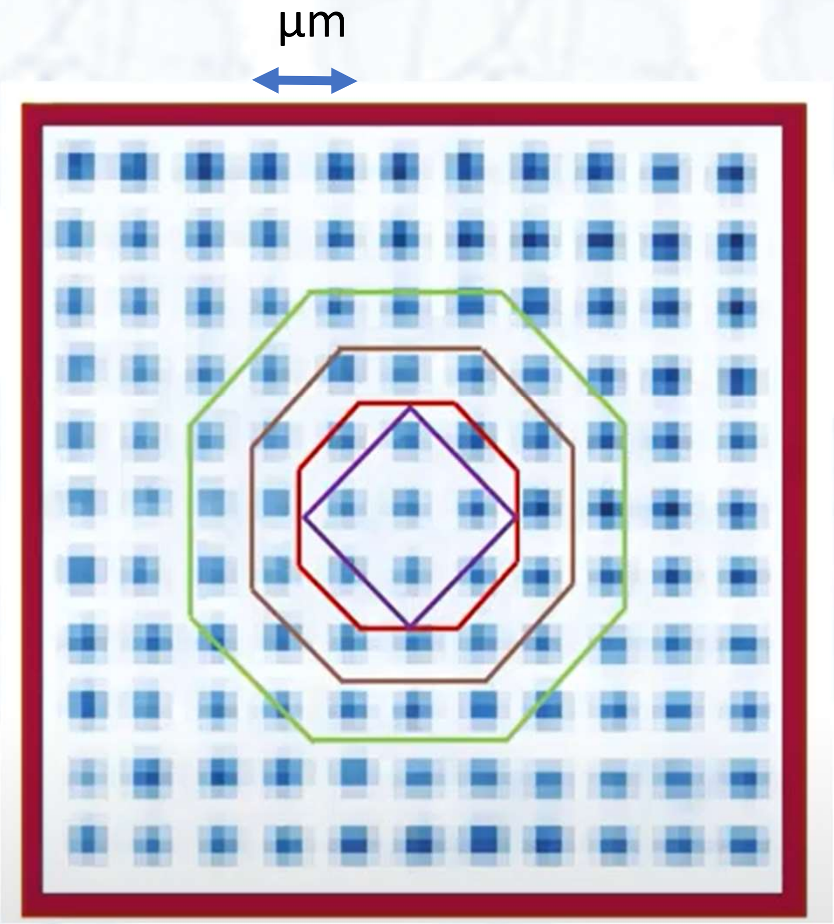




Quantum radar



Rydberg blockade entangling gate

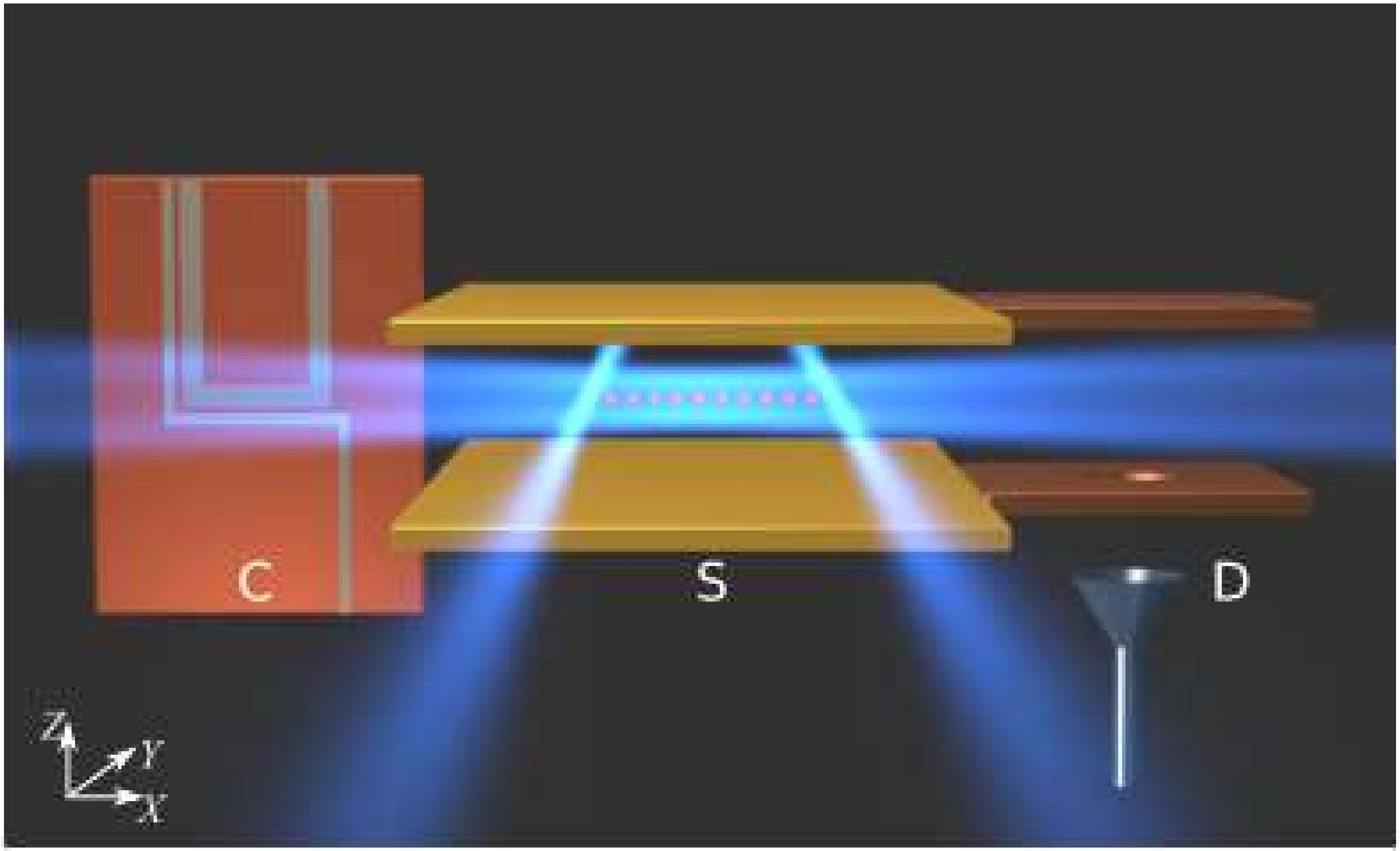


ColdQuanta
The Quantum Atomics Company

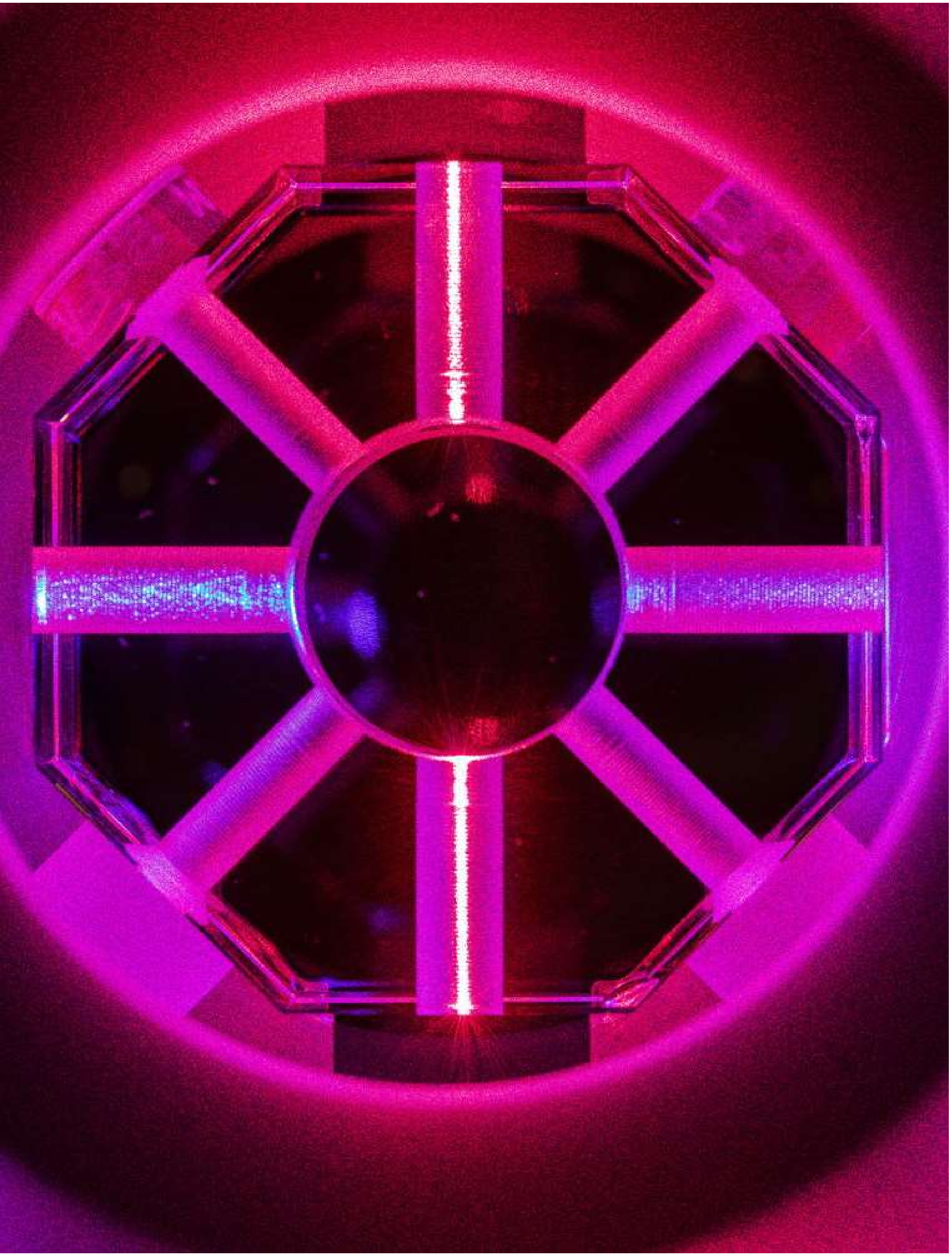
Single Cs atom per site controlled by lasers.
Two-qubit entangling gates are not limited to near neighbors.

Laboratoire Kastler Brossel: S. Haroche

Circular Rydberg atoms



Towards Quantum Simulation with Circular Rydberg Atoms
T. L. Nguyen et al. Phys. Rev. X **8**, 011032, 2018

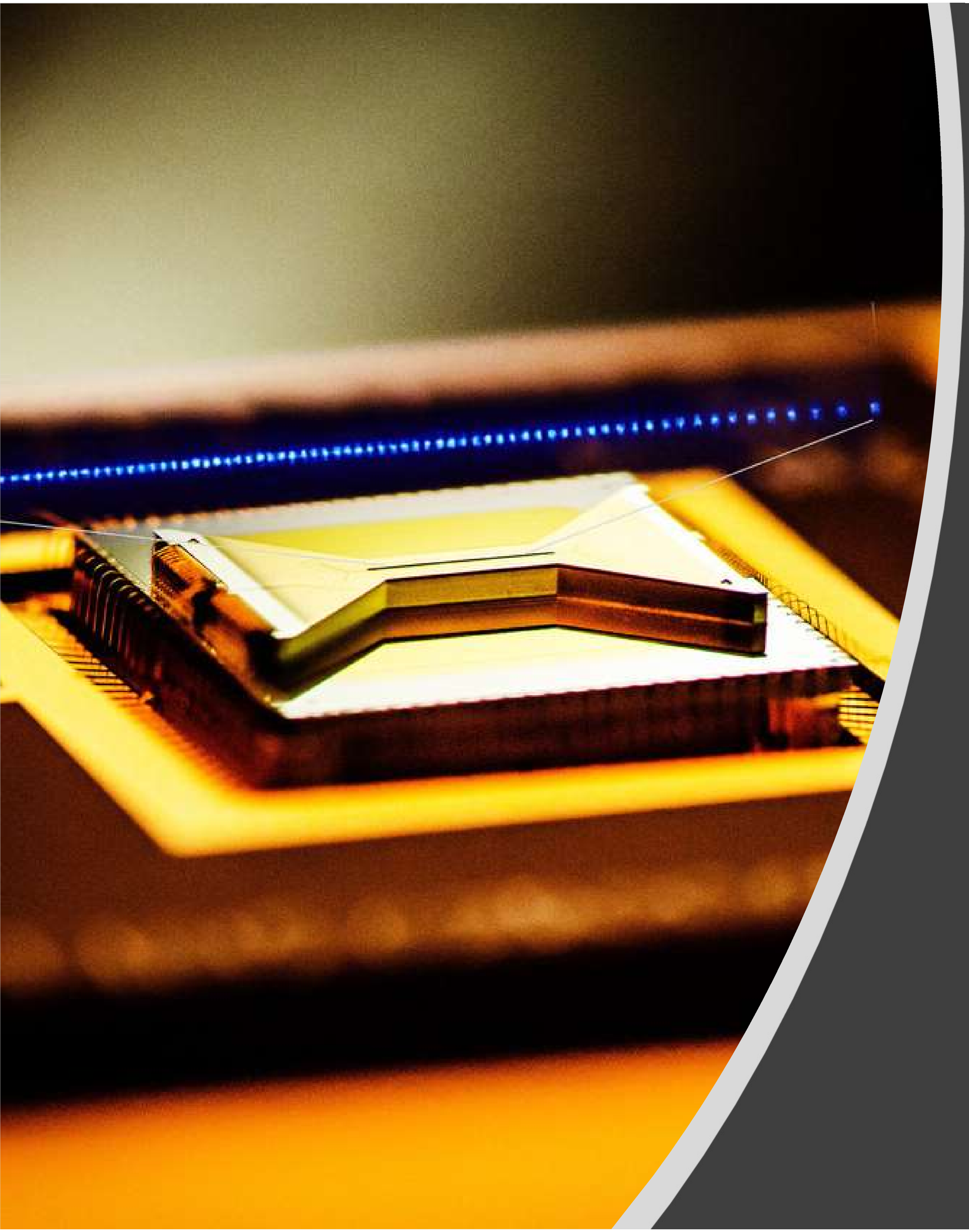


Planqc quantum processor

Optical resonator developed at MPQ. Neutral atoms become qubits for planqc's future quantum computers.

The technology is already designed for scaling to high numbers of qubits.

Image: Axel Griesch, MPQ



Trapped ion qubits

IonQ

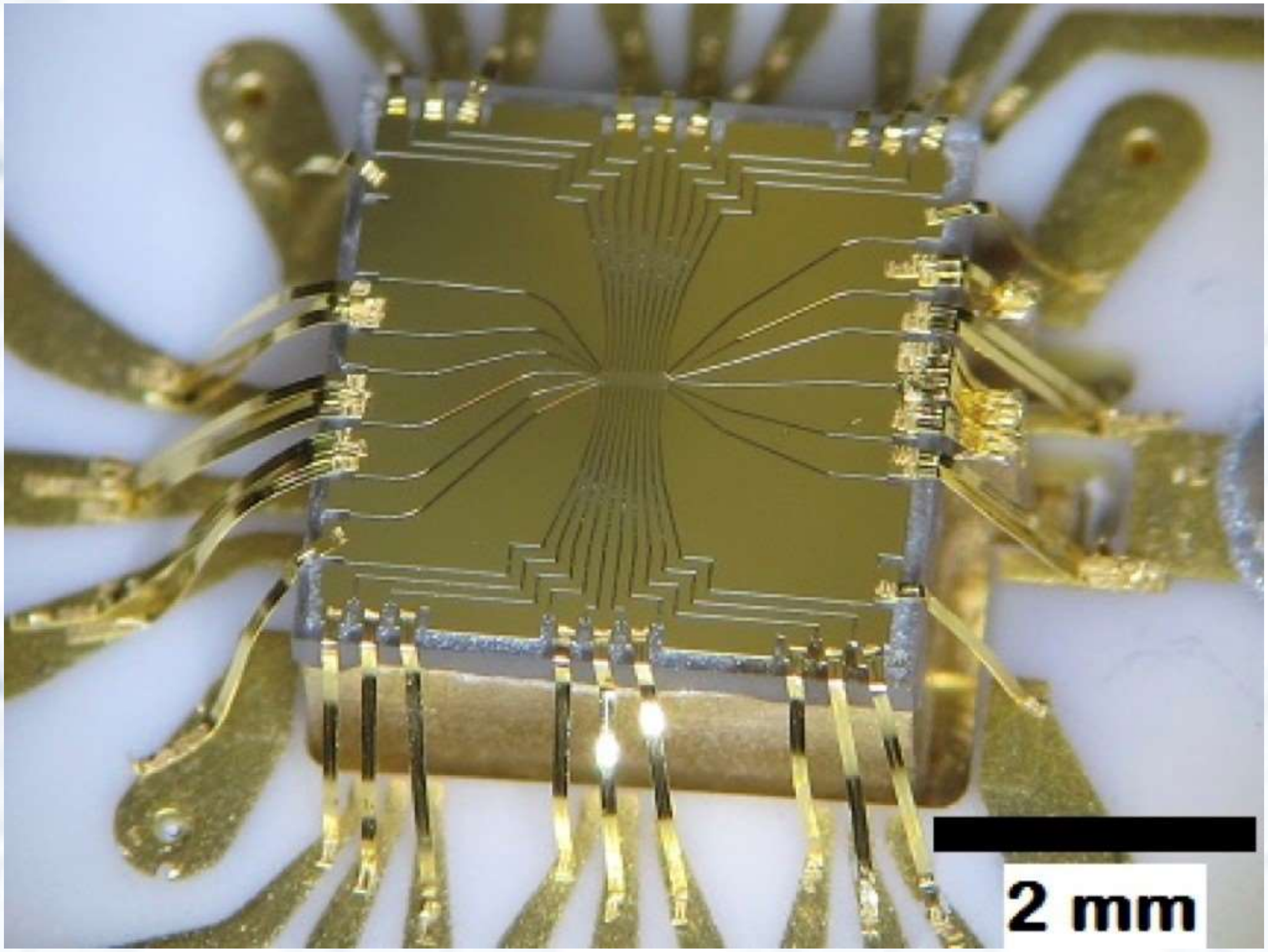
AQT

Honeywell

Universal Quantum

NIST Ion Storage Group

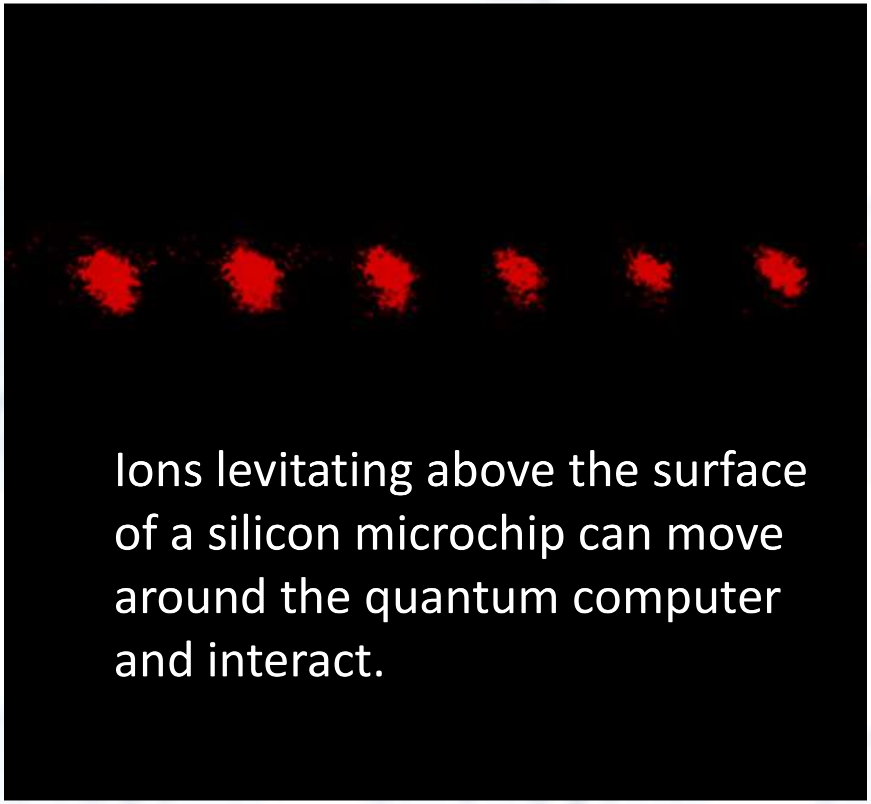
Flat RF- ion trap. Quantum logic gates controlled by magnetic fields.



Universal Quantum

Electronic modules based on silicon technology, connected using ultrafast electric field links. Operating at 70K

Awarded the 2022 Institute of Physics (IOP) Business Start-up Award for its work developing the world's first million-qubit quantum computer.

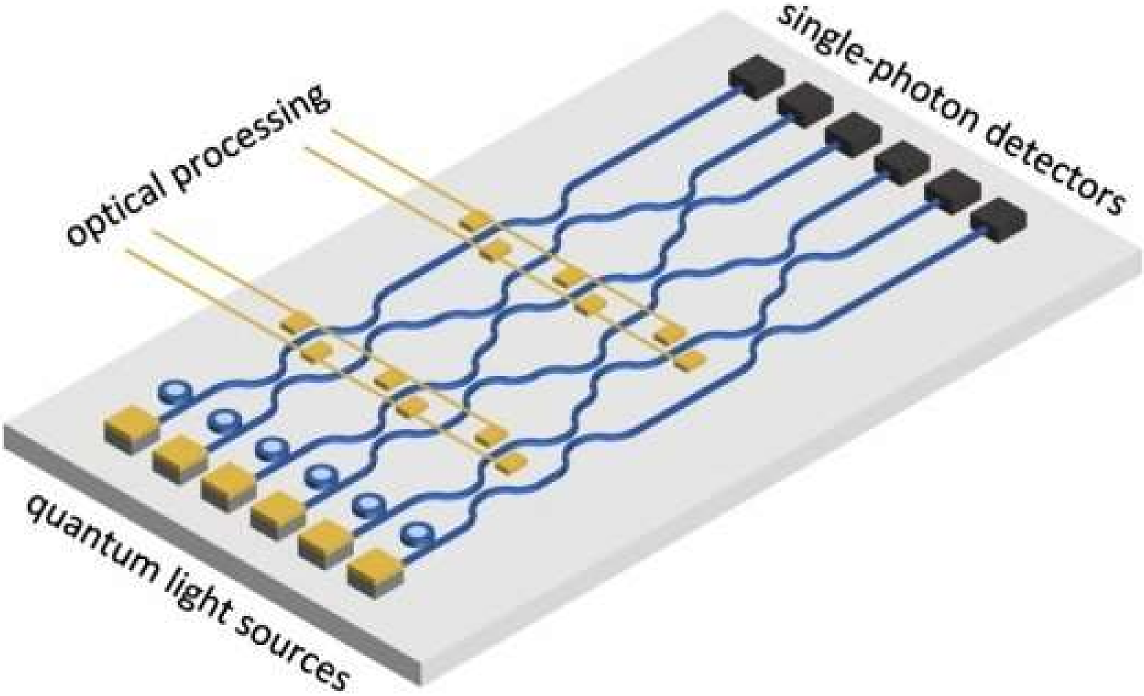


Ions levitating above the surface of a silicon microchip can move around the quantum computer and interact.

Photonics qubits

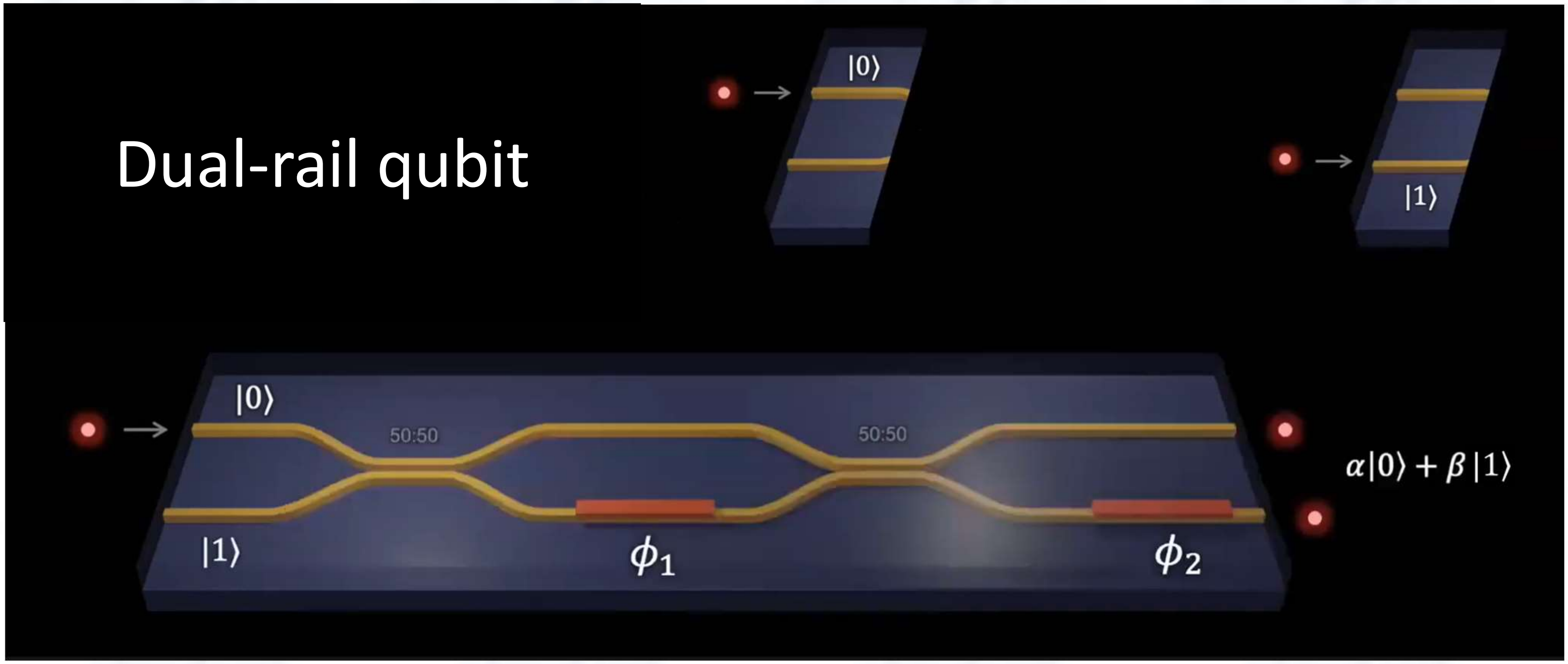
PsiQuantum

Xanadu



PsiQuantum: (Palo Alto, California) $215 million

- Fast measurement and clock speed
- Low noise: No quantum crosstalk
- Scalable: No geometrically constrained, no mK temperature
- Dual-rail qubits: two waveguides per qubit
- Linear optics operations



Consequences…

Advanced Encryption Standard (AES)

Official encryption method of the USA used for bank transactions.

256-bit key:
Fastest classic computer: 2^{256}
317 x 10^6 qubits: 1 hour
13 x 10^6 qubits: 1 day
Grover algorithm

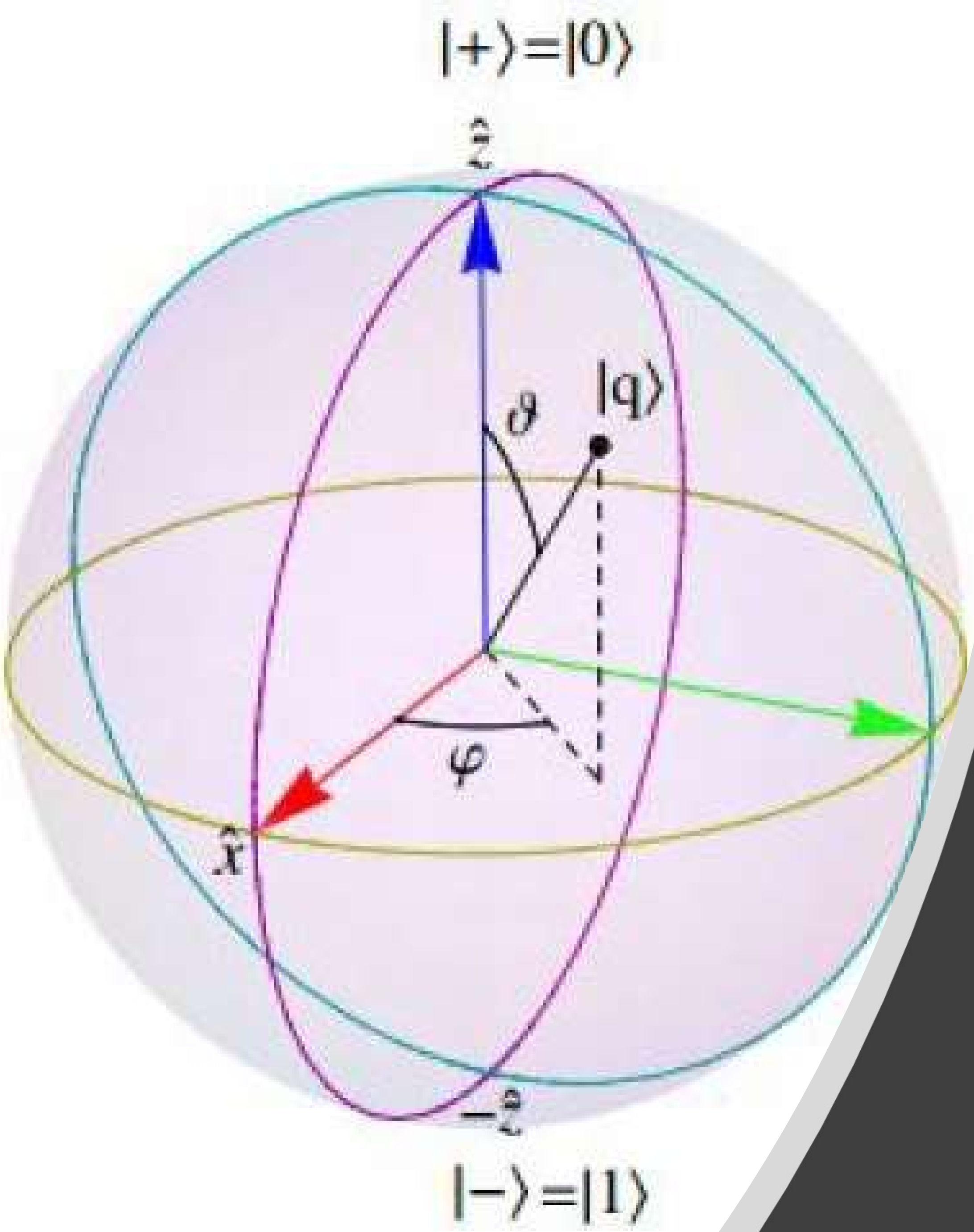
Powerful tool for deciphering encryption codes!!!

Post-Quantum Cryptography (PQC)

- NIST: New standard by the end of 2024.

- May 2022: US National Security Memorandum on promoting US Leadership in Quantum Computing while mitigating risks to vulnerable cryptographic systems.
- US$1.2 Billion into Quantum computing research and development.

- France committed 150 Million euro to quantum-resistant cryptography. From 1.8 Billion euro for quantum technologies up to 2030. On last Nov 30th , France sent first PQ encrypted message by CryptoNext (startup that emerged from INRIA, CNRS and Sorbonne) containing a memorandum on cooperation with the US.
- Action plan to migrate to PQC in 2023.



Gracias por su atención!