Quantum Mechanics and its peculiarities: an overview with an historical flavour

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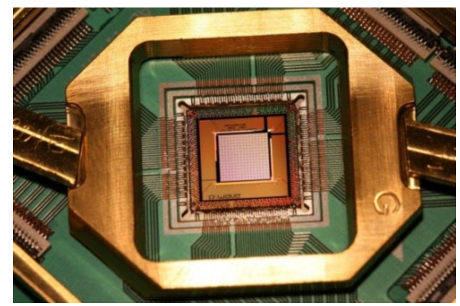
https://www.quantumweeks.it/

1900-1925: Pre-quantum period: new concepts (quantization, Bohr rule for spectra, wave-particle complementarity) without a coherent framework

1925-1930: development of a coherent quantum theory (Schrödinger, Heisenberg, Bohr, Born, Dirac….)

But, as Dirac said, "*physical intepretation was much more difficult than writing the equations*"



After many years we are facing with:

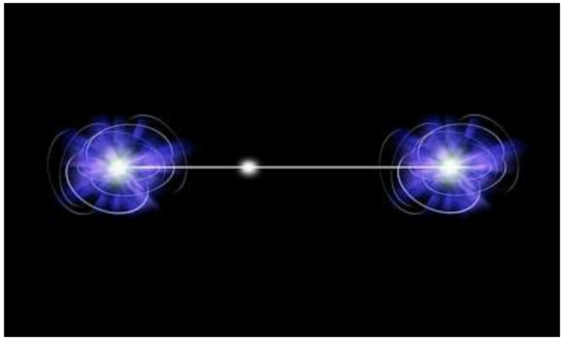
1. **A huge number of experimental verifications** and **technological applications** on the one hand

2. **Many paradoxical phenomena** (dead-and-alive cats, spooky actions at a distance….) at the same time…

EINSTEIN-BOHR DEBATE

1927-1936: **Established Quantum Theory dissatisfies some of his founders**: **Einstein**, and later, **Schrodinger**

Einstein first criticised its probabilistic nature ("God does not play dice", 1927,1930);
then he focused on its *incompleteness and apparent nonlocality*
(Einstein-Podolsky-Rosen, Phys.Rev. 1935, "spooky action at a distance")



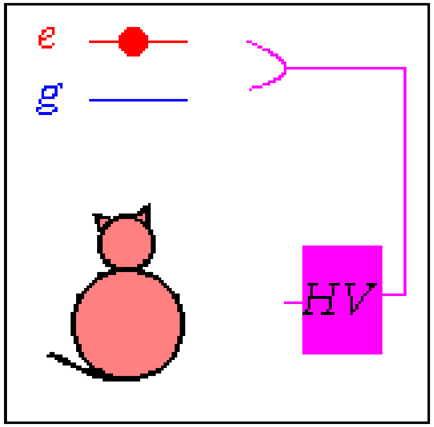
Decay generates a simultaneous eigenstate of total momentum and relative distance (EPR *entangled state*)

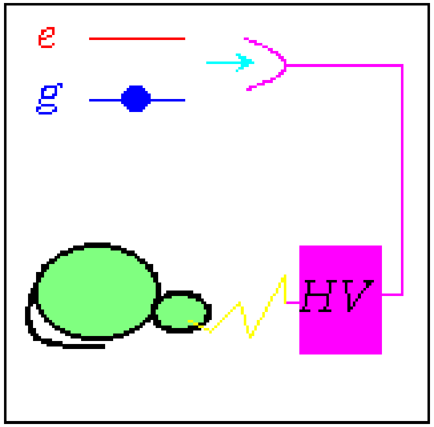
Schrodinger (1935): "entanglement (verschränkung) **is not one, but THE** characteristic trait of quantum theory…."

Schrodinger's cat paradox (1935)

Entanglement can be even extended into the macroscopic domain

$$\frac{1}{\sqrt{2}}\left[|e\rangle|alive\rangle_{cat} + |g\rangle|dead\rangle_{cat}\right]$$





Atom and cat are quantum correlated; "ridicolous case" (Schrodinger, 1935) of a **coherent superposition of two macroscopically distinct states**

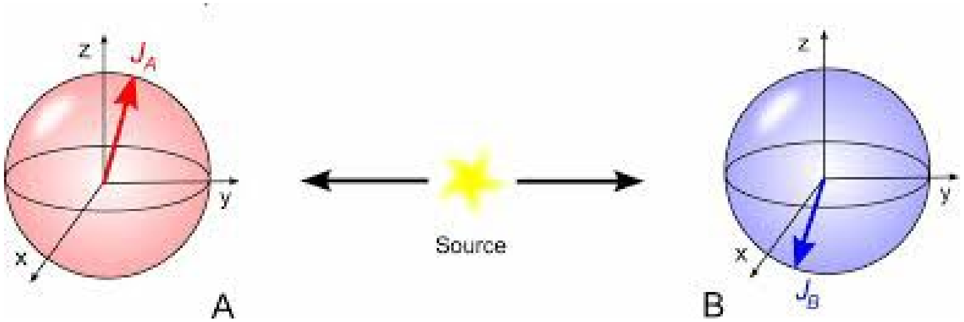
No further relevant contribution from Schrodinger.

Einstein devoted himself to *local hidden variable* theories able to "complete" the description provided by QM, which would remain a sort of "statistical" description.

Bell's theorem (1964) and Bell inequalities

$$|\psi\rangle = \frac{1}{\sqrt{2}}\{|\uparrow\rangle_1|\downarrow\rangle_2 - |\downarrow\rangle_1|\uparrow\rangle_2\}$$

EPR state revisited with spin rather than position-momentum variables (Bohm, Aharonov 1957)



Quantum mechanics and local hidden variables are incompatible and this fact can be tested

$A_j = \pm1$, j=0,1 (measured by A)
$B_j = \pm1$, j=0,1 (measured by B)

$$\langle A_0 B_0\rangle + \langle A_0 B_1\rangle + \langle A_1 B_0\rangle - \langle A_1 B_1\rangle \leq 2$$

CHSH inequality (1969), derived assuming that:

i) underlying physical properties A_j,B_j exist independently of being observed or measured ("**realism**");

ii) choice of action in A cannot influence B results or viceversa ("**locality**")

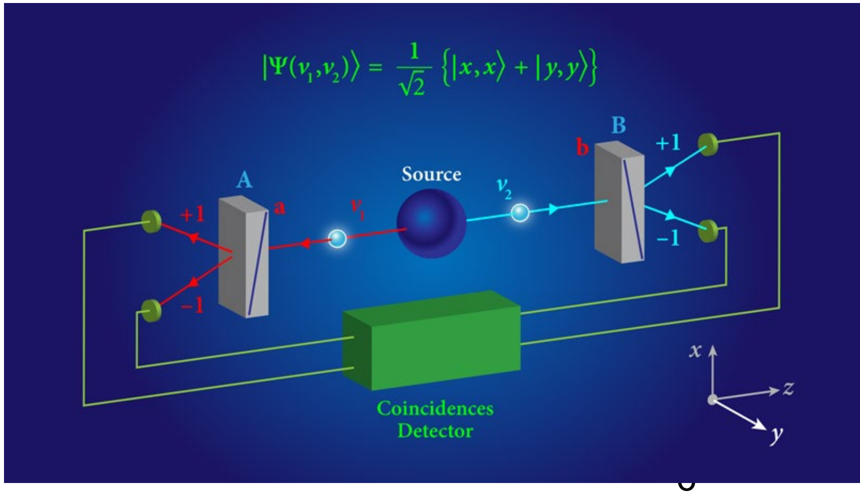
QM allows violation up to $2\sqrt{2}$ (when B Paulis are rotated by 45 degrees wrt A Paulis)

Bell experiments (Nobel 2022)

• **J. Clauser-S. Freedman** (1972) (with two-photon cascade in Ca atoms). No loophole closed

• **A. Aspect et al., (1982)**: the first one to close the **locality loophole** (the detections are done with a **spacelike separation**, so that the result of one measurement cannot influence the other without contradicting relativity)

• **In 2015 three experiments (A. Zeilinger group, R. Hanson group, P. Kwiat group)** closing simultaneously **both the locality and detection loophole** (a large enough fraction of the generated entangled photons are detected in the experiment, making it impossible to explain the data with local hidden variables by assuming that the detected particles are an unrepresentative sample).



No-signalling theorem

No superluminal transmission of signals can be obtained as a consequence of the standard quantum theory of measurement. (Ghirardi, Rimini, Weber, Lett. Nuovo. Cim. 1980)

No-signaling principle is a no-go theorem: during measurement of an entangled quantum state, it is not possible for one observer, by making a measurement of a subsystem of the total state, to communicate information to another observer.

Abner Shimony's "peaceful coexistence" between quantum mechanics and relativity

Schrodinger's cat and the quantum-classical boundary

The combination of **the superposition (linearity), and of the tensor product postulate for composite systems** implies entanglement, even at **macroscopic scales**

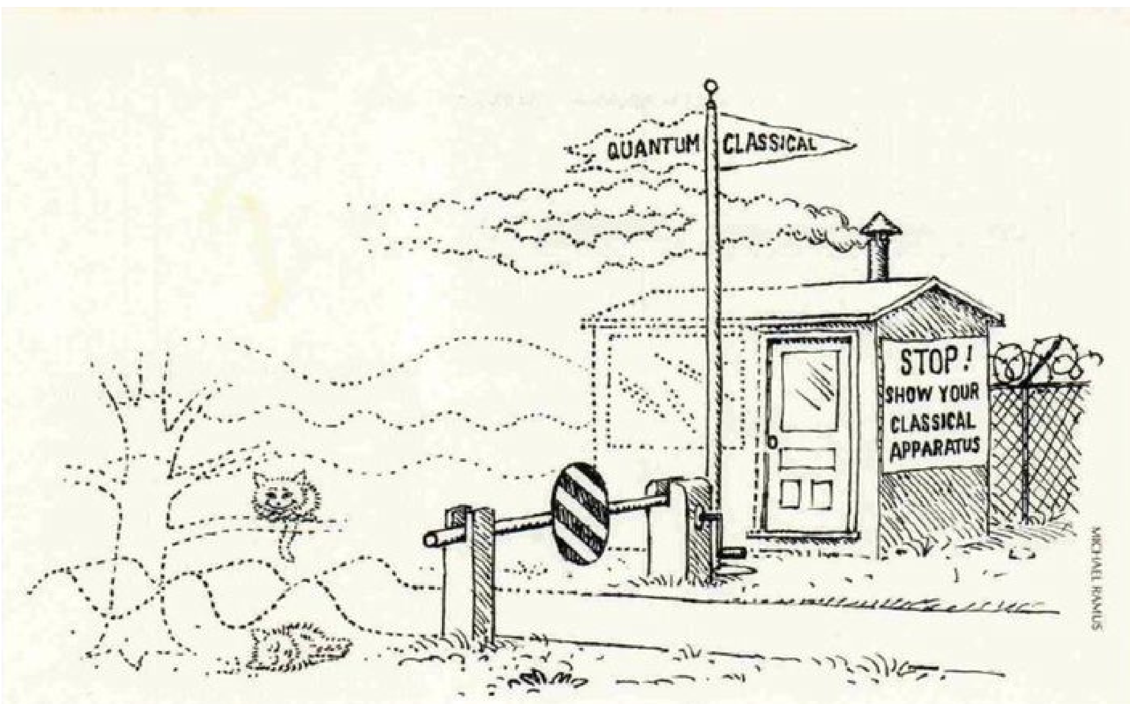
$$\frac{1}{\sqrt{2}}\left[|e\rangle|alive\rangle_{cat} + |g\rangle|dead\rangle_{cat}\right]$$

- **Why we do not detect these "cat" states ?** ("cat" = linear superposition in which a macroscopic number of particles N »1 is in two (or more) classically distinct states

- Is there a boundary between the **microscopic world ruled by QM**, and the **macroscopic world ruled by classical physics** ?

- This is strongly related to the **measurement problem**: the **measurement apparatus** is macroscopic and it must always yield definite values: it **cannot be in a cat state**

Peculiar **relationship between classical and quantum physics**: classical physics is not only its limit for $\hbar \to 0$; **it is a necessary element of the theory,** needed to describe the measurement process**: the measurement apparatus MUST behave in a classical manner.**



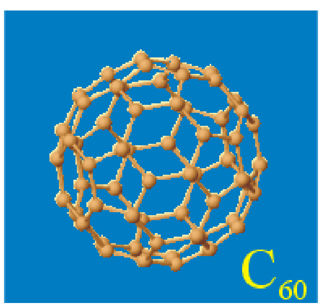
Zurek (Phys. Today 1991) cartoon of the Copenhagen interpretation

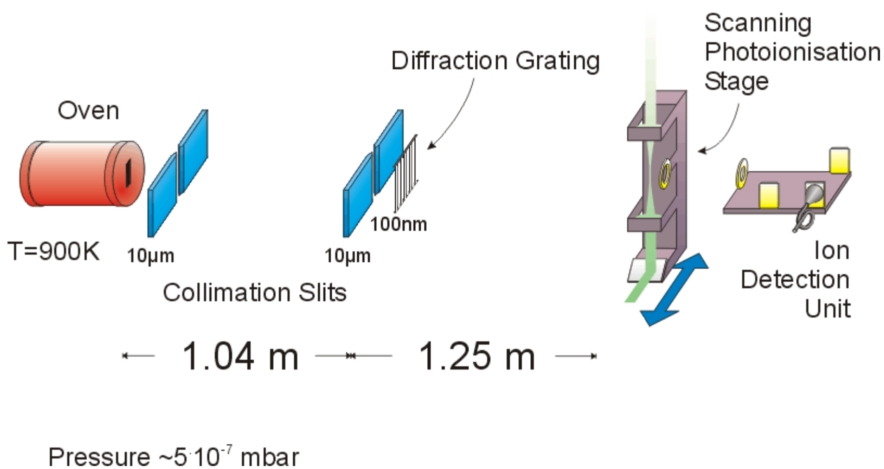
Lessons from recent experiments

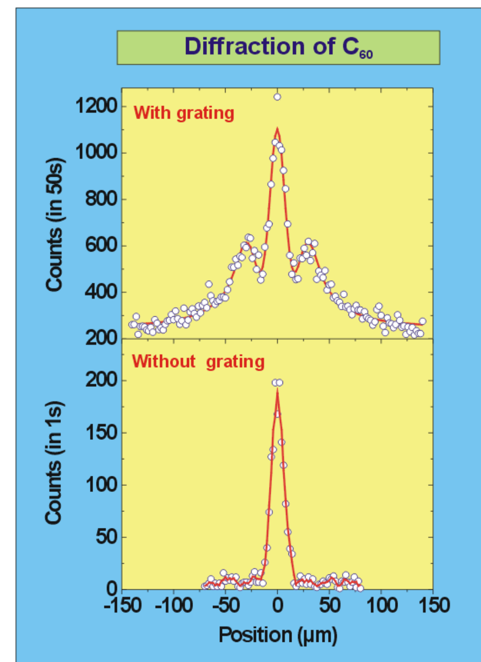
Many recents real (and not only “gedanken”) experiments have shown **quantum behavior of more and more macroscopic degrees of freedom**. **We did not find any “boundary” up to now.**

Some examples

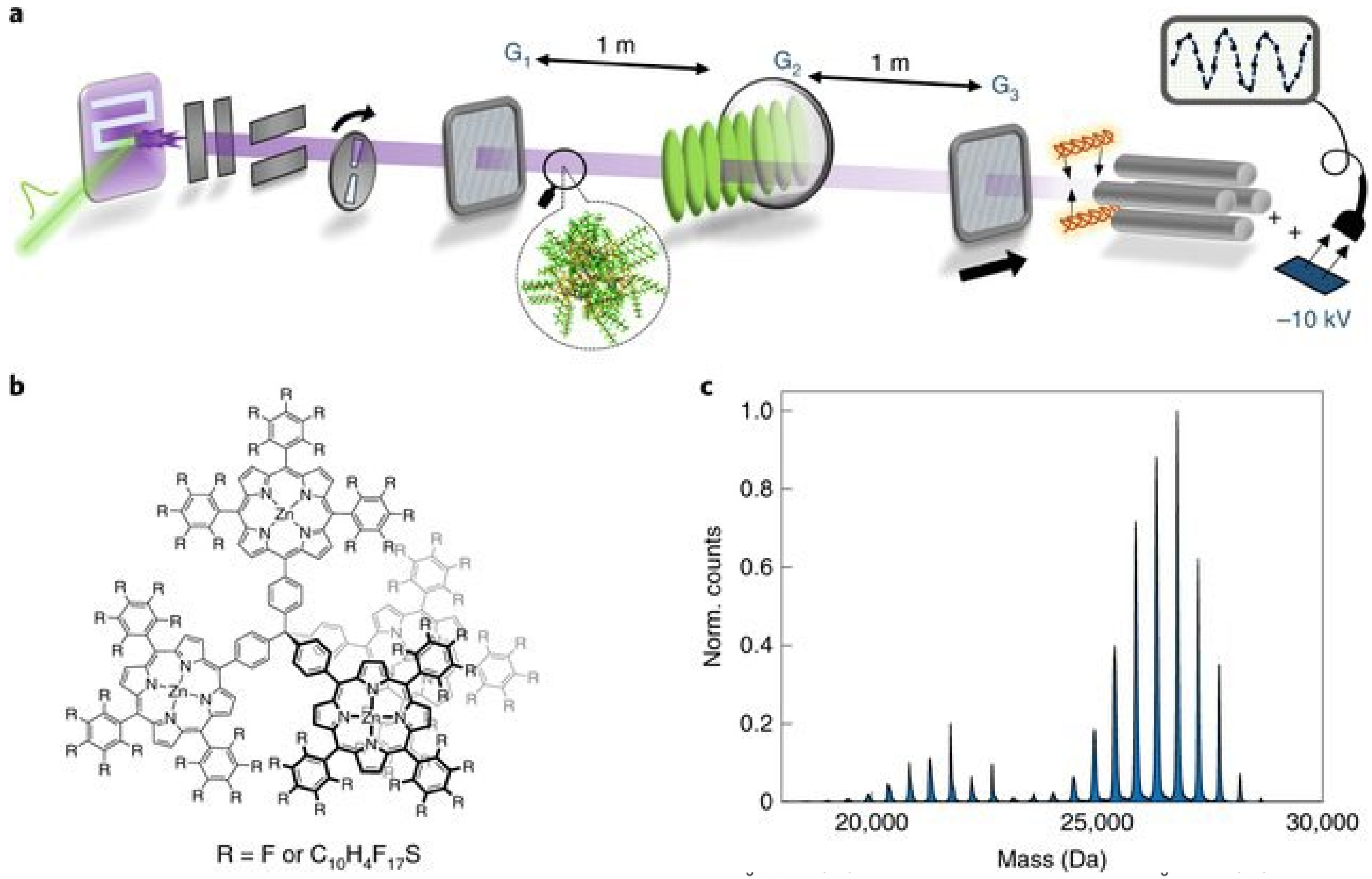
1. Young-like interference of macromolecules



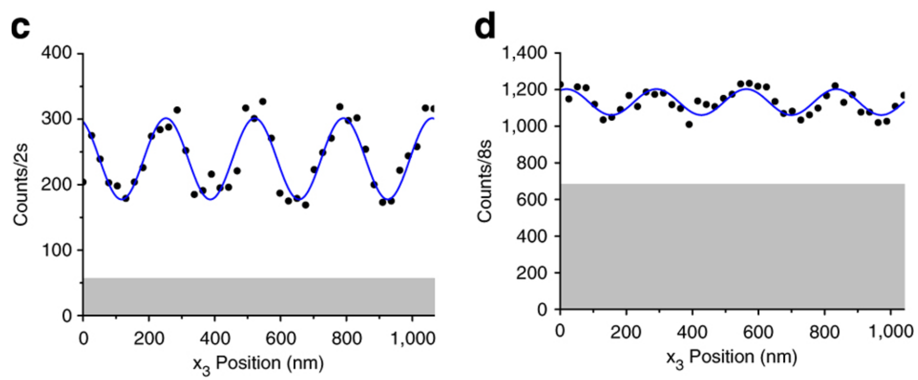




M. Arndt et al., Zeilinger group, Nature 401, 680 (1999)



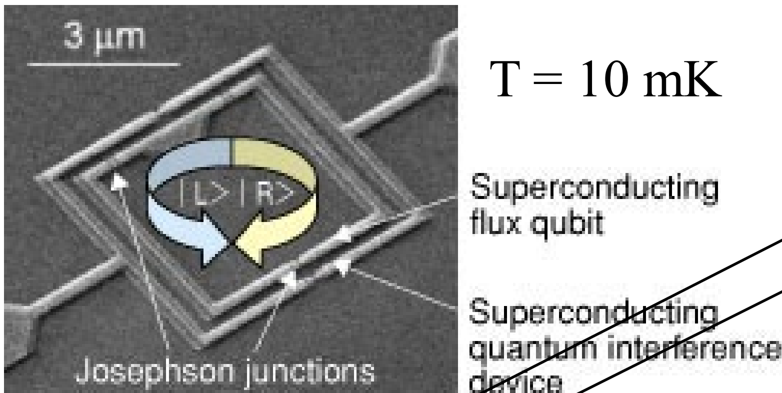
Current record ≈ 2000 atoms (2019, Vienna)
M = 25000 amu (porphyrin)



2. Superposition of flux states in a SQUID

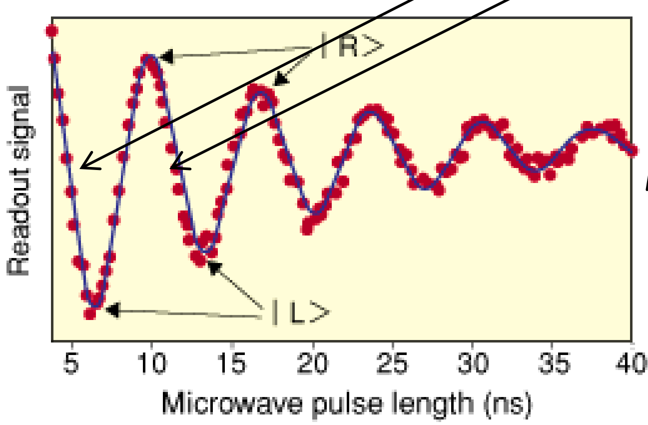
N ~10^6 – 10^{10} electrons

T = 10 mK



$$\frac{1}{\sqrt{2}}\left(|L\rangle + |R\rangle\right)$$

Coherent superposition, able to produce intereference effects

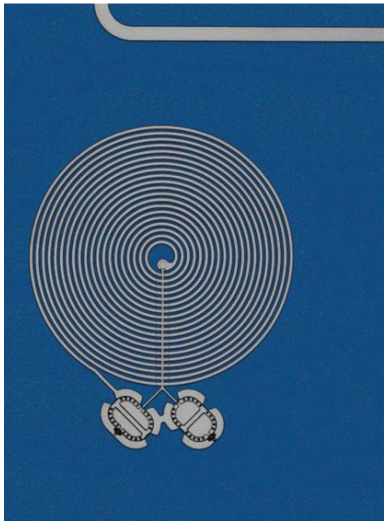


Coherent oscillations of the flux state, showing that we have a quantum coherent superposition and **not a (classical) statistical mixture,** which appears only at long time, when dephasing occurs.

$$\frac{1}{2}\left(|L\rangle\langle L| + |R\rangle\langle R|\right)$$

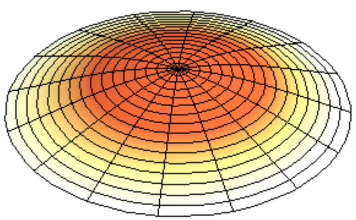
Either in |L> or in |R>

3. Entanglement of the motional state of Al microdrums in a superconducting LC circuit



EPR-like entanglement between position and momentum of two mechanical drum resonators

$$|\psi\rangle \approx \frac{1}{\sqrt{2}}\left\{|up\rangle_1|down\rangle_2 + |down\rangle_1|up\rangle_2\right\}$$



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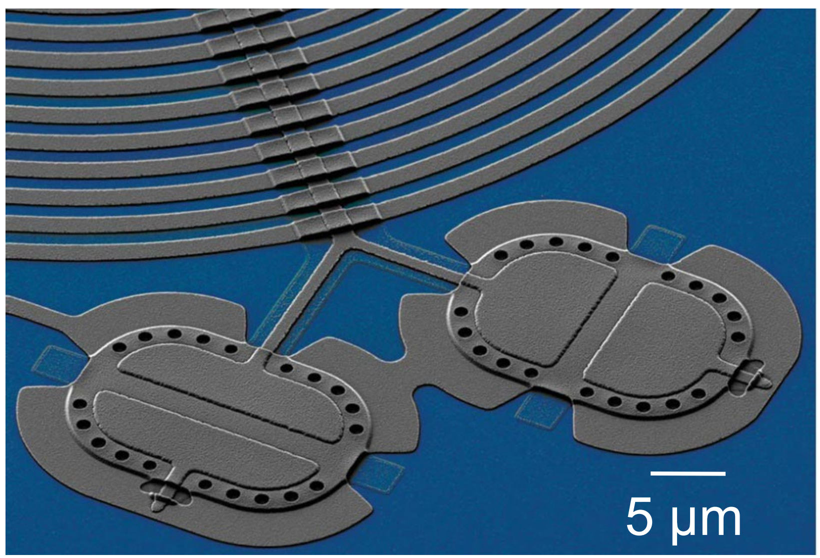
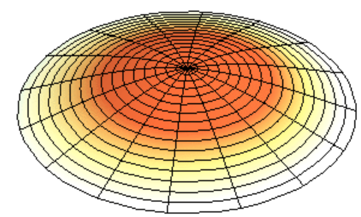




N ~1.6 x 10^{12} atoms

Kotler et al., Science 372, 622–625 (2021); preliminary in Sillanpaa et al., (2018)

Therefore…

1. No hint up to now of any "intrinsic" limit on the "cat size": it seems to depend upon the experimenters' ability only.

2. This class of experiments also teach us **why it is so hard to generate, and (more important) to detect cat states**: the experimentally verified practical explanation is **environmentally-induced decoherence**.

The more macroscopic the system, **the more difficult it is to isolate it** from uncontrollable degrees of freedom ("environment")

The environment unavoidably interacts and "measures" a macroscopic object, recording in some way its state (e.g. photon scattered in different directions)

In a short time, the environment correlates two different (quasi-orthogonal) states **$|a\rangle_{env}$** and **$|d\rangle_{env}$** , to the two cat state components

$$|\psi\rangle = |e\rangle|alive\rangle_{cat}|a\rangle_{env} + |g\rangle|dead\rangle_{cat}|d\rangle_{env}$$

The more distinguishable $|d\rangle_{env}$ and $|a\rangle_{env}$ are, the more any quantum interference visibility will be suppressed $\Rightarrow$

$$|\psi\rangle = |e\rangle|alive\rangle_{cat} + |g\rangle|dead\rangle_{cat}$$

quickly transforms (decoheres) into the corresponding classical statistical mixture (mutually exclusive occurrences)

$|e\rangle|alive\rangle_{cat}$ **or** $|g\rangle|dead\rangle_{cat}$ with 50% probability

Quantum decoherence provides also an explanation of the measurement problem: "collapse" of the state = transition from the coherent superposition to the statistical mixture

$$\frac{1}{\sqrt{2}}\left\{|\uparrow\rangle+|\downarrow\rangle\right\}|A_0\rangle_{app}|E_0\rangle_{amb} \rightarrow \frac{1}{\sqrt{2}}\left\{|\uparrow\rangle|A_\uparrow\rangle_{app}|E_\uparrow\rangle_{amb}+|\downarrow\rangle|A_\downarrow\rangle_{app}|E_\downarrow\rangle_{amb}\right\}$$

We cannot observe the environment $\langle E_\downarrow \| E_\uparrow\rangle_{amb} \approx 0$

The state of measured system and detector is the mixture

$$\rho_{mix}=\frac{1}{2}\left\{|\uparrow\rangle\langle\uparrow\| A_\uparrow\rangle_{app}\langle A_\uparrow|+|\downarrow\rangle\langle\downarrow\| A_\downarrow\rangle_{app}\langle A_\downarrow|\right\}$$

i.e., 50% up e 50% down, in perfect correlation with the state of the pointer

and not the superposition $|\psi\rangle=\frac{1}{\sqrt{2}}\left\{|\uparrow\rangle|A_\uparrow\rangle_{app}+|\downarrow\rangle|A_\downarrow\rangle_{app}\right\}$

providing the **same measurement statistics**, but which can be distinguished from the mixture by means of proper system-apparatus measurements

Conceptual difficulties of the decoherence approach

1. **The transition from the coherent superposition to the statistical mixture does not work at the single measurement level**, but only statistically ("epistemic" and not "ontic" description of the quantum state).

(This is also related to the fact that there is no unique decomposition of a mixed state in terms of pure states)

2. At the **cosmological** level: what happens for the Universe, which does not have an environment ?

3. Is an **alternative realistic interpretation** of the quantum state possible ? See Angelo Bassi's talk

From quantum foundations to quantum technologies

1. **Quantum computation**
2. Quantum transducers, quantum internet & cryptography
3. Quantum sensing and metrology

They exploit entanglement and nontrivial quantum correlations for **performing tasks better than any classical device processing only “classical” states (quantum “advantage”)**

See also P. Verrucchi and C. Braggio’s talks

QUANTUM FLAGSHIP https://qt.eu/

Quantum vs classical information

- Classical information: in bit, physical systems that can assume only two states, 0 and 1; n bit $\Rightarrow 2^n$ states

- **Quantum information**: in qubit, physical systems that can assume an **infinite number of states**, $a|0\rangle + b|1\rangle$, $|a|^2 + |b|^2 = 1$, due to the superposition principle

Quantum computer idea: Benioff 1980, Feynman 1982, Deutsch 1985: systems of qubits evolving in a quantum coherent way, with negligible “noise”, **i.e., negligible “environmental decoherence”**

Quantum computation = quantum coherent time evolution = implementation of a quantum algorithm

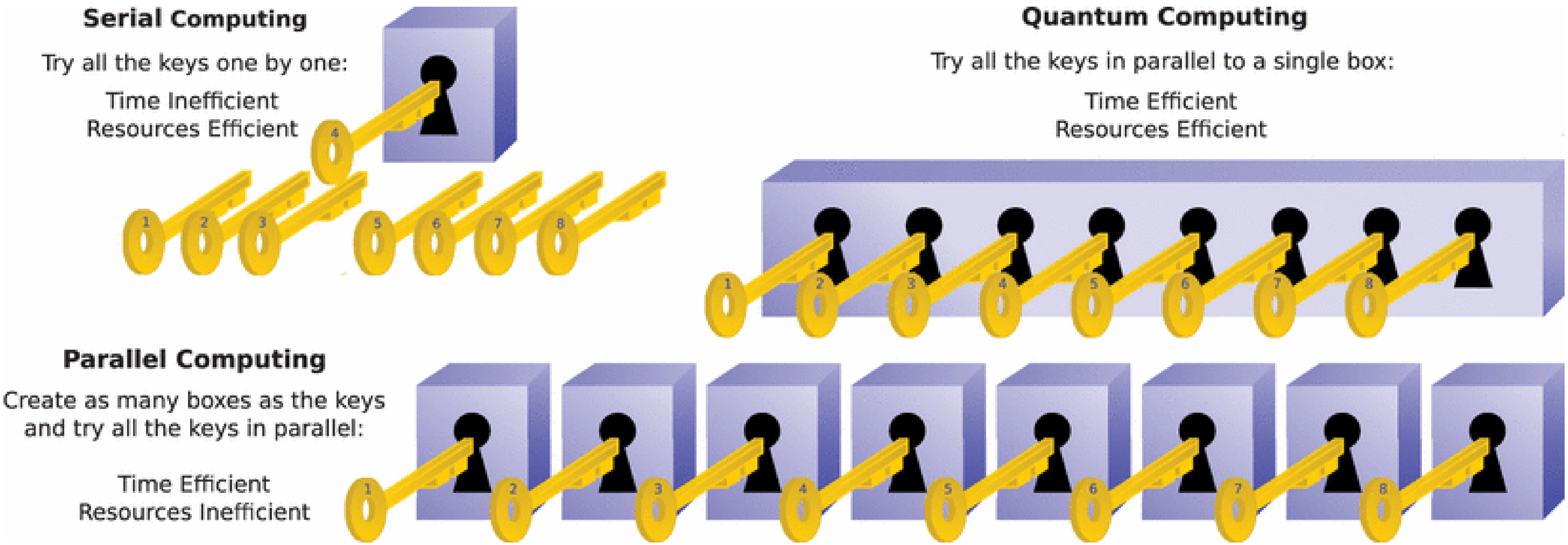
Basic properties of a quantum computer

- **It solves the same problems of a classical computer**, and it satisfies the Church-Turing hypothesis (quantum Turing machine)

- However some algorithms are **performed more efficiently** (Shor factorization 1994, simulation of a quantum system, HHL for linear systems of equations) (exponential speed-up).

- **Further example: search within an unstructured database of N elements**; classically: N/2 steps on average; Grover quantum algorithm (1996): $\sqrt{N}$ steps and it has been proven to be optimal.

Quantum parallelism thought to be at the basis of the exponential speed up

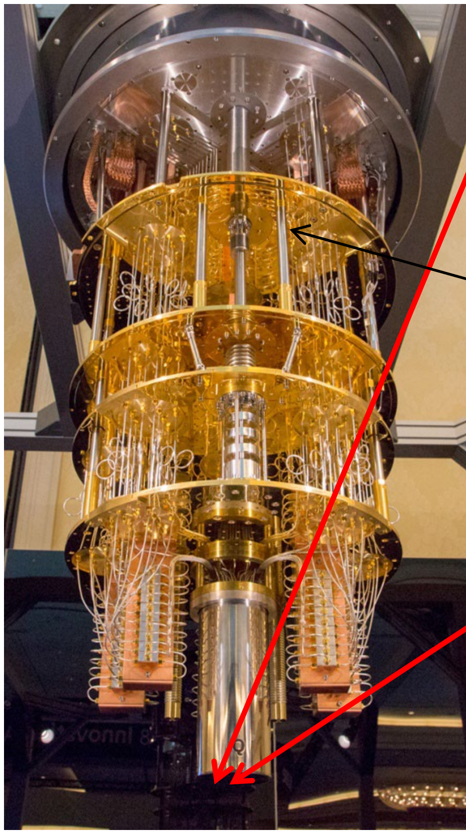


A quantum computer ideally processes **highly entangled states of n qubits**: each term of the 2^n in total performs a "calculation".

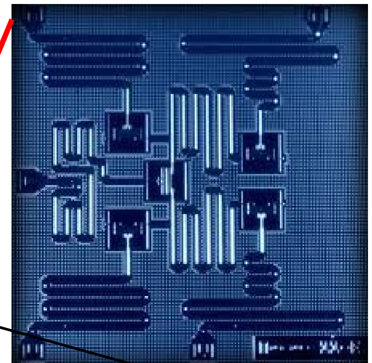
$$|\psi\rangle = c_0|0\rangle|0\rangle|0\rangle + c_1|0\rangle|0\rangle|1\rangle + c_2|0\rangle|1\rangle|0\rangle + c_2|0\rangle|1\rangle|1\rangle + \ldots\ldots$$

Decoherence is the enemy: **it transforms a quantum computer into a probabilistic classical computer**

Current NISQ (noisy intermediate-scale quantum) computers processes Schrodinger cat states



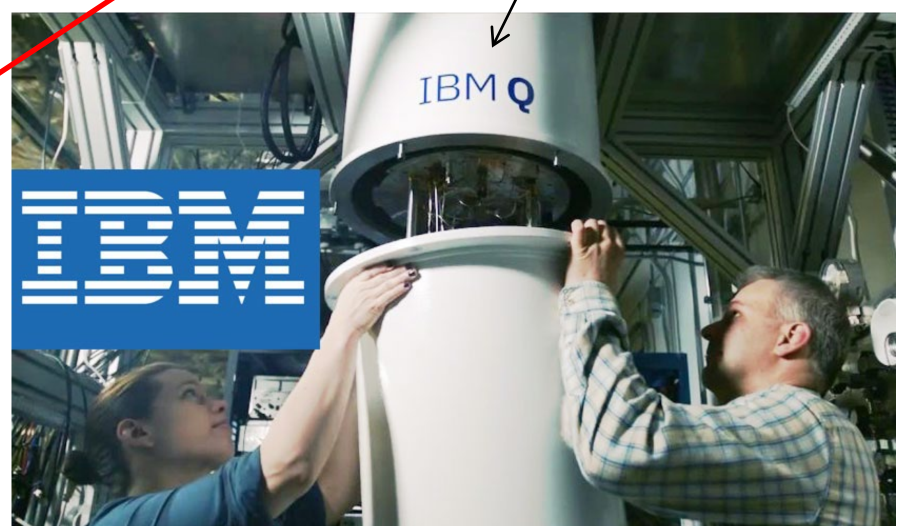
IBM QC a 50 qubit



Superconducting chip

Google, IBM, Rigetti QC with superconducting qubits

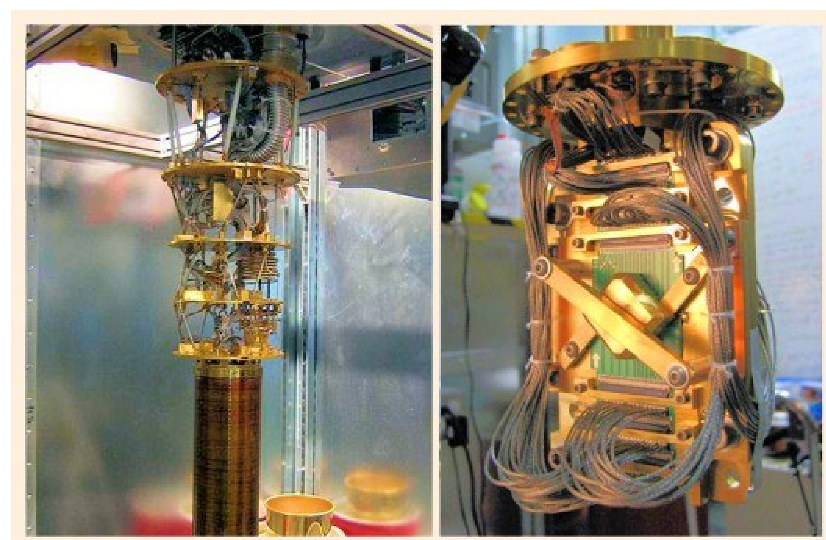
He3-He4 dilution fridge at 10 mK



China Google copy with 64 qubit:
IBM has announced a 127 qubit QC and 1000 qubit in two years

D-WAVE: same superconducting technology, but no quantum gates; it is an annealer, exploiting adiabatic quantum computing

- Pegasus P16: - 5640 qubits
- Simulation of quantum systems: it can be used for optimizing graphs and similar problems (e.g. maximum independent set)



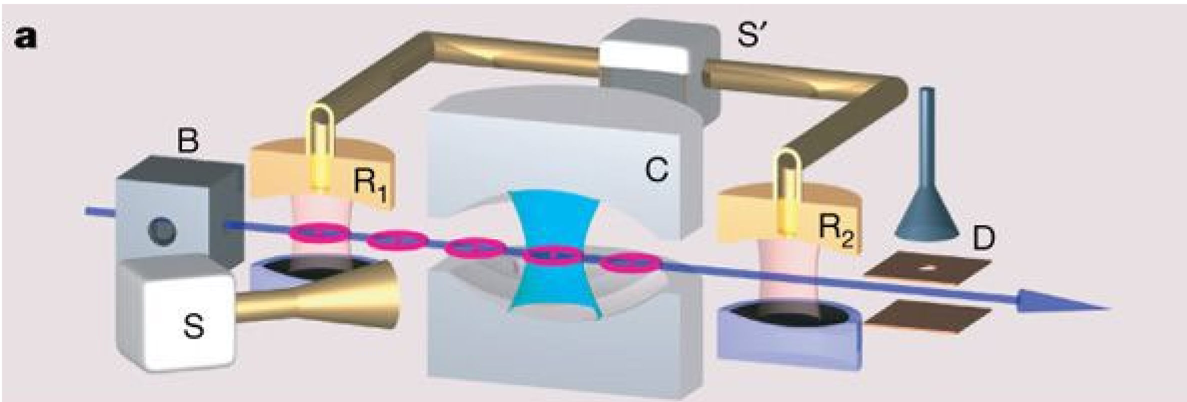
CONCLUSIONS

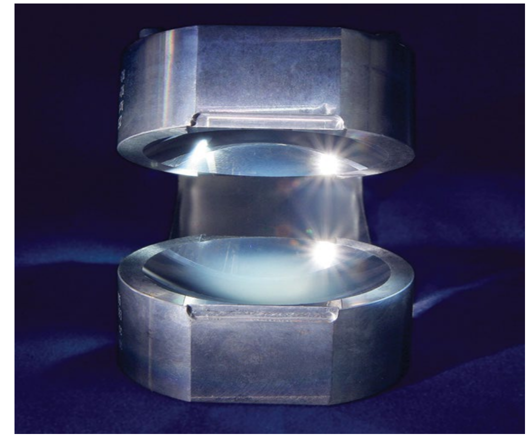
1. Recent experimental results suggests that even though hard, it is possible to **push the limits toward more and more macroscopic quantum** phenomena

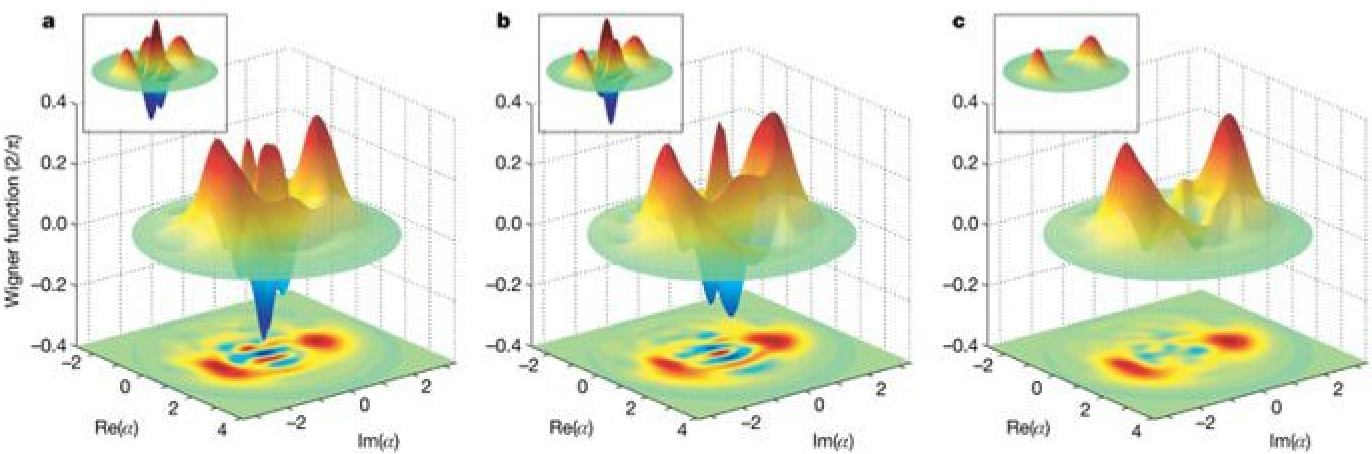
2. **Environmental decoherence theory provides an explanation of the quantum-classical transition** and of the measurement problem valid "**for all practical purposes**" (even though this is not over….)

3. A deeper understanding of quantum mechanics and of the its foundation has opened the new era of the "**second quantum revolution**"

e.m. field in a microwave cavity in a superposition of two opposite phases





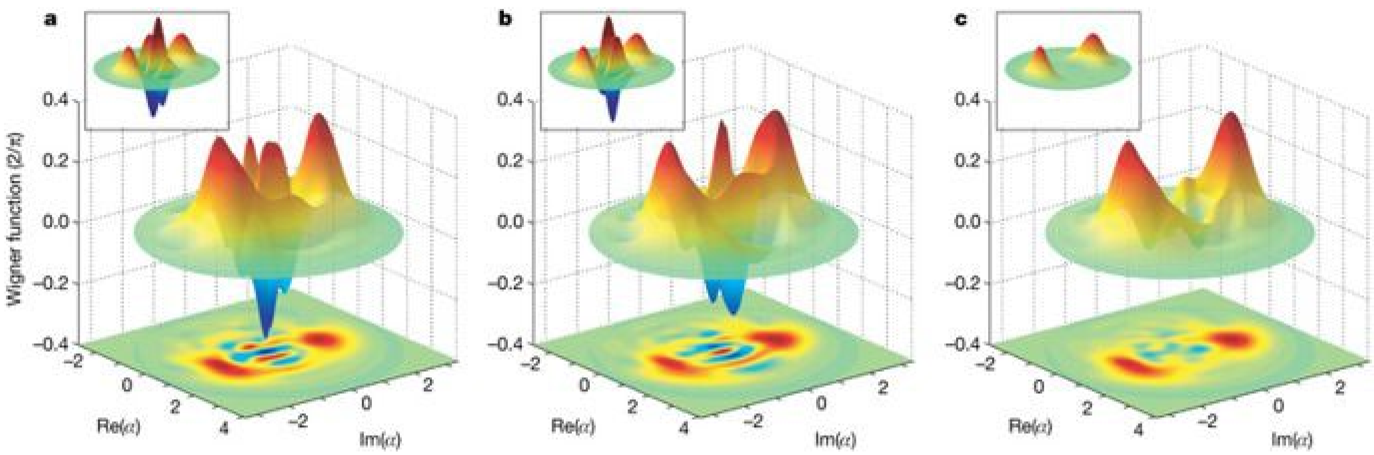


S. Deleglise et al., Nature 2008
S. Haroche, Nobel 2012

Progressive decoherence of a cat state of 10 photons in the cavity. Experimental reconstruction of the Wigner function in phase space of the field quantum state.

Ancora sulla funzione di Wigner. I due picchi a destra e sinistra rappresentano i due stati macroscopici (le due fasi macroscopicamente distinte) e le oscillazioni tra valori positivi e negativi tra i due picchi (frange di interferenza) sono la manifestazione della coerenza quantistica, ovvero della distinzione tra sovrapposizione coerente e miscela statistica. La funzione di Wigner ricostruita sperimentalmente mostra da a) a c) la transizione dalla sovrapposizione coerente (gatto di Schrodinger) $|\psi\rangle$ alla miscela statistica classica ρ_{mix}

$$|\psi\rangle = \sum_{i=1,2} c_i |\psi_i\rangle \rightarrow \rho_{mix} = \sum_{i=1,2} |c_i|^2 |\psi_i\rangle\langle\psi_i|$$



QC a ioni intrappolati

- Prima proposta completa (Cirac-Zoller 1995)

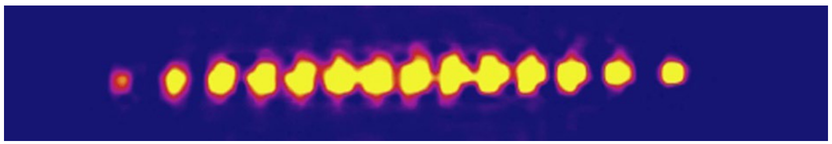
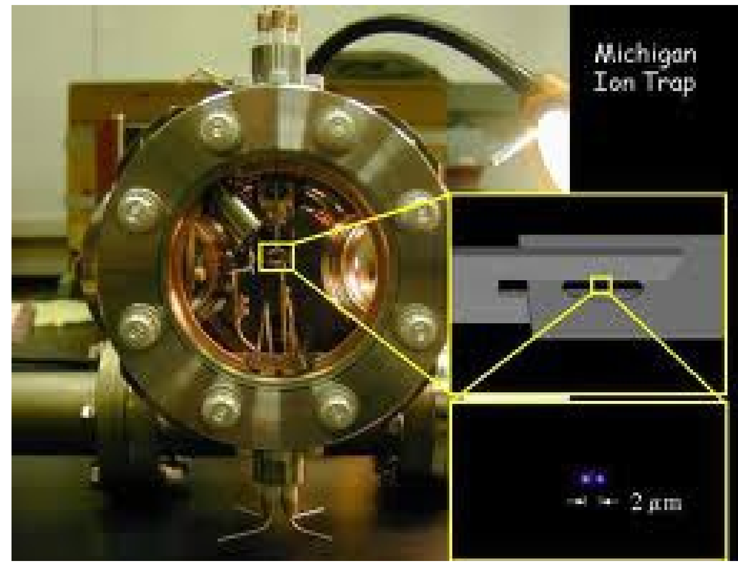
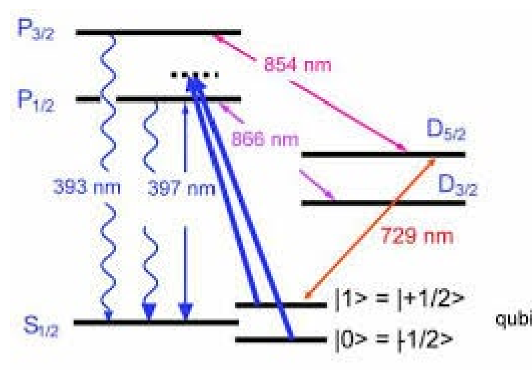


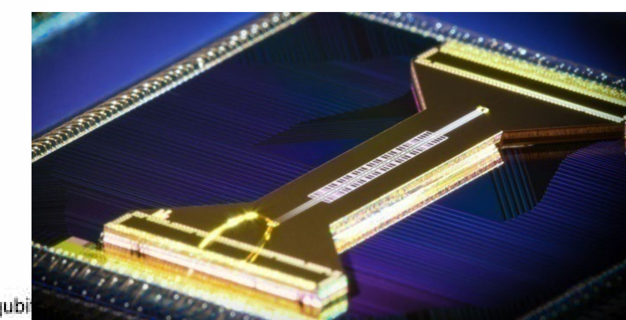
Immagine su ccd di ioni



Qubit = due livelli interni dello ione (spin nucleare)
1-qubit gate = impulsi laser
2 qubit gate = impulsi laser che usano un "quantum bus vibrazionale"

AQT (Innsbruck), IonQ (Honeywell) Funziona a temperatura ambiente (32 qubit)





Prototipi disponibili online su cloud

https://aws.amazon.com/it/braket/

Amazon braket: cloud service: si possono mandare programmi a pagamento su Ion-Q, Rigetti..

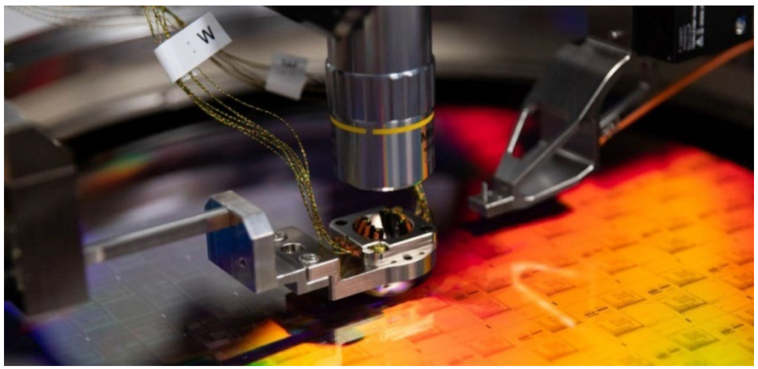
https://quantum-computing.ibm.com/ (sui prototipi IBM)

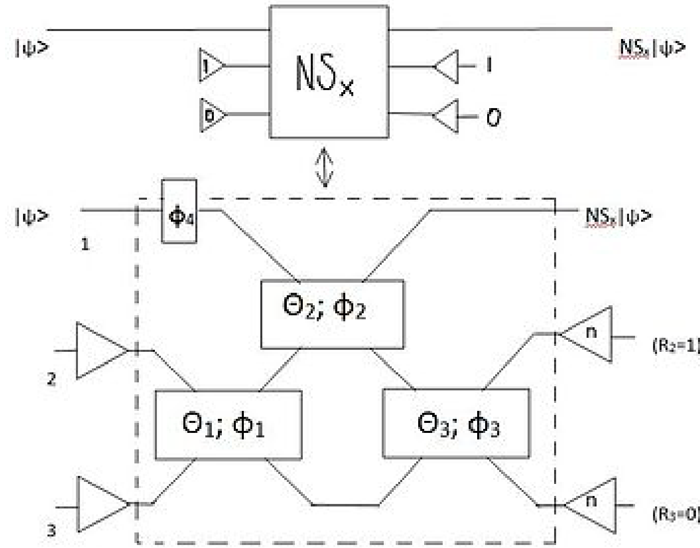
https://ionq.com/

Linear optics quantum computer

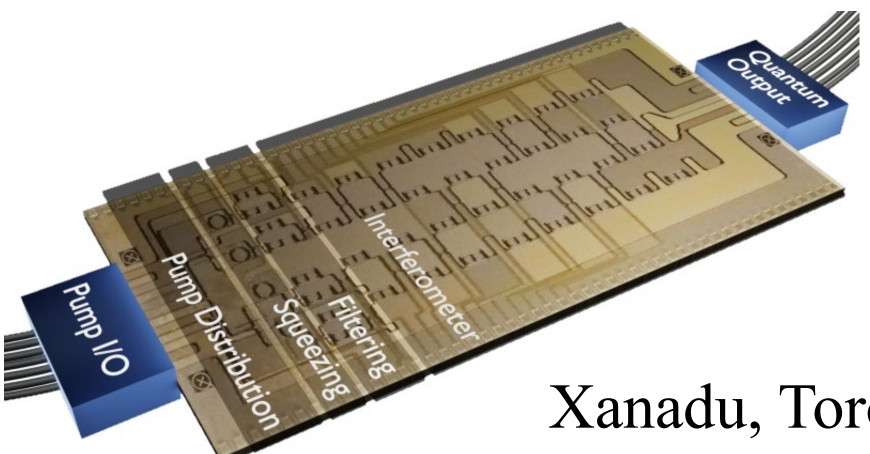
PsiQuantum (California)

Singoli fotoni su chip di silicio





Schema semplificato di circuito



Xanadu, Toronto