université PARIS-SACLAY

INSTITUT d'OPTIQUE GRADUATE SCHOOL

cnrs

Physics of Quantum Information: qubits, entanglement, measurement & decoherence

Antoine Browaeys

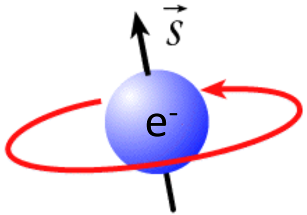
LCF, Institut d'Optique

Laurent Sanchez-Palencia

CPHT, Ecole Polytechnique

Quantum theory = a precisely-tested theory…

Magnetic moment of the electron

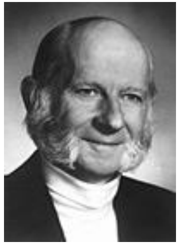


$$\frac{\mu_{\rm exp}}{2\mu_{\rm B}} = 1.001\ 159\ 652\ 180\ \underline{73}(28)$$

$$\frac{\mu_{\rm theo}}{2\mu_{\rm B}} = 1.001\ 159\ 652\ 153\ \underline{4}(240)$$

1989

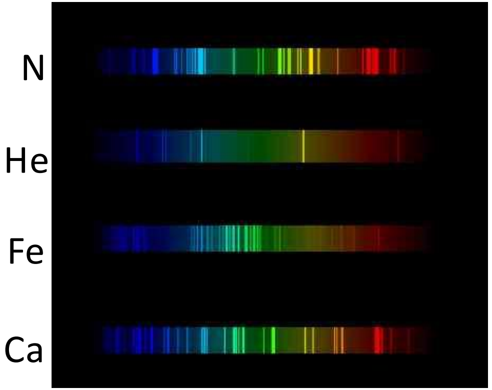
H. Dehmelt



Spectroscopy of atoms

Ex: Hydrogen $$f^{\rm exp}_{1s-2s} = 2\ 466\ 061\ 413\ 187\ \underline{018}(11)\ {\rm Hz}$$

$$f^{\rm theo}_{1s-2s} = 2\ 466\ 061\ 413\ 187\ \underline{103}(46)\ {\rm Hz}$$

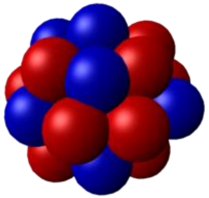


International system of units

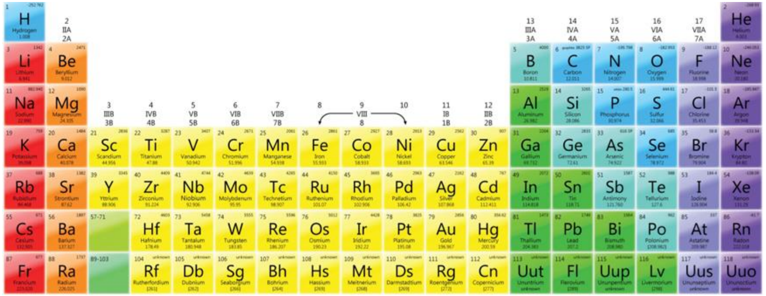
$$\hbar = 6.62607004 \times 10^{-34}\ {\rm kg.m^2/s}$$

now exact (2019)!

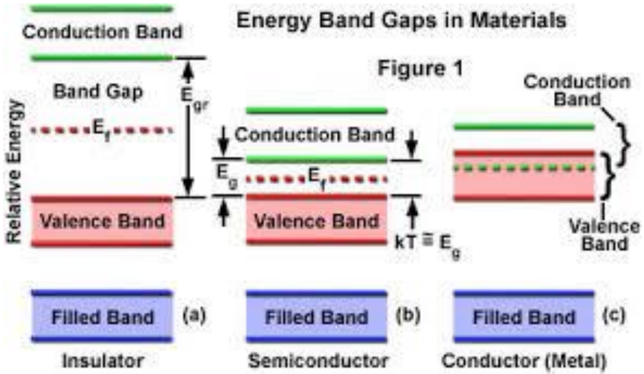
Explaining all aspects of our world (but gravitation…)



Nucleus



Atoms & chemistry

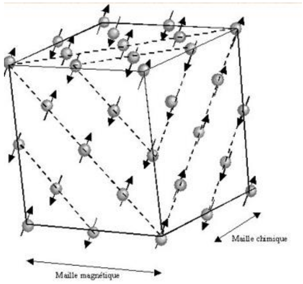


U. Warwick

Band structures

superfluidity

superconductivity

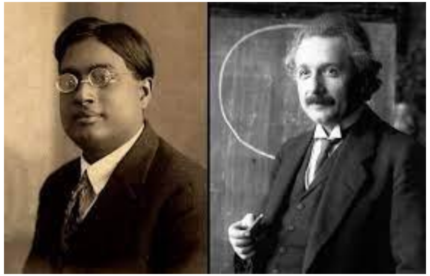


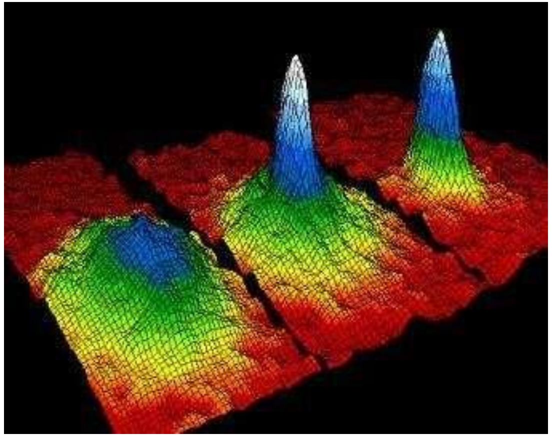
magnetism

neutron star

With predictive power…

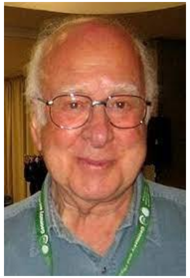
Bose-Einstein condensate: prediction 1924 / experiment 1995





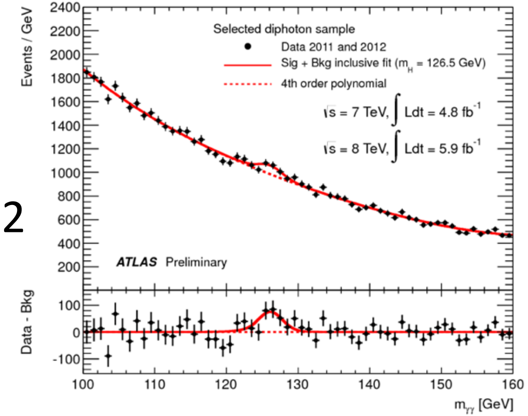
Existence of the Higgs boson

Predicted 1960's



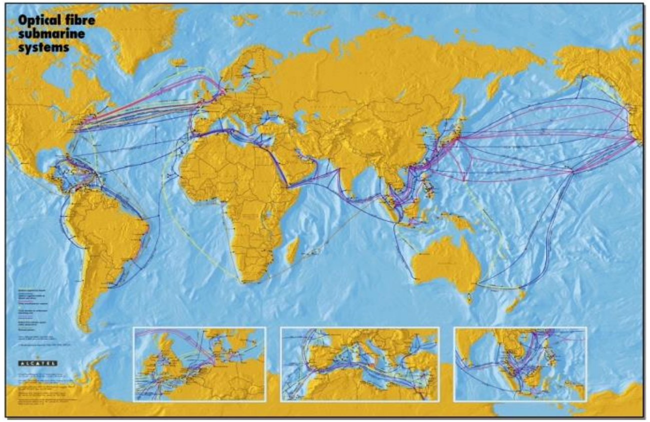
2013

CERN
2011-2012



And with many, many, many… applications…

laser

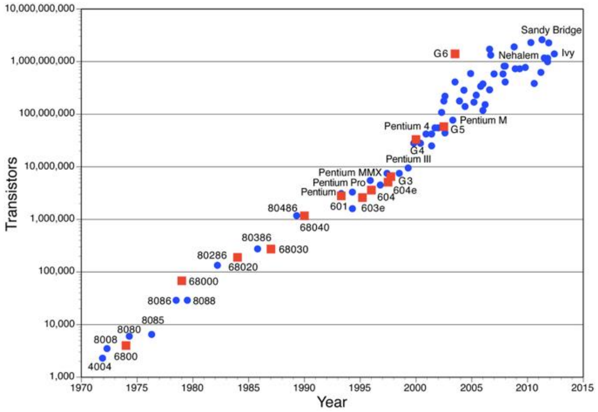


Information world

Transistors

~ 14 nm

Intel
2015

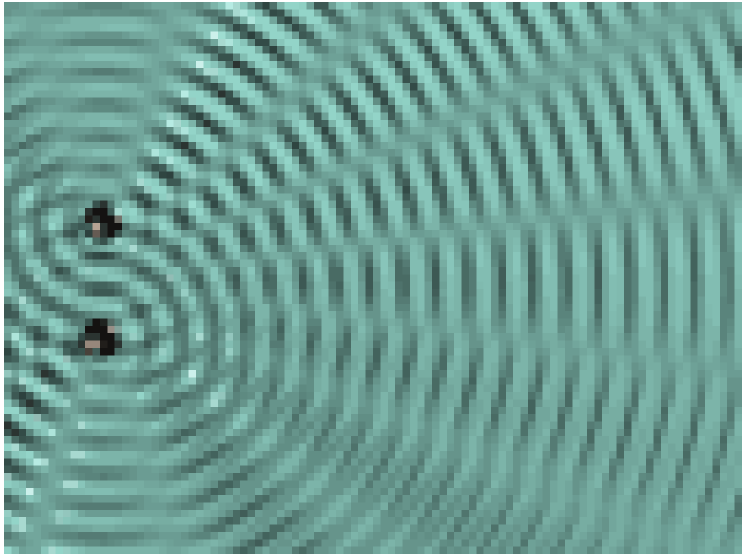


NMR

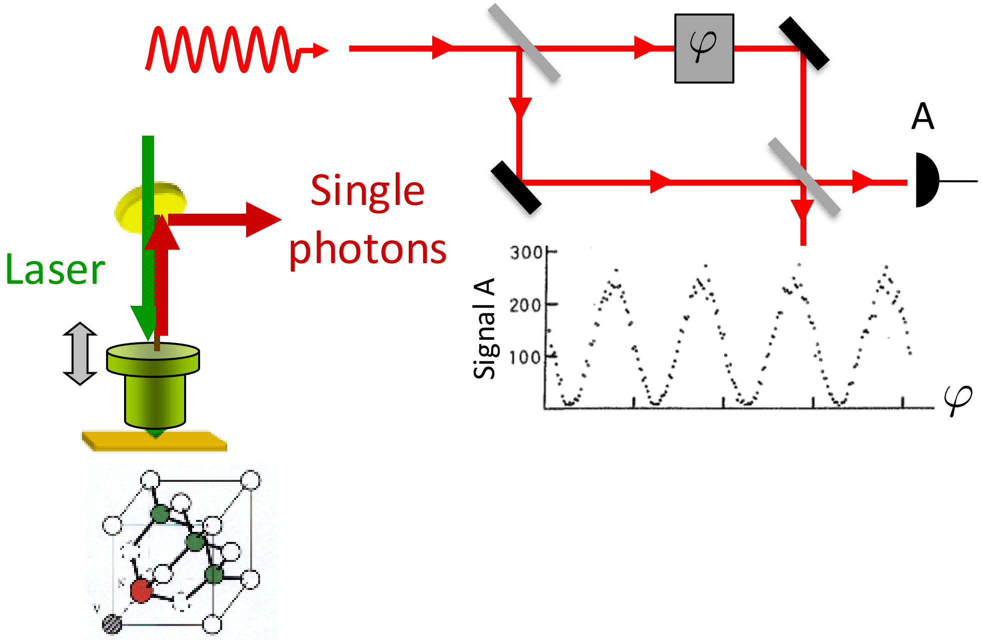
The essence of quantum physics: superposition

Quantum objects can be in
several states at the same time…

$$\psi = \psi_1 + \psi_2$$



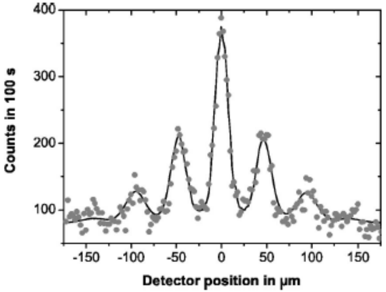
Proof: interferences

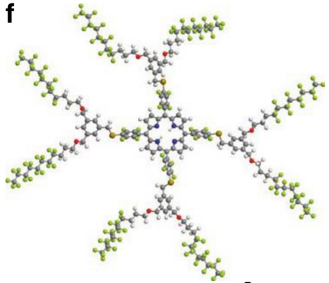


Tests of the superposition principle: examples

Atoms, molecules…

Nature 1999



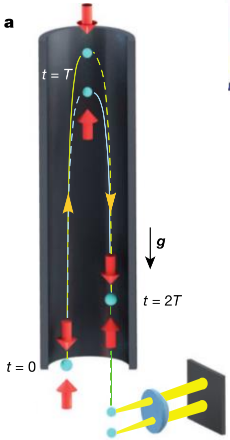


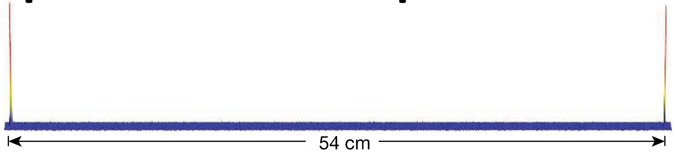
$C_{168}H_{94}F_{152}O_8N_4S_4$

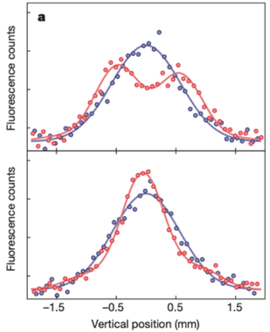
Nat. Comm. 2013

Electrons

Spatial separation of wavepacket

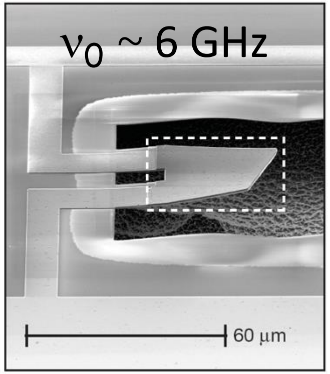


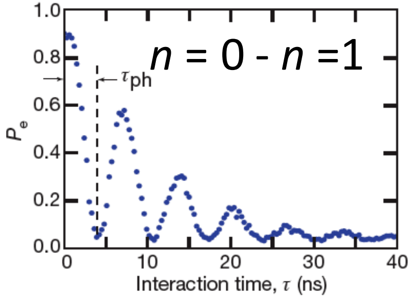




Nature 2016

Nanomechanical resonator

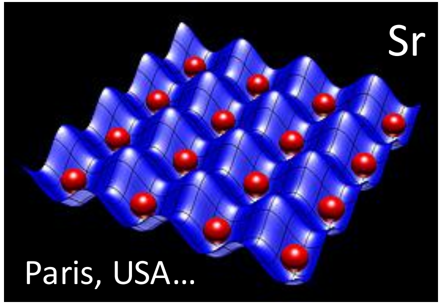




Nature **464**, 697 (2010)

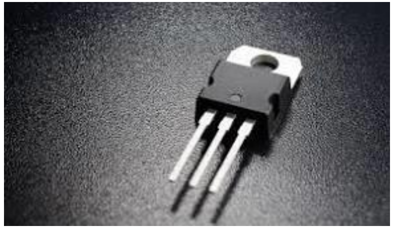
The superposition principle in our daily lives…

Atomic clock

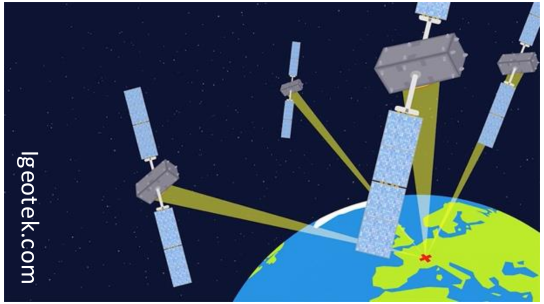


Magnetic resonance imaging

transistors

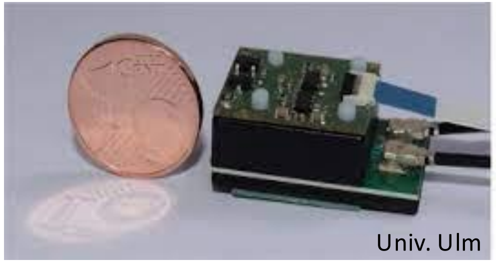


GPS



Sensors: gravity, rotation, magnetic field…

iXblue

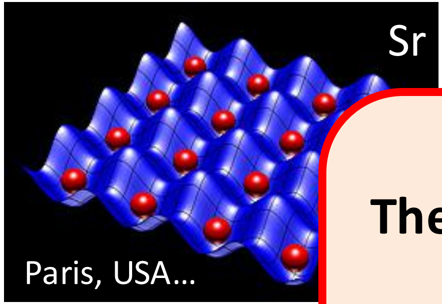


miniaturised magnetometer

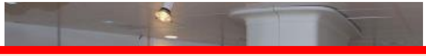
nanotesla sensitivity

The superposition principle in our daily lives…

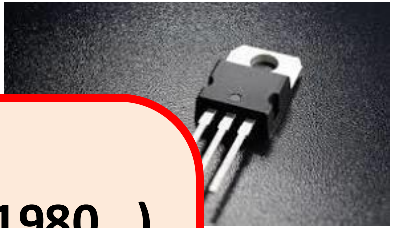
Atomic clock



Magnetic resonance imaging



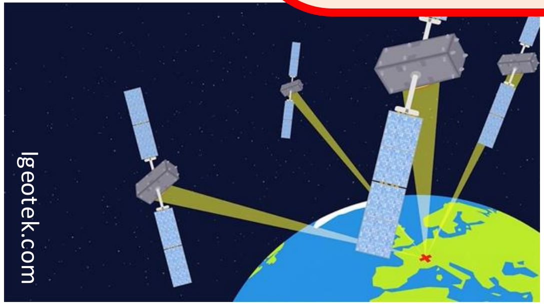
transistors



The First Quantum Revolution (1920-1980…)

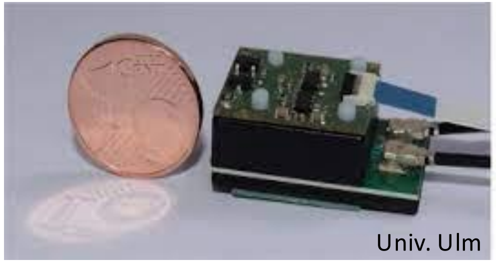
SUPERPOSITION

(single-particle…)



iXblue

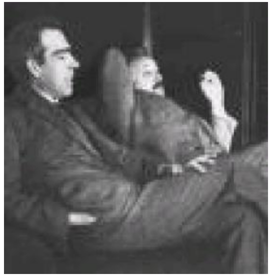
tic field…



miniaturised magnetometer

nanotesla sensitivity

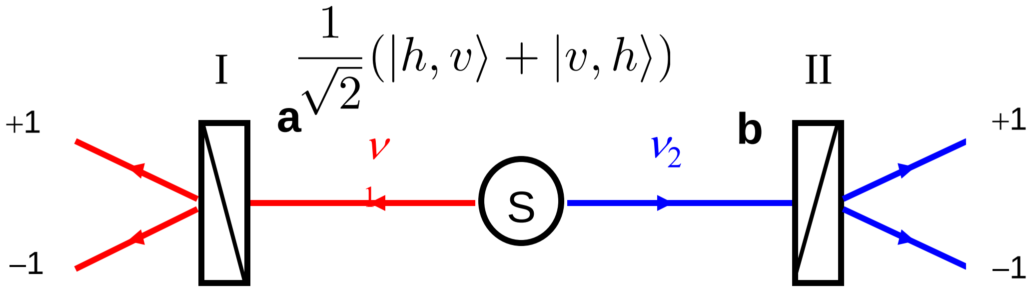
Superposition principle for 2 objects ⇒ entanglement



MAY 15, 1935 PHYSICAL REVIEW VOLUME 47

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

A. EINSTEIN, B. PODOLSKY AND N. ROSEN, *Institute for Advanced Study, Princeton, New Jersey*
(Received March 25, 1935)



J. Bell

1964

Strong quantum correlations!!

2022

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)

« There is plenty of room at the bottom …»

R.P. Feynman

“There's Plenty of Room at the Bottom: An Invitation to Enter a New Field of Physics”
R.P. Feynman, Caltech (1959)

Problem: exponential complexity

2 d. of freedom (spin…) $\psi_i = \begin{pmatrix} a \\ b \end{pmatrix}$

Many-body wavefunction: $\Psi = \Psi(1, 2, ..., N) \Rightarrow \Psi$ requires 2^N numbers

Record *ab-initio* calculation (2024) $N \sim 50 \Rightarrow 2^{50} \sim 10^{15}$ = 1000 Tb RAM !!

Worldwide computer memory (2024): 10 zetabytes (10^{22}) $\Rightarrow N \sim 70$!!

Huge challenge to calculate complex quantum systems

BUT… opportunity if properly harnessed

Isolating & manipulating single quantum particles

The point of view of a founding father…

In the first place it is fair to state that we are not *experimenting* with single particles, anymore than we can raise Ichtyosauria in the zoo.

…., this is the obvious way of registering the fact, that we **never** experiment with just **one** electron or atom or (small) molecule. In thought-experiments we sometimes assume that we do; this envariably entails **ridiculous** consequences.

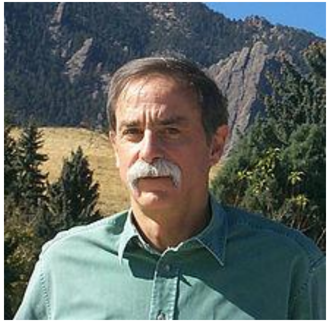
E. Schrödinger

British Journal of the Philosophy of Science III (10), (1952)

60 years later…

2012

S. Haroche (France)

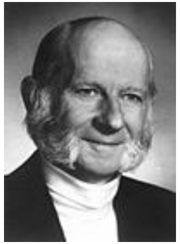


D. Wineland (USA)

"for ground-breaking experimental methods that enable measuring and manipulation of individual quantum systems"

Trapping individual particles: the early days…

H. Dehmelt



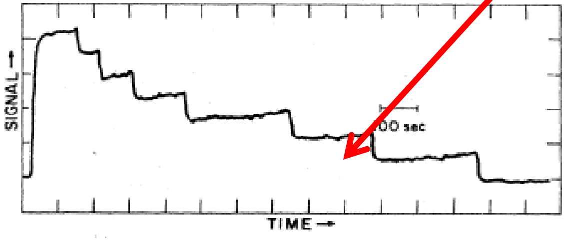
1989

VOLUME 31 19 NOVEMBER 1973 NUMBER 21

Monoelectron Oscillator

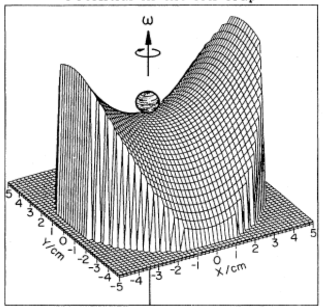
D. Wineland, P. Ekstrom, and H. Dehmelt
Department of Physics, University of Washington, Seattle, Washington 98195
(Received 13 August 1973)

Single electron



W. Paul: ion trapping techniques

Potential in the Ion Trap



PHYSICAL REVIEW A VOLUME 22, NUMBER 3 SEPTEMBER 1980

Localized visible Ba^{+} mono-ion oscillator

W. Neuhauser, M. Hohenstatt, and P. E. Toschek
Institut für Angewandte Physik I der Universität Heidelberg, D-69 Heidelberg, Federal Republic of Germany

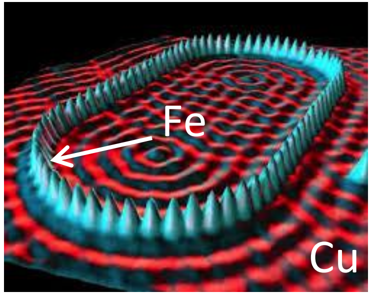
H. Dehmelt
Department of Physics, University of Washington, Seattle, Washington 98195
(Received 11 September 1979)

1st single ion

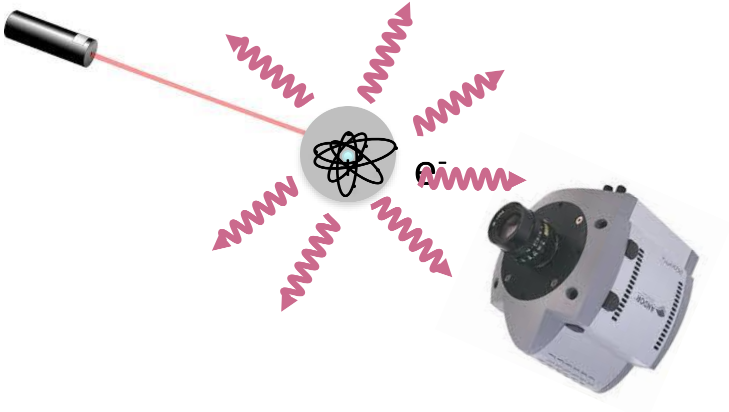
Today, we can « see » atoms

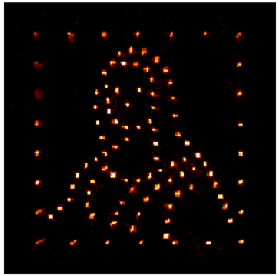
Scanning tunnel microscope (IBM, 1981)

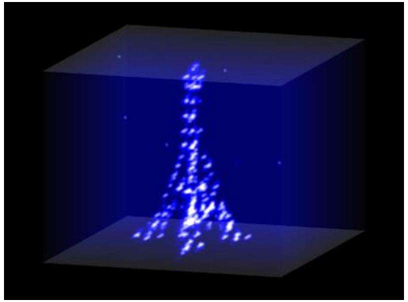
« see » electronic cloud



Light scattered by a single atom: see directly…







PASQAL

828 atoms

The second Quantum Revolution (1990 - …)

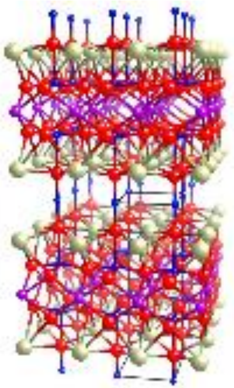
Entanglement

+

Manipulation of individual quantum systems

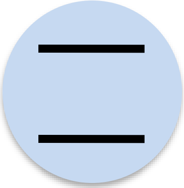
Quantum state engineering: create controlled quantum states

Quantum Simulation



Quantum metrology

^{133}Cs



F=4

F=3

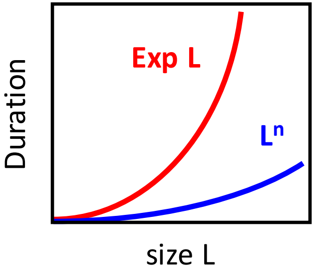
1 sec = 9 192 631 770 cycles

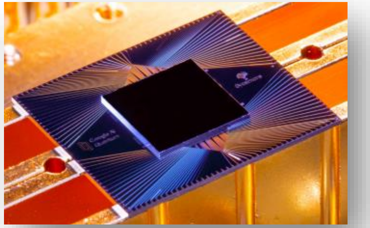
$$\frac{\Delta\nu}{\nu_0} \propto \frac{1}{\sqrt{N}} \xrightarrow{\text{qu. states}} \frac{\Delta\nu}{\nu_0} \propto \frac{1}{N}$$

Quantum Communication

Message

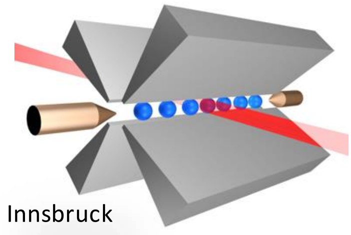
Quantum Computation



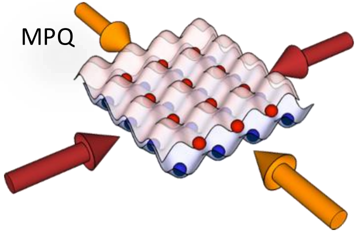


Sycamore processor, Google Inc.

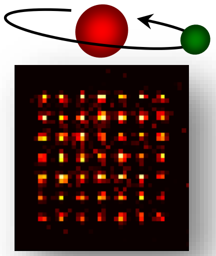
Engineering with individual quantum systems



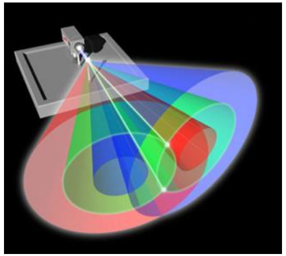
Trapped ions



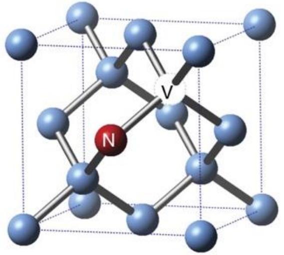
Cold atoms & molecules



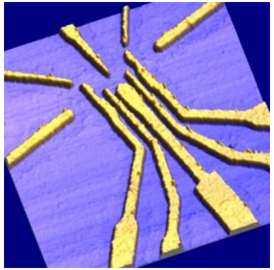
Rydberg atoms



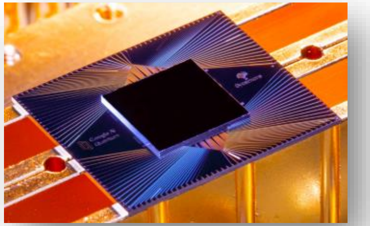
Photons



NV center, SiV

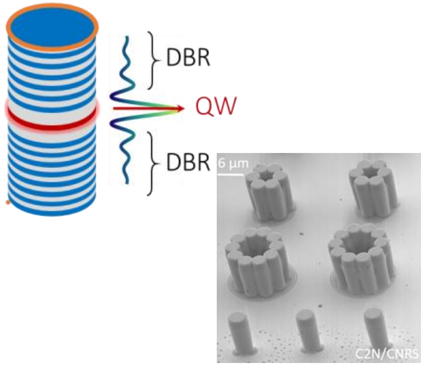


Quantum dots



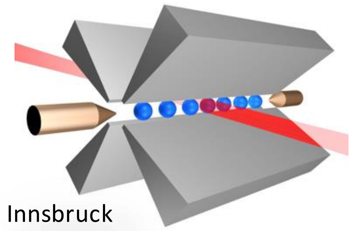
Sycamore processor, Google Inc.

Superconducting circuits

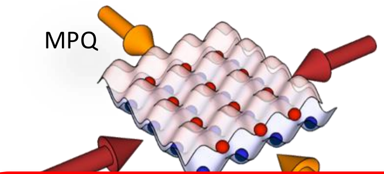


Polaritons in semi-conductors

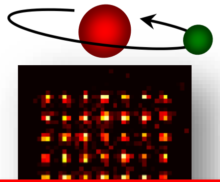
Engineering with individual quantum systems



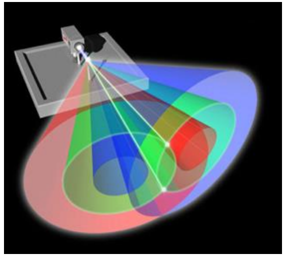
Trapped ions



Cold atoms & molecules

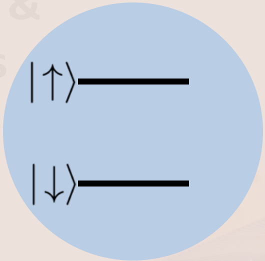


Rydberg atoms

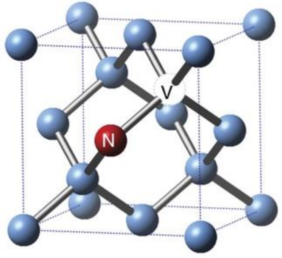


Photons

Two-level systems to encode a spin:



Addressable + **controlled** interactions

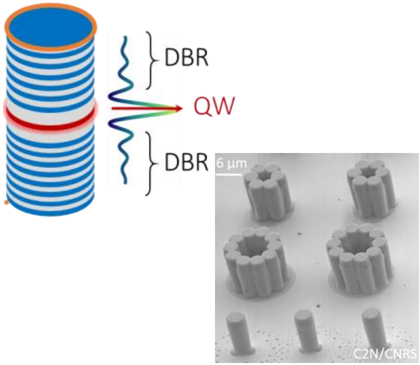


NV center, SiV

Quantum dots

Sycamore processor, Google Inc.

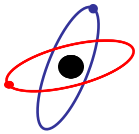
Superconducting circuits



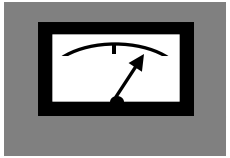
Polaritons in semi-conductors

Why is it so difficult?

Quantum superposition = **very fragile**!! **Decoherence**



$\alpha|g\rangle + \beta\,|e\rangle$

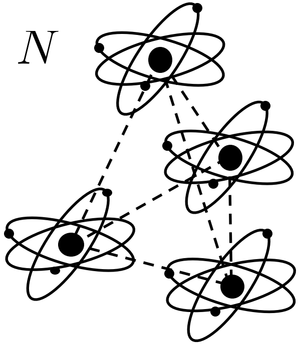


Environment
"measures"

Statistical mixture
(classical)
$|g\rangle, |\alpha|^2$ or $|e\rangle, |\beta|^2$

The larger, the more decoherence…

N



$N\,\Gamma$

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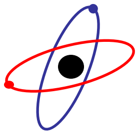
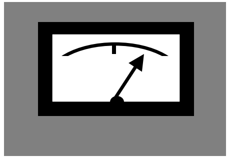


$\alpha|g\rangle + \beta|e\rangle$



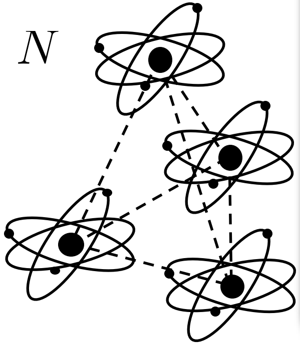
Environment

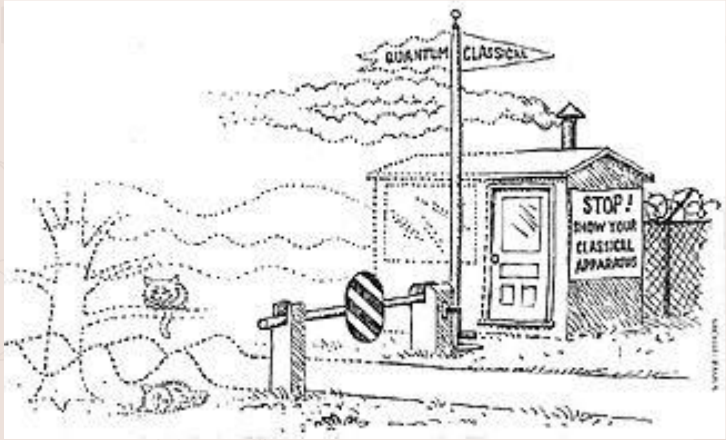
“measures”

Statistical mixture (classical)

$|g\rangle, |\alpha|^2$ or $|e\rangle, |\beta|^2$

Transition quantum / classical ?





Academia, many industrial players and startups

[redacted]

Alice & Bob

Welinq

Quandela

µQuans

Total

Pasqal

MyCryoFirm
Cryodevices & Consulting

EDF

CryoConcept

Many job opportunities for you...!

Objectives of this course

Understand the concepts of the Second Quantum Revolution
= **modern presentation** of quantum physics

Discuss recent experiments using quantum technologies
= understand opportunties, challenges and…dreams…

Main topics:

Qubits and harmonic oscillators in practice

Entanglement and its characterization

Measurements in quantum physics

Description of open quantum systems

Decoherence and transition to classicality

Stochastic wavefunction methods

Warning note: what this course is *not* about…

Not a course on Quantum Information:

No discussion of quantum algorithms

No discussion of error correction codes

No profound discussion on information theory…

More details in specialized courses (semester 2)

Quantum communication & cryptography,
Ultra-cold atoms and quantum simulation,
Manipulation of simple quantum systems
…