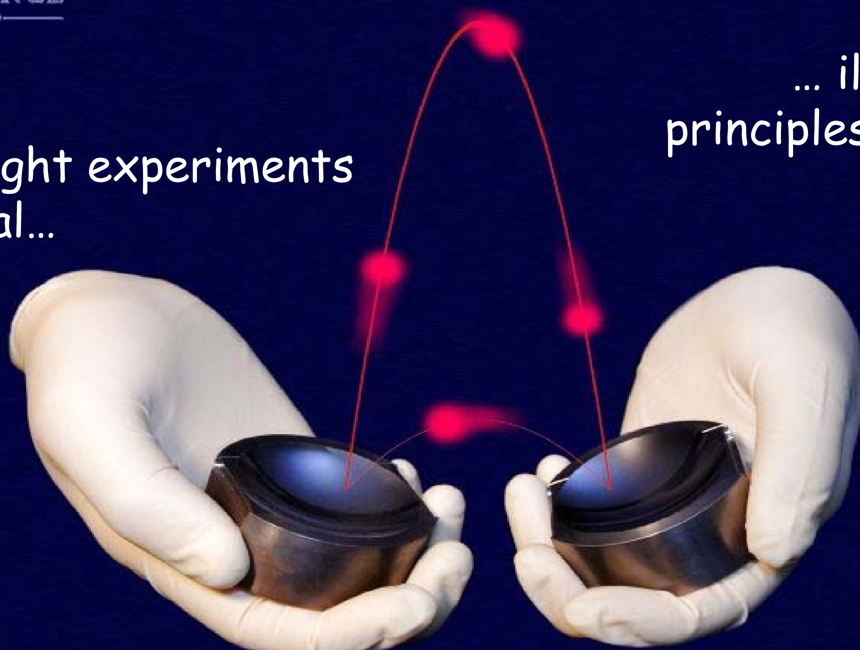
# Photons in a box & "Schrödinger cats of light"

Serge Haroche

When thought experiments become real…

… illustrate the principles of quantum physics…



…and demonstrate basic steps of quantum information

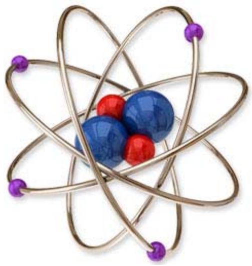
# Light and the Quantum

Quantum physics, which has given us the keys of the microscopic world of atoms and photons, has been triggered by the necessity to understand properties of light which could not be explained by classical physics

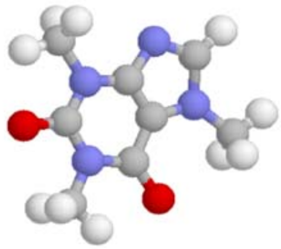
"Nobody understands quantum physics" (R. Feynman)

Quantum physics obeys to strange laws ***(state superposition, entanglement)*** which challenge our intuition, even if this strangeness illustrated by the Schrödinger cat metaphor, remains veiled at the macroscopic level

Recent experiments using the interaction of light with atoms to *control single particles* lead us to believe that the microscopic strangeness of the quantum could be harnessed to develop new tools for communication or computing

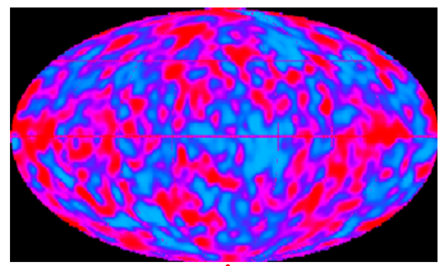


atoms



Molecules and chemistry

solids



cosmology

Quantum physics: a theory of everything

# Examples of Quantum technologies

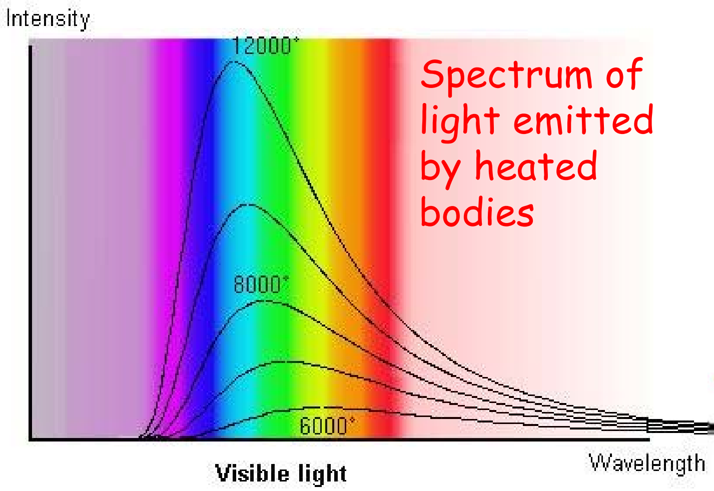
Computers

Atomic clocks and GPS

Lasers

MRI scanners

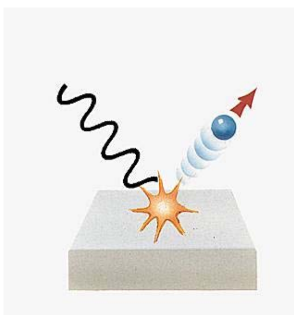
# The birth of quantum theory: early models and thought experiments



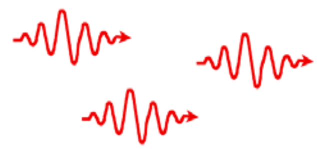

Spectrum of light emitted by heated bodies

Einstein in 1905….

The birth of quantum physics



Photoelectric effect



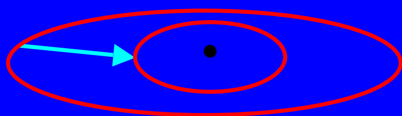
The photon

$$E = h\nu$$

$\nu$: light frequency

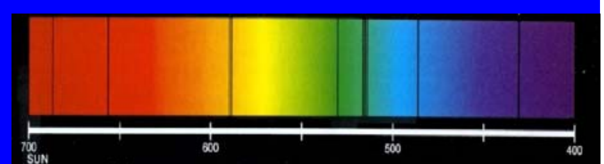
h: Planck constant


# The Bohr atom: like light, atoms are quantized

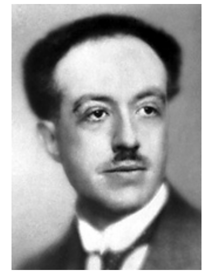


The electron jumps between quantized orbits by emitting or absorbing a photon with frequency $v$ such that
$E_2-E_1=hv$

*It quantitatively explains the discreetness of atomic spectra…and introduces the concept of quantum jumps in physics…*

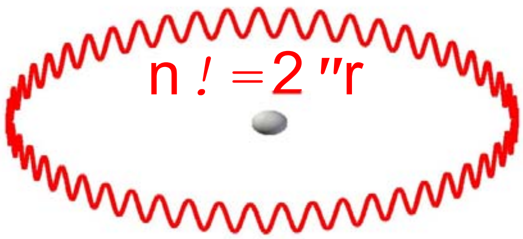


# Bohr’s model interpreted by de Broglie: matter has wavelike features



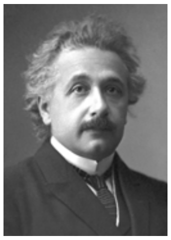
1913 Electron of velocity v has wavelength $\lambda = h/mv$ 1923

Bohr’s quantization corresponds to resonance condition of integer number of de Broglie waves around orbit:



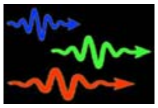

The electron is a running matter wave around the nucleus. The principal quantum number n counts the number of wavelengths around the orbit

# The early theories of quanta have led physics step by step into a strange world…



1905

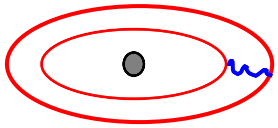
light waves are quantized…



Photon

1913

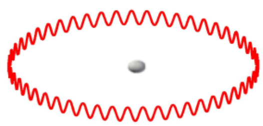
…as are electronic orbits in atoms…



Quantum jump

1923

… suggesting that electrons are also waves…

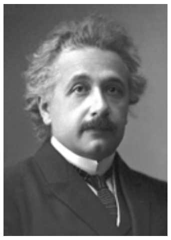


Progressive lifting of the "great veil"

Wave-particle dualism introduced the superposition principle in physics, challenging classical ideas about determinism and physical reality

Quantum theory: Heisenberg, Schrödinger, Dirac (1926)

# Quantum physics is based on the wave-particle duality and the superposition principle



Light is a wave *and* an ensemble of photons (Einstein 1905)

Atoms are particles *and* matter waves (de Broglie, 1923)

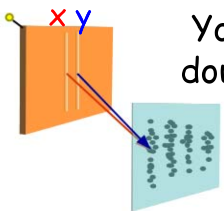

Which aspect is observed…

..depends on experimental set-up

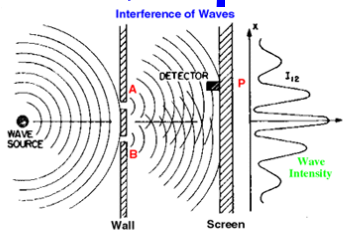
**Bohr's complementarity**

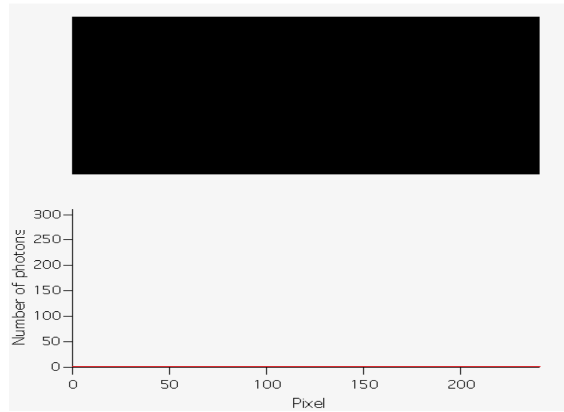
*"If you are not shocked by quantum physics, you have not understood it" (Niels Bohr)*

# A strange dualism: matter and light are at the same time particles and waves




Young double slit




How do photons arrive only on bright fringe if they pass one by one through one slit or the other?

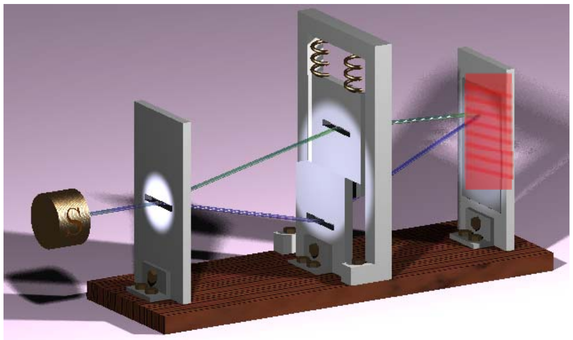
*Credit to J-F Roch (ENS Cachan- Labo Aimé Cotton)*

Each photon must pass "through both holes at once" : no classical trajectory and superposition principle:

$$|\Psi\rangle = |X\rangle + |Y\rangle$$

Same dilemma for matter: electrons, atoms..molecules are waves and particles (de Broglie, 1923) and the superposition principle applies to them («Schrödinger cat» suspended between two different realities)

# A thought experiment illustrating complementarity and entanglement



*Einstein-Bohr discussion at Solvay meeting 1927*

Einstein: To find path, detect momentum transfer to moveable upper slit…

Bohr: this requires to define slits initial momentum with *very small uncertainty Δp*. Hence, position uncertainty Δx is large according to Heisenberg relation $\Delta x . \Delta p > h$. If Δx large, fringes are blurred…

The concept of entanglement:

$$|\text{particle crosses upper slit}\rangle|\text{upper slit moves}\rangle + |\text{particle crosses lower slit}\rangle|\text{upper slit doesn't move}\rangle$$

**This looks like a "Schrödinger cat"**

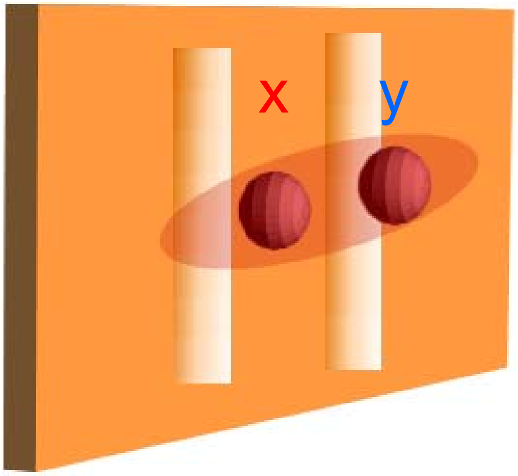
# Schrödinger cat and entanglement: A large system coupled to a single quantum particle ends up in strange superposition…

1935


For interacting systems, the superposition principle leads to quantum entanglement…

… which for large systems, raises the issue of the quantum-classical boundary

# Quantum physics and state superpositions

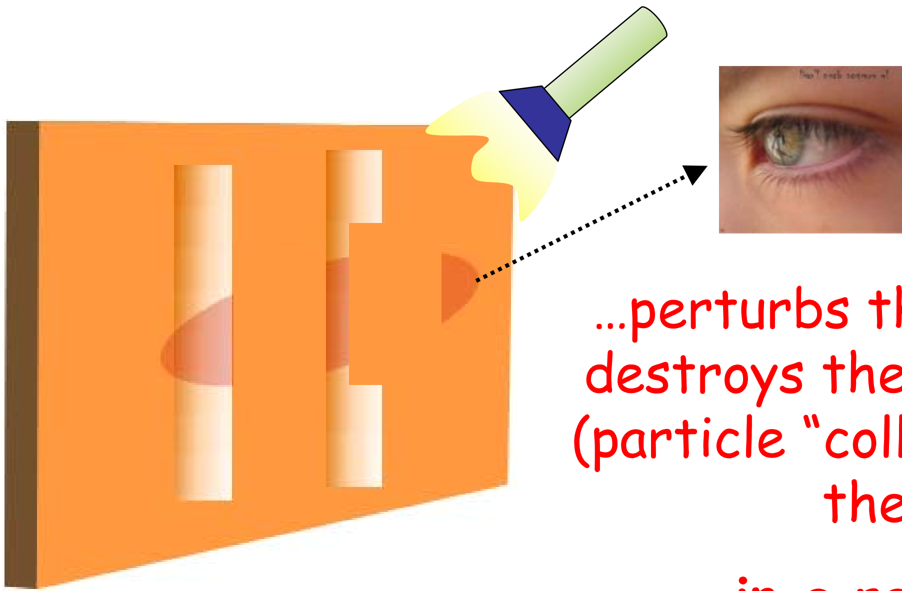



Superposition of position states…

$$|\Psi\rangle = |x\rangle + |y\rangle$$

…or superpositions of energy states..

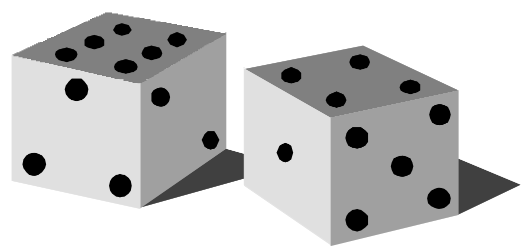
# The measurement …



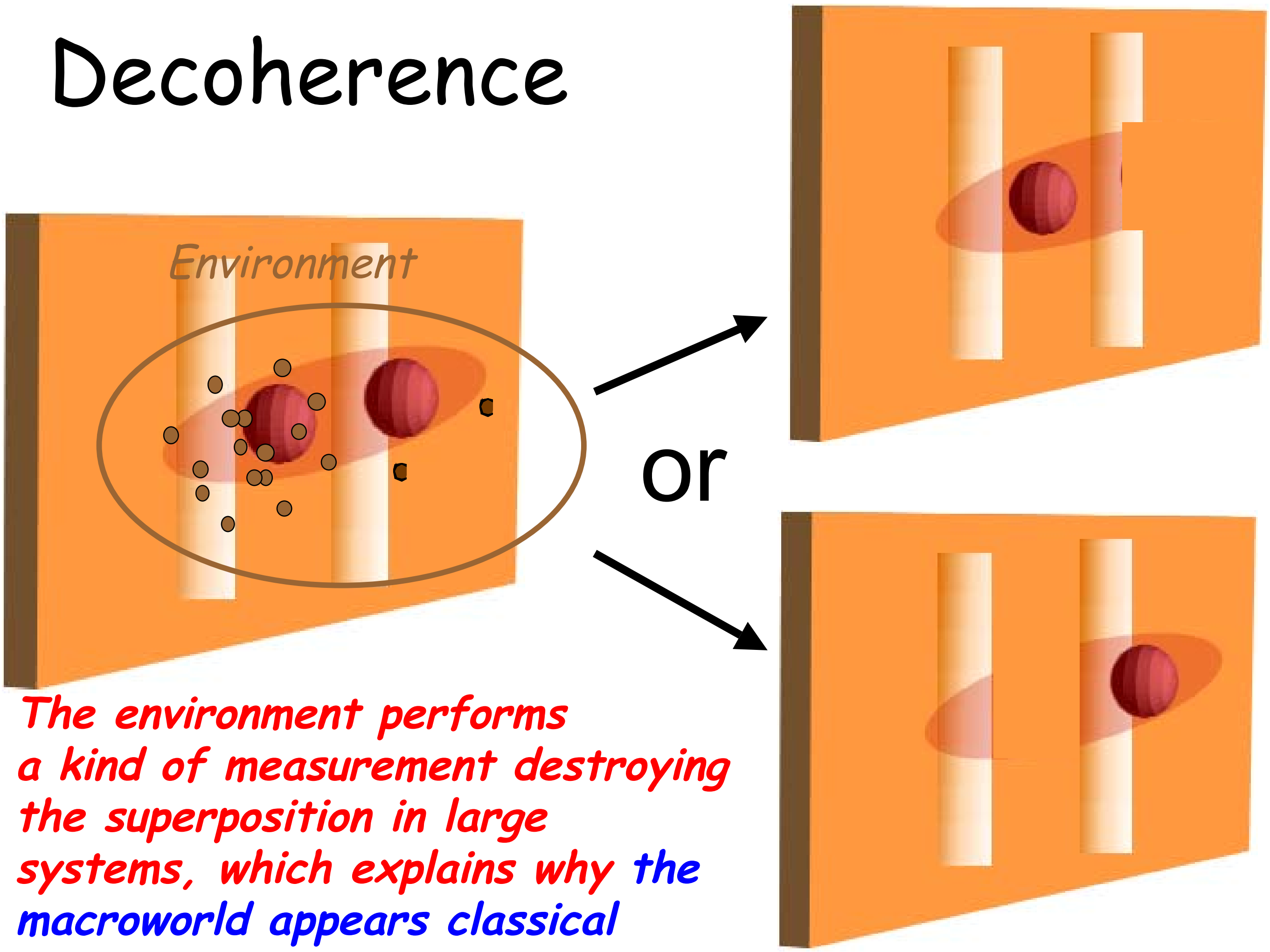
…perturbs the system and destroys the superposition (particle "collapses" here ***or*** there)…

**…in a random way…**

*« God is playing dice »*
*(Einstein did not like it)*



# Decoherence

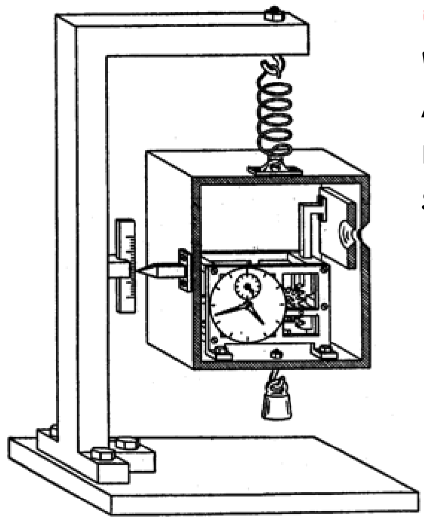



The environment performs a kind of measurement destroying the superposition in large systems, which explains why the macroworld appears classical

# Another thought experiment: can photons be trapped and counted like marbles in a box?

Einstein and Bohr at Solvay, 1930

Would this violate time-energy Heisenberg uncertainty relation?



Einstein: weigh box with arbitrary small $\Delta E$ before and after releasing photon in short time interval $\Delta T$

Bohr: be careful with measurement of time due to box motion in gravitational field during weighing process…

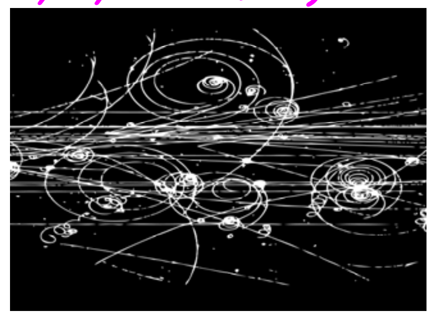
The photon box experiment involves a clock to time the escape of light quanta…

# What Schrödinger thought about thought experiments…

*« We never experiment with single electrons, atoms or small molecules…In thought experiments we assume that we do. It always results in ridiculous consequences… »* ***(Schrödinger, British Journal for the Philosophy of Sciences, 3, 233 1952)***

Schrödinger knew that single particles could be detected, but, as he said, this was through « post mortem » observations which destroyed the observed object…

**Bubble chamber (CERN)**

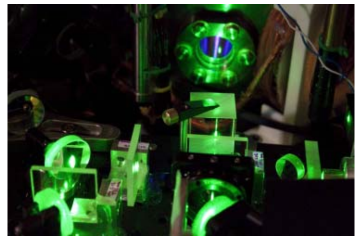


*"…It is fair to state that we are not experimenting with single particles, any more than we can raise Ichthyosauria in the zoo. We are scrutinising records of events long after they have happened."* (Schrödinger, ibid)

# How "thought experiments" controlling a zoo of particles became real

## New quantum technologies:

Tunable lasers

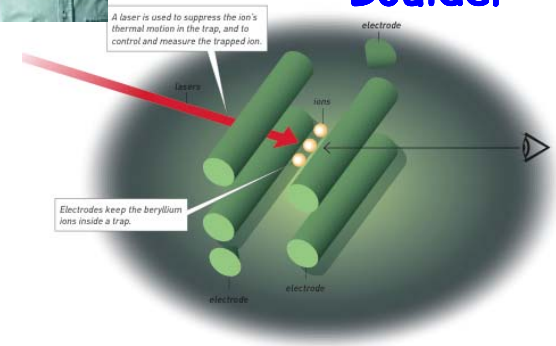


Fast computers

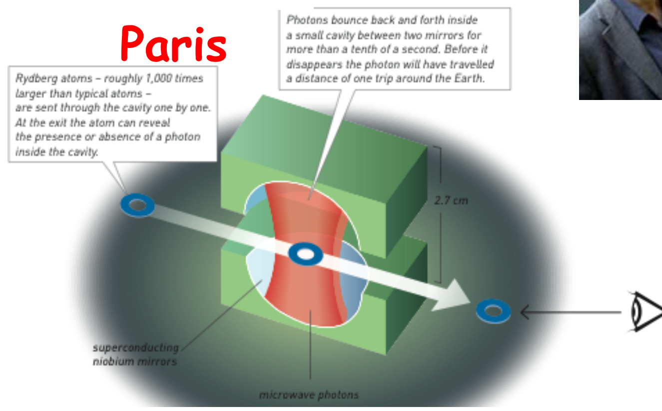
Superconducting materials

# «Particle control in a quantum world»

Boulder




Paris

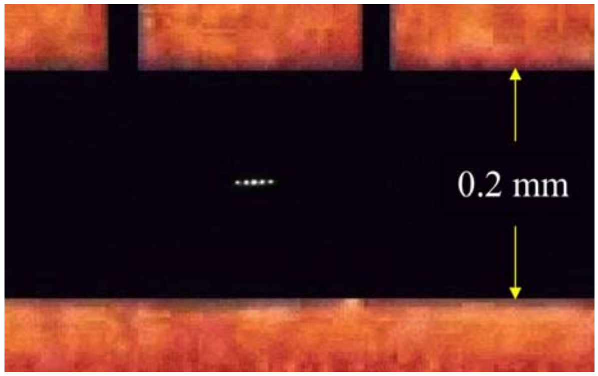



**Two sides of the same coin:manipulating non destructively single atom with photons or single photon with atoms**

## Light matter interaction at most fundamental level

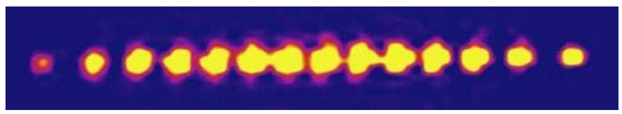
*Many groups in the world are controlling single particles for quantum information*

Five Berrylium ions in the lab of David Wineland (2000)…

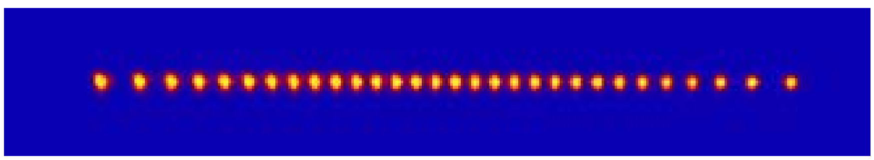



Each atom is a quantum bit (qubit) which can be brought in a superposition of two quantum states

… and 14… then 30 Calcium ions in the lab of R. Blatt in Innsbruck (2012-2013)



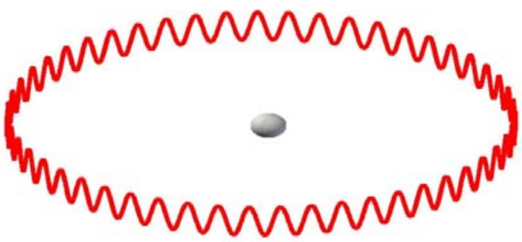
Each ion is a qubit: $2^{30}$ states!

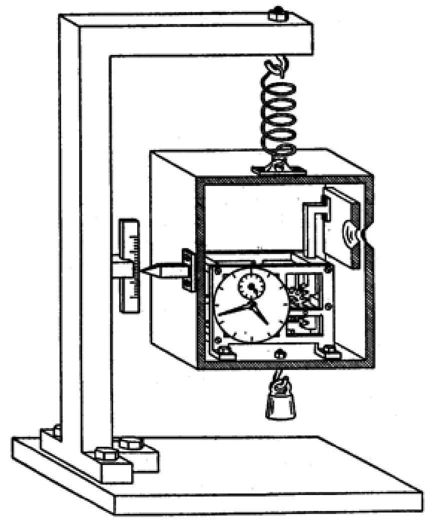


$2^{30}$ ~ 1 Billion!

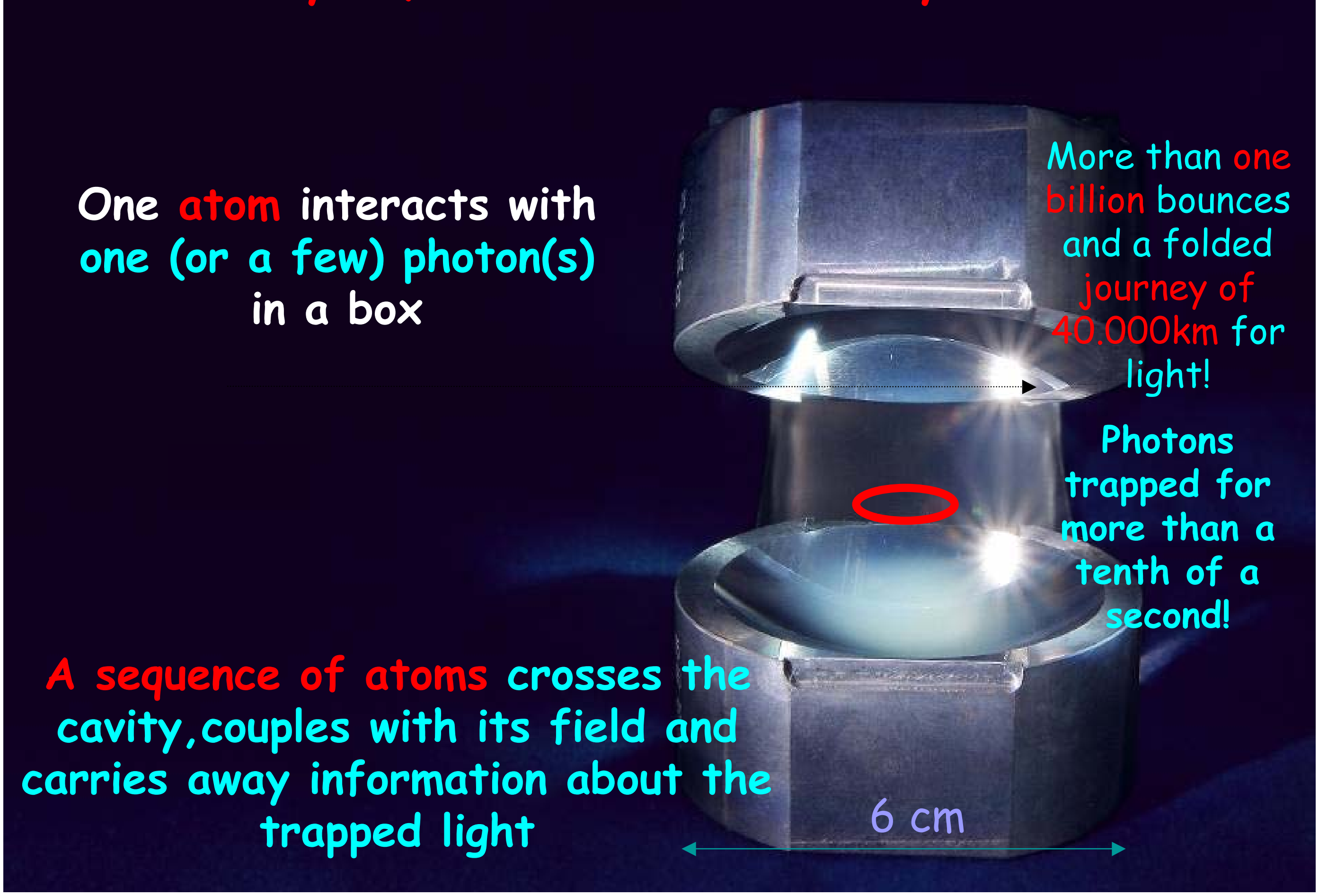
An atomic abacus for quantum information

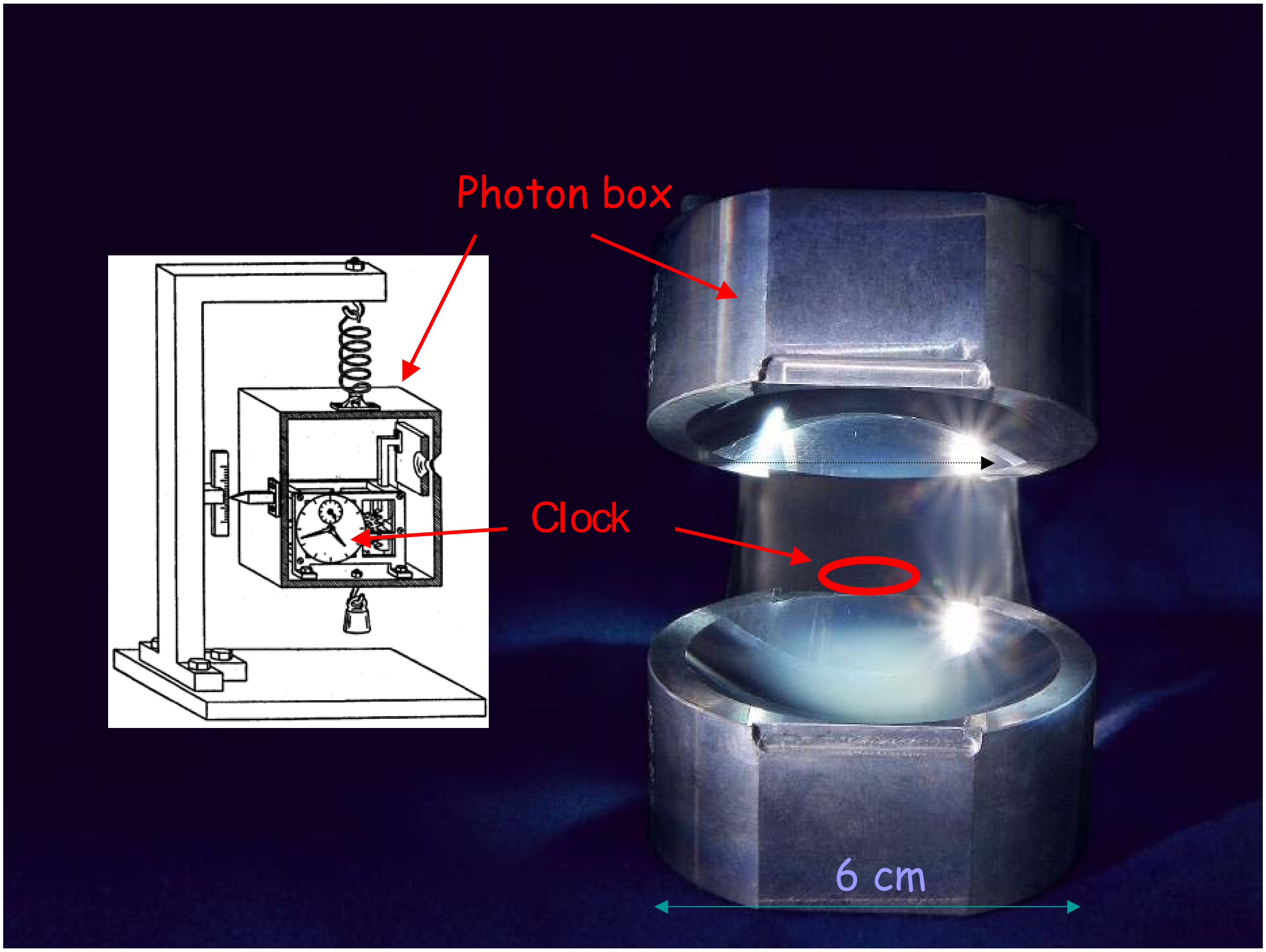
# Cavity Quantum Electrodynamics with Rydberg atoms
# (Bohr's atom in Einstein's photon box)





# Cavity Quantum Electrodynamics:




Photon box
Clock
6 cm

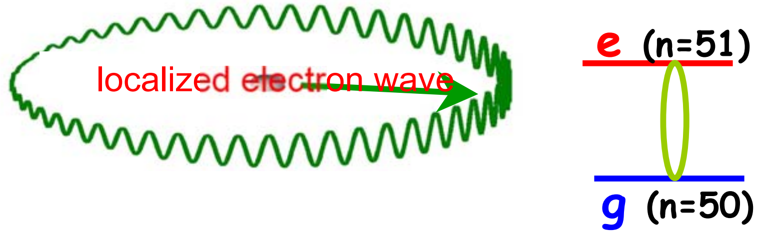
# The circular Rydberg-Bohr atom

Rydberg

Bohr
(1913)

Atom in ground state:
**electron** on $10^{-10}$ m diametre orbit

Atom in circular Rydberg state:
**electron on giant circle orbit**
(tenth of a micron diameter)

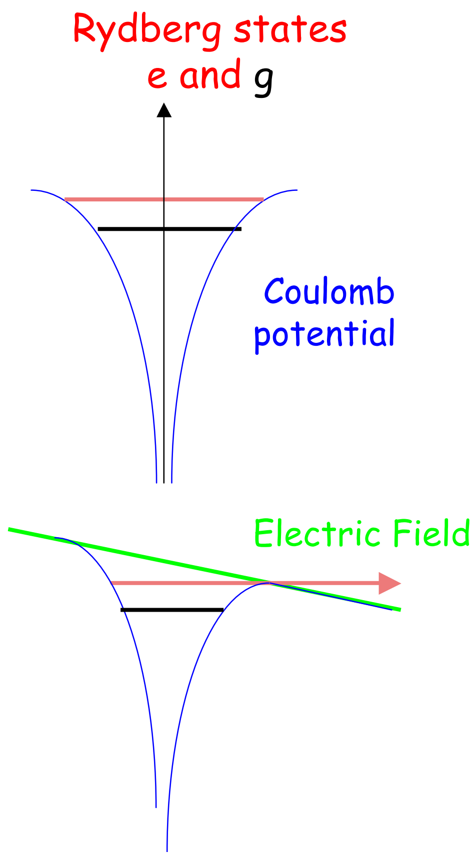


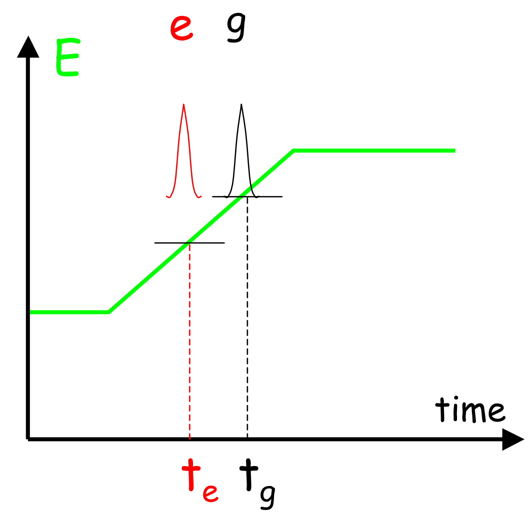

*Electron is localised on orbit by a microwave pulse preparing superposition of two adjacent Rydberg states:* $|e\rangle \rightarrow |e\rangle + |g\rangle$

D.Kleppner
(1983)

**The localized wave packet revolves around nucleus at 51 GHz like a planet around the sun or like a clock's hand on a dial.**

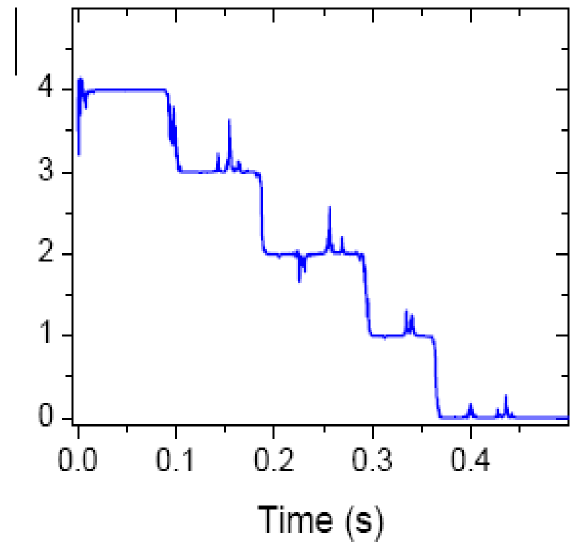
# State selective detection of Rydberg states by field ionization



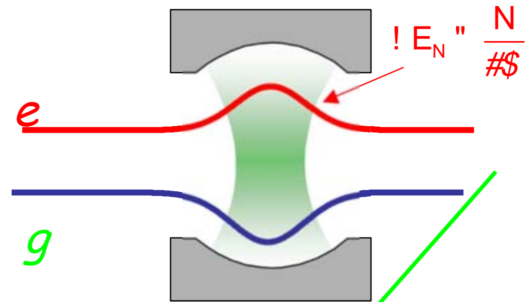




A bit of information
per atom!

# Counting photons in the box without destroying them and observing when they escape (quantum jumps)



**When atom interact with *non-resonant* light ($\delta\omega=\omega_{eg}-\omega_{cav}\neq 0$) its energies are modified by light shift effect (Cohen-Tannoudji, 1961)**

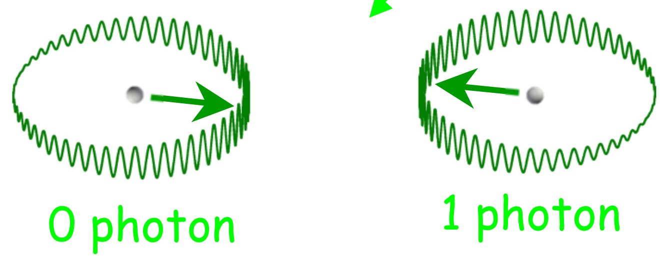



*Atom undergoes a light-shift proportional to photon number N, with opposite signs for e and g*

Phase shift of atomic dipole:

$$\Delta\Phi(N)=N\phi_0\ ;\ \phi_0=2\int\frac{\Delta E_1}{\hbar}\frac{dz}{v}$$

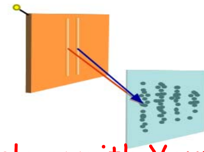
$\phi_0$: phase shift per photon can reach the value $\pi$




Measuring $\Delta\Phi$ amounts to a "Quantum Non Demolition" (QND) photon counting

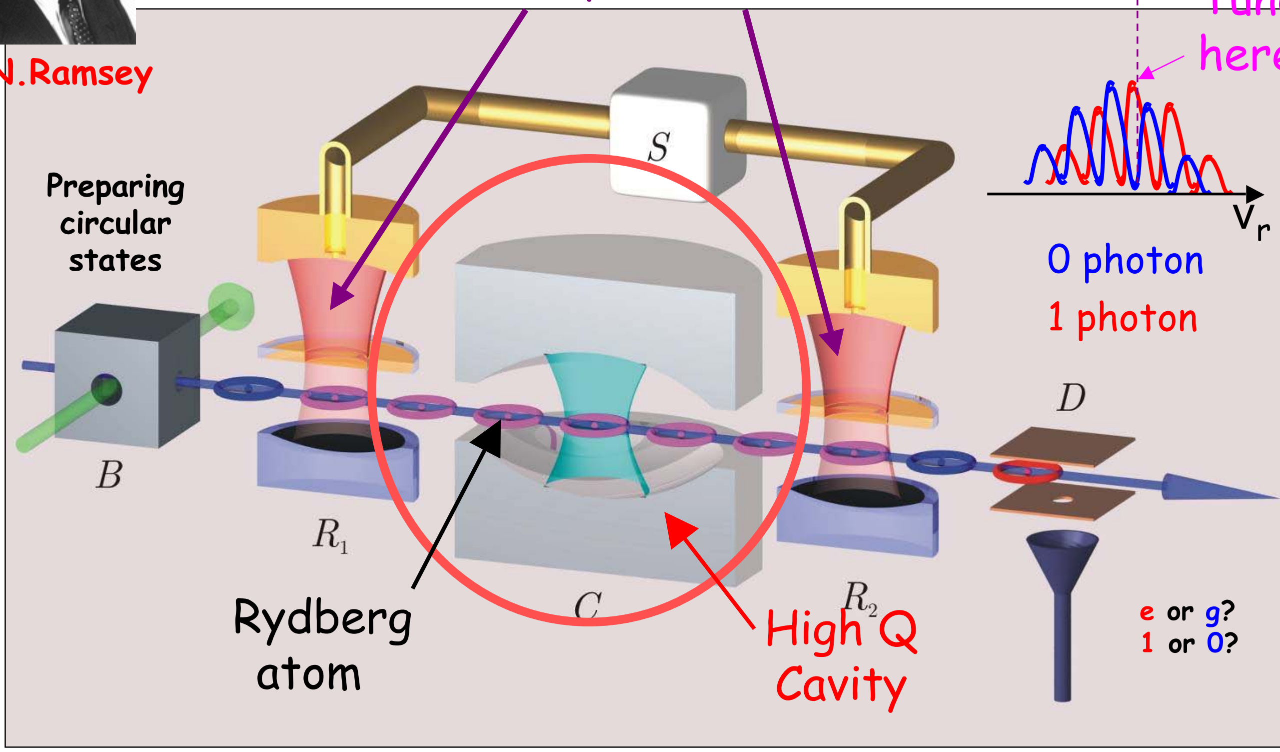
N.Ramsey

# The experimental scheme



Analogy with Young

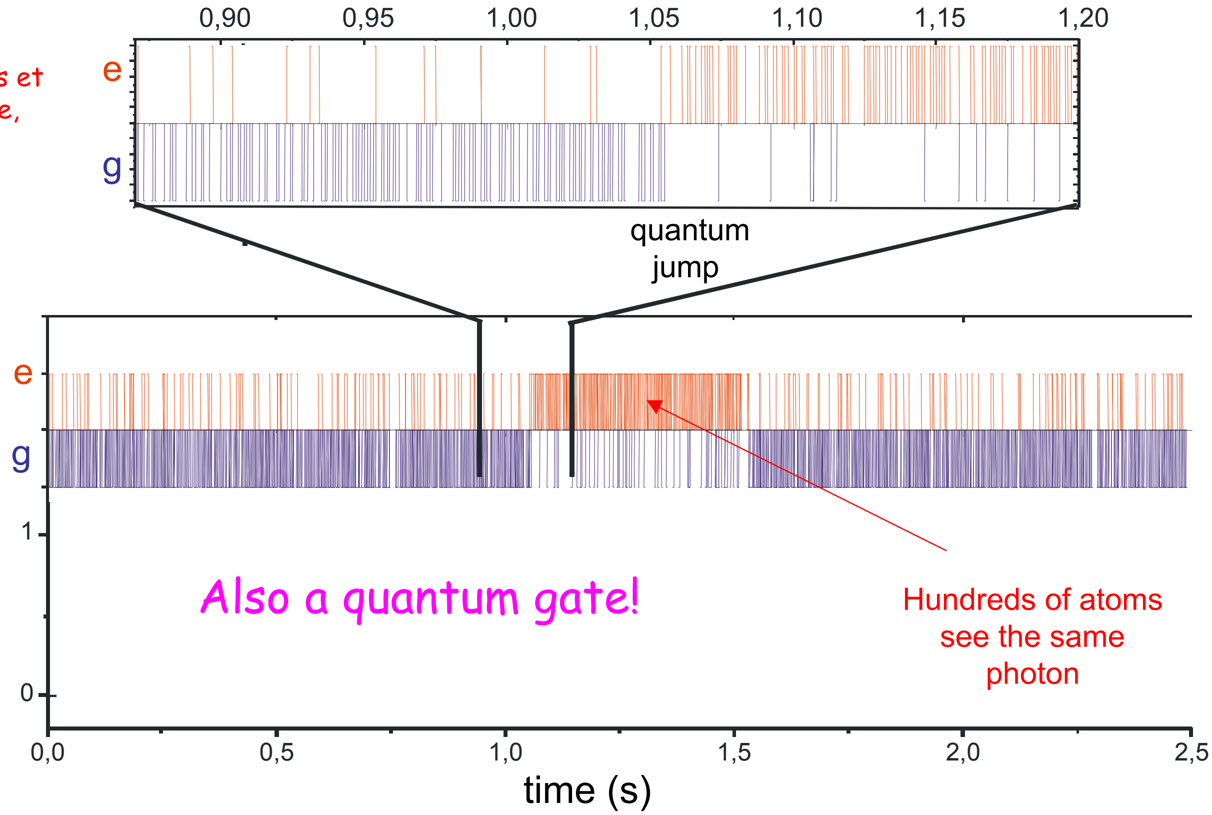
Classical pulses
(Ramsey interferometer)




An atomic clock delayed by photons trapped inside

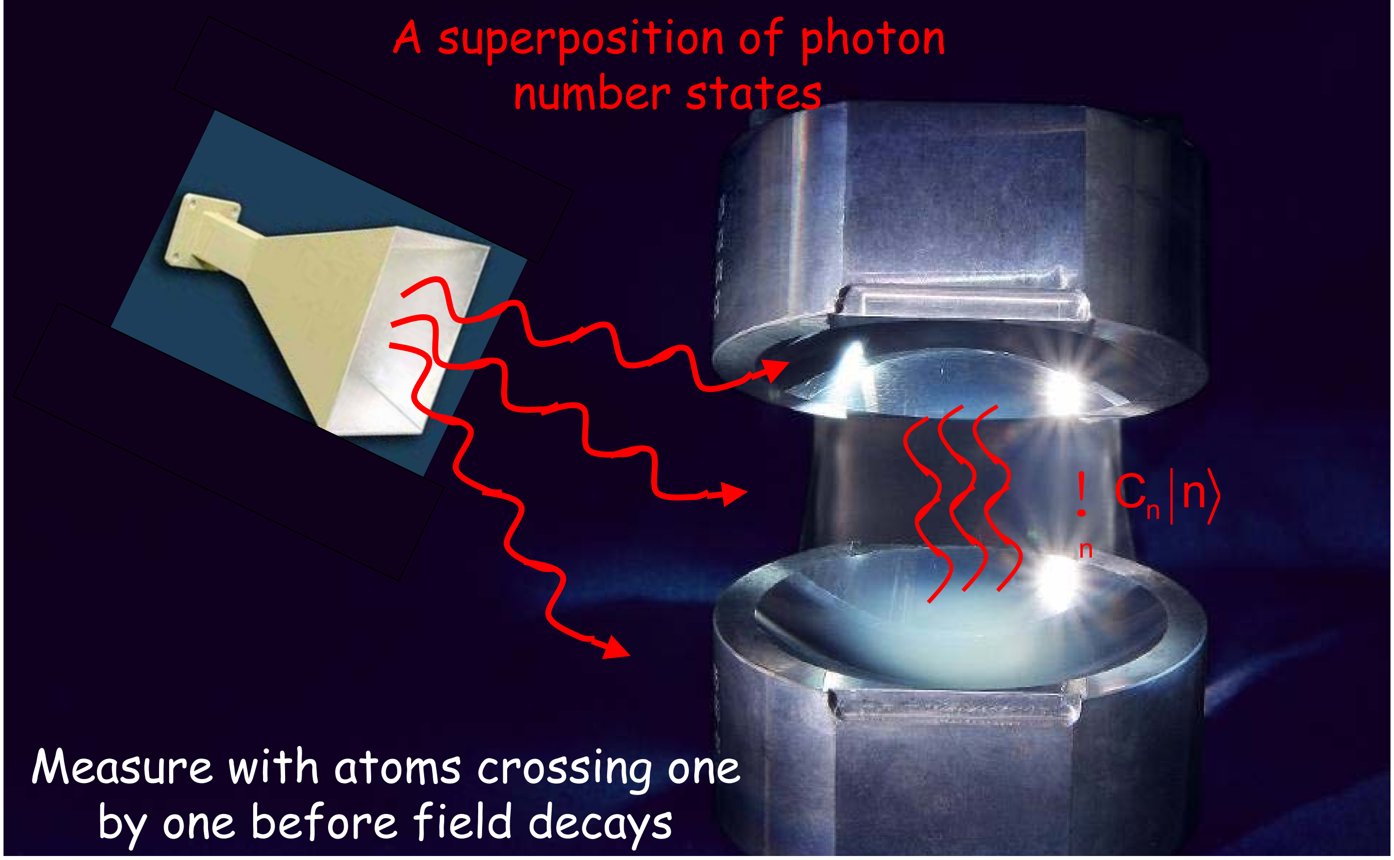
# Birth, life and death of a photon

S.Gleyzes et al, Nature, 446, 297 (2007)

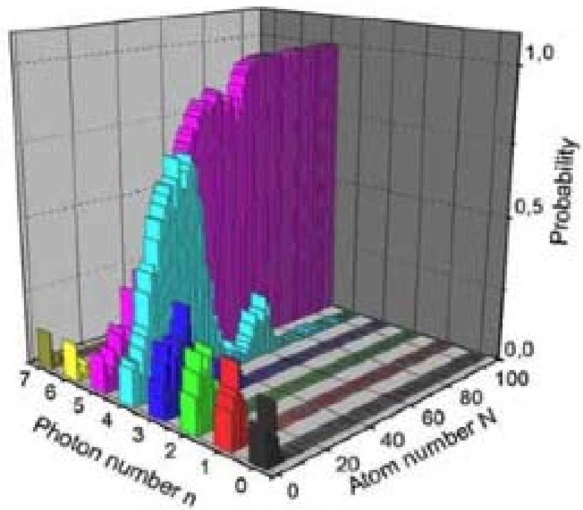


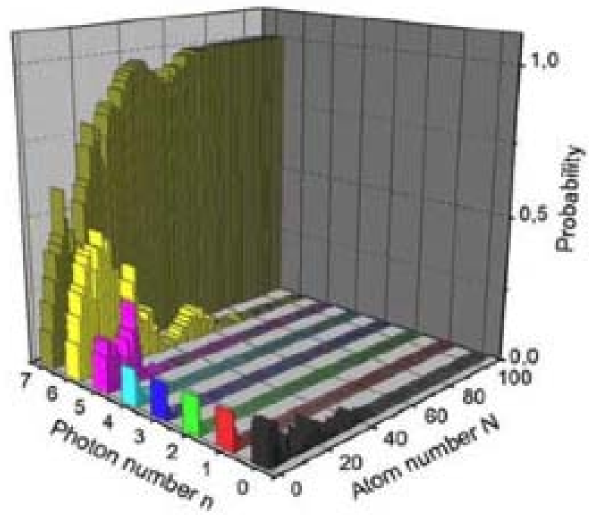

Also a quantum gate!

# Preparing a coherent microwave field in the cavity and measuring its photon number



## Counting photons by extracting information from successive atoms: progressive field projection on photon number state



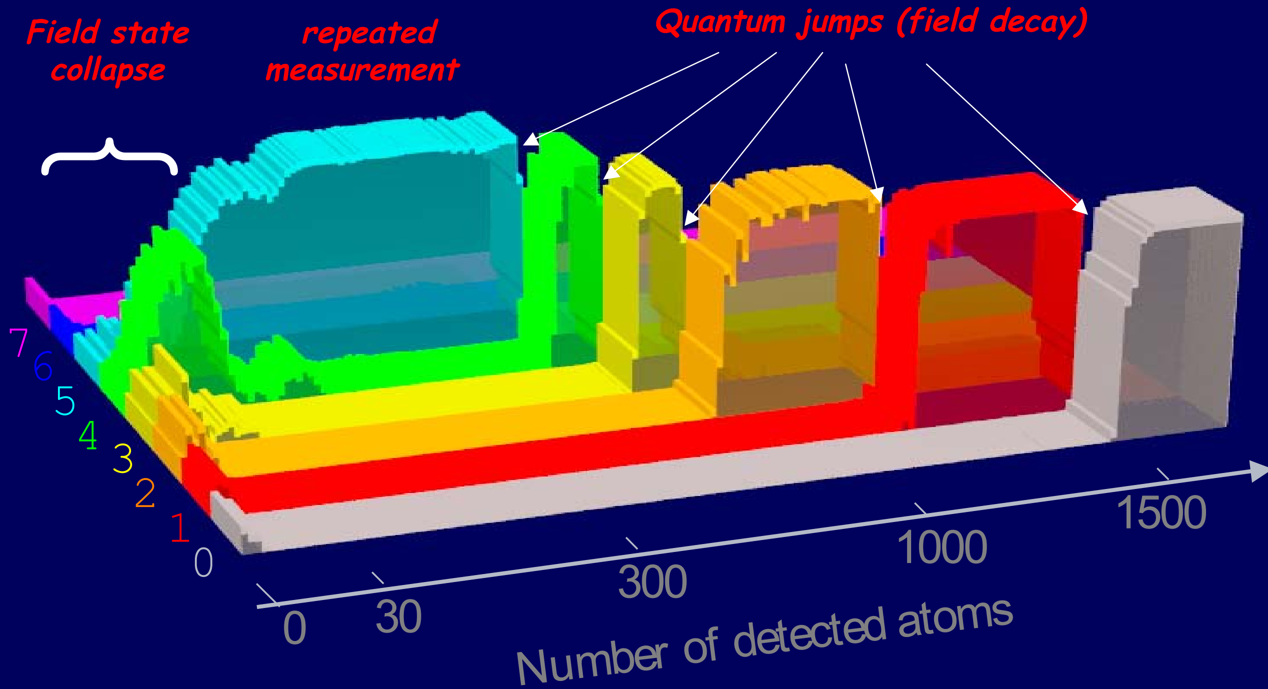

*Convergence towards n=5* *Convergence towards n=7*

Evolution of the inferred photon number distribution along independent sequences measuring an initial coherent state with photon numbers comprised between 0 and 7:

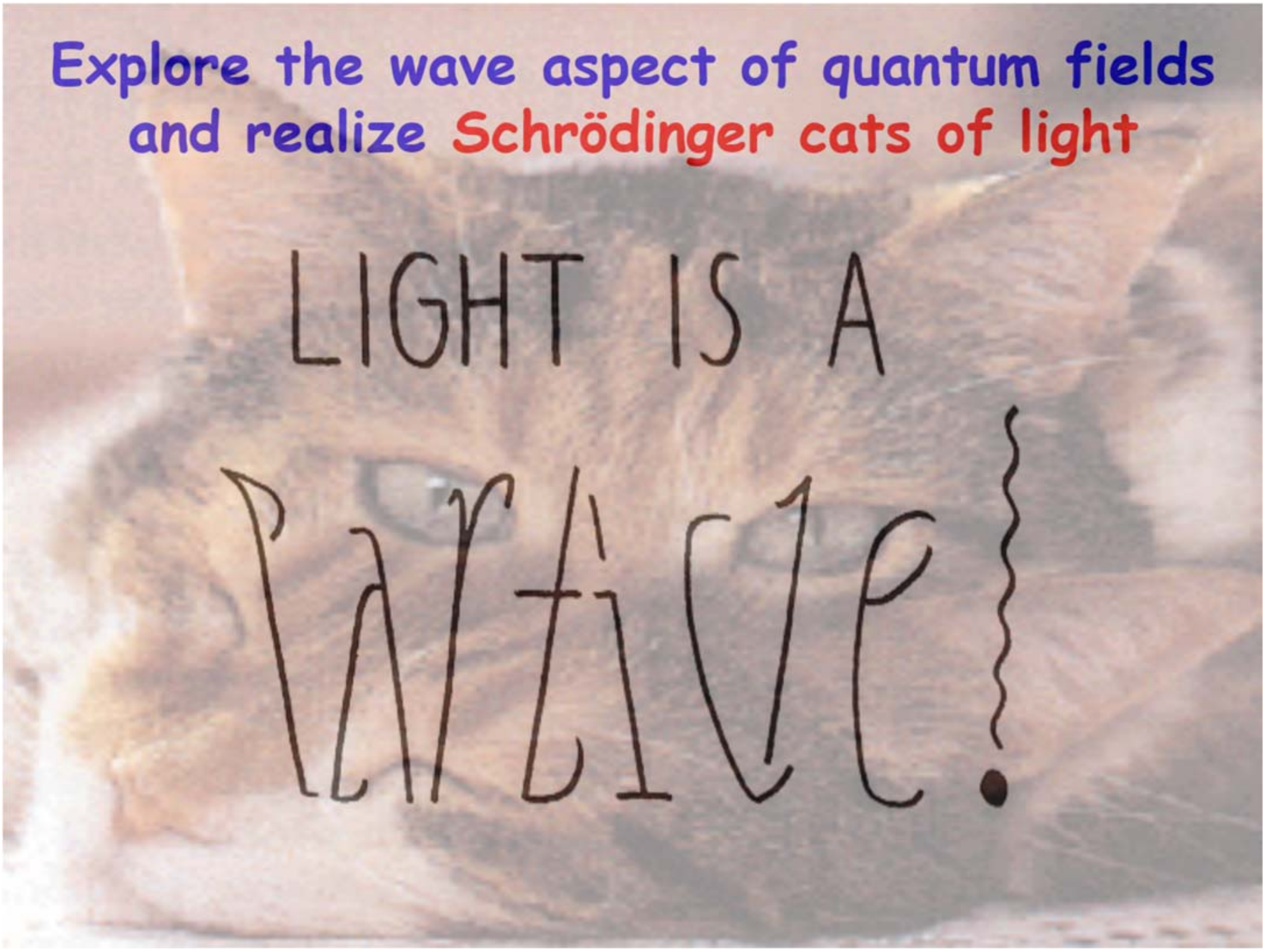
« God plays dice »

*C.Guerlin et al, Nature, 448, 889 (2007)*

# Evolution of photon number during a long measurement: field quantum jumps




A single field "trajectory"

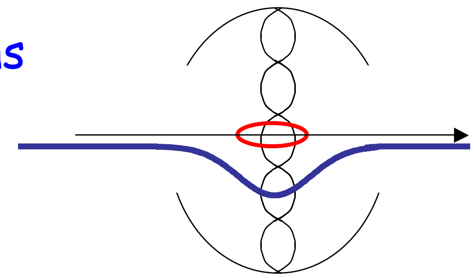

Explore the wave aspect of quantum fields
and realize Schrödinger cats of light
LIGHT IS A
particle!

# Single atom index effect

Non-resonant atom crossing cavity adiabatically changes field frequency

Atom in N-photon light-potential gains kinetic energy

$! E_N = N ! E_1$



Energy is borrowed from field whose frequency becomes ω−δ, N photons losing energy

$N ! !$

Energy conservation: $! = \frac{" E_1}{!}$

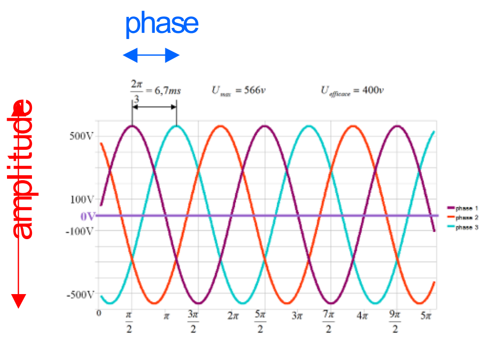
During atom-cavity crossing time, field undergoes phase shift:

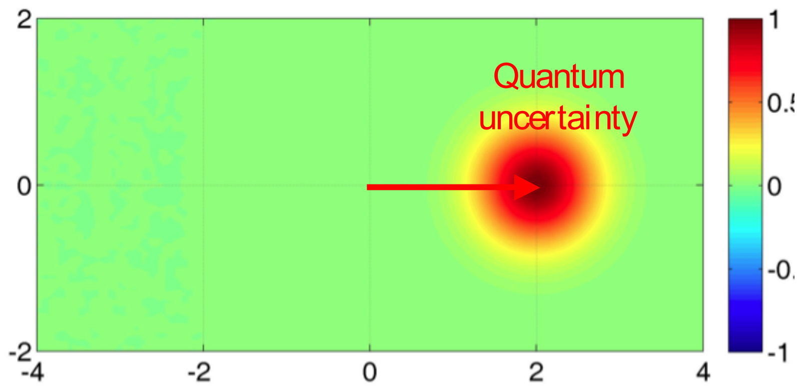
$\Delta\varphi \sim \pm \pi/2$

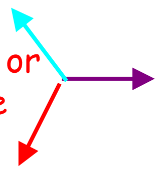
$! " = \pm \# \frac{! E_1(z)}{!} \frac{dz}{v} = \pm \frac{\$_0}{2}$

Sign depends on atom's state (upper or lower state of transition)

# A coherent state is represented in field oscillator phase space by a vector with fuzzy tip



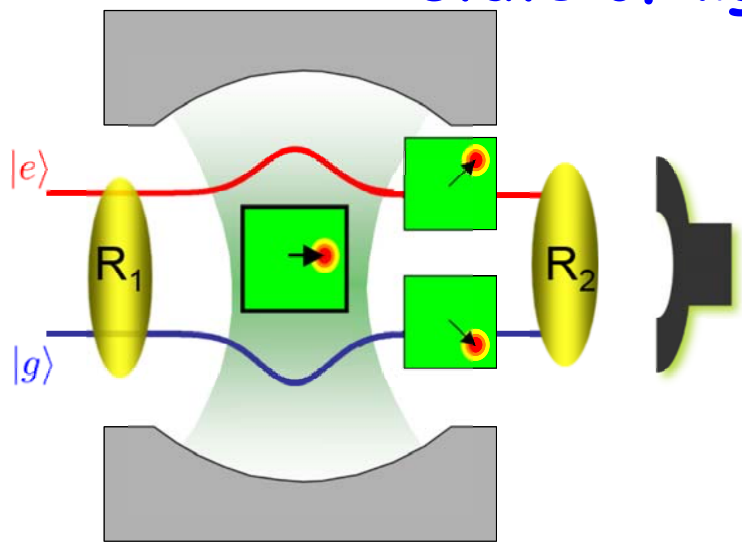



Fresnel plane or phase space

The coherent field quantum state is represented by a Gaussian distribution in phase space, shown here in coded colours (Wigner function).

# How single atom prepares Schrödinger cat state of light



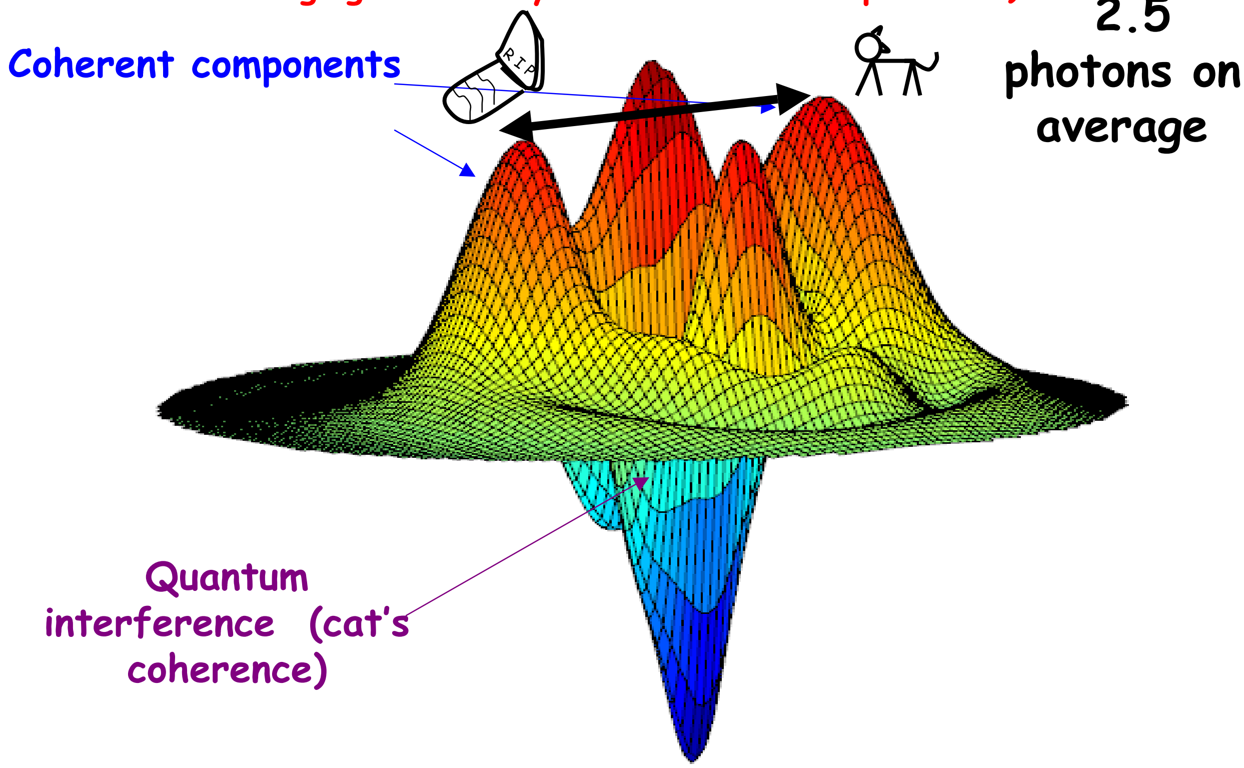

1. Coherent field injected in cavity.
2. Single atom is prepared in $R_1$ in a superposition of e and g
3. Atom shifts the field phase in two opposite directions as it crosses C: superposition leads to entanglement in typical Schrödinger cat situation: field is a 'meter' reading atom's energy

4. Atomic states mixed again in $R_2$ maintains cat's ambiguity:

5. Detecting atom in e or g projects field into cat state superposition!

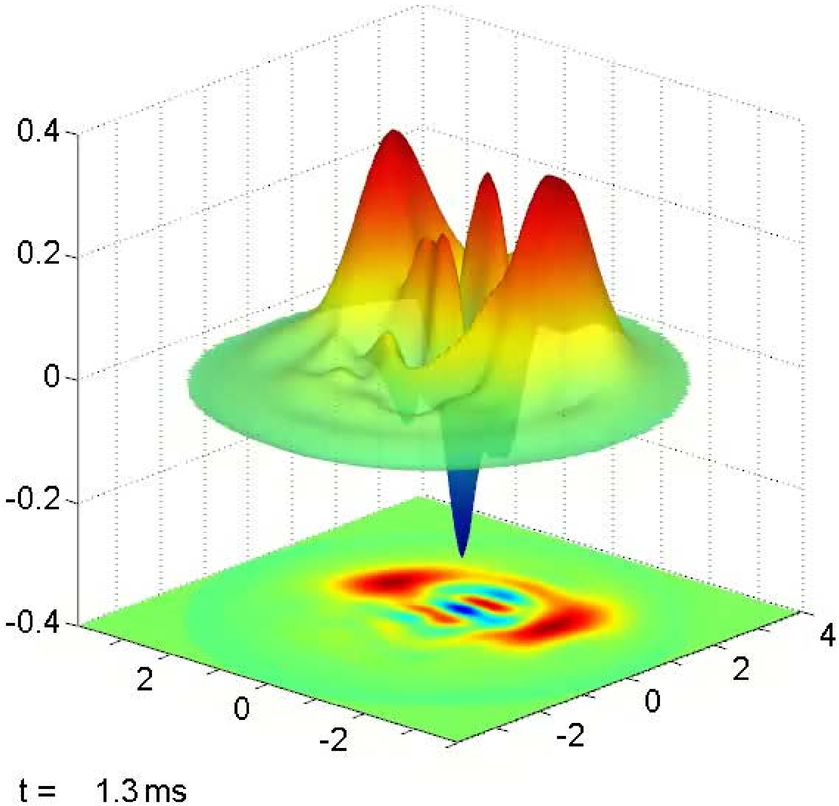
# Reconstructed quantum state of a cat

(modified version of QND measurement using sequence of atoms crossing C and averaging over many realizations of experiment)




S.Deléglise et al, Nature, 455, 510 (2008)

# Fifty millseconds in the life of a Schrödinger cat (a movie of decoherence)

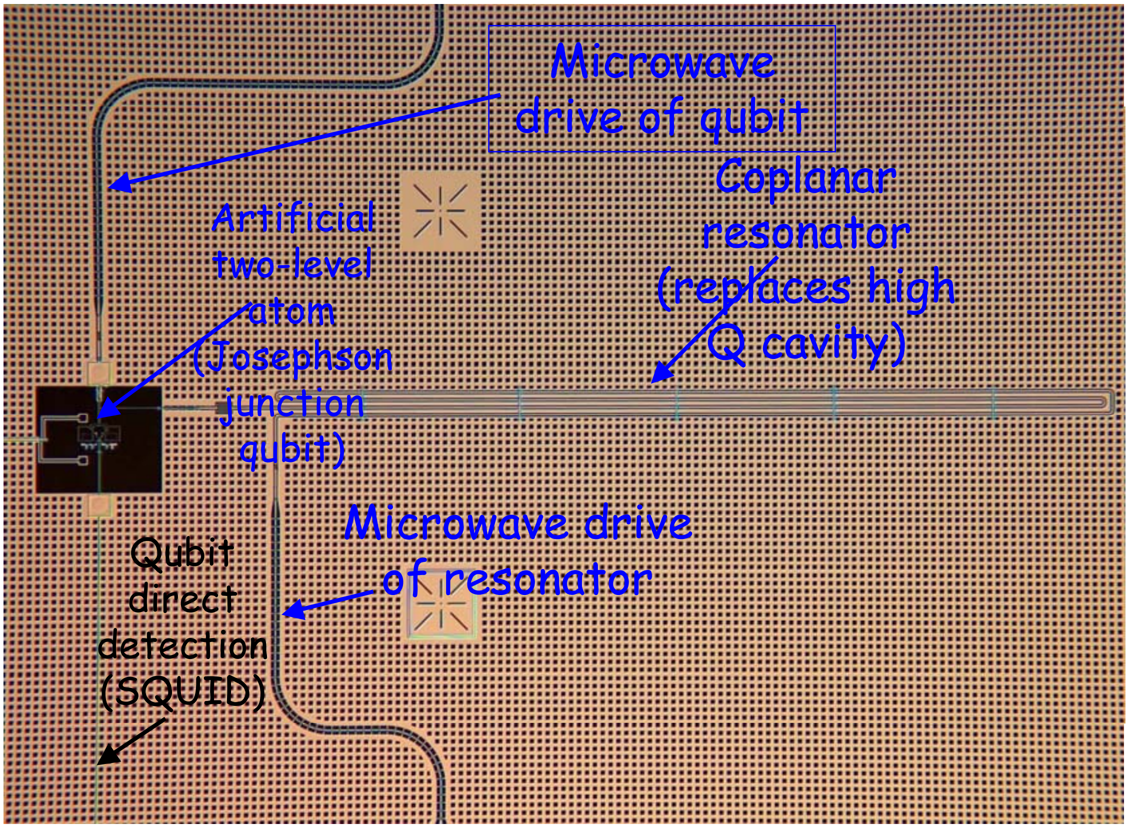



W.Zurek

Physics Today, **44**, 36 (1991)

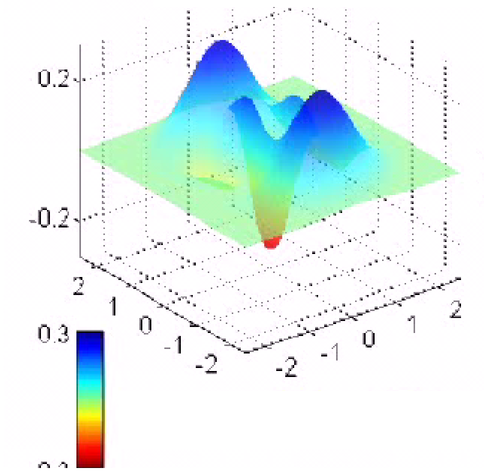
Decoherence rate increases with “cat size”: quantum/ classical boundary

# Cavity QED on a superconducting chip (USBC, Yale, ETH, CEA, Chalmers….)

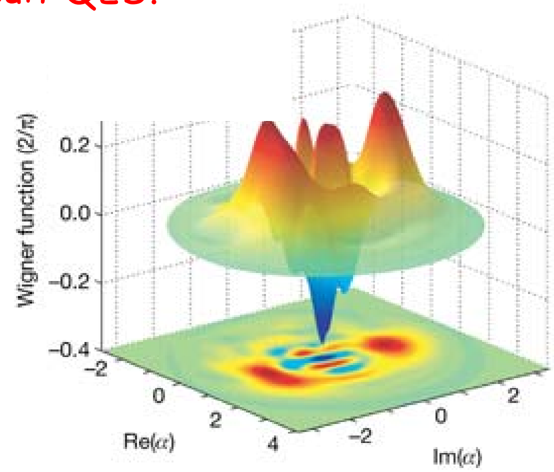


# Comparison with CQED

Circuit QED and Cavity QED experiments prepare and reconstruct non-classical field states with similar methods. In both cases, states can be reconstructed versus time, yielding decoherence movies. Data collection is faster in  Circuit QED.

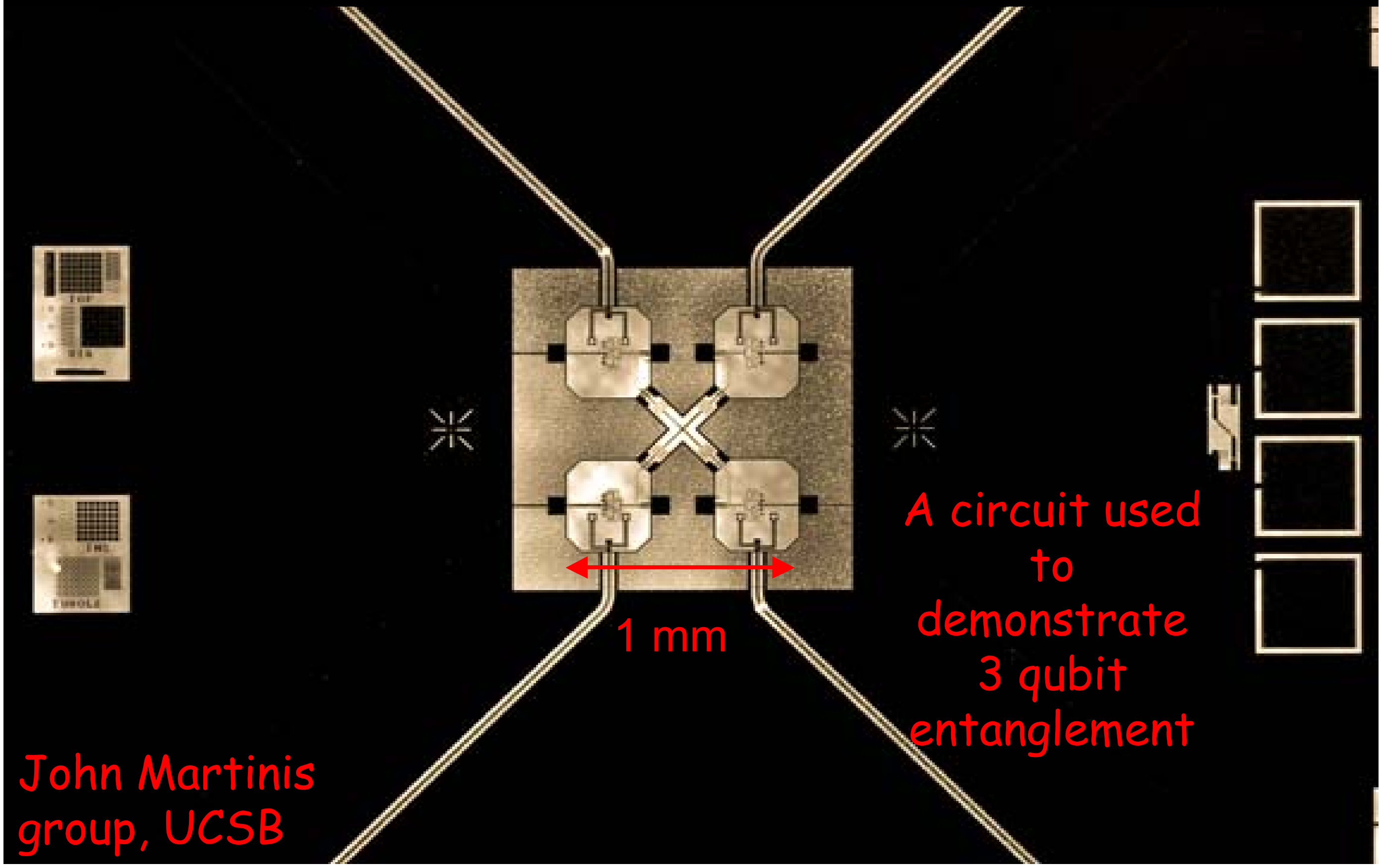



«cat» state prepared and reconstructed in Circuit QED (Martinis group, USBC)

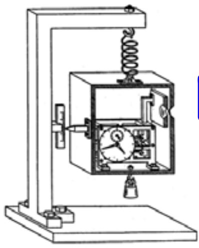


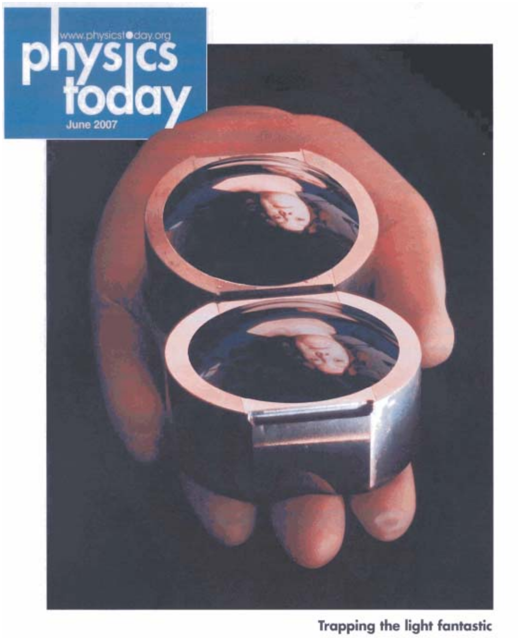

«cat» state prepared and reconstructed in CQED at ENS

# Quantum gates with artificial atoms (Superconducting qubits)



# We have come a long way since Bohr's atom and Einstein's photon box






June 2007
(Cavity QED)

Shuffling photons between real or artificial atoms may lead to applications in quantum information

So far, factoring 15= 5x3…. with a few qubits (UCSB)

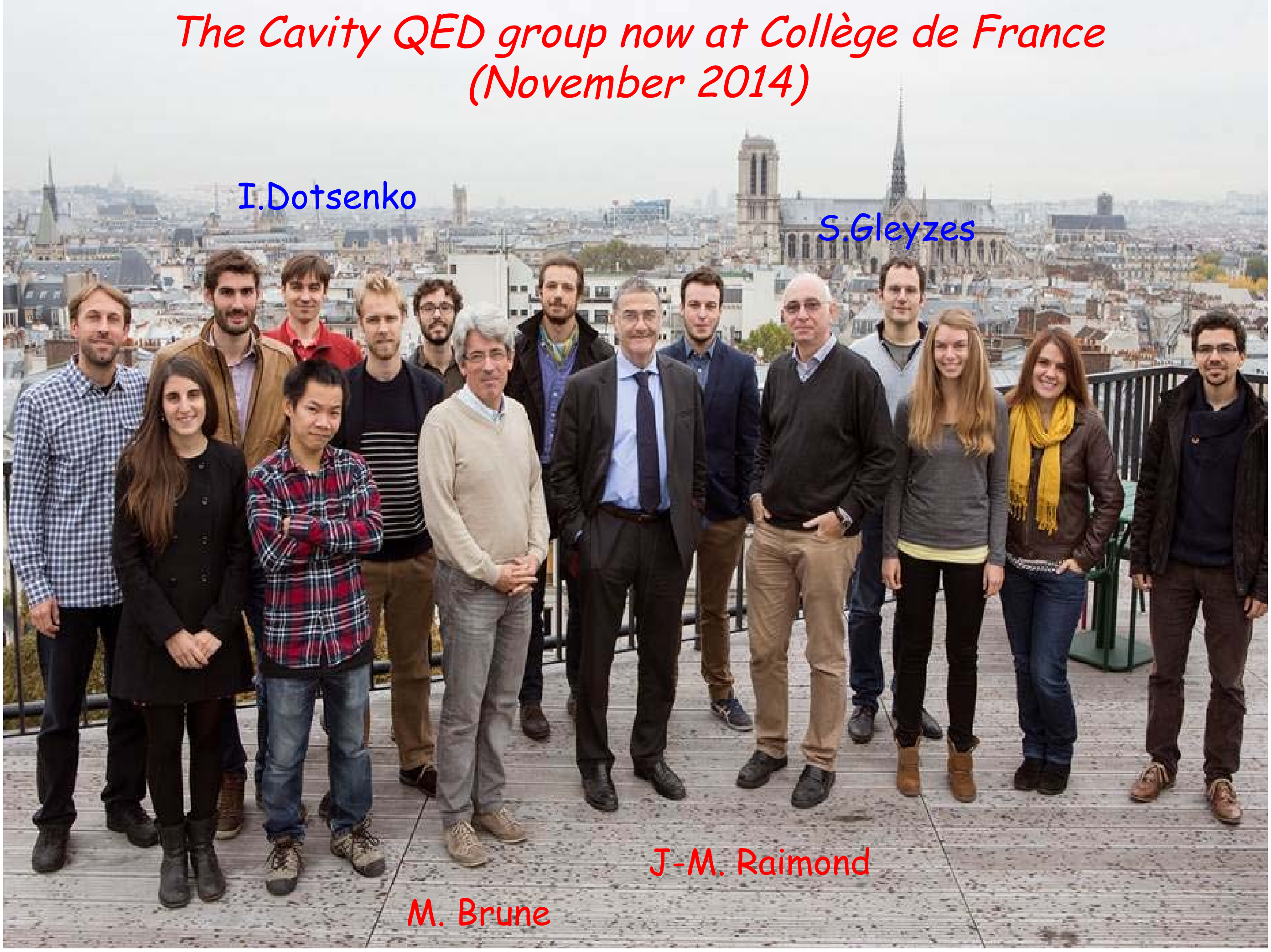

April 2011
(Circuit QED)

October 1966, on the day of Kastler's Nobel Prize announcement

C.Cohen-Tannoudji A.Kastler S.H J.Brossel

I have been lucky to start my career as a physicist in Kastler-Brossel laboratory, at the beginning of the laser…


Same room 46 years later (october 2012)
I.Dotsenko
S.Gleyzes
JM.Raimond
M.Brune


The Cavity QED group now at Collège de France
(November 2014)
I.Dotsenko
S.Gleyzes
J-M. Raimond
M. Brune

# Forty years of research

- Michel Gross
- Claude Fabre
- Philippe Goy
- Pierre Pillet
- Jean-Michel Raimond
- Guy Vitrant
- Yves Kaluzny
- Jun Liang (Chine)
- Michel Brune
- Valérie Lefèvre-Seguin
- Jean Hare
- Jacques Lepape
- Aephraim Steinberg (Canada)
- Andre Nussenzveig (Brésil)
- Frédéric Bernardot
- Paul Nussenzveig (Brésil)
- Laurent Collot
- Matthias Weidemuller (Allemagne)
- François Treussart
- Abdelamid Maali (Algerie)
- David Weiss (USA)
- Vahid Sandoghdar (Iran)
- Jonathan Knight (Afrique du Sud)
- Nicolas Dubreuil
- Peter Domokos (Hongrie)
- Ferdinand Schmidt-Kaler (Allemagne)
- Jochen Dreyer (Allemagne)
- Ed Hagley (USA)
- Xavier Maître
- Christoph Wunderlich (Allemagne)
- Gilles Nogues
- Vladimir Ilchenko (Russie)
- Jean-François Roch
- Stefano Osnaghi (Italie)
- Arno Rauschenbeutel (Allemagne)
- Wolf von Klitzing (Allemagne)
- Erwan Jahier
- Patrice Bertet
- Alexia Auffèves
- Romain Long
- Sébastien Steiner
- Paolo Maioli (Italie)
- Philippe Hyafil
- Tristan Meunier
- Perola Milman (Brésil)
- Jack Mozley (Grande-Bretagne)
- Stefan Kuhr (Allemagne)
- Sébastien Gleyzes
- Christine Guerlin
- Thomas Nirrengarten
- Cédric Roux
- Julien Bernu
- Ulrich Busk-Hoff (Danemark)

~ 1/2 foreigners
20 countries

- Angie Quarry (Israël)
- Andreas Emmert (Allemagne)
- Adrian Lupascu (Roumanie)
- Jonas Mlynek (Allemagne)
- Igor Dotsenko (Ukraine)
- Samuel Deléglise
- Clément Sayrin
- Xingxing Zhou (Chine)
- Bruno Peaudecerf
- Raul Teixeira (Brésil)
- Sha Liu (Chine)
- Theo Rybarczyk
- Carla Hermann (Chili)
- Adrien Signoles
- Adrien Facon
- Eva Dietsche (Allemagne)
- Stefan Gerlich (Autriche)
- Than Long Nguyen (Vietnam)
- Mariane Penasa
- Dorian Grosso
- Tigrane Cantat
- Samuel Briole…