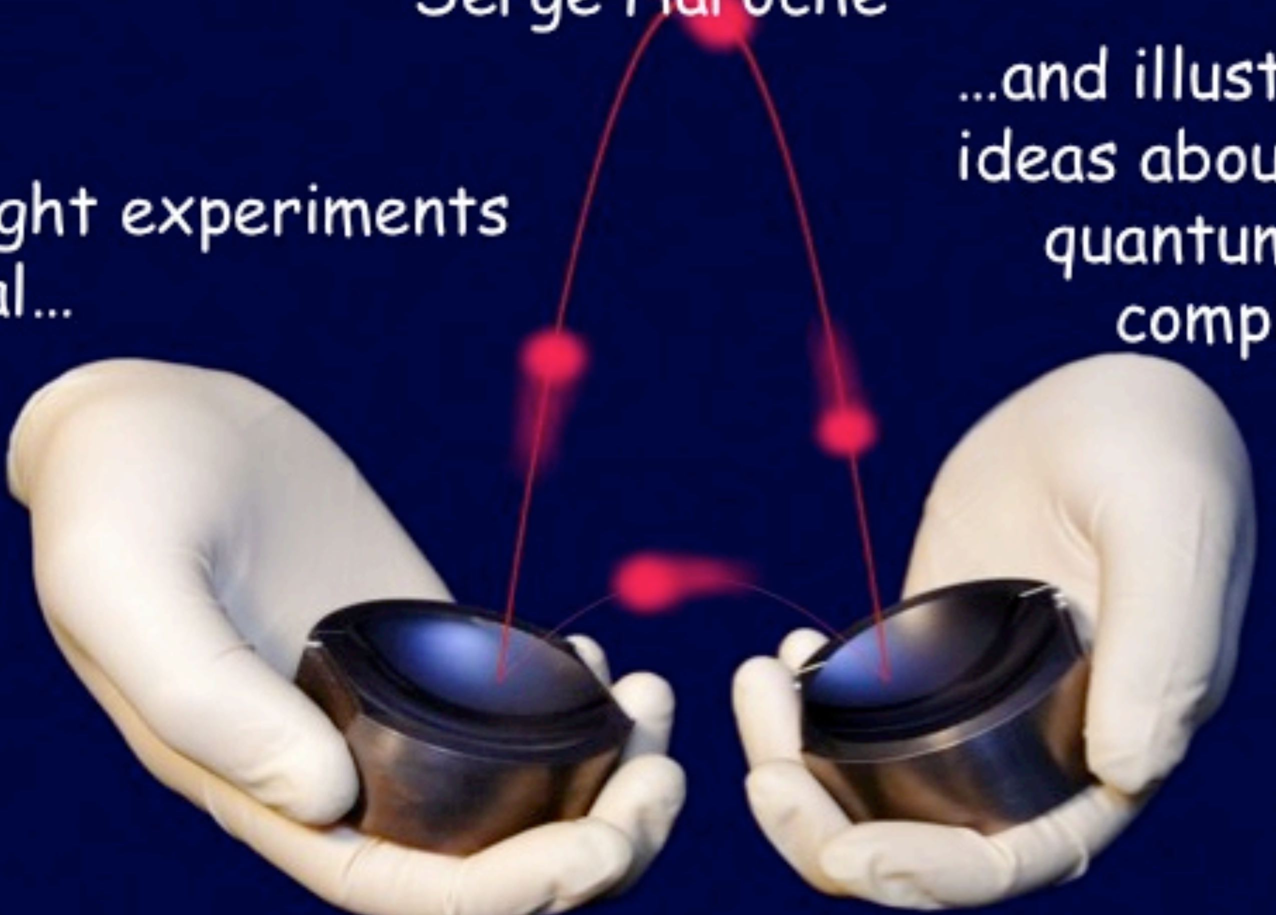
Bohr's legacy in Cavity QED

COLLÈGE
DE FRANCE
1530

Serge Haroche



When thought experiments become real…

…and illustrate Bohr's ideas about the atom, quantum jumps and complementarity


Bohr (1913)

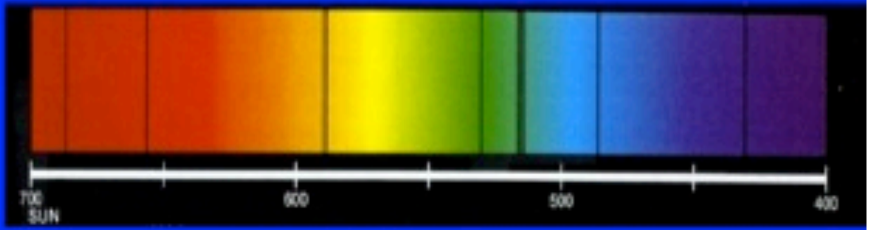
The Bohr atom is a hundred years old

The birth of quantum physics and modern spectroscopy

The electron jumps between quantized orbits by emitting or absorbing a photon with frequency ν such that

$$E_2\text{-}E_1=h\nu$$

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

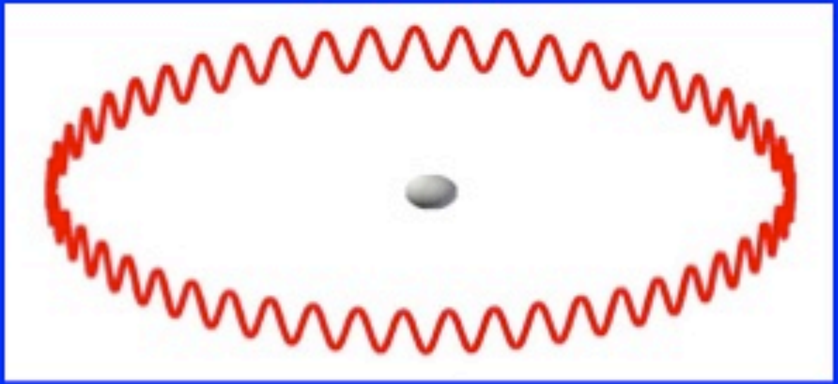


Bohr's model interpreted by de Broglie

Electron of velocity v has wavelength λ = h/mv

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

$$n\lambda = 2\pi r \quad \rightarrow \quad mvr = n\hbar$$

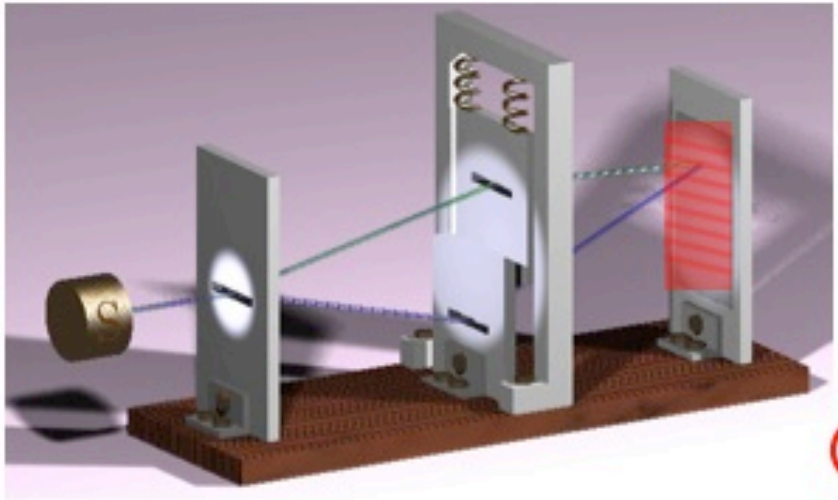


The electron is a running matter wave around the nucleus. The principal quantum number n counts the number of wavelengths around the orbit

Bohr's complementarity

Particles and waves are the two sides of the same reality. Which aspect is observed depends upon experimental setup...

A thought experiment to test wave particle complementarity



Einstein-Bohr discussion at Solvay meeting 1927

Already a Schrödinger cat!

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

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

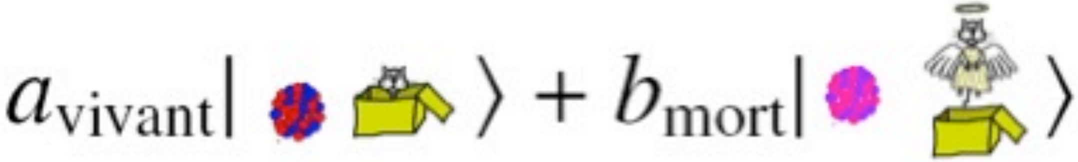
Entanglement is here:

$$|\textit{particle crosses upper slit}\rangle \qquad + |\textit{particle crosses lower slit}\rangle$$

Slit-particle entanglement kills coherence

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

1935



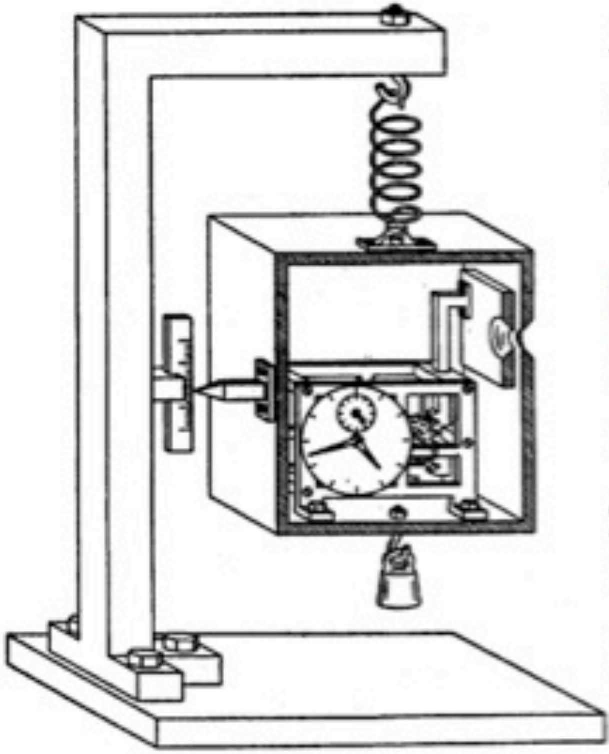
$$a_{\text{vivant}}|\ \rangle + b_{\text{mort}}|\ \rangle$$

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

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

What about time-energy Heisenberg uncertainty ($\Delta E.\Delta T>h$) ?

Einstein and Bohr
at Solvay, 1930



Einstein: weigh box with arbitrary small ΔE before and after releasing photon in short time interval ΔT

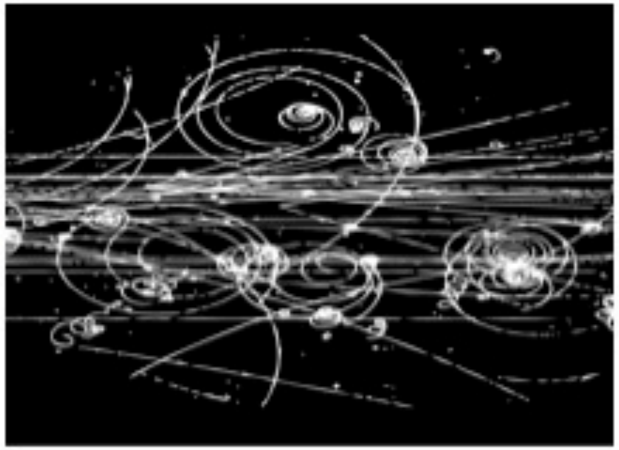
Bohr: be careful with measurement of time due to box motion in gravitational field during weighing process...

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

What the founders of quantum theory 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…

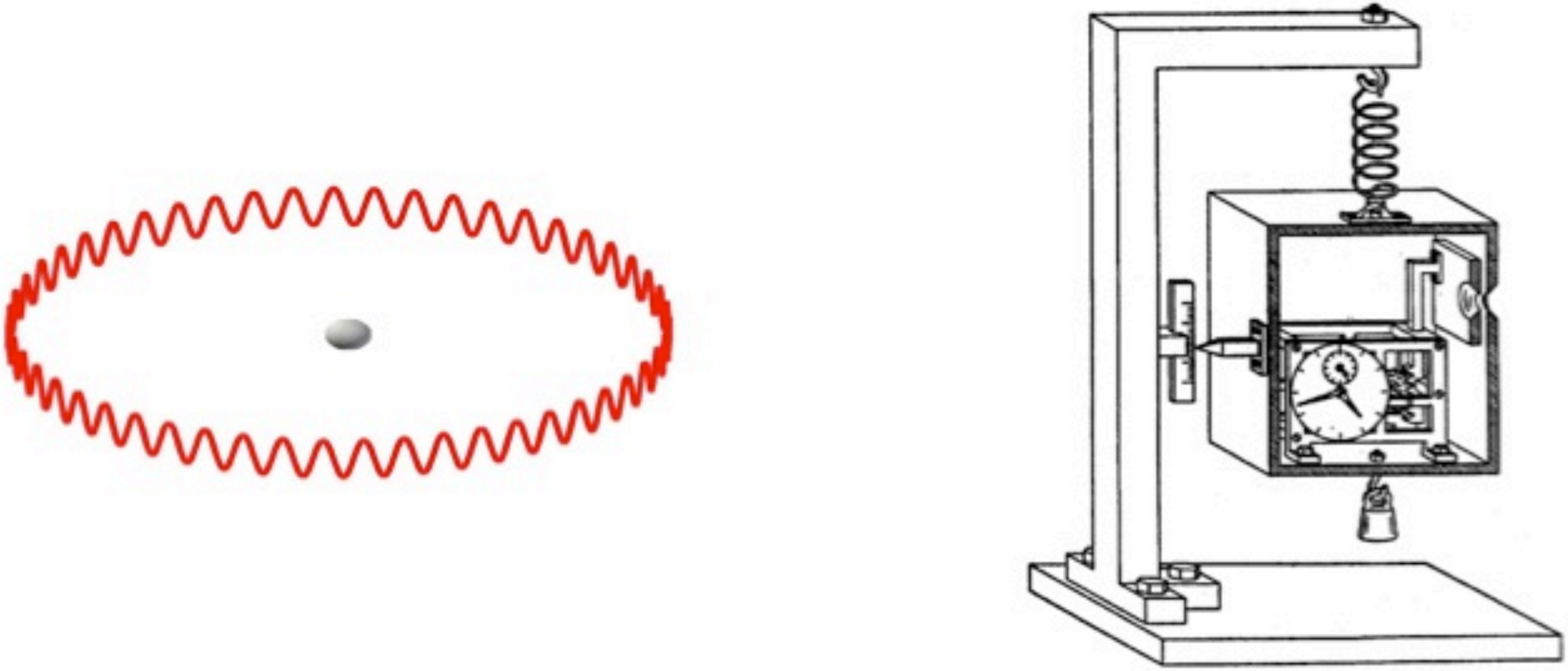


Bubble chamber (CERN)

"…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)

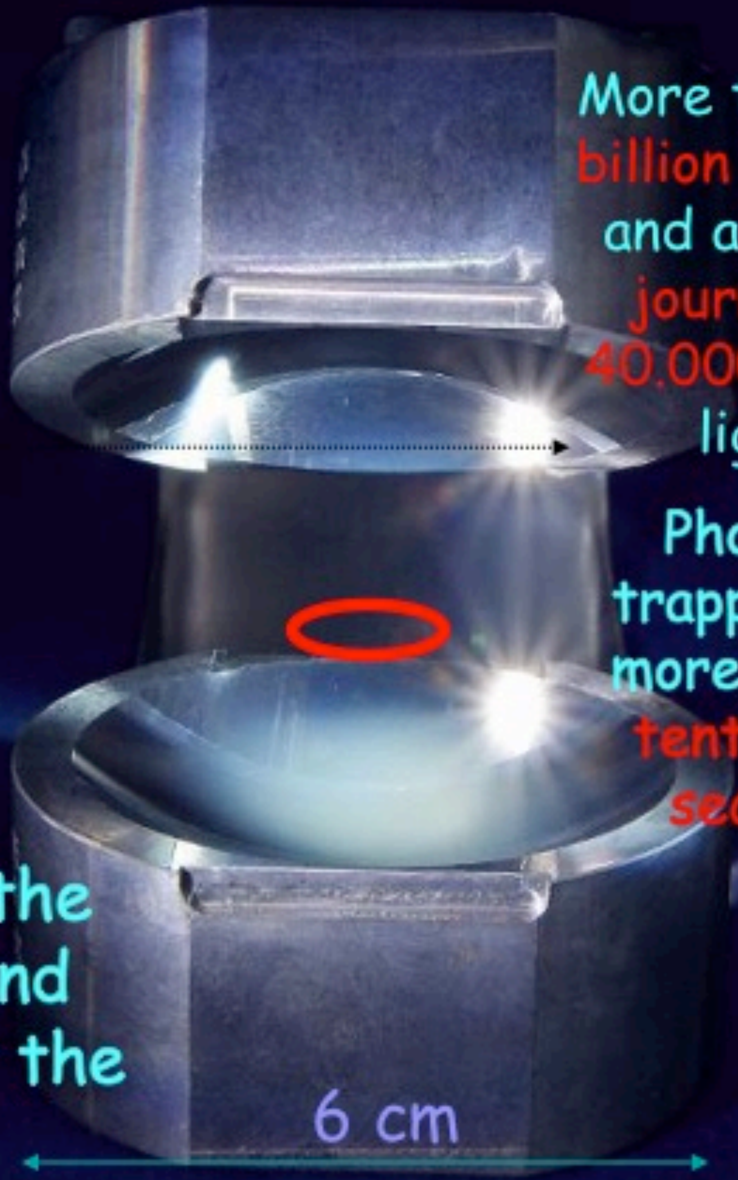
Experimenting with single photons "in vivo":

Cavity Quantum Electrodynamics with Rydberg atoms (Bohr's atom in



Cavity Quantum Electrodynamics:

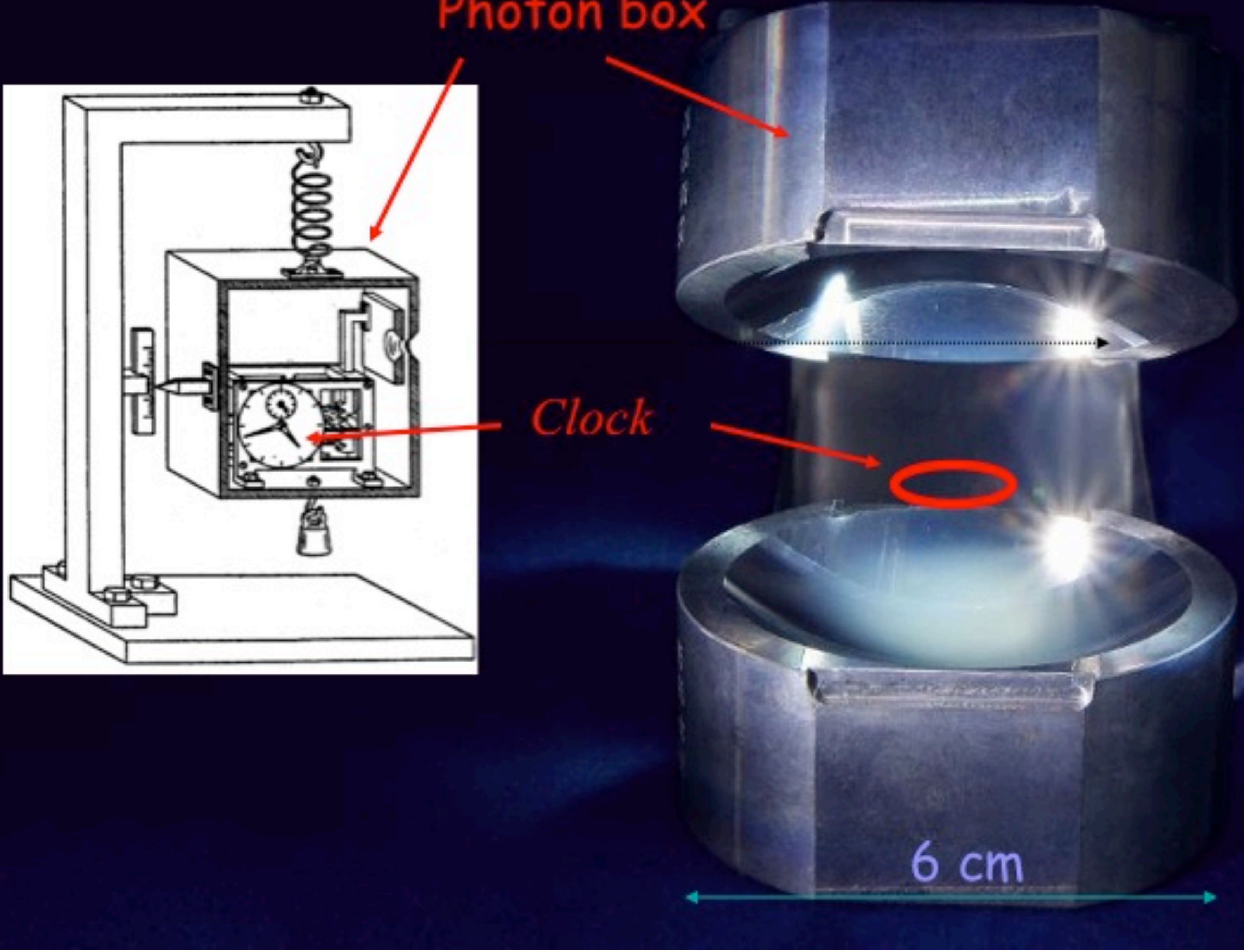
One atom interacts with one (or a few) photon(s) in a box



More than one billion bounces and a folded journey of 40.000km for light!

Photons trapped for more than a tenth of a second!

A sequence of atoms crosses the cavity,couples with its field and carries away information about the trapped light



Photon box

Clock

The circular Rydberg-Bohr atom

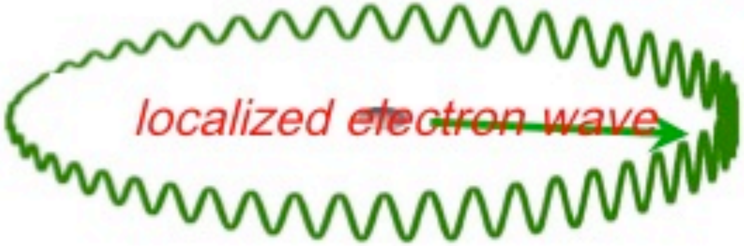
Rydberg

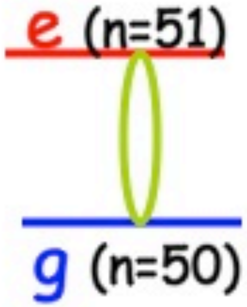
Bohr
(1913)

Illustration of Bohr's correspondence principle

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.

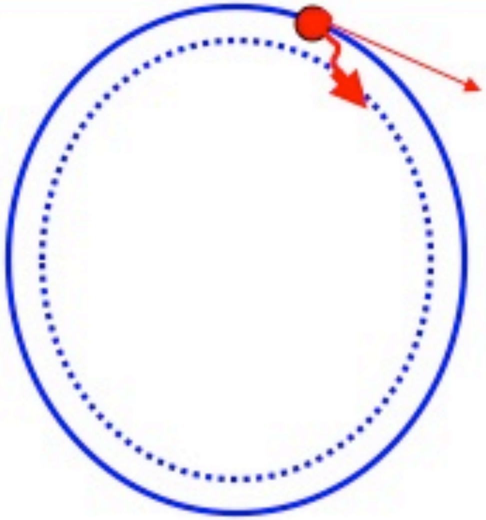
Lifetime of the circular Rydberg state scales as n^5 by correspondence principle

$t_n \sim n^5$

$n = 50 \rightarrow n^5 \sim 3.10^8$

$t_{50} \sim 0.03$ second

Very long lifetime of the order of photon lifetime



Orbit radius: $r \sim n^2$

Electron period T (3rd Kepler law):

$T^2 \sim r^3 \rightarrow T \sim r^{3/2} \sim n^3$

Electron acceleration on orbit:

$a \sim r / T^2 \sim n^{-4}$

Radiated power (Larmor):

$P \sim a^2 \sim n^{-8}$

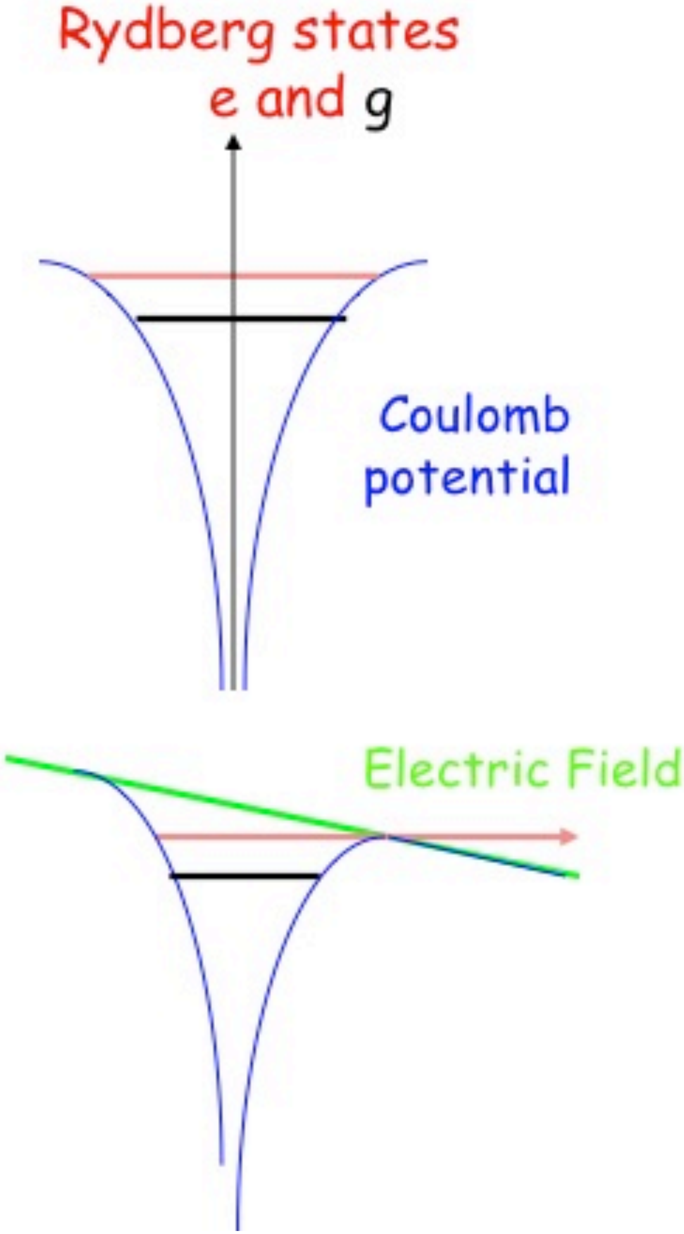
Energy of radiated photon:

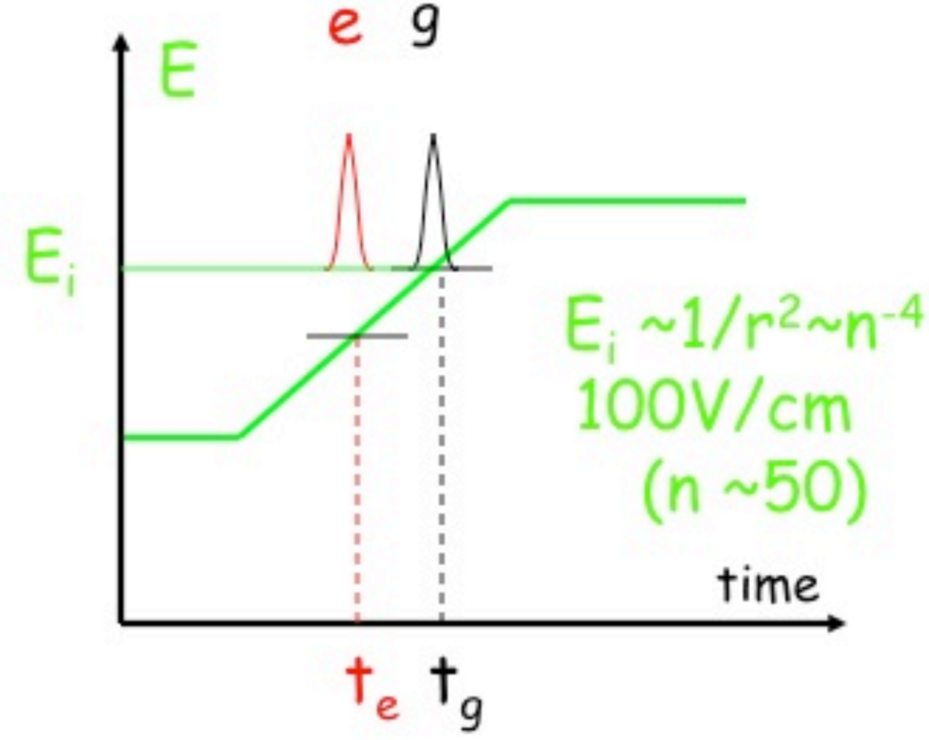
$E_{photon} \sim h/T \sim n^{-3}$

Radiative lifetime on orbit t_n:

$P \sim E_{photon}/t_n \rightarrow t_n \sim E_{photon}/P \sim n^5$

State selective detection of Rydberg states by field ionization

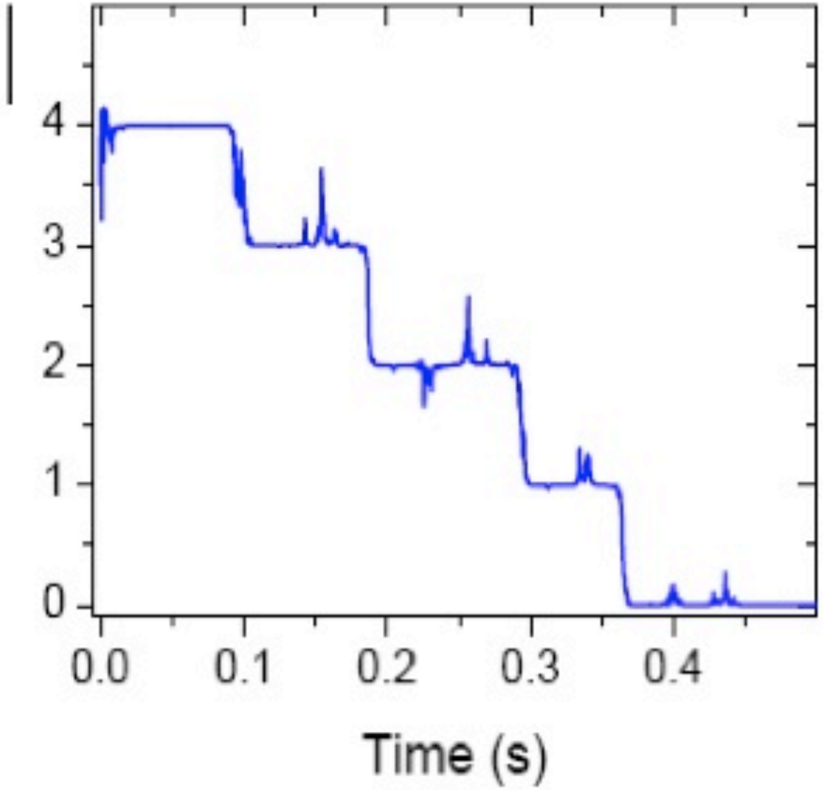




$E_i \sim 1/r^2 \sim n^{-4}$
100V/cm
($n \sim 50$)

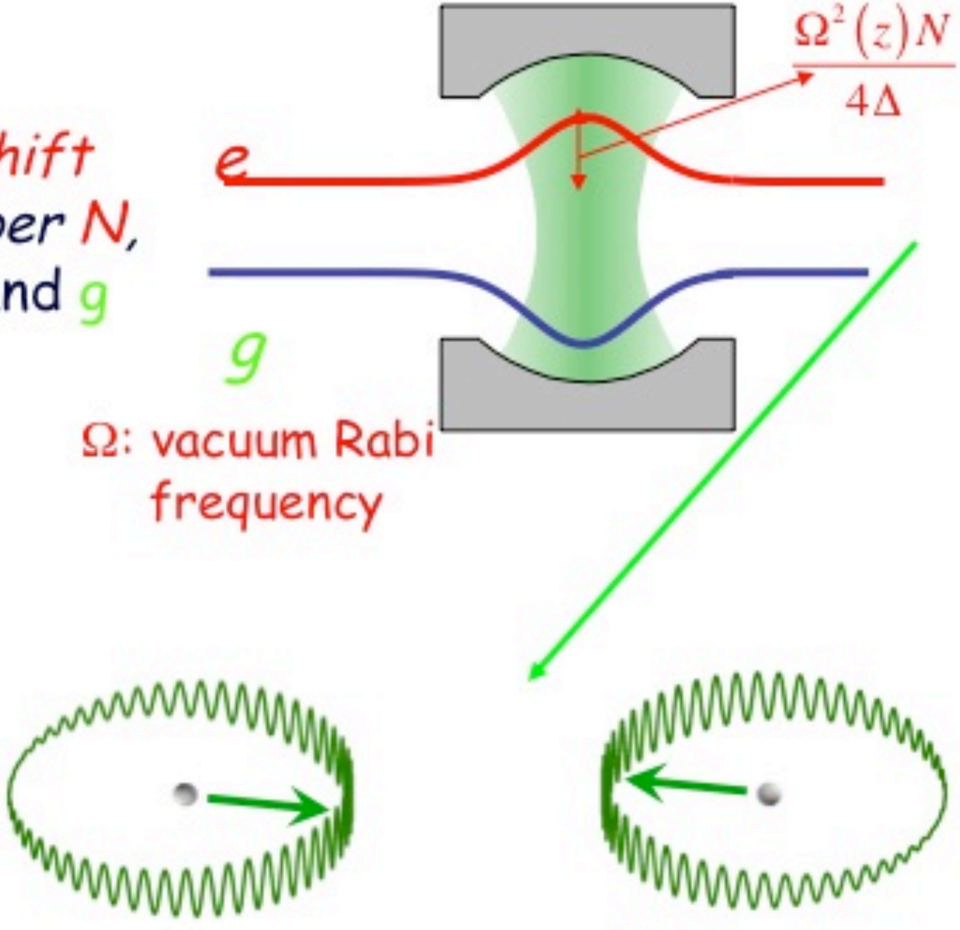
A bit of information per atom!

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



When atom interact with *non-resonant* light (detuning Δ) 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:

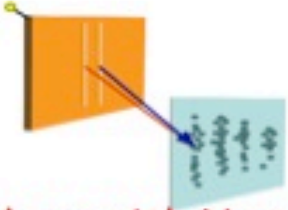
$$\Delta\Phi(N) = N\varphi_0 \quad ; \quad \varphi_0 = \int \frac{\Omega^2(z)}{2\Delta}\frac{dz}{v}$$

φ_0 : phase shift per photon can reach the value π

Measuring ΔΦ amounts to a QND photon counting

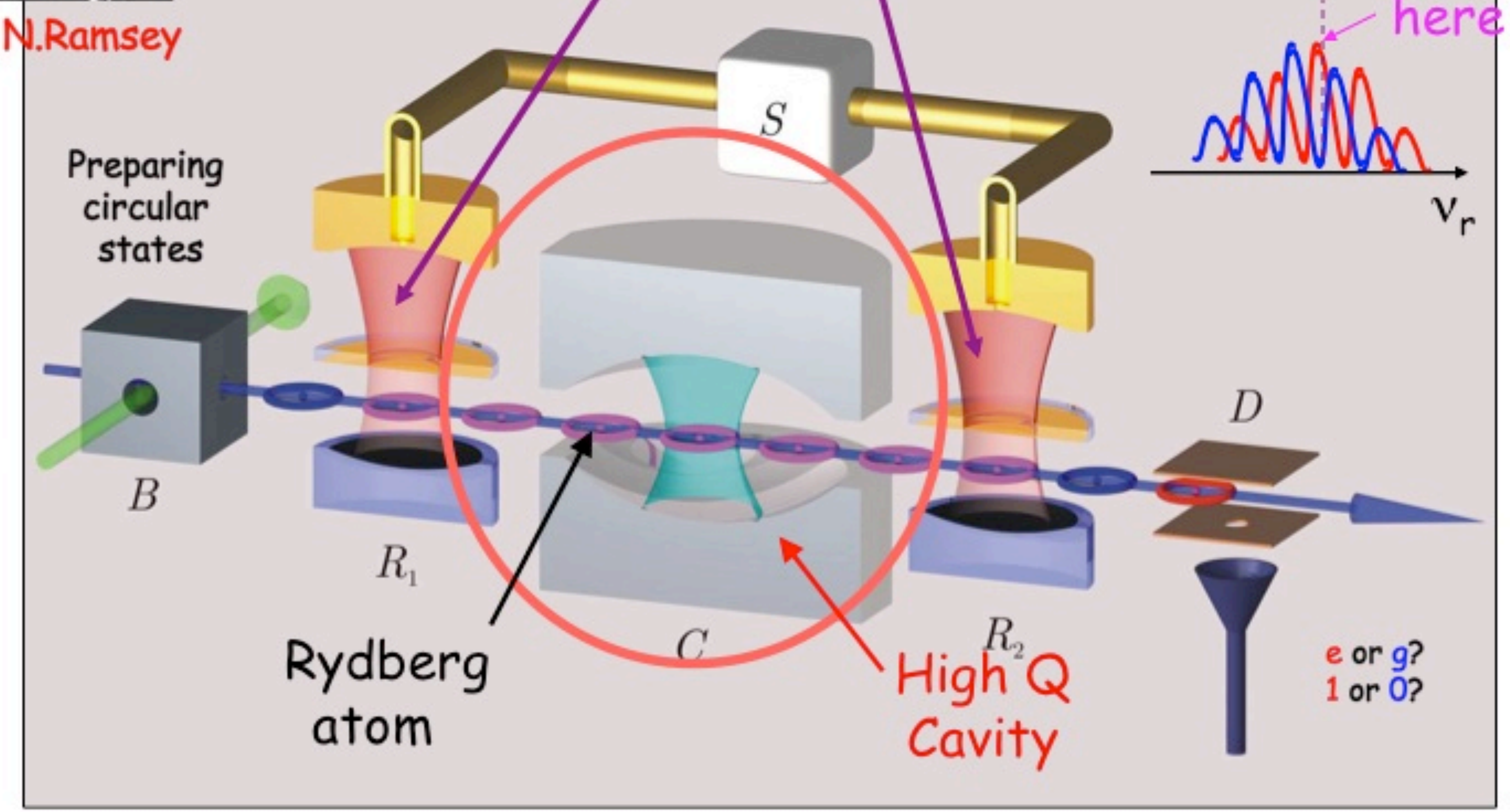
The experimental set-up

N.Ramsey



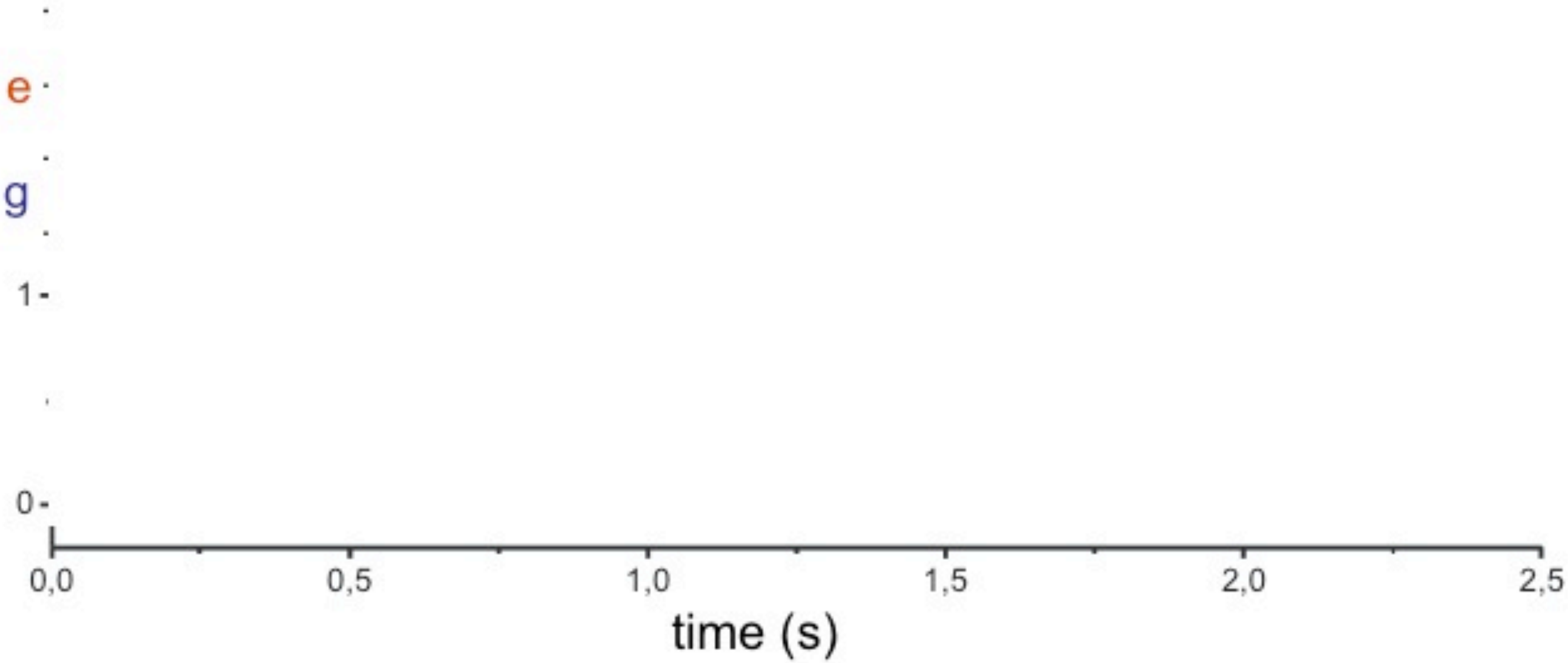
Analogy with Young

Classical pulses
(Ramsey interferometer)



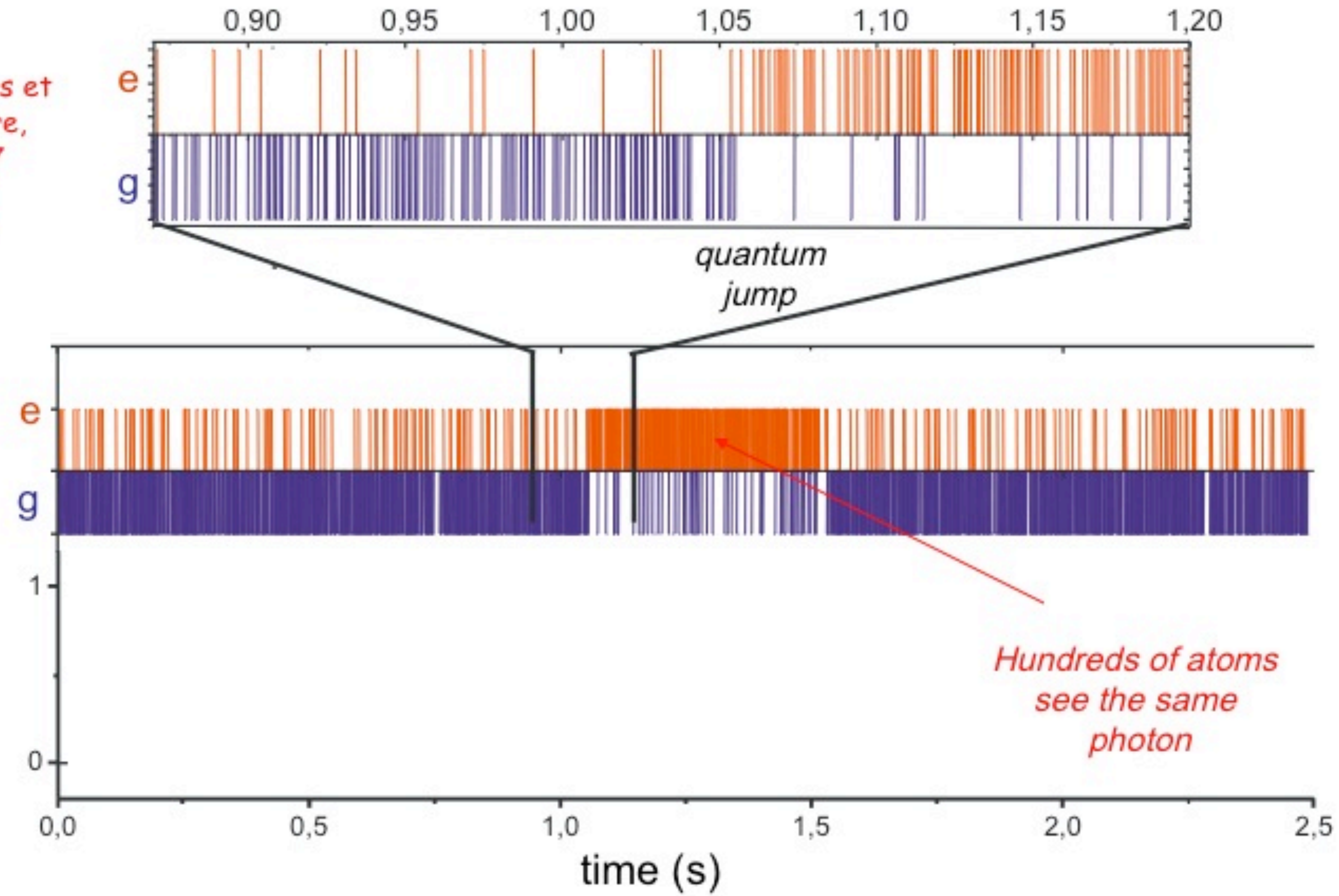
An atomic clock delayed by photons trapped inside

Birth, life and death of a photon



Birth, life and death of a photon

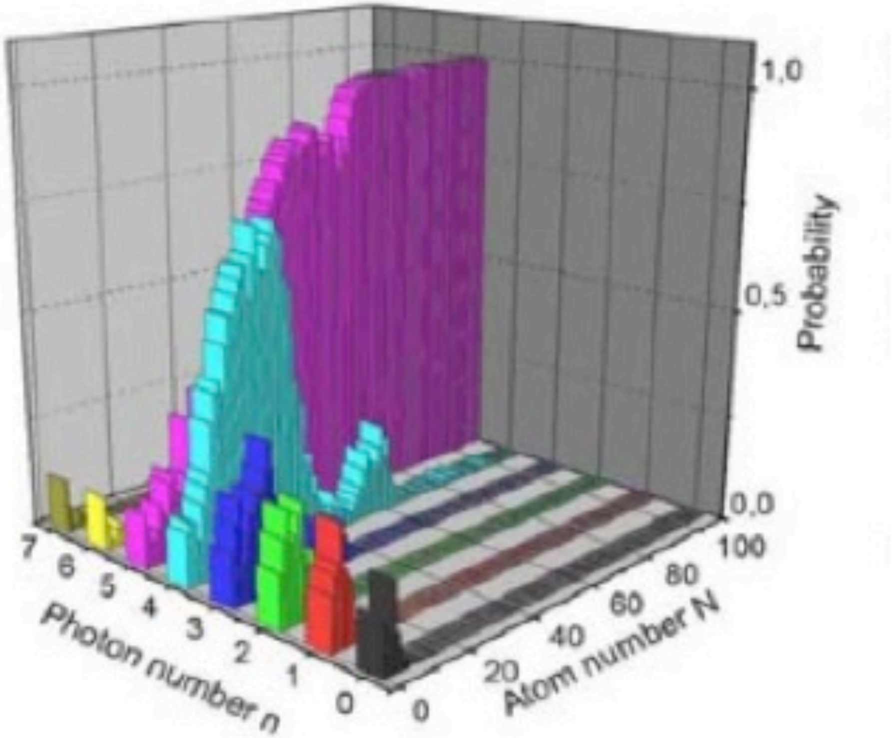
S.Gleyzes et al, Nature, 446, 297 (2007)



quantum jump

Hundreds of atoms see the same photon

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



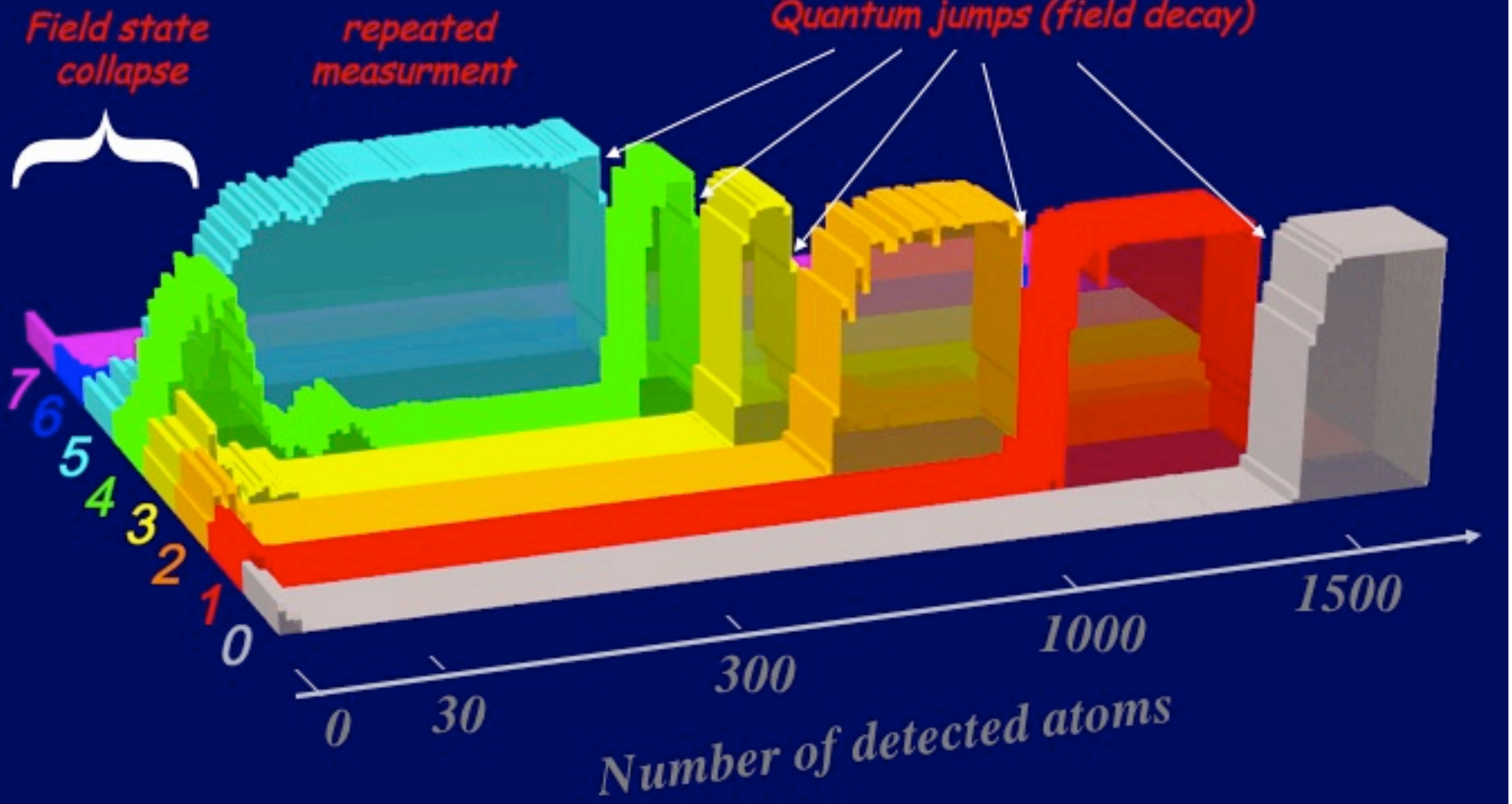
Convergence towards n=5   *Convergence towards n=7*

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

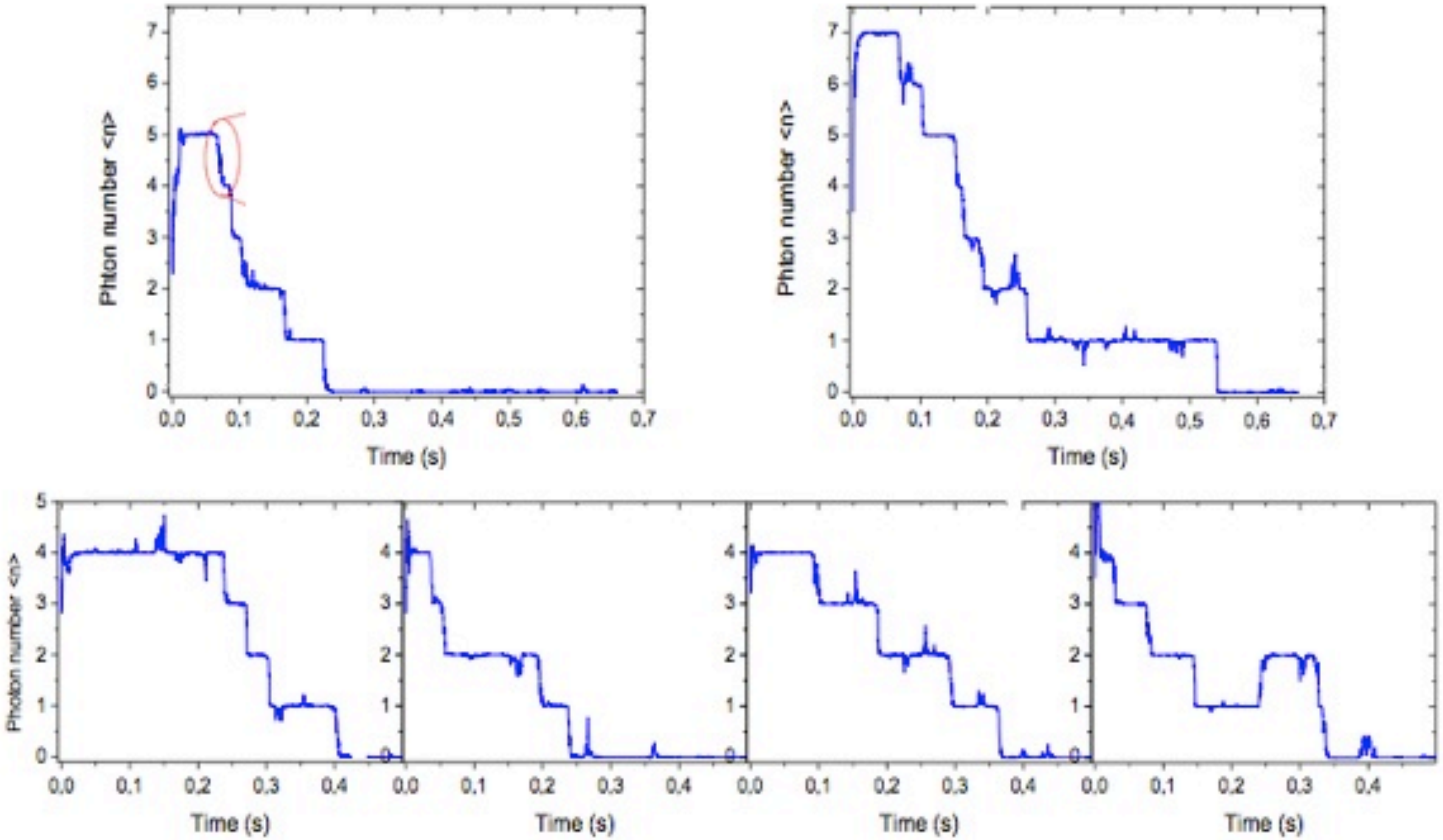

Field state collapse

repeated measurment

Quantum jumps (field decay)

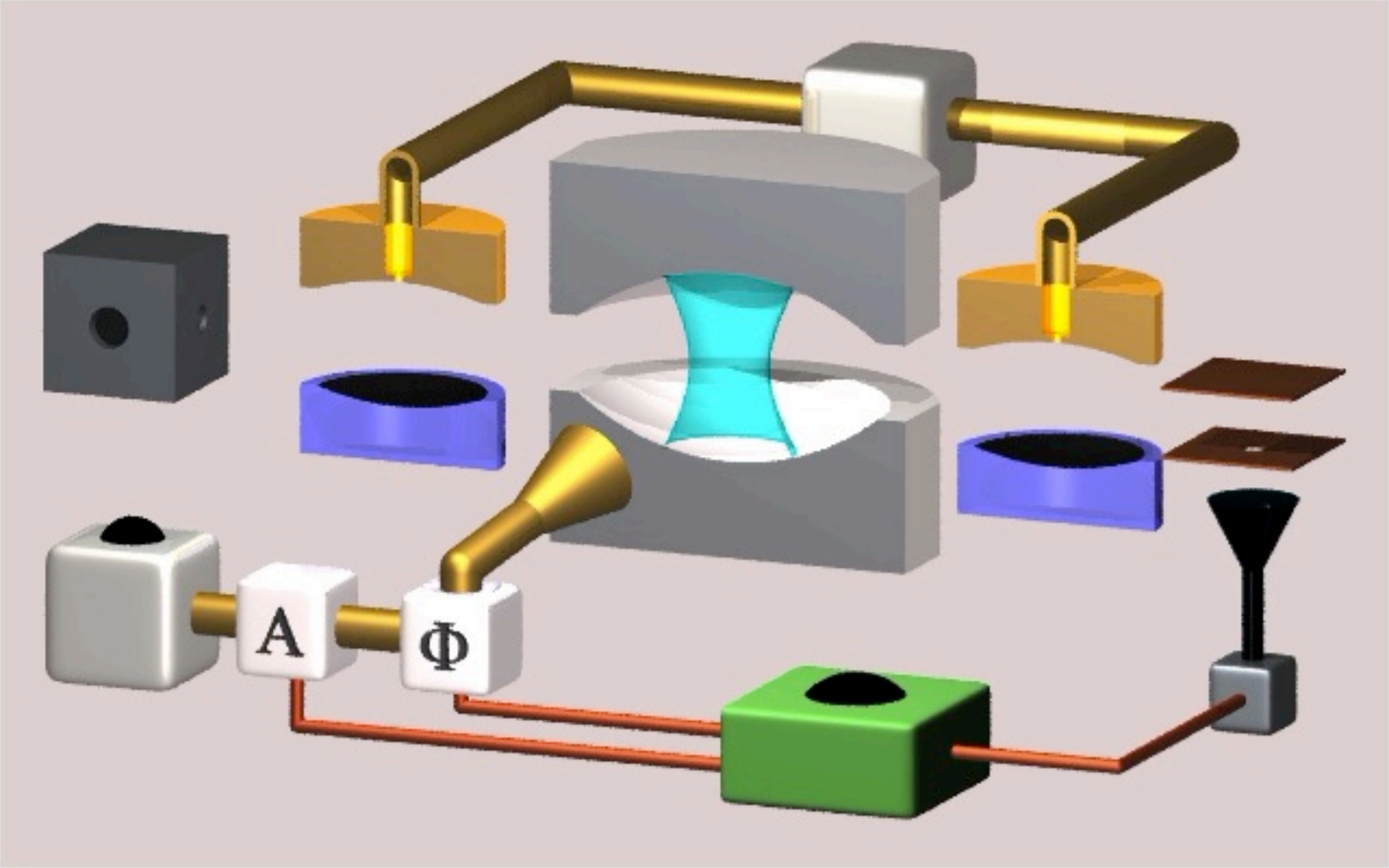
A single field "trajectory"

Observing the escape time of photons



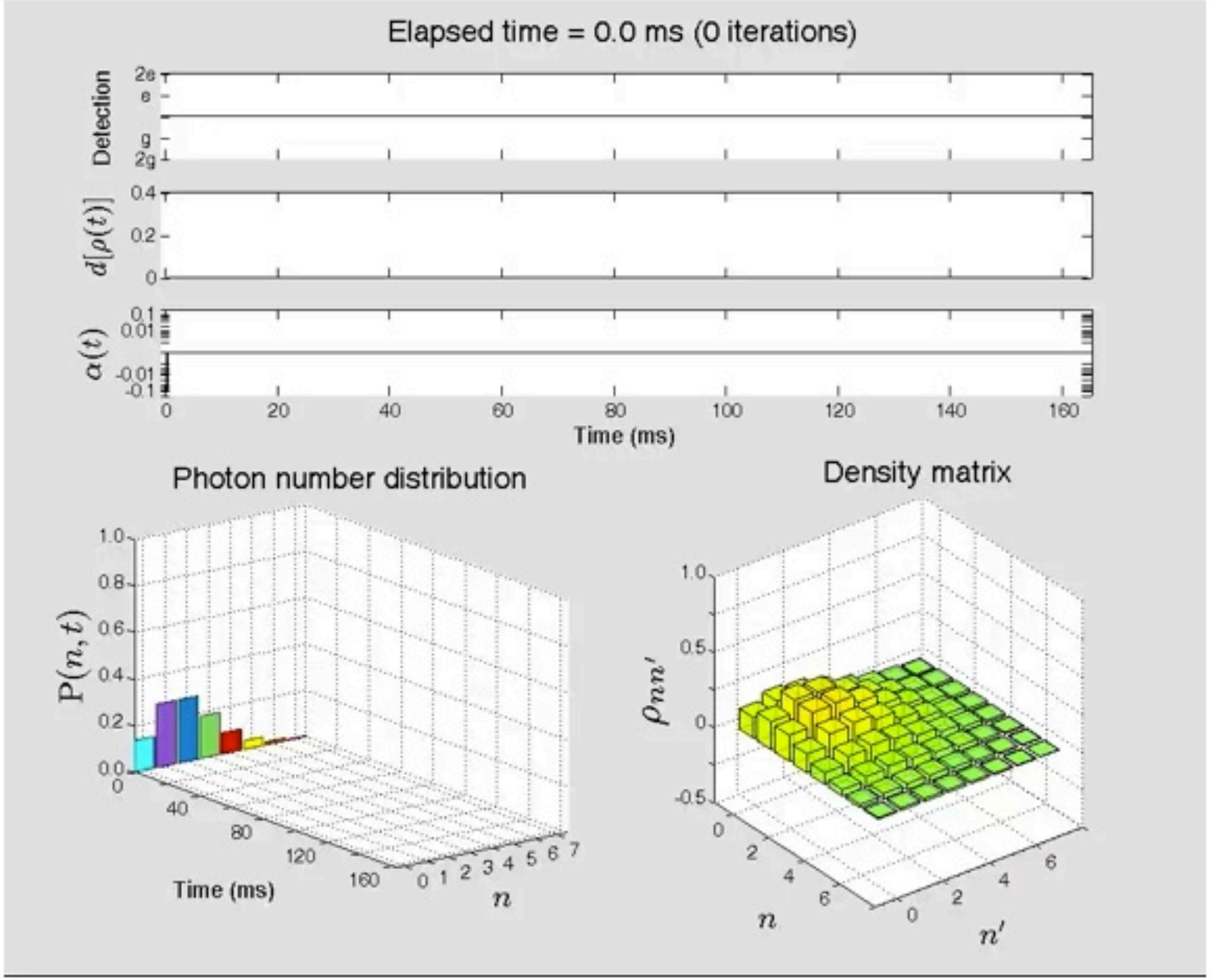
Quantum jumps of the field oscillator similar to the ion jumps in ion trap experiments

Undoing quantum jumps by quantum feedback with classical actuator

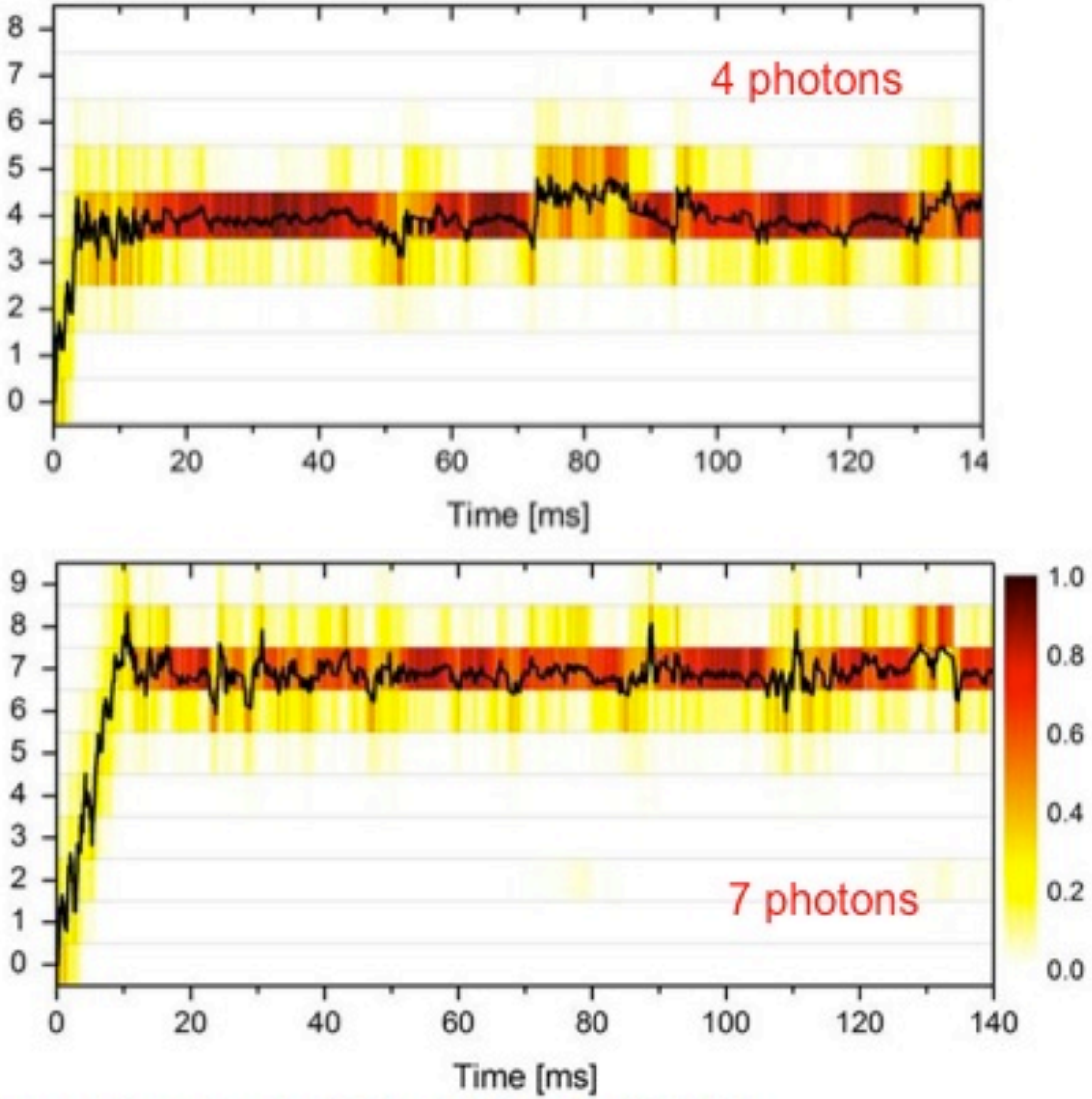


C.Sayrin et al, Nature, London, 477, 73 (2011)

Stabilization of n=2 Fock state



Photon number states stabilized by quantum feedback with atomic actuators



X. Zhou et al., *Phys. Rev. Lett.* 108, 243602 (2012)

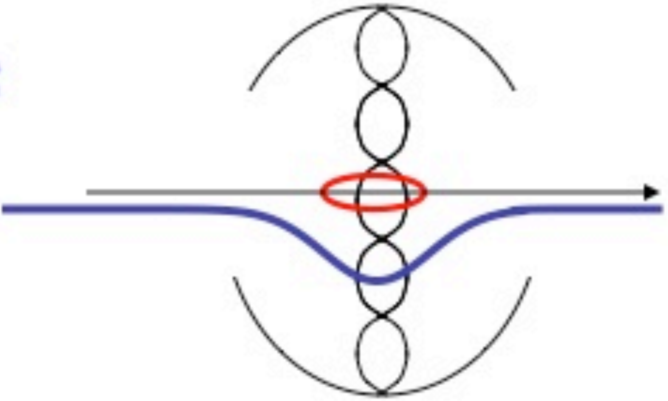
Experimenting with Schrödinger's cat: complementarity and decoherence

Single atom index effect

Non-resonant atom crossing cavity adiabatically changes field frequency

Atom in n-photon light-potential gains kinetic energy

$$n\hbar\frac{\Omega^2(z)}{4\Delta}$$



Energy is borrowed from field whose frequency becomes $\omega-\delta$, n photons losing energy

$$n\hbar\delta$$

Energy conservation: $\delta(z)=\frac{\Omega^2(z)}{4\Delta}$

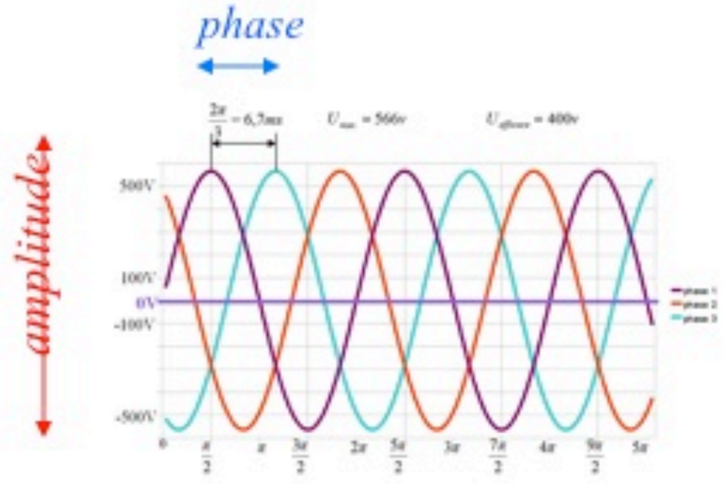
During atom-cavity crossing time, field undergoes phase shift:

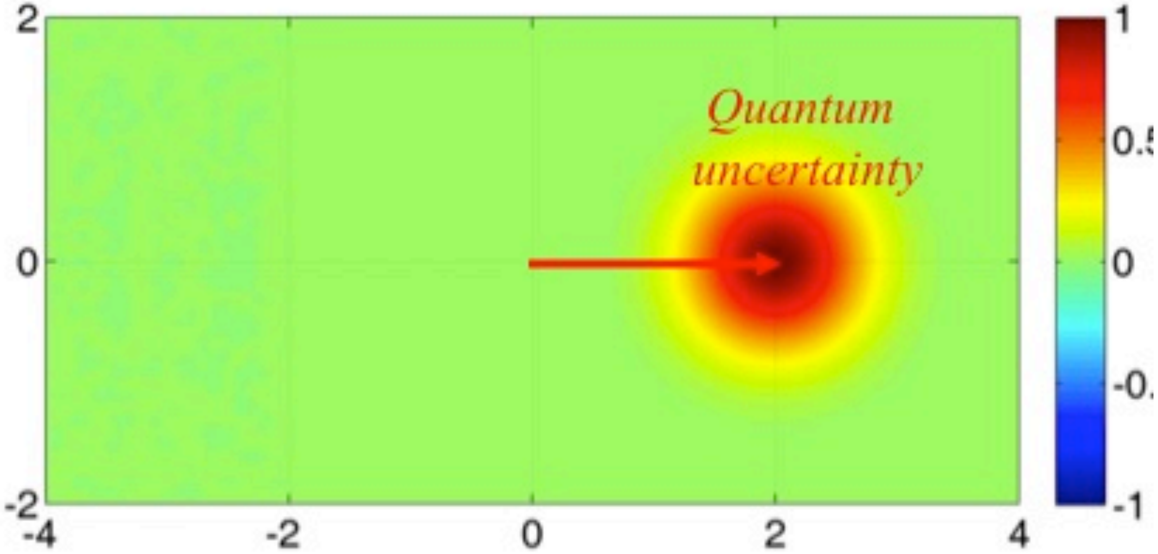
$$\Delta\phi=\pm\int\frac{\Omega^2(z)}{4\Delta}\frac{dz}{v}$$

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

$$\Delta\phi\sim\pi$$

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

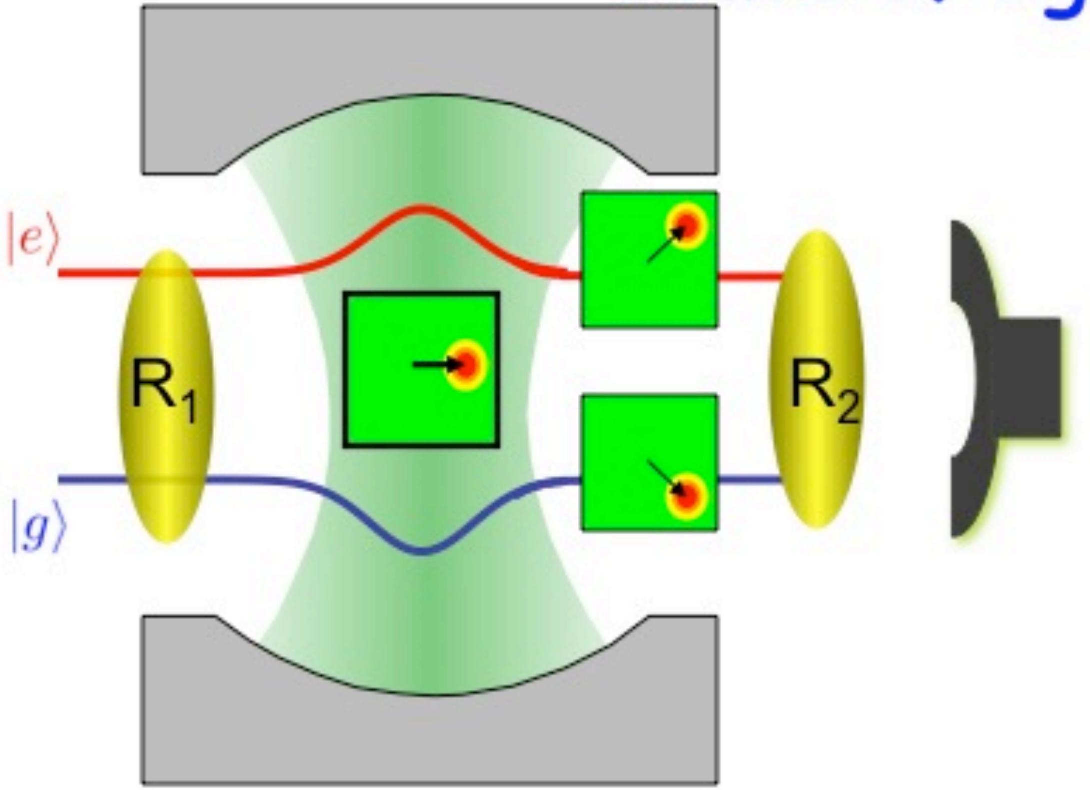




Fresnel plane or phase space

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

How single atom prepares Schrödinger cat state of light



1. Coherent field injected in cavity.

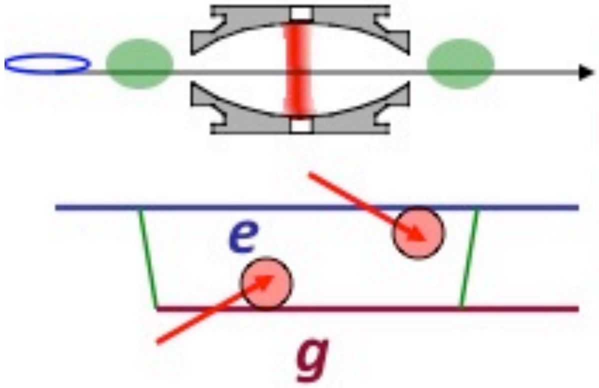
3. Atom shifts the field phase in two opposite directions as it crosses C: superposition leads to entanglement in typical Schrödinger cat situation: field is a ‘meter’ reading atom’s energy

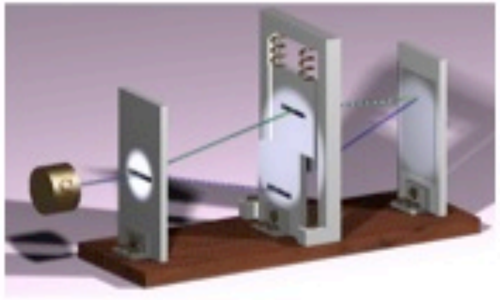
4. Atomic states mixed again in R_2 maintains cat’s ambiguity:

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

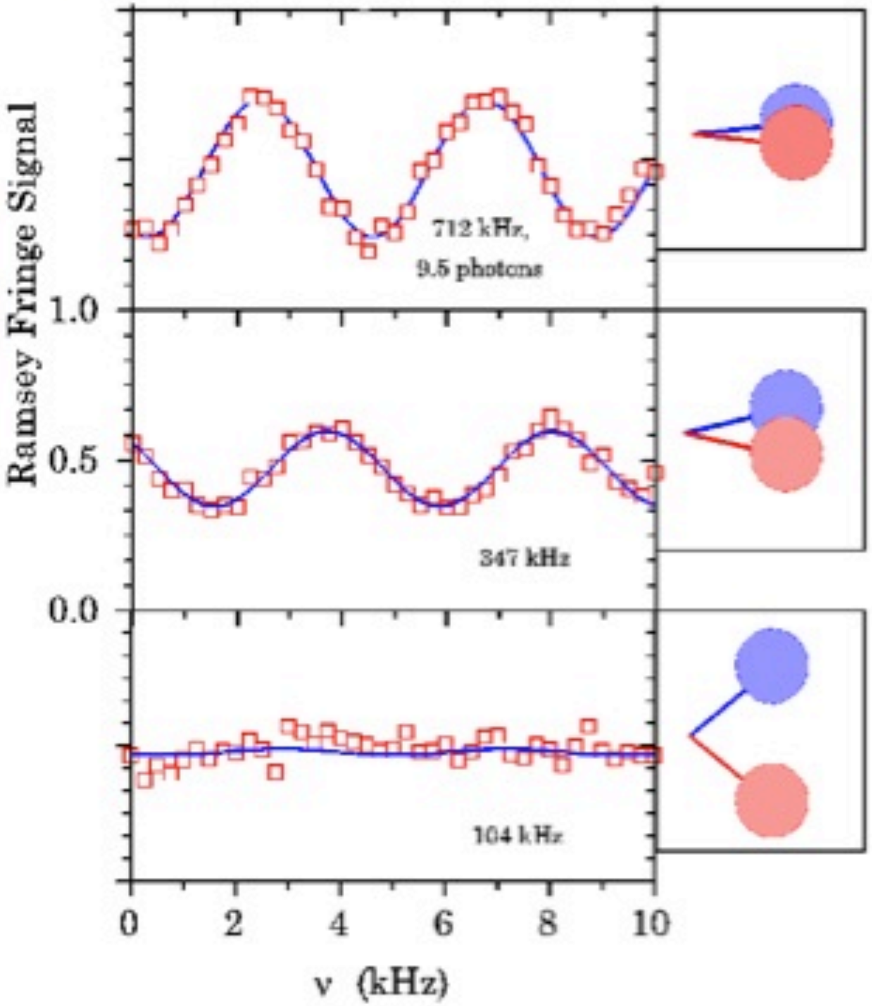
Schrödinger cat generation seen by atom: a complementarity experiment

Atom preparing the cat state crosses a Ramsey interferometer





Field in C behaves as a «meter» providing info. about atom's path. The fringes have a contrast proportional to the overlapping of the coherent final states
(same as Young double slit)



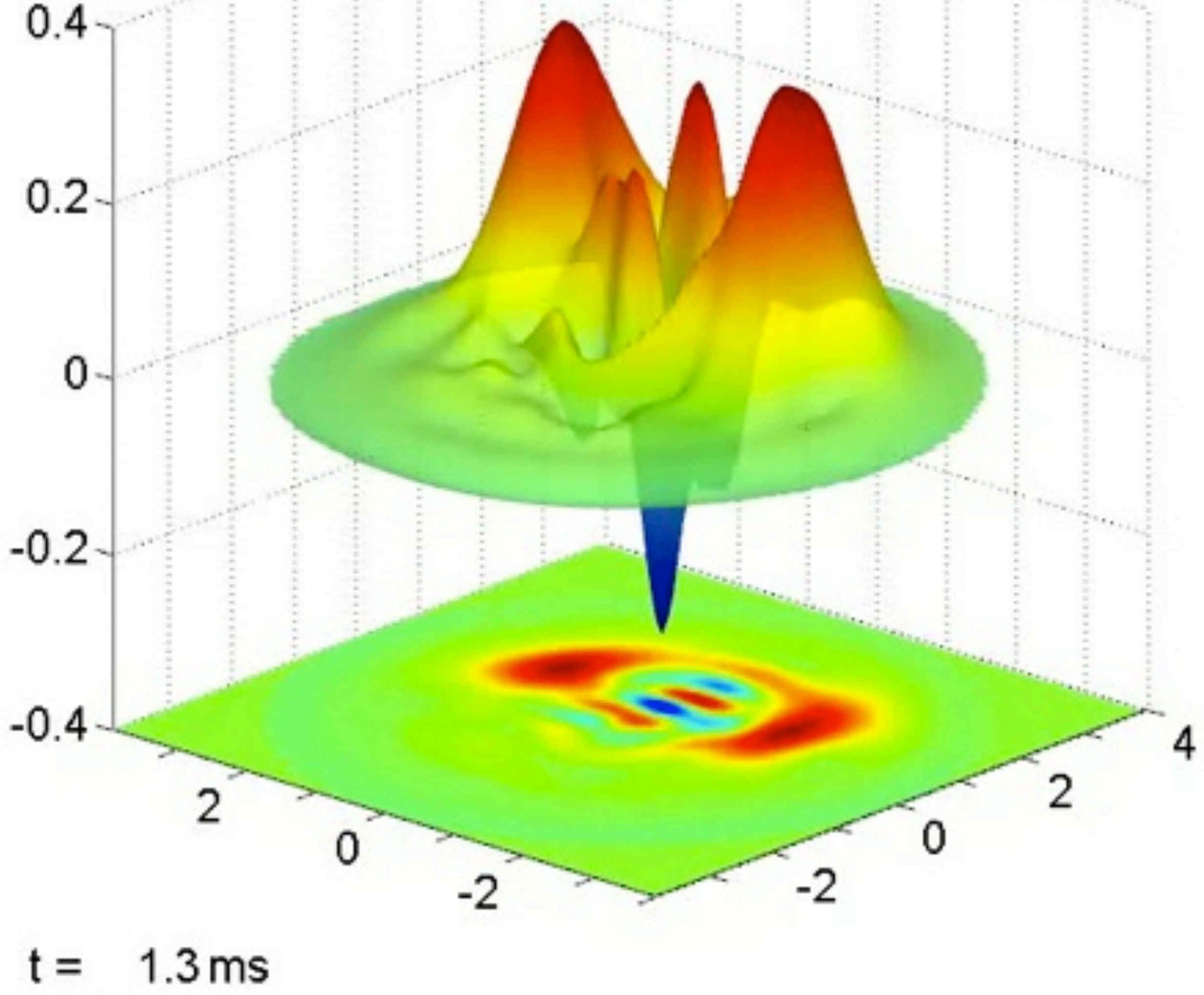
Phase-shift controlled by detuning Δ

Bohr's complementarity illustrated

M.Brune, E.Hagley, J.Dreyer, X.Maître, A.Maali, C.Wunderlich, J-M.Raimond et S.Haroche, Phys.Rev.Lett. 77, 4887 (1996).

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

Experimentally reconstructed W function by generalized QND procedure

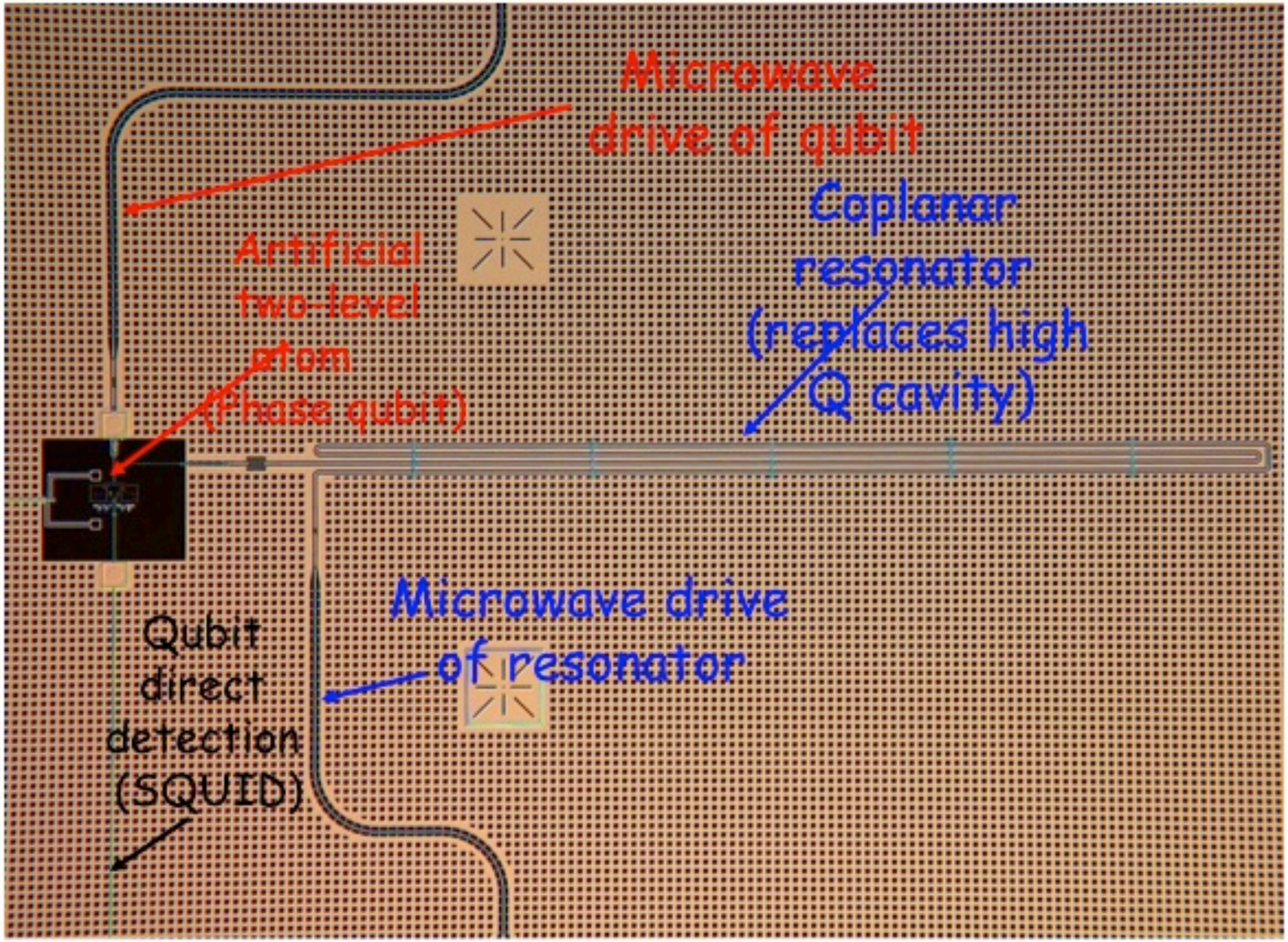


W.Zurek

Physics Today, 44, 36 (1991)

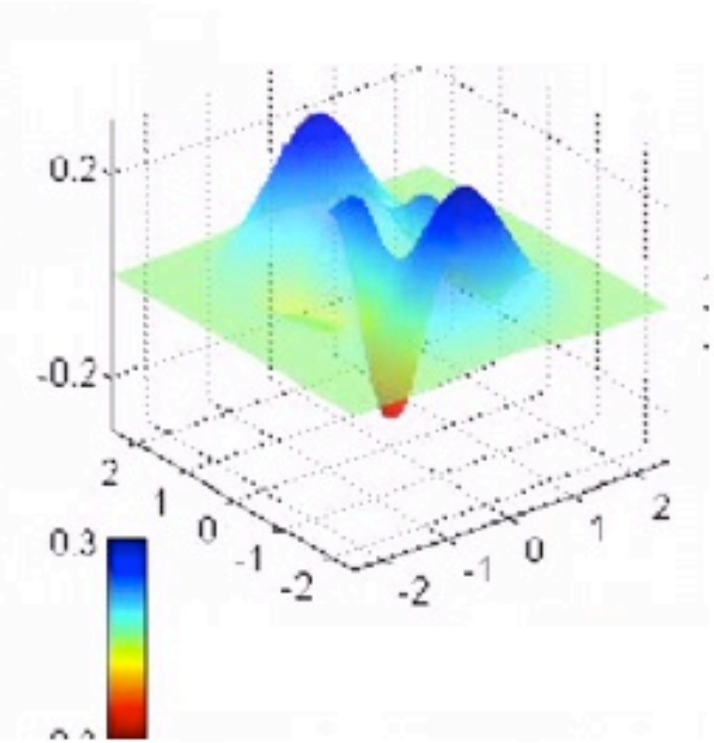
Decoherence rate increases with "cat size": quantum/ classical boundary

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

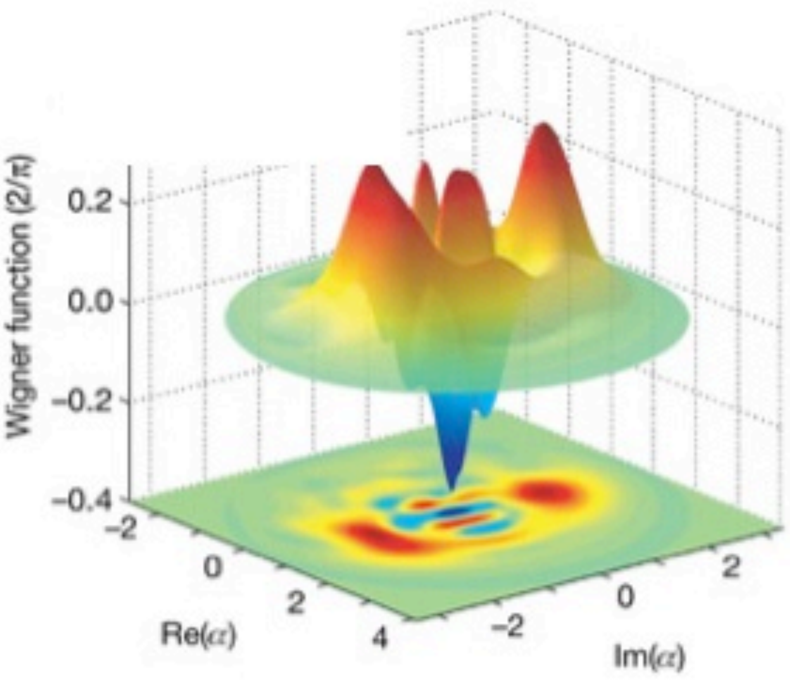


Comparison with CQED

Circuit QED and Cavity QED allow us to prepare and reconstruct non-classical field states with similar methods. In both cases, states can also 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)



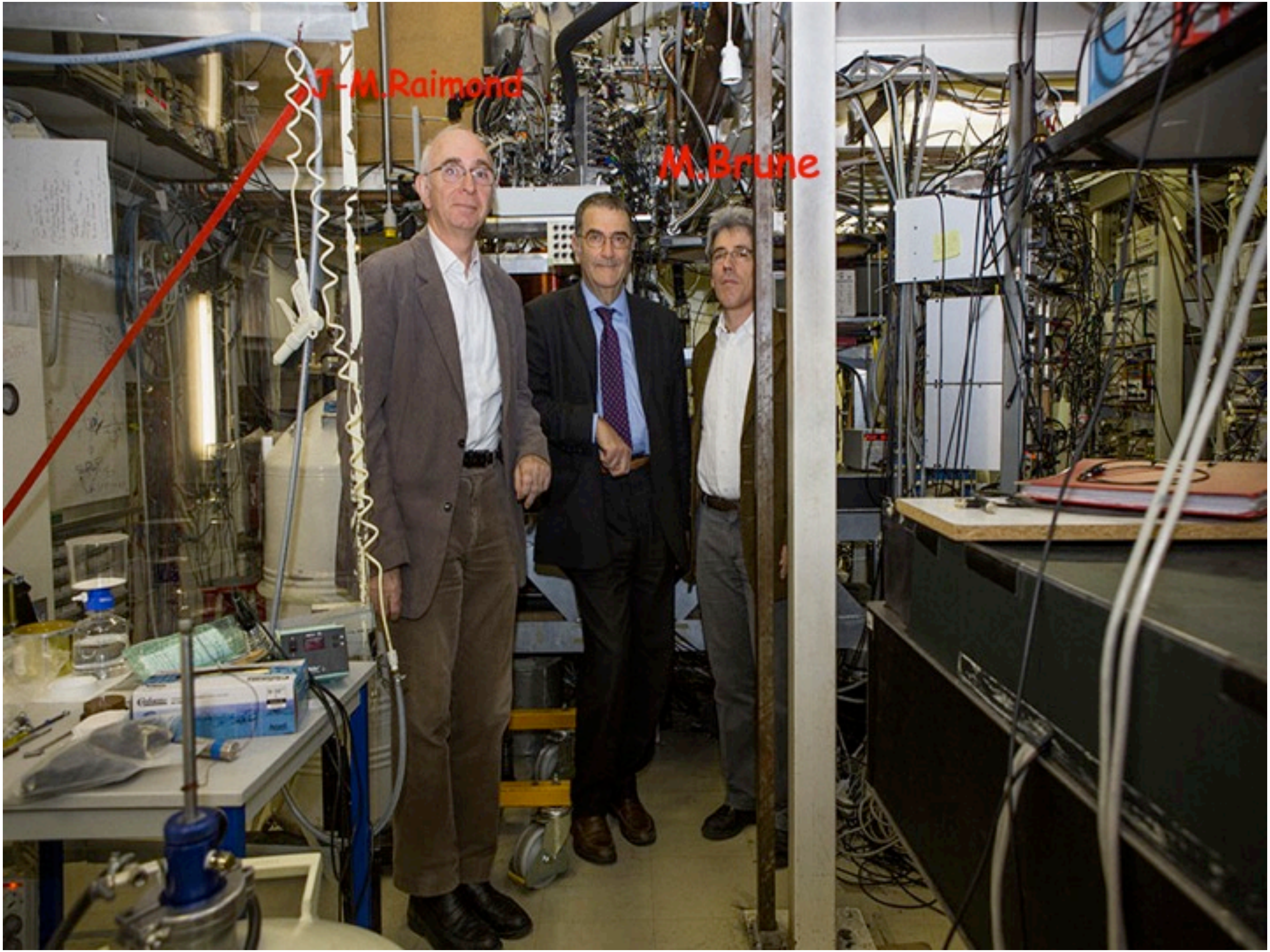
« cat » state prepared and
reconstructed in CQED at ENS

Bohr's ideas about quantum physics directly illustrated by Cavity QED-Rydberg atom experiments

The circular Rydberg atoms are described by Bohr's model. Most of their properties can be derived by classical arguments (correspondence principle)

The non-destructive detection of photons illustrates the Copenhagen view about measurement in quantum physics (quantum jumps and "God plays dice")

The Schrödinger cat experiments directly illustrate the complementarity principle...


J-M.Raimond
M.Brune

With a great team!