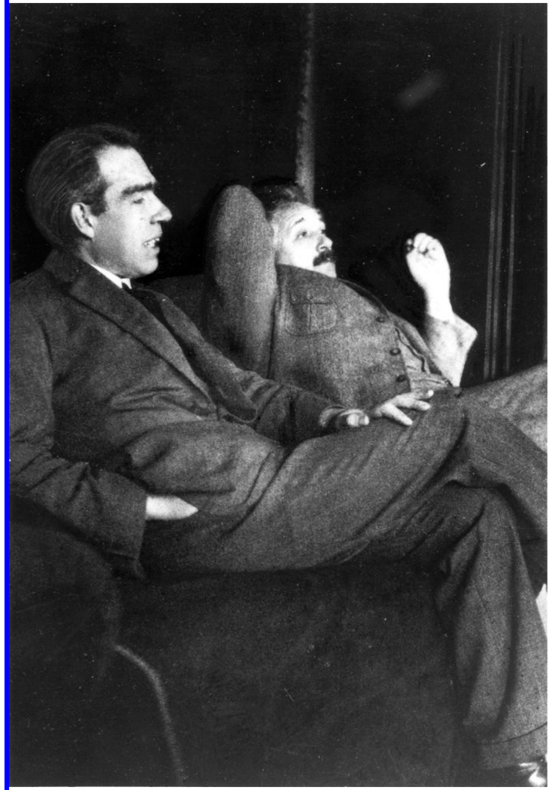
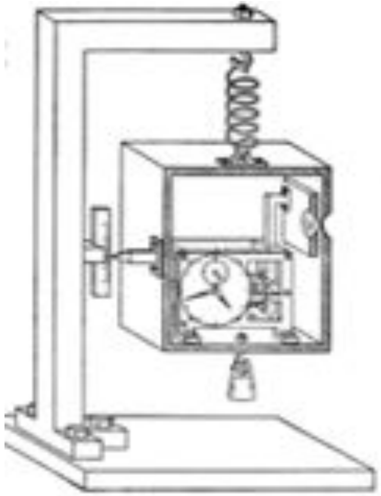
Controlling photons in a box and exploring the quantum to classical boundary

Serge Haroche

Thought experiments

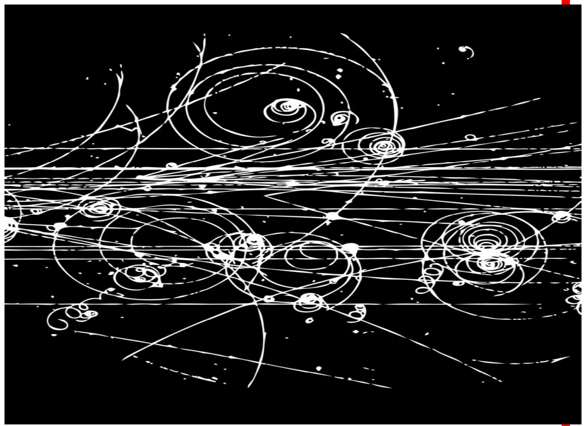




Einstein, Bohr and their Photon Box…

a kind of experiment that Schrödinger considered impossible to realize….

Single particle detection was known to Schrödinger, but, as he put it, it was « *post mortem* » physics, destroying the object under investigation…



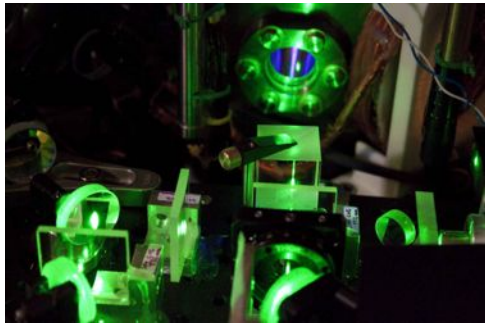
Bubble chamber (CERN)

"…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, 1952)

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

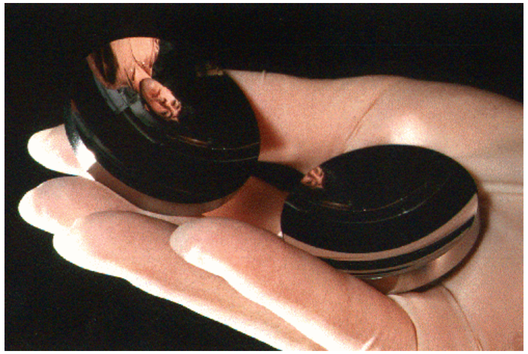
New quantum technologies:

Tunable lasers



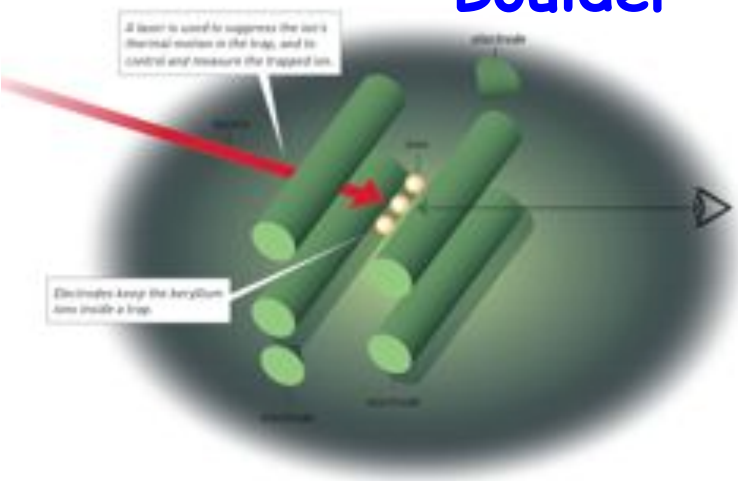
Fast computers

Superconducting materials

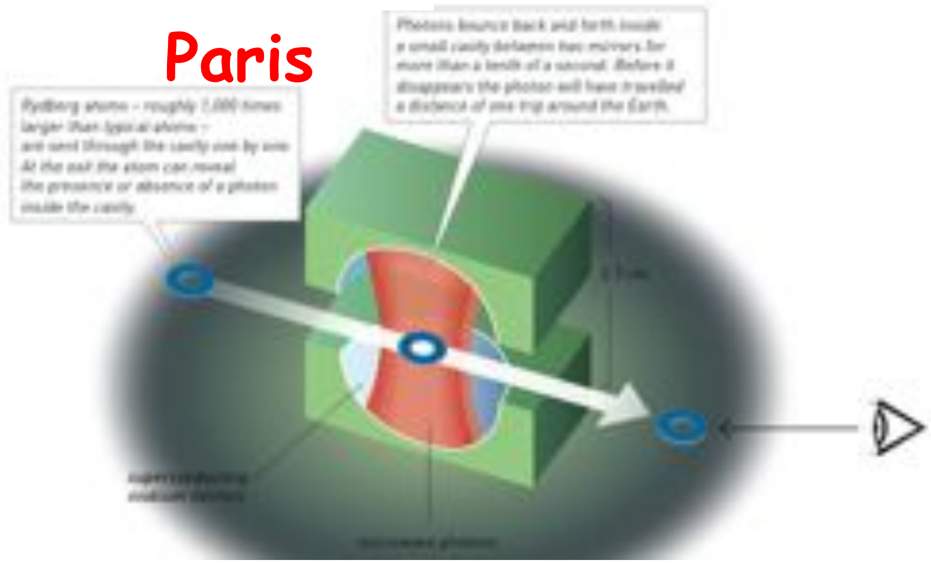


«Particle control in a quantum world»

Boulder

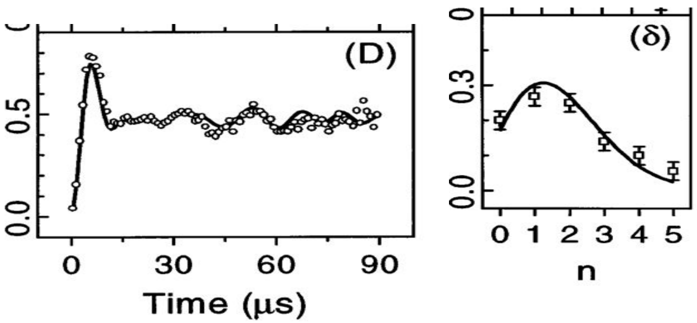


Paris

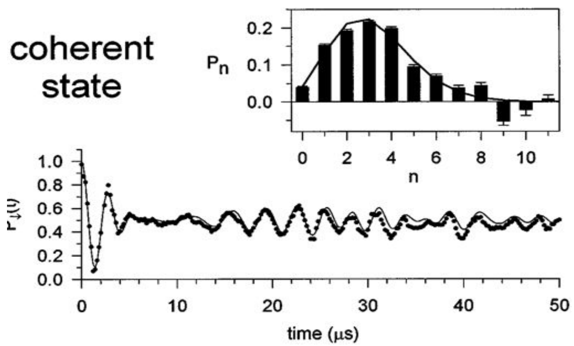


Two sides of the same coin: manipulating non destructively single atom with photons or single photon with atoms

Trapped photons (CQED):
Brune et al, PRL, 76, 1800 (1996)



Trapped ions:
Meekhof et al, PRL, 76, 1796 (1996).



Boboli Gardens, Florence (August 1996)

PhD with Claude Cohen-Tannoudji (1967-71)

1997

Optical pumping experiments &
Dressed atom formalism

(1921-1999)

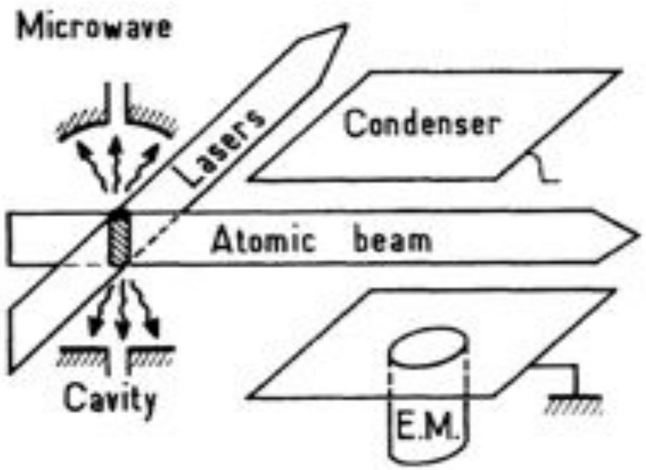
Postdoc with Arthur Schawlow (1972-73)

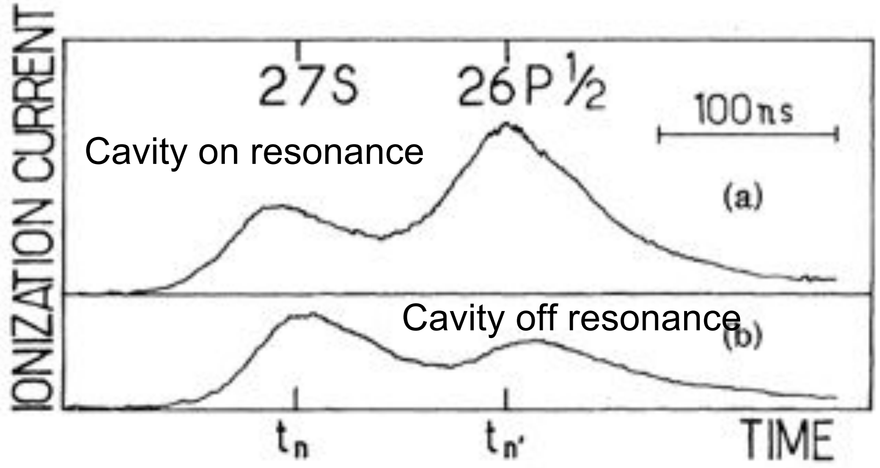
1981

Quantum beats excited by dye lasers
(time evolution of
state superpositions)

…but the story really started with the first studies of Rydberg atom masers in the late 1970's

M. Gross, C. Fabre, S. Haroche, J.M. Raimond, PRL **43**, 343 (79)





Open cavity

An insightful comment…and the beginning of Cavity Quantum Electrodynamics

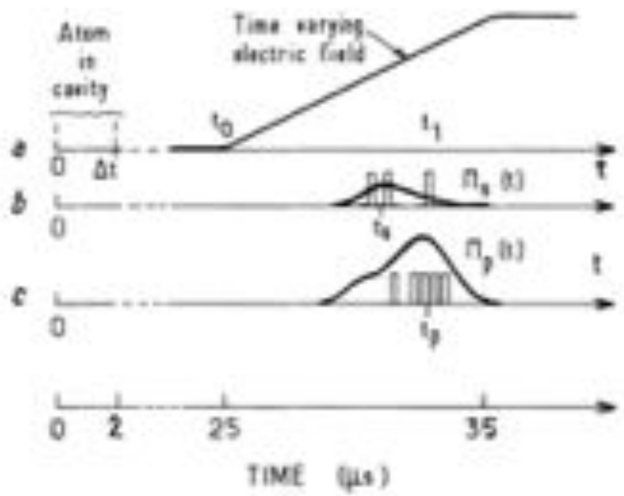
More fundamentally, we believe that these experiments open the way to the study of even smaller emitting systems (i.e., samples smaller than the atomic wavelength or with very small absolute atom number), a domain where there is still no comparison available between experiments and theory.

Observation of Cavity-Enhanced Single-Atom Spontaneous Emission

P. Goy, J. M. Raimond, M. Gross, and S. Haroche
Laboratoire de Physique de l'Ecole Normale Supérieure, F-75231 Paris Cedex 05, France
(Received 1 April 1983)

It has been observed that the spontaneous-emission lifetime of Rydberg atoms is shortened by a large ratio when these atoms are crossing a high-Q superconducting cavity tuned to resonance with a millimeter-wave transition between adjacent Rydberg states.

PACS numbers: 32.80.-t, 32.90.+a, 42.50.+q

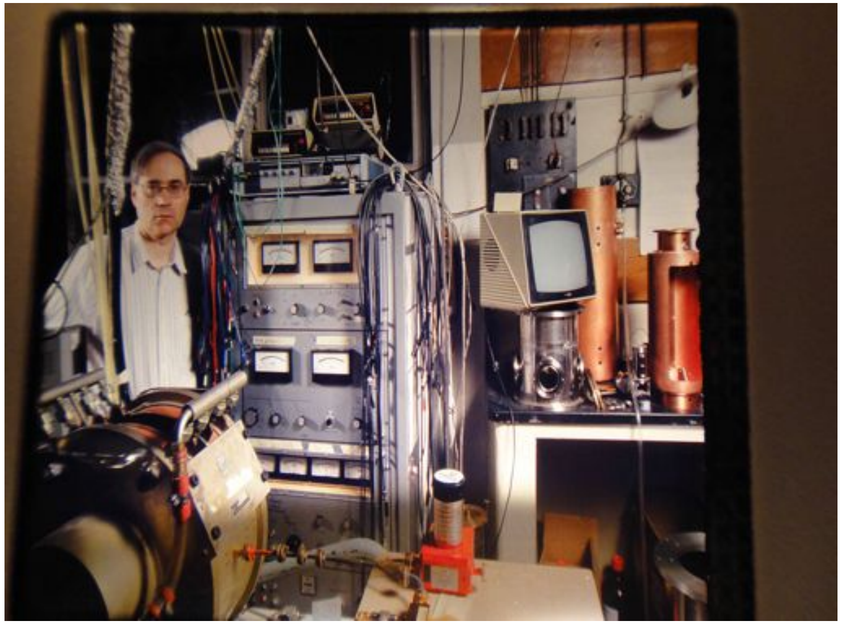


In this respect, the effect described in this Letter can be considered as the limiting case of a transient maser approaching threshold with only one or two atoms in the inverted medium.

With a tenfold increase in Q, Γ_{cav} and $2\pi\nu/Q$ would become of the same size and the emitted photon would be stored in the cavity long enough for the atom to be able to reabsorb it.

This would correspond to a regime of quantum mechanical oscillations between a two-level atom and a single electromagnetic field mode[4] which should be observable with an improved version of our setup.

With Michel Gross and Claude Fabre (1977?)



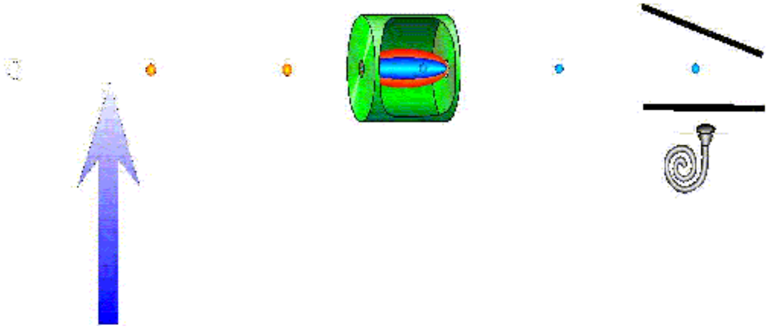
Philippe Goy and his microwave equipment (1978?)

With Yves Kaluzny, Claude Fabre and Jean-Michel Raimond (1980?)

The Micromaser (1984)

H.Walther
(1935-2006)

The regime of atom-photon quantum mechanical oscillation (« strong coupling regime » of Cavity QED) was achieved first in the cw micromaser



D.Meschede
(in 1987)

A cylindrical cavity with a very long photon life-time…but atomic superpositions are perturbed by passing through small holes

Photon detection by photoelectric effect: « chronicle of a foretold death »

$$|1\rangle \xrightarrow[\text{clic}]{} |0\rangle$$

A clic projects the field onto the vacuum:
the photon dies upon delivering its message

A Quantum Non-Demolition (QND) measurement should instead realize:

$$|1\rangle \xrightarrow[\text{clic}]{} |1\rangle \xrightarrow[\text{clic}]{} |1\rangle \xrightarrow[\text{clic}]{} \cdots\cdots \xrightarrow[\text{clic}]{} |1\rangle \quad ?$$

V.Braginsky

We need a non-demolition detector at single photon level…
and a very good box to keep the photons alive long enough

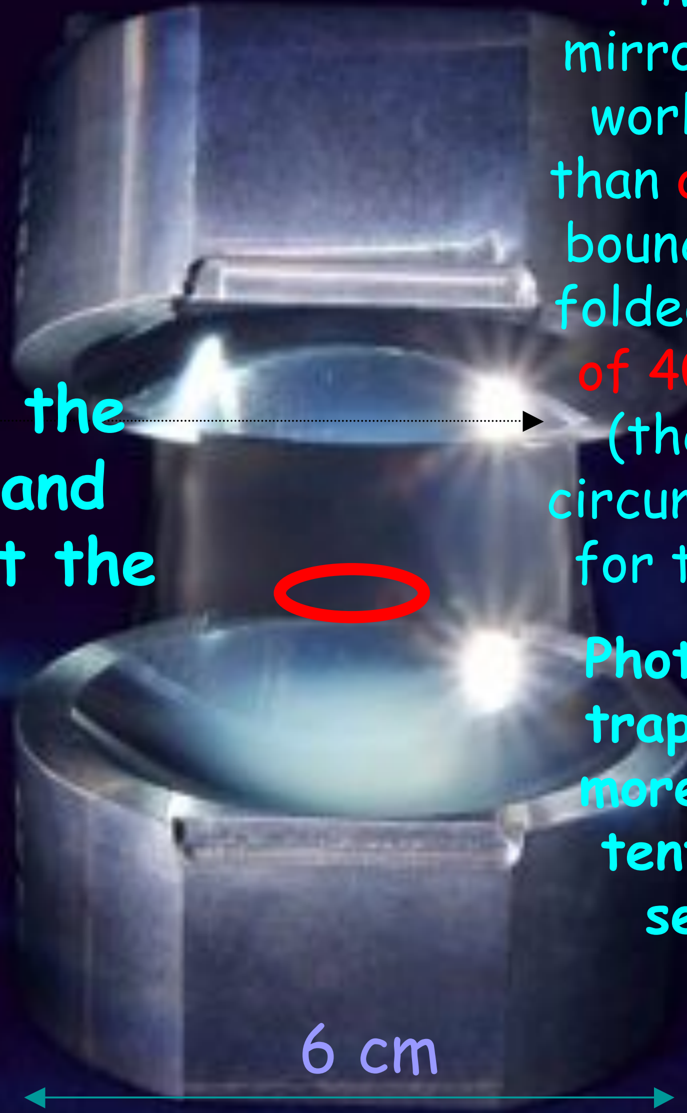
Cavity Quantum Electrodynamics:

a stage to witness the interaction between light and matter at the most fundamental level

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

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

Photons bouncing on mirrors pass many many times on the atom: the cavity enhances tremendously the light-matter coupling



The best mirrors in the world: more than one billion bounces and a folded journey of 40.000km (the earth circumference) for the light!

Photons are trapped for more than a tenth of a second!

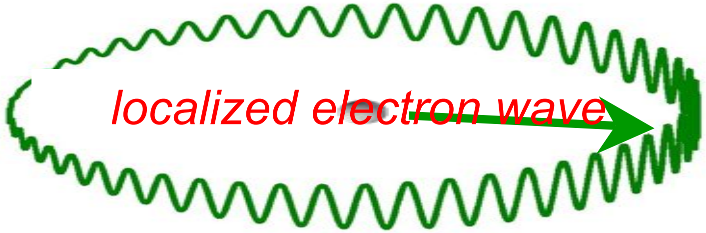
Rydberg

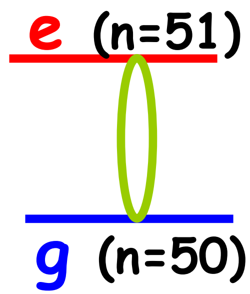
An extremely sensitive detector: the circular Rydberg atom

D.Kleppner

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

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





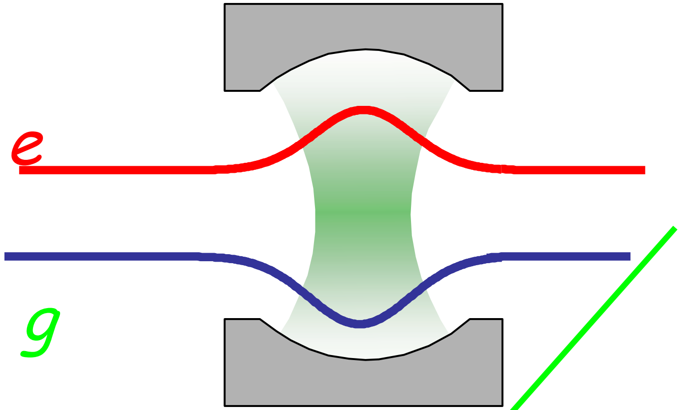
Electron is localised on orbit by a microwave pulse preparing superposition of two adjacent Rydberg states: |e› → |e› + |g›

Schrödinger kitten

The localized wave packet revolves around nucleus at 51 GHz like a clock's hand on a dial.

When atom interacts with non-resonant light, the clock frequency is slightly modified by the light shift effect (Cohen-Tannoudji, 1961)

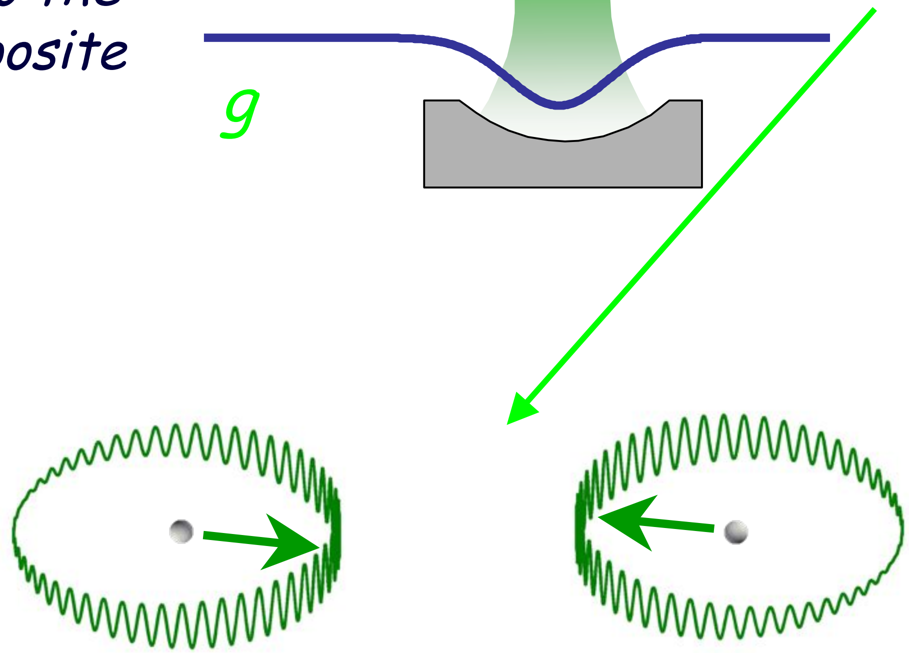
Non-resonant atom experiences *light-shifts proportional to the photon number N, with opposite signs* in levels e and g



The shifts result in a phase shift of the atomic dipole when atom crosses the cavity:

$$\Delta\Phi(N) = N\varphi_0$$

φ_0 : phase shift per photon can be as large as π

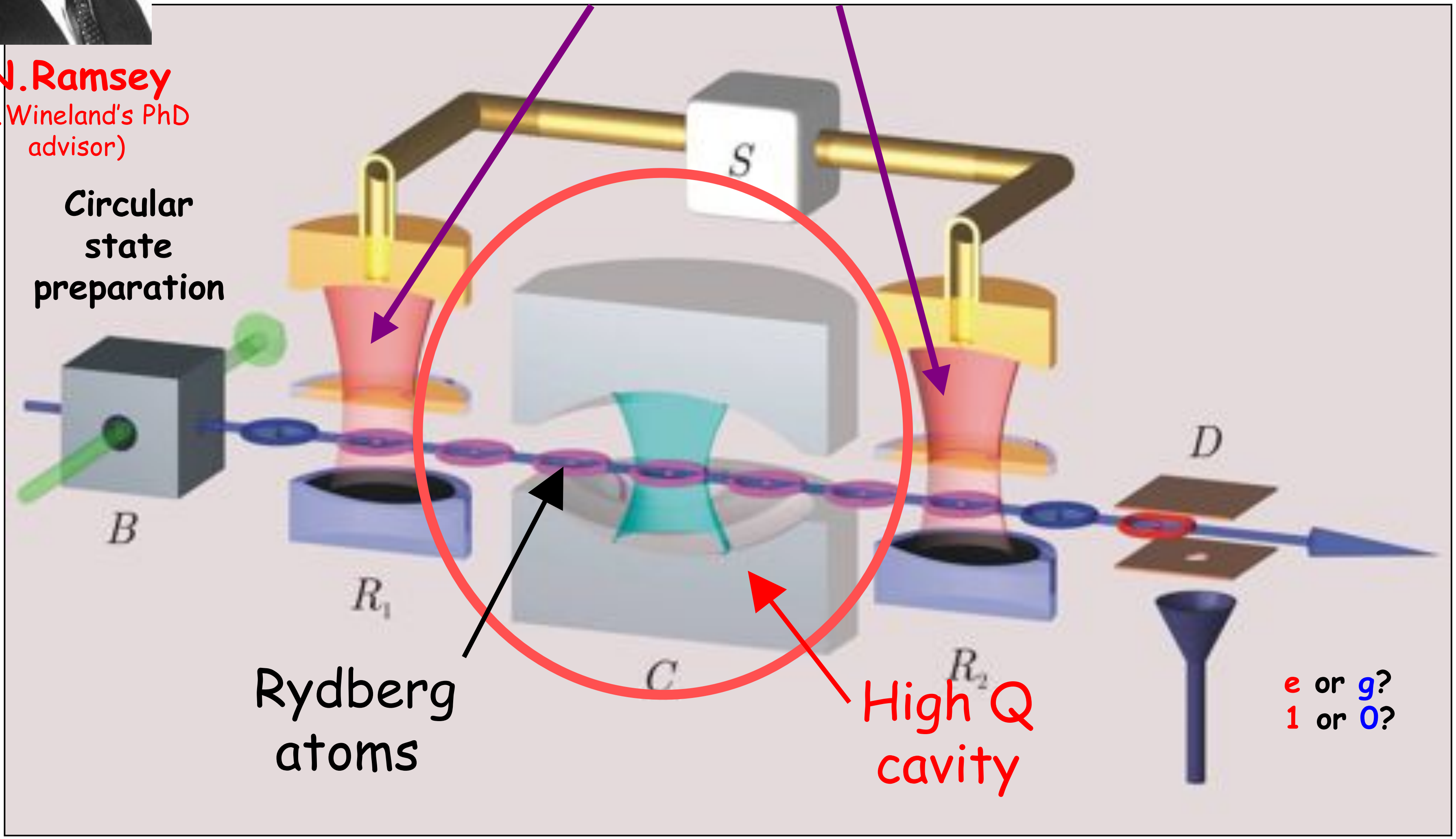


Measuring $\Delta\Phi$ amounts to a QND photon counting

An artist's view of set-up…

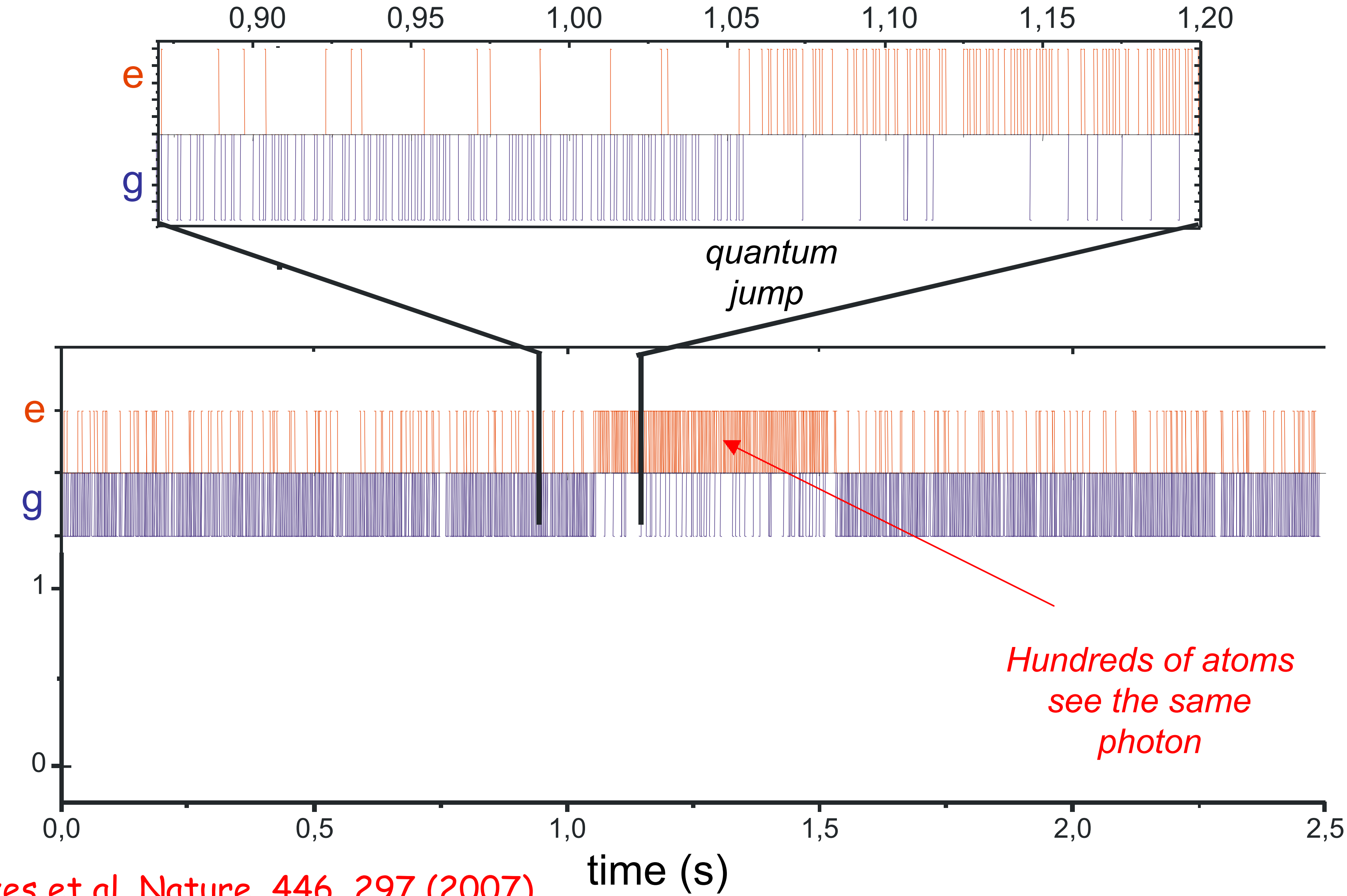
N.Ramsey
(D.Wineland's PhD advisor)

Classical pulses
(Ramsey interferometer)



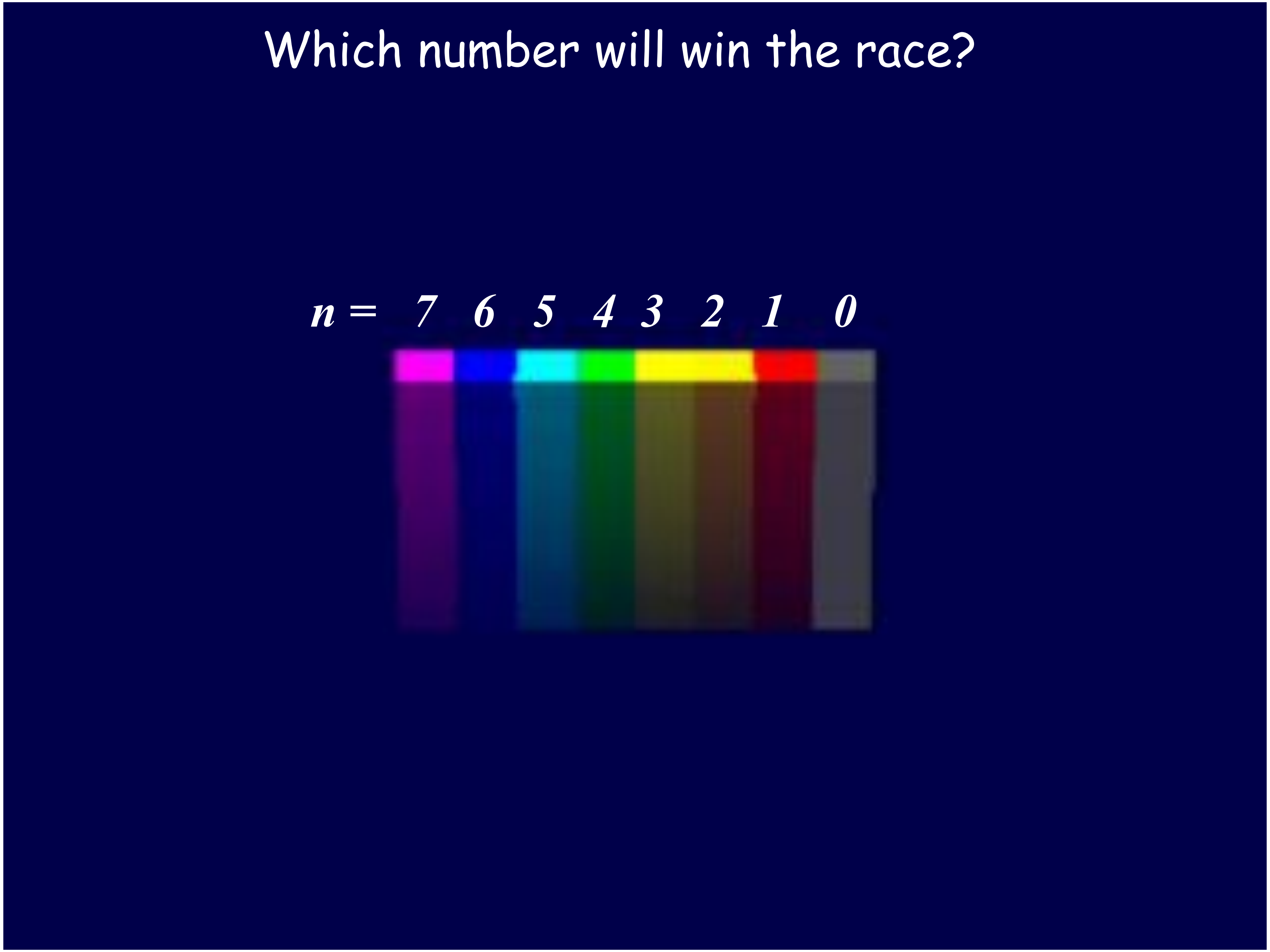
An atomic clock delayed by photons trapped inside

Birth, life and death of a photon



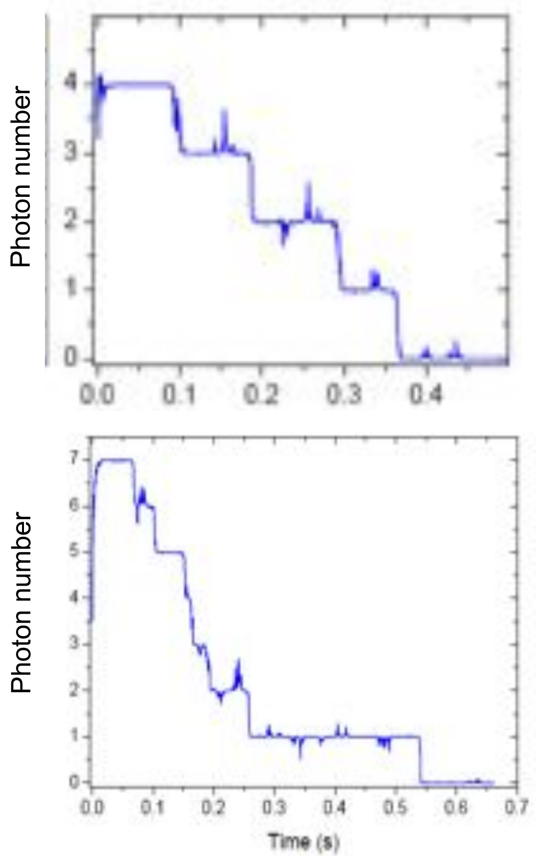
S.Gleyzes et al, Nature, 446, 297 (2007)

Progressive collapse as n is pinned down to one value



Field quantum jumps

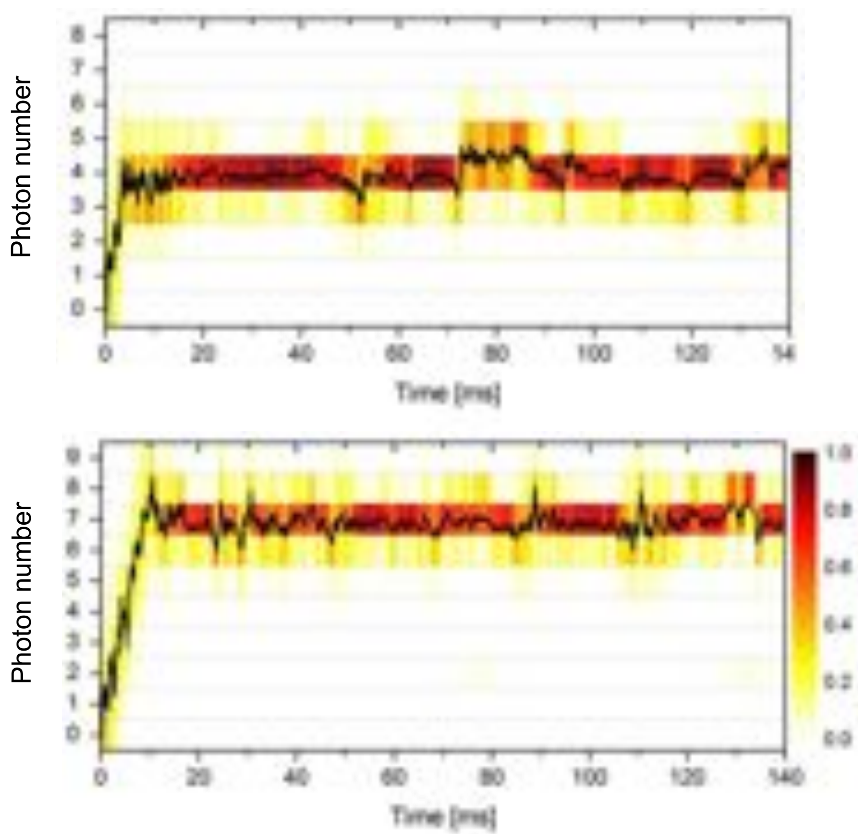
due to cavity losses



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

Photon number states stabilized by quantum feedback

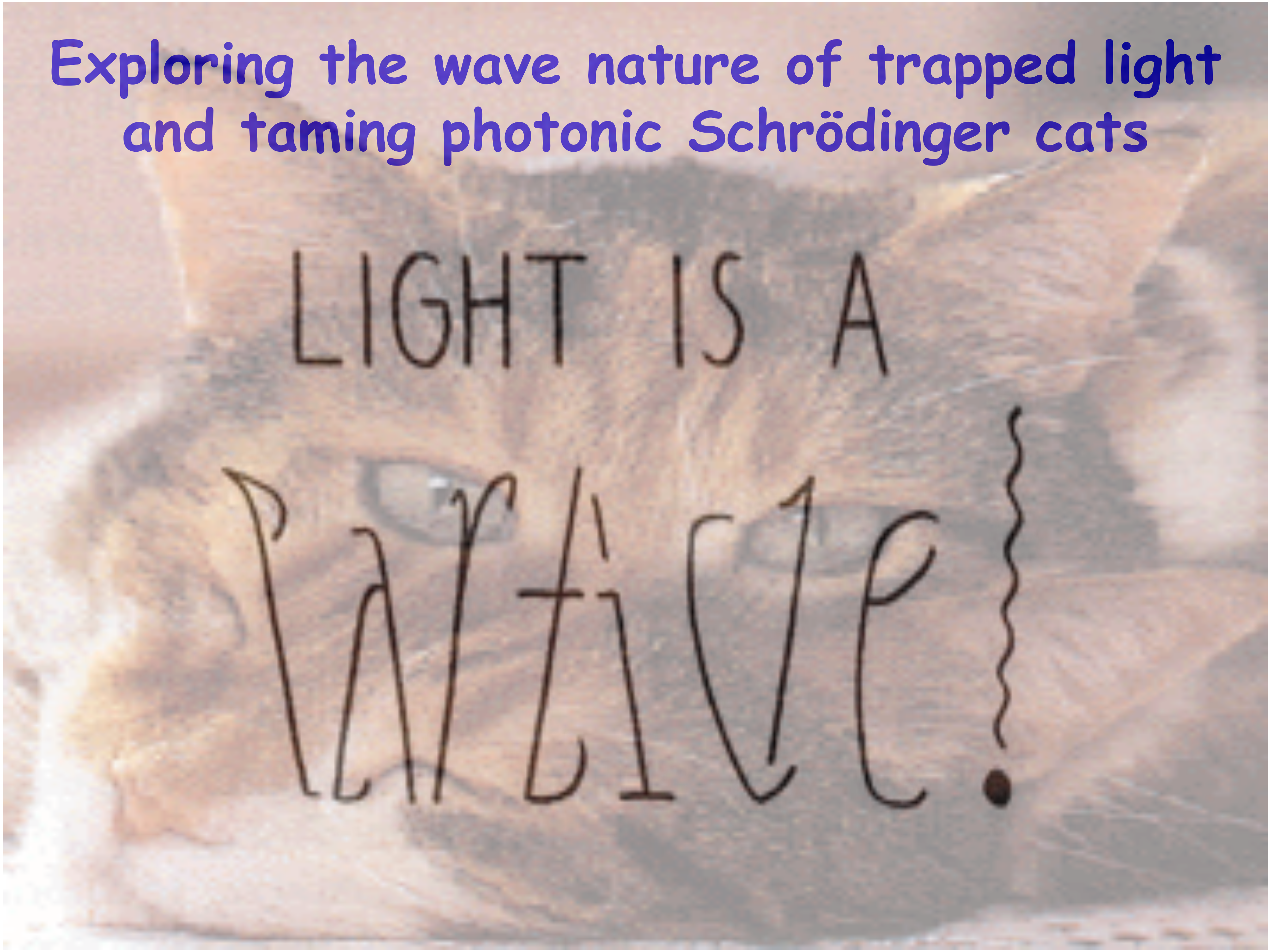
(4 and 7 photons)



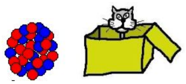
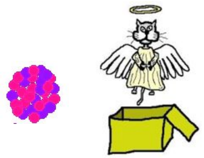
C. Sayrin et al., *Nature* **477,** 73 (2011)

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

Exploring the wave nature of trapped light and taming photonic Schrödinger cats

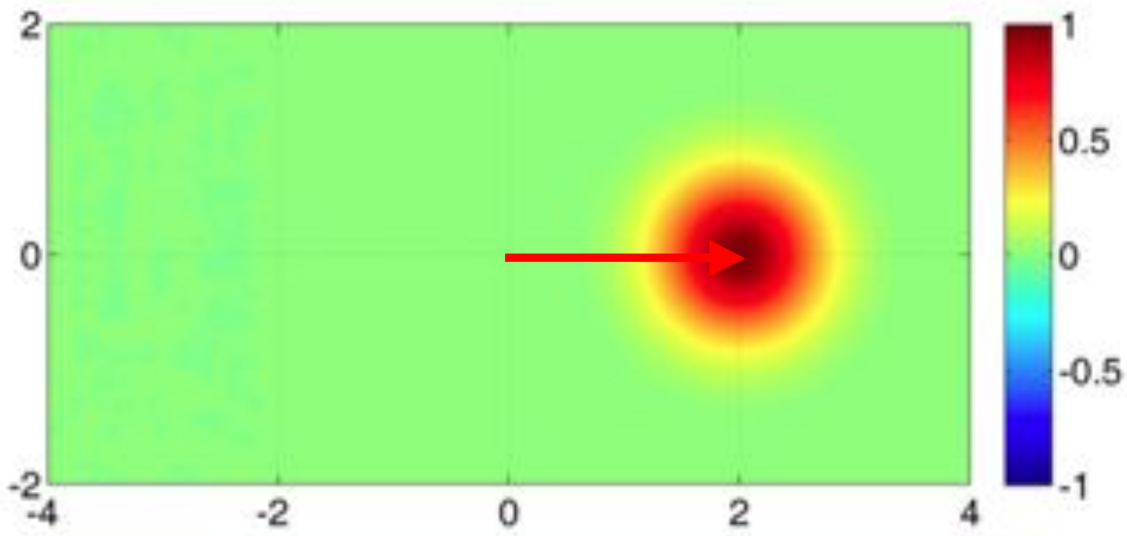


Schrödinger cat story:
A large system coupled to a single atom ends up in a strange superposition…

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

Our version: a coherent field coupled to a single atom collapses into a superposition of two fields with opposite phases

A coherent state of light frozen at a given time



The Wigner function is a 2D real function describing the state of the field

M.Brune

L.Davidovich

PHYSICAL REVIEW A VOLUME 45, NUMBER 7 1 APRIL 1992

Manipulation of photons in a cavity by dispersive atom-field coupling: Quantum-nondemolition measurements and generation of "Schrödinger cat" states

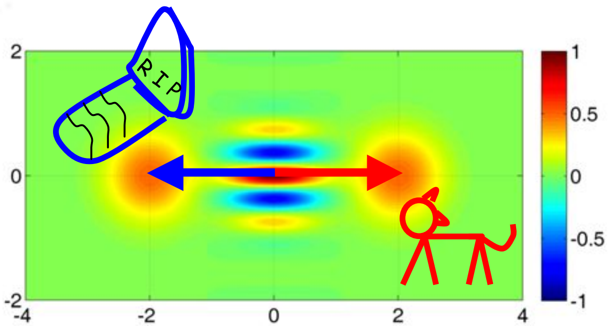
M. Brune, S. Haroche, and J. M. Raimond
Laboratoire de Spectroscopie Hertzienne de l'Ecole Normale Supérieure, 24 rue Lhomond, 75231 Paris CEDEX 05, France

L. Davidovich and N. Zagury
Departamento de Física, Pontifícia Universidade Católica, 22453 Rio de Janeiro, Brazil
(Received 1 November 1991)

A quantum-nondemolition method to measure the number of photons stored in a high-Q cavity, introduced by Brune et al. [Phys. Rev. Lett. 65, 976 (1990)], is described in detail. It is based on the detection of the dispersive phase shift produced by the field on the wave function of nonresonant atoms crossing the cavity. This shift can be measured by atomic interferometry, using the Ramsey separated-oscillatory-field method. The information acquired by detecting a sequence of atoms modifies the field step by step, until it eventually collapses into a Fock state. At the same time, the field phase undergoes a diffusive process as a result of the back action of the measurement on the photon-number conjugate variable. Once a Fock state has been generated, its evolution under weak perturbation can be continuously monitored, revealing quantum jumps between various photon numbers. When applied to an initial coherent field, the intermediate steps of the measuring sequence produce quantum superpositions of classical fields, known as "Schrödinger cat states." Ways to prepare and detect these states in a cavity subjected to a weak relaxation process are discussed. The effects analyzed in this article could realistically be observed by using circular Rydberg atoms and very high-Q superconducting microwave cavities. The possibility of photon "manipulation" through nonresonant atom-field interactions opens a domain in cavity QED studies.

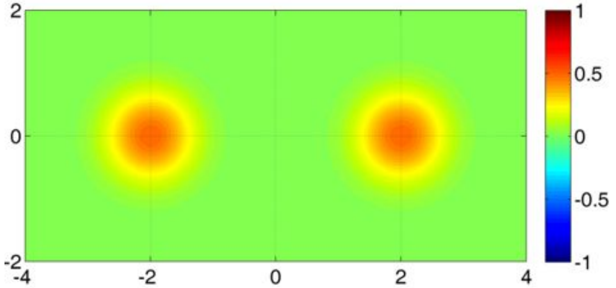
J-M.Raimond

N.Zagury



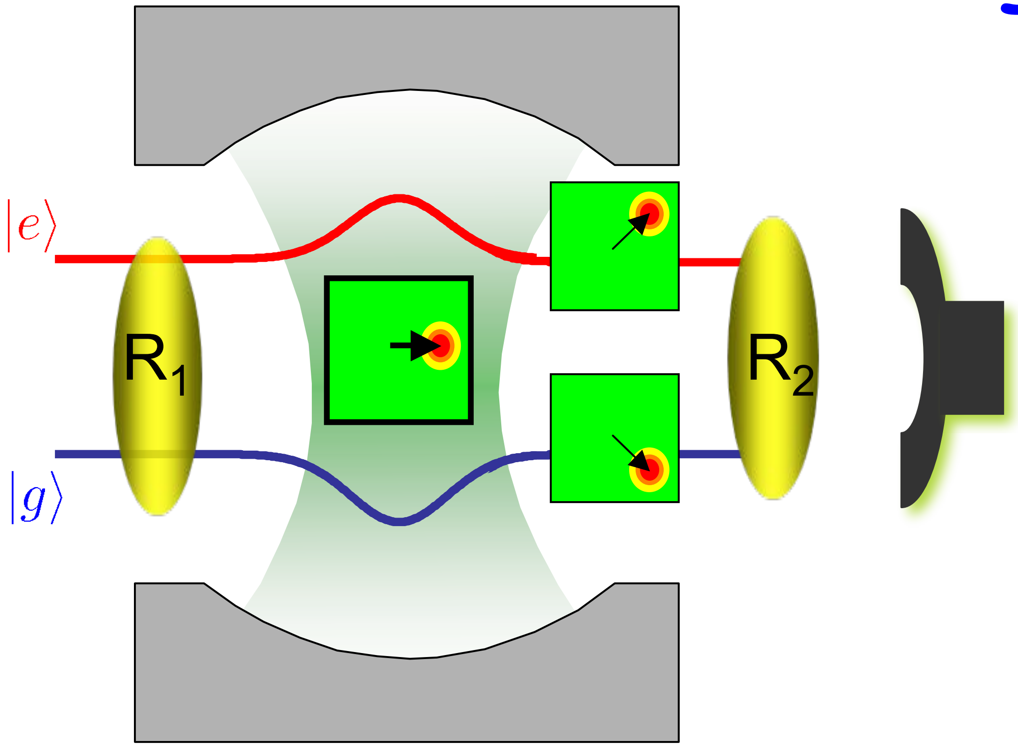
Schrödinger cat state

decoherence



Classical mixture of « live » and « dead » states

How single atom prepares Schrödinger cat state of light



1. Single atom is prepared in R_1 in a superposition of e and g

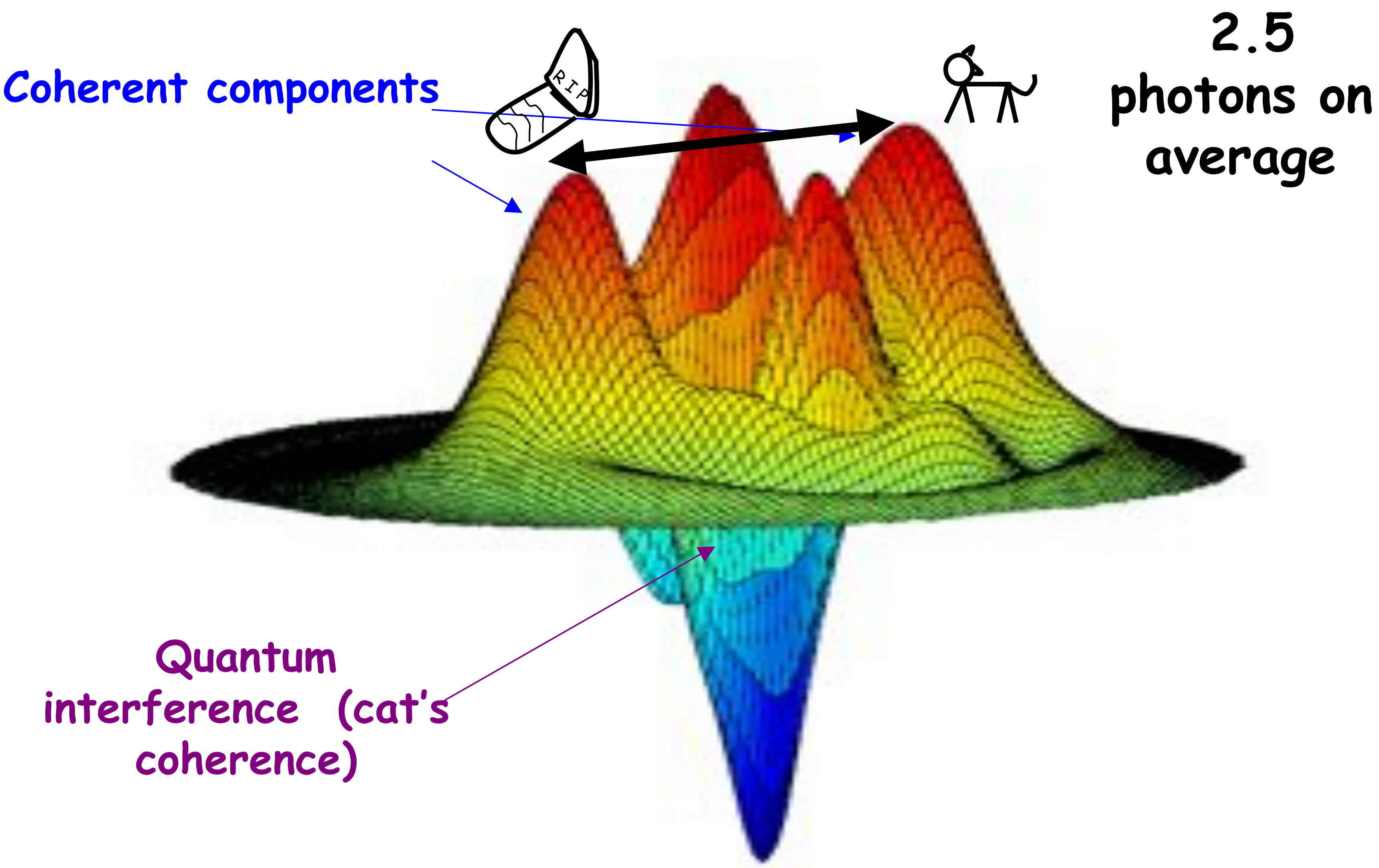
2. Atom shifts the field phase in two opposite directions as it crosses C: superposition leads to entanglement in typical Schrödinger cat situation: field is a 'meter' reading atom's energy

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

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

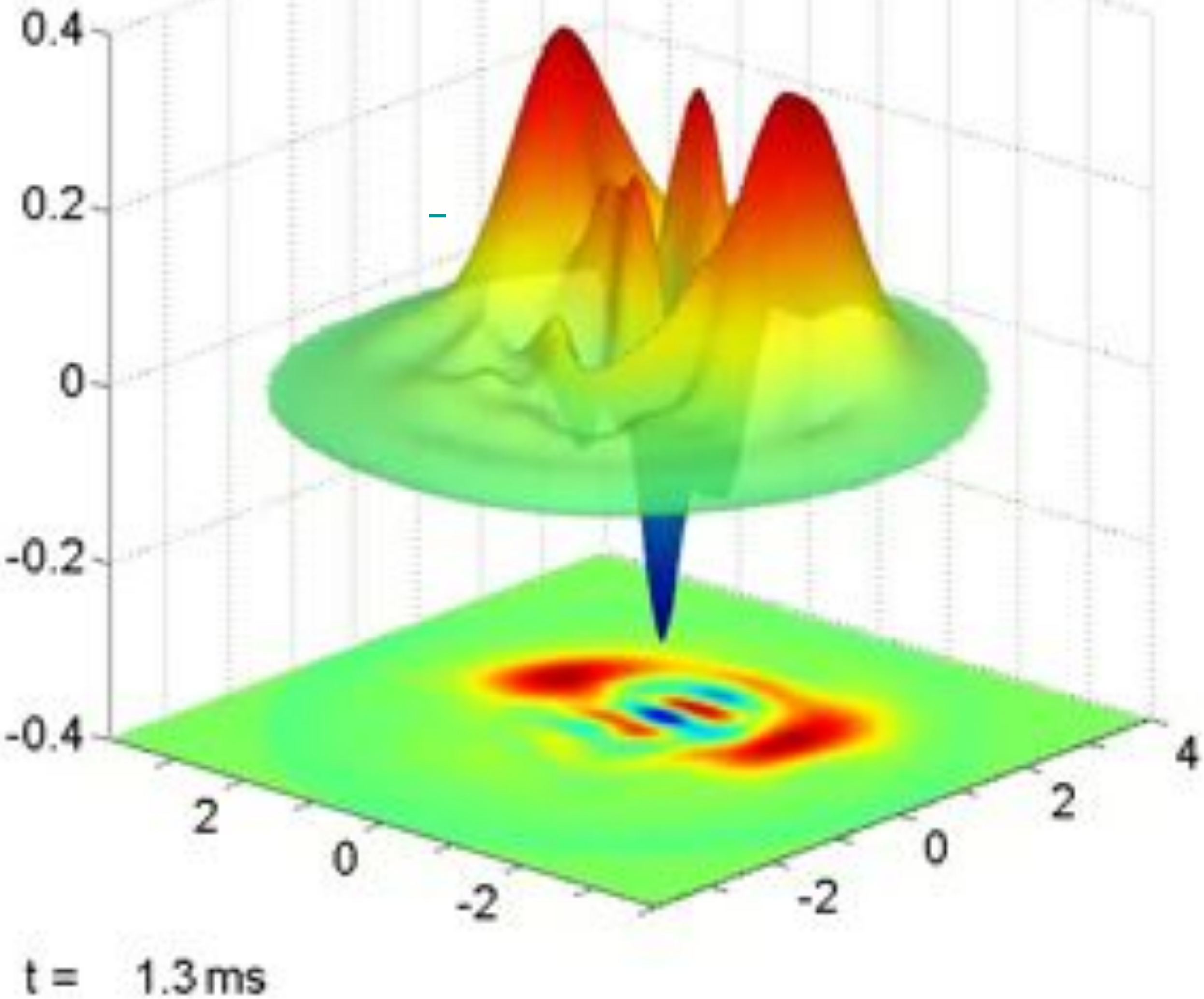
Reconstructed Wigner function of a cat

(modified version of QND measurement using sequence of atoms crossing C)



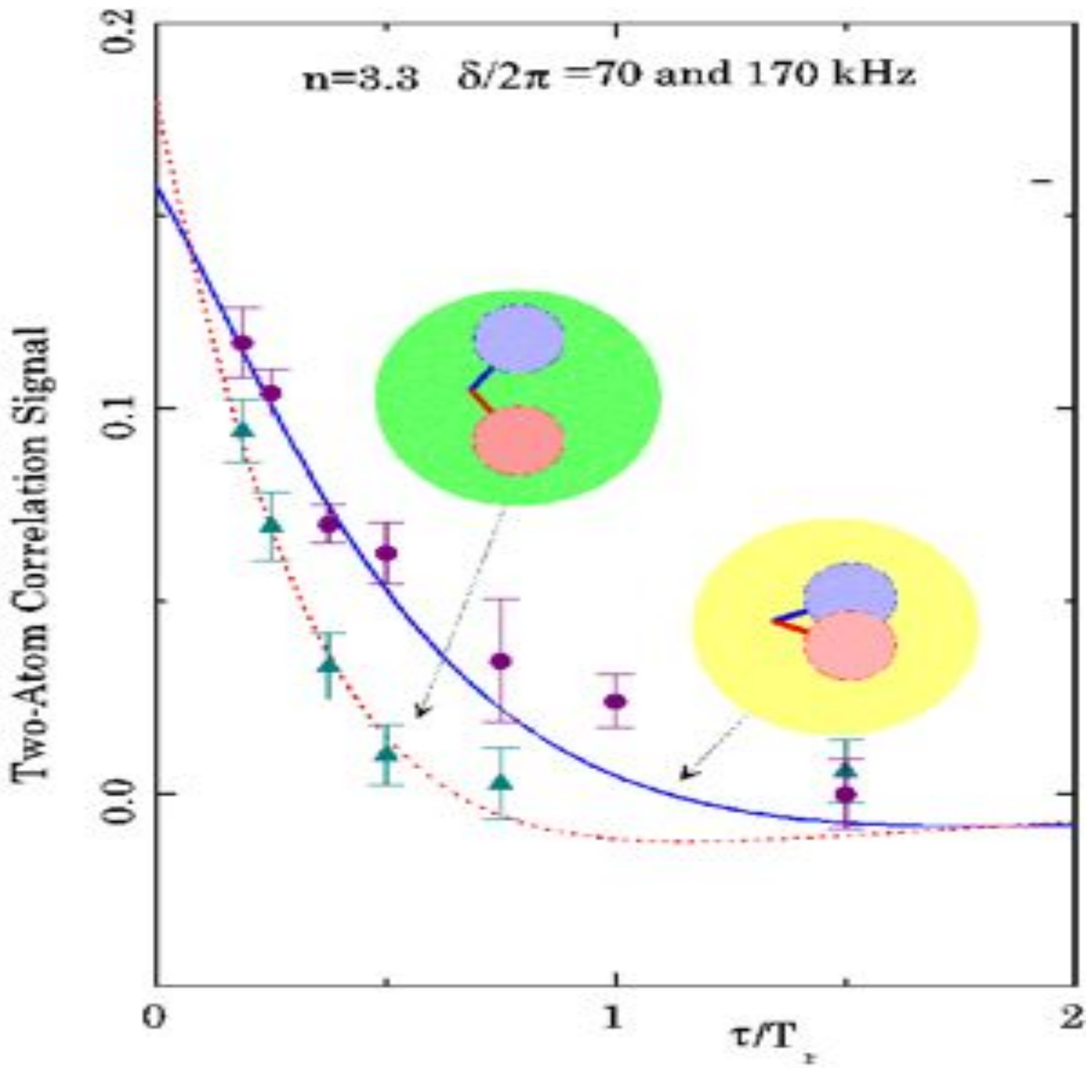
S.Deléglise et al, Nature, 455, 510 (2008)

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

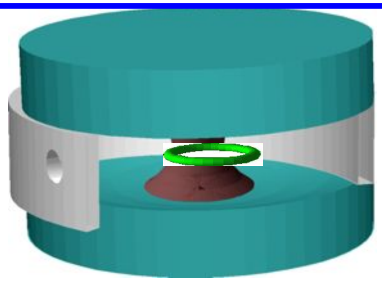


W.Zurek

Earlier version of experiment:
Brune et al, PRL,**77**, 4887 (1996)

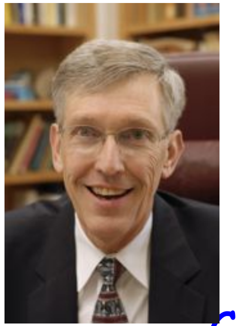


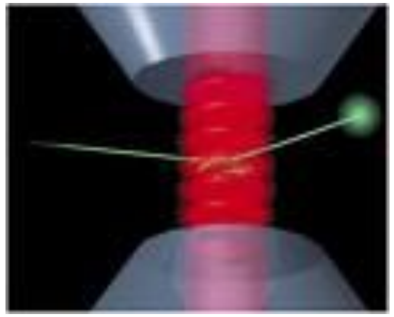
Cavity QED: coupling real or artificial atoms to a field trapped in a resonator



Rydberg atoms and microwaves in superconducting cavity (ENS)

H.Kimble,

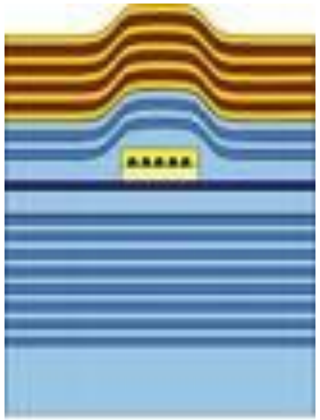




G.Rempe

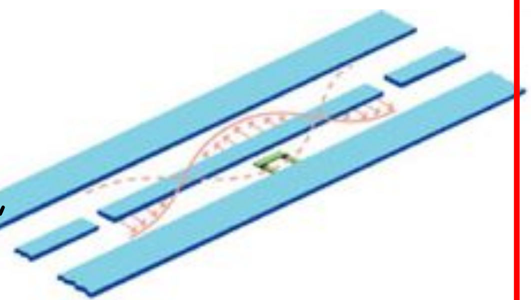
Cold atoms in optical cavities/microchips

Atoms or quantum dots coupled to optical microresonators



Quantum dots in semiconductors. Photonic bandgaps

Yale,
USBC,
Saclay,
ETH,
Chalmers,
NEC, NIST,
Delft,MIT,
Berkeley,
Grenoble,
etc...

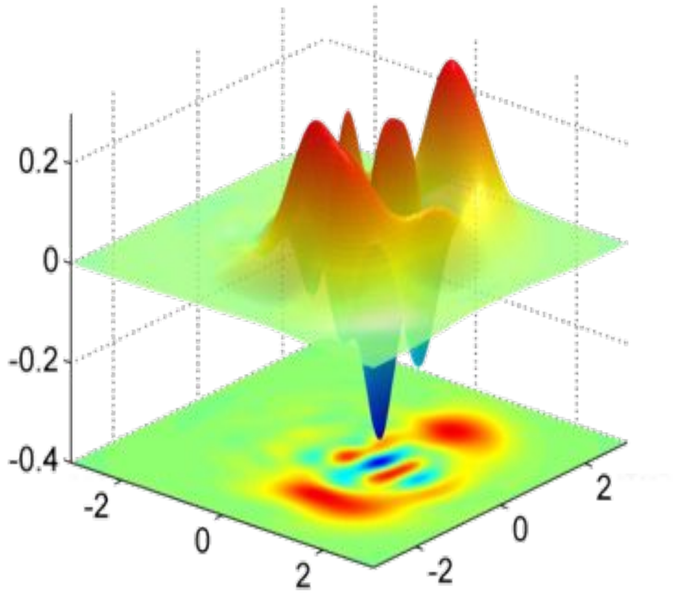


Circuit QED with Josephson junctions coupled to coplanar lines or 3D photon boxes

A zoo of Schrödinger cats

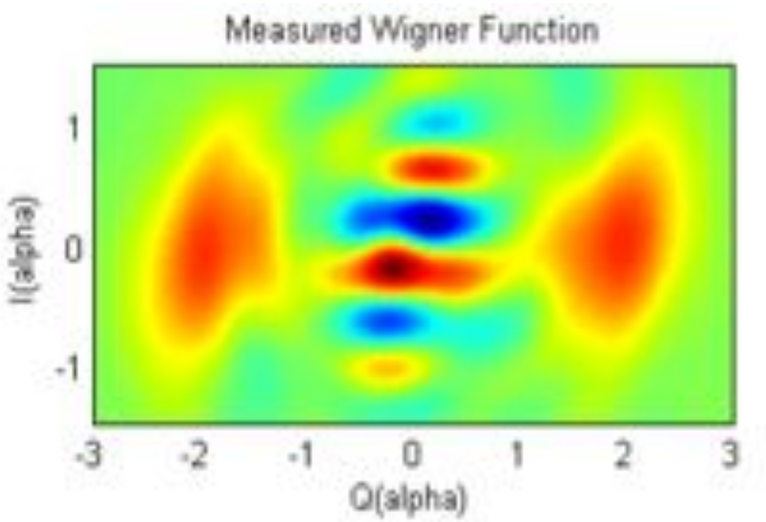
Atomic CQED

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



Schrödinger cat generated by single atom index effect

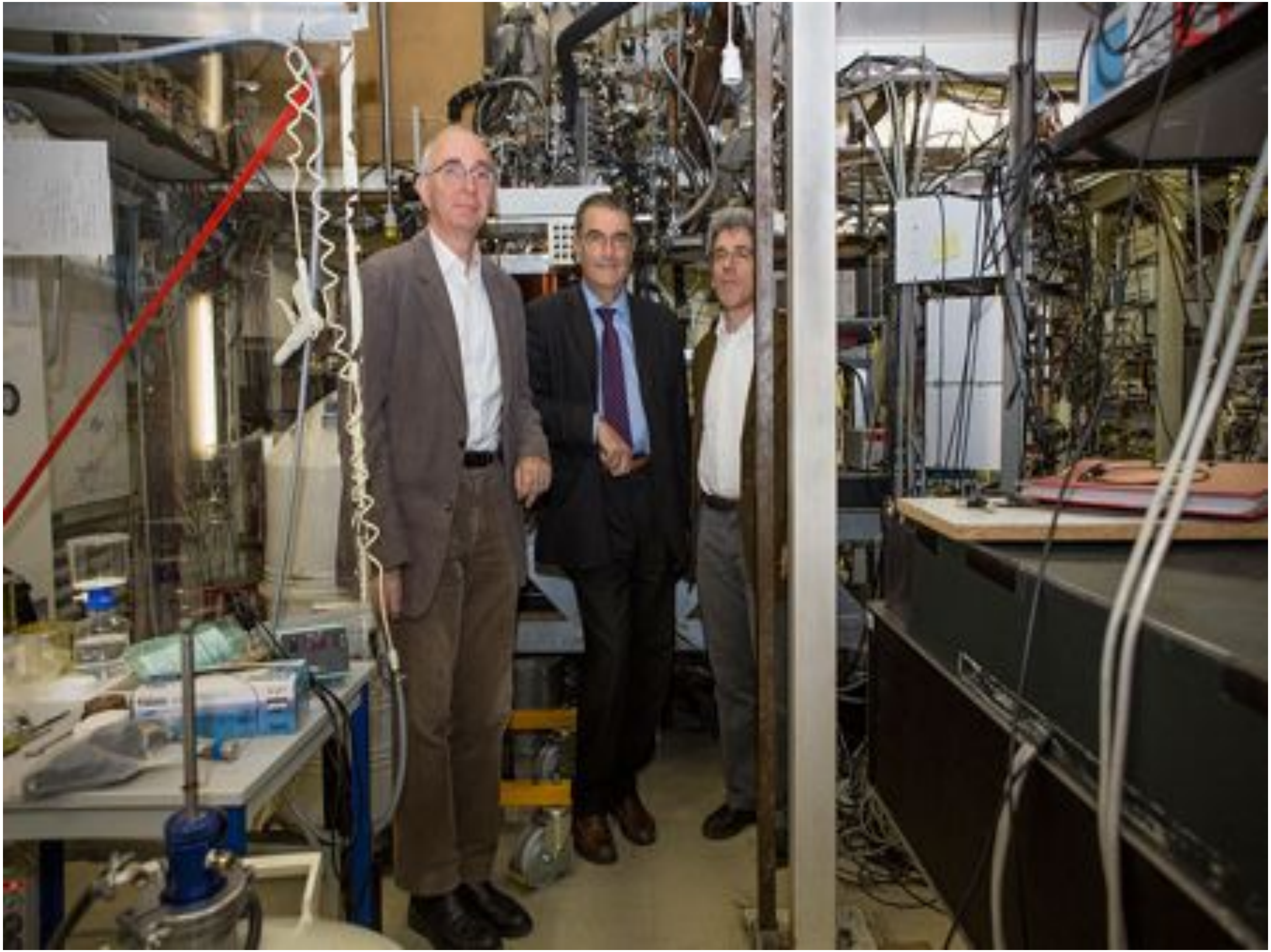
Circuit QED (Yale)



G.Kirchmair, B.Vlastakis, M.Mirrahimi, Leghtas et al, in preparation (2012)

Schrödinger cat state generated by Kerr effect

Other circuit QED cats raised at USBC (Santa Barbara)




October 10 2012
I.Dotsenko
S.Gleyzes
J-M.Raimond
M.Brune

F.Laloë — *C.Cohen-Tannoudji, Nobel 1997* — *A.Kastler, Nobel 1966* — *S.H* — *J.Brossel* — *A.Omont*