École Normale Supérieure, CNRS, Université Pierre et Marie Curie

Quantum measurement with "trapped" microwave photons in a SRF cavity

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« Ridiculous » quantum phenomena

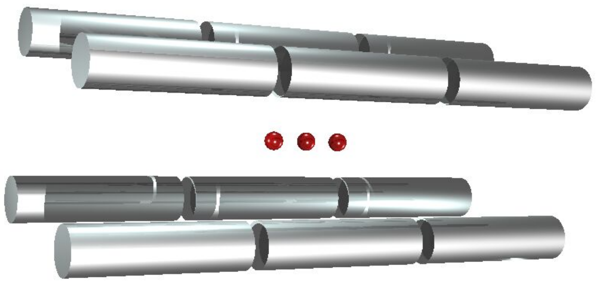
Schrödinger 1952 :

« one never experiments with just one electron, one atom or one molecule. In thought experiments we sometimes assume that we do, this invariably entails **ridiculous consequences**... »

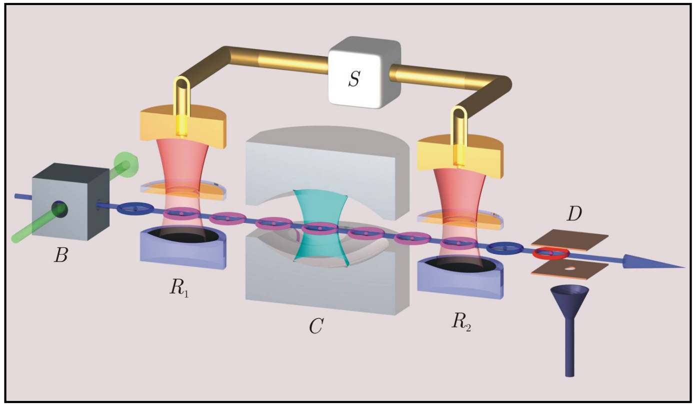
(British Journal of the Philosophy of Sciences, vol 3, 1952)

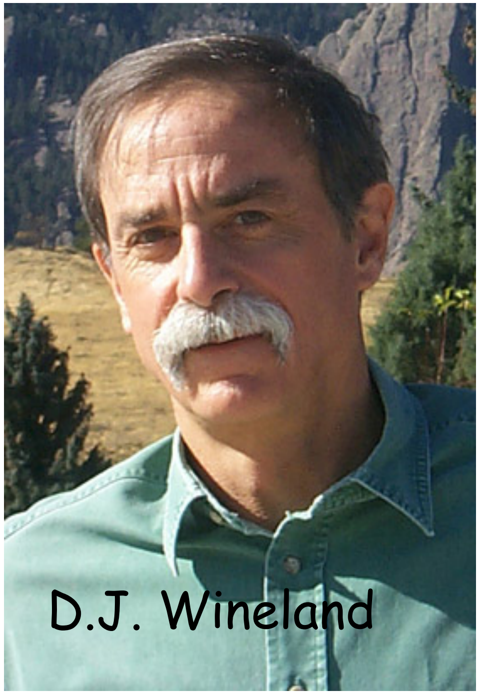
Two "spin and spring" experiments

- Ion traps

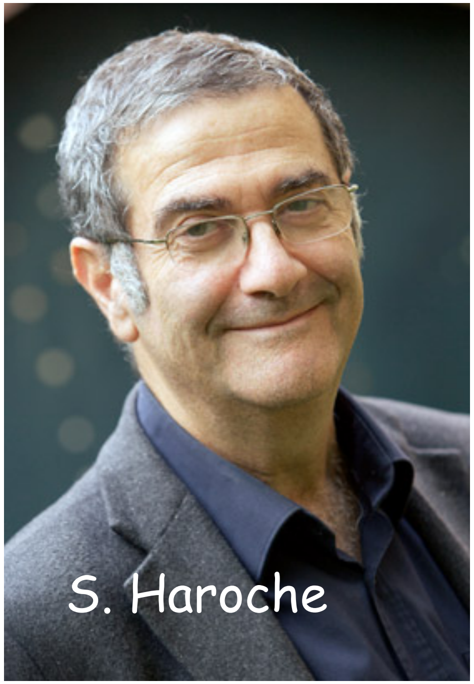


- Atoms and cavities

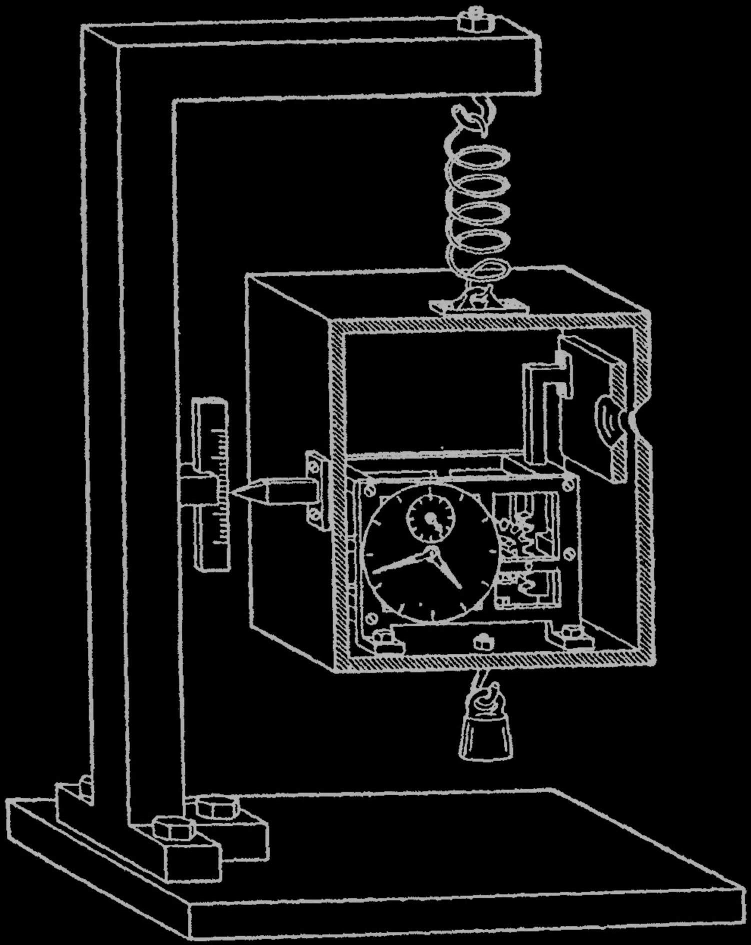




Different systems with strong similarities



The « photon box » though experiment

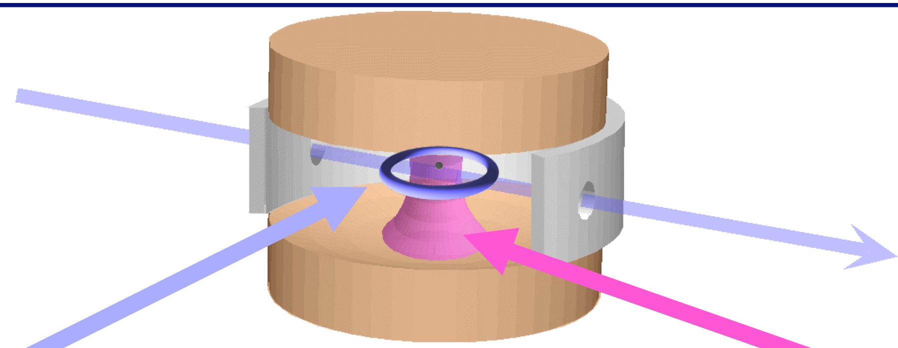


The « photon box » though experiment

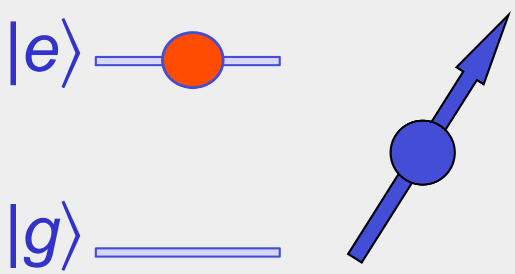
Experiments on QND counting
of trapped photons

The tools: spin and spring

A cavity QED experiment

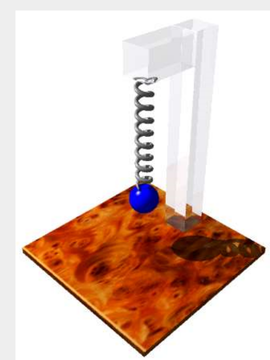


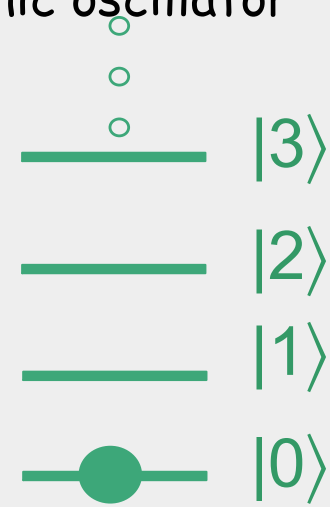
The SPIN:
One atom, two levels



Electric dipole coupling Ω_0

The SPRING:
One high Q cavity mode as an harmonic oscillator

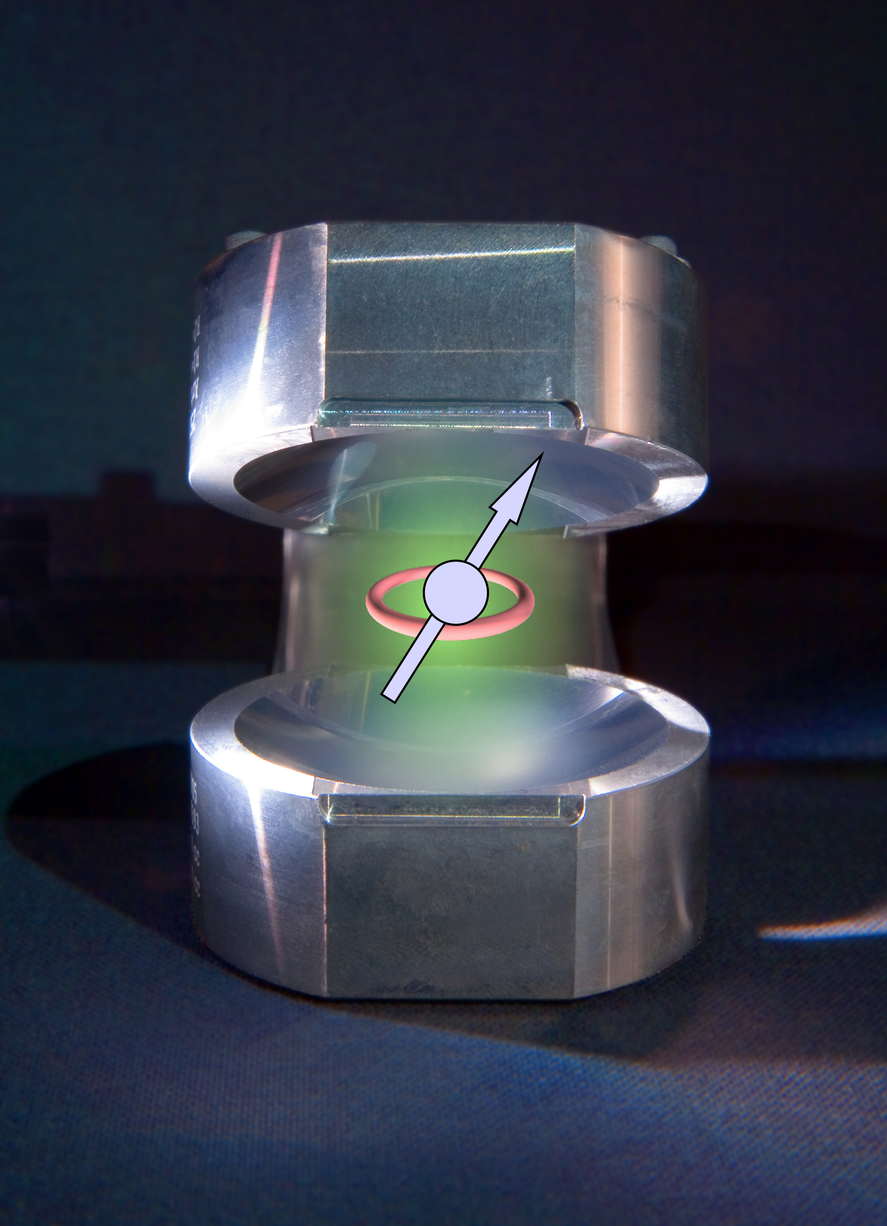




➔ Nearly ideal realization of a simple generic system

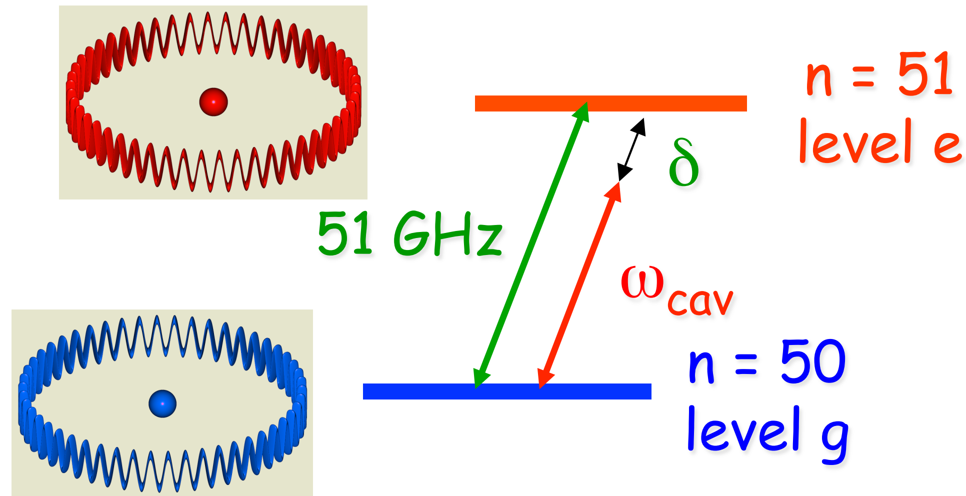
The "Spin"

- Photon box

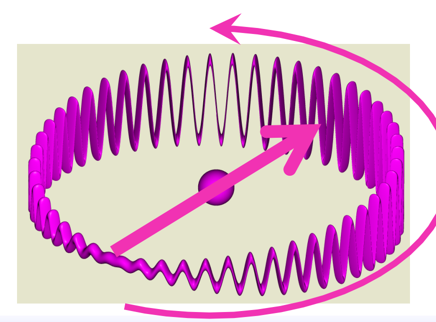


- Photon probes

Circular Rydberg atoms



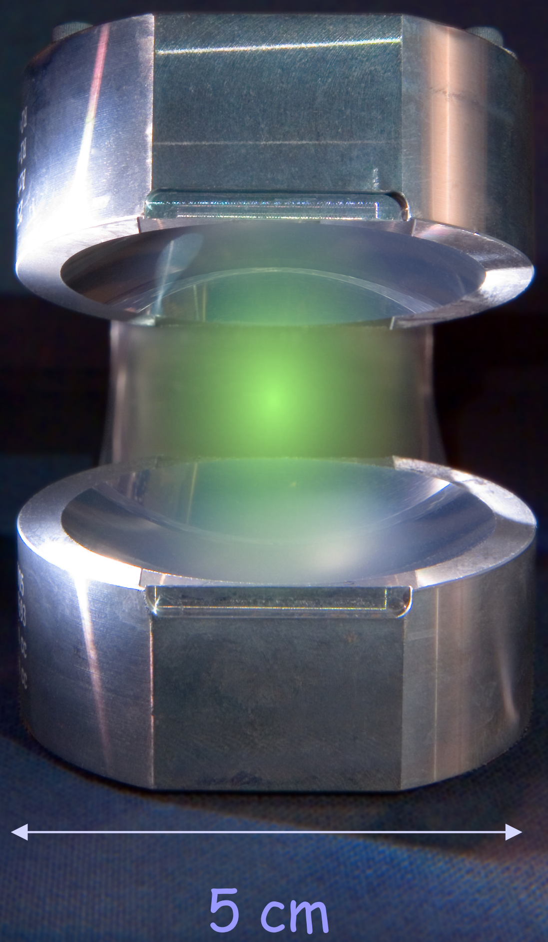
Superposition State |e>+|g>

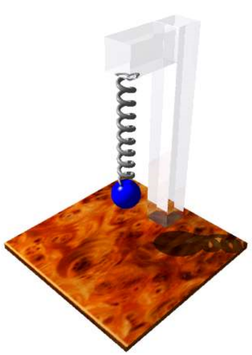


The “spring”

- Photon box

Superconducting mirors





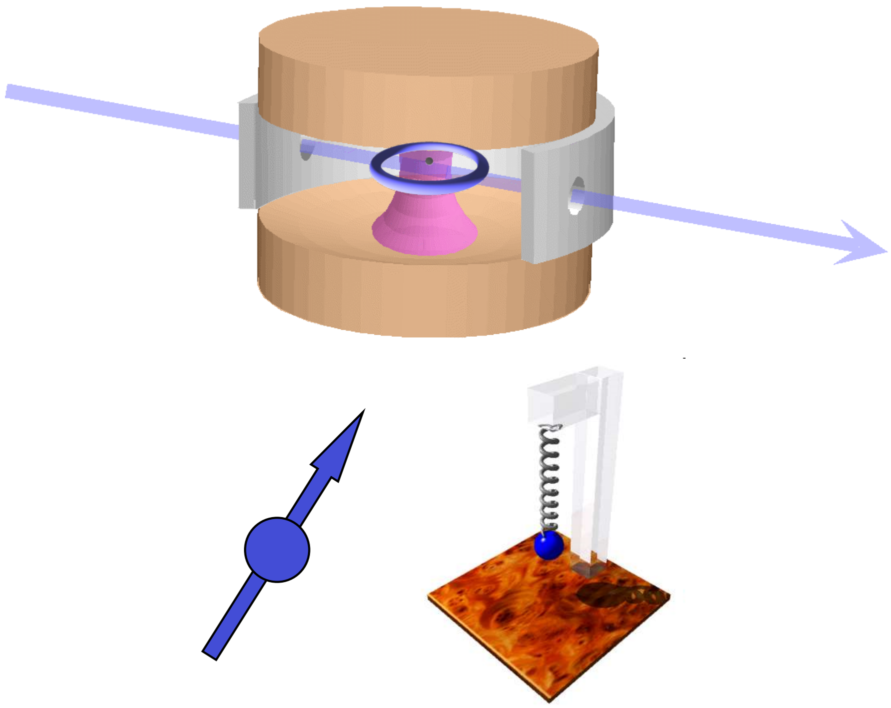
- Storing microwave photons @ ν_{cav} = 51 GHz

-Photon lifetime:

T_{cav}= from 2 μs …

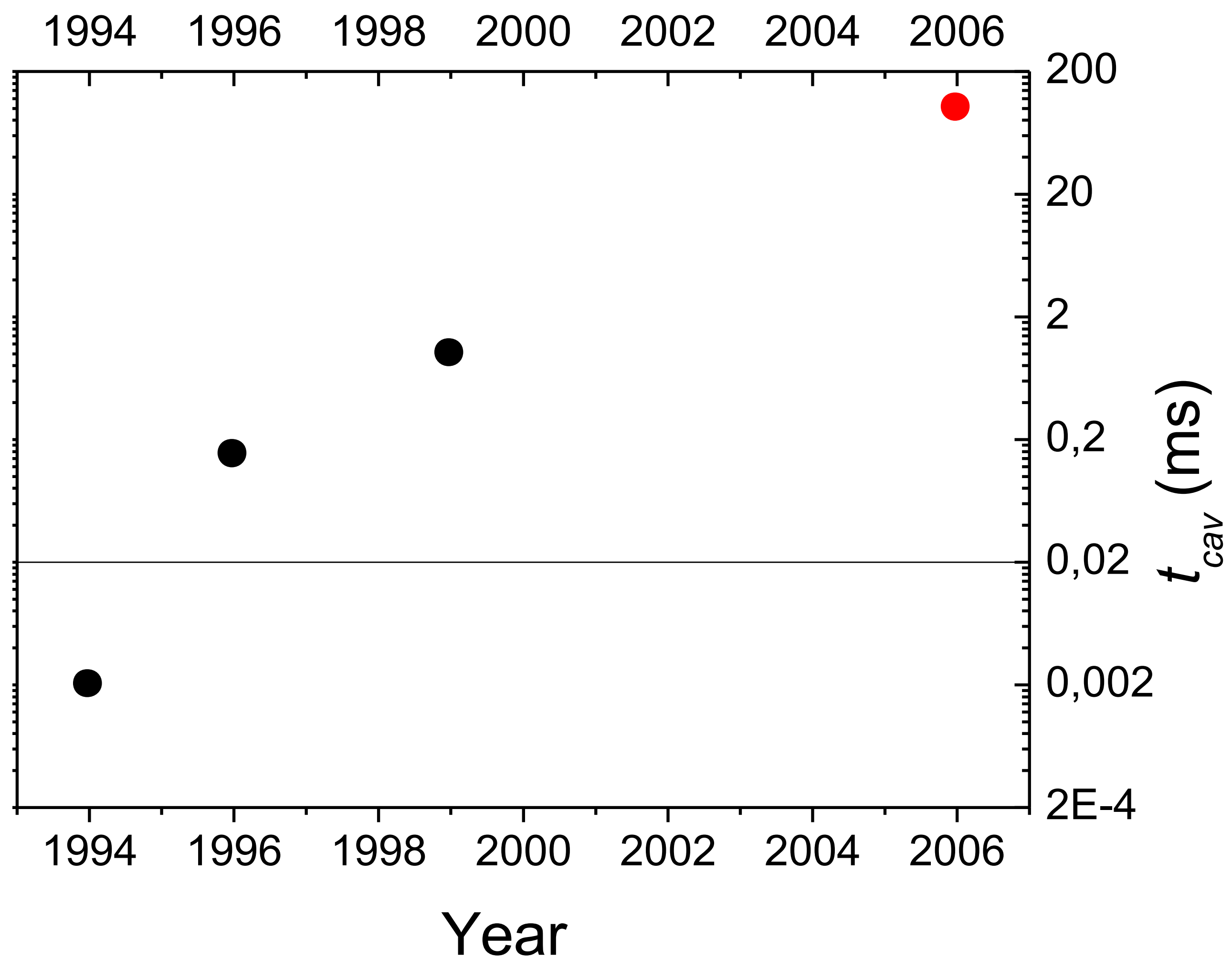
… to 0.130*s*

I. Cavity QED spin and spring: Brief history



Cavity technology

- Our version of Moore's law:



The beginning of the story …

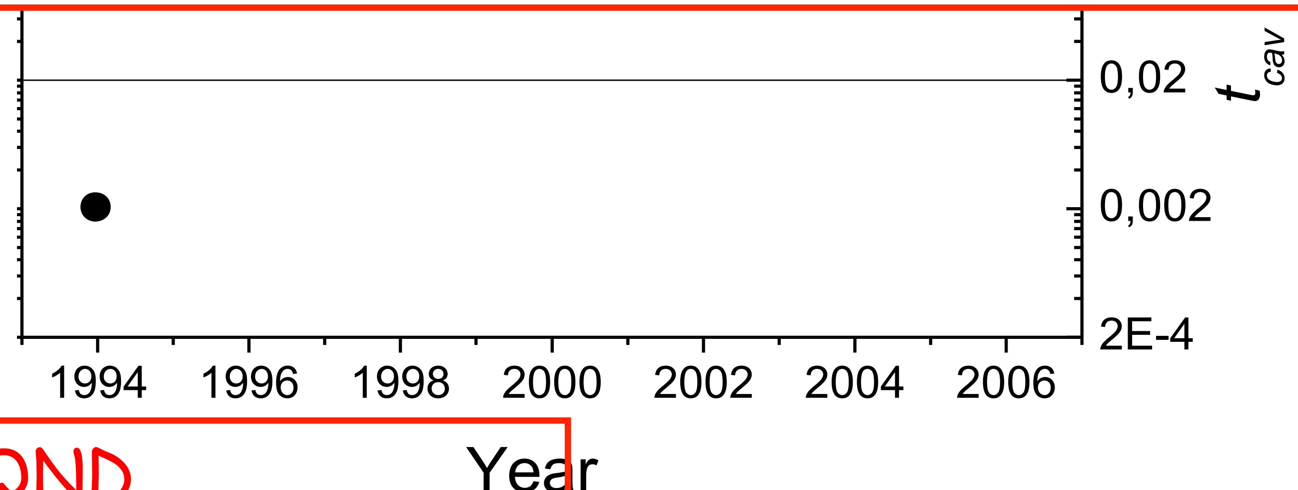
VOLUME 65, NUMBER 8 PHYSICAL REVIEW LETTERS 20 AUGUST 1990

Quantum Nondemolition Measurement of Small Photon Numbers by Rydberg-Atom Phase-Sensitive Detection

M. Brune, S. Haroche, V. Lefevre, J. M. Raimond, and N. Zagury[a]
Département de Physique de l'Ecole Normale Supérieure, Laboratoire de Spectroscopie Hertzienne, 24 rue Lhomond, F-75231 Paris CEDEX 05, France

(Received 18 April 1990)

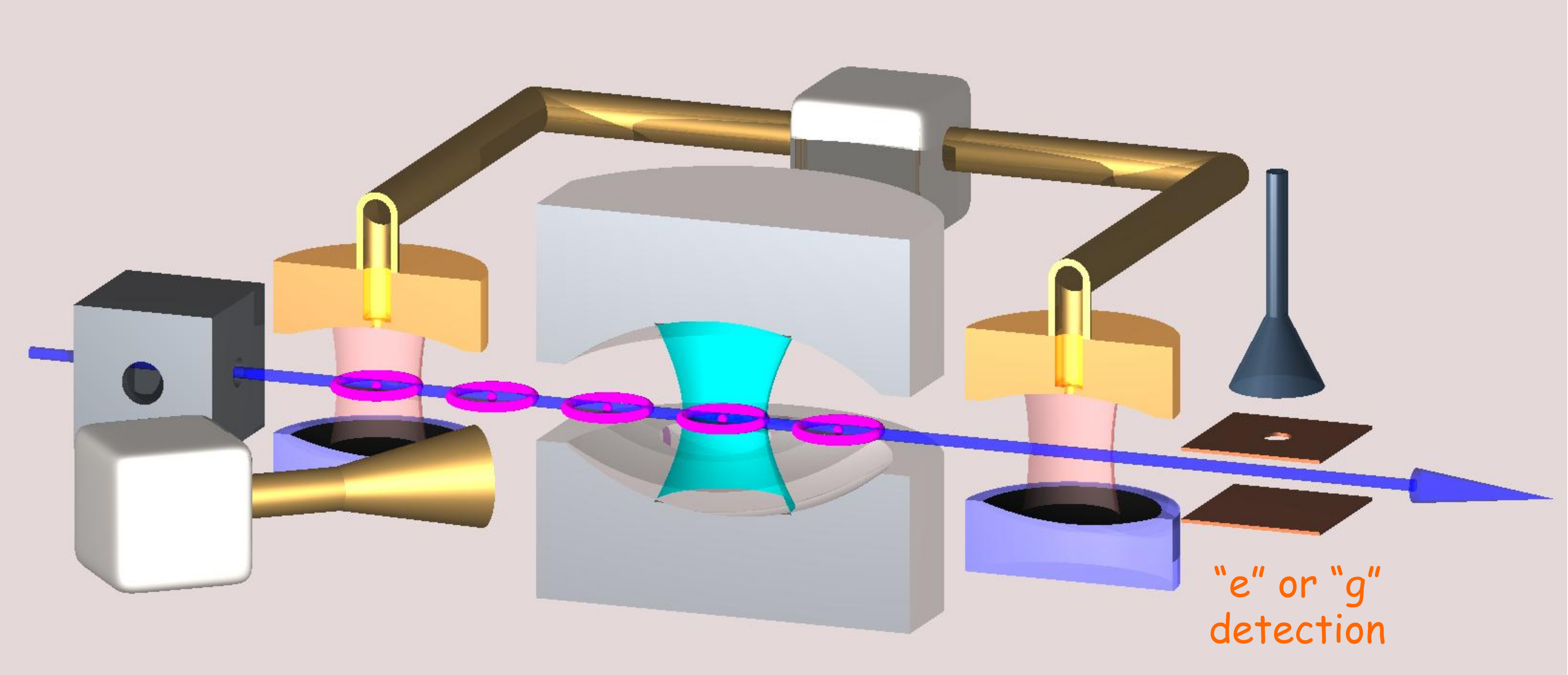
We describe a new quantum nondemolition method to monitor the number N of photons in a microwave cavity. We propose coupling the field to a quasiresonant beam of Rydberg atoms and measuring the resulting phase shift of the atom wave function by the Ramsey separated-oscillatory-fields technique. The detection of a sequence of atoms reduces the field into a Fock state. With realistic Rydberg atom-cavity systems, small-photon-number states down to $N=0$ could be prepared and continuously monitored.



1990

Initial QND measurement proposal

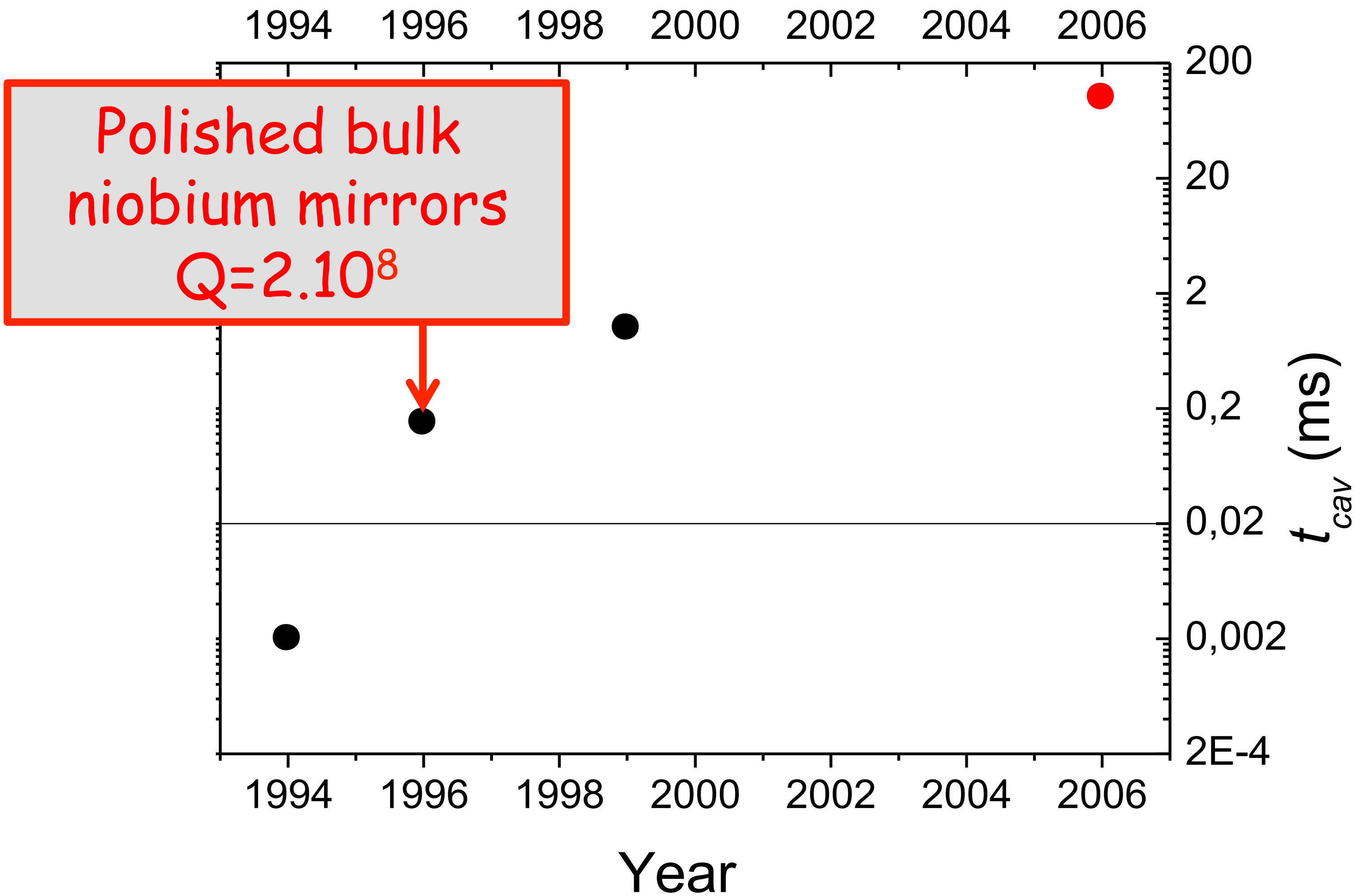
… with a simple experimental scheme



- An atomic clock (Ramsey setup) made of Rydberg for probing light-shifts induced by "trapped" photons
- State selective detection of atoms by field ionization: Atoms detected on "e" or "g" one by one

Cavity technology

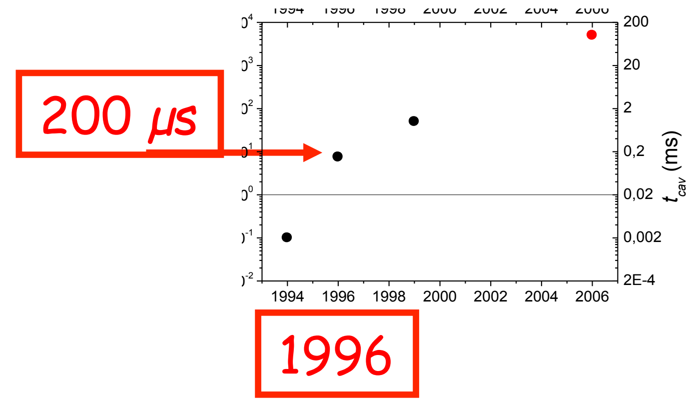
- Our version of Moore's law:

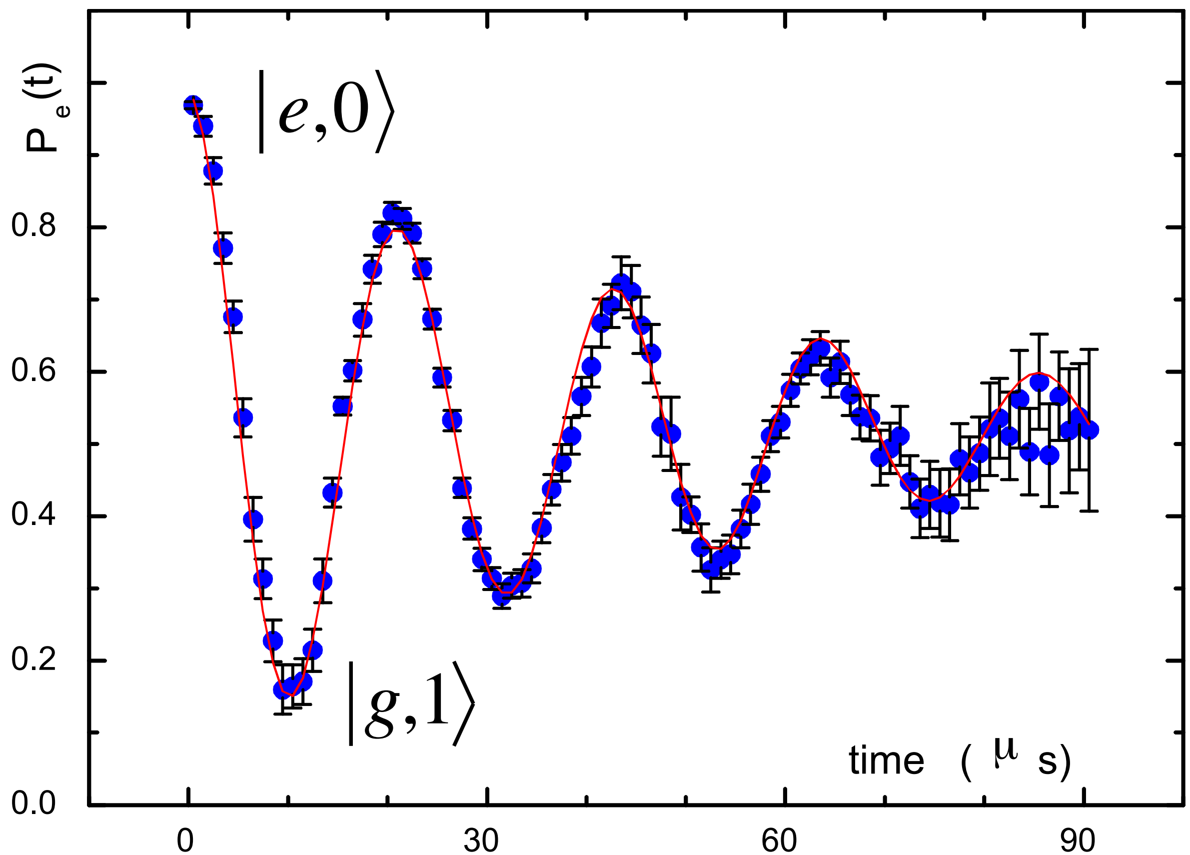


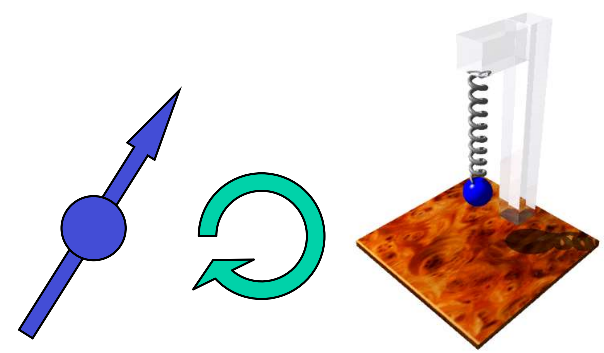
Mirrors fabrication: collaboration with H. Saffa and C. Antoine, CEA Saclay

Strong coupling: quantum Rabi oscillations

- Resonant atomic emission in an empty cavity



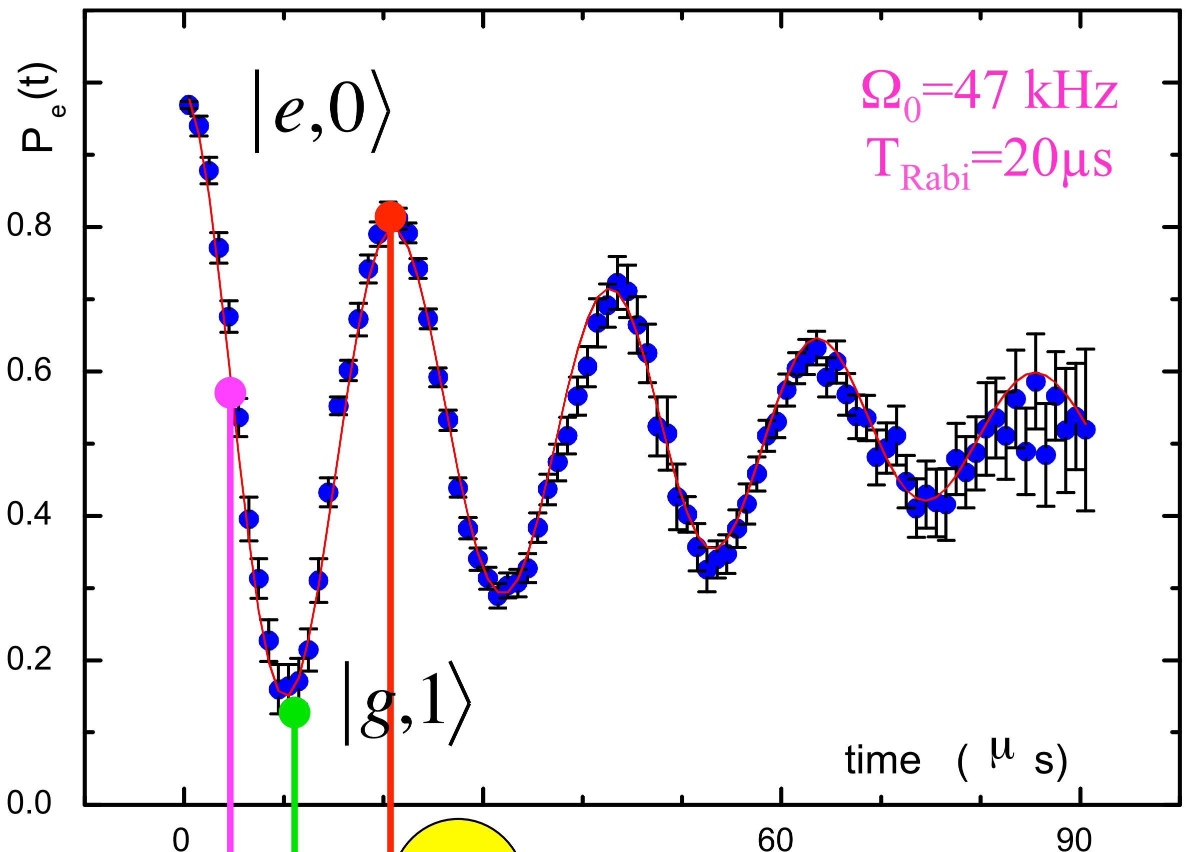


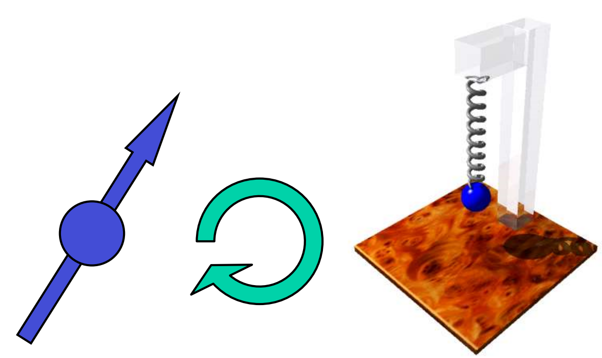


Resonant energy exchange like with coupled oscillators

*M. Brune, , F. Schmidt-Kaler, A. Maali, J. Dreyer, E. Hagley, J.M. Raimond, S. Haroche, PRL **76,** 1800 (96)*

Quantum logic operations





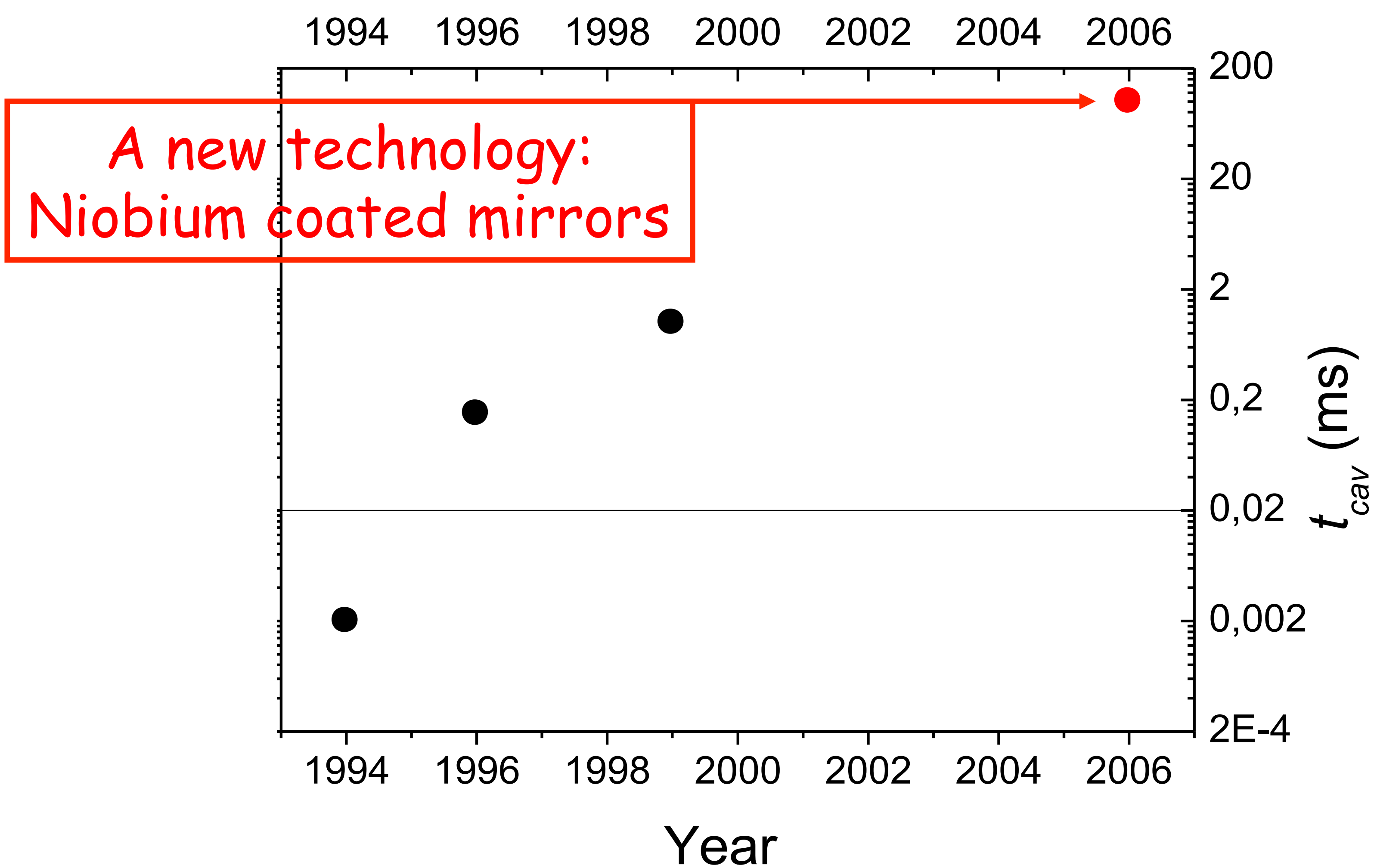
2π • Phase gate, QND detection of a single photon (but not twice)

π •Atom-field state exchange

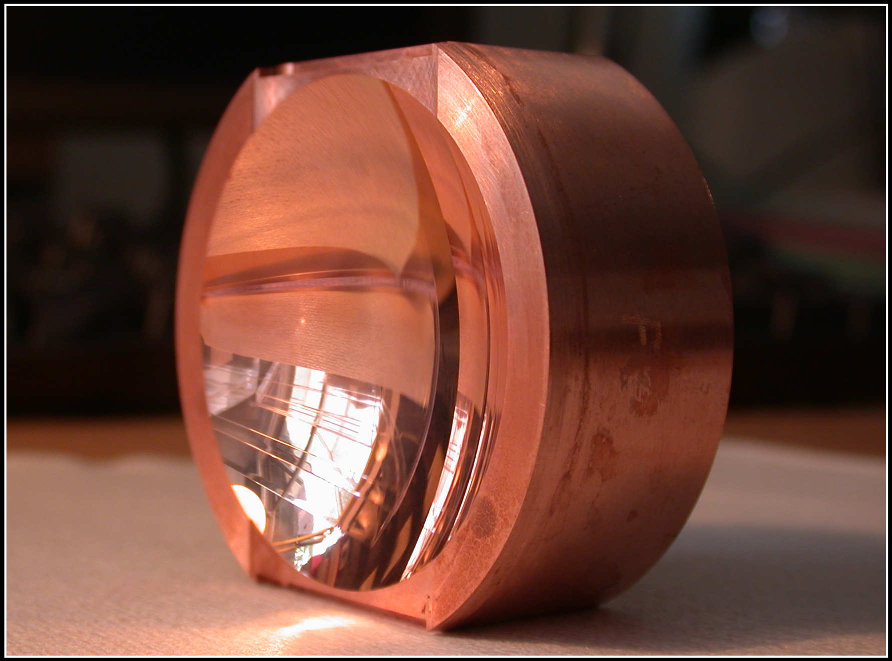
π/2 • EPR pair preparation

Cavity technology

- Our version of Moore's law:

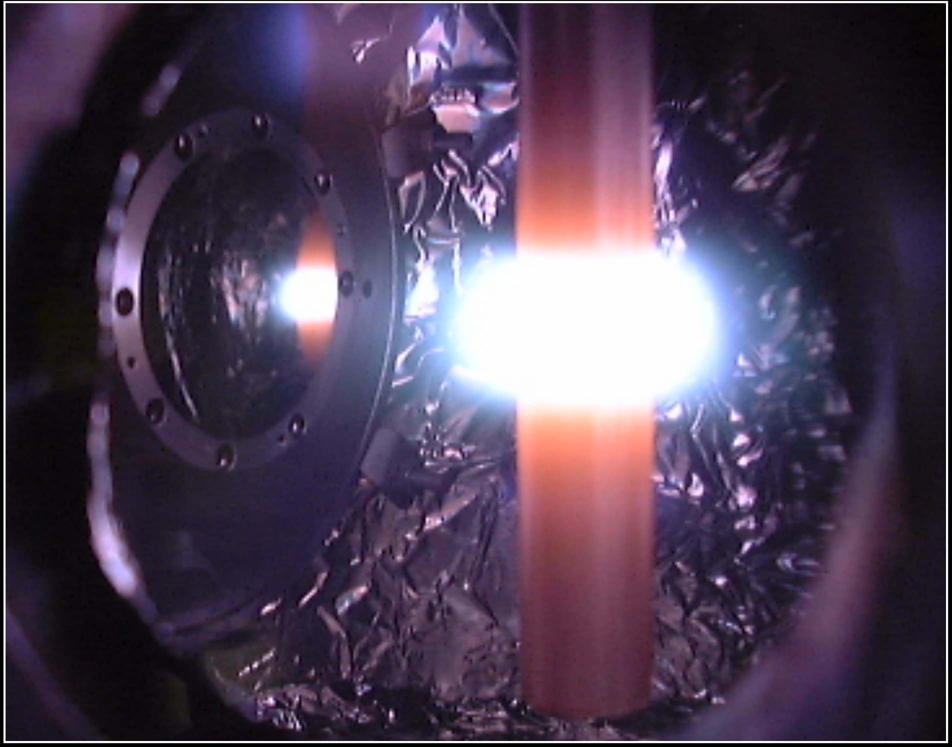


Niobium coated copper mirrors



- Copper mirrors
  - Diamond machined
    - ~1 μm ptv form accuracy
    - ~10 nm roughness
  - Toroidal ➔ single mode

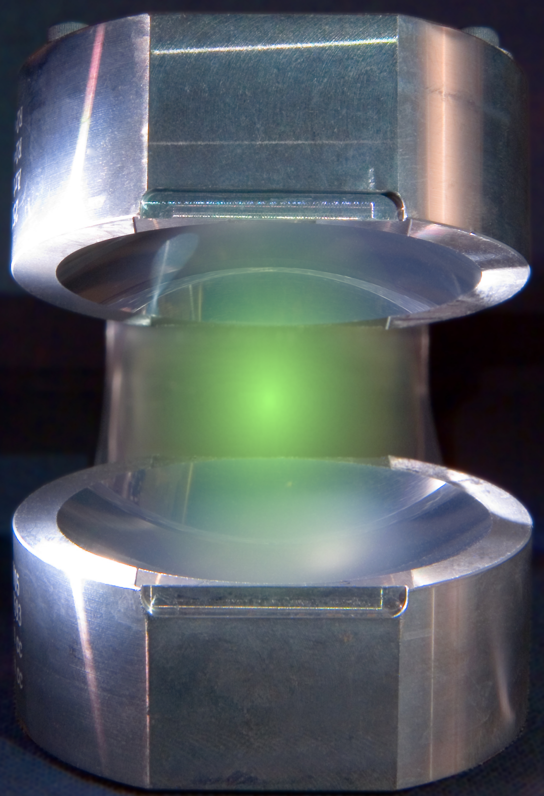
- Sputter 12 μm of Nb
  - Particles accelerator technique
  - Process done at CEA, Saclay
  - *[E. Jacques, B. Visentin, P. Bosland]*



The photon box

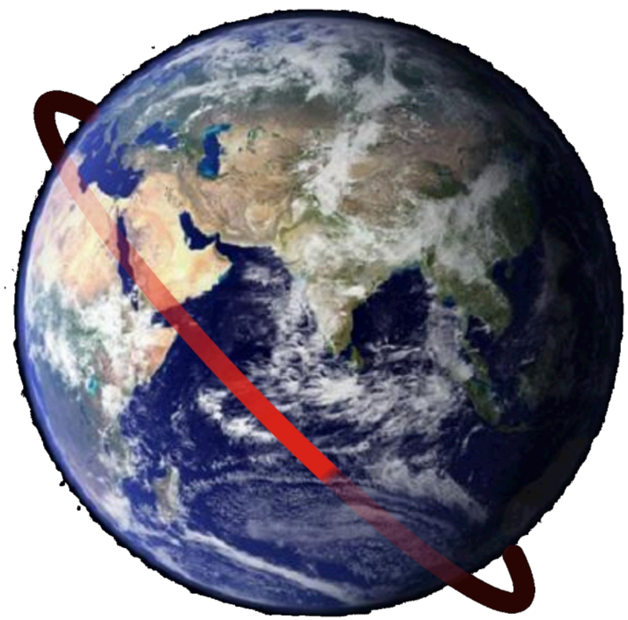
- Photon box

Superconducting cavity



$T_{\mathrm{cav}} = 130\,\mathrm{ms}$

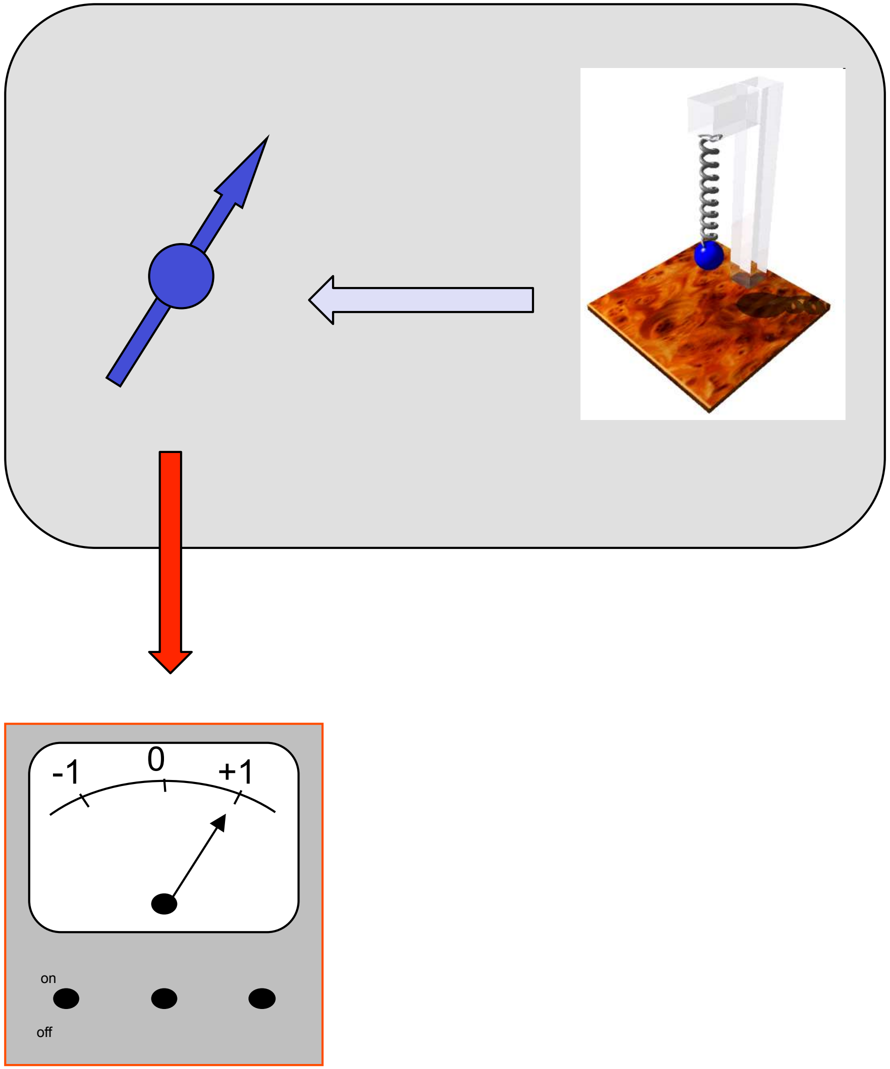
- Resonance @ $\nu_{cav} = 51$ GHz
- Q factor = $4.2 \cdot 10^{10}$
- finesse= $4.\ 10^{9}$



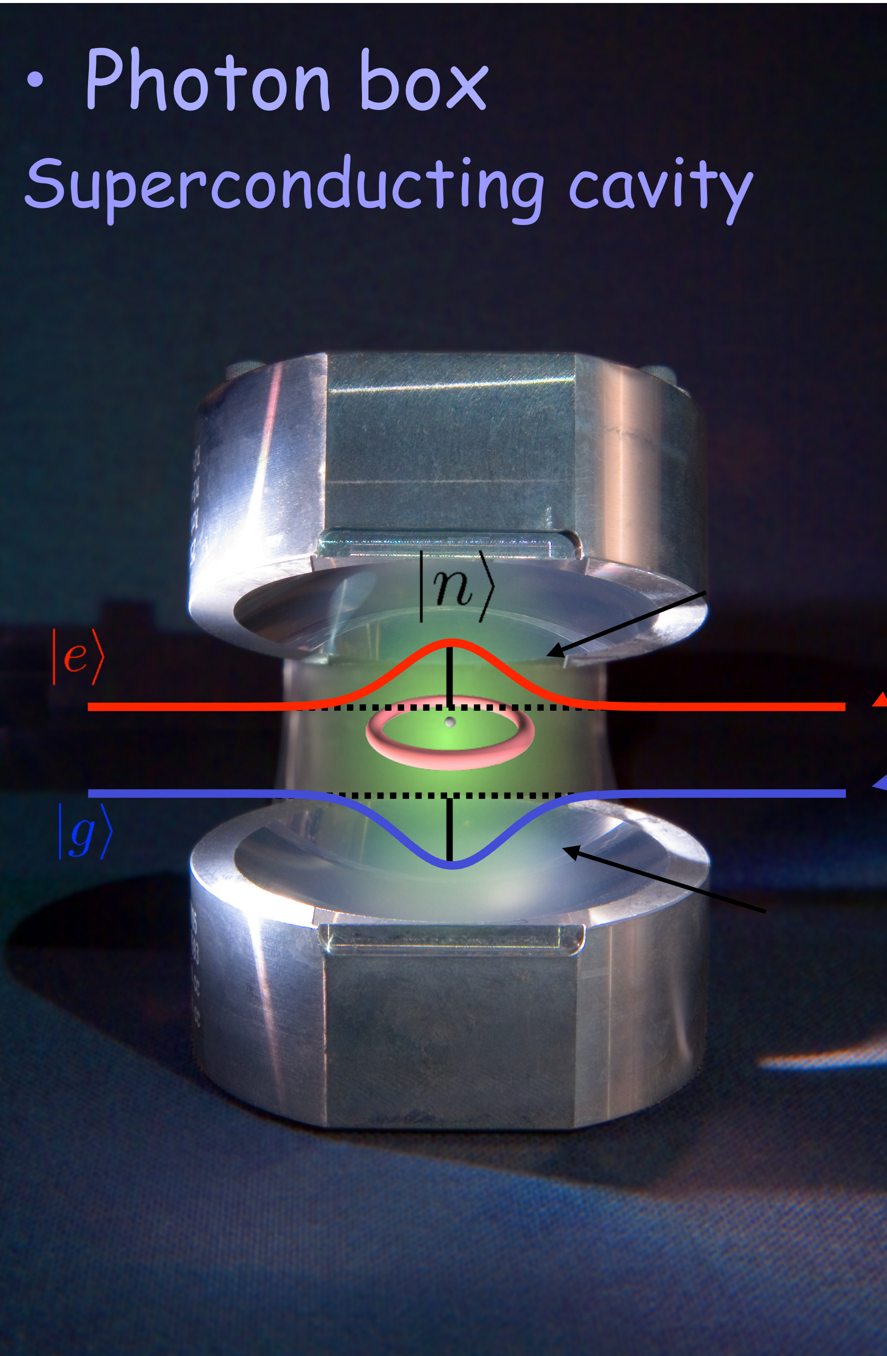
Photons running for 39 000 km in the box before dying!

II - QND photon counting in the box

Measuring the "spring" with the "spin"



QND detection of photons: the tools



• Photon probes

Circular Rydberg atoms

• Non-resonant interaction

$\Rightarrow$ light shifts

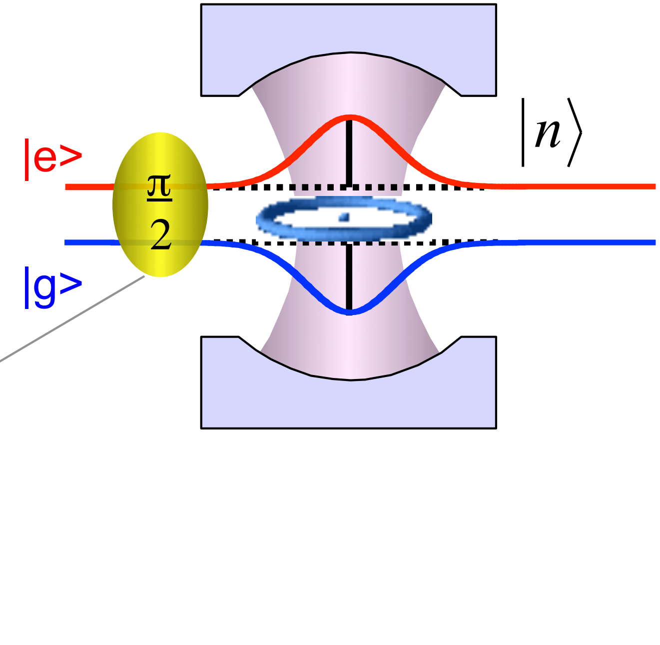
$$\Delta E_e = \hbar \frac{\Omega_0^2}{4\delta}(n+1)$$

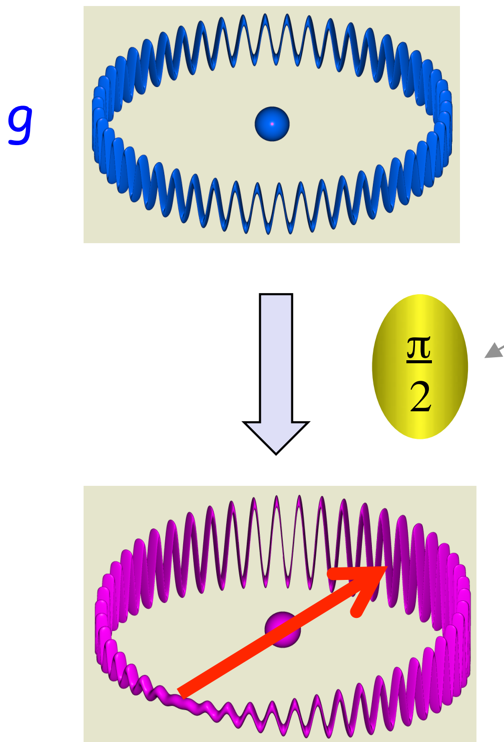
$$\Delta E_g = -\hbar \frac{\Omega_0^2}{4\delta} n$$

Atoms used as clock for counting n by measuring light shifts

Detecting 0 or 1 photon

1. Trigger of the clock.

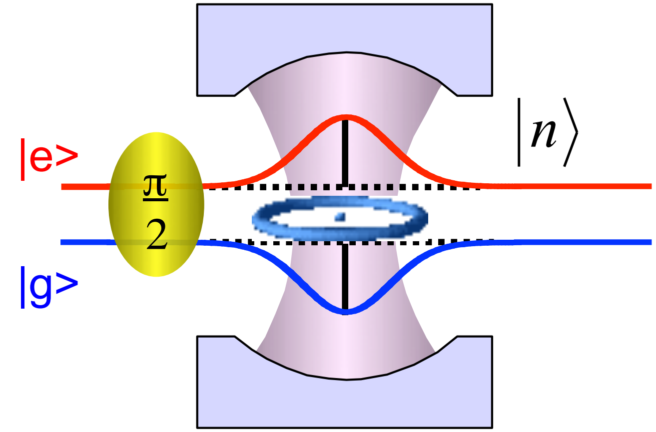


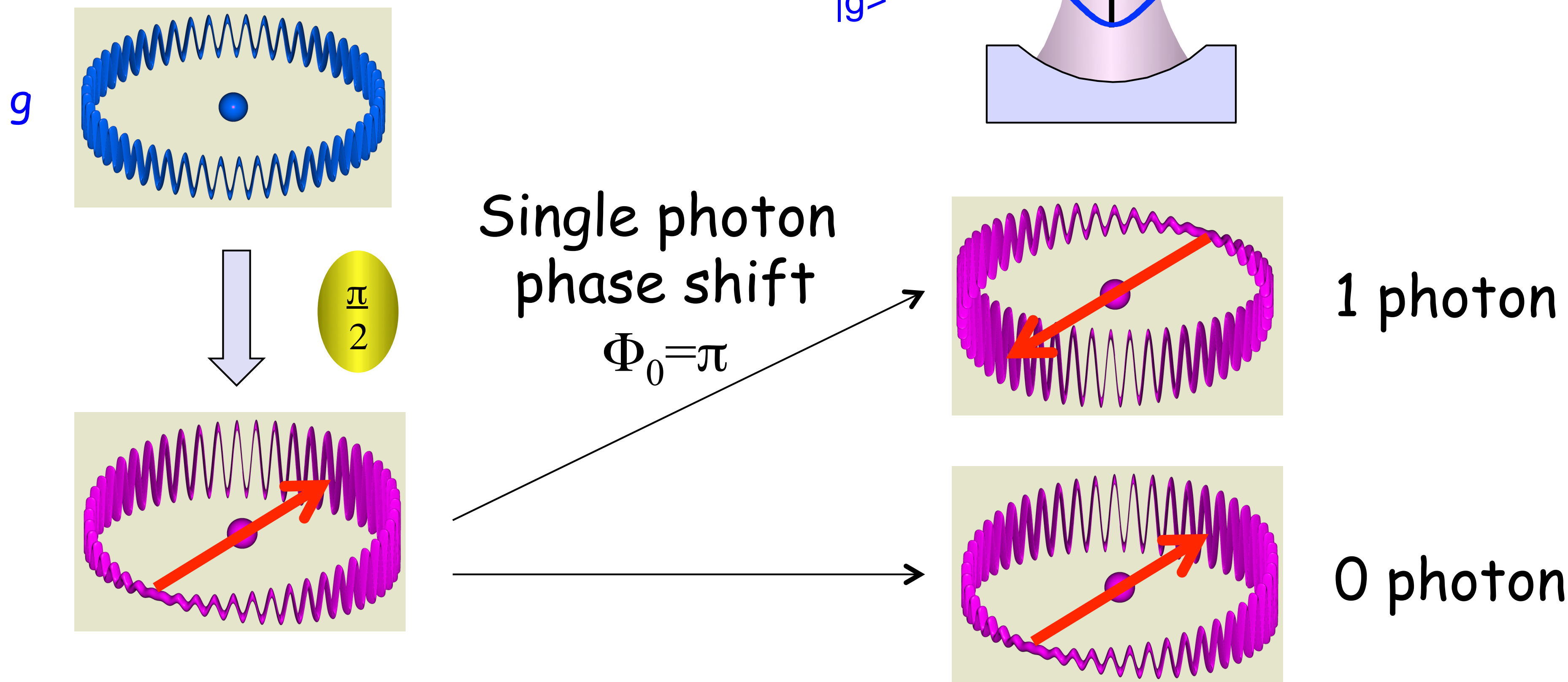


The π/2 pulse prepares a superposition states of “e” and “g”. This corresponds to an induced atomic dipole oscillating at the atomic frequency.

Detecting 0 or 1 photon

1. Trigger of the clock.
2. Let the dipole precess

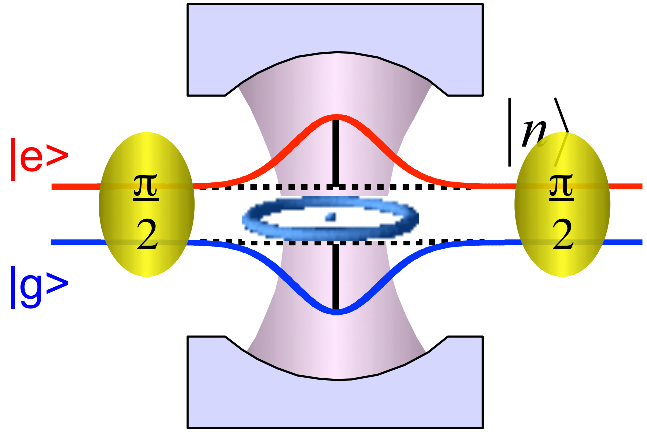


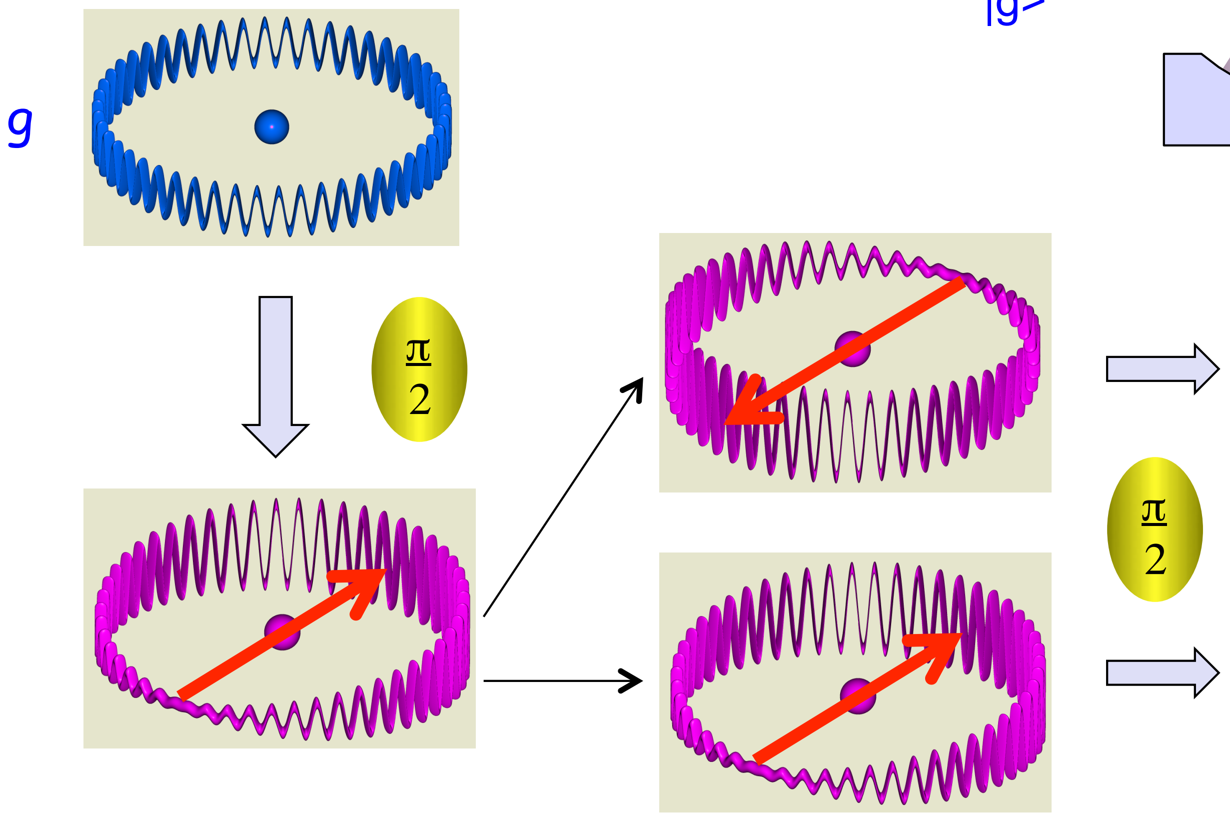


Due to "light-shifts", dispersive interaction with the cavity delays the dipole oscillation.

Detecting 0 or 1 photon

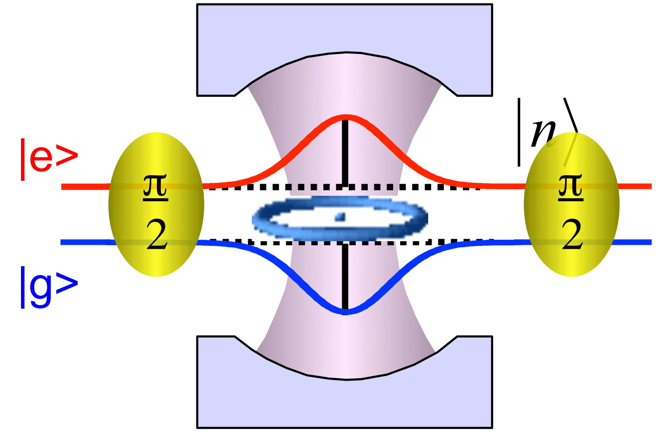
1. Trigger of the clock.
2. Let the dipole precess
3. Detect the atom

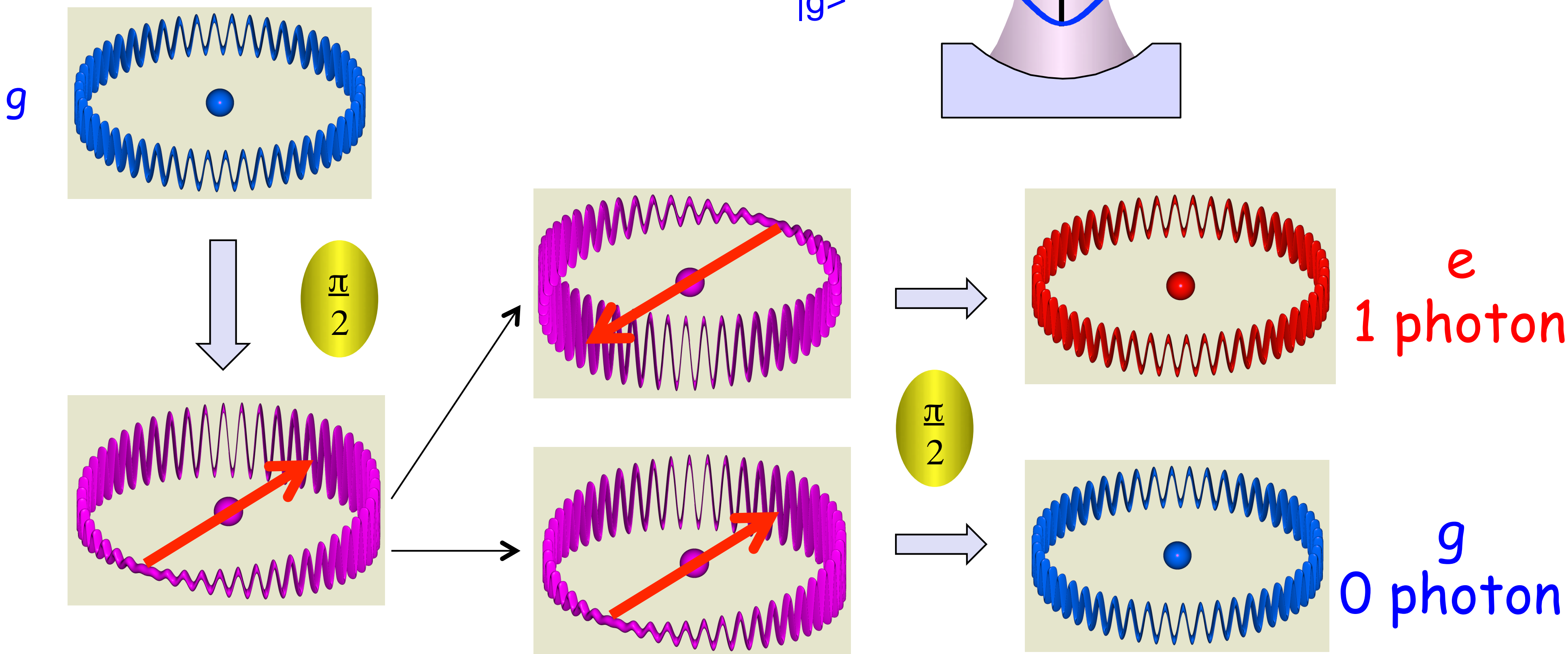




Detecting 0 or 1 photon

1. Trigger of the clock.
2. Let the dipole precess
3. Detect the atom



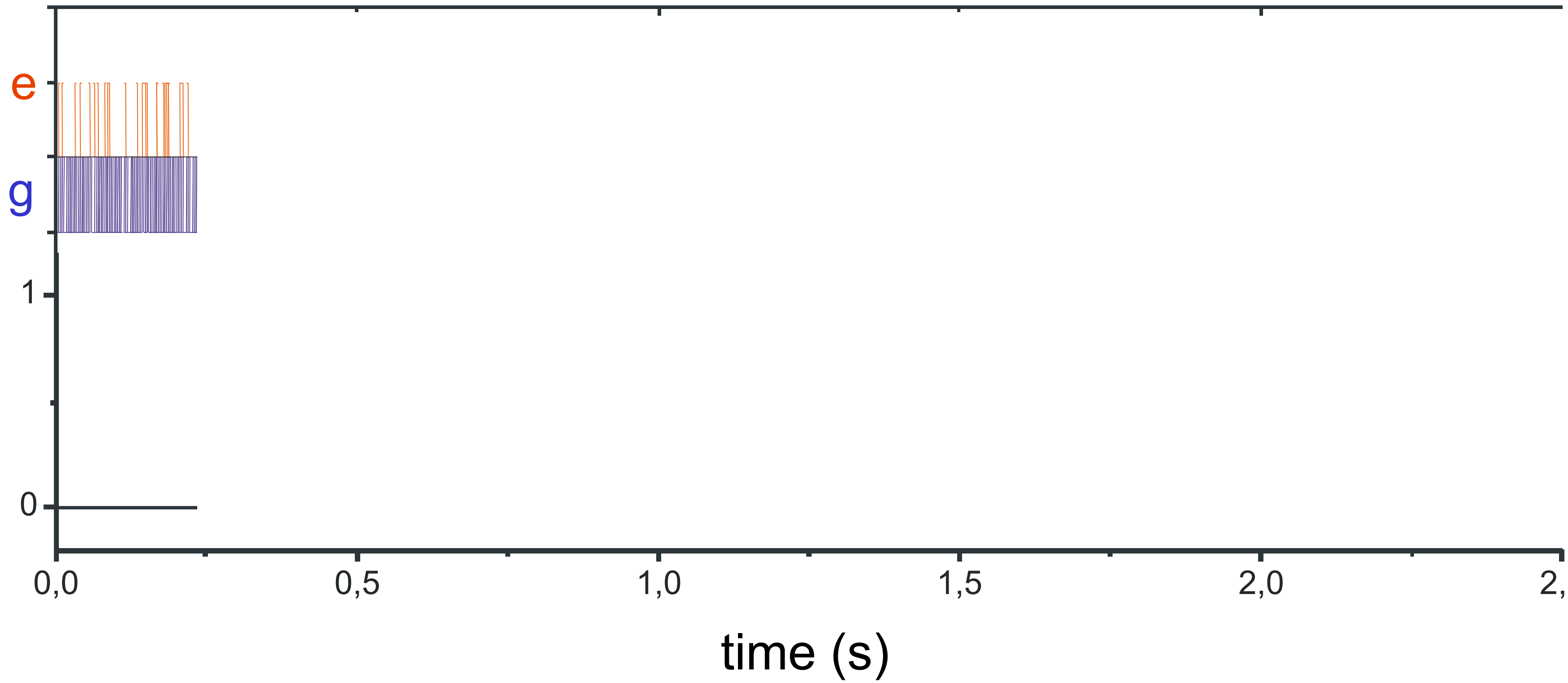


Second π/2 pulse converts phase information into atomic energy state

Detecting blackbody photons

g ➡ field projected on |0>

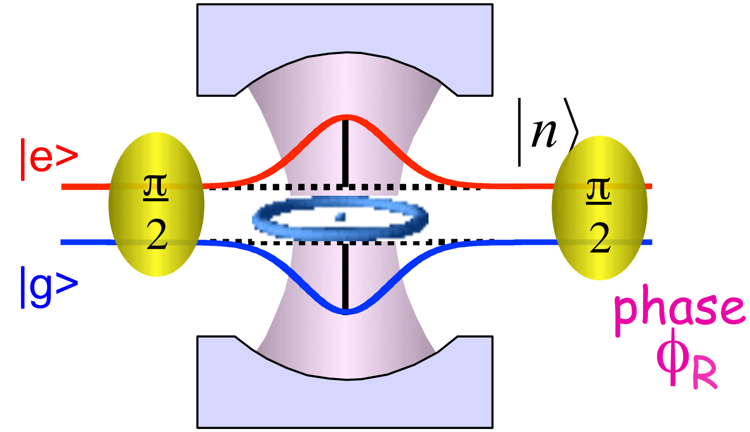
e ➡ field projected on |1>

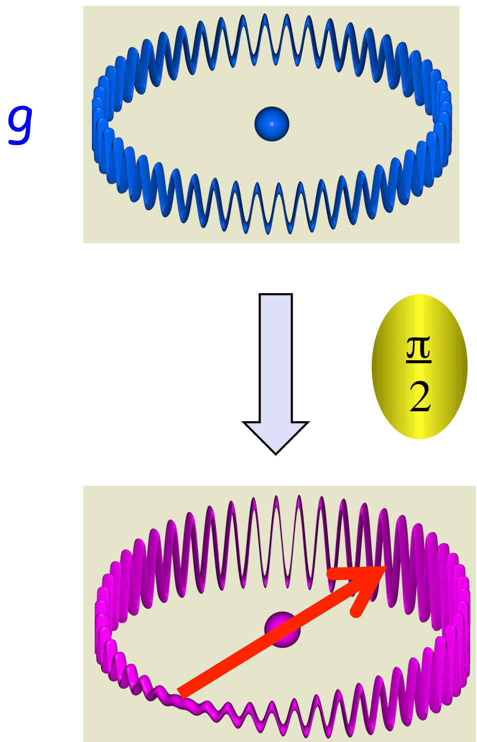


$T = 0.8\ \mathrm{K} \rightarrow n_{th} = 0.05$ (proba. of n=2 is negligible)

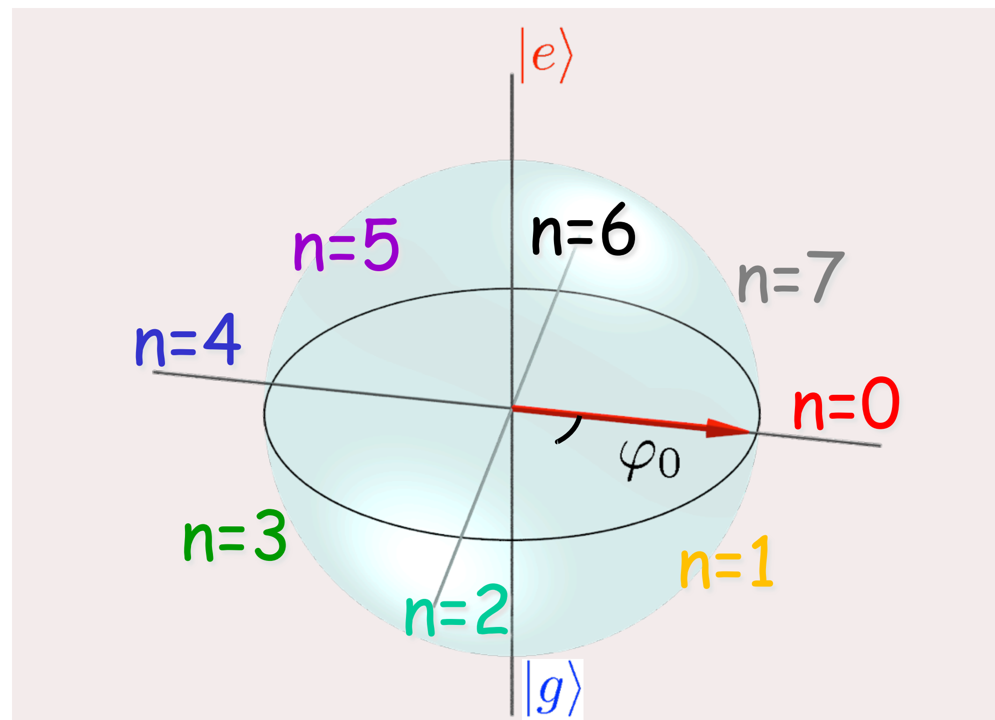
*S. Gleyzes, S. Kuhr, C. Guerlin, J. Bernu, S. Deléglise, U. Busk Hoff, M. Brune, J.M. R, S. H., Nature **446**, 297 (07)*

"Seeing" more photons





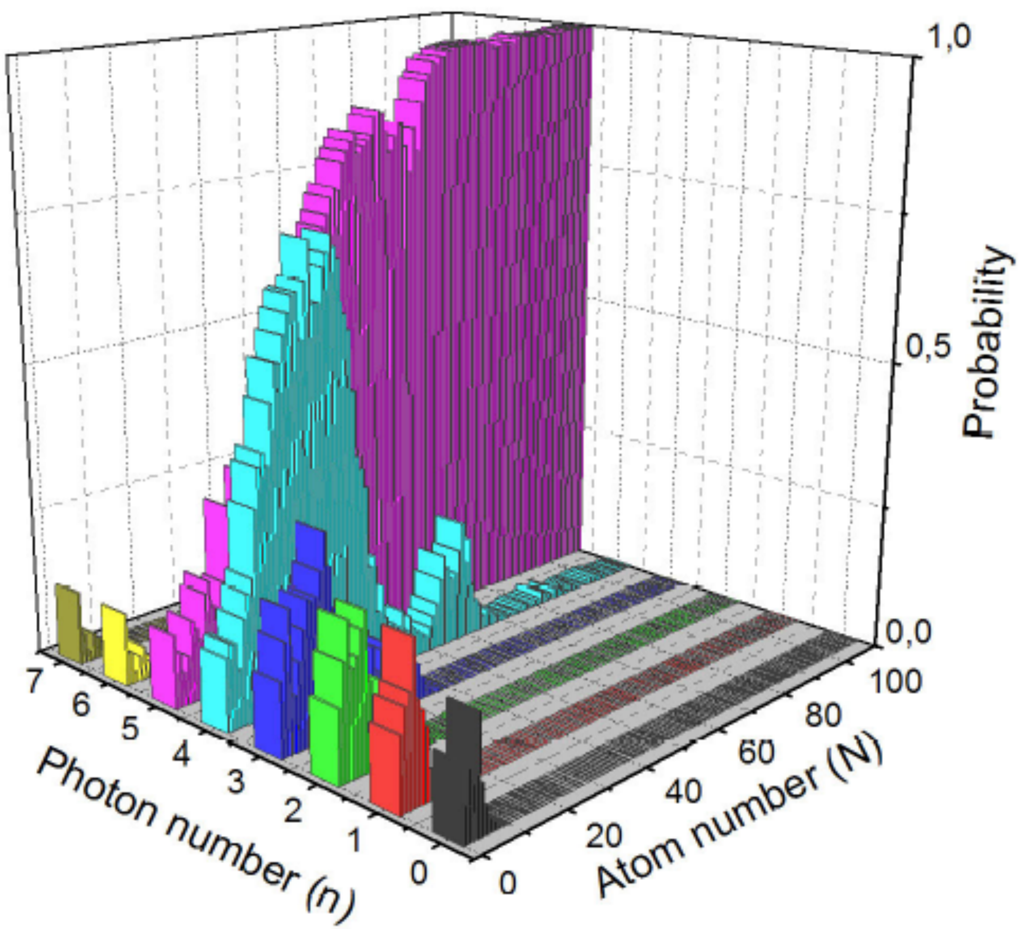
$$\Phi_0 = \pi/4$$



Depending on the photon number, the atomic dipole is the hand of a clock which can point in 7 different direction.

Atom by atom analysis of the measurement process

For each detected atom, one projects the field state according to the measurement result e or g



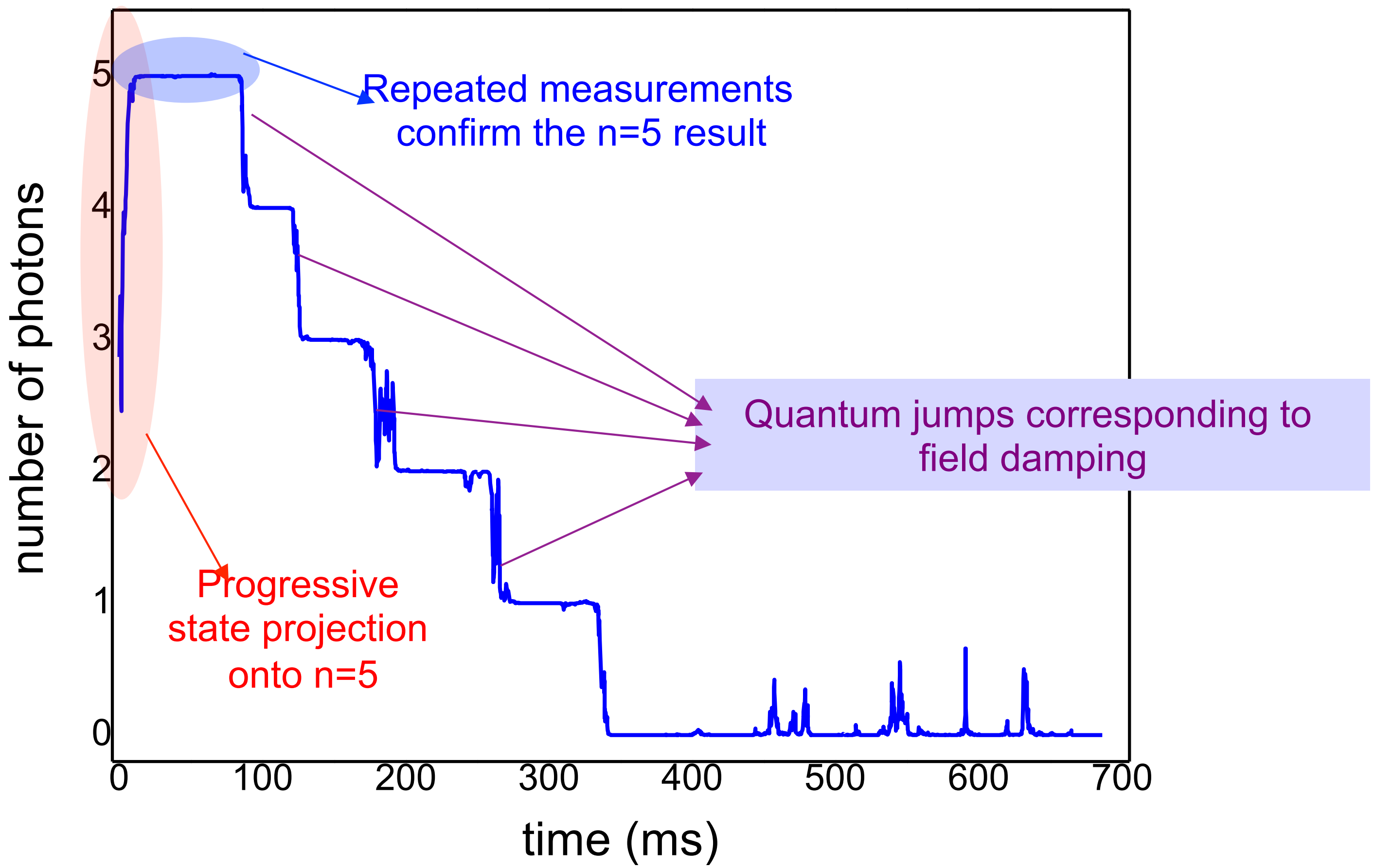
Measurement of a coherent field <n>=3.7 (±0.008)

Progressive collapse of the field state on n=5

Initial knowledge of the photon number distribution is not needed

C. Guerlin, J. Bernu, S. Deléglise, C. Sayrin, S. Gleyzes, S. Kuhr, M. Brune, J.M. R., S. H. Nature ***448****, 889 (07)*

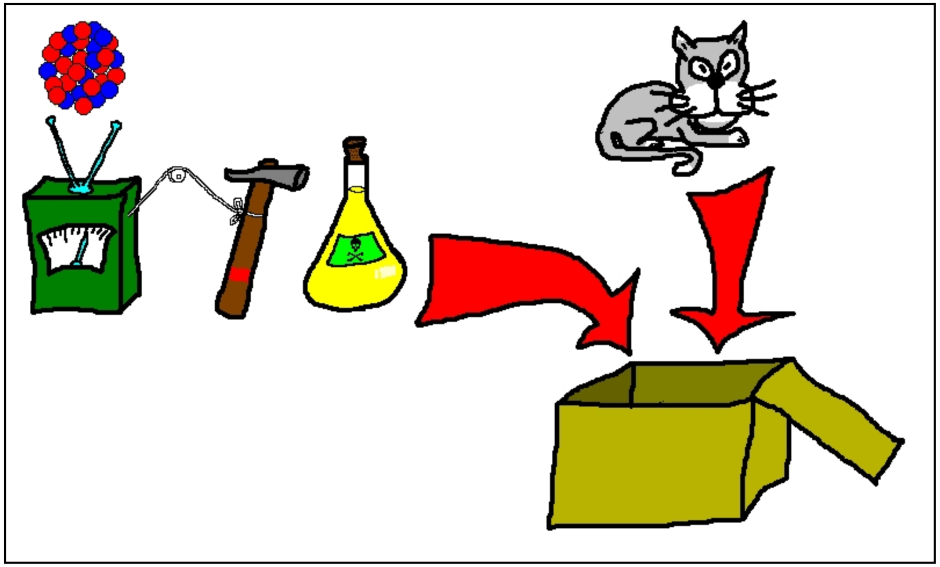
Repeated measurements: evolution of a continuously monitored field



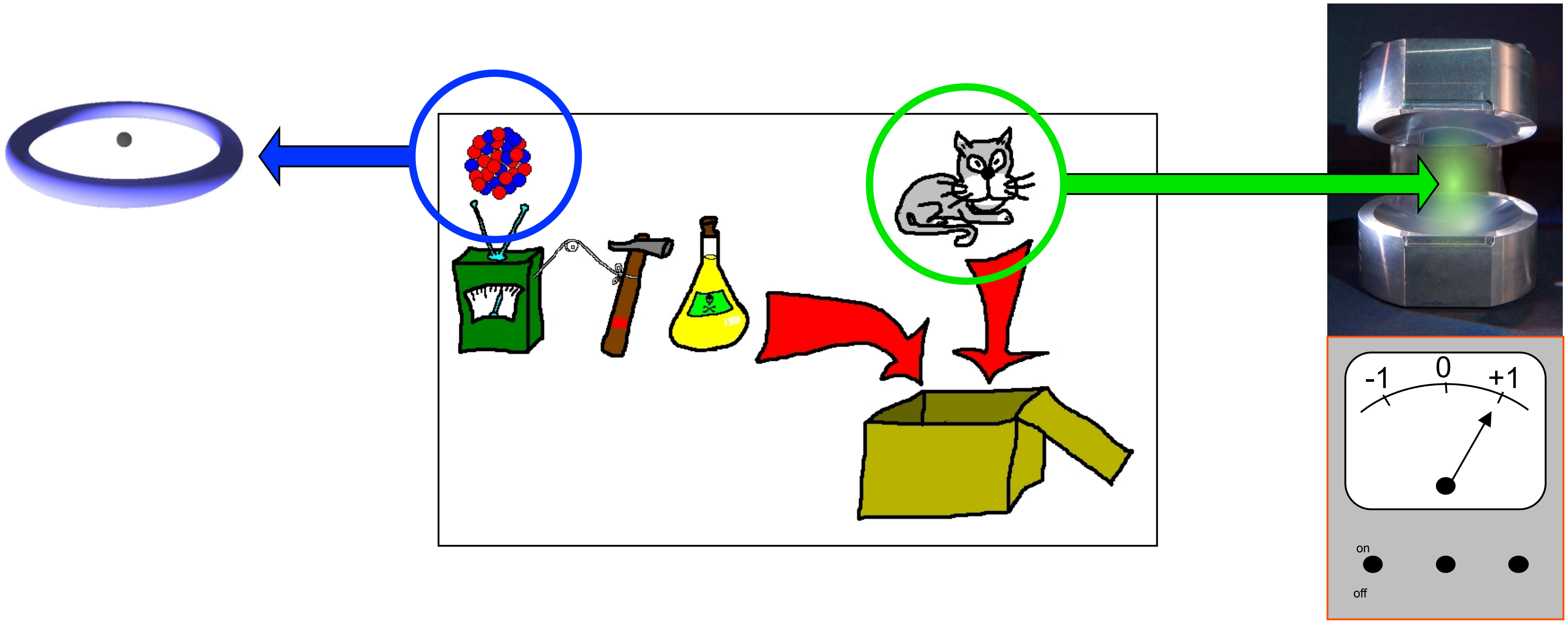
Field evolution due to cavity damping: not to QND measurement

- Exhibits all features of quantum theory of measurement:
  - State collapse
  - Random result
  - repeatability

III. Preparing a Schrödinger cat state



Measuring one atom **with the field**

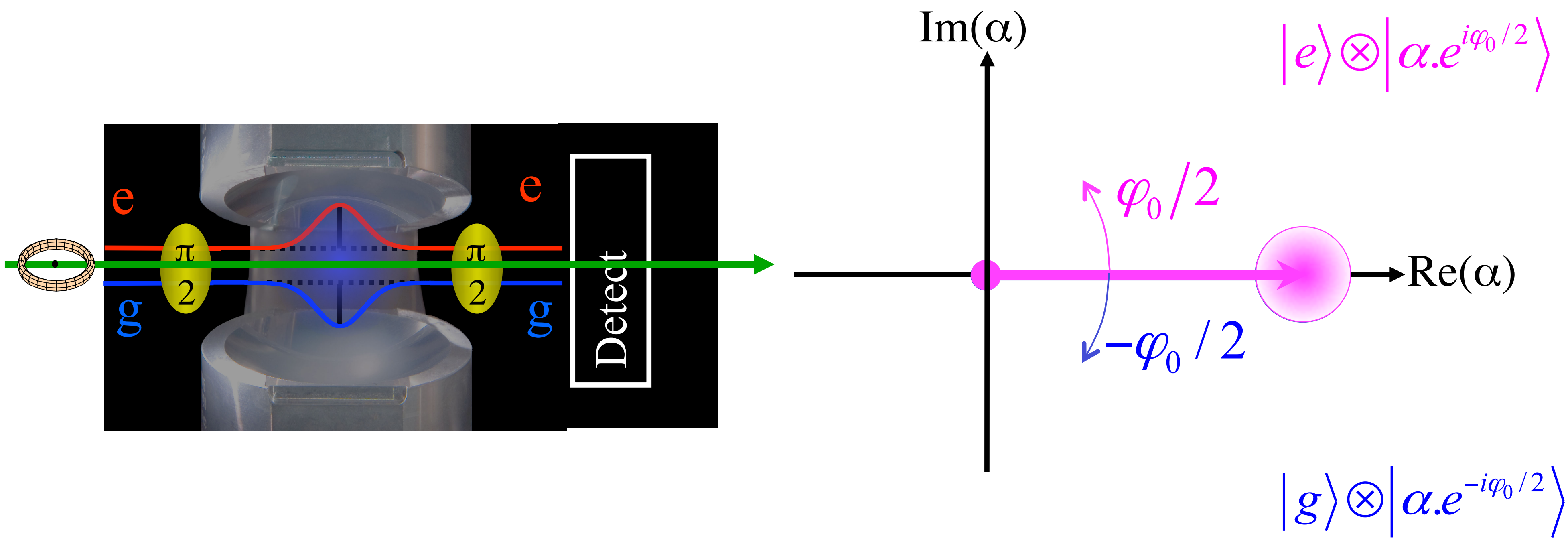


Distribution of roles:

- The radioactive atom: one Rydberg atom
- The cat: a mesoscopic field in the cavity.

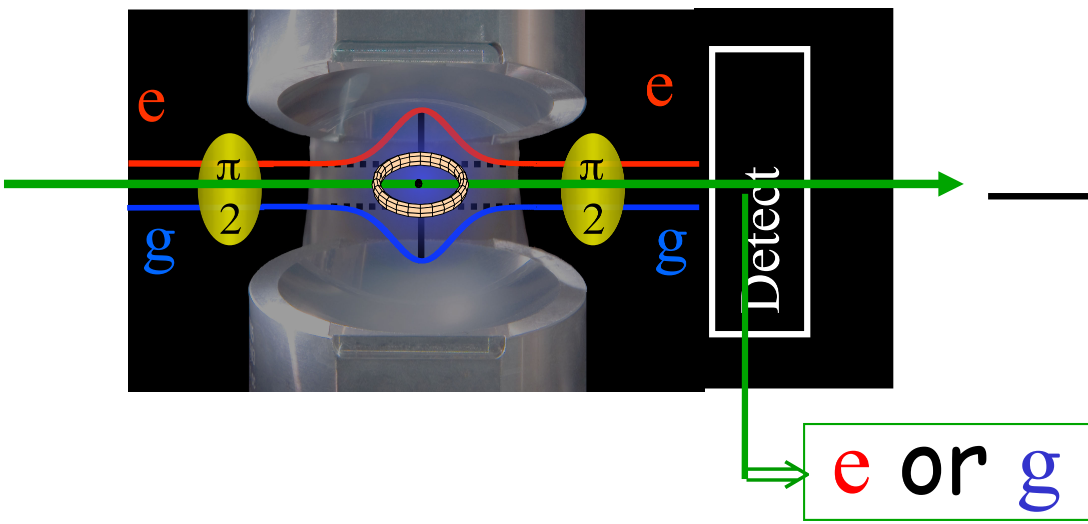
The “size” (i.e. the photon number) of the cat can be varied for explorong the quantum to classical transition

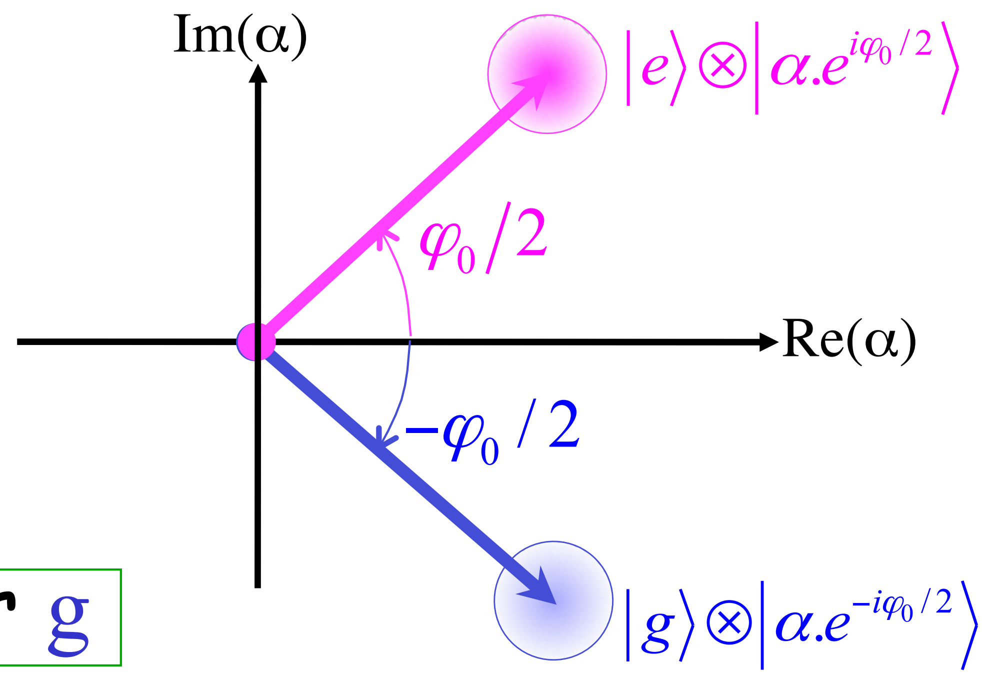
Preparing a phase Schödinger cat state



$\Rightarrow$ the field phase is controlled by the atomic energy state

Preparing a phase Schödinger cat state





Detection of the atom projects the field on:

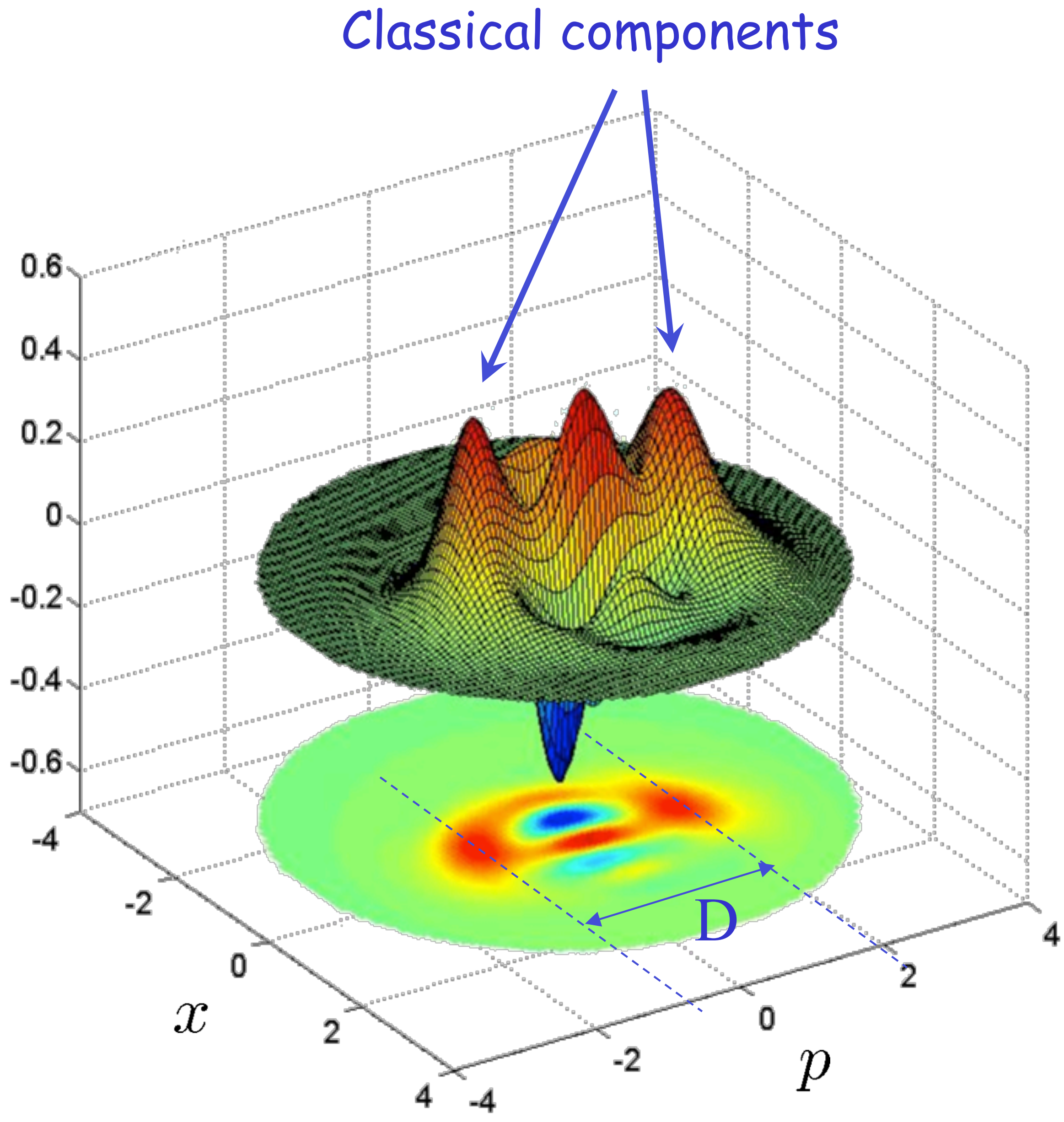
$$\frac{1}{\sqrt{2}}\left(\left|\alpha.e^{i\varphi_0/2}\right\rangle \pm \left|\alpha.e^{-i\varphi_0/2}\right\rangle\right)$$

±: depends on detected state e or g

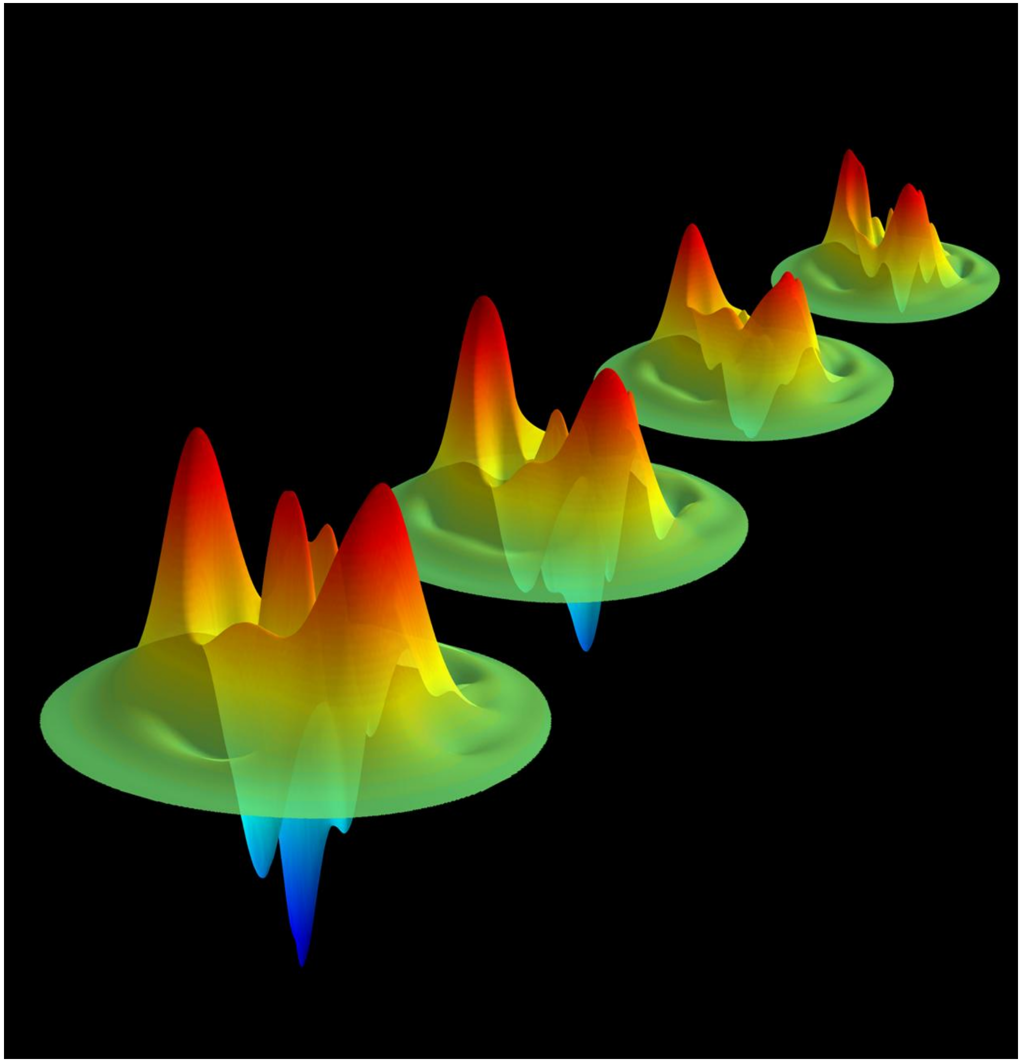
Reconstructed Wigner function

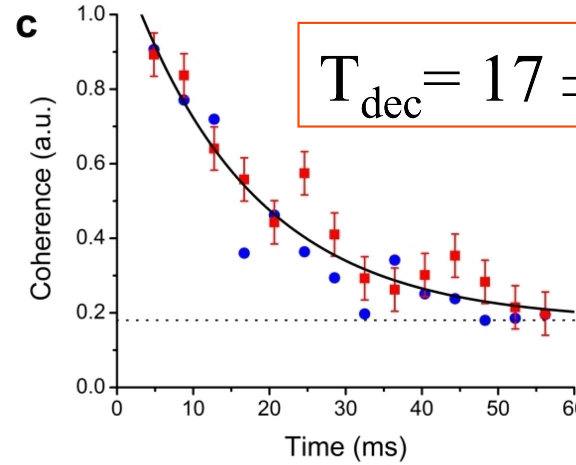
cat size:
$D^2 \approx 7.5$ photons

coherent components are well separated:
$D^2 >> 1$



Decoherence of a D^2=11.8 photon cat state





$T_{dec} = 17 \pm 3$ ms

$T_{\text{meas}} \approx 4\,\text{ms} < T_{\text{dec},\,\bar{n}_{\text{th}}}$

Theory:

$T_{dec} = 2T_{cav}/D^2 = 22$ ms

+ small blackbody contribution @ 0.8 K

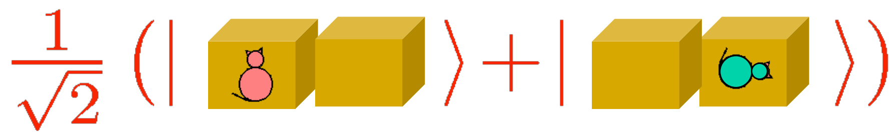
The future?

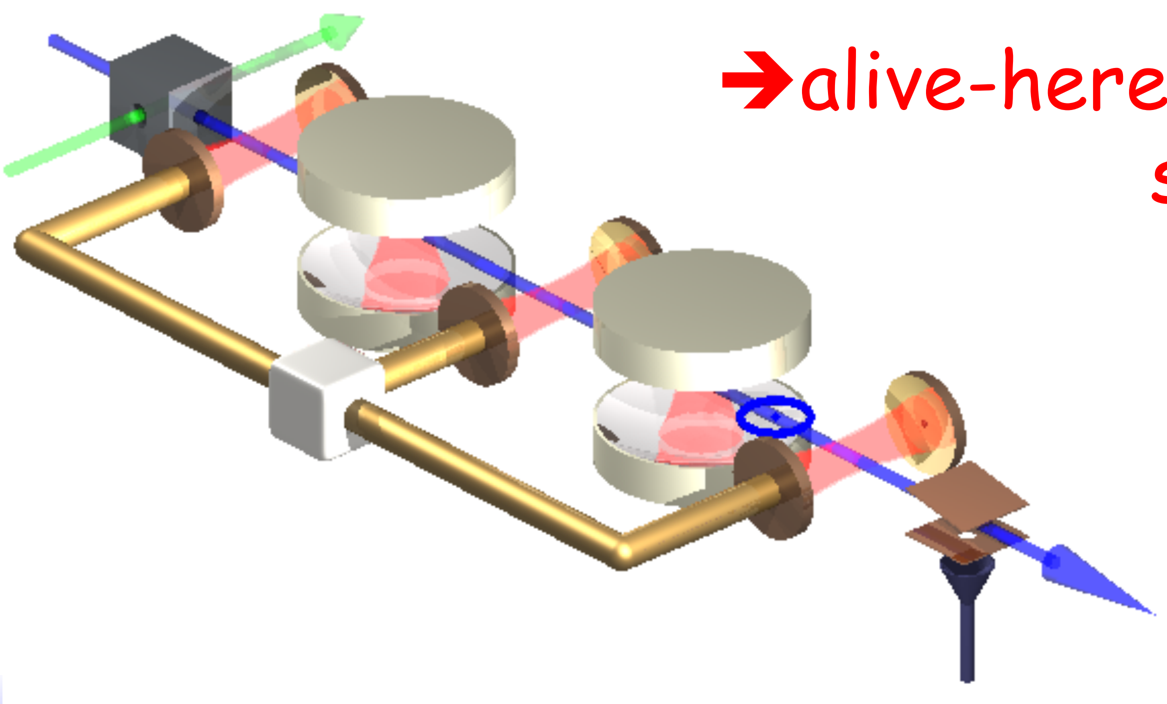
41

Perspectives

Experiments with 2 cavities

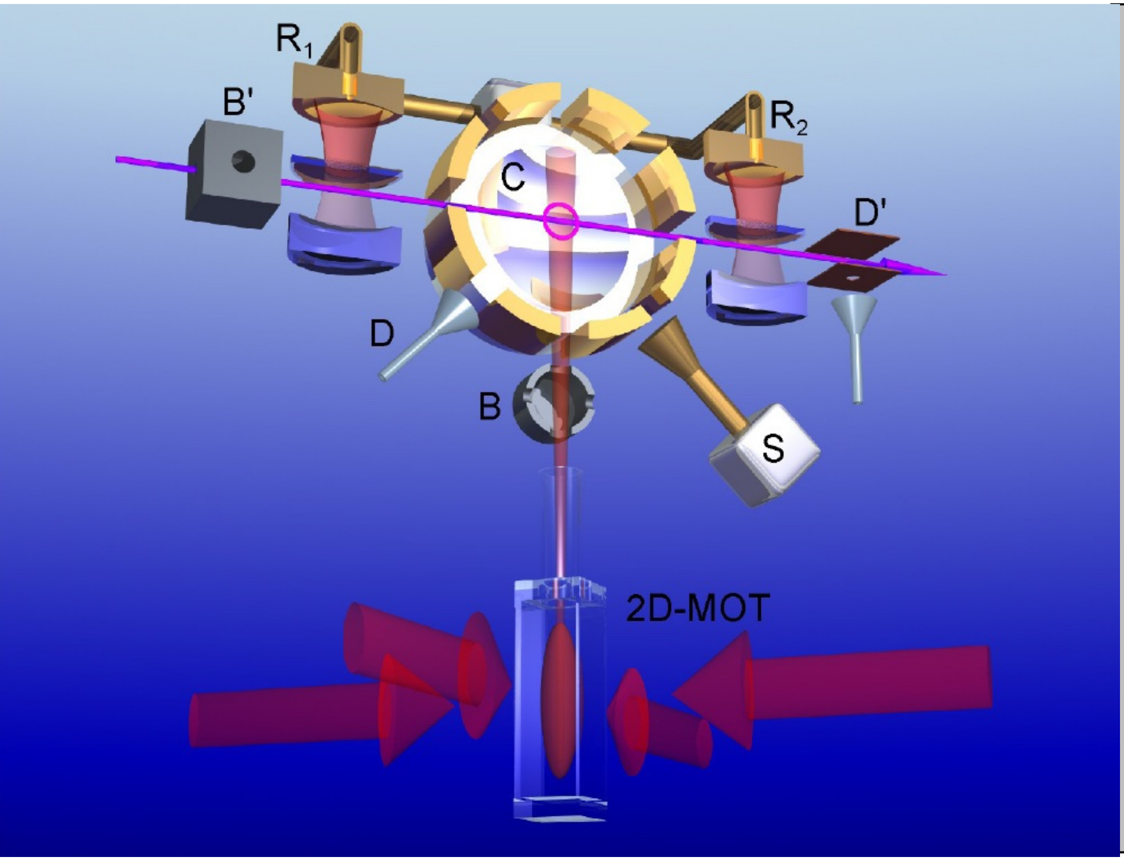
$$\frac{1}{\sqrt{2}}\left(|\alpha\rangle|0\rangle+|0\rangle|-\alpha\rangle\right)$$





➔alive-here-and-dead-there state

Stationnary atoms in a cavity

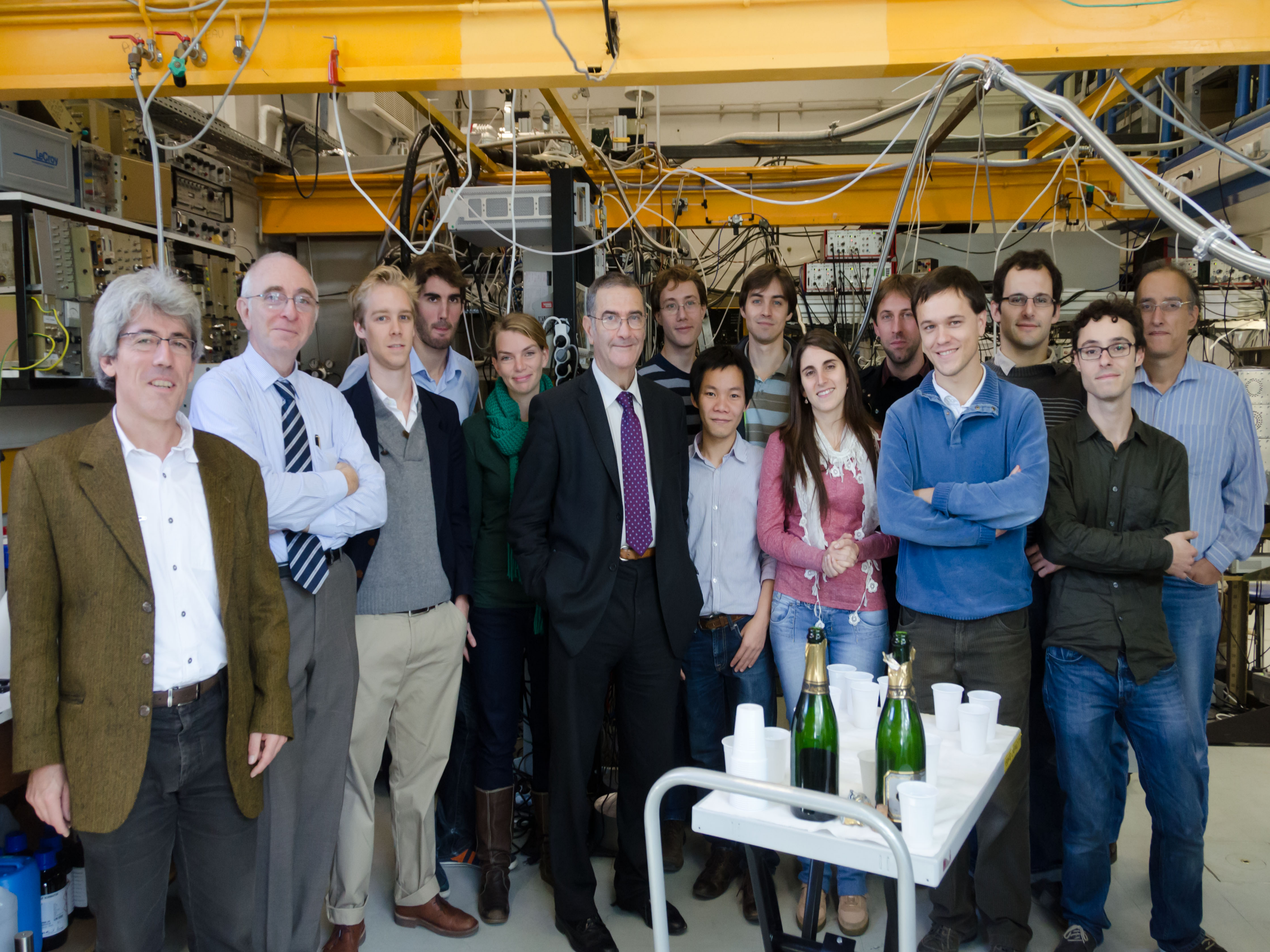


- Very long interaction times (few ms)

⇒ Large cats
Decoherence metrology
⇒ Quantum random walks
⇒ Quantum Zeno dynamics
⇒ Reservoir engeneering

And things would not have been like that…

… without Serge and Jean-Michel


LeCroy

The team

- Starring,
  by order of apparition

- Serge Haroche
- Michel Gross
- Claude Fabre
- Philippe Goy
- Pierre Pillet
- Jean-Michel Raimond
- Guy Vitrant
- Yves Kaluzny
- Jun Liang
- Michel Brune
- Valérie Lefèvre-Seguin
- Jean Hare
- Jacques Lepape
- Aephraim Steinberg
- Andre Nussenzveig
- Frédéric Bernardot
- Paul Nussenzveig
- Laurent Collot
- Matthias Weidemuller
- François Treussart
- Abdelamid Maali
- David Weiss
- Vahid Sandoghdar
- Jonathan Knight
- Nicolas Dubreuil
- Peter Domokos
- Ferdinand Schmidt-Kaler
- Jochen Dreyer

- Peter Domokos
- Ferdinand Schmidt-Kaler

- Ed Hagley
- Xavier Maître
- Christoph Wunderlich
- Gilles Nogues
- Vladimir Ilchenko
- Jean-François Roch
- Stefano Osnaghi
- Arno Rauschenbeutel
- Wolf von Klitzing
- Erwan Jahier
- Patrice Bertet
- Alexia Auffèves
- Romain Long
- Sébastien Steiner
- Paolo Maioli
- Philippe Hyafil
- Tristan Meunier
- Perola Milman
- Jack Mozley
- Stefan Kuhr
- Sébastien Gleyzes
- Christine Guerlin
- Thomas Nirrengarten
- Cédric Roux
- Julien Bernu

- Ulrich Busk-Hoff
- Andreas Emmert
- Adrian Lupascu
- Jonas Mlynek
- Igor Dotsenko
- Samuel Deléglise
- Clément Sayrin
- Xingxing Zhou

- Bruno Peaudecerf
- Raul Teixeira
- Sha Liu (post-doc)
- Theo Rybarczyk
- Carla Hermann
- Adrien Signolles
- Adrien Facon
- Eva Dietsche
- Stefan Gerlich (post-doc)
- Than Long Nguyen