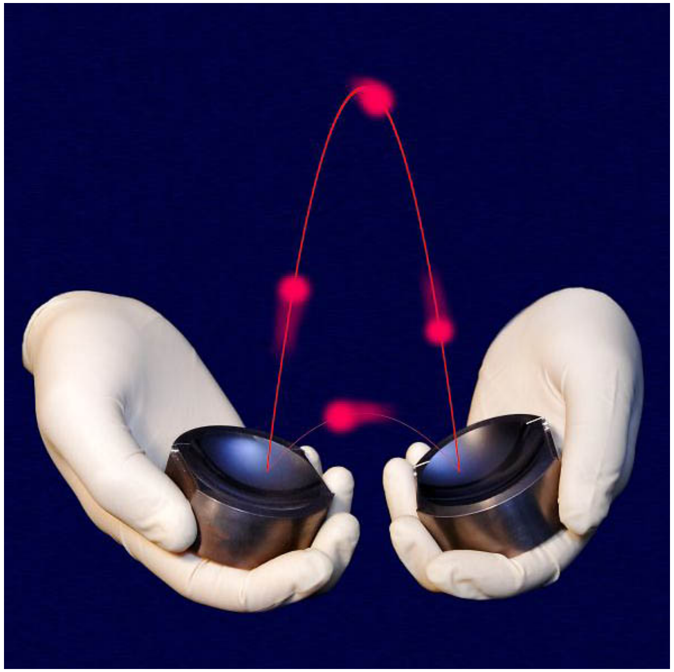
Measuring and controlling non destructively photons in cavities

J.M. Raimond

Université Pierre et Marie Curie

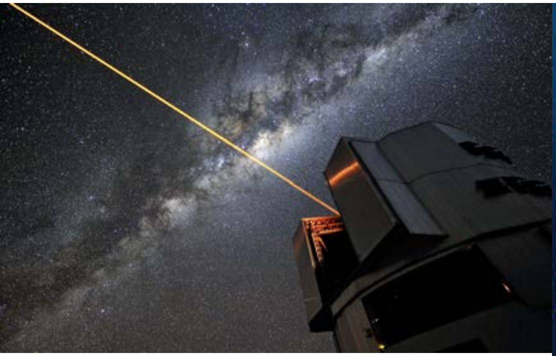
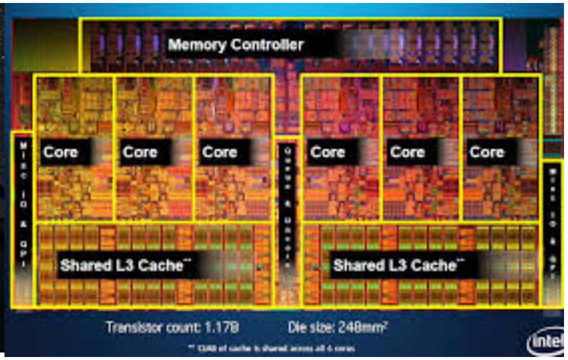
Laboratoire Kastler Brossel
Physique quantique et applications

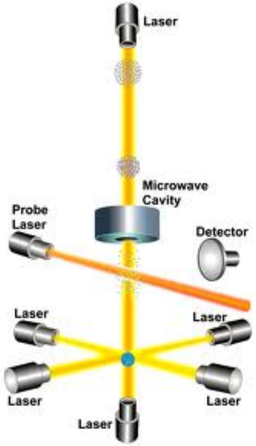


The impressive sucess of the quantum

- A remarkably sucessful theoretical frame
  - Unified interactions (but gravity)
  - Extreme precision (10^{-12} level)
  - All scales, from elementary particles to cosmic background

- Countless applications which have shaped the society
  - Laser, solid-state electronics, clocks, MRI

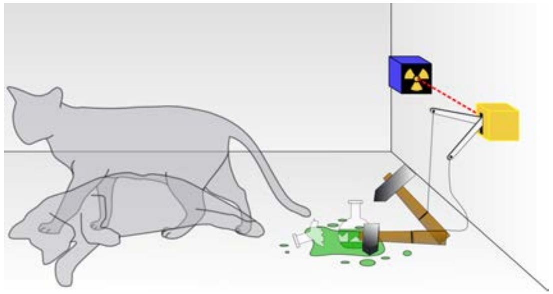





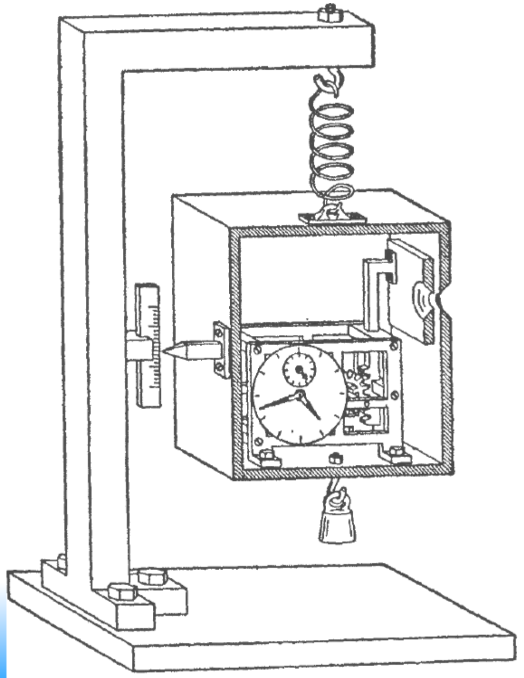
- An astounding example of the societal impact of curiosity-driven fundamental research on the long time

The impressive success of the quantum

- …and provided us with extraordinary experimental tools
  - Lasers, computers allow us to manipulate quantum systems
    - Quantum technology makes it possible to explore the quantum.
    - The gedankenexperiments are made real
      - And quantum mechanics passes the test !

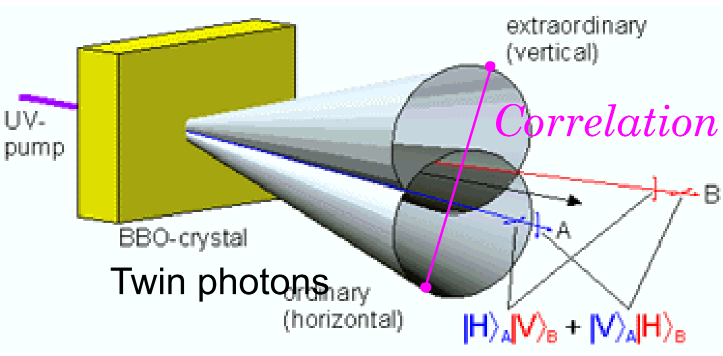


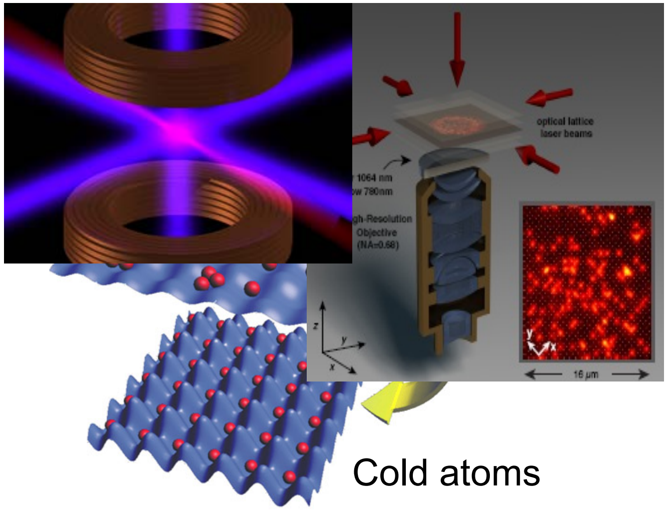
  - Why exploring the quantum 100 years after Bohr?
    - Better confidence in the quantum
    - Better understanding of the interpretation(s)
    - Insights into new quantum technologies
      - Quantum simulation
      - Quantum information processing



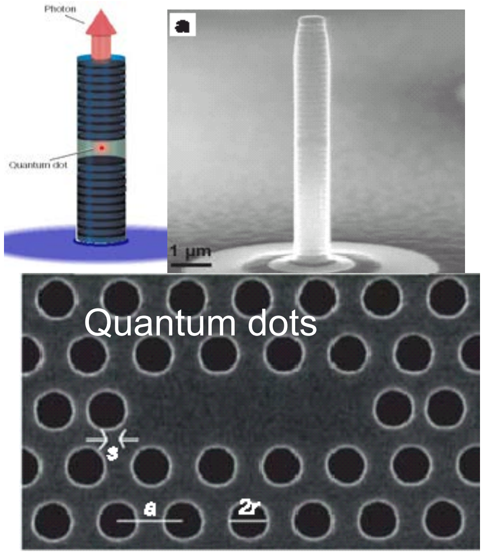
A thriving field worldwide

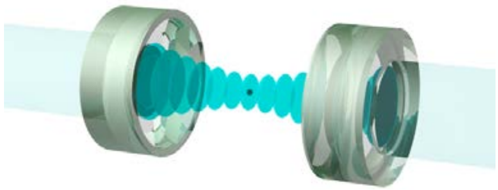
- Many experimental schemes manipulate individual quantum systems



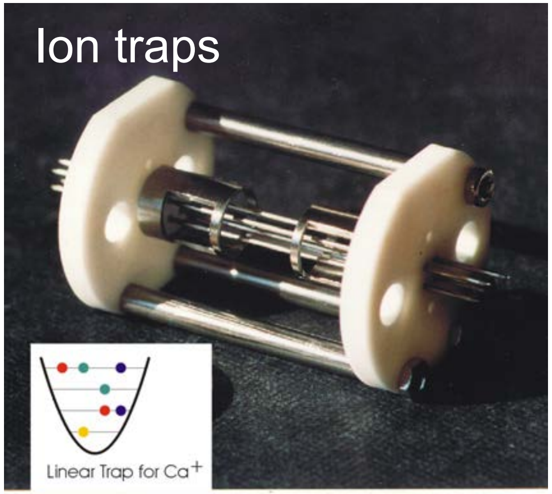


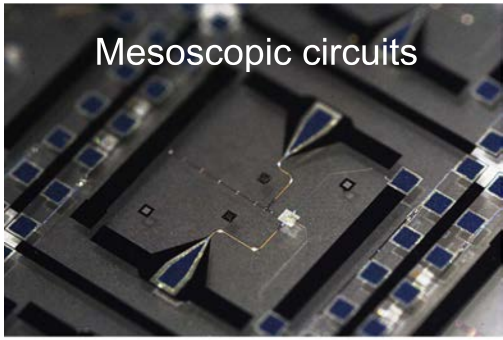
Cold atoms





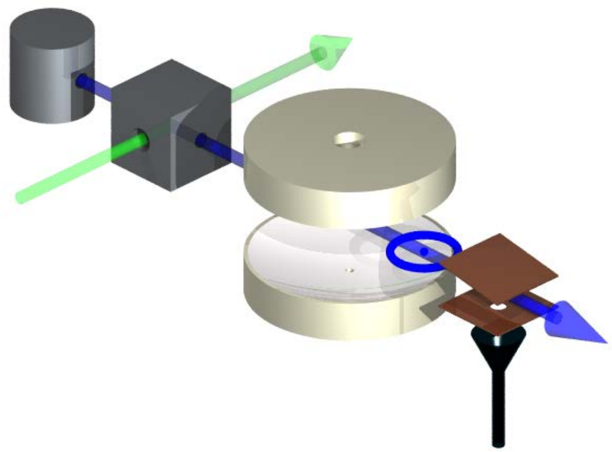
Atoms and cavities





Cavity Quantum Electrodynamics

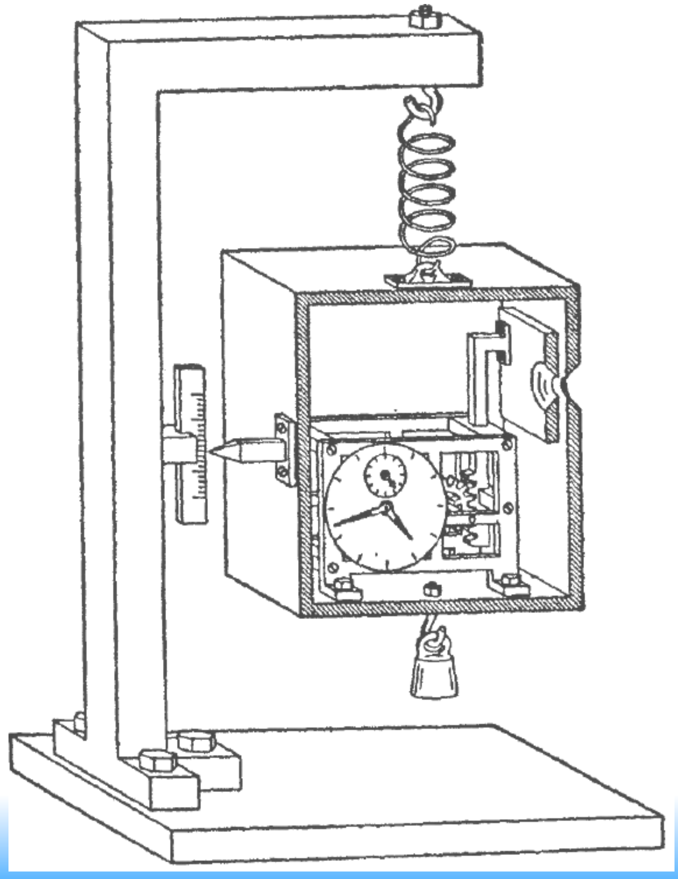
- A spin and a spring



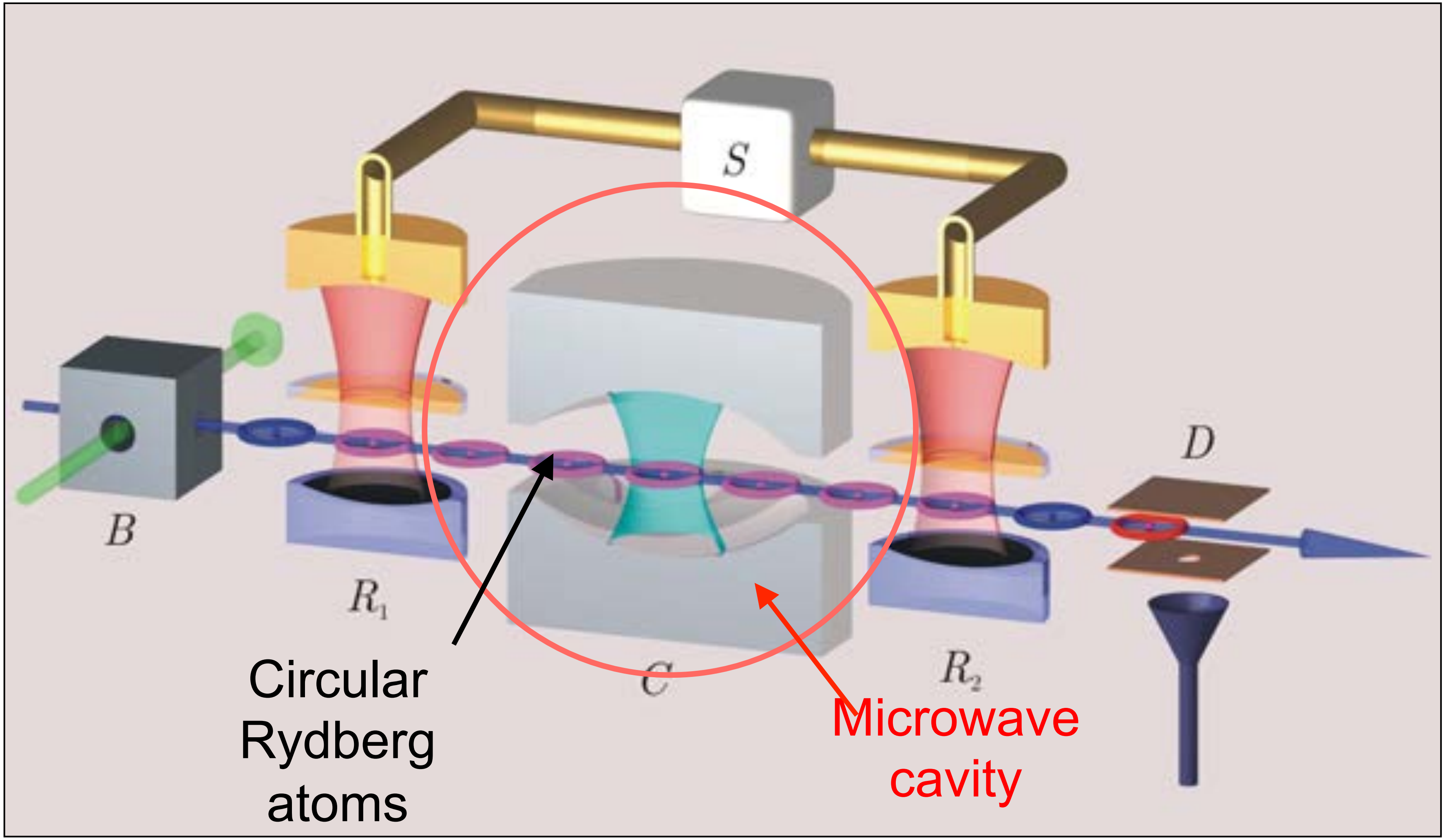
  - Realizes the simplest matter-field system: a single atom coherently coupled to a few photons in a single mode of the radiation field.
  - Specific tools
    - Circular Rydberg atoms
    - Superconducting millimeter-wave cavities
  - Direct illustrations of quantum postulates
    - Measurement
      - Ideal quantum measurement of photon number and applications
        - » Quantum feedback

An ideal photon counter ?

- All standard detectors destroy the incoming photons
  - A Quantum Non Demolition photodetector operating at the individual photon level
- A photon ‘box’ able to store a photon for a long time
  - back to Einstein-Bohr’s dream: weighing a photon

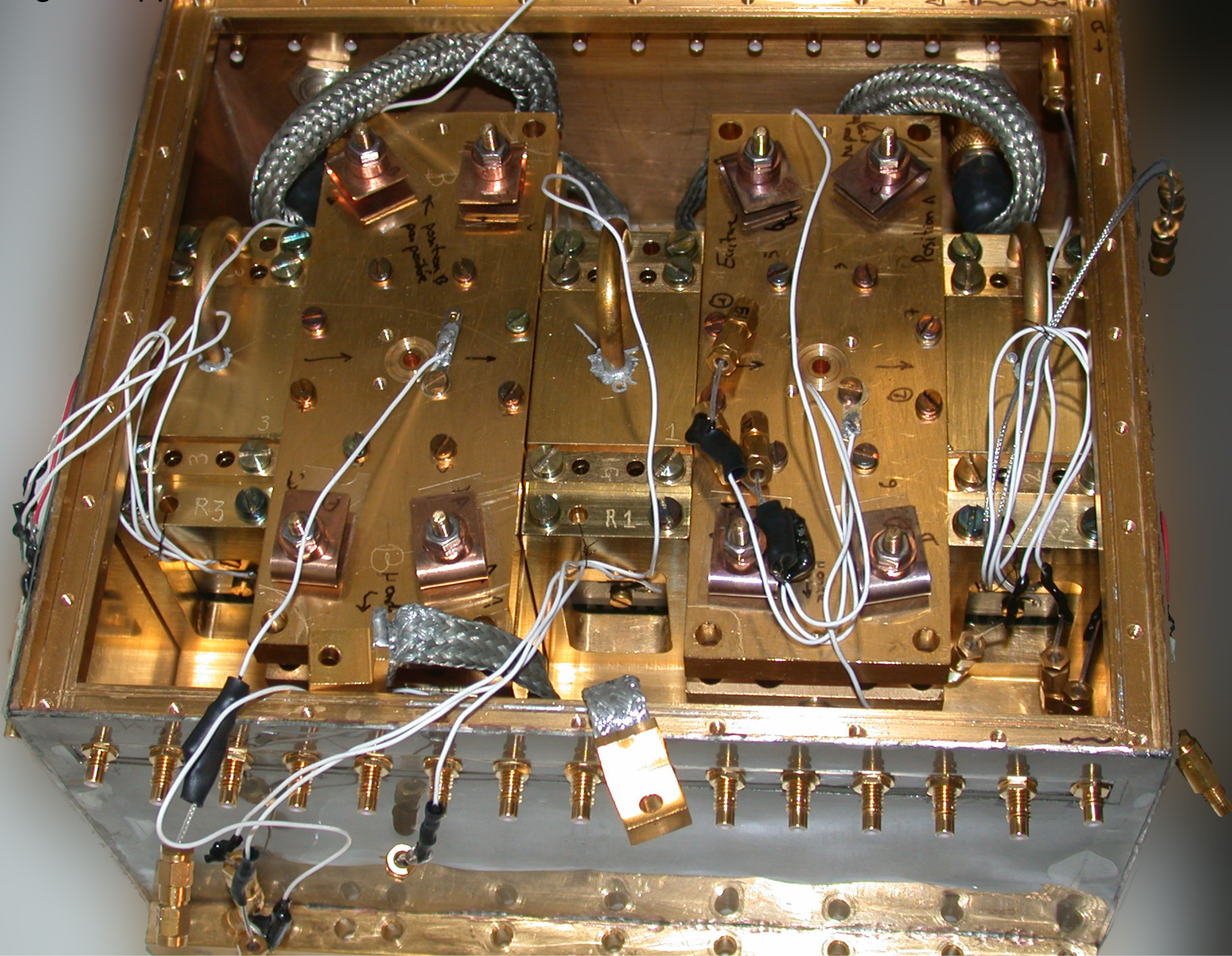


Experimental set-up



RMP **73**, 565

40 kg of copper at 0.8 K



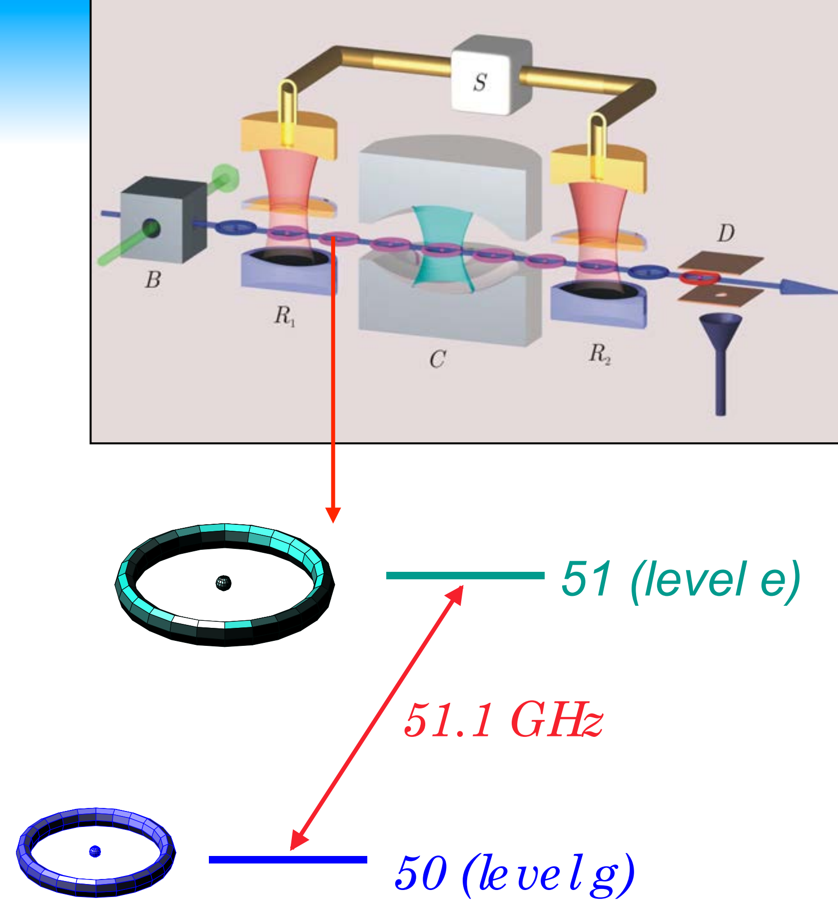
Circular Rydberg atoms

High principal quantum number

Maximal orbital and magnetic quantum numbers

- Long lifetime (30ms)
- Microwave two-level transition
- Huge dipole matrix element
- Stark tuning
- Field ionization detection
  - selective and sensitive

- Velocity selection by lasers and TOF
  - v=250 m/s
  - Controlled interaction time
  - Well known sample position

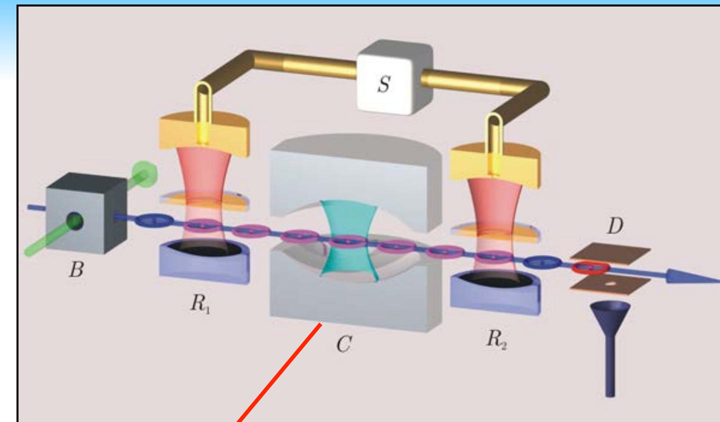


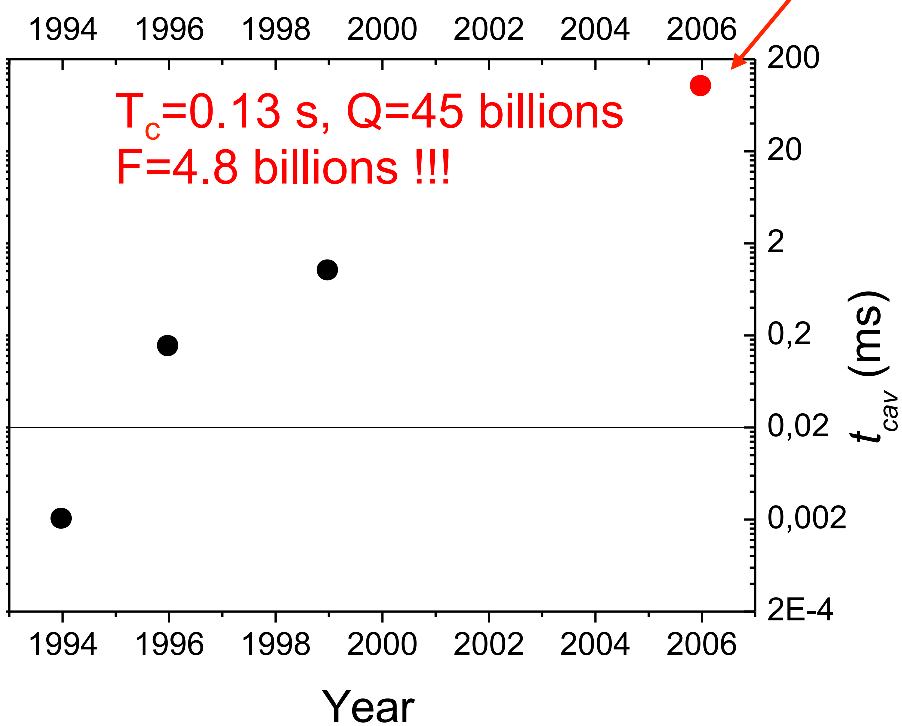
Complex preparation (53 photons !)

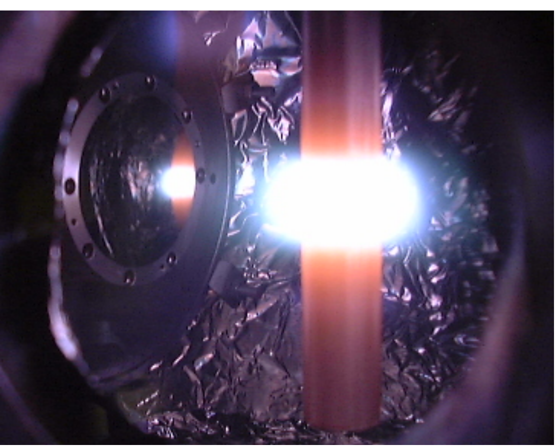
Stable only in a weak directing electric field

A box for microwave photons

- optimization of the cavity quality
  - a long process
    - our pet Moore's law

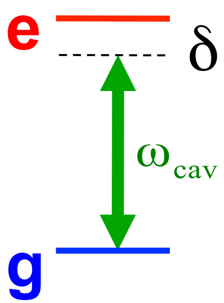


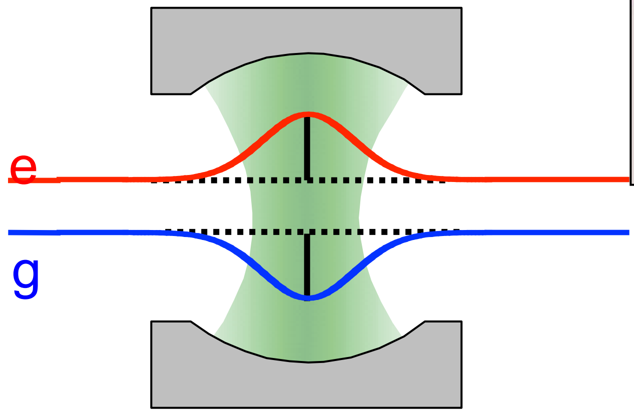


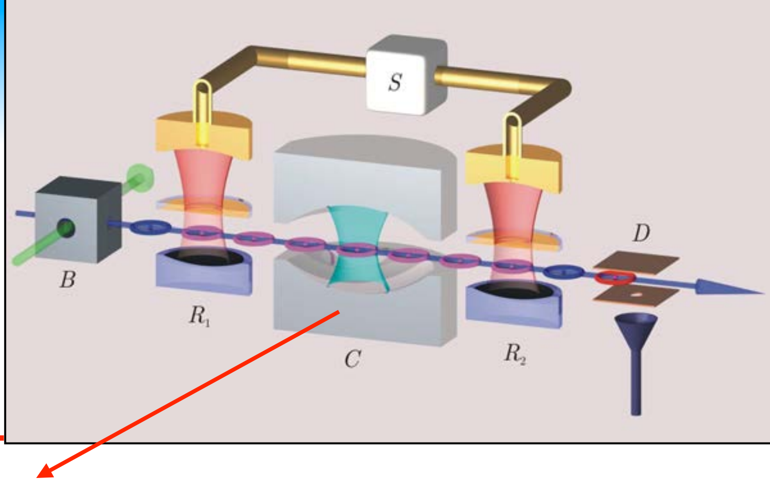


QND measurement

- Quantized light-shifts in the cavity







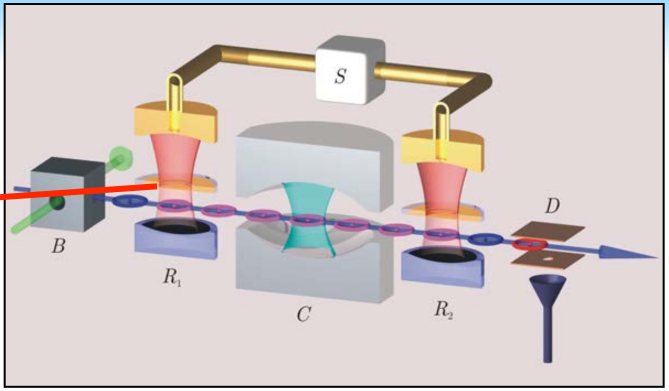
- Atomic clock modified by the interaction with the field
- Modification measured by Ramsey interferometry
  - A state superposition, prepared by a π/2 pulse in R_1, accumulates a phase shift $\phi_0 \left(n + 1/2 \right)$

$$\Phi_0 = \frac{\Omega_0^2}{2\delta} t_i$$

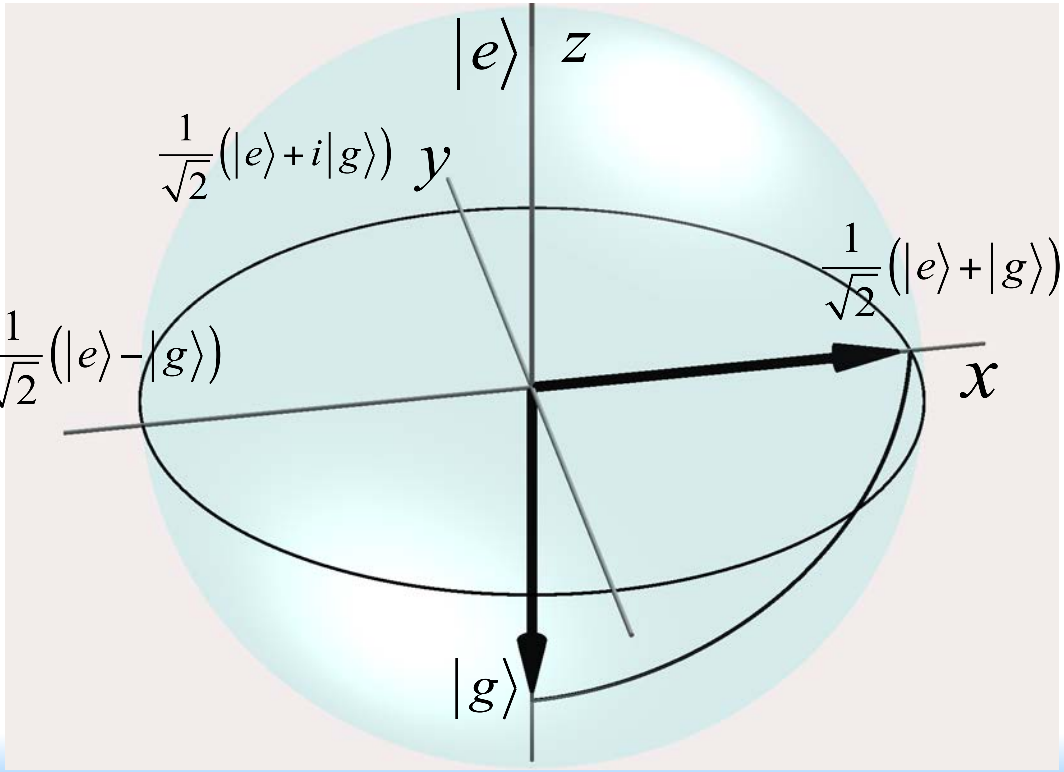
  - Phase shift read out by a second π/2 pulse in R_2 and final atomic state detection in D

State preparation

- Create an atomic coherence
  - In R_1 : $|g\rangle \rightarrow \frac{1}{\sqrt{2}}\left(|g\rangle + |e\rangle\right)$

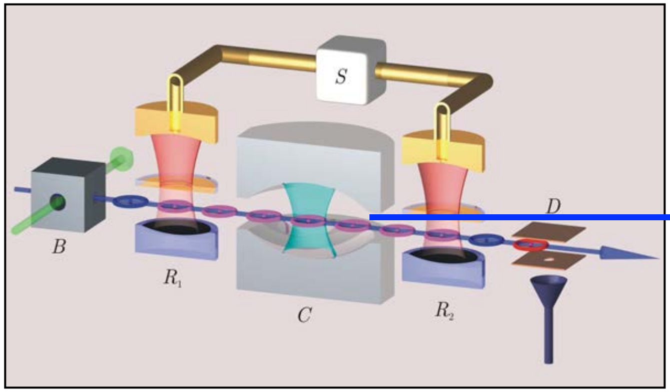


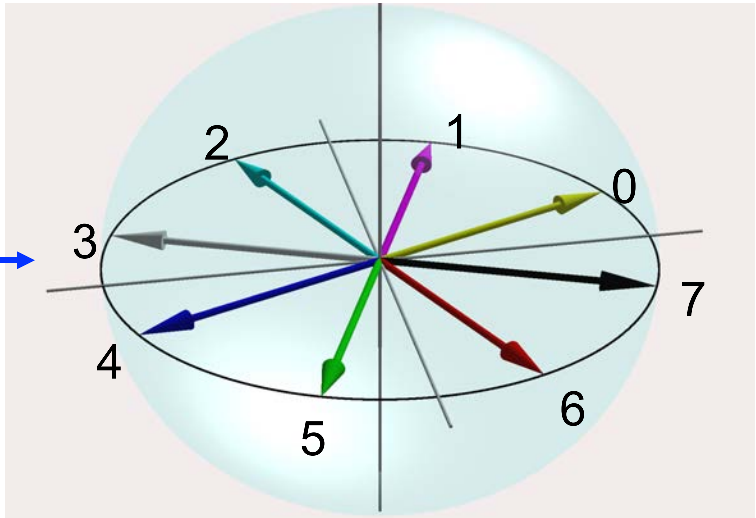
  - A simple geometrical representation: Bloch sphere for the spin ½ representing the two-level atomic transition



Quantized rotation of the atomic spin

- Photon-number dependent phase shift of the atomic coherence



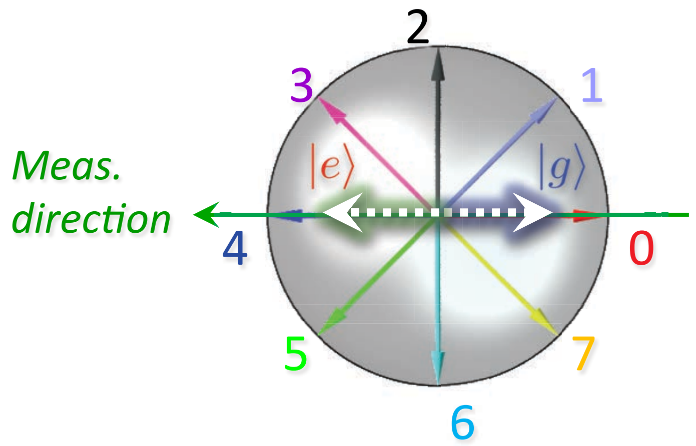


$$\phi_0 = \frac{\pi}{4}$$

- The Bloch vector direction reveals the photon number
- In general non-orthogonal final atomic states correspond to different photon numbers: A single atom does not tell all the story
- But Bloch vector direction correlated to photon number
  - Each atomic detection provides partial information on the field

Atomic spin read out

- Second Ramsey pulse and state-selective detection
  - Equivalent to a measurement of the atomic spin in a selected direction in the equatorial plane of the Bloch sphere



- Direction chosen at will through the phase ϕ_r of the Ramsey interferometer
  - Atomic detection probability is an oscillating function of the photon number

$$\pi_e(\phi_r|n) = 1 - \pi_g(\phi_r|n) = \frac{1}{2}\left(1 + \cos\left[\phi_r + \phi_0(n + 1/2)\right]\right)$$

Baysian inference of the photon number

- Action of a measurement on the photon distribution (Bayes law)

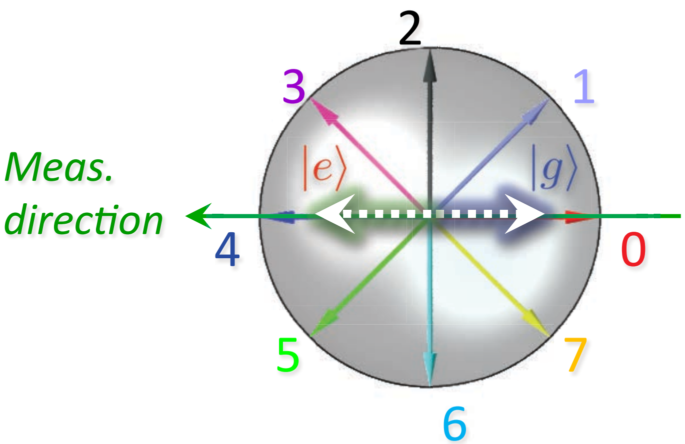
$$P(n|j,\phi_r) = \frac{\pi_j(\phi_r|n)}{\pi_j(\phi_r|\rho)} P(n)$$

$$\pi_e(\phi_r|n) = 1 - \pi_g(\phi_r|n) = \frac{1}{2}\left(1 + \cos\left[\phi_r + \phi_0(n+1/2)\right]\right)$$

$$\pi_j(\phi_r|\rho) = \sum_n P(n)\pi_j(\phi_r|n)$$

  - Each atomic detection multiplies the photon number distribution by a sine

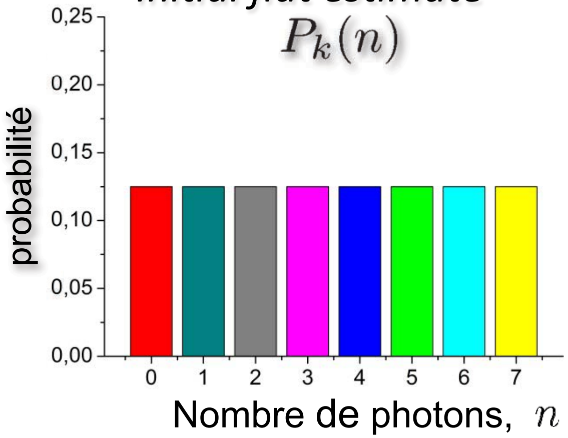
Single atom detection



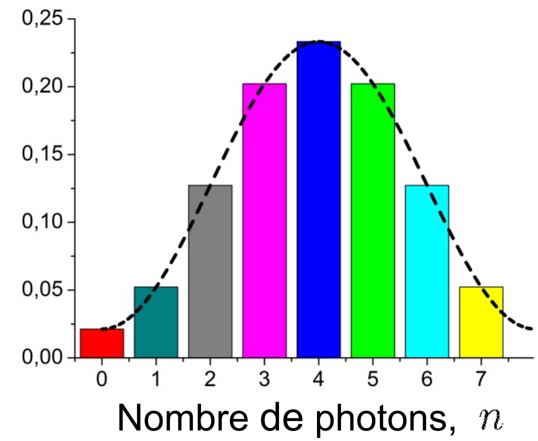
Each detection brings partial information on the photon number

Initial flat estimate

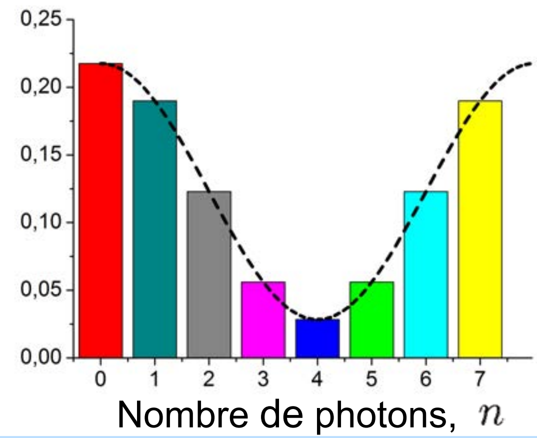
$P_k(n)$



detection $|e\rangle$



detection $|g\rangle$



Photon number decimation process

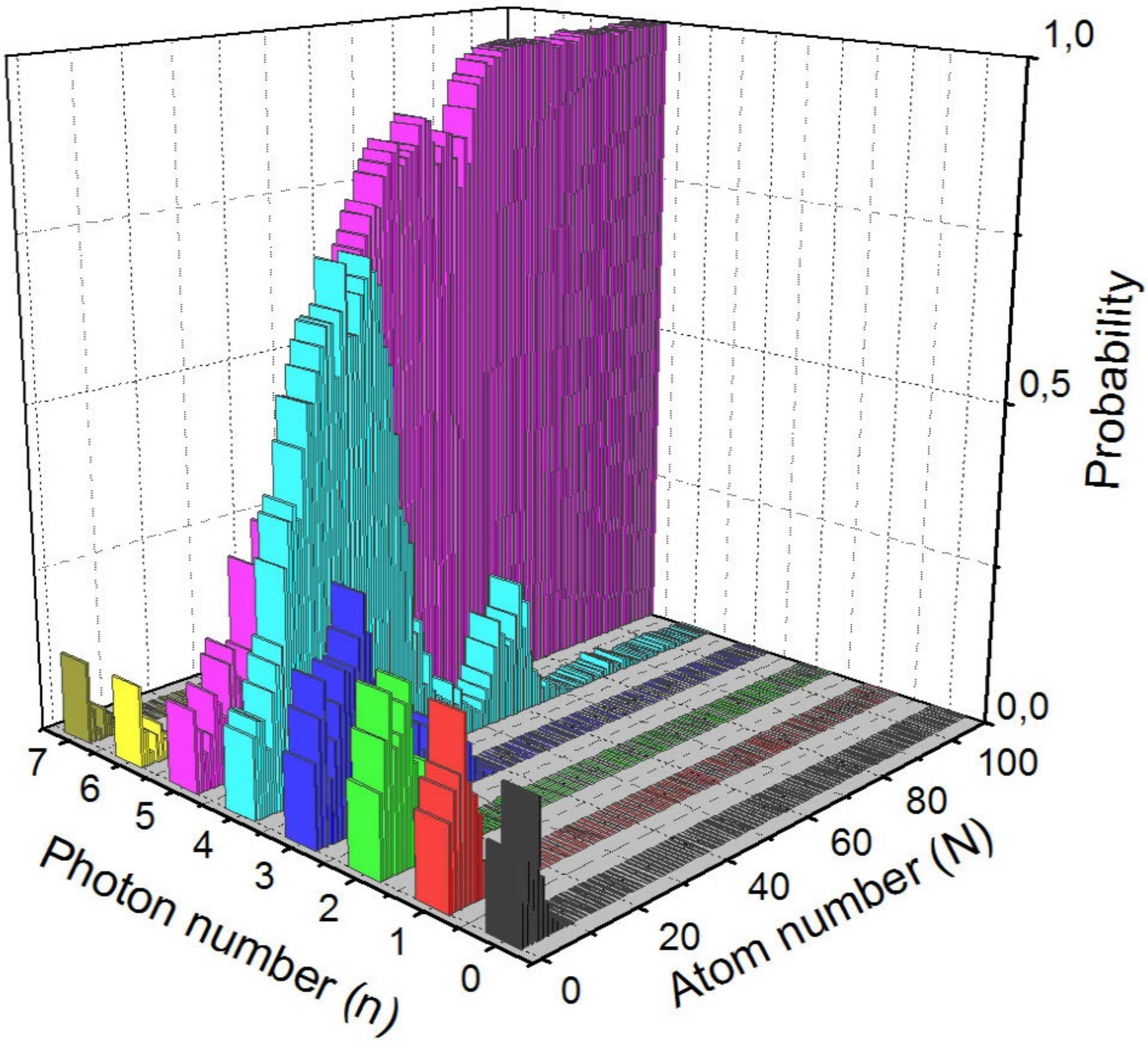
- Each atomic detection multiplies P(n) by a sine
  - Reduces the probability of some photon numbers
  - Decimation of the photon number distribution

- Cumulative decimation of the photon number distribution pins down the photon number
  - Unconditional convergence — Bauer and Bernard, PRA **84**, 044103
  - Use four randomly chosen settings of the measurement direction
    - Removes any ambiguity and speeds up decimation

$$P_{N_a}(n) = \frac{P_0(n)}{Z} \prod_{i=1}^{N_a} \pi_{j_i}(\phi_{r,i}|n)$$

  - Again about n_m^2 atoms to distinguish n_m photon states
    - Statistical noise on the atomic detections

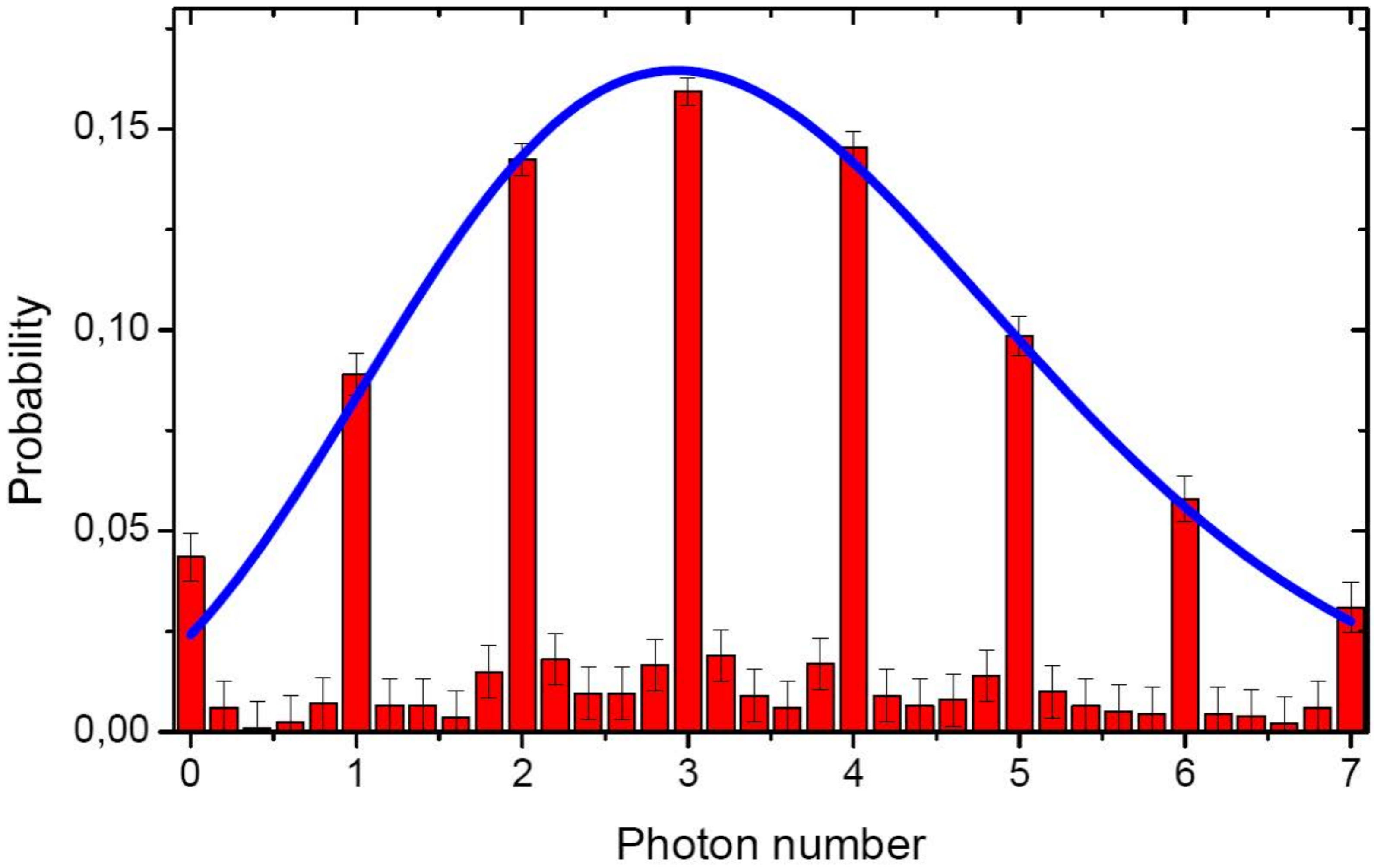
Wave-function collapse in real time



- Evolution of P(n) while detecting 110 atoms in a single sequence
- Initial coherent field with 3.7photons
- Initial inferred distribution flat (no information) but final result independent of initial choice
- Progressive collapse of the field state vector during information acquisition

C. Guerlin et al, Nature, **448**, 889

Photon number statistics

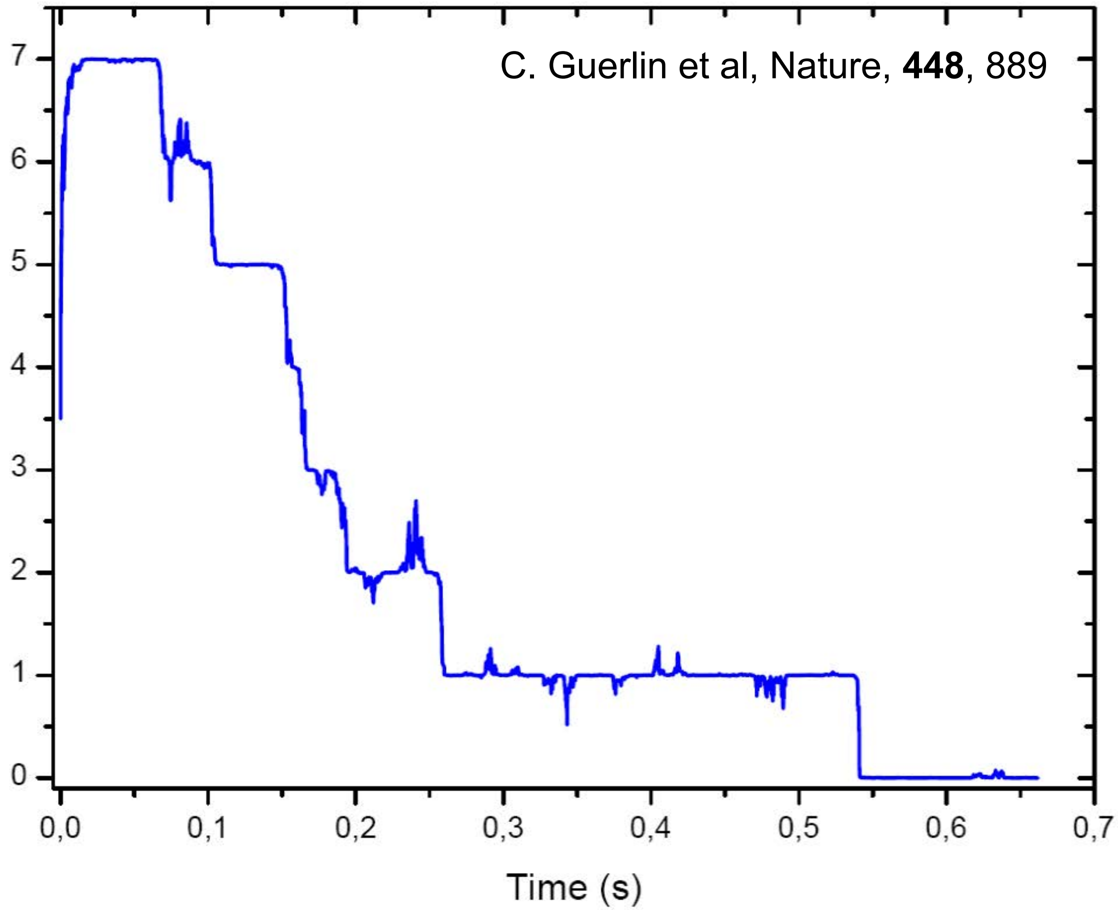


Excellent agreement with the expected Poisson distribution

A vivid illustration of quantum measurement postulates

Witnessing the field quantum jumps

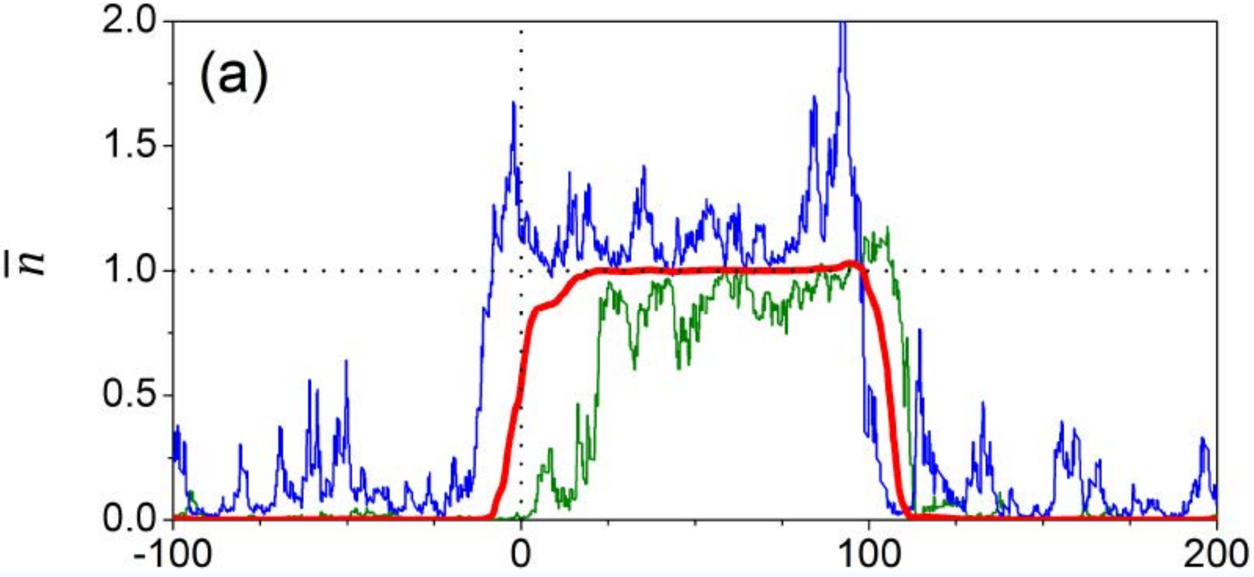
- Keep sending atoms through the cavity
  - Evaluation based on the last 110 atomic detections



  - Noise mainly due to statistical fluctuations in atomic detections.

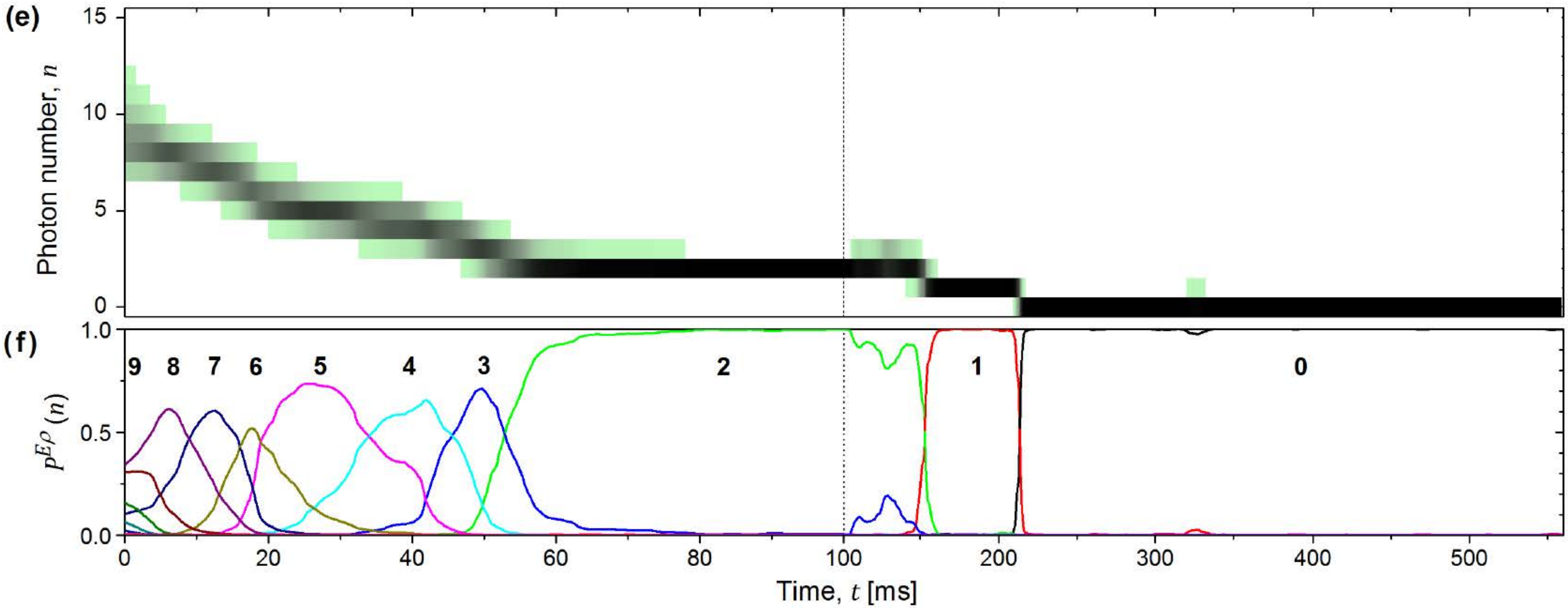
The past quantum state approach

- A considerable improvement in the photon number assignation
  - Based the evaluation at *t* on all data acquired before *t* *and after t*
    - Formalism in Gammelmark et al, PRL 111, 160401
    - Here equivalent to the forward-backward smoothing method
  - Photon number distribution at *t* product of two distributions, evaluated forward (as before) and backwards in time
    - Both take into account atomic detections and cavity relaxation
- Reconstruction of a single photon injection at *t*=0



Quantum trajectories in the past quantum state approach

- Noise reduction

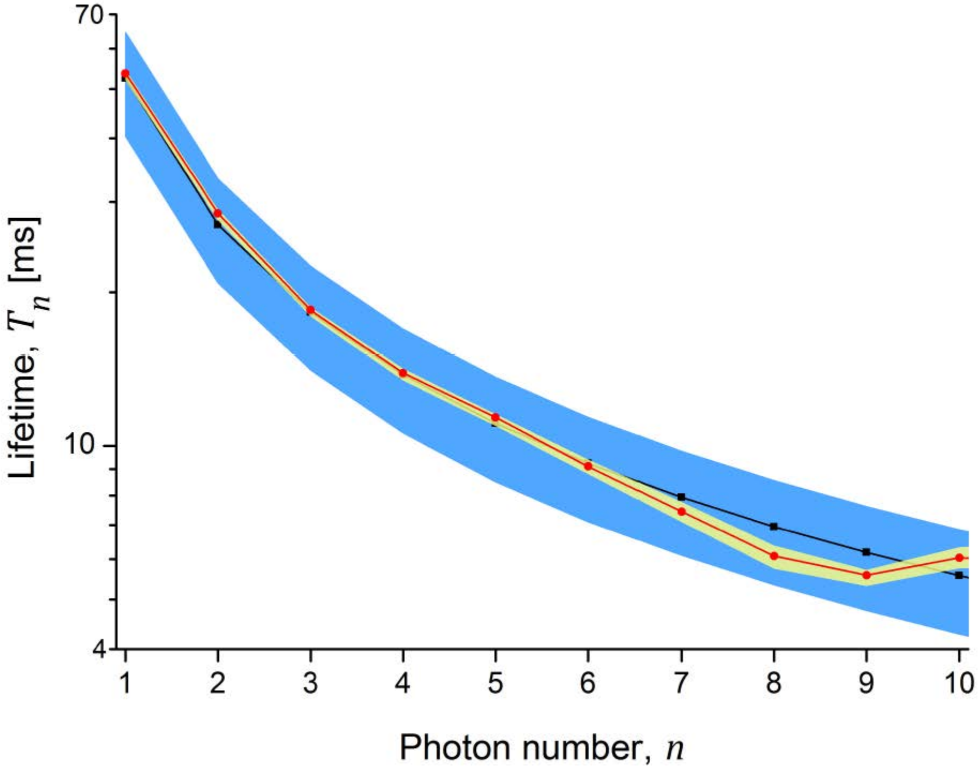


  – And measurements of photon numbers above 7 ! Further evolution lifts ambiguities due to the periodic nature of the measurement

T. Rybarczyk et al, submitted

Quantum trajectories in the past quantum state approach

- Lifetime of the photon-number states
  - From the statistics of the quantum jumps

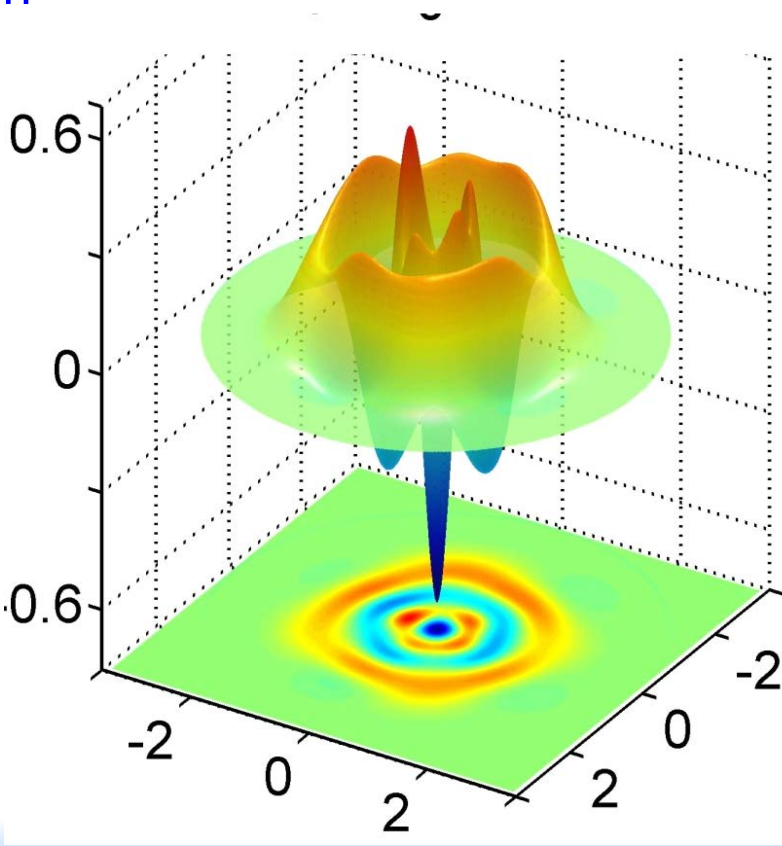


  - Lifetime varies as T_c/n
    - A typical decoherence effect for mesoscopic nonclassical states
      - Much more in next talk

For an earlier determination: Brune et al, PRL 101 240402

An ideal quantum measurement

- Illustrates all quantum postulates
  - Random results
  - Predictable probabilities
  - Projection on an eigenstate
- A simple method for Fock states preparation
  - Non-classical states
  - Complete state tomography
  - Negativities in the Wigner distribution



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

Fock state preparation

- QND measurement prepares Fock states but:
  - Random selection of the prepared photon number
    - God is playing dice
  - Produced state rapidly decays due to decoherence

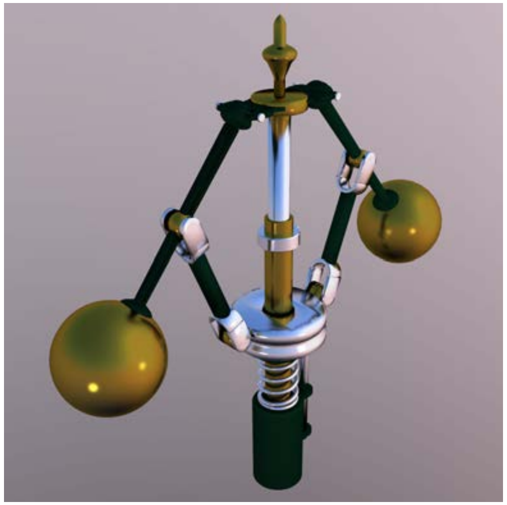
- Fock states are an interesting resource
  - e.g. quantum communication or computation

- Can we
  - Prepare a Fock state on demand?
  - Preserve this fragile resource against decoherence?

- YES
  - Using quantum feedback

Feedback: a universal technique

- Classical feedback is present in nearly all control systems
  - A SENSOR measures the system's state
  - A CONTROLLER compares the measured quantity with a target value
  - An ACTUTATOR reacts on the system to bring it closer to the target



- Quantum feedback has the same aims for a quantum system
  - Stabilizing a quantum state against decoherence
  - Must face a fundamental difficulty:
    - measurement changes the system state

Two quantum feedback experiments

- Prepare and preserve a Fock state in the cavity
  - Target state: the photon number state n_t
- Feedback loop
  - Get information on the cavity state
    - QND quantum sensor atoms sent at 82 μs time interval
  - Estimate cavity state and distance to target
    - Fast real-time computer (ADWin Pro II)
      - A complex computation taking into account all known imperfections
    - Decide upon actuator action
  - Actuator action
    - Drives the cavity state as close as possible to the target

Two experiments

- Classical actuator
  - Actuator is a coherent source
    - Displacement of the cavity field
    - Technically simple
    - Not optimal: complex procedure to correct for single photon loss
    - Preparation and protection of Fock states up to n=4

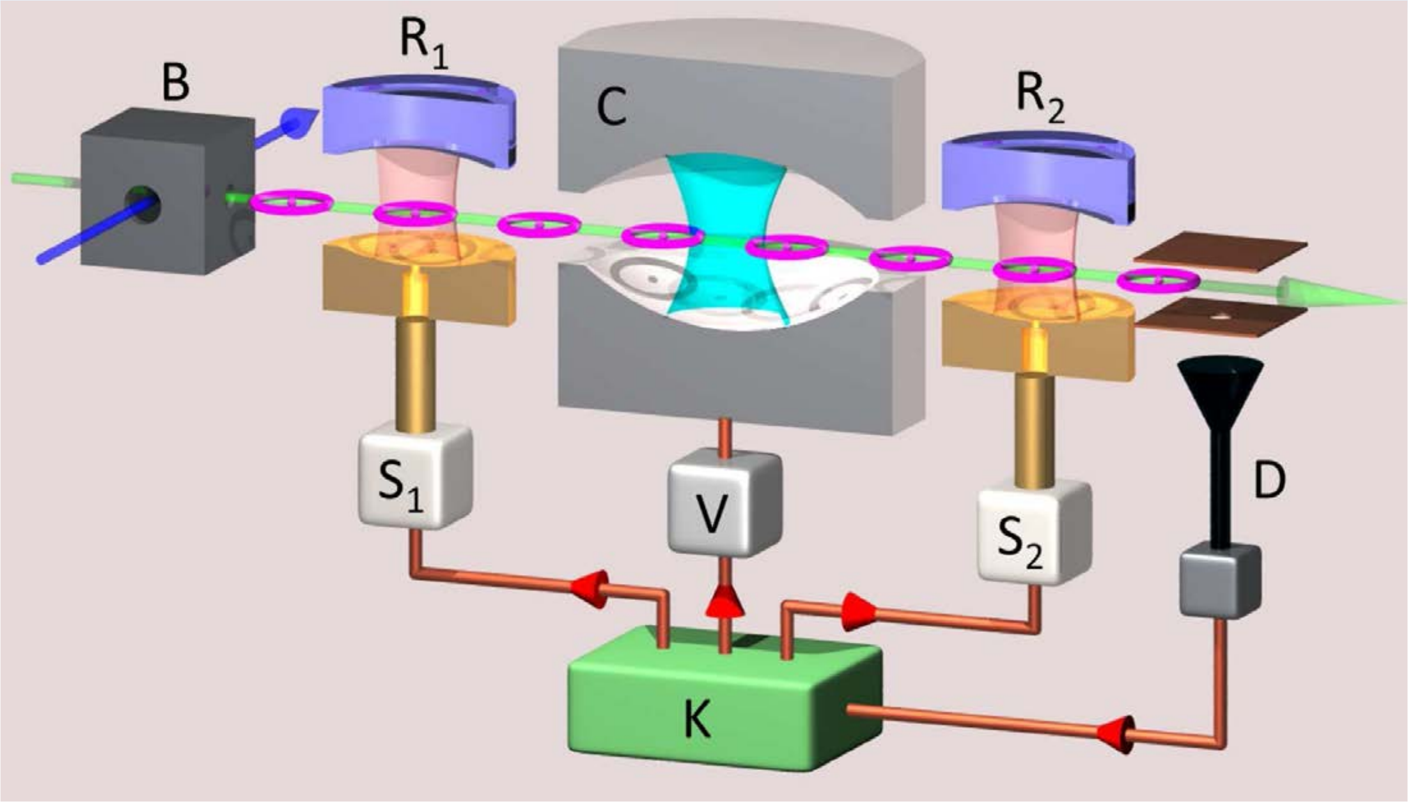
I. Dotsenko, M. Mirrahimi, M. Brune, S. Haroche, J.M. Raimond, P. Rouchon, Phys. Rev. A. 80, 013805 (2009)

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

- Quantum actuator
  - Resonant atoms used to inject/subtract photons
  - More demanding experimentally
  - Faster quantum jumps correction
  - Stabilization of Fock states up to n=7

X. Zhou *et al.,* PRL **108**, 243602 (2012)

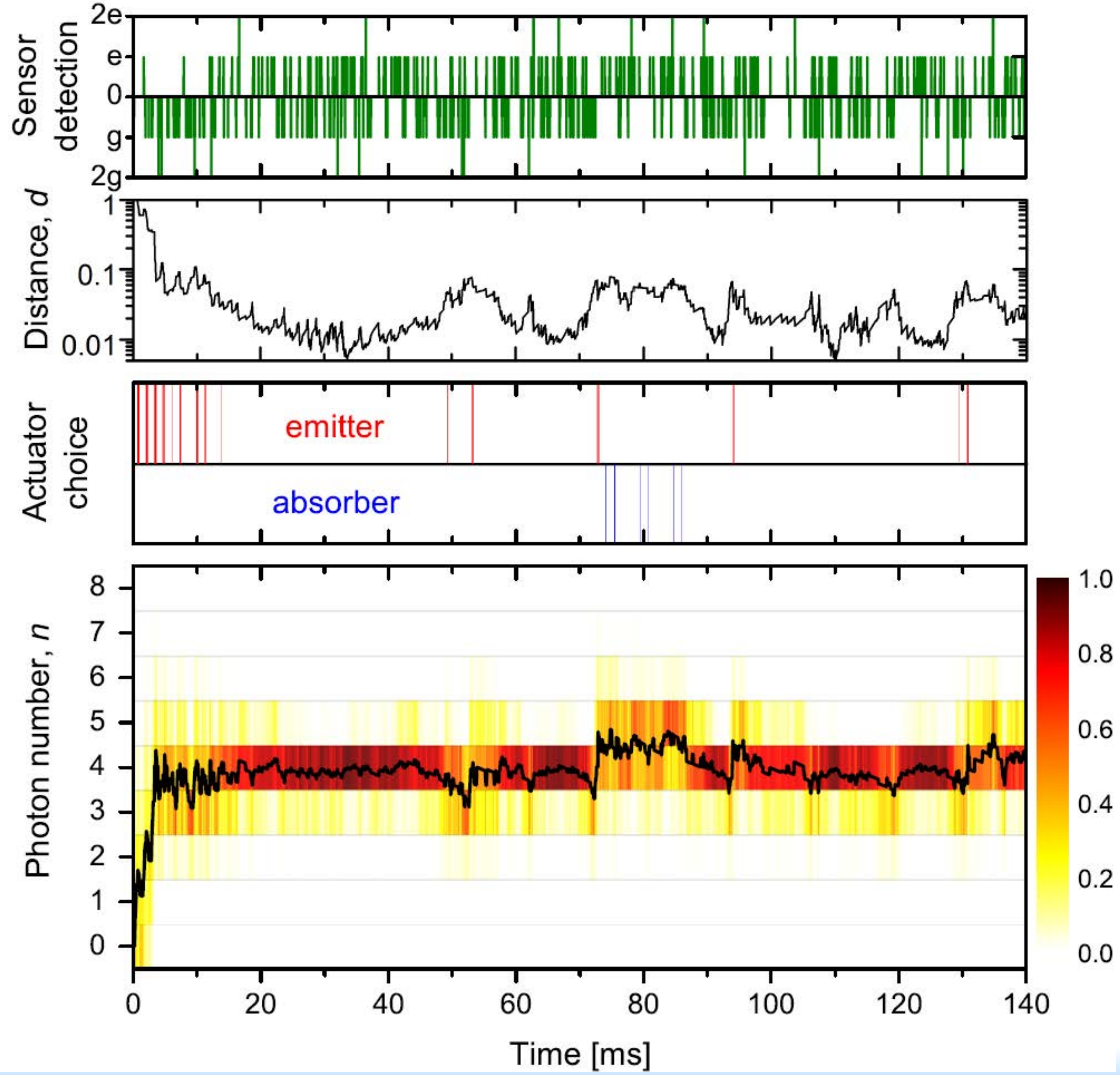
Scheme of the quantum actuator experiment



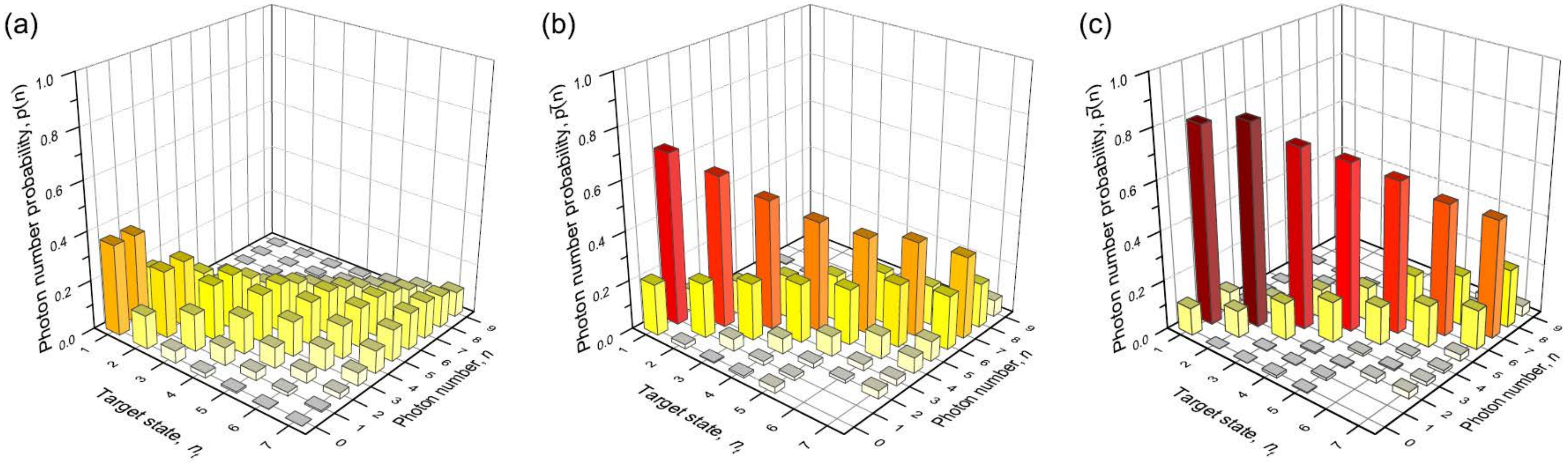
- Atomic samples
  - Sent in the cavity every 82 μs
  - Two types
    - Sensor QND samples (dispersive interaction)
    - Control samples (used by controller for feedback)
      - Absorbers, emitters or mere sensors

A single trajectory: closed loop

- Target photon number $n_t=4$



Feedback for high photon numbers



Reference
coherent state with
n_t photons on the average

Steady state
- stops loop at 140 ms
- independent QND estimation of average photon number distribution *P(n)*

Optimal stop
- Stops loop when $p(n_t)>0.8$
- Independent QMD estimation of *P(n)*

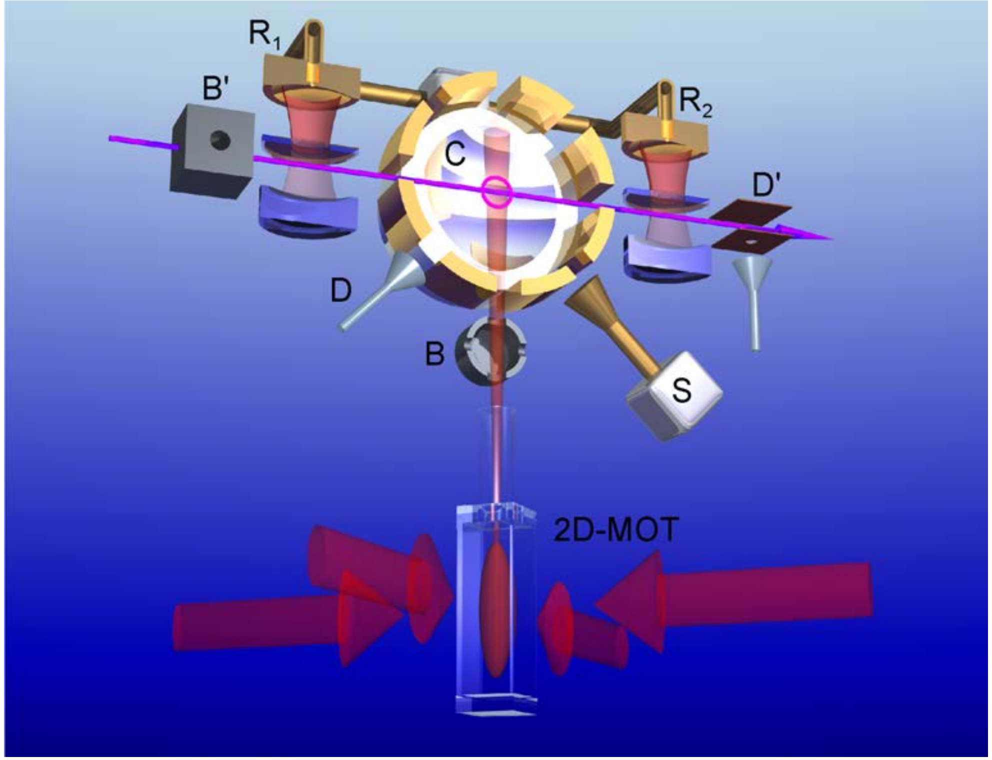
- Stabilization of photon numbers up to 7
- Convergence twice as fast as that of the feedback with coherent source

Conclusions and perspectives

- A nearly ideal quantum measurement of the photon number
  - Illustrates all measurement postulates
  - An insight into the fragility of mesoscopic quantum resources
- A quantum feedback mechanism
  - Prepares Fock states on demand
  - Preserves them against decoherence by reverting the quantum jumps
- Perspectives
  - An information optimal QND measurement
  - Quantum reservoir engineering: another route towards state protection
  - Quantum Zeno dynamics: tailor the Hilbert space for nonclassical state generation

A new cavity QED set-up

- A strong limitation of present experiments
  - Atom-cavity interaction time << both systems lifetime
    - 100 μs << 30ms, 0.13 s
- Achieving long interaction times
  - A set-up with a stationary Rydberg atom in a cavity

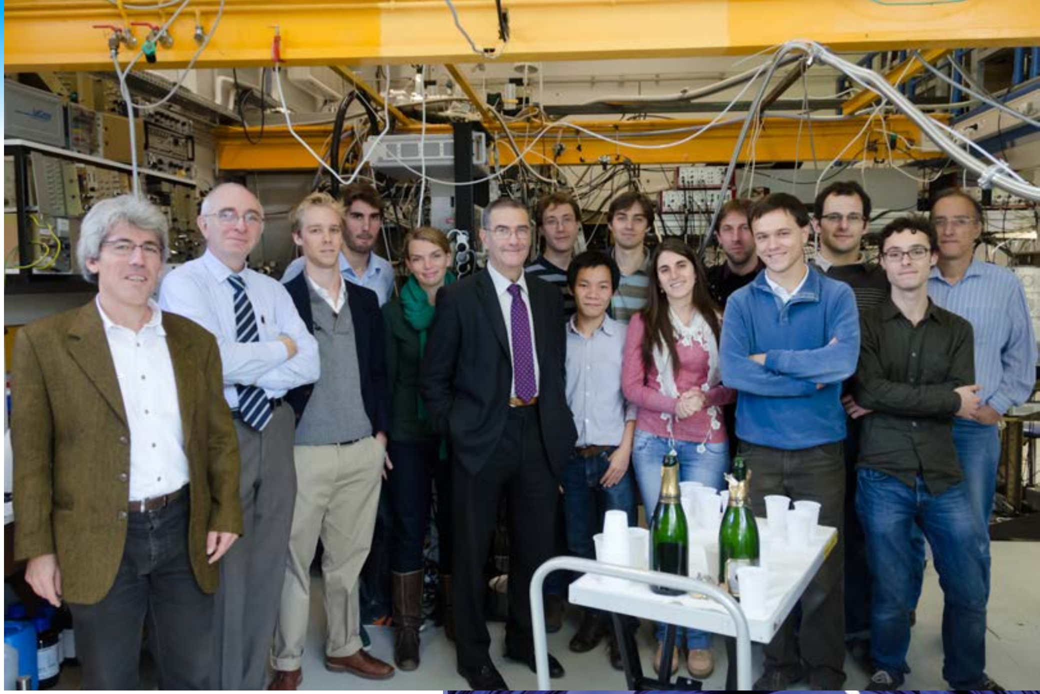


  - Circular state preparation and detection in the cavity
  - Interaction time ms range

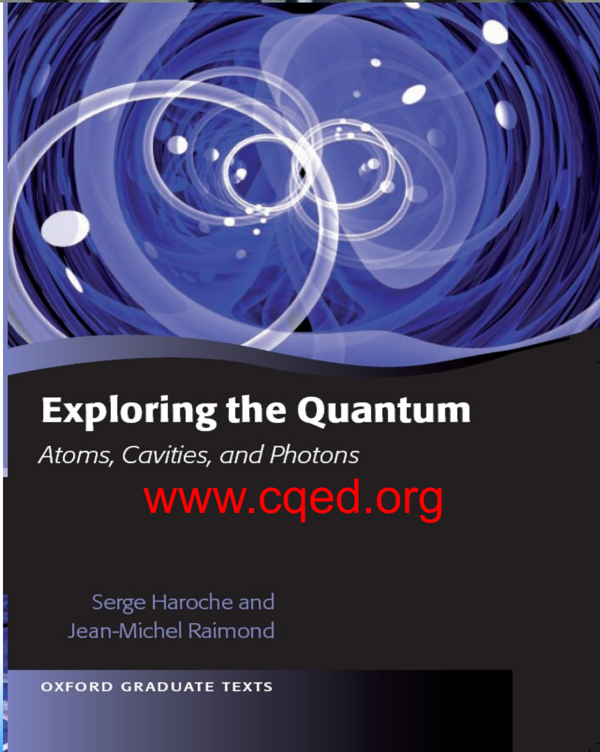
Large cats, QZD and reservoir engineering

A team work

- S. Haroche, M. Brune,
  JM Raimond, S. Gleyzes, I. Dotsenko,
- Cavity QED experiments
  - S. Gerlich
    T. Rybarczyk, A. Signoles,
    A. Facon, D. Grosso, E.K. Dietsche



- Superconducting atom chip
  - R. Teixeira, C. Hermann,
  - Thanh Long Nguyen, T. Cantat-Moltrecht
- Collaborations:
  - Cavités: P. Bosland, B. Visentin, E. Jacques
    - CEA Saclay (DAPNIA)
  - Rétroaction: P. Rouchon, M. Mirrahimi, A. Sarlette
    - Ecole des Mines Paris
  - QZD: P. Facchi, S. Pascazio
    - Uni. Bari and INFN
- €€:ERC (Declic), EC (SIQS, RYSQ, CCQED),
  - ANR (QUSCO),CNRS, UMPC, IUF, CdF



A team work… along the years

- By order of appearance

  - 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
  - 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
  - Angie Qarry
  - 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
  - Theo Rybarczyk
  - Carla Hermann
  - Adrien Signoles
  - Adrien Facon
  - Eva Dietsche
  - Stefan Gerlich
  - Than Long Nguyen
  - Mariane Penasa
  - Dorian Grosso
  - Tigrane Cantat
  - Mehdi Hamoumi
  - …