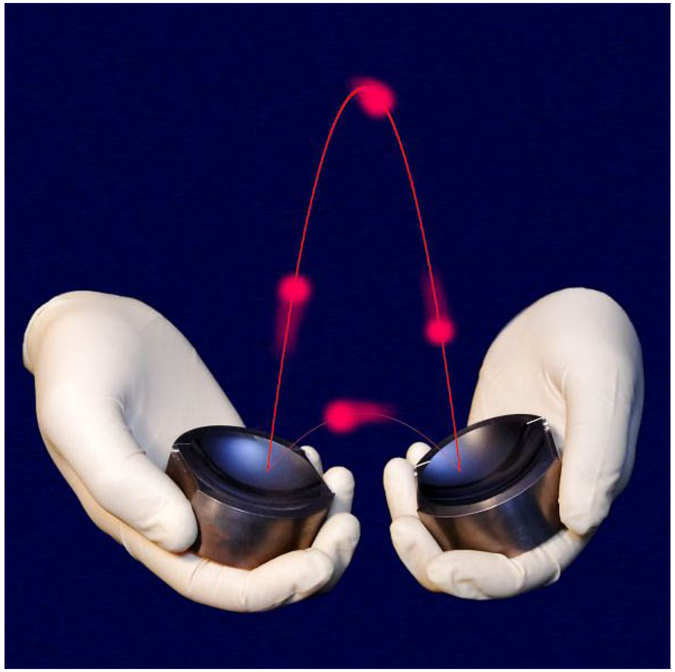
A 30 years walk in the quantum with atoms and cavities

J.M. Raimond

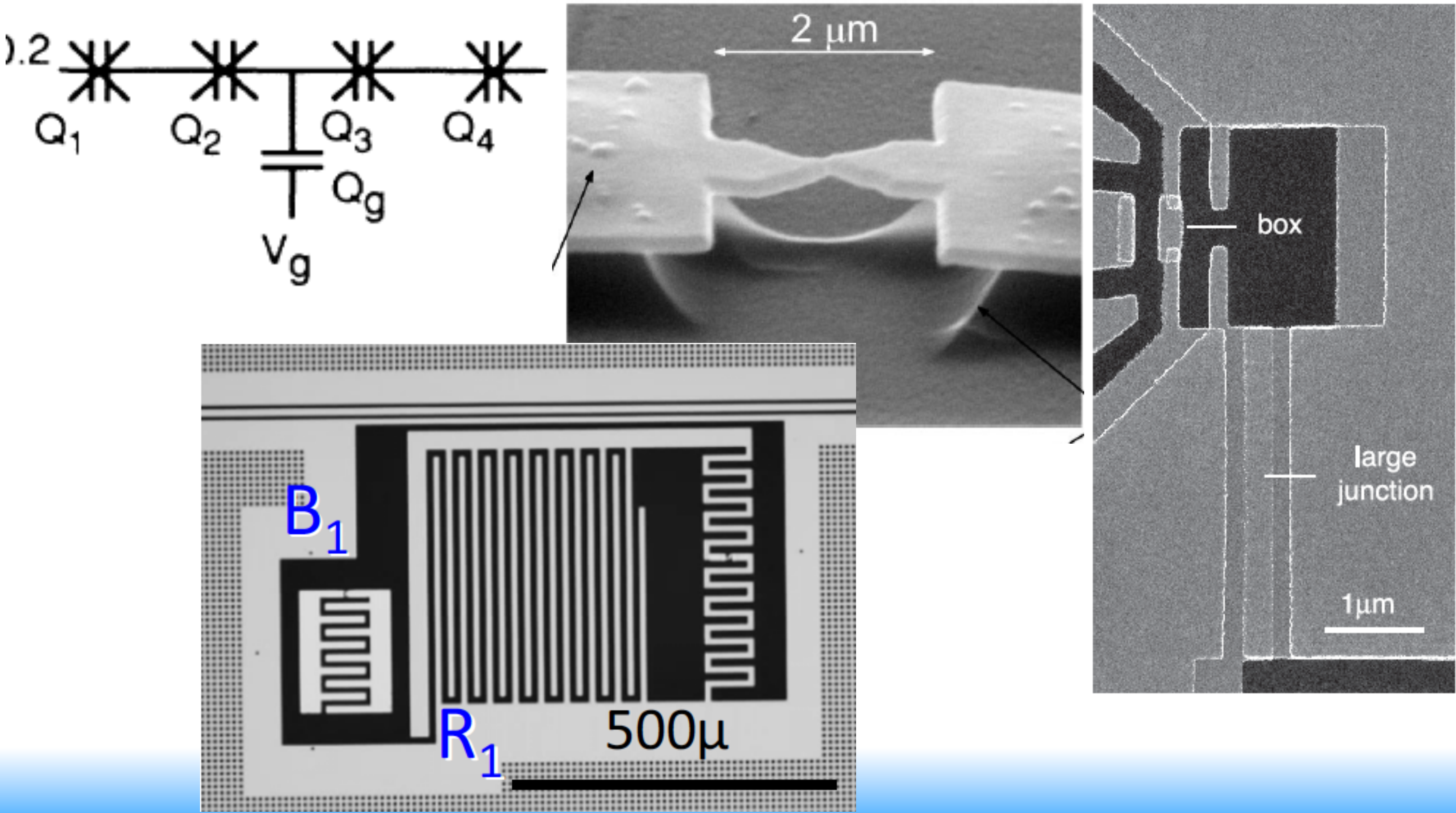
Université Pierre et Marie Curie

Laboratoire Kastler Brossel
Physique quantique et applications



Happy anniversary, Quantronics

- 30 years of (very successful) quantum world exploration
  - From tunnel effect in junctions to single electron control
  - From Quantronium to circuit QED



Happy anniversary, quantronics

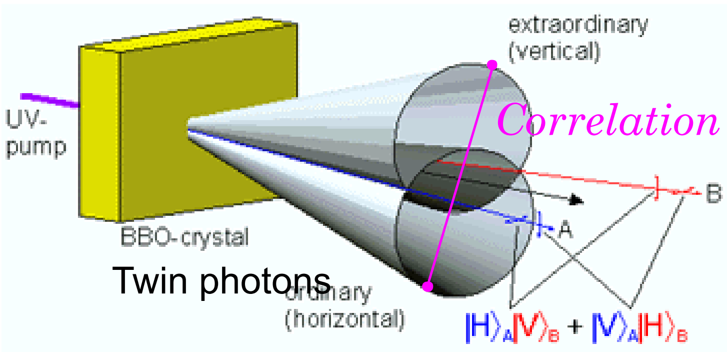
- Curiosity-driven research on basic quantum phenomena
  - Quantum coherence
  - Quantum measurement
  - Quantum entanglement

- Leading to a better understanding of the quantum
  - Quantum and information
  - Quantum postulates
  - Limits of the quantum world
    - Why is the classical world classical at all?

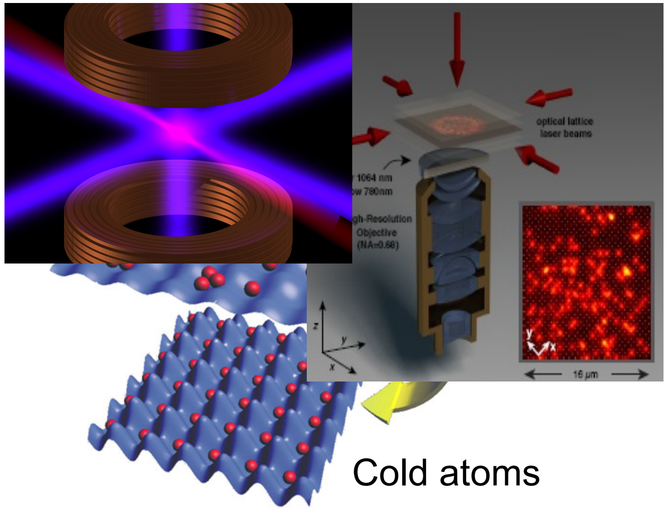
- And to possible applications
  - Quantum metrology
  - Quantum simulation
  - Quantum communication and computing

A thriving field worldwide

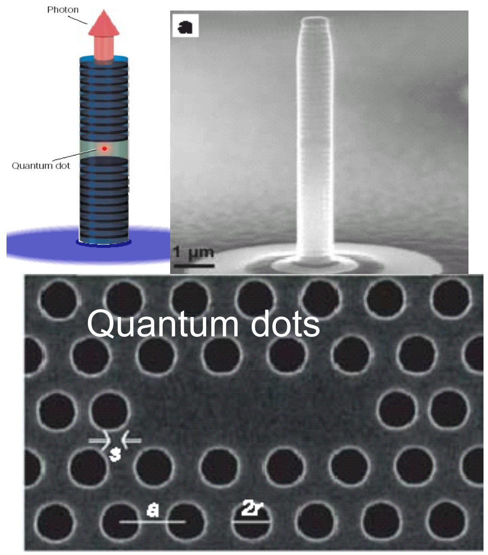
- Many other experiments explore fundamental quantum physics



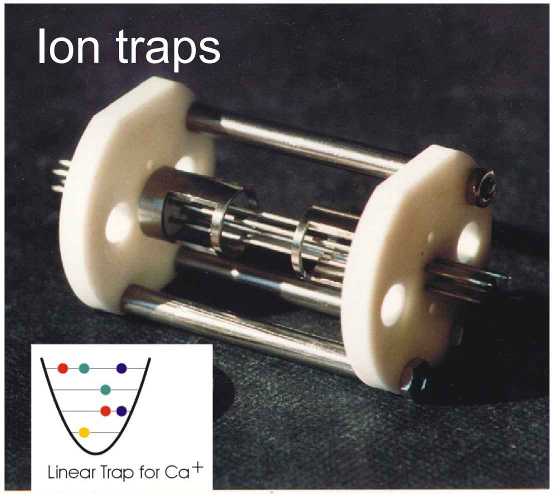
Twin photons



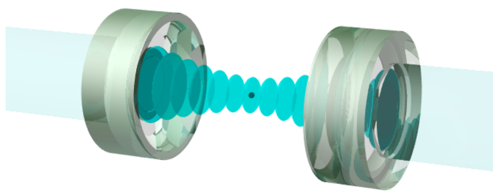
Cold atoms



Quantum dots



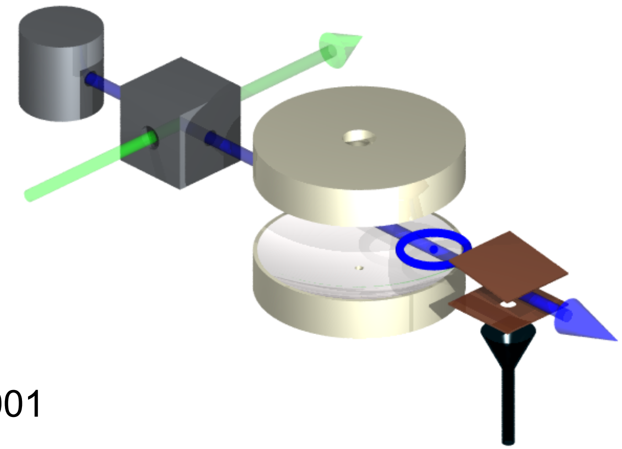
Ion traps



Atoms and cavities

Cavity Quantum Electrodynamics

- A spin and a spring



J.M. Raimond and M. Brune, EPL **110**, 200001

  – Realizes the simplest matter-field system: a single atom coherently coupled to a few photons in a single mode of the radiation field.
    - Direct illustrations of quantum postulates

- CQED group at ENS
  – 30 years + of CQED
    - In parallel with the Quantronics group, with similar aims
    - And with a similar group organization
      – Kernel of senior permanent people

A history of CQED: the origin

- Purcell 1946
  - spontaneous emission rate modification for a spin in a resonant circuit
  - Definition of the 'Purcell factor'
  - Brief but seminal
- Kleppner 81
  - Inhibition of spontaneous emission

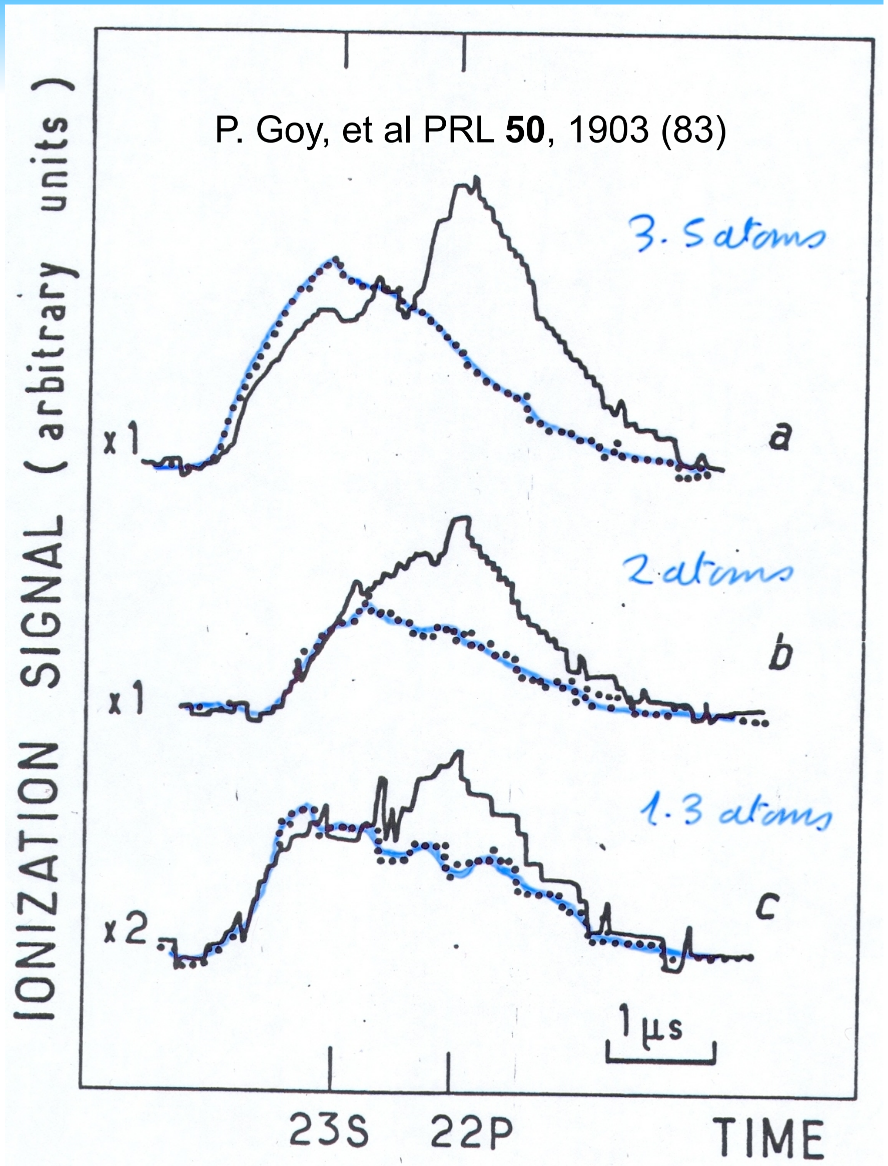
B10. Spontaneous Emission Probabilities at Radio Frequencies. E. M. PURCELL, *Harvard University.*—For nuclear magnetic moment transitions at radio frequencies the probability of spontaneous emission, computed from

$$A_\nu = (8\pi\nu^2/c^3)h\nu(8\pi^3\mu^2/3h^2)\ \text{sec.}^{-1},$$

is so small that this process is not effective in bringing a spin system into thermal equilibrium with its surroundings. At 300°K, for $\nu = 10^7$ sec.$^{-1}$, $\mu = 1$ nuclear magneton, the corresponding relaxation time would be 5×10^{21} seconds! However, for a system coupled to a resonant electrical circuit, the factor $8\pi\nu^2/c^3$ no longer gives correctly the number of radiation oscillators per unit volume, in unit frequency range, there being now *one* oscillator in the frequency range ν/Q associated with the circuit. The spontaneous emission probability is thereby increased, and the relaxation time reduced, by a factor $f = 3Q\lambda^3/4\pi^2V$, where V is the volume of the resonator. If a is a dimension characteristic of the circuit so that $V\sim a^3$, and if δ is the skin-depth at frequency ν, $f\sim\lambda^3/a^2\delta$. For a non-resonant circuit $f\sim\lambda^3/a^3$, and for $a<\delta$ it can be shown that $f\sim\lambda^3/a\delta^2$. If small metallic particles, of diameter 10^{-3} cm are mixed with a nuclear-magnetic medium at room temperature, spontaneous emission should establish thermal equilibrium in a time of the order of minutes, for $\nu = 10^7$ sec.$^{-1}$.

First single-atom experiments

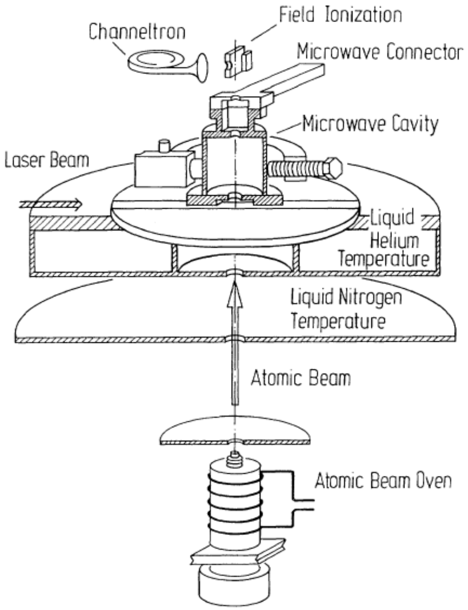
- Spontaneous emission enhancement
  - Superconducting FP cavity
    - Q α 10^6
    - 340 GHz transition
  - Acceleration x 530
  - First experimental evidence of Purcell effect
- Spontaneous emission inhibition
  - Gabrielse and Dehmelt (85)
  - Hulet, Hilfer and Kleppner (85)

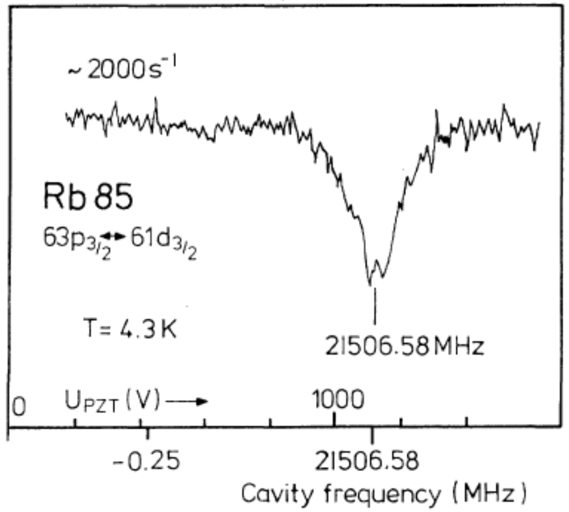


- Spontaneous emission can be altered at will by imposing limiting conditions to the field

The Micromaser

- H. Walther and D. Meschede, 85
  - Cumulative emissions in the cavity in the strong coupling regime





  - A maser with less than one atom at a time in the cavity
  - A new type of quantum oscillator. Role of quantum fluctuations
  - Strong coupling regime
    - Single-Atom-cavity coupling overwhelms dissipation

The four time scales of CQED

- Atomic levels lifetime

$$T_{at} = 1/\Gamma$$

- Cavity lifetime

$$T_c = 1/\kappa$$

- Atom-cavity coupling

$$\Omega_0 = 2g = 1/T_{res}$$

- Atom-cavity interaction time

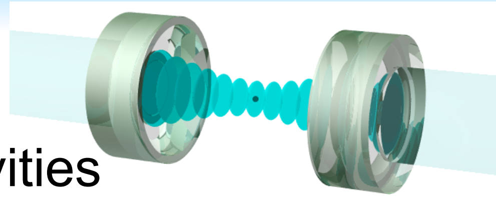
$$T_{\text{int}}$$

- Strong coupling conditions

$$T_{\text{int}}\Omega_0 \approx 1; \quad T_{res}, T_{\text{int}} << T_{at}, T_c$$

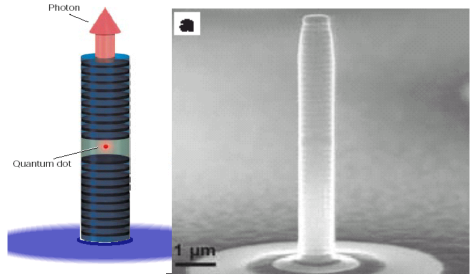
The four flavours of modern CQED

- Optical CQED
  - Ordinary atomic transitions and high finesse FP cavities



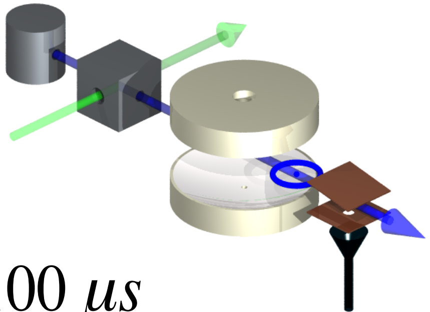
$$g \approx 50\ \text{MHz};\ \kappa \approx 100\ \text{kHz};\ \Gamma \approx 10\ \text{MHz};\ T_{\text{int}} \approx 1\text{s}$$

- Solid-state CQED
  - Quantum dots coupled to bragg mirrors/PBG



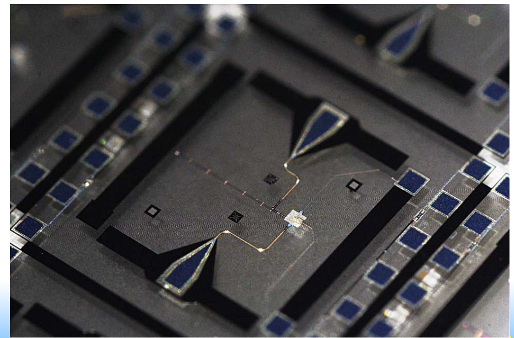
$$g \approx 10\ \text{GHz};\ \kappa \approx 1\ \text{GHz};\ \Gamma \approx\ 1\text{GHz};\ T_{\text{int}} = \infty$$

- Microwave CQED
  - (Circular) Rydberg atoms and superconducting cavities



$$g \approx 10\ \text{kHz};\ \kappa \approx 1\ \text{Hz};\ \Gamma \approx 30\ \text{Hz};\ T_{\text{int}} \approx 100\ \mu s$$

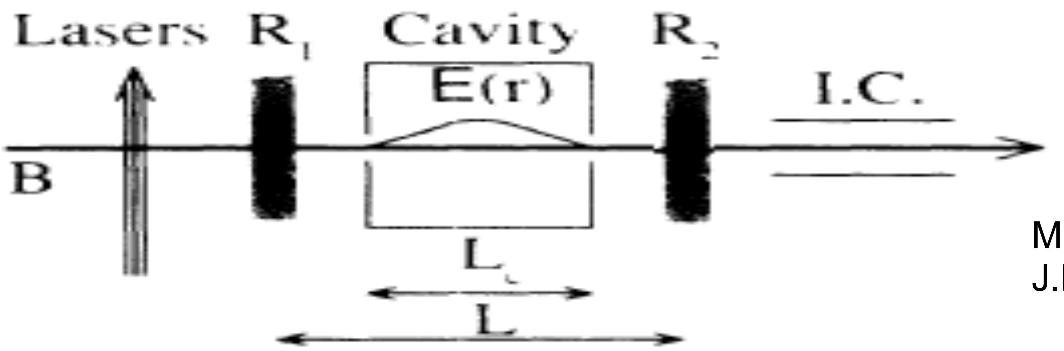
- Circuit QED
  - Solid-state qubits and microwave cavities



$$g \simeq 100MHz; \Gamma \ll \kappa \simeq 1MHz; T_{int} = \infty$$

The ‘modern age’ of microwave CQED

- 25 years ago: a proposal
  - Use dispersive atom-field interaction to perform a QND photon counting
    - Measurement of quantized light shifts with a Ramsey set-up

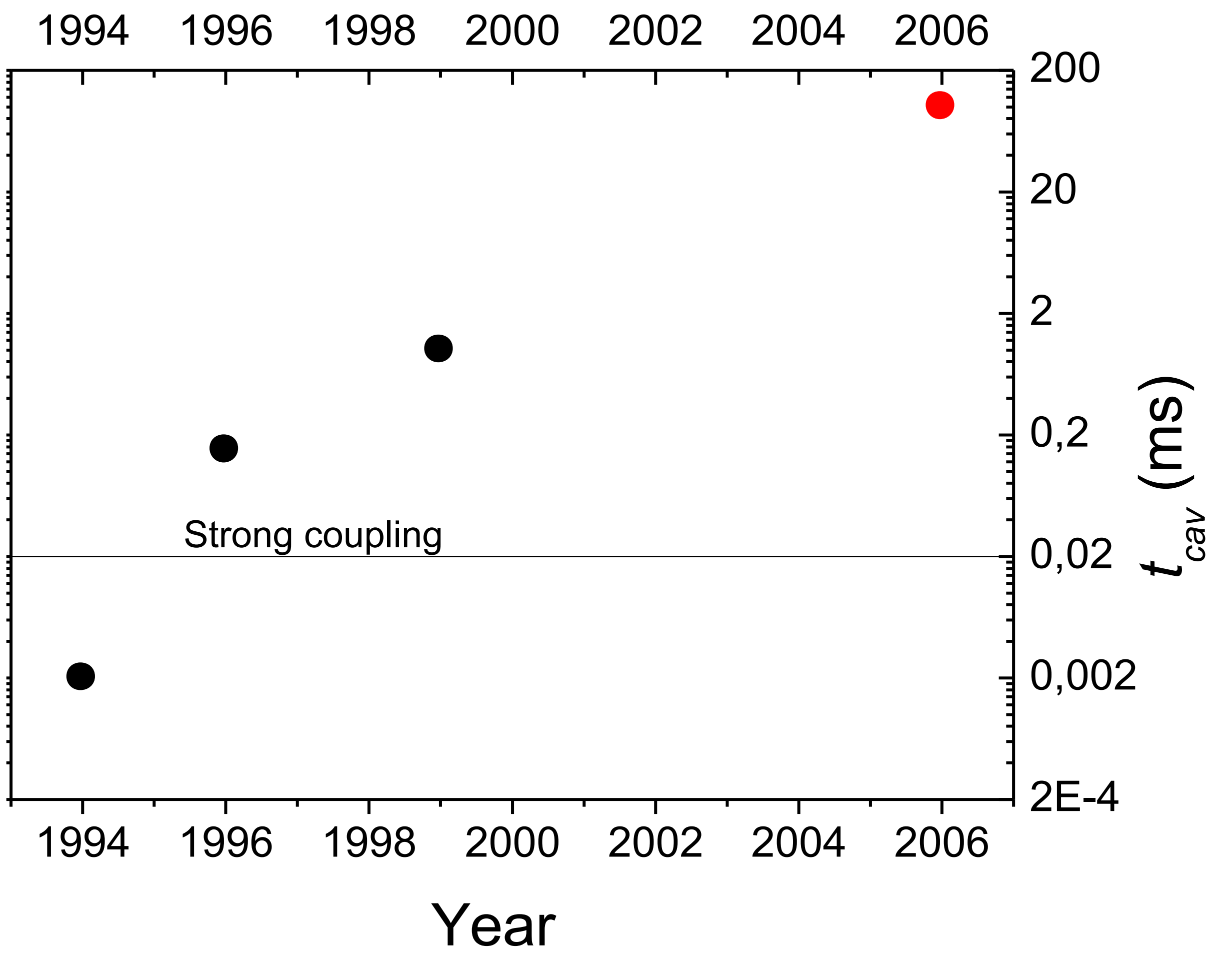


M. Brune, S. Haroche, V. Lefèvre, J.M. Raimond, N. Zagury, PRL **65**, 976 (1990)

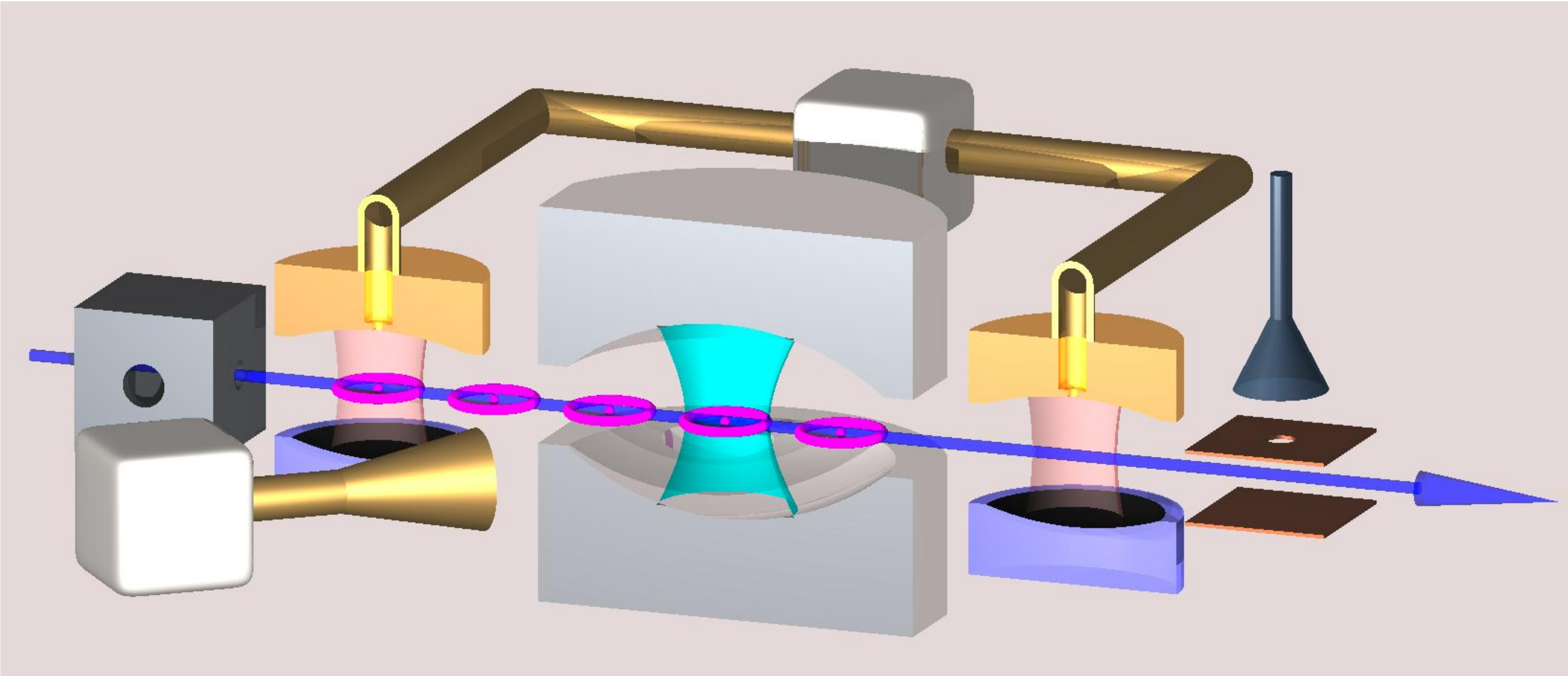
- The beginning of a long quest
  - Severe experimental requirements
    - Long atomic lifetimes
      - Circular Rydberg atoms
    - Even longer cavity storage times
      - Superconducting Fabry Perot cavities
    - Extreme shielding from outer perturbations
      - Many technical developments

Progress at the (slow) pace of cavity technology…

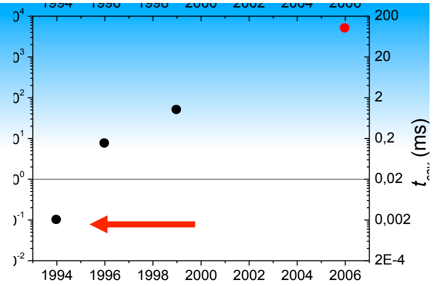
- Time evolution of photon life expectancy…



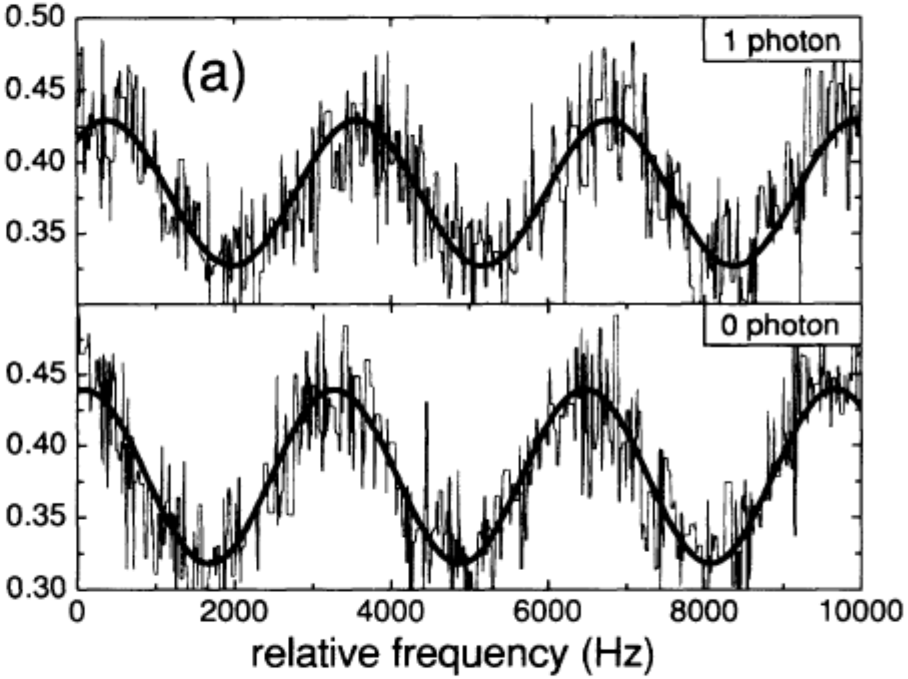
… with a simple experimental scheme

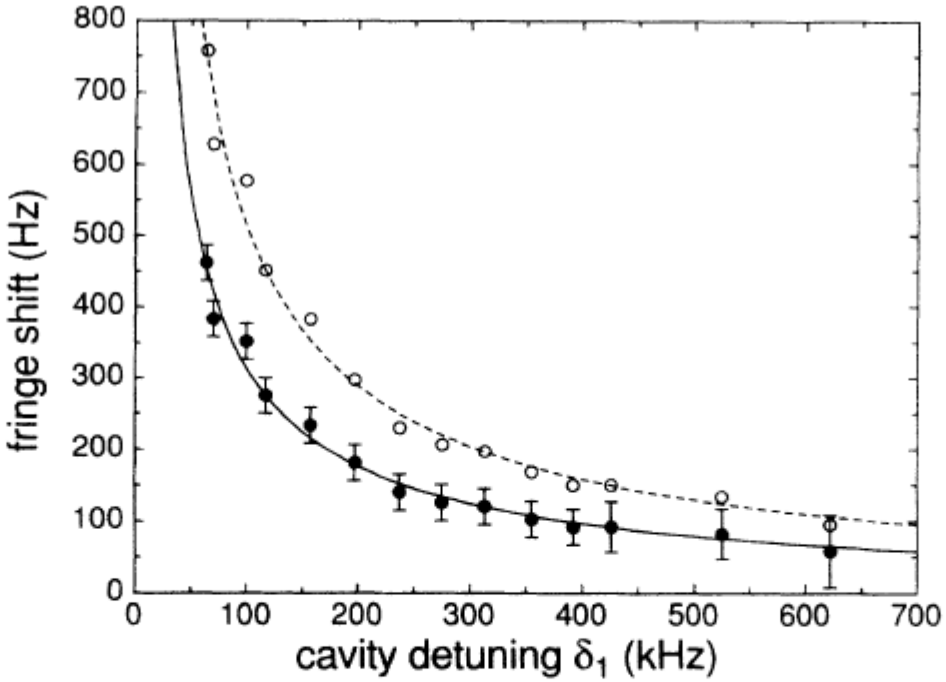


Early days: Lamb shifts and Light shifts



- Weak coupling regime
  - Cavity damping time = 1/10 atomic transit time !
    - Observation of Light shifts (no field quantization effect yet) and cavity-vacuum induced Lamb shift

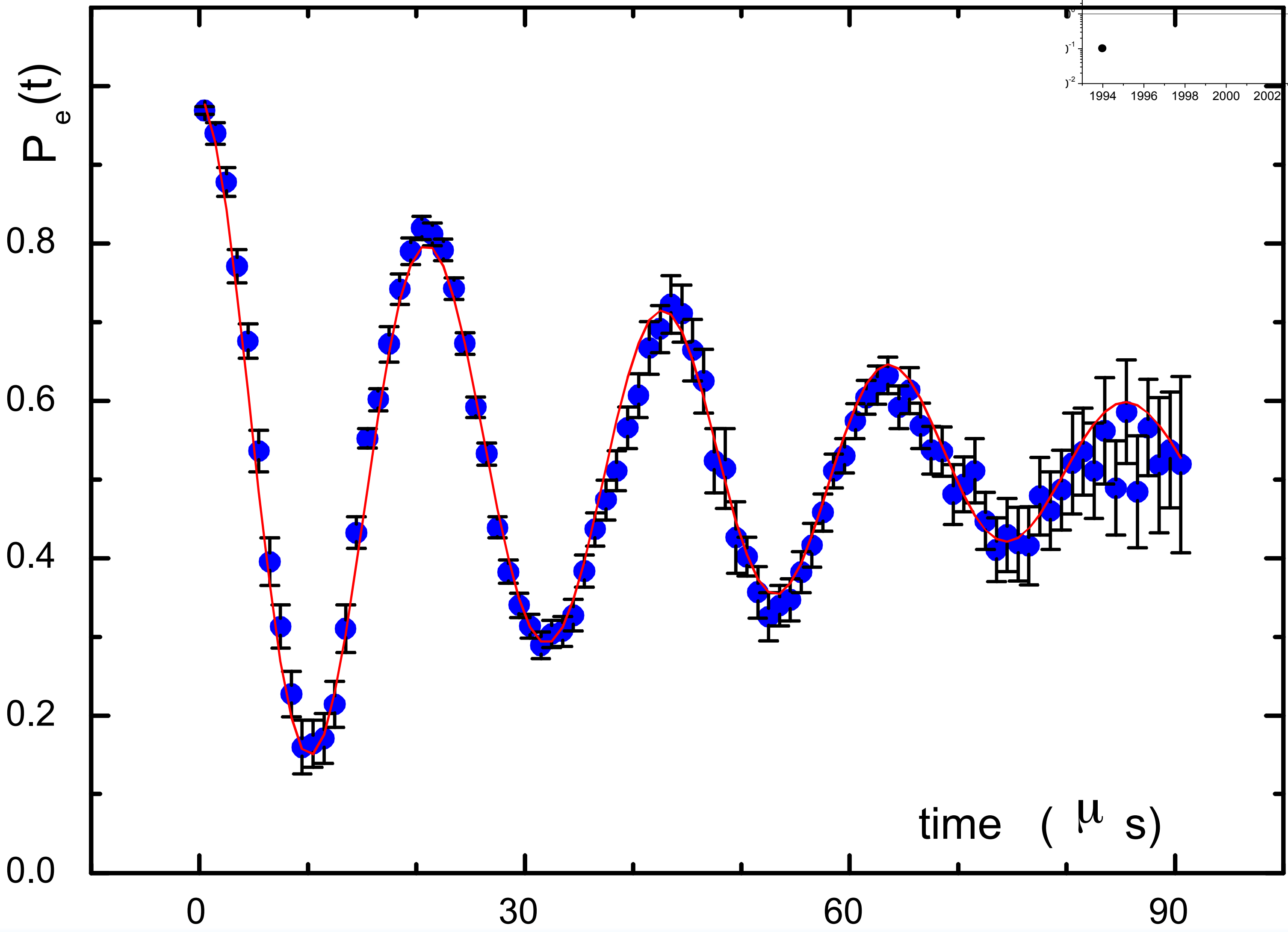


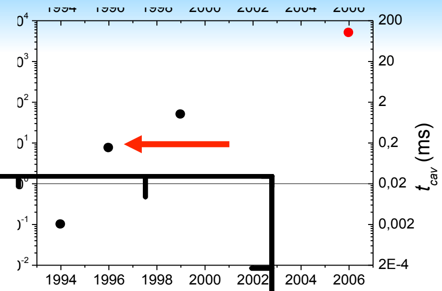


M. Brune, P. Nussenzveig, F. Schmidt-Kaler, F. Bernardot, A. Maali, J.M. Raimond, S. Haroche, PRL **72**, 3339 (94)

Strong coupling regime: quantum Rabi oscillations

- Resonant atomic emission in an empty cavity

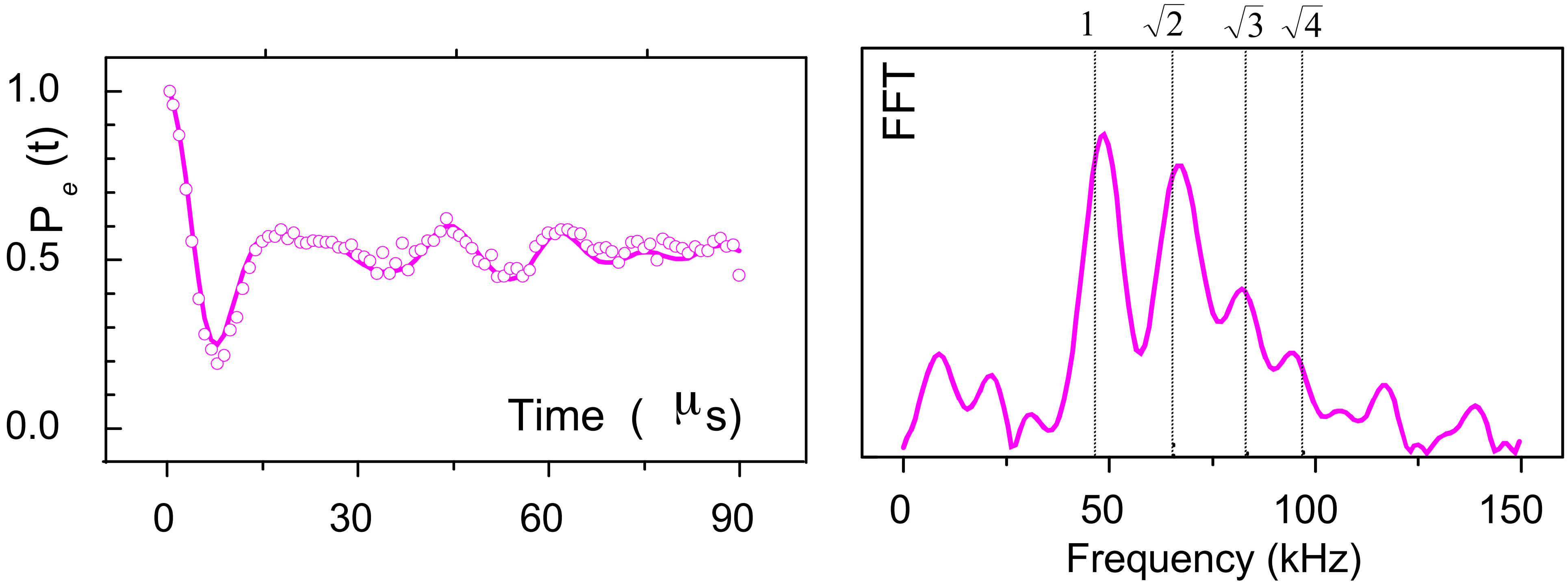




M. Brune, , F. Schmidt-Kaler, A. Maali, J. Dreyer, E. Hagley, J.M. Raimond, S. Haroche, PRL **76,** 1800 (96)

Strong coupling regime: quantum Rabi oscillations

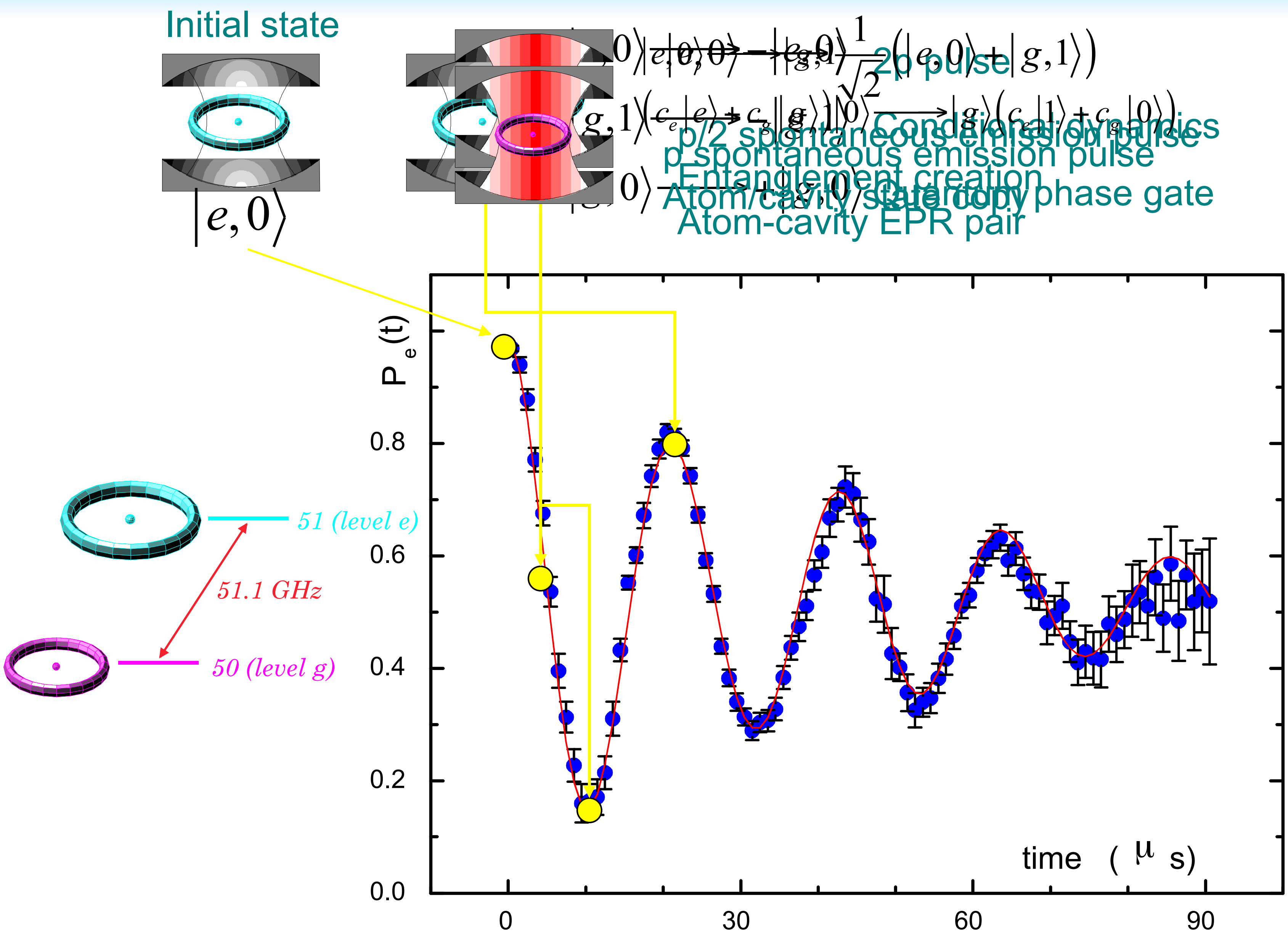
- Rabi oscillation in a small (0.85 photon) coherent field



  – A visceral evidence of field quantization

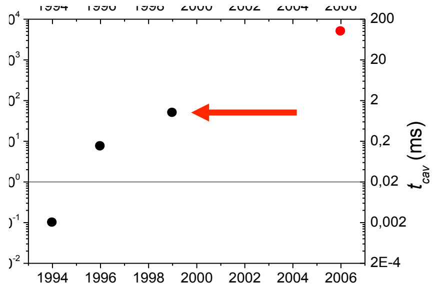
M. Brune, , F. Schmidt-Kaler, A. Maali, J. Dreyer, E. Hagley, J.M. Raimond, S. Haroche, PRL **76,** 1800 (96)

Quantum Rabi oscillations: state transformations



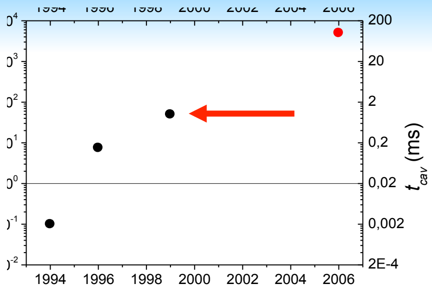
Three "stitches" to "knit" quantum entanglement

Combine elementary transformations to create complex entangled states



- State copy with a π pulse
  - Quantum memory : PRL **79**, 769 (97)
- Creation of entanglement with a $\pi/2$ pulse
  - EPR atomic pairs : PRL **79**, 1 (97)
- Quantum phase gate based on a 2π pulse
  - Quantum gate : PRL **83**, 5166 (99)
  - Absorption-free detection of a single photon: Nature **400**, 239 (99)
- Entanglement of three systems (six operations on four qubits)
  - GHZ Triplets : Science **288**, 2024 (00)
- Entanglement of two radiation field modes
  - Phys. Rev. A **64**, 050301 (2001)
- Direct entanglement of two atoms in a cavity-assisted collision
  - Phys. Rev. Lett. **87**, 037902 (2001)

The cavity field as a mesoscopic quantum object



Coherent state in the cavity field : a mesoscopic object.

- Low photon number: large quantum fluctuations
- High photon number : essentially a classical field

Very well isolated from the environment (long cavity damping time)

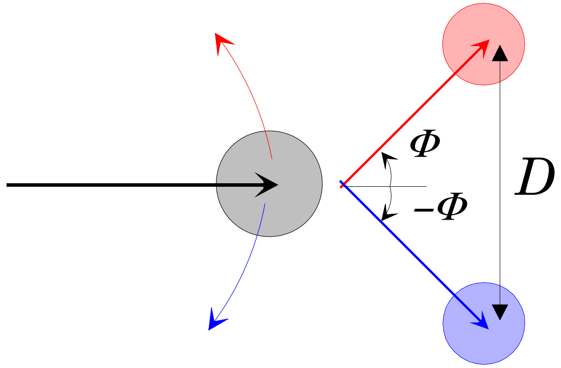
An excellent tool to study the quantum/classical limit

A few problems addressed in 1996-2005

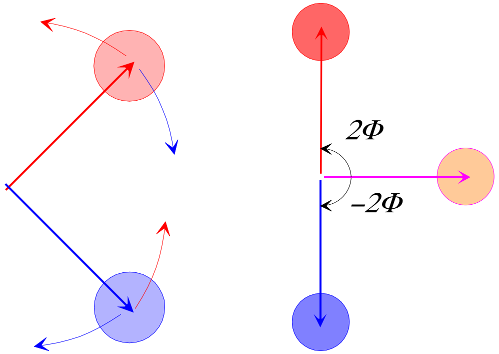
- Complementarity
  - P. Bertet, S. Osnaghi, A. Rauschenbeutel, G. Nogues, A. Auffeves, M. Brune, J.M. R., S. Haroche, Nature, **411**, 166 (2001)
- Decoherence of a mesoscopic state quantum superposition:
  - a Schrödinger cat experiment
- Creation of large cats by resonant atom-field interaction
  - A. Auffèves, P. Maioli, T. Meunier, S. Gleyzes, G. Nogues, M. Brune, J.M. R., S. Haroche, PRL **91**, 230405 (2003); T. Meunier, S. Gleyzes, P. Maioli, A. Auffeves, G. Nogues, M. Brune, J.M. R., S. Haroche, Phys. Rev. Lett. **94**, 010401 (2005)

A laboratory version of Schrödinger's cat

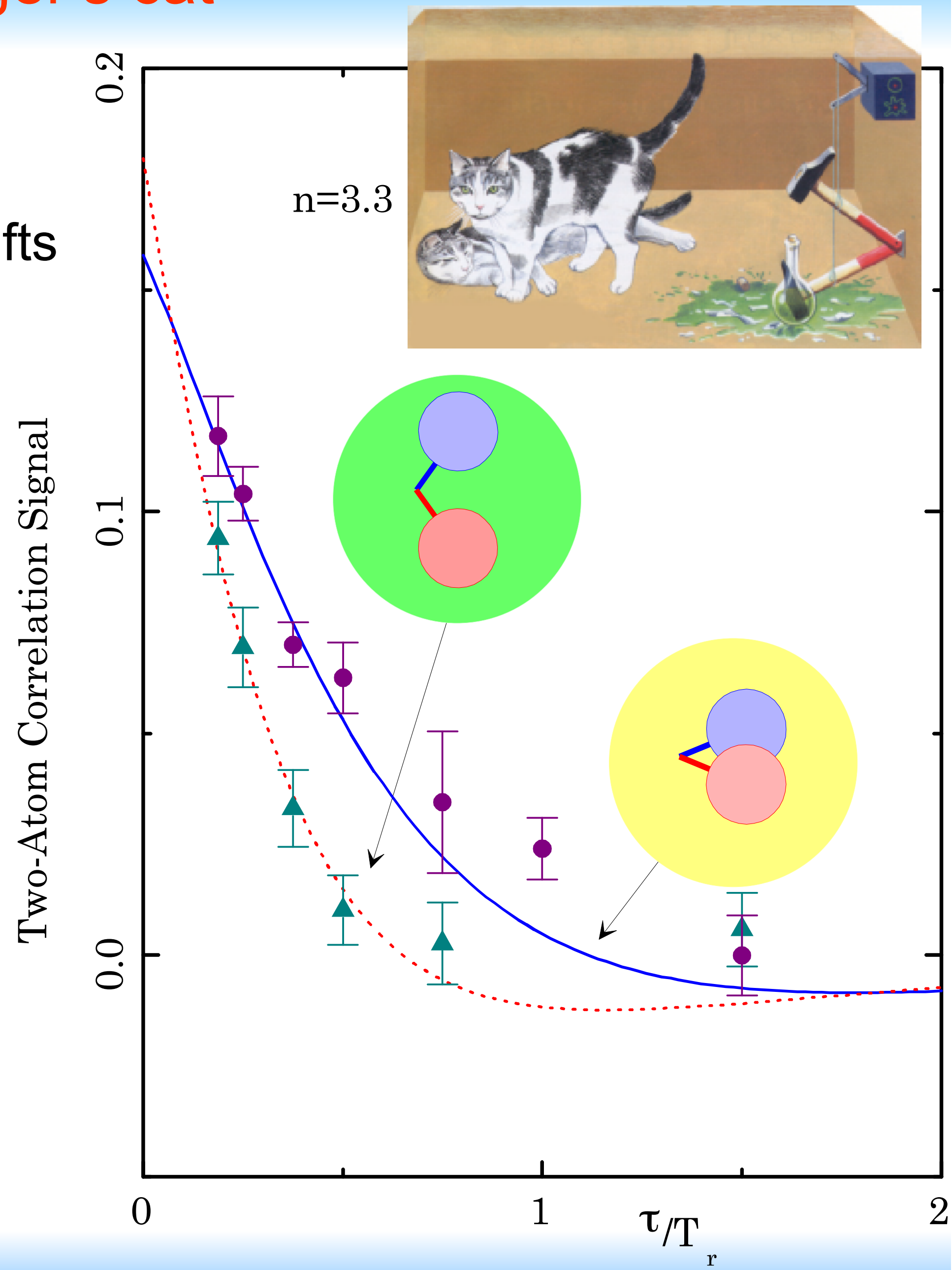
- Dispersive atom-field interaction
  - Atom in level superposition creates superposition of phase shifts



  - Second atom probes it

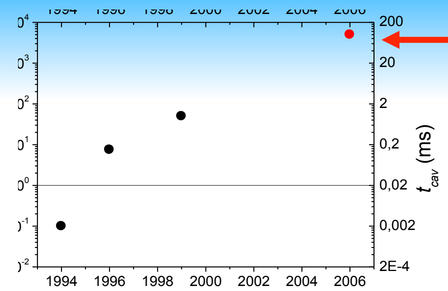


  - Correlation signal measures quantumness

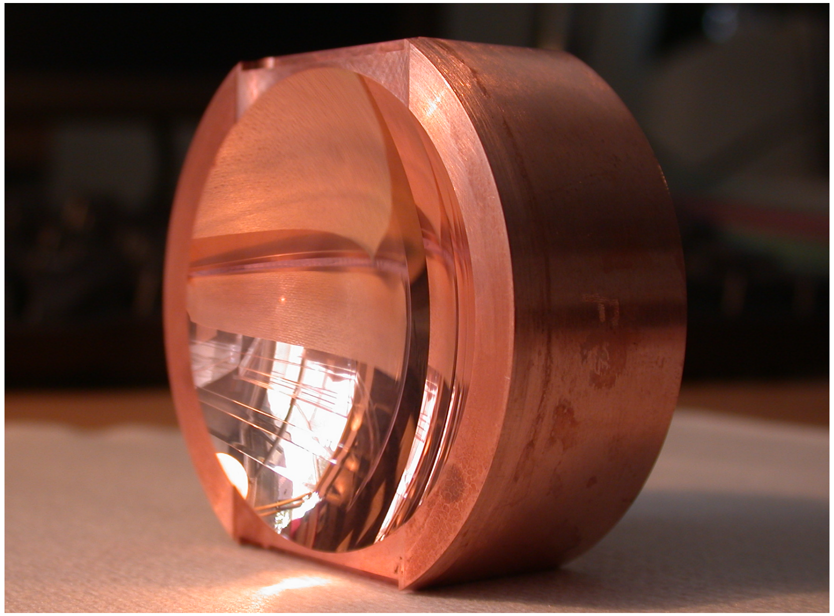


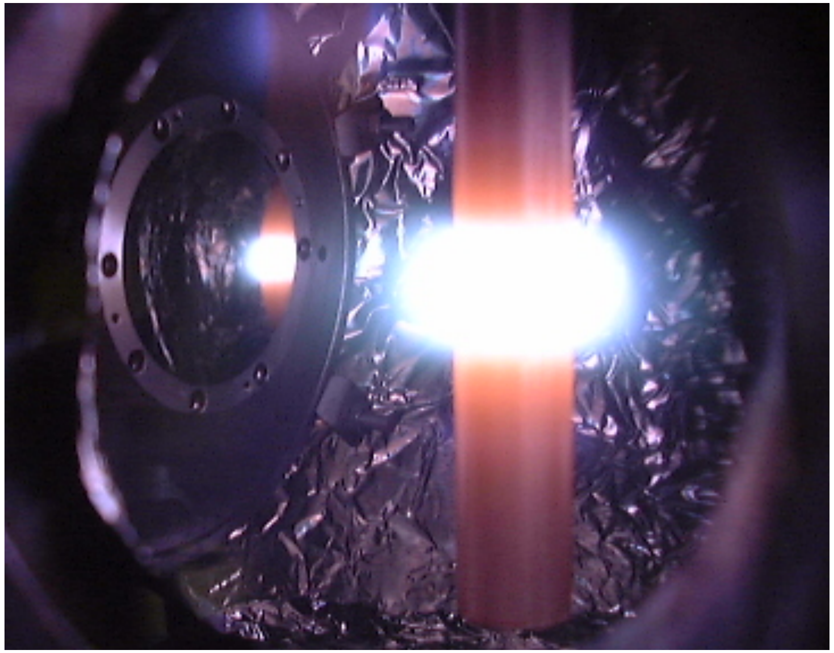
M. Brune, E. Hagley, J. Dreyer, X. Maître, A. Maali, C. Wunderlich, J.M. R., S. Haroche, PRL **77**, 4887 (1996)

A quantum jump in cavity quality



- The key bottleneck
  - Cavity lifetime:
    - A new technology
      - Niobium on diamond machined copper





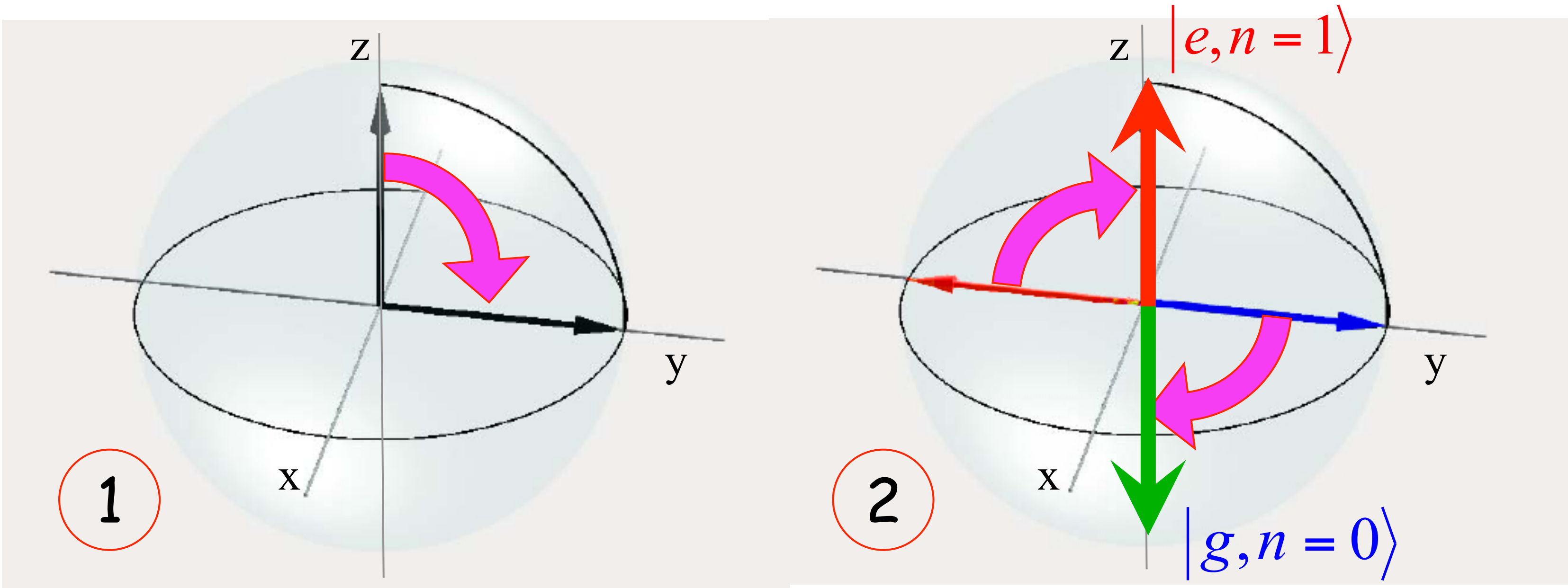
  - Unprecedented lifetime
    - T_c=0.13 s
    - Q=4.2 10^{10}, F=4.6 10^{9}

CEA, Saclay
[E. Jacques, B. Visentin, P. Bosland]

S. Kuhr, S. Gleyzes, C. Guerlin, J. Bernu, U. B. Hoff, S. Deléglise, S. Osnaghi, M. Brune, J.M. R., S. Haroche, E. Jacques, P. Bosland, B. Visentin, APL, **90**, 164101

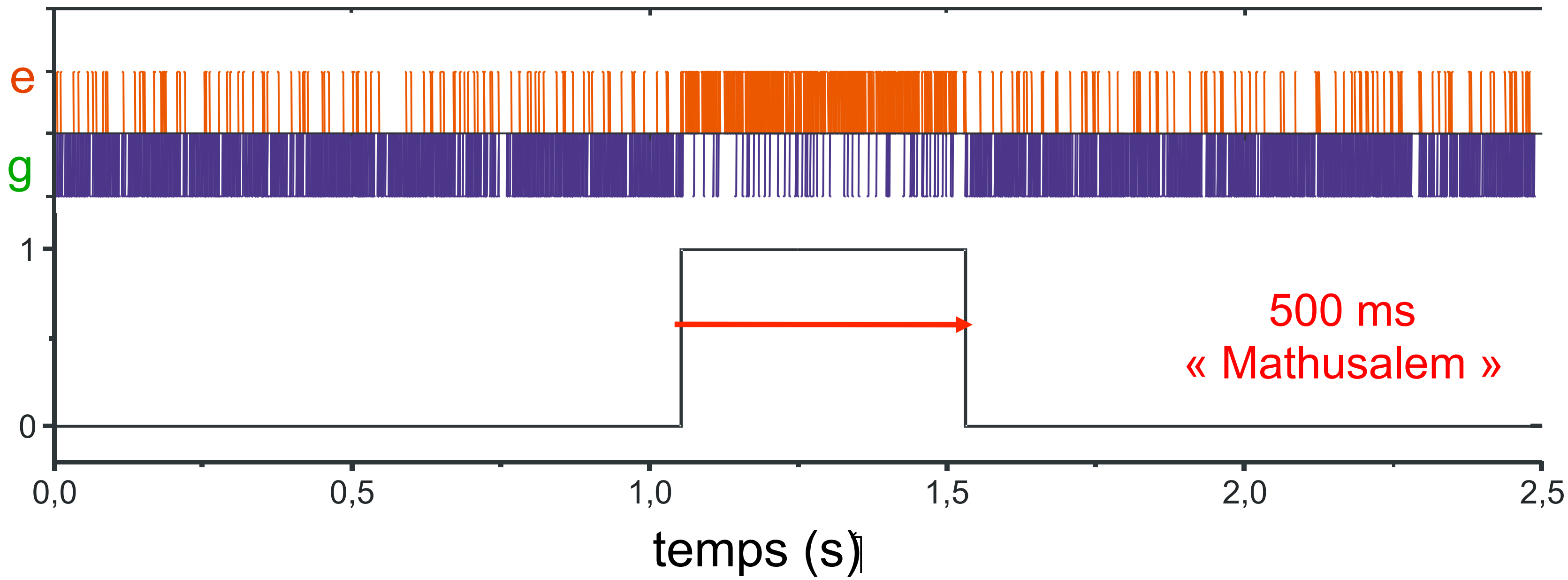
Realization of the 1990 proposal in a simple case

- A zero/one photon measurement
  - π phase shift per photon



  - in an ideal experiment, the final atomic state directly reveals the photon number
    - *g* for zero photon
    - *e* for one photon

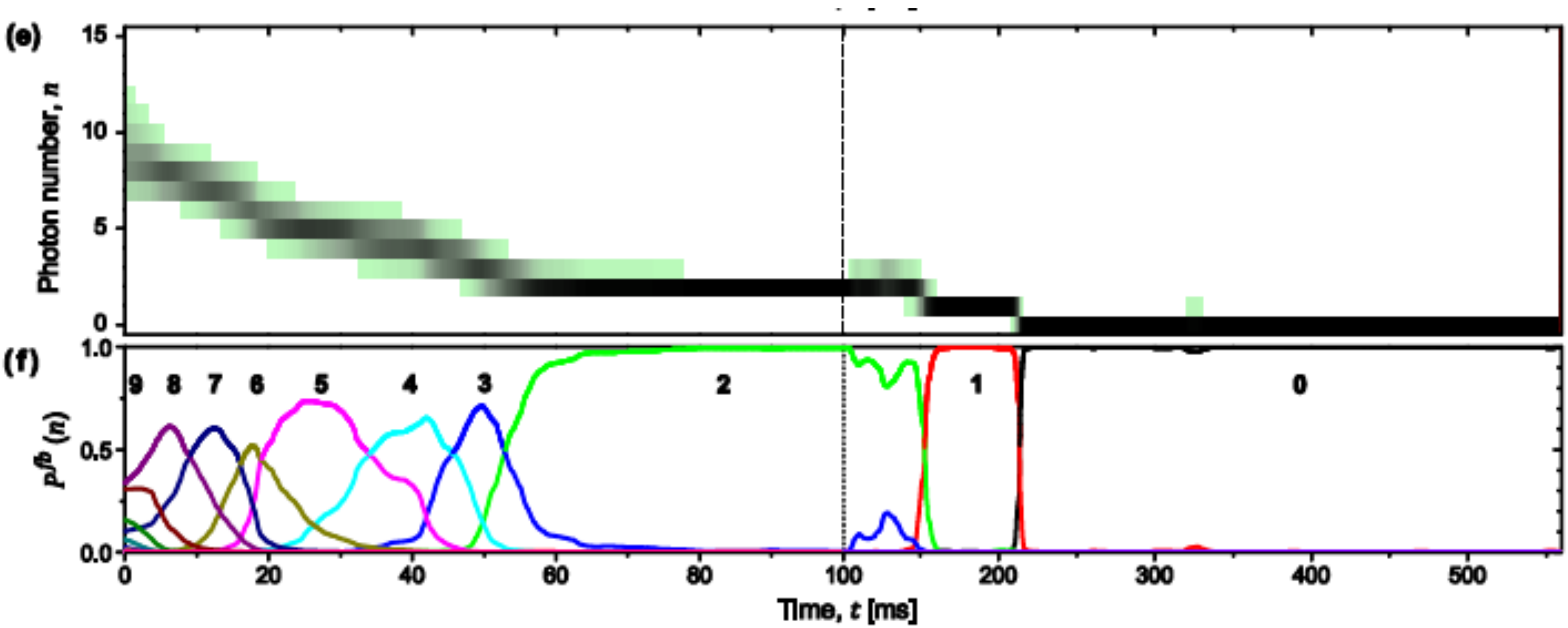
Birth, life and death of a single photon



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

Photon number quantum jumps

- A single quantum trajectory



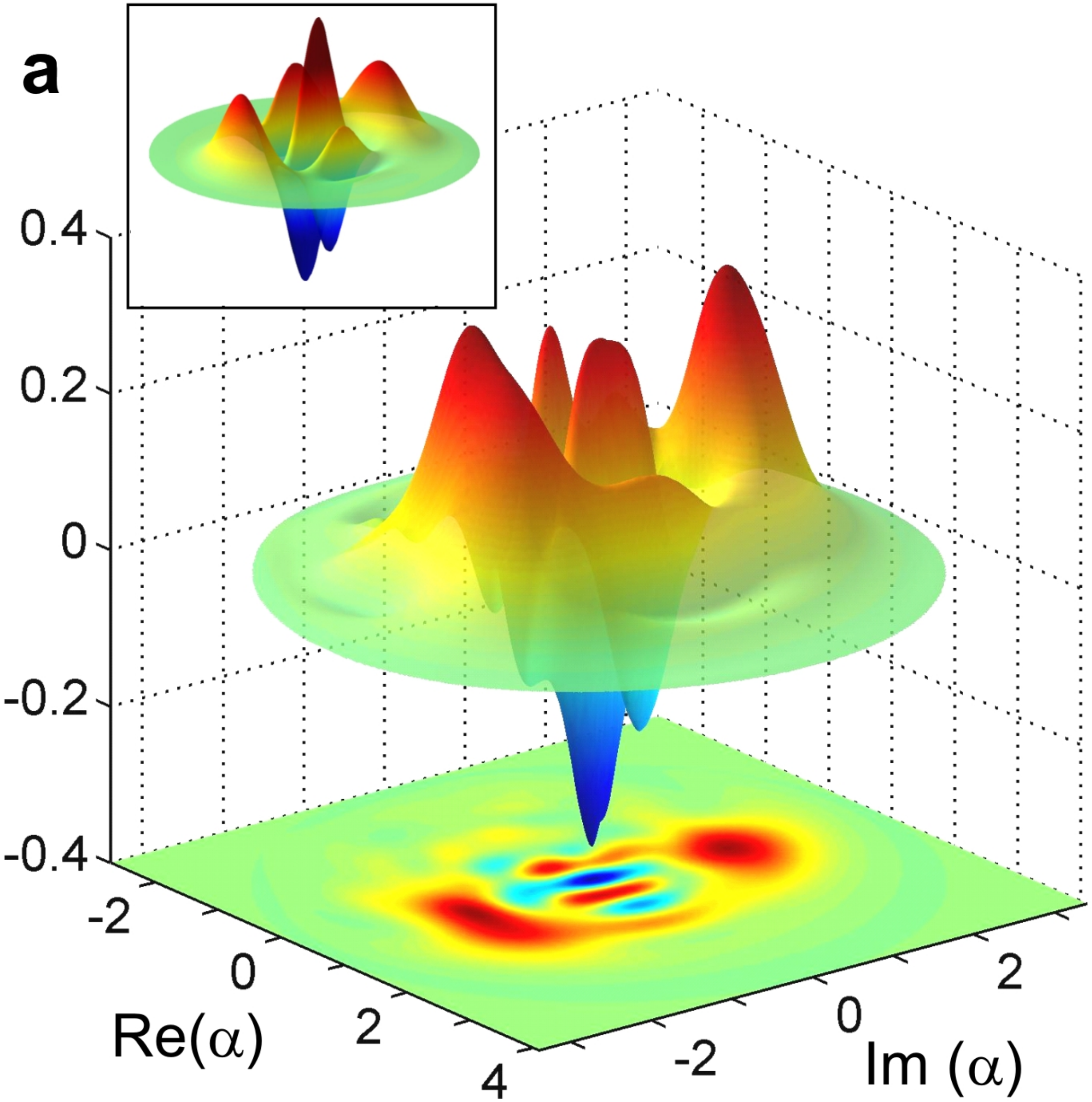
  – Optimized reconstruction of the photon number evolution based on the Past Quantum State formalism
    (S. Gammelmak et al. PRL 111, 160401)

T. Rybarczyk et al., PRA **91** 062116

Schrödinger cat states

- Even cat

- 3.5 photons
- $\zeta=0.37\pi$
- $D^2=11.8$ photons



S. Deléglise, I. Dotsenko, C. Sayrin, J. Bernu, M. Brune, J.M. R., S. Haroche, Nature, **455**, 510 (2008)

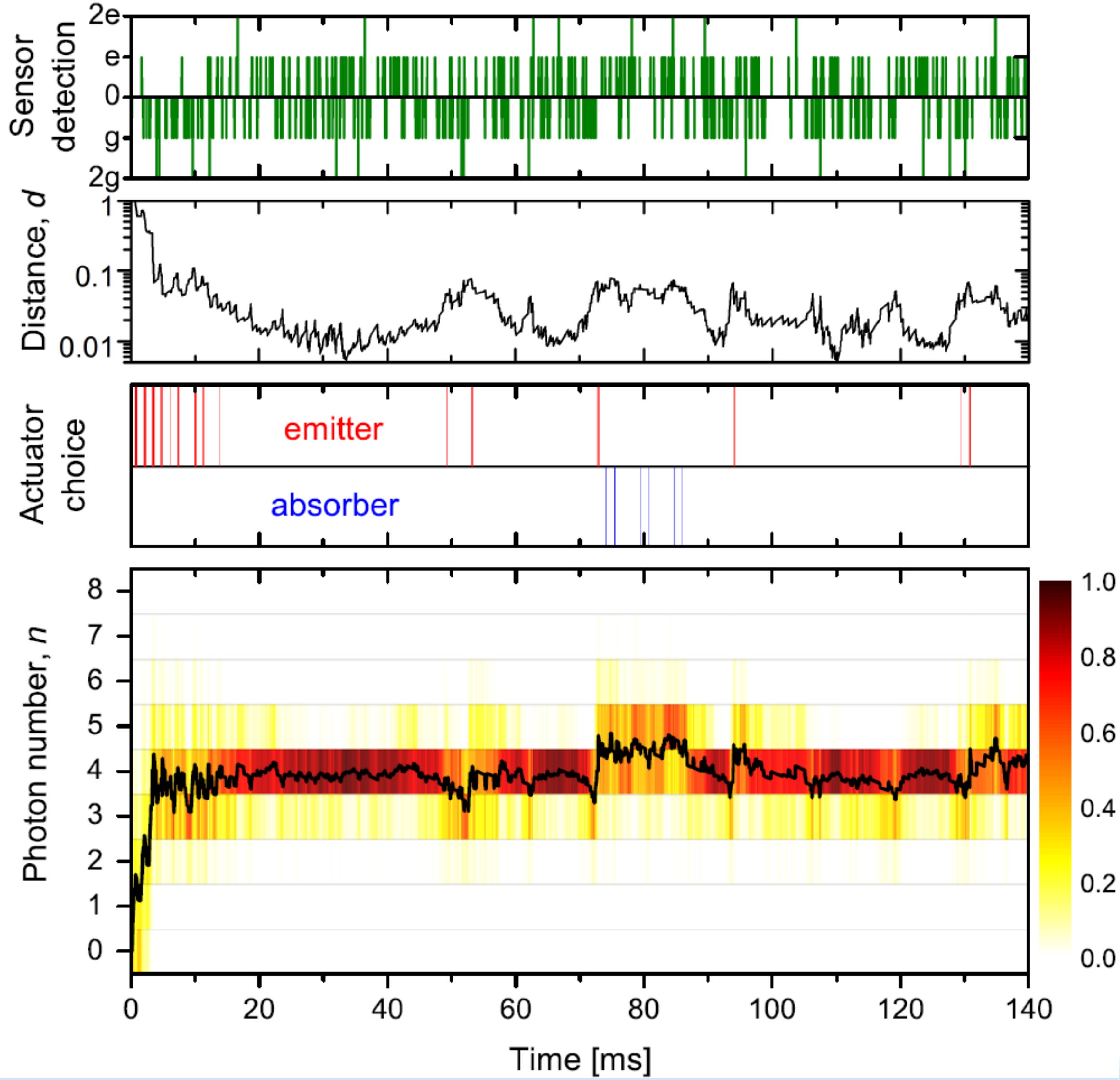
Fighting decoherence

- Quantum feedback
  - Prepare and stabilize quantum states on demand
    - Get information by a quantum measurement
    - Estimate state after measurement
    - React to optimize overlap with target state
    - Iterate loop.
  - Must face a fundamental difficulty:
    - measurement changes the system state
- Our goal
  - Prepare and stabilize a photon-number state in the cavity
    - Get information by QND atoms
    - React

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

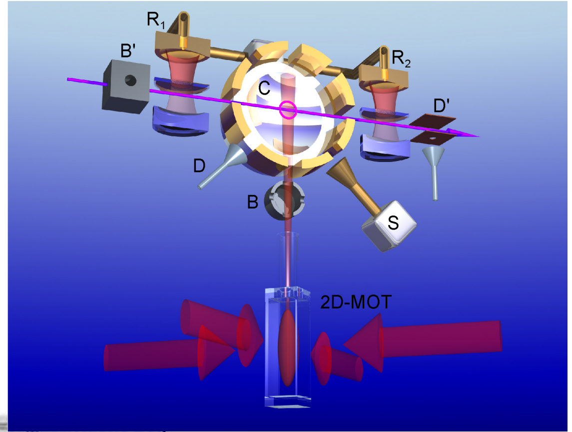
A single trajectory

- Target photon number n_t=4



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 nearly stationary Rydberg atom in a cavity
  - Circular state preparation and detection in the cavity
  - Interaction time ms range
  - Large cats
  - Quantum Zeno dynamics



"About your cat, Mr. Schrödinger—I have good news and bad news."

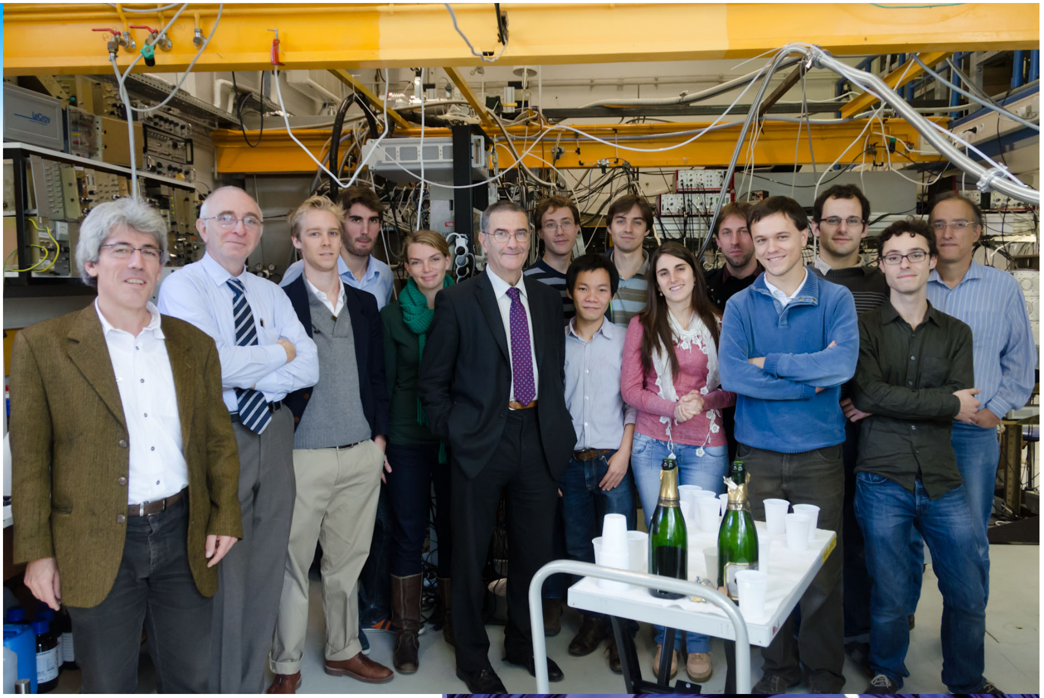
J.M. Raimond et al PRL **105**, 213601

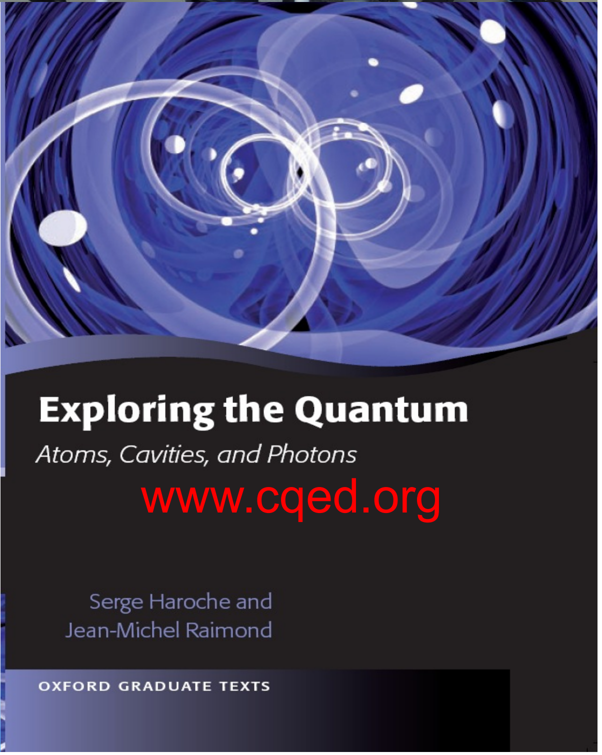
A. Signoles et al. Nature Physics 10,715

A team work

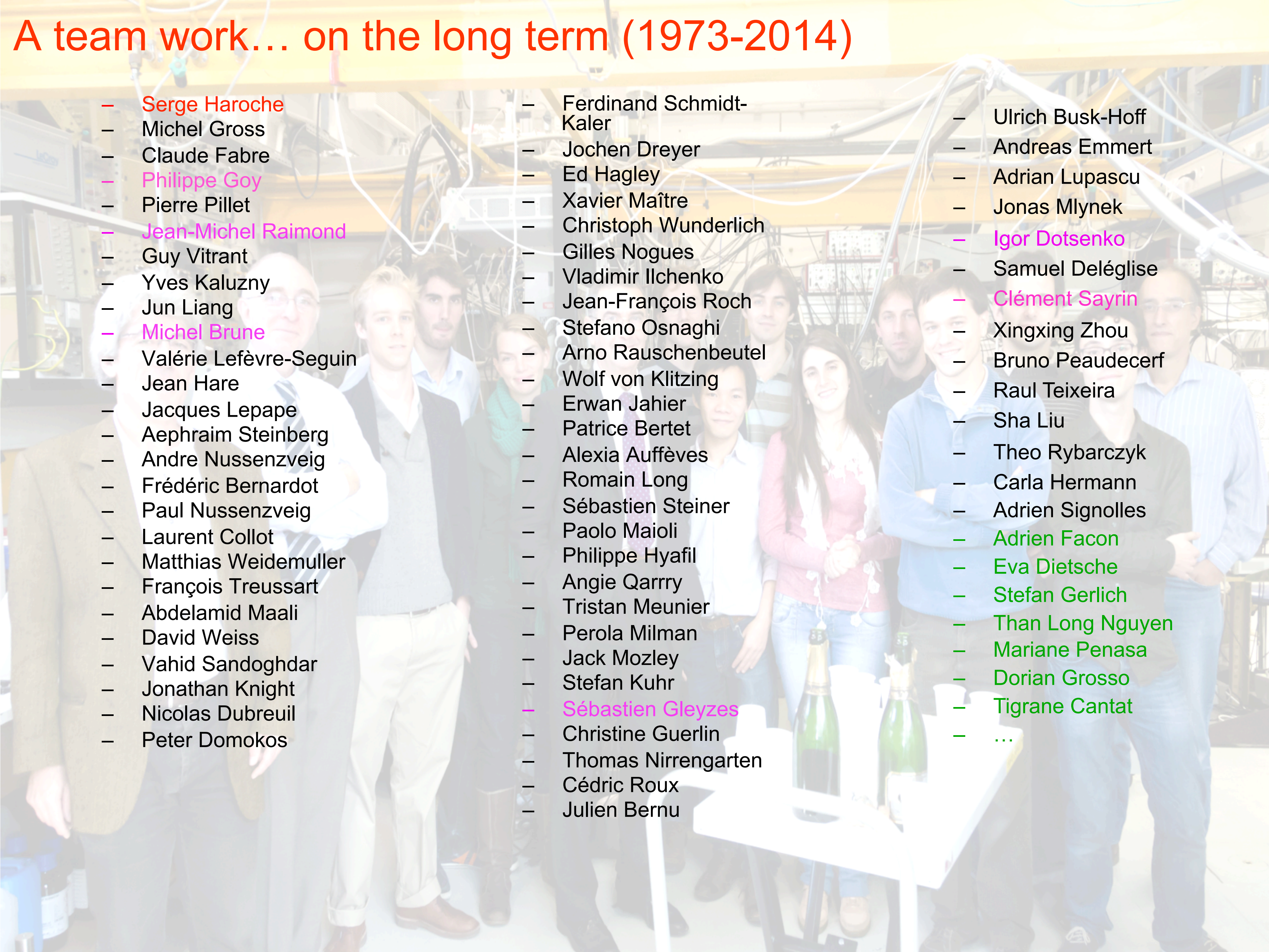
- S. Haroche, M. Brune,
  JM Raimond, S. Gleyzes, I. Dotsenko

- Cavity QED experiments
  - S. Gerlich
    T. Rybarczyk, M. Penasa,
    A. Facon, D. Grosso,
    E.K. Dietsche,
- Superconducting atom chip
  - 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),
  - CNRS, UMPC, ENS, CdF





A team work… on the long term (1973-2014)



- 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 Qarrry
- 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 Signolles
- Adrien Facon
- Eva Dietsche
- Stefan Gerlich
- Than Long Nguyen
- Mariane Penasa
- Dorian Grosso
- Tigrane Cantat
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