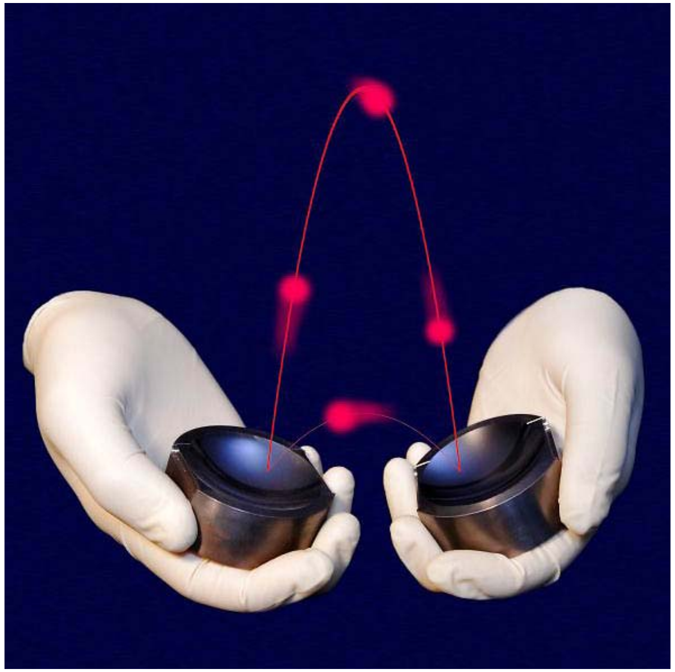
Quantum measurement and feedback in cavity QED



J.M. Raimond

Université Pierre et Marie Curie

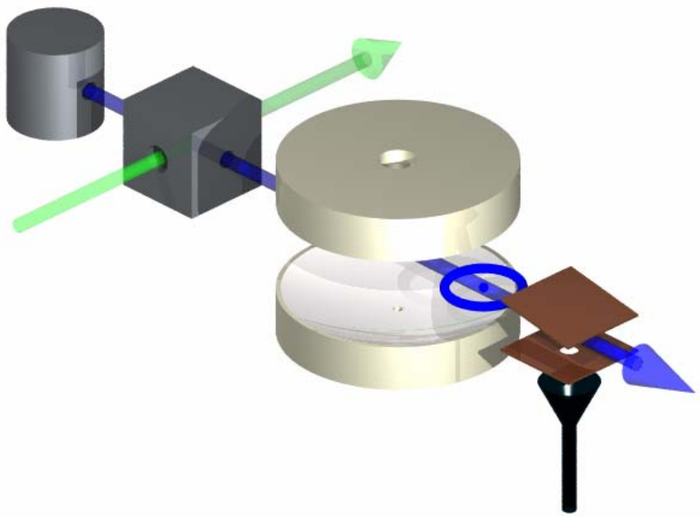
Laboratoire Kastler Brossel
Physique quantique et applications

Individual quantum system control

- A renewed interest for fundamental quantum mechanics
  - Experiments manipulate individual quantum systems in a carefully controlled environment.
    - atoms, ions, photons, superconducting circuits, mechanical oscillators…
  - Possible realization of the thought experiments used by the founding fathers of quantum theory
    - photon boxes, Schrödinger cats…
  - A new light shed on intimate quantum phenomena
    - improved fundamental understanding
      - quantum measurement
    - prototypes of quantum information manipulation

Cavity Quantum Electrodynamics

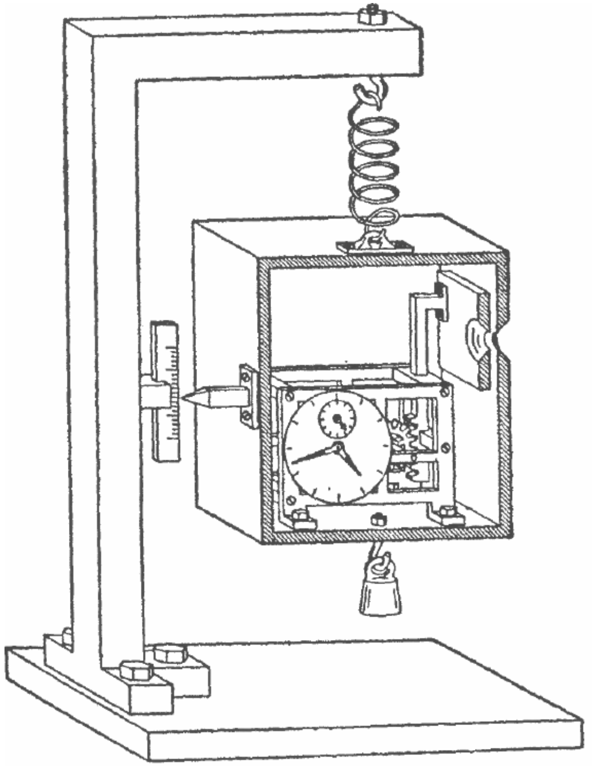
- A spin and a spring

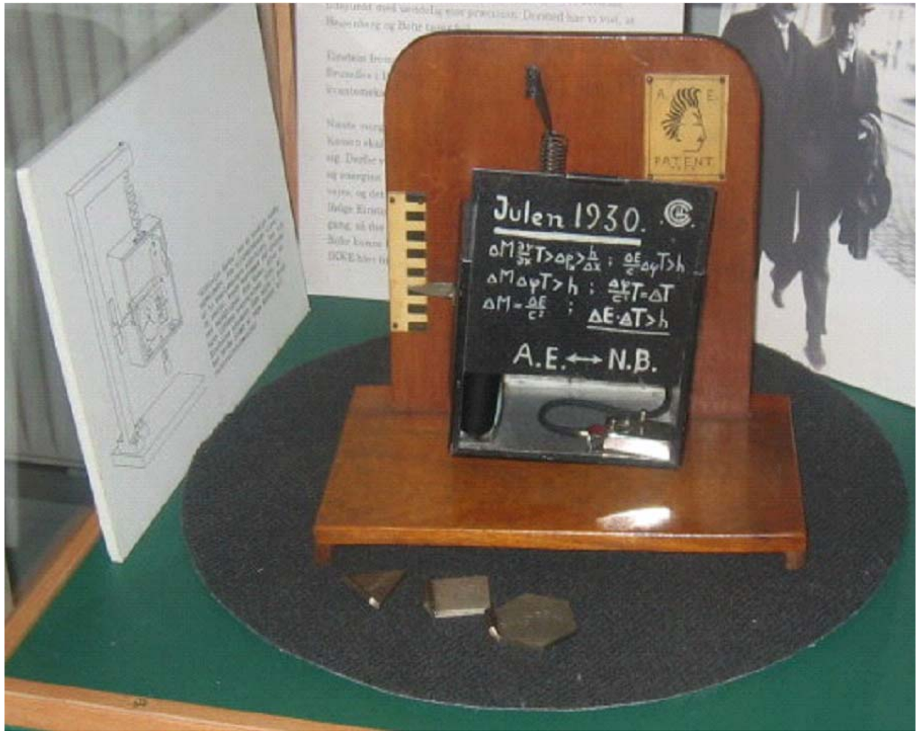


  - Realizes the simplest matter-field system: a single atom coherently coupled to a few photons in a single mode of the radiation field, sustained by a high quality cavity.
  - Early demonstration of quantum gates
  - Direct illustrations of quantum postulates
    - Measurement
      - Ideal quantum measurement of photon number and applications
        - » State preparation
        - » Adaptive quantum measurements
        - » Quantum feedback

An ideal photon counter ?

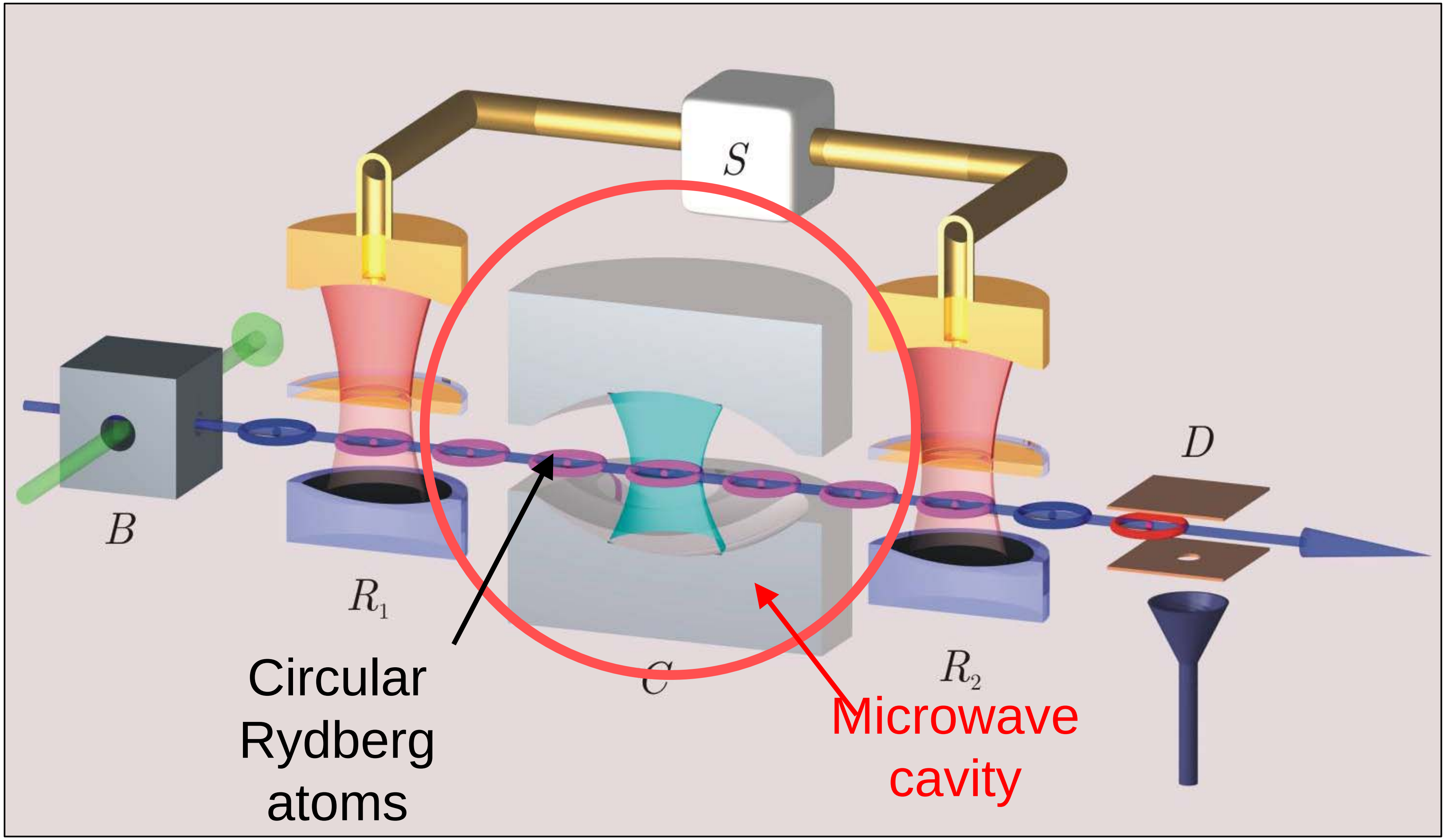
- A QND photodetector operating at the individual photon level
  - Matter ultra-sensitive to the field
- A photon ‘box’ able to store a photon for a long time
    - back to Einstein-Bohr’s dream





- Circular Rydberg atoms and superconducting millimeter-wave cavities

Experimental set-up



RMP **73**, 565

Circular Rydberg atoms

High principal quantum number

Maximal orbital and magnetic quantum numbers

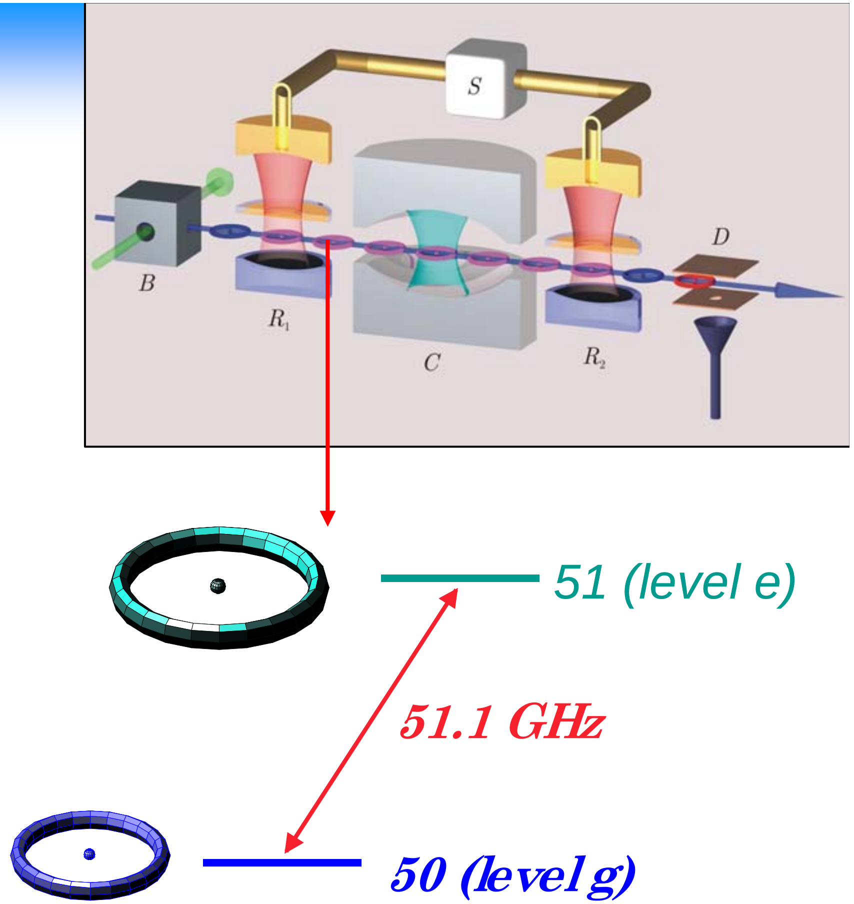
- Long lifetime (30ms)
- Microwave two-level transition
- Huge dipole matrix element
- Stark tuning
- Field ionization detection
  - selective and sensitive

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

Atoms individually addressed

(centimeter separation between atoms)

Full control of individual transformations



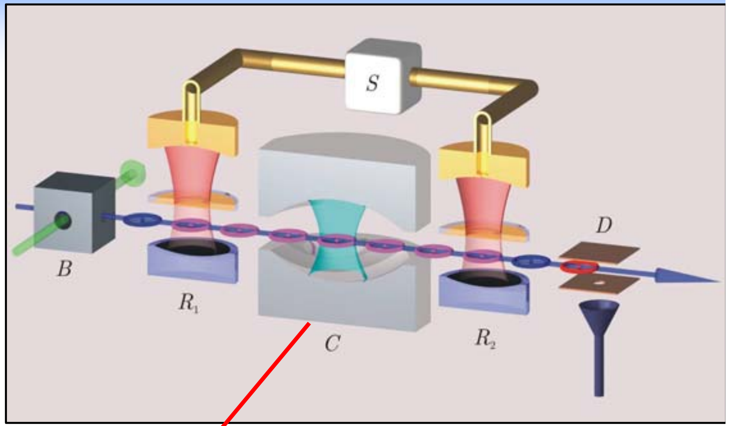
Complex preparation (53 photons !)

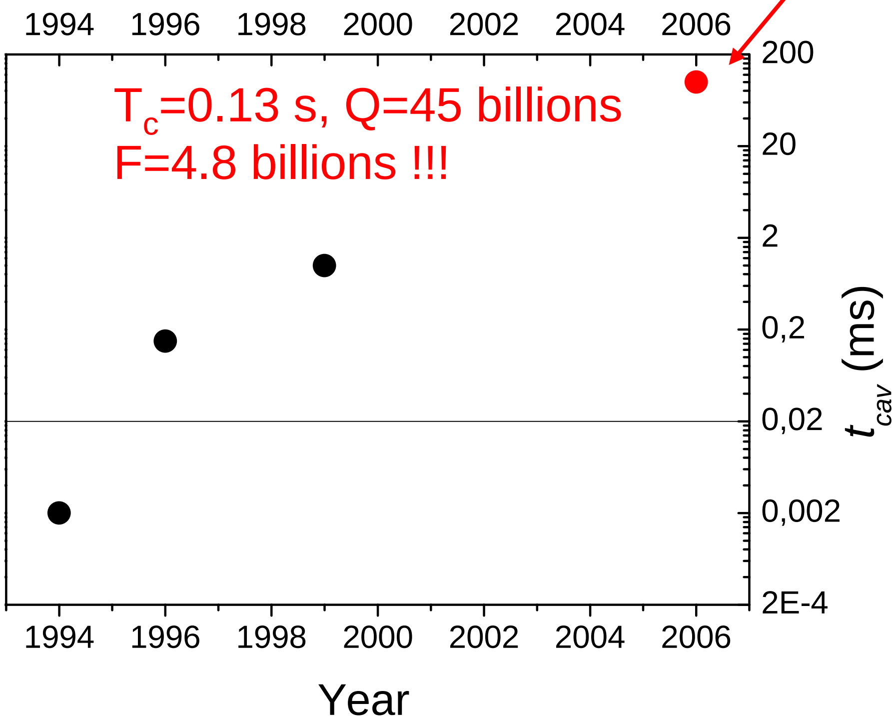
could be optimized (T. Calarco)

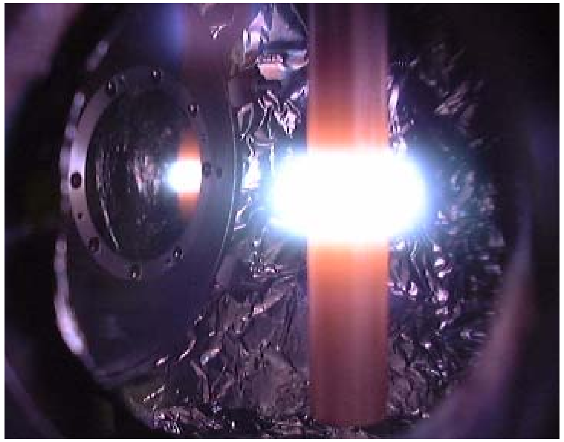
Stable in a weak directing electric field

A box for microwave photons

- optimization of the cavity quality
  - a long (painful !!) process
    - our pet Moore's law



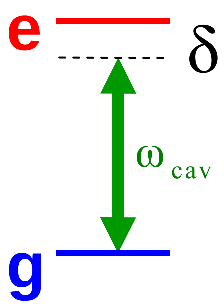


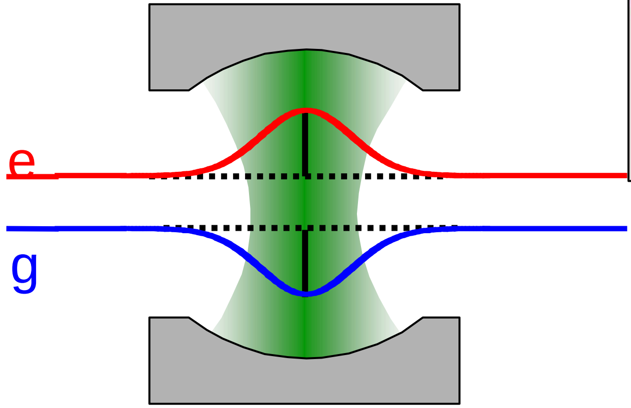


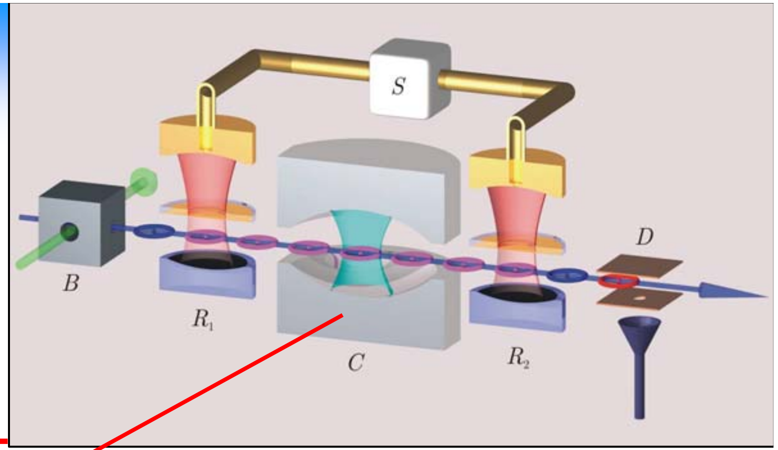
- extrapolations might not be safe….

QND measurement

- Quantized light-shifts in the cavity







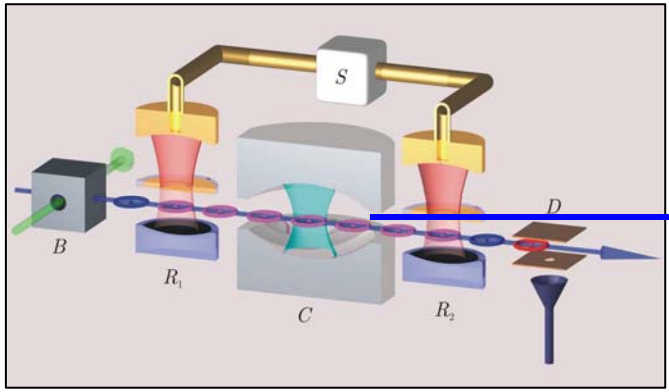
- Measured by Ramsey interferometry
  - A state superposition, prepared by a $\pi/2$ pulse in R_1, accumulates a phase shift

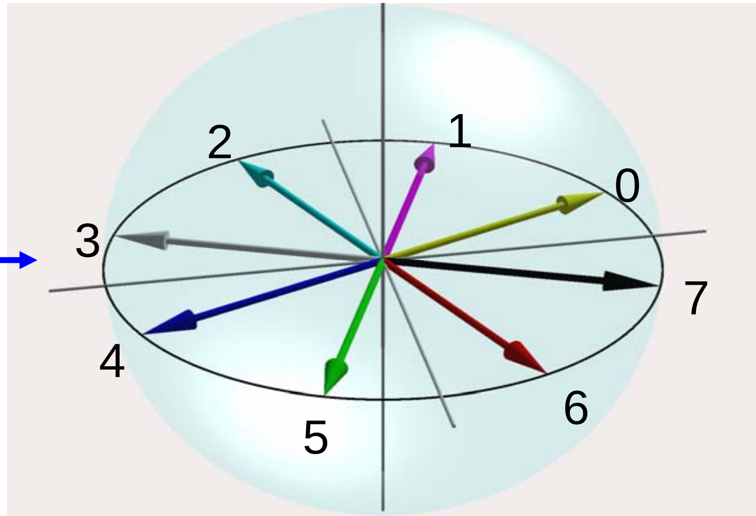
$$\phi_0 \left(n + 1/2 \right)$$

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

Quantized rotation of the atomic spin

- Photon-number dependent phase shift of the atomic coherence

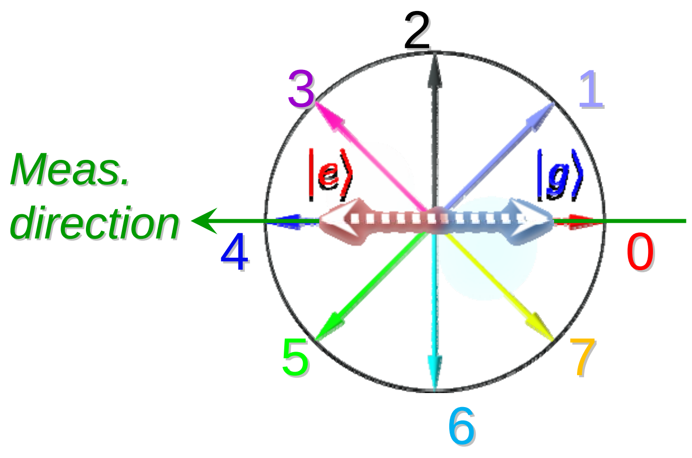




$$\phi_0 = \frac{\pi}{4}$$

  - The Bloch vector direction reveals the photon number
  - In general non-orthogonal final atomic states correspond to different photon numbers: A single atom will not tell all the story
  - By chosing the phase of the pulse in R_2, measure the component of the spin in any direction of the equatorial plan

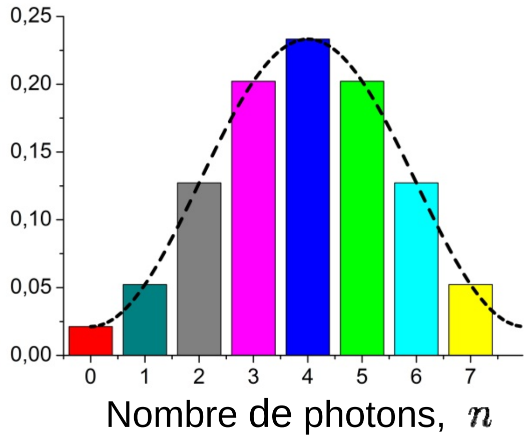
Single atom detection



Each detection brings partial information on the photon number

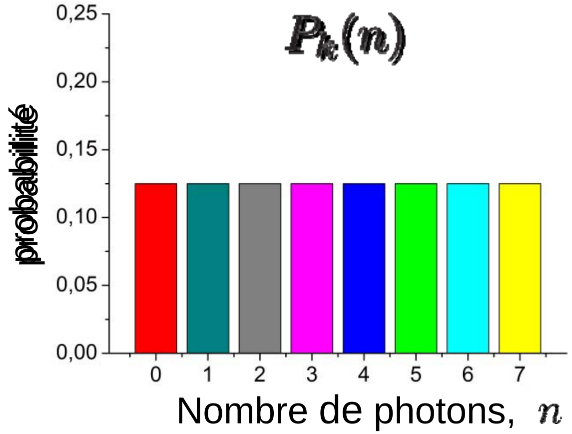
$$P_{k+1}(n) \propto p(e|n) P_k(n)$$

detection $|e\rangle$

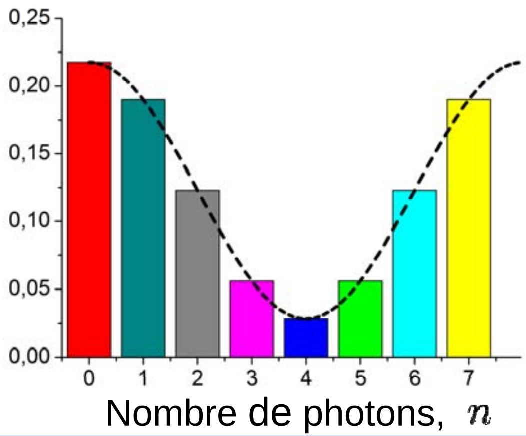


Initial flat estimate

$P_k(n)$



detection $|g\rangle$



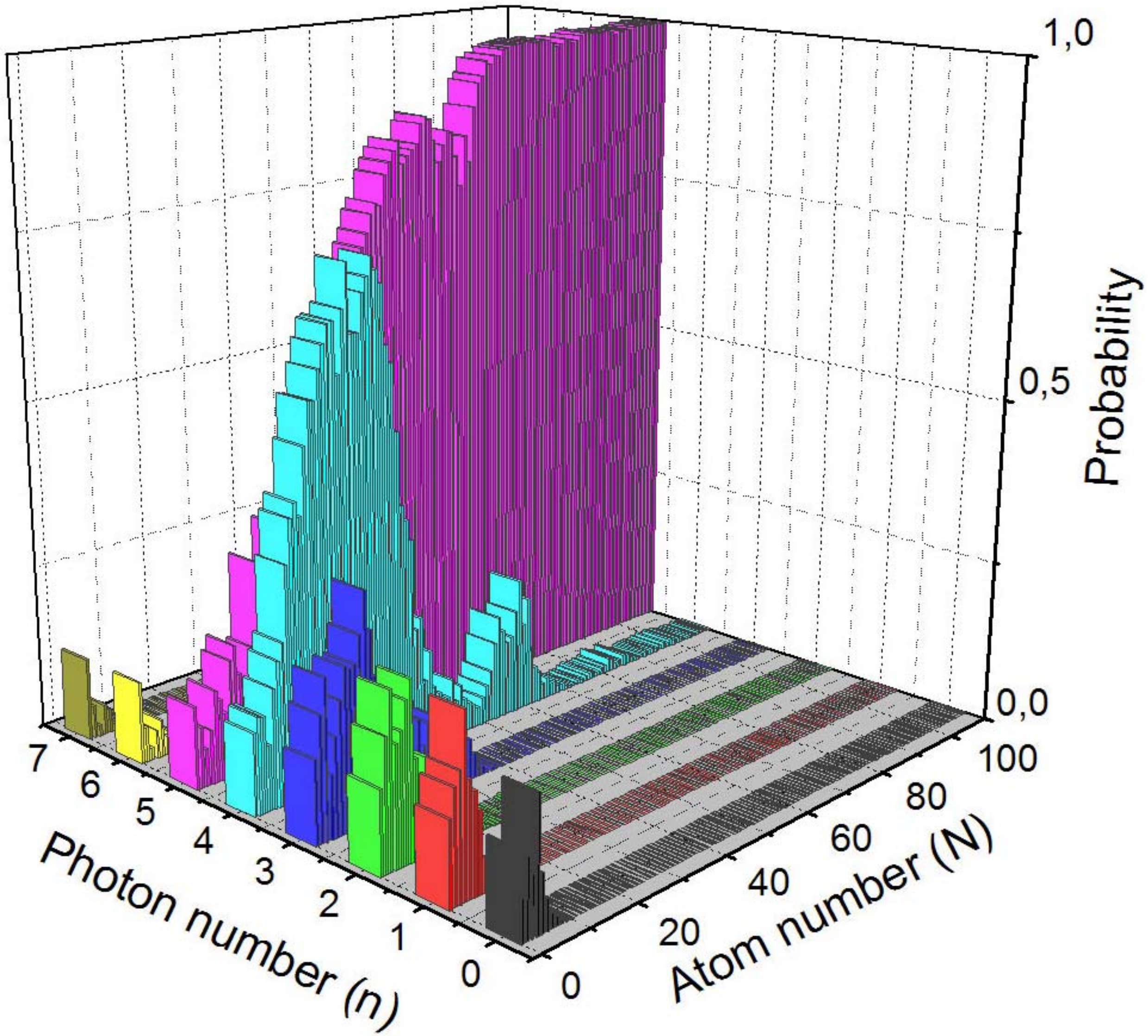
Bayesian inference of the photon number distribution

- Each atom brings partial information on the photon number
  - Recording atomic state changes our inference of the photon number distribution P(n)
    - P(n) multiplied by a sine function after each atomic detection

      (probability to get the atom in the detected state as a function of the photon number
      - Some photon numbers nearly ruled out

- Cumulative decimation of the photon number distribution pins down the photon number
  - Use four settings of the measurement direction chosen randomly
    - Removes any ambiguity and speeds up decimation
  - Requires about n_m^2 atoms to distinguish n_m photon states
    - Statistical noise on the atomic detections

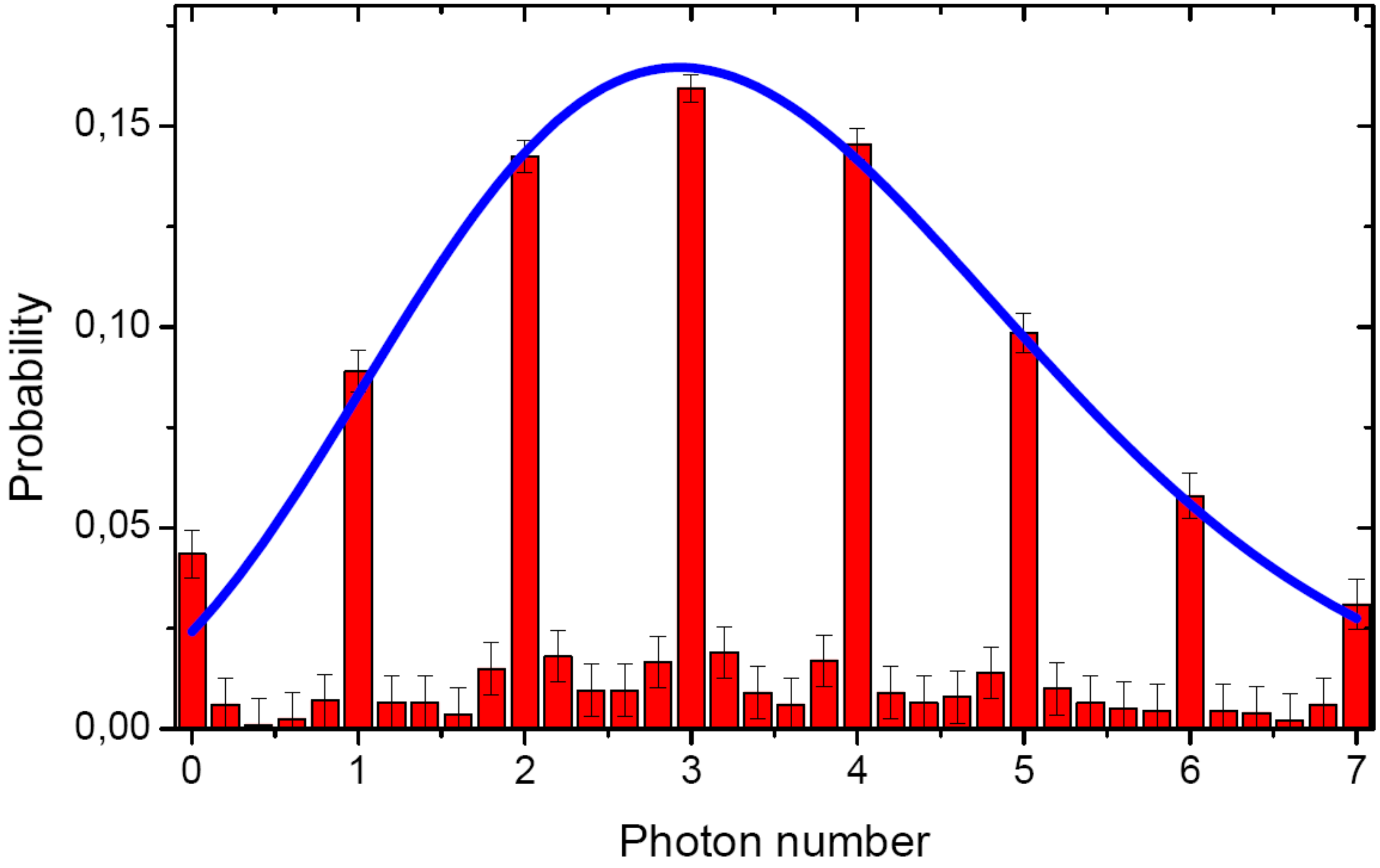
Wave-function collapse in real time



- 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

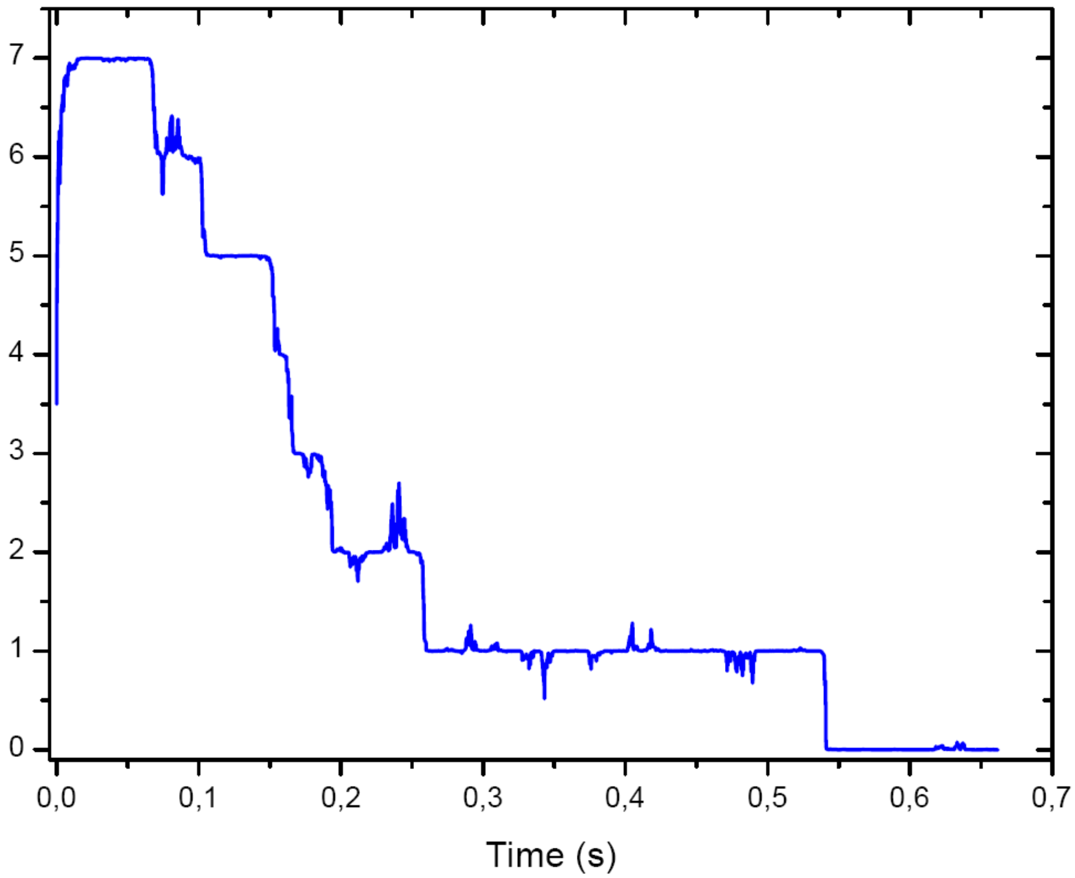
Photon number statistics



Excellent agreement with the expected Poisson distribution

Monitoring the decoherence of a Fock state

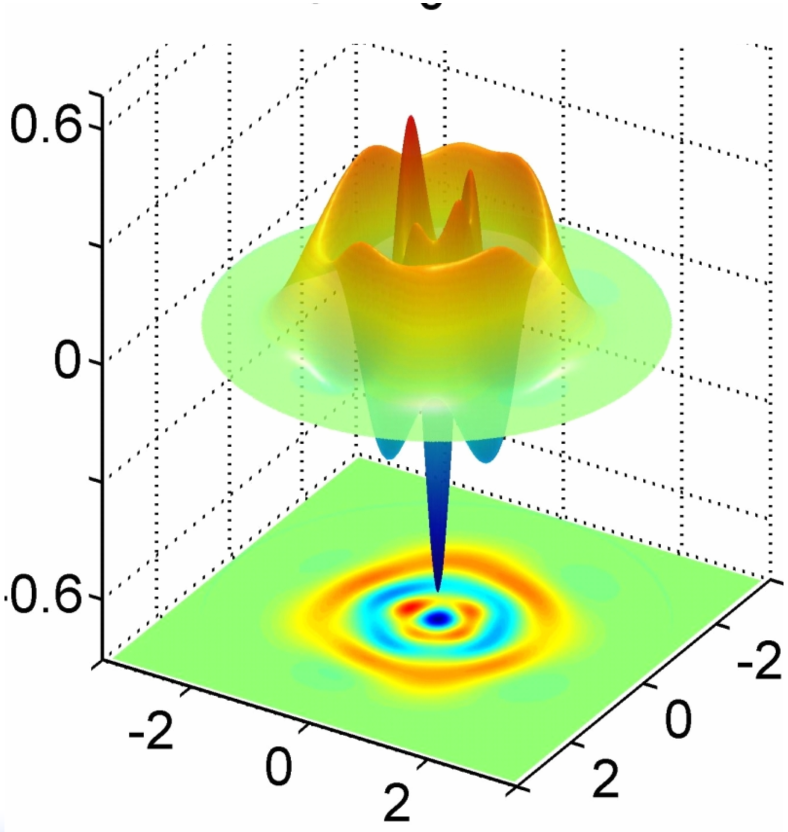
- Keep sending atoms through the cavity



  – Direct evidence of the quantum jumps of light

An ideal quantum measurement

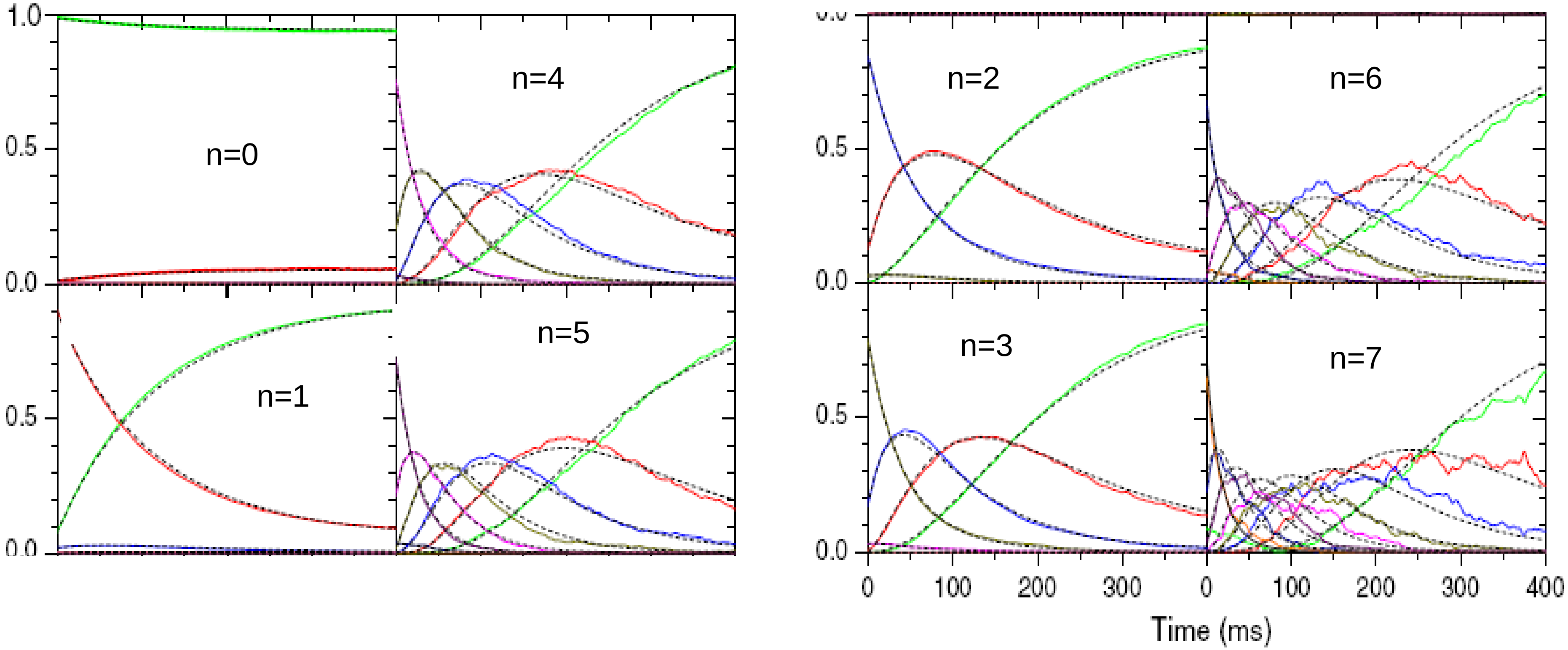
- Illustrates all quantum postulates
  - Random results
  - Predictable probabilities
  - Projection on an eigenstate
- A simple method for Fock states preparation
  - Non-classical states
  - Complete state tomography
  - Negativities in the Wigner distribution
  - Expect rapid decoherence of these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



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

Quantitative measurement of decoherence

- Analyse many quantum jumps trajectories
  - Following the preparation of Fock states from 0 to 7
  - Extract the evolution of the photon number distribution versus time



- Cascade down the Fock states ladder

M. Brune et al PRL **101**, 240402

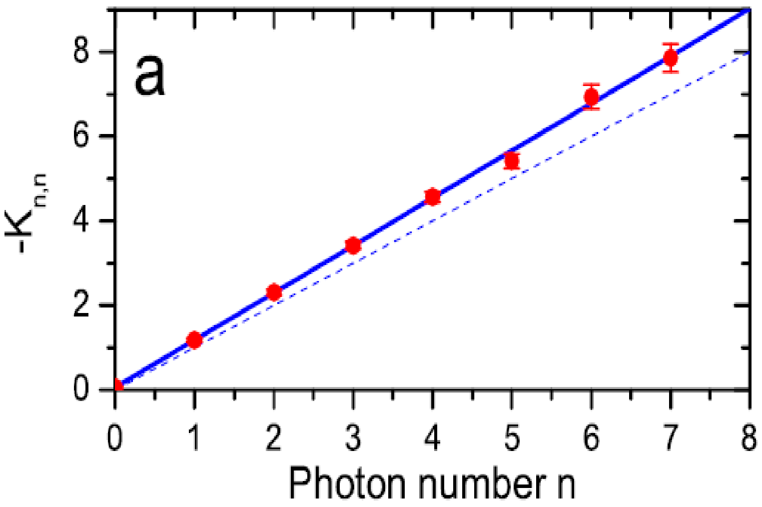
Partial quantum process tomography

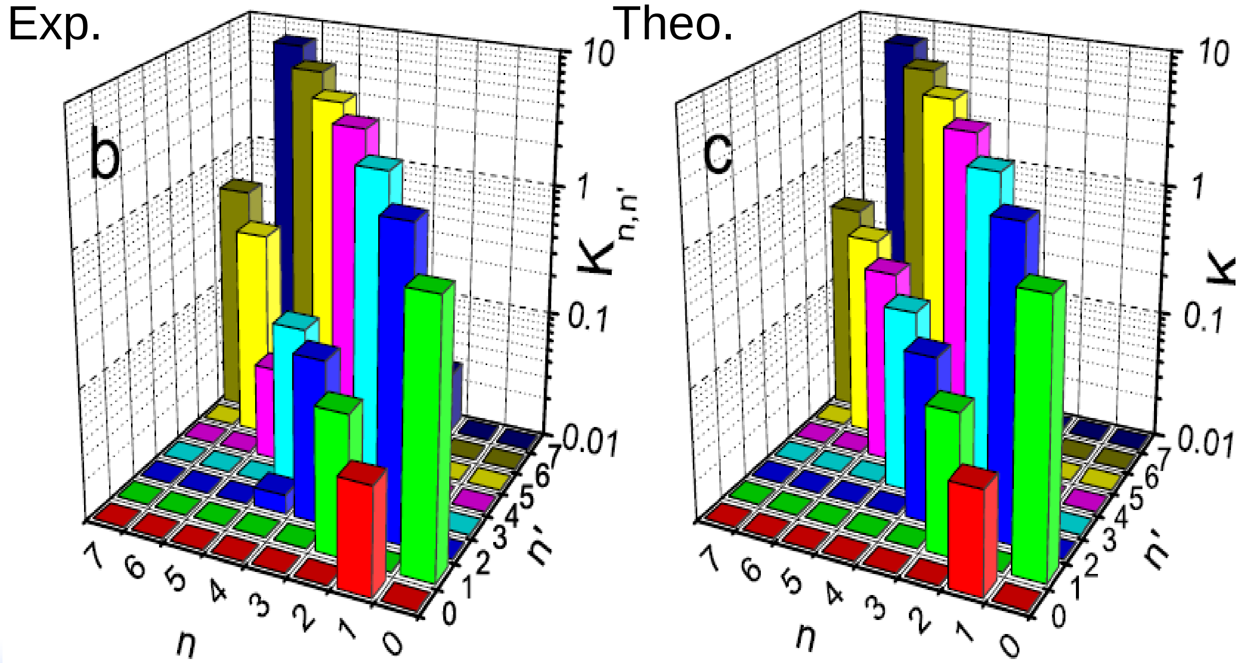
- Assume a general rate equation

$$\frac{dP(n,t)}{dt} = \sum_{n'} K_{n,n'} P(n',t).$$

- Fit its coefficients on the experimental data

- A precise determination of photon number distribution master equation

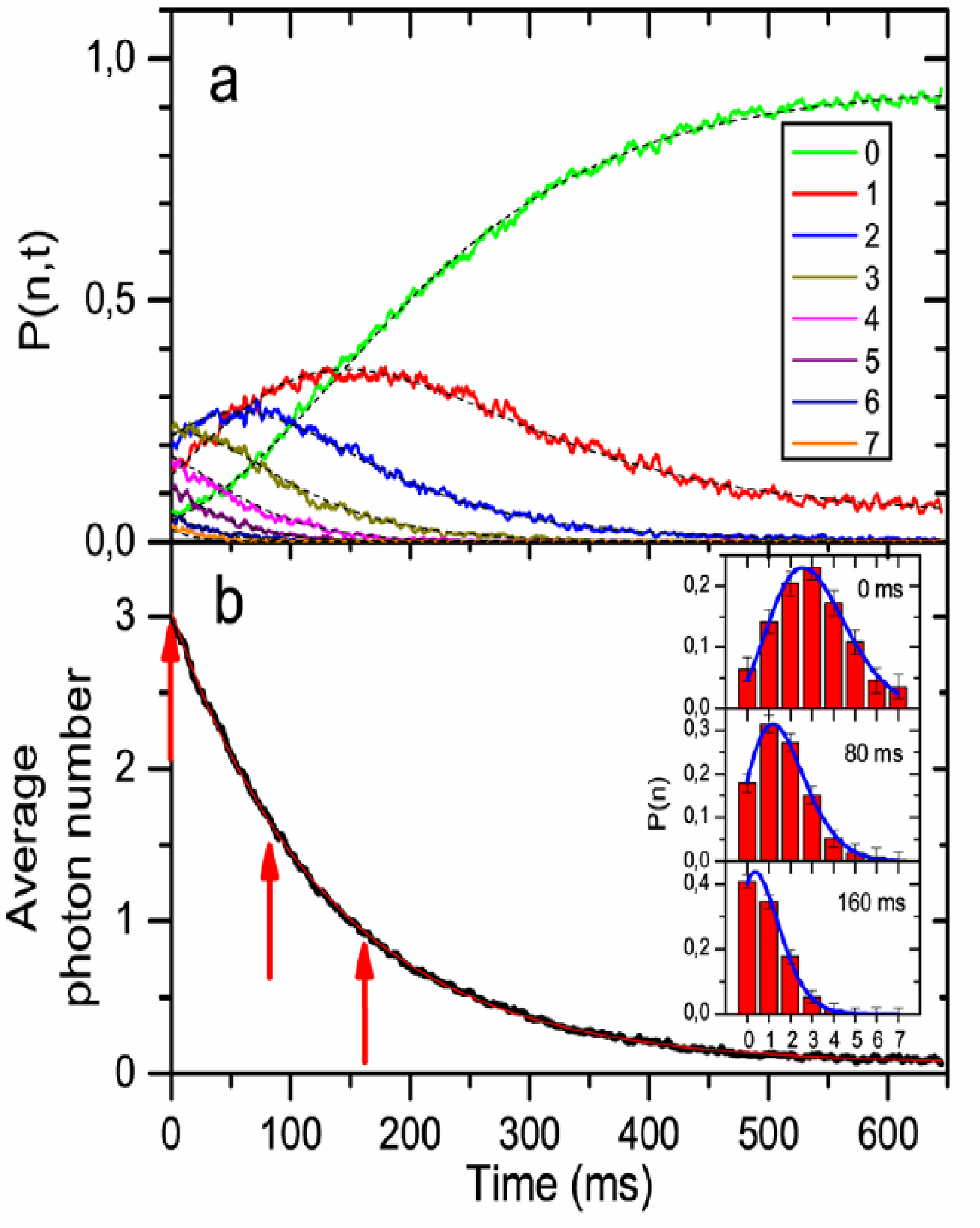




Relaxation of a coherent state

- A relaxing coherent state remains poissonian

- The average energy decays exponentially as in classical physics



M. Brune et al PRL 101, 240402

Adaptive quantum measurement

- Finite decoherence time of Fock states
  - QND measurement must be performed on a much shorter time scale
- Passive QND method
  - Randomly choses the phase of the Ramsey interferometer for each atomic sample
  - Requires n_m^2 atoms to measure n_m photons
- Adaptive measurement
  - Optimizes in real time the measurement based on all available information
    - Spin detection direction dynamically chosen to maximise information flux

H. M. Wiseman, PRL, **75**, 4587 (1995)

Information flux

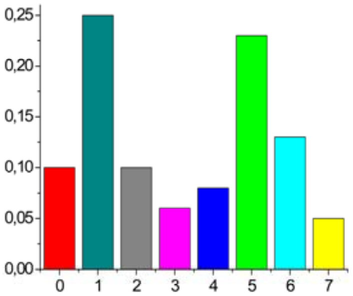
Von Neumann entropy $$S[P] = -\sum_n P(n)\log(P(n))$$

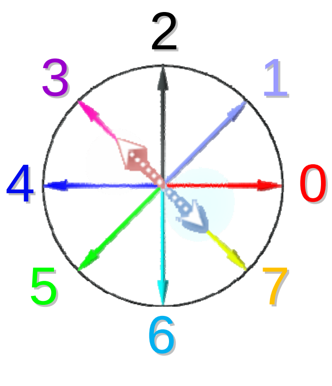
Weak measurement reduces entropy on the average :

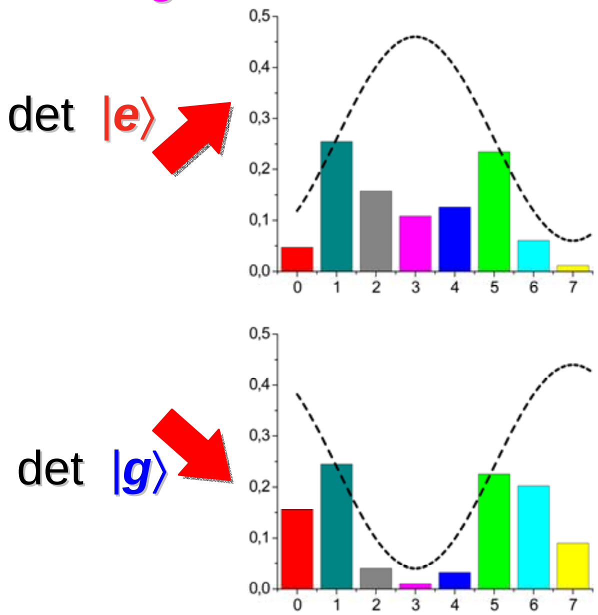
$$\langle S[P_{\rm proj}]\rangle = \sum_j \pi_j S[P_{\rm proj}(j)] \leq S[P]$$

Selected measurement directions bring more information

$S[P] = 1{,}93$







$\langle S[P_{\rm proj}]\rangle = 1{,}82$

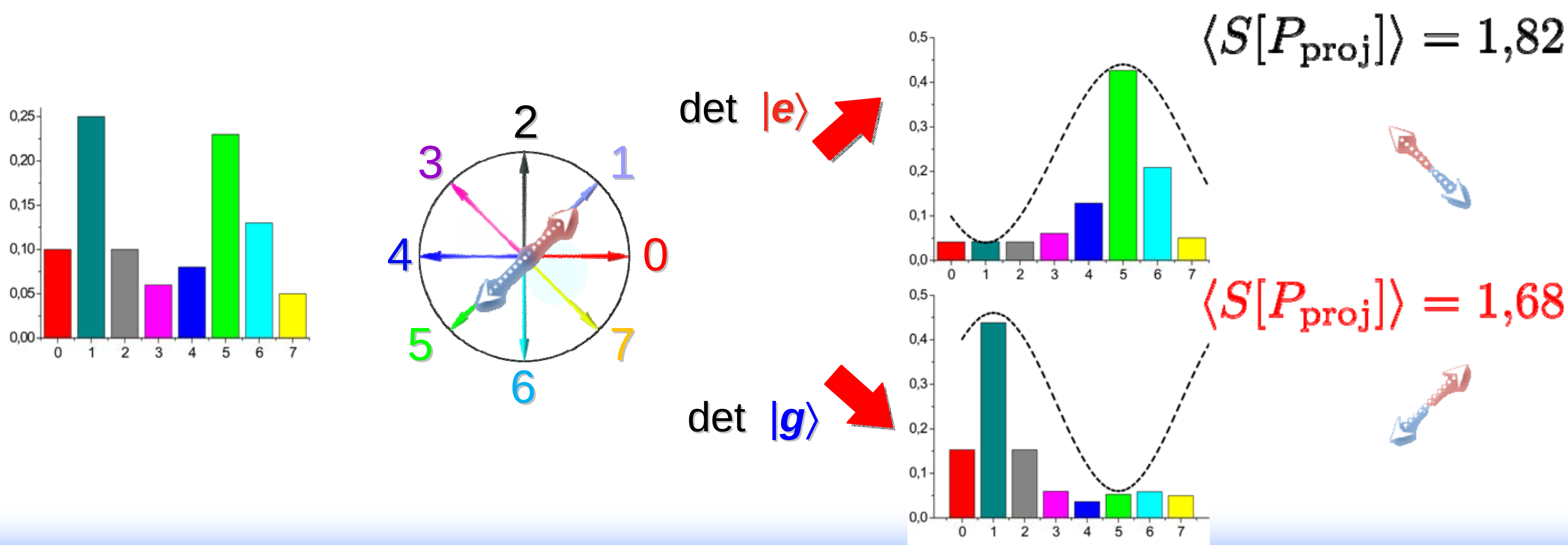
Information flux

Von Neumann entropy
$$S[P] = -\sum_n P(n)\log(P(n))$$

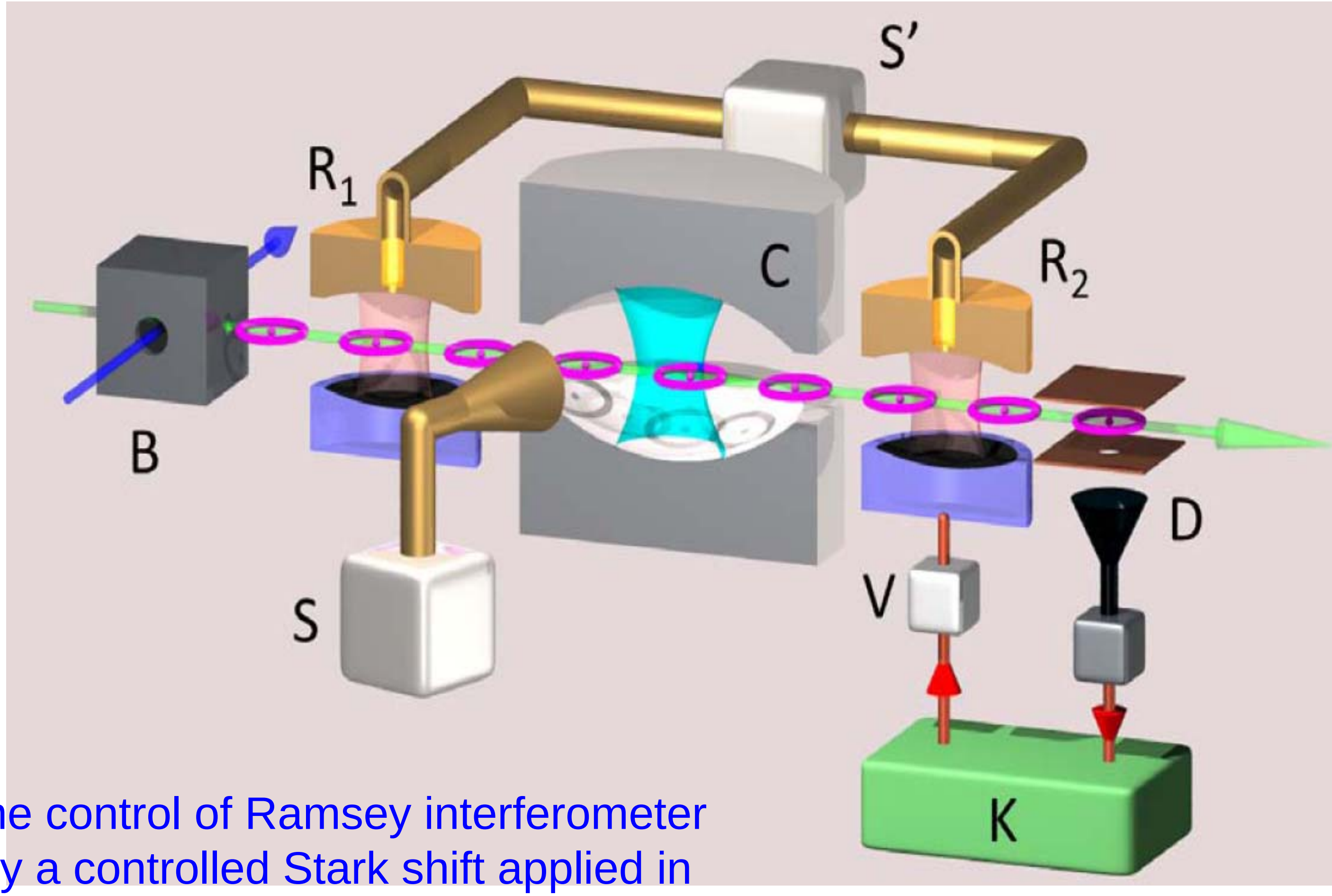
Weak measurement reduces entropy on the average :

$$\langle S[P_{\mathrm{proj}}]\rangle = \sum_j \pi_j S[P_{\mathrm{proj}}(j)] \leq S[P]$$

Selected measurement directions bring more information



Adaptive measurement scheme



Real-time control of Ramsey interferometer phase by a controlled Stark shift applied in R_2 before second $\pi/2$ pulse

Adaptive measurement algorithm

- At each atomic detection, the controller
  - Estimates the photon number distribution based upon all available information
  - For each of the four possible phase choice estimates the expectation value of the entropy reduction for the next measurement
  - Applies the proper Stark voltage in R_2
- All computations must be performed in the 82µs time interval between atomic samples
  - A fast real time computer
    - AdWinProII Jäger Messteknik
  - A carefully optimized code

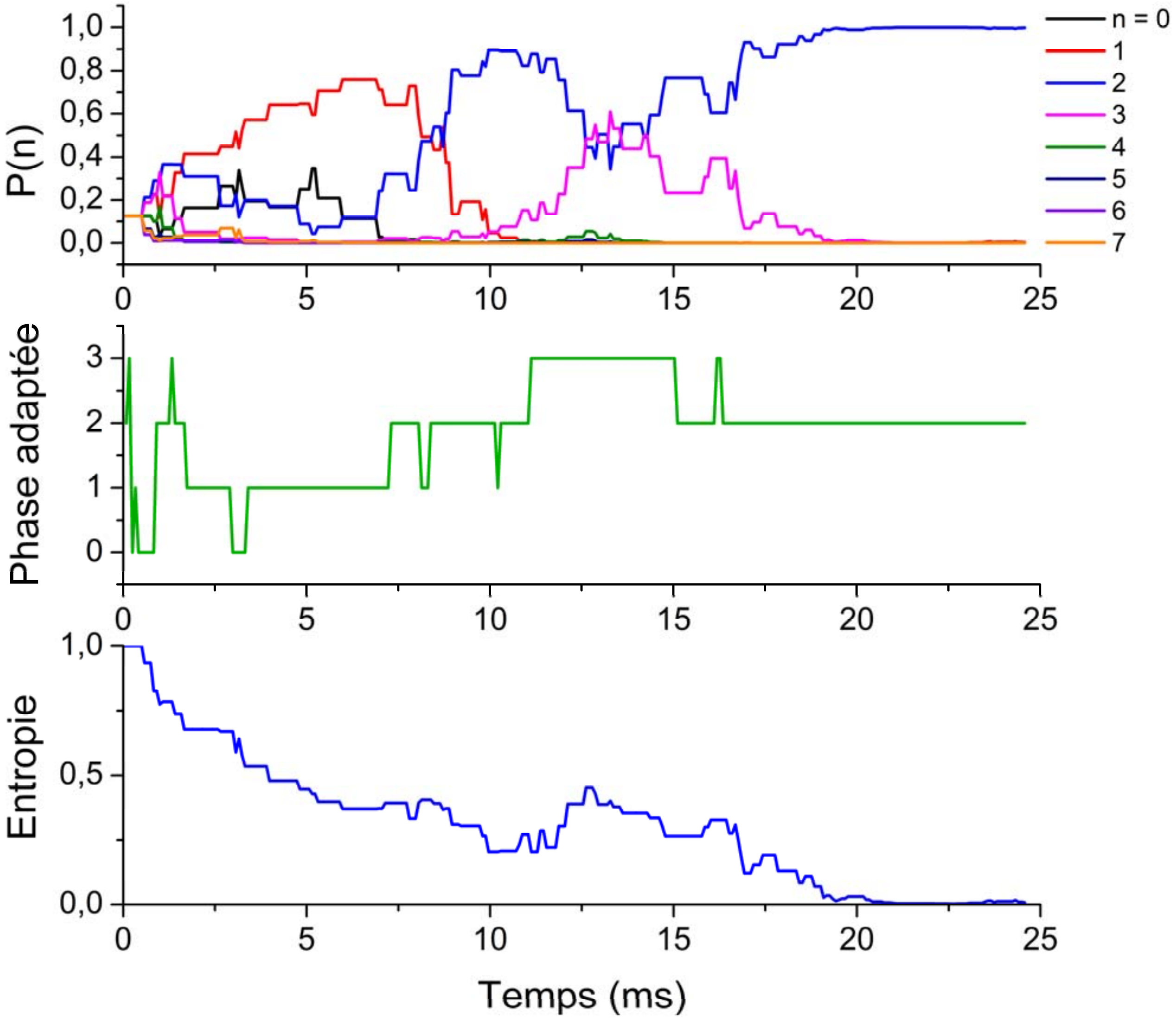
Assessing the information gain

- Get rid of cavity relaxation during measurement

  - A three-part experimental sequence
    - A first passive QND measurement prepares a Fock state
    - A final passive QND measurement checks that the photon number has remained constant
    - In-between either:
      - A passive QND sequence
      - An adaptive QND sequence

  - Compare the entropy reduction of the central passive and adaptive sequence

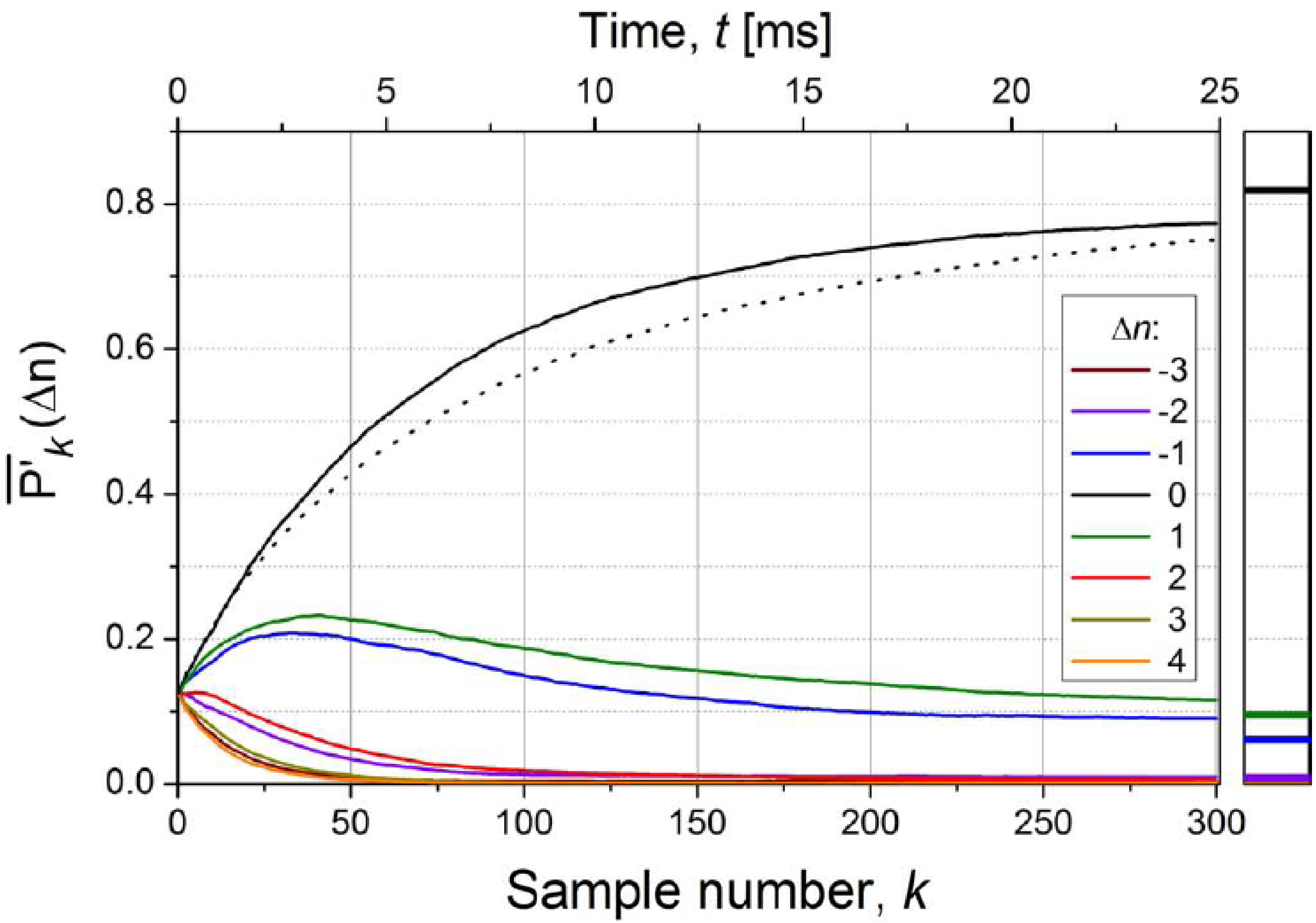
A single adaptive sequence trajectory



$n_I = n_F = 2$

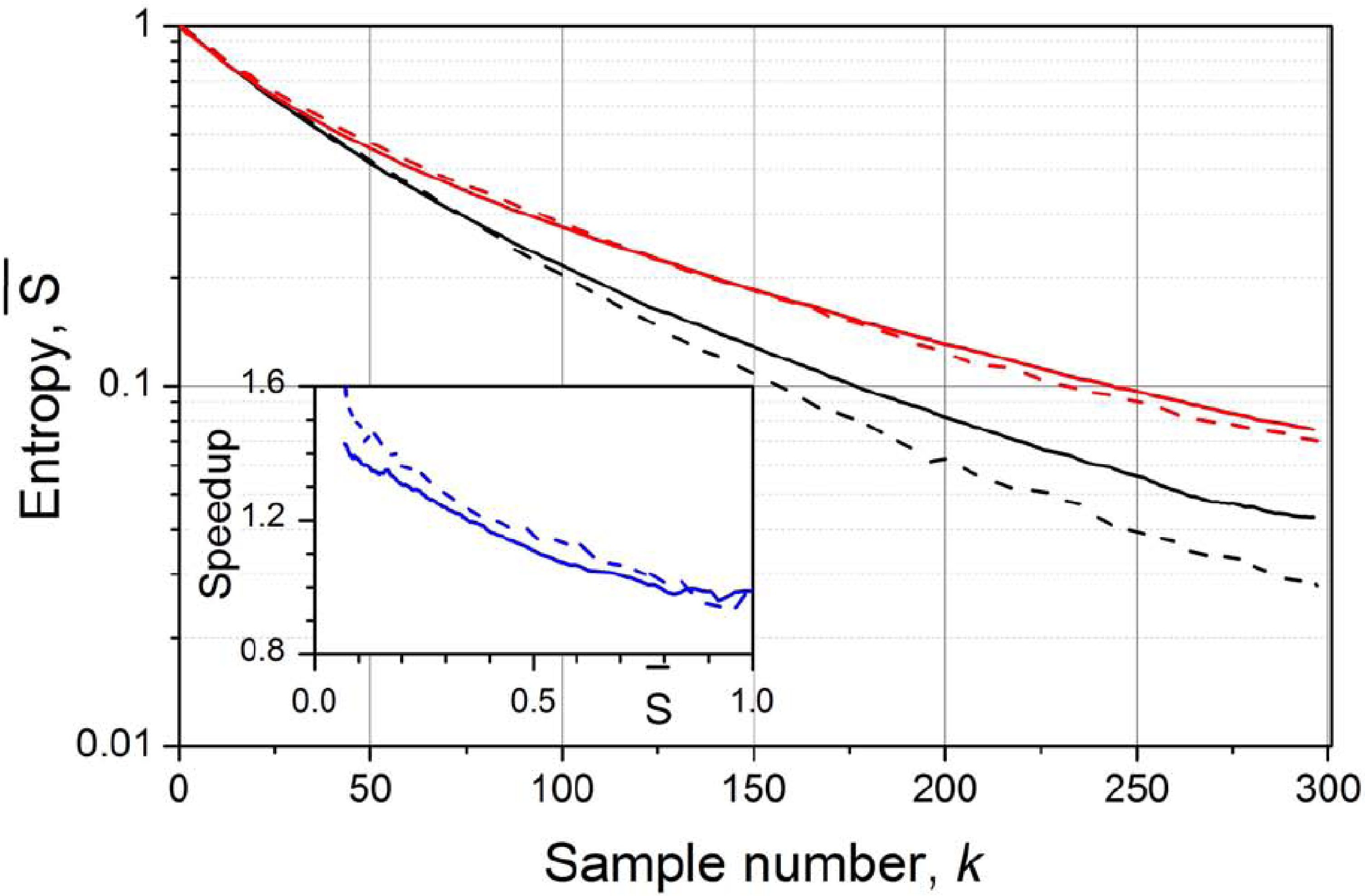
Evolution of the photon number distribution

- Relative to the selected photon number



Evolution of the entropy

- And speedup of information acquisition



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

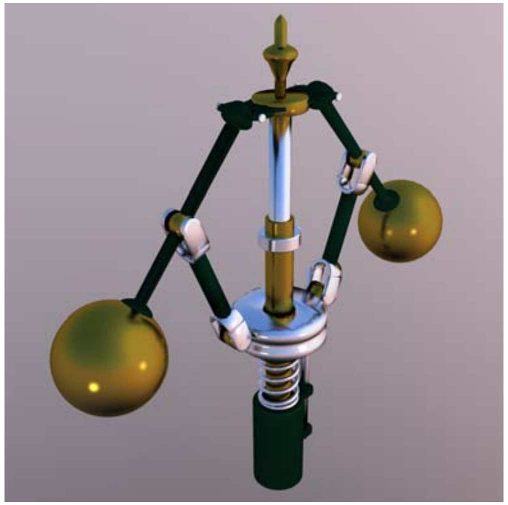
- Fock states are an interesting resource
  - e.g. quantum communication or computation

- 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 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

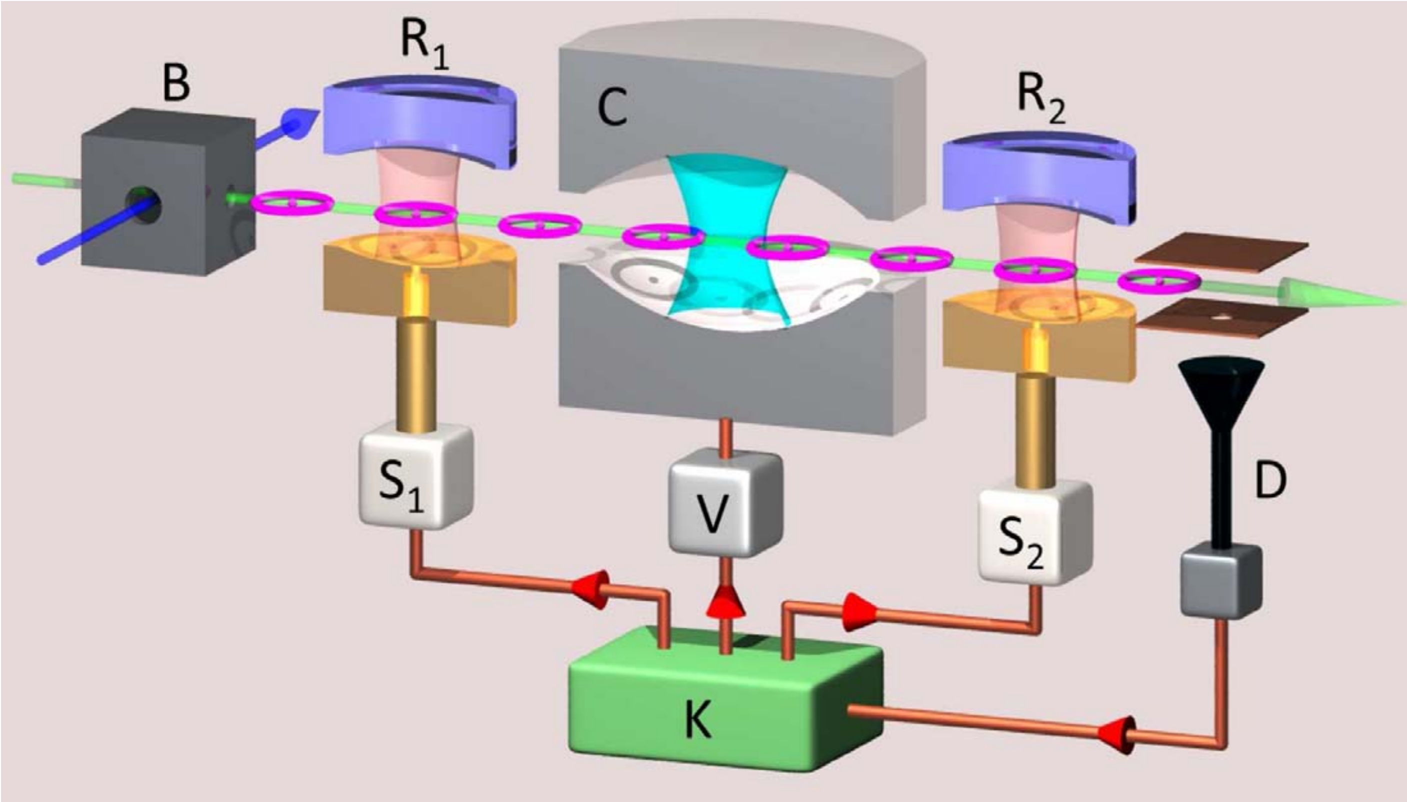
I. Dotsenko, M. Mirrahimi, M. Brune, S. Haroche, J.M. Raimond, P. Rouchon, Phys. Rev. A. 80, 013805 (2009)

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

State estimation

- Field state
  - Entirely defined by the photon number distribution p(n)
    - No initial phase information (empty cavity)
    - No final phase information (Fock state)
      - Relatively simple calculations

- Get a good estimate of the photon number distribution in the cavity
  - Bayesian inference of p(n)
  - Use all available knowledge
    - Calibrated experimental parameters
    - Calibrated experimental imperfections
    - All detections and actions so far
      - QND sensor atoms
        - » Simple procedure, one step in a QND measurement
      - Actuator samples
        - » Precisely calibrate resonant interaction

Distance to target

- A weighted sum of photon number probabilities

$$d = \sum \left(n - n_t\right)^2 p(n)$$

  - A simple expression in terms of mean photon number and variance

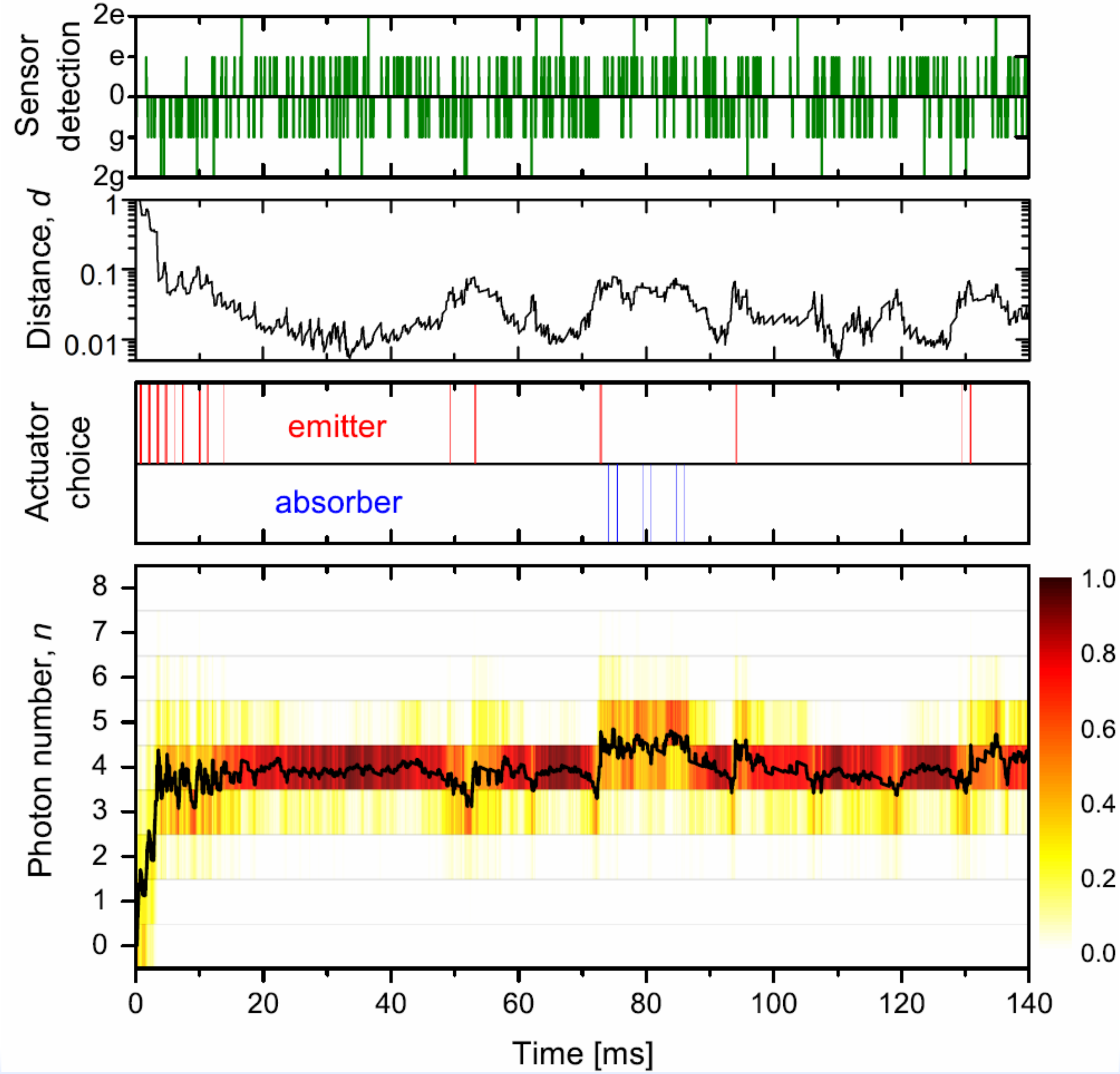
$$d = (\overline{n} - n_t)^2 + \Delta n^2$$

    - Minimal when minimal variance around n_t photons

- Decision algorithm
  - For each control sample
    - Estimates state after its interaction with field for three choices (emitter, absorber acutator or sensor)
    - Selects option corresponding to minimal distance
    - Programs the microwave and d.c. pulse accordingly

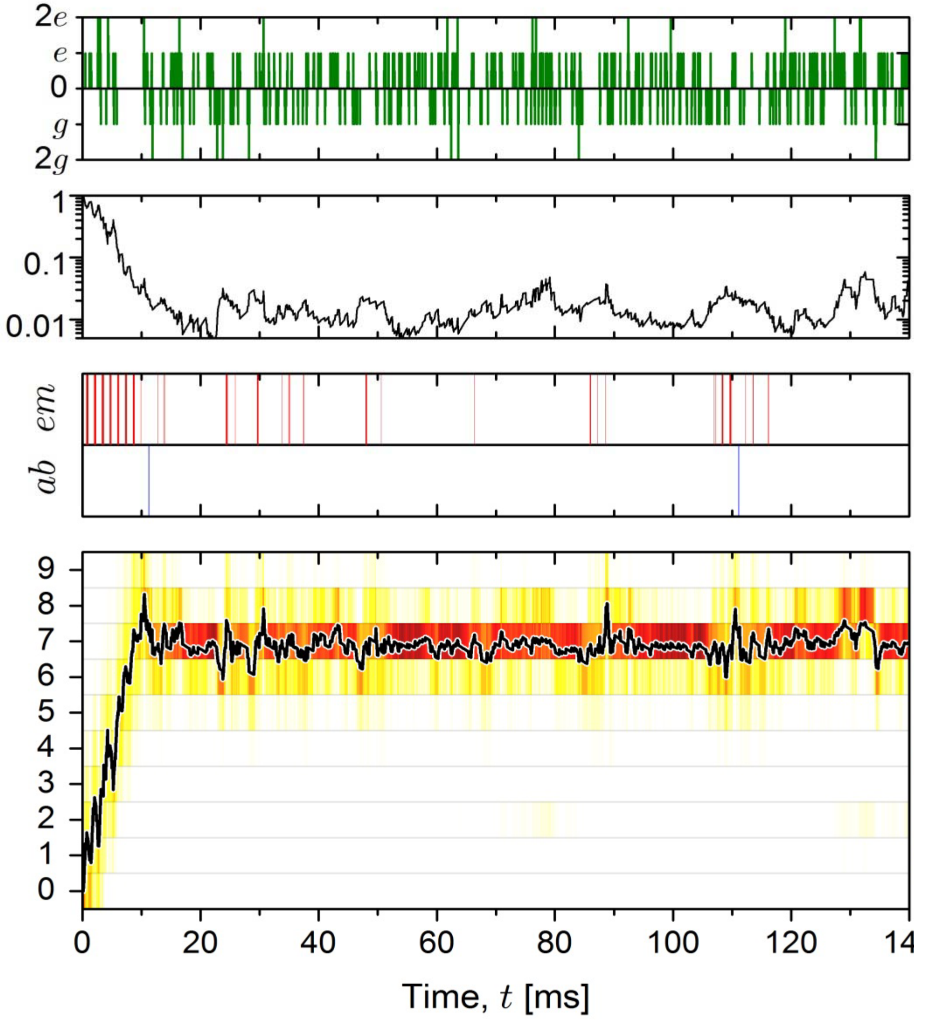
A single trajectory: closed loop

- Target photon number n_t=4

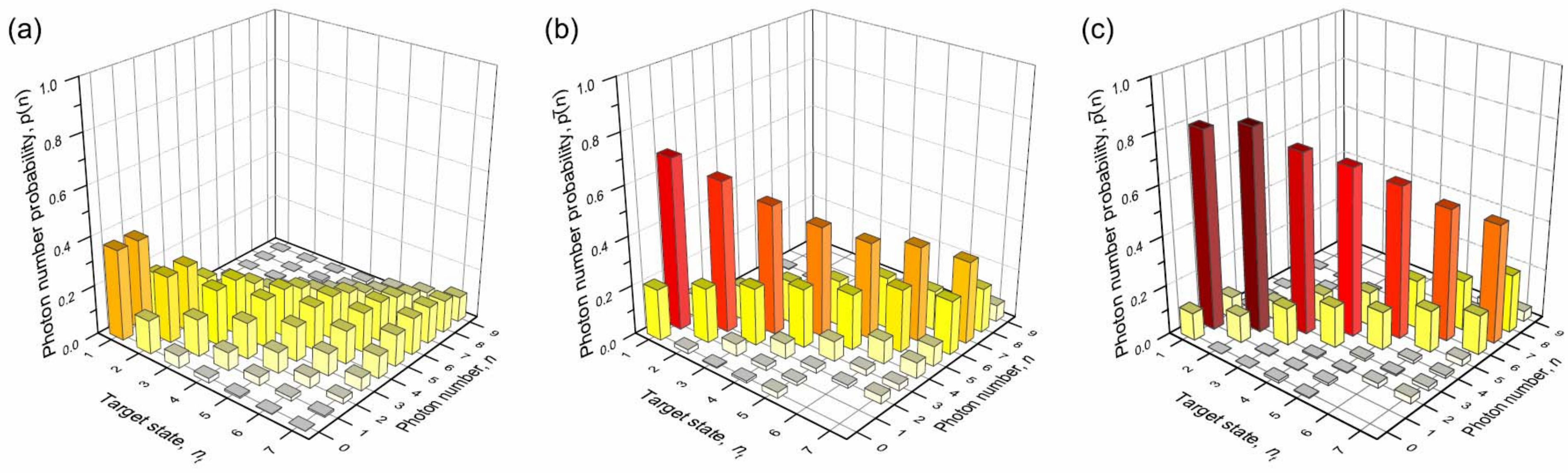


A single trajectory

- Target photon number n_t=7



Feedback for high photon numbers

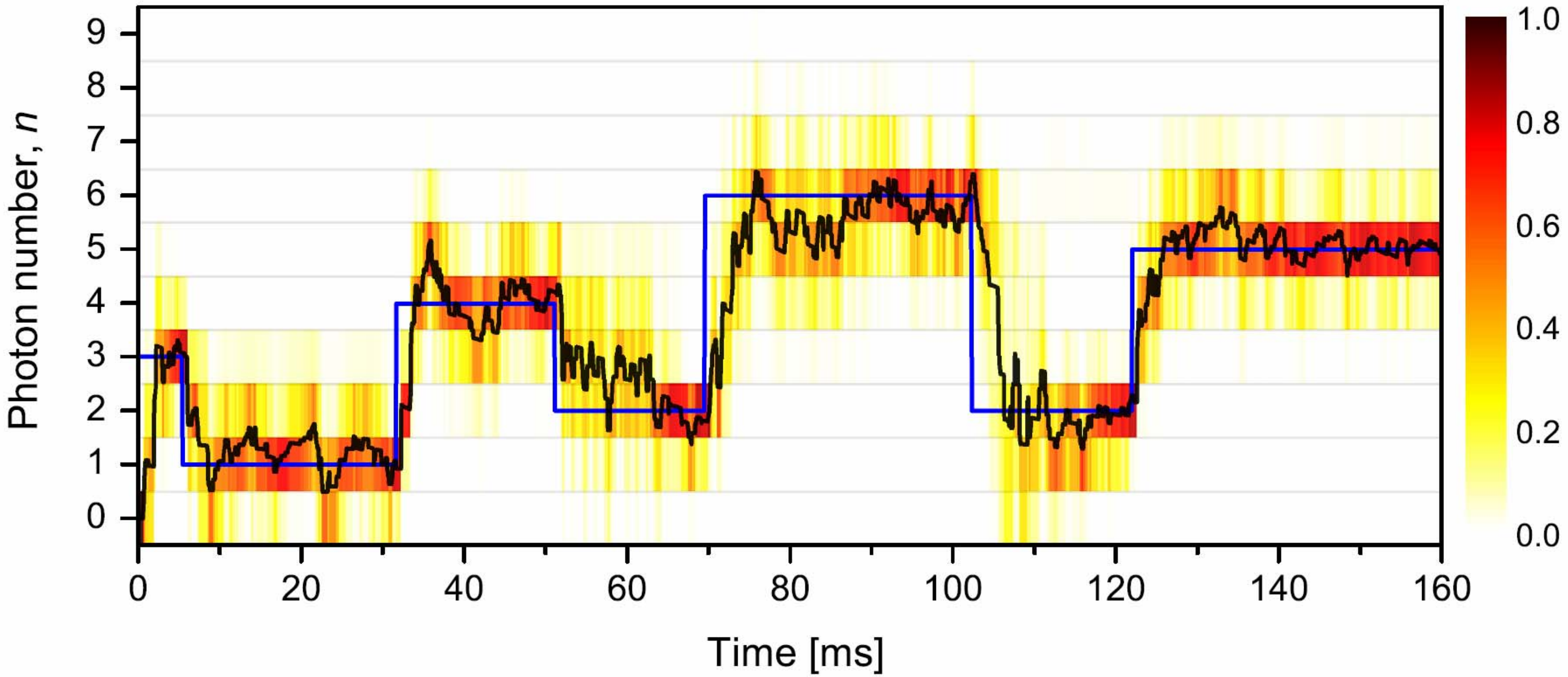


Reference	Steady state	Optimal stop
coherent state with n_t photons on the average	• stops loop at 140 ms • independent QND estimation of average photon number distribution *P(n)*	• Stops loop when $p(n_t)>0.8$ • Independent QMD estimation of *P(n)*

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

Sequential preparation of Fock states

- Predetermined sequence of target states
  - Commutation when 80% fidelity reached



  - Prepares Fock states as a resource for fundamental experiments or quantum information processing

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 fast adaptive quantum measurement
- 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
  - Quantum Zeno dynamics

Towards an optimal QND measurement

- Spin tomography method
  - Easy but uses n_m^2 atoms to count up to n_m photons
    - Far from the information theory optimum
- A simple optimal scheme in an ideal setting
  - Assume n<8 (0 through 7 photons)
  - First atom sent in *g* with $\phi_0=\pi$, and ramsey interferometer at $\phi_r=0$
    - Detected state tells the field parity
      - Detected in *e* when empty or even photon number
      - Detected in *g* when odd photon number
    - Atom gives the Least significant bit of photon number
    - Projects the field on a parity eigenstate (cat if initial state coherent)
  - Second atom sent with $\phi_0=\pi/2$
    - Phase ϕ_r adjusted to distinguish
      - 0,4 from 2,6 if parity even
      - 1,5 from 3,7 if parity od
    - Atom gives the second bit of the photon number

Towards an optimal QND measurement

- A simple scheme in an ideal setting
  - Third atom sent with $\phi_0=\pi/4$
    - Ramsey phase set to remove the last ambiguity
    - Atom gives the third bit of the photon number
  - Measurement of photon number from 0 to 7 with 3 atoms
    - Instead of 110 (passive)

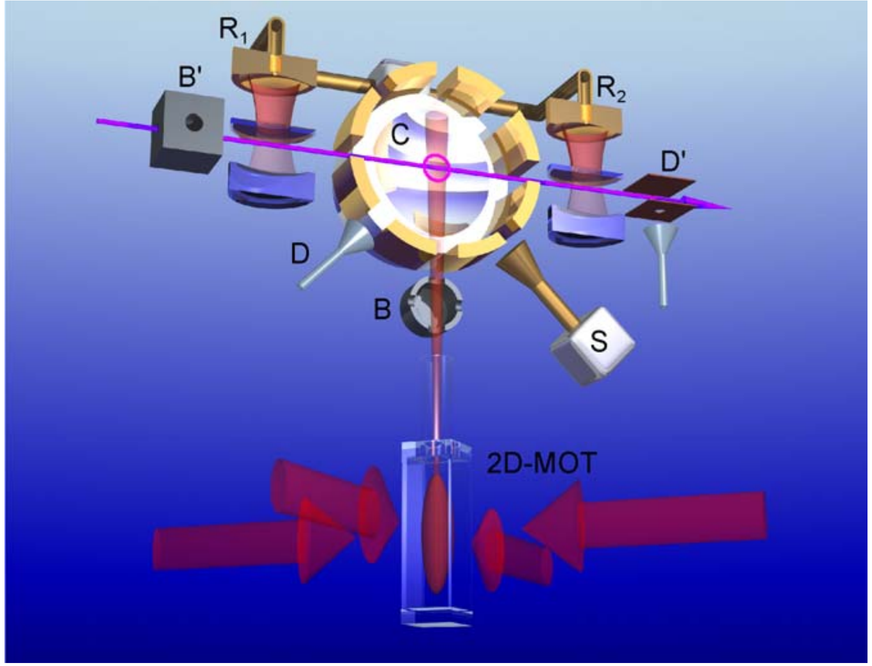
- Straigthforward generalization
  - Measurement of photon number from 0 to n_m-1 with $\log_2(n_m)$ atoms
  - Optimum set by information theory
  - An optimal quantum digital/analog converter
  - Complex protocol (real-time control of atomic velocity)

S. Haroche et al., J. Phys. II, **2**, 659 (1992)

- In a real experiment
  - Determination of photon number with ~$5\log_2(n_m)$

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
  - Quantum Zeno dynamics



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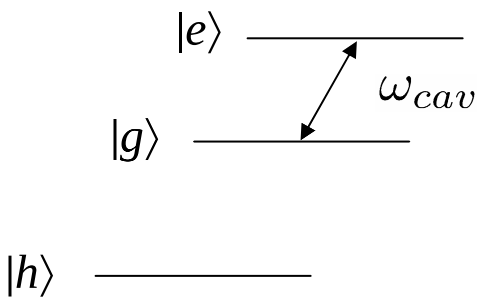
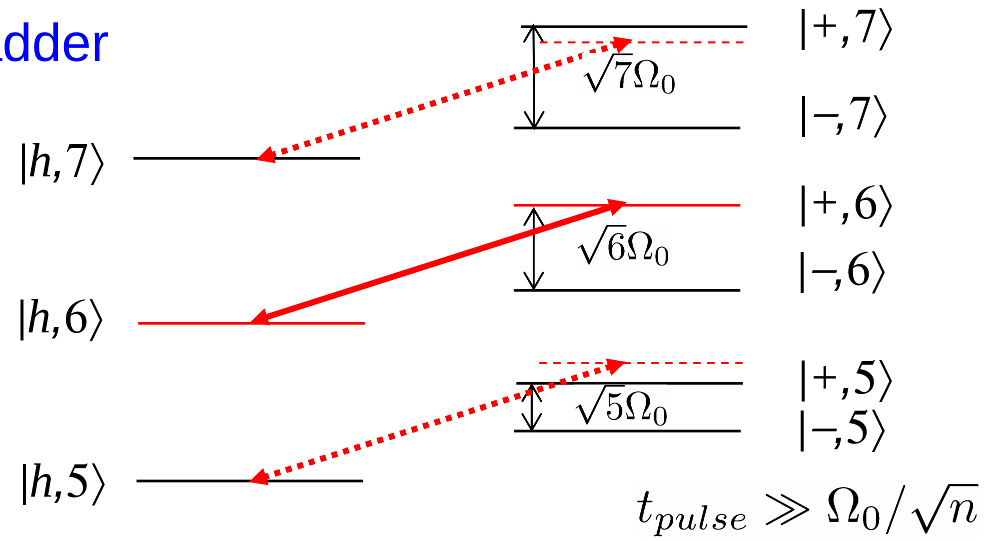
Quantum Zeno effect and quantum Zeno dynamics

- Quantum Zeno dynamics
  - Repeated measurement of an observable with a degenerate eigenvalue μ (eigenspace $\mathscr{H}_\mu$, projector P_μ)
    - State initially in $\mathscr{H}_\mu$ remains in $\mathscr{H}_\mu$ and evolves under the effective hamiltonian $H_\mu = P_\mu H P_\mu$
      - Restriction of evolution in a subspace may have surprising and interesting effects
  - Alternative route towards quantum Zeno dynamics:
    - Repeated actions of a unitary Kick operator U_K, with the same eigenspaces $\mathscr{H}_\mu$
      - Related to 'bang-bang' control techniques
  - Our proposal:
    - Realization of a quantum Zeno dynamics for the cavity field in a subspace.

A photon number selective measurement

- Probing the dressed states ladder

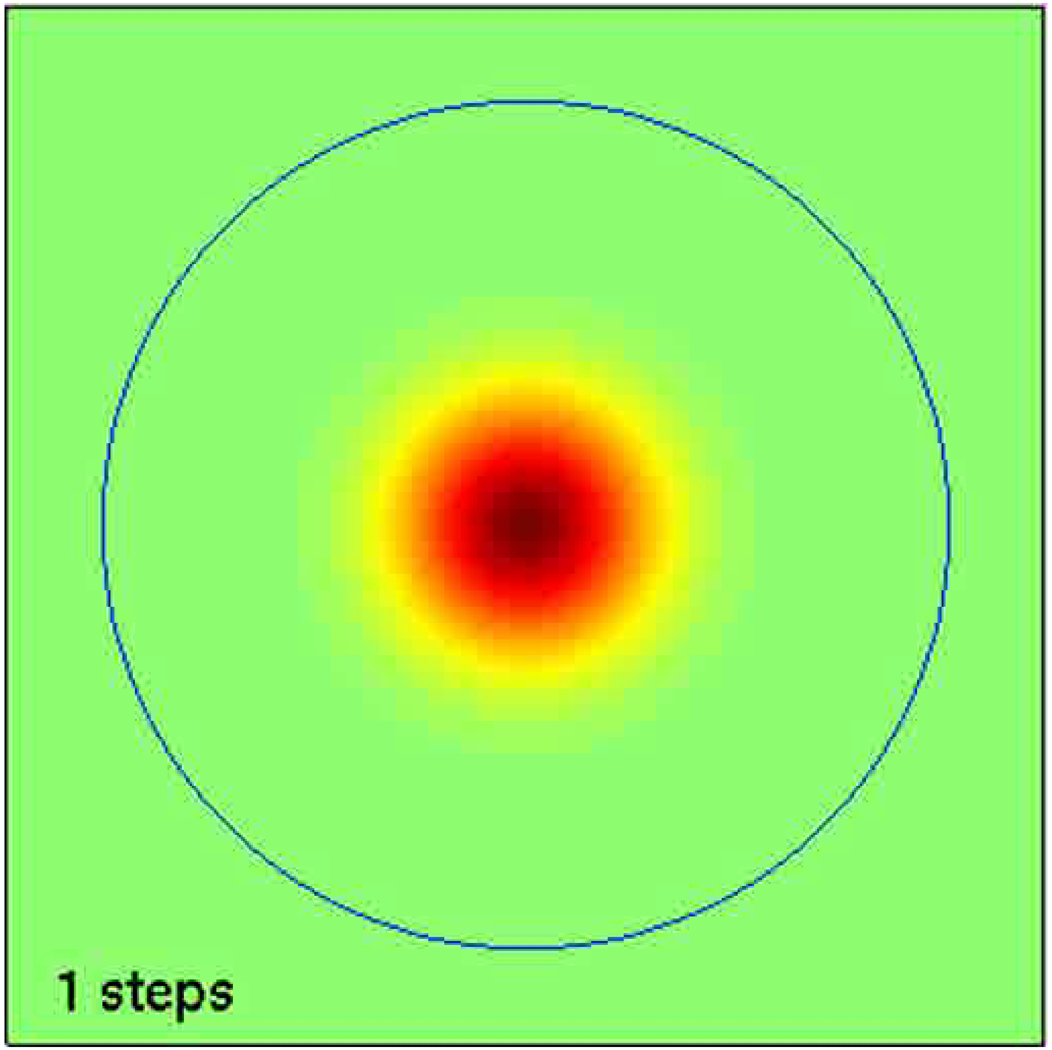




  - Resonant pulse on the $|h,s\rangle \rightarrow |+,s\rangle$ transition
    - π pulse: final atomic state [*h* or (*e*,*g*)] tells out the photon number
      - Atom in *e* or *g*: the photon number is exactly *s*
      - Atom in *h*: the photon number is NOT *s*
    - 2π pulse: $|h,s\rangle \rightarrow -|h,s\rangle$
      - Atom stays in *h*. Photon number selective unitary kick on the field: $U_k = 1 - 2|s\rangle\langle s|$)
      - Same atom can be used for a new operation.
        - » Focus on this situation in the following

Dynamics inside the exclusion circle

- 150 steps, N_s=6



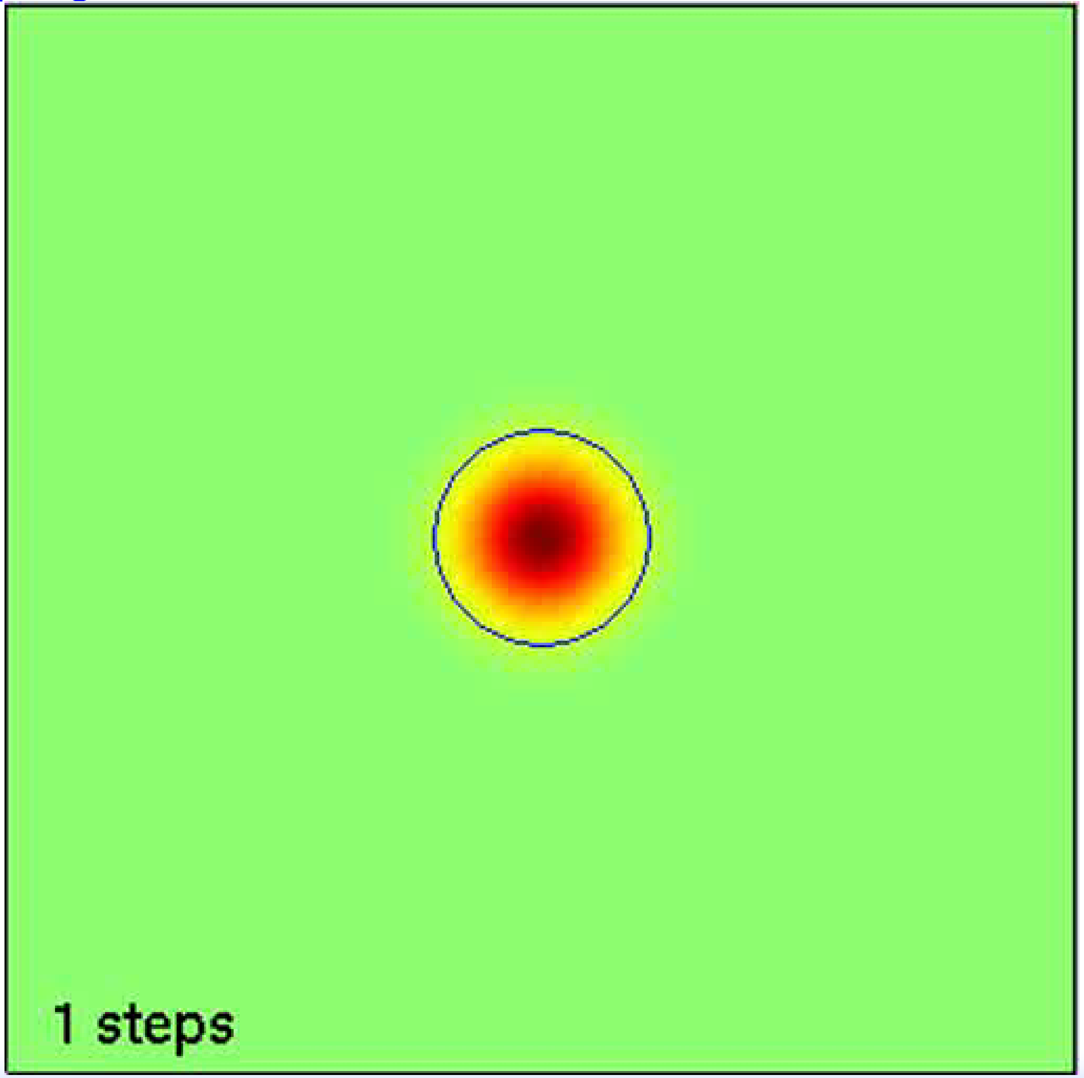
Phase space tweezers

- A radius 1 EC (s=1)
  - Blocks a coherent component
    - No evolution at all

- Phase space tweezer
  - An EC with N_s=1 and a slowly varying center. No free dynamics
    - The 'blocked' coherent component adiabatically follows the slow motion of the EC even in the absence of other source of evolution
      - A means to pick at will a coherent component and to displace it arbitrarily without affecting others
      - A quantum analogue of the optical tweezers

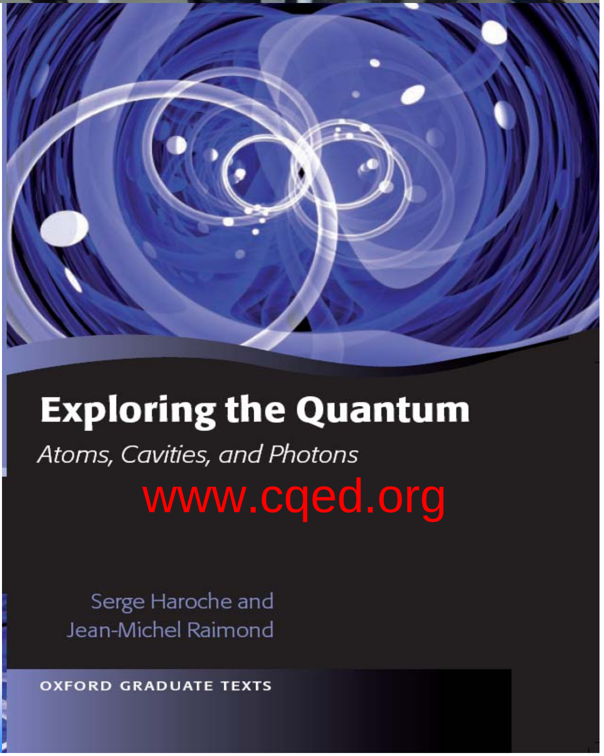
Nearly arbitrary state synthesis

- Use tweezers to generate from vacuum a prescribed superposition of non-overlapping coherent states



The ENS team

- S. Haroche, M. Brune,
  JM Raimond, S. Gleyzes
- Cavity QED experiments
  - I. Dotsenko, S. Gerlich
    C. Sayrin, X. Zhou,
    B. Peaudecerf, T. Rybarczyk,
    A. Signolles, A. Facon, E. Dietsche
- Superconducting atom chip
  - Sha Liu
  - R. Teixeira, C. Hermann, Than Long
- Collaborations:
  - Cavities: P. Bosland, B. Visentin, E. Jacques
    - CEA Saclay (DAPNIA)
  - Feedback: P. Rouchon, M. Mirrahimi, A. Sarlette
    - Ecole des Mines Paris
  - QZD: P. Facchi, S. Pascazio
    - Uni. Bari and INFN
- €€:ERC (Declic), EC (Aqute, CCQED),
  - ANR (QUSCO),CNRS, UMPC, IUF, CdF



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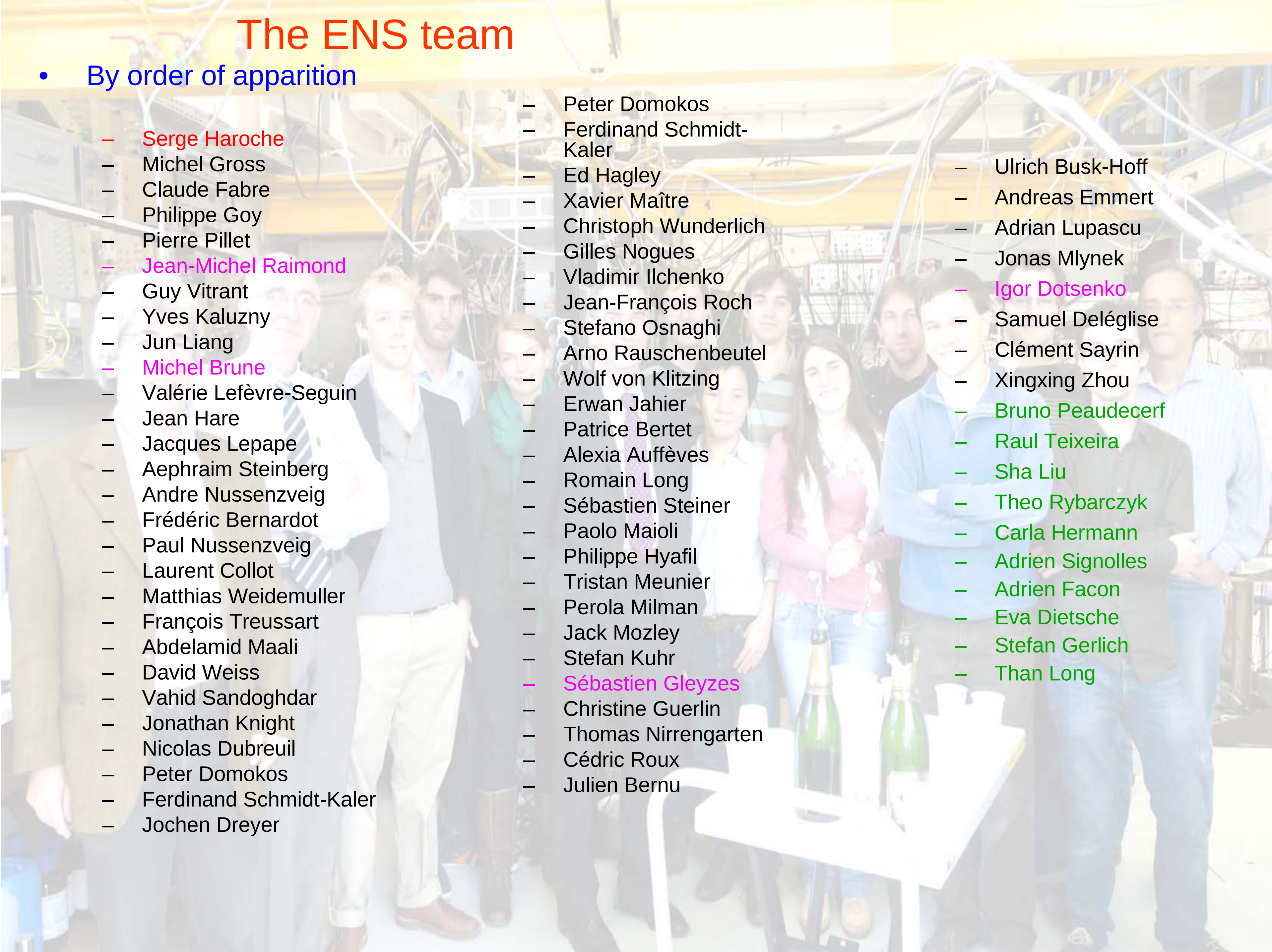

The ENS team

- 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
  - Theo Rybarczyk
  - Carla Hermann
  - Adrien Signolles
  - Adrien Facon
  - Eva Dietsche
  - Stefan Gerlich
  - Than Long