Observation of light quantum jumps and time-resolved reconstruction of field states in a cavity

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ICAP, Storrs, July 29th 2008

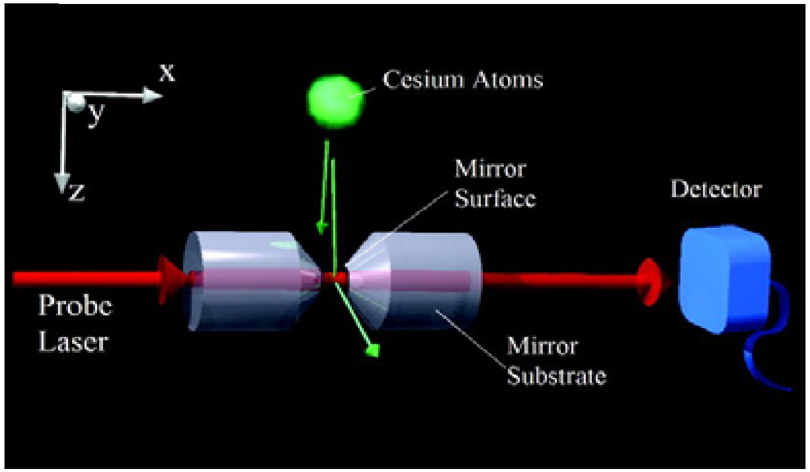
Light as « an object of investigation », trapped for long times, manipulated and observed non-destructively for fundamental tests and quantum information purposes

The context:

Cavity Quantum Electrodynamics:

the physics of a qubit (two-level real or artificial atom) coupled to a harmonic oscillator (field mode)

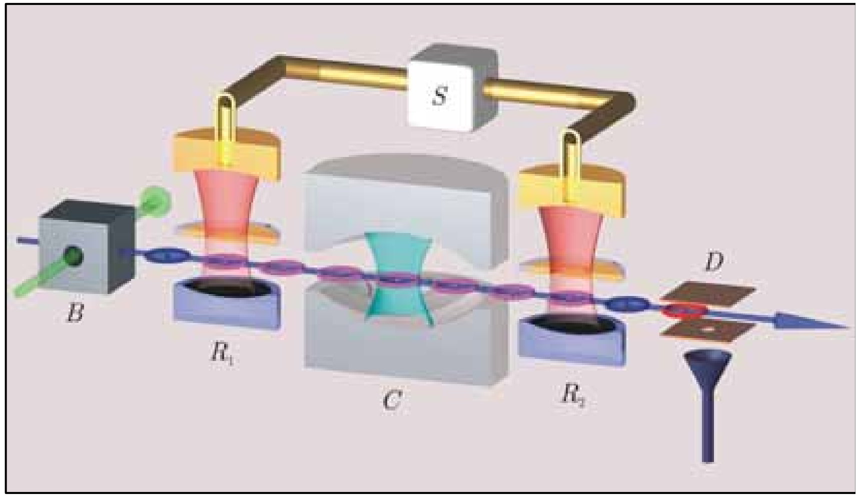
Atomic cavity QED



...in the optical domain

Atom-cavity spectrum
Single photon on demand
Single atom detection
atom-cavity forces, cavity cooling
Photon blockade
Ions trapped between mirrors (R.Blatt)
Atomic ensembles in cavities (next 2 talks)

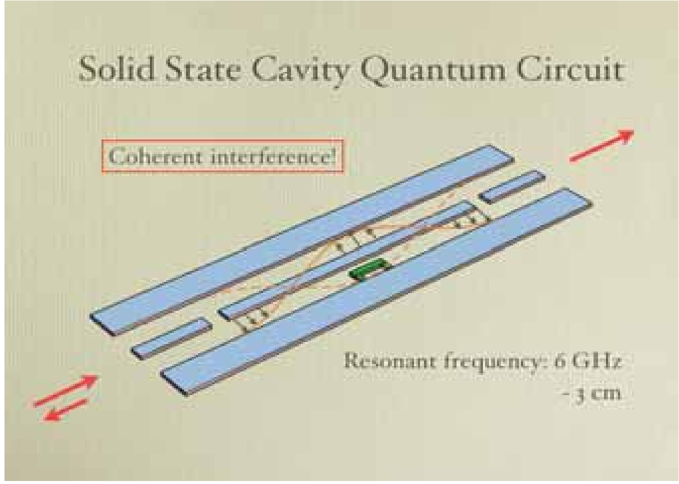
...and in the microwave domain



- Micromaser
- Two-photon maser
- Atom-photon and atom-atom entanglement, quantum gates...
- Photonic memory
- Photonic Schrödinger cats and decoherence

Complementary strong-coupling regime experiments with single photon-single atom sensitivity

Solid State Cavity QED



Circuit QED

Superconducting qubits coupled to strip-line microwave resonators

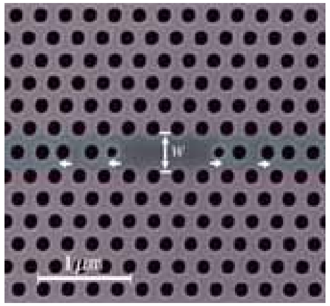
Ultra strong coupling regime

(R.Schoelkopf in Hot topic II sessions)

Yale, NIST, Santa Barbara, U.of Wisconsin, ETH, Saclay etc…

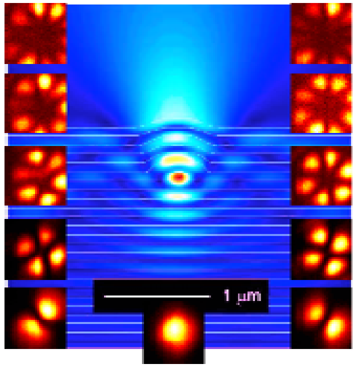
Optical micro-cavities to be coupled to atoms or quantum dots

Toroidal microcavity (for CQED and optomechanical devices)



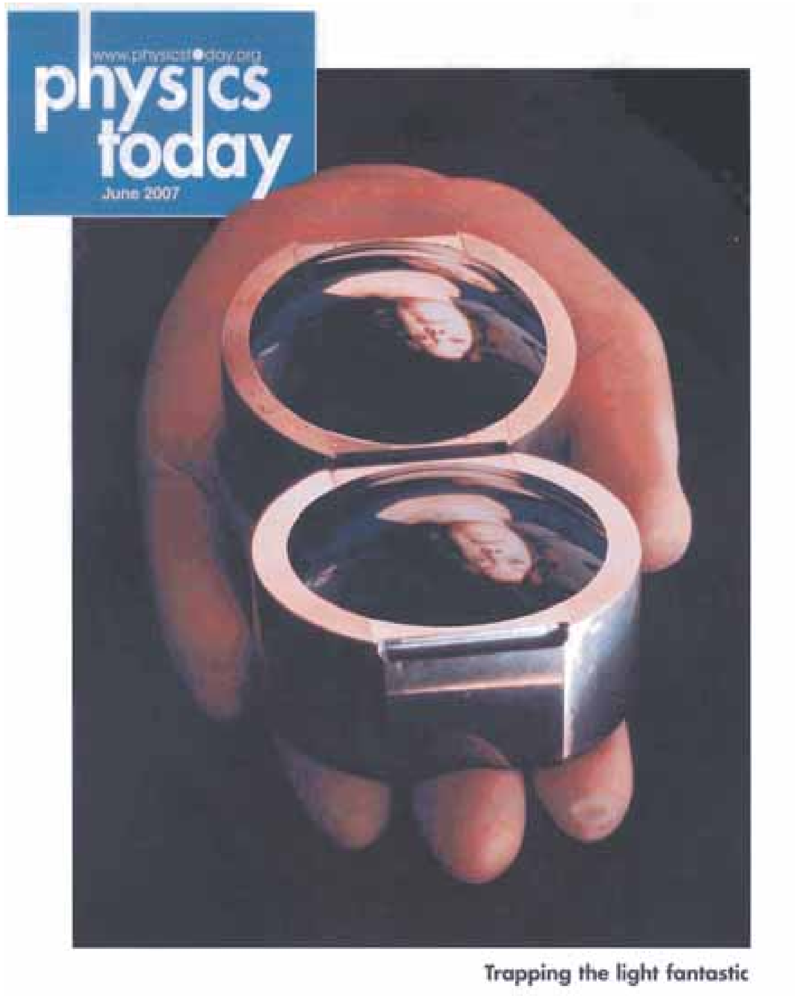
Photonic crystal…

Semiconductor epitaxial microcavity



Much more about CQED in Monday Poster session…

Trapped microwave photons counted non-destructively by Rydberg atoms



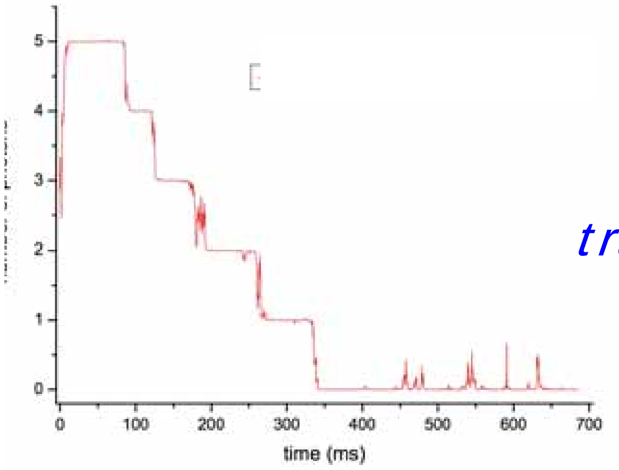
Instead of trapping atoms…

Wineland et al, Boulder

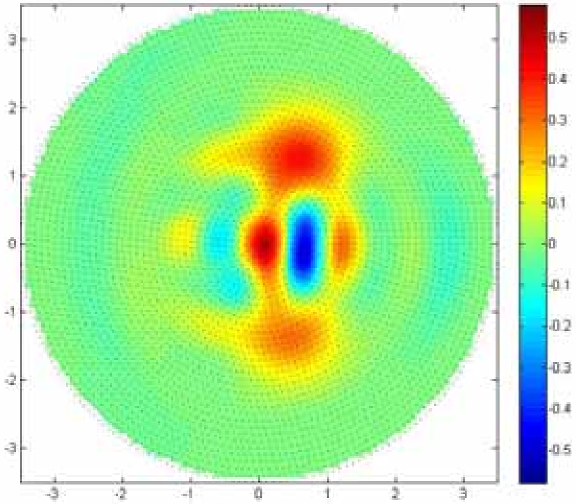
…and manipulating them with beams of light

…we trap light and manipulate it with a beam of atoms

Trapping photons for a long time in a very high-Q cavity and counting them non-destructively with a stream of atoms realizes a new way to look at light, opening many perspectives in quantum optics



From the observation of individual field quantum trajectories to the generatio and reconstruction of «strange» non-classical states….



Outline

1. Our set-up: a photon trap inside a Rydberg atom clock

2. QND counting of photons & the quantum jumps of light

3. Reconstruction of trapped field quantum states by QND photon counting

4. Preparing and reconstructing Schrödinger cat states of light: **a movie of decoherence**

5. Conclusion and perspectives

Microwave photons in a box

- Superconducting mirrors
- Resonance @ $\nu_{cav} = 51$ GHz
- Lifetime of photons

  $T_{cav} = 130$ ms
- Q factor = $\omega T_{cav} = 4.2 \cdot 10^{10}$
- Finesse $F = 4.6 \cdot 10^{9}$

- best mirrors ever

- 1.5 billion photon bounces

- Light travels 40 000 km
  (Earth circumference)

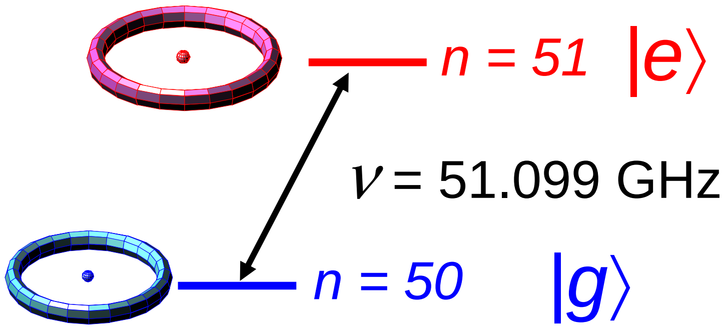
Hundreds of atoms cross cavity one at a time during T_{cav}

*S. Kuhr et al, APL **90**, 164101 (2007)*

Special detectors: Circular Rydberg Atoms

R.Hulet and D.Kleppner, Phys.Rev.Lett. 51, 1430 (1983)

^{85}Rb



$n = 51$ $|e\rangle$

$\nu = 51.099$ GHz

$n = 50$ $|g\rangle$

- n large, $l = |m| = n - 1$
- life time: 30 ms → weak dissipation
- huge electric dipole → very sensitive to microwave
- Two-level atom behaves as «spin»

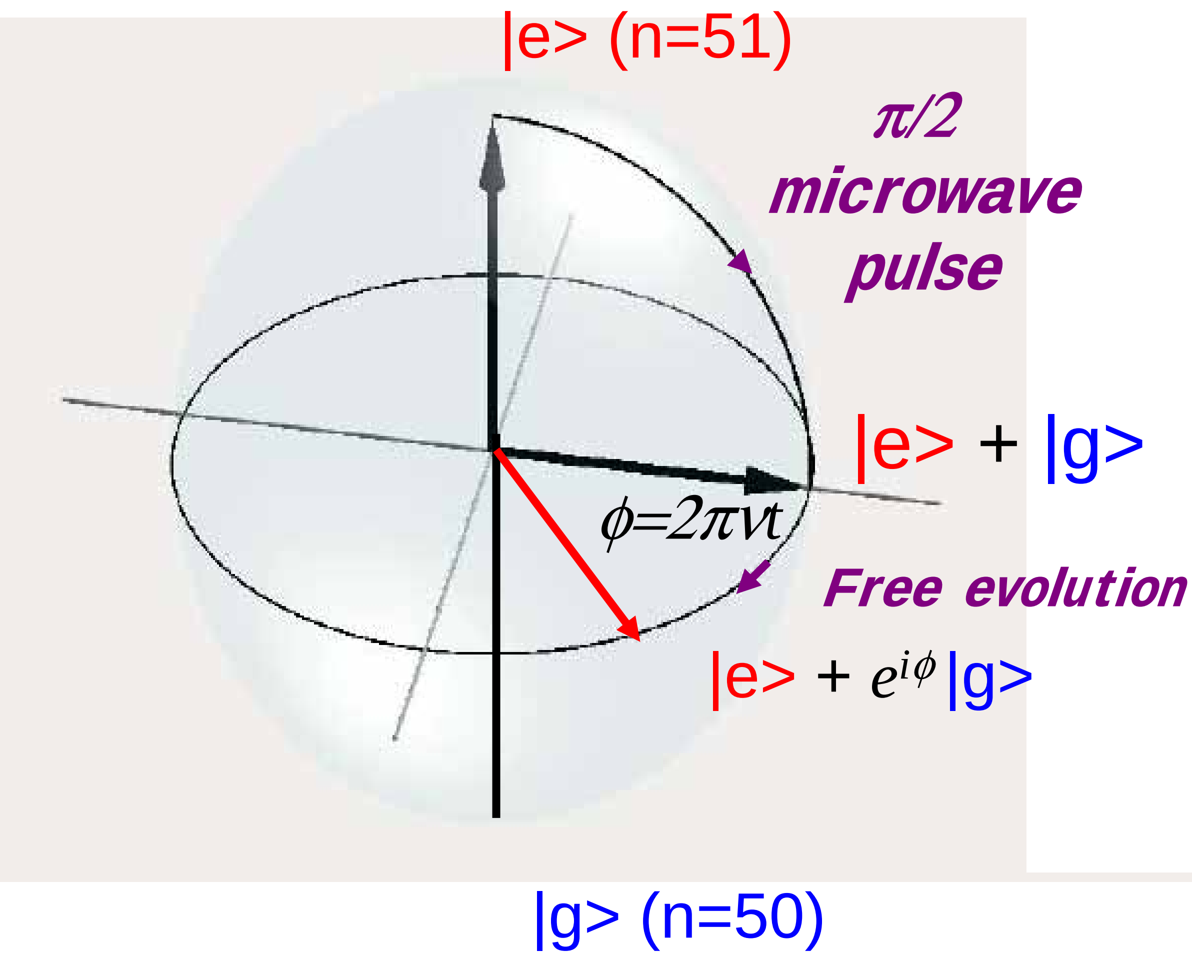
But:

- complex preparation
- requires a « directing » E field → cavity **must be open**

Raimond, Brune and Haroche, RMP, 73, 565 (2001)

Bloch sphere representation of the two-level Rydberg atom

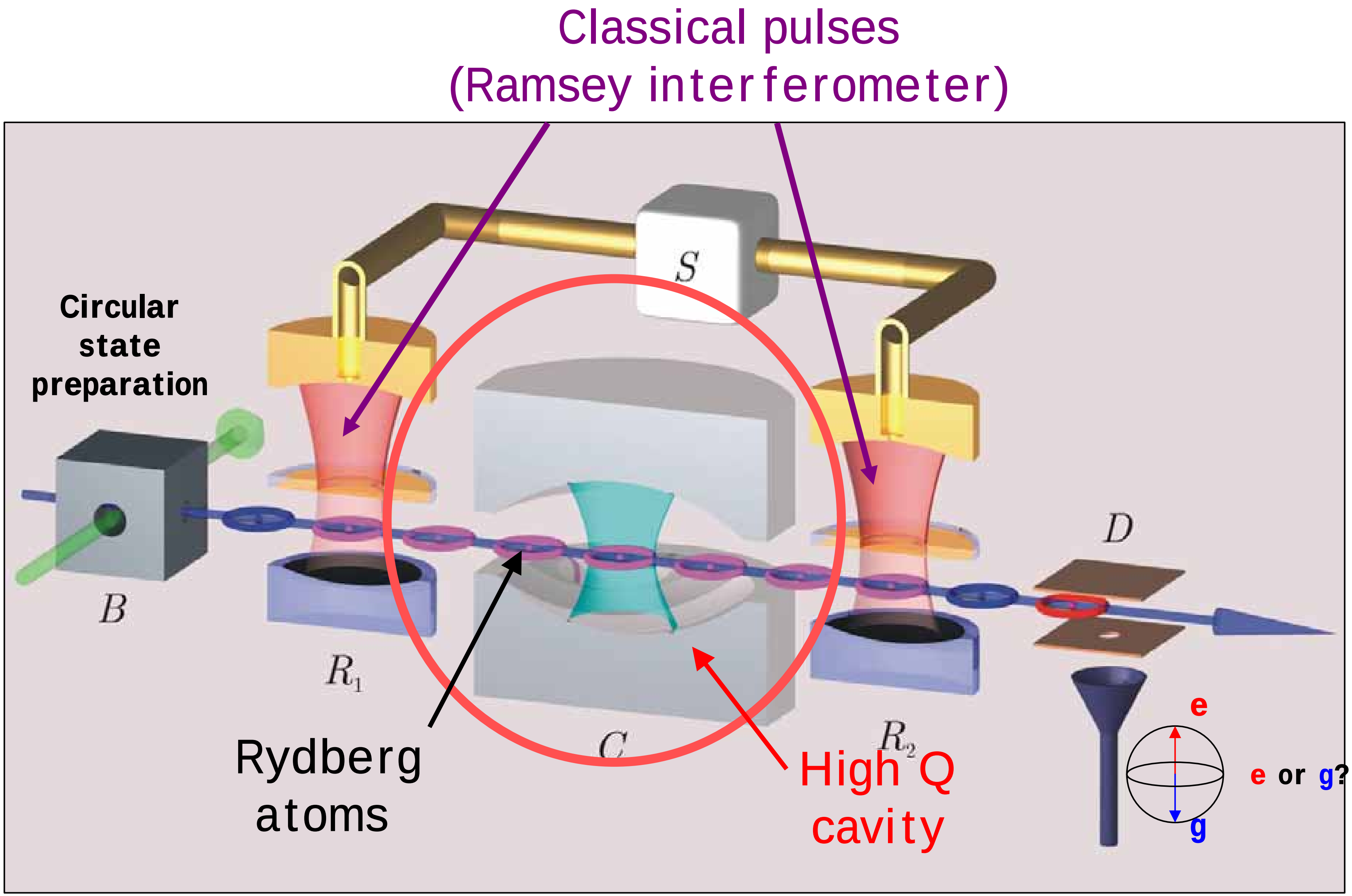
Equatorial plane of Bloch sphere is the dial and the ‘spin’ is the hand of an atomic clock



Phase shift per photon adjusted by changing atom-cavity detuning

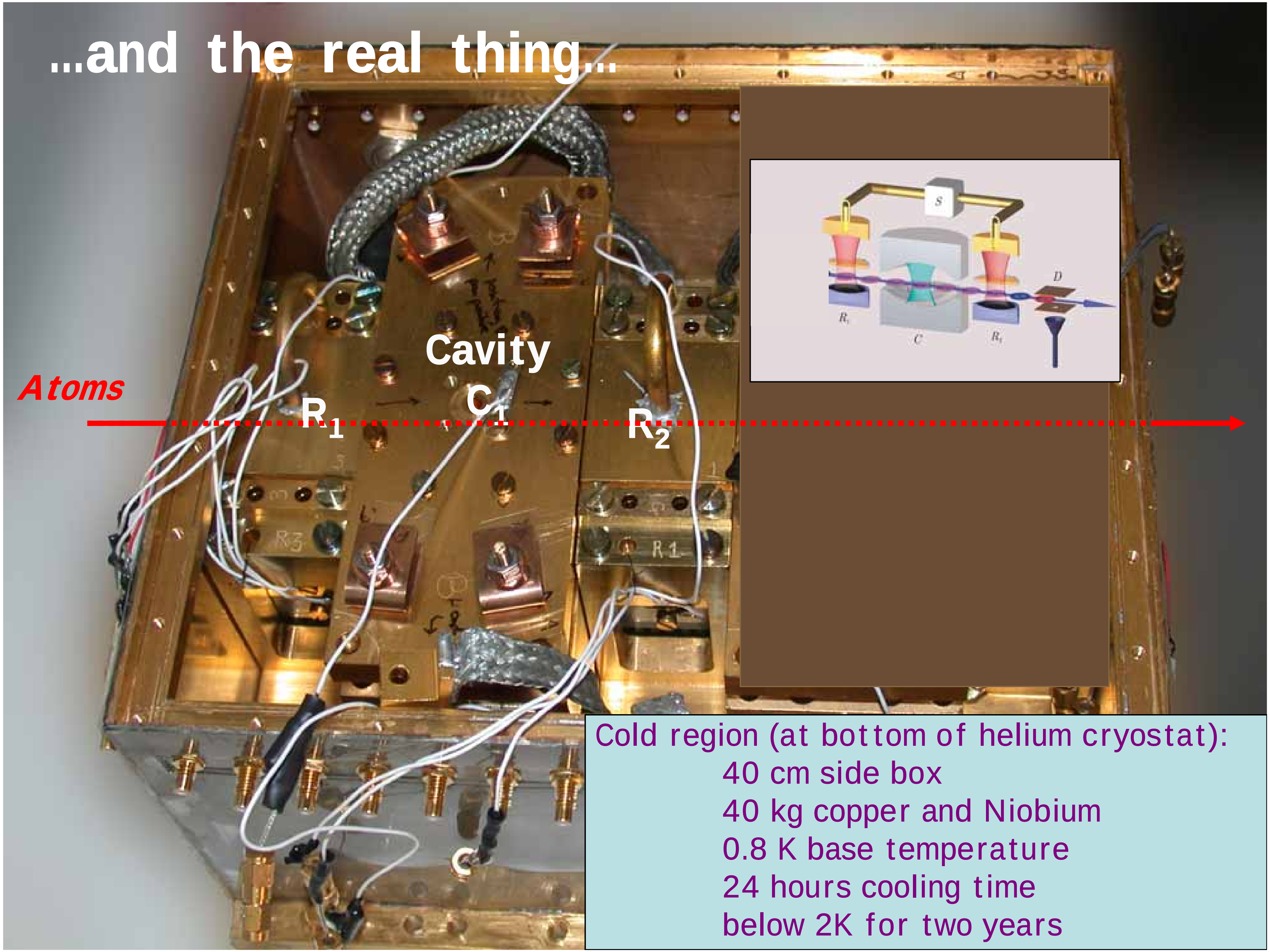
Atoms are off-resonant and cannot absorb light, but spins are delayed by light-shift effect. One photon can make the «spin hand» miss half a turn while atom crosses cavity **(π phase shift per photon).**

An artist's view of the set-up…



An atomic clock delayed by photons trapped inside

...and the real thing...



Cold region (at bottom of helium cryostat):
- 40 cm side box
- 40 kg copper and Niobium
- 0.8 K base temperature
- 24 hours cooling time
- below 2K for two years

2.

QND counting of photons & the quantum jumps of light

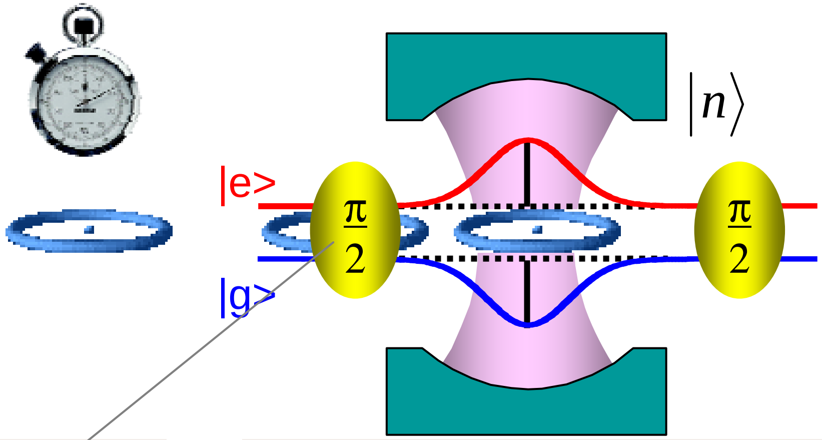
S.Gleyzes, S.Kuhr, C.Guerlin, J.Bernu, S.Deléglise, U.Busk Hoff, M.Brune, J-M.Raimond and S.Haroche,
Nature 446, 297 (2007)

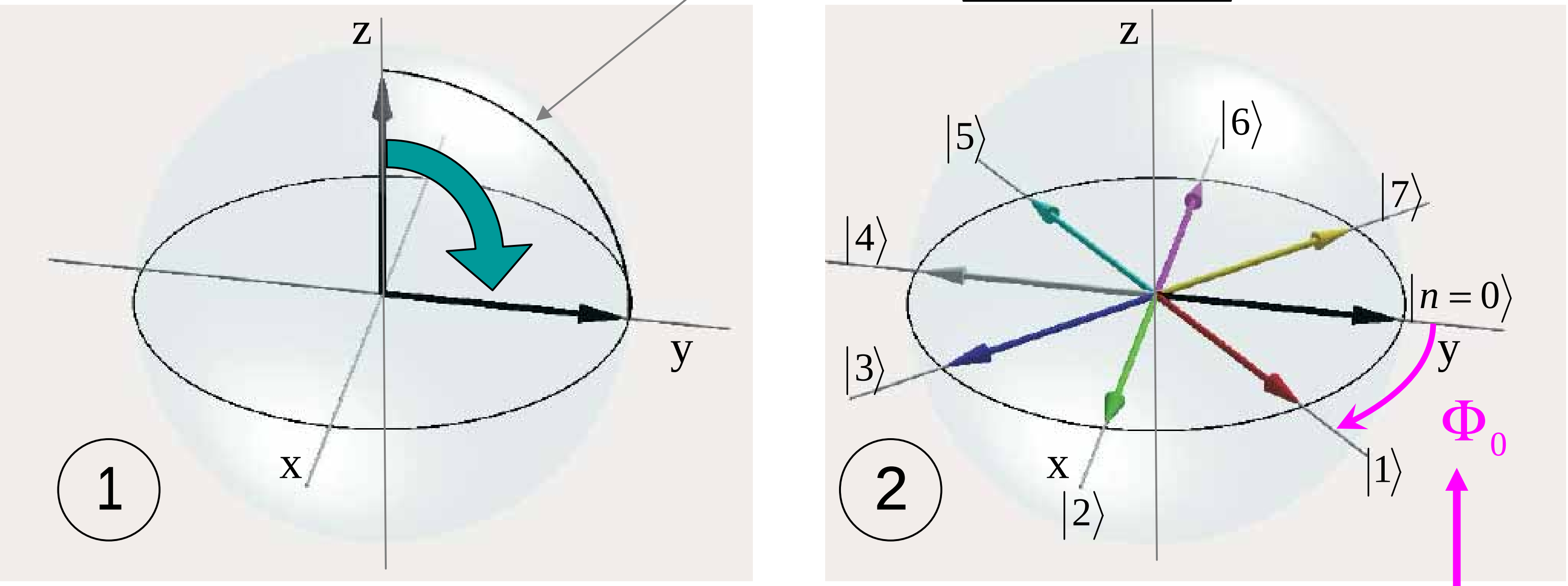
C.Guerlin, S.Deléglise, C.Sayrin, J.Bernu, S.Gleyzes, S.Kuhr, M.Brune, J-M.Raimond and S.Haroche,
Nature, 448, 889 (2007)

Each atom is a clock whose rate is affected by light

1. Reset the “stopwatch” (1st Ramsey pulse).

2. precession ot the spin through the cavity: clock ticks.





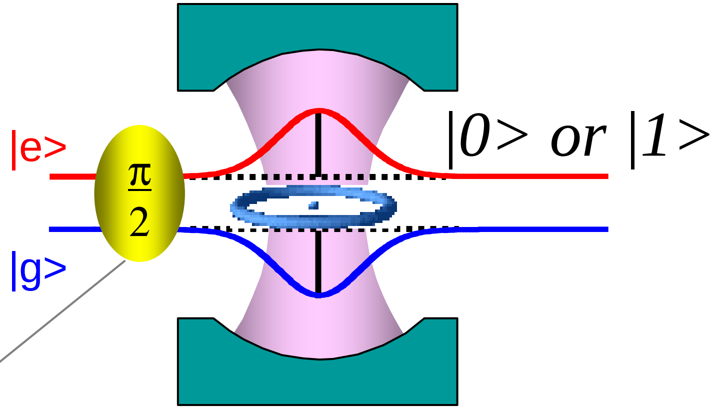
The clock’s shift is proportional to n: non-demolition photon counting by measuring spin direction (using 2nd Ramsey pulse)

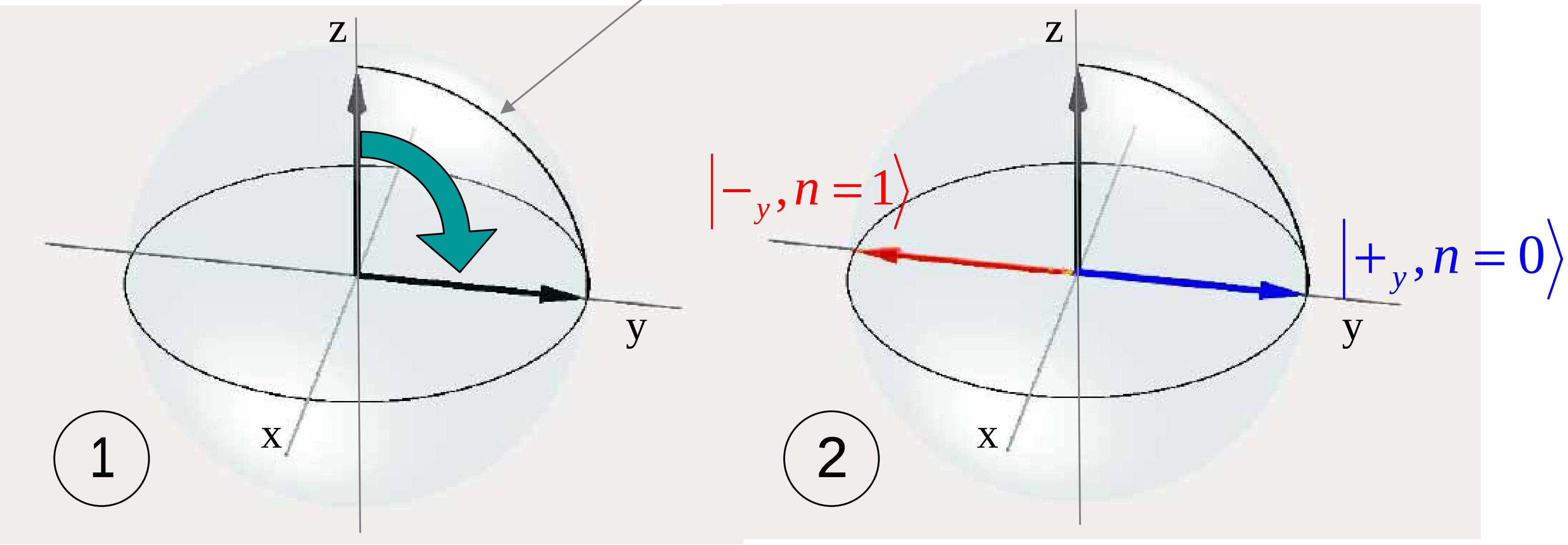
phase shift per photon

Detecting 0 or 1 photon

Strong dispersive coupling:

$$\boxed{\Phi_0 = \pi}$$



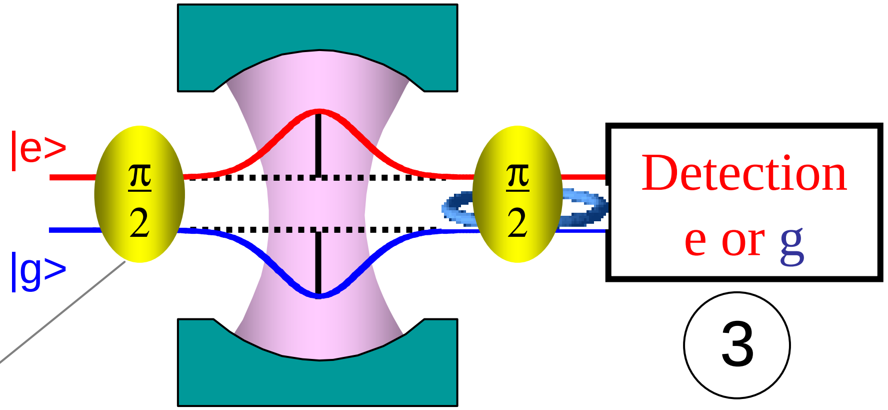


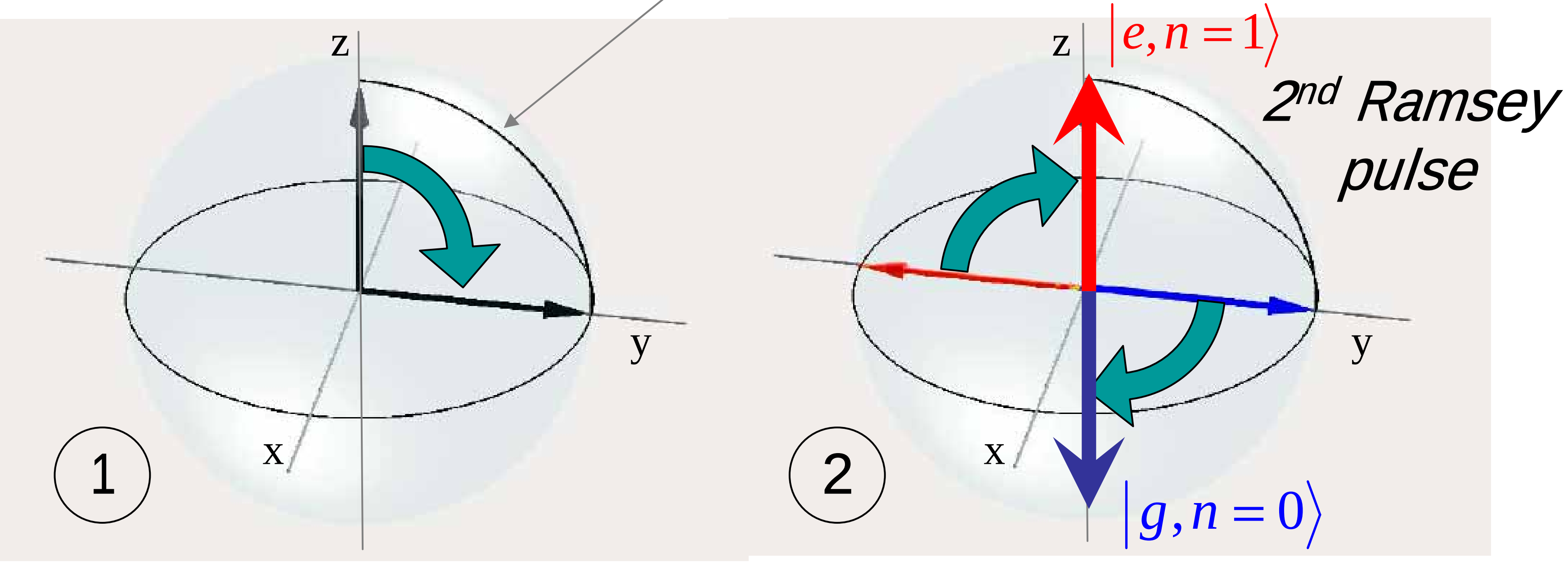
One atom = one bit of information (+ or - spin along y) perfectly correlated with the photon number.

Detecting 0 or 1 photon

Strong dispersive coupling:

$$\boxed{\Phi_0 = \pi}$$





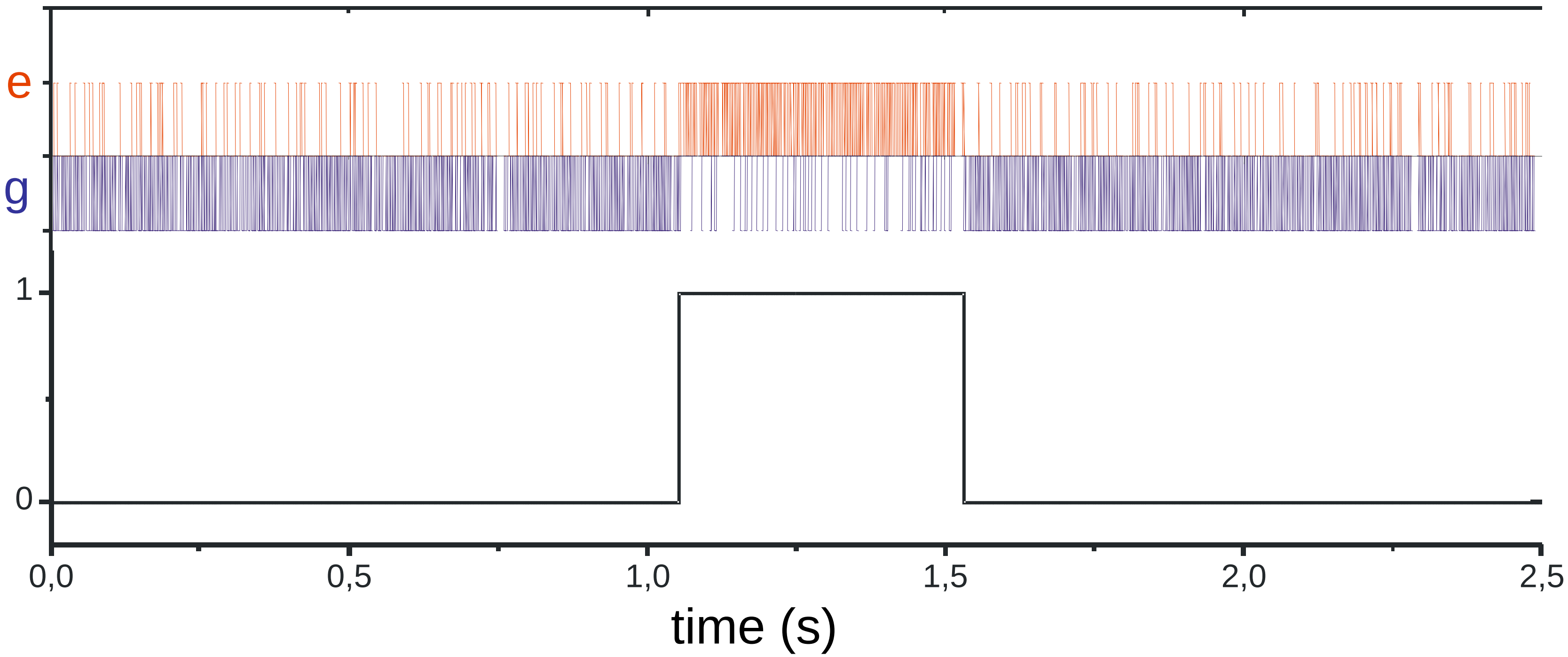
2^{nd} Ramsey pulse

g → field projected onto |0>

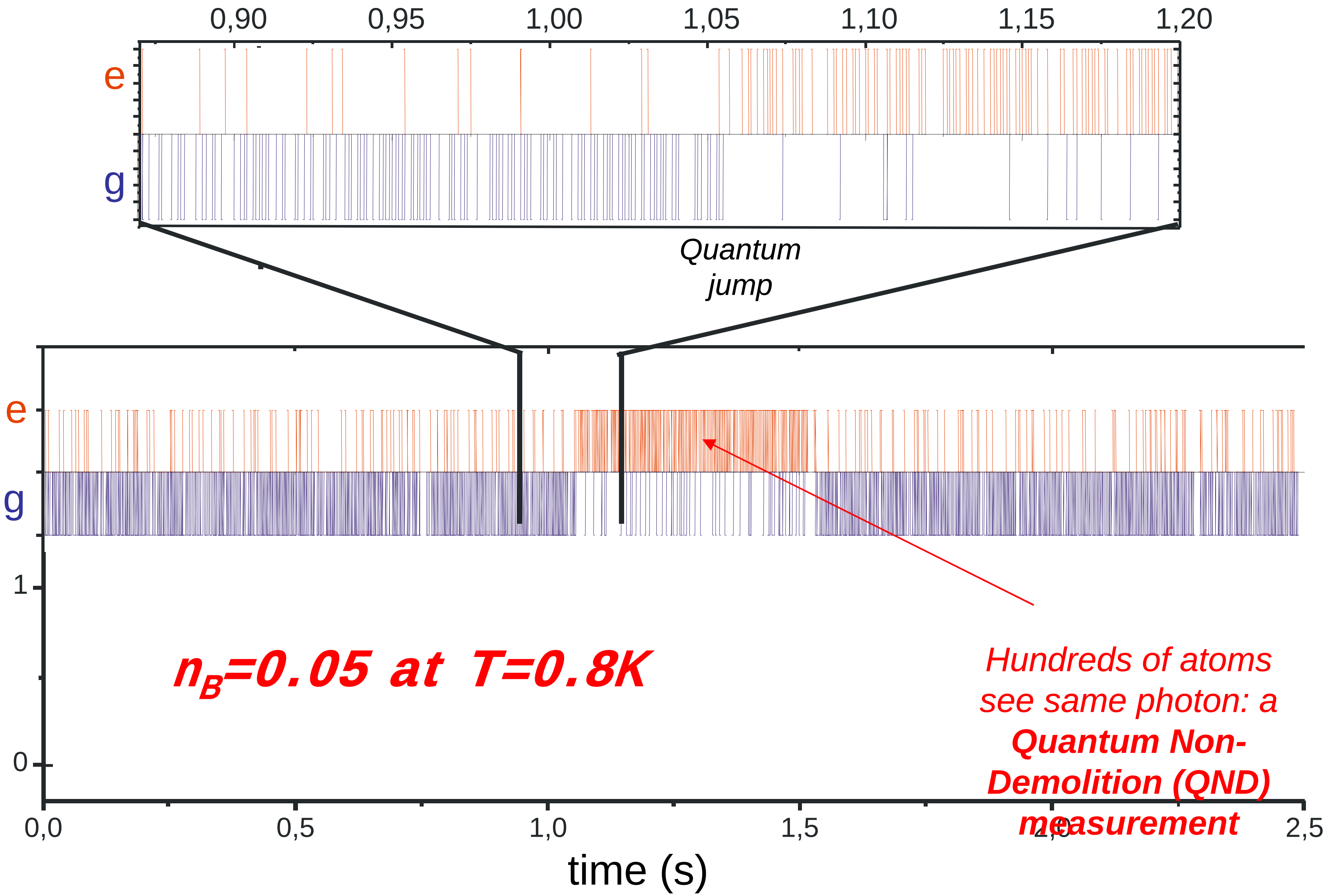
e → field projected onto |1>

Birth and death of a photon

(thermal field at 0.8K)



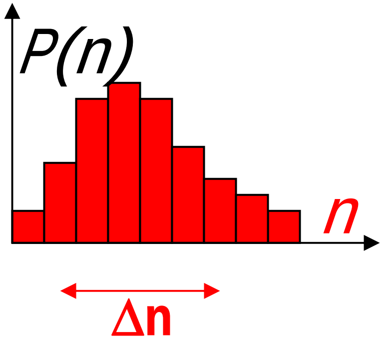
Birth and death of a photon



n_B=0.05 at T=0.8K

Hundreds of atoms see same photon: a **Quantum Non-Demolition (QND) measurement**

QND measurement of arbitrary photon numbers: progressive collapse of field state



A coherent field (Glauber state) has uncertain photon number:

$\Delta n \Delta \phi \geq 1/2$

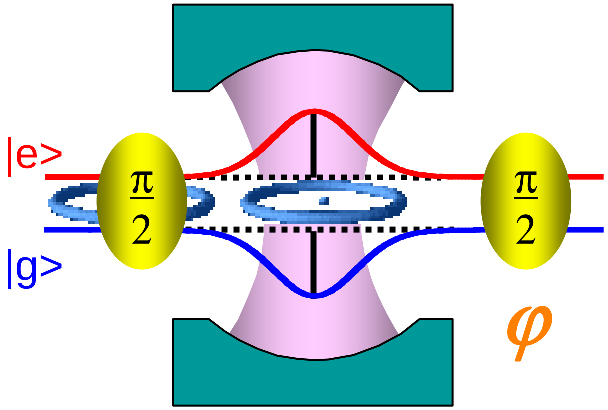
Heisenberg relation

A small coherent state with Poissonian uncertainty and $0 \leq n \leq 7$ is initially injected in the cavity and its photon number is progressively pinned-down by QND atoms

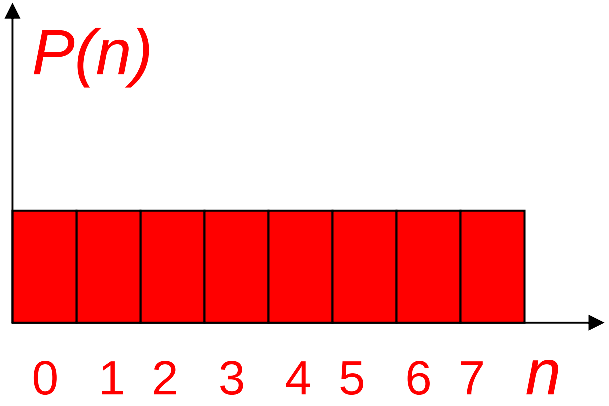
Experiment illustrates on light quanta the three postulates of measurement: state collapse, statistics of results, repeatability.

Counting larger photon numbers: 1st atom effect on inferred photon distribution

Chose $\Phi_0=\pi/4$

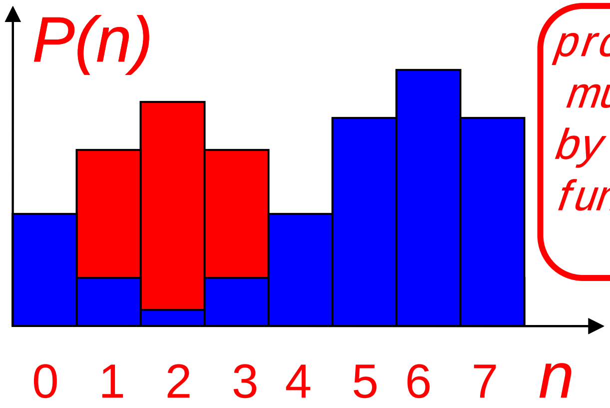


2nd Ramsey pulse maps a direction in equatorial plane back into Oz before detection

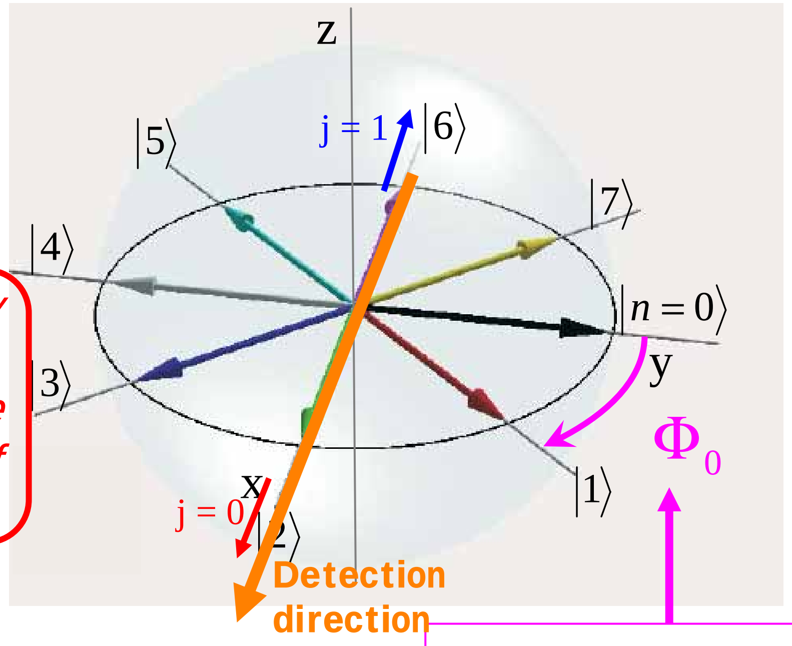


If «spin» found in state - (j=1) (along n=6)

If «spin» found in state + (j=0) (along n=2)



probability multiplied by a cosine function of n



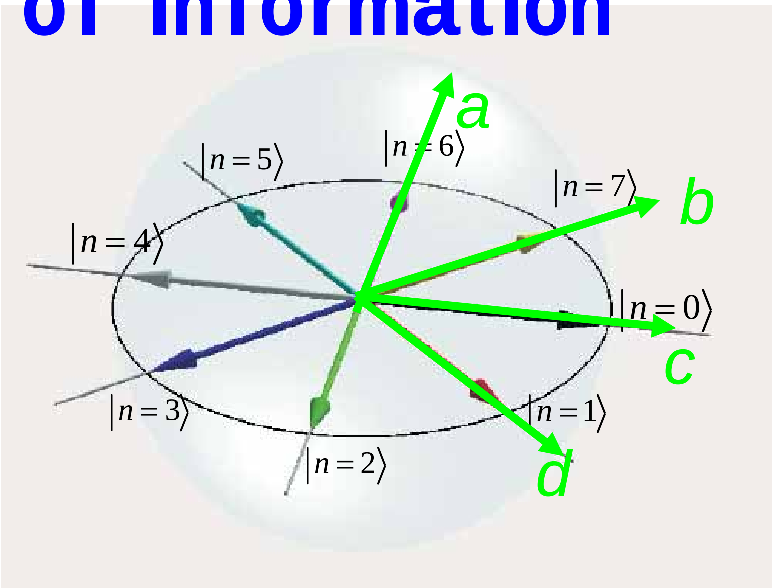
Detection direction

phase shift per photon

Random decimation of photon number

projection postulate (or Bayes law)

A step-by-step acquisition of information



To pin down photon number, send a sequence of atoms one by one....

...and change direction of spin detection to decimate ***different*** numbers

$$P^{(N)}(n)=\frac{P^{(0)}(n)}{2Z}\prod_{k=1}^{N}\left[1+\cos\left(n\Phi_0-\underbrace{\phi(k)}_{a/b/c/d}-\underbrace{j(k)}_{0/1}\pi\right)\right]/2$$

Spin reading 000101101010001011001°K

Direction abdcadb cbadcaa bcbacd b°K

$$P^{(N)}(n)\longrightarrow\delta(n-n_0)$$

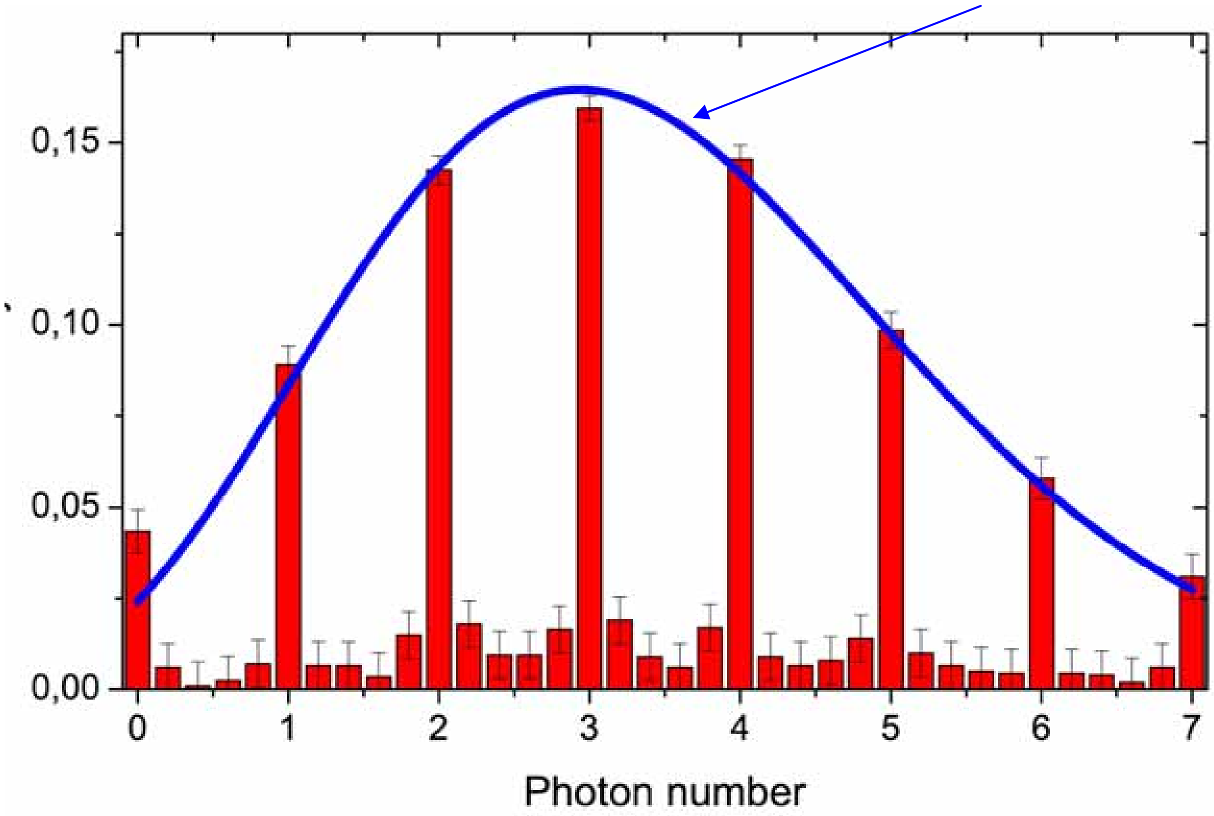
Progressive collapse!

A progressive collapse: *which number wins the race?*

QuickTime™ et un
décompresseur codec YUV420
sont requis pour visionner cette image.

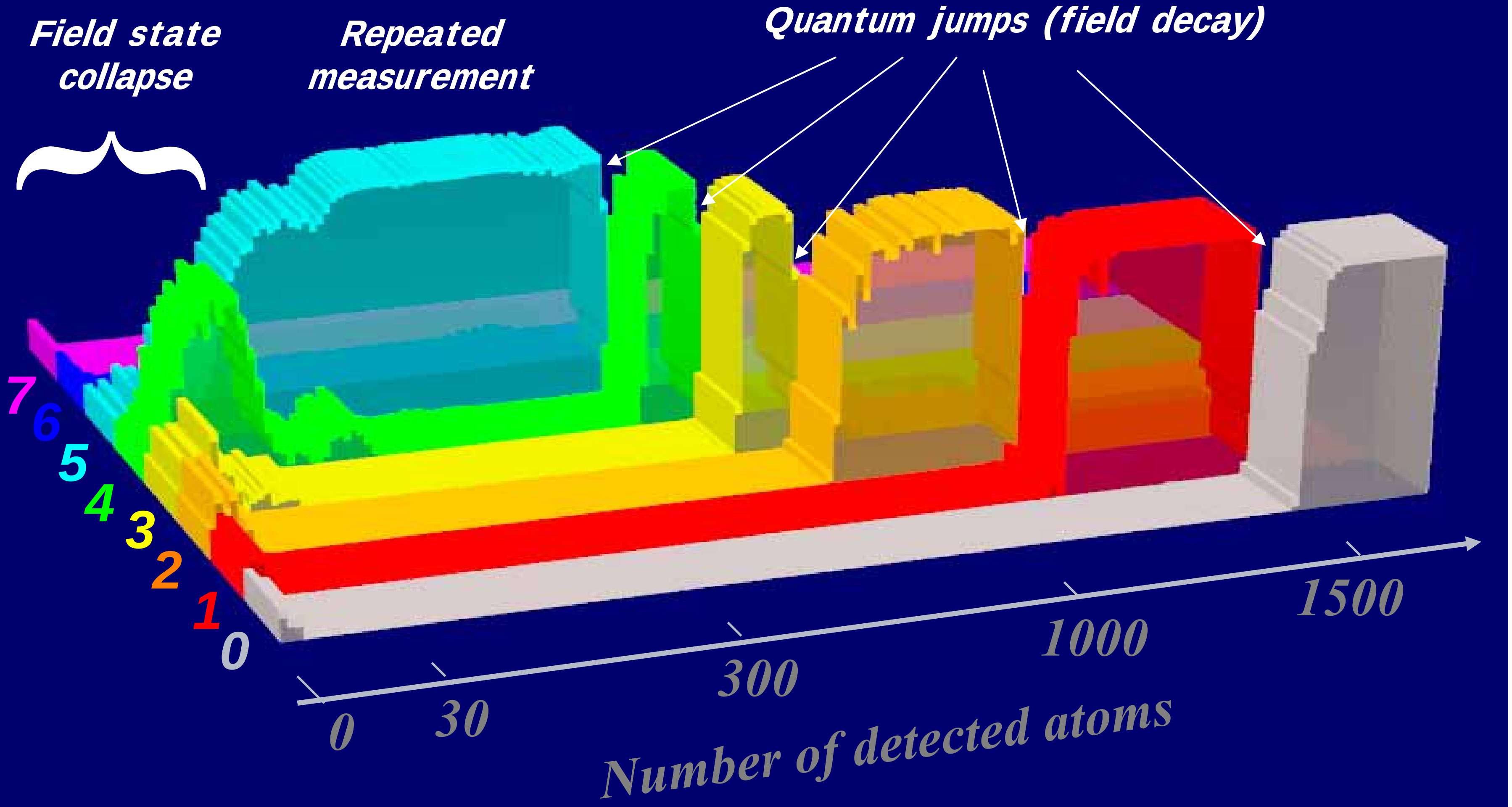
Statistical analysis of 2000 sequences: histogram of the Fock states obtained after collapse

Coherent field with
<n>=3.43



Illustrates quantum measurement postulate about statistics

Evolution of the photon number probability distribution in a long measuring sequence



Single realization of field trajectory: real Monte Carlo

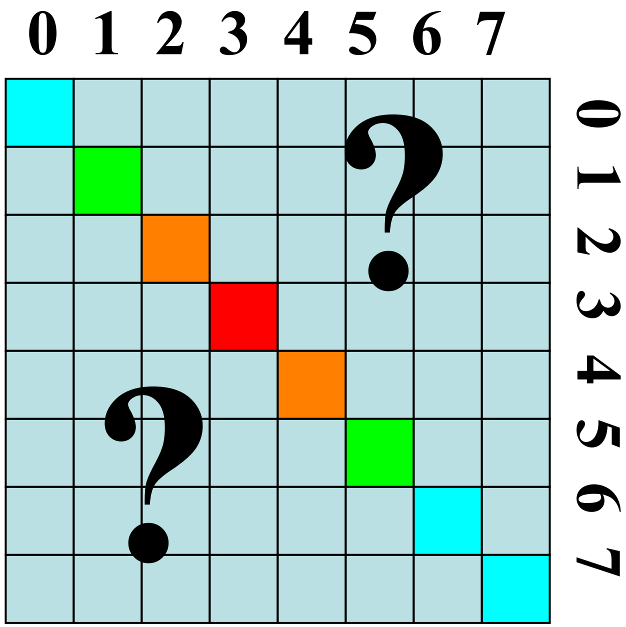
4.

Reconstruction of trapped field quantum states by QND photon counting

S.Deléglise, I.Dotsenko, C.Sayrin, J.Bernu, M.Brune,
J-M.Raimond & S.Haroche, Nature, to be published (2008)

« Reconstruction of non-classical cavity field states and movie of their decoherence »

QND photon counting and field state reconstruction

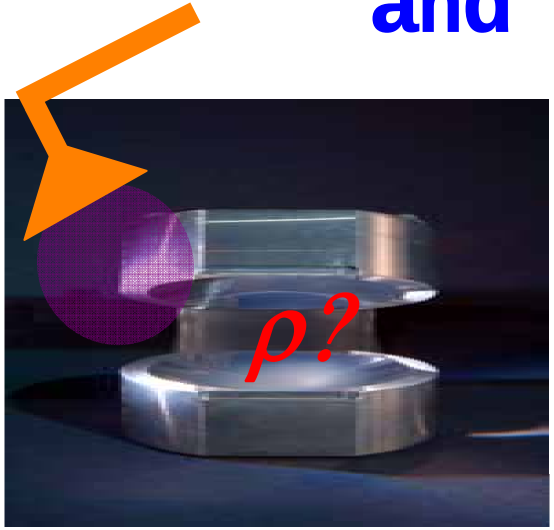


Repeated QND photon counting on copies of field determines the diagonal ρ_{nn} elements of the density matrix, but leaves the off-diagonal coherences $\rho_{nn'}$ unknown

Recipe to determine the off-diagonal elements and completely reconstruct ρ:

translate the field in phase space by homodyning it with coherent fields of different complex amplitudes and count (on many copies) the photon number in the translated fields

Reconstructing field state by homodyning and QND photon counting



$$\rho \rightarrow \rho^{(\alpha)} = D(\alpha)\,\rho\,D(-\alpha)$$

Field translation operator (Glauber):

$$D(\alpha) = \exp(\alpha a^{\dagger} - \alpha^{*} a)$$

The homodyning translation in phase space admixes field coherences $\rho_{n'n''}$ into the diagonal matrix elements $\rho^{(\alpha)}_{nn}$ of the translated field:

$$\boxed{\text{measured } \rho^{(\alpha)}_{nn} = \sum_{n',n''} D_{nn'}(\alpha)\;\rho_{n'n''}\,D_{n''n}(-\alpha)}$$

We determine the $\rho^{(\alpha)}_{nn}$s by QND photon counting on a large number of copies of translated fields, for many α values, and get a set of linear equations constraining all the $\rho_{n'n''}$s.

Requires many copies: quantum state is a **statistical** concept

From the density operator ρ to the Wigner function W

W is a real distribution of the field's complex amplitude in phase space, defined as:

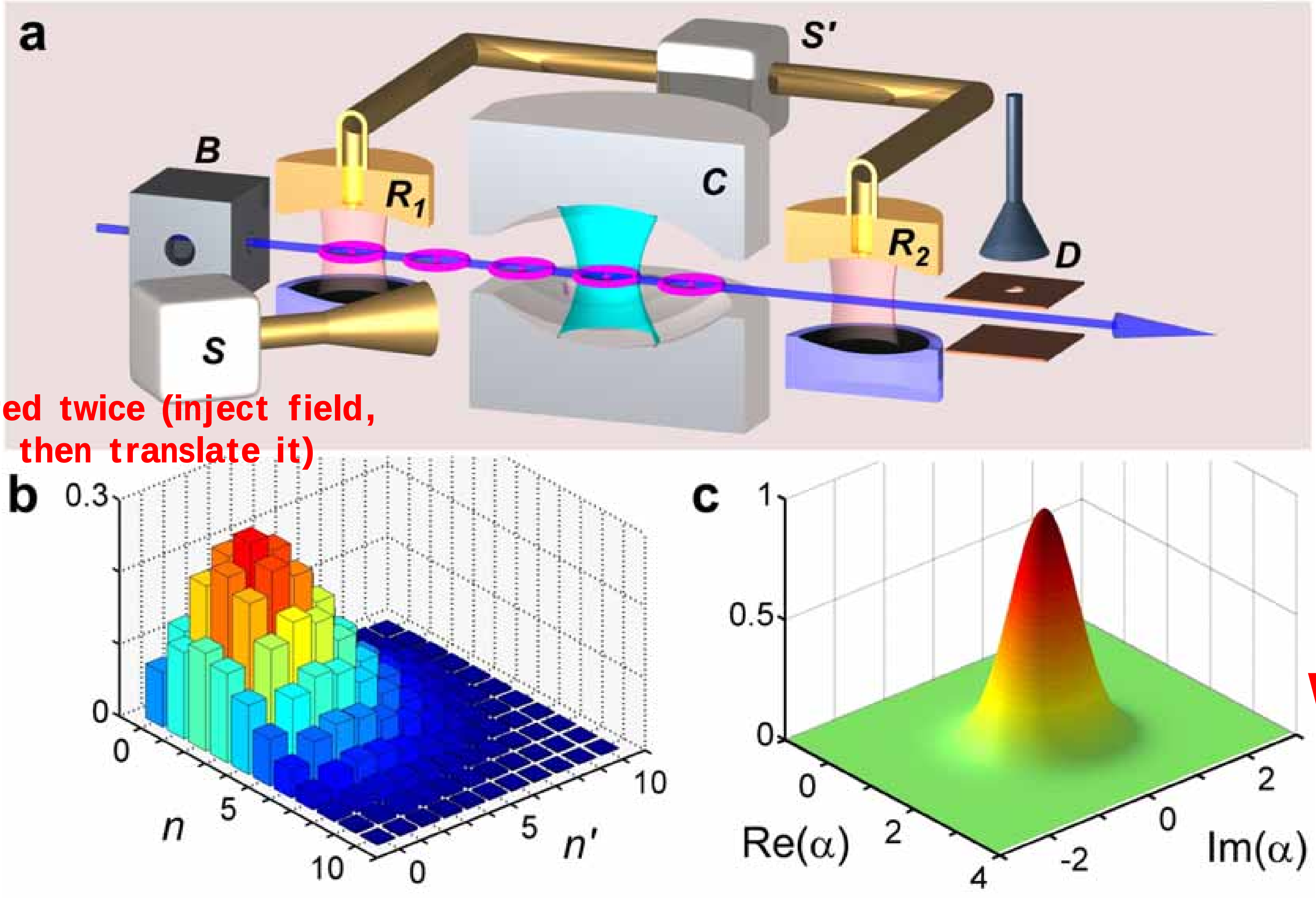
$$W(\alpha) = \frac{1}{\pi}\int e^{\alpha\lambda^* - \alpha^*\lambda}\,\mathrm{Tr}\left[\hat{\rho}\, e^{-i\left(\lambda^*\hat{a} - \lambda\hat{a}^\dagger\right)}\right] d\lambda$$

Once ρ is known, the Wigner function W(α) is obtained by an invertible mathematical formula: ρ and W(α) contain the same information, which completely defines the state

Classical fields (such as coherent laser fields or thermal fields) have Gaussian Wigner functions.

Non-classical fields (**Fock or Schrödinger cats**) exhibit oscillating features with negative values which are signatures of quantum interferences. These features are very sensitive to coupling with environment (**decoherence**)

Reconstructing a coherent state



Fired twice (inject field, then translate it)

ρ

W

Fidelity F=0.98

Requires subpicometer mirror stability

Reconstructing Fock states

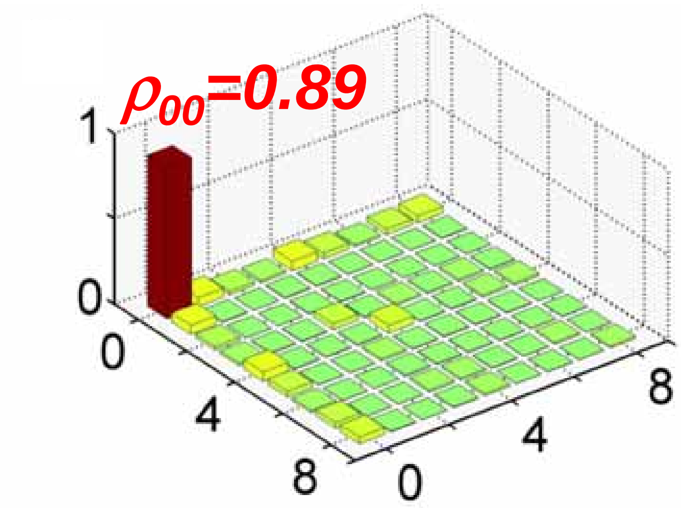
1) Prepare coherent state in C

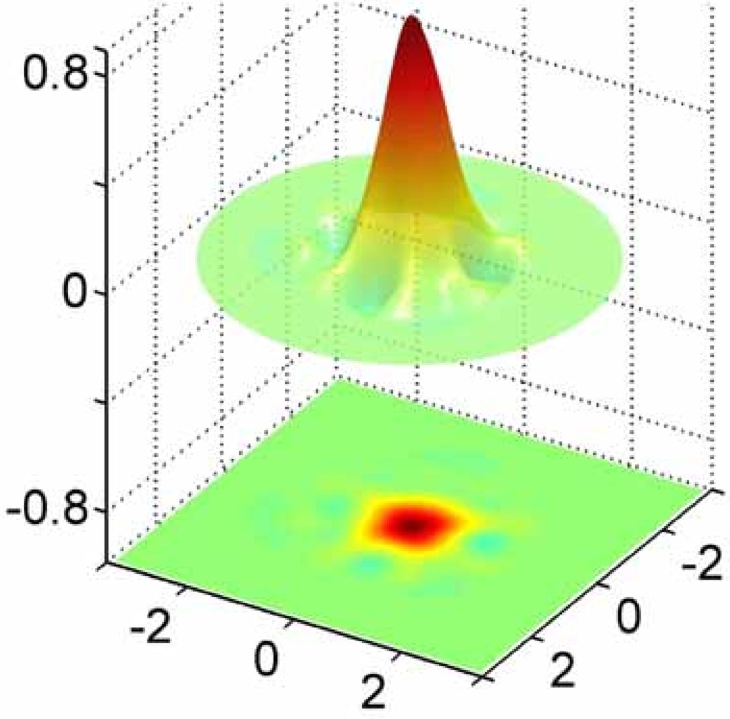
2) Turn it into a Fock state by (random) projective QND measurement of photon number with first sequence of atoms

3) Reconstruct the Fock state density operator by field translations followed by QND photon counting with second sequence of atoms. Statistics performed on many copies

4) Compute W from the reconstructed ρ

N = 0





Reconstructing Fock states

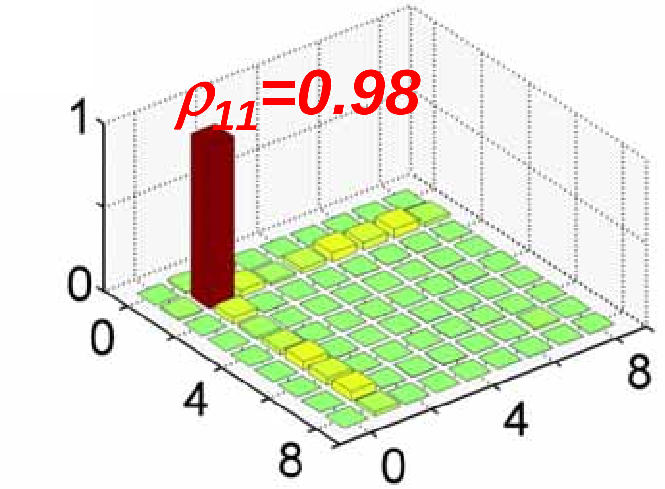
1) Prepare coherent state in C

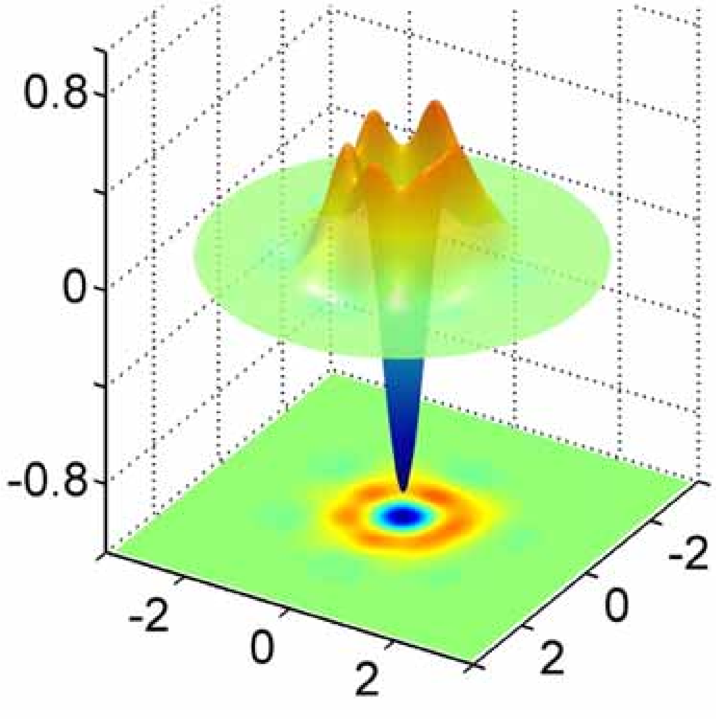
2) Turn it into a Fock state by (random) projective QND measurement of photon number

3) Reconstruct the Fock state density operator by field translations followed by (new) QND photon counting on many copies

4) Compute W from the reconstructed ρ

N = 1





Reconstructing Fock states

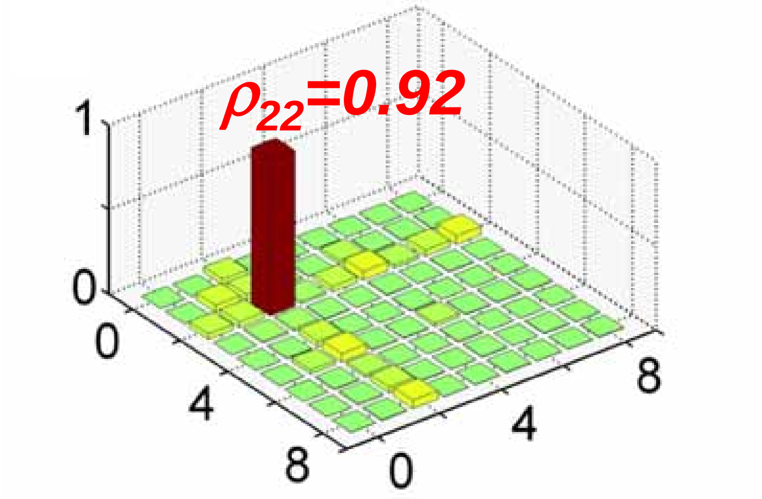
1) Prepare coherent state in C

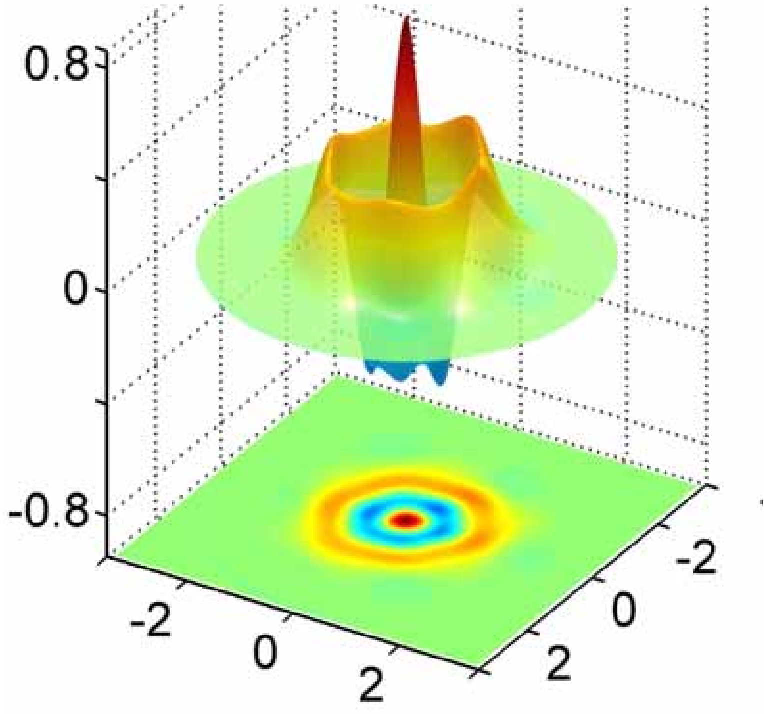
2) Turn it into a Fock state by (random) projective QND measurement of photon number

3) Reconstruct the Fock state density operator by field translations followed by (new) QND photon counting on many copies

4) Compute W from the reconstructed ρ

N = 2





Reconstructing Fock states

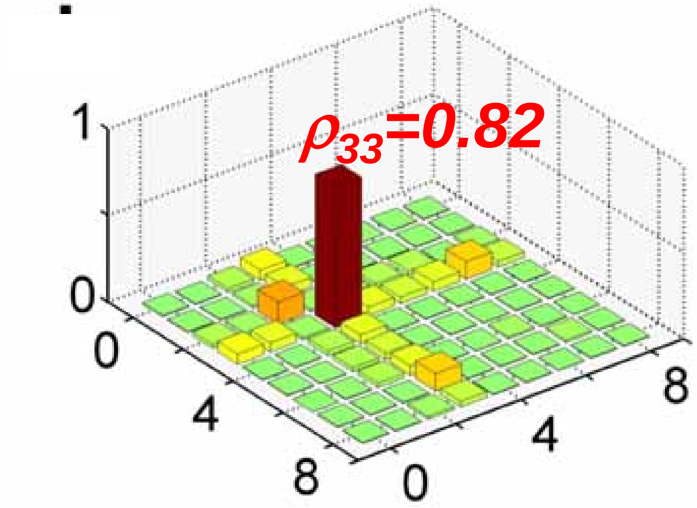
1) Prepare coherent state in C

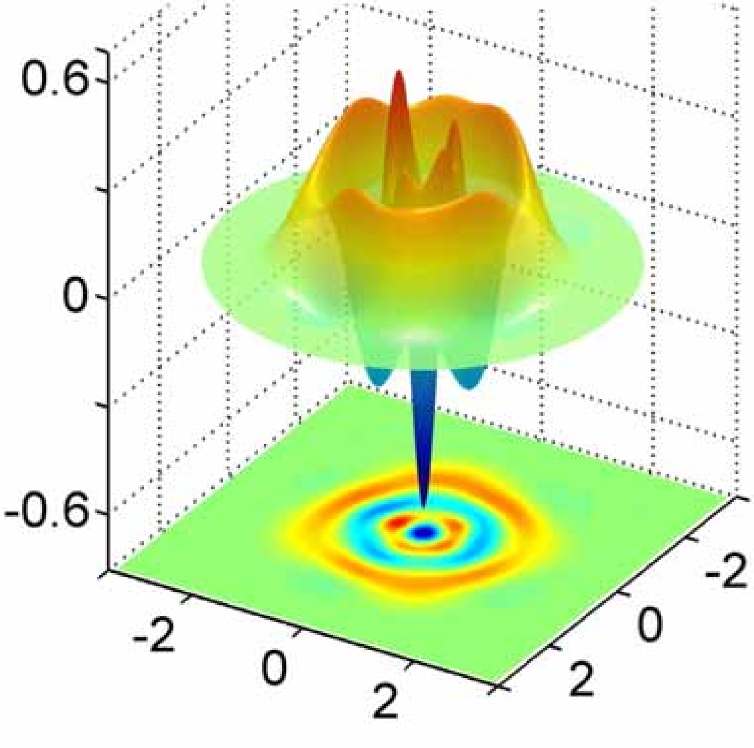
2) Turn it into a Fock state by (random) projective QND measurement of photon number

3) Reconstruct the Fock state density operator by field translations followed by (new) QND photon counting on many copies

4) Compute W from the reconstructed ρ

N = 3





Reconstructing Fock states

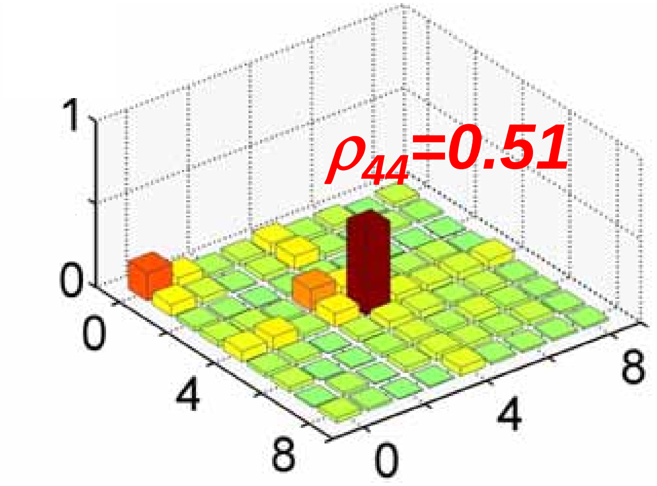
1) Prepare coherent state in C

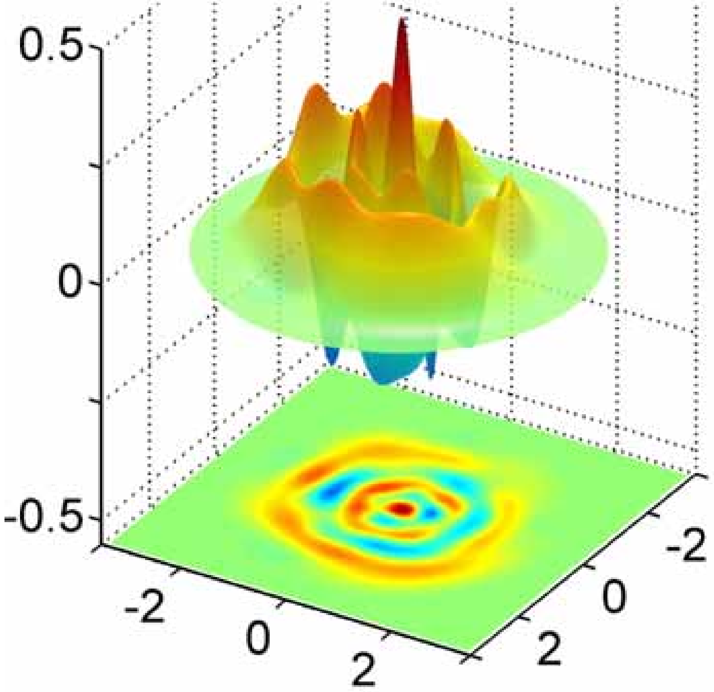
2) Turn it into a Fock state by (random) projective QND measurement of photon number

3) Reconstruct the Fock state density operator by field translations followed by (new) QND photon counting on many copies

4) Compute W from the reconstructed ρ

N = 4



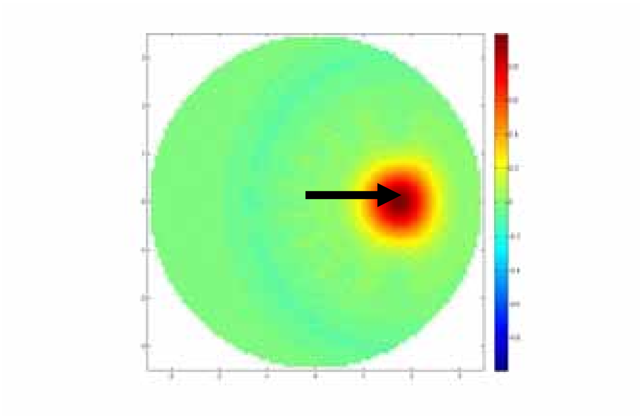


The 1,2,3 steps must be realized before 1 photon is lost !

4.

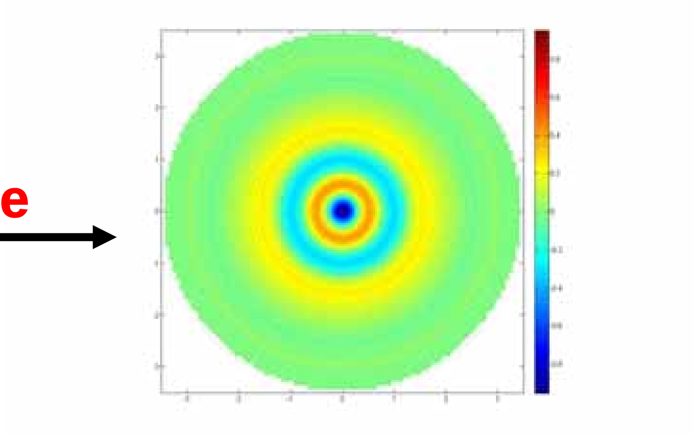
Preparing and reconstructing Schrödinger cat states of light: a movie of decoherence

Back action of QND counting: phase blurring (Wigner function)



Coherent state

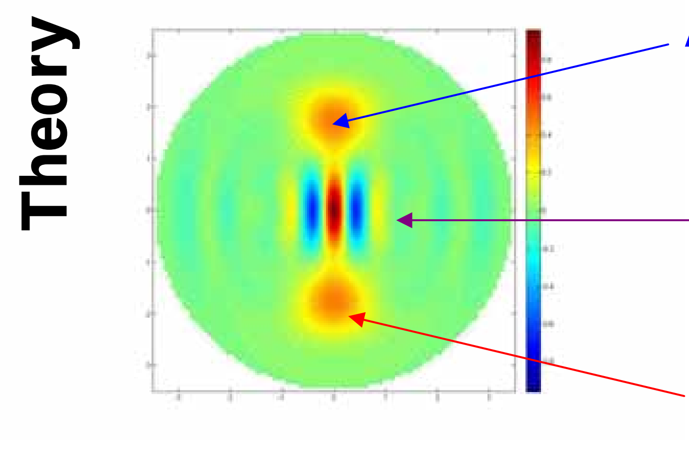
Progressive collapse



Fock state
(no phase)

After 1st QND atom: phase is split into two components:

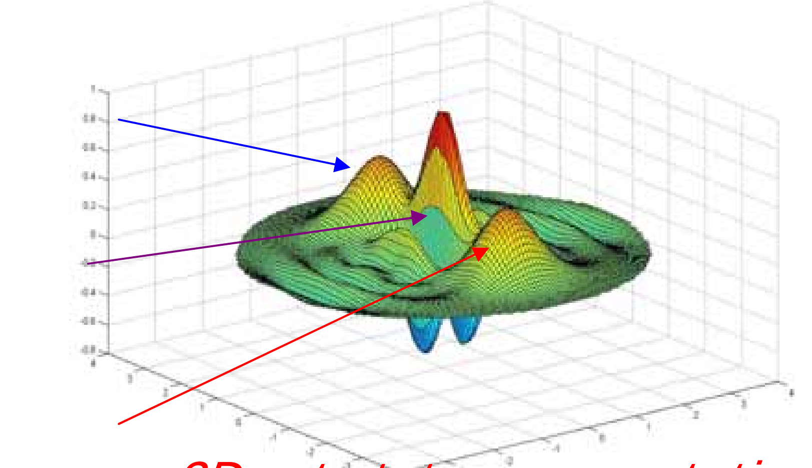
Theory



Atom crosses C in e
(« alive cat »)

Quantum interference

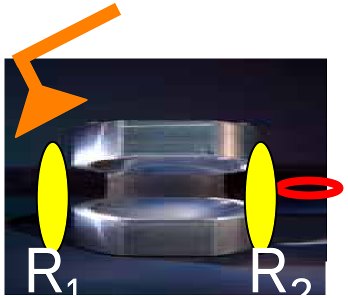
Atom crosses C in
(« dead cat »)



3D cat state representation

Recipe to prepare and reconstruct the cat

Coherent field prepared by first field injection

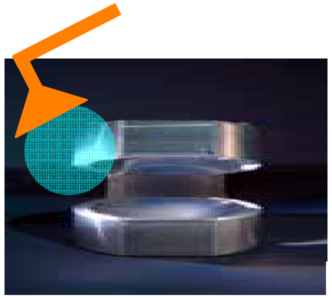


First QND atom generates cat state

$$|\Psi_{cat}\rangle = |\beta\rangle \pm |-\beta\rangle$$

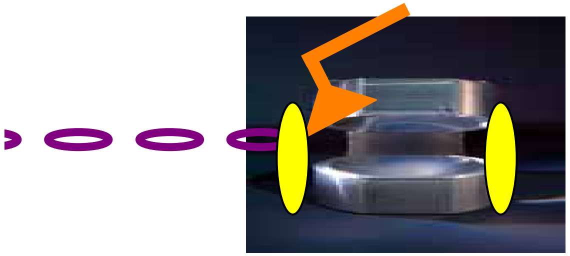
$$\rho = |\Psi_{cat}\rangle\langle_{cat}\Psi|$$

Sign depends on detected atom state (e or g)



Cat state translated in phase plane by second field injection:

$$\rho^{(\alpha)} \quad D(\alpha) \quad \Psi_{cat} \quad {}_{cat}\Psi \quad D(-\alpha)$$



QND probe atoms measure field translated by different α_i's and yield the $\rho^{(\alpha)}_{nn}$ **from which ρ is determined**

Reconstructed 3D-Wigner function of cat $|\beta>+|-\beta>$

Gaussian components (correlated to atom crossing cavity in e or g)

D^2

D^2= 8 photons

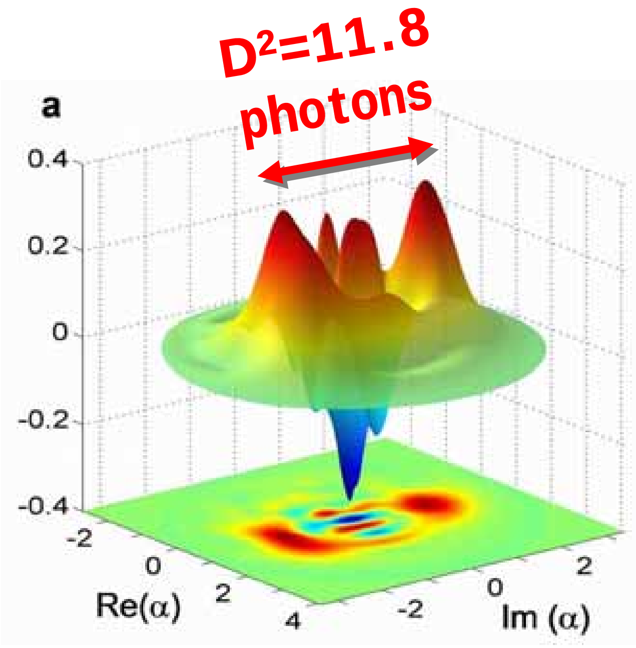
Fidelity: 0.72

QuickTime™ et un décompresseur sont requis pour visionner cette image.

Quantum interference (cat’s coherence) due to ambiguity of atom’s state in cavity

Non-classical states of freely propagating fields with similar W function (and smaller photon numbers) have been generated in a different way (Ourjoumtsev et al., Nature 448, 784 (2007))

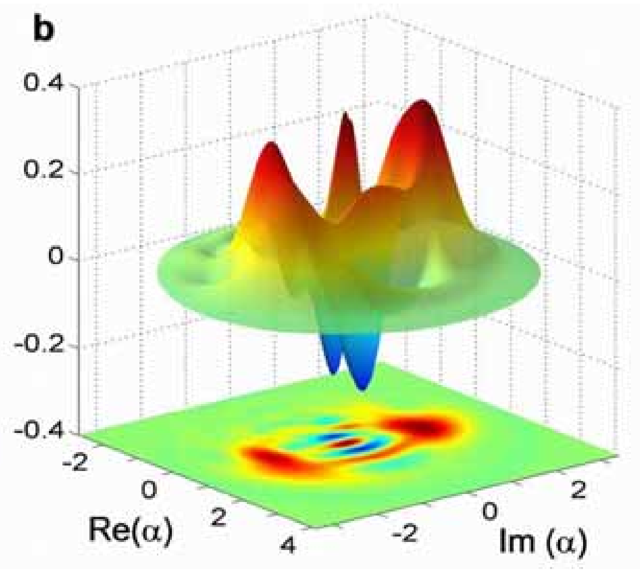
Various brands of cats....



Even cat

$|\beta e^{i\chi}> + | \beta e^{-i\chi} >$

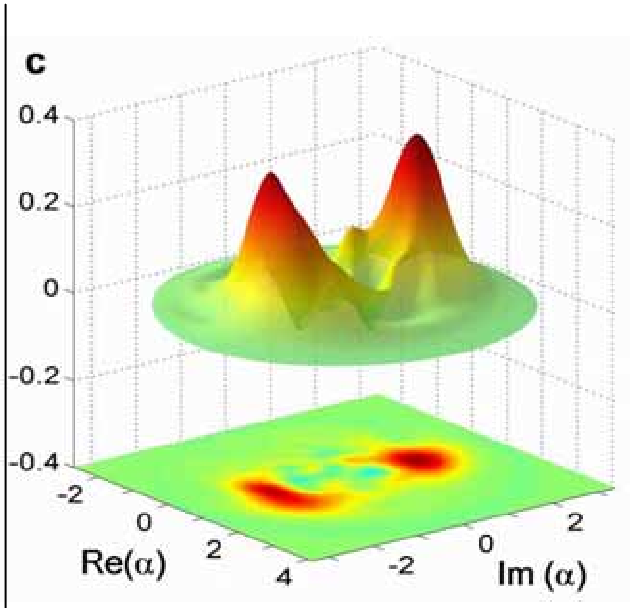
(preparation atom detected in e)



Odd cat

$|\beta e^{i\chi}> - | \beta e^{-i\chi} >$

(preparation atom detected in g)

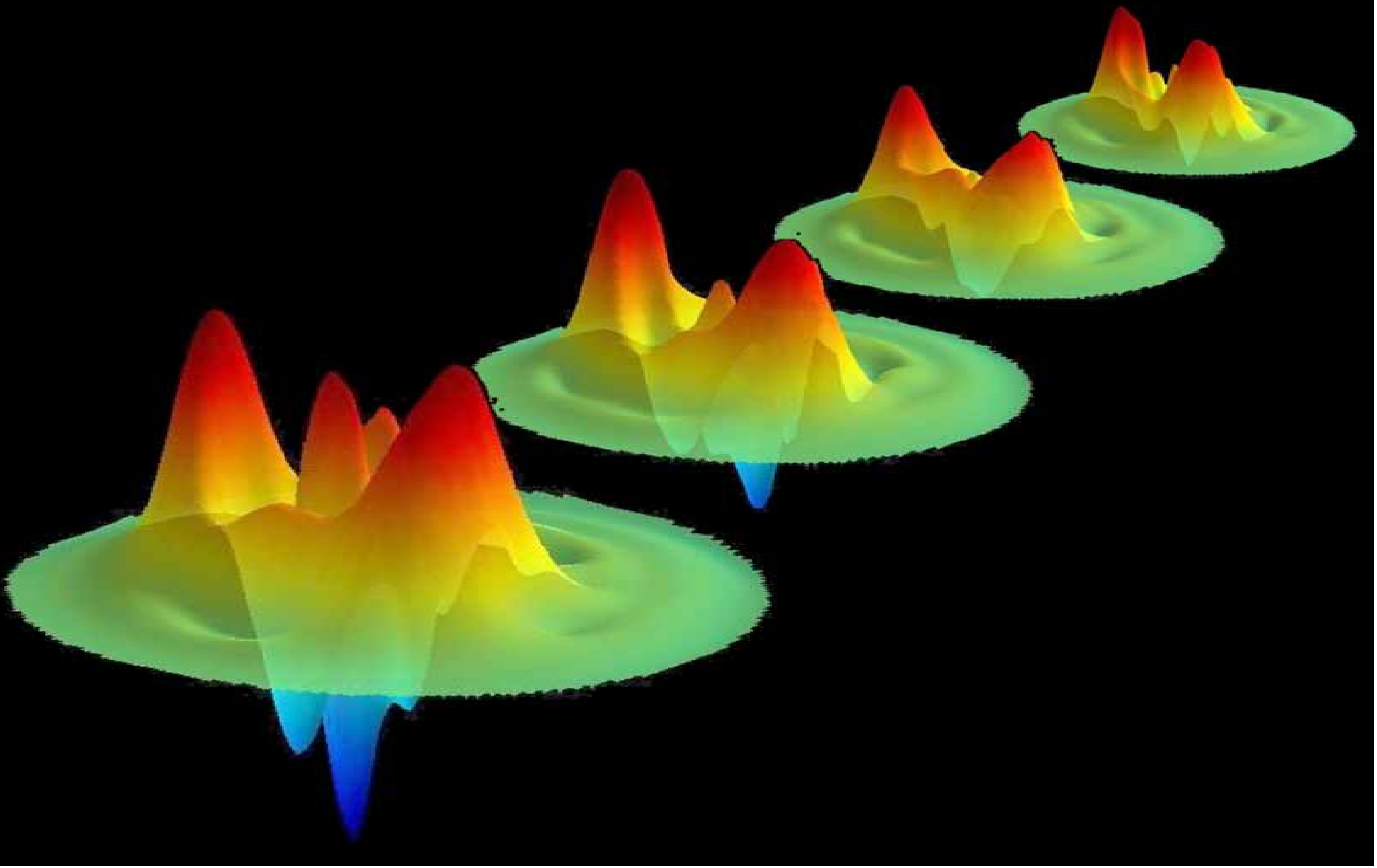


Statistical Mixture

$|\beta e^{i\chi}> <\beta e^{i\chi}| + |\beta e^{-i\chi}> <\beta e^{-i\chi}|$

(preparation atom detected without discrimating e and g)

A JOURNEY FROM QUANTUM TO CLASSICAL



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

QuickTime™ et un
décompresseur mpeg4
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The cat’s quantumness vanishes (evolution of difference between even and odd cat states)

Supplementary
material on line
accompanying
Nature Letter

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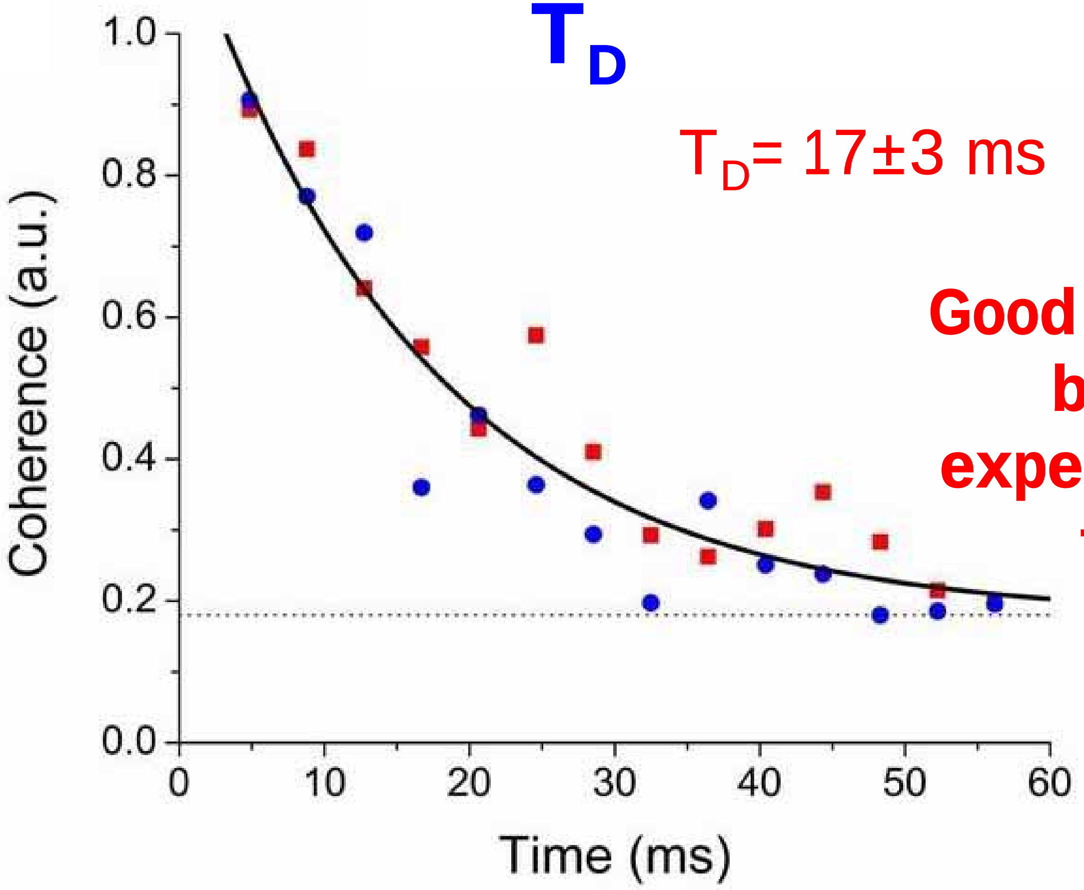
Exponential decay of cat's quantum interference term yields decoherence time T_D

Earlier work on decoherence of cats with « bad » cavity: Brune et al, PRL, ***77*** *4887, (1996)):*

T_D was in microsecond range



$T_D = 17 \pm 3$ ms

Good agreement between experiment and theory

Theoretical model (T=0K):
$T_D = 2T_c/D^2 = 22$ ms

W.Zurek,PhysToday,Oct 1991

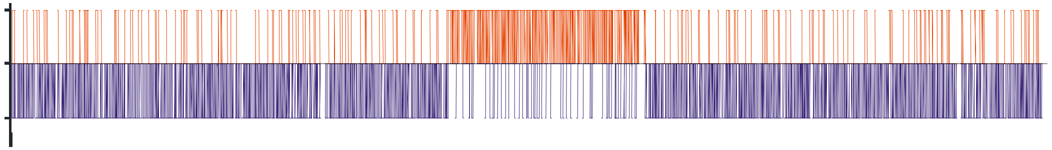
Correction at finite temp. (T = 0.8K):
$T_D = 2T_c/[D^2(2n_B+1)+4n_B] = 19.5$ ms

Mean number n_B of blackbody photons = 0.05

Kim & Buzek, Phys.Rev.A. 46, 4239 (1992)

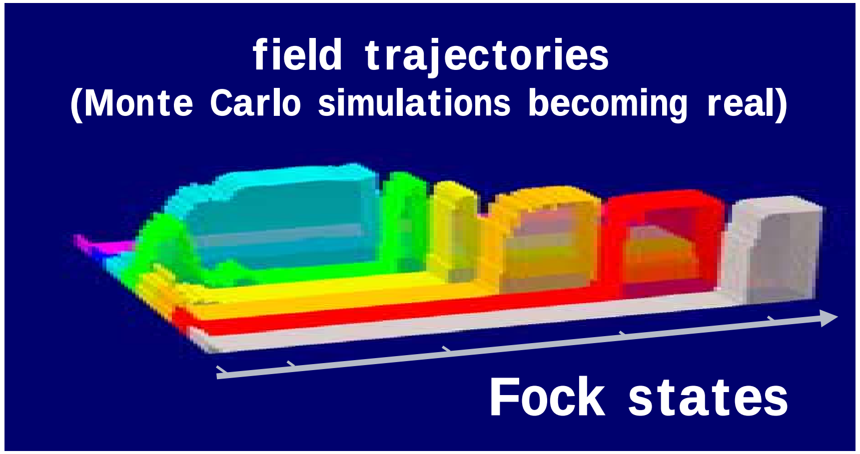
5.Conclusion and perspectives

Field quantum jumps




Trapping the light fantastic

Super-mirrors make new ways to look possible: trapped photons become like trapped atoms


field trajectories
(Monte Carlo simulations becoming real)

Fock states

**Preparing and reconstructing cats
and other non-classical states**

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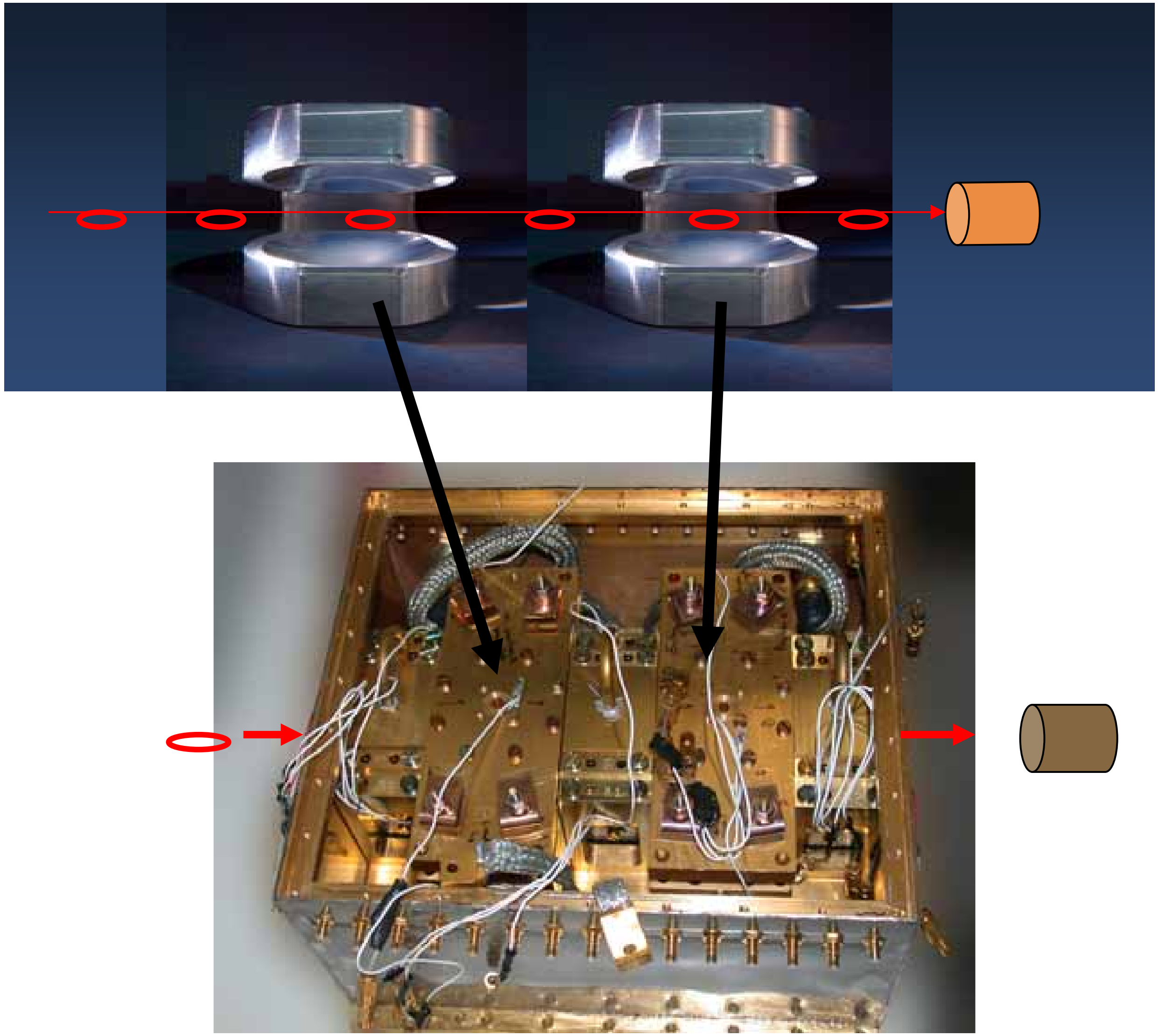
Soon, channelling field towards desired state by quantum feedback..

Experiments extended soon to two cavities: non-locality in mesoscopic field systems

Davidovich et al,
PRL, 71, 2360
(1993)

Davidovich et al,
PRA, 53, 1295
(1996)



P.Milman et al,
EPJD, 32,233
(2005)

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CQED Experiments

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Superconducting atom chips

Gilles Nogues
A.Lupascu
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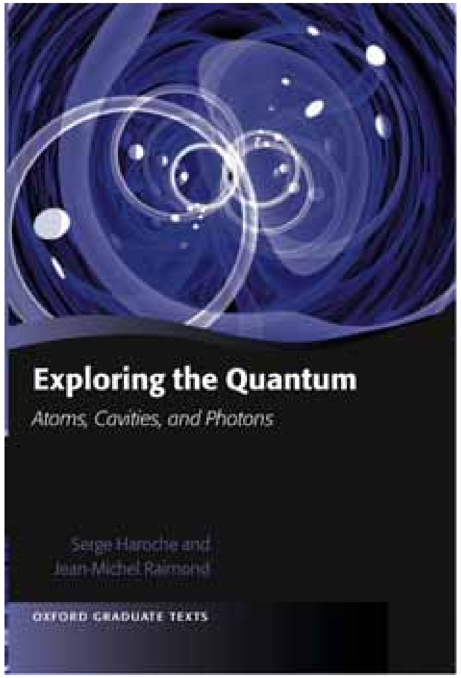
C.Roux*
Poster TU73

F.Schmidt-Kaler, E.Hagley, C.Wunderlich, P.Milman, A. Qarry, F.Bernardot, P.Nussenzweig, A.Maali, J.Dreyer, X.Maître, A.Rauschenbeutel, P.Bertet, S.Osnaghi, A.Auffeves, T.Meunier, P.Maioli, P.Hyafil, J.Mosley



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