Counting non-destructively photons in a cavity, reconstructing Schrödinger cat states of light & realizing movies of their decoherence

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International Workshop on Fundamentals of Light-Matter Interactions, Recife, Brazil
October 20th 2008

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

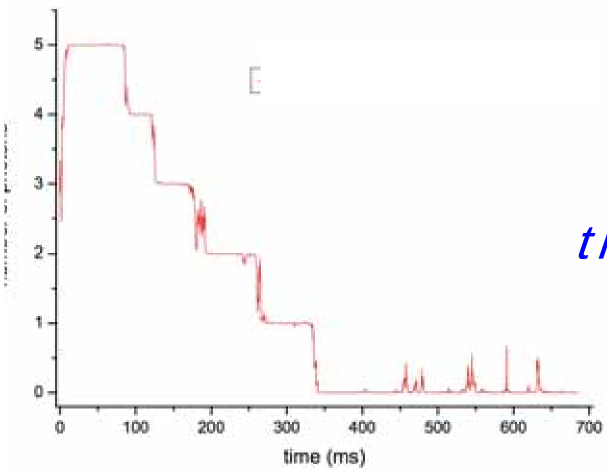
The context: Cavity Quantum Electrodynamics: physics of a qubit coupled to a harmonic oscillator

Instead of trapping atoms…

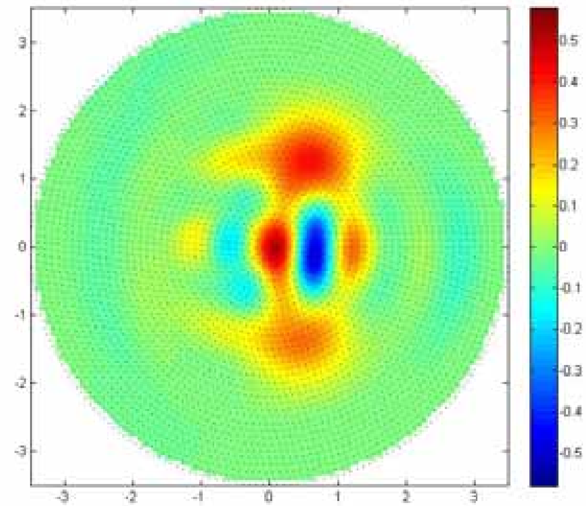
…and manipulating them with beams of light

…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 generation 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.Back action of QND photon counting on the field's phase
& the quantum Zeno effect of light

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

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

6. 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

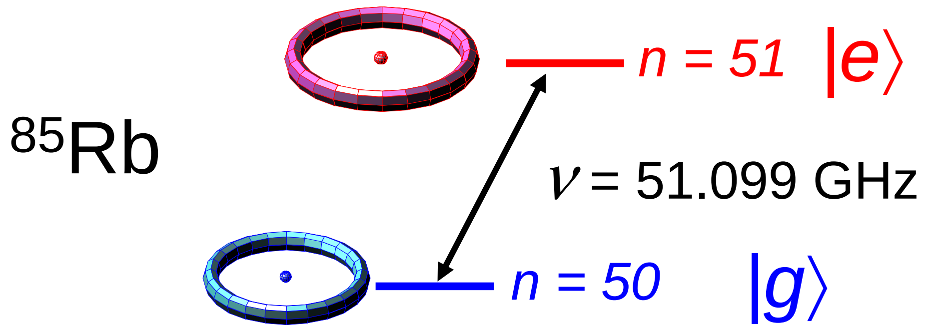
- 1.5 billion photon bounces

- Light travels 40 000 km
  (Earth circumference)

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

Special detectors: Circular Rydberg Atoms

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



- 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»

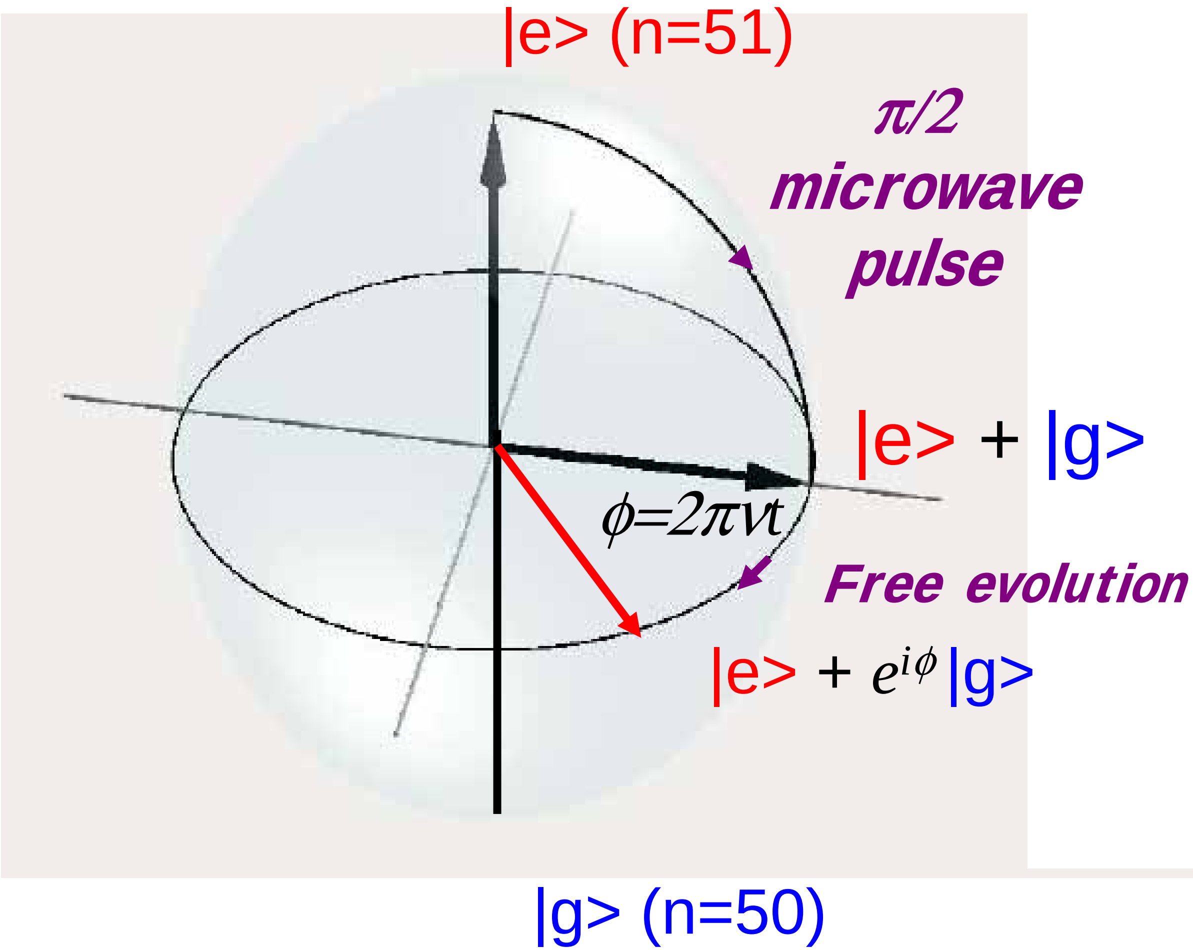
<u>But:</u>

- 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

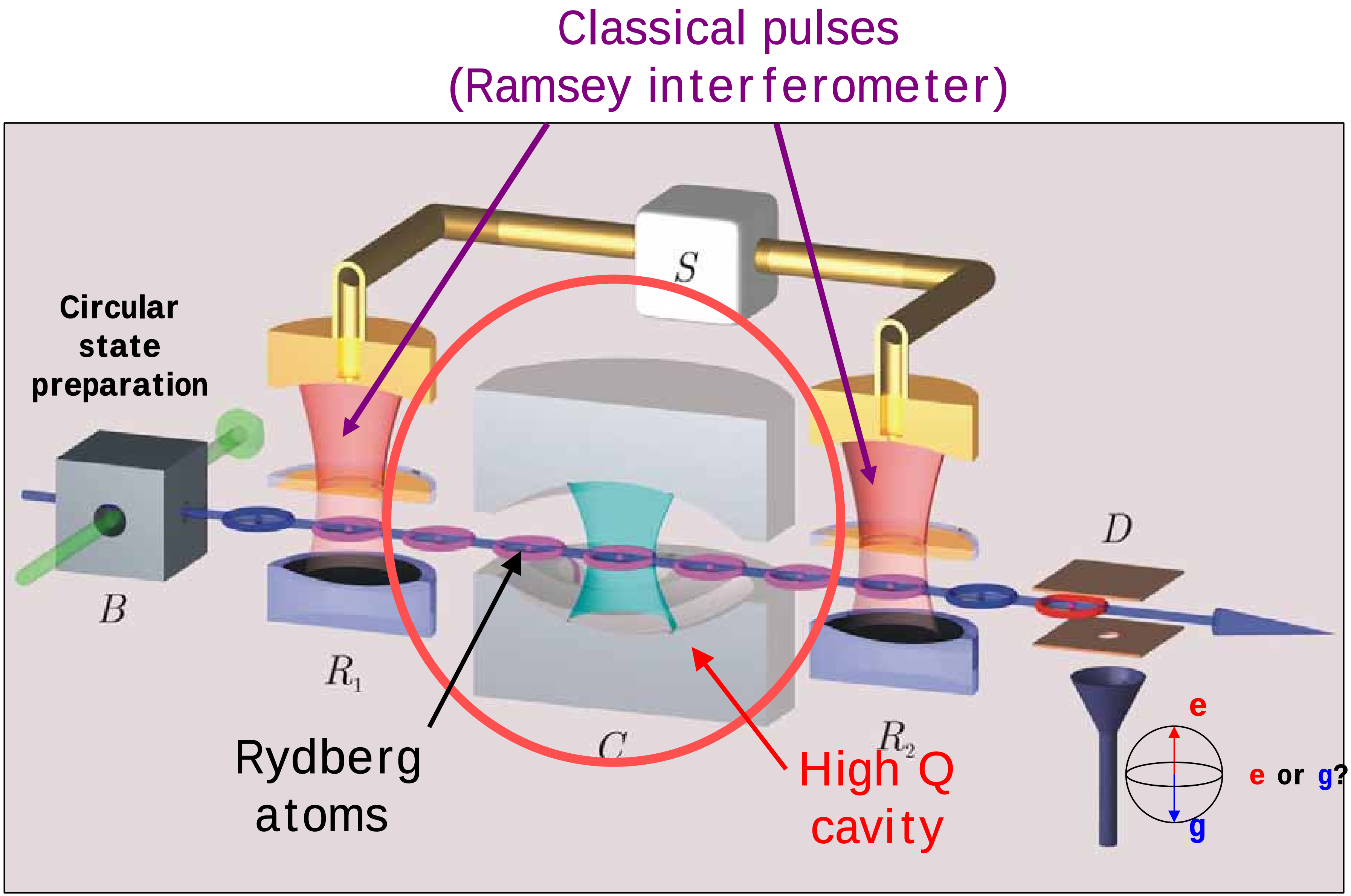
Equatorial plane of Bloch sphere is the dial and the 'spin' is the hand of an atomic clock



Phase shift per photon adjusted by changing atom-cavity detuning

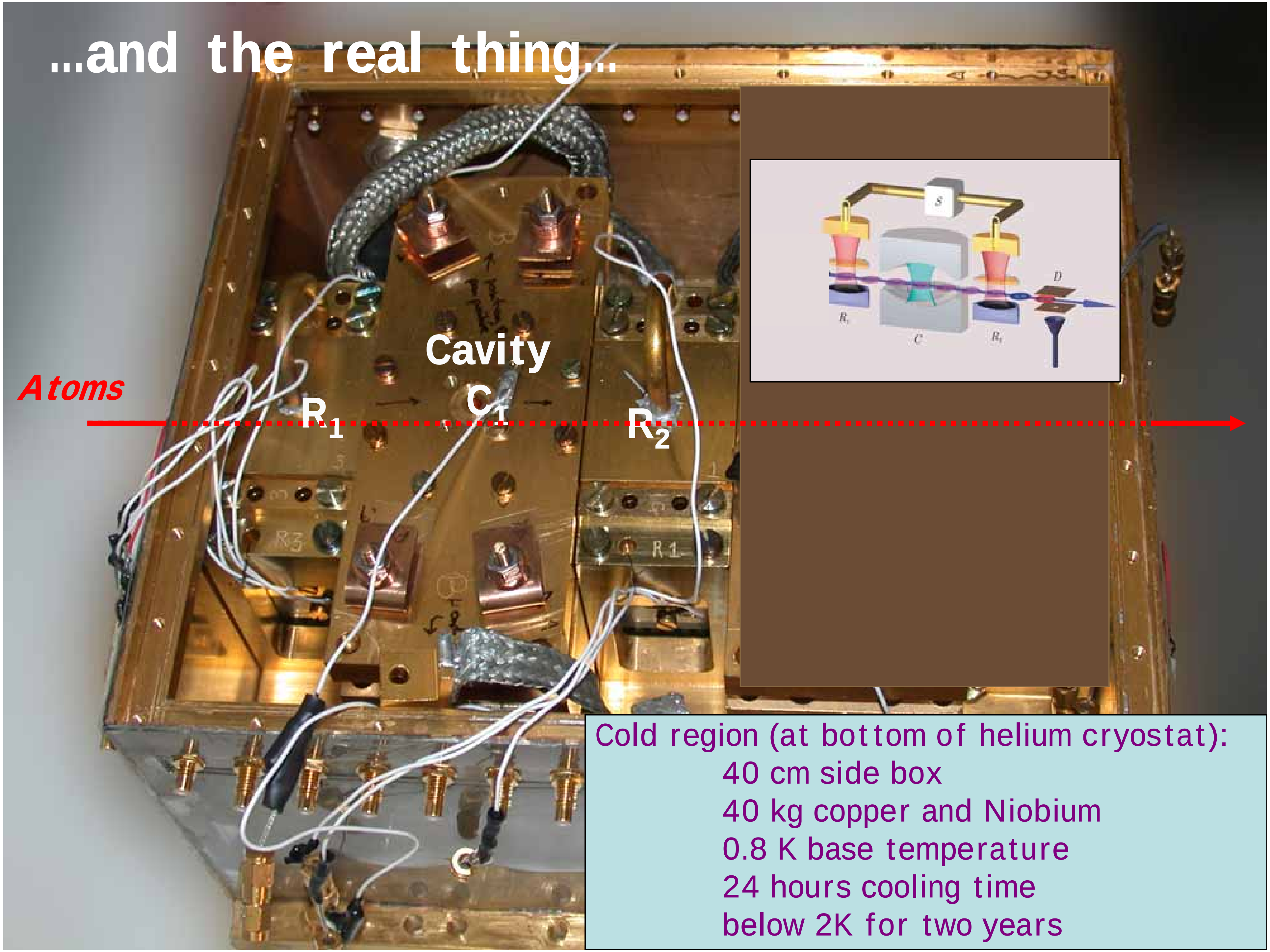
Atoms are off-resonant and cannot absorb light, but spins are delayed by light-shift effect. One photon can make the «spin hand» miss half a turn while atom crosses cavity **(π phase shift per photon).**

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

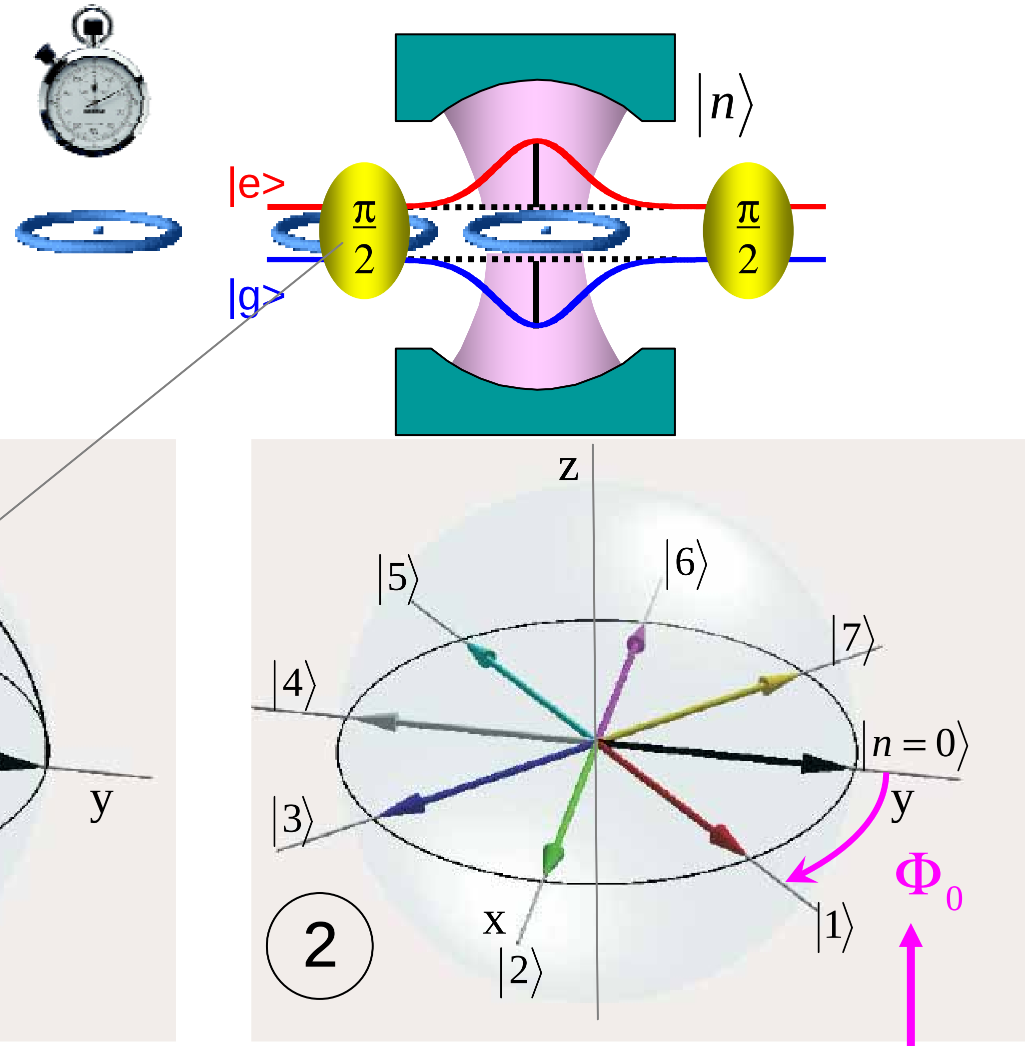
S.Gleyzes, S.Kuhr, C.Guerlin, J.Bernu, S.Deléglise, U.Busk Hoff, M.Brune, J-M.Raimond and S.Haroche,
Nature 446, 297 (2007)

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" (1^{st} Ramsey pulse).

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



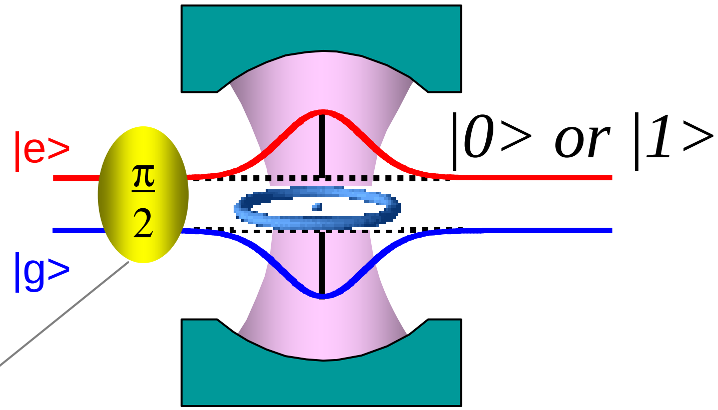
The clock's shift is proportional to n: non-demolition photon counting by measuring spin direction (using 2^{nd} Ramsey pulse)

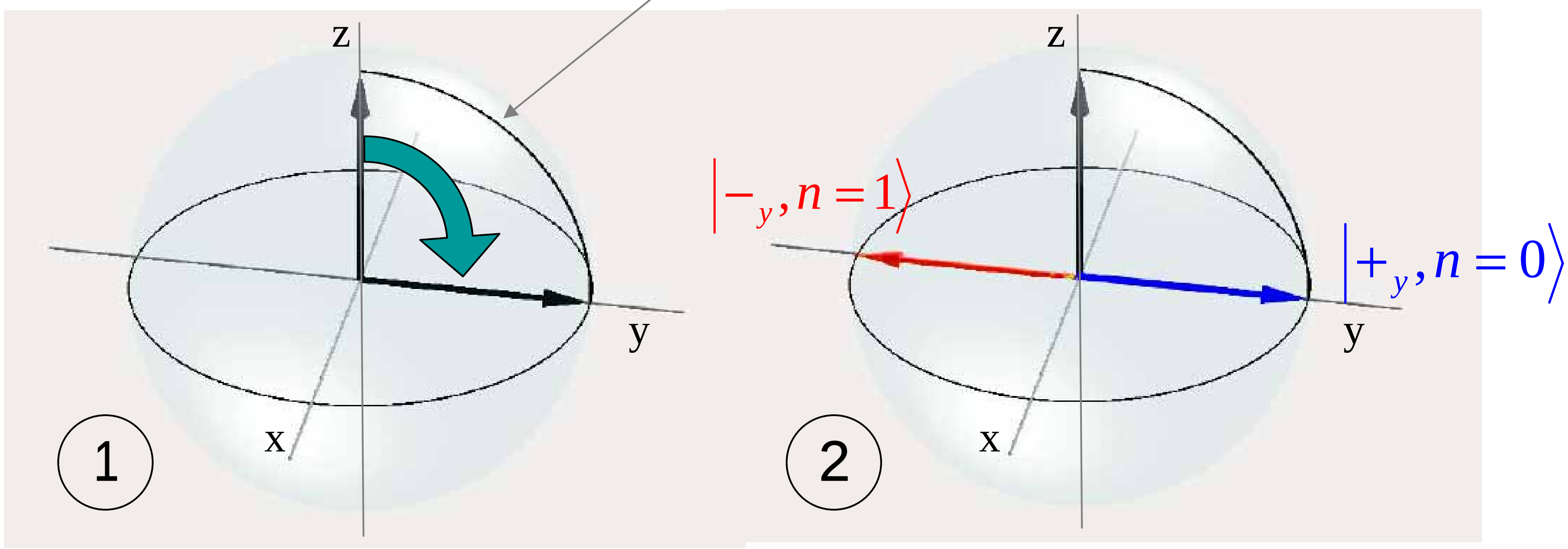
phase shift per photon

Detecting 0 or 1 photon

Strong dispersive coupling:

$$\Phi_0 = \pi$$



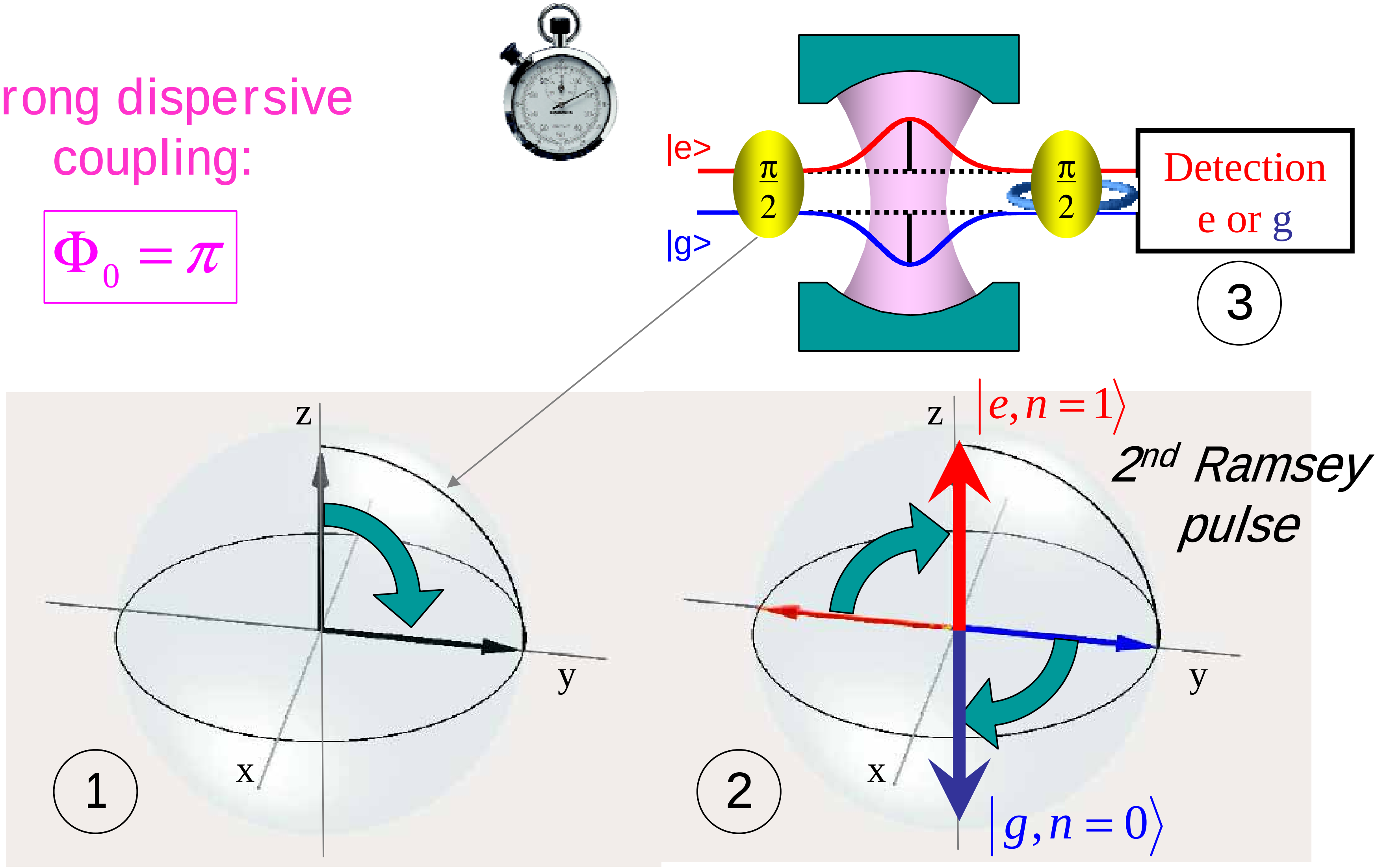


One atom = one bit of information (+ or - spin along y) perfectly correlated with the photon number.

Detecting 0 or 1 photon

Strong dispersive coupling:

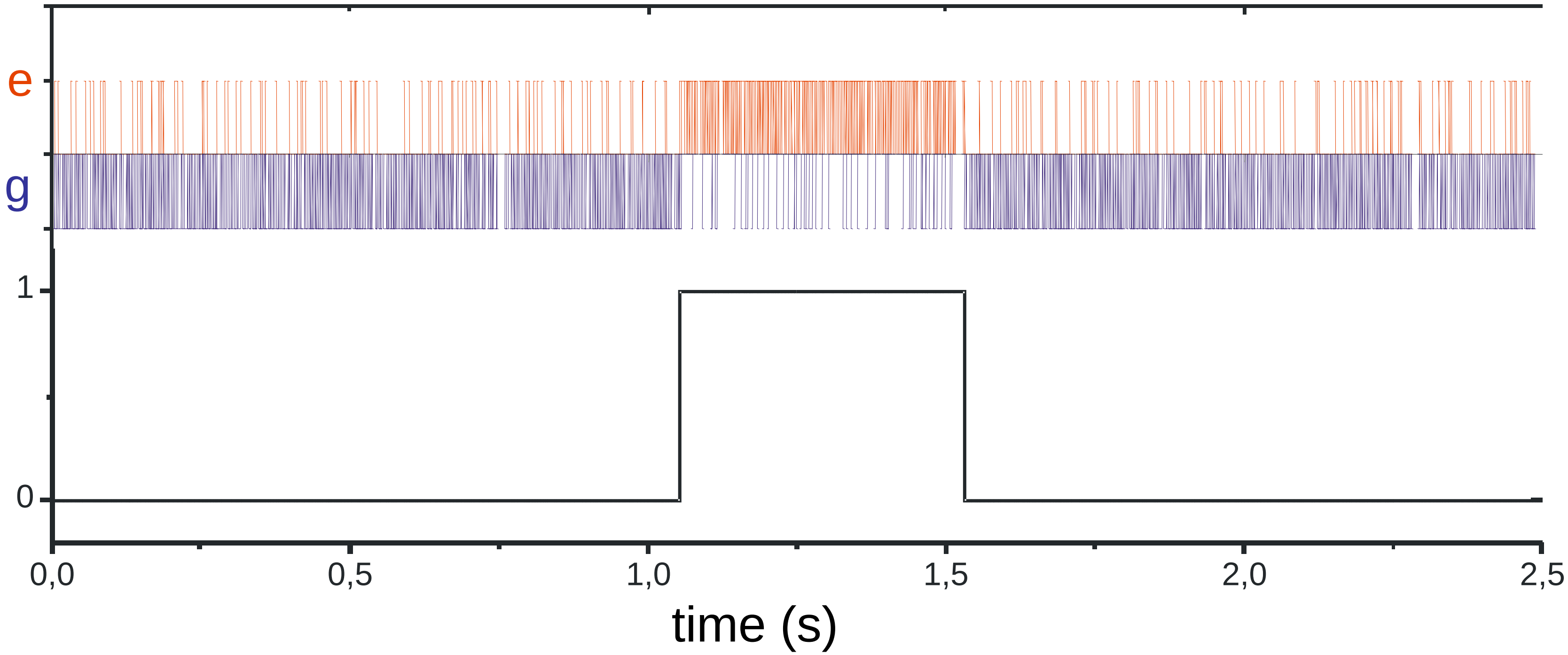
$\Phi_0 = \pi$



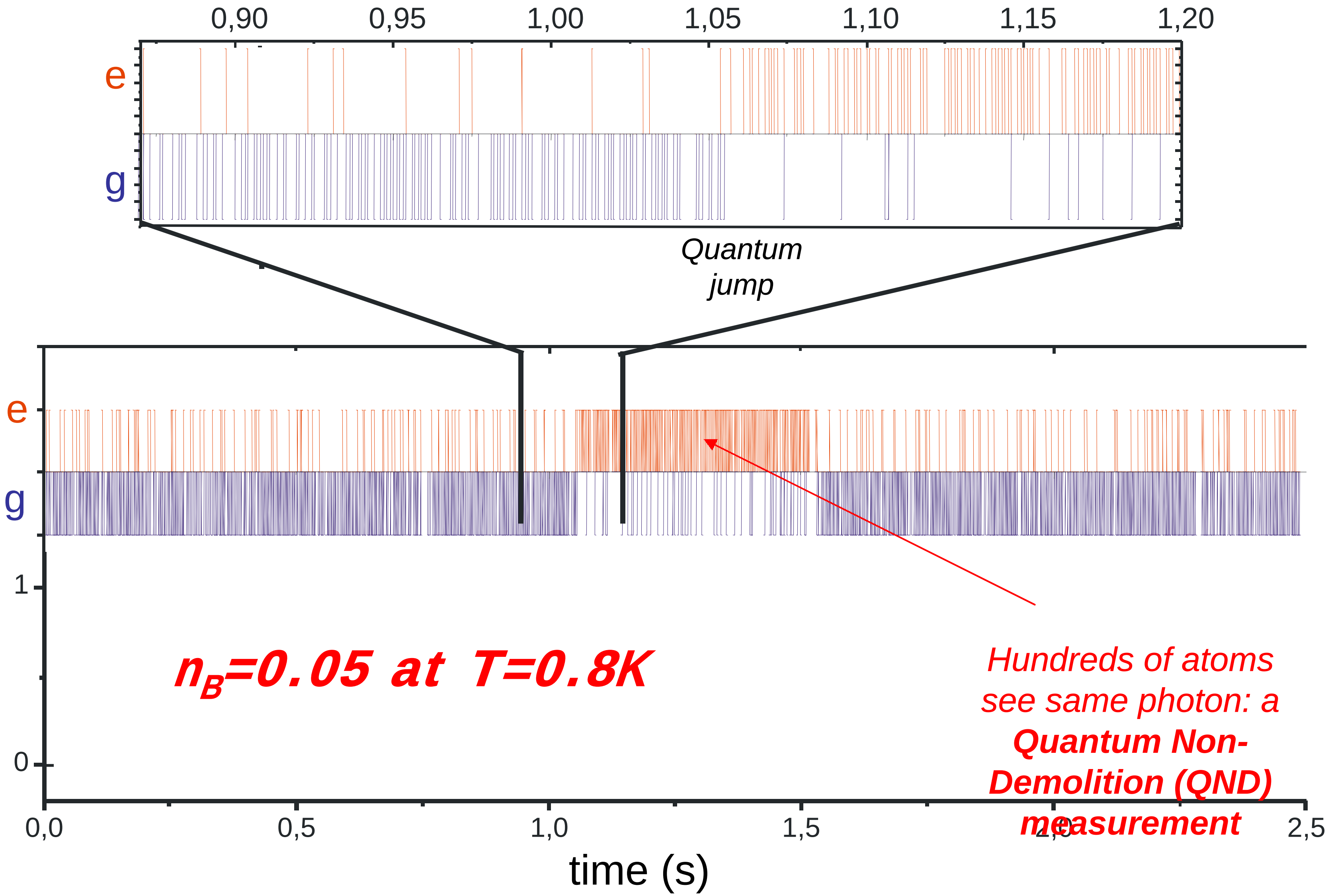
g → field projected onto |0>

e → field projected onto |1>

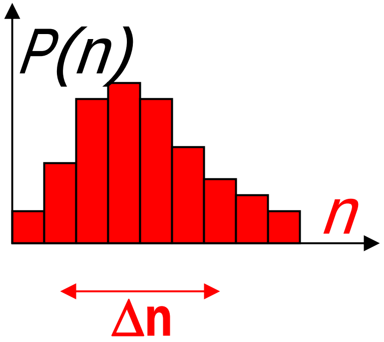
Birth and death of a photon
(thermal field at 0.8K)



Birth and death of a photon



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



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

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

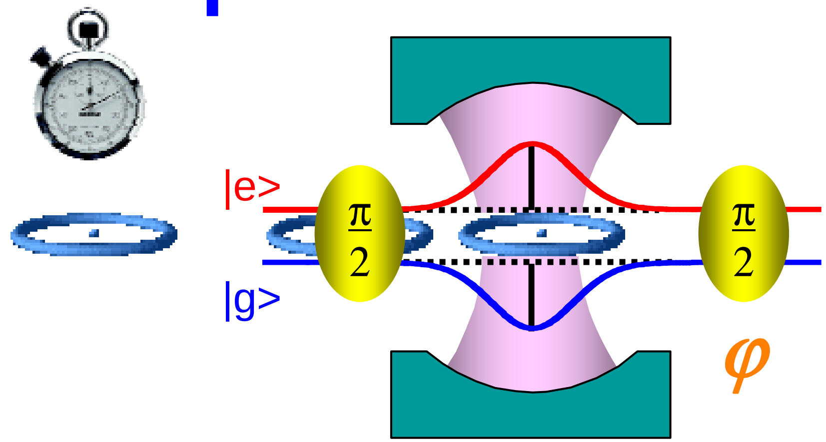
Heisenberg relation

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

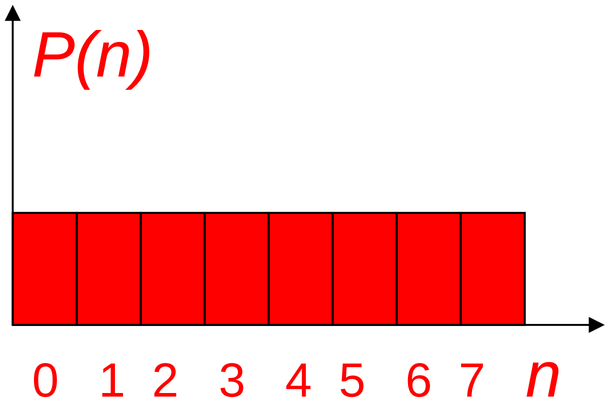
Experiment illustrates on light quanta the three postulates of measurement: state collapse, statistics of results, repeatability.

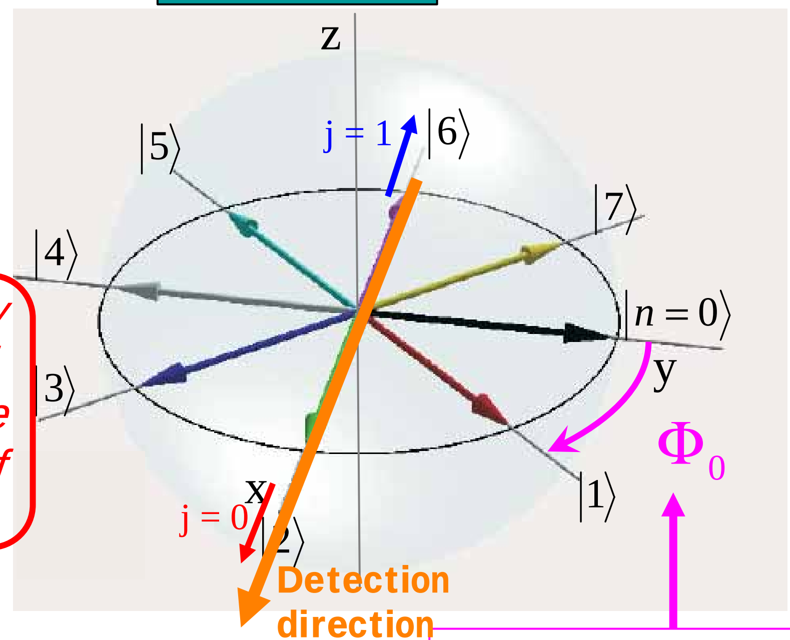
Counting larger photon numbers: 1st atom effect on inferred photon distribution

Chose $\Phi_0=\pi/4$

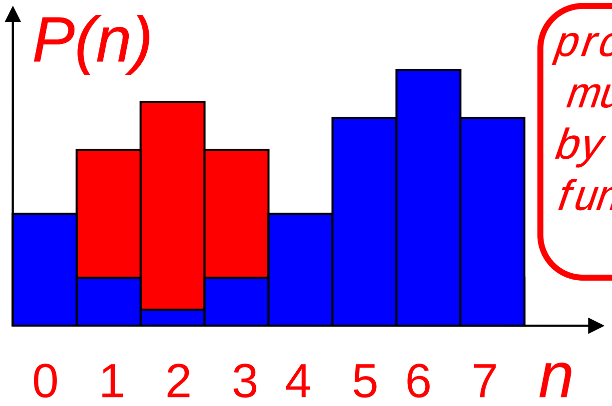


2nd Ramsey pulse maps a direction in equatorial plane back into Oz before detection





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



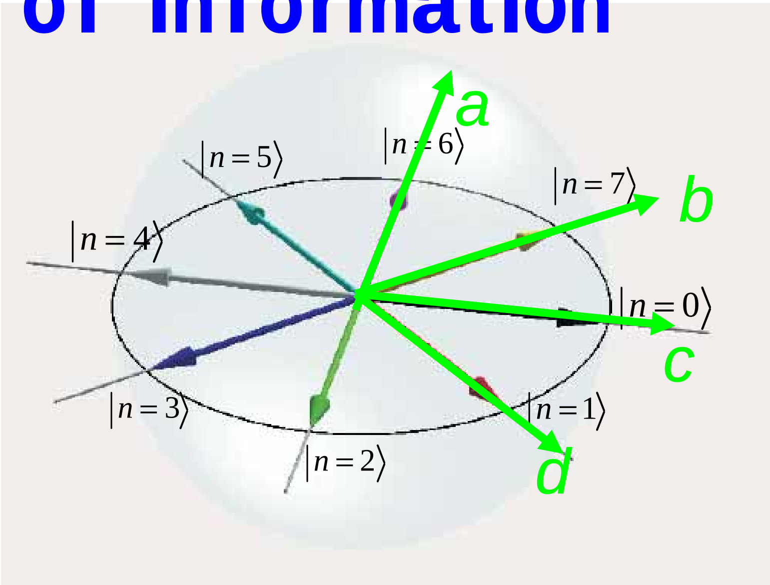
probability multiplied by a cosine function of n

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

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

$\phi(k)$: a/b/c/d

$j(k)$: 0/1

Spin reading $000101101010001011001 \ldots$

Direction $abdcadb\,cbadcaa\,bcbacd\,b \ldots$

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

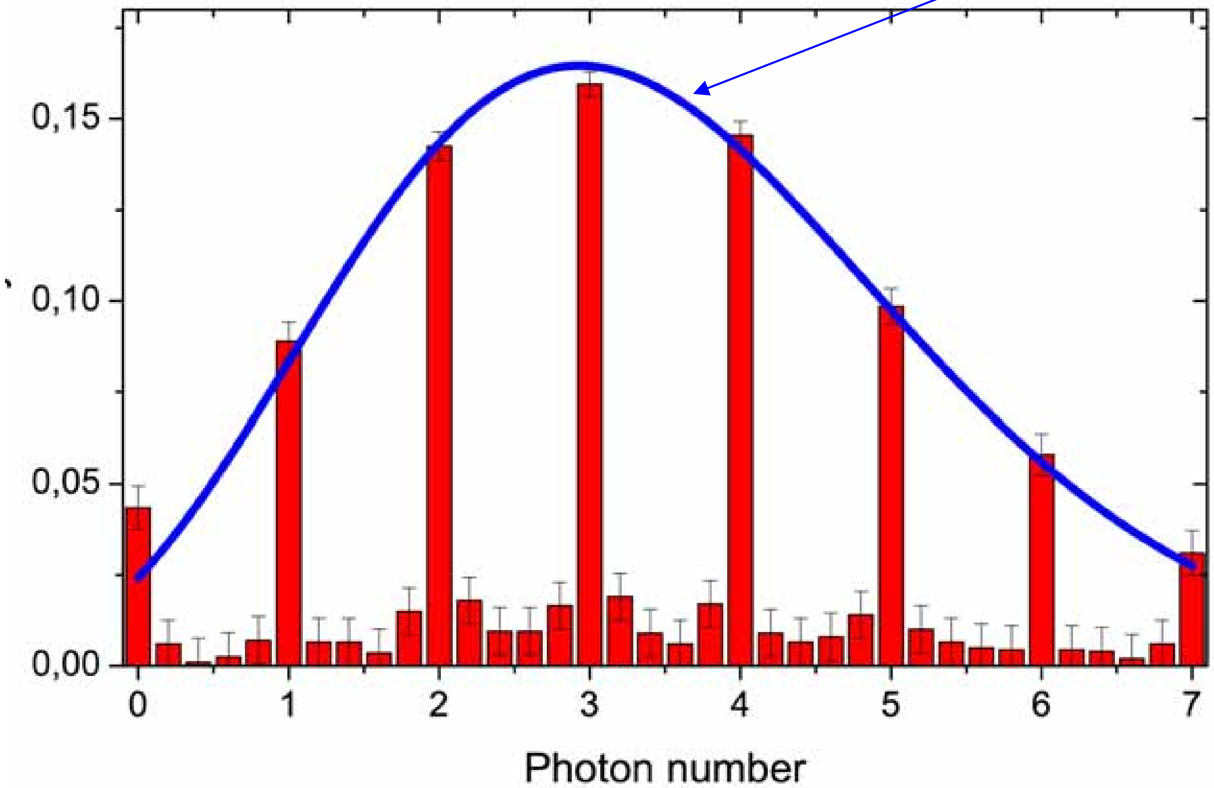
Progressive collapse!

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

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

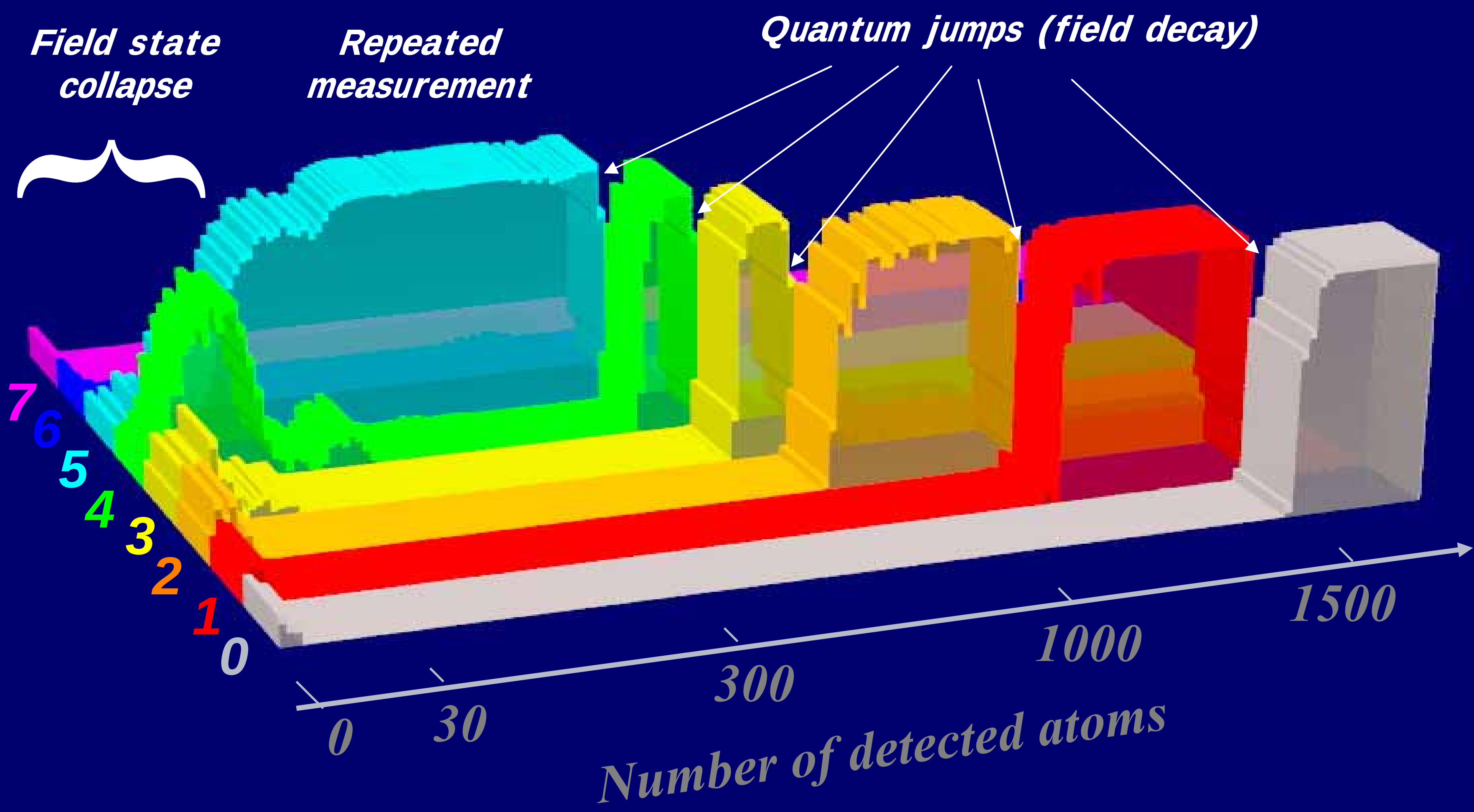
Statistical analysis of 2000 sequences: histogram of the Fock states obtained after collapse

Coherent field with <n>=3.43



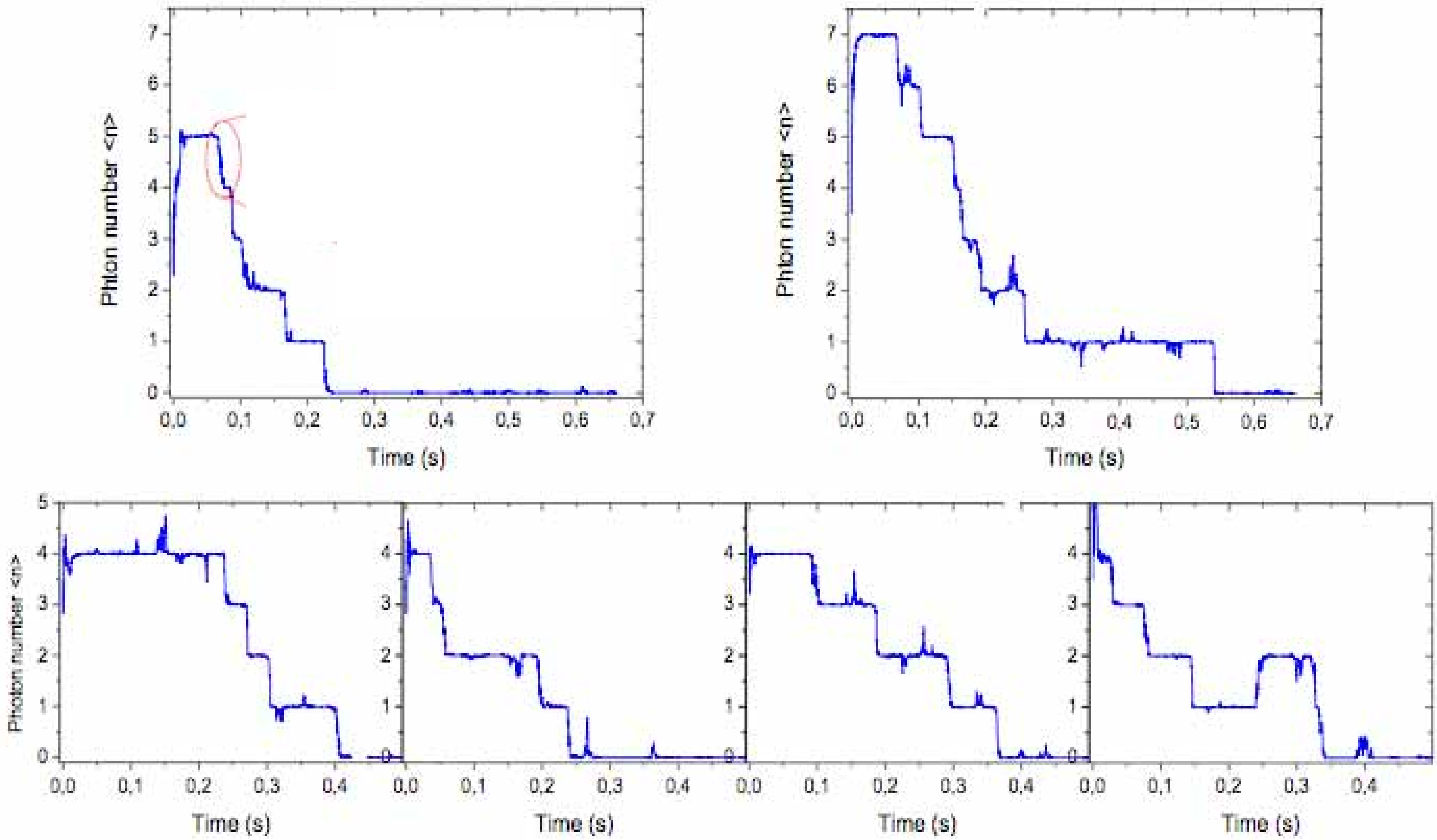
Illustrates quantum measurement postulate about statistics

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



Single realization of field trajectory: real Monte Carlo

Photon number trajectories



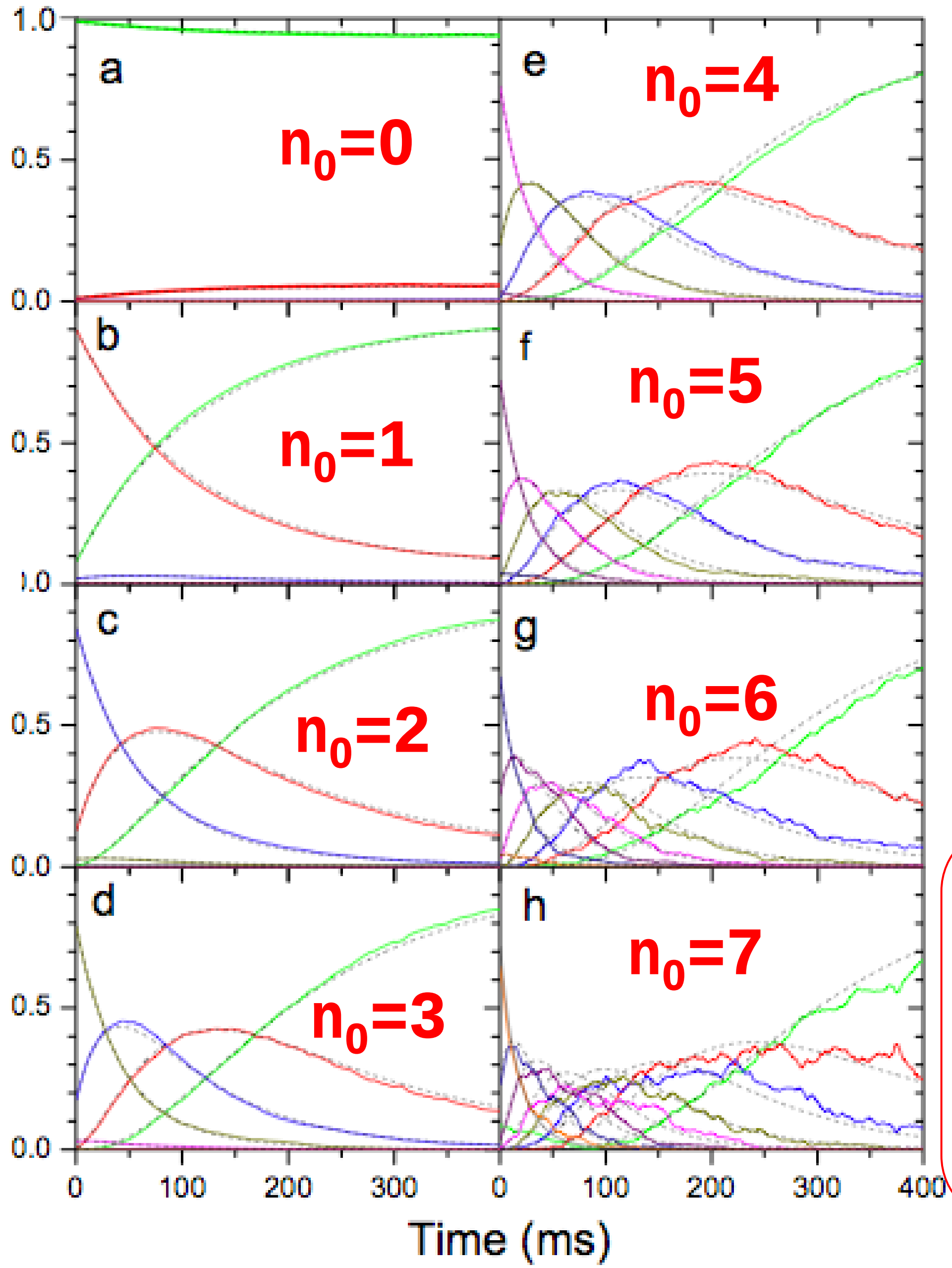
Four trajectories following collapse into n=4

An inherently random process (durations of steps widely fluctuate and only their statistics can be predicted)

Relaxing Fock states: quantitative analyzis

Decay of $|n_0\rangle$ Fock state:

Sort out ensemble of realizations passing through $|n_0\rangle$ (at random times redefined as t=0) & reconstruct the photon number distribution of these ensembles at subsequent times.



Rate equations:

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

Jump rates (κ=1/T_c)

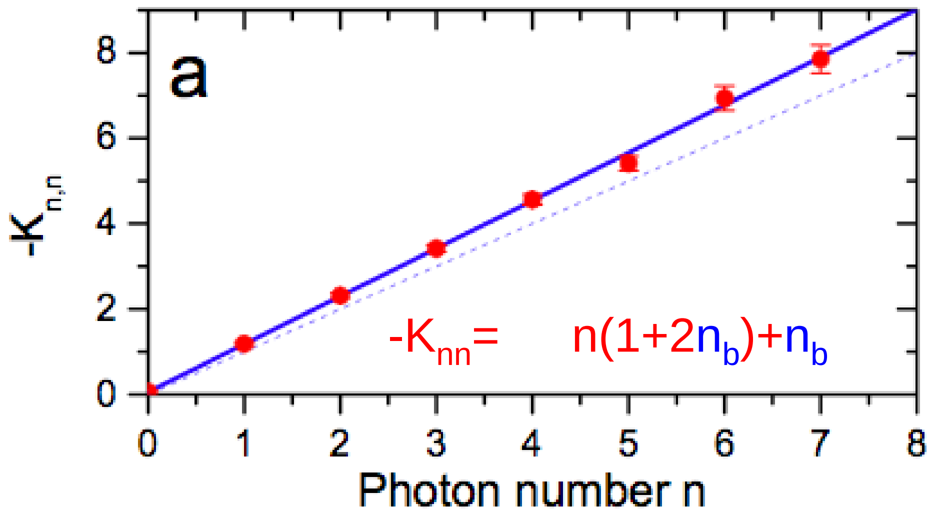
$K_{n-1,n}=\kappa(1+n_b)n$

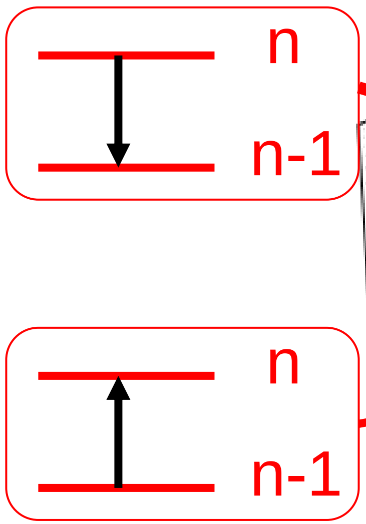
$K_{n,n-1}=\kappa n_b n$

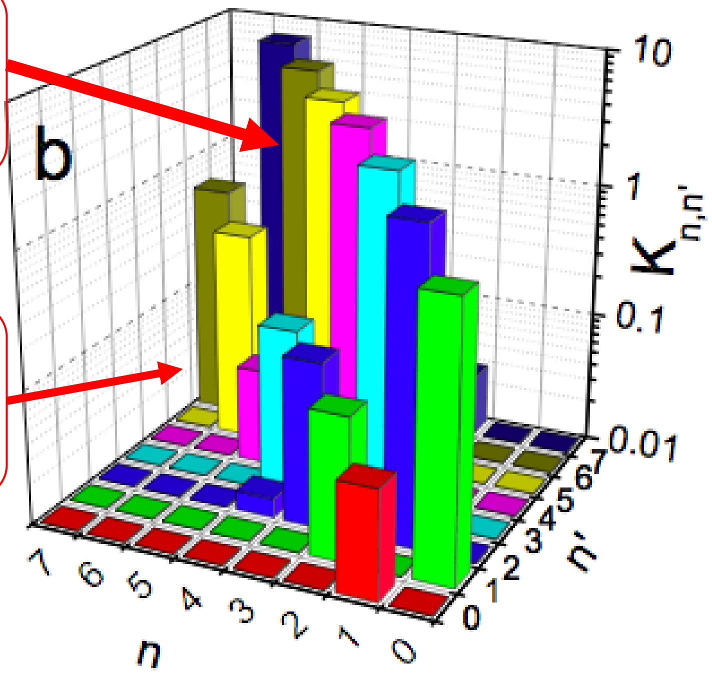
$K_{n,n}=-K_{n-1,n}-K_{n+1,n}=-\kappa[(1+n_b)n+n_b(n+1)]$

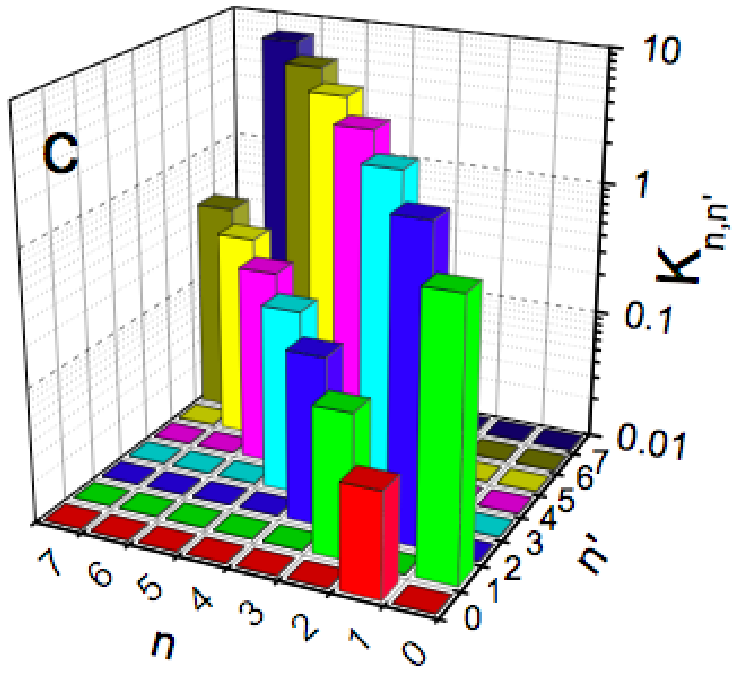
Brune et al, Phys.Rev.Lett. To be published & arXiv 0809.1511 (September 2008)

Decay rate of |n> state is linear in n







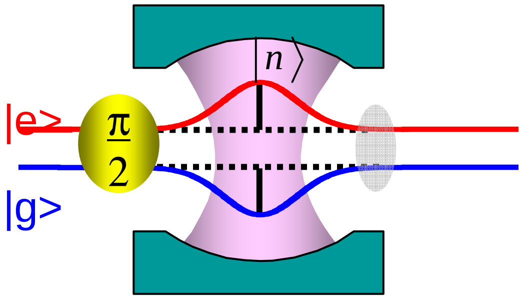


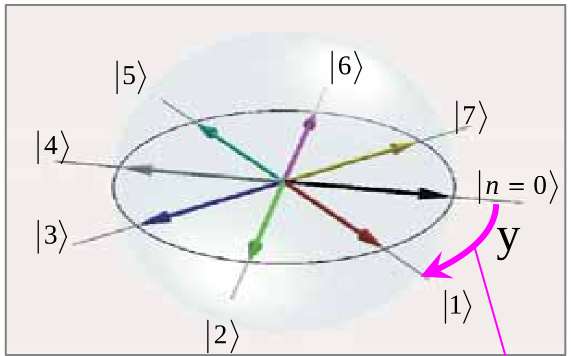
Jump rates (Log scale)

experiment

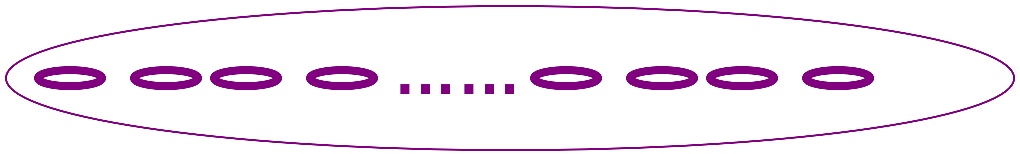
Theory

Alternative view of QND photon counting: the «meter» is a N-atom sample entangled with field





$\Phi_0 = \frac{\pi}{4}$

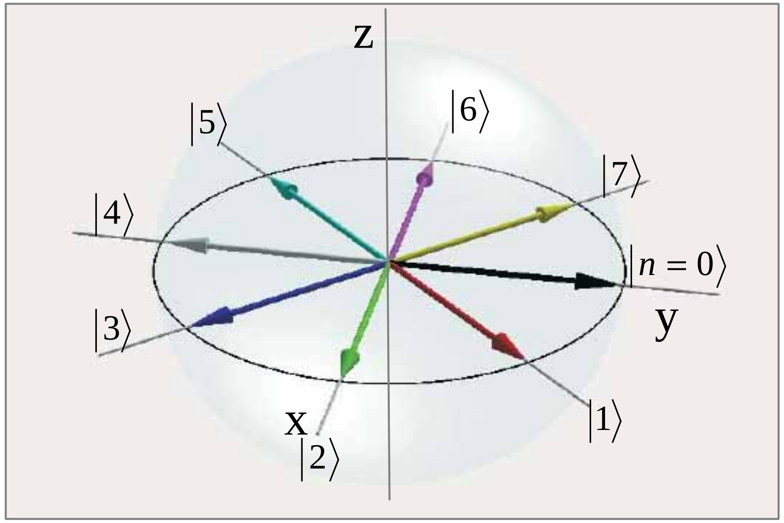


QND procedure does not depend upon order or timing of individual spin measurements:
instead of detecting N atoms one by one, we could store them before detecting their collective spin at once.
Result would be the same.

$$|\Psi\rangle = \sum_n C_n \{|spin_n\rangle\}^N \otimes |n\rangle$$

Photon number coded in a sample of N atoms, all pointing in a direction correlated to photon number: mesoscopic entanglement!

Decoding photon number by spin tomography



$$|\Psi\rangle = \sum_n C_n \{|spin_n\rangle\}^N \otimes |n\rangle$$

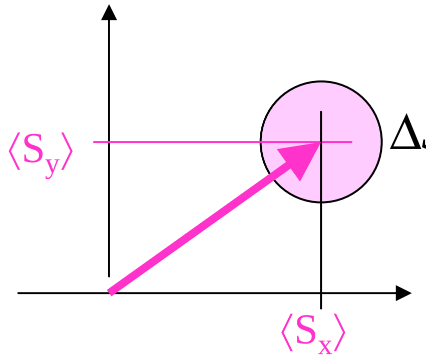
For each n value, N identical copies of state $|spin_n>$

Measuring ensemble average of two spin-components:

N atoms

N/2 atoms: measure $\langle S_x \rangle$

N/2 atoms: measure $\langle S_Y \rangle$



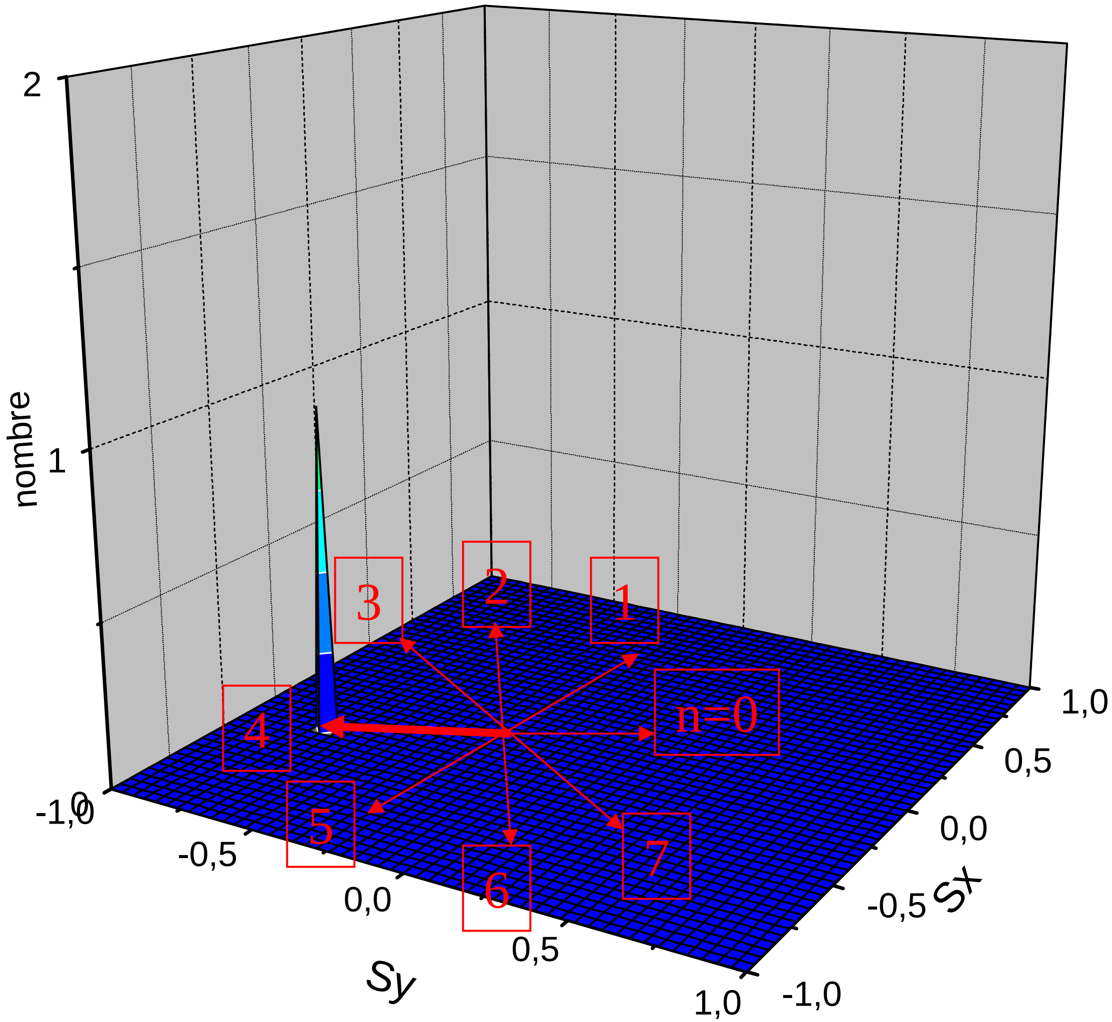
$$\Delta S \propto \frac{1}{\sqrt{N}}$$

N ~ 100 is a large enough sample to distinguish between different n values

In practice, measurement is done one spin at a time, but global N-atom tomography can be extracted from data for each field trajectory

Measuring a coherent field by atomic tomography

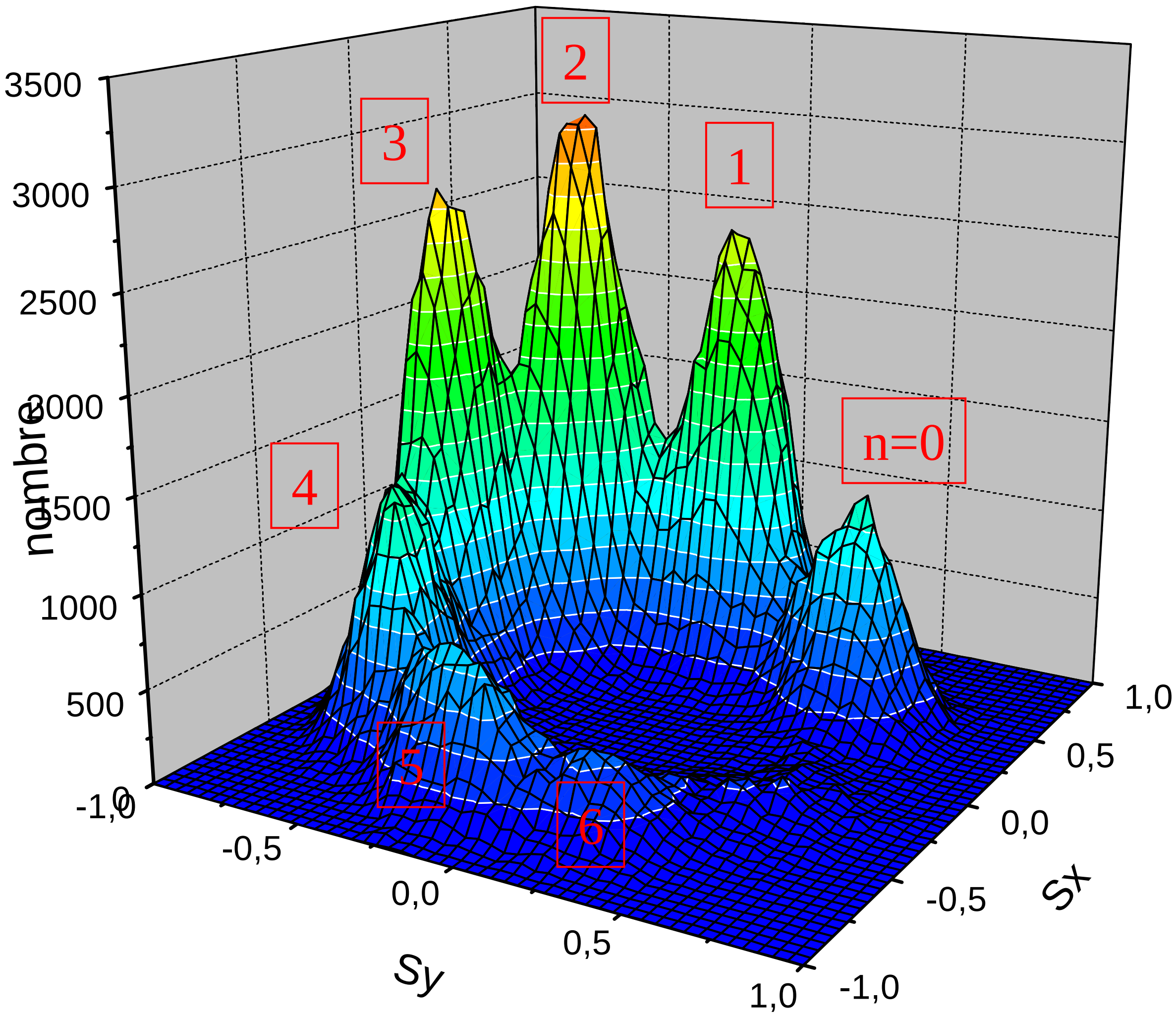
Sample of N = 110 first atoms crossing cavity in T_{meas} = 26 ms



One measurement

n = 4

Statistics of measurements performed on many realizations of same coherent field



Spins point in discrete directions:

Each peak corresponds to a well-defined photon number

<n>=2.4 photons

⇒ A kind of Stern-Gerlach experiment giving visceral evidence of field quantization

3.

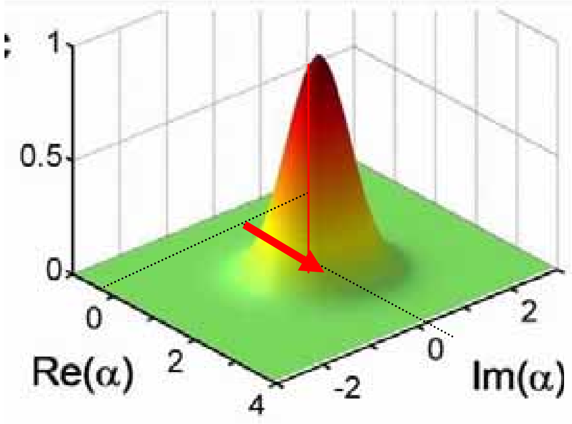
Back action of QND photon counting on the field's phase
&
the quantum Zeno effect of light

J.Bernu, S.Deléglise, C.Sayrin, S.Kuhr, I.Dotsenko, M.Brune, J-M.Raimond and S.Haroche,

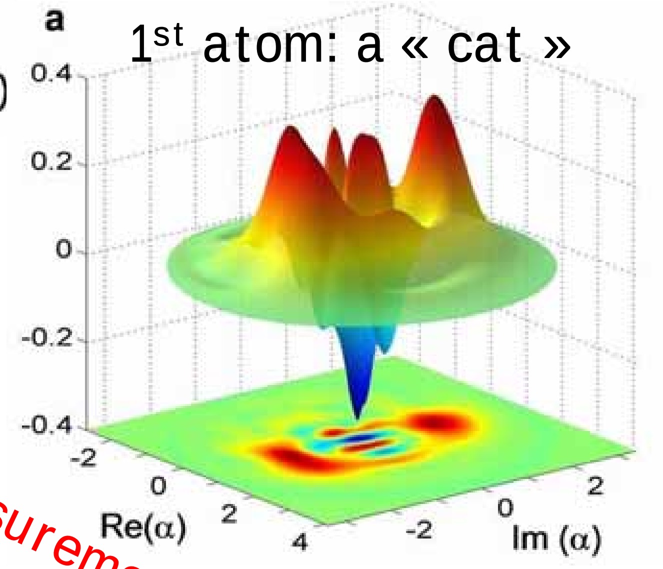
Phys.Rev.Lett., Oct 2008, to be published
arXiv 0809-4388

Back action of QND photon counting on field's phase distribution (ΔnΔΦ ≥1/2)

Initial coherent state (phase 0)

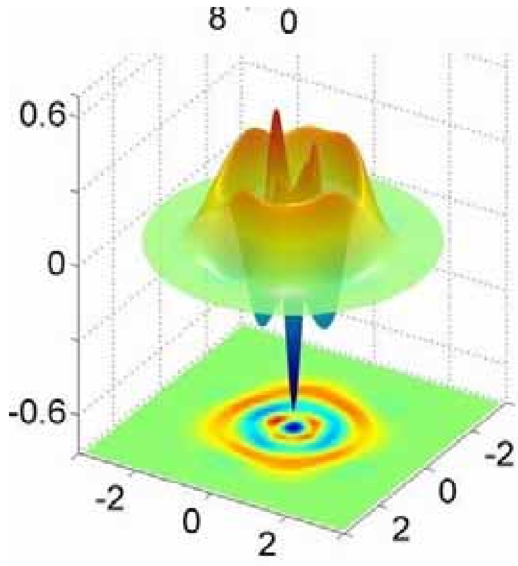


Field state after 1^{st} atom: a « cat »



Progressive QND measurement

Field state after ~50 atoms: Fock state (here n=3)



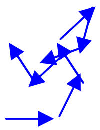
Progressive phase blurring observed on the reconstructed Wigner functions of field (more on this later)

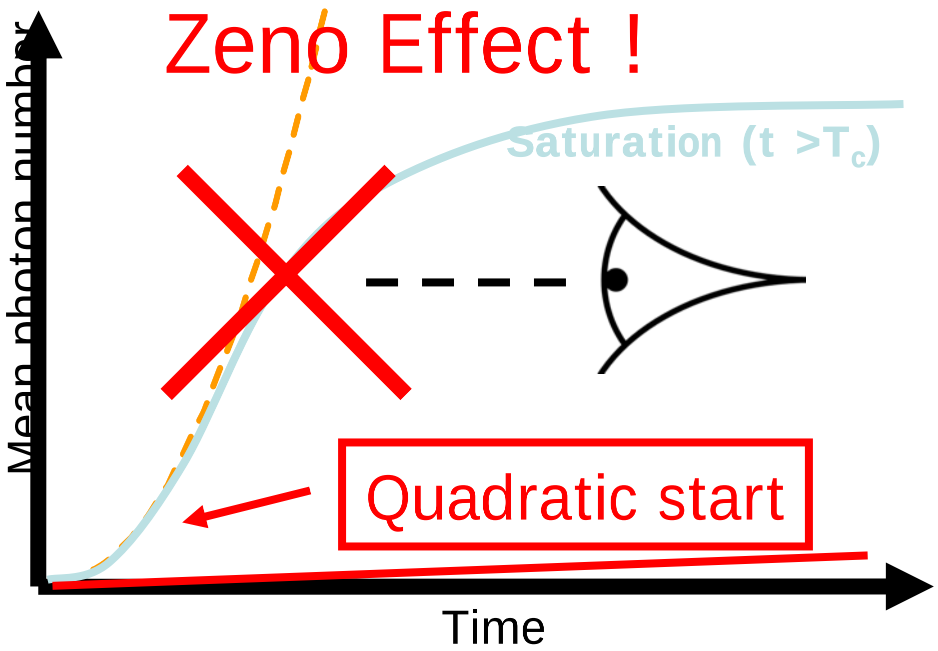
Freezing the field in vacuum state by repeated measurement

Cavity is resonantly coupled to a repeatedly pulsed source of coherent light.

If field is not measured until end of experiment, amplitude builds up linearly with number of pulses and mean photon number increases quadratically as t^2

If photons are QND counted between pulses, phase is randomized by measurement and amplitude undergoes Brownian motion near phase space origin: amplitude grows as $\sqrt{t}$ and photon number as t. Rate of intensity increase goes to 0 as number of injections goes to infinity.

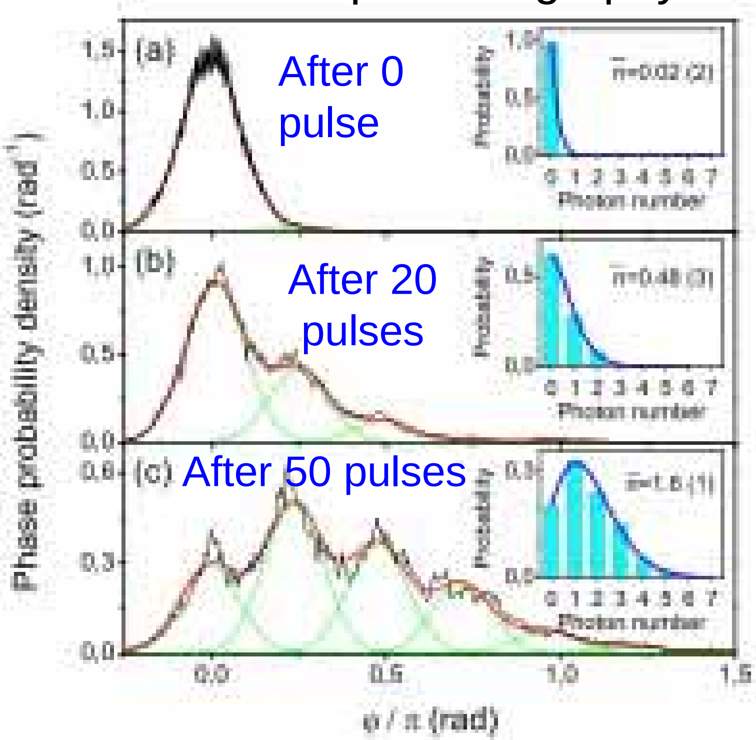




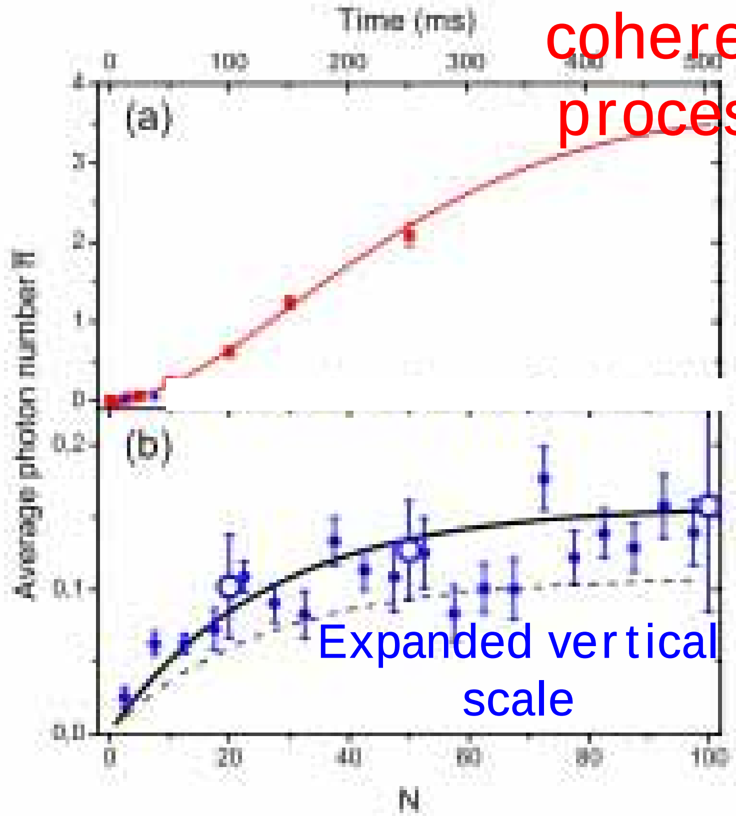
Equivalently, each measurement projects field back into vacuum

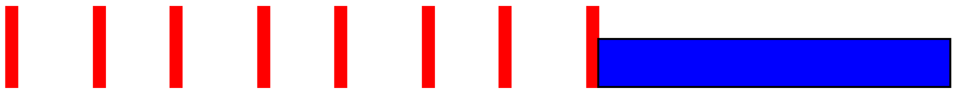
The Zeno effect of light

Atomic spin tomography



Observed only on coherent process!

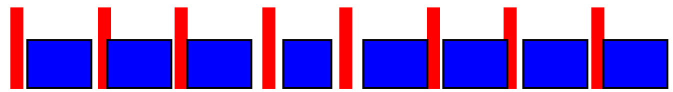




N coherent injection pulses

QND Measurement

time



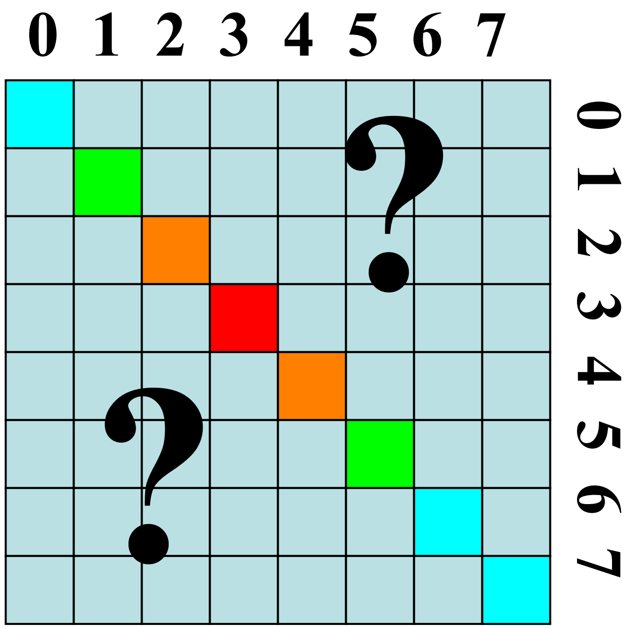
QND measurements between pulse injections

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, 455, 510 (2008)

QND photon counting and field state reconstruction



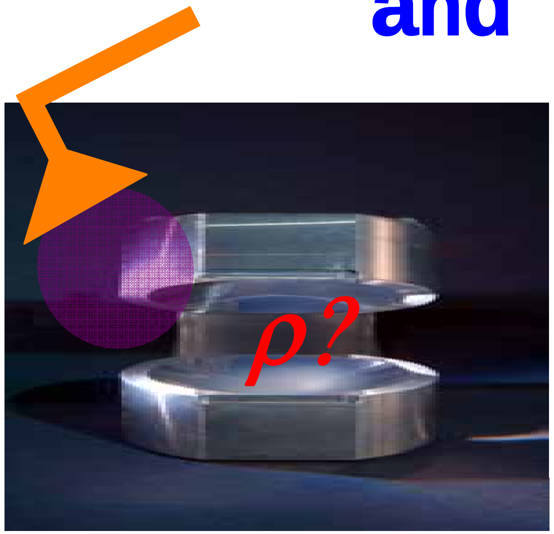
Repeated QND photon counting on copies of field determines the diagonal ρ_{nn} elements of the density matrix, but leaves the off-diagonal coherences $\rho_{nn'}$ unknown

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

Tomography of trapped light

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:

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

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

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

From the density operator ρ to the Wigner function W

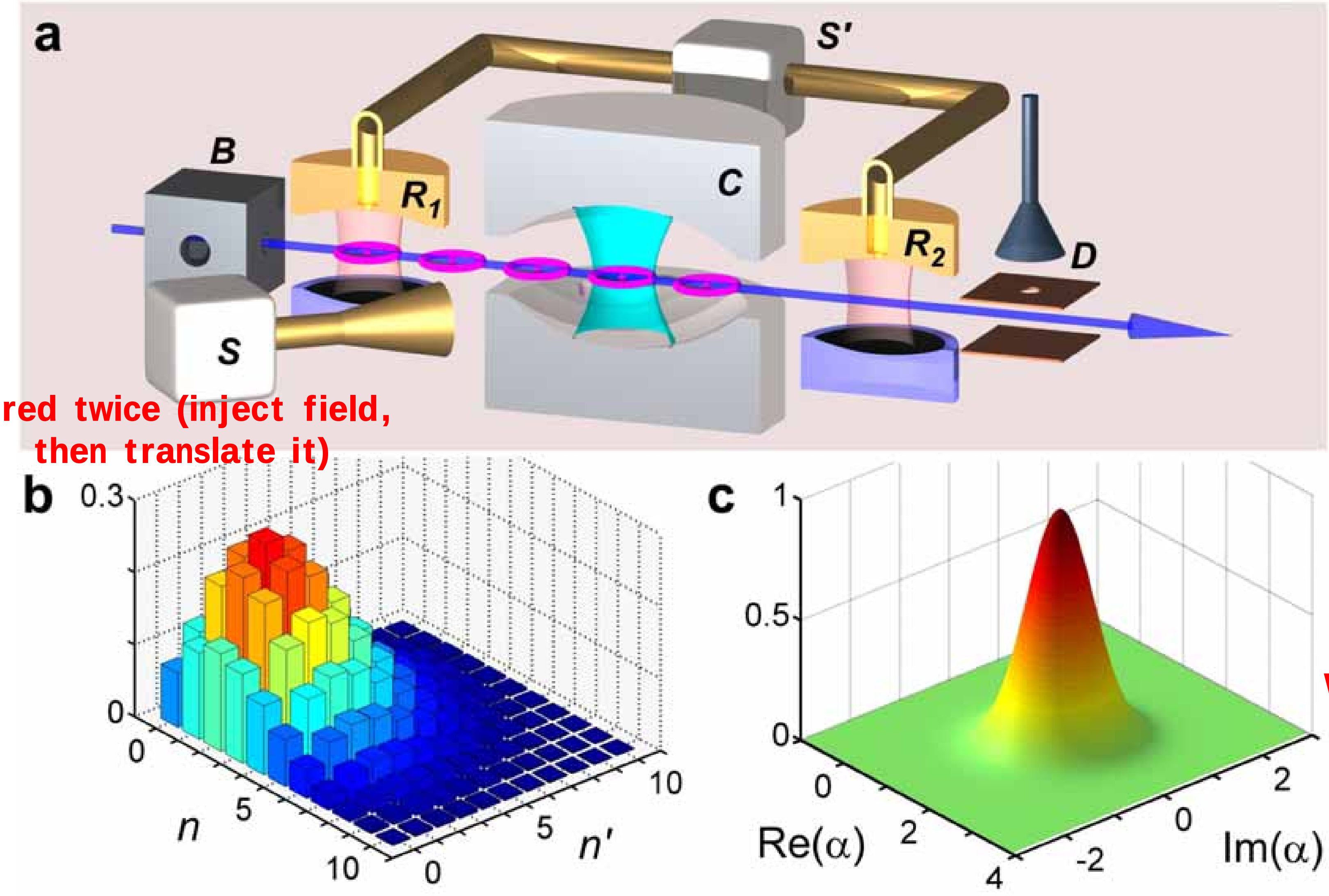
W is a real distribution of the field's complex amplitude in phase space, defined as:

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

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

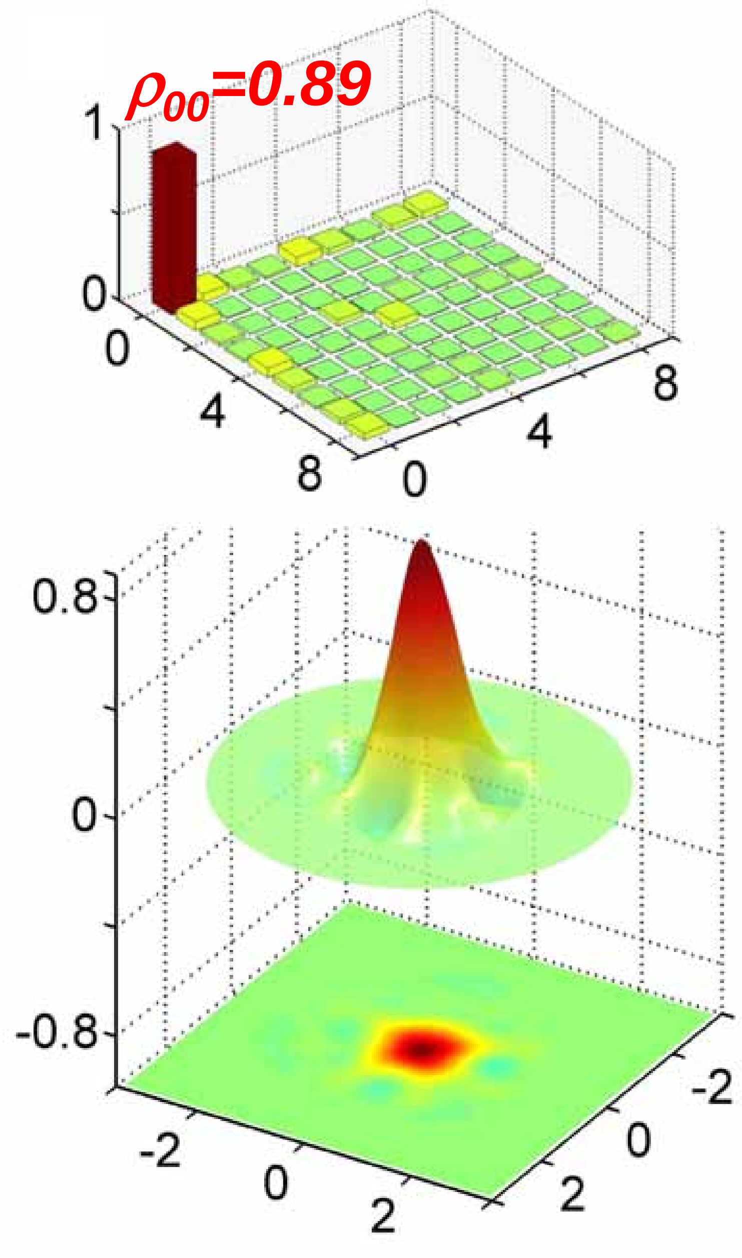
1) Prepare coherent state in C

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

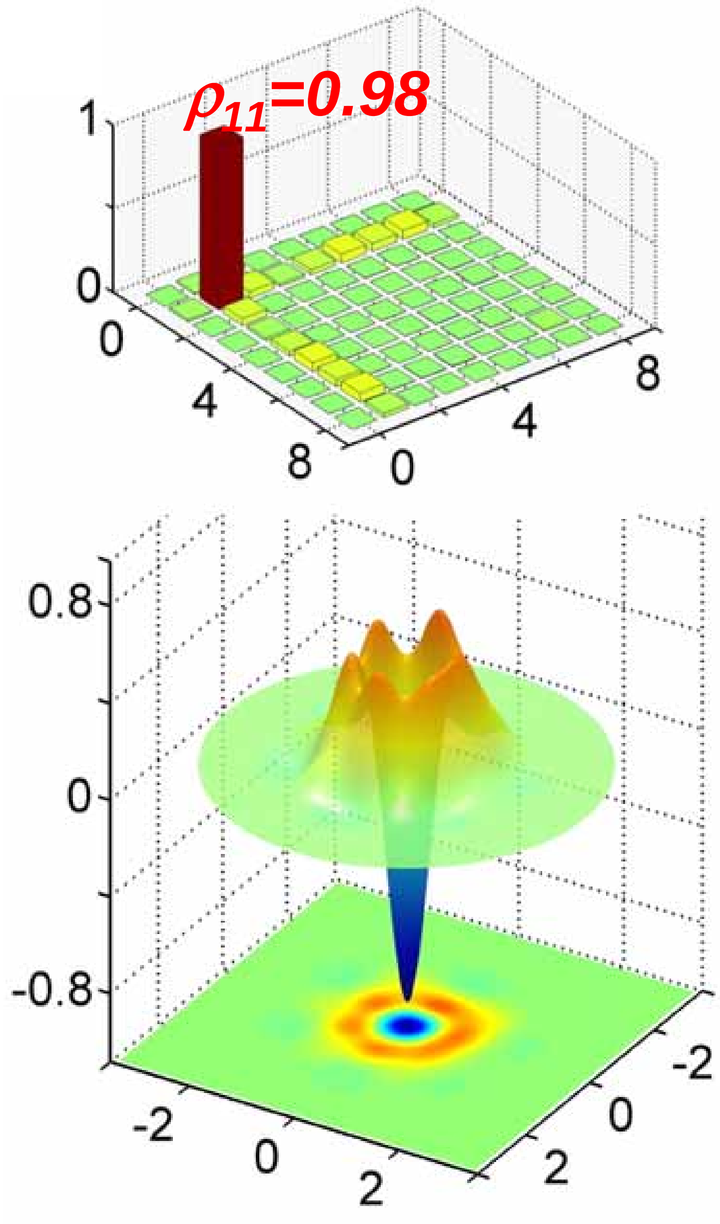
1) Prepare coherent state in C

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

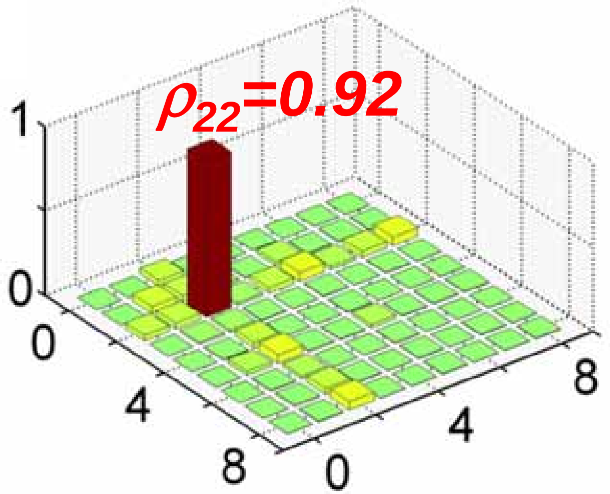
1) Prepare coherent state in C

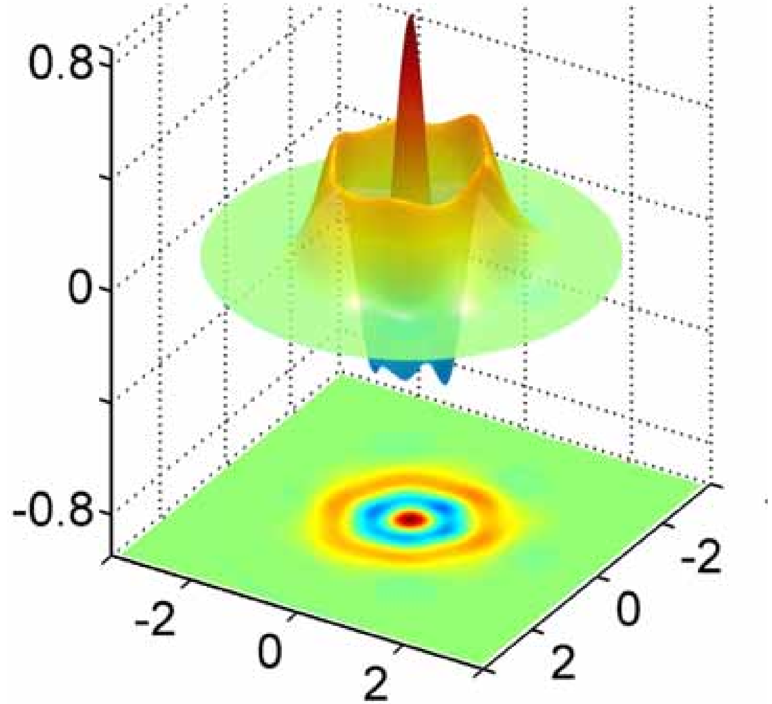
2) Turn it into a Fock state by (random) projective QND measurement of photon number

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

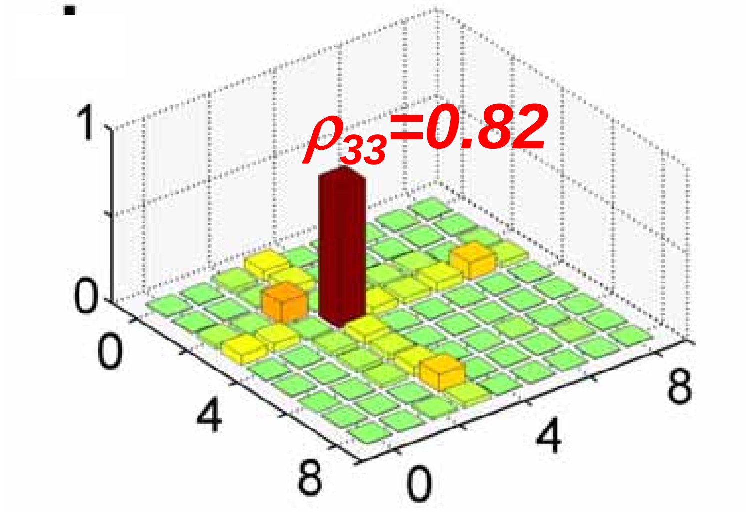
1) Prepare coherent state in C

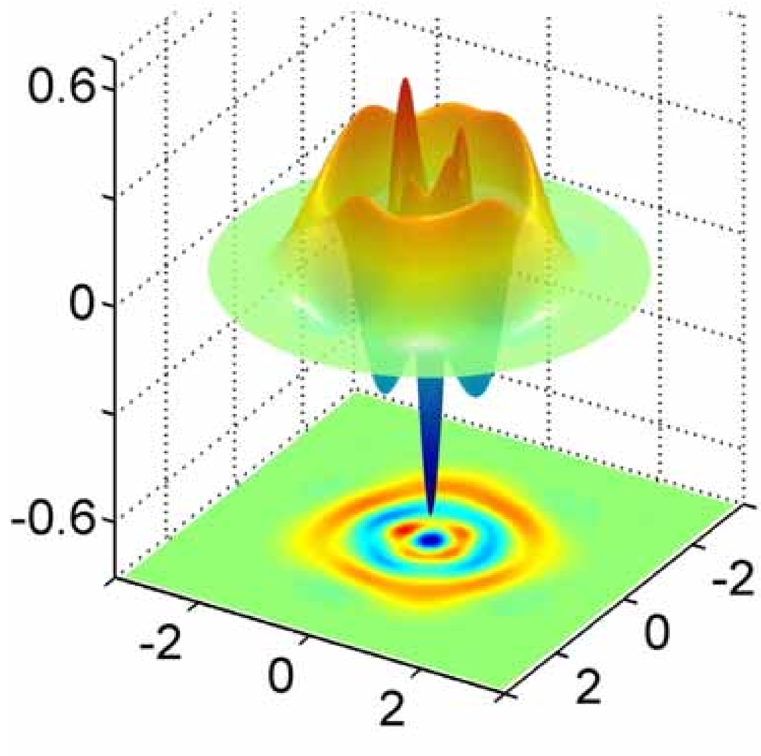
2) Turn it into a Fock state by (random) projective QND measurement of photon number

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

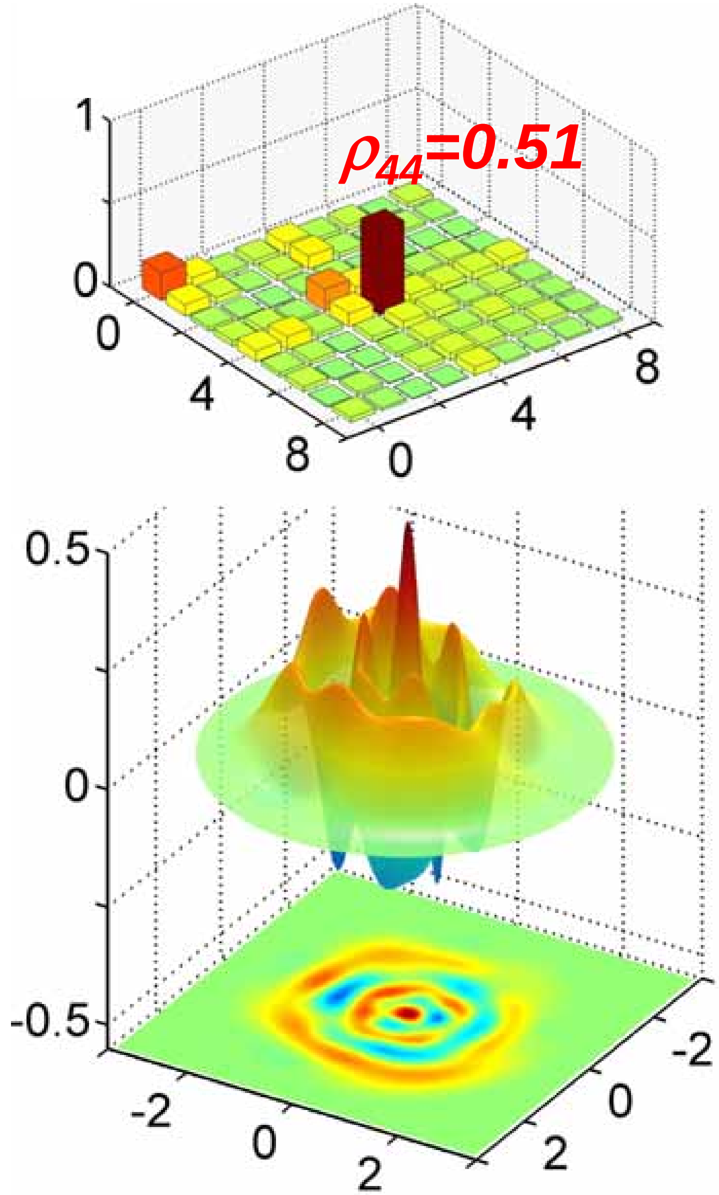
1) Prepare coherent state in C

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 !

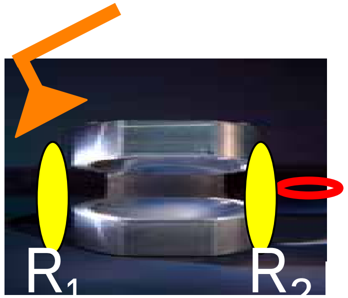
5.

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

S.Deléglise, I.Dotsenko, C.Sayrin, J.Bernu, M.Brune, J-M.Raimond & S.Haroche, Nature, 455, 510 (2008)

Recipe to prepare and reconstruct the cat

Coherent field prepared by first field injection

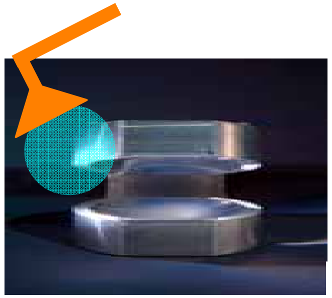


First QND atom generates cat state

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

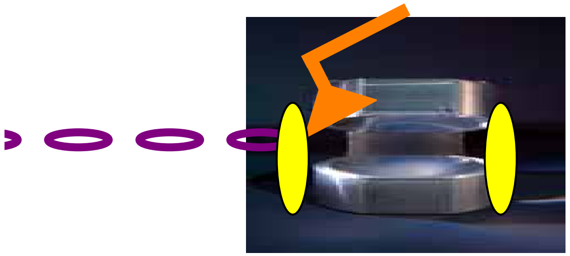
$$\rho = |\Psi_{cat}\rangle\langle \Psi_{cat}|$$

Sign depends on detected atom state (e or g)



Cat state translated in phase plane by second field injection:

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



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 $|\beta\rangle+|-\beta\rangle$

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

D^2

$D^2 = 8$ photons

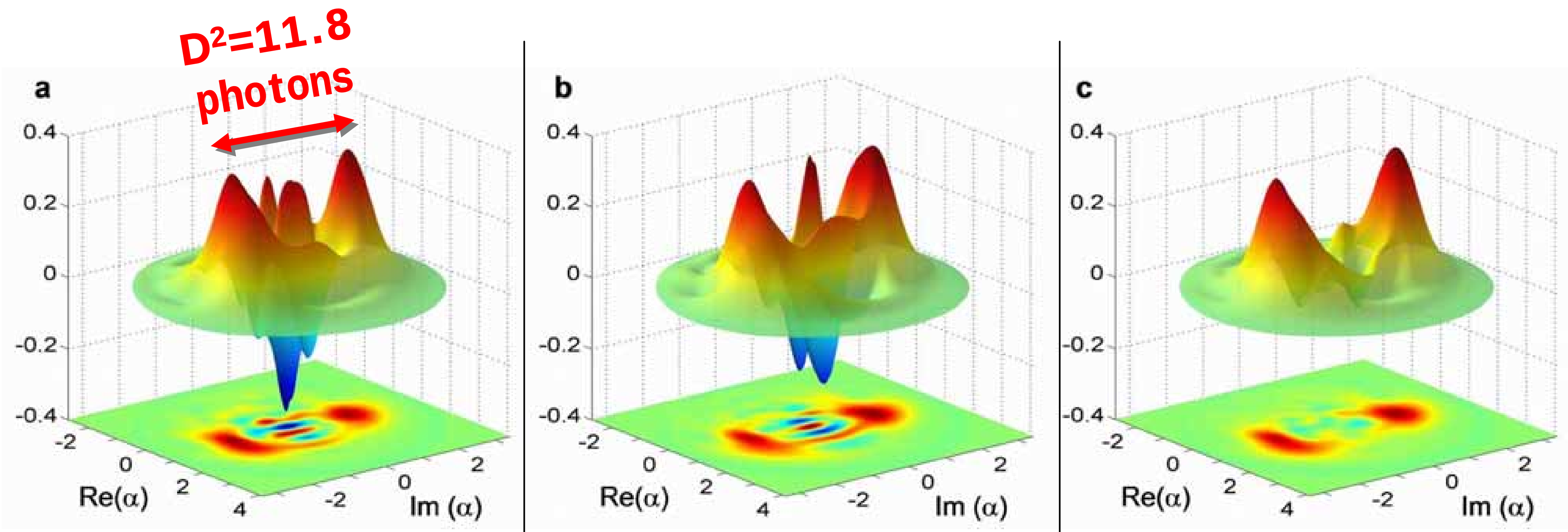
Fidelity: 0.72

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

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

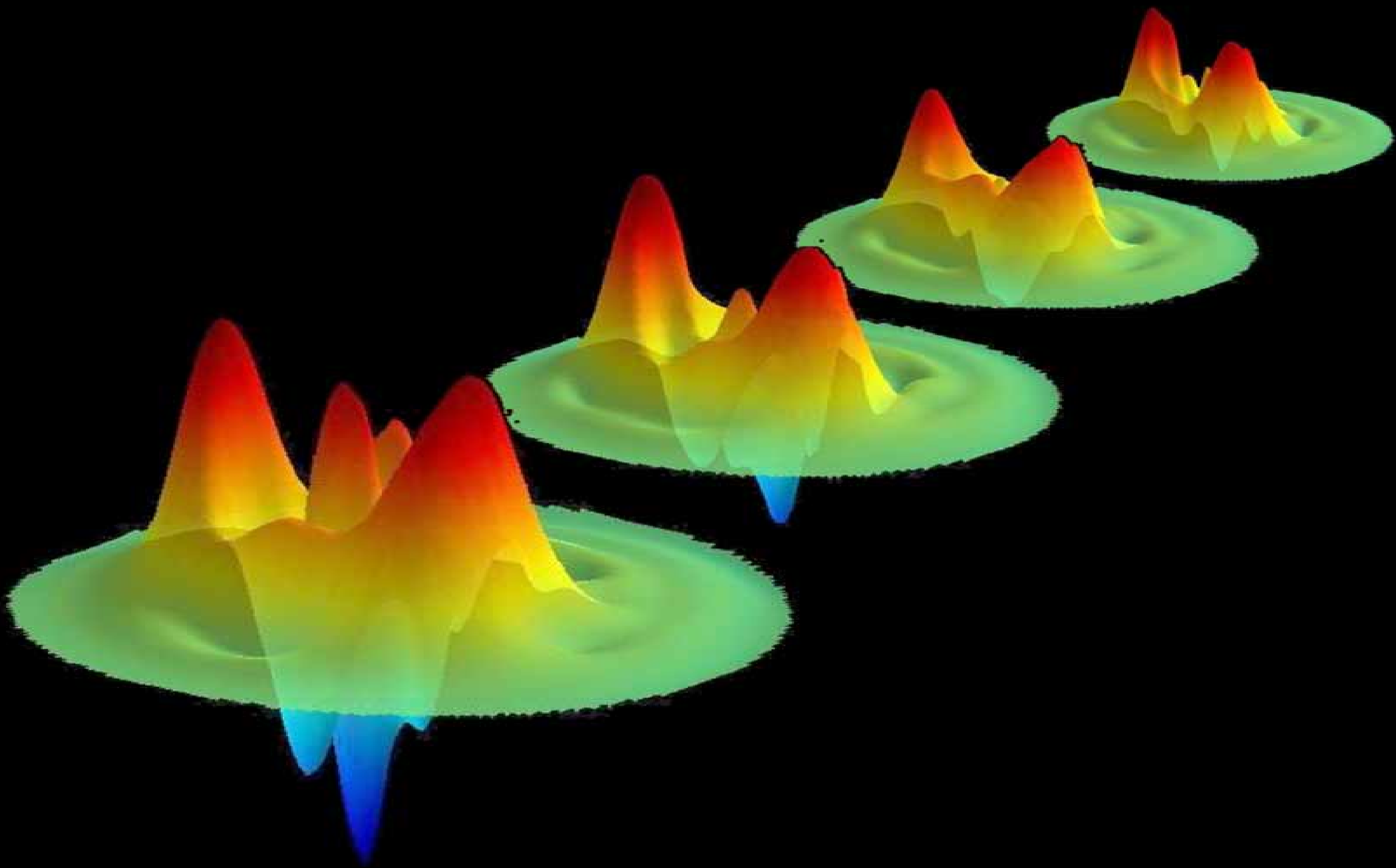
Non-classical states of freely propagating fields with similar W function (and smaller photon numbers) have been generated in a different way (Ourjoumtsev et al., Nature 448, 784 (2007))

Various brands of cats….



Even cat	Odd cat	Statistical Mixture
$\vert\beta e^{i\chi}> + \vert\beta e^{-i\chi}>$	$\vert\beta e^{i\chi}> - \vert\beta e^{-i\chi}>$	$\vert\beta e^{i\chi}><\beta e^{i\chi}\vert + \vert\beta e^{-i\chi}><\beta e^{-i\chi}\vert$
(preparation atom detected in e)	(preparation atom detected in g)	(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
sont requis pour visionner cette image.

The cat's quantumness vanishes (evolution of difference between even and odd cat states)

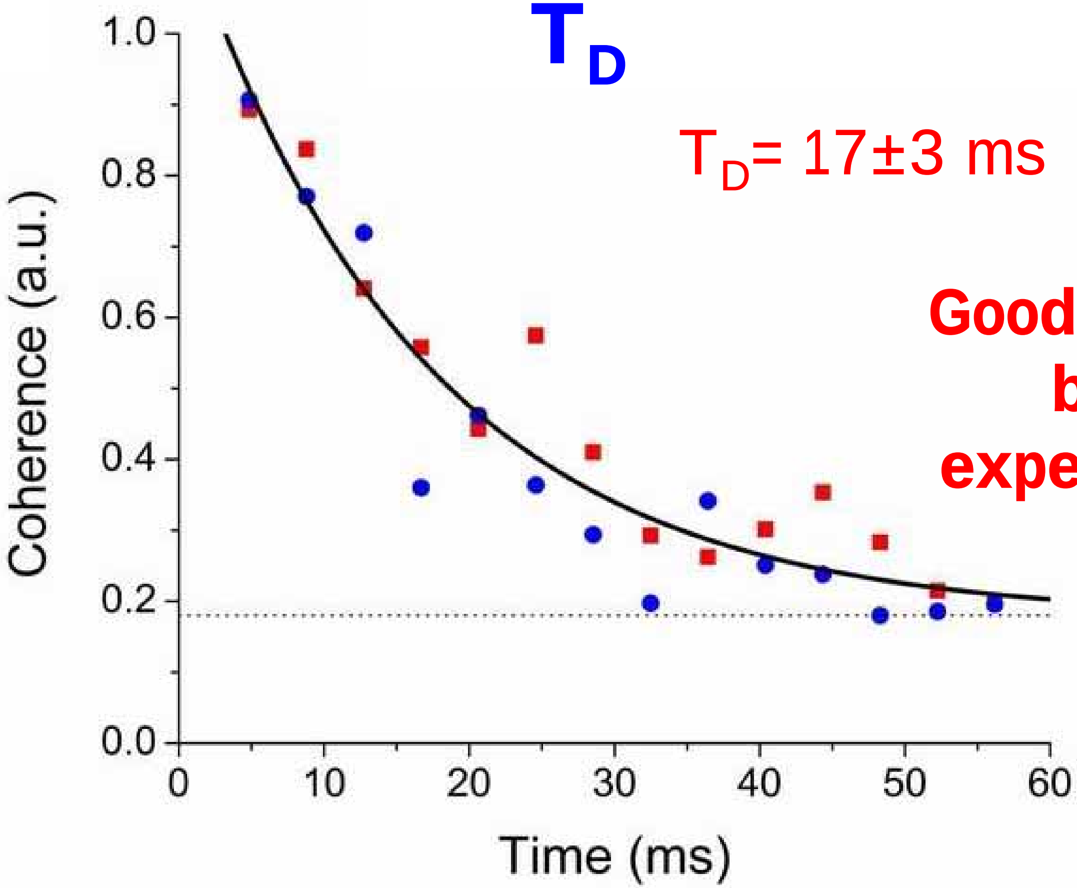
Supplementary material on line accompanying Nature Letter

QuickTime™ et un
décompresseur mpeg4
sont requis pour visionner cette image.

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±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

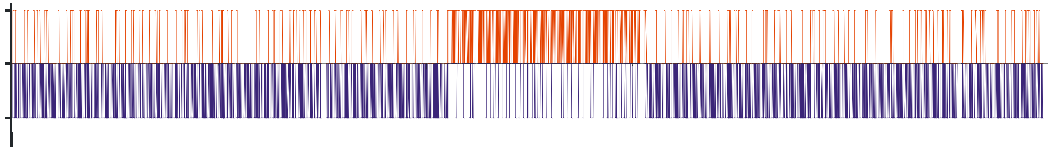
Correction at finite temp. (T = 0.8K):
$T_D = 2T_c/[D^2(2n_B+1)+4n_B] = 19.5$ ms

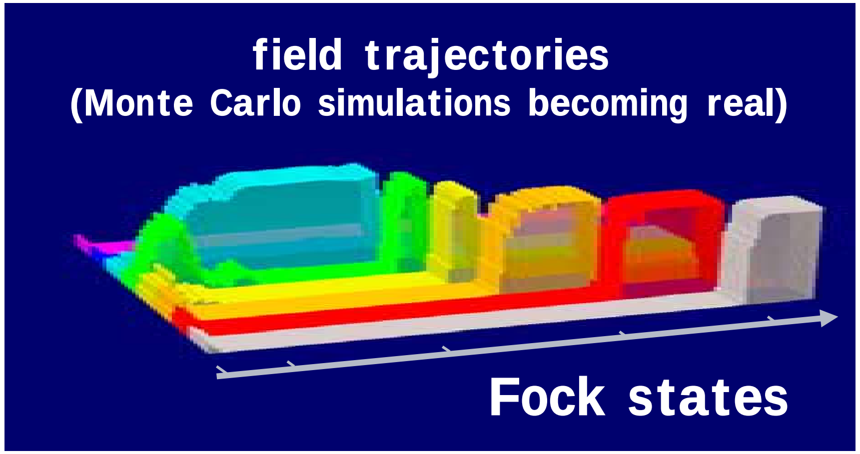
Mean number n_B of blackbody photons = 0.05

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

6.Conclusion and perspectives

Field quantum jumps





Preparing and reconstructing cats and other non-classical states

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

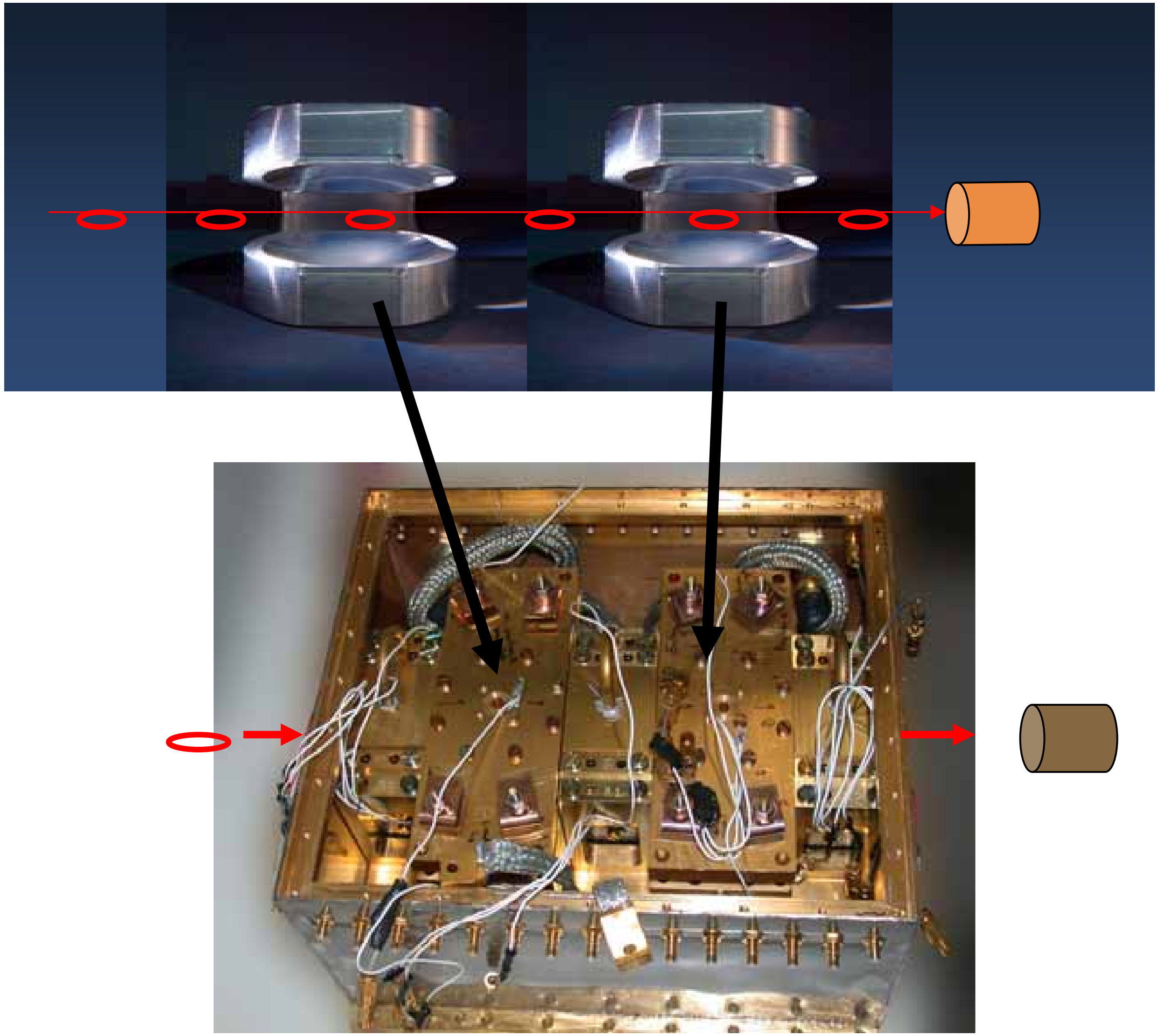
Super-mirrors make new ways to look possible: trapped photons become like trapped atoms

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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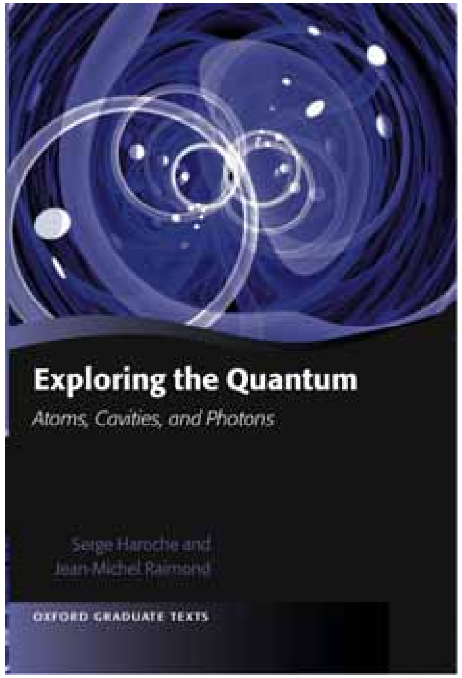
Xing-Xing

Superconducting atom chips

Gilles Nogues
A.Lupascu
T.Nirrengarten*
A.Emmert
C.Roux*

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, U.Busk Hoff



Exploring the Quantum
Atoms, cavities and Photons

S.Haroche and J-M.Raimond

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