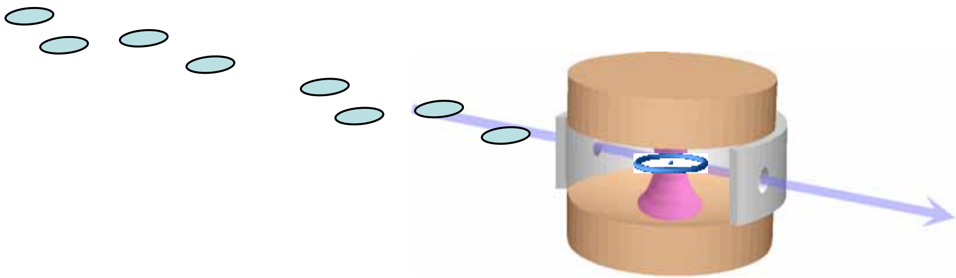
Quantum non-demolition measurement of photons in a cavity: observing the quantum jumps of light

Serge Haroche, ENS
and Collège de France, Paris

FRISNO-Les Houches; February 12 2007



Continuous Quantum Non Demolition (QND) monitoring of a field in a cavity

Requires a very long cavity damping time: photons should survive the passage of many atoms interacting with them one at a time.

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Quantum Nondemolition Measurement of Small Photon Numbers by Rydberg-Atom Phase-Sensitive Detection

M. Brune, S. Haroche, V. Lefevre, J. M. Raimond, and N. Zagury[a]

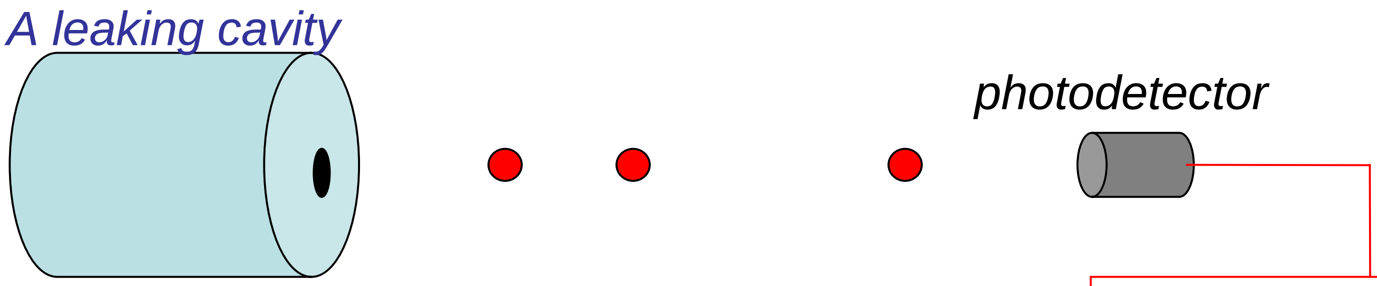
Département de Physique de l'Ecole Normale Supérieure, Laboratoire de Spectroscopie Hertzienne, 24 rue Lhomond, F-75231 Paris CEDEX 05, France

(Received 18 April 1990)

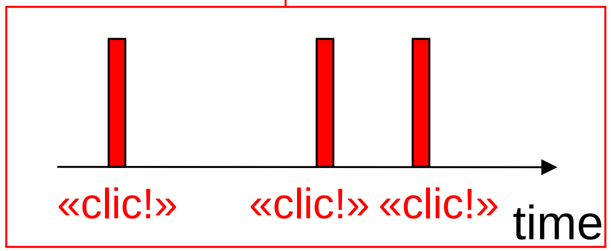
We describe a new quantum nondemolition method to monitor the number N of photons in a microwave cavity. We propose coupling the field to a quasiresonant beam of Rydberg atoms and measuring the resulting phase shift of the atom wave function by the Ramsey separated-oscillatory-fields technique. The detection of a sequence of atoms reduces the field into a Fock state. With realistic Rydberg atom-cavity systems, small-photon-number states down to $N=0$ could be prepared and continuously monitored.

It has been a very long quest!

QND detection of photons is fundamentally different from usual photodetection



Normal photon counters absorb light (transforming it in an electron current). A clic indicates that ***there was*** *a photon. Successive clics correspond to different photons*



$$|1\rangle \xrightarrow[clic]{} |0\rangle$$

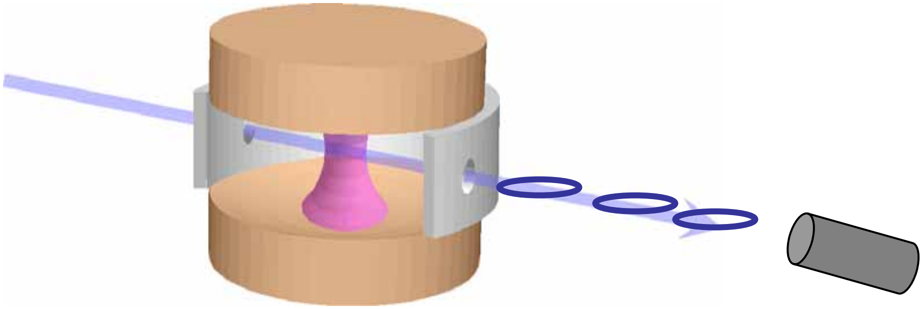
A clic projects the field onto the vacuum!

This is at odds with the postulate students learn in text book quantum physics:
«upon measurement, the system is projected onto an eigenstate of the measured observable, so that the measurement can be repeated, yielding the same value again and again».

Can we realize the following QND measurement repetition:

$$|1\rangle \xrightarrow[clic]{} |1\rangle \xrightarrow[clic]{} |1\rangle \xrightarrow[clic]{} \ldots \xrightarrow[clic]{} |1\rangle \quad ?$$

QND detection of photons is essential to observe the quantum jumps of the field

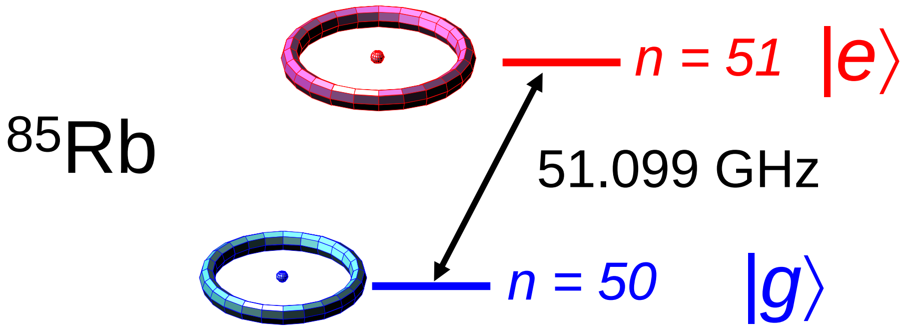


The number of photons in the box can change suddenly at random times, due to absorption or emission from the walls (quantum jumps). QND monitoring should reveal these jumps, while usual photon absorption cannot!

We want to observe the spontaneous jumps of the field, not the trivial ones produced by the absorption in a detector

…We need transparent atoms, which pick up information from the field without exchanging energy with it. Cavity QED with Rydberg atoms and microwave superconducting cavities provides an elegant way to do exactly that by atomic interferometry…

Circular Rydberg Atoms



- n large, $l = |m| = n - 1$
- life time: 30 ms → weak dissipation
- huge electric dipole → large coupling to field
- Two-level system

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

Outline

1. New circular Rydberg atom CQED set-up with super-high-Q cavities

2. Repetitive QND measurement of a single light quantum: Witnessing the birth, life and death of a photon

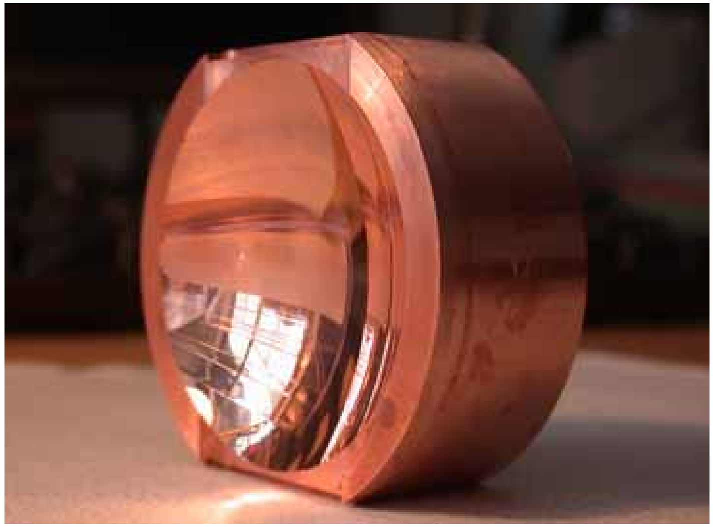
3. QND measurement of larger photon numbers

4. Conclusion and perspectives

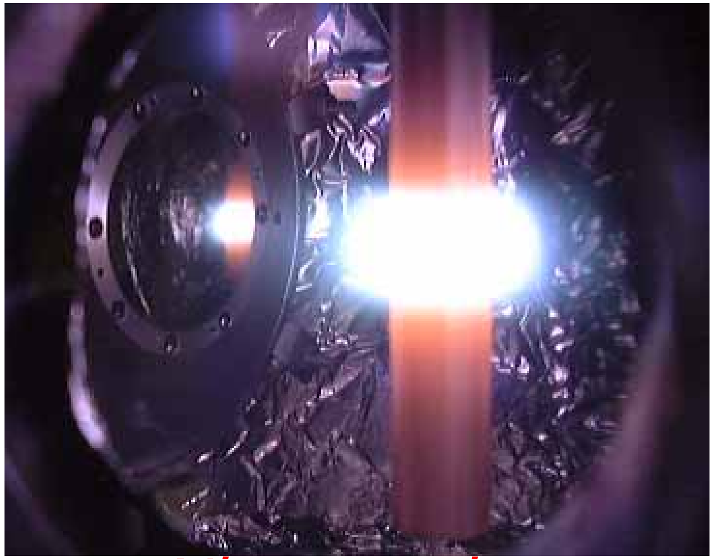
1.

A Circular Rydberg atom CQED set-up with super-high-Q cavities

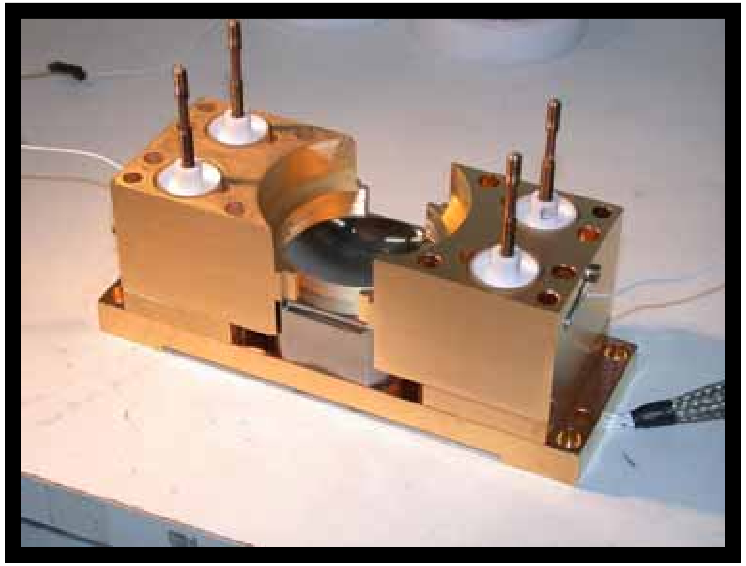
Very high Q cavities (June 2006)

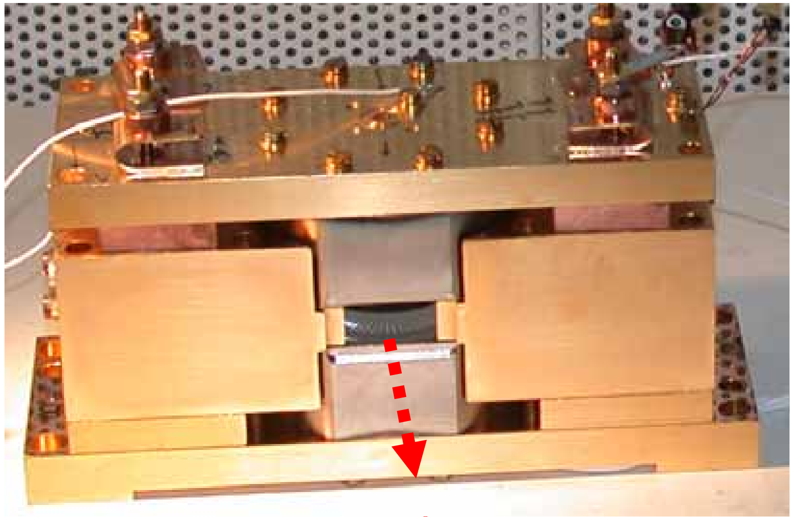


Precision machined (8 nm roughness) copper mirrors



Nb sputtering (P.Bosland et al in Saclay)

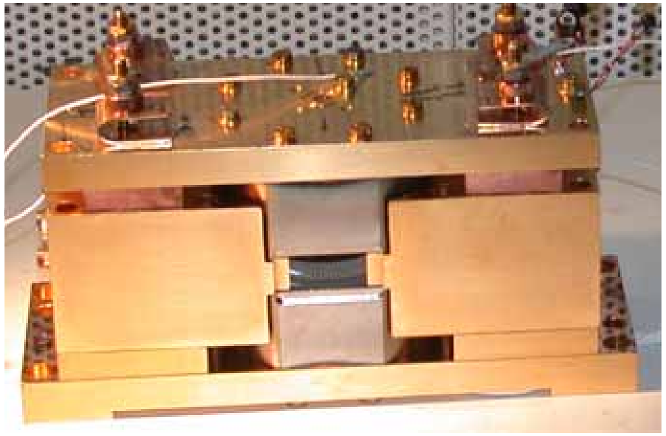




atoms

A very good cavity at 0.8K

S.Kuhr et al, in preparation



$T_c = 0.130$ s $\quad Q = \omega T_c = 4.2\ 10^{10}$

(as high as the Q of the best closed micromaser cavities of Walther et al)

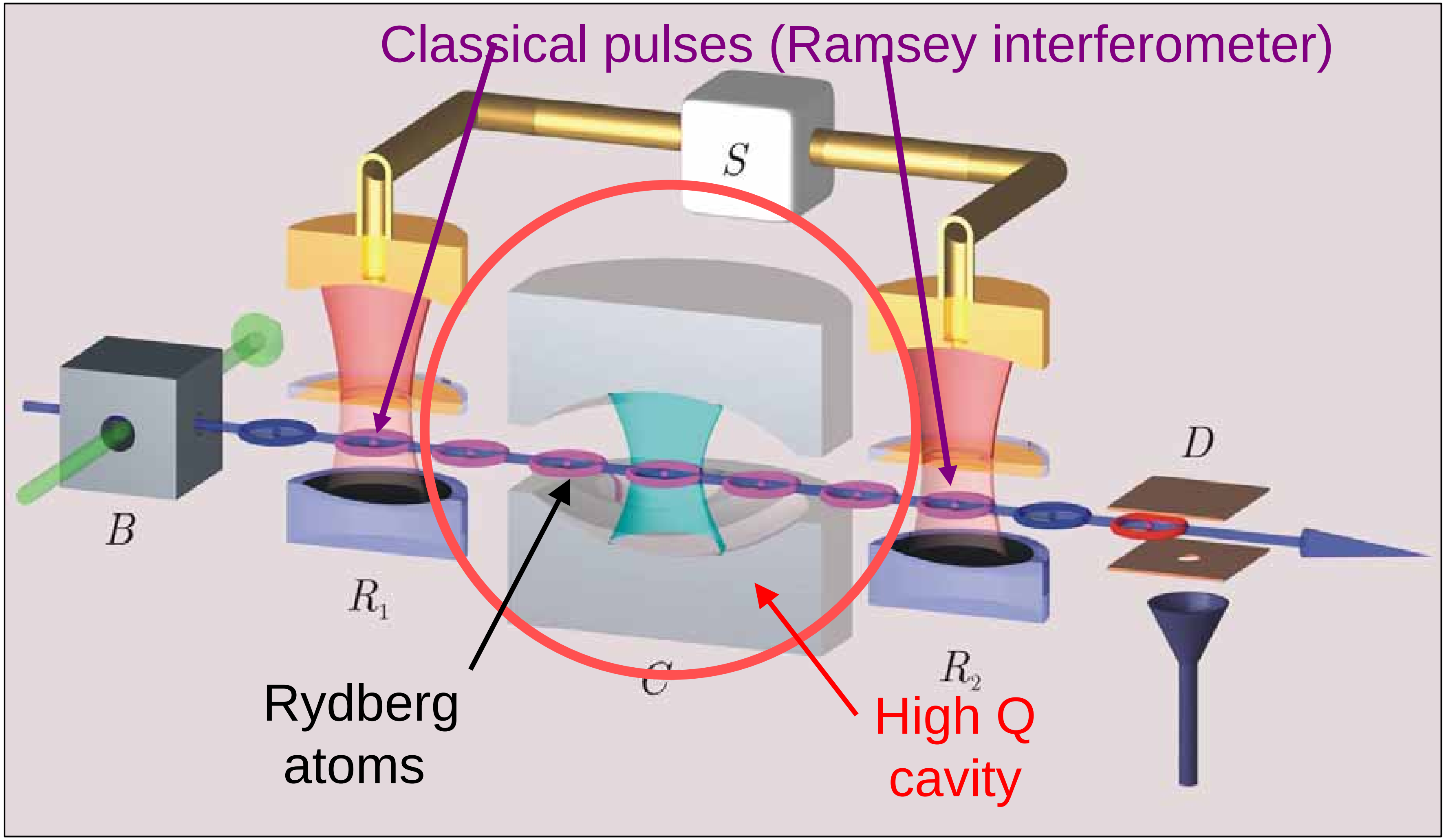
Photon life time seems to be limited by surface roughness of mirrors (8.7 nm r.m.s. measured value)

A photon bounces on average 1.3 billion times on mirrors before decaying! This is the largest finesse for an open FP resonator at any frequency: $f = Q/9 = 4.6\ 10^9$ $(R = 0.999999999)$

Light travels between mirrors over a distance equal to the Earth circumference during 1/e damping….

…and some (lucky) photons travel over half the Moon to Earth distance!

An artist's view of the set-up

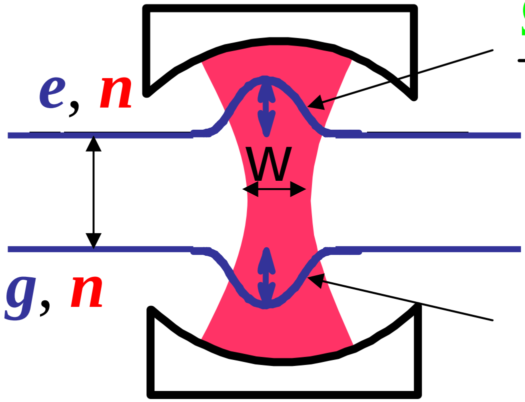


2.

Repetitive QND measurement of a single light quantum: Witnessing the birth, life and death of a photon

S.Gleyzes et al, to be published in Nature in March (quantph/ 0612031)

Non resonant atoms with π phase shift per photon



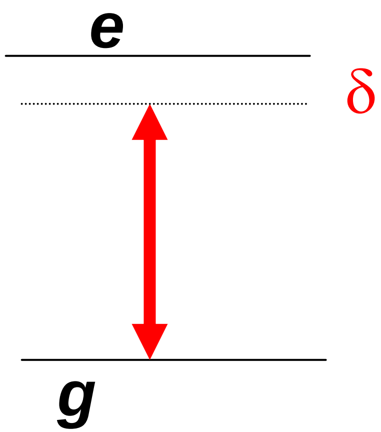
$$\frac{\Omega^2(n+1)}{4\delta}$$

$$-\frac{\Omega^2 n}{4\delta}$$

No absorption
even if $\delta \sim \Omega$
(adiabatic atomic evolution)

Vacuum Rabi frequency

$$\frac{\Omega}{2\pi} = 50kHz$$



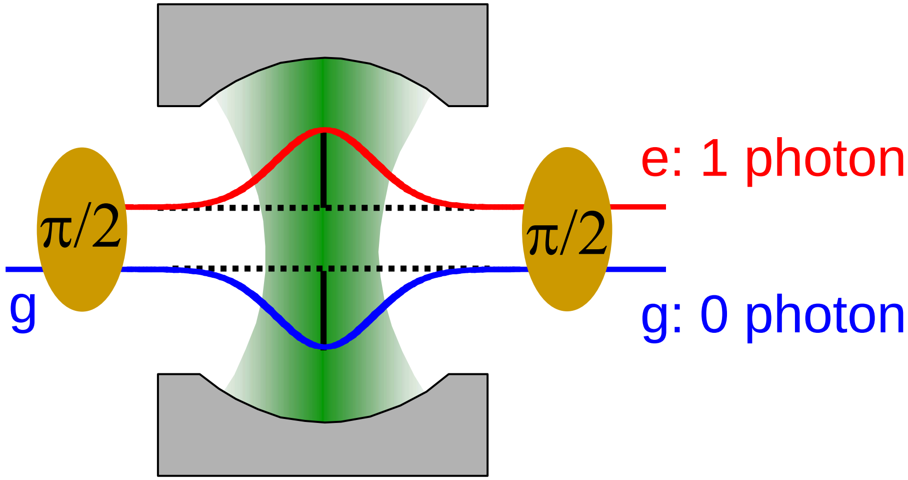
Light shift *Lamb shift*

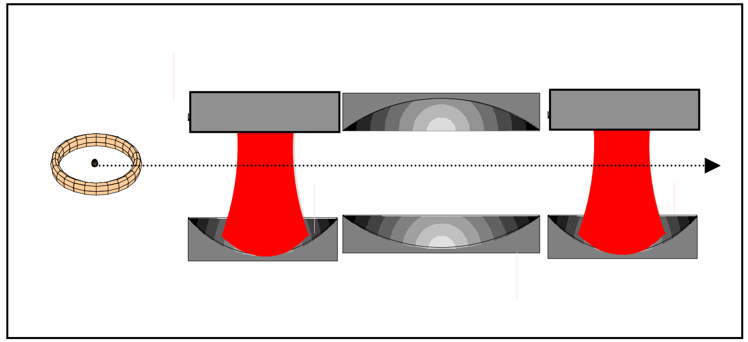
$$\Delta\Phi = \frac{\Omega^2(n+1/2)}{2\delta}t \quad \rightarrow$$

$$\frac{\Omega^2 t}{\delta} = \frac{\Omega^2}{\delta}\sqrt{\frac{\pi}{2}}\frac{w}{v} = 2\pi$$

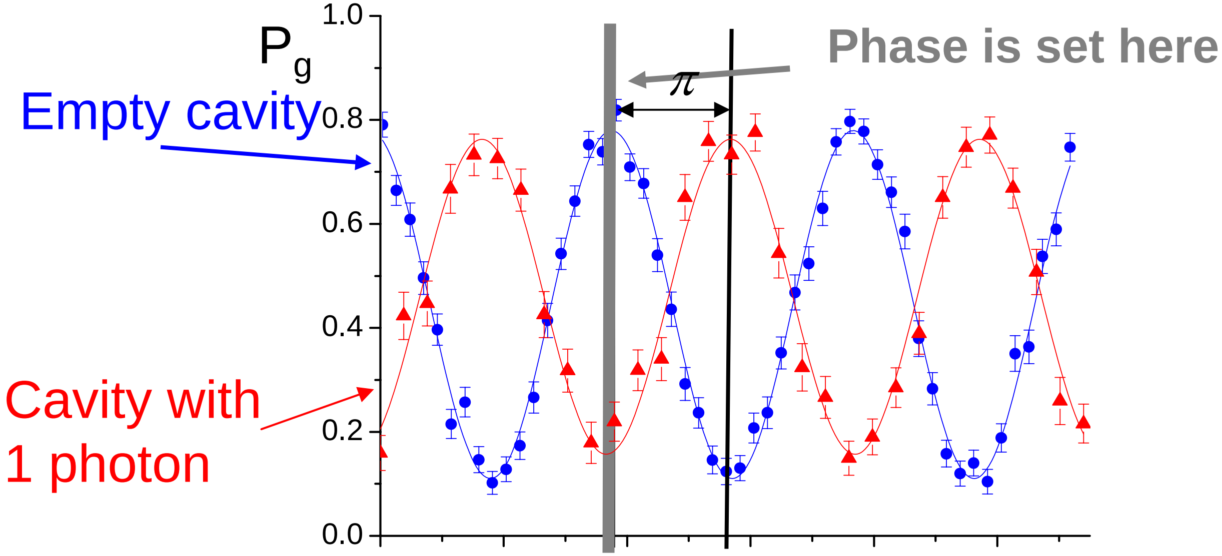
70 kHz *250 m/s*

Ramsey Interferometer





Nogues et al, Nature, 400, 239 (1999)



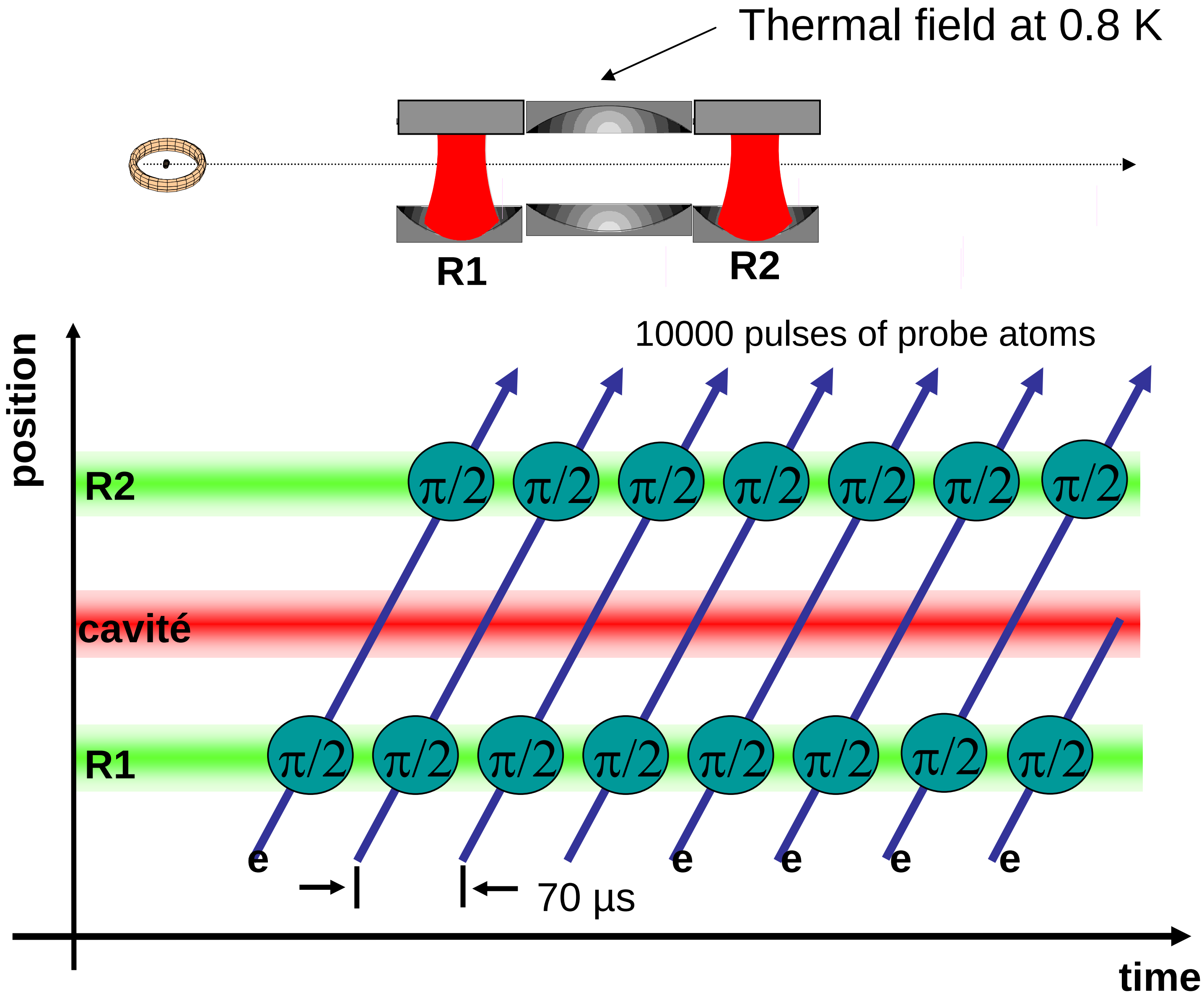
Interferometer phase (Ramsey zone frequency tuning)

$$\Delta\Phi(n) = \frac{\Omega^2 t}{2\delta}\left(n + \frac{1}{2}\right)$$

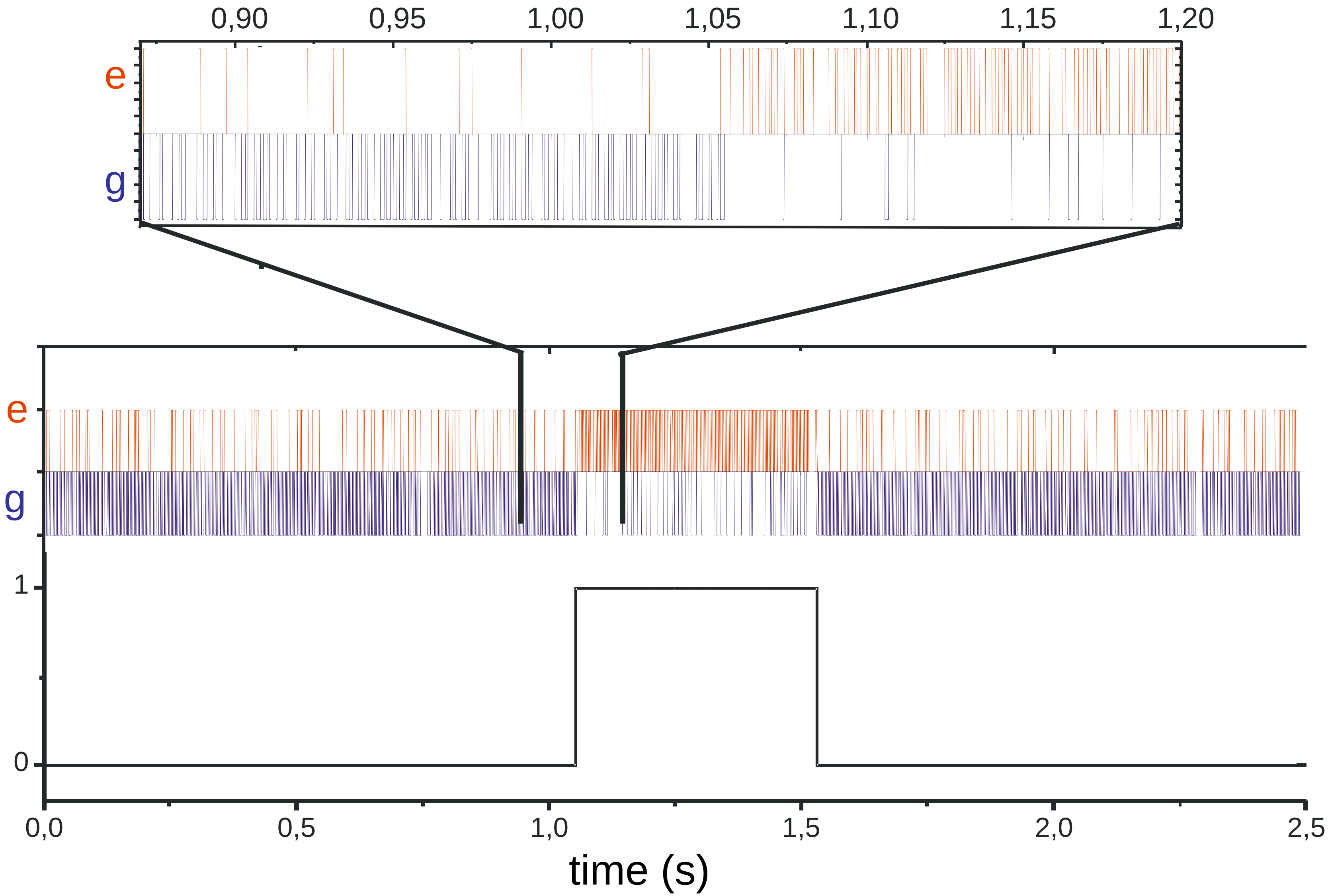
$$\downarrow$$

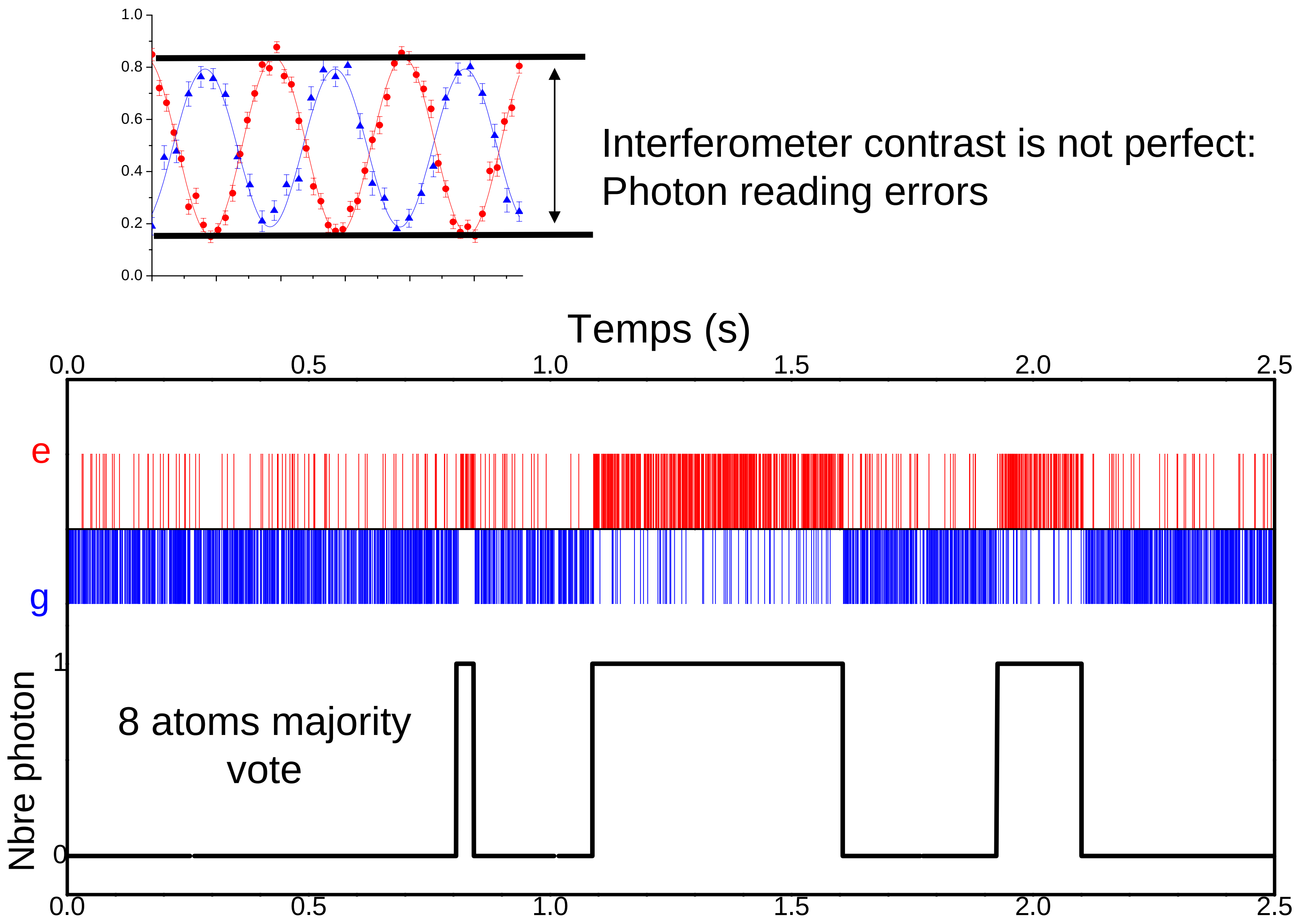
$$\pi$$

Repeated measurement of a thermal field



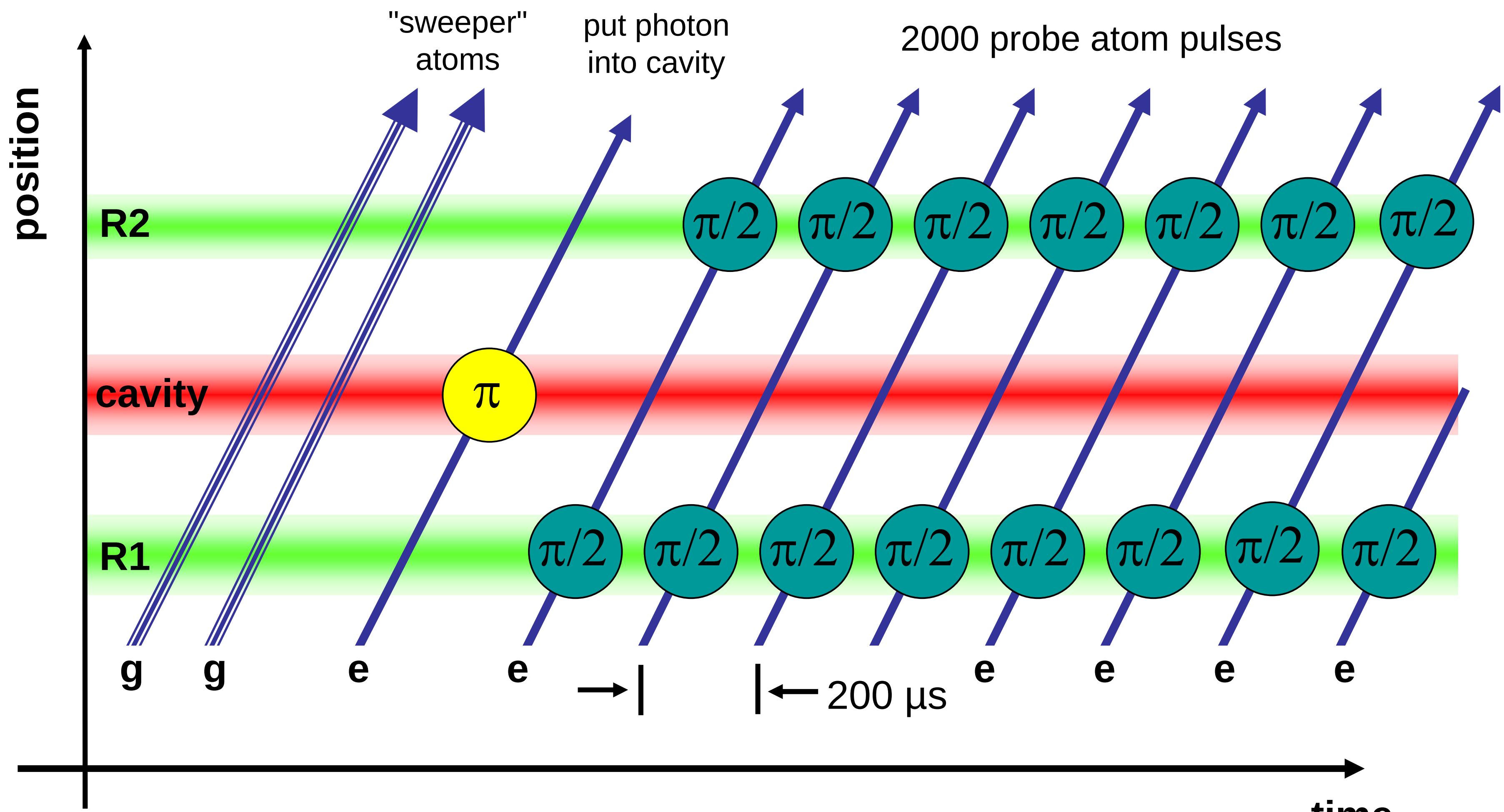
Birth and death of a photon





1.0
0.8
0.6
0.4
0.2
0.0
Interferometer contrast is not perfect:
Photon reading errors
Temps (s)
0.0
0.5
1.0
1.5
2.0
2.5
e
g
Nbre photon
1
0
8 atoms majority vote

Preparing a photon and measuring it in QND way



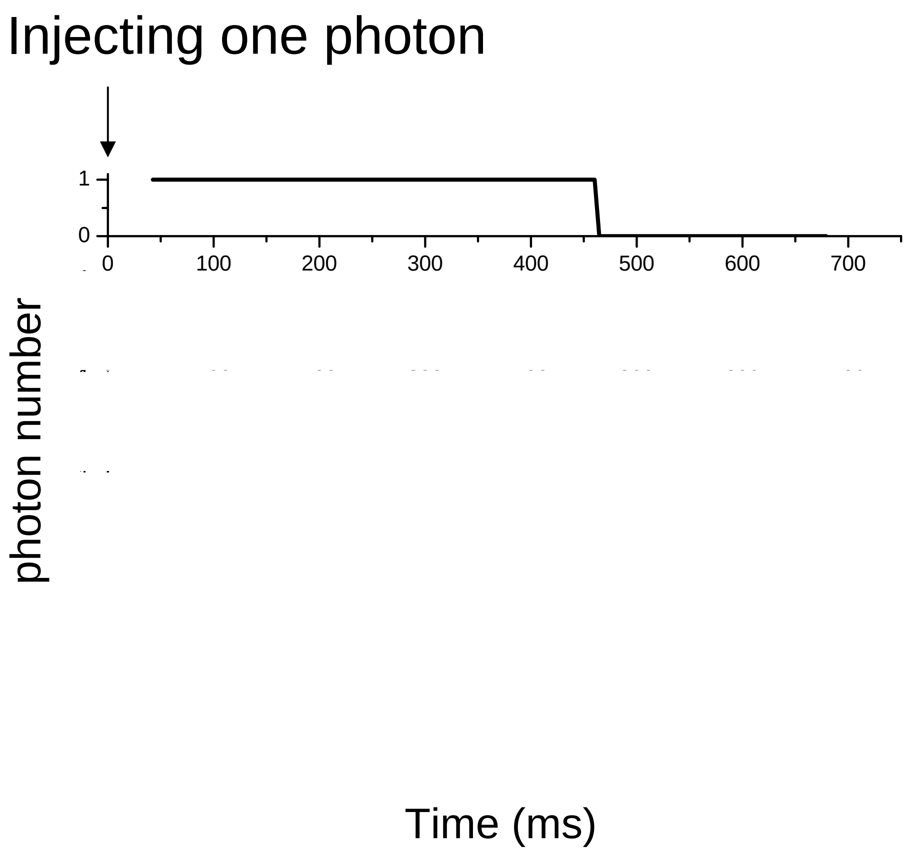
Resonant atoms in g reset field to vacuum

Single resonant atom injects a photon

Long sequence of non-resonant QND probe atoms

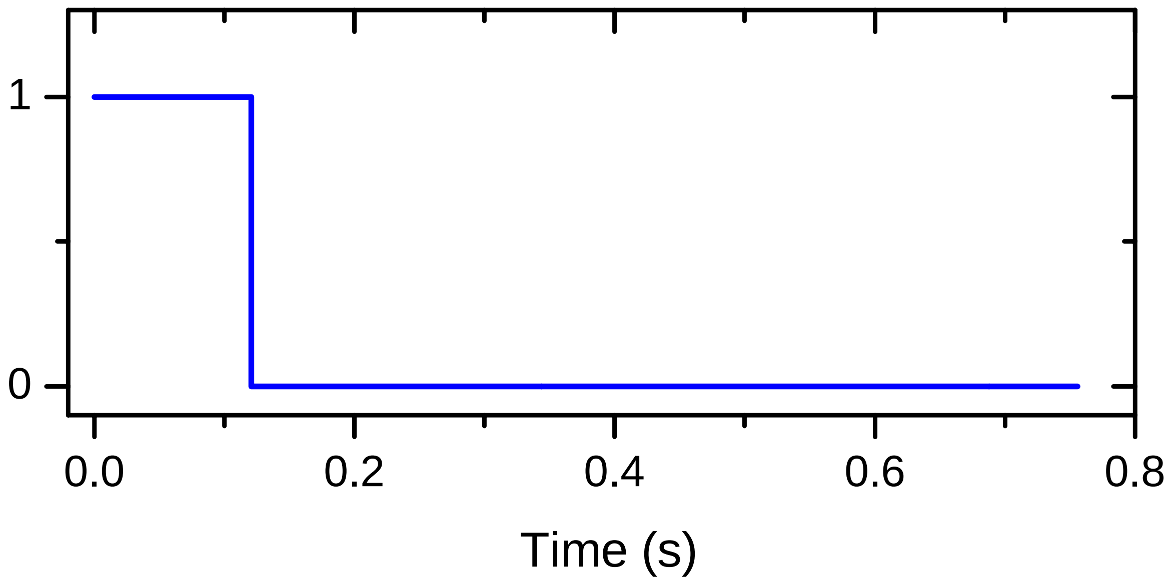
Quantum jump of a single photon

$$T = 0.8\ \mathrm{K} \rightarrow n_{th} = 0.05$$

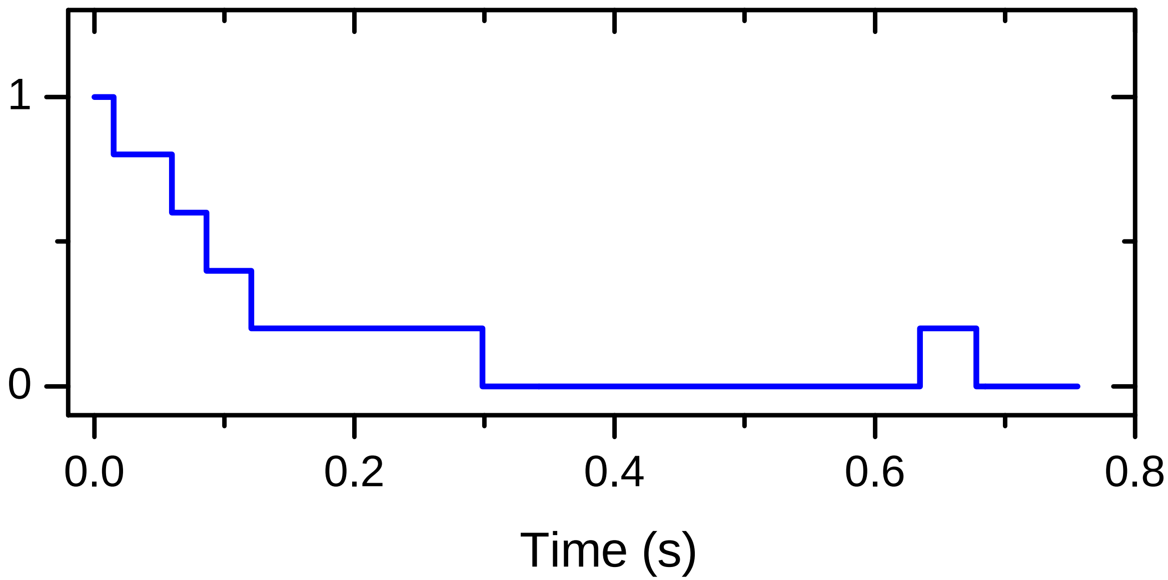


Averaging single photon trajectories

1 trajectory :

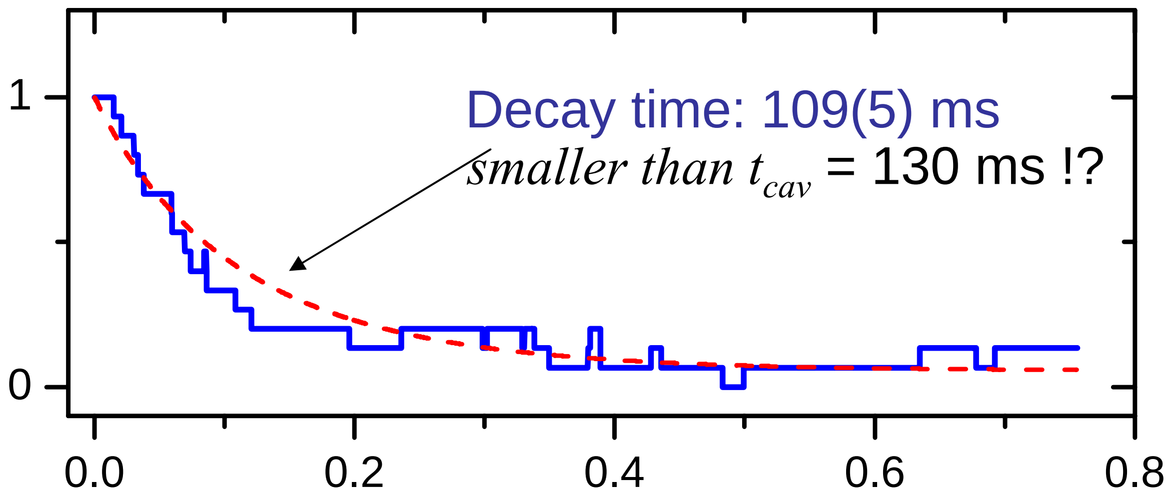


5 trajectories :



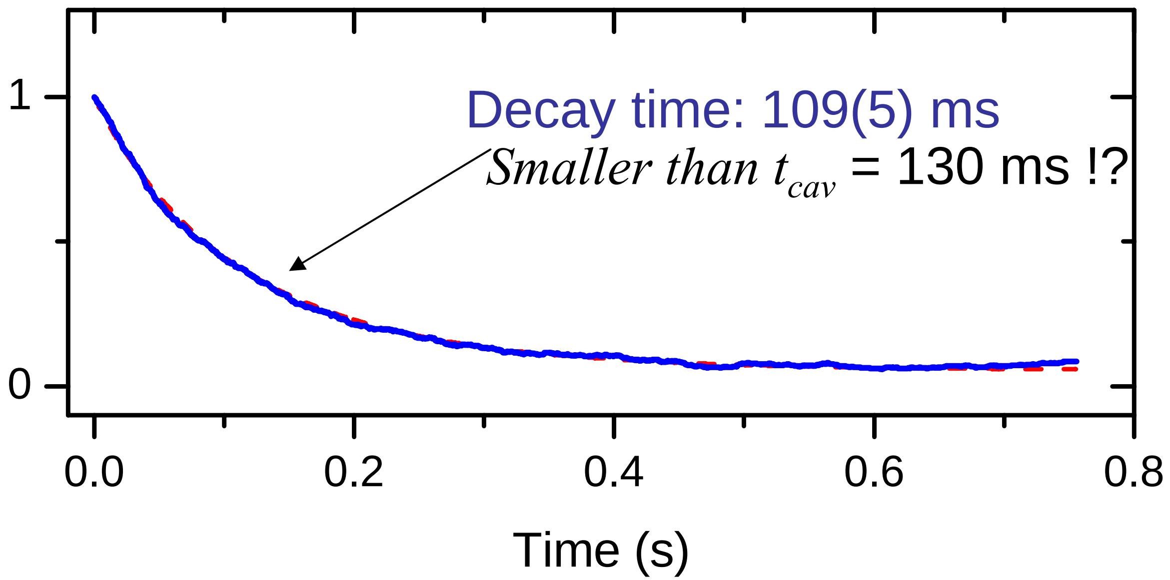
In red: solution of Master equation of field evolution

15 trajectories :



In red: solution of Master equation of field evolution

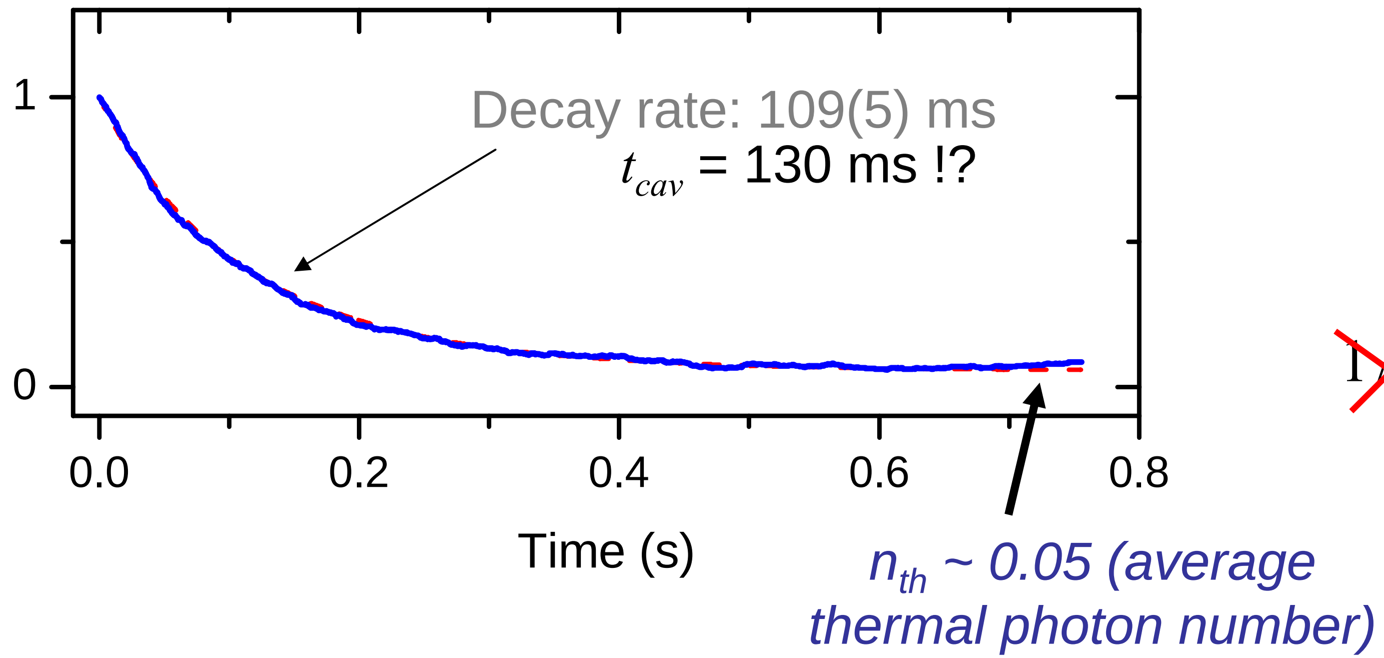
904 trajectories :

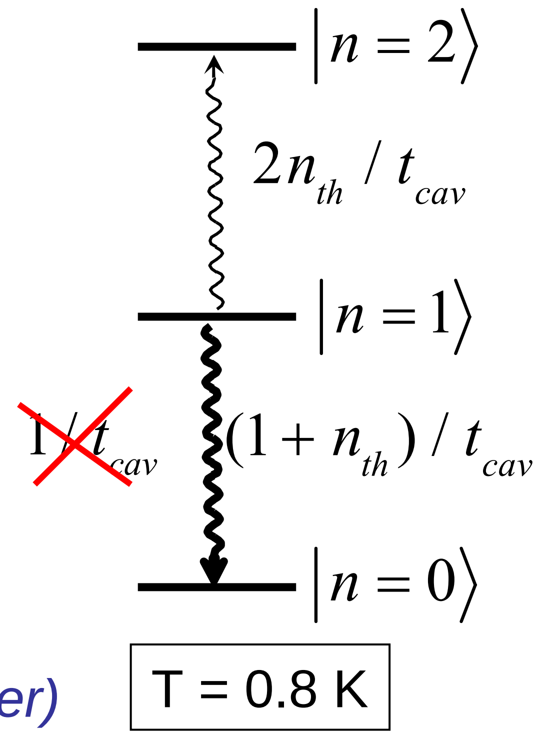


Can we explain the difference?

Life time of |n=1> at finite T

904 trajectories :





Life time of $|n=1\rangle$: $t_{cav}/(1+3n_{th}) = 112 \quad ms$

3.

QND measurement of larger photon numbers

Very recent results (unpublished) were presented at the workshop

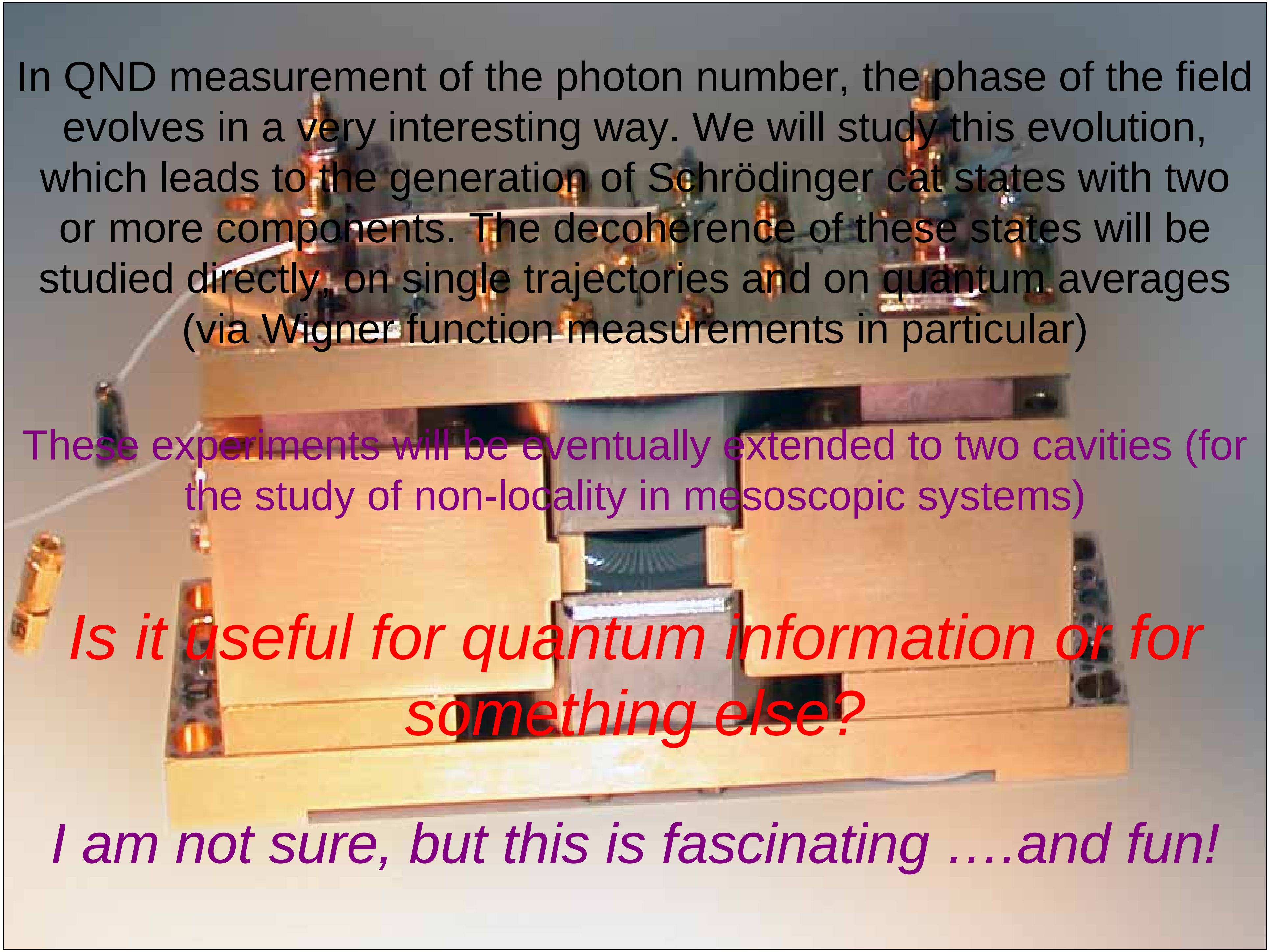
Conclusion and perspectives

The development of super high Q Fabry-Perot microwave cavities opens the way to new classes of experiments:

Single photons can be continuously observed over “macroscopic times” without being destroyed. The field becomes an “object” of investigation as ions or atoms in traps…

This amounts to the repeated action of a CNOT gate in which the photon (or the atom which has deposited it in the cavity) is the control and the successive QND atoms are the targets. Hundreds of gate operations realized in succession. This can produce very large GHZ states.

Several photons can be counted in a QND way, as one counts marbles in a box. The progressive collapse of the wave function in a continuous QND measurement can be observed for the first time. The experiment generates, also for the first time, Fock states of the field with N>2. A huge amount of data is available (among which the life times of individual Fock states)



In QND measurement of the photon number, the phase of the field evolves in a very interesting way. We will study this evolution, which leads to the generation of Schrödinger cat states with two or more components. The decoherence of these states will be studied directly, on single trajectories and on quantum averages (via Wigner function measurements in particular)

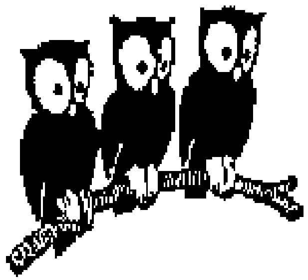
These experiments will be eventually extended to two cavities (for the study of non-locality in mesoscopic systems)

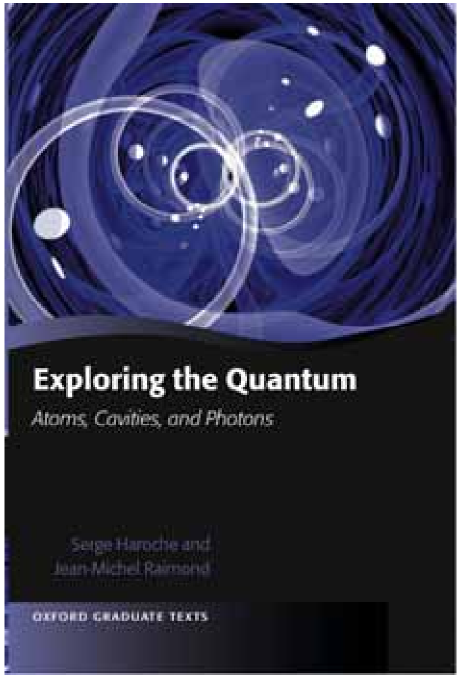
Is it useful for quantum information or for something else?

I am not sure, but this is fascinating ….and fun!

ENS-Collège de France

S. H.
Jean-Michel Raimond
Michel Brune





CQED Experiments

Stefan Kuhr
Gleyzes C.Guerlin
Bernu
Busk S.Deléglise

Superconducting atom chips

Gilles Nogues
Angie Qarry
A.Lupascu
H. T.Nirrengarten
A.Emmert C.Roux

Exploring the Quantum
Atoms, cavities and Photons

S.Haroche and J-M.Raimond
OUP (September 2006)

JST (ICORP, Japan), EC, CNRS, UMPC, IUF, CdF