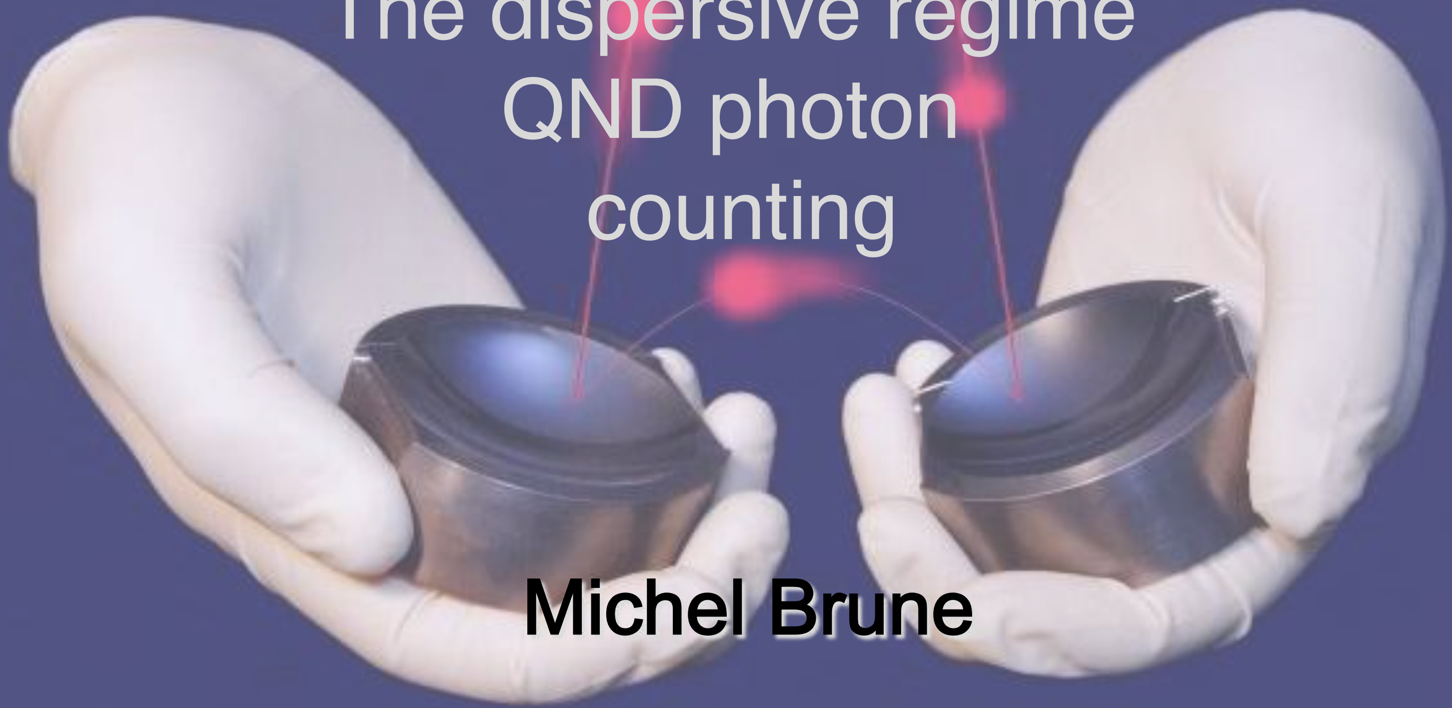
From cavity QED to quantum simulations with Rydberg atoms

Lecture 2

The dispersive regime QND photon counting



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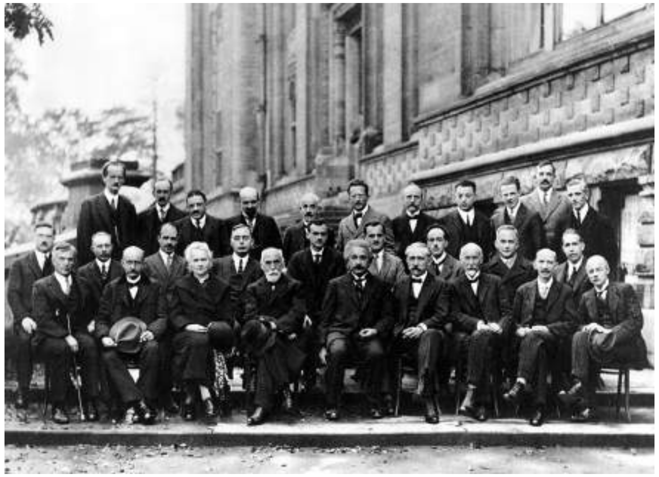
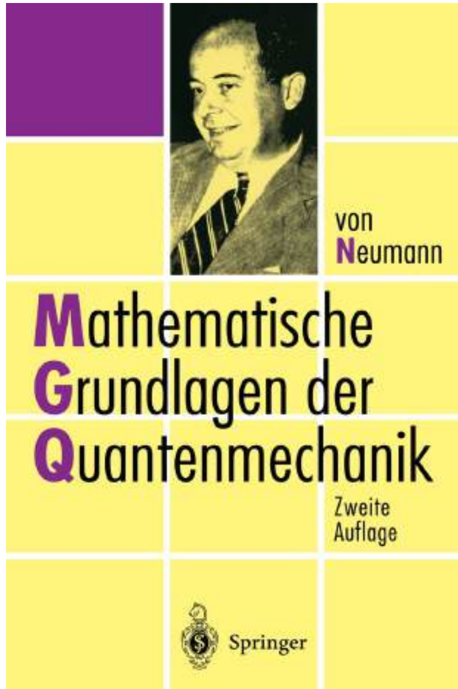
Collège de France, Paris

Quantum Physics and measurement

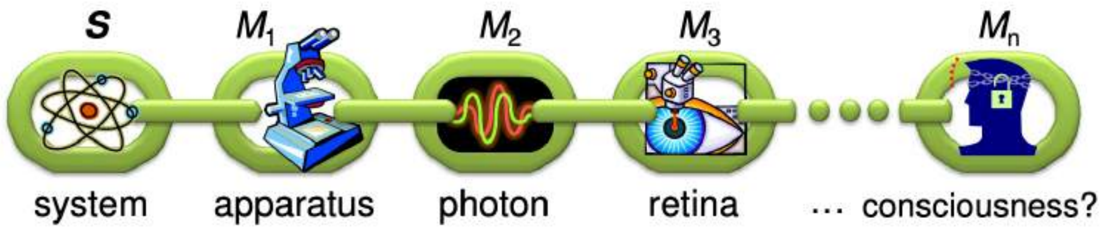
1927 Solvay conference



1935: First synthetic textbook on mathematical formalism and interpretation of QM



Von Neumann's measurement chain



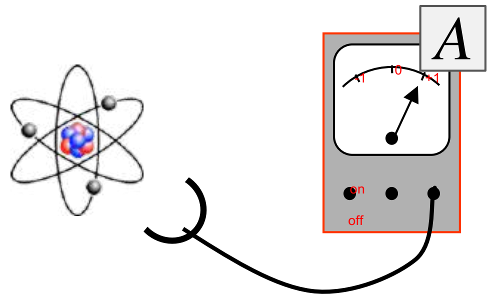
Credit: Piani et al. PRA 2012

This lecture: exploring the QM problem with the point of view of CQED experiments performed in Paris

1. Basic reminder on ideal quantum measurement

The weird theory of measurement

- The measurement postulates
  - fundamental randomness of results
  - Hermitian operators
  - Projection postulate



$$\stackrel{?}{=} \hat{A}$$

→ very efficient but very abstract and formal: does not tell much about how to build a real measurement apparatus

→ kind of shocking consequences:

discontinuous "projection" → **quantum jumps**

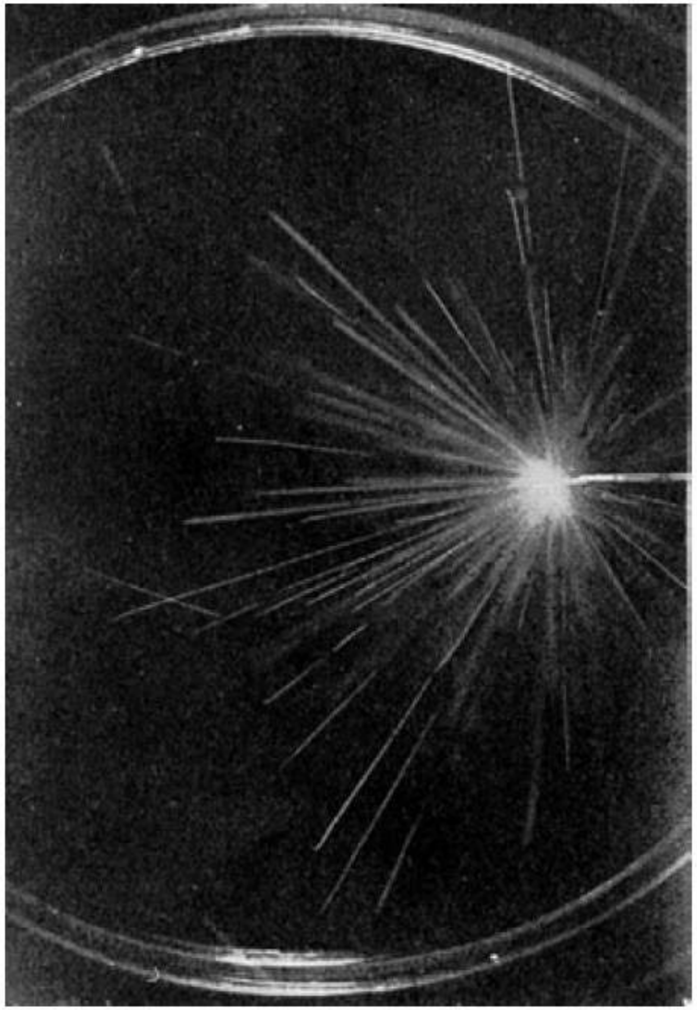
- seems not to match with the the continuous unitary evolution corresponding to Schrödinger equation?
- a natural question:

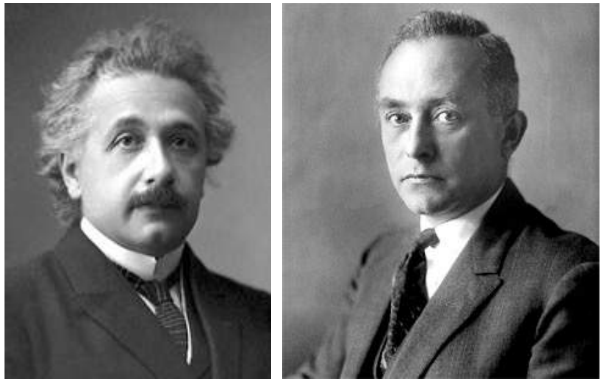
  when does the "real projection" occurs?

→the famous **"Schrödinger cat" problem**

The projection postulate: the origin

Alpha particle trajectories in a bubble chamber





- Born (Solvay 1927):

" Mr. Einstein has considered the following problem: A radioactive sample emits α-particles in all directions; these are made visible by the method of the Wilson cloud chamber. Now, if one associates a spherical wave with each emission process, how can one understand that the track of each α-particle appears as a (very nearly) straight line? "

➞ Born's solution:

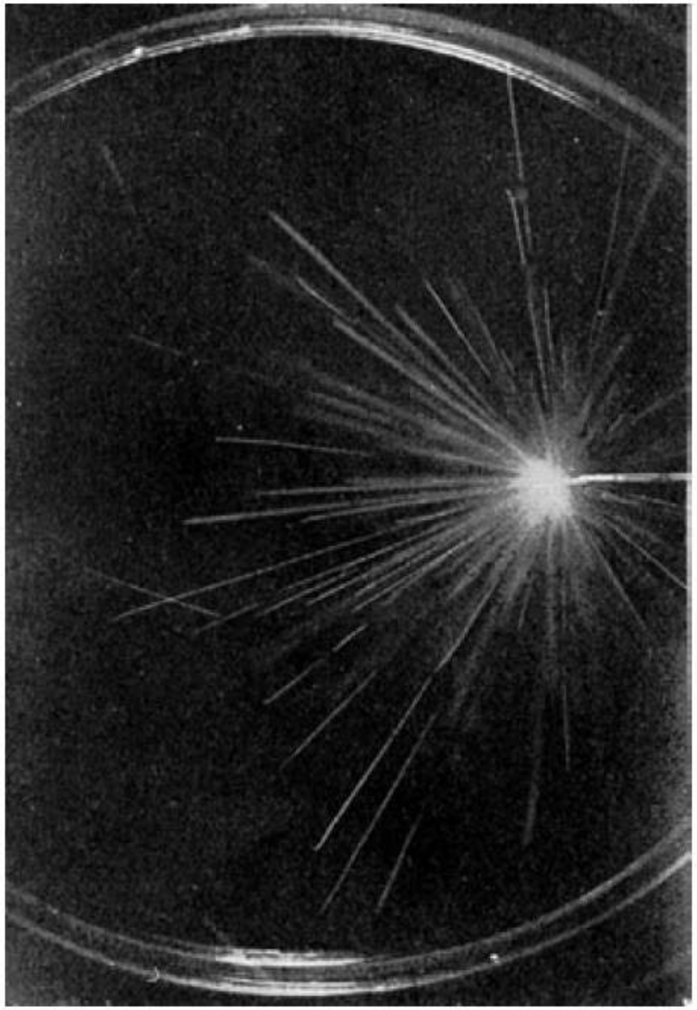
" As soon as such ionization is shown by the appearance of cloud droplets, in order to describe what happens **afterwards** one must **reduce the wave packet** in the immediate vicinity of the drops. One thus obtains a wave packet in the form of a ray, which corresponds to the corpuscular character of the phenomenon"

Radium source   Wilson 1911

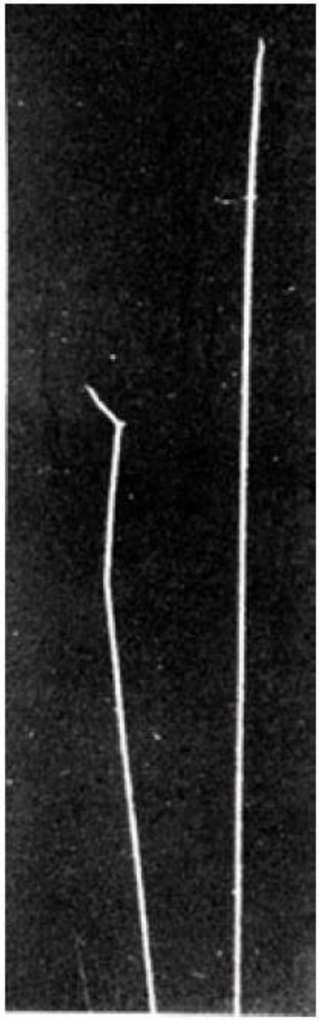
R. Figari arXiv:1209.2665 (2012)

The projection postulate: the origin

Alpha particle trajectories in a bubble chamber

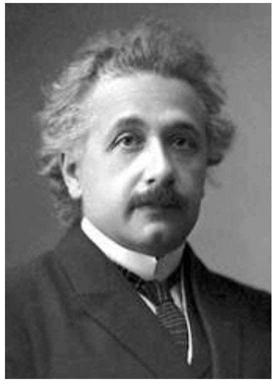


Radium source



Wilson 1911

N.F. Mott



A. Einstein

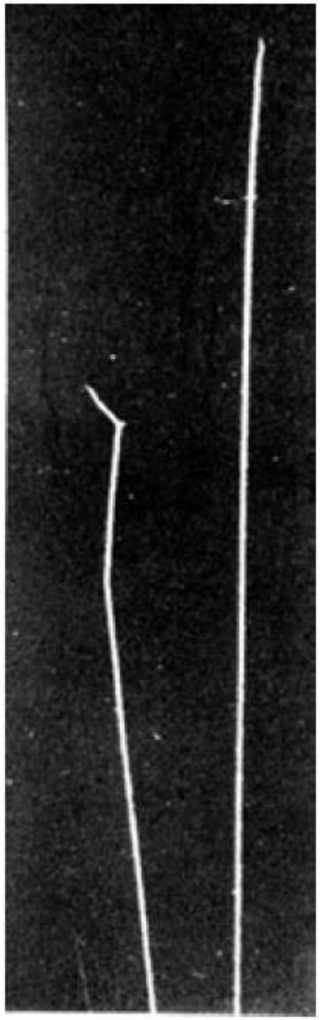
M. Born

➞ Mott (1929) pushed the analysis further and showed that a particle submitted to repeated observations (by the environment) follows the classical trajectories

➞ can be seen as the first recognition of the role of environment induced "decoherence" in the emergence of classical trajectories

Mott N.F., "The wave mechanics of α-ray tracks" Proc. R. Soc. Lond. A,126, 79-84, 1929. Reprinted in: WheelerJ.A., Zurek W.

Consequence of postulates: Quantum jumps



Extension to the repeated observation of a **discrete observable**

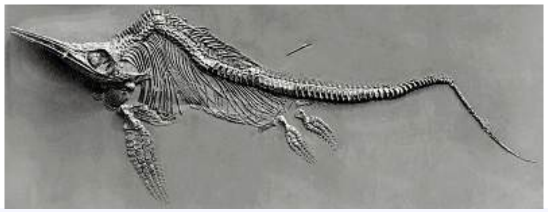
→ Evolution should result in **quantum jumps**

Schrödinger 1952

"Are there quantum jumps?"

"In the first place it is fair to state that we are not experimenting with single particles, any more than we can raise Ichthyosauria in the zoo. We are scrutinising records of events long after they have happened".

In the spirit of Schrödinger, single particle detection is **"post-mortem" analysis**: the system under observation is destroyed well before one sees the record



→ **real time observation of jumps is impossible**

"Are there quantum jumps?", Schrödinger 1952 ,The British journal for the philosophy of science

« Ridiculous » quantum phenomena

The Schrödinger cat: just another animal in the zoo of impossible events

« one never experiments with just one electron, one atom or one molecule. In thought experiments we sometimes assume that we do, this invariably entails **ridiculous consequences**… »

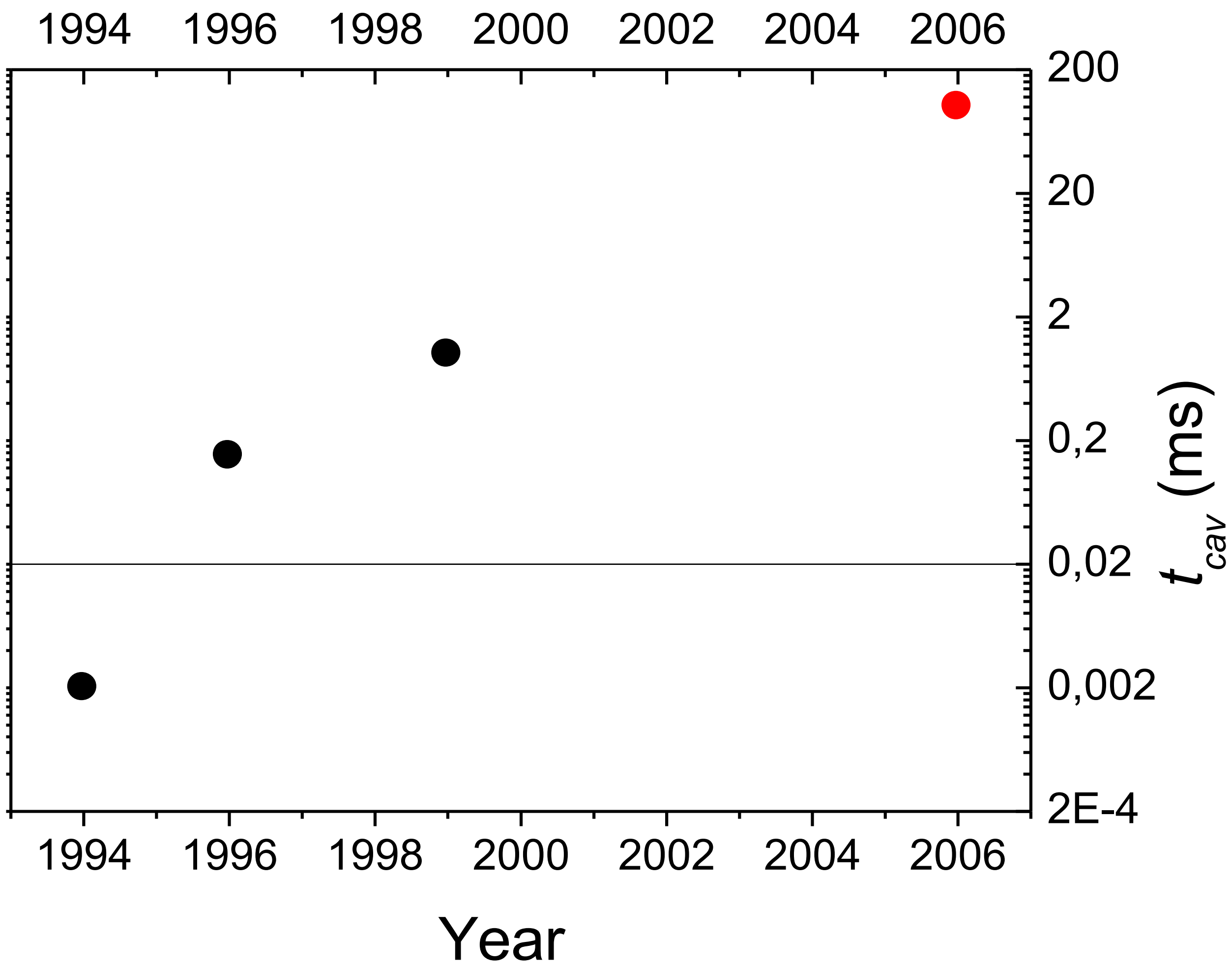
(British Journal of the Philosophy of Sciences, vol 3, 1952)

2. Non-destructive single photon counting

The quantum theory of measurement
at work in a real experiment

The photon box for QND photon counting

- Our version of Moore's law:



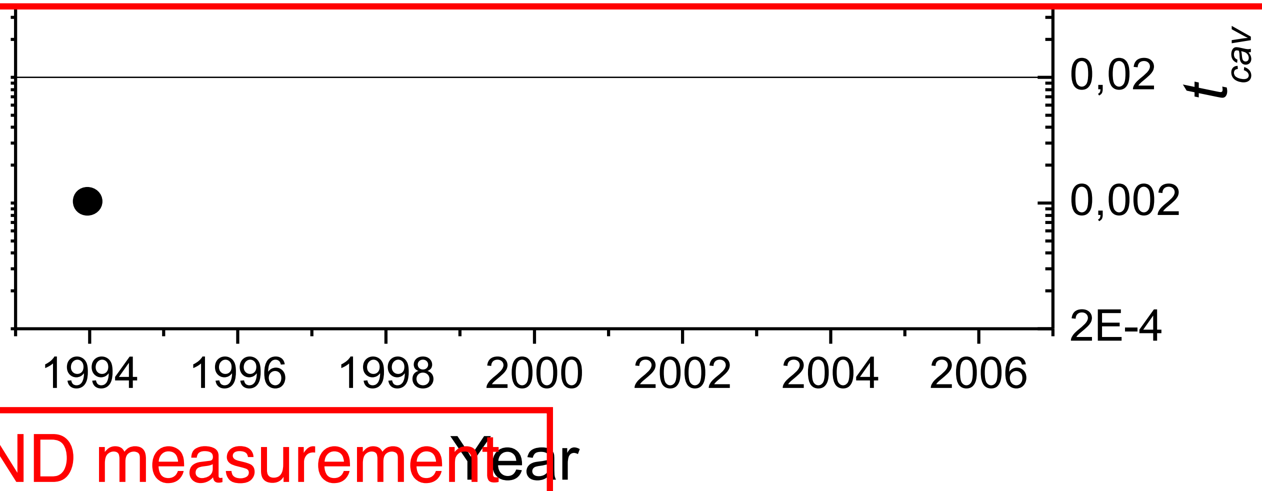
QND photon counting:
The beginning of the story …

VOLUME 65, NUMBER 8 PHYSICAL REVIEW LETTERS 20 AUGUST 1990

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.

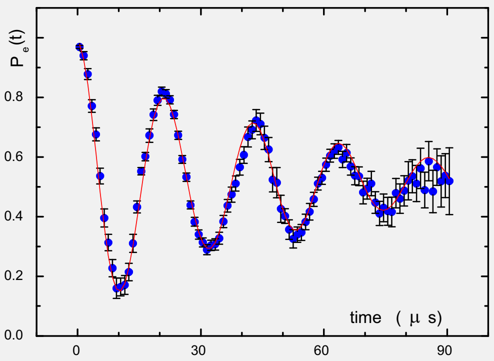


1990

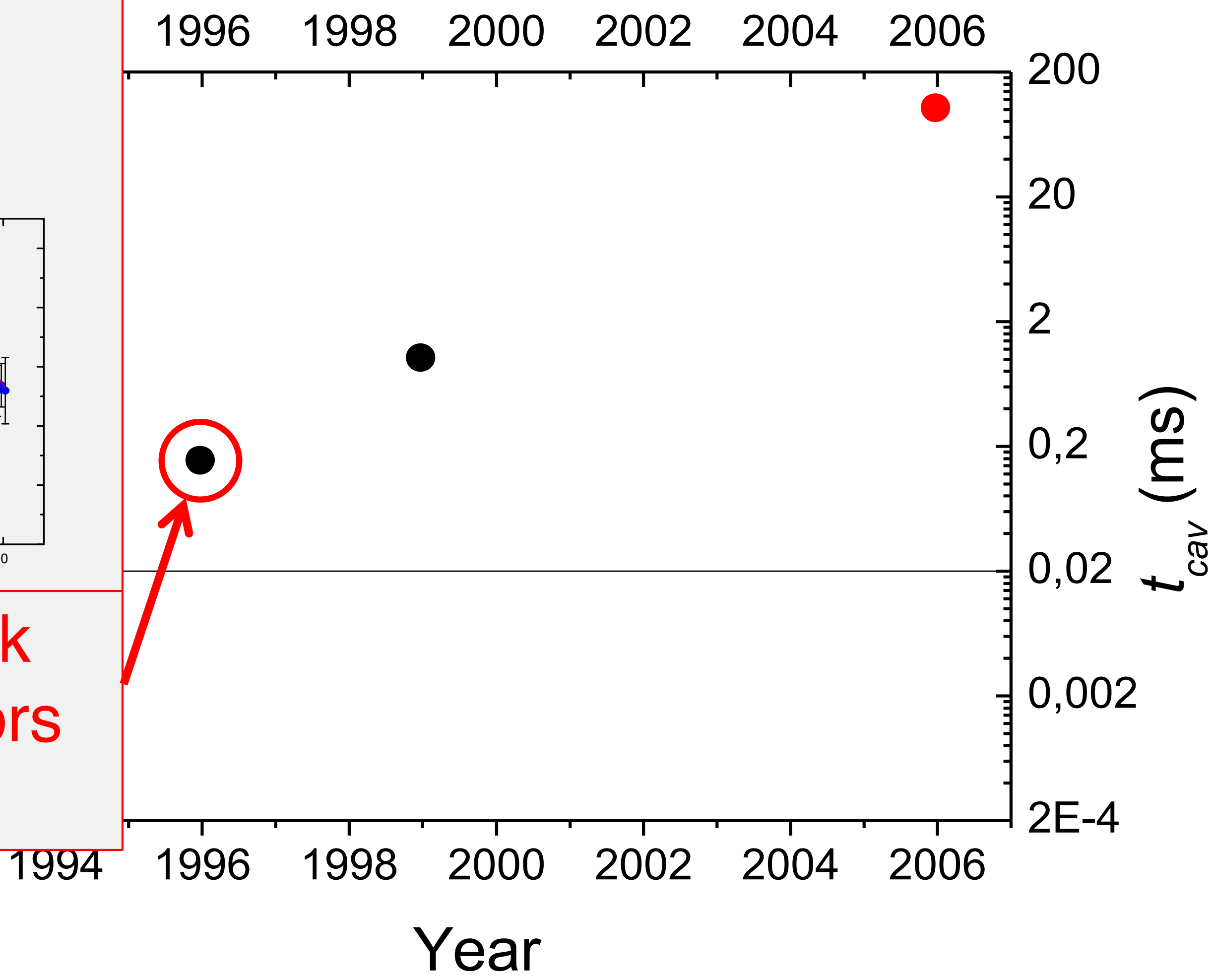
Initial QND measurement proposal

The vacuum Rabi oscillation

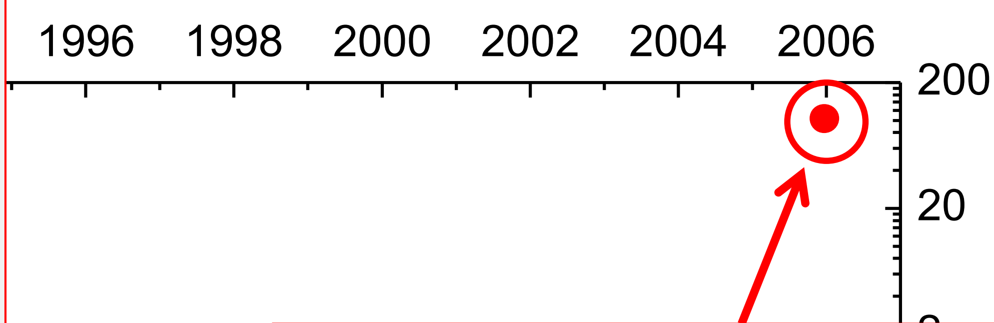
1996
Resonant Rabi oscillations



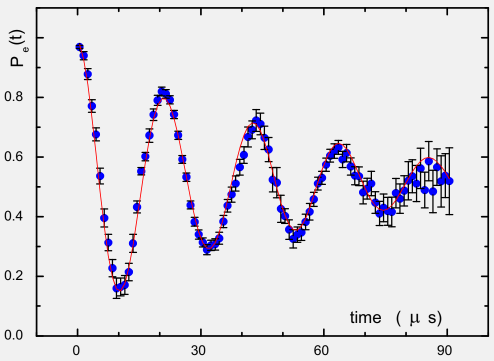
Polished bulk niobium mirrors
Q=2.10[8]



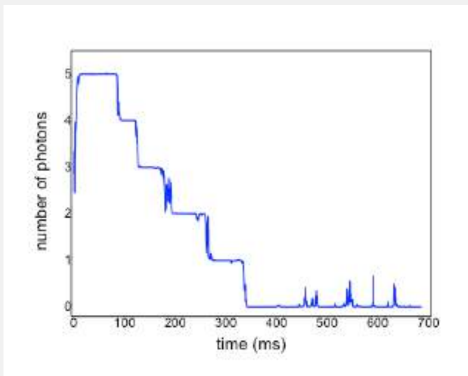
New cavity technology



1996
Resonant Rabi oscillations

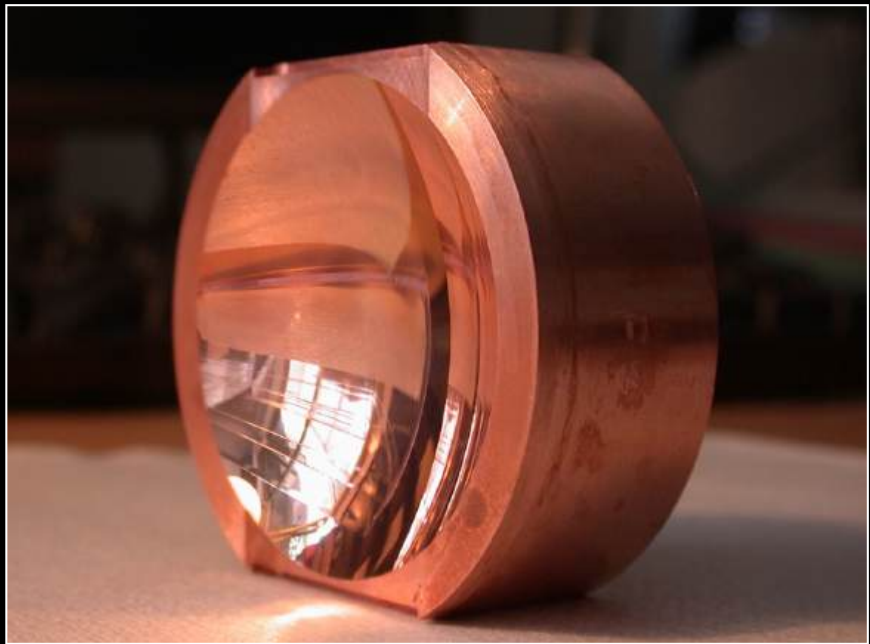


Polished bulk niobium mirrors
$Q=2.10^8$



Sputtered niobium mirrors
$Q=5.\ 10^{10}$

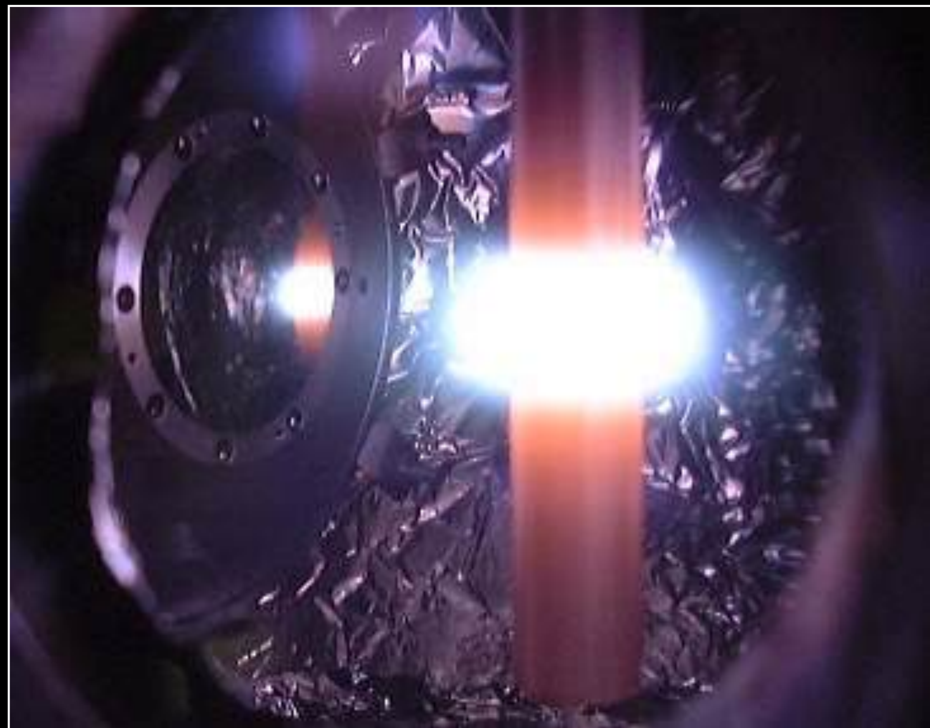
Niobium coated copper mirrors



- Copper mirrors
  - Diamond machined
    - ~1 µm ptv form accuracy
    - ~10 nm roughness
  - Toroidal è single mode

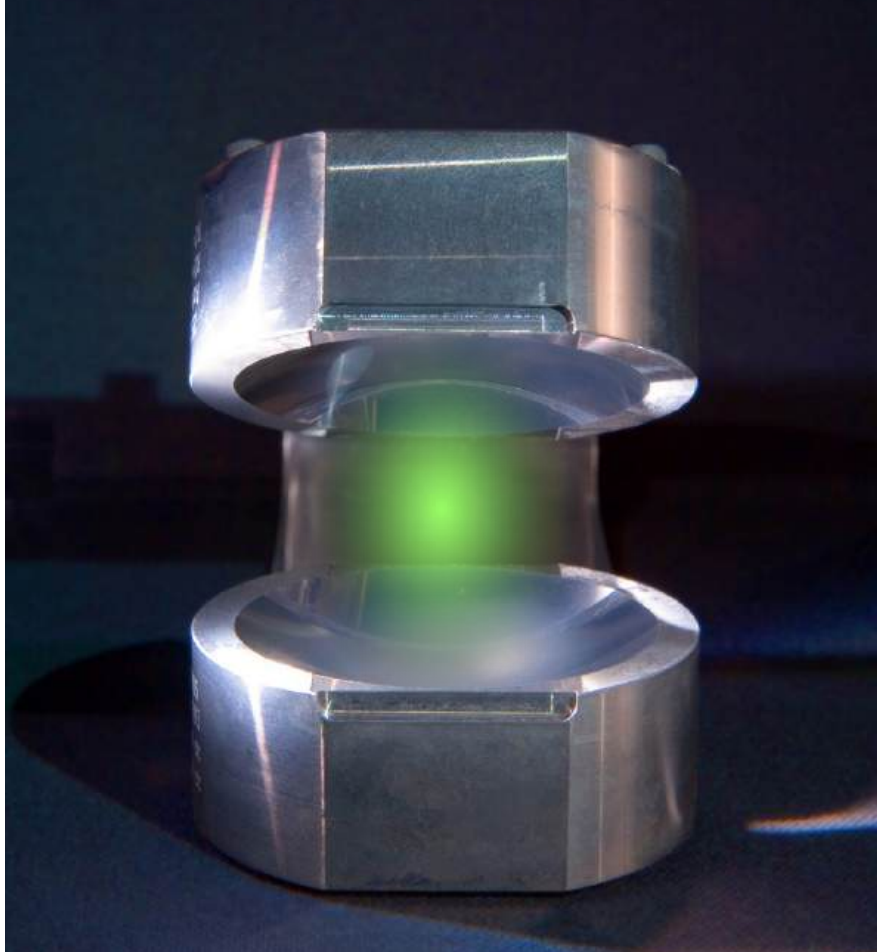
- Sputter 12 µm of Nb
  - Particles accelerator technique
  - Process done at CEA, Saclay

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



The best photon box

Superconducting cavity resonance: $\nu_{cav} = 51$ GHz

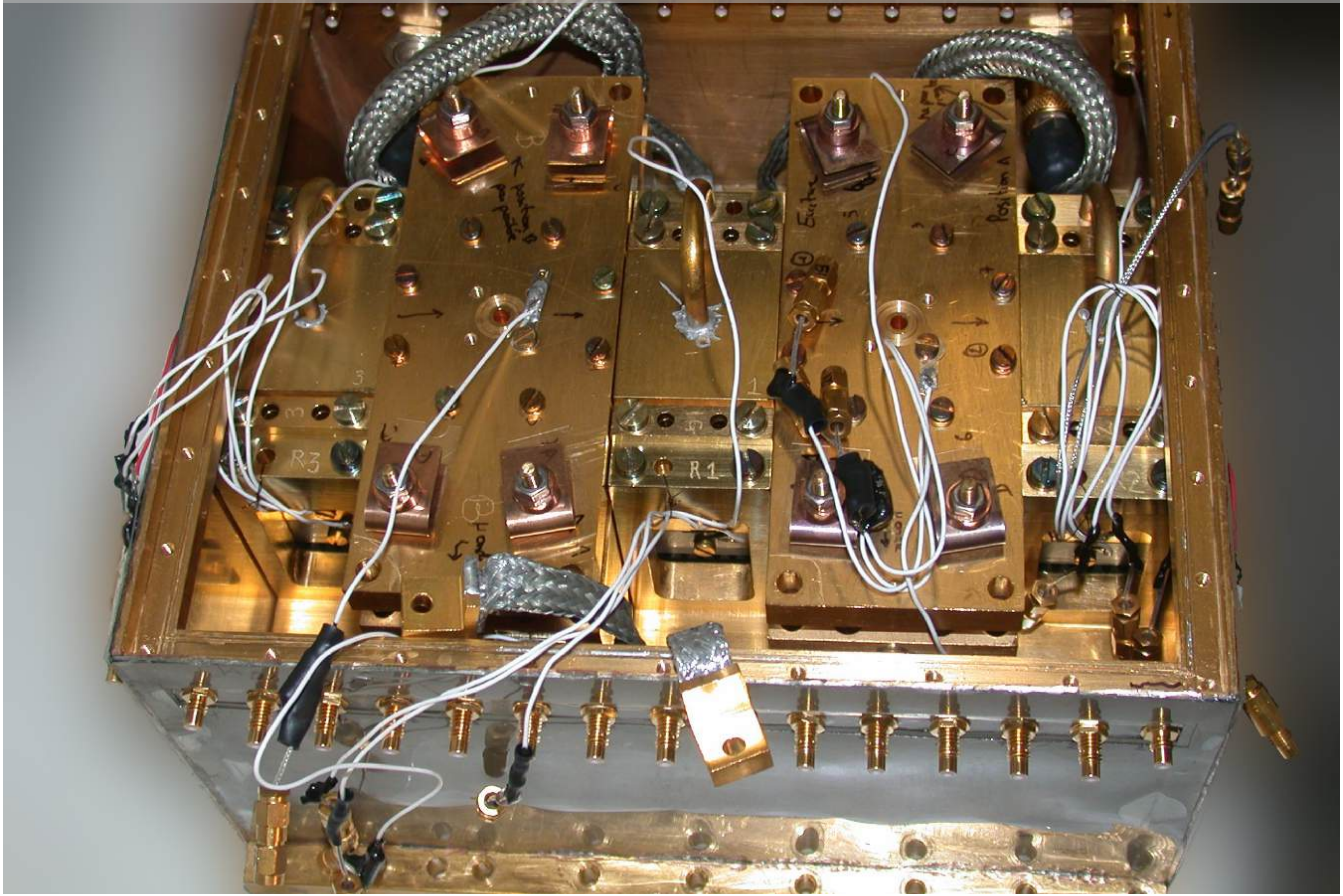


$T_{cav} = 130$ ms

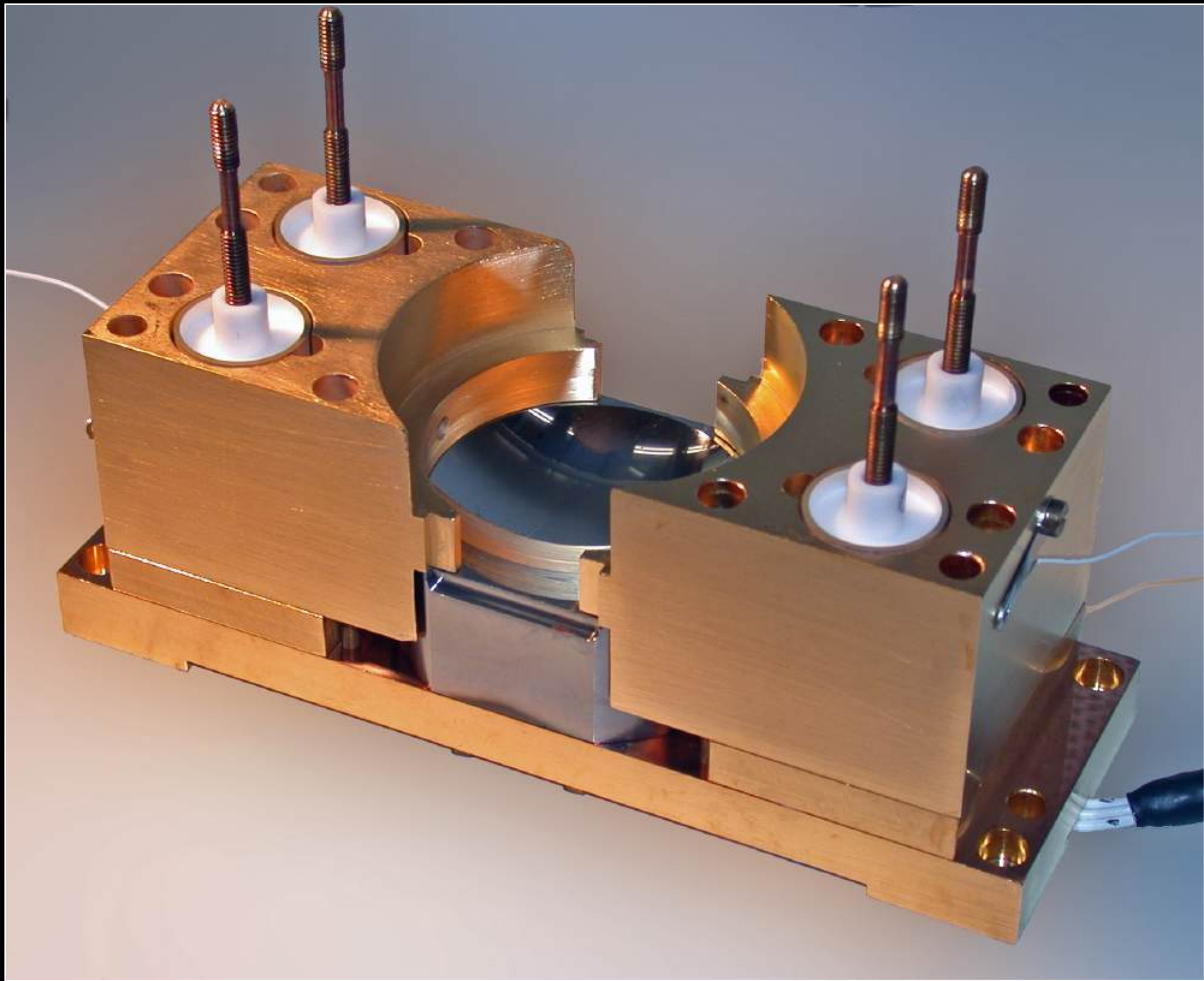
- Q factor $= 4.2 \cdot 10^{10}$
- finesse $= 4.\ 10^{9}$

Photons running for 39 000 km in the box before dying!

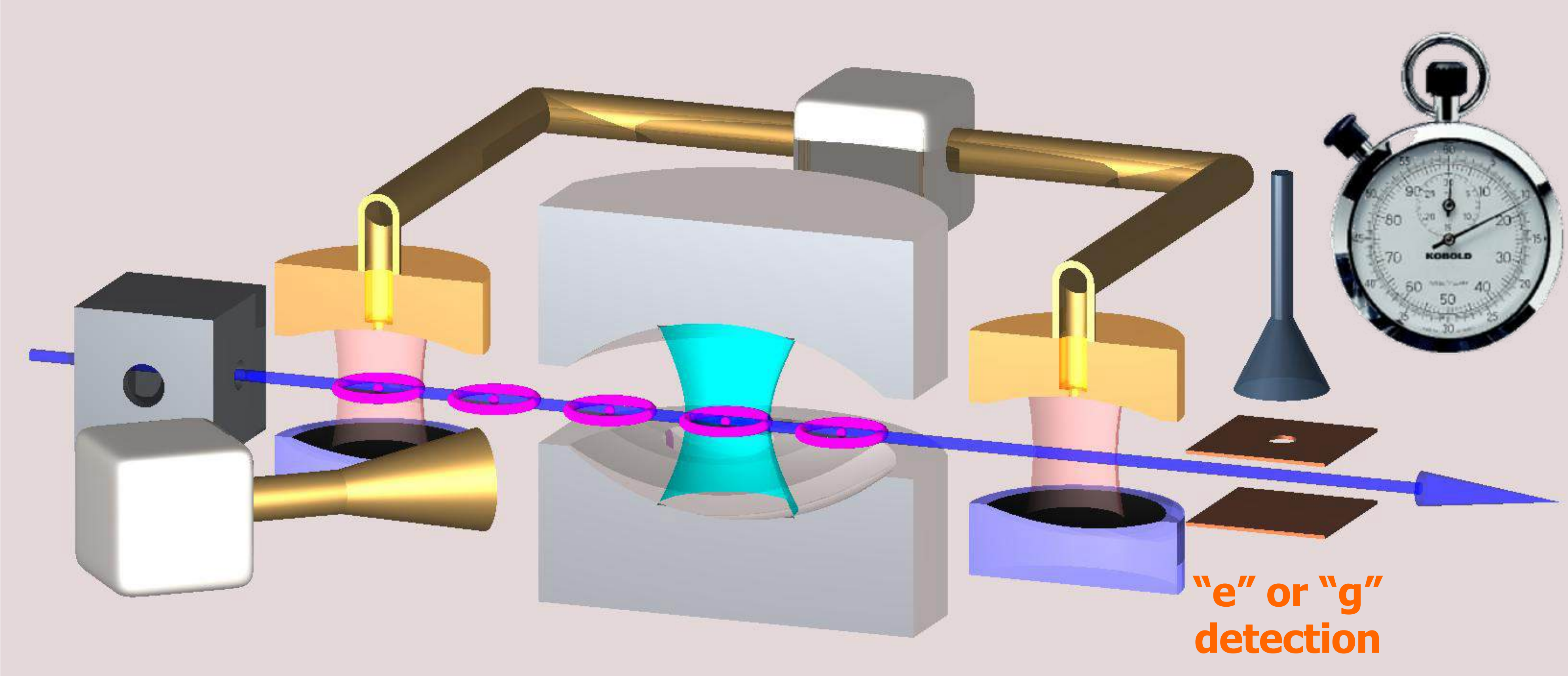
The real photon box setup



A new cavity setup



Experimental setup: an atomic clock

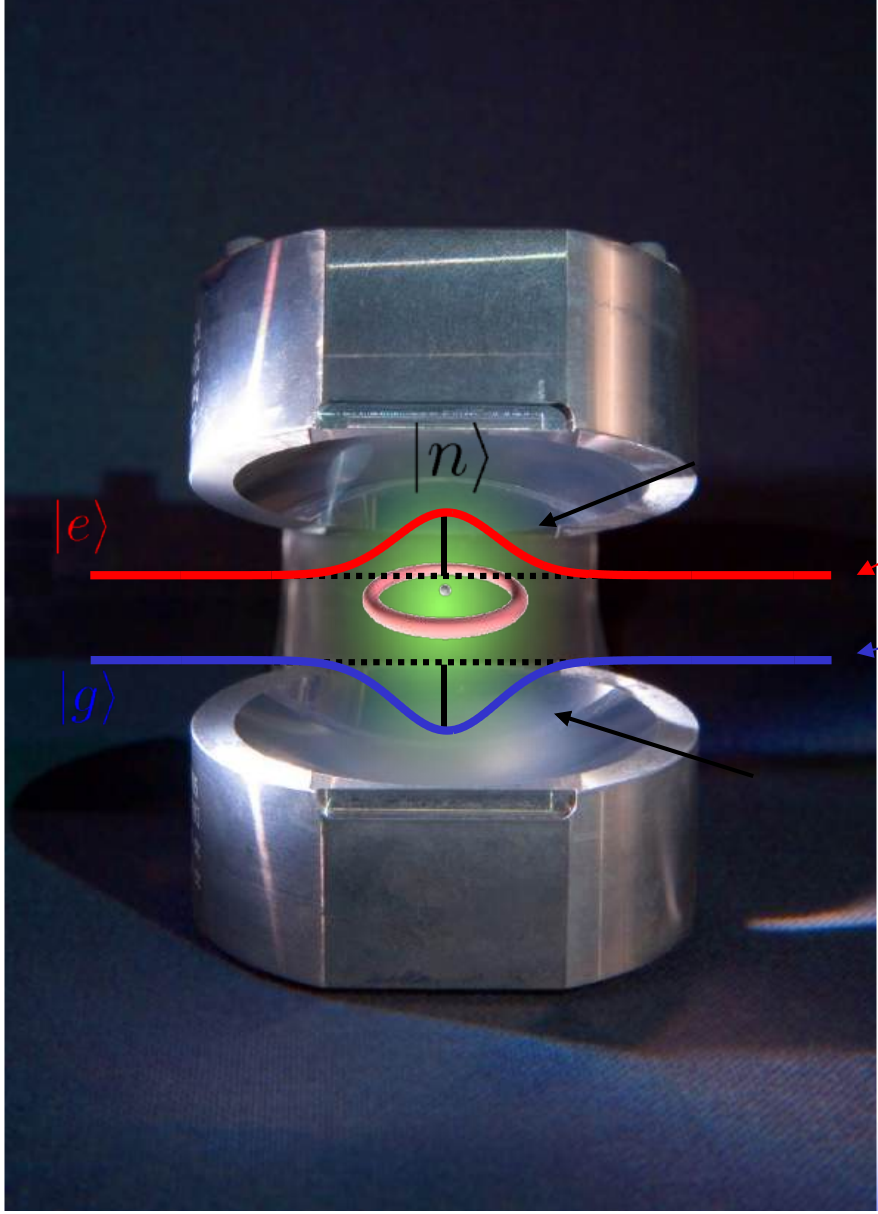


- An atomic clock (Ramsey setup) made of Rydberg for probing light-shifts induced by "trapped" photons

- State selective detection of atoms by field ionization: Atoms detected on "e" or "g" one by one

QND detection of photons: the principle

- Photon box



- Photon probes

Circular Rydberg atoms

- Non-resonant interaction

$\Rightarrow$ light shifts

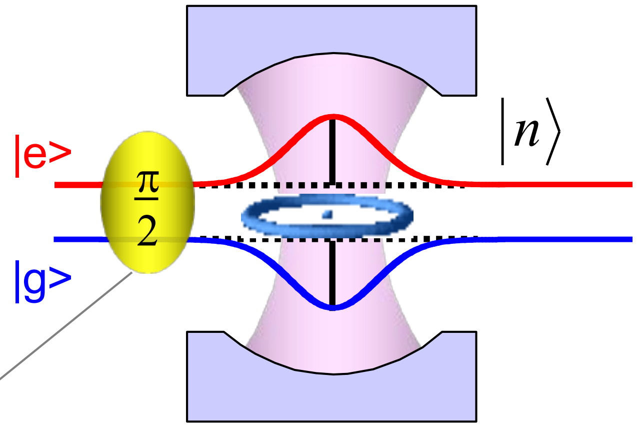
$$\Delta E_e = \hbar \frac{\Omega_0^2}{4\delta}(n+1)$$

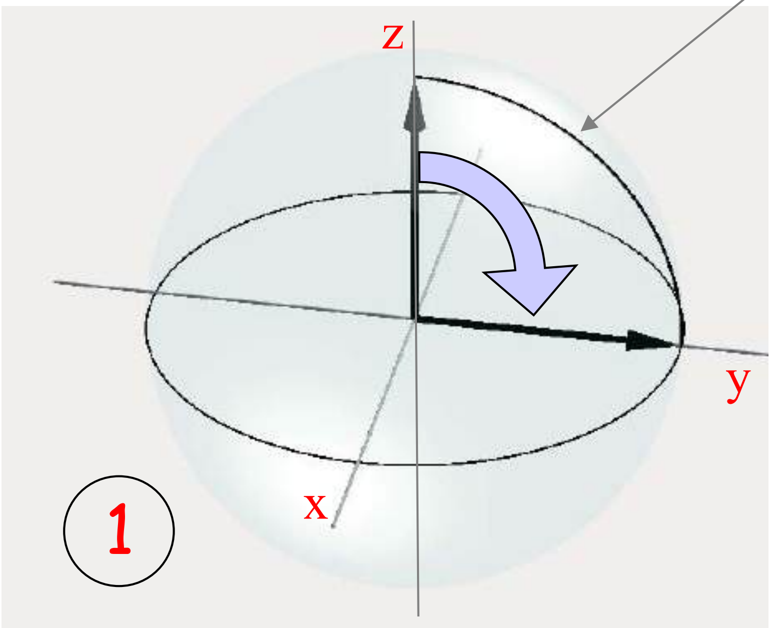
$$\Delta E_g = -\hbar \frac{\Omega_0^2}{4\delta} n$$

Atoms used as clock
for counting n by
measuring light shifts

QND detection of 0 or 1 photon

1. Trigger of the clock.





$$|e\rangle \rightarrow \frac{1}{\sqrt{2}}\left(|e\rangle + i|g\rangle\right) = |+_x\rangle$$

In term of a spin ½, this is a $\pi/2$ rotation around the Ox axis

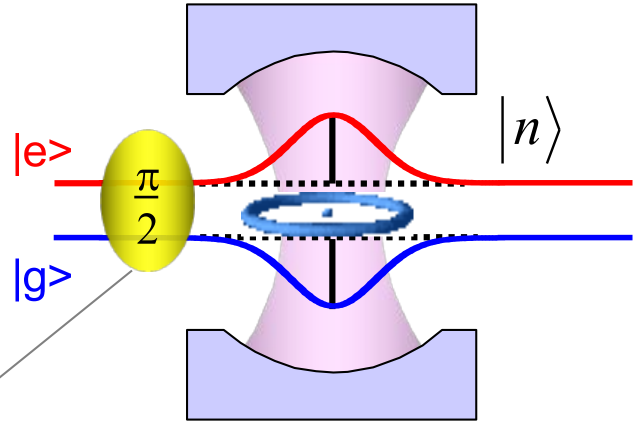
QND detection of 0 or 1 photon

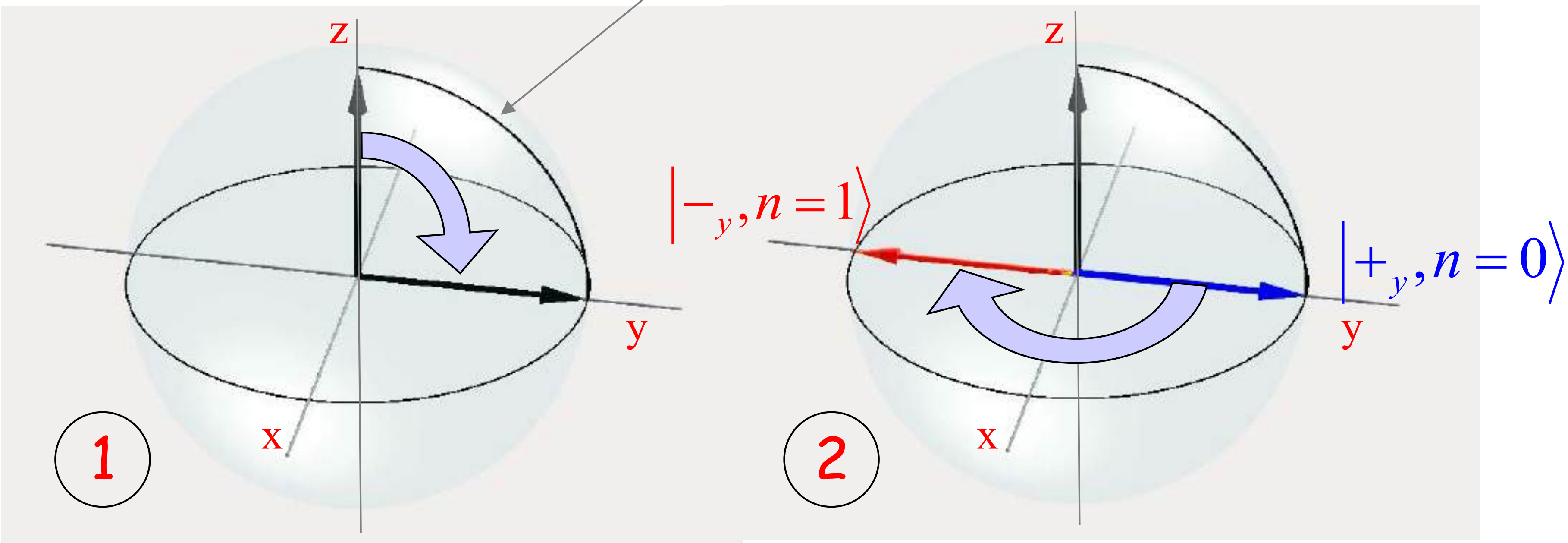
1. Trigger of the clock.

2. precession of the spin through the cavity during T

Phase shift per photon

$$\Phi_0 = \pi$$





$$\rightarrow \frac{1}{\sqrt{2}}\left(|e\rangle + ie^{i\delta_{\text{mw}}T}|g\rangle\right) = |+_\phi\rangle$$

$$\delta_{\text{mw}} = \omega_{\text{mw}} - \omega_{\text{at}}$$

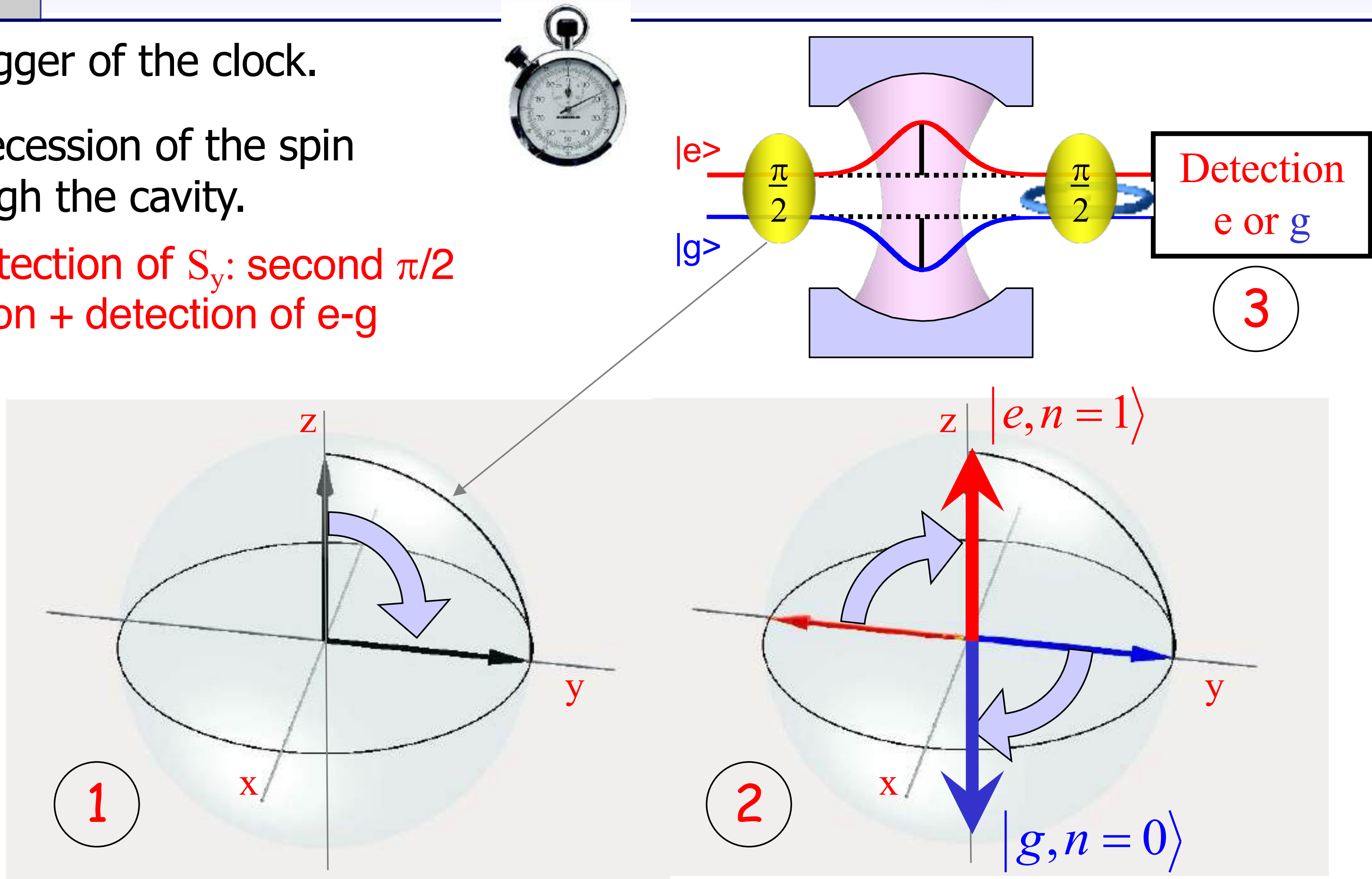
rotation by angle $\phi = \delta_{\text{mw}} T$ around the Oz axis

QND detection of 0 or 1 photon

1. Trigger of the clock.

2. precession of the spin through the cavity.

3. Detection of S_y: second $\pi/2$ rotation + detection of e-g



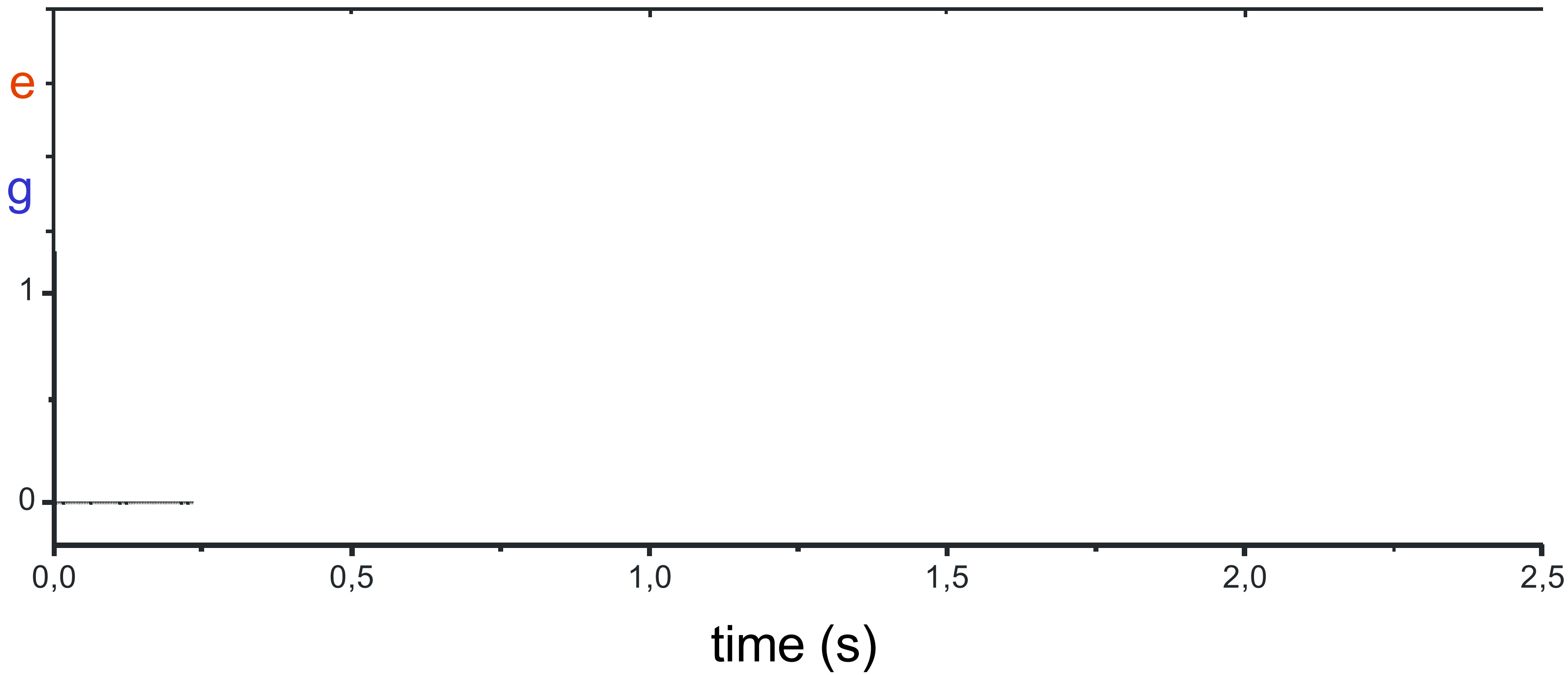
Atom detected in e ➡ field projected on |1>

g ➡ field projected on |0>

Detecting blackbody photons

g ➡ field projected on |0>

e ➡ field projected on |1>



$T = 0.8\ \mathrm{K} \rightarrow n_{th} = 0.05$ (proba. of n=2 is negligible)

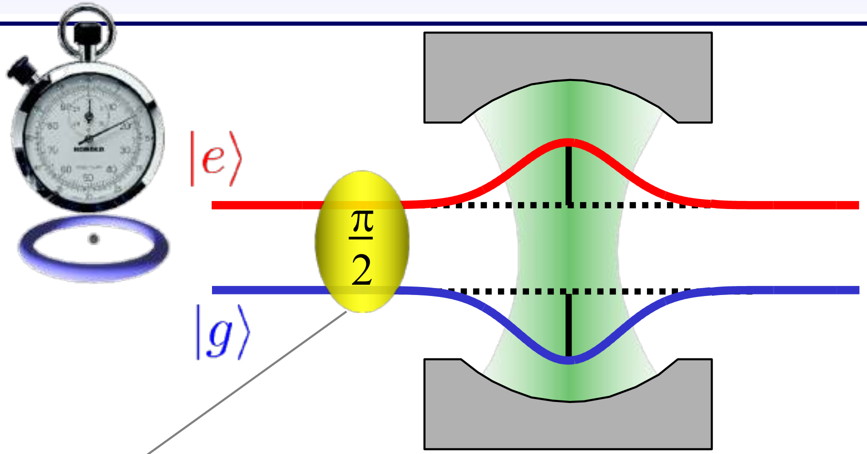
*S. Gleyzes, S. Kuhr, C. Guerlin, J. Bernu, S. Deléglise, U. Busk Hoff, M. Brune, J.M. R, S. H., Nature **446**, 297 (07)*

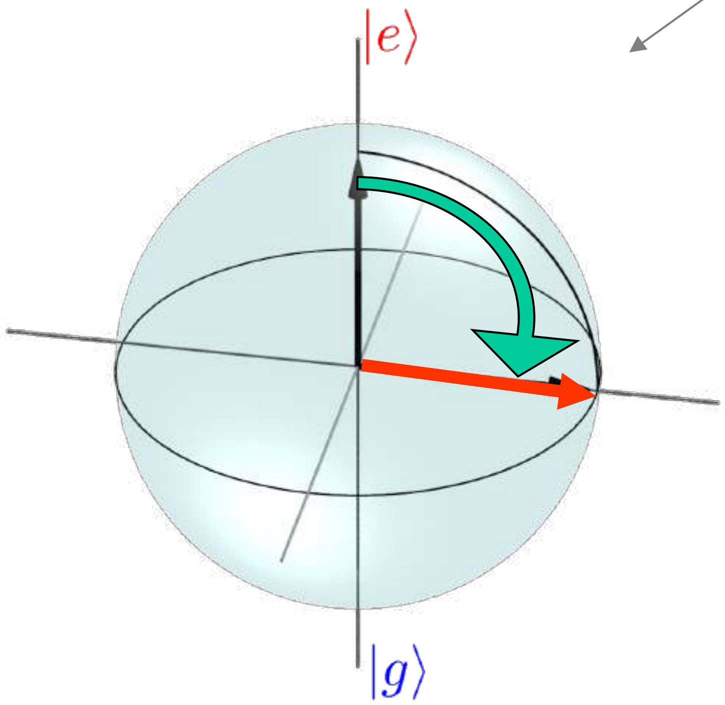
3. Counting more photons

32

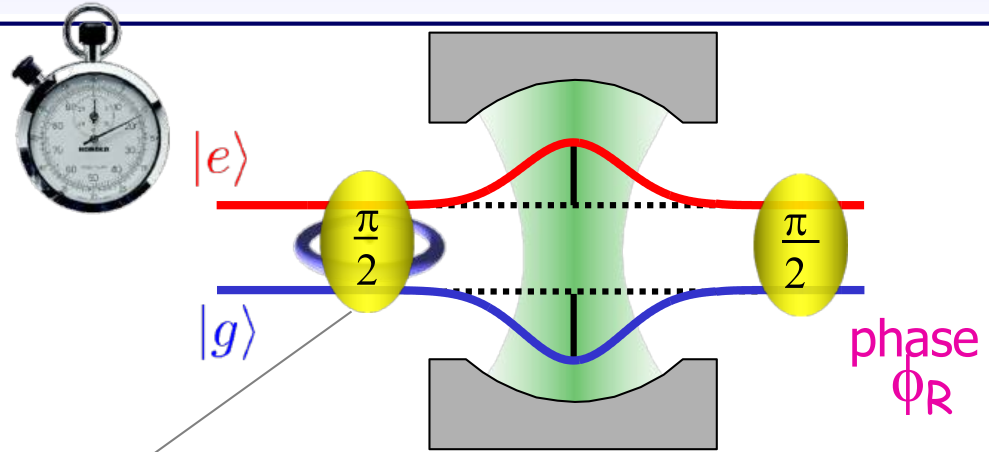
Seeing more photons

1. Trigger of the atom clock: resonant $\pi/2$ pulse



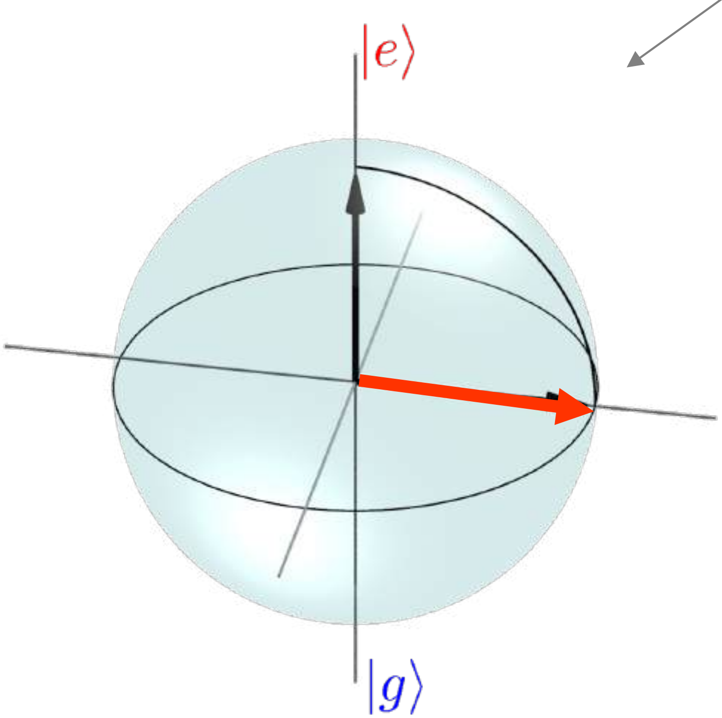


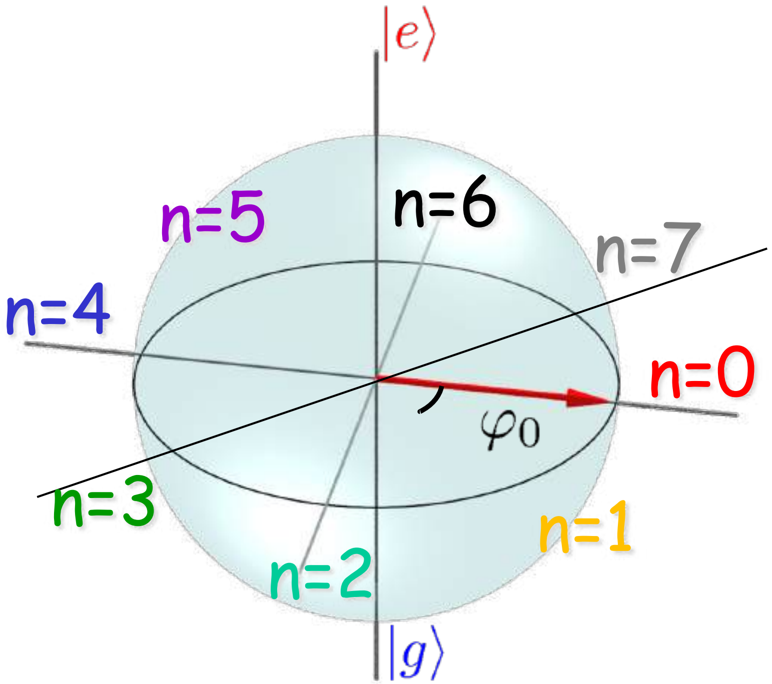
Seeing more photons



1. Trigger of the atom clock: resonant π/2 pulse

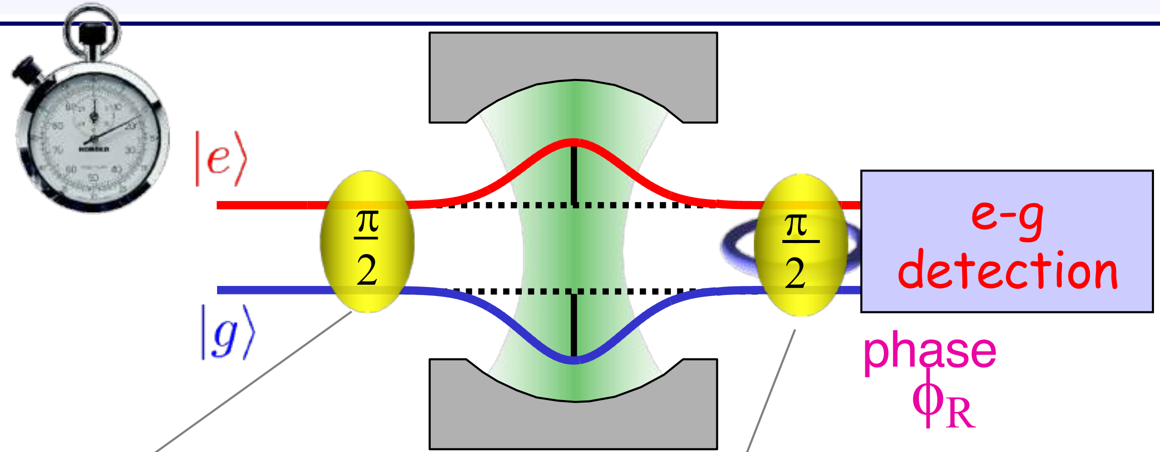
2. Dephasing of the clock: interaction with the cavity field



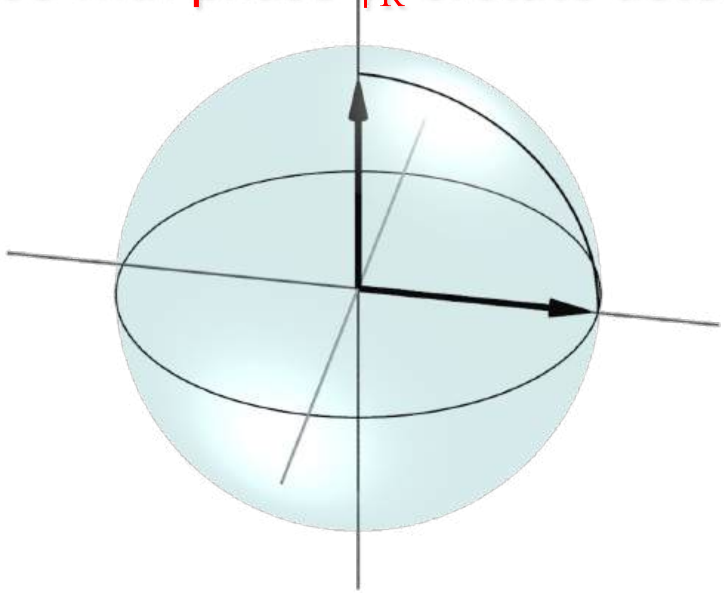


Phase shift per photon $\Phi_0 = \pi/4$

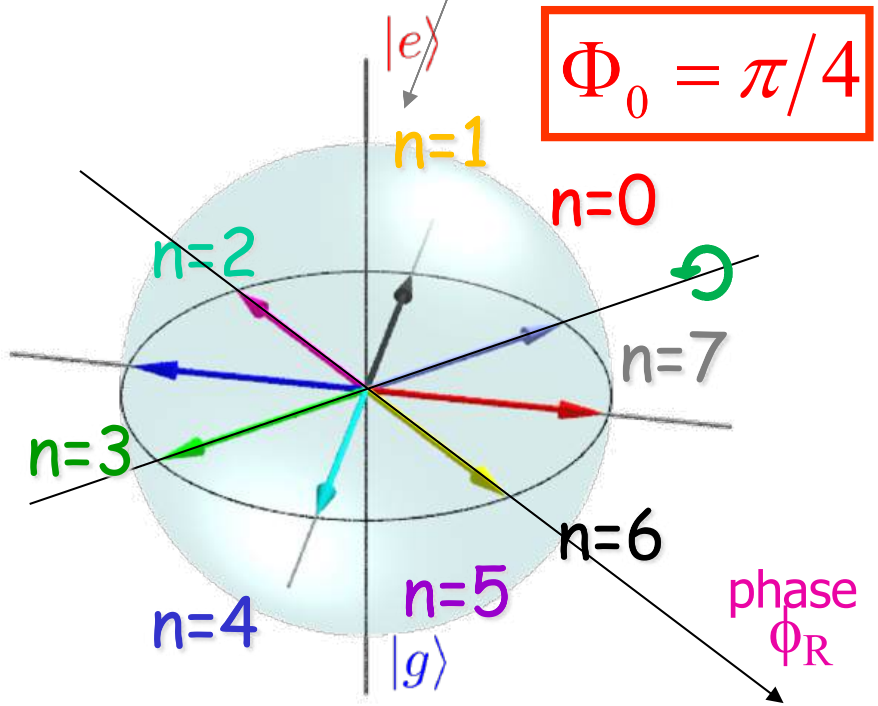
Seeing more photons



1. Trigger of the atom clock: resonant $\pi/2$ pulse
2. Dephasing of the spin: interaction with the cavity field
3. Measurement of the spin: $\pi/2$ pulse with phase ϕ_R & state detection



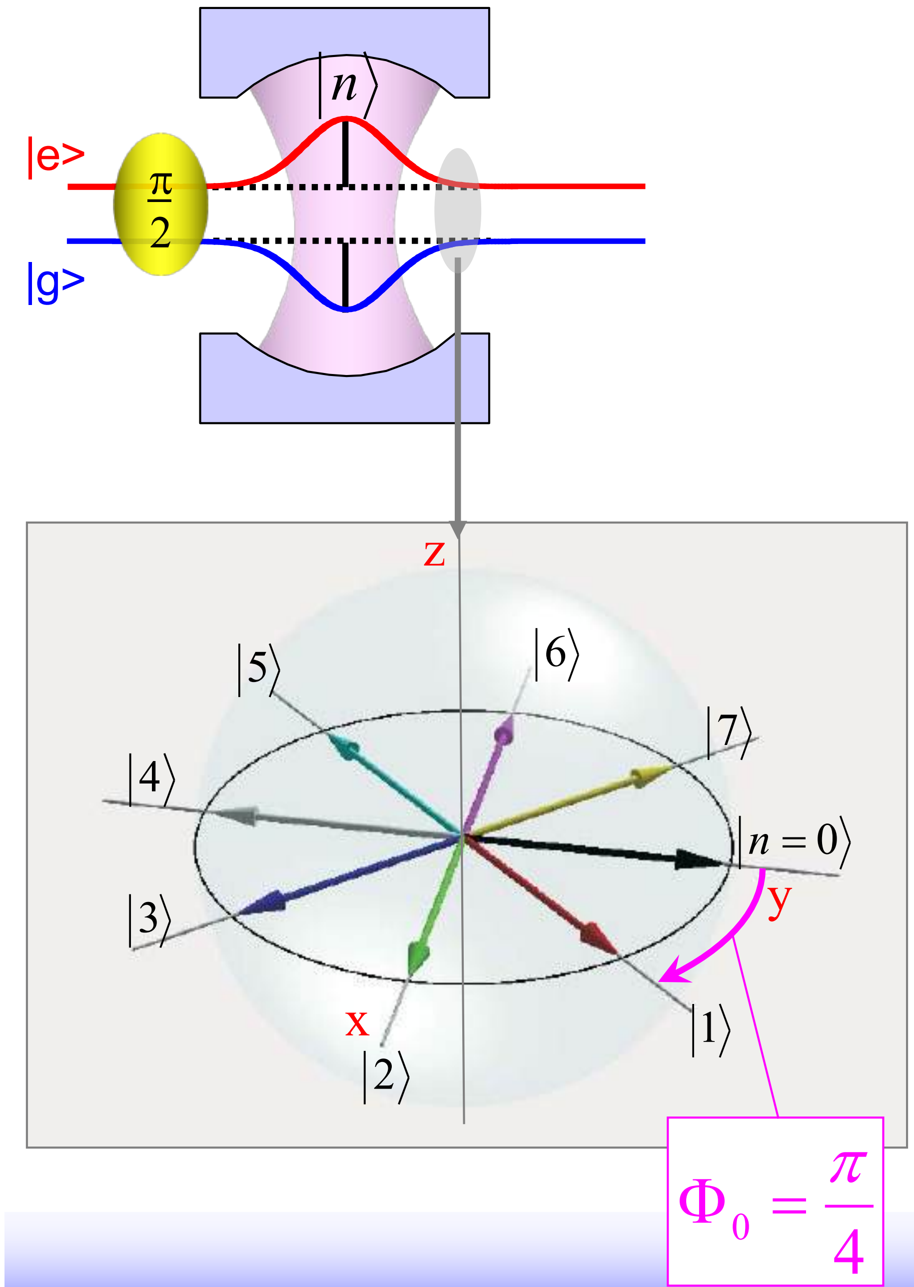
$$\Phi_0 = \pi/4$$



Pseudo-spin measurement in arbitrary direction determined by ϕ_R

$$P_e - P_g = \langle \sigma_{\phi_R} \rangle$$

Detection of n>1



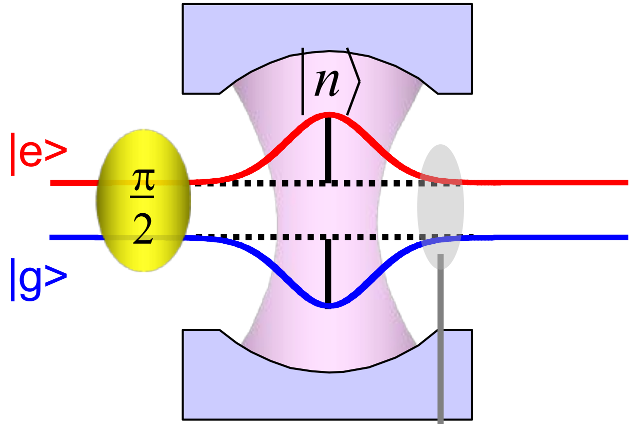
Chose $\Phi_0 = \frac{\pi}{4}$

$\Rightarrow$ Photon numbers from 0 to 7 correspond to 8 different final position of the atom "spin"

But hese states are not orthogonal

$\Rightarrow$ detecting one atom is not enough to determine n.

Detection of n>1



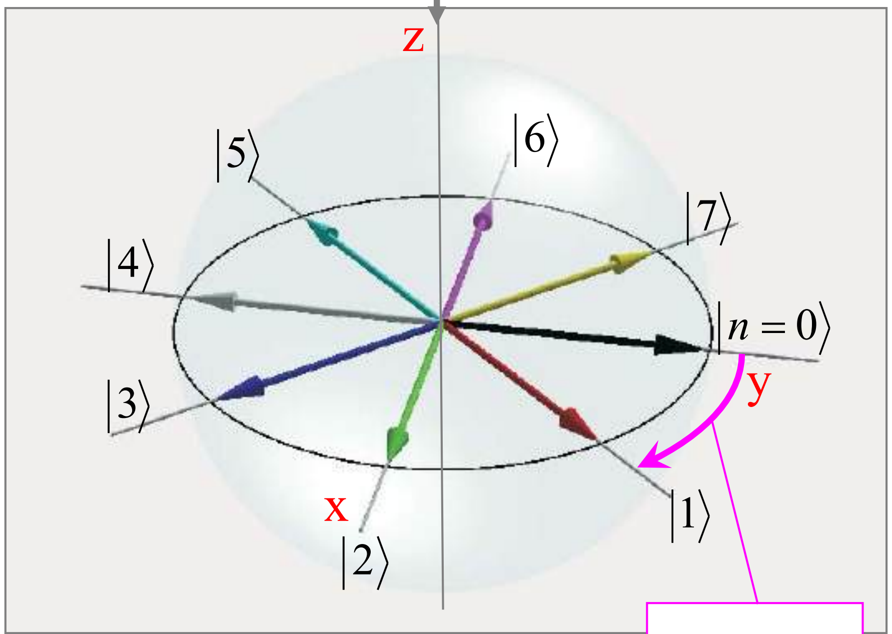
Interaction with one atom prepares:

$$\left|\Psi\right\rangle = \sum_n C_n \left|+_{n\Phi_0}\right\rangle \otimes \left|n\right\rangle$$

$\Rightarrow$ Repeat measurement

N atoms

$$\left|\Psi\right\rangle = \sum_n \left|+_{n\Phi_0}\right\rangle^N \otimes \left|n\right\rangle$$



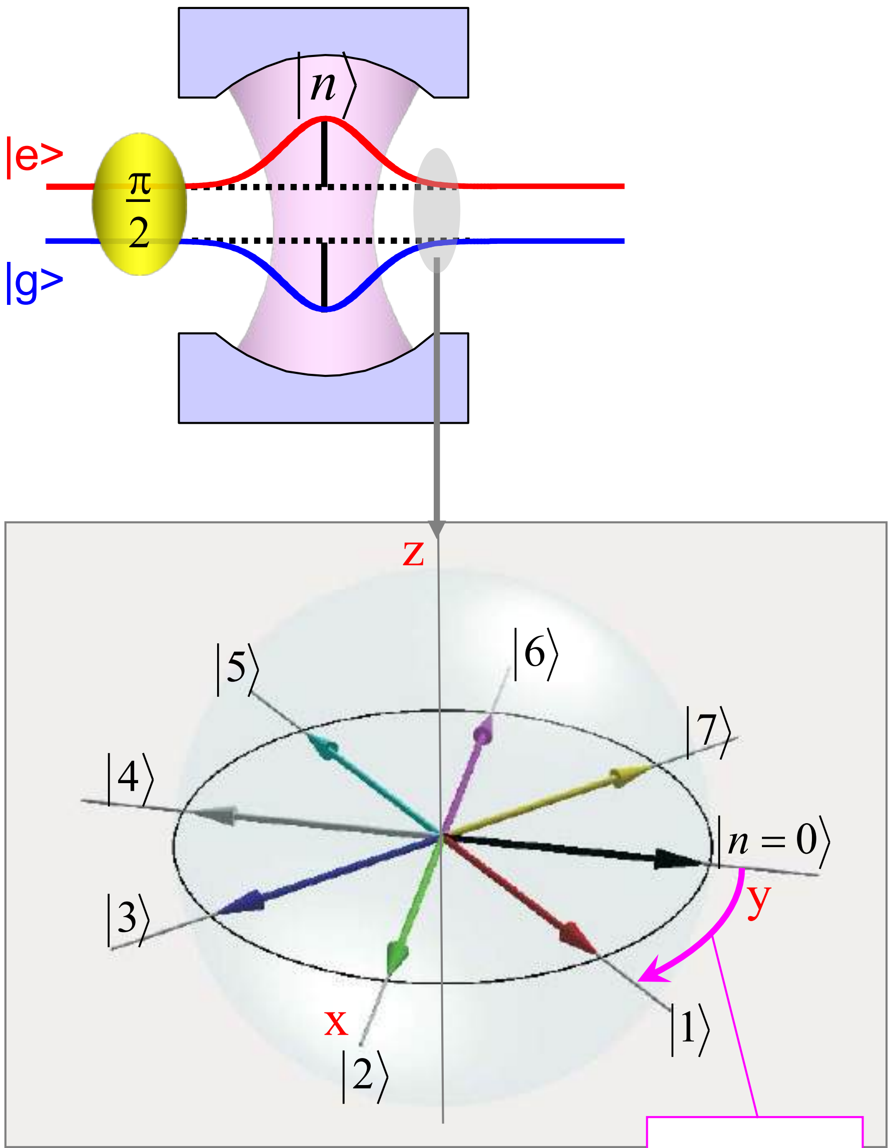
$$\Phi_0 = \frac{\pi}{4}$$

The photon number is now encoded in a mesoscopic sample of atoms.

$$\left|\left\langle +_{n'\Phi_0} \middle| +_{n\Phi_0} \right\rangle\right|^N \approx 0$$

Orthogonal states if N large enough

Detection of n>1



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

Interaction with one atom prepares:

$$\left|\Psi\right\rangle = \sum_n C_n \left|+_{n\,\Phi_0}\right\rangle \otimes \left|n\right\rangle$$

$\Rightarrow$ Repeat measurement

N atoms

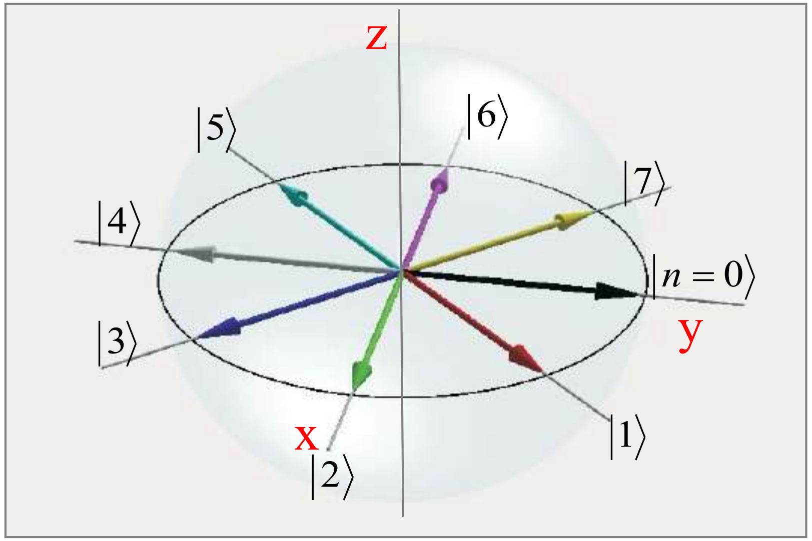
$$\left|\Psi\right\rangle = \sum_n \left|+_{n\,\Phi_0}\right\rangle^N \otimes \left|n\right\rangle$$

The photon number is now encoded in a mesoscopic sample of atoms.

That is a Schrödinger cat state:

the N atom collective spin points in a direction indicating the photon number

Décoding the photon number



$$\left|\Psi\right\rangle = \sum_n C_n \left|+_{n\Phi_0}\right\rangle^N \otimes \left|n\right\rangle$$

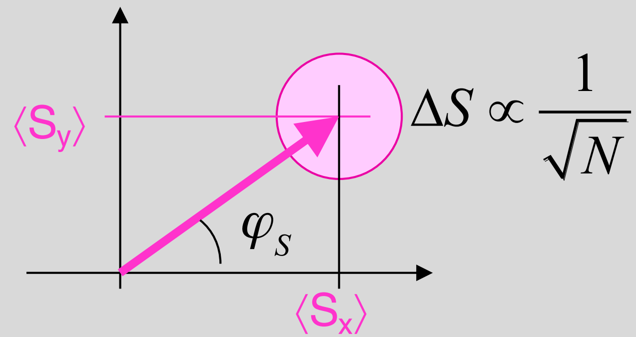
For each n, on detects N identical copies of the atomic state

$\left|+_{n\Phi_0}\right\rangle$

Determination of atom spin by « tomography »:

N atoms → $N/4$ atoms: measure $\left\langle S_{\phi_R}\right\rangle$ with 4 different setings of ϕ_R

→ calculate $\langle S_x \rangle$ and $\langle S_y \rangle$

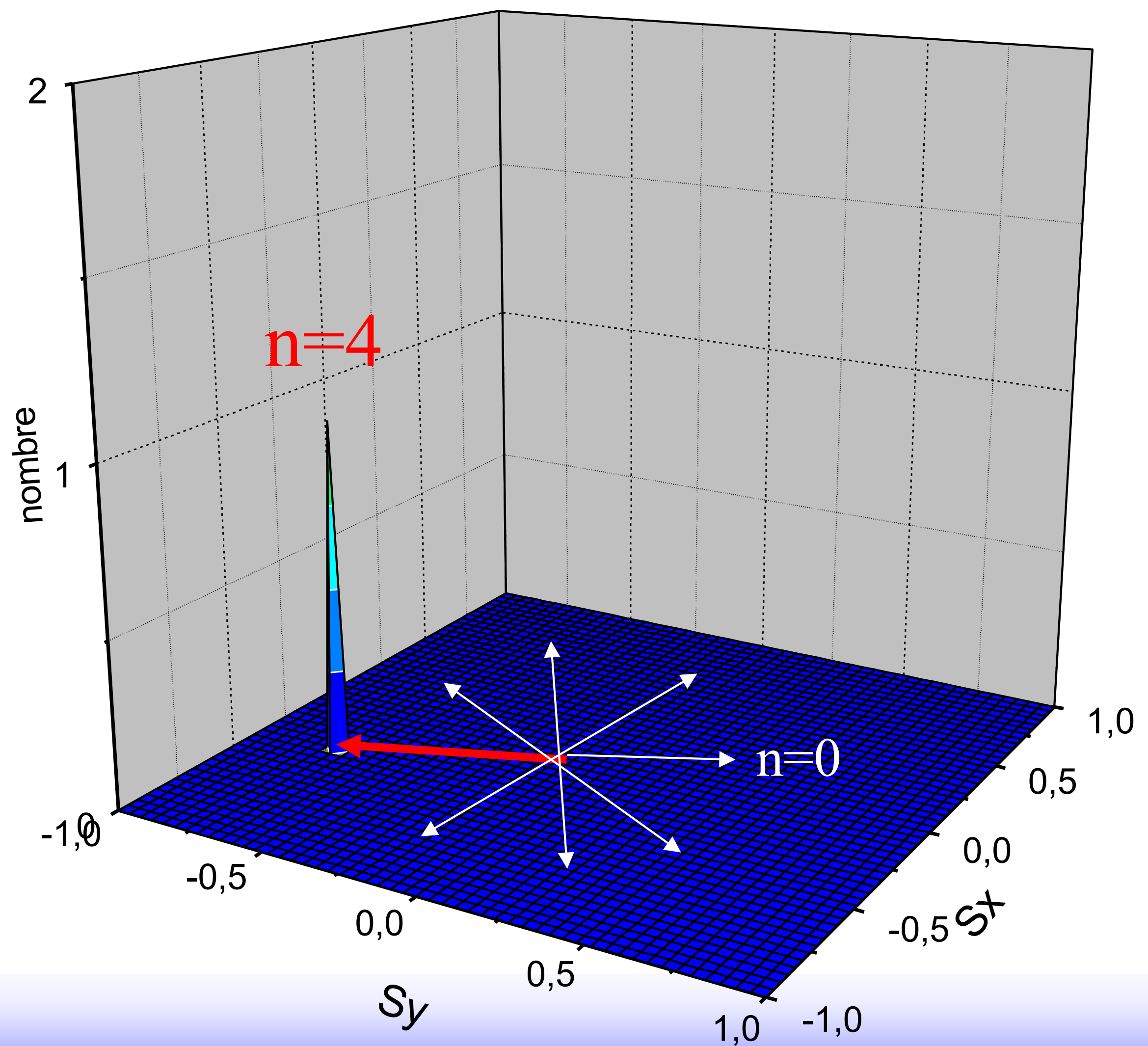


For large enough N, $\Delta\varphi_S \propto \frac{1}{\sqrt{N}} < \Phi_0$ and different photon numbers should be distinguished

Atom spin state tomography

Method: 1- inject a coherent field ⟨n⟩=3.5 photons.

2- detection of 110 consecutive atoms, $T_{measure}$=26 ms



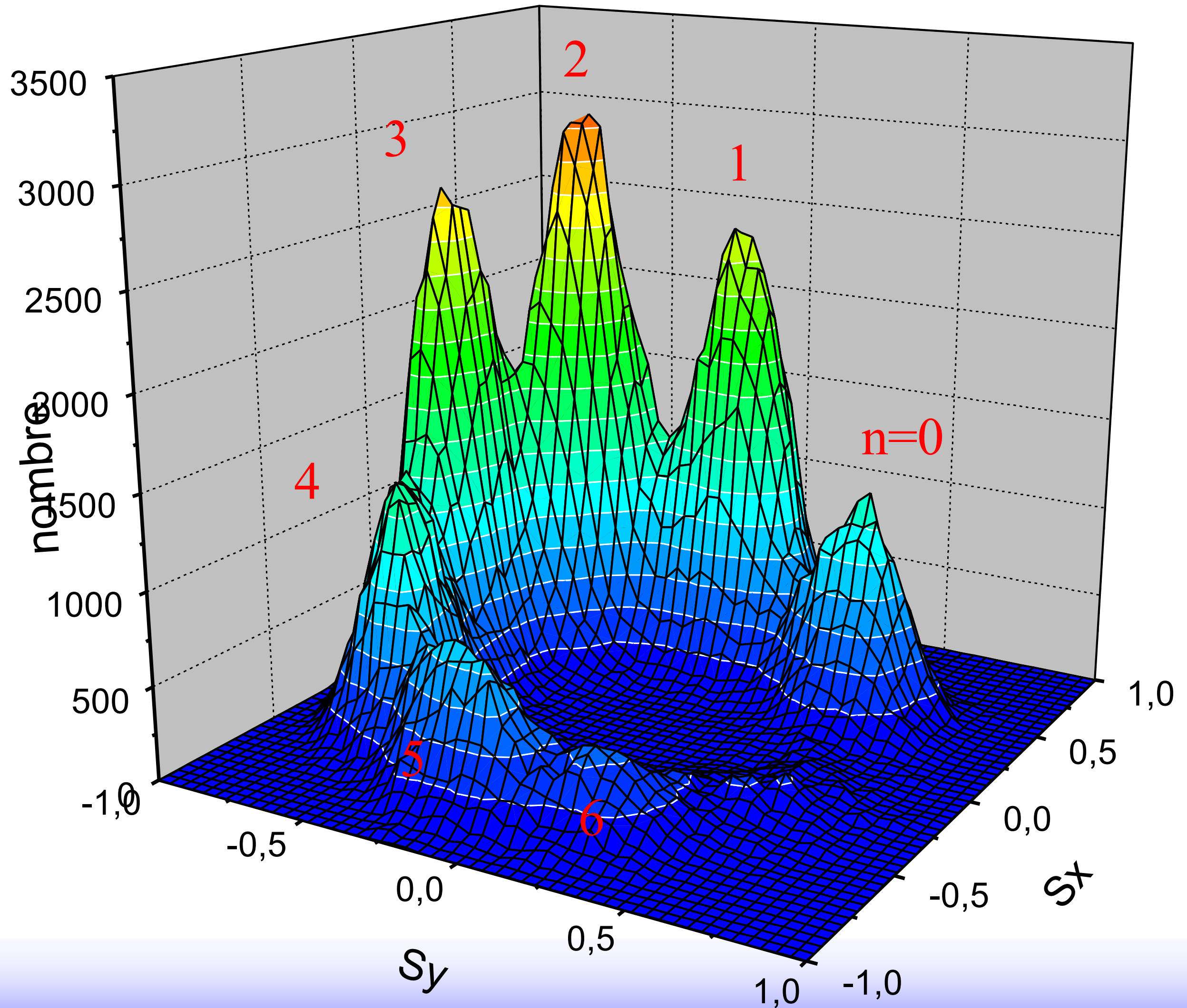
One measurement

➞ $n = 4$

Tomographie de l'état atomique

Method: 1- inject a coherent field ⟨n⟩=3.5 photons.

2- detection of 110 consecutive atoms, $T_{measure}$=26 ms



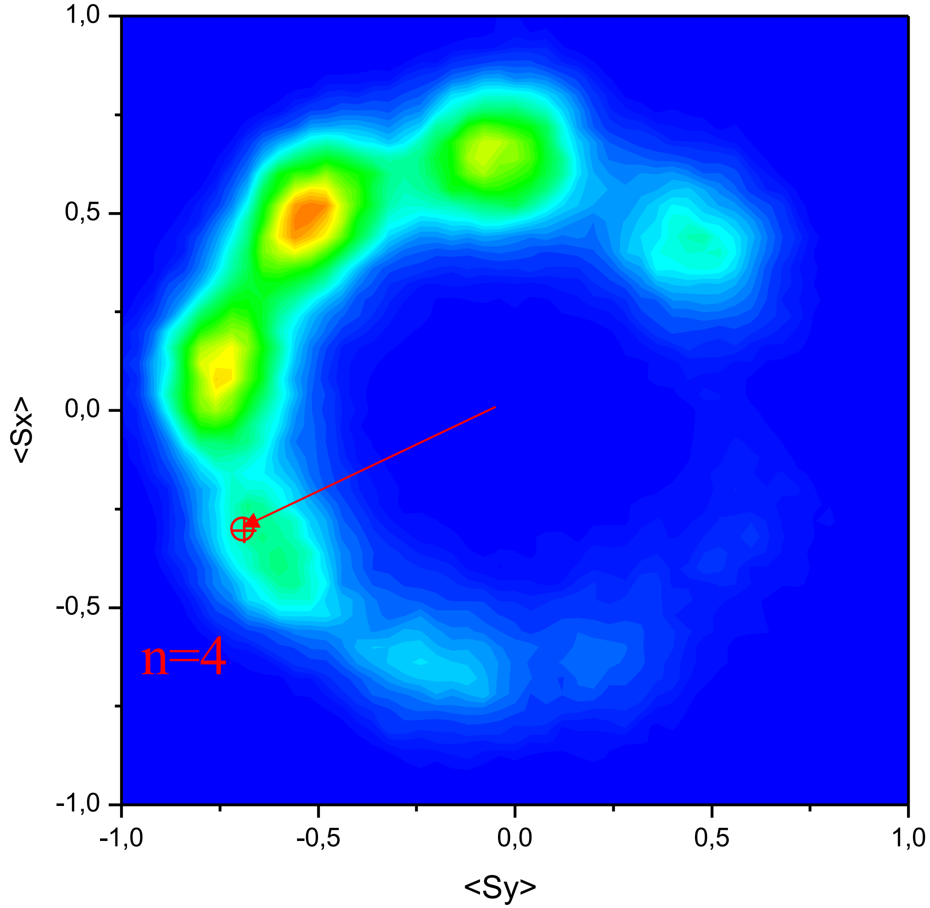
<n>=2.4 photons

The collective spin og N atoms points in discrete direction

⇒ n is obviously quantized

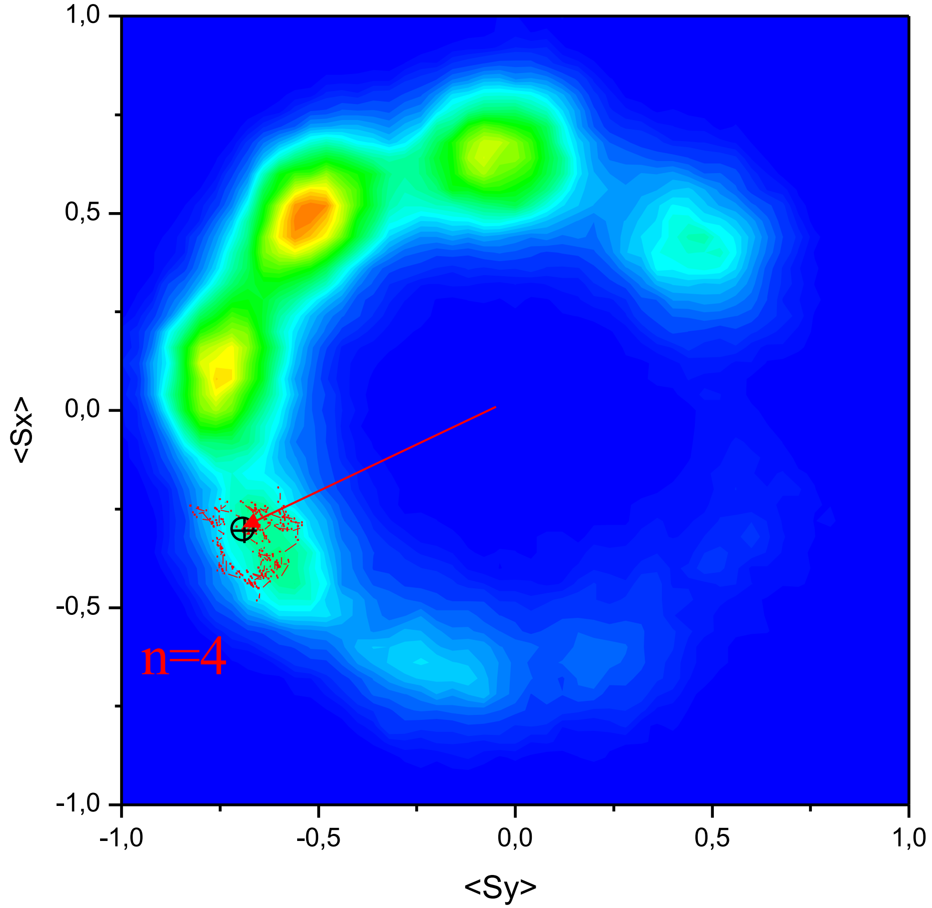
Detecting a collection of 110 atoms is enough to fully determine the photon number

Observing field decay directly on the collective atom spin



- Preparation of an initially coherent 3.5 photons field

-First measurement: projection on n=4

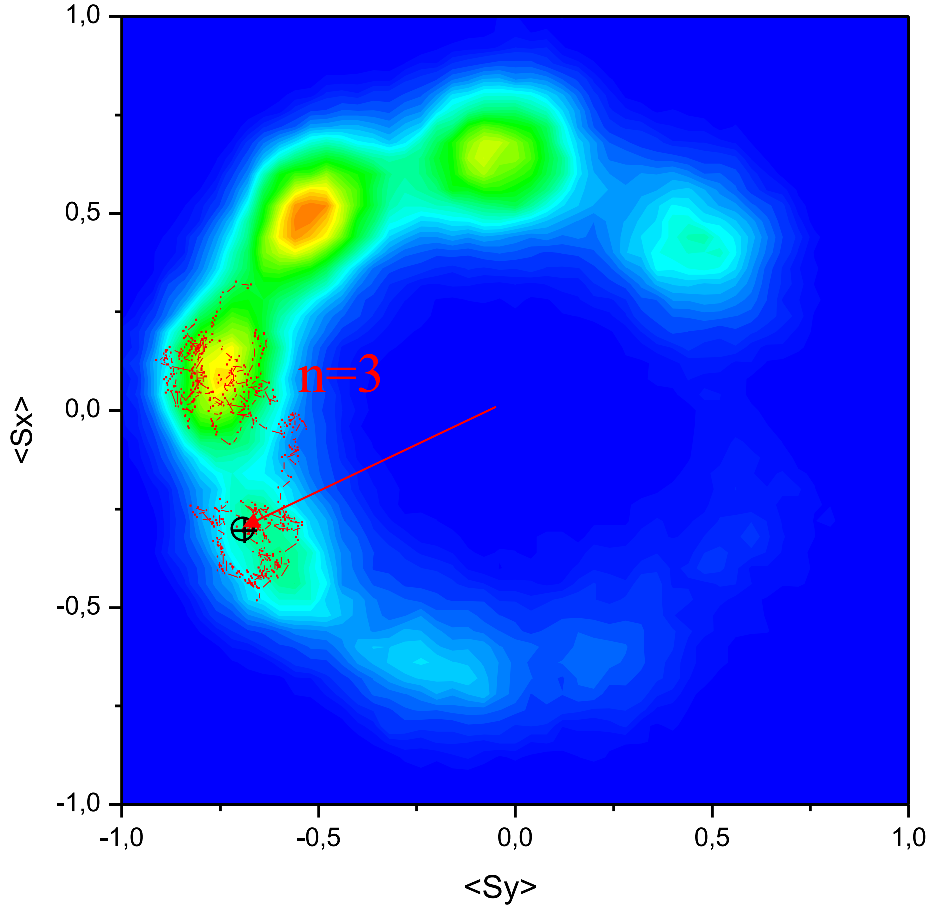


- Preparation of an initially coherent 3.5 photons field

-First measurement: projection on n=4

Due to statistical noise the spin fluctuates around n=4

Observing field decay directly on the collective atom spin

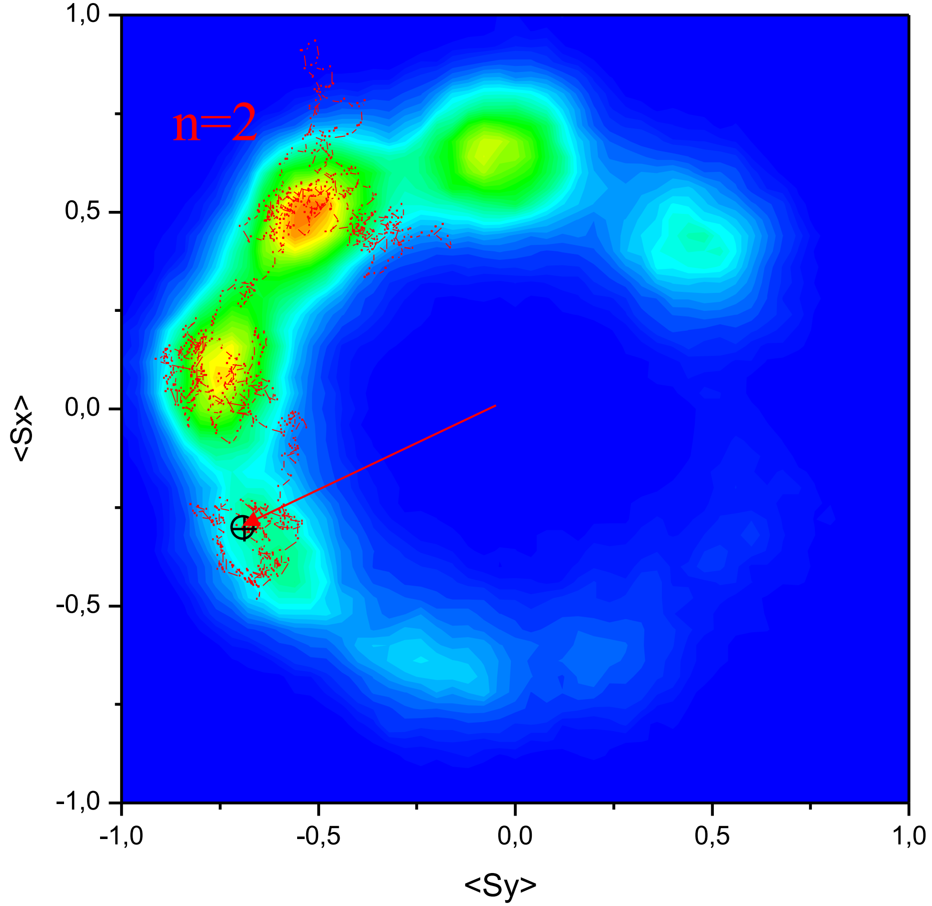


- Preparation of an initially coherent 3.5 photons field

-First measurement: projection on n=4

- quantum jump to n=3

Observing field decay directly on the collective atom spin

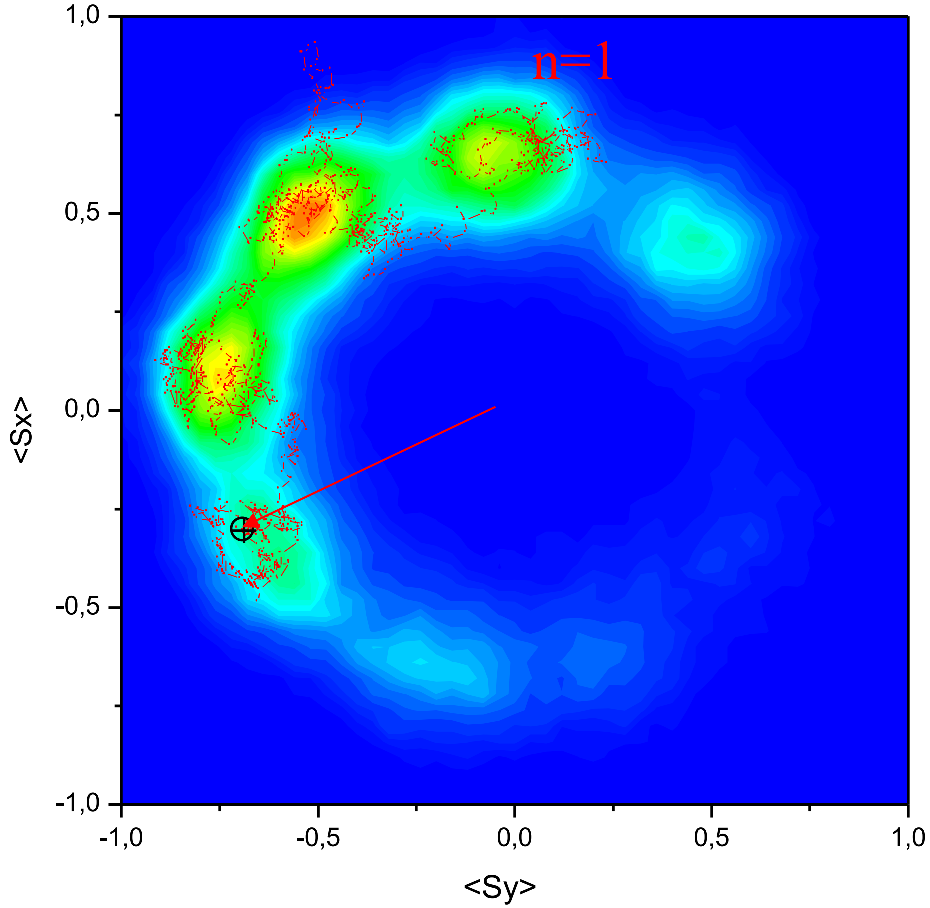


- Preparation of an initially coherent 3.5 photons field

-First measurement: projection on n=4

- quantum jump to n=3, 2

Observing field decay directly on the collective atom spin

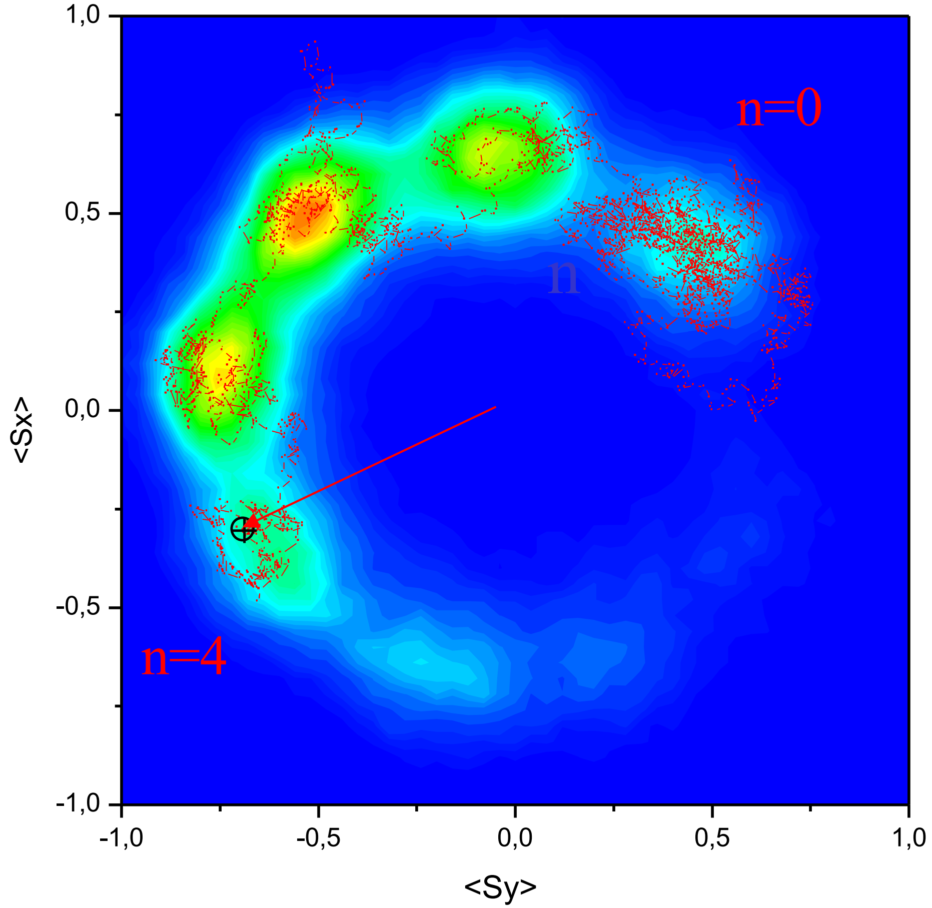


- Preparation of an initially coherent 3.5 photons field

-First measurement: projection on n=4

- quantum jump to n=3, 2 1….

Observing field decay directly on the collective atom spin

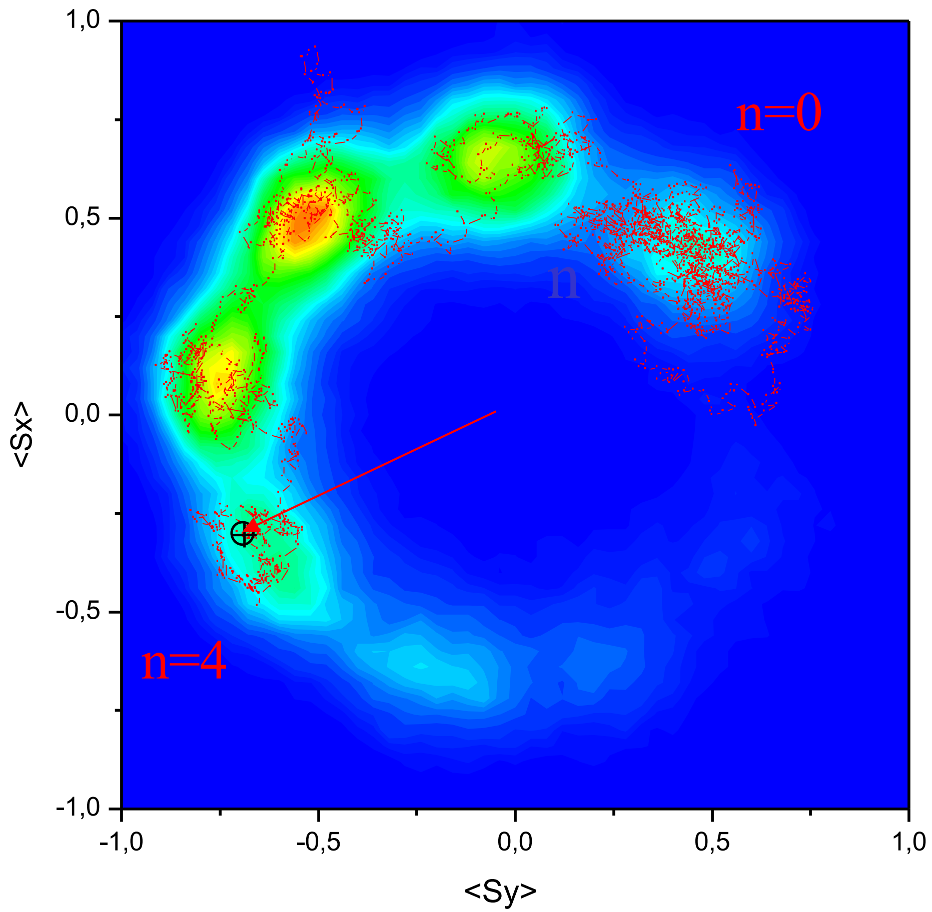


- Preparation of an initially coherent 3.5 photons field

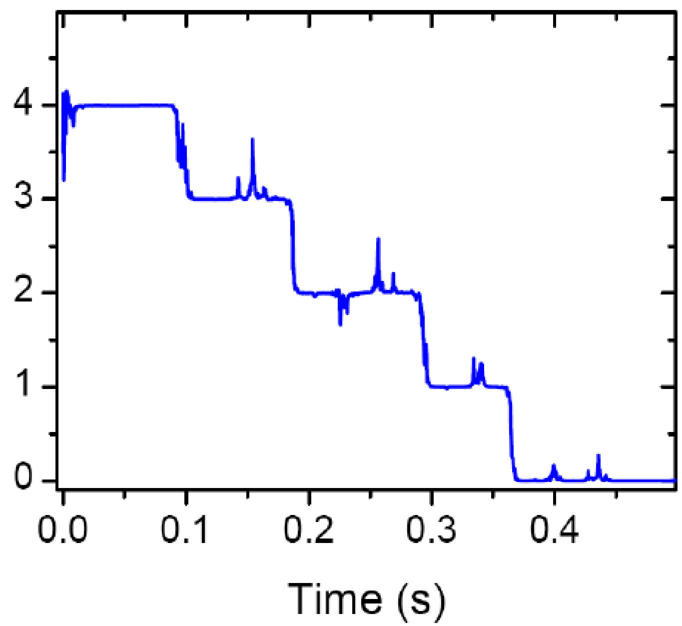
-First measurement: projection on n=4

- quantum jump to n=3, 2 1…. 0

Observing field decay directly on the collective atom spin



Average photon number evolution



Quantum jumps down to n=0.

→ now describe this process in term of progressive acquisition of information by applying the projection postulate atom by atom

Progressive accumulation of information

Apply the projection postulate at each atom detection.

$P_0(n)$ 1- Initial field state

$\Downarrow$

$P_1(n)$

$\Downarrow$

$P_2(n)$

....

$P_N(n)$

Progressive accumulation of information

Apply the projection postulate at each atom detection.

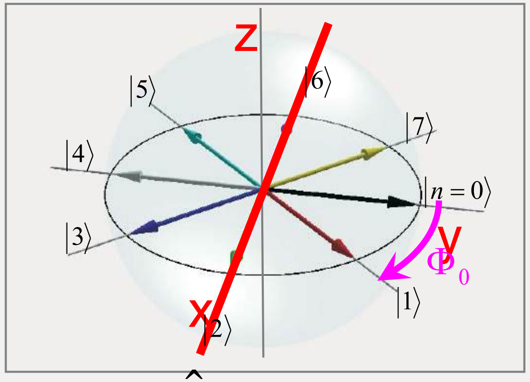
$P_0(n)$ 1- Initial field state

ϕ_R randomly chosen among 4 values aligned on the 4 possible spin directions

2- First measurement of $\hat{S}_{\phi_R}$ ➞ résult: $+_j$ or $-_j$

➞ Projection of the atom-field state:

$\Downarrow$



$\hat{S}_{\phi_R}$

$P_1(n)$

$\Downarrow$

$P_2(n)$

....

$P_N(n)$

Progressive accumulation of information

Apply the projection postulate at each atom detection.

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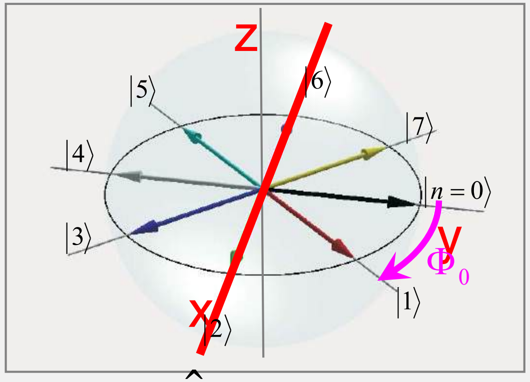

$\hat{S}_{\phi_R}$

Bayse law

$P_1(n)$

$$P_1(n) = P(n/\pm_\varphi) = P_0(n).P(\pm_\varphi / n).\frac{1}{Z}$$

$Z = P(\pm_\varphi)$ norm. factor

$\Downarrow$

$P_2(n)$

....

$P_N(n)$

Progressive accumulation of information

Apply the projection postulate at each atom detection.

$P_0(n)$ 1- Initial field state

ϕ_R randomly chosen among 4 values aligned on the 4 possible spin directions

2- First measurement of $\hat{S}_{\phi_R}$ → résult: $+_j$ or $-_j$

→ Projection of the atom-field state:

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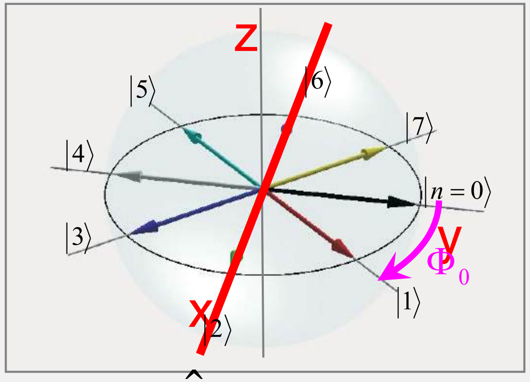


Bayse law

$P_1(n)$

$$P_1(n) = P(n/\pm_\varphi) = P_0(n).P(\pm_\varphi/n).\frac{1}{Z}$$

$Z = P(\pm_\varphi)$ norm. factor

$\Downarrow$

$P_2(n)$

....

3- iterate the process until detection of N atoms

$P_N(n)$

Note: field coherence do not play any role, P((n) is enough here.

Information acquisition by detecting 1 atom

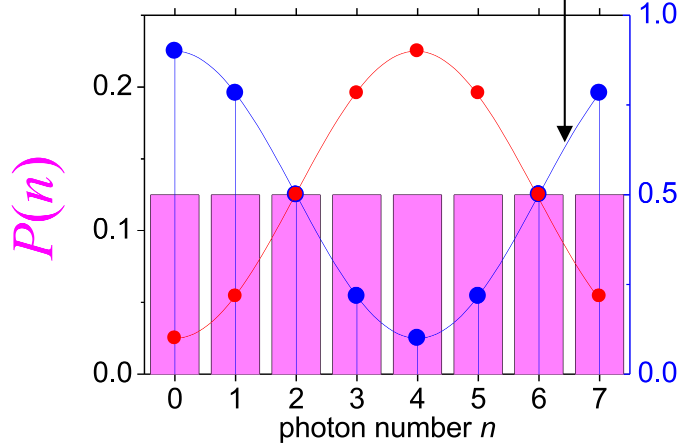
Bayes law:

$$P_{after}(n) = P(n / j_{\phi_R}) = P_{before}(n).\frac{P(j_{\phi_R} / n)}{P(j_{\phi_R})}$$

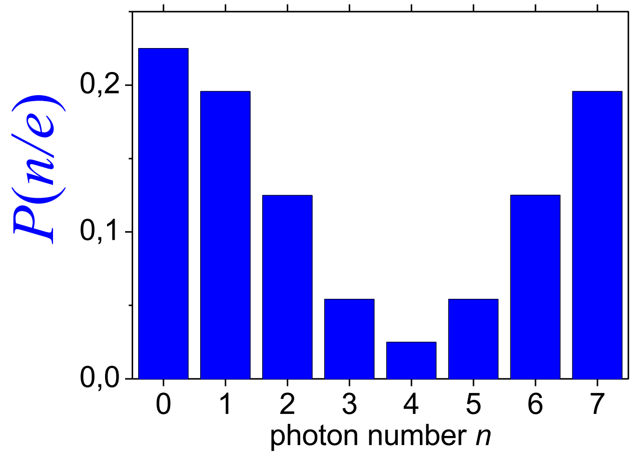
$j_{\phi R} = 1$ or -1
$= e$ or g

$\phi_R = 0$

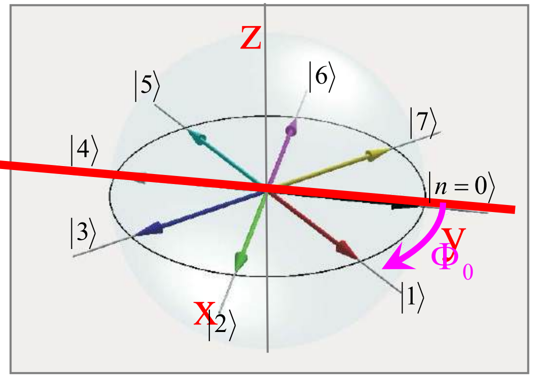
$$P\left(+_{\phi_R} / n\right) = \left|\left\langle +_{\phi_R} \middle| +n \right\rangle\right|^2$$



e



$\phi_R = 0$



Probability of *n* that are incompatible with the measurement result are cancelled.

Repeating the measurement with other values of j decimates other photon numbers

Information acquisition by detecting 1 atom

Bayes law: $$P_{after}(n) = P(n / j_{\phi_R}) = P_{before}(n).\frac{P(j_{\phi_R} / n)}{P(j_{\phi_R})}$$

$j_{\phi R} = 1$ or -1

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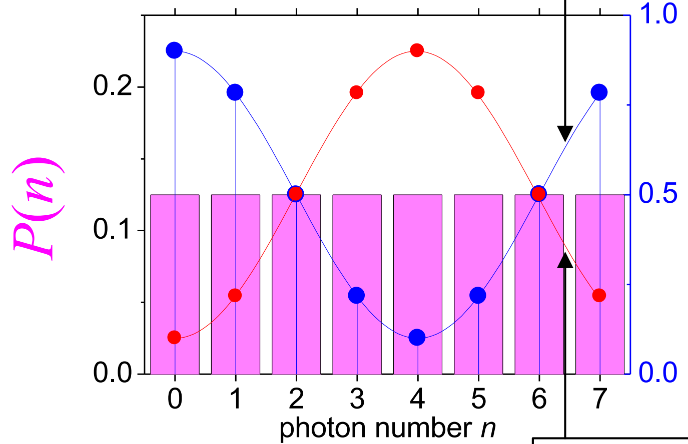
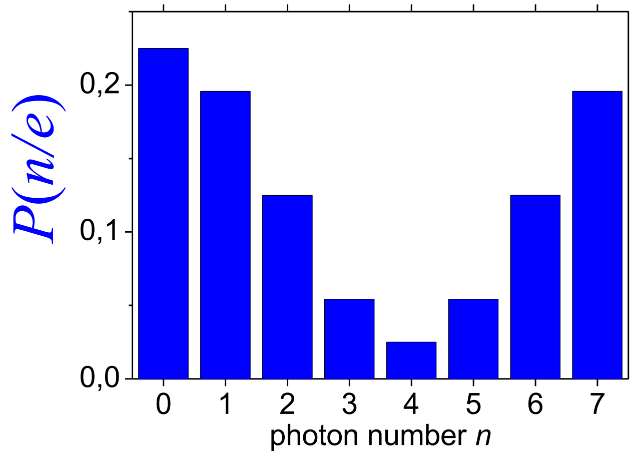
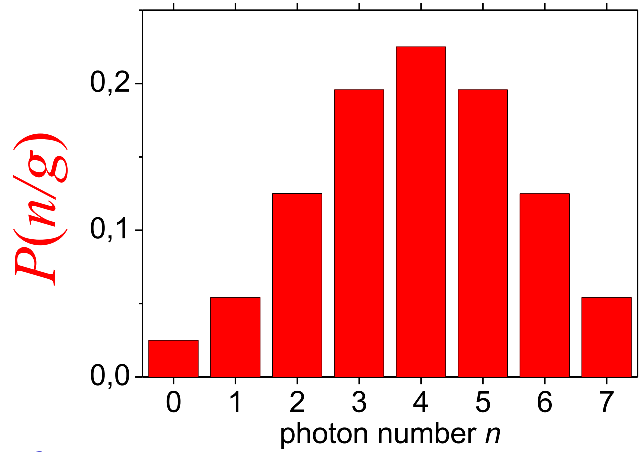


$$P\left(-_{\phi_R} / n\right)$$

e

g





Probability of *n* that are incompatible with the measurement result are cancelled.

Repeating the measurement with other values of j decimates other photon numbers

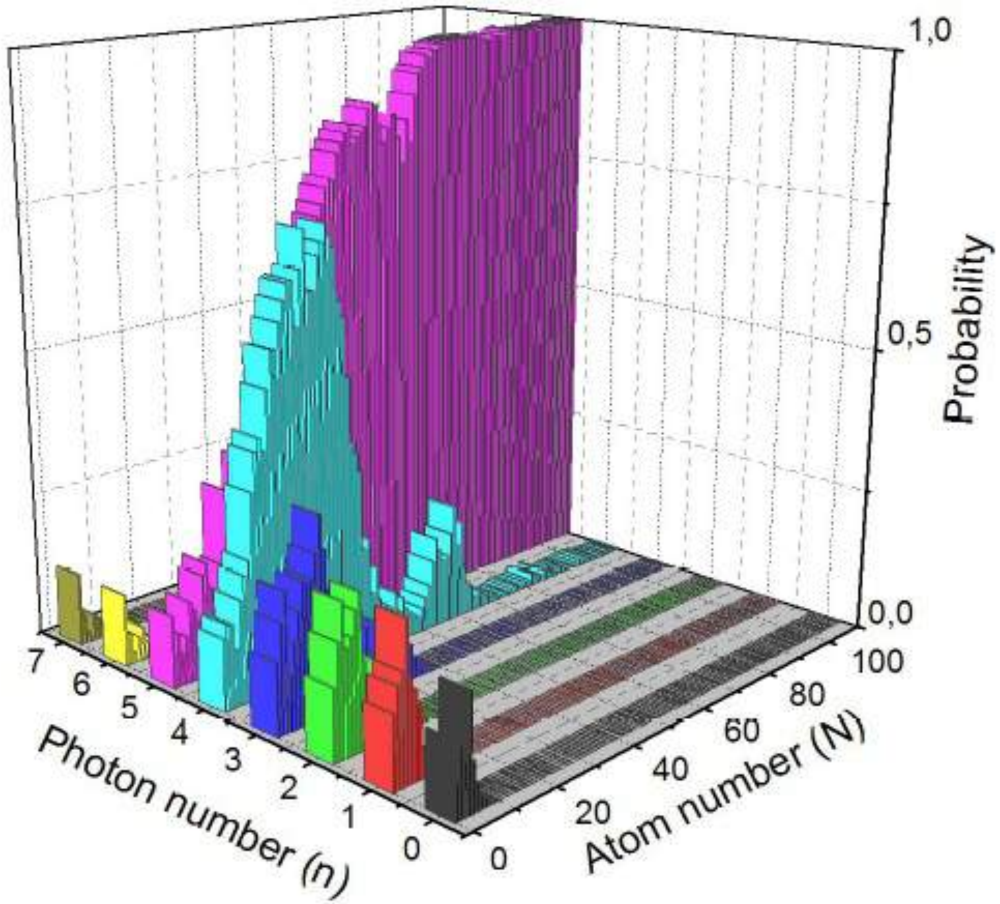
Progressive field collapse

$j(k)$ 110111111110011101101111010100110101010110101111

$\phi_R(k)$ ddcbccabcdaadaabadddbadbcdababbaacbccdadccdcbaaacc

k= atom index

Decoding (real data, not simulation)



Initial coherent state
<n>=3.7 (±0.008)

Flat initial photon number distribution.
The measurement result is determined by the real field

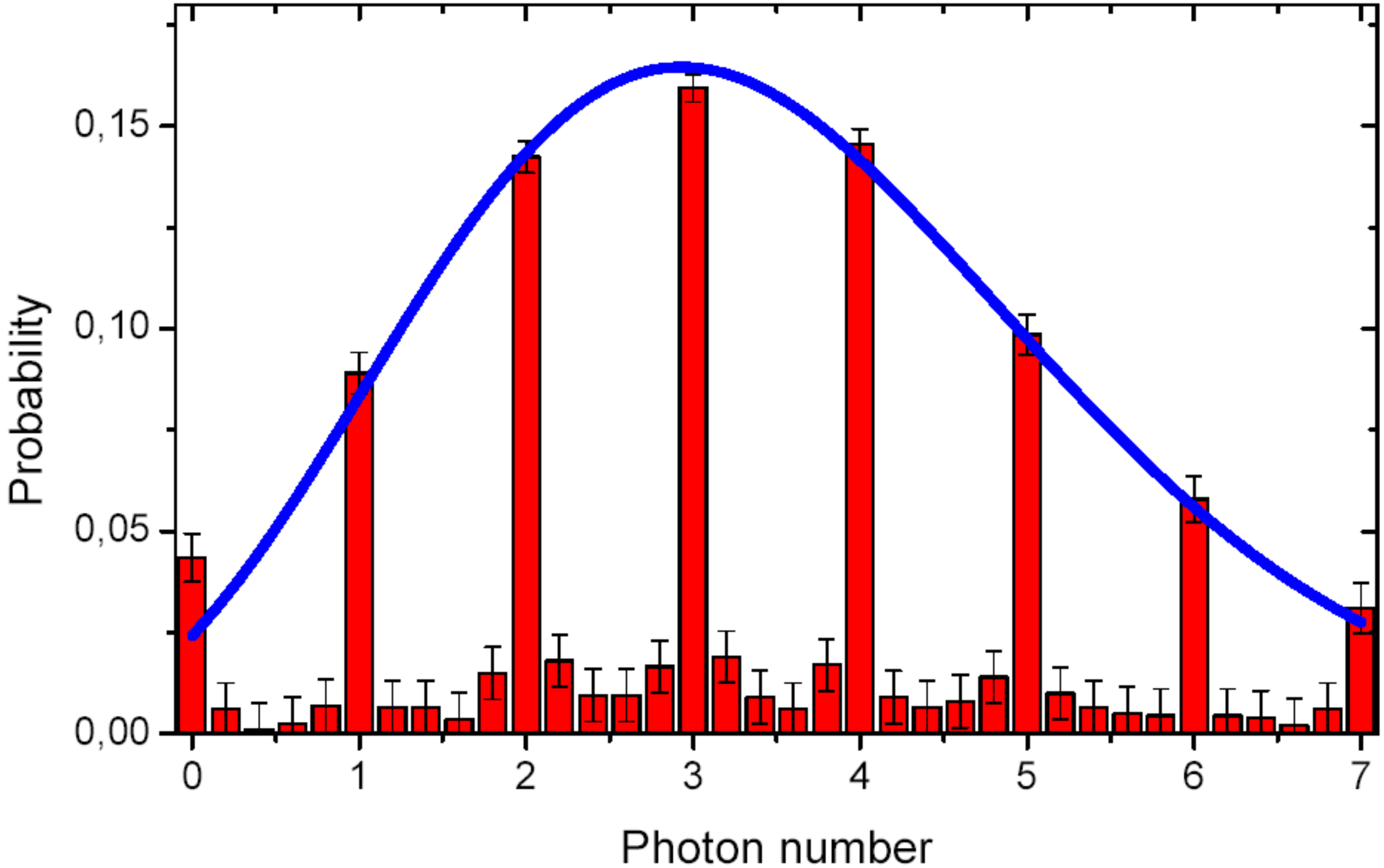
Progressive projection of the field on n=5 number state

C. Guerlin . *et al. Nature* August 23 (2007).

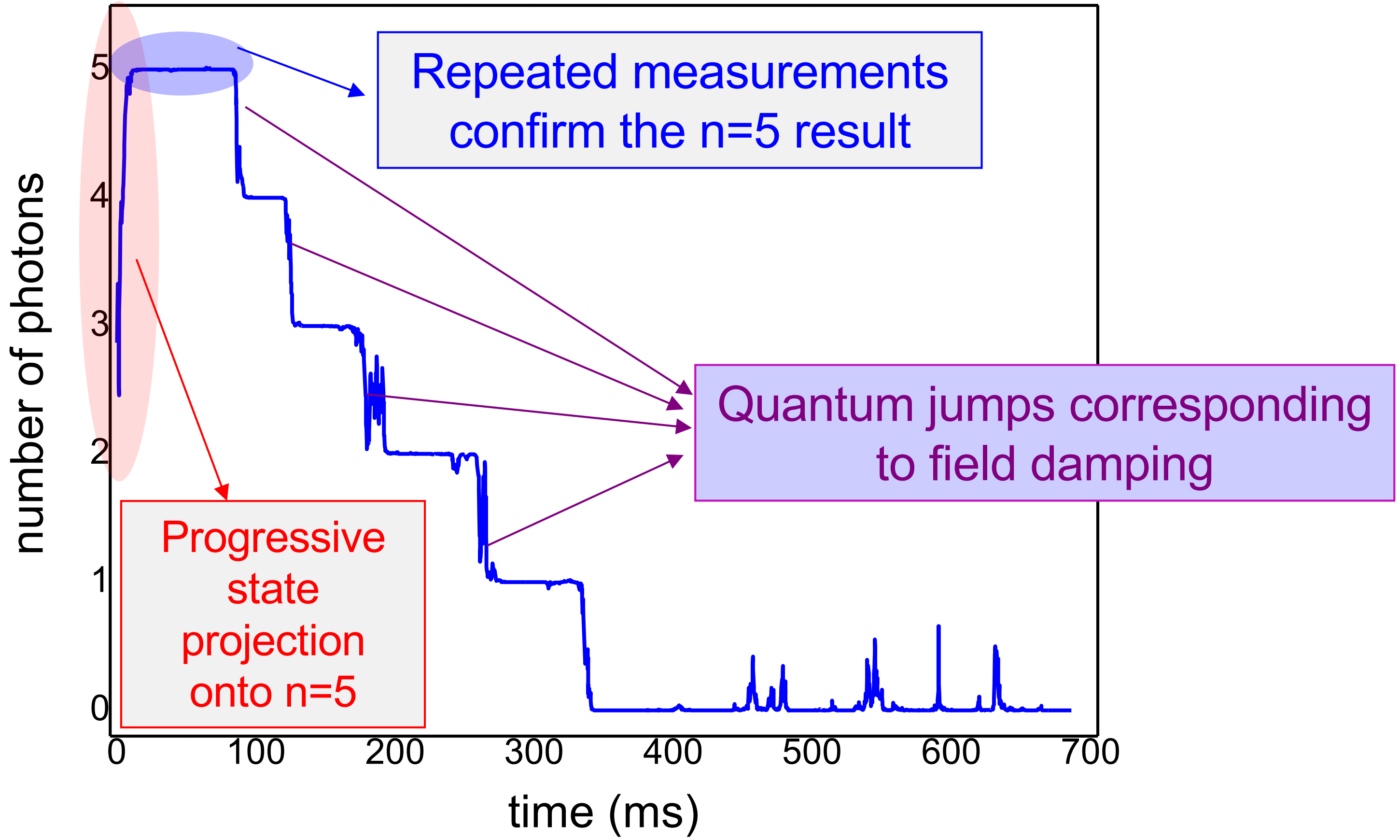
Reconstructing the photon number statistics

Coherent field at measurement time

$$\langle n \rangle = 3.4 \pm 0.008$$



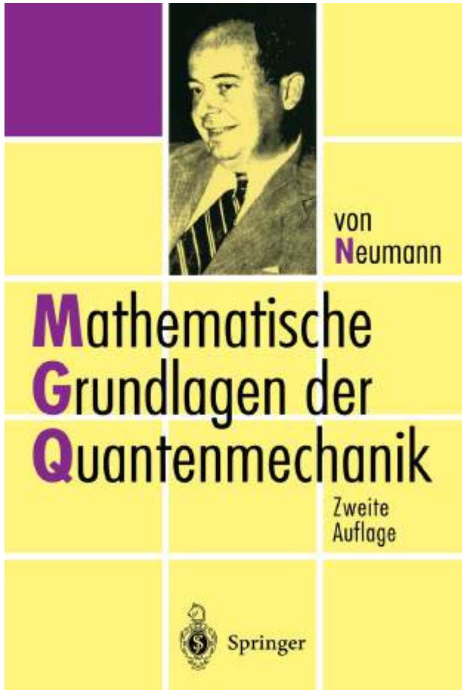
Repeated measurements: evolution of a continuously monitored field



Field evolution due to cavity damping: not to QND measurement

- Exhibits all features of quantum theory of measurement:
  - State collapse / Random result / repeatability

Conclusion: Back to Von Neumann

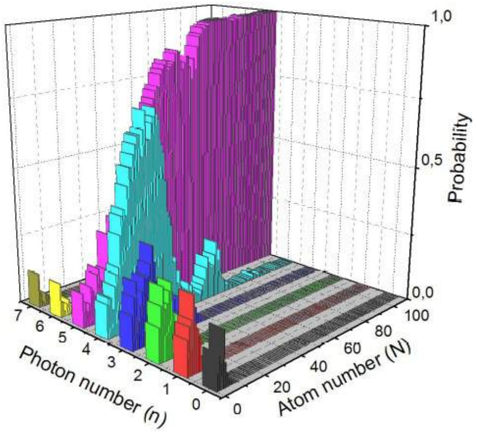


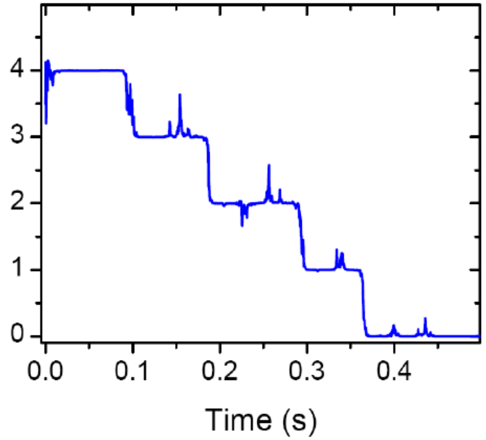
J. Von Neumann clearly pointed out a strange aspect of quantum theory of measurement:

Coexistence of two kind of evolution

1- Hamiltonian evolution

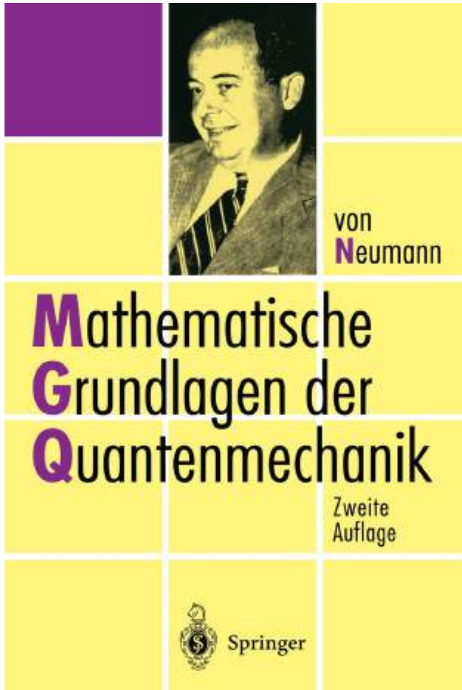
2- State projection





We have presented a real measurement apparatus performing an Ideal Quantum Non Demolition measurement according to postulates

Back to Von Neumann



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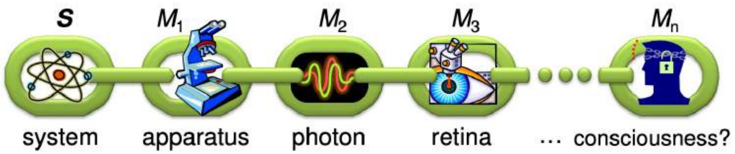

What is breaking the chain?
→Decoherence point of view

Thi is the topic of next lecture

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