Giambiani Winter School
Buenos Aires July 2019

From cavity QED to quantum simulations with Rydberg atoms

Lecture 2

QND photon counting and decoherence of a Schrödinger cat state

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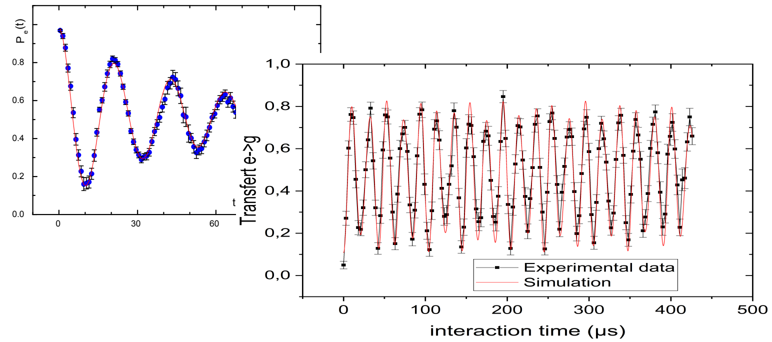
Collège de France, Paris

outline of lecture 1:

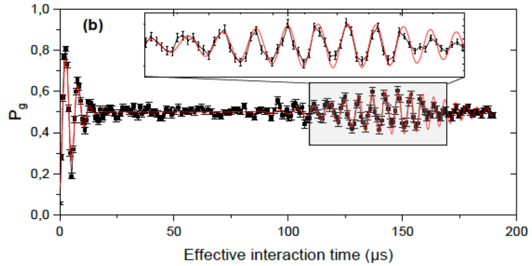
Cavity QED with microwave photons and circular Rydberg atoms:

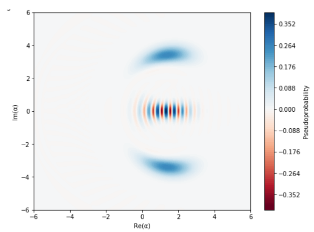
... a powerfull tool for:

- Achieving strong coupling between single atoms single photons

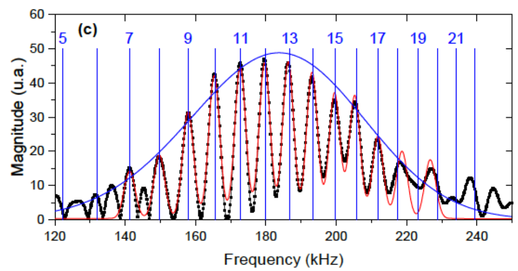


- Observing collapse, revival of Rabi oscillation





- Preparing "large" Schrödinger cat State: equivalent to superposition of 0 and 44 photons



Outline of the course

Topic of lectures 1-2:

CQED with Rydberg atoms

- Cavity QED in the strong coupling regime:
  - ❑ Resonant interaction: vacuum Rabi oscillations
- Non-destructive photon counting

  Seeing the same one photon again and again

  Quantum jump of light and
- Schrödinger cat state decoherence

Lecture 3:

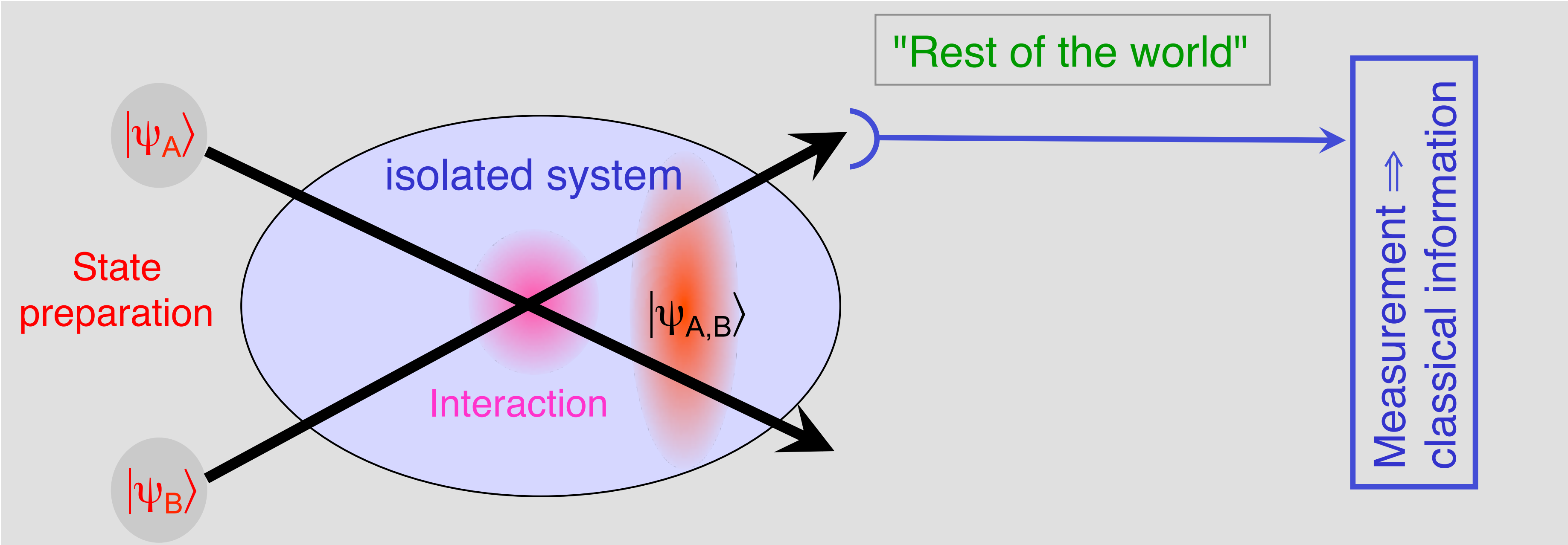
Toward a circular Rydberg atom quantum simulator

of XXZ spin Hamiltonian

1. Quantum Non-Demolition photon counting: single photon detection

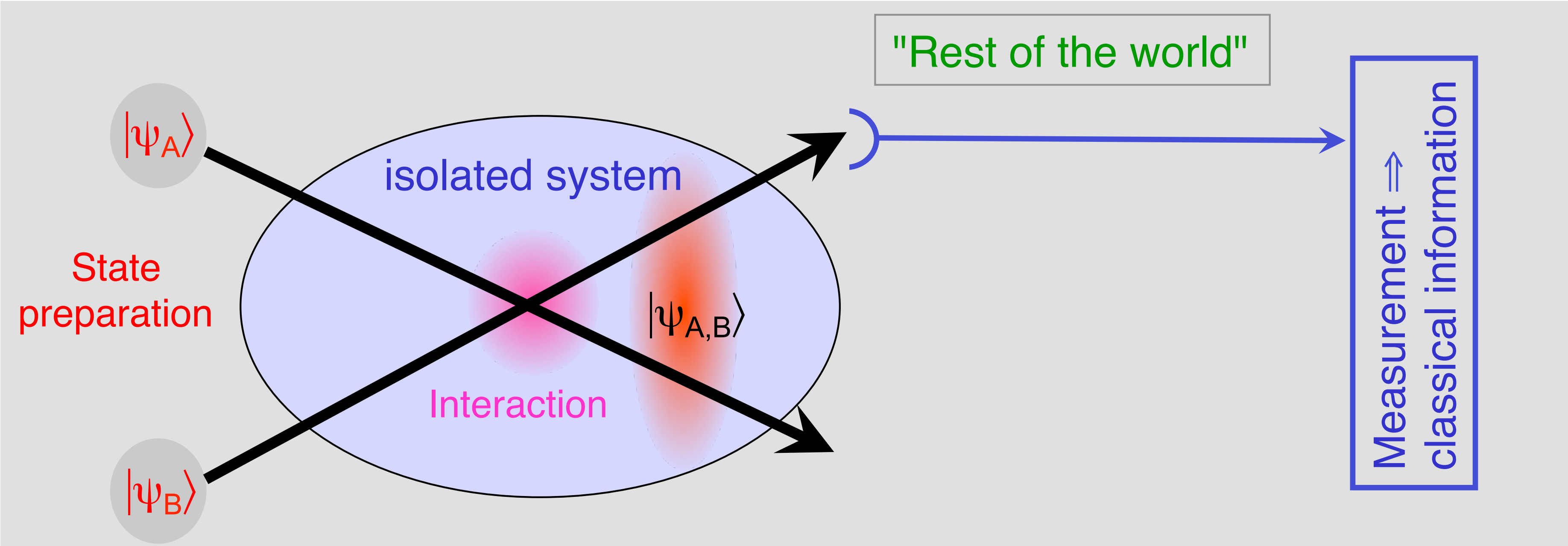
- Ideal quantum measurement
- Experimental realization with Rydberg atoms

Quantum measurement: basic ingredients



- Description of quantum objects
  - interaction: Schrödinger equation.
  - measurements: the state determines the statistics of results.
  - Indirect measurement: measuring B provides information on A
- Quantum theory: the art of extracting classical information out of microscopic systems.

Quantum measurement: basic ingredients



- Entanglement: "The essence of quantum physics" (Heisenberg)

Created by interaction, describes all correlations between quantum systems.

- irreversibility introduced by dissipation: macroscopic systems are dissipative.

Dissipation plays a fundamental role in the coherence of quantum theory: explains the "decoherence" step during a quantum measurement

Ideal quantum measurement

- The postulates:
  - Fundamentally random result of individual measurements
  - Possible results: eigenvalues a_n of an hermitian operator $\hat{A}$ (observable).
  - Probability of results if system in state $|\psi\rangle$:

$$p(a_n) = \langle\psi|P_n|\psi\rangle$$

where P_n = projector on the eigenspace associatet to a_n.

  - State after measurement:

$$|\psi_{after}\rangle = \frac{P_n|\psi\rangle}{\sqrt{p(a_n)}}$$

→ state collapse: the system's states changes discontinuously during the measurement process

The postulates, comments

- locks like a recipe:
  - ❑ does not tell what is a measurement apparatus
  - ❑ does not tell how to built an apparatus measuring a given observable
- locks like a strange recipe:

  a quantum system seems to be subjected to two kinds of evolution:

  → continuous evolution according to Schrödinger equation between measurements

  → state collapse during measurements

  But a measurement apparatus is made of quantum objects obeying to Schrödinger equation: why should evolution during measurement deserve a special treatment?

  Goal of the lecture: → look at this with a real experiment

1. Quantum Non-Demolition photon counting

- Ideal quantum measurement
- Experimental realization with Rydberg atoms

QND photon counting: The beginning of the story …

Initial QND measurement proposal: 1990

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]

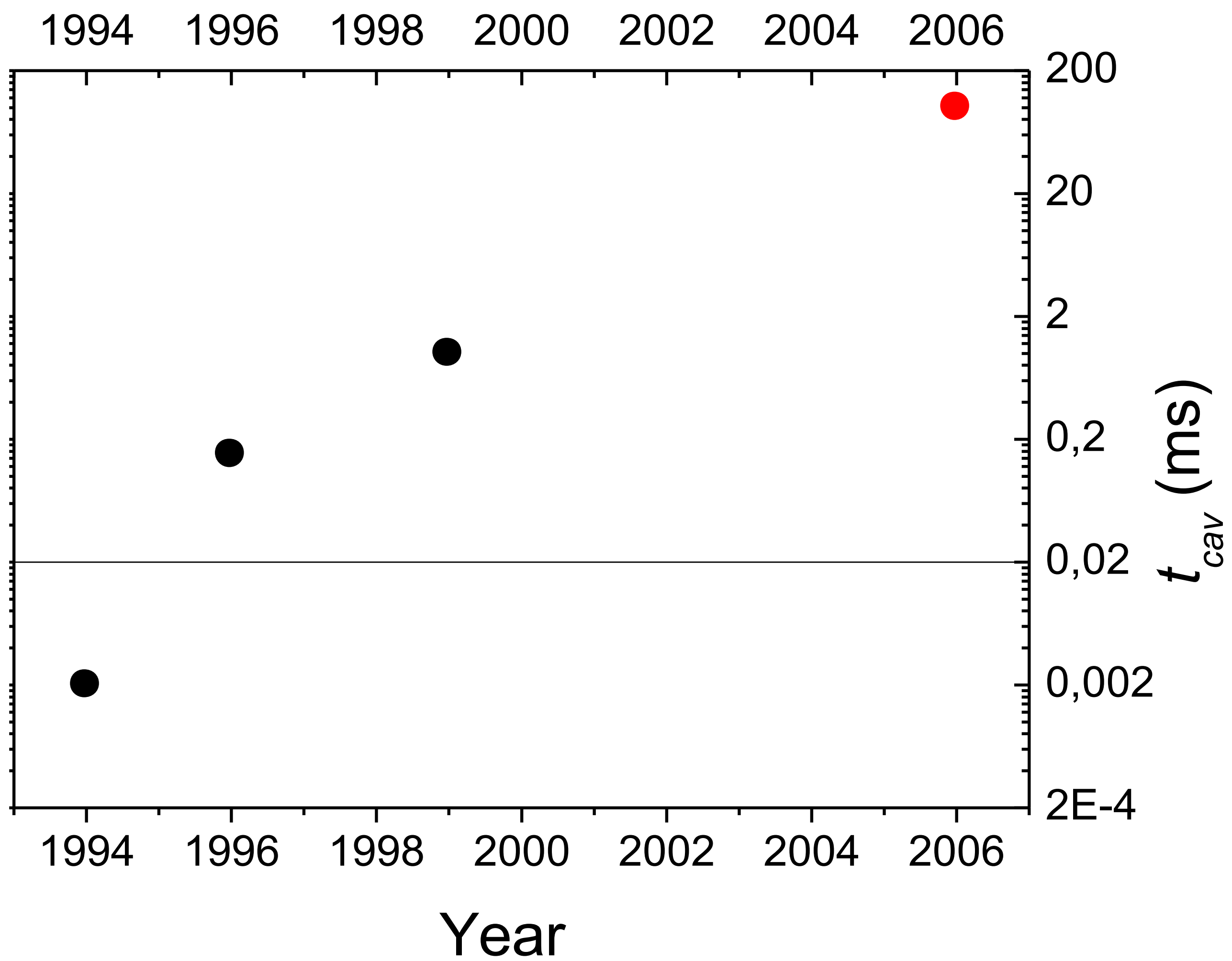
Département de Physique de l'Ecole Normale Supérieure, Laboratoire de Spectroscopie Hertzienne, 24 rue Lhomond, F-75231 Paris CEDEX 05, France

(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.

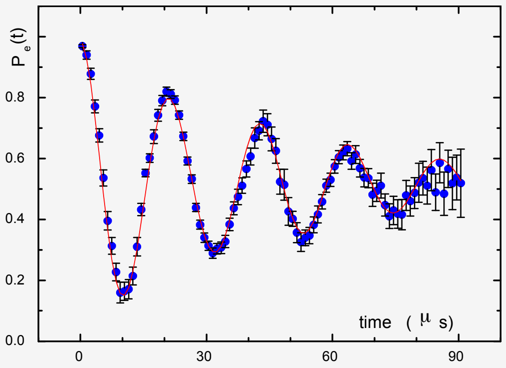
The photon box for QND photon counting

- Our version of Moore's law:

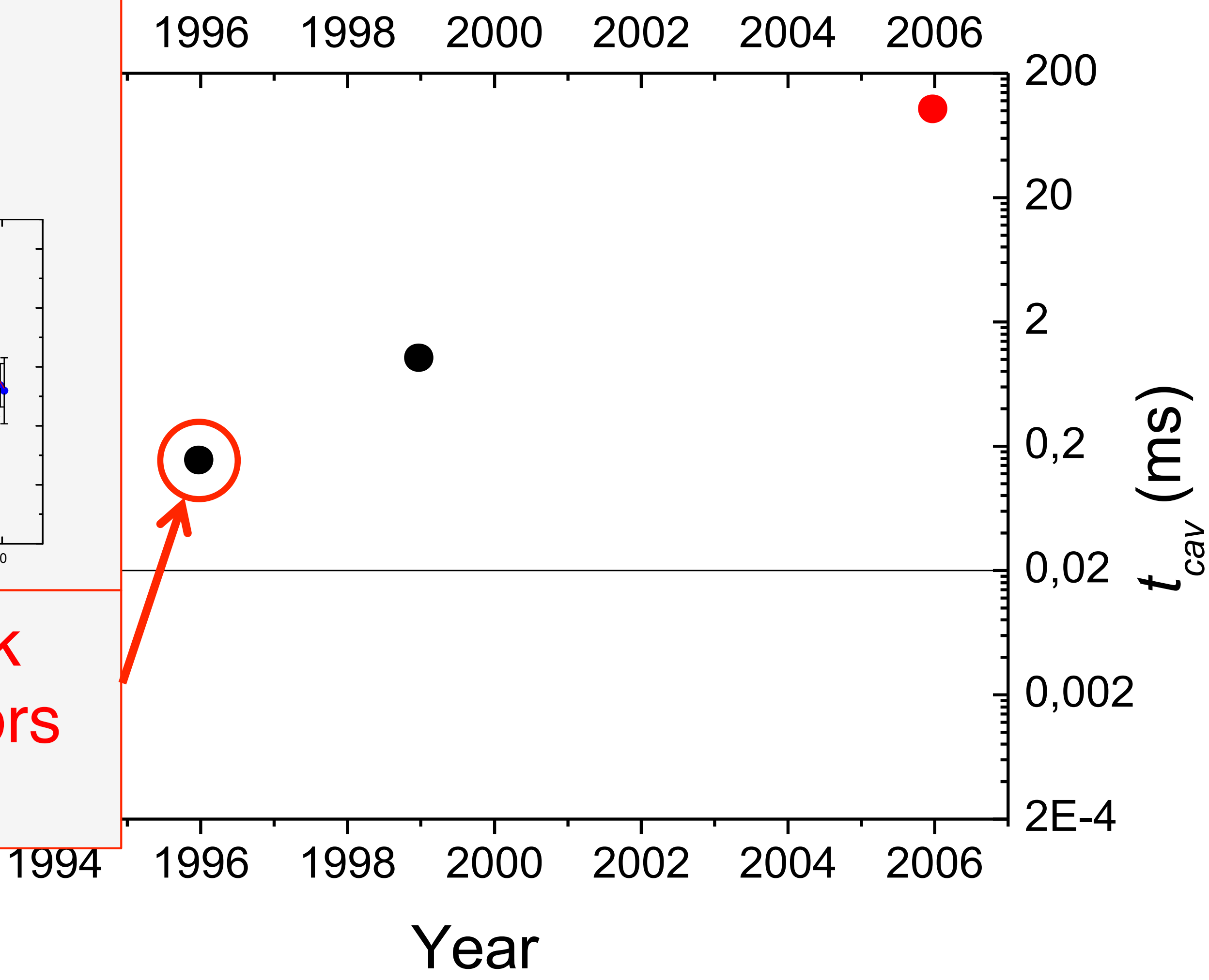


The vacuum Rabi oscillation

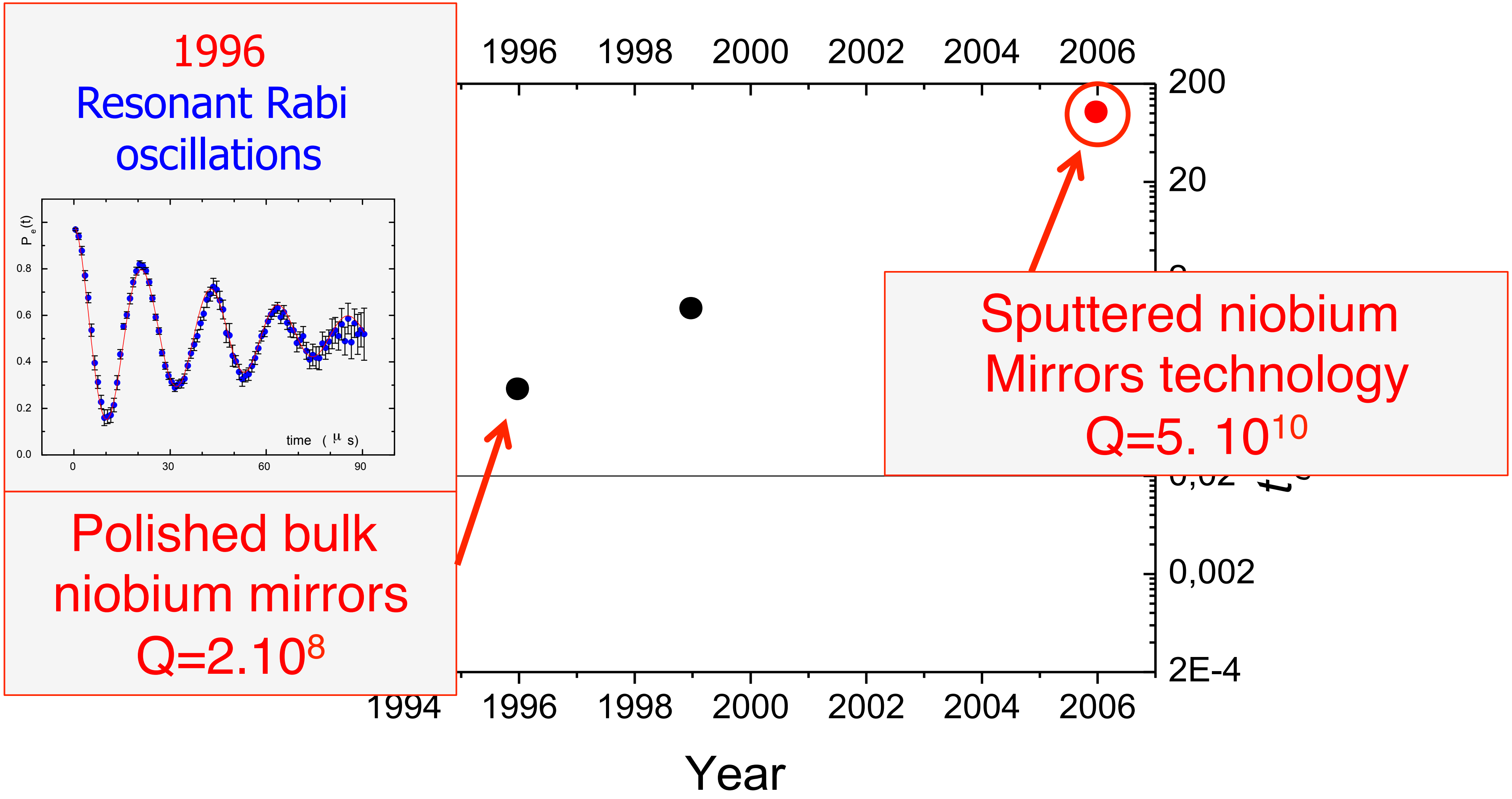
1996
Resonant Rabi oscillations



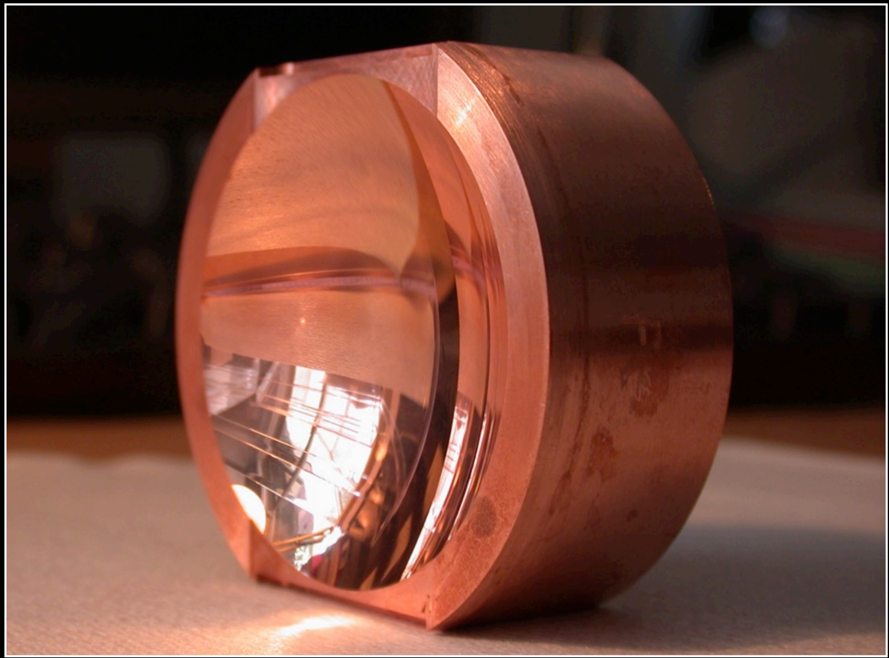
Polished bulk niobium mirrors
$Q=2.10^8$



New cavity technology



Niobium coated copper mirrors

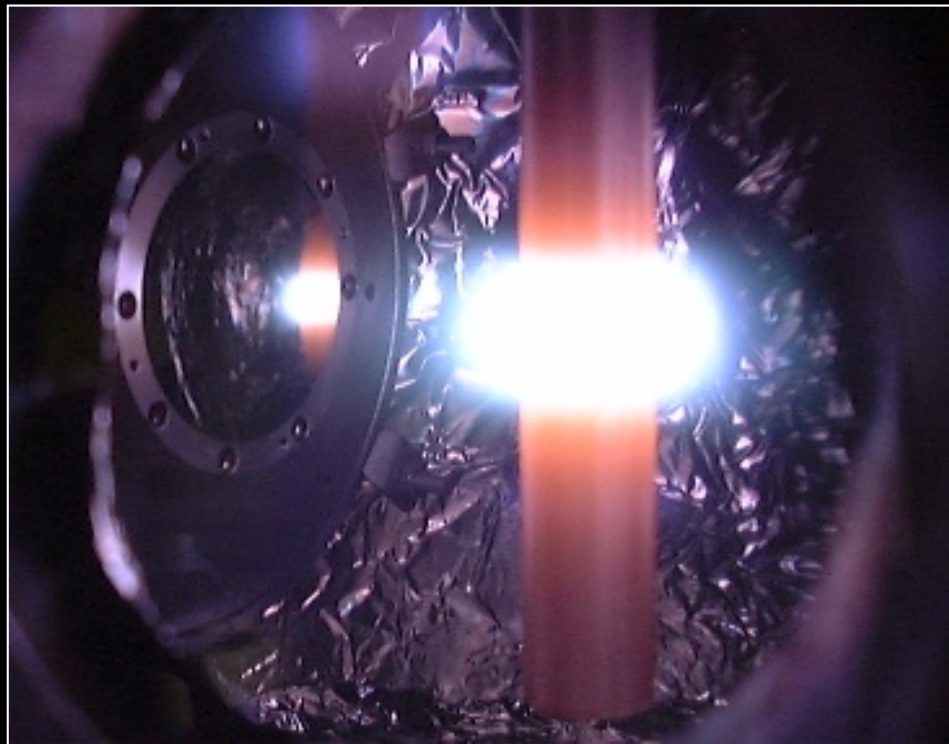


- Sputter 12 µm of Nb

  Particles accelerator technique

  Process done at CEA, Saclay

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



- Copper mirrors

  Diamond machined

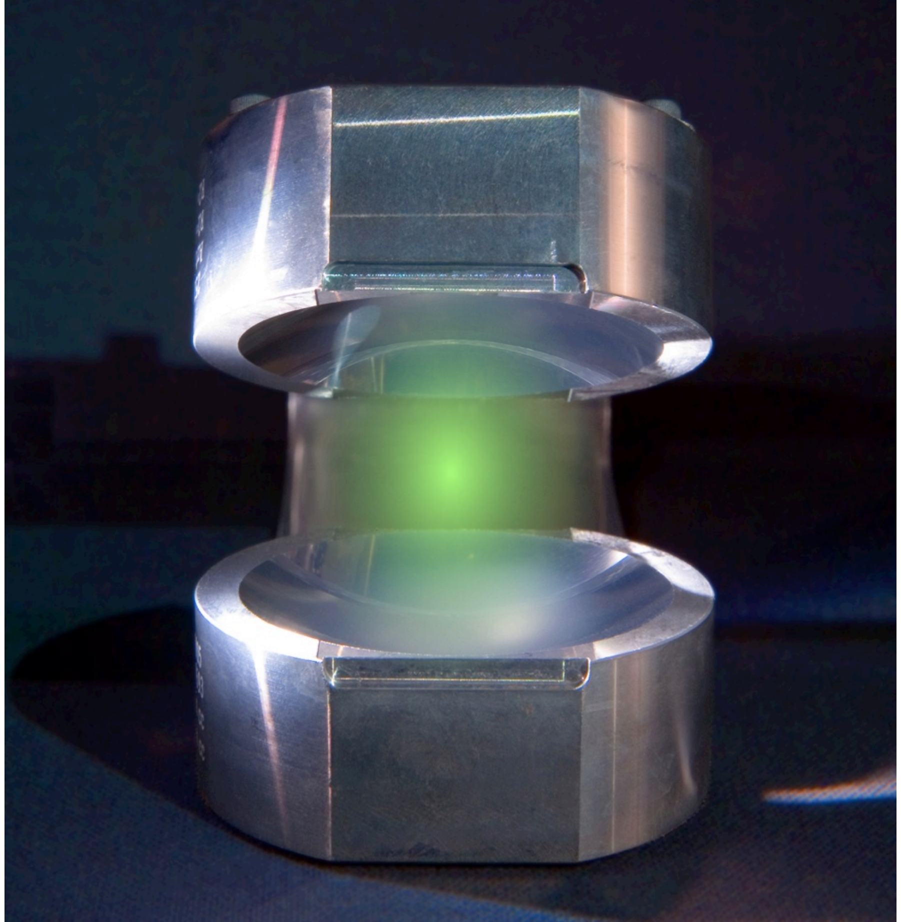
  ~1 µm ptv form accuracy

  ~10 nm roughness

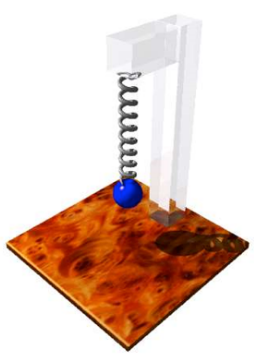
  Toroidal è single mode

The best photon box

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



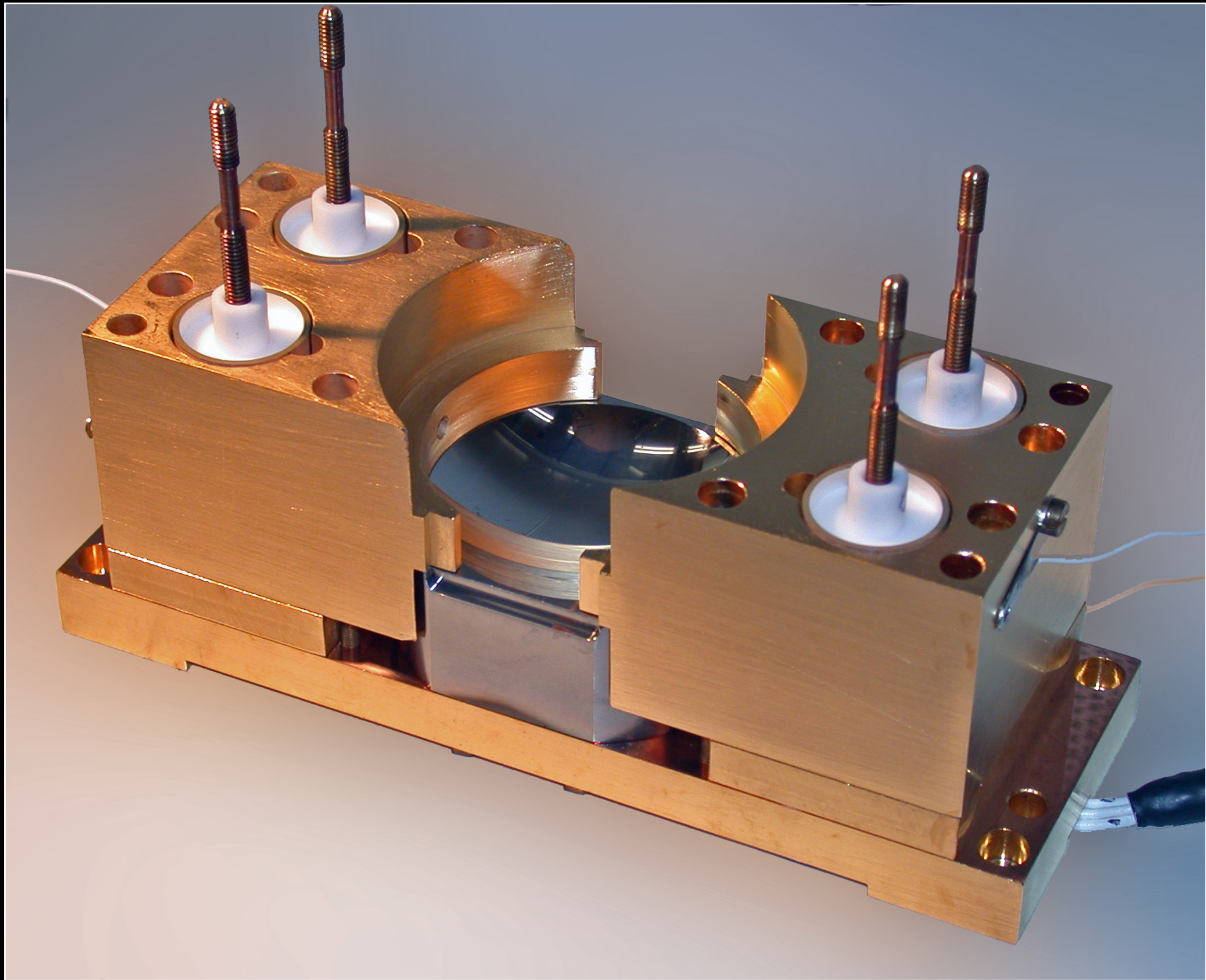
$$T_{cav} = 130 \text{ ms}$$



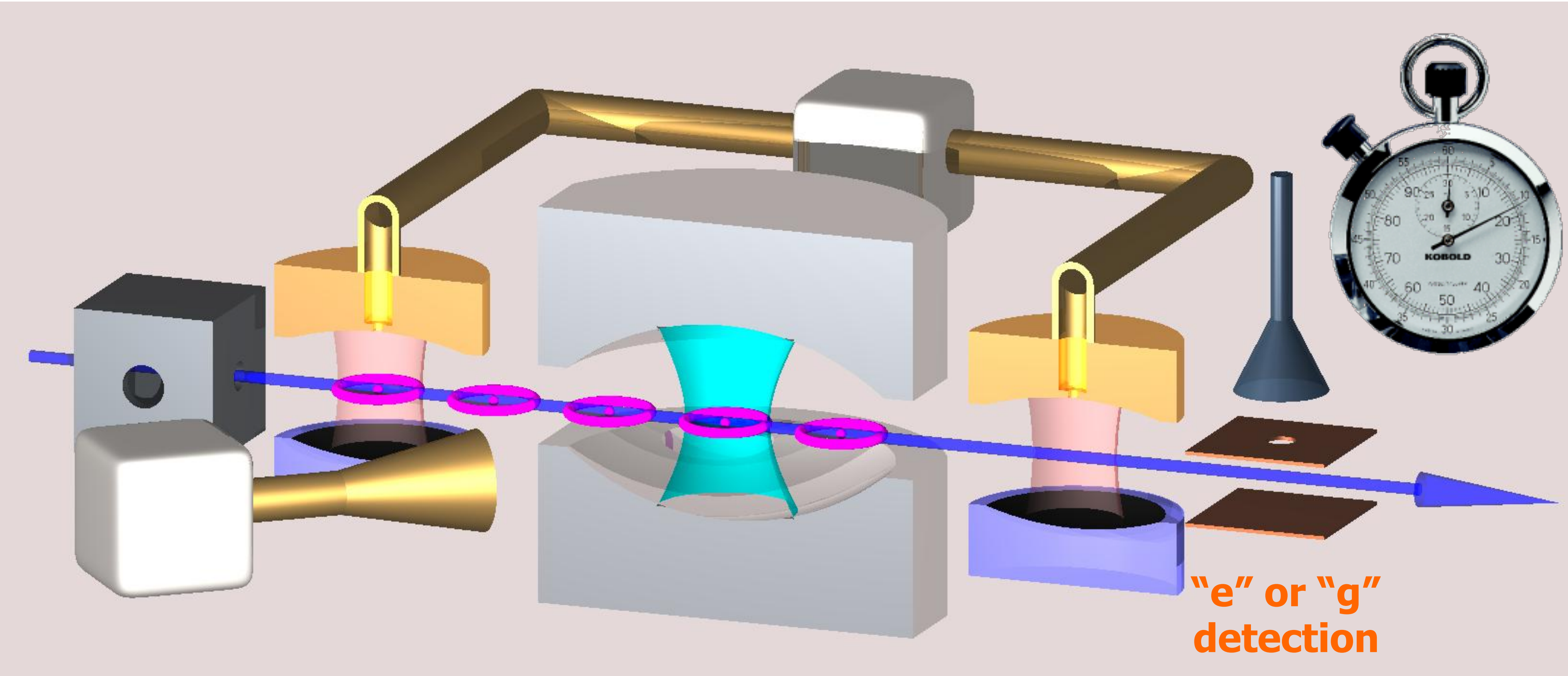
- Q factor = $4.2 \cdot 10^{10}$
- finesse= $4.\ 10^{9}$

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

A new cavity setup



Experimental setup: an atomic clock

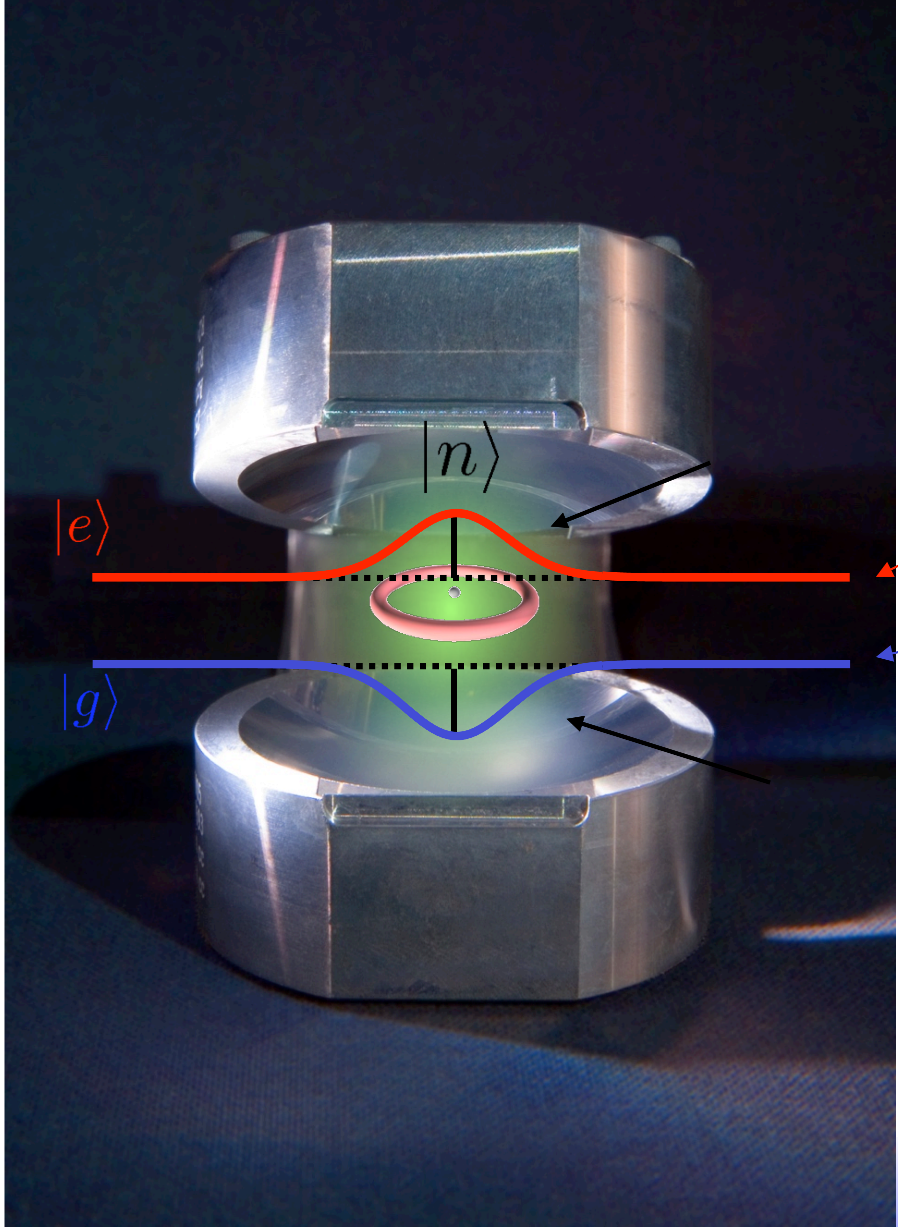


- An atomic clock (Ramsey setup) made of Rydberg for probing light-shifts induced by "trapped" photons

- 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

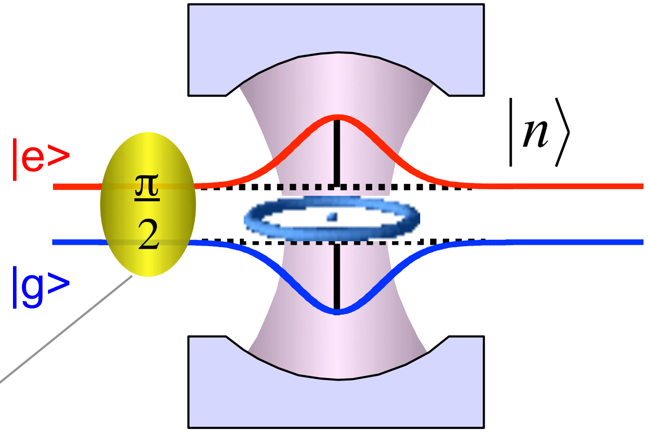
$$\Delta E_e = \hbar \frac{\Omega_0^2}{4\delta}(n+1)$$

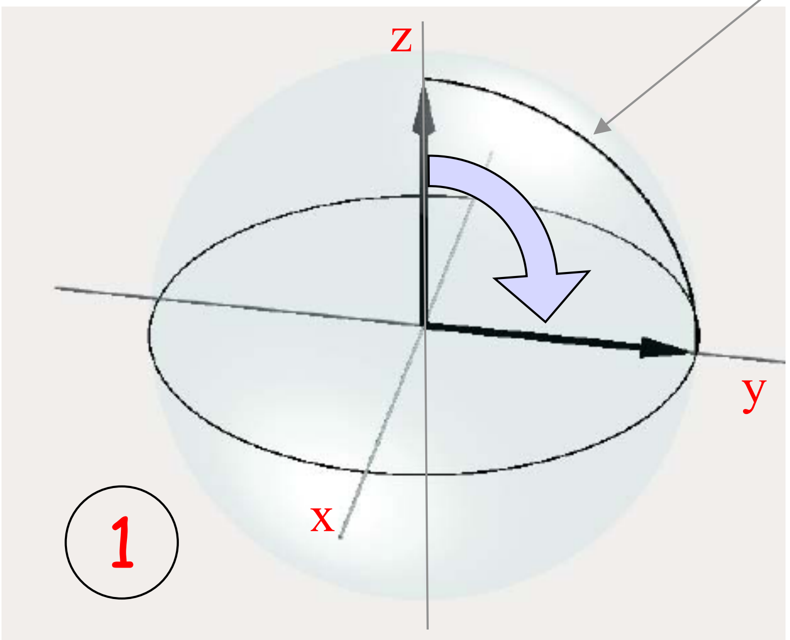
$$\Delta E_g = -\hbar \frac{\Omega_0^2}{4\delta} n$$

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 π/2 rotation around the Ox axis

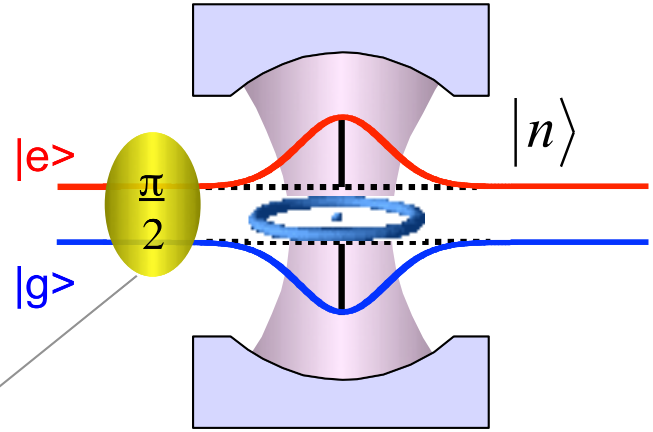
QND detection of 0 or 1 photon

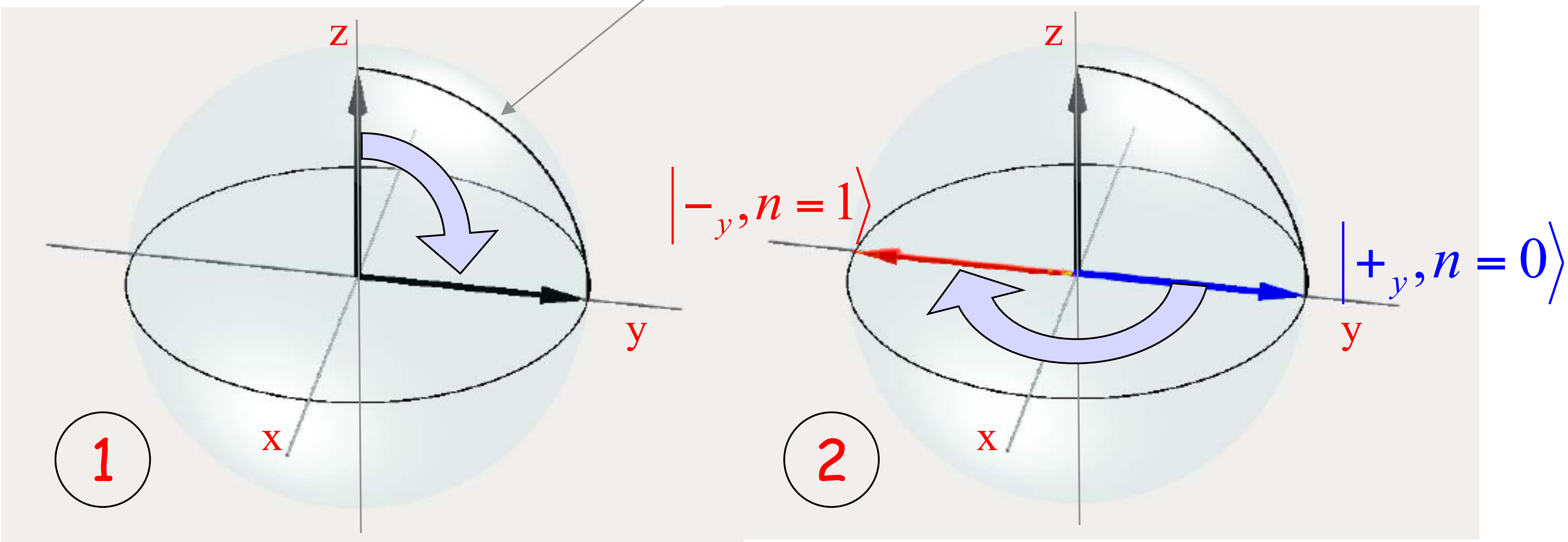
1. Trigger of the clock.

2. precession of the spin through the cavity during T

Phase shift per photon

$$\Phi_0 = \pi$$





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

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

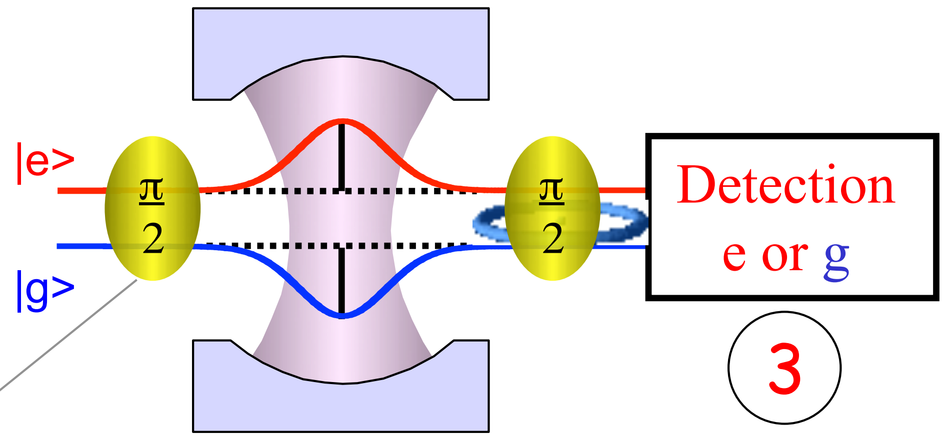
rotation by angle $\phi = \delta_{\mathrm{mw}} T$ around the Oz axis

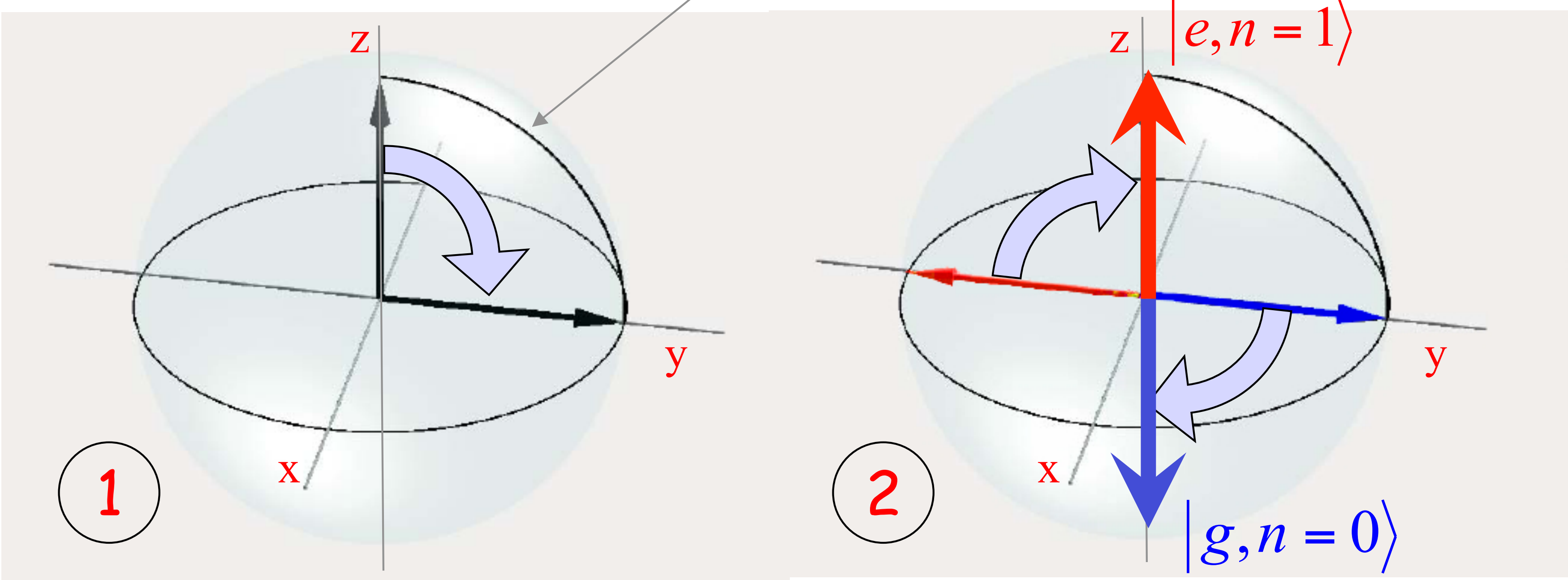
QND detection of 0 or 1 photon

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





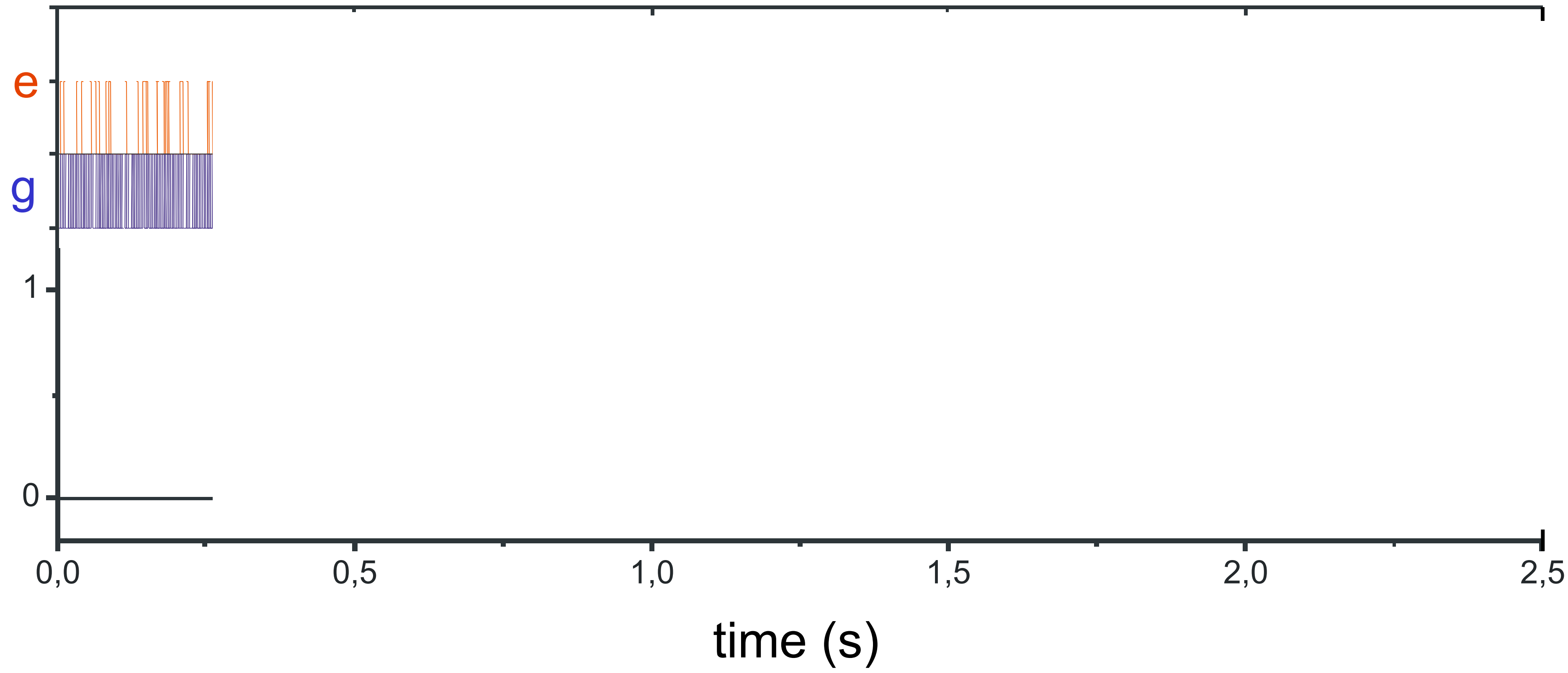
Atom detected in e ➡ field projected on |1>

g ➡ field projected on |0>

Detecting blackbody photons

g ➡ field projected on |0>

e ➡ field projected on |1>

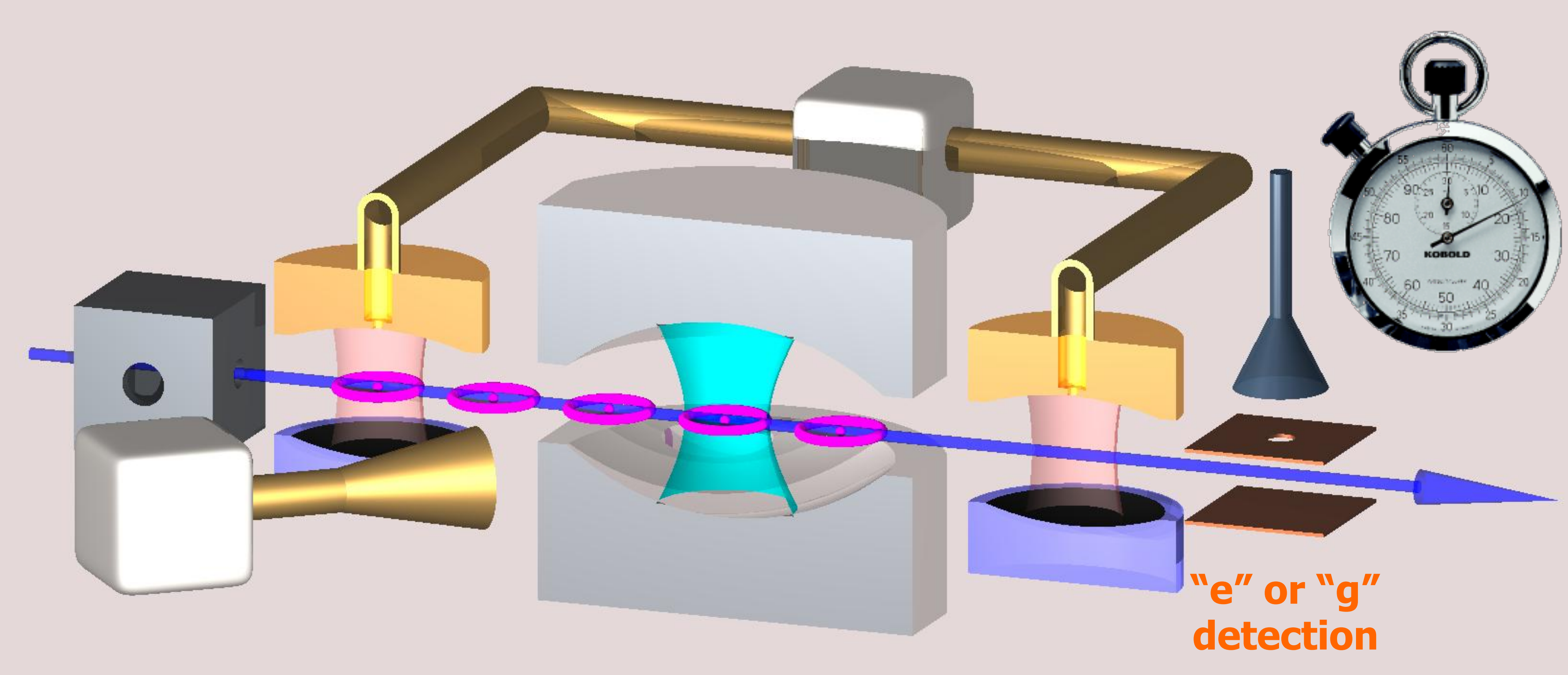


$T = 0.8\ \mathrm{K} \ \longrightarrow \ n_{th} = 0.05$ (proba. of $n=2$ is negligible)

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

2. QND counting more than 1 photons

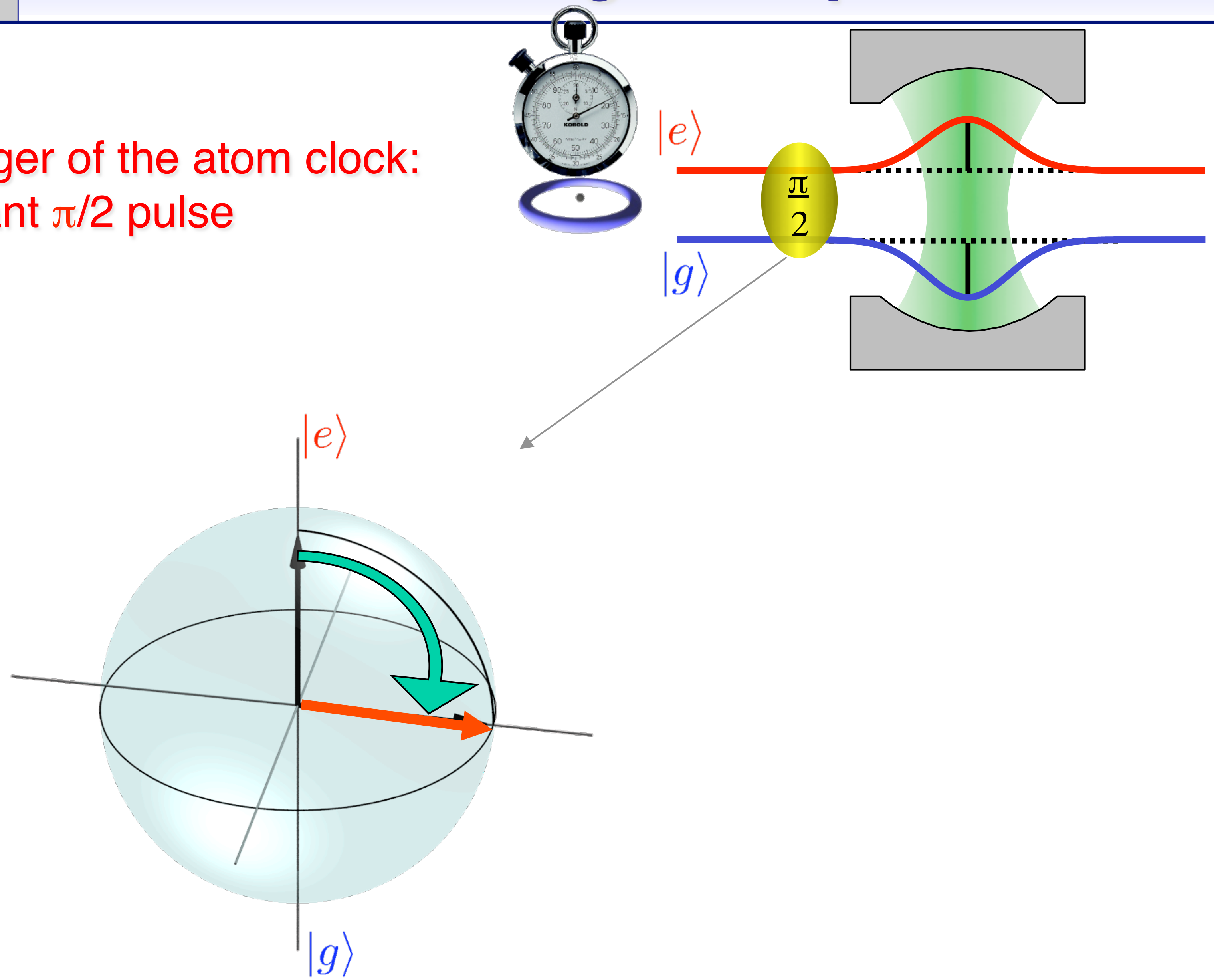
Experimental setup: an atomic clock



Use again the same atomic clock

Seeing more photons

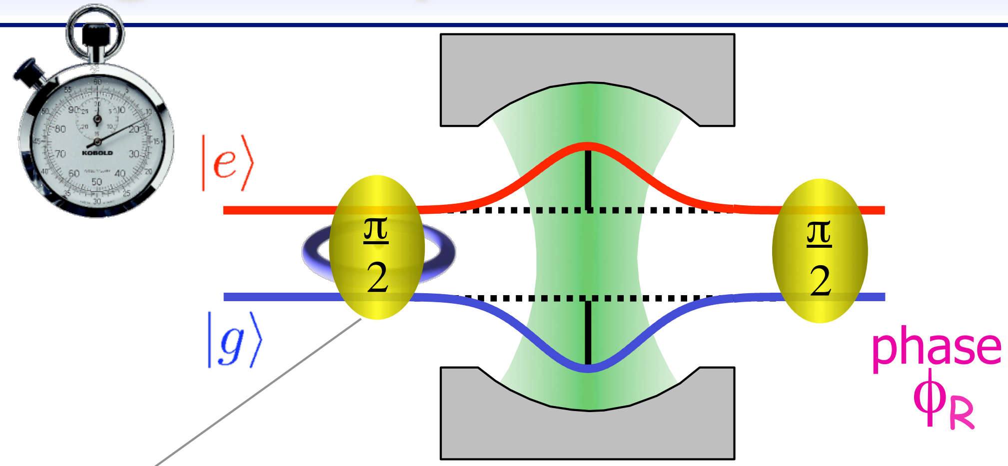
1. Trigger of the atom clock: resonant π/2 pulse

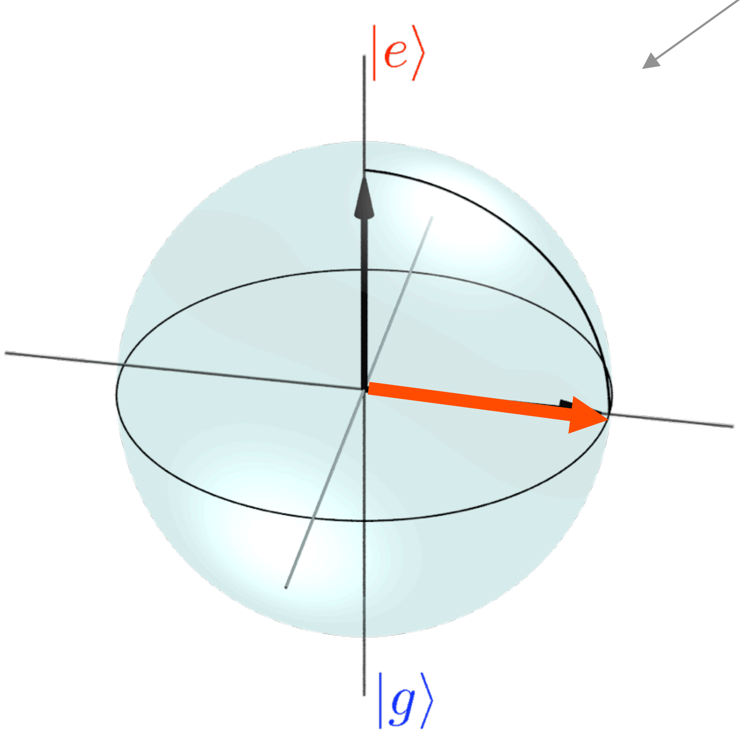


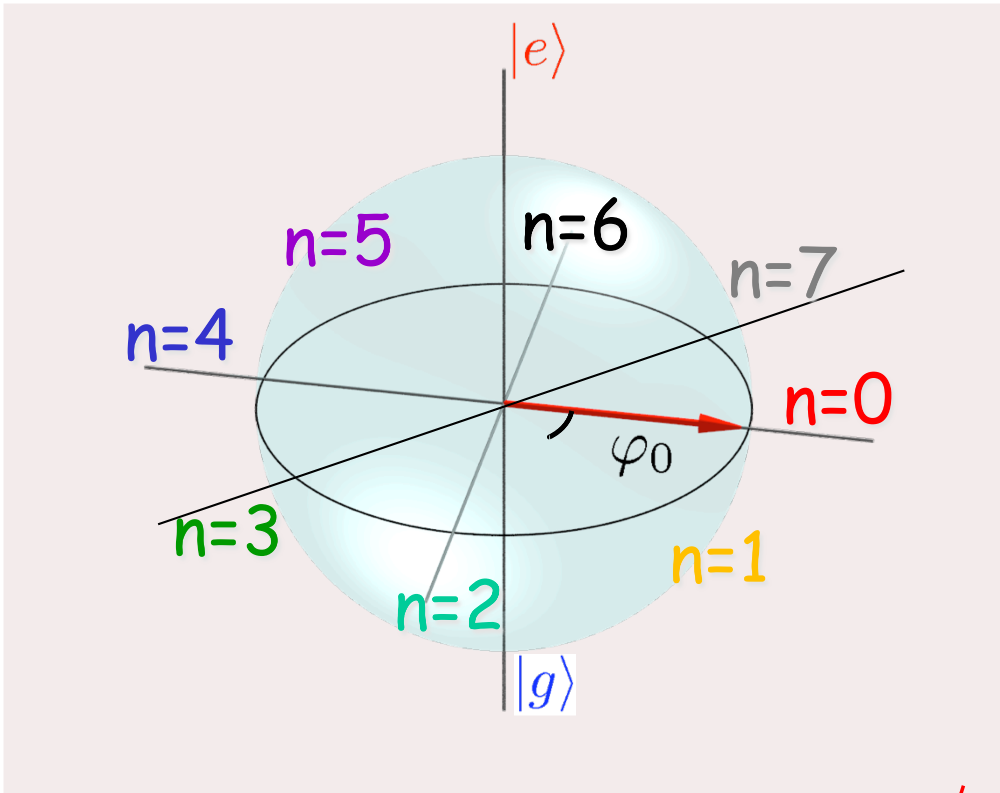
Seeing more photons

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

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

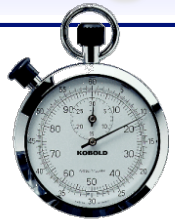


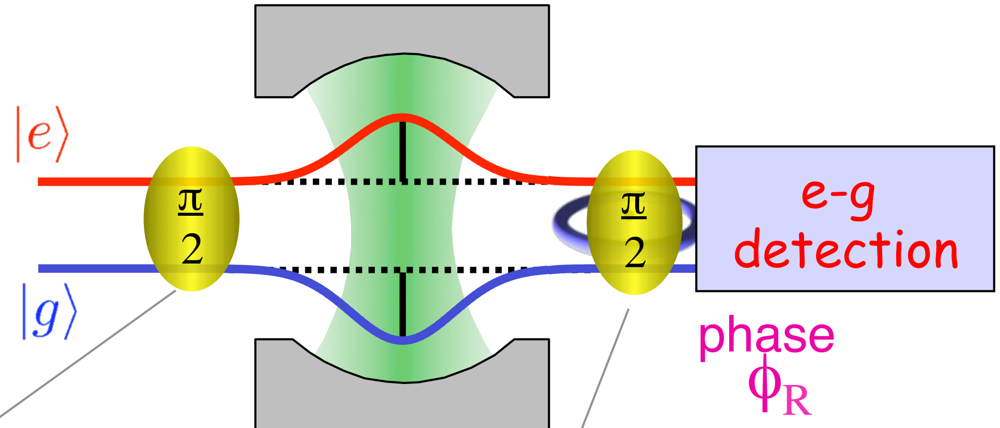




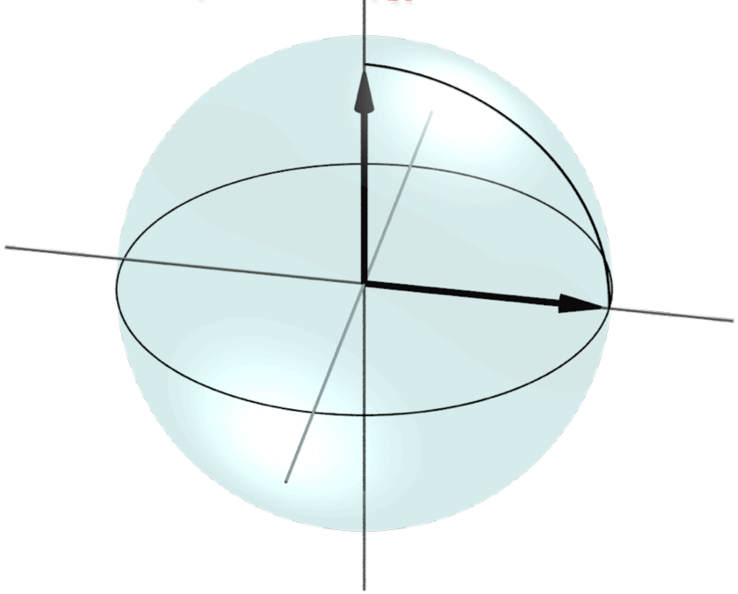
Larger detuning ➞ phase shift per photon reduced to $\Phi_0 = \pi/4$

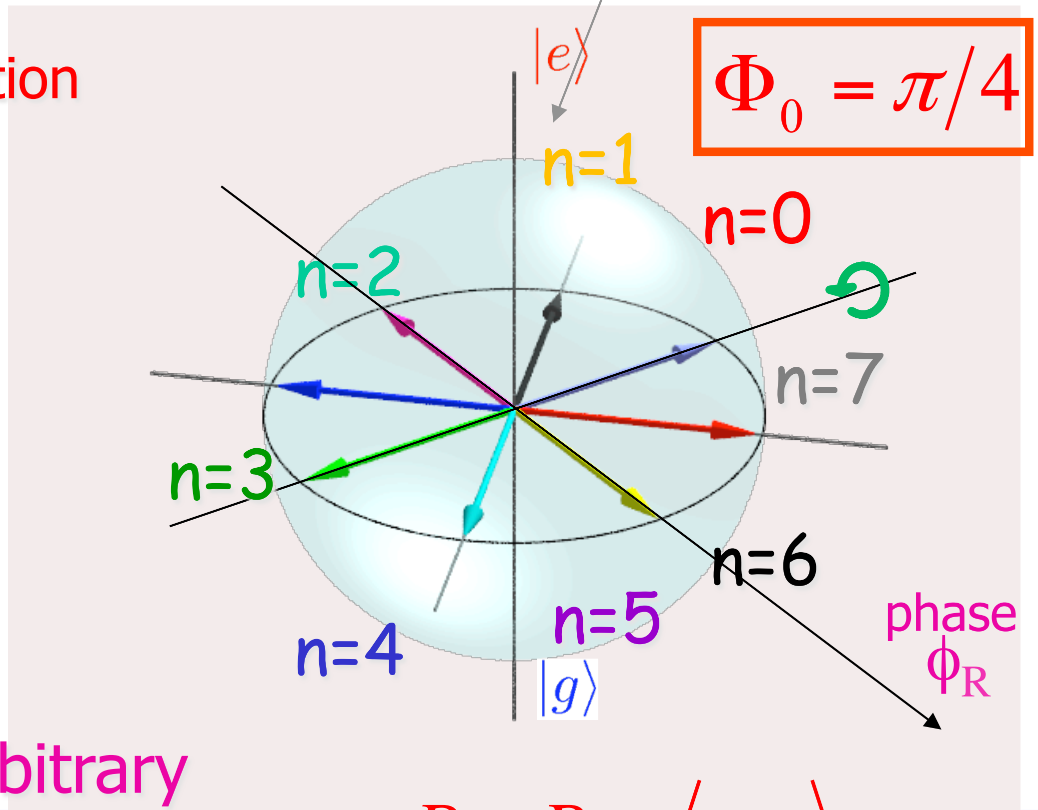
Seeing more photons





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

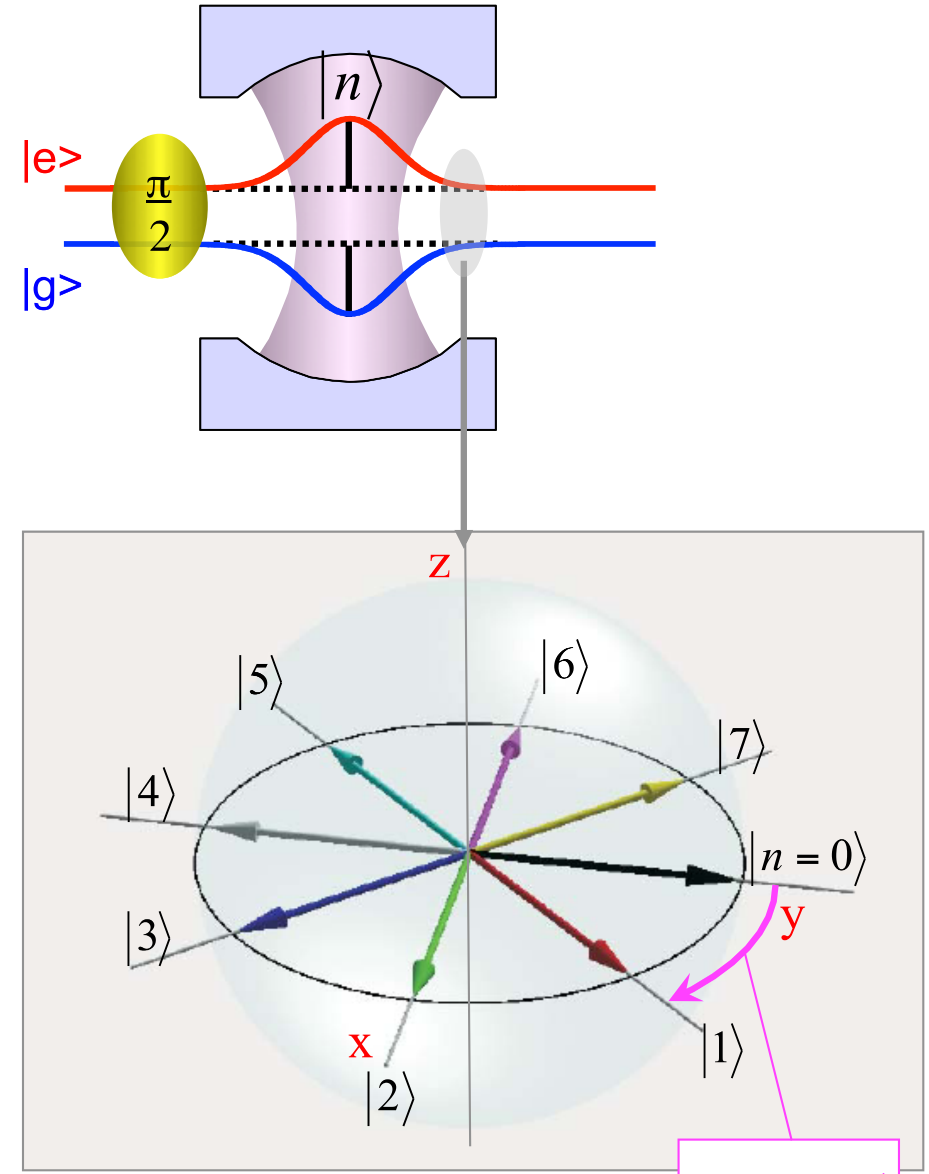




Pseudo-spin measurement in arbitrary direction determined by ϕ_R

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

Detection of $n>1$



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

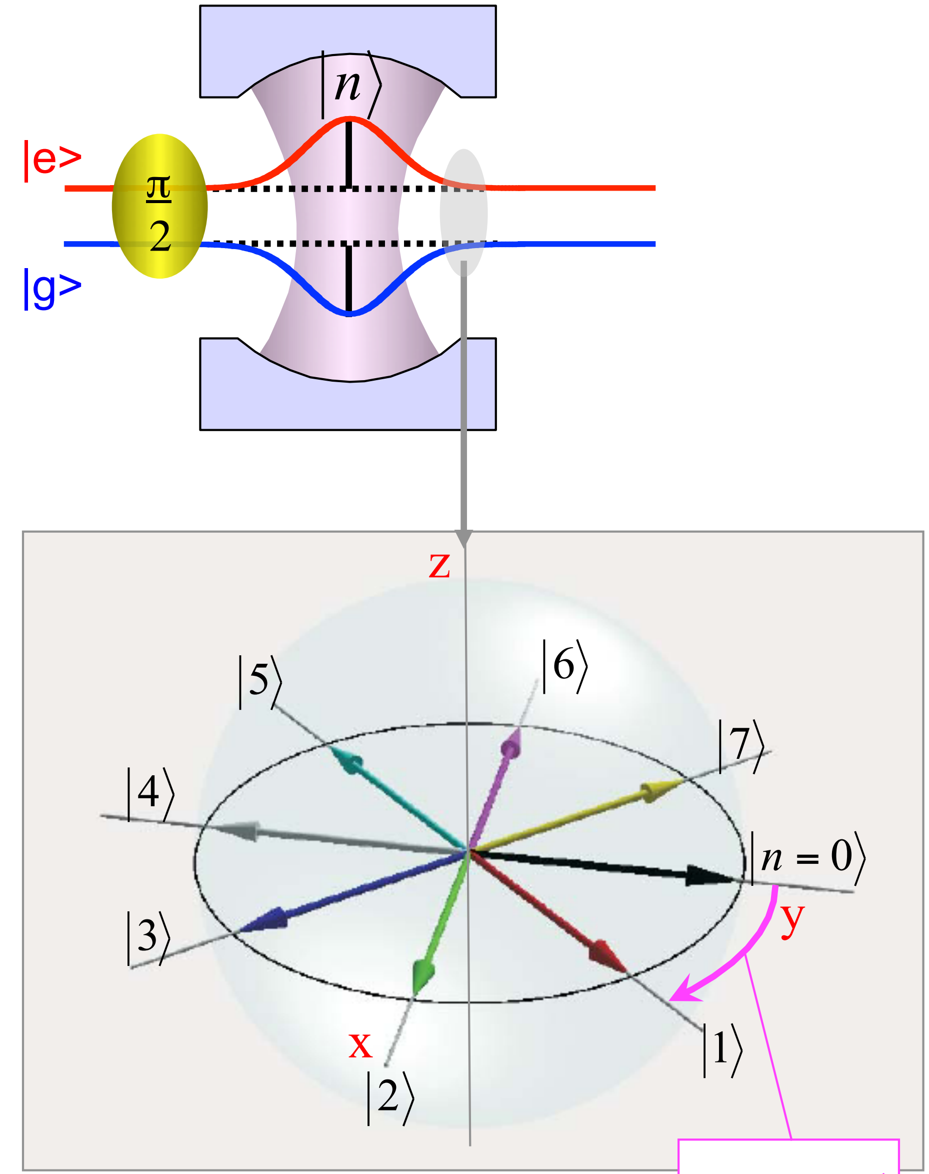
Chose $\Phi_0 = \frac{\pi}{4}$

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

But hese states are not orthogonal

⇒ detecting one atom is not enough to determine n.

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

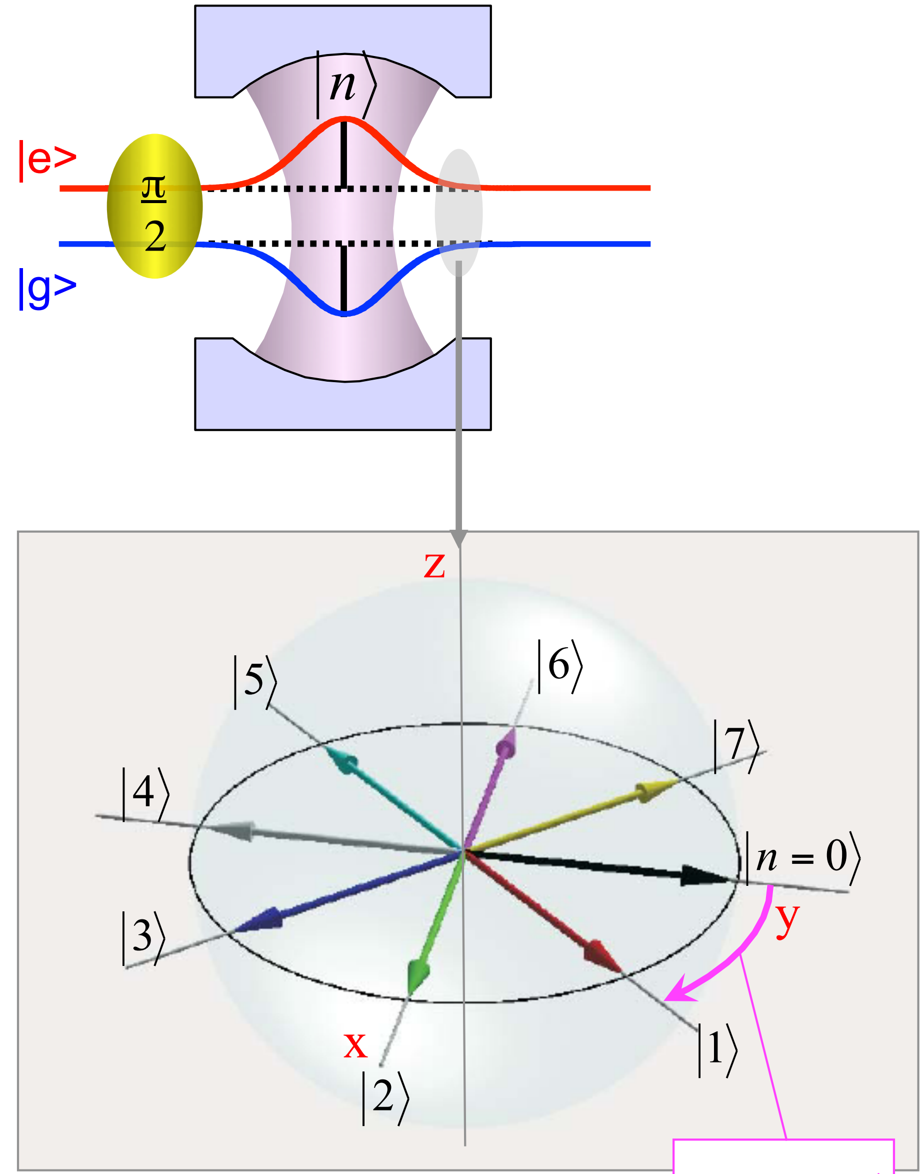
$$\left|\Psi\right\rangle = \sum_n \left|+_{n\,\Phi_0}\right\rangle^N \otimes \left|n\right\rangle$$

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

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

Orthogonal states if N large enough

Detection of n>1



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

Interaction with one atom prepares:

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

⇒ Repeat measurement

N atoms

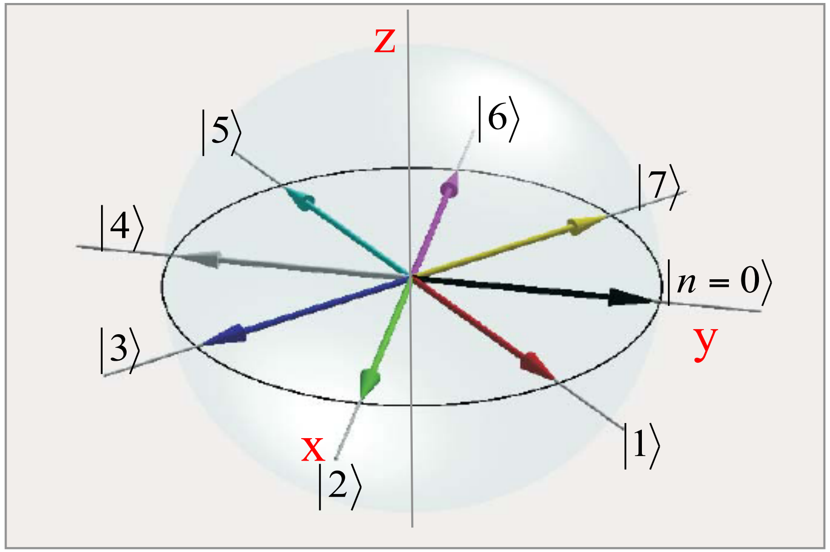
$$|\Psi\rangle = \sum_n \left|+_{n\Phi_0}\right\rangle^N \otimes |n\rangle$$

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



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

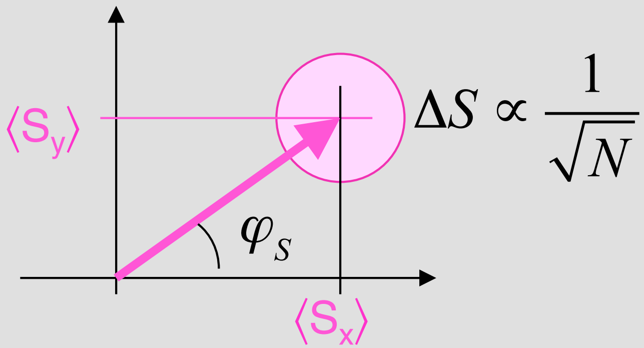
For each n, on detects N identical copies of the atomic state

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

Determination of atom spin by « tomography »:

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

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

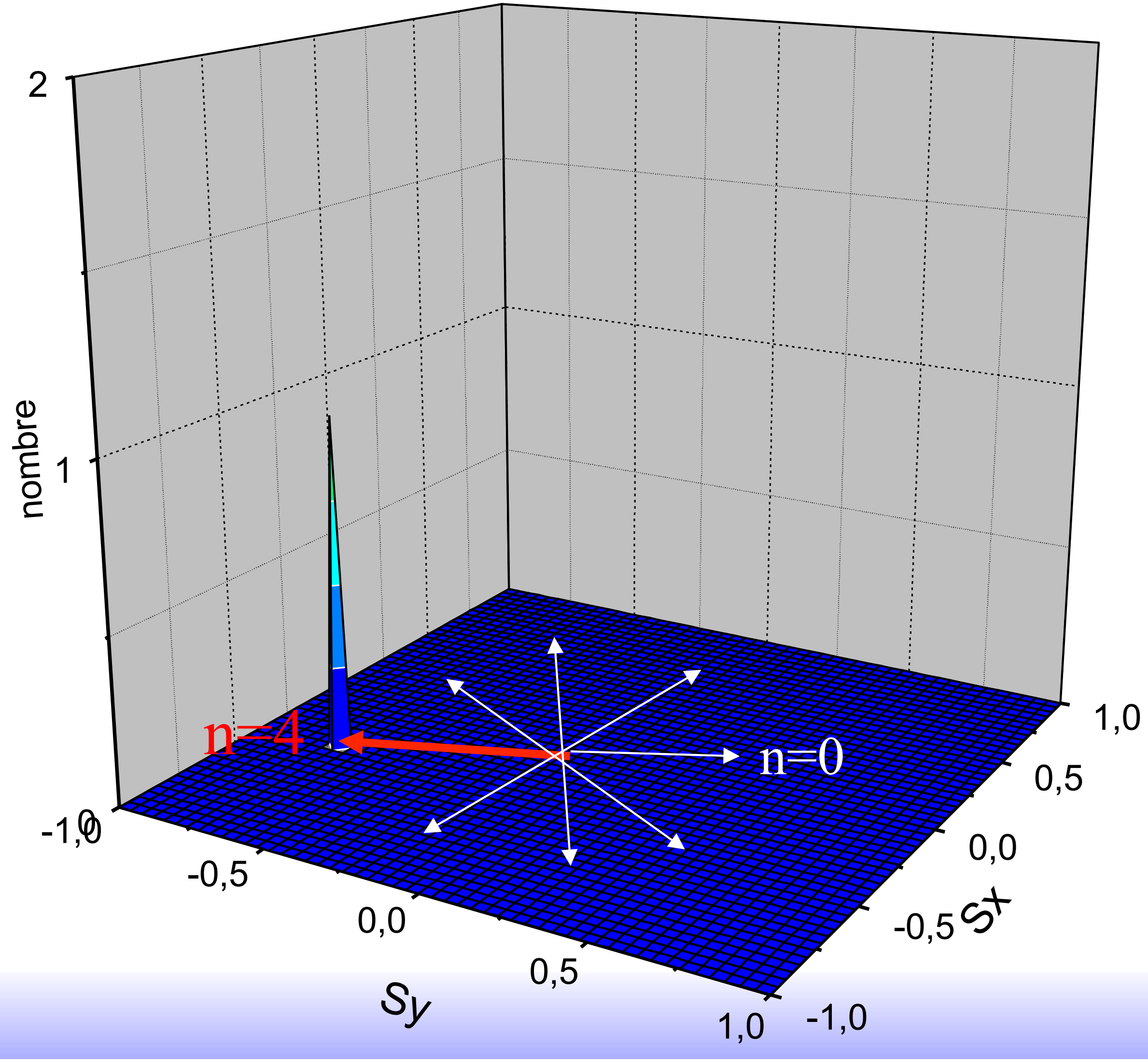


For large enough N, $\Delta\varphi_S \propto \frac{1}{\sqrt{N}} < \Phi_0$ and different photon numbers should be distinguished

Atom spin state tomography

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

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



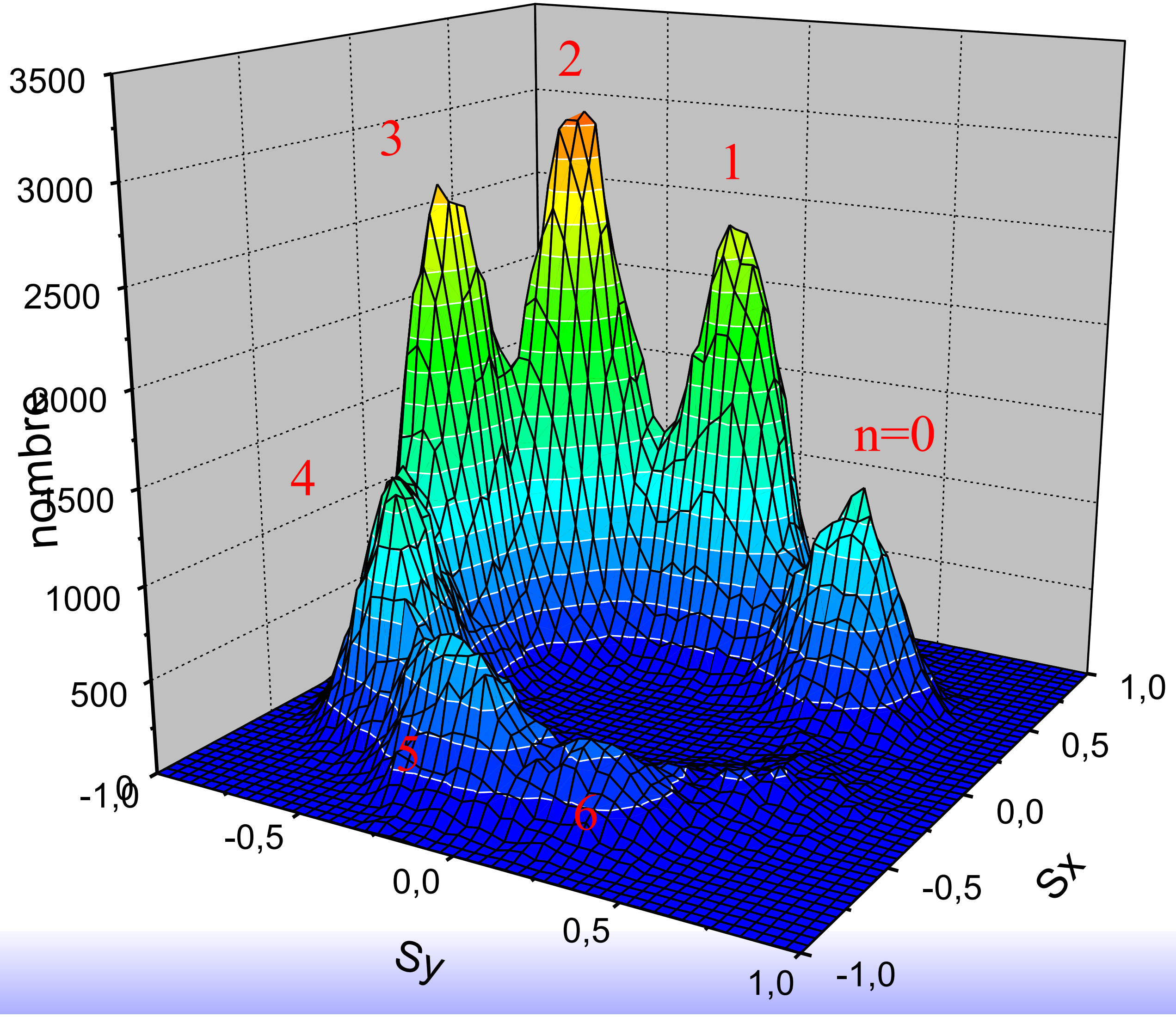
One measurement

➞ n = 4

Atom spin state tomography

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

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



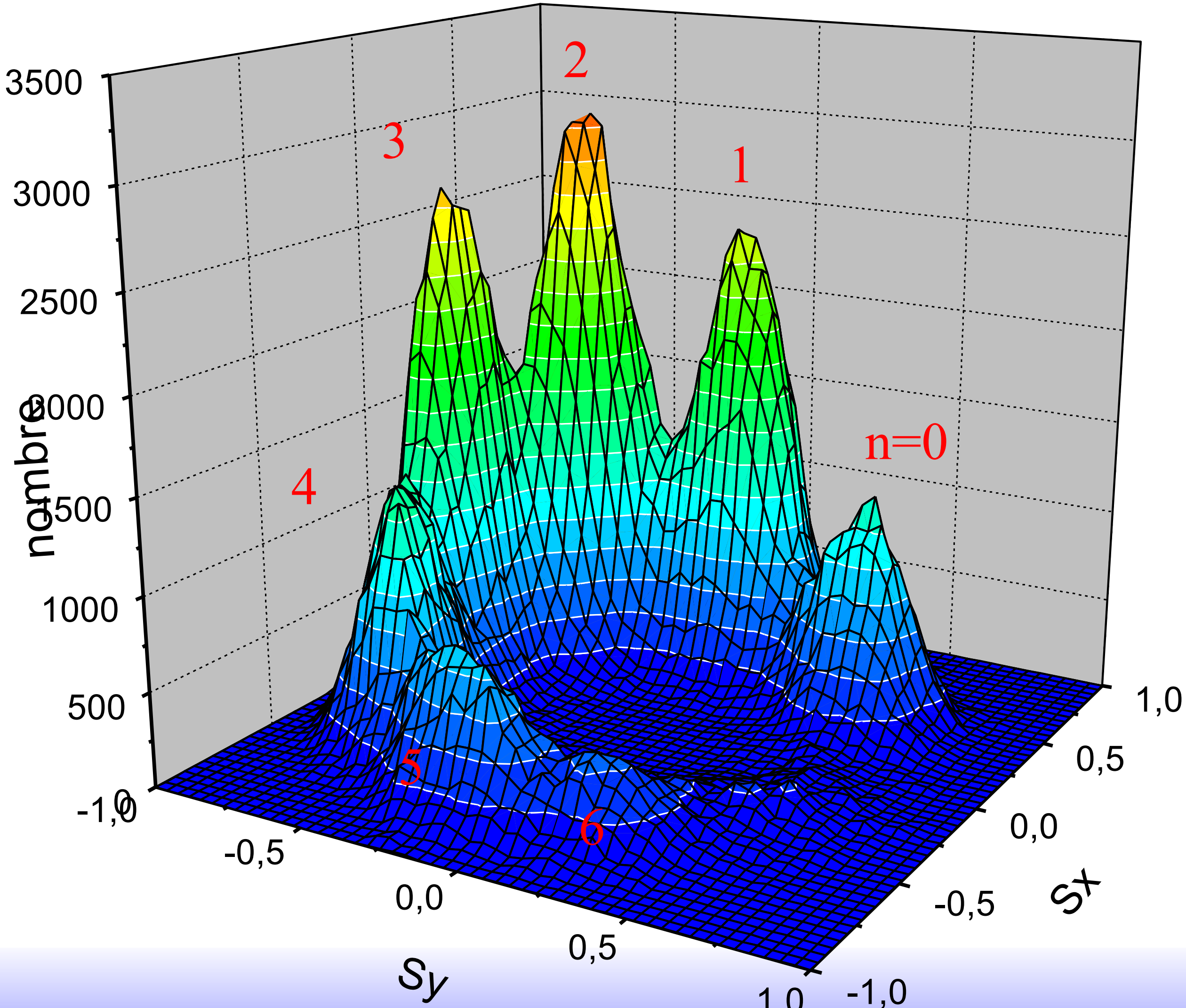
One measurement

➞ n = 4

Repeat many times and accumulate measurement results measurement

Atom spin state tomography

Method: 1- inject a coherent field ⟨n⟩=3.5 photons.
2- detection of 110 consecutive atoms, $T_{measure}$=26 ms



The collective spin of N atoms points in discrete direction
⇒ n is obviously quantized

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

<n>=2.4 photons

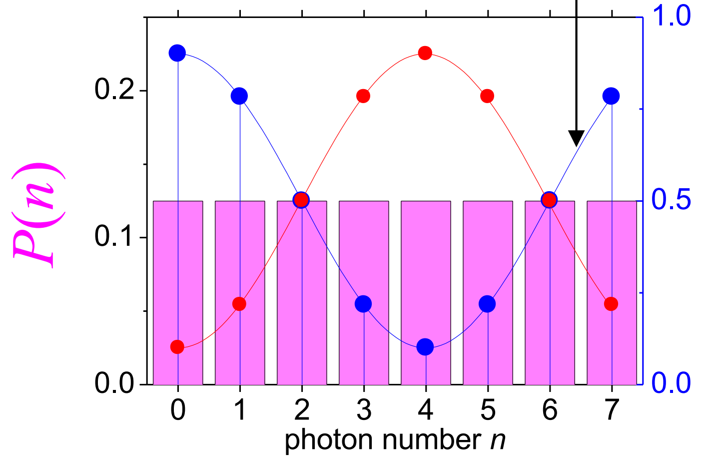
Information acquisition by detecting 1 atom

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

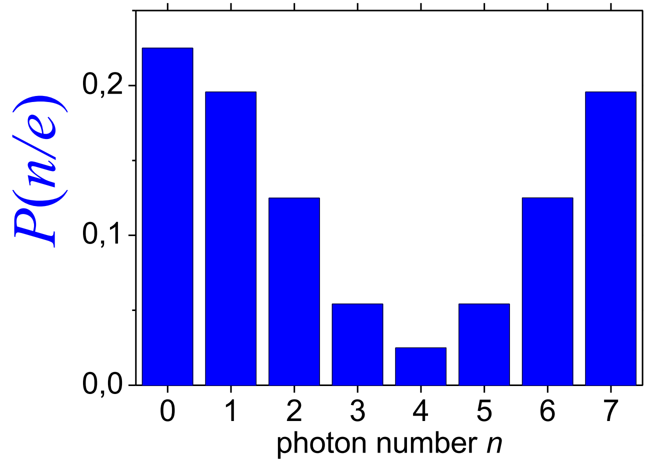
$j_{\phi R} = 1$ or -1
$= e$ or g

$\phi_R = 0$

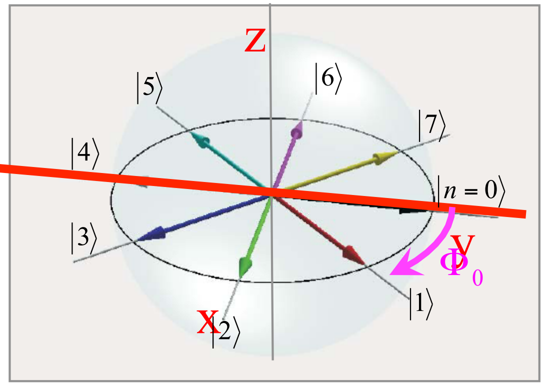
$$P\left(+_{\phi_R} / n\right) = \left|\left\langle +_{\phi_R} \middle| +n \right\rangle\right|^2$$



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

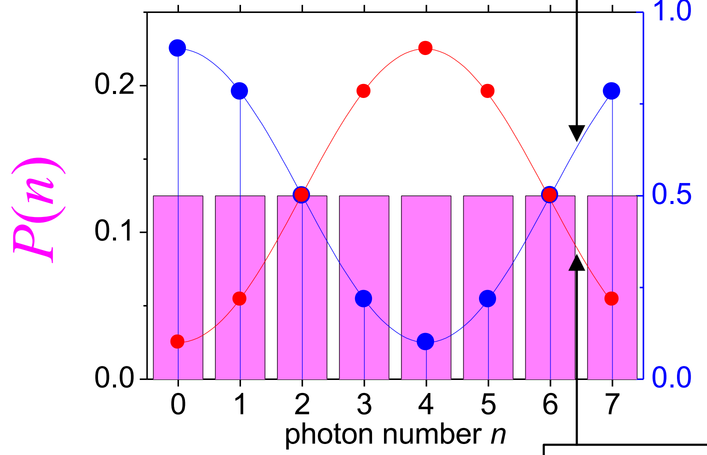
Bayes law:

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

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

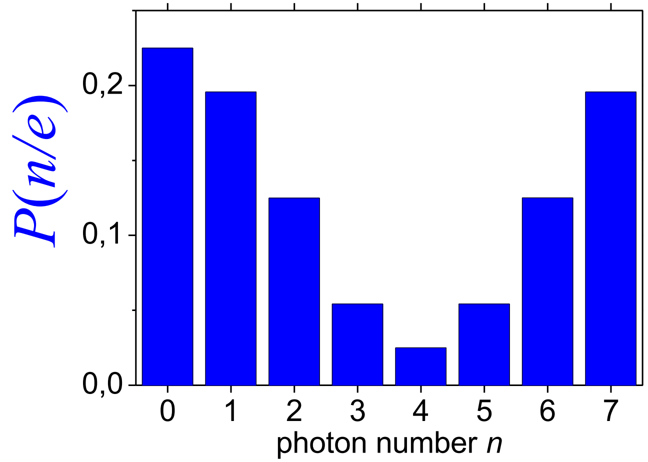
$\phi_R = 0$

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



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

e



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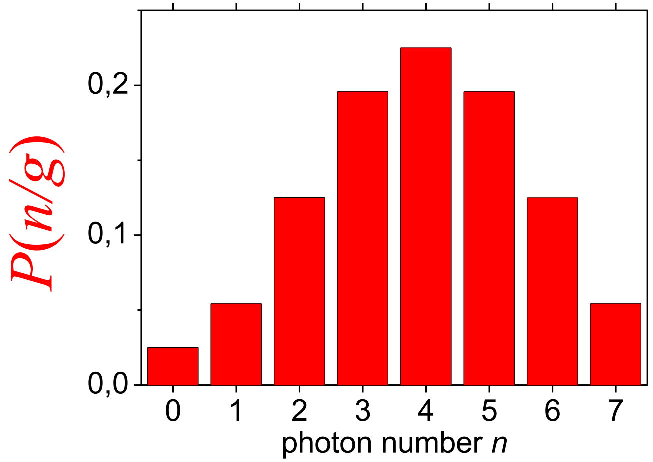
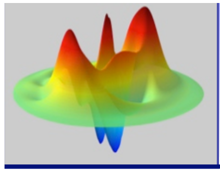


Probability of *n* that are incompatible with the measurement result are cancelled.

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

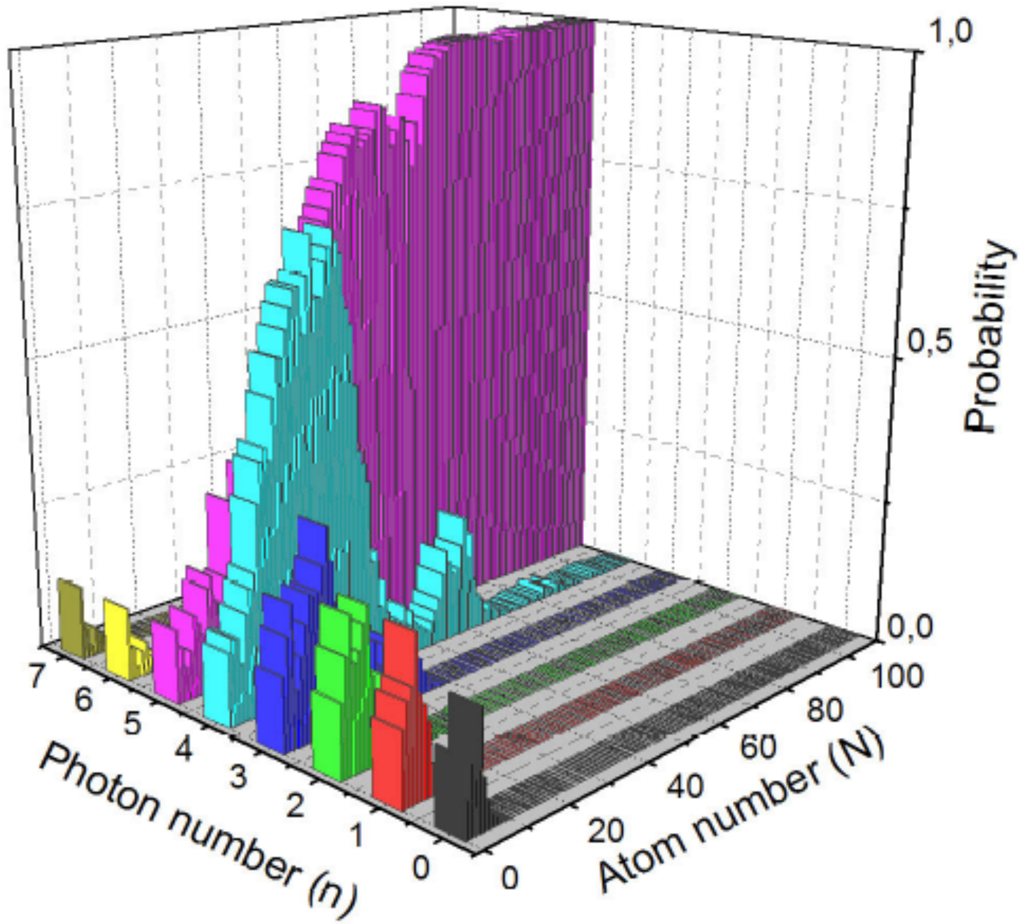


Progressive field collapse

$j(k)$ 11011111111001110110111101010011010101011010111111
$\phi_R(k)$ 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

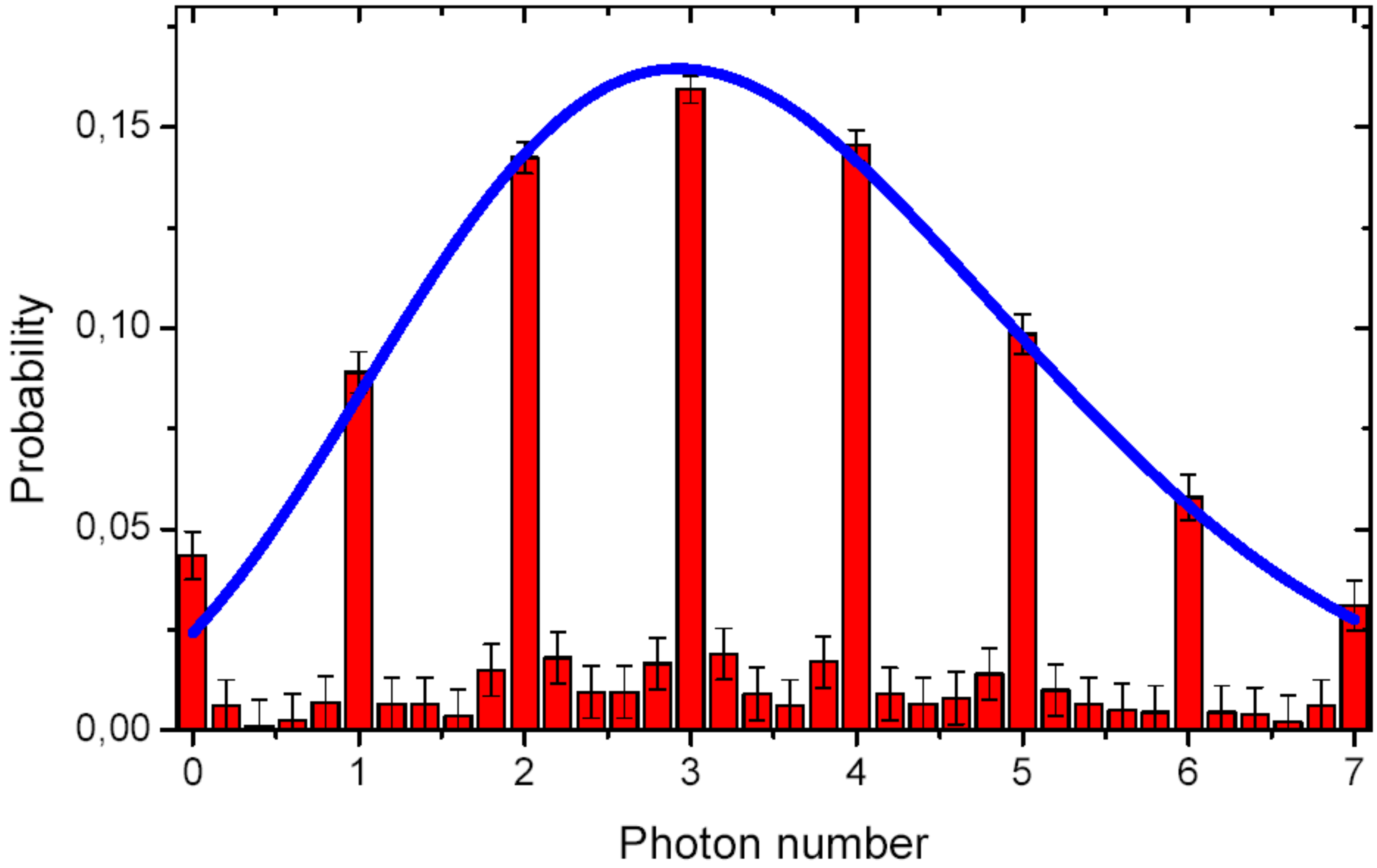
Progressive projection of the field on n=5 number state

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

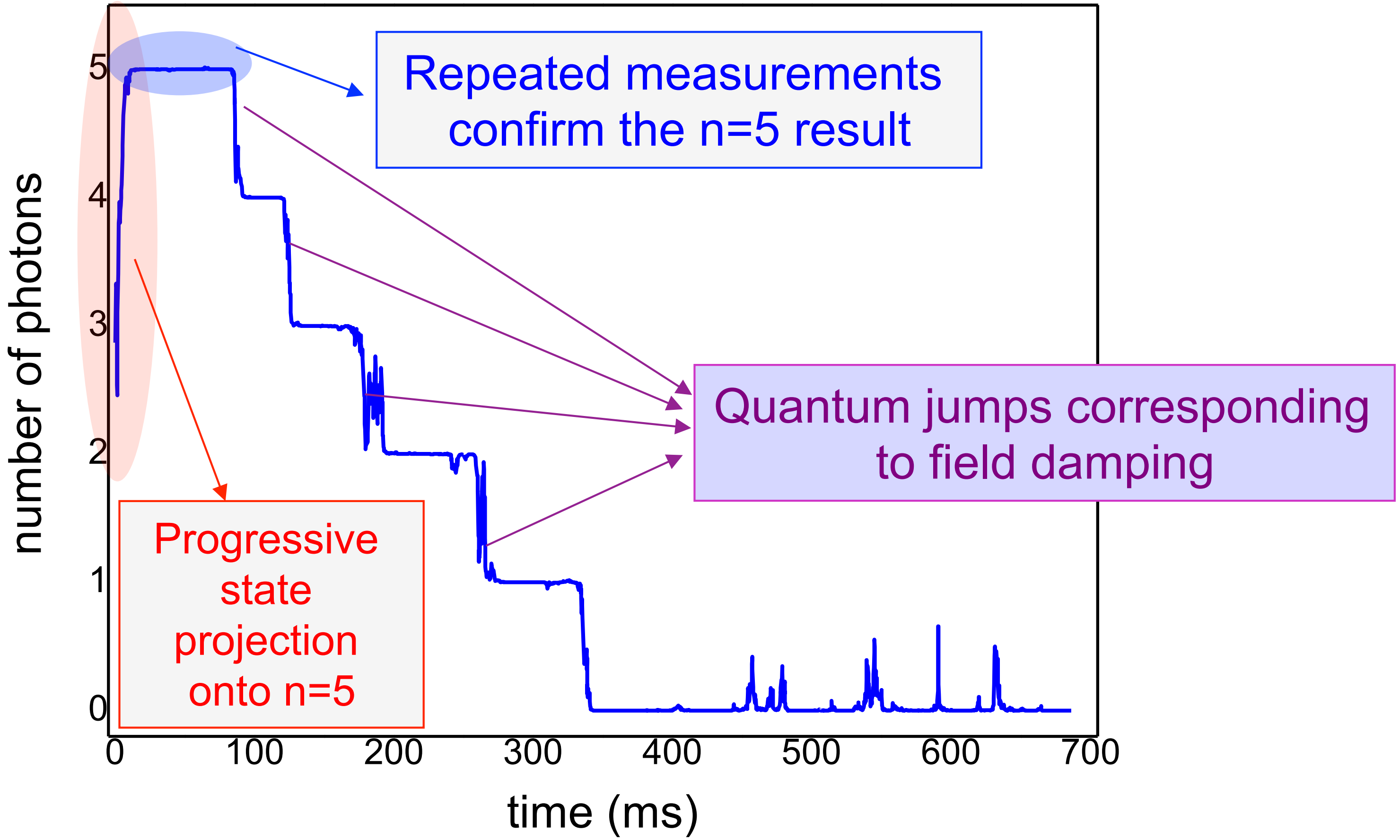
Reconstructing the photon number statistics

Coherent field at measurement time

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



Repeated measurements: evolution of a continuously monitored field

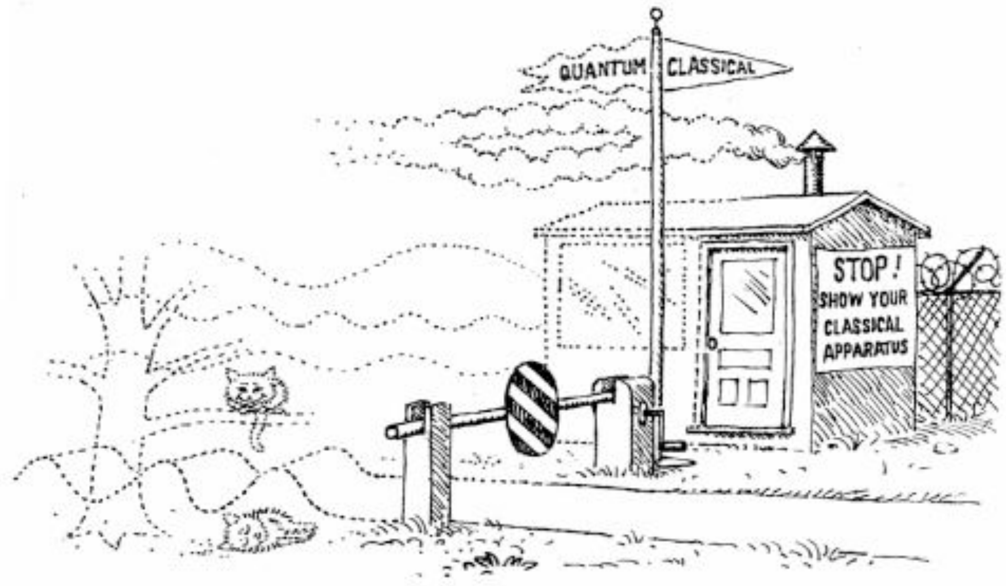


Field evolution due to cavity damping: not to QND measurement

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

3. The "Schrödinger cat" and the quantum measurement problem

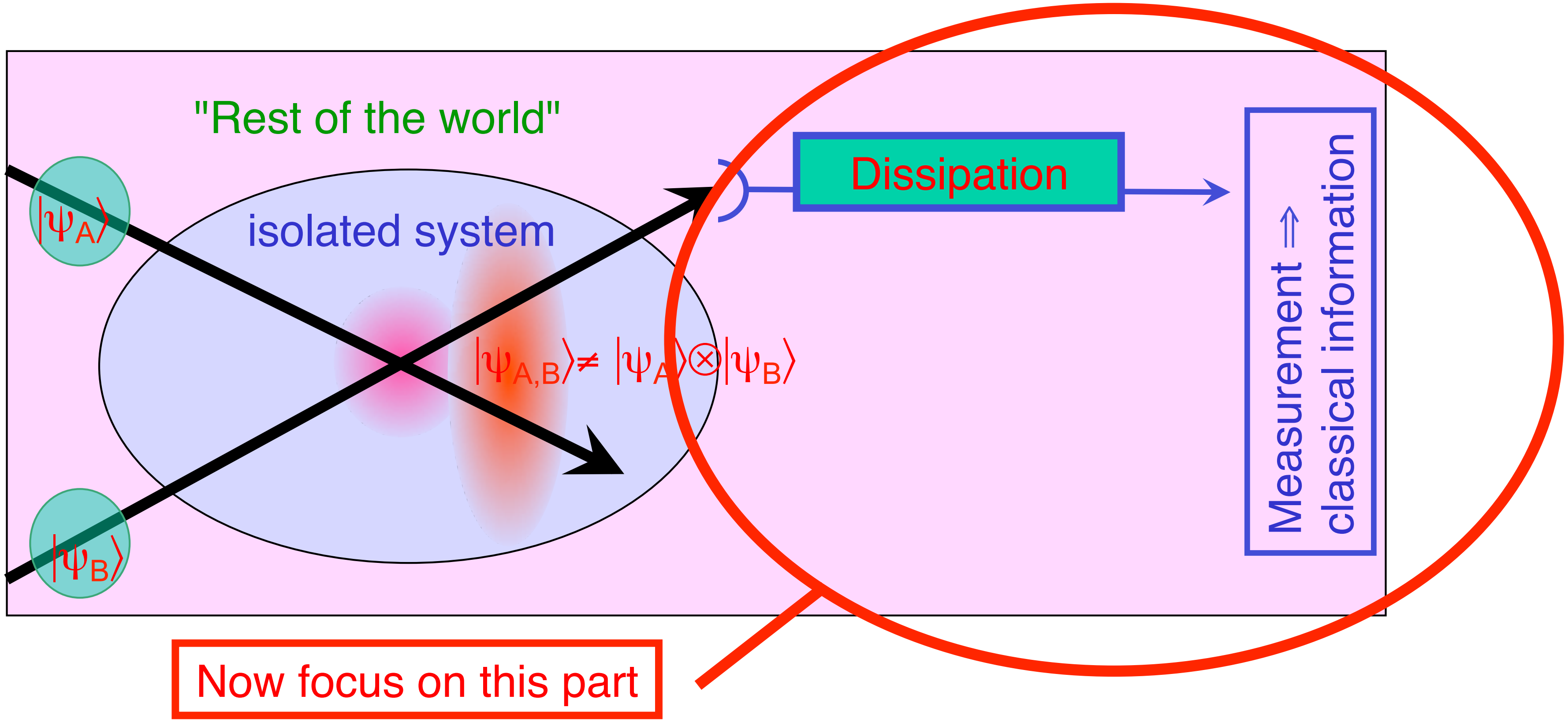
The border separation quantum and classical behavior



Delineating the border between the quantum realm ruled by the Schrödinger equation and the classical realm ruled by Newton's laws is one of the unresolved problems of physics. **Figure 1**

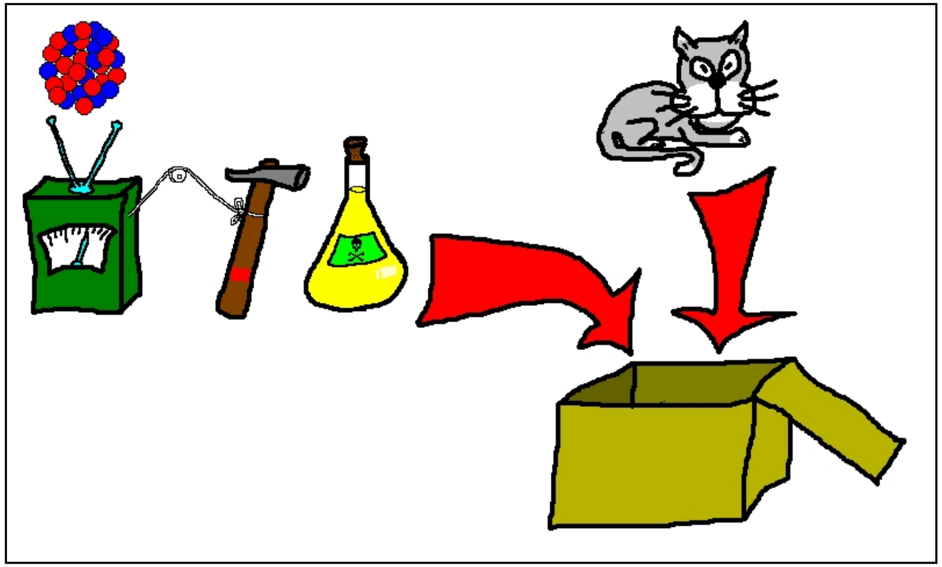
Zurek, Physics Today (1991)

Quantum measurement: basic ingredients



- We have shown how to built an ideal QND meter of the photon number
- This detector is based on a destructive detector of the atom energy.
- Let us now built a more complete, fully quantum, model of detector including the dissipative part

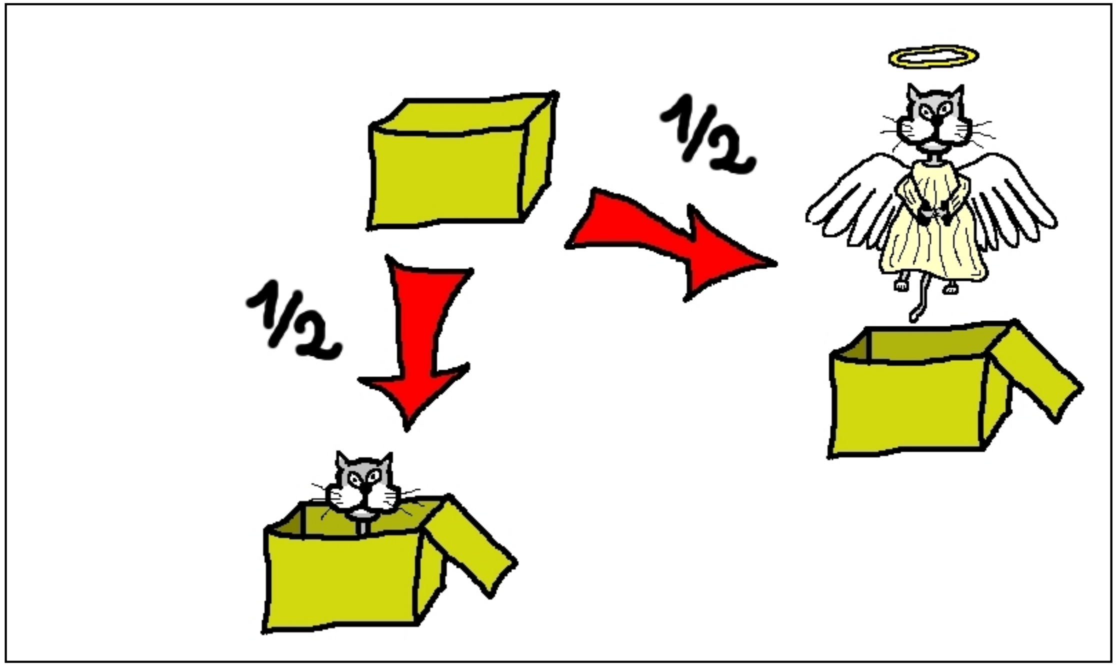
Quantum description of a meter: the "Schrödinger cat" problem



One encloses in a box a cat whose fate is linked to the evolution of a quantum system: one radioactive atom.

The "Schrödinger cat"

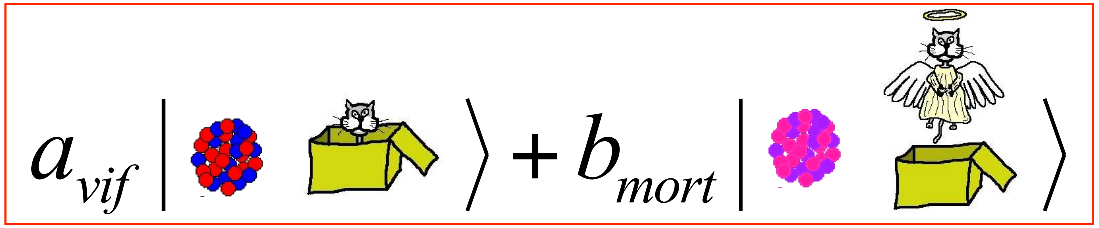
- One closes the box and wait until the atom is disintegrated with a probability 1/2



?

- When opening the box is the cat dead, alive or in a superposition of both?

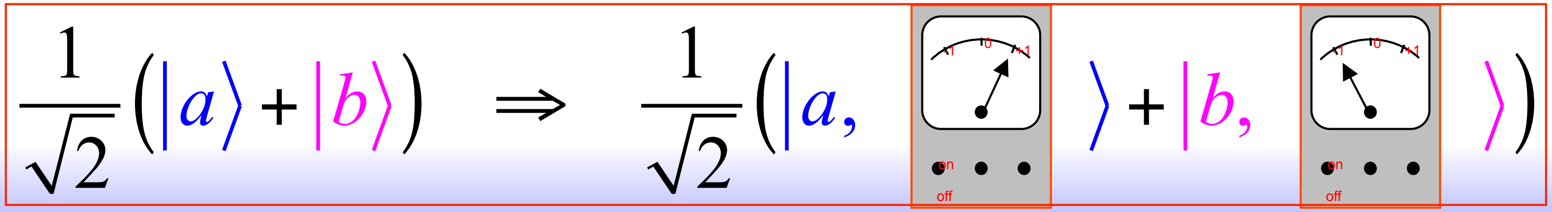
Schrödinger cat and quantum measurement



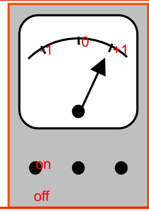
- Before opening the box, the system is isolated and unitary evolution prepares a maximally atom-meter entangled state
- Does this state "really" exists?

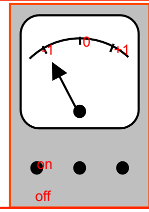
  → a more relevant question: can one perform experiments demonstrating cat superposition state? Up to which limit?

- That is a fundamental question for the quantum theory of measurement: how does the unphysical entanglement of SC state vanishes at the macroscopic scale. That is the problem of the transition between quantum and classical world



Schrödinger cat and quantum measurement

$\frac{1}{\sqrt{2}}\left(|e\rangle+|g\rangle\right) \Rightarrow \frac{1}{\sqrt{2}}\left(|e,\right.$ 

$\left.\rangle+|g,\right.$ 

$\left.\rangle\right)$

- Schrödinger point of view: unitary evolution should "**obviously**" not apply any more at "some scale".
- It seems that the atom-meter space contains to many states for describing reality
- Including dissipation due to the coupling of the meter to the environment will provide a physical mechanism "selecting" the physically acceptable states: Zurek's "pointer states".

Let's lock at this in a real experiment using a meter whose size can be varied from microscopic to macroscopic world.

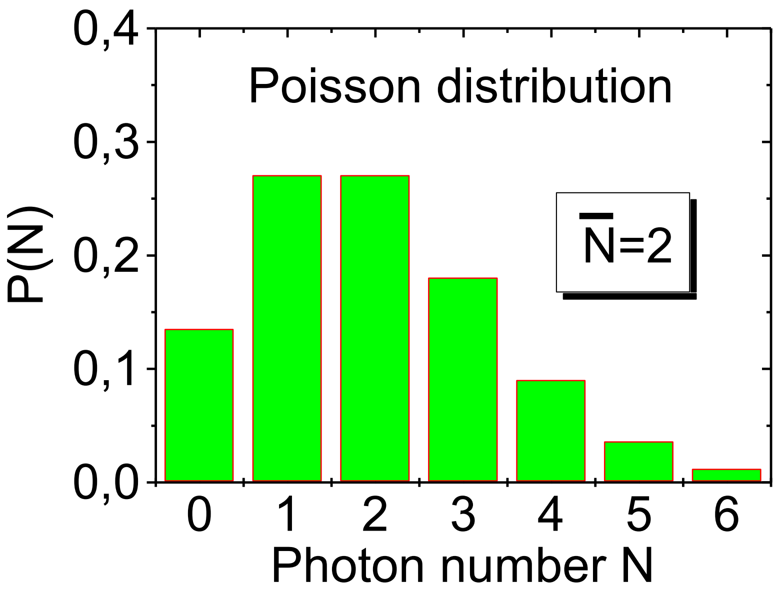
4. A mesoscopic field as atomic state measurement apparatus

A mesoscopic "meter": coherent field states

- Number state: $\left|N\right\rangle$
- Quasi-classical state: $\left|\alpha\right\rangle = e^{-|\alpha|^2/2}\sum_N \frac{\alpha^N}{\sqrt{N!}}\left|N\right\rangle \quad ; \quad \alpha = |\alpha| e^{i\Phi}$

•Photon number distribution

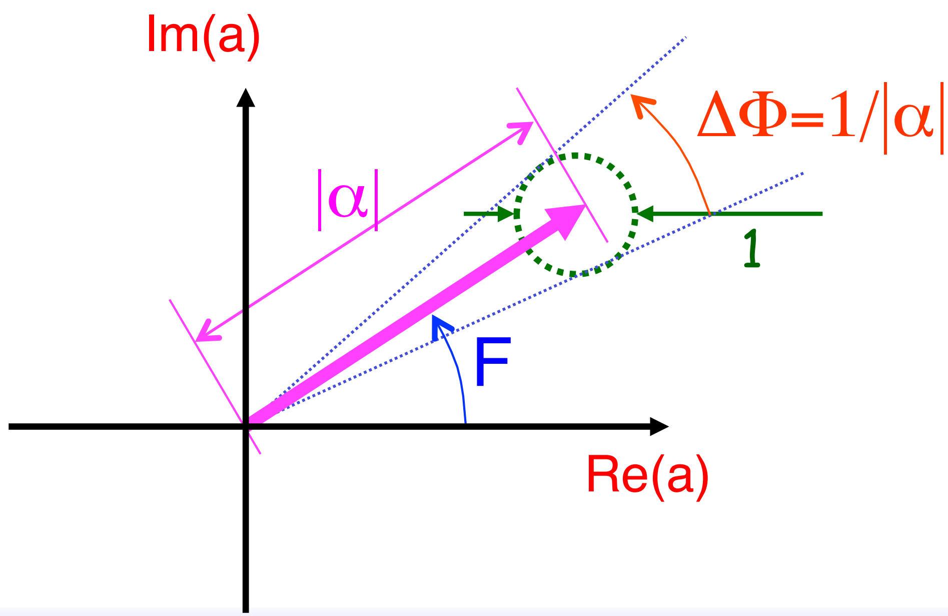
$$P(N) = e^{-\bar{N}}\frac{\bar{N}^N}{N!} \quad ; \quad \bar{N} = |\alpha|^2$$



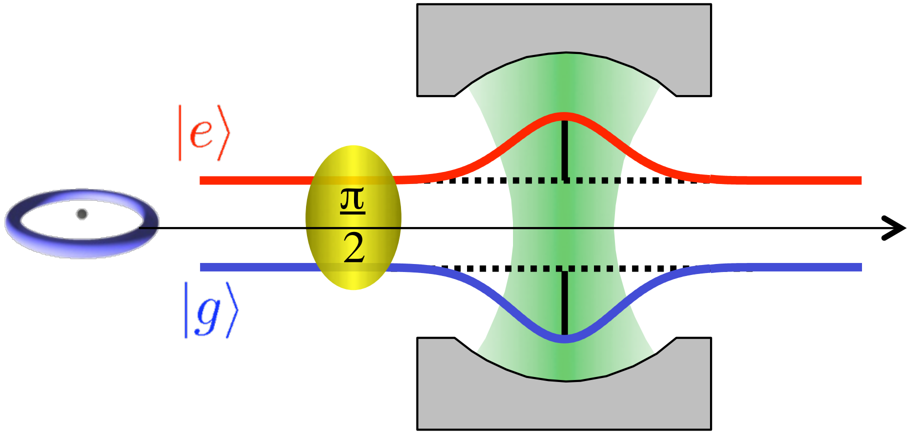
$\Delta N = 1/|\alpha|$

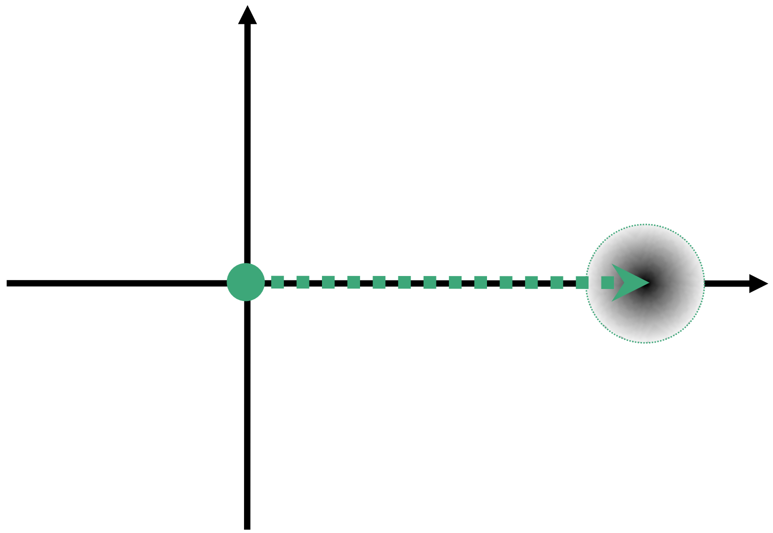
• Phase space representation

$\Delta N \,.\, \Delta\Phi > 1$

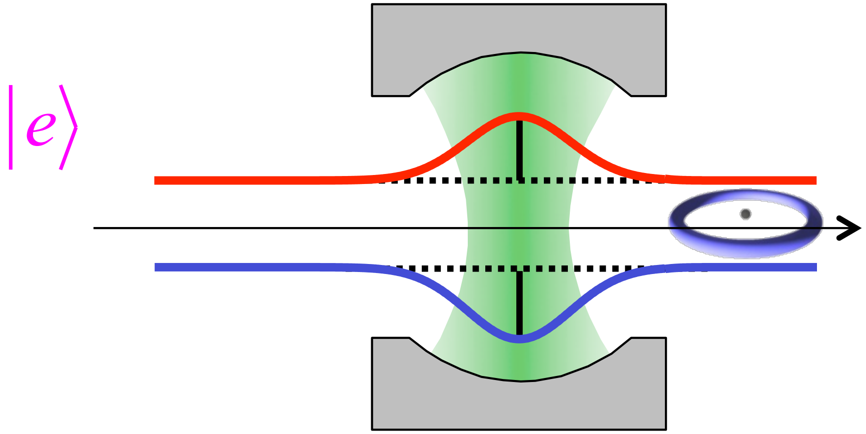


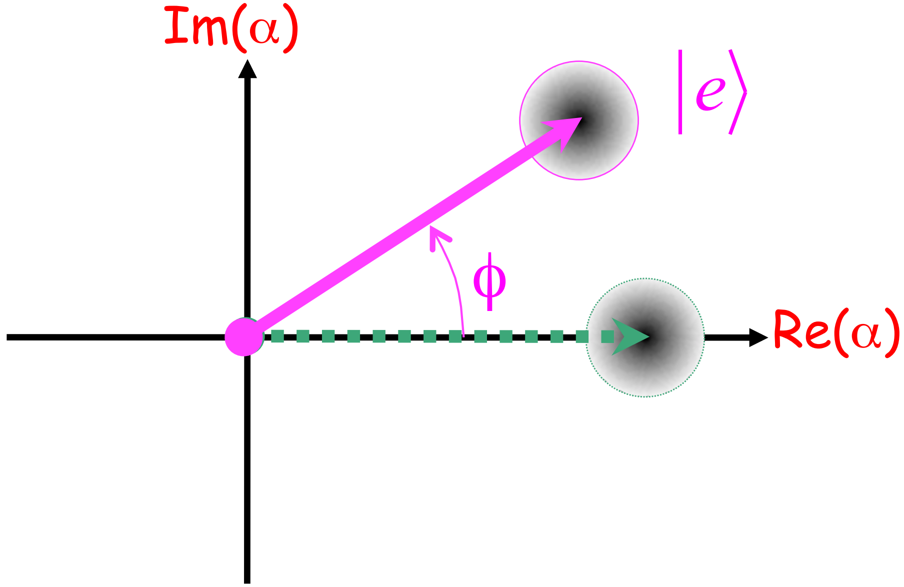
QND detection of atoms using non-resonant interaction with a coherent field





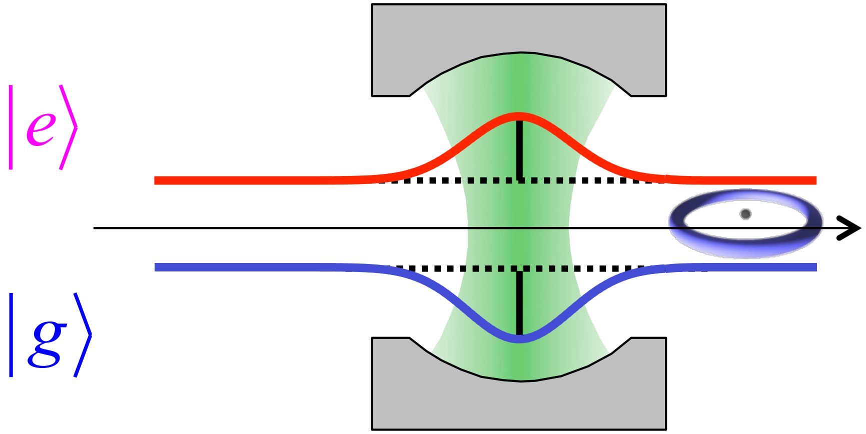
QND detection of atoms using non-resonant interaction with a coherent field

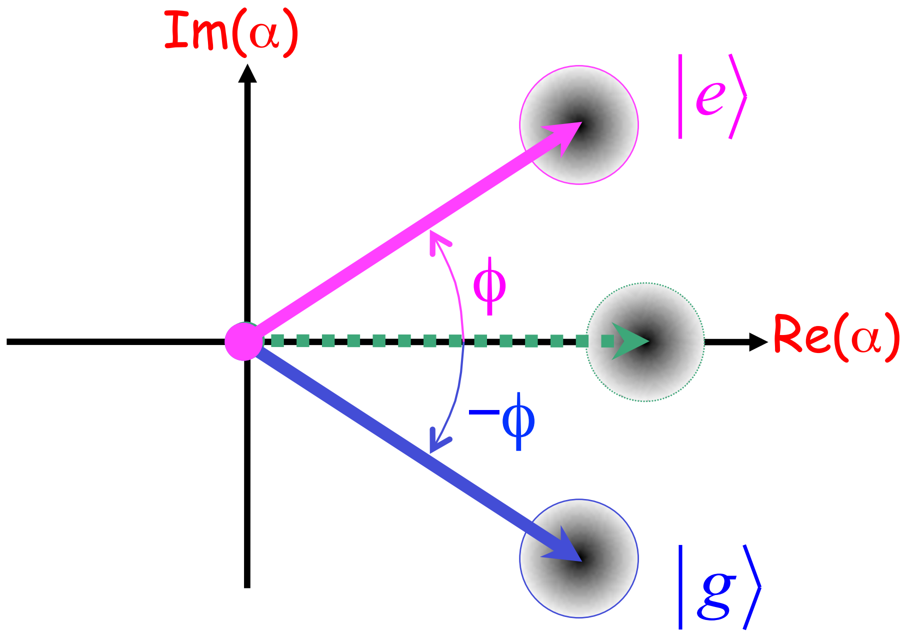




$$|e\rangle \otimes |\alpha\rangle \rightarrow |e\rangle \otimes |\alpha . e^{i\Phi_0}\rangle$$

QND detection of atoms using non-resonant interaction with a coherent field



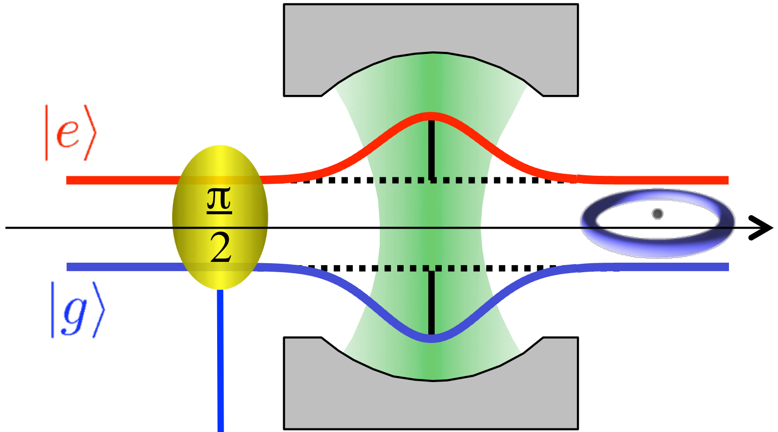


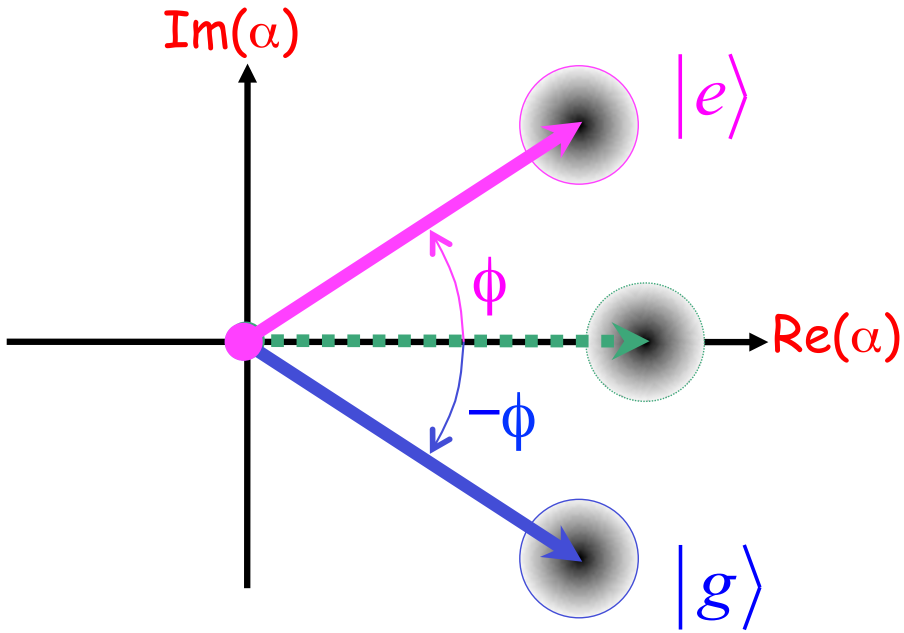
$$|e\rangle \otimes |\alpha\rangle \rightarrow |e\rangle \otimes |\alpha.e^{i\Phi_0}\rangle$$

$$|g\rangle \otimes |\alpha\rangle \rightarrow |g\rangle \otimes |\alpha.e^{-i\Phi_0}\rangle$$

a single atom controls the phase of the field

QND detection of atoms using non-resonant interaction with a coherent field





π/2 pulse prepares e-g superposition state

$$|e\rangle \otimes |\alpha\rangle \rightarrow |e\rangle \otimes |\alpha.e^{i\Phi_0}\rangle$$

$$|g\rangle \otimes |\alpha\rangle \rightarrow |g\rangle \otimes |\alpha.e^{-i\Phi_0}\rangle$$

a single atom controls the phase of the field

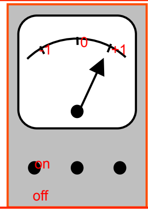
$$\frac{1}{\sqrt{2}}\left(|e\rangle + |g\rangle\right) \otimes |\alpha\rangle \rightarrow \frac{1}{\sqrt{2}}\left(|e\rangle \otimes |\alpha.e^{i\Phi_0}\rangle + |g\rangle \otimes |\alpha.e^{-i\Phi_0}\rangle\right)$$

→ The field phase "points" on the atomic state

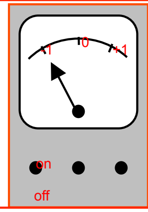
Atom-meter entanglement

$$\frac{1}{\sqrt{2}}\left(|e\rangle + |g\rangle\right)\otimes|\alpha\rangle \;\rightarrow\; \frac{1}{\sqrt{2}}\left(|e\rangle\otimes\left|\alpha.e^{i\Phi_0}\right\rangle + |g\rangle\otimes\left|\alpha.e^{-i\Phi_0}\right\rangle\right)$$

$$\frac{1}{\sqrt{2}}\left(|e\rangle + |g\rangle\right) \;\Rightarrow\; \frac{1}{\sqrt{2}}\Big(\big|e,$$



$$\big\rangle + \big|g,$$



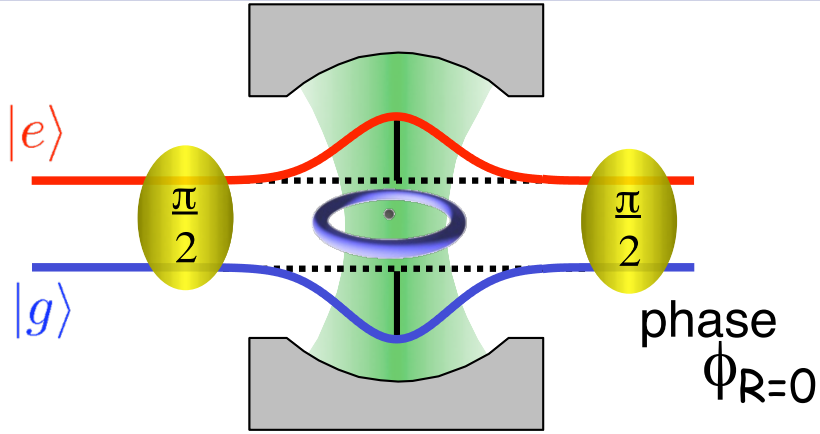
$$\big\rangle\Big)$$

This is a "Schrödinger cat state"

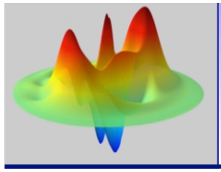
Preparation of the cavity cat state

Phase shift per photon

Φ_0

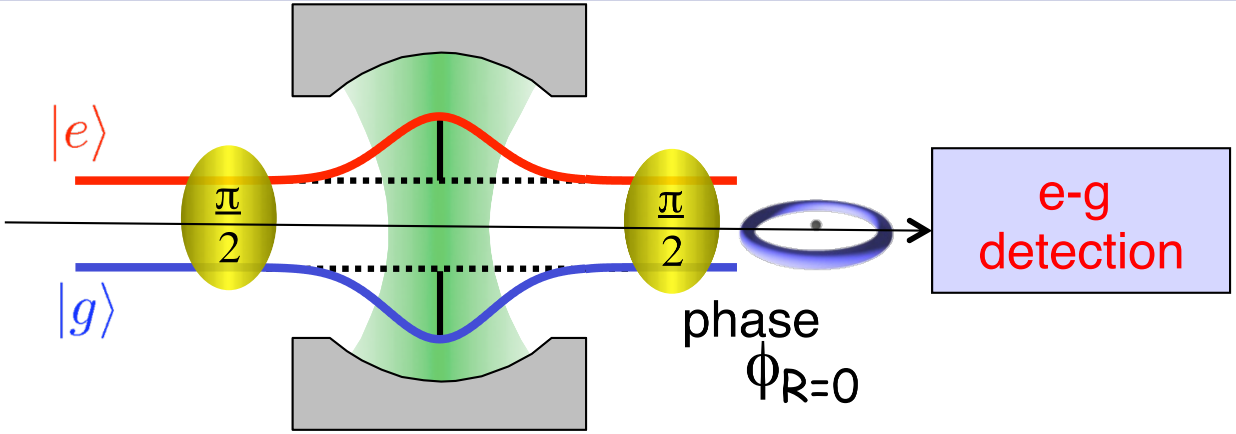


$$\frac{1}{\sqrt{2}}\left(\left|e\right\rangle+\left|g\right\rangle\right)\otimes\left|\alpha\right\rangle \Rightarrow \frac{1}{\sqrt{2}}\left(\left|e\right\rangle\otimes\left|\alpha.e^{i\Phi_0/2}\right\rangle+\left|g\right\rangle\otimes\left|\alpha.e^{-i\Phi_0/2}\right\rangle\right)$$



Preparation of the cavity cat state

Phase shift per photon Φ_0



$$\frac{1}{\sqrt{2}}\left(|e\rangle+|g\rangle\right)\otimes|\alpha\rangle \Rightarrow \frac{1}{\sqrt{2}}\left(|e\rangle\otimes\left|\alpha.e^{i\Phi_0/2}\right\rangle+|g\rangle\otimes\left|\alpha.e^{-i\Phi_0/2}\right\rangle\right)$$

- Field state after detection:

$$\Rightarrow \frac{1}{\sqrt{2}}\left(\left|\alpha.e^{i\Phi_0/2}\right\rangle+\left|\alpha.e^{-i\Phi_0/2}\right\rangle\right) \quad \text{if "e" detected}$$

$$+\frac{1}{\sqrt{2}}\left(\left|\alpha.e^{i\Phi_0/2}\right\rangle-\left|\alpha.e^{-i\Phi_0/2}\right\rangle\right) \quad \text{if "g" detected}$$

$$\Phi_0 = \pi$$

e → even cat state

g → odd cat state

Depending on the detected atomic state the cat has a well defined photon number parity.

For π per photon phase shift, one atom measures just the field parity.

Projection on a cat state is the "back-action" of parity measurement.

5. Schrödinger cat states reconstruction a movie of decoherence

Measuring the field density operator?

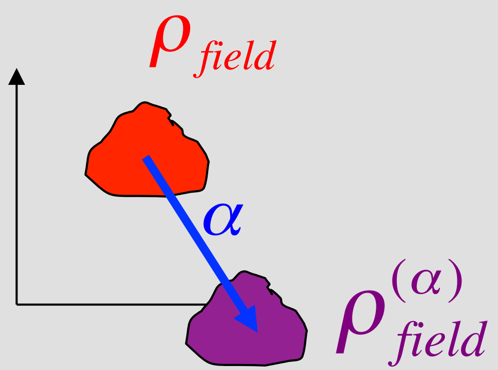
General field state description: density operator

$$\rho_{field} = \begin{bmatrix} \rho_{00} & \rho_{01} & \rho_{02} & . \\ \rho_{10} & \rho_{11} & \rho_{12} & . \\ \rho_{20} & \rho_{21} & \rho_{22} & . \\ . & . & . & . \end{bmatrix}$$

QND counting of photons
⇒ measurement of diagonal elements ρ_{nn}

How to measure the off-diagonal elements of ρ_{field} ?

⇒ by counting photons after applying "displacement"



$$\rho_{field}^{(\alpha)} = \hat{D}(\alpha)\rho_{field}\hat{D}^{+}(\alpha)$$

$$\hat{D}(\alpha) = e^{\alpha a^{+} - \alpha^{*} a} \quad \text{Displacement operator}$$

The displacement operator is the unitary transform corresponding to the coupling to a classical source. It mixes diagonal and off-diagonal matrix elements of ρ_{field}. Measuring the photon number after displacement for a large number of different a gives information about all matrix elements of ρ_{field}.

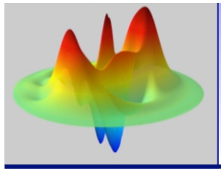
Choice of reconstruction method

- Various possibilities:
  - ❑ Direct fit of ρ_{field} of the measured data $P_{e,g}\left(\hat{D}(\alpha)\rho_{field}\hat{D}^{+}(\alpha)\right)$
  - ❑ Maximum likelihood: find ρ_{field} which maximizes the probability of finding the actually measured results g_i.
  - ❑ Maximum entropy principle: find ρ_{field} which fits the measurements and additionally maximizes entropy $S=\rho_{field}\log(\rho_{field})$.

V. Bužek and G. Drobný, *Quantum tomography via the MaxEnt principle*, Journal of Modern Optics **47**, 2823 (2000)

Estimates the state only on the basis of measured information: in case of incomplete set of measurements, gives a "worse estimate of ρ_{field}.

In practice the two last methods give the same result provided one measures enough data completely determining the state.



State reconstruction: experimental method

1- prepare the state to be measured $|\psi_{cat}\rangle$

2- measure $P_{e,g}\left(\hat{D}\left(\alpha\right)\rho_{field}\hat{D}^{+}\left(\alpha\right)\right)$ for a large number of different values of displacement $D(\alpha)$ (400 to 600 values).

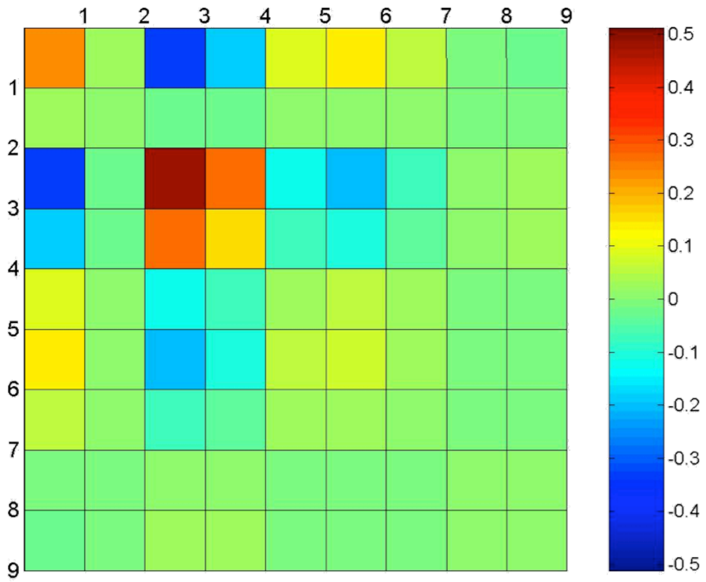
3- reconstruct ρ_{field} by maximum entropy method

4- calculate Wigner function from ρ_{field}.

Reconstructed density matrix (real part)

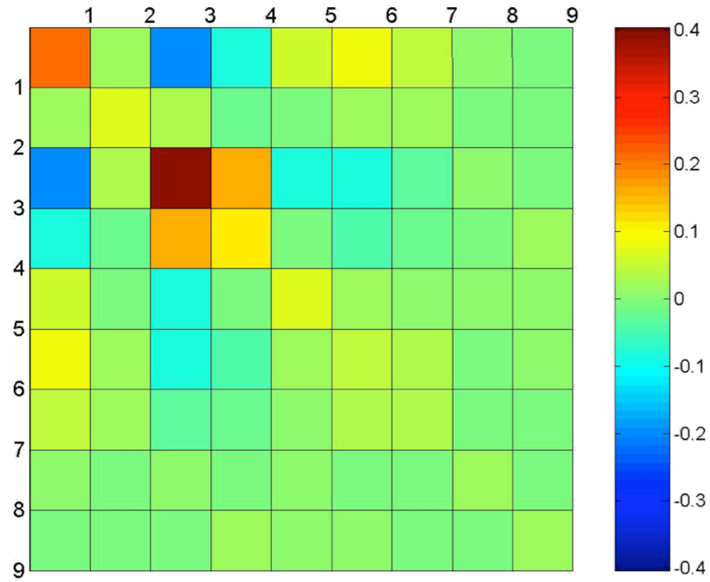
Even (odd) cat has even (odd) photon number statistics

expectation
(even cat)



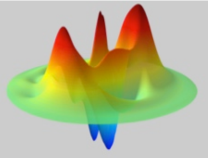
($\bar{n}_{inj} \approx 2.1$ photons)

reconstruction
(even cat)



($\langle n \rangle = 2.2$ photons)

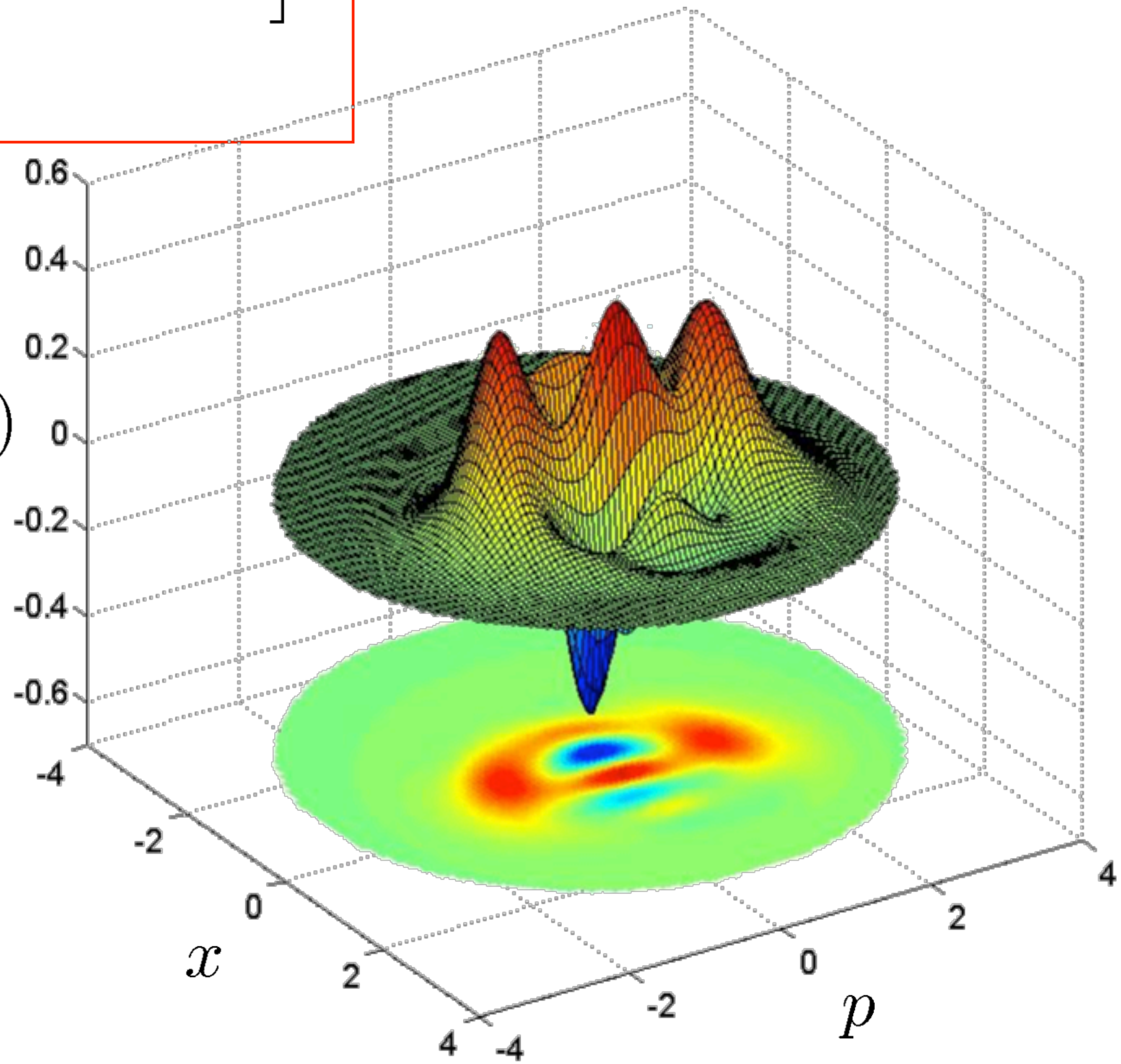
Fidelity of the preparation and reconstruction - 66%
(71% for the odd state)



Reconstructed Wigner function

$$W(\alpha) = \mathrm{Tr}\left[\hat{\rho}_{\mathrm{me}}\,\hat{D}(-\alpha)\,e^{i\pi\hat{a}^{\dagger}\hat{a}}\,\hat{D}(\alpha)\right]$$

$$\alpha = x + i\,p$$



No a priori knowledge on a prepared state except for the size of the Hilbert space of $N_{\mathrm{Hilbert}} = 9$

Deleglise et al. Nature **455**, 510 (2008)

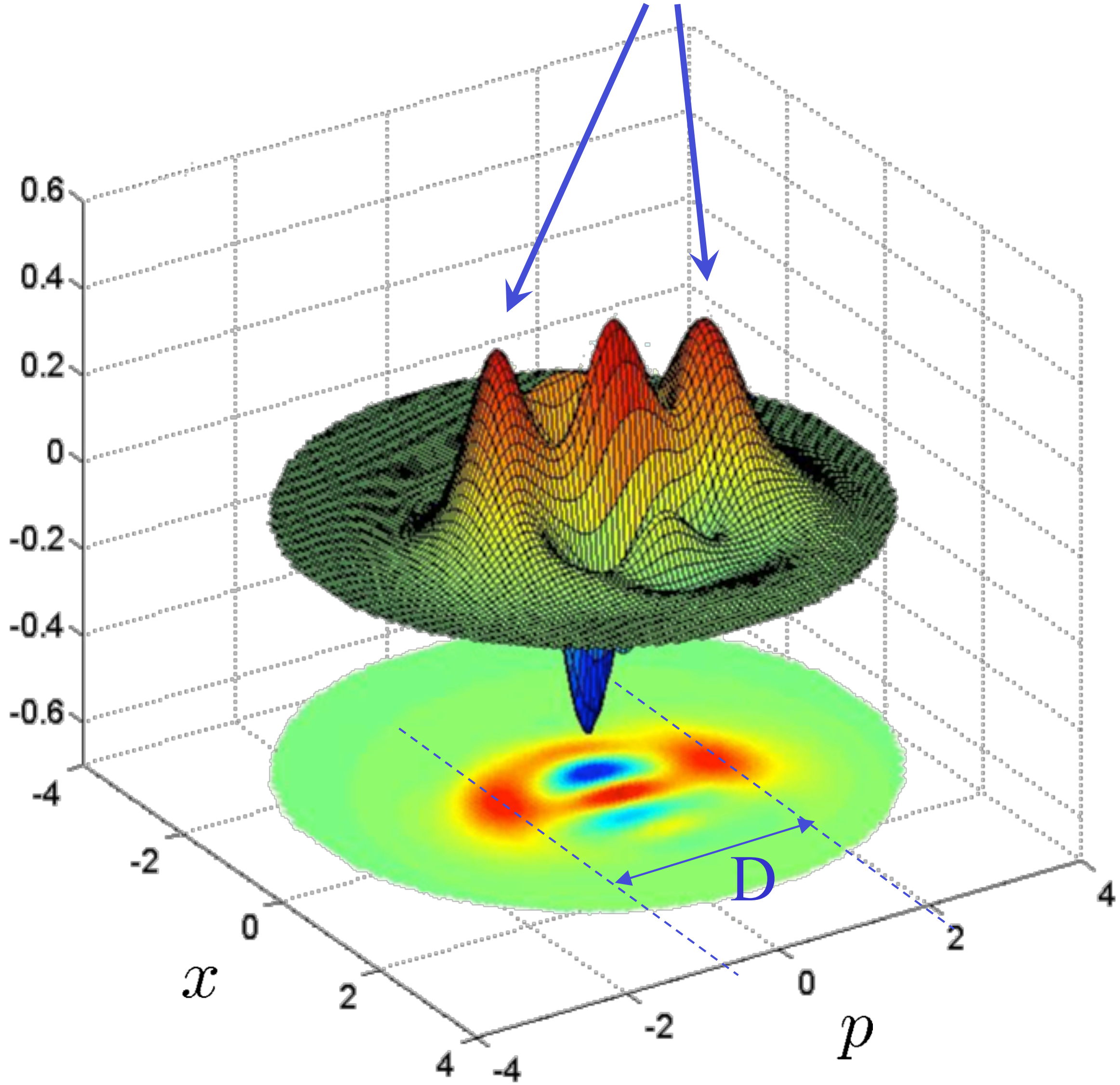
Reconstructed Wigner function

Classical components

≈2.1 photons in each classical component *(amplitude of the initial coherent field)*

cat size $D^2 \approx 7.5$ photons

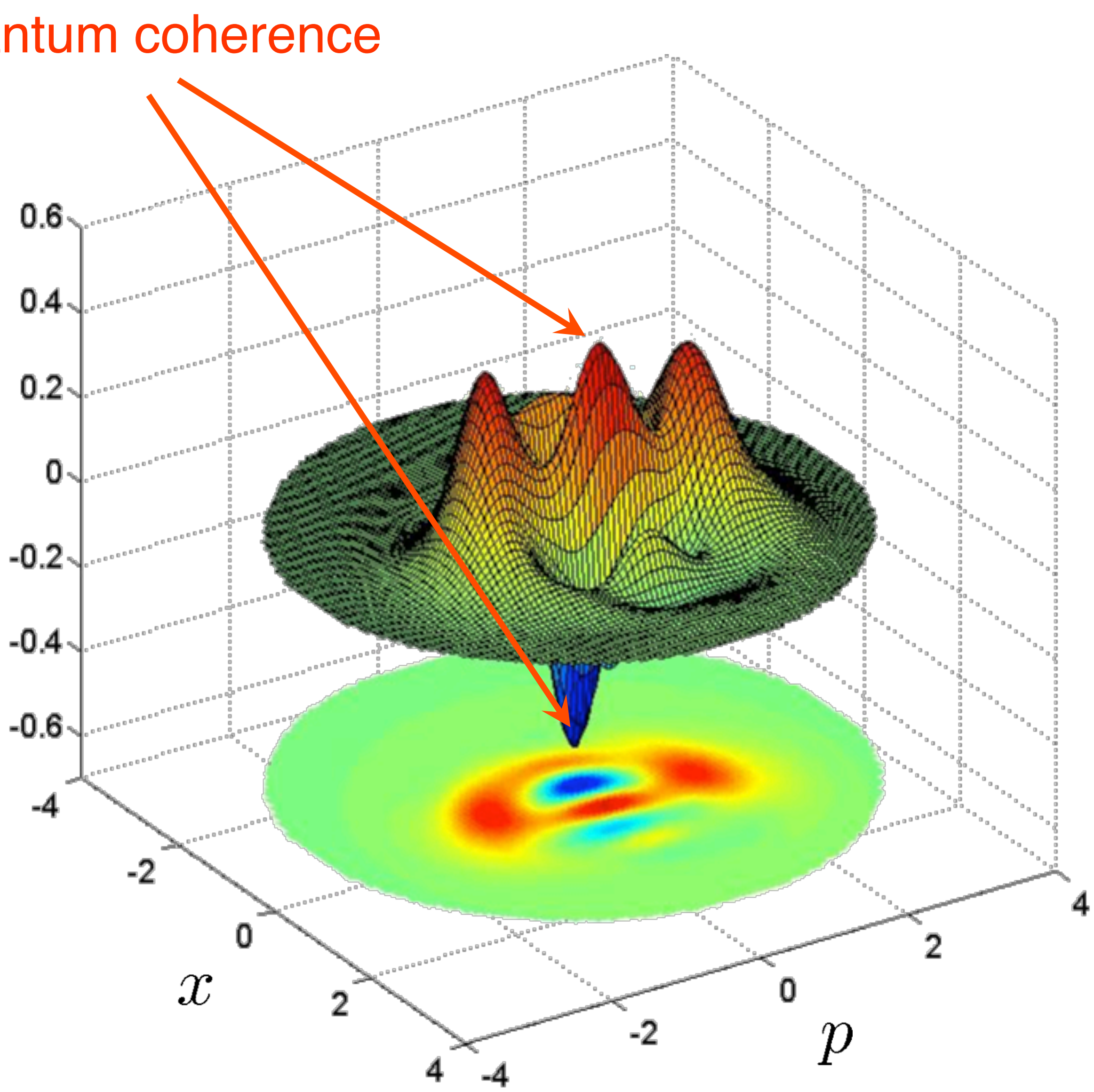
coherent components are completely separated *(D > 1)*



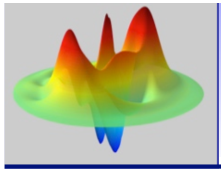
Reconstructed Wigner function

quantum superposition
of two classical fields
(interference fringes)

quantum signature of
the prepared state
*(negative values of
Wigner function)*

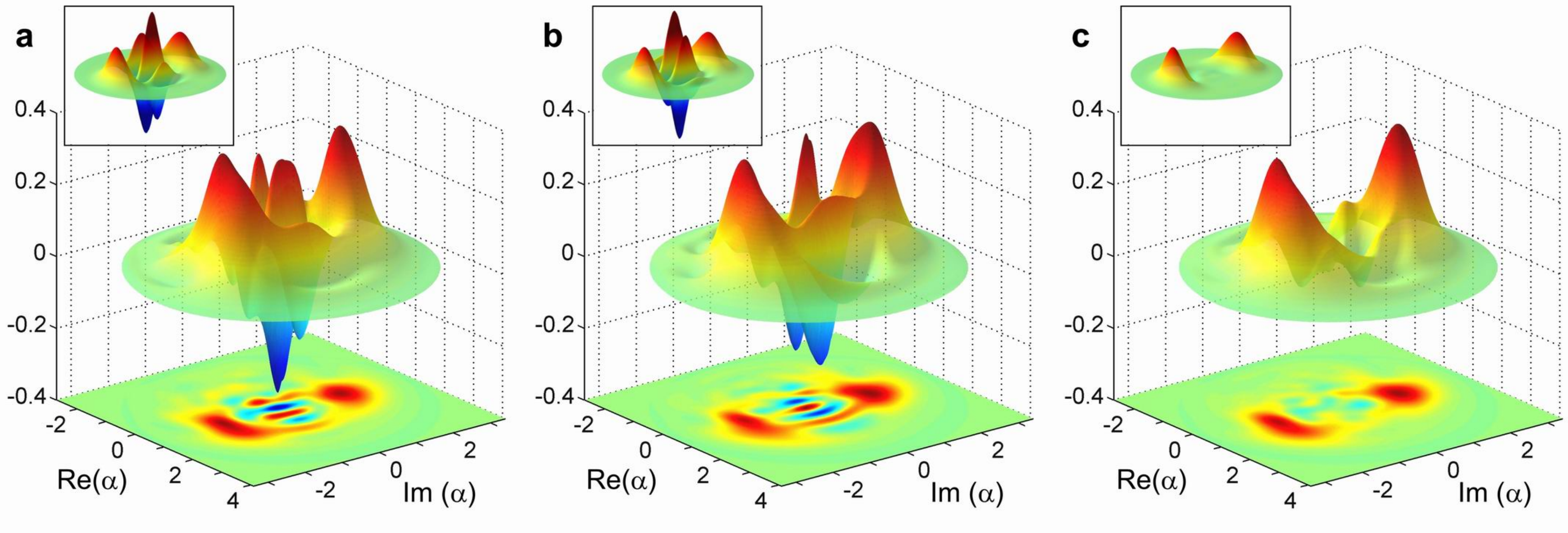


Deleglise et al. Nature **455**, 510 (2008)



A larger cat for observing decoherence

- Initial coherent field $\beta^2 = 3.5$ photons
- Measurement for 400 values of α.



Even cat

Odd cat

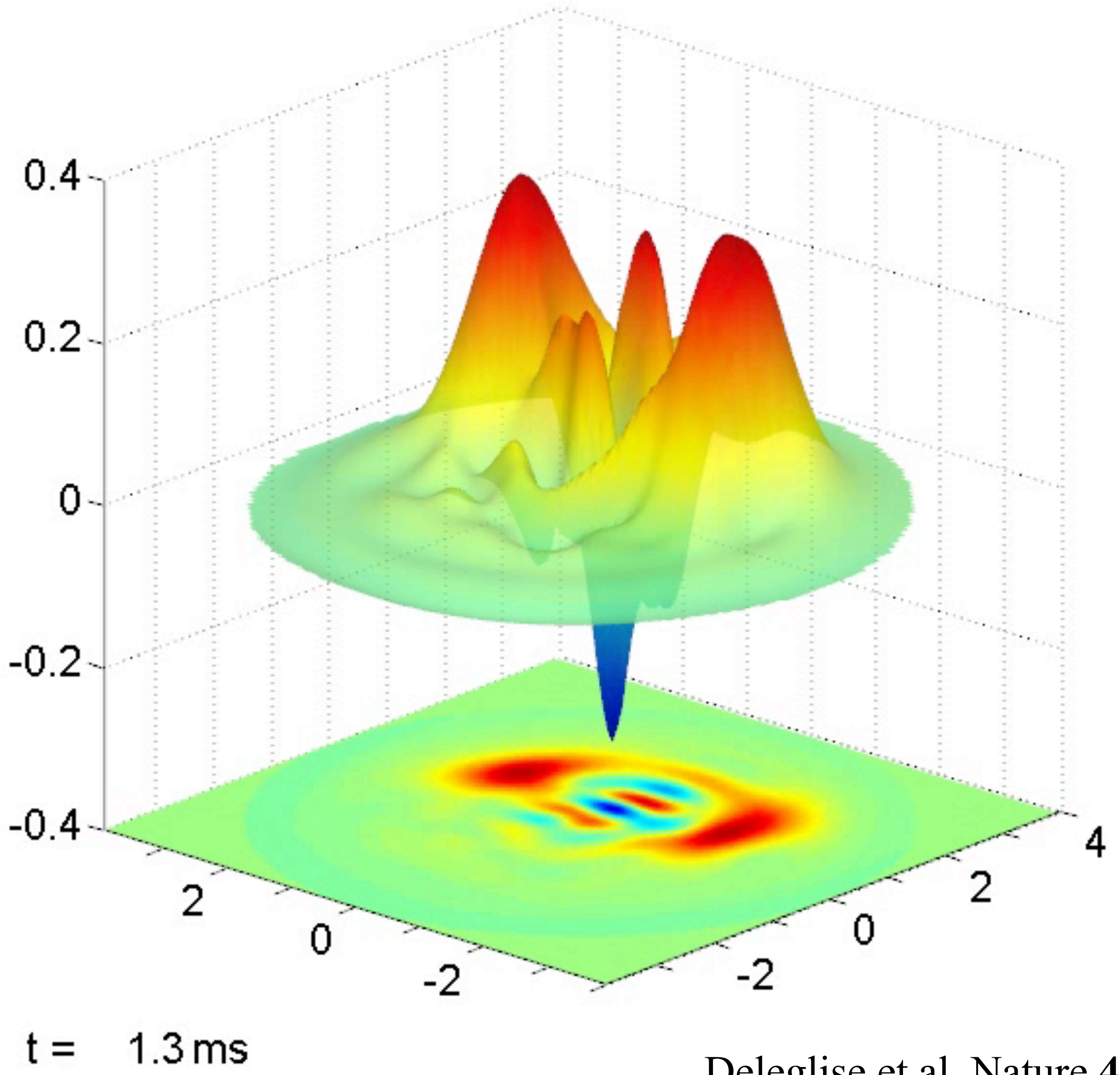
Sum of two WF:
Statistical mixture

State fidelity with respect to the expected state including phase shift non-ineariry (insets)

$F = 0.72$

Deleglise et al. Nature **455**, 510 (2008)

Movie of decoherence



Deleglise et al. Nature **455**, 510 (2008)

The role of the "environment":

- For long atom-cavity interaction time field damping couples the system to the outside world

→ a complete description of the system must take into account the state of the field energy "leaking" in the environment.

- General method for describing the role of the environment:

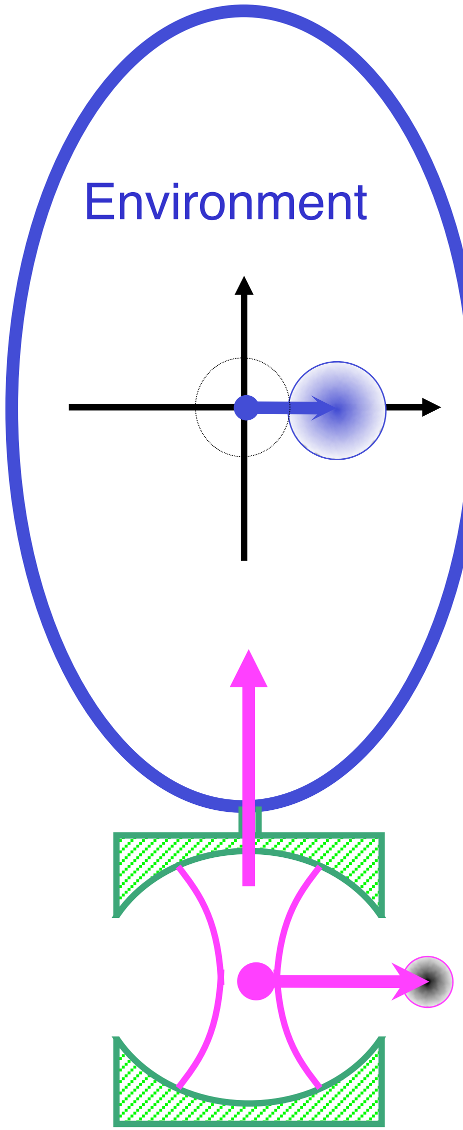
$$\frac{d\rho^{field}}{dt} = -\frac{1}{2T_{cav}}\left[a^{+}a,\rho^{field}\right]_{+} + \frac{1}{T_{cav}}a\rho^{field}a^{+}$$

master equation of the field density matrix

- Physical result: decoherence

$$\tau_{dec} \approx \frac{\tau_{cav}}{\overline{N}}$$

The origin of decoherence: entanglement with the environment



- Decay of a coherent field:

$$\left|\alpha(0)\right\rangle \otimes \left|vacuum\right\rangle_{env} \rightarrow \left|\alpha(t)\right\rangle \otimes \left|\beta(t)\right\rangle_{env}$$

$$\alpha(t) = \alpha(0).e^{-t/\tau_{cav}}$$

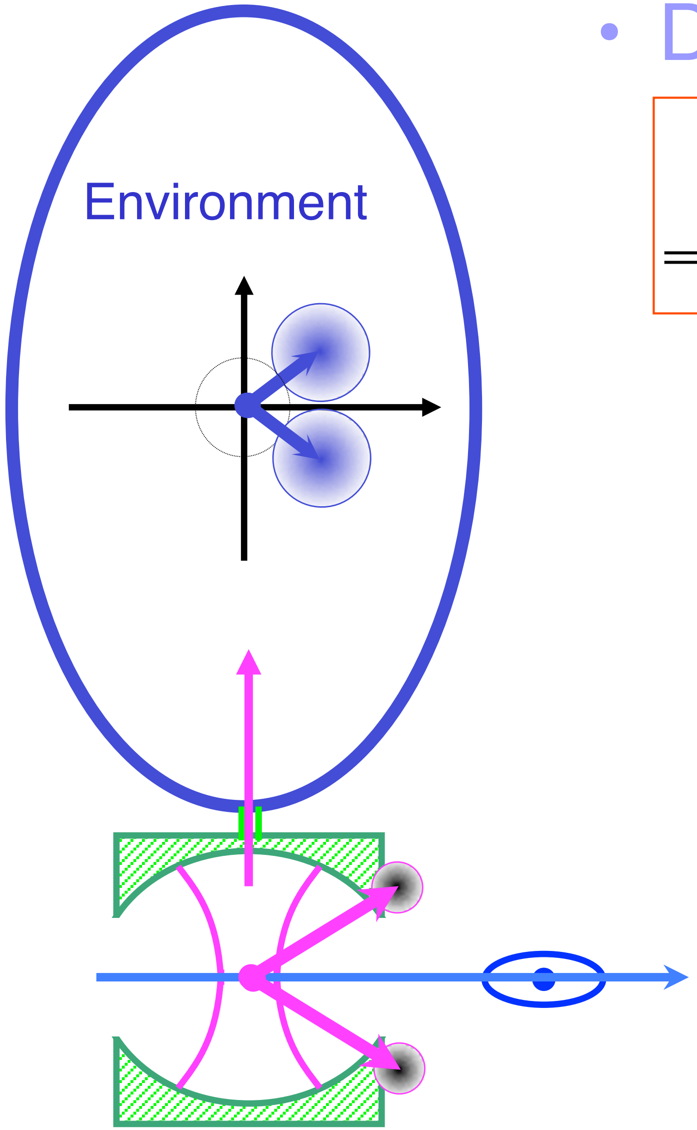
- ❑ the cavity field remains coherent
- ❑ the leaking field has the same phase as α
- ❑ no entanglement during decay:

That is a property defining coherent states: coherent state are the only one which do not get entangled while decaying

The origin of decoherence: entanglement with the environment

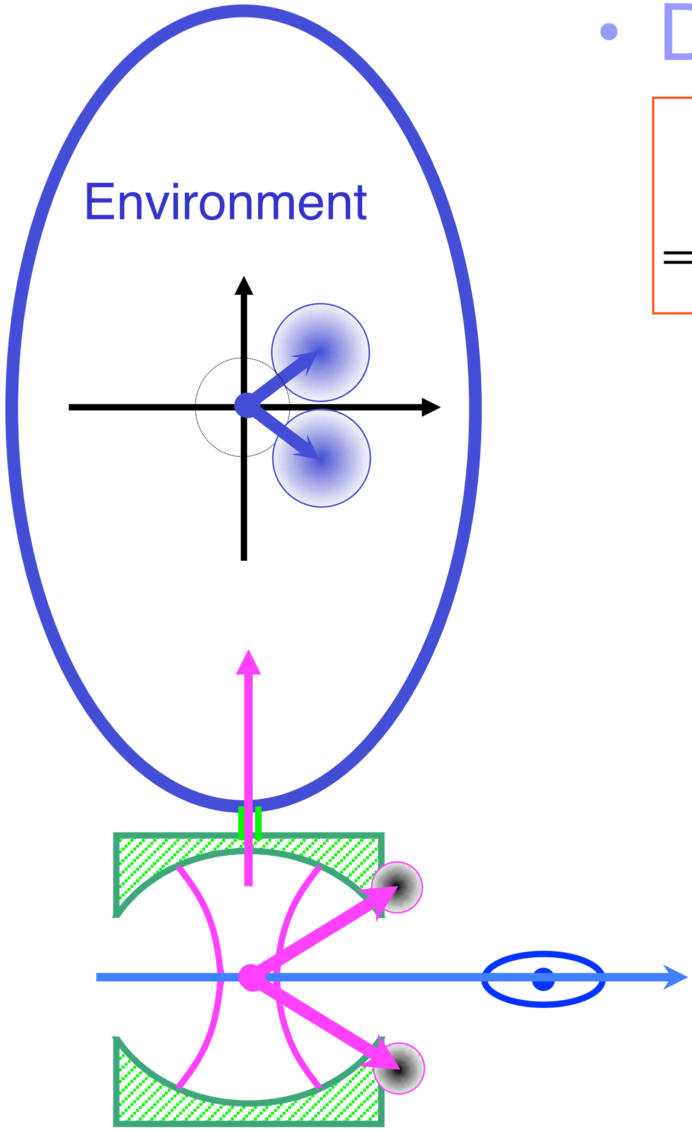
- Decay of a "cat" state:

$$\left|\Psi_{cat}\right\rangle \otimes \left|vacuum\right\rangle_{env}$$
$$\Rightarrow 1/\sqrt{2}\left(\left|\alpha_+(t)\right\rangle \otimes \left|\beta_+(t)\right\rangle_{env} + \left|\alpha_-(t)\right\rangle \otimes \left|\beta_-(t)\right\rangle_{env}\right)$$



Detailed calculation in
PHYSICA SCRIPTA T78, 29 (1998)

The origin of decoherence: entanglement with the environment



Detailed calculation in
PHYSICA SCRIPTA T78, 29 (1998)

- Decay of a "cat" state:

$$|\Psi_{cat}\rangle \otimes |vacuum\rangle_{env}$$
$$\Rightarrow 1/\sqrt{2}\left(|\alpha_+(t)\rangle \otimes |\beta_+(t)\rangle_{env} + |\alpha_-(t)\rangle \otimes |\beta_-(t)\rangle_{env}\right)$$

- ❑ cavity-environment entanglement: the leaking field "broadcasts" phase information
- ❑ trace over the environment

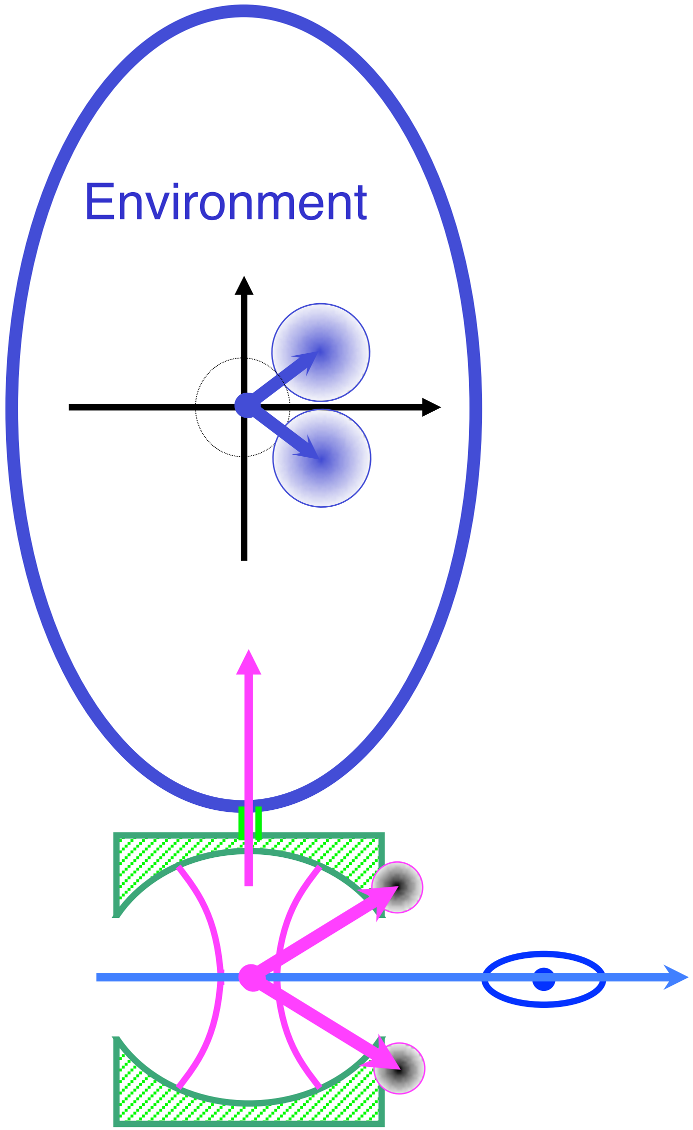
⇒ decoherence (=diagonal field reduced density matrix) as soon as:

$$\langle \beta_-(t) | \beta_+(t) \rangle_{env} \approx 0$$

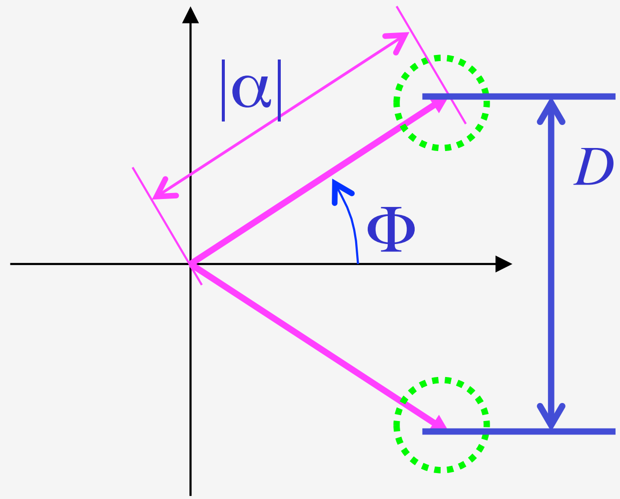
This occurs for

$$|\beta(t)|^2 \approx 1 \Rightarrow t > \frac{T_{cav}}{\bar{N}} \approx T_{dec}$$

The decoherence time



Detailed calculation in
PHYSICA SCRIPTA T78, 29 (1998)



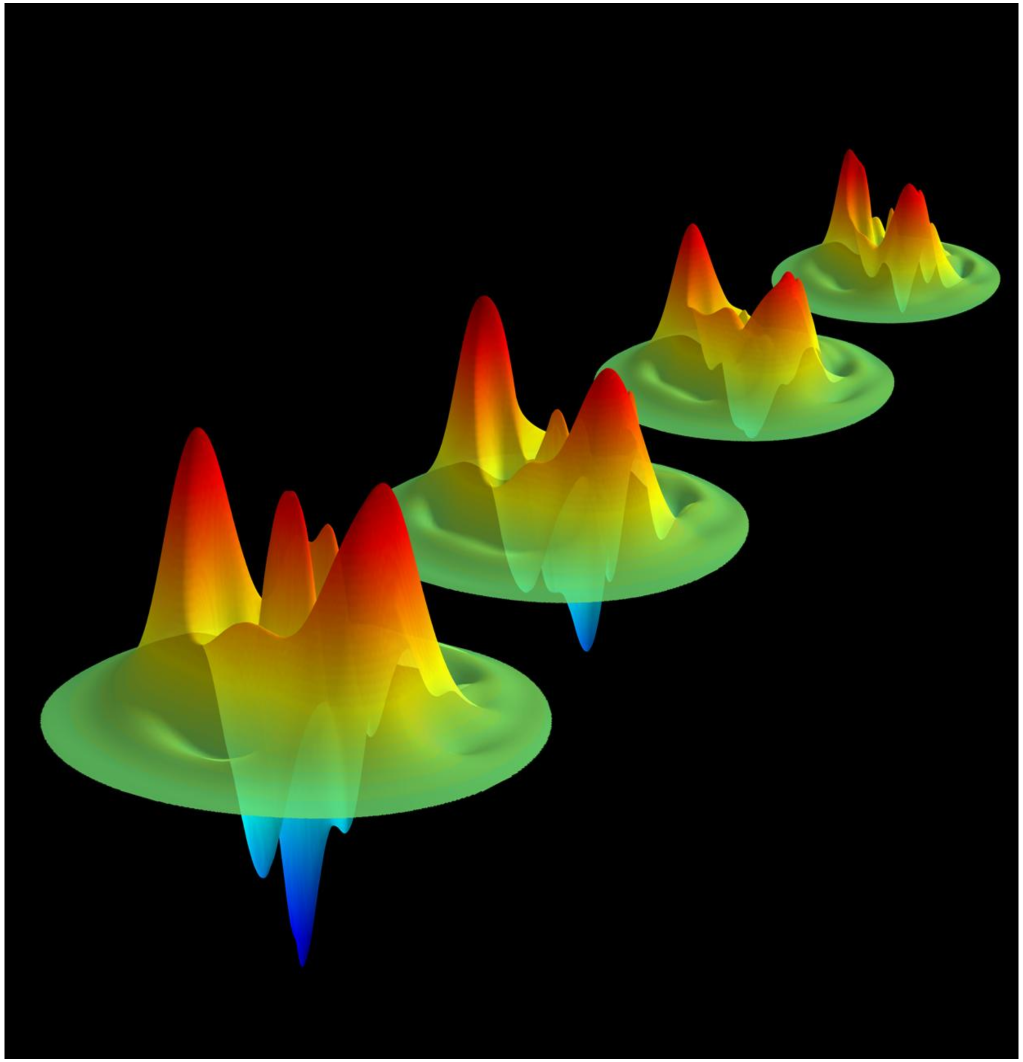
D: "Distance" between the two fields components.

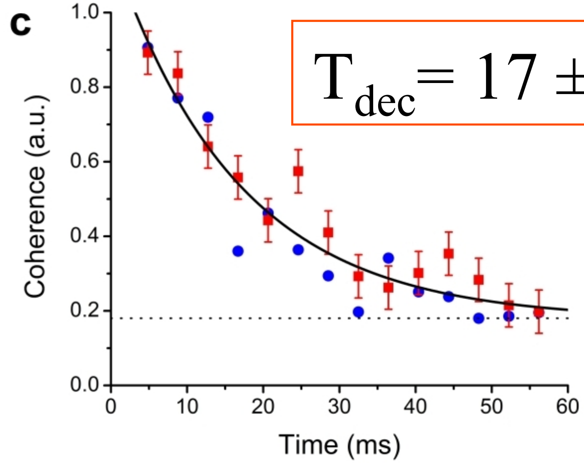
Rigorous expression of decoherence time

$$T_{decoh} = \frac{2T_{cav}}{D^2} = \frac{T_{cav}}{\bar{N}.2\sin^2(\Phi)}$$

Infinitely short decoherence time for macroscopic fields. The Schrödinger cat does not exist for "long" time.

Decoherence of a D^2=11.8 photon cat state





T_{dec}= 17 ± 3 ms

$$T_{\mathrm{meas}} \approx 4\,\mathrm{ms} < T_{\mathrm{dec},\,\bar{n}_{\mathrm{th}}}$$

Theory:

T_{dec}= $2T_{cav}/D^2$ = 22 ms

+ small blackbody contribution @ 0.8 K

T_{dec}= 19.5 ms

M.S. Kim and V. Bužek, *Schrödinger-cat state at finite temperature*, Phys. Rev. A **46**, 4239 (1992)

Quantum measurement: the role of the environment 1

⇒ Physical origin of decoherence:

leak of information into the environment.

⇒ The Schrödinger cat problem: the experimentalist does not kill the cat when opening the box. The environment "knows" whether the cat is dead or alive well before one opens the box.

⇒ The environment continuously performs unread repeated measurement of the cat state: the environment is looking at the box for you!

The "collapse" of the quantum state can be considered as a shortcut to describe this complex physical process

Does it solves "the measurement problem"?

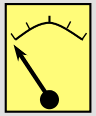
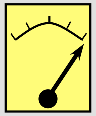
No: if the problem consists in telling how or why nature is fundamentally random (no hidden variables, impossibility to tell "at which time" nature makes a choice).

Yes: once one a priori accepts the statistical nature of quantum theory, which describes the statistics of classical events, decoherence is the mechanism providing classical probabilities for these events.

Quantum measurement: the role of the environment 2

⇒ Definition of "pointer basis" of a meter: (Zurek)

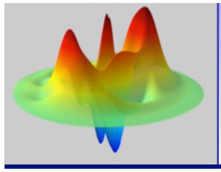
- the pointer state of the meter is a classical state
- once decoherence occurs, the physical state of a meter is described by a diagonal density matrix in the pointer basis:

$|e,$  $\rangle$ $|g,$  $\rangle$

$$\rho_{dec} = \begin{pmatrix} P_e & 0 \\ 0 & P_g \end{pmatrix}$$

⇒ at this level, quantum description only involves classical probabilities and no macroscopic superposition states.

⇒ The decoherence is the physical process defining "pointer states" of a meter. It is fine to have a definition not relying on experimentalist's intuition!



Summary

Exploring the quantum with trapped photons and Rydberg atoms:

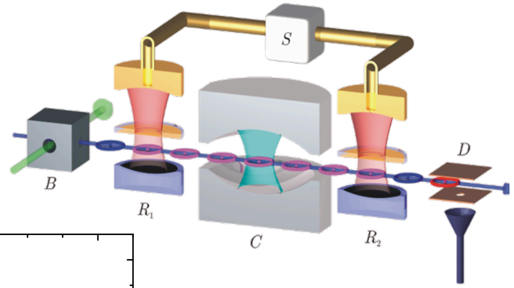
- The strong coupling regime

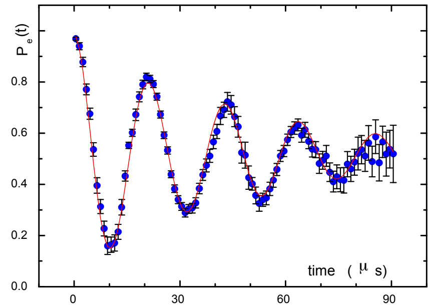
- QND photons counting:

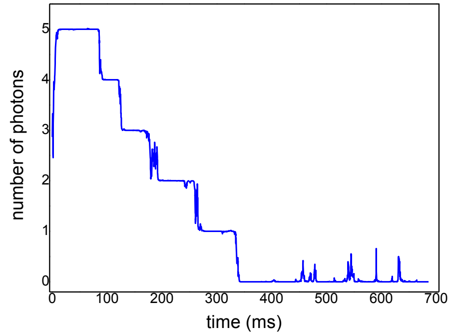
The quantum jumps of light

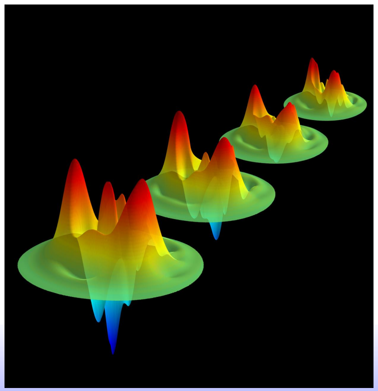
- Generation of cat states in a cavity and full state reconstruction

- Time evolution and decoherence of the cat state





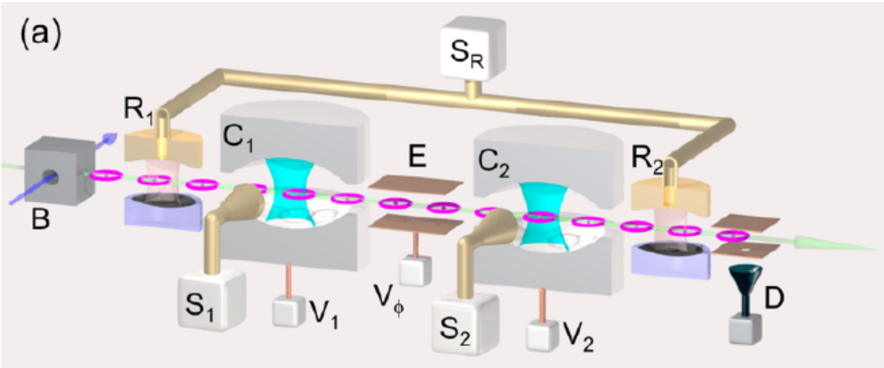




Cavity QED perspective: two-cavity experiment

- Principle:

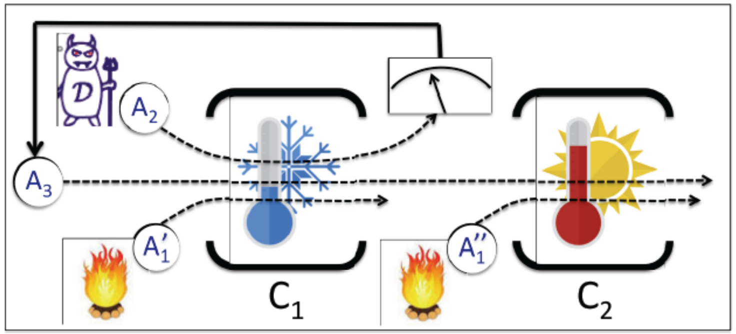
Fast atoms crossing two microwave high-Q cavities



- Projects

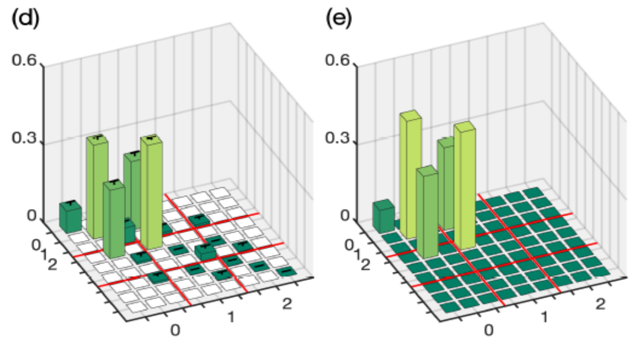
Quantum thermodynamics

(ANR with A. Auffeves and P. Sénellart)



- Recent result: Reconstruction of a two mode non-local state

$$\frac{1}{\sqrt{2}}\left(|1,0\rangle + |0,1\rangle\right)$$



arXiv:1904.04681v2

Heat going from cold to hot using information!
Exp. In progress

- People: Igor Dostenko (Ass. Prof. CdF) and Valentin Métillon (PhD)

A work starting in 1991

Jean-Michel Raimond   Serge Haroche   Michel Brune

The LKB-ENS cavity QED team

- Staring, in order of apparition

- Serge Haroche
- Michel Gross
- Claude Fabre
- Philippe Goy
- Pierre Pillet
- Jean-Michel Raimond
- Guy Vitrant
- Yves Kaluzny
- Jun Liang
- Michel Brune
- Valérie Lefèvre-Seguin
- Jean Hare
- Jacques Lepape
- Aephraim Steinberg
- Andre Nussenzveig
- Frédéric Bernardot
- Paul Nussenzveig
- Laurent Collot
- Matthias Weidemuller
- François Treussart
- Abdelamid Maali
- David Weiss
- Vahid Sandoghdar
- Jonathan Knight
- Nicolas Dubreuil
- Peter Domokos
- Ferdinand Schmidt-Kaler
- Jochen Dreyer

- Peter Domokos
- Ferdinand Schmidt-Kaler
- Ed Hagley
- Xavier Maître
- Christoph Wunderlich
- Gilles Nogues
- Vladimir Ilchenko
- Jean-François Roch
- Stefano Osnaghi
- Arno Rauschenbeutel
- Wolf von Klitzing
- Erwan Jahier
- Patrice Bertet
- Alexia Auffèves
- Romain Long
- Sébastien Steiner
- Paolo Maioli
- Philippe Hyafil
- Tristan Meunier
- Perola Milman
- Jack Mozley
- Stefan Kuhr
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- Christine Guerlin
- Thomas Nirrengarten
- Cédric Roux
- Julien Bernu

- Ulrich Busk-Hoff
- Andreas Emmert
- Adrian Lupascu
- Jonas Mlynek
- Igor Dotsenko
- Samuel Deléglise
- Clément Sayrin
- Xingxing Zhou
- Bruno Peaudecerf
- Raul Teixeira
- Sha Liu
- Theo Rybarczyk
- Carla Hermann
- Adrien Signolles
- Adrien Facon
- Stefan Gerlich
- Than Long Nguyen

- Eva Dietsche
- Dorian Grosso
- Frédéric Assémat
- Athur Larrouy
- Valentin Métillon
- Tigrane Cantat-Moltrecht

Collaboration: L davidovich, N. Zaguri, P. Rouchon, A. Sarlette, S Pascazio, K. Mölmer …

Cavity technilogy: CEA Saclay, Pierre Bosland

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