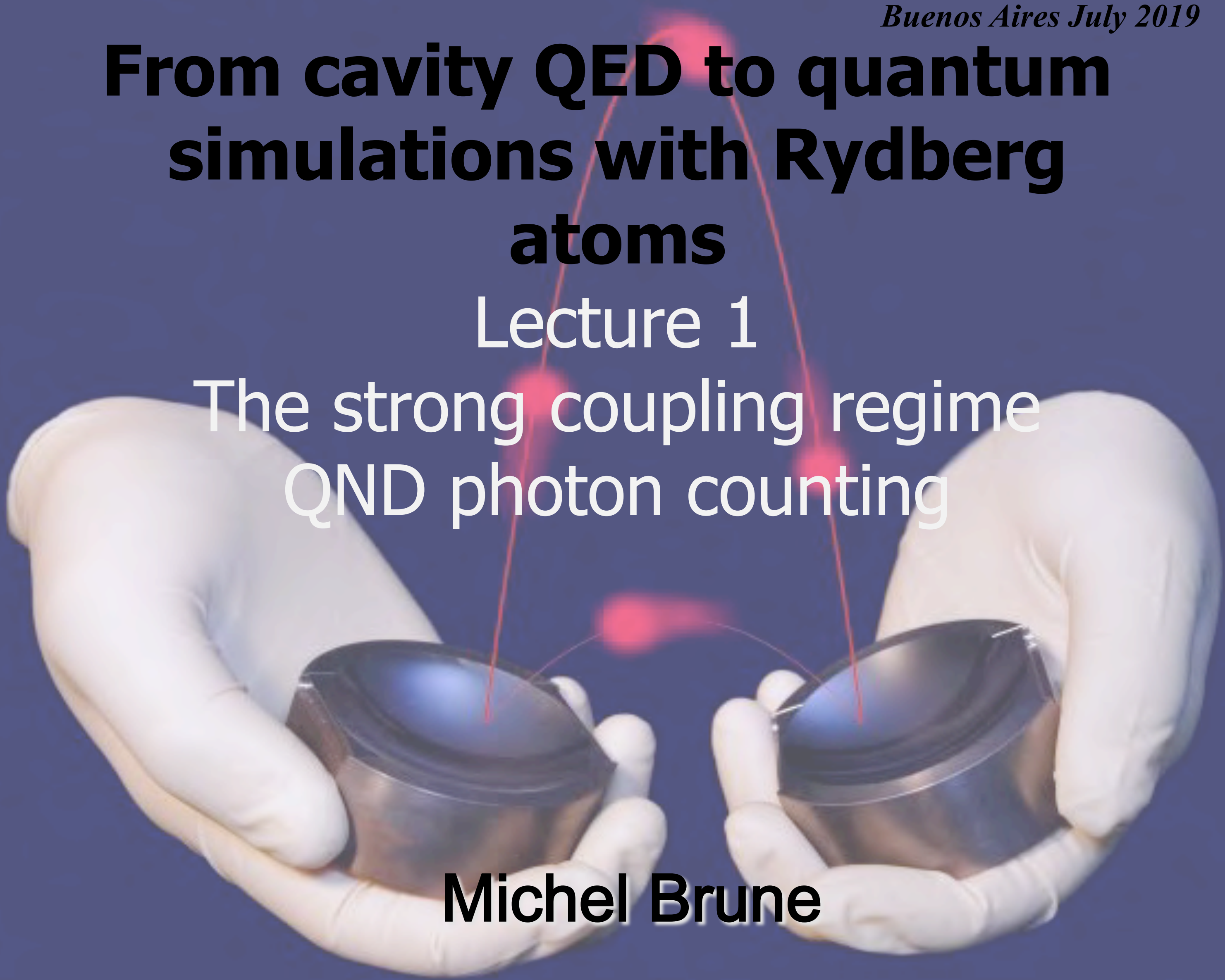
Giambiani Winter School
Buenos Aires July 2019

From cavity QED to quantum simulations with Rydberg atoms

Lecture 1

The strong coupling regime
QND photon counting



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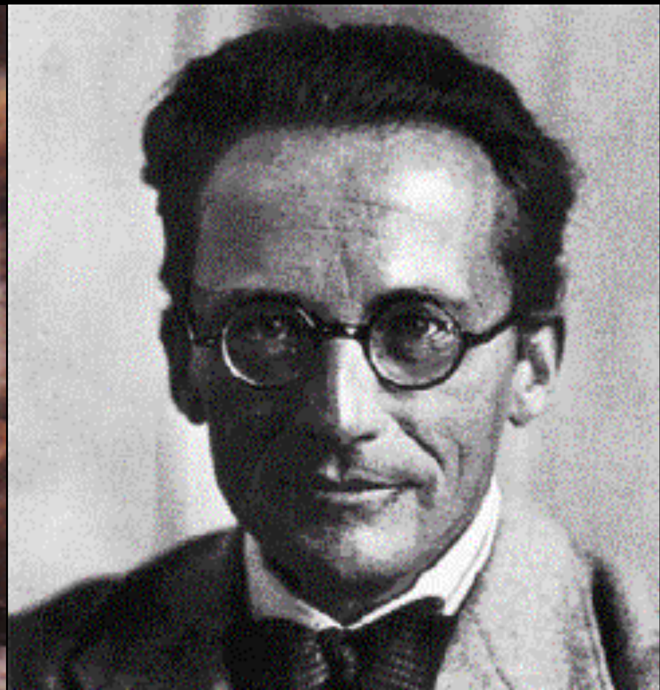
« Ridiculous » quantum phenomena

Schrödinger 1952 :

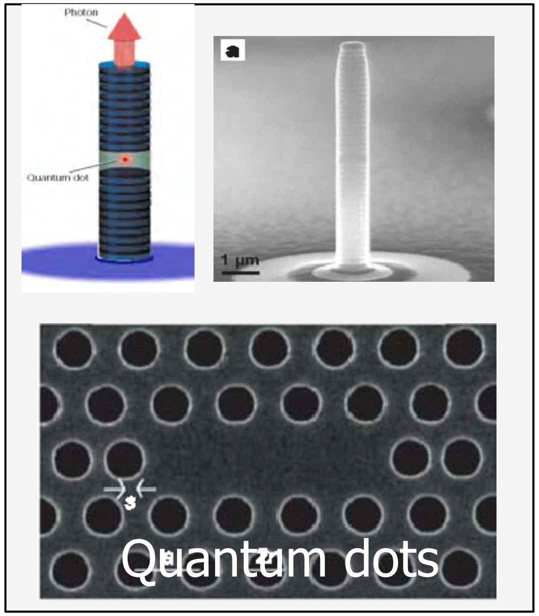
« one never experiments with just one electron, one atom or one molecule. In thought experiments we sometimes assume that we do, this invariably entails **ridiculous consequences**… »

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

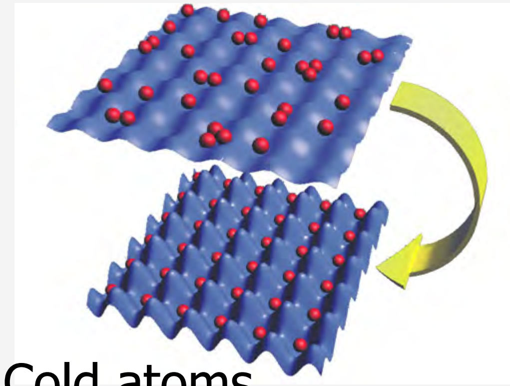


Experiment with individual quantum systems

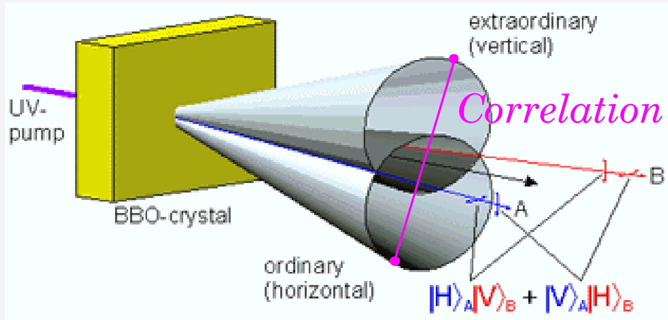
- A thriving field worldwide



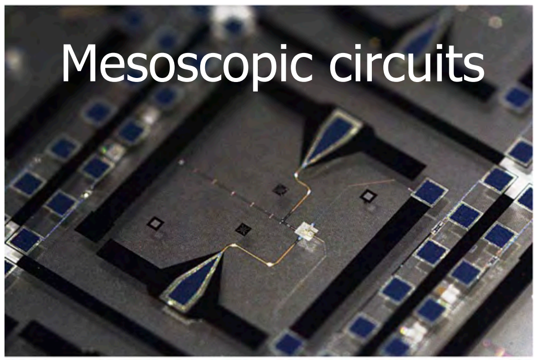
Quantum dots



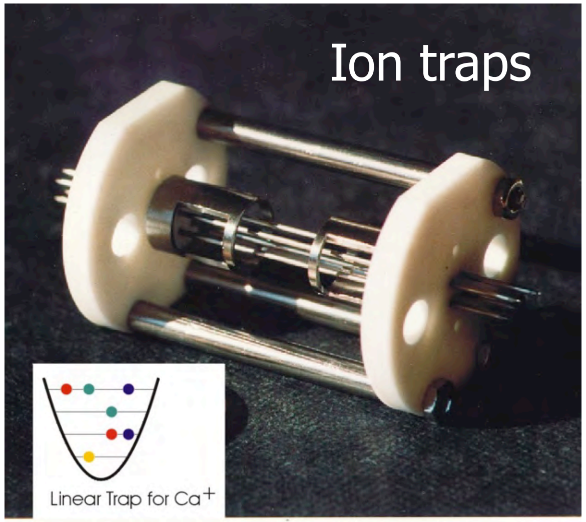
Cold atoms



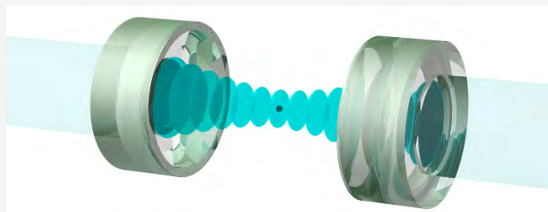
Twin photons



Mesoscopic circuits



Ion traps

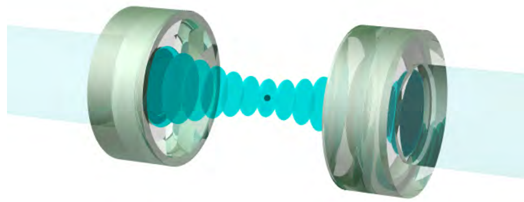


Atoms and cavities

The four flavors of modern CQED

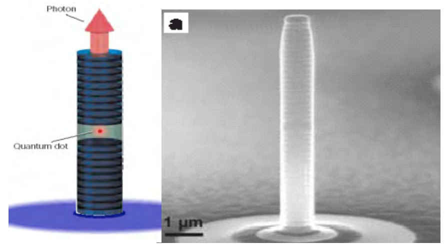
- Optical CQED
  - Ordinary atomic transitions and high finesse FP cavities

$$g \approx 50\ \text{MHz};\ \kappa \approx 100\ \text{kHz};\ \Gamma \approx 10\ \text{MHz};\ T_{\text{int}} \approx 1\text{s}$$



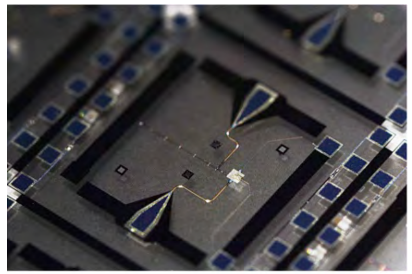
- Solid-state CQED
  - Quantum dots coupled to bragg mirrors/PBG

$$g \approx 10\ \text{GHz};\ \kappa \approx 1\ \text{GHz};\ \Gamma \approx\ 1\text{GHz};\ T_{\text{int}} = \infty$$



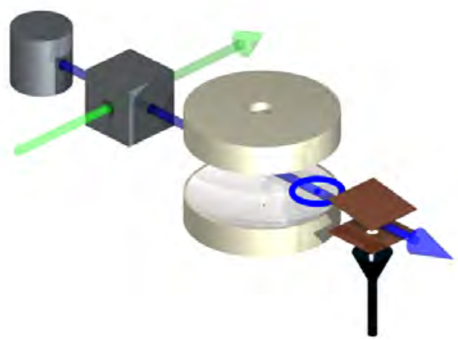
- Circuit QED
  - Solid-state qubits and stripline cavities

$$g \simeq 100MHz; \Gamma \ll \kappa \simeq 1MHz; T_{int} = \infty$$



- Microwave CQED
  - (Circular) Rydberg atoms and superconducting cavities

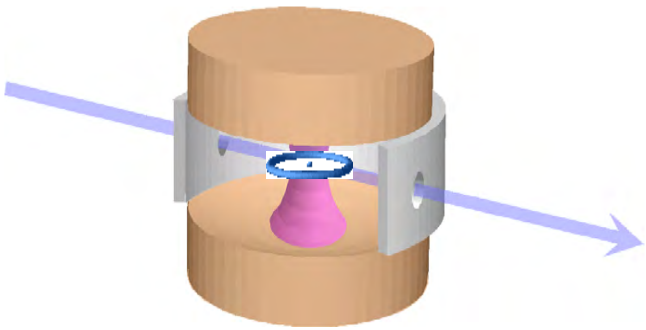
$$g \approx 10\ \text{kHz};\ \kappa \approx 1\ \text{Hz};\ \Gamma \approx 30\ \text{Hz};\ T_{\text{int}} \approx 100\ \mu s$$



Main topic of the course

Exploring the quantum with Rydberg atoms

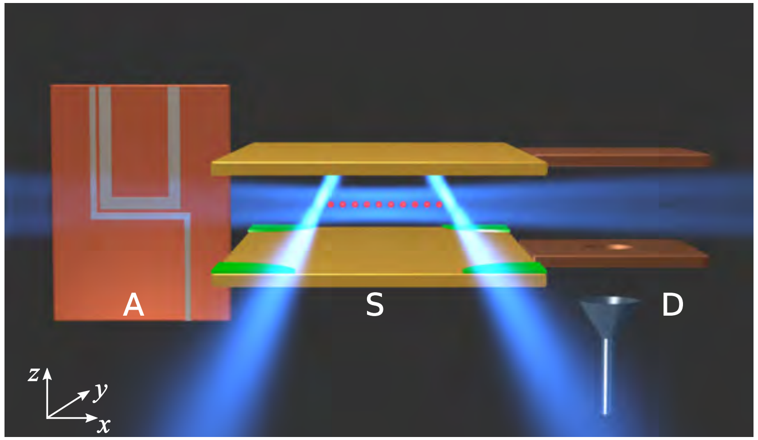
With photons and cavities



→cavity QED exploration of the fundamental aspects of quantum measurement:
- QND photon counting:
- Schrödinger cat and decoherence

→Topic of lectures 1-2

With trapped Rydberg atoms



→High potential for performing quantum simulation of XXZ spin Hamiltonian

→Topic of lectures 3

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

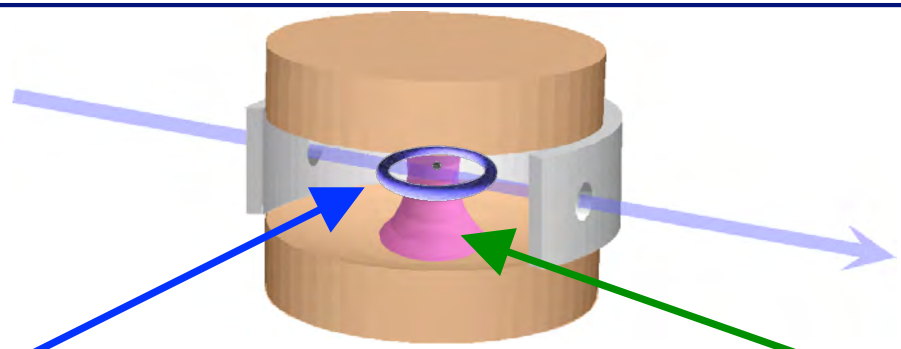
A work starting in 1991

Jean-Michel Raimond **Serge Haroche** **Michel Brune**

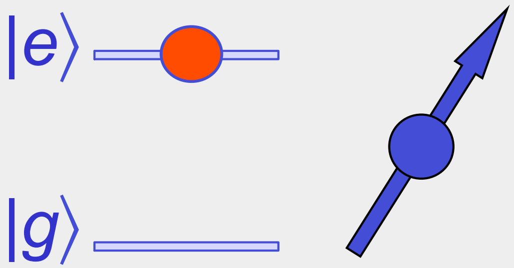
1. One atom, one mode, the Jaynes-Cummings model

Cavity QED: spin and spring

A cavity QED experiment

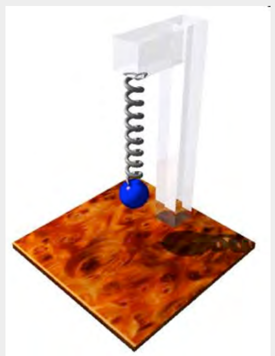


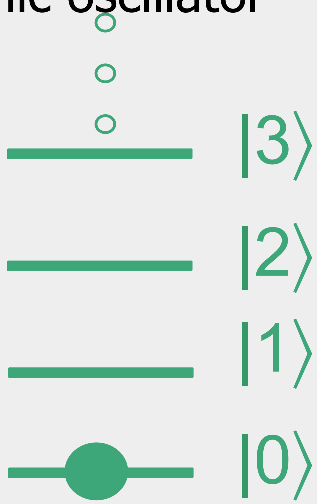
The SPIN:
One atom, two levels



Electric dipole coupling Ω_0

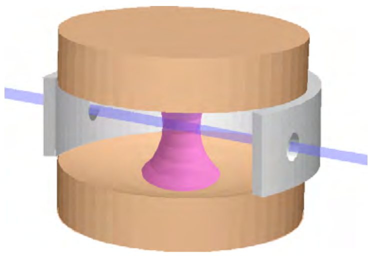
The SPRING:
One high Q cavity mode as an harmonic oscillator

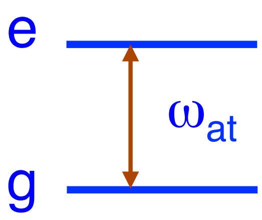




➔ Nearly ideal realization of a simple generic system

The Jaynes Cummings model:





+ a single two level atom, frequency ω_{at}
+ a single field mode, frequency ω_c
+ dipole coupling
+ negligible damping

• Atom-field Hamiltonian: $H = H_{at} + H_{cav} + V_{at\text{-}cav}$

$$H_{at} = \frac{\hbar\omega_{at}}{2}\left[|e\rangle\langle e| - |g\rangle\langle g|\right]$$

$$H_{cav} = \hbar\omega_c\left[a^+ a + 1/2\right]$$

$$V_{at-cav} = -\vec{d}.\hat{\vec{E}}(\vec{r})$$

$$\vec{d} = \vec{d}_{eg}\left[|e\rangle\langle g| + |g\rangle\langle e|\right]$$

Condition of validity:

- ω_c close to a single atomic transition: $|\delta| = |\omega_c - \omega_{at}| << \omega_c, \omega_{at}$

- small cavity: only one mode close to resonance $FSR >> \delta$

The Jaynes Cummings hamiltonian

- Rotating wave approximation (RWA):

$$V_{at-cav} = \hbar\Omega(\vec{r})/2\left[a|e\rangle\langle g| + a|g\rangle\langle e| + a^{+}|g\rangle\langle e| + a^{+}|e\rangle\langle g|\right]$$

Non-resonant terms are neglected

$$V_{at-cav} \approx \hbar\Omega(\vec{r})/2\left[a|e\rangle\langle g| + a^{+}|g\rangle\langle e|\right]$$

$$H_{JCM} = H_{at} + H_{cav} + V_{at-cav}$$

- Vacuum Rabi frequency: $\Omega(\vec{r}) = -2d_{eg}.\vec{f}(\vec{r}).E_{\omega} = \Omega_0.\left|\vec{f}(\vec{r})\right|$

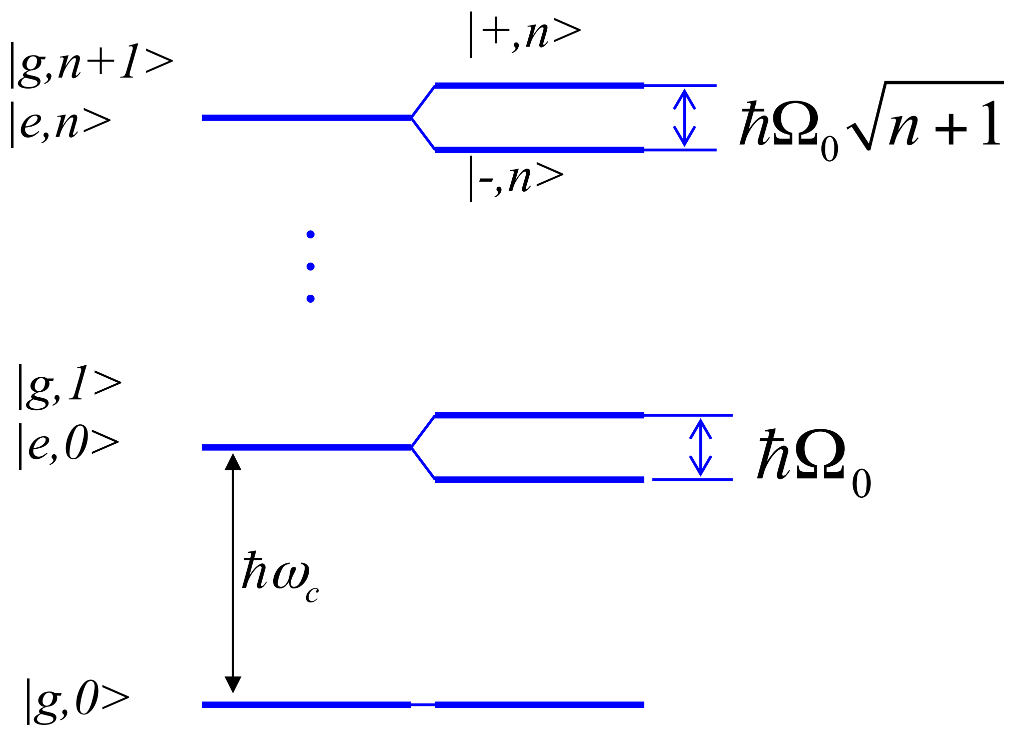
Maximum coupling at cavity center

$$\Omega_0 = 2d_{eg}.\sqrt{\frac{\hbar\omega}{2\varepsilon_0 V_{cav}}}$$

spatial field amplitude distribution in the cavity $\vec{f}(\vec{r})$

- Validity of RWA: $\Omega_0 \ll \omega_{at}, \omega_c$

Dressed energy levels at resonance $(\omega_{at}=\omega_c)$



- Levels just couple by pairs (except the ground state)
- level splitting scales as the Field amplitude

- Eigenvalues: $E_{\pm n} = \hbar\omega_c(n+1/2) + \hbar\omega_{at} \pm \hbar\Omega_0/2\sqrt{n+1}$
- Eigenstates: $|\pm n\rangle = 1/\sqrt{2}\left[|e,n\rangle \pm |g,n+1\rangle\right]$

2. Rydberg atoms in a cavity: achieving the strong coupling regime

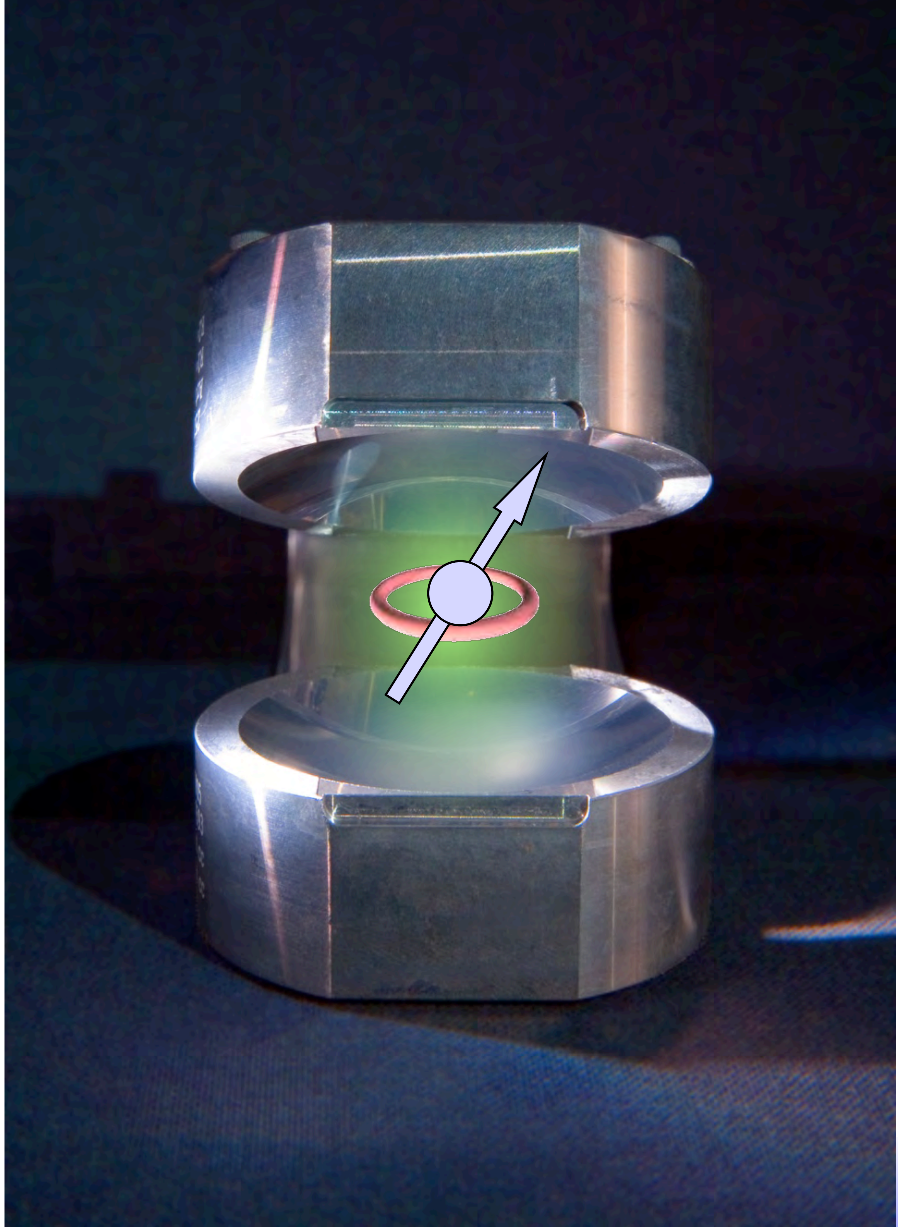
One photon and one atom

in a box:

- Photon box: superconducting microwave cavity
- “circular" Rydberg atoms

Microwave Rydberg atom CQED

- Photon box



Two essential ingredients:

- Photon trap:

the "spring"

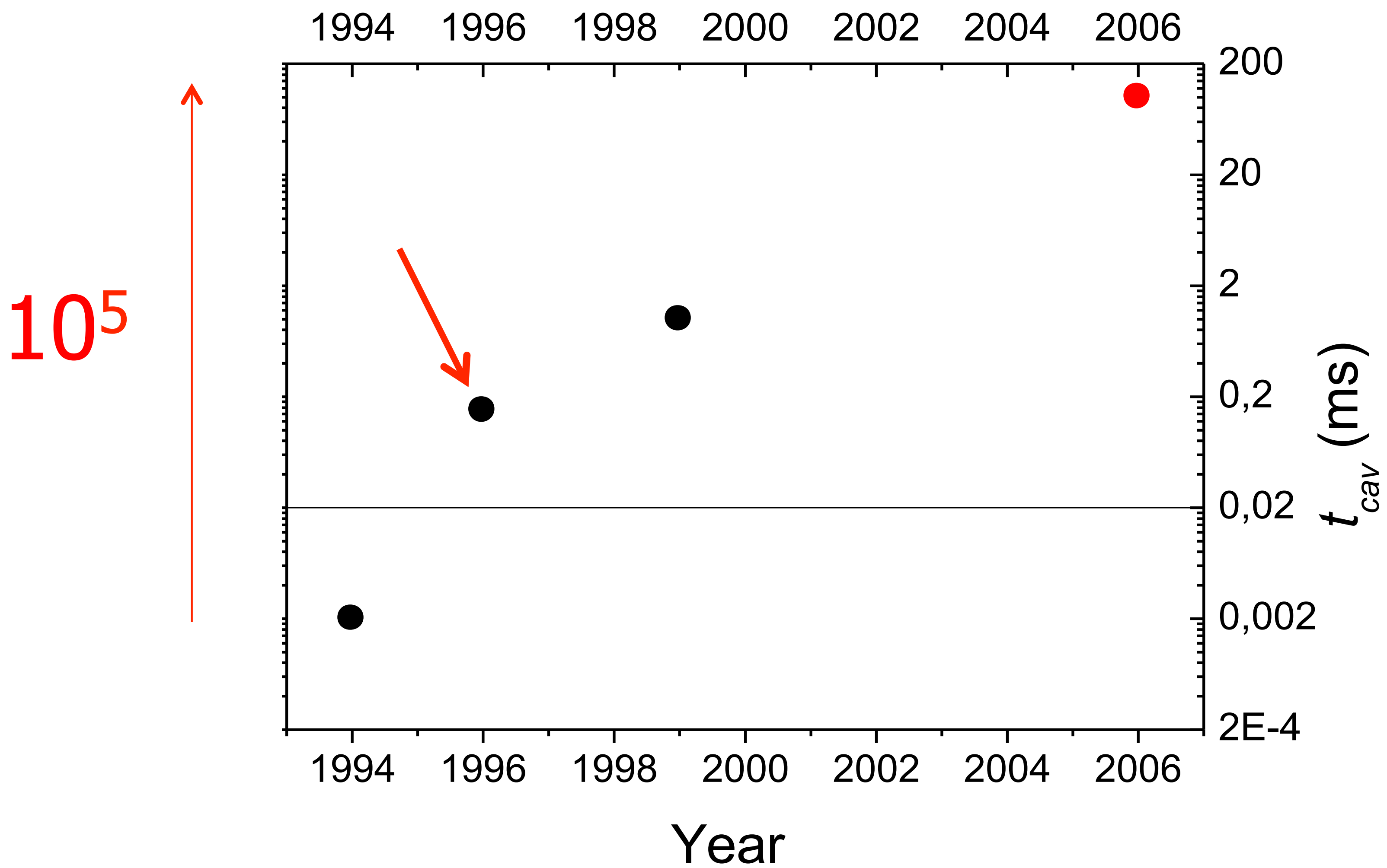
- Photon probe:

the spin

Single Rydberg atoms

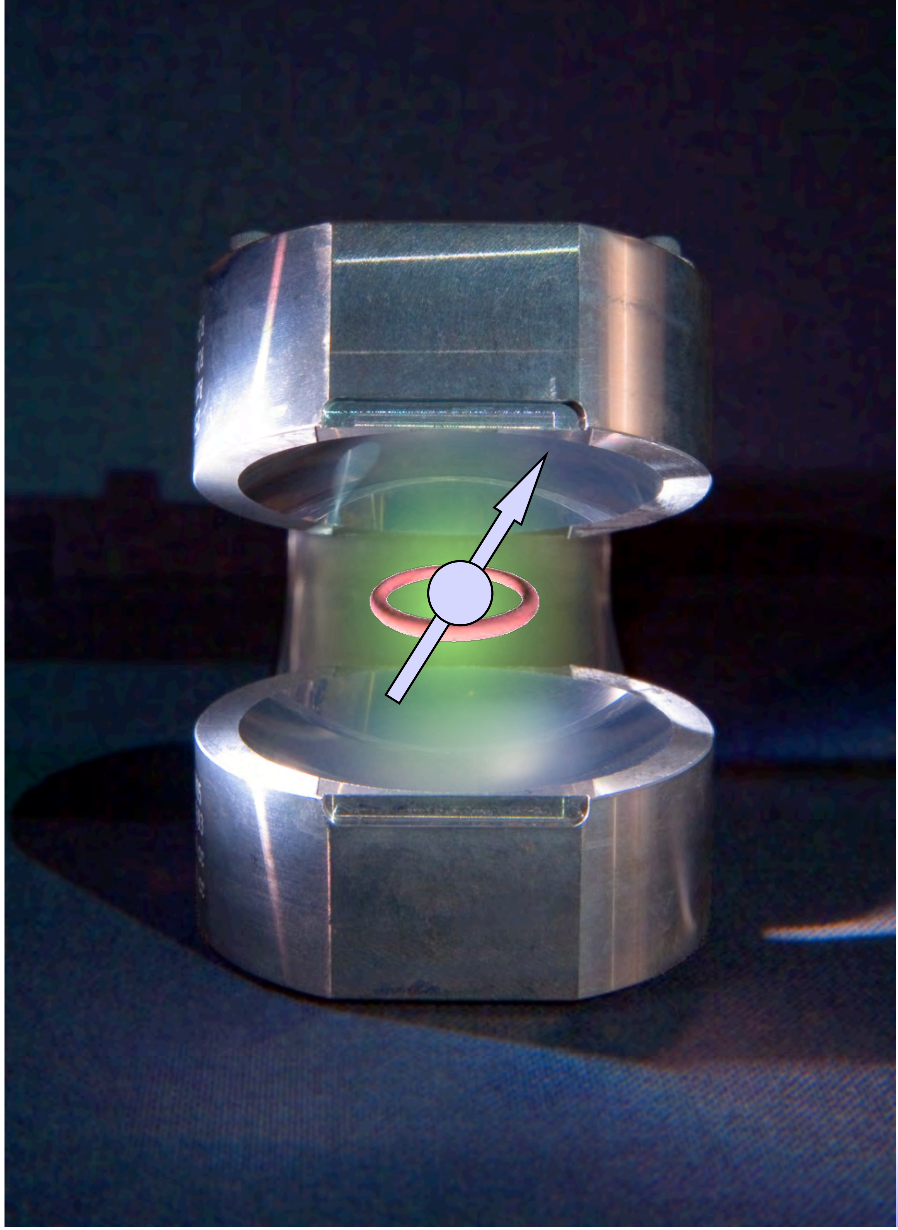
Superconducting cavity technology

- Our version of Moore's law:



The "Spin": Circular Rydberg atoms

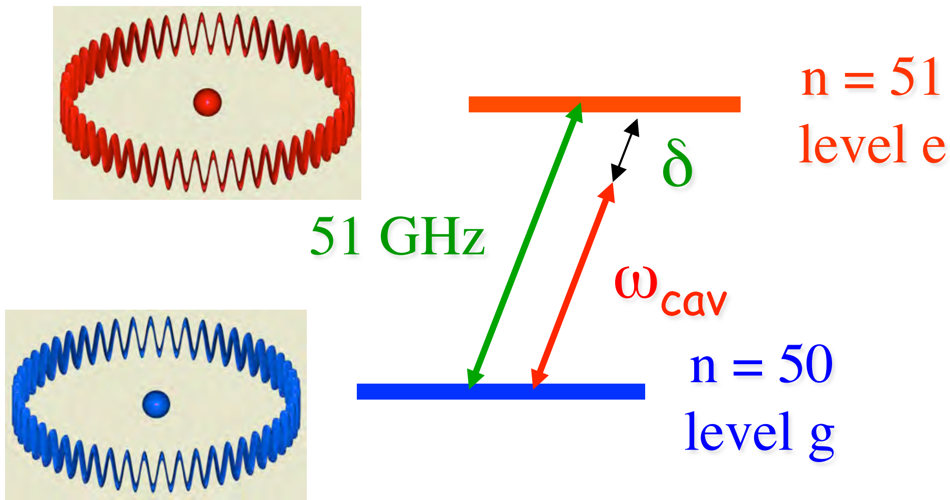
- Photon box



- Photon probes

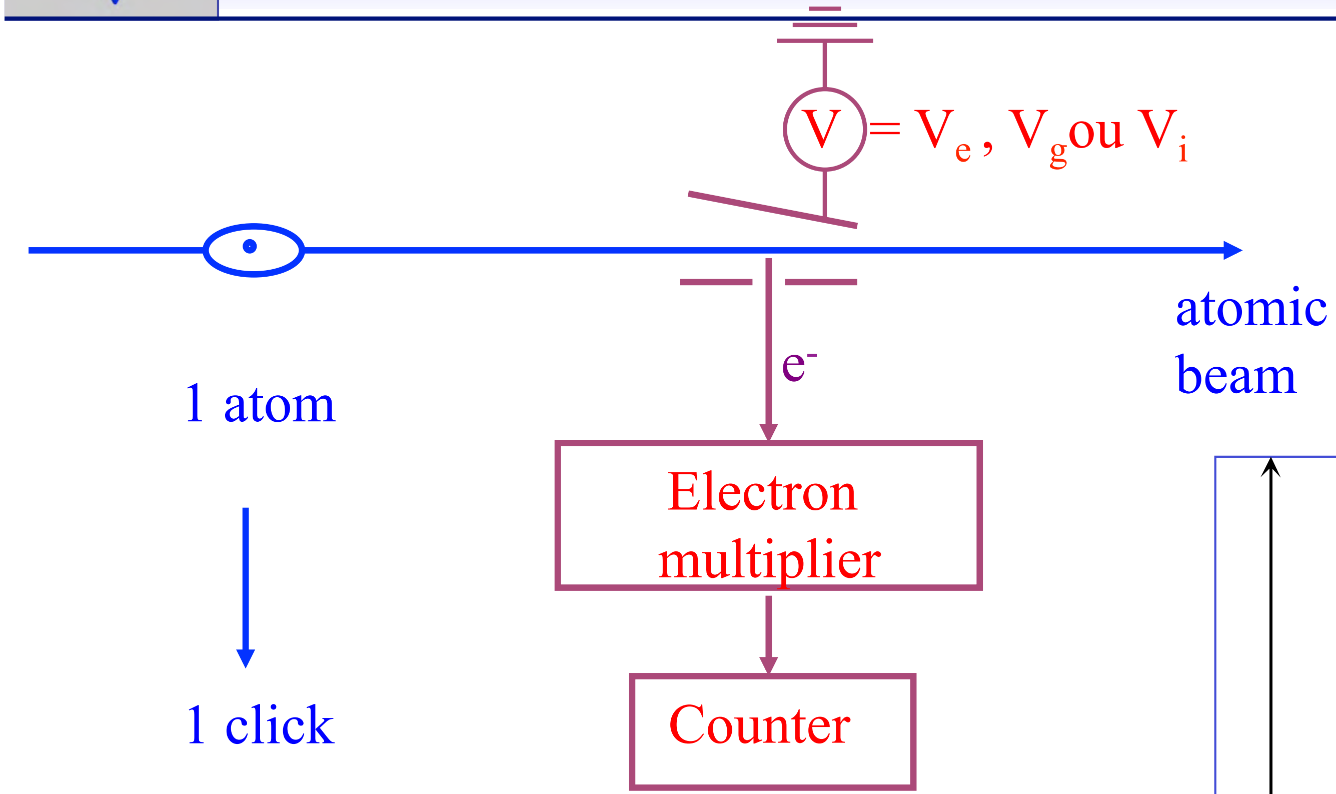
Circular Rydberg atoms:

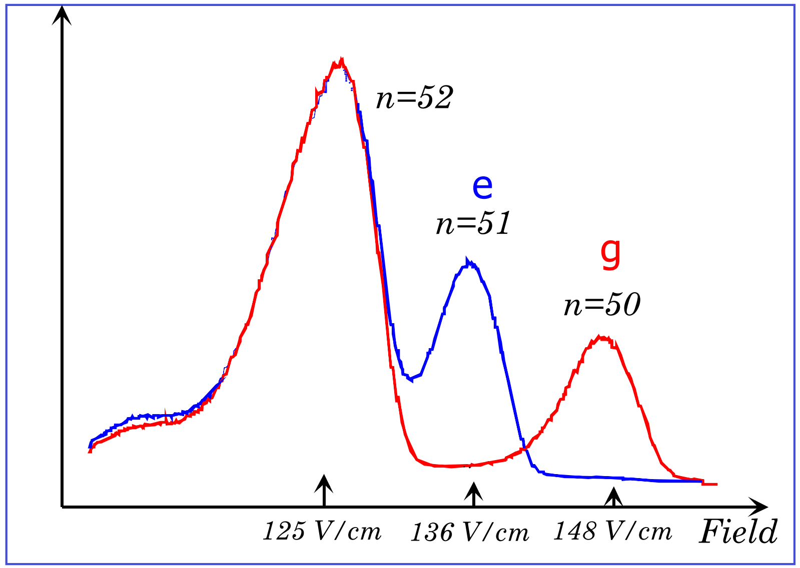
$l = |m| = n-1$



- Large dipole 1500 au
- Long lifetime: 30ms
- detected une by one

Detection of Rydberg atoms (1)





- atoms detected one by one by selective ionization in an electric field

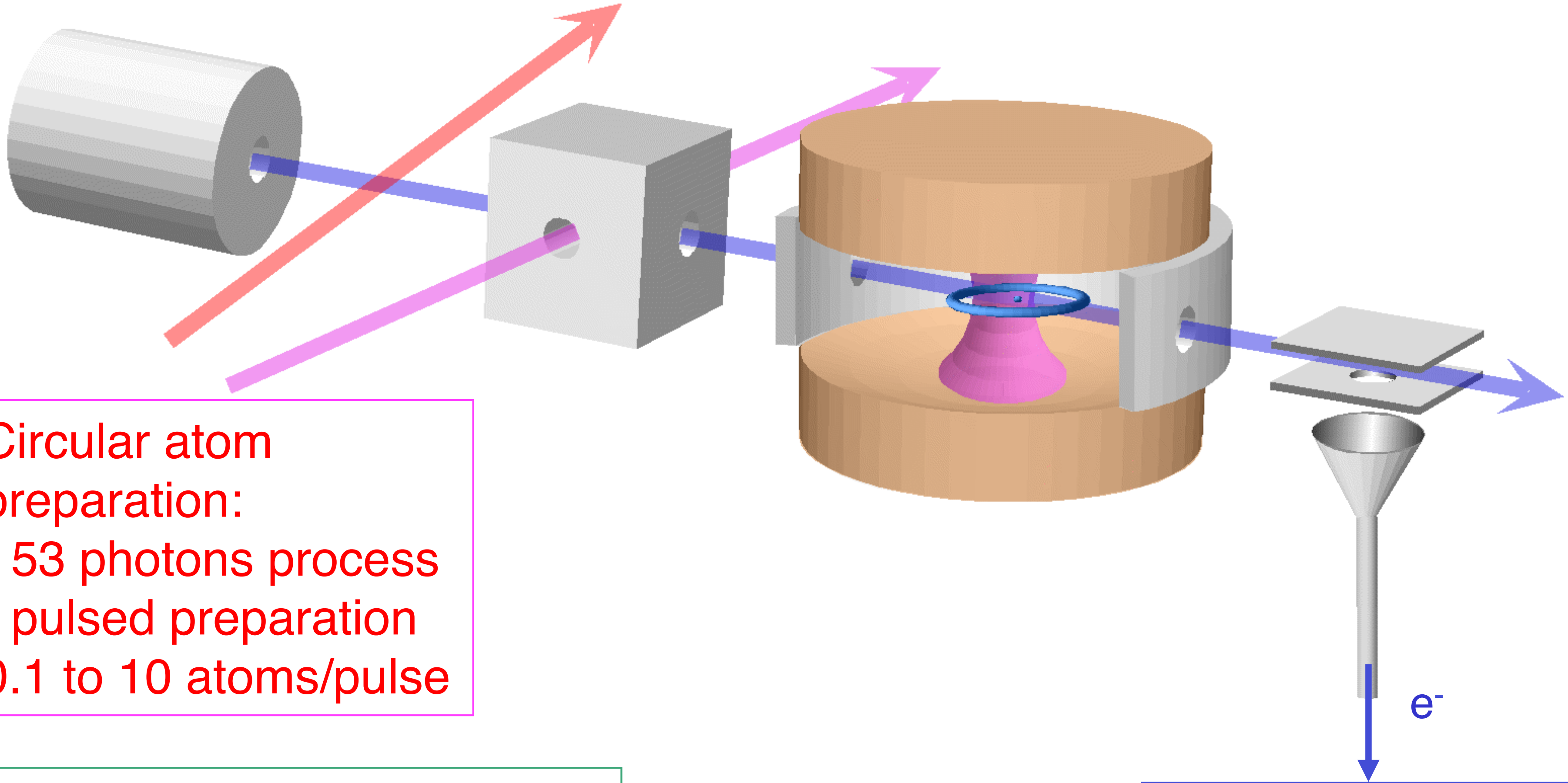
→ measurement of internal energy state of the atom after interaction with C

→ in term of "spin": σ_z measurement

Experimental set-up

^{85}Rb

Laser velocity selection



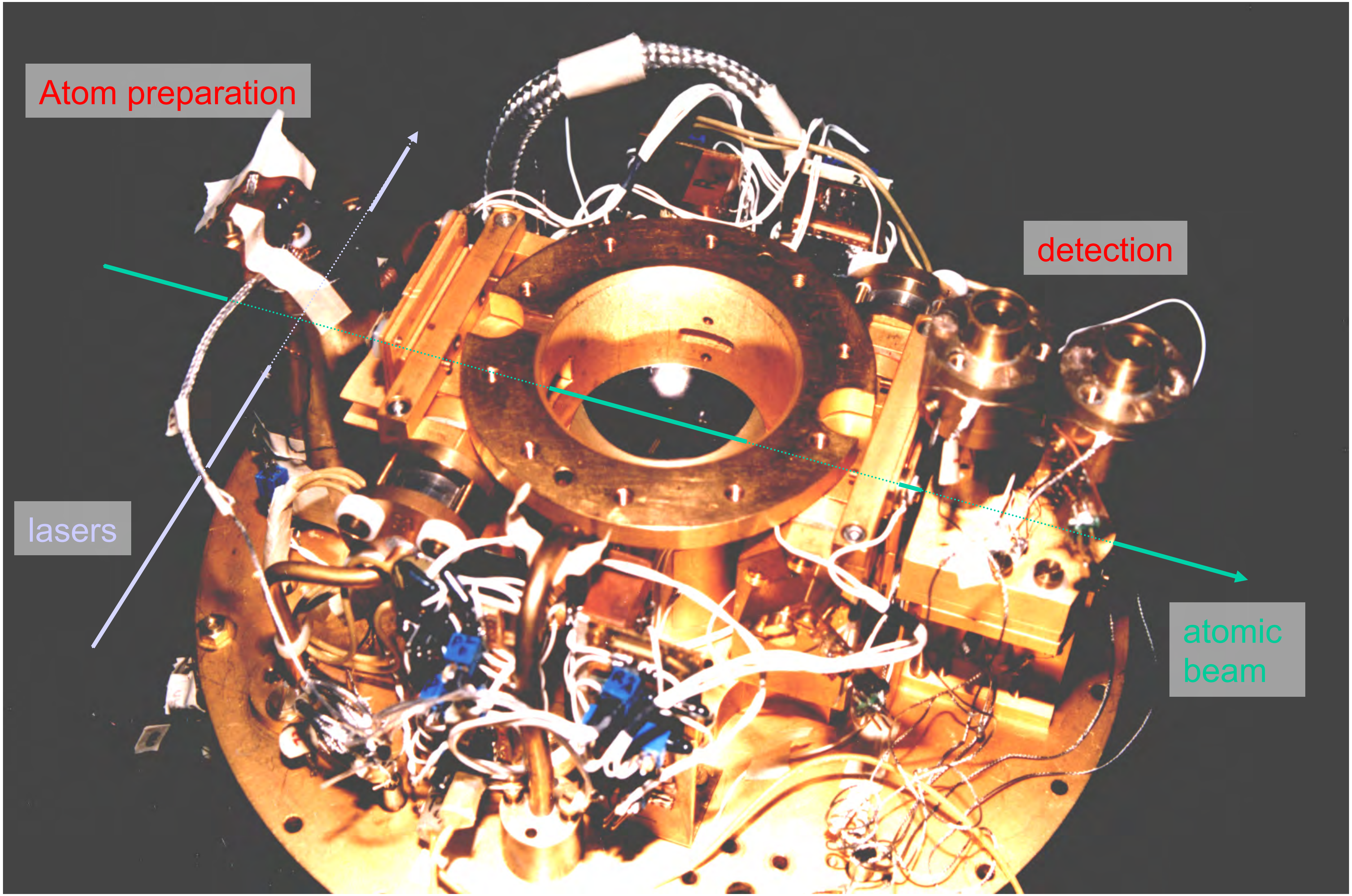
Circular atom preparation:
- 53 photons process
- pulsed preparation

0.1 to 10 atoms/pulse

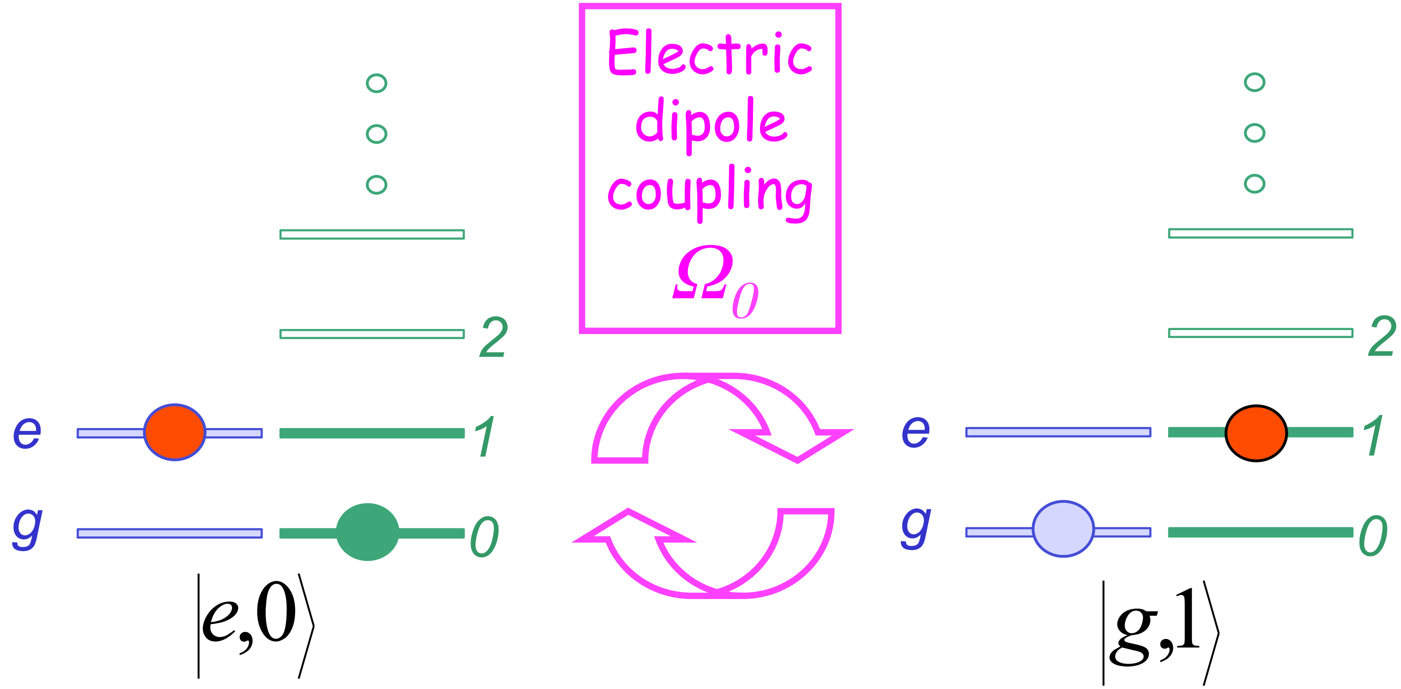
Cryogenic environment
T=0.6 to 1.3 K
→weak blackbody radiation

State selective detector
One atom = one click

Experimental setup (Version1)



Resonant atom-field coupling: dynamic point of view



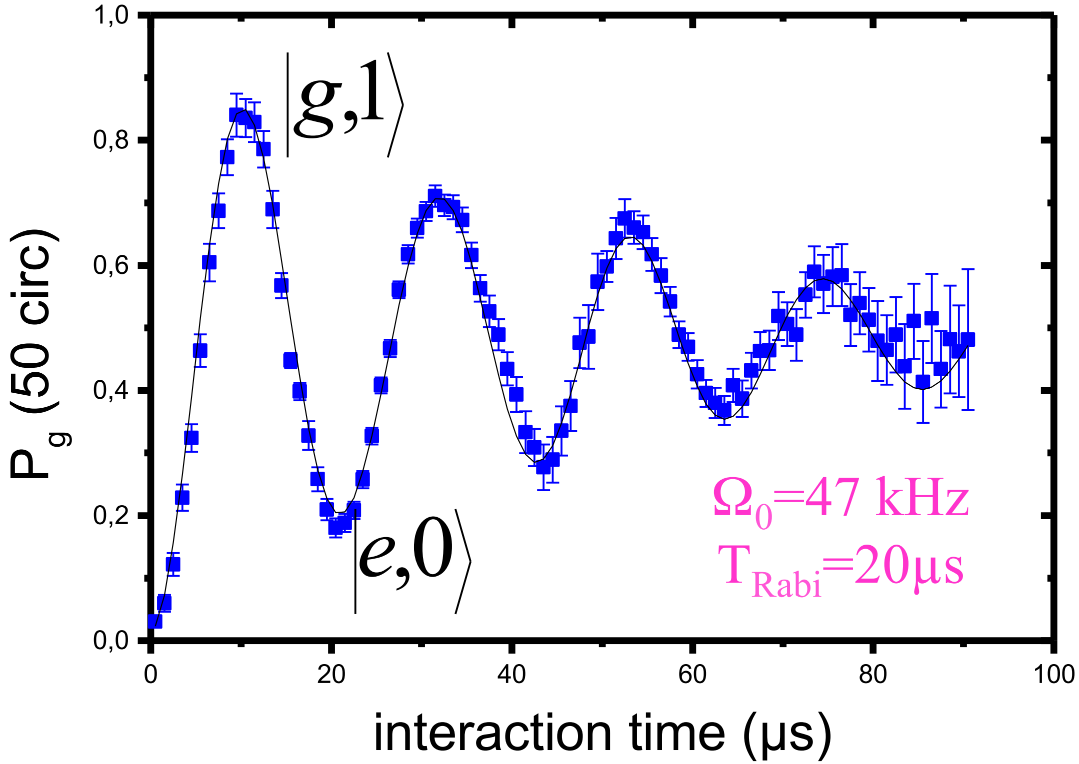
$\Omega_0/2\pi = 50\ kHz$

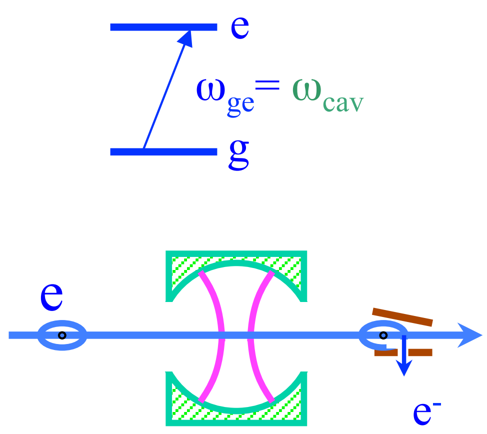
$T_{rabi} = 20\ \mu s$

$$|e,0\rangle \rightarrow \cos\left(\frac{\Omega_0 t}{2}\right)\cdot|e,0\rangle - i\sin\left(\frac{\Omega_0 t}{2}\right)\cdot|g,1\rangle$$

→ Coherent Rabi oscillation

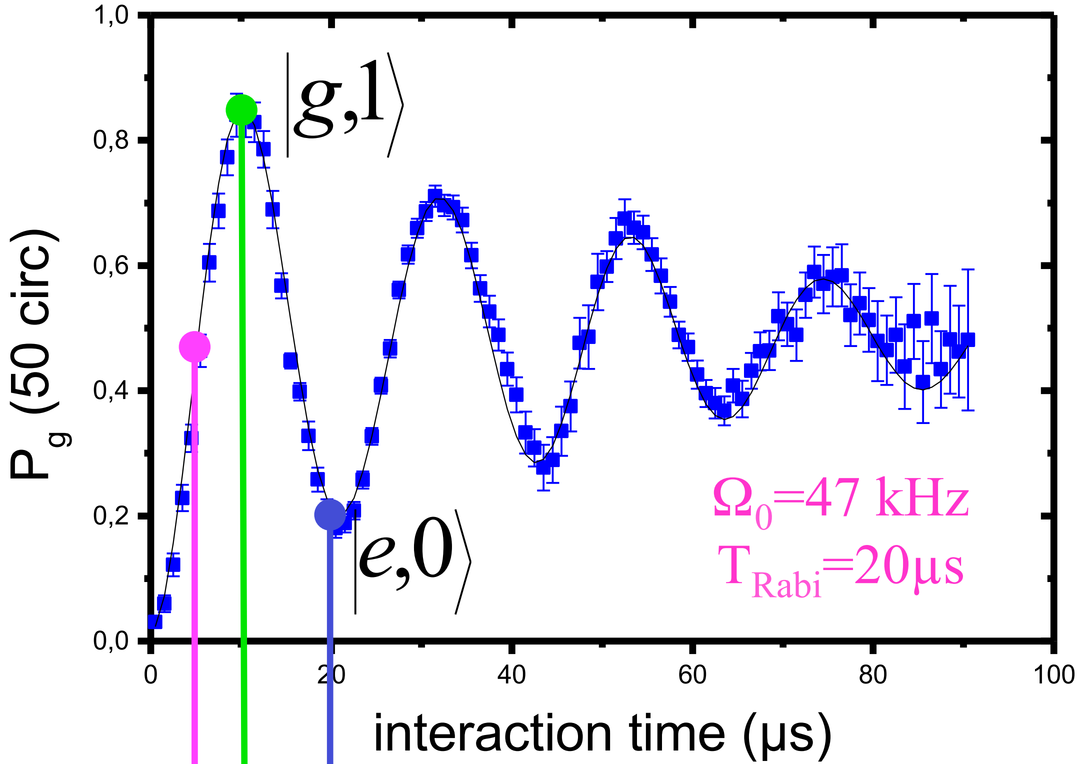
Single photon induced Rabi oscillation

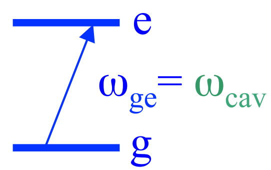


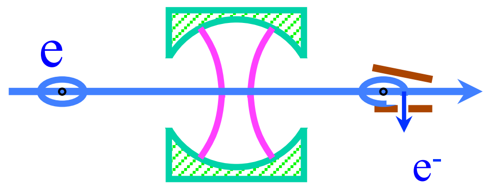


Coherent Rabi oscillation
replaces irreversible damping
by spontaneous emission

Vacuum Rabi oscillation and quantum gates







2π • Phase gate, QND detection of a single photon

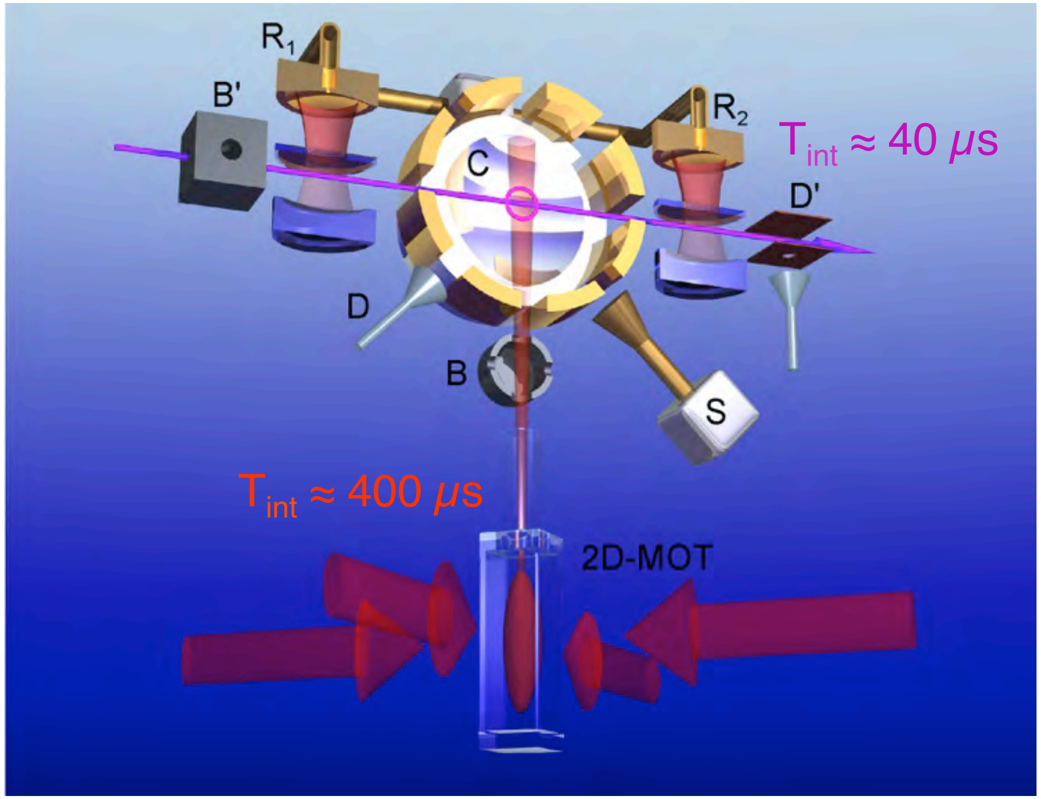
π •Atom-field state exchange

π/2 • EPR pair preparation

3. Resonant interaction with slow atoms

Direct observation
of discrete Rabi frequencies

The new, slow-atoms cavity QED setup



- Technical challenges

- preparation of Circular Rydberg atoms inside the cavity

- detection of Rydberg atoms inside the cavity: not yet implemented

- fabrication of a new superconducting cavity setup

$$T_{cav} = 8\ \mathrm{ms}$$

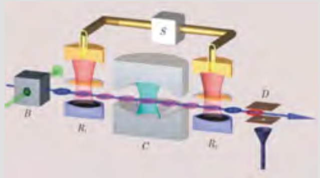
Not the best ever … but good-enough for what follows

⇒ Cavity QED experiment in a new regime with 10 m/s atoms:

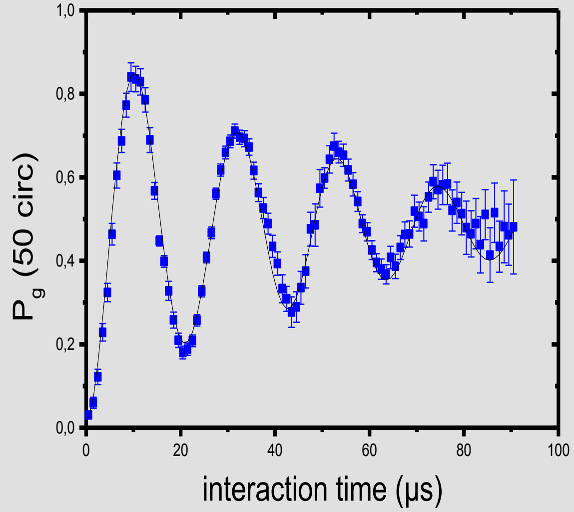
- Resolution of atom-cavity dressed states by microwave spectroscopy using the classical source S
- Observation of resonant interaction over unprecedented timescale

➞ Preparation of large "Schrödinger cat" sates

Rabi oscillation in a small coherent field



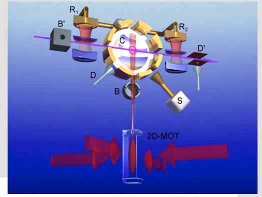
M. Brune et al., Phys. Rev. Lett. 76, 1800 (1996).

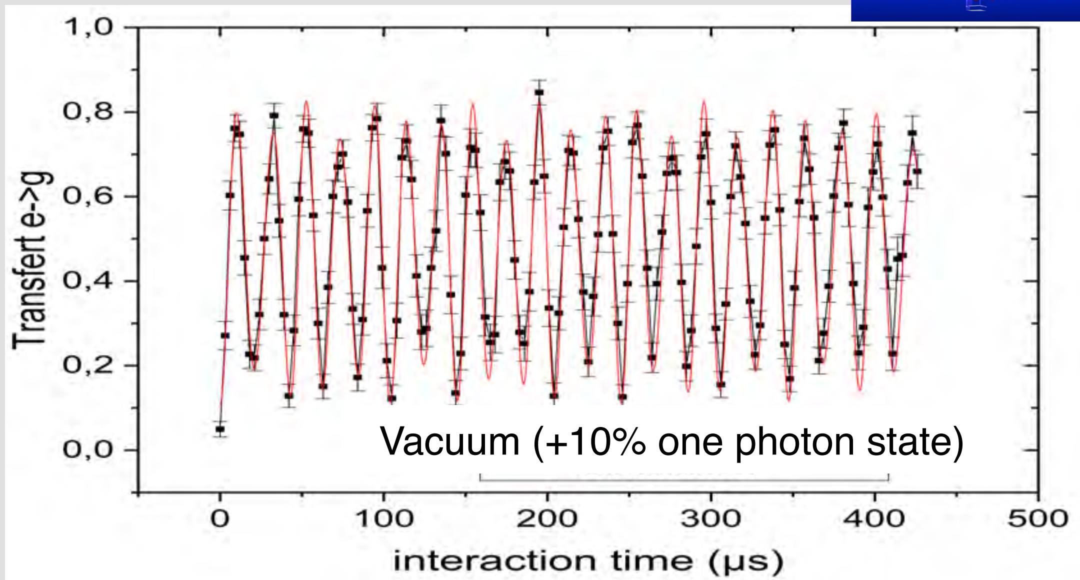


Vacuum Rabi oscillations

Fast thermal beam V=250 m/s

F. Assémat et al., in preparation(2018)





Slow 2D-MOT beam V=10 m/s

Theoretical fit with:

- Finite contrast
- 0.1 blackbody field
- No damping visible

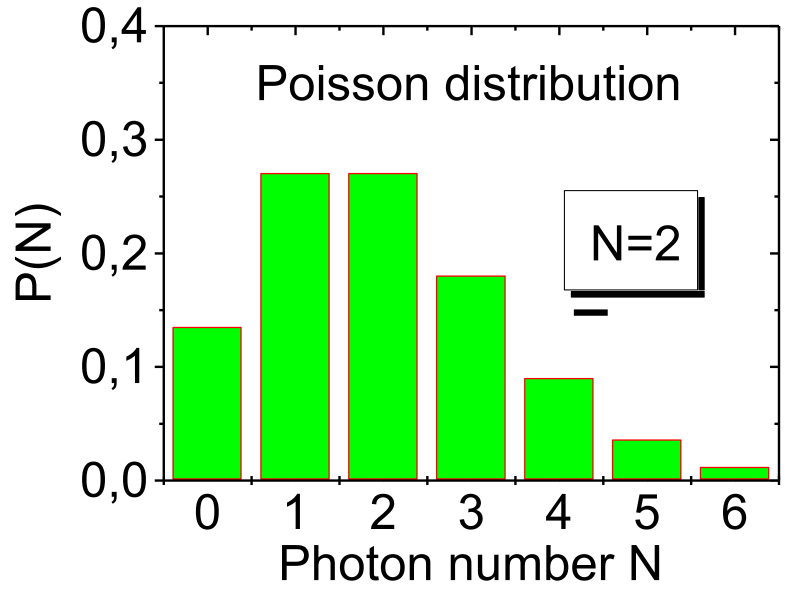
(T_{cav}= 8 ms)

Coherent field states

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

Photon number distribution:

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

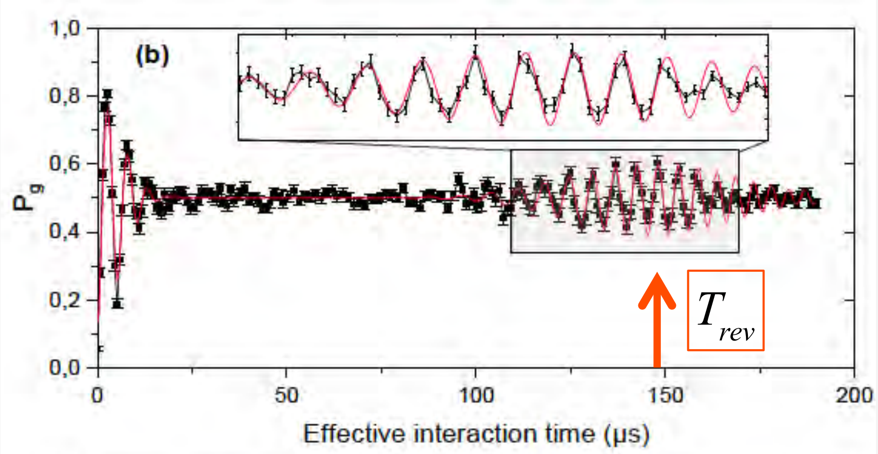


- Rabi oscillation in a coherent field:

$$P_g(t) = \sum_N P(N) \frac{1}{2}\left(1 - \cos\left(\Omega_0 t \sqrt{N+1}\right)\right)$$

Revival and photon graininess

- Rabi oscillation in a coherent state



Eberly et al. PRL **44**, 1323 (1980)

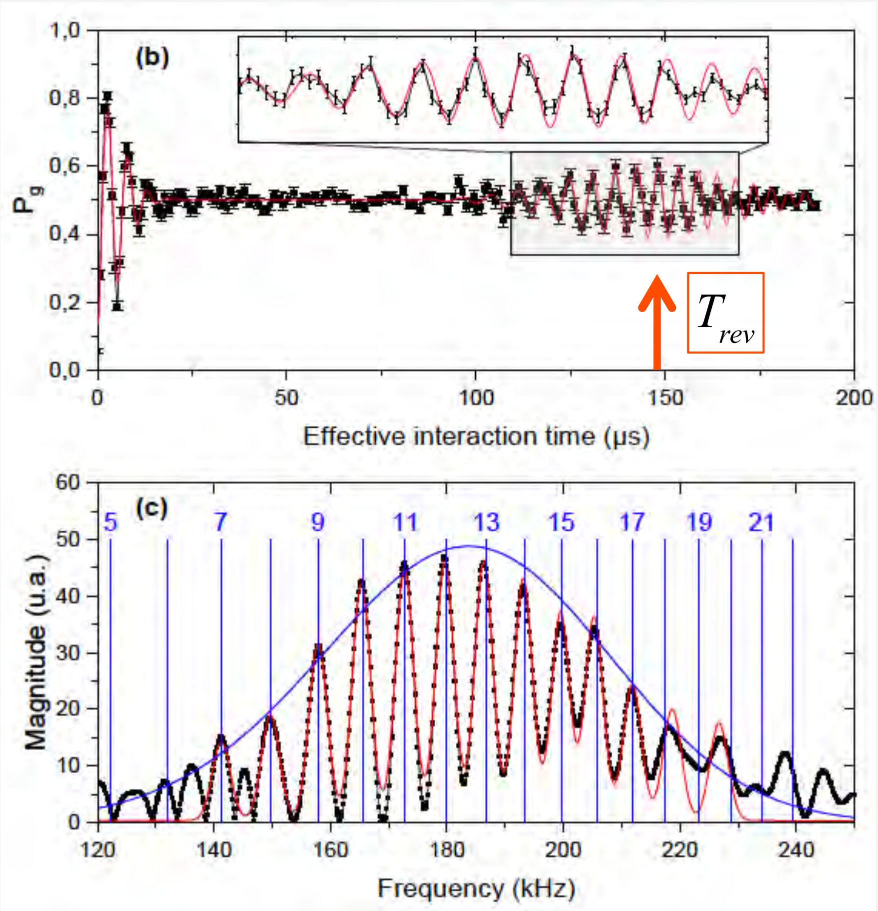
Revival time

$$T_{rev} = 2T_0\sqrt{\overline{n}}$$

T_0 Vacuum Rabi oscillation period

Revival and photon graininess

- Rabi oscillation in a coherent state



➠ Revival as a direct manifestation of photon graininess

Eberly et al. PRL **44**, 1323 (1980)

Revival time

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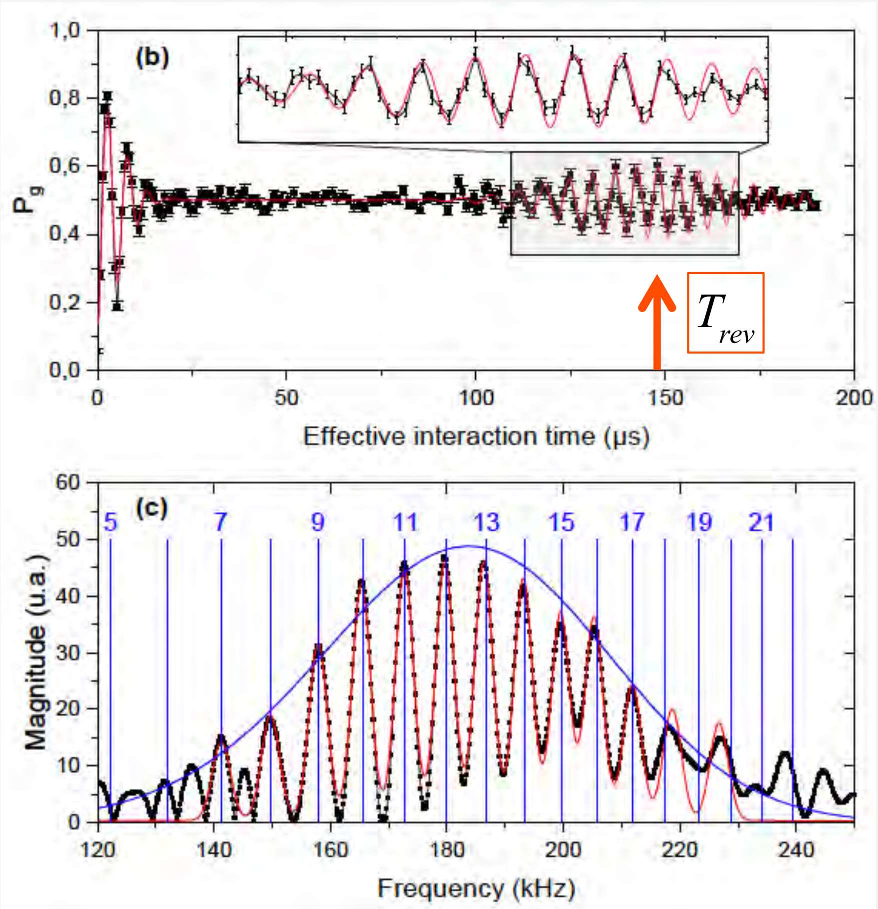
T_0 Vacuum Rabi oscillation period

Revival and photon graininess

- Rabi oscillation in a coherent state



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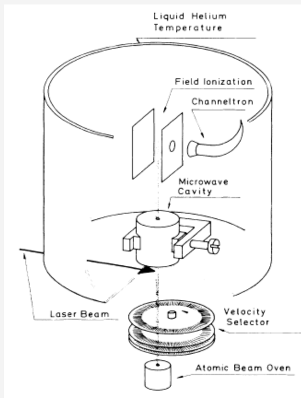
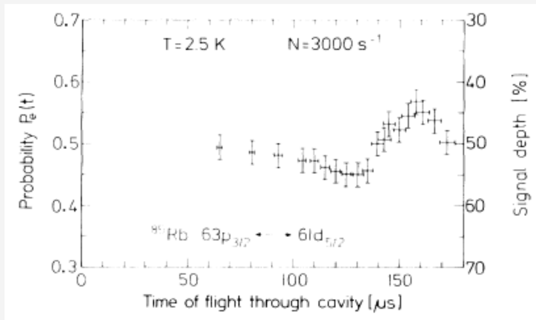
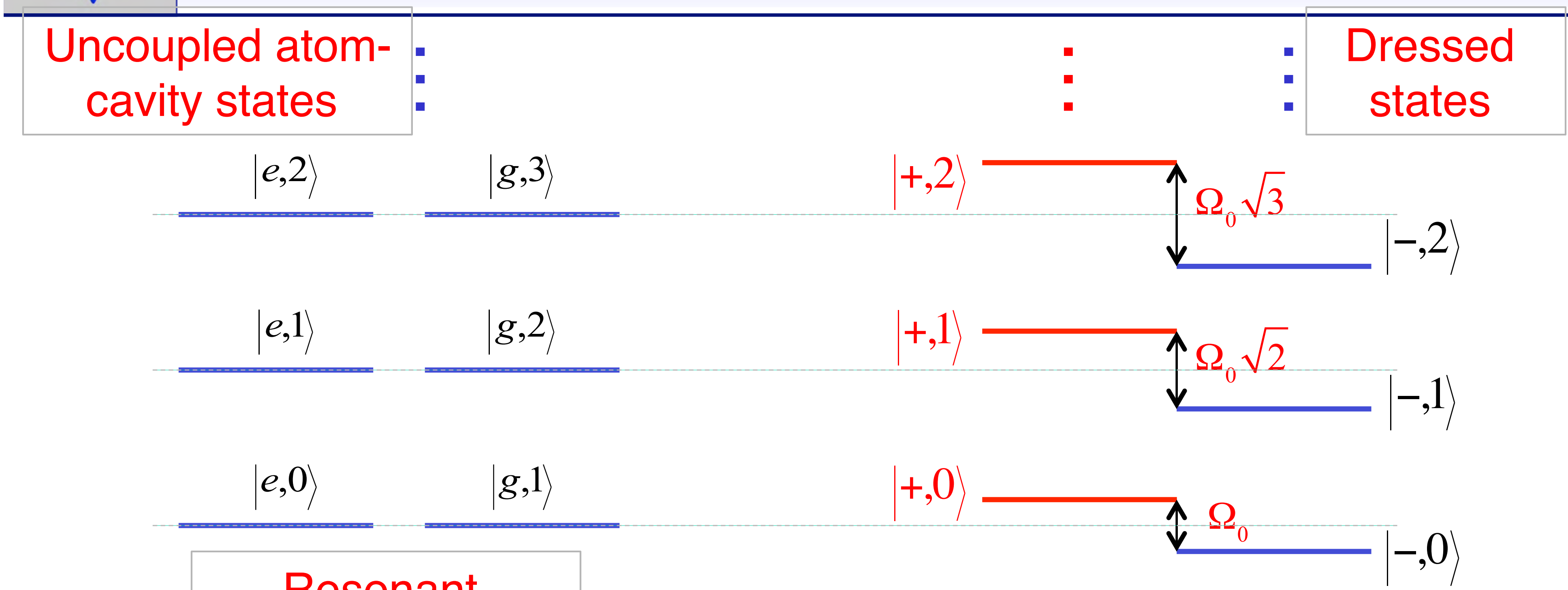
Rempe, et al., *PRL* **58**, 353–356 (1987)





Revival in the micromaser

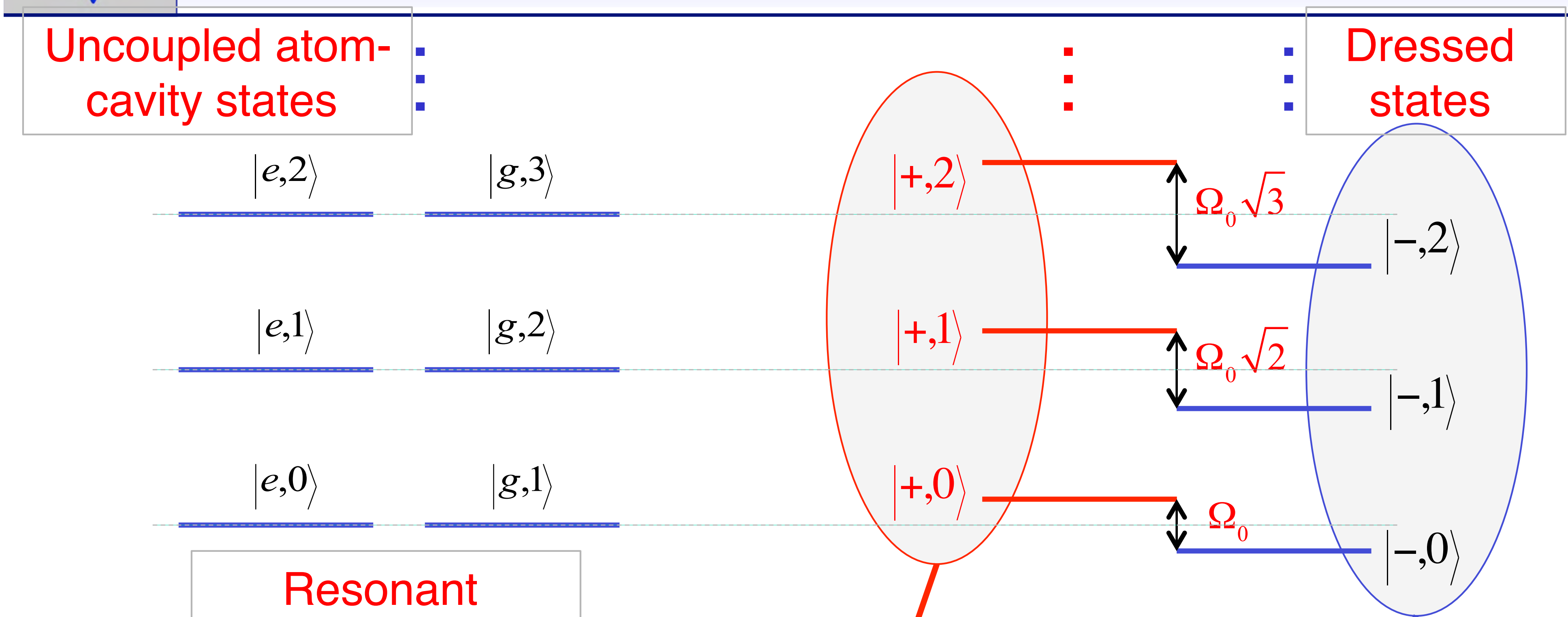
Rabi oscillation in a small coherent field



Resonant interaction

→ the spectrum splits into two nearly harmonic scales

Rabi oscillation in a small coherent field



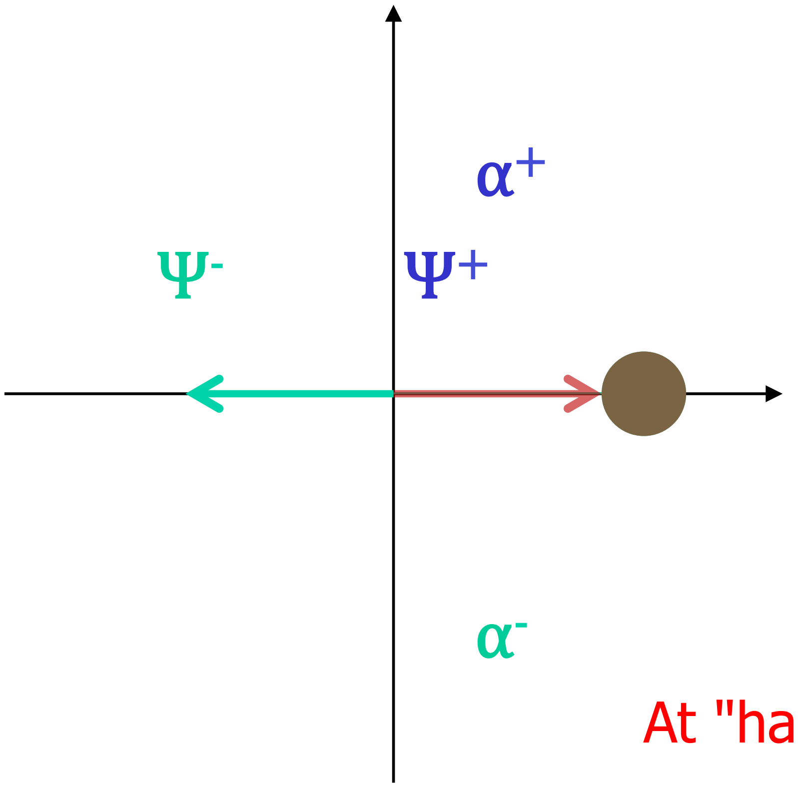
→ the spectrum splits into two nearly harmonic scales

Initial state

$$|e,\alpha\rangle \qquad \Rightarrow |\psi(t)\rangle \approx \frac{1}{\sqrt{2}}\left(\left|\alpha e^{+i\Phi(t)}\right\rangle \otimes \left|\psi_{at,+}(t)\right\rangle + \left|\alpha e^{-i\Phi(t)}\right\rangle \otimes \left|\psi_{at,-}(t)\right\rangle\right)$$

$$\Phi(t) = \Omega_0 . t / 4\sqrt{\bar{N}}$$

Rabi oscillation in a small coherent field



- Initially: coherent field |α>
- Resonant interaction with atom in |e> during time t_1

➞The atom undergoes Rabi oscillations

➞The field splits into two components rotating in opposite directions

➞The atomic state also rotates on the Bloch sphere

At "half revival" the atom is disentangled

$$|e,\alpha\rangle \Rightarrow |\psi_{\text{at-field}}(t)\rangle \approx \frac{1}{\sqrt{2}}\left(|\alpha e^{+i\pi}\rangle + .|\alpha e^{-i\pi}\rangle\right) \otimes \left|\psi_{at}\left(\frac{t_{\text{rev}}}{2}\right)\right\rangle$$

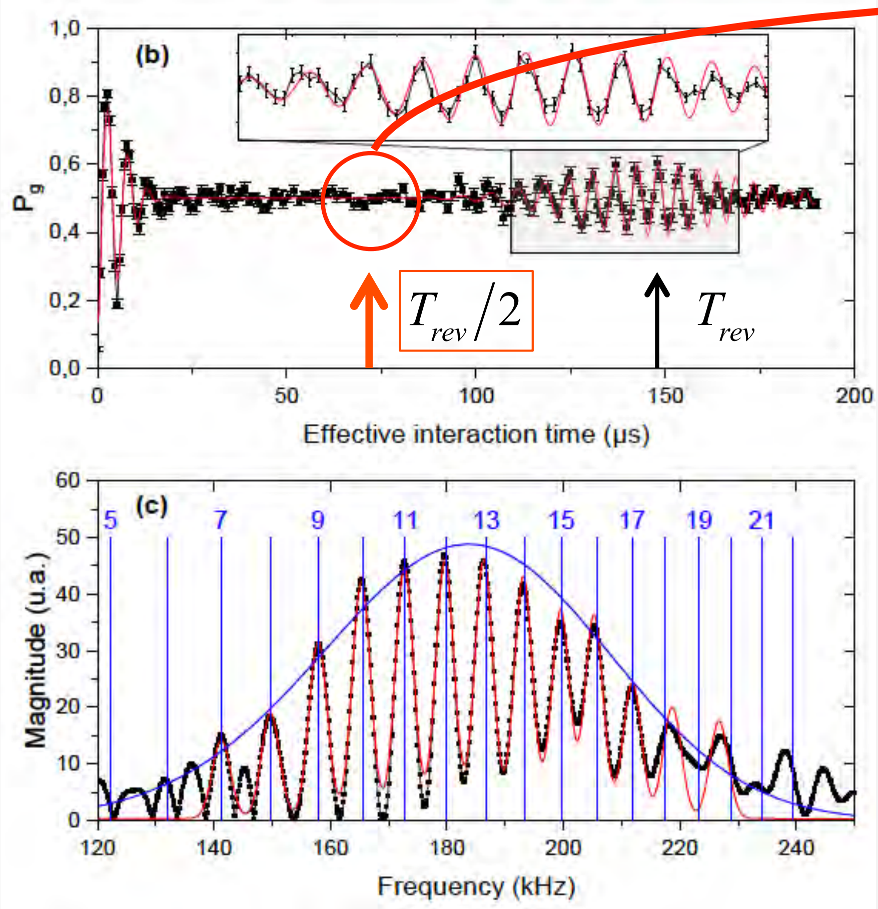
➟ Preparation of a field "cat state" (more in tecture 2)

J. Gea-Banacloche, PRL. 65, 3385 (1990)
G. Morigi et al. Phys. Rev. A 65, 040102 (2002)
Meunier et al. PRL 010401 (2005)

Field state at "half revival"

- Rabi oscillation in a coherent state

Eiselt, et al. Opt. Comm. 72, 351 (1989)
Gea-Banacloche, PRL 65, 3385 (1990)



➟ Revival as a direct manifestation of photon graininess

Atom-field state at half revival:

$$\left|\psi_{at,field}\right\rangle \approx \left|\psi_{at}\right\rangle \otimes \left|\psi_{cat}\right\rangle$$

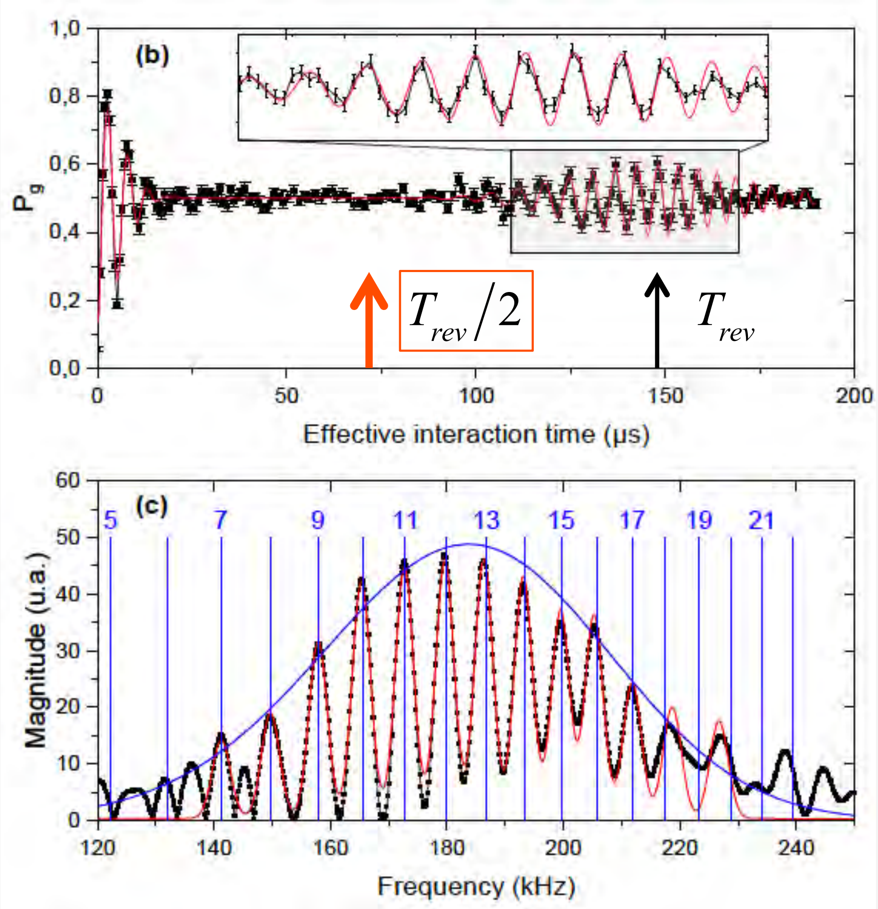
$$\left|\psi_{cat}\right\rangle = \frac{1}{\sqrt{2}}\left(\left|i\beta\right\rangle - \left|-i\beta\right\rangle\right)$$

"Odd" cat state

Resonant interaction: the fastest cat preparation

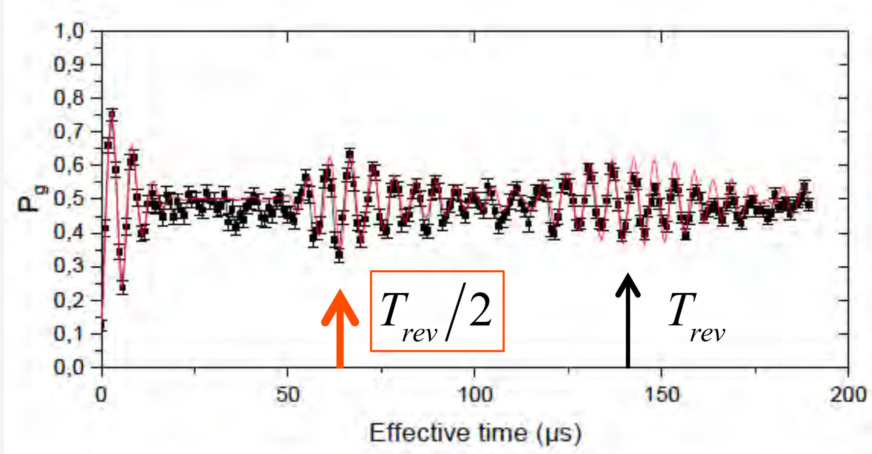
Revival and photon graininess

- Rabi oscillation in a coherent state



- Rabi oscillation in a cat state

$$\left|\psi_{cat}\right\rangle = \frac{1}{\sqrt{2}}\left(\left|i\beta\right\rangle - \left|-i\beta\right\rangle\right)$$



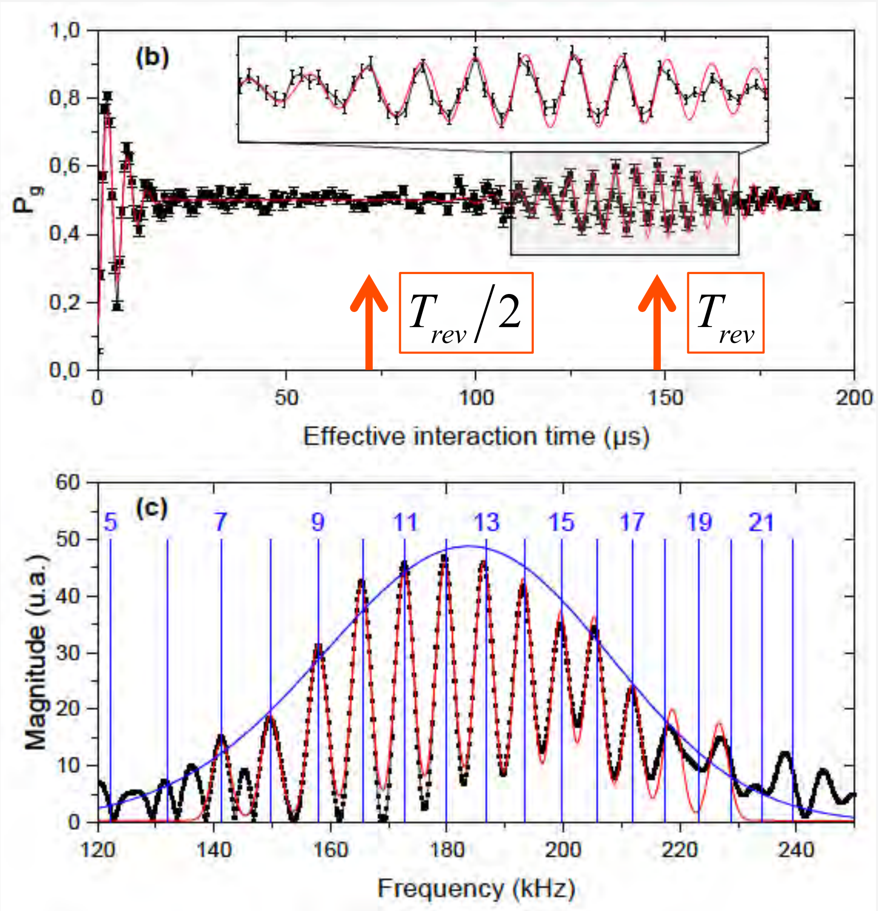
Atom "reset" in e after "half revival" interaction time

→ the same atom starts a new Rabi oscillation in the cat state

→ Revival at $T_{rev}/2$ is the signature of odd photon number distribution

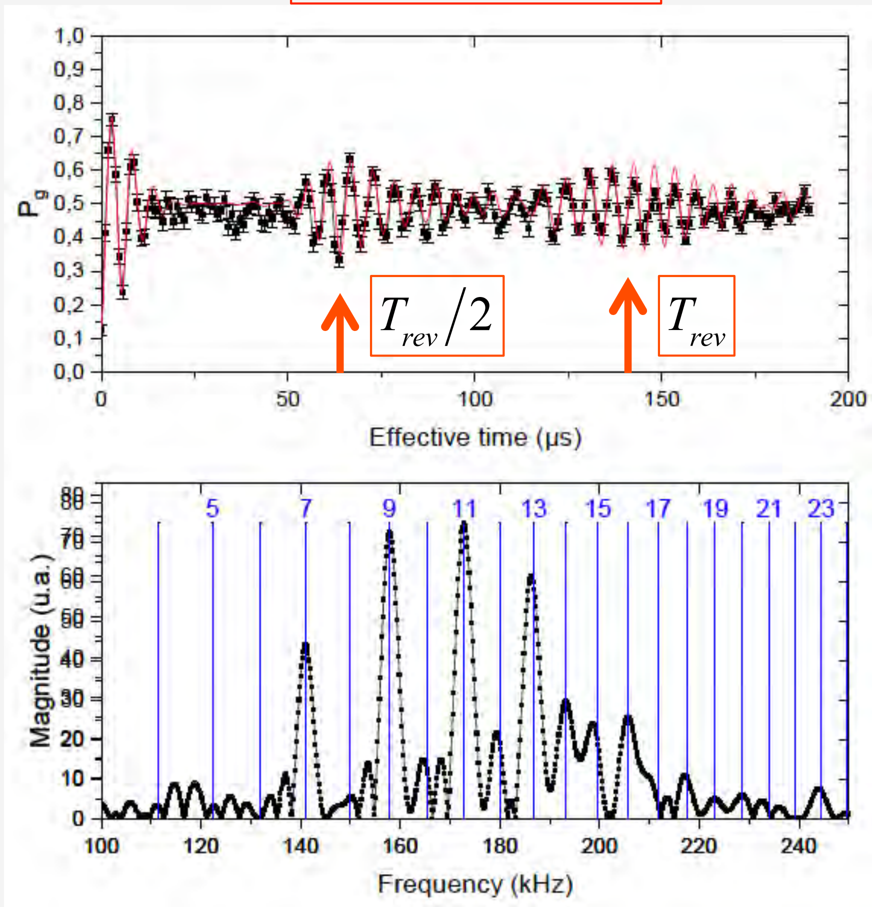
Revival and photon graininess

- Rabi oscillation in a coherent state



- Rabi oscillation in a cat state

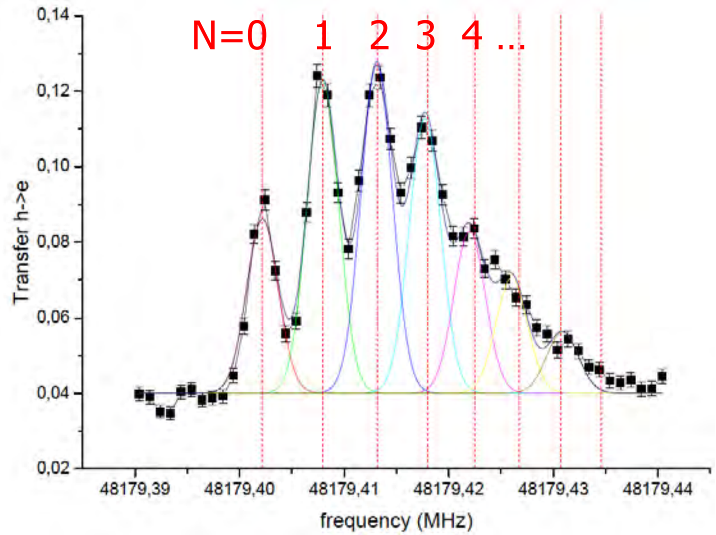
$$|\psi_{cat}\rangle = \frac{1}{\sqrt{2}}\left(|i\beta\rangle - |-i\beta\rangle\right)$$



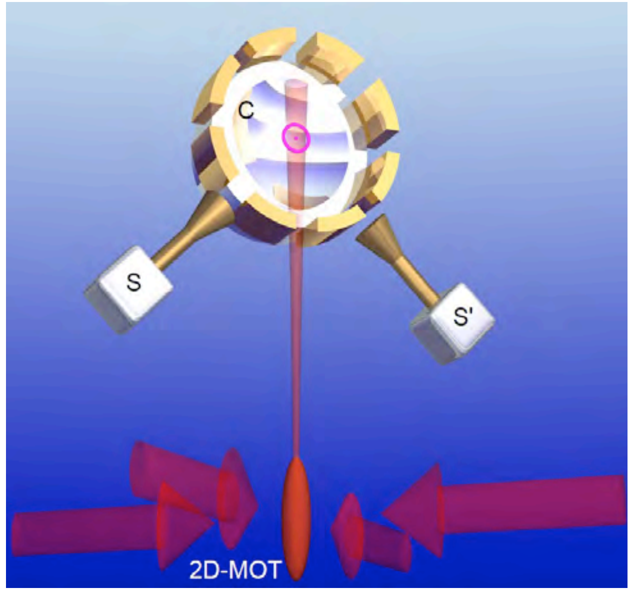
"Odd" cat state: the Rabi oscillation spectrum reveals the cat parity

An atomic fountain experiment

- Another interesting direction
  - ❑ Dressed states spectroscopy



F. Assémat et al. In preparation



➟ spectroscopic resolution of dressed states with different photon numbers

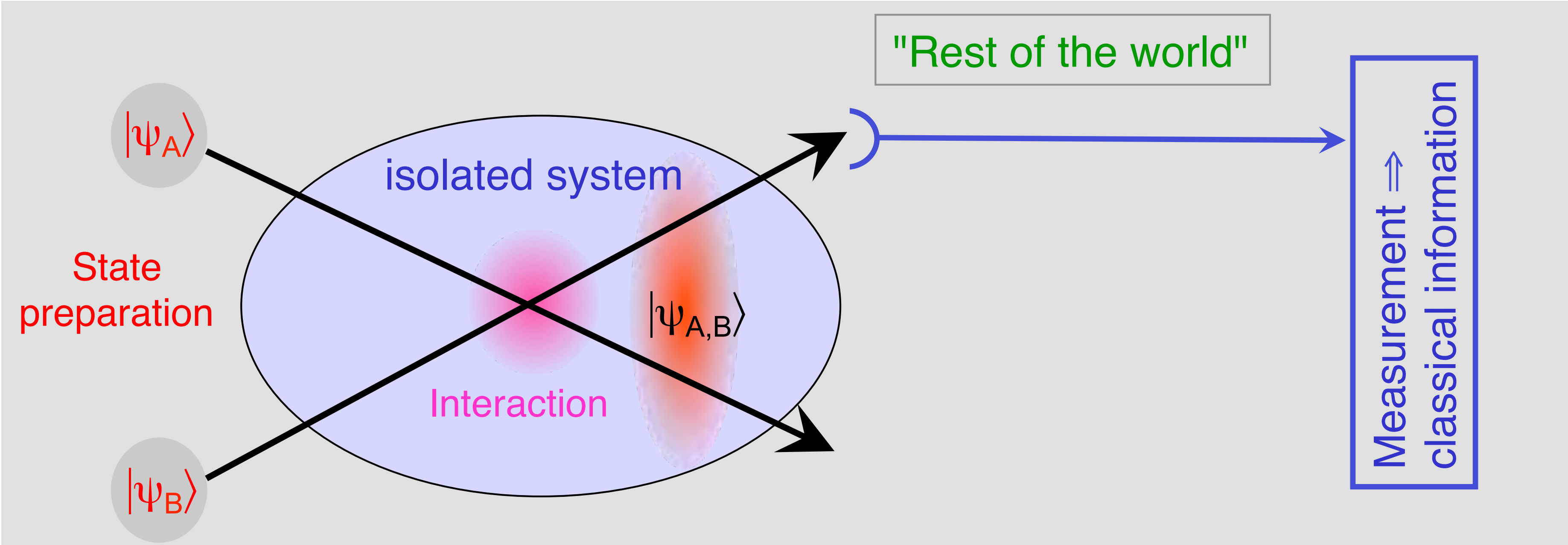
➟ open new possibilities for quantum state manipulation: "Quantum Zeno dynamics"

*J.M. Raimond et al PRL **105**, 213601 (2010)*

4. Quantum Non-Demolition photon counting

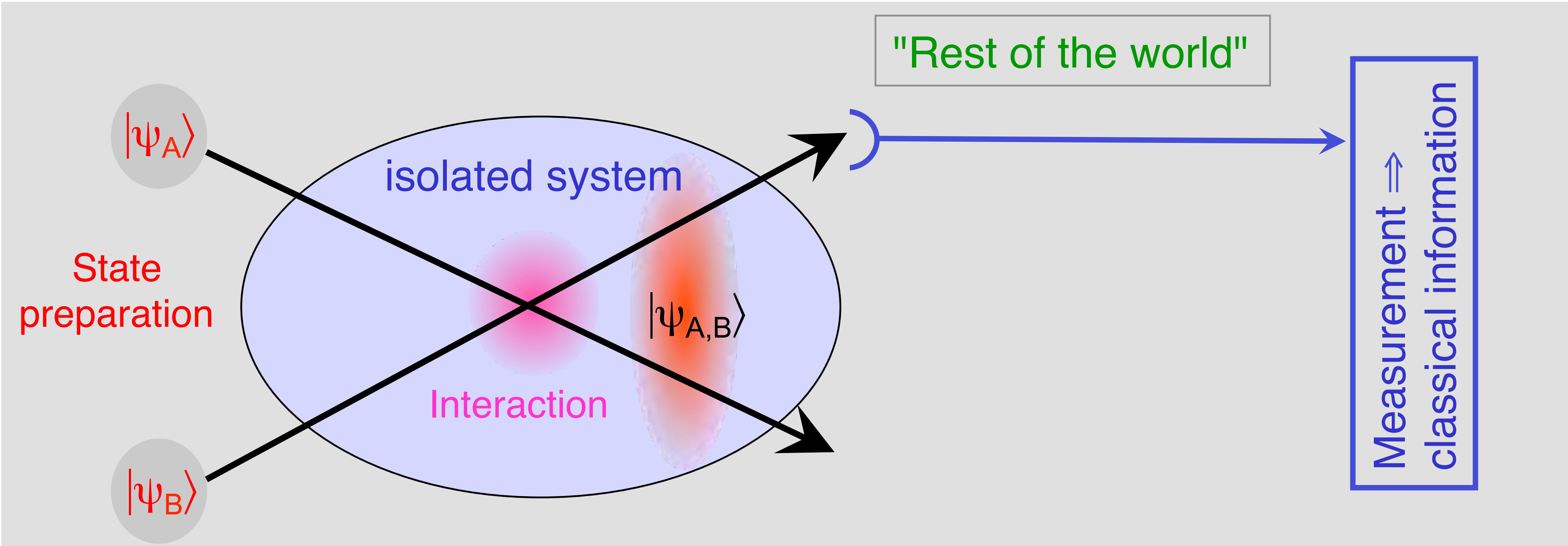
- Ideal quantum measurement
- Experimental realization with Rydberg atoms

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

4. 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

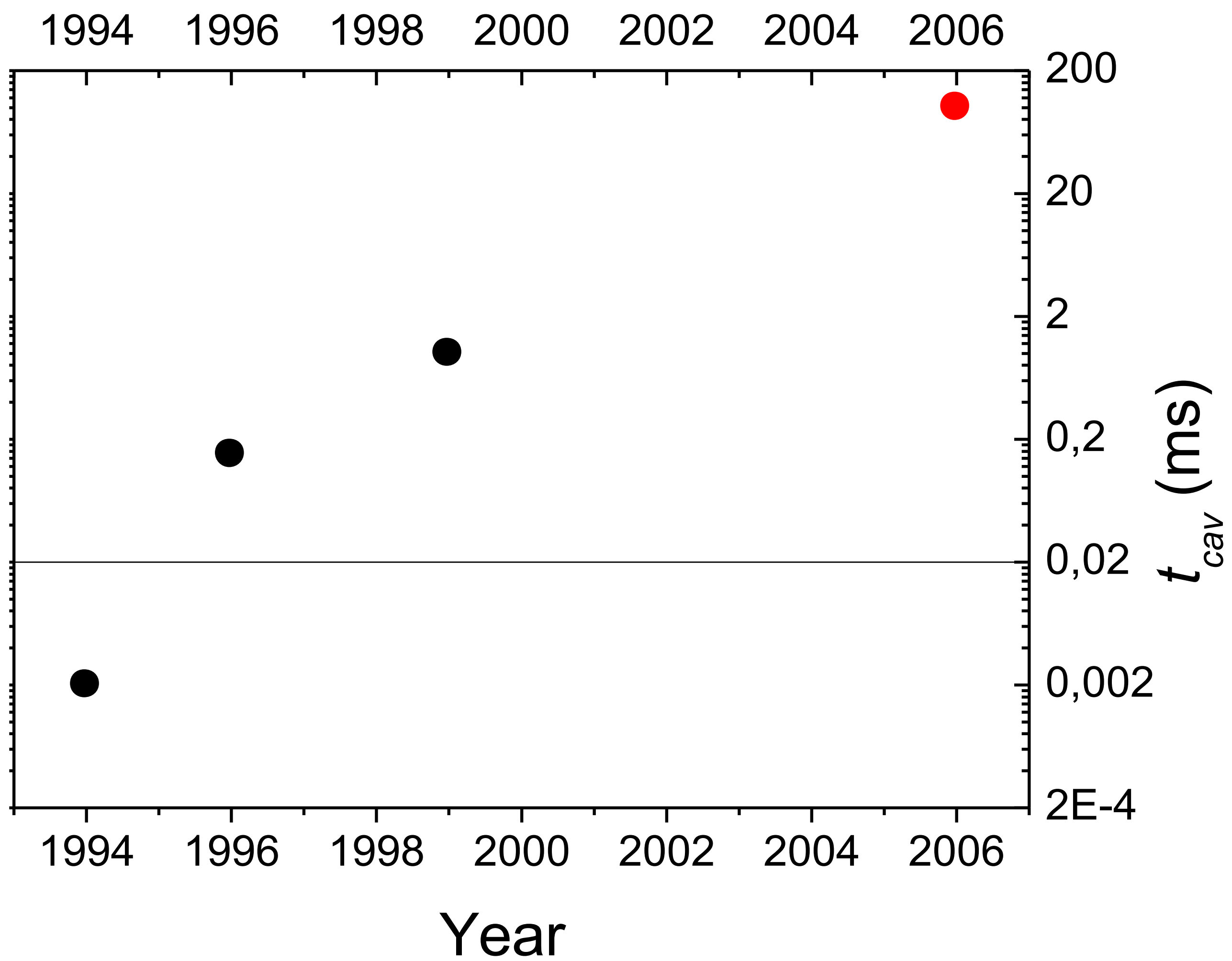
Quantum Nondemolition Measurement of Small Photon Numbers by Rydberg-Atom Phase-Sensitive Detection

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

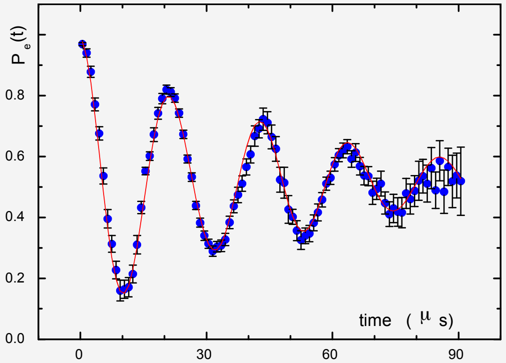
- Our version of Moore's law:



The vacuum Rabi oscillation

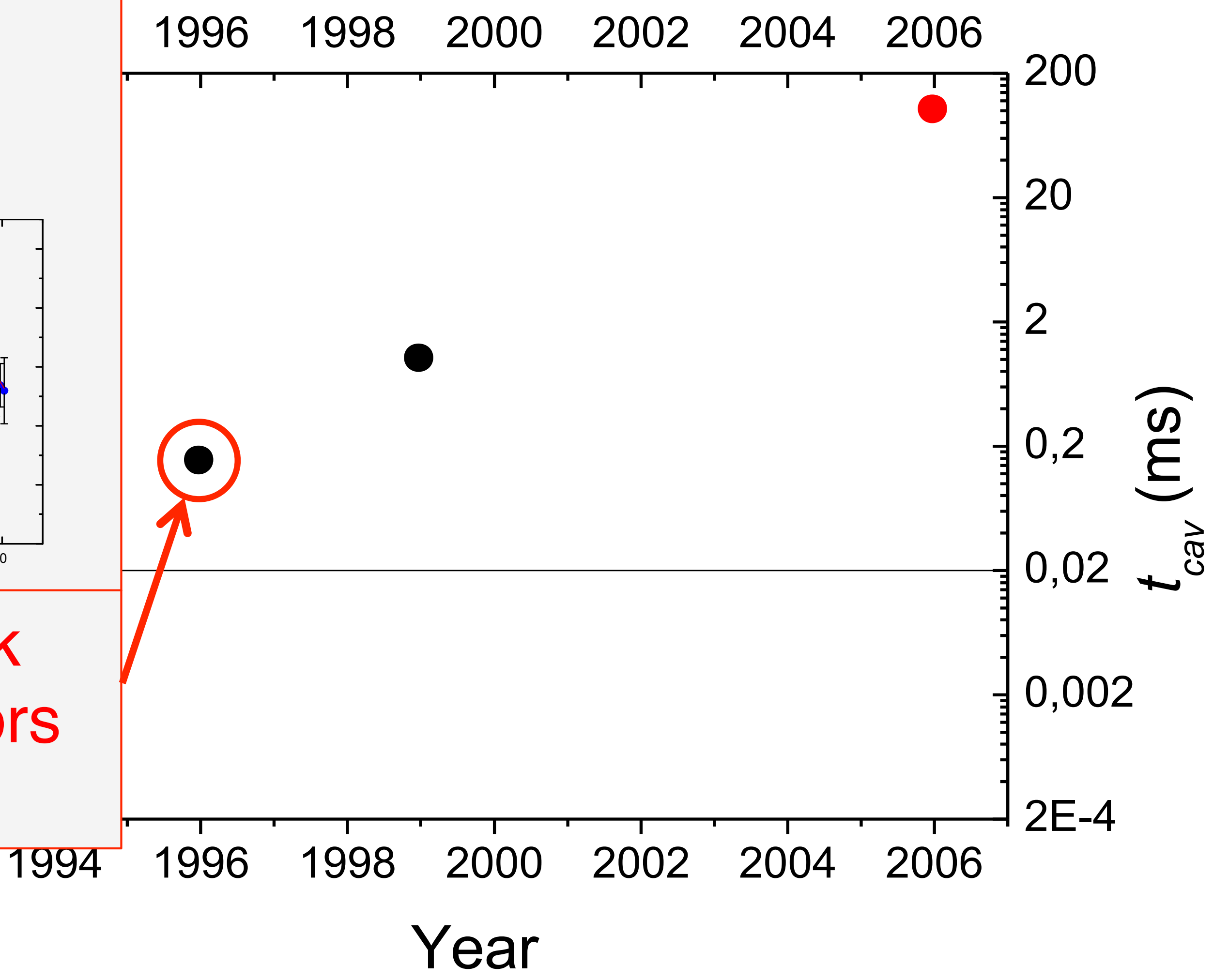
1996

Resonant Rabi oscillations



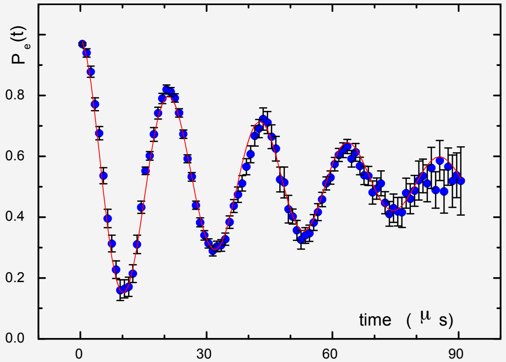
Polished bulk niobium mirrors

Q=2.10^8

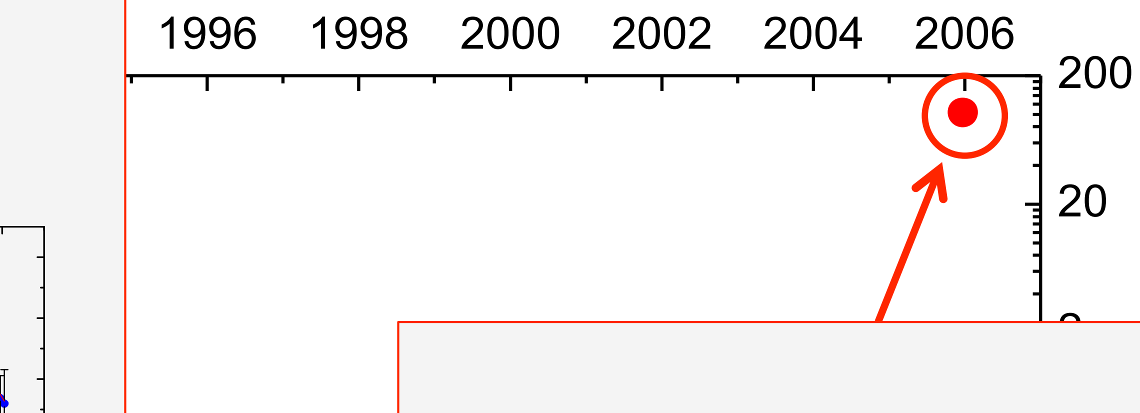


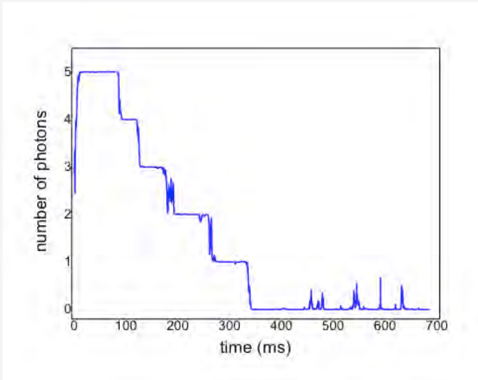
New cavity technology

1996
Resonant Rabi oscillations



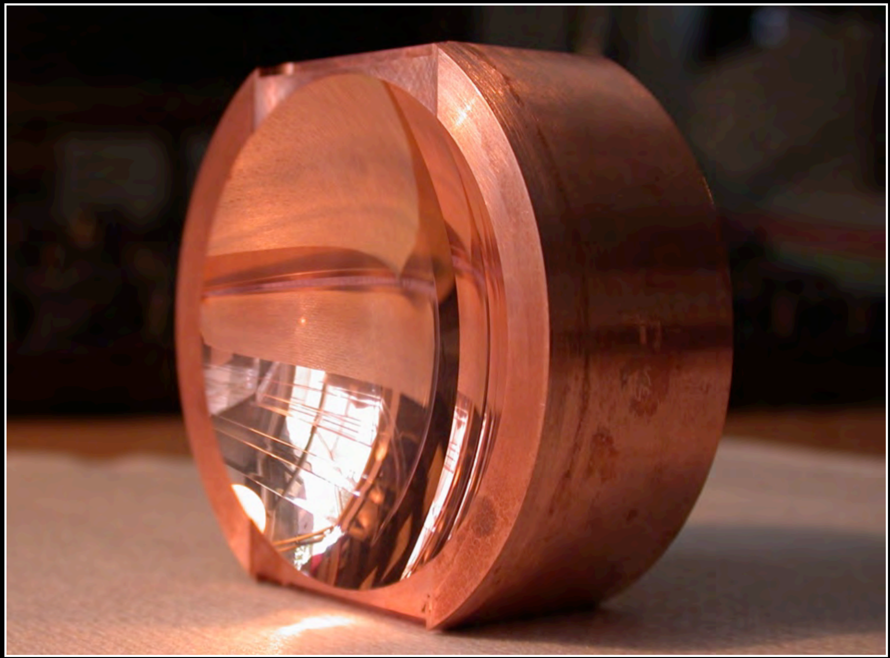
Polished bulk niobium mirrors
$Q=2.10^8$





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

Niobium coated copper mirrors



- Copper mirrors

  Diamond machined

  ~1 µm ptv form accuracy

  ~10 nm roughness

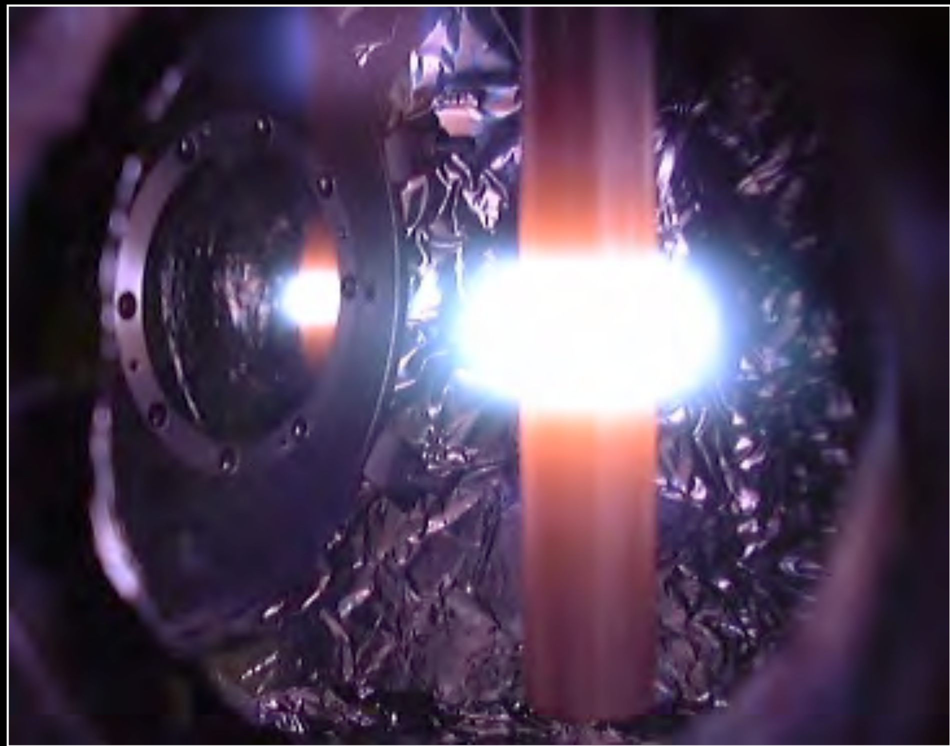
  Toroidal è single mode

- Sputter 12 µm of Nb

  Particles accelerator technique

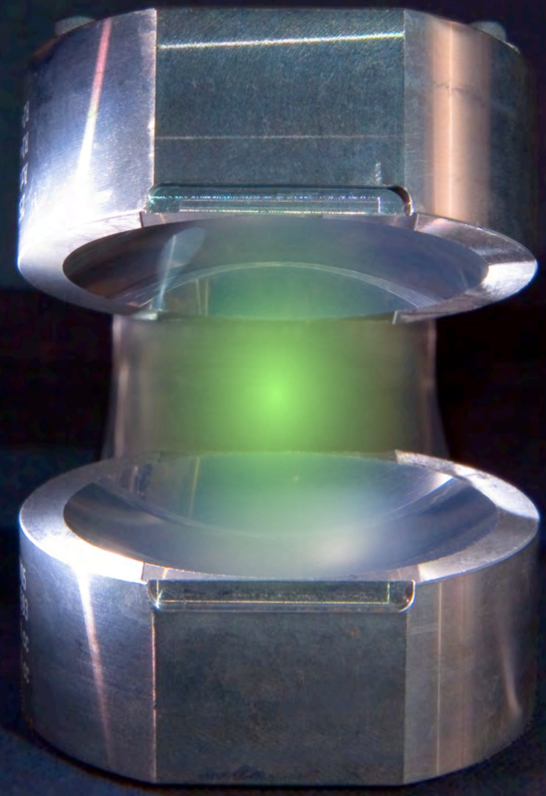
  Process done at CEA, Saclay

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

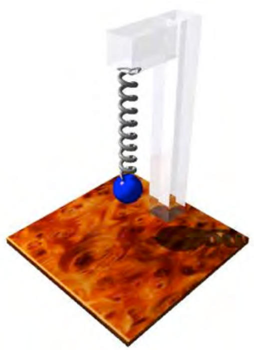


The best photon box

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



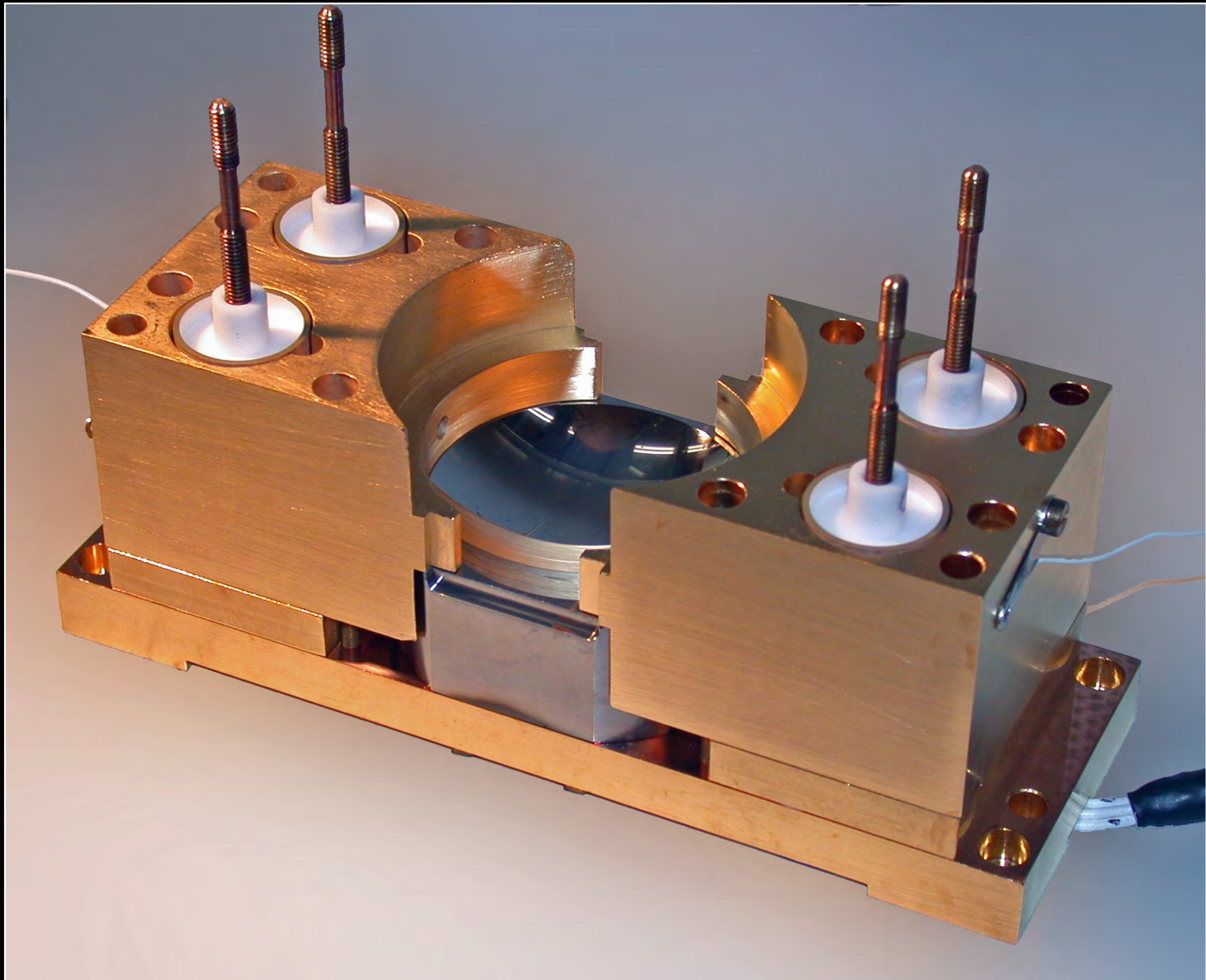
$T_{cav} = 130$ ms



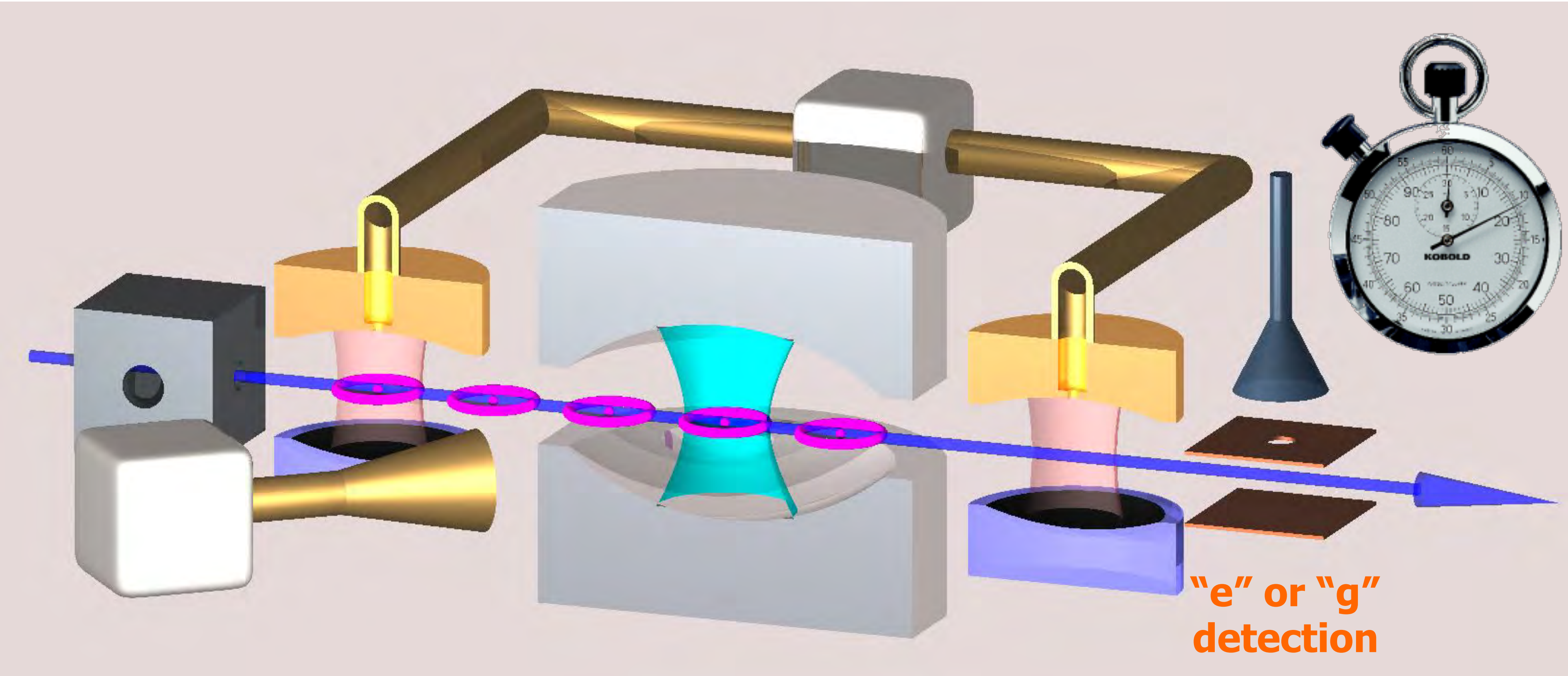
- Q factor $= 4.2 \cdot 10^{10}$
- finesse$= 4.\ 10^{9}$

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

A new cavity setup



Experimental setup: an atomic clock

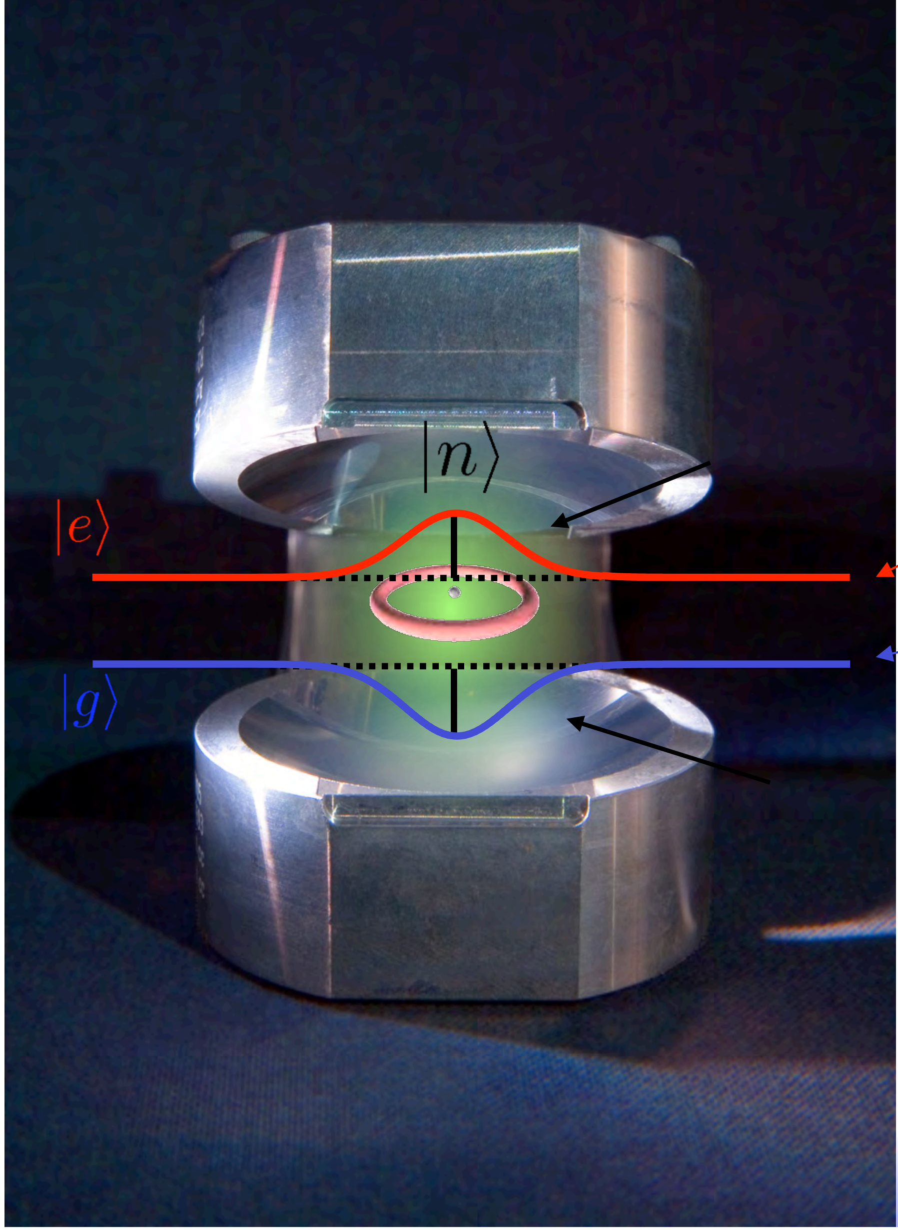


- An atomic clock (Ramsey setup) made of Rydberg for probing light-shifts induced by "trapped" photons

- 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

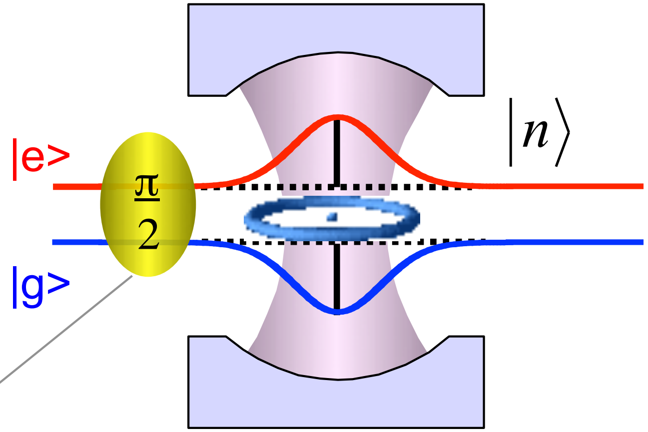
$$\Delta E_e = \hbar \frac{\Omega_0^2}{4\delta}(n+1)$$

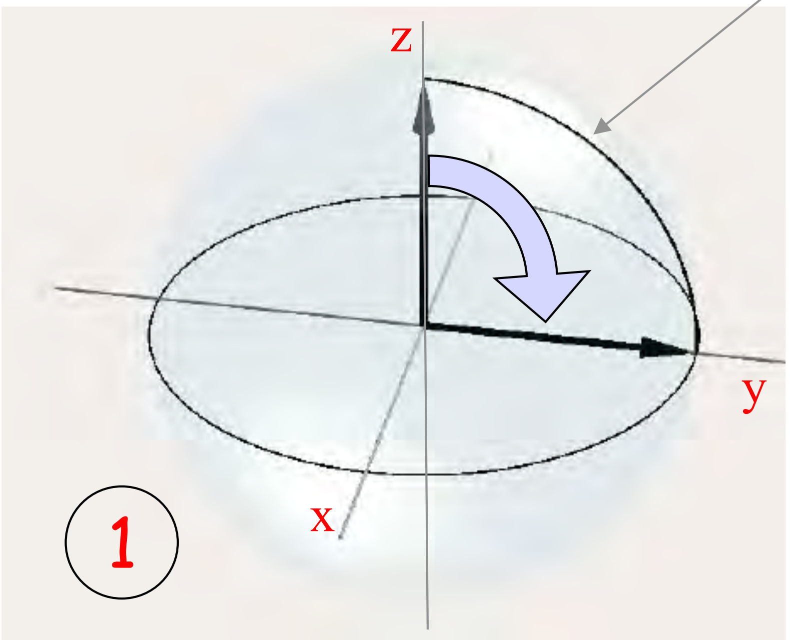
$$\Delta E_g = -\hbar \frac{\Omega_0^2}{4\delta} n$$

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

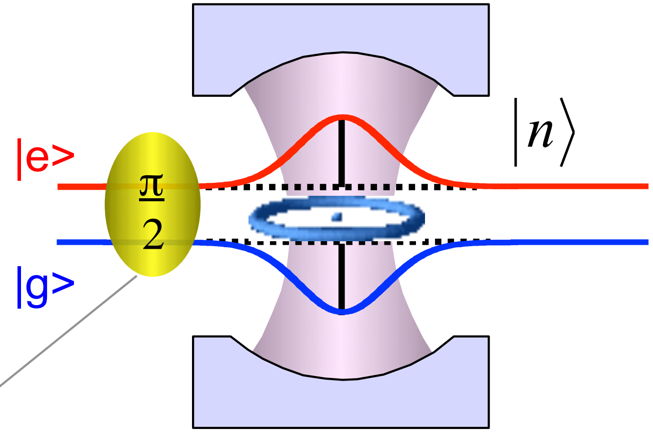
QND detection of 0 or 1 photon

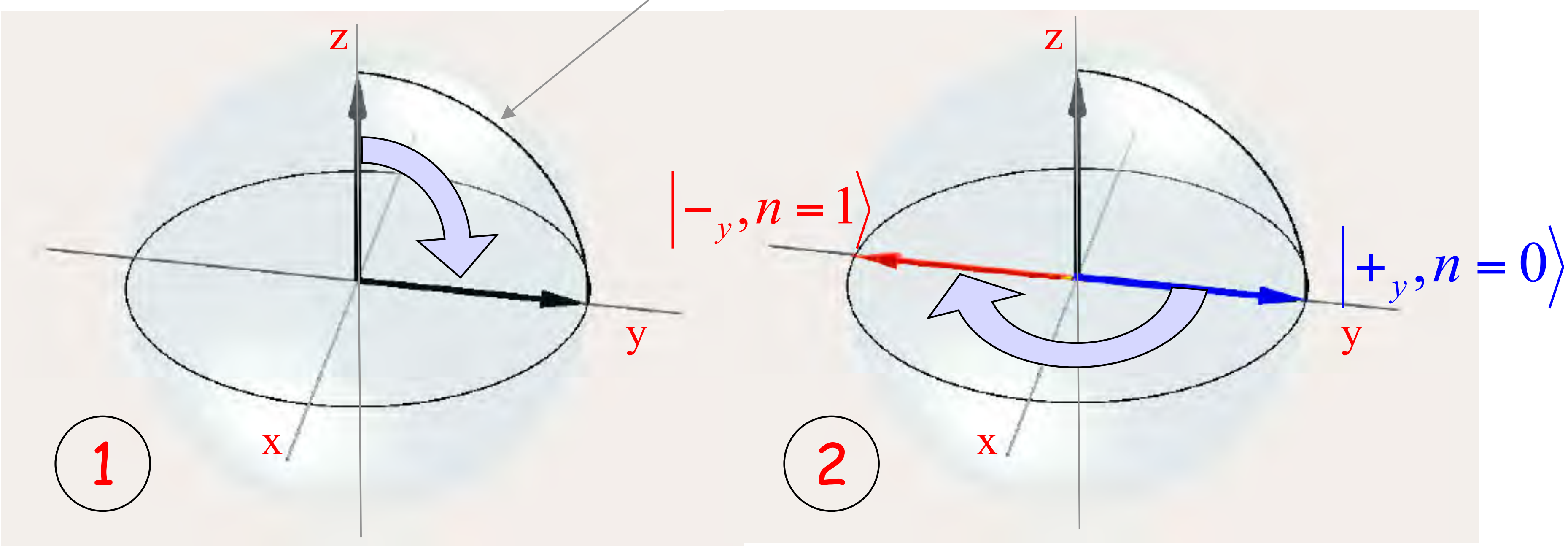
1. Trigger of the clock.

2. precession of the spin through the cavity during T

Phase shift per photon

$$\Phi_0 = \pi$$





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

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

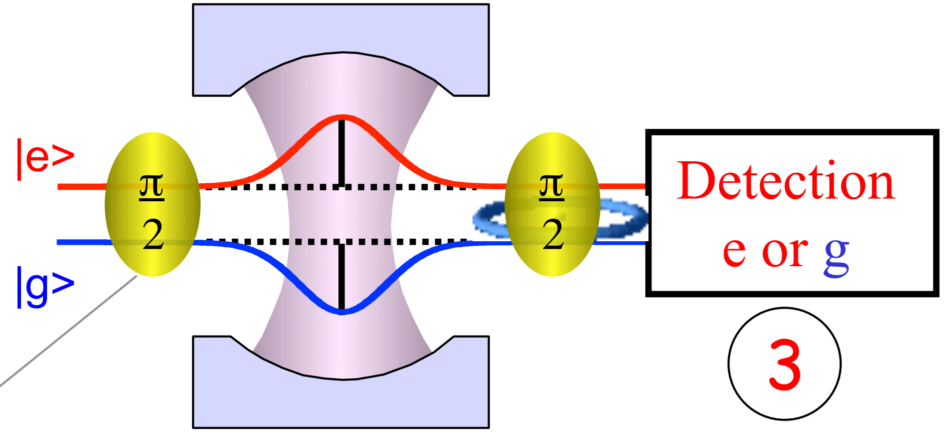
rotation by angle $\phi = \delta_{\text{mw}} T$ around the Oz axis

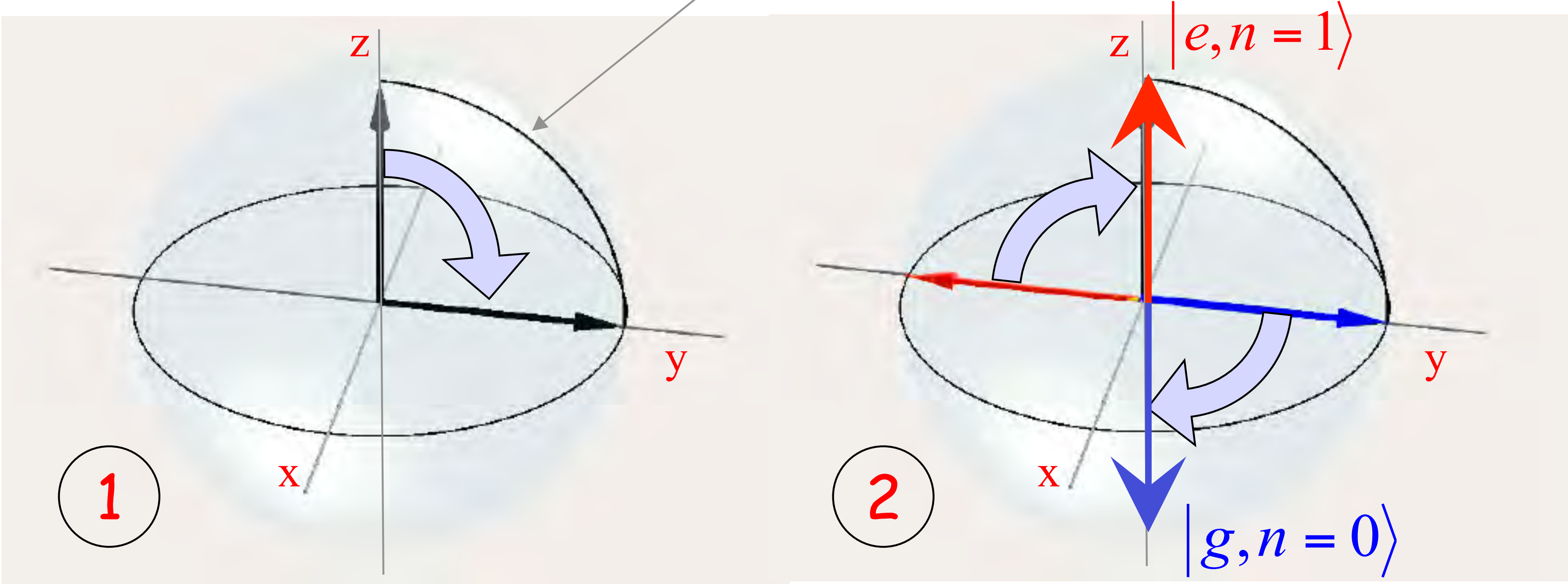
QND detection of 0 or 1 photon

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





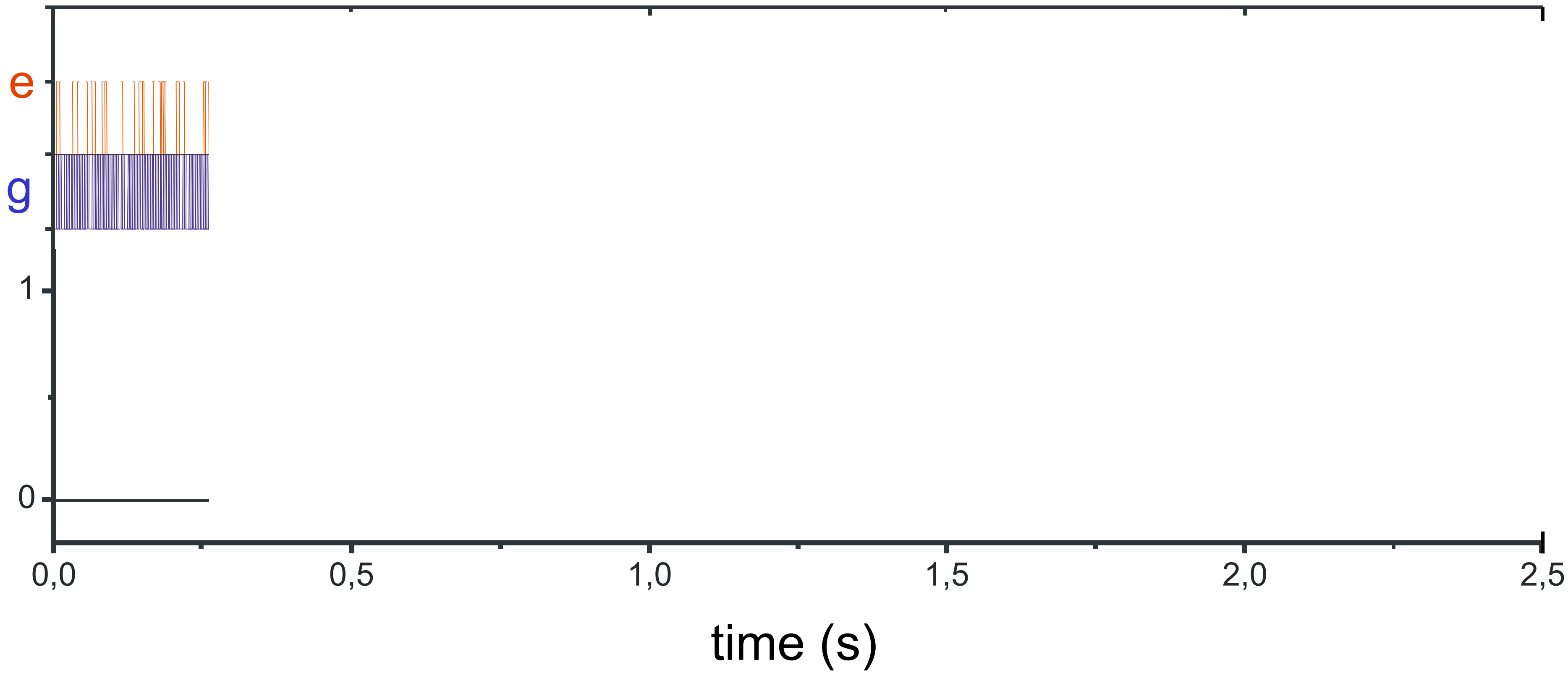
Atom detected in e ➡ field projected on |1>

g ➡ field projected on |0>

Detecting blackbody photons

g ➡ field projected on |0>

e ➡ field projected on |1>



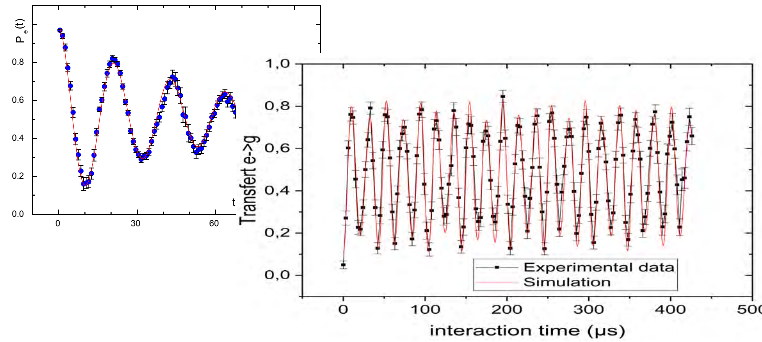
$T = 0.8\text{ K} \rightarrow n_{th} = 0.05$ (proba. of n=2 is negligible)

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

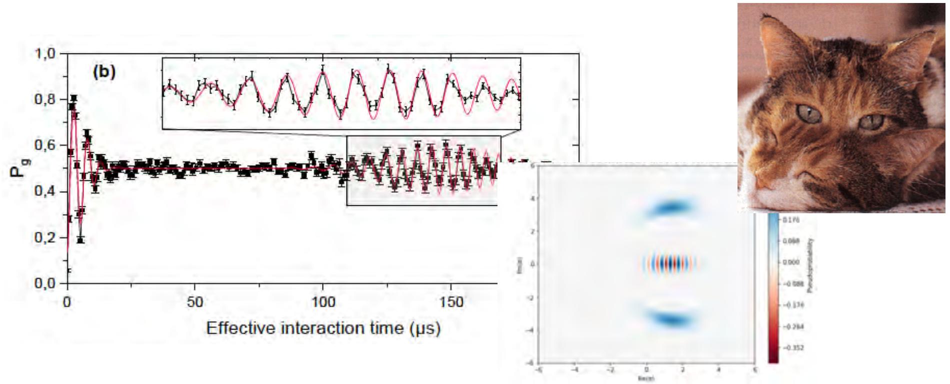
Conclusion of lecture 1:

Cavity QED with microwave photons and circular Rydberg atoms:

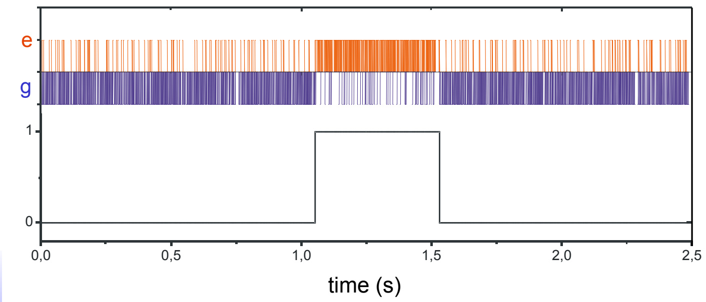
... a powerfull tool for:



- Achieving strong coupling between single atoms single photons



- Observing collapse, revival of Rabioscillation and Schrödinger cat State



- Realizing an ideal projective detection of single photons

[redacted]

References (1)

- **Strong coupling regime in CQED experiments:**

  - F. Bernardot, P. Nussenzveig, M. Brune, J.M. Raimond and S. Haroche. "Vacuum Rabi Splitting Observed on a Microscopic atomic sample in a Microwave cavity". Europhys. lett. **17**, 33-38 (1992).
  - P. Nussenzveig, F. Bernardot, M. Brune, J. Hare, J.M. Raimond, S. Haroche and W. Gawlik. "Preparation of high principal quantum number "circular" states of rubidium". Phys. Rev. **A48**, 3991 (1993).
  - M. Brune, F. Schmidt-Kaler, A. Maali, J. Dreyer, E. Hagley, J. M. Raimond and S. Haroche: "Quantum Rabi oscillation: a direct test of field quantization in a cavity". Phys. Rev. Lett. **76**, 1800 (1996).
  - J.M. Raimond, M. Brune and S. Haroche : "Manipulating quantum entanglement with atoms and photons in a cavity", Rev. Mod. Phys. vol.73, p.565-82 (2001).
  - P. Bertet, S. Osnaghi, A. Rauschenbeutel, G. Nogues, A. Auffeves, M. Brune, J.M. Raimond and S. Haroche : "Interference with beam splitters evolving from quantum to classical : a complementarity experiment". Nature 411, 166 (2001).
  - E. Hagley, X. Maître, G. Nogues, C. Wunderlich, M. Brune, J.M. Raimond and S. Haroche: "Generation of Einstein-Podolsky-Rosen pairs of atoms", PRL 79,1 (1997).
  - P. Bertet, S. Osnaghi, A. Rauschenbeutel, G. Nogues, A. Auffeves, M. Brune, J.M. Raimond and S. Haroche : "Interference with beam splitters evolving from quantum to classical : a complementarity experiment". Nature **411**, 166 (2001).

References (2)

- **Gates: QPG or C-Not, algorithm:**
  - M. Brune et al., Phys. Rev. Lett, **72**, 3339(1994).
  - Q.A. Turchette et al., Phys. Rev. Lett. **75**, 4710 (1995).
  - C. Monroe et al., Phys. Rev. Lett. **75**, 4714 (1995).
  - A. Reuschenbeutel et al., PRL. G. Nogues et al. Nature **400**, 239 (1999).
  - S. Osnaghi, P. Bertet, A. Auffeves, P. Maioli, M. Brune, J.M. Raimond and S. Haroche, Phys. Rev. Lett. **87**, 037902 (2001)
  - F. Yamaguchi, P. Milman, M. Brune, J-M. Raimond, S. Haroche: "Quantum search with two-atom collisions in cavity QED", PRA **66**, 010302 (2002).
- **Q. memory:**
  - X. Maître et al., Phys. Rev. Lett. **79**, 769 (1997).
- **Atom EPR pairs:**
  - CQED: E. Hagley et al., Phys. Rev. Lett. **79**, 1 (1997).
  - Ions: Q.A. Turchette et al., Phys. Rev. Lett. **81**, 3631 (1998).

Reference (3)

- QND detection of photons:

  - G. Nogues, A. Rauschenbeutel, S. Osnaghi, M. Brune, J.M. Raimond and S. Haroche: "Seeing a single photon without destroying it", Nature, **400**, 239 (1999).
  - S. Gleyzes, S. Kuhr, C. Guerlin, J. Bernu, S. Deléglise, U. Busk Hoff, M. Brune, J.-M. Raimond and S. Haroche, Nature 446, 297-300 (2007): “Quantum jumps of light recording the birth and death of a photon in a cavity”.
  - C. Guerlin, J. Bernu, S. Deléglise, C. Sayrin, S. Gleyzes, S. Kuhr, M. Brune, J.-M. Raimond and S. Haroche, Nature, article, Nature **448**, 889 (2007) : "Progressive field-state collapse and quantum non-demolition photon counting".

- High Q superconducting cavity:

  - S. Kuhr, S. Gleyzes, C. Guerlin, J. Bernu, U. B. Hoff, S. Deleglise, S. Osnaghi, M. Brune, J.-M. Raimond, S. Haroche, E. Jacques, P. Bosland, and B. Visentin, Appl. Phys. Lett. 90, 164101 (2007): “Ultrahigh finesse Fabry-Pérot superconducting resonator”.