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SMR/1438 - 5

JOINT ICTP-INFM SCHOOL/WORKSHOP ON "ENTANGLEMENT AT THE NANOSCALE"

(28 October – 8 November 2002)

"Controlled entanglement with Rydberg atoms and cavities"

presented by:

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Controlled entanglement with Rydberg atoms and cavities

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Experiments at the single quantum particle level

- Schrödinger 1952 :

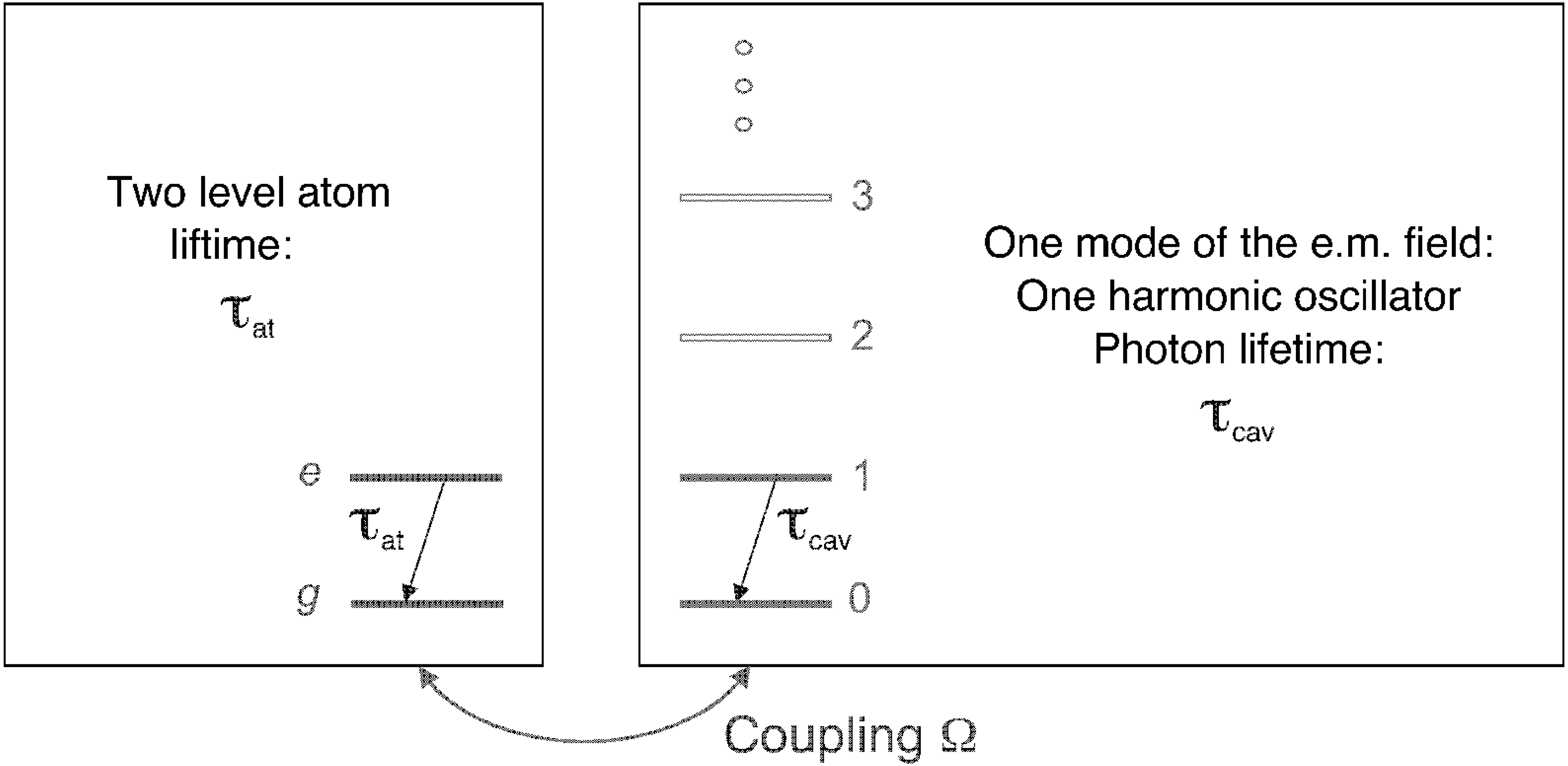
  « one never experiments with just one electron, one atom or one molecule. In thought experiments we sometimes assume that we do; this invariably entails **ridiculous consequences…** » (British Journal of the Philosophy of Sciences, vol 3, 1952)

- Of course we do:
  - EPR photon pairs (parametric down conversion)
  - trapped ions,
  - single electron on islands
  - Cavity QED: manipulating single atoms and a few photons

Most *"gedanken"* experiments become *real* experiments:

Quantum theory is definitely stranger than ridiculous!

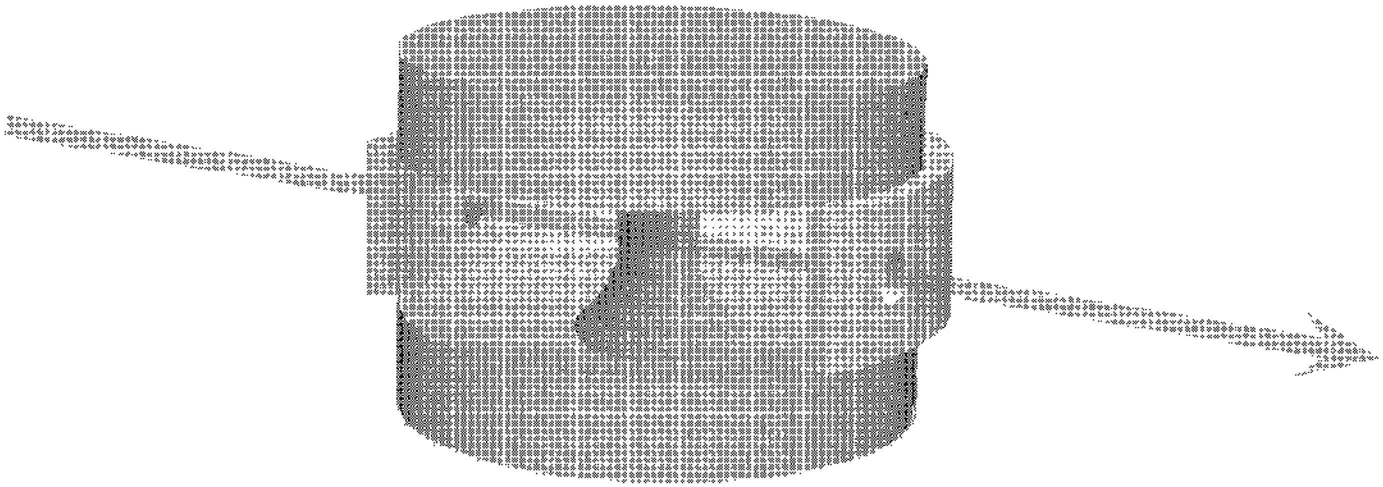
Cavity QED: manipulating single atoms and photons

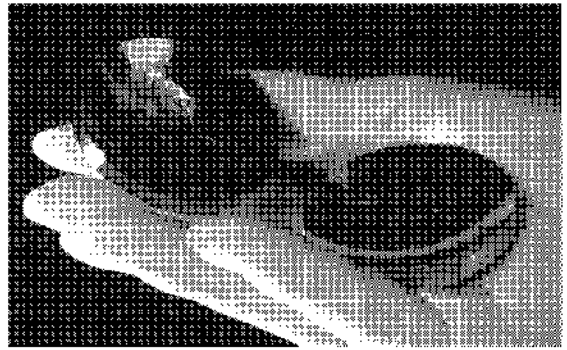


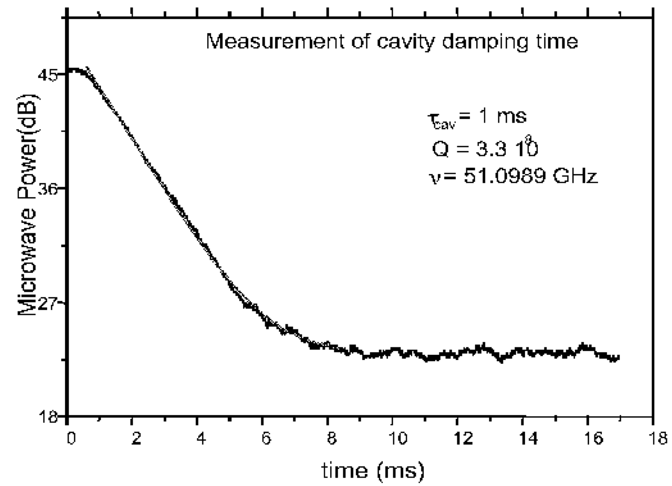
Requirement:

- $\Omega . T_{int} > 2\pi$ strong atom-field coupling
- $T_{int} << \tau_{at}, \tau_{cav}$ weak coupling with the rest of the world

The microwave superconducting cavity







<u>Cavity geometry:</u>

- two spherical niobium mirrors
- a nearly closed aluminum ring
- microwave resonance:

λ=6mm, ν_{cav}=51GHz

-superconducting mirrors:

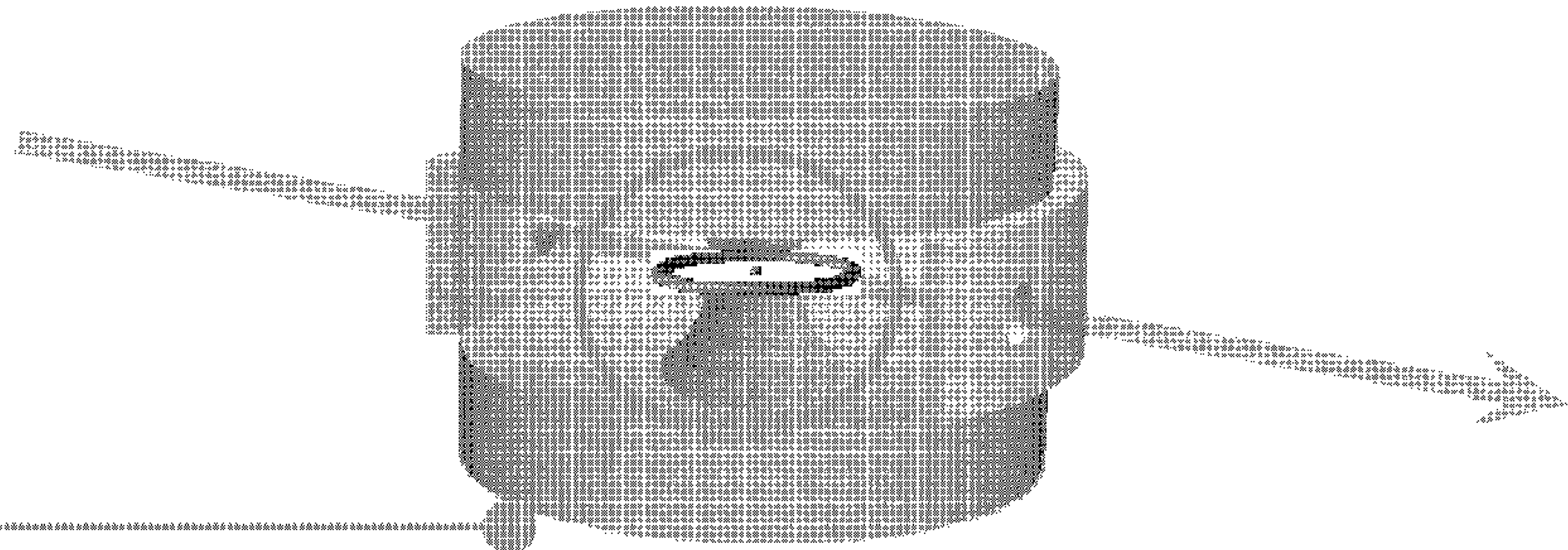
photon lifetime:

Tcav=1ms

<u>a photon "box":</u>

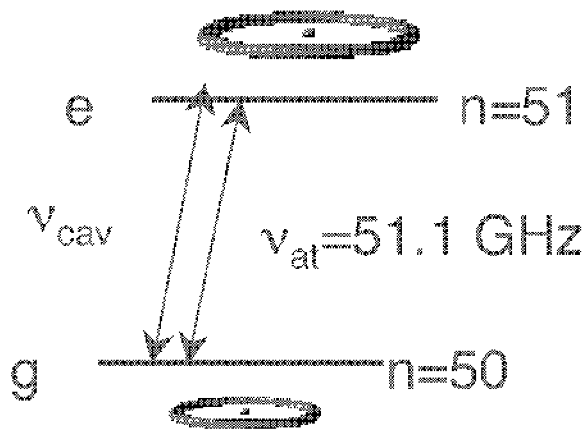
- one mode
- a few photons

Circular Rydberg atoms



"Circular Rydberg atoms":

$l=|m|=n-1$



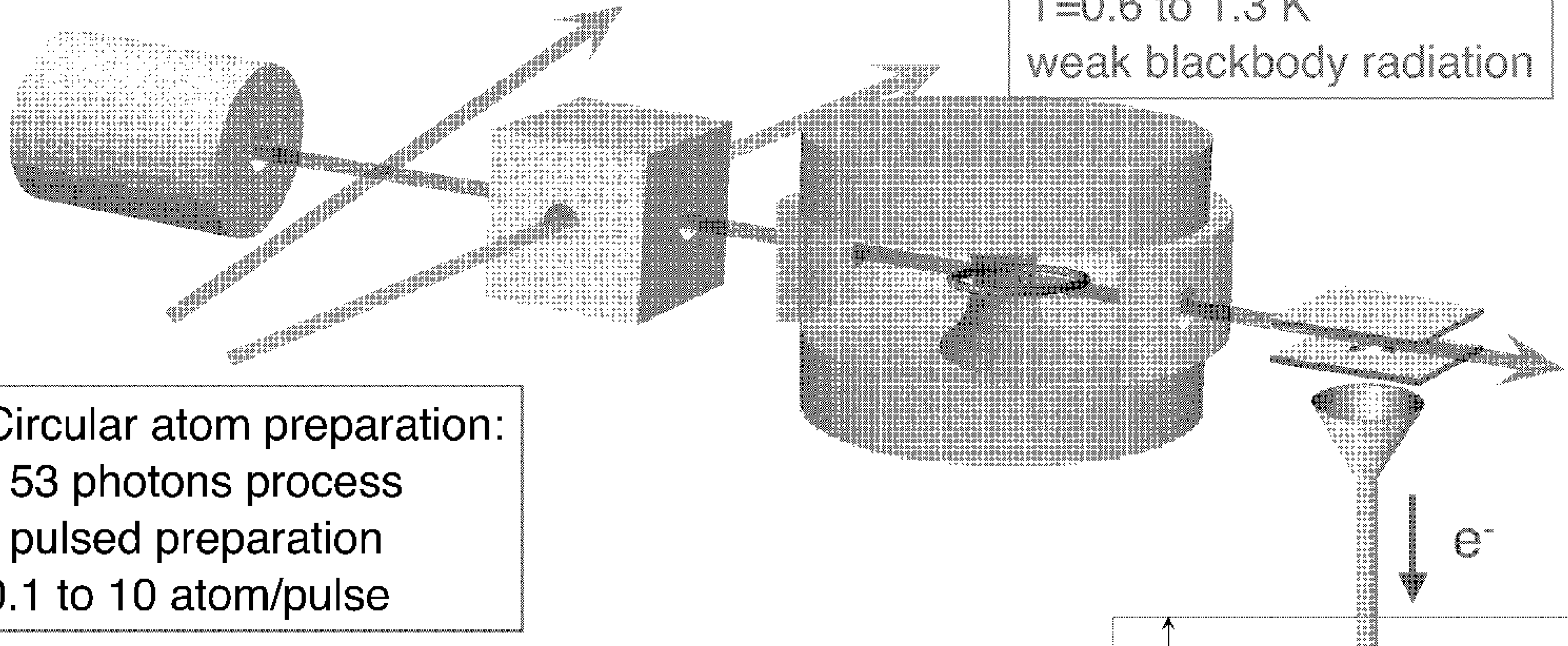
- long lifetime: 30 ms
- Large dipole: $a_0.n^2$
- ideal closed two level system

Experimental set-up

^{85}Rb

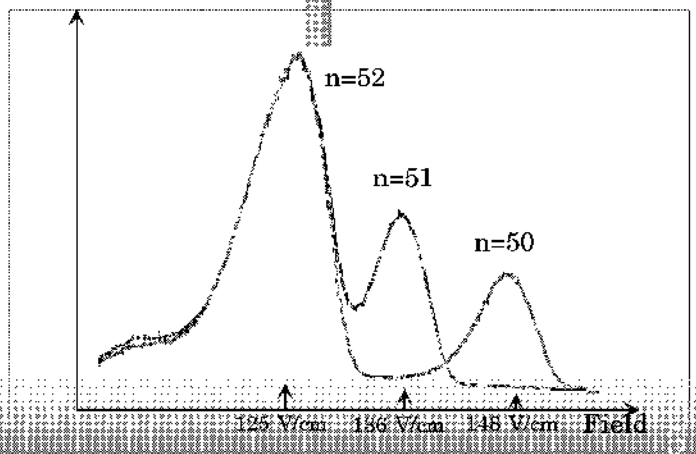
Laser velocity selection

Cryogenic environment
T=0.6 to 1.3 K
weak blackbody radiation

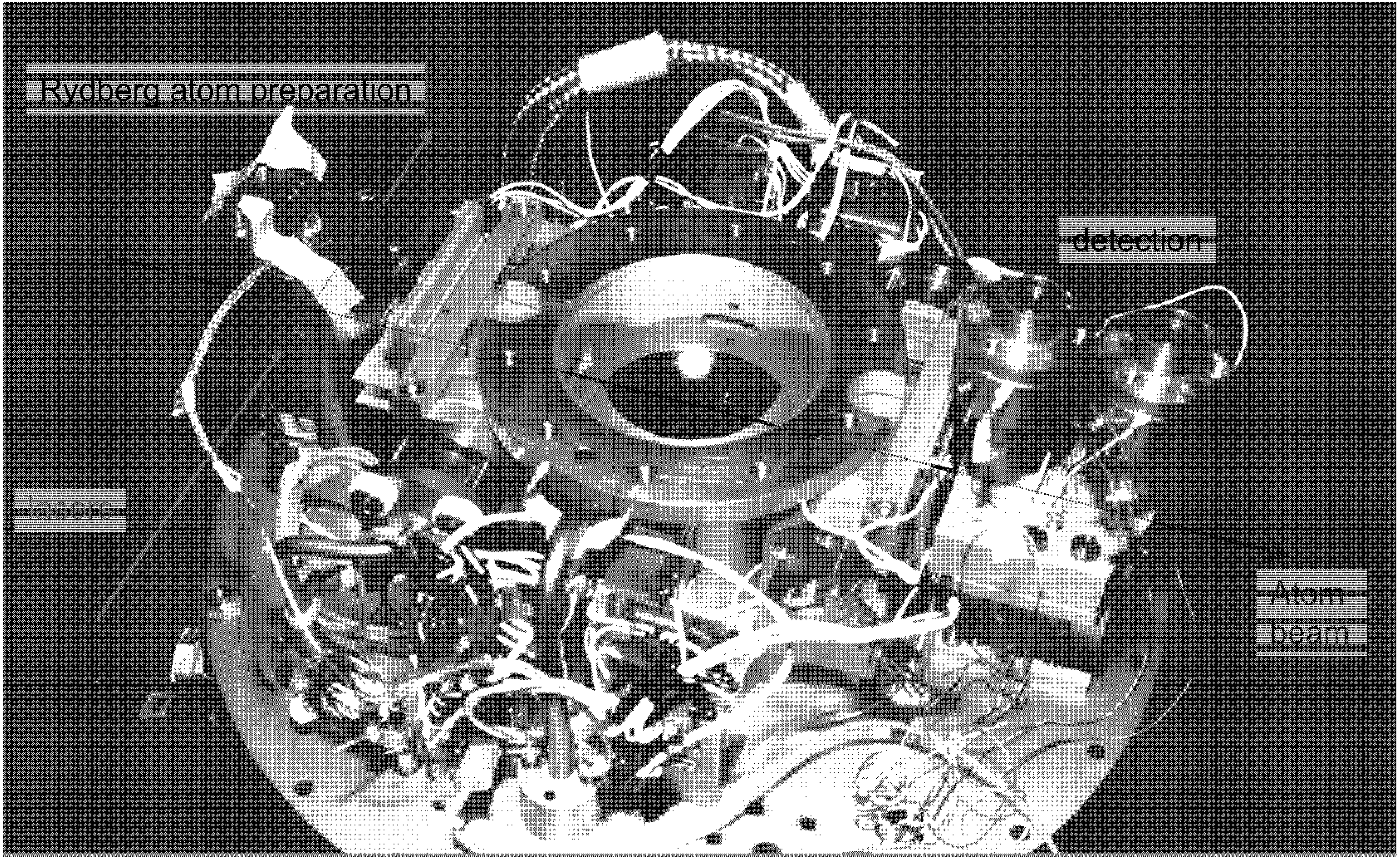


Circular atom preparation:
- 53 photons process
- pulsed preparation
0.1 to 10 atom/pulse

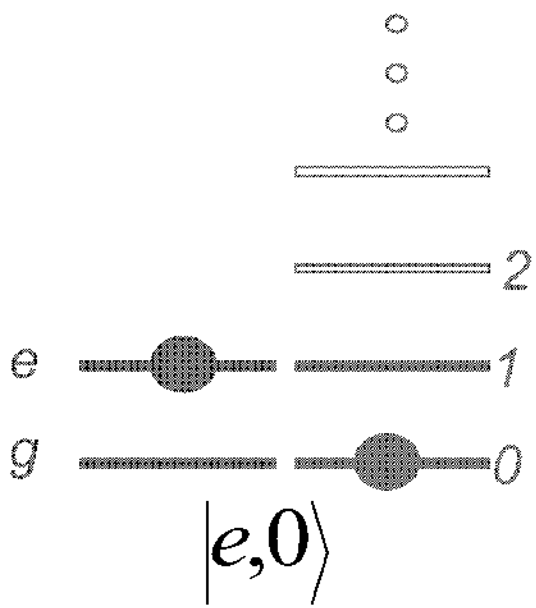
State selective
detector Atoms detected
one by one



Our Cavity QED setup



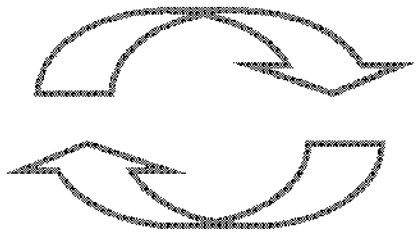
One atom-one photon: the strong coupling

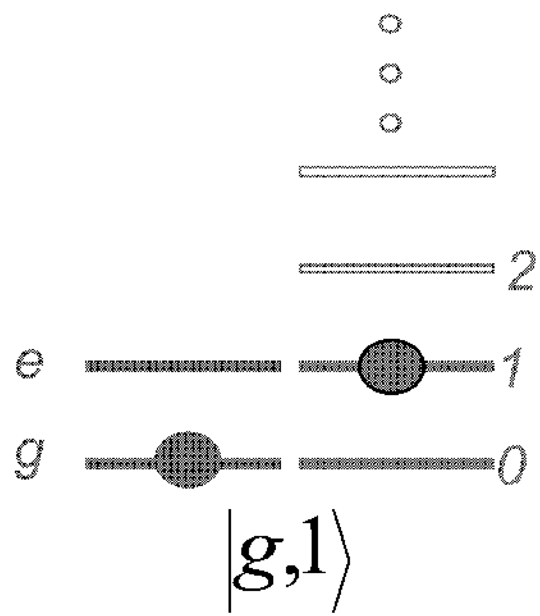


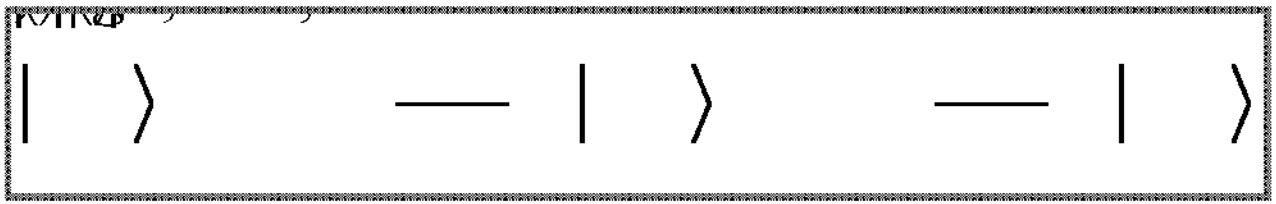
Vacuum Rabi frequency:

$\Omega_0/2\pi = 50$ kHz

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

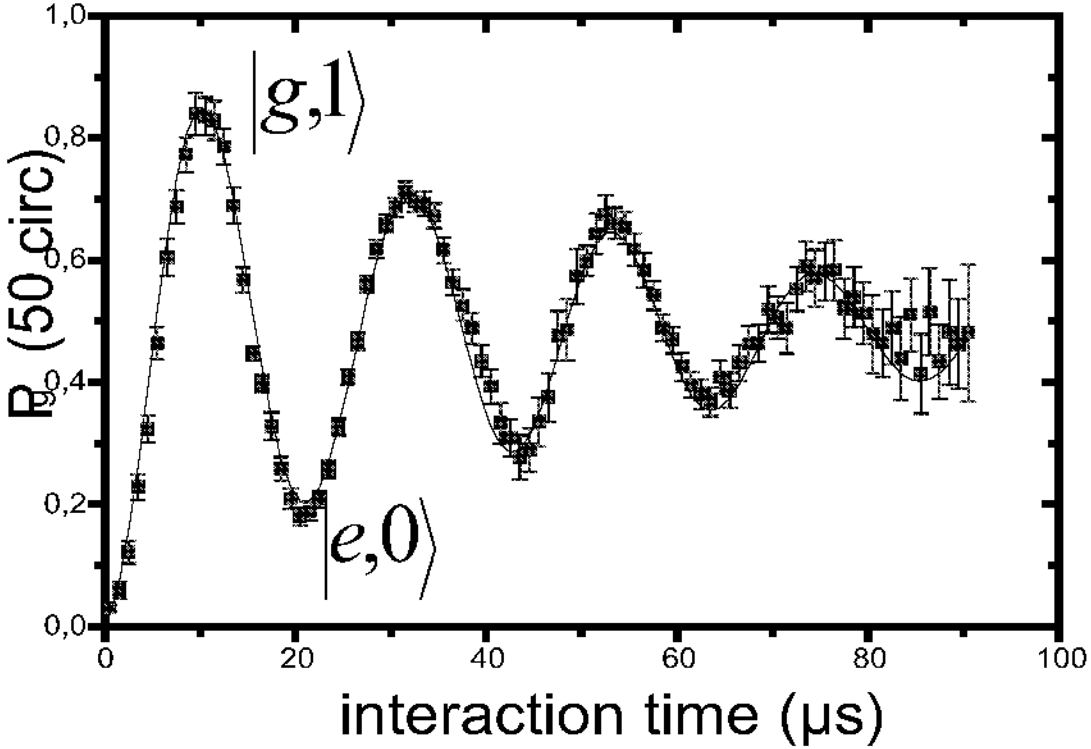


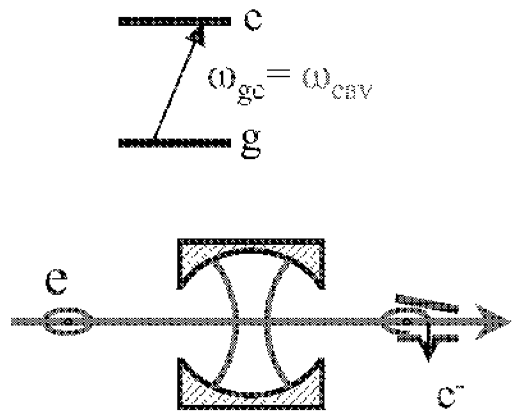




- Coherent Rabi oscillation without any external field: reversible emission and absorption of one photon

Vacuum Rabi oscillation signal





Ω_0=47 kHz

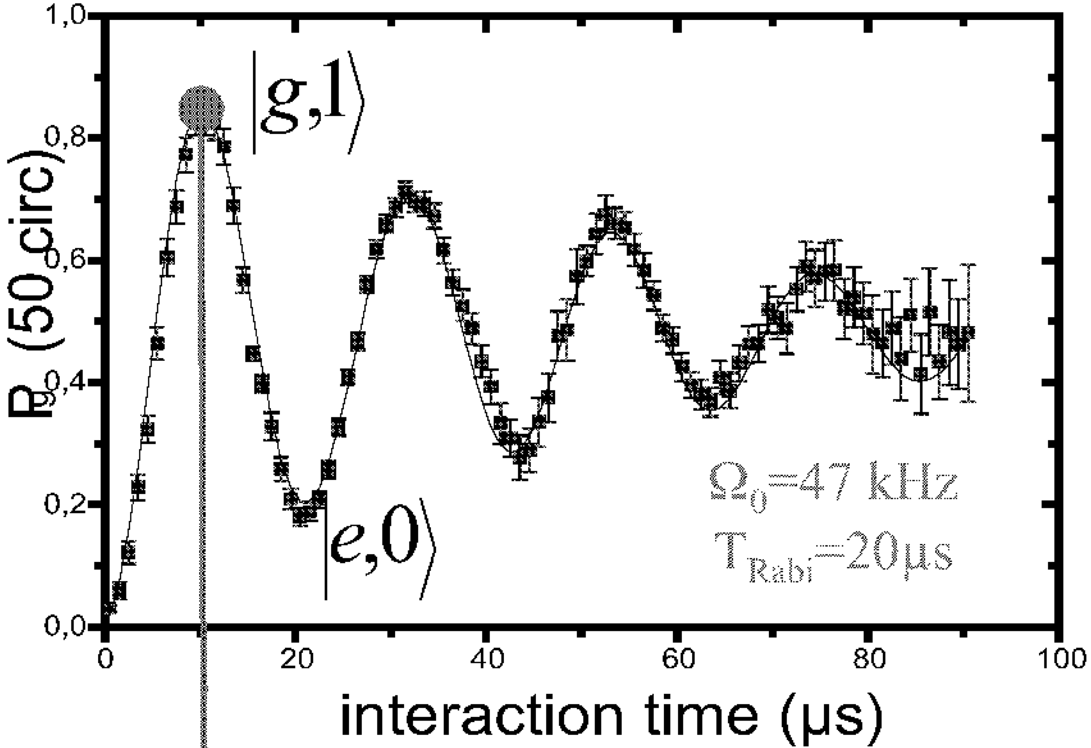
T_{Rabi}=20µs

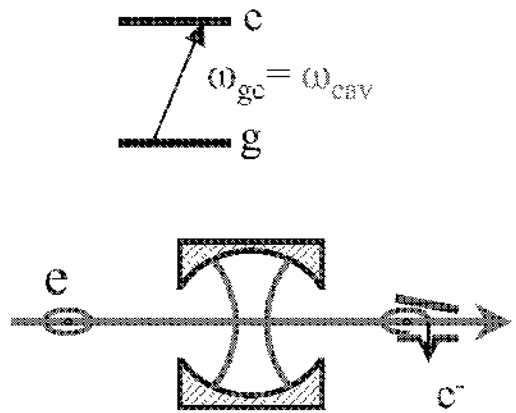
T_{cav}=220 µs

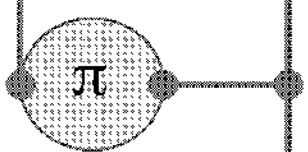
T_{at}=30ms

⇒ Strong coupling

Quantum gates based on vacuum Rabi oscillation



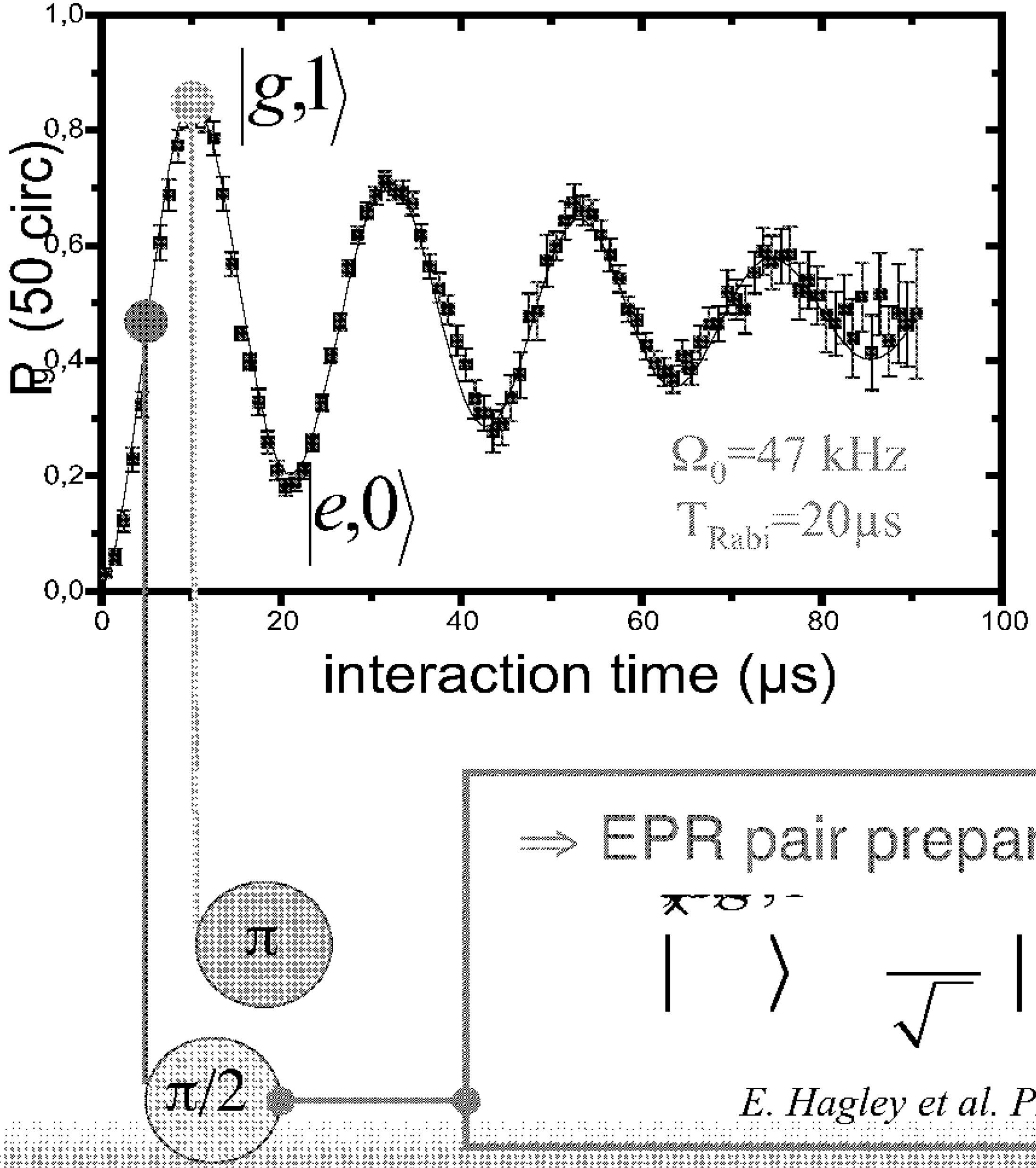


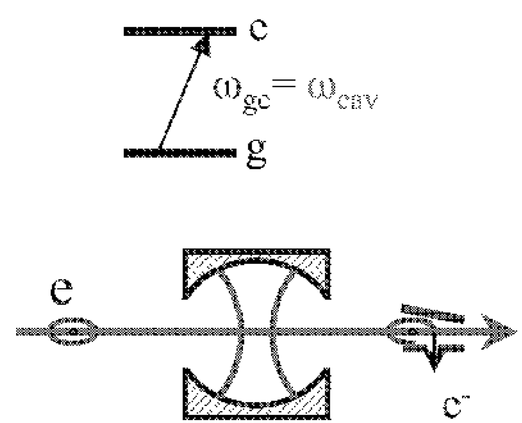


Emission/absorption of one photon

"Quantum memory", X. Maître et al. PRL 79,769 (1997)

Quantum gates based on vacuum Rabi oscillation

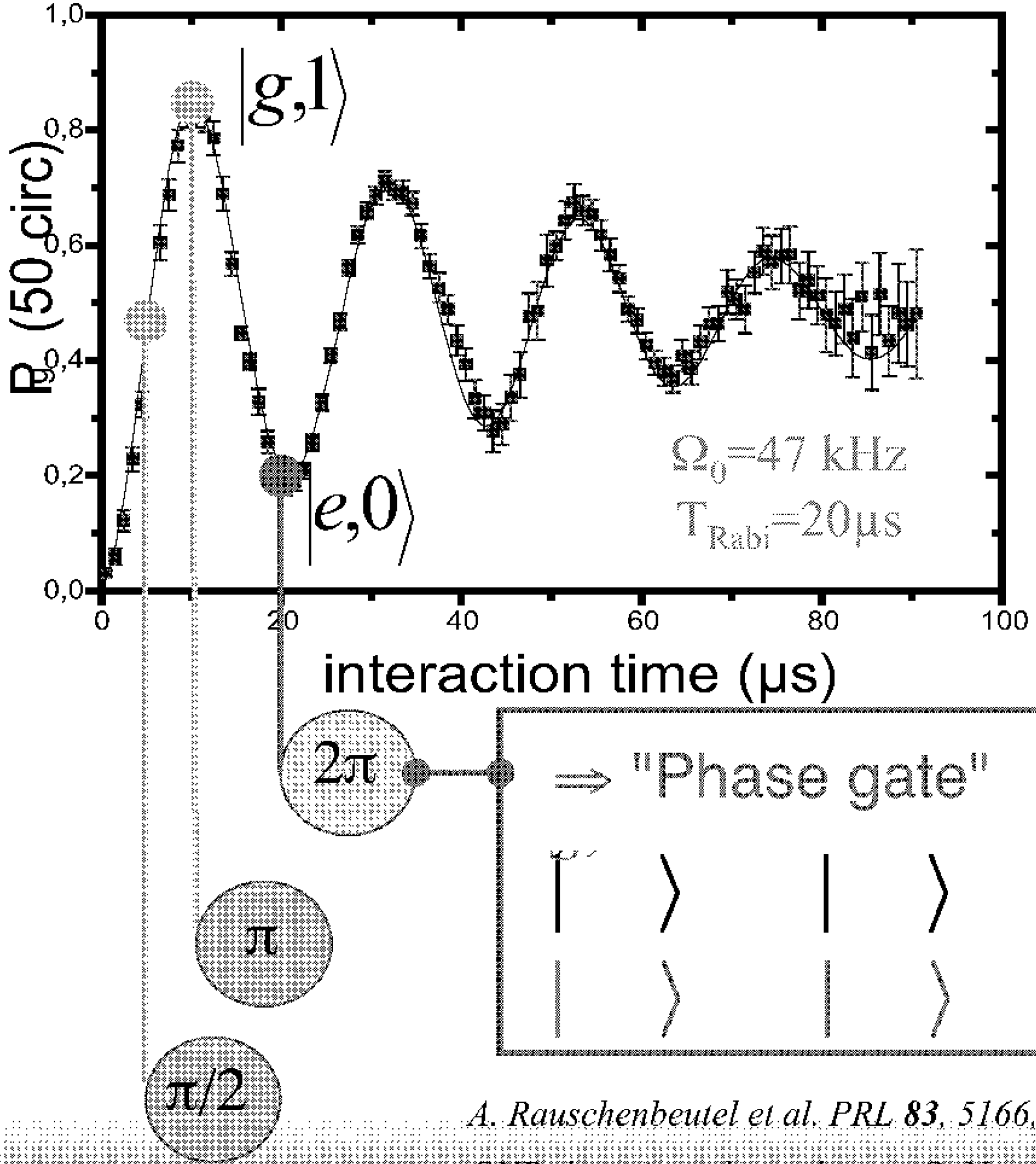


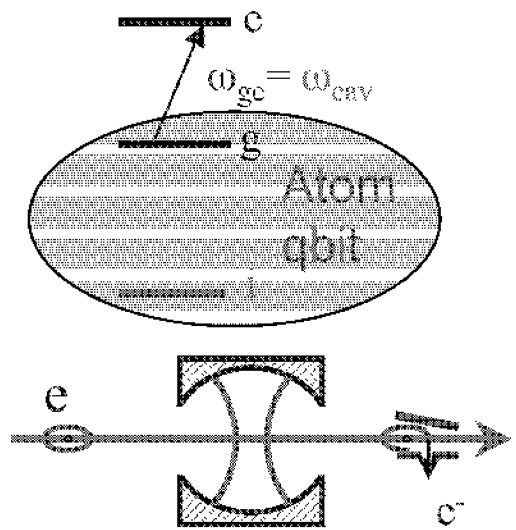


⇒ EPR pair preparation

E. Hagley et al. PRL 79,1 (1997)

Quantum gates based on vacuum Rabi oscillation



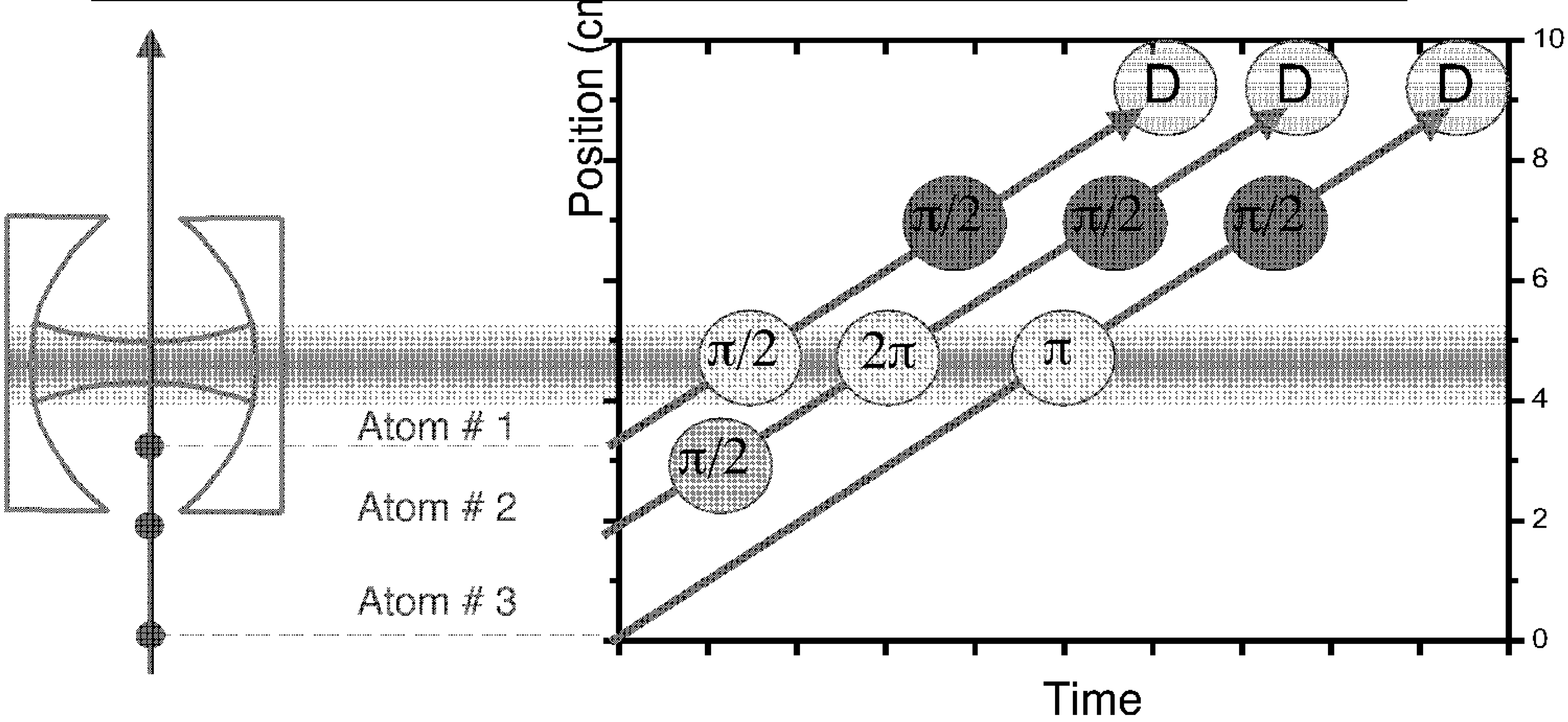


⇒ "Phase gate"

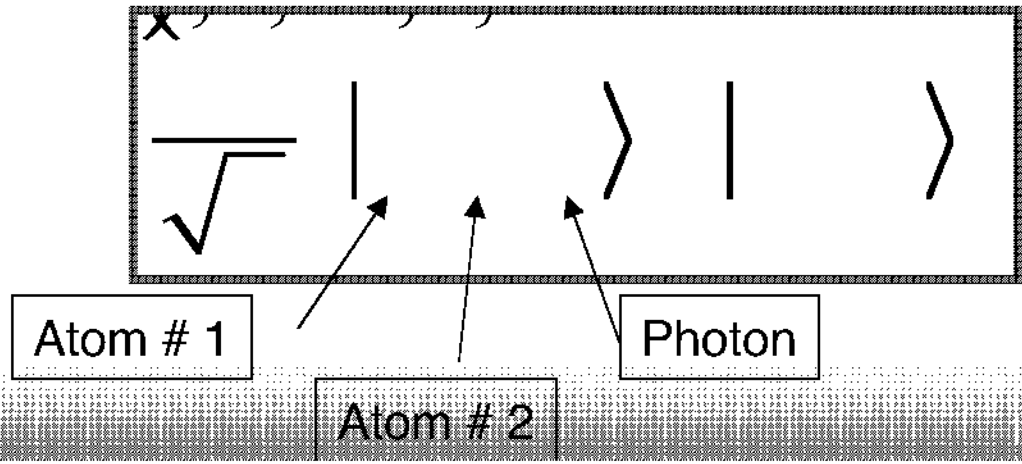
A. Rauschenbeutel et al. PRL ***83****, 5166, (1999)*

QND detection of one photon: G. Nogues et al. Nature ***400****, 239 (1999)*

Step by step preparation of a GHZ triplet

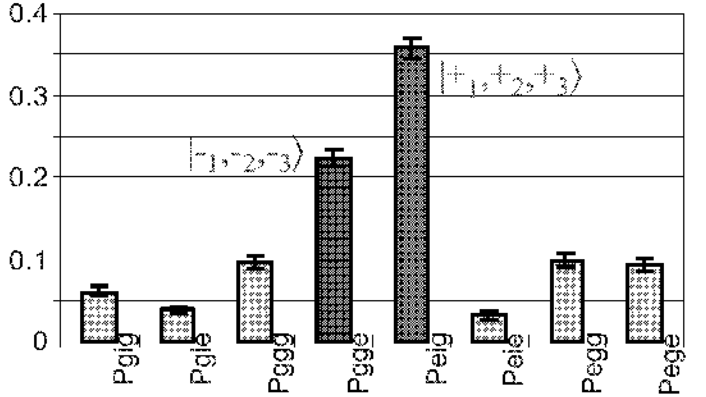


- θ • Resonant Rabi oscillation in C
- π/2 π/2 •Classical π/2 pulse
- D • Détection



Fidelity of preparation of the GHZ state

- Measurement of populations

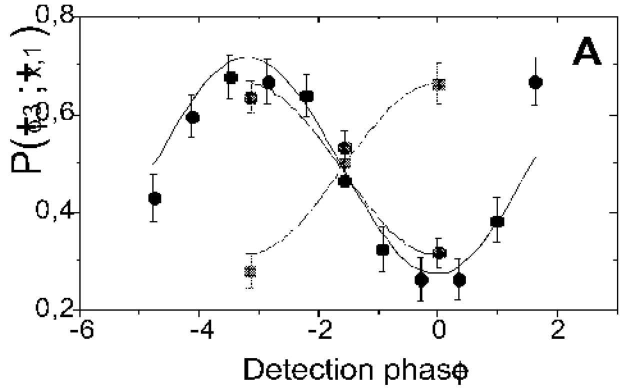


Rauschenbeutel et al., Science **288**, 2024 (2000)

Measurement of: "$\sigma_{z1} \cdot \sigma_{z2} \cdot \sigma_{z3}$"

$\Longrightarrow P_{long} = P_{+++} + P_{---} = 0.58\ (0.02)$

- Measurement of coherences



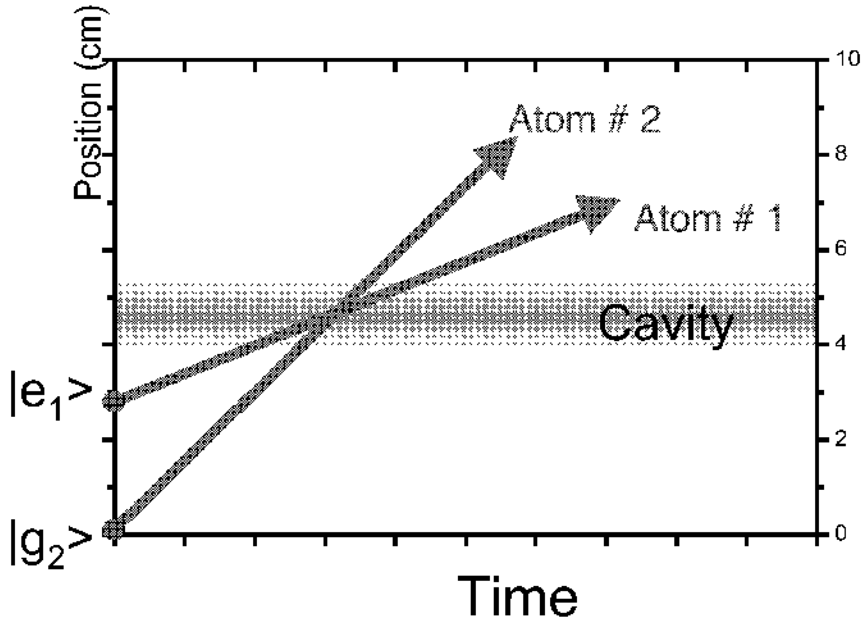
•Measurement of: $\sigma_{x1} \cdot \sigma_{x2} \cdot \sigma_{x3}$

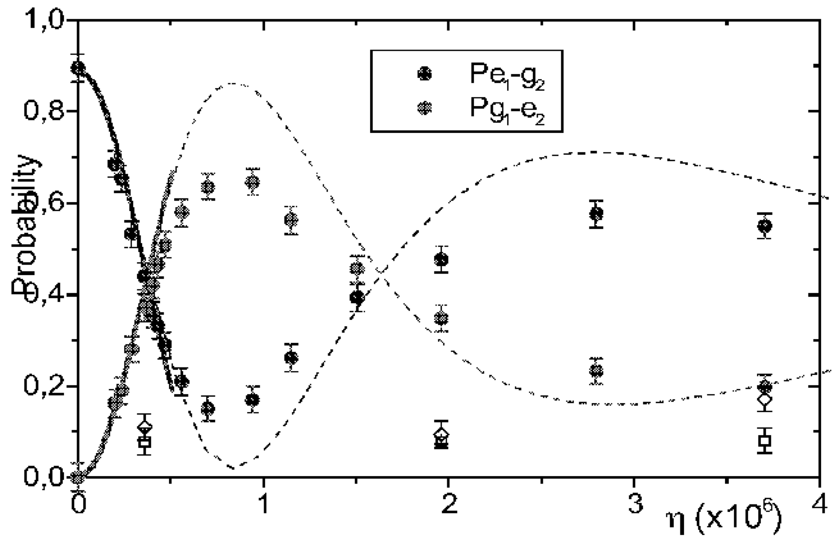
$\Longrightarrow A = \langle \sigma_{x1} \cdot \sigma_{x2} \cdot \sigma_{x3} \rangle = -0.28\ (0.03)$

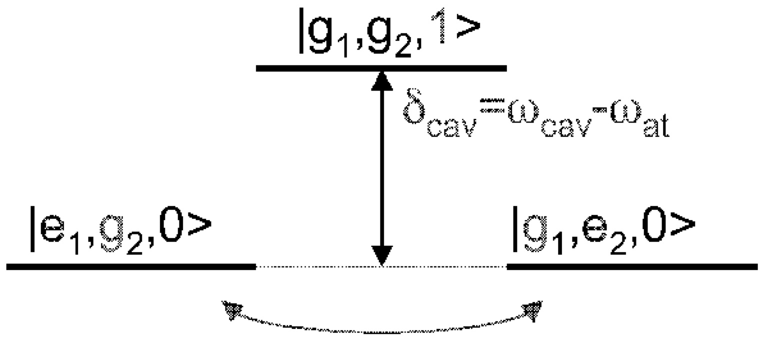
$\Longrightarrow$ The prepared state is not separable

Direct atom-atom entanglement: non-resonant interaction with the cavity

- Two atoms with different velocity cross the cavity at the same time:





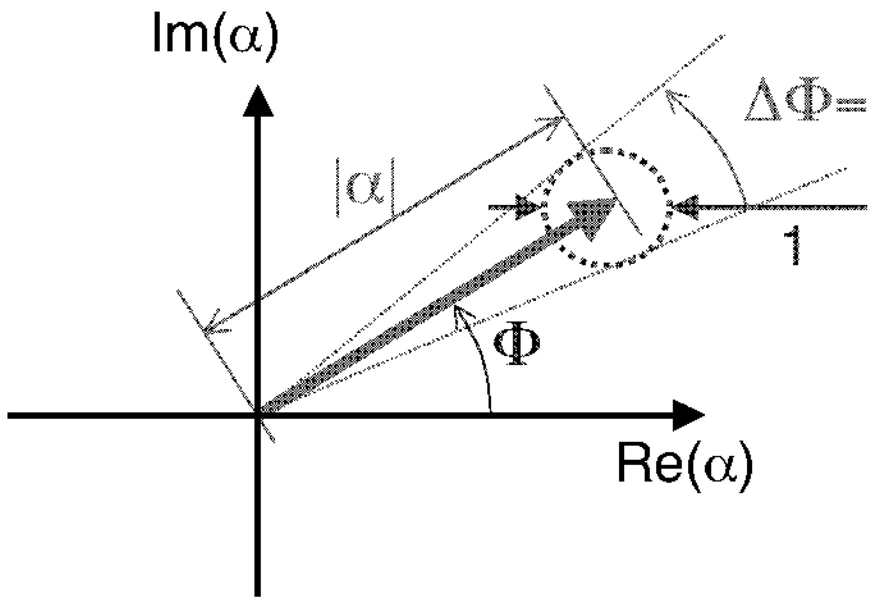


Effective coupling:

Rabi oscillation
⇒ Entanglement
Unsensitive
to cavity damping

Coherent state of the field

• Representation in the complex plane (Fresnel vector):

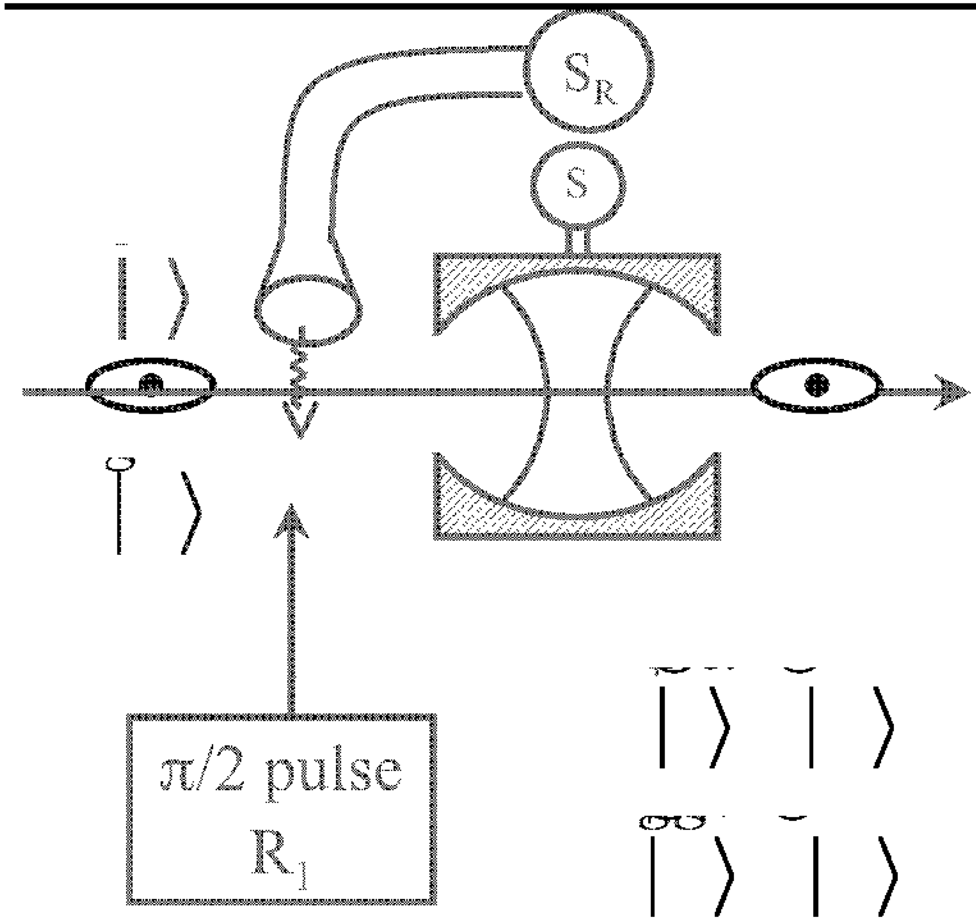


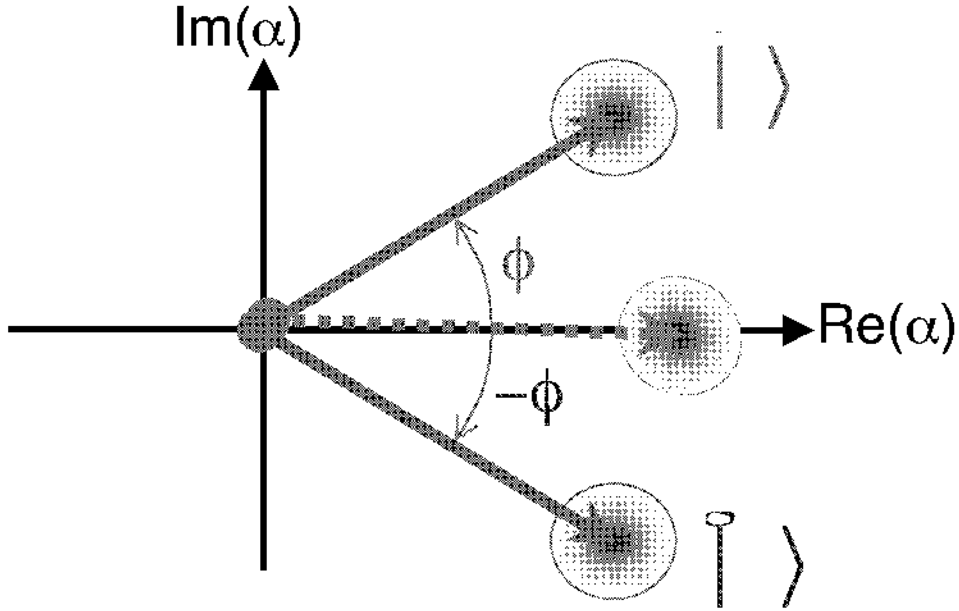
$\Delta N = 1/|\alpha|$

•Heisenberg uncertainty relation: $\Delta N \,.\, \Delta\Phi > 1$

• 0 to tenth of photons easily injected in C
using a classical source

Entanglement by non-resonant interaction
manipulation of the classical phase



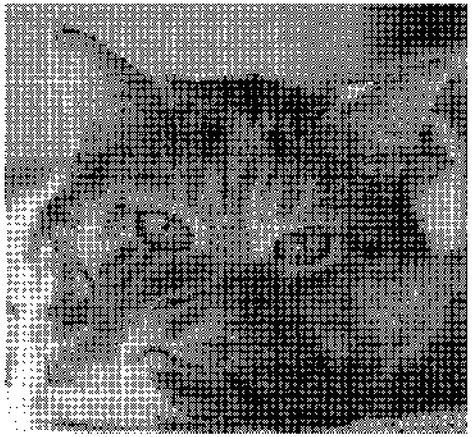


One atom controls the field phase

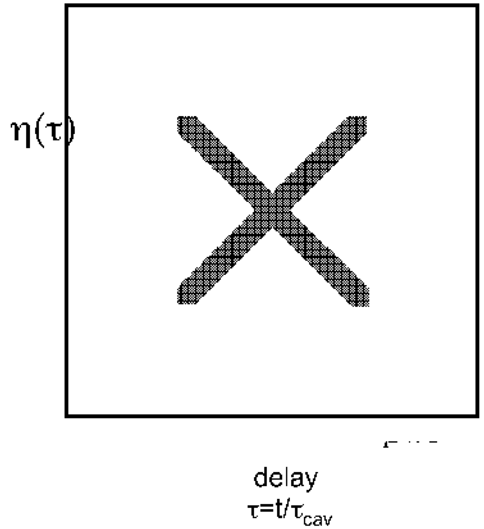
Single atom phase shift: 45° !

"Schrödinger cat" and decoherence

$$\left|\Psi_{cat}\right\rangle = 1/\sqrt{2}\left(\left|e, \nearrow\right\rangle + \left|g, \searrow\right\rangle\right)$$



Decoherence time



M. Brune et al.,
Phys. Rev. Lett. 77, 4887 (1996)

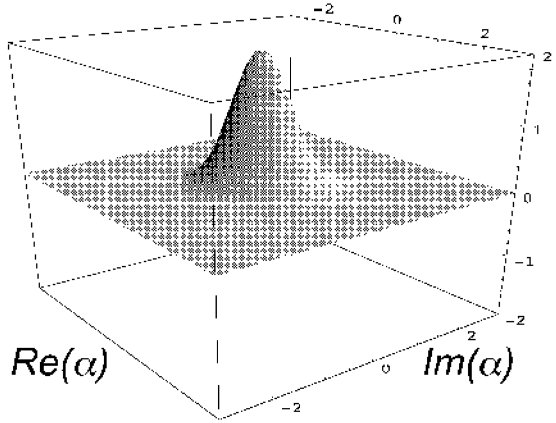
⇒ Observe decoherence for larger fields

⇒ measure the complete field state: Wigner distribution

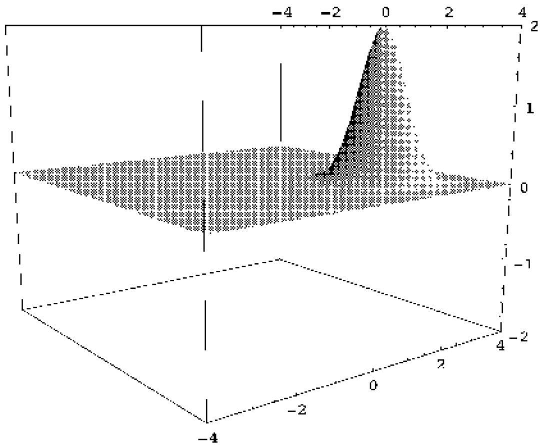
Examples of Wigner functions

- Classical states

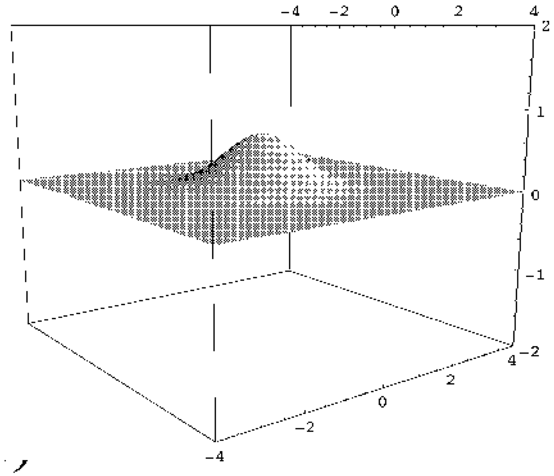
Vacuum |0>



Coherent state |α>
(α=1.5+1.5i)

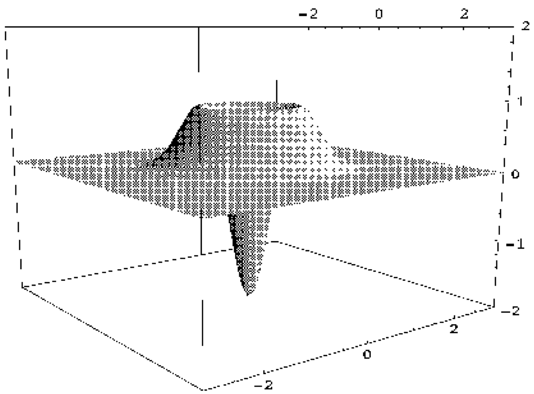


Thermal field n_{th}=1

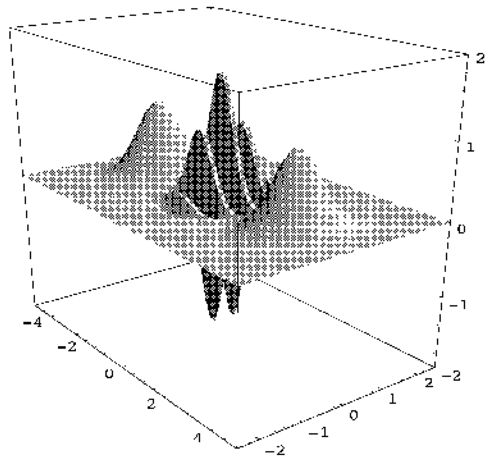


- Quantum states

Fock state |1>

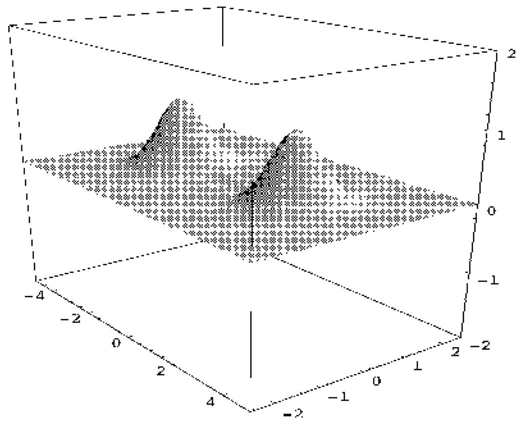


Schrödinger cat's state



t=0

(α=3)



t=0.5 T_{cav}

Negativity of W is a good criterion of quantumness

Principle: measure W(α) by measuring field "parity"

- Based on : *Cahill and Glauber, PR 177, 1857 and 1882 (1969)*

Displaced field density operator

| ⟩ if n even

| ⟩ if n odd

« parity » operator

⇒ Method of measurement of W:

A) Apply D(-a) ⟺ Classical source coupled to the cavity mode : easy

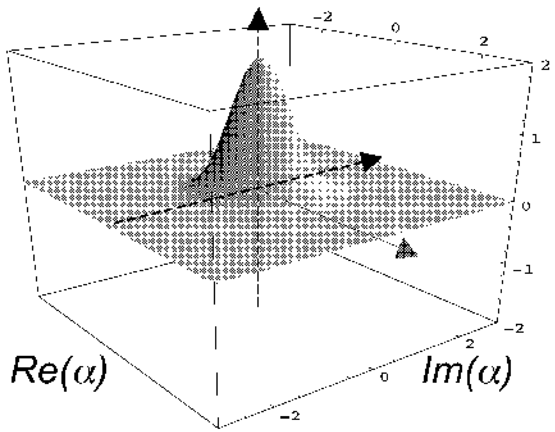
B) Measure parity operator

B. Englert et al., Opt. Comm. ***100****, 526 (1993),*

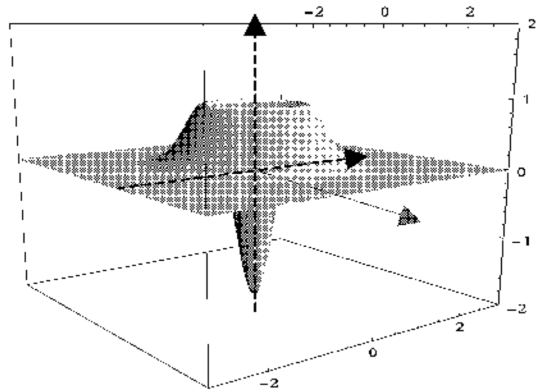
Lutterbach and Davidovich, PRL ***78*** *(1997) 2547*

Measuring W(a) for vacuum or one photon state:

Vacuum |0>



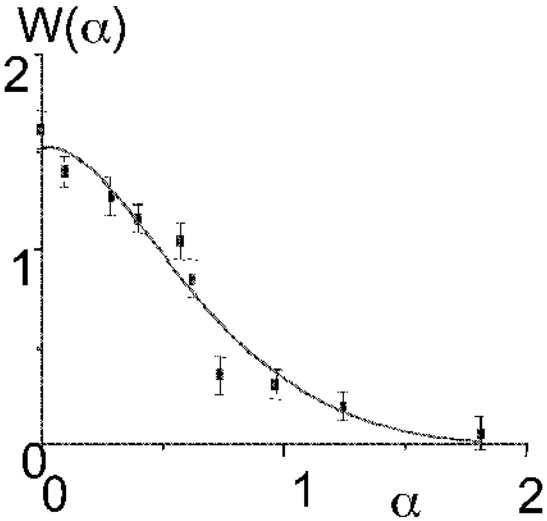
Fock state |1>

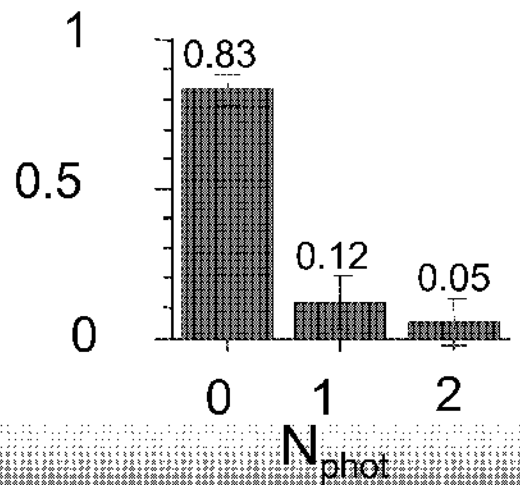


These distributions have a cylindrical symmetry
We only measure a radial cut
by varying lal at a fixed phase

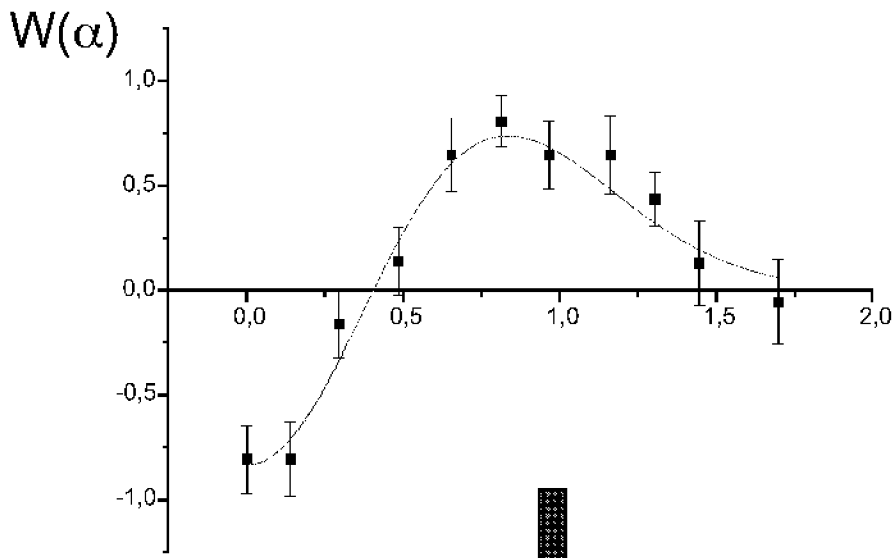
Measured Wigner functions

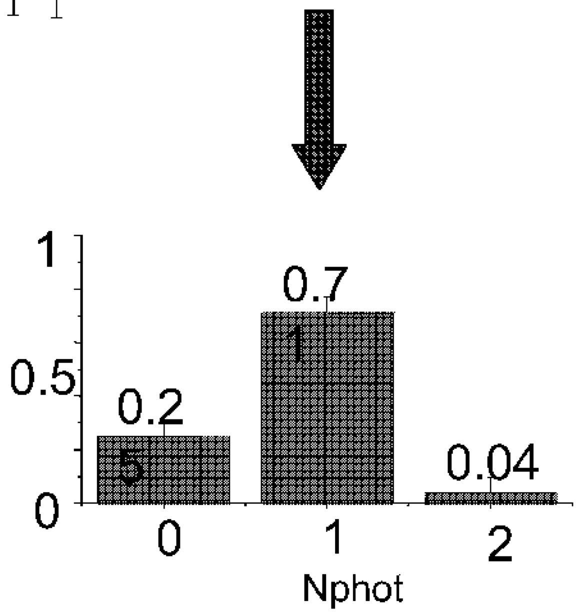
"Vacuum"





One photon Fock state





Conclusion and perspectives

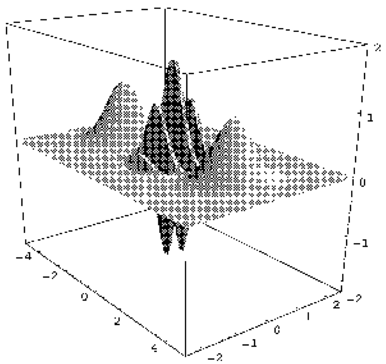
Rydberg atoms and cavities:

efficient tools for entanglement "engeneering":

- manipulation of entangled qbits:
  - longer cavity damping time
  - better detection efficiency
  - use of non-resonant gates

  ⇒ Manipulation of up to 6 atoms and two cavity modes

  ⇒demonstration of elementary quantum algorithm: error correction, Grover
- Preparing and characterizing mesoscopic superposition states:



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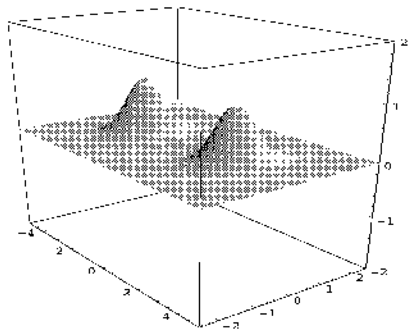

⇒ Observing a movie of decoherence?