Single Atom Experiments and the Test of Quantum Physics

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Schrödinger: July 1952

„… You may object that in some cases, after all, we *are* experimenting with single particles. You may point to the linear traces or trajectories in the photographic plate and in the Wilson chamber, the collisions, the stars, the decaying particles etc. This range of phenomena, very fashionable now, seem to form an unconquerable stronghold for the particle view. I shall summarize my attitude towards these things in a few brief remarks.

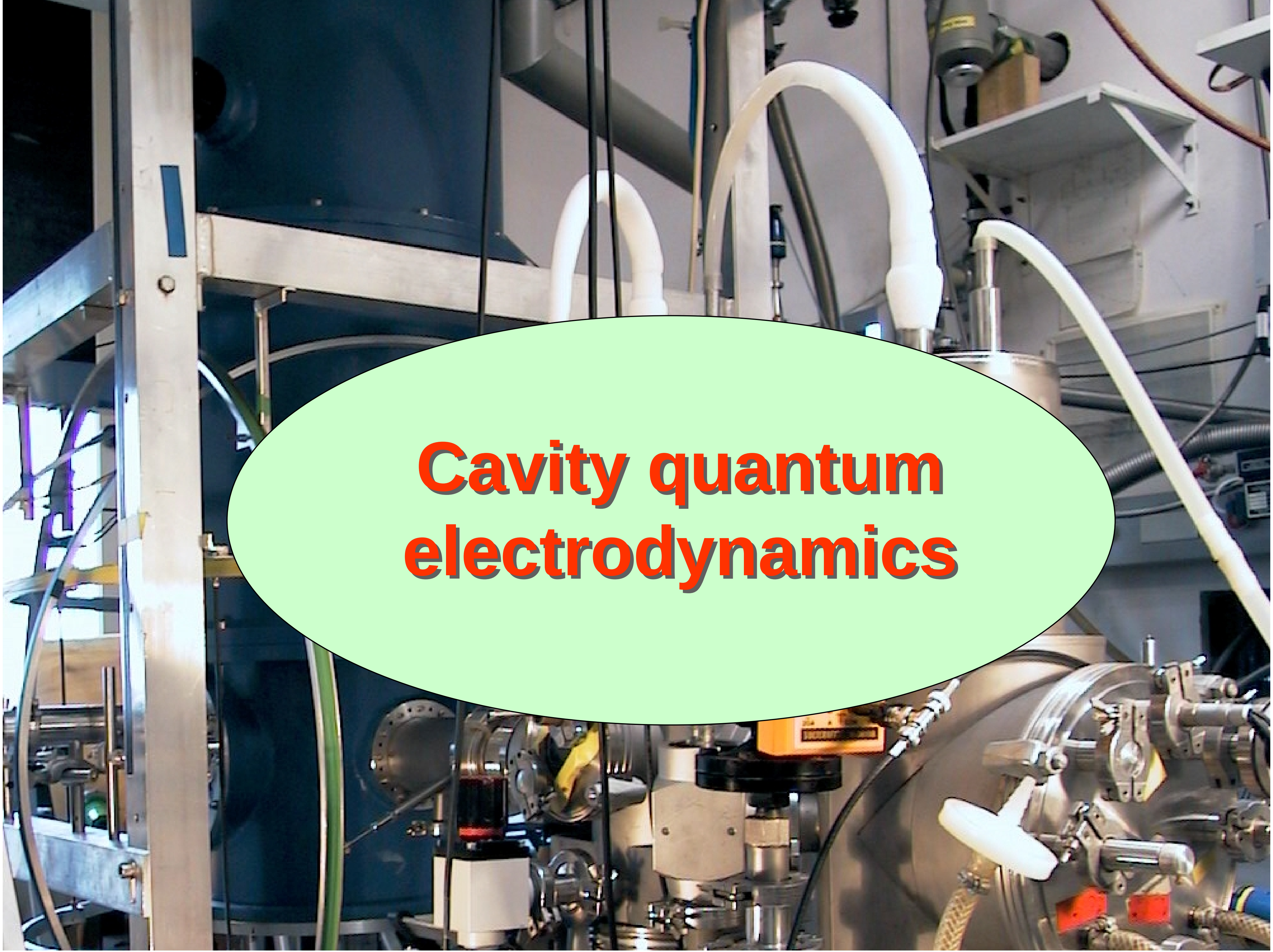
- We do not in these cases *experiment* with single particles; we are scrutinizing records. We cannot repeat any of them under planfully varied conditions – the typical procedure of the experimenter.

Survey

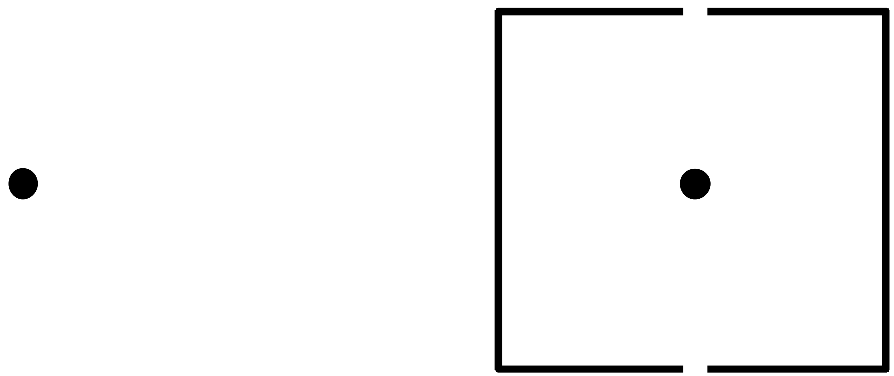
Quantum Interaction of Single Atoms

- Cavity quantum electrodynamics
  - Entanglement of atoms through radiation field
  - Generation of number states of the radiation field
  - Wigner function of a single photon field in a cavity
  - Cavity quantum electrodynamics with trapped ions
- New frequency standard on the basis of a single trapped ion

Cavity quantum electrodynamics



Free Atom versus Atom in Cavity



New field: Cavity quantum electrodynamics

Free Atom <u>versus</u> Atom in Cavity

QED Effects

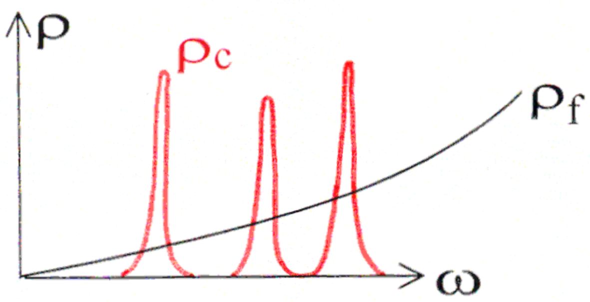
- Modification of spontaneous emission rate
- Level shifts

Interaction with the Radiation Field

- Oscillatory energy exchange (determined by photon statistics)

Principle of Cavity Quantum Electrodynamics

Free space versus cavity



γ : emission rate of an atom $e \rightarrow g$

$$\gamma = 2\pi \int d\Omega_k (d_{eg}^k \rho(\omega_k))_{\omega_k = \omega_o}$$

d_{eg}^k : dipole matrix element between states $|e,0\rangle$ and $|g,1_k\rangle$

Free Space:

$$\rho_f(\omega_k) d\omega_k = \left(\frac{1}{2}\right)\left(\frac{1}{4\pi}\right) \frac{\omega_k^2 \, d\omega_k}{\pi^2 c^3}$$

Q: quality factor $Q = \frac{\omega_k}{\Delta\omega_k}$

Cavity:

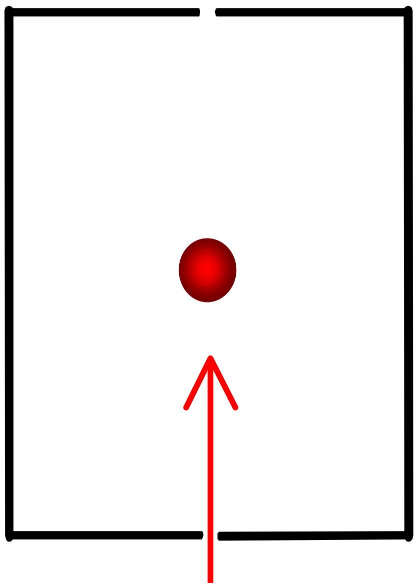
Atom does not see full vacuum spectrum

$$\gamma_c = \gamma_f \frac{\rho_c(\omega_k)}{\rho_f(\omega_k)} \longrightarrow \gamma_f \frac{(\lambda_k^3)}{V} Q$$

E. Purcell 1946
K. H. Drexhage 1974
D. Kleppner 1981
S. Haroche 1983
M. Feld 1987

One-Atom Maser

Single atom - Single mode of a cavity



Atom in
excited state

Resonant superconducting cavity

Atom

↕ **coupling constant g (Rabi-frequency)**

Cavity field

↕ **coupling constant** $\frac{\omega}{Q}$

Cavity walls

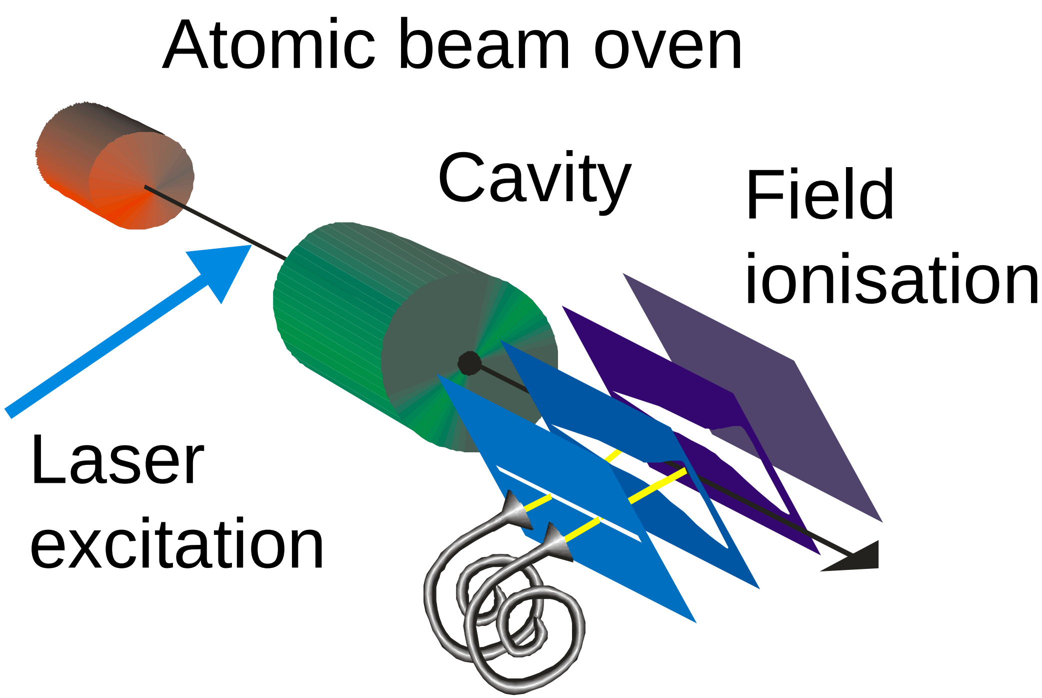
Strong coupling $g > \frac{\omega}{Q}$

Steady state field is generated:

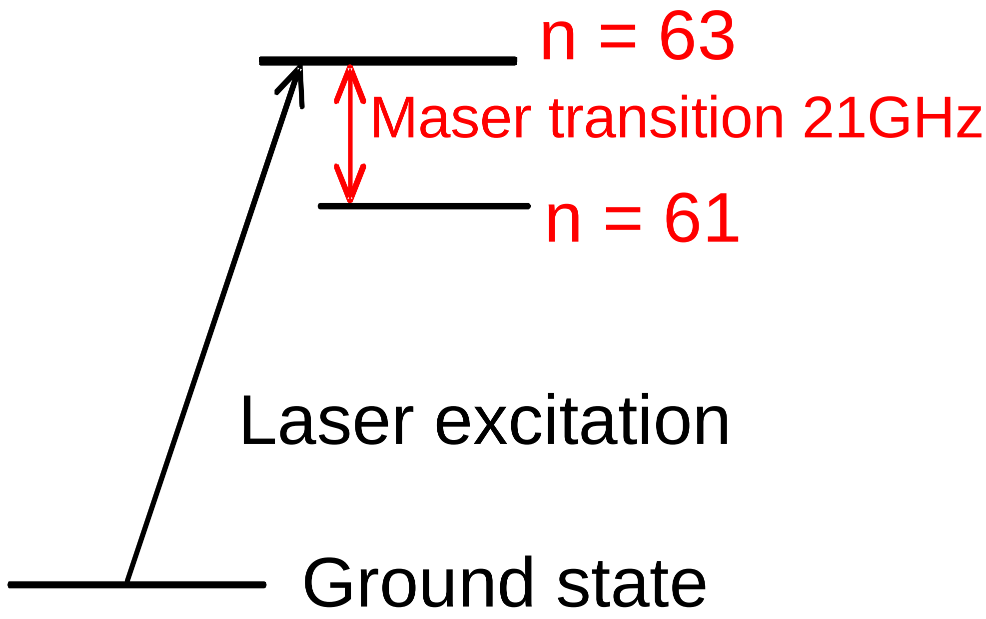
In most of the parameter regions sub-Poissonian statistics is obtained i.e. nonclassical fields

One-Atom Maser

Scheme



Levels



Velocity selected atoms $\frac{\Delta v}{v} = 1 - 4\ \%$

Single photon Rabi frequency: $g \approx 40\,000\ s^{-1}$

Quality factor of cavity $Q = 4 \cdot 10^{10} \rightarrow \tau_{cav} = 0.3\ s$

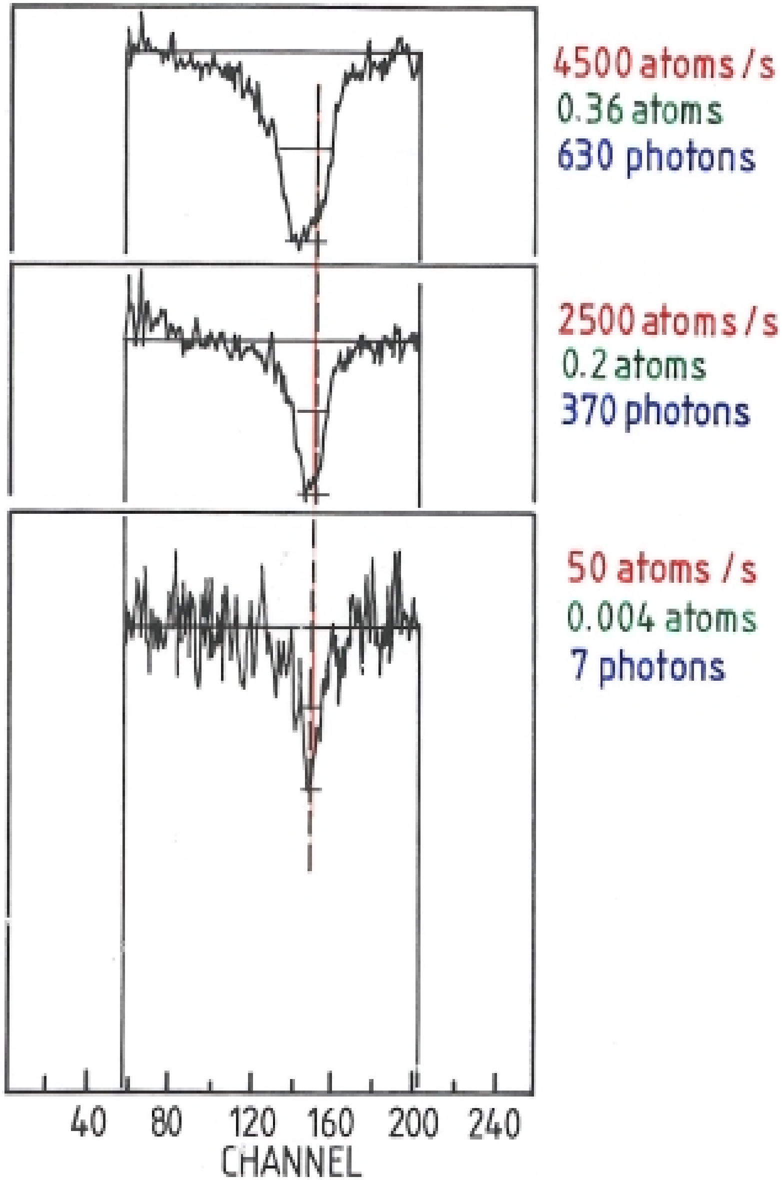
$\Big\}\ g \gg \frac{\omega}{Q}$

Temperature of the cavity $\approx$**140 mK**

Maser Resonance

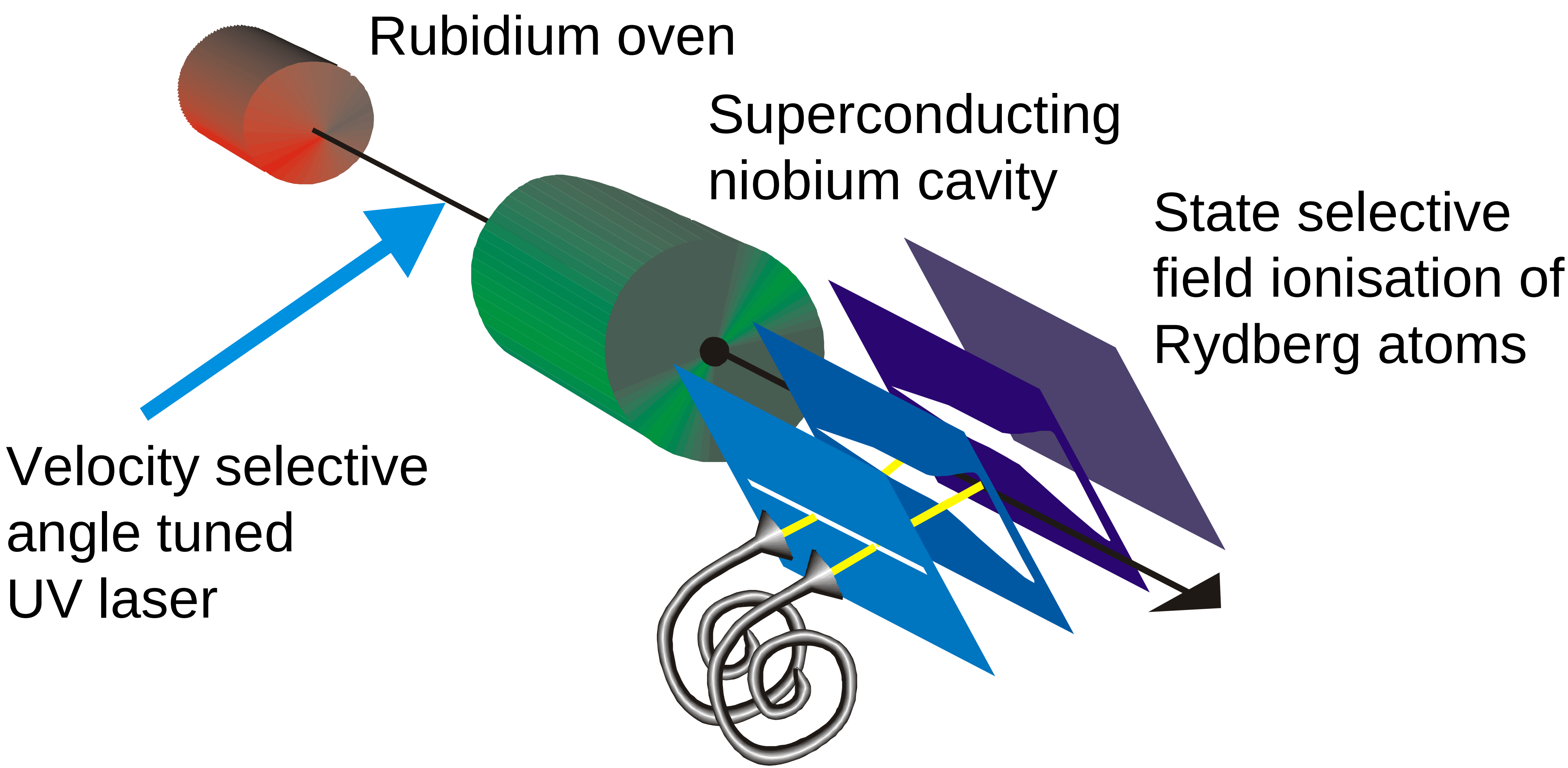
$Q = 3 \cdot 10^{10}$
$T = 0.5$ K
$\gamma^{1} = 0.2$ s

H. Walther, Phys. Rep. 219, 263 (1992)



Rb^{85} $63p_{3/2} – 61\ d_{5/2}$
Resonance frequency:
21.456 GHz

One-Atom Maser



Atoms leaving the cavity are entangled with the generated field

$$|e, n\rangle \rightarrow \cos(\phi\sqrt{n+1})\,|e, n\rangle - i\sin(\phi\sqrt{n+1})\,|g, n+1\rangle$$

Experimental Results with the Micromaser

Dynamics of the photon exchange (MPQ)

Test of micromaser theory – photon statistics (MPQ)

Two-photon maser (ENS)

Entanglement atom – field (MPQ-ENS)
atom – subsequent atom(s) (MPQ-ENS)

Bistability and quantum jumps (MPQ)

Excitation exchange between subsequent atoms (ENS)

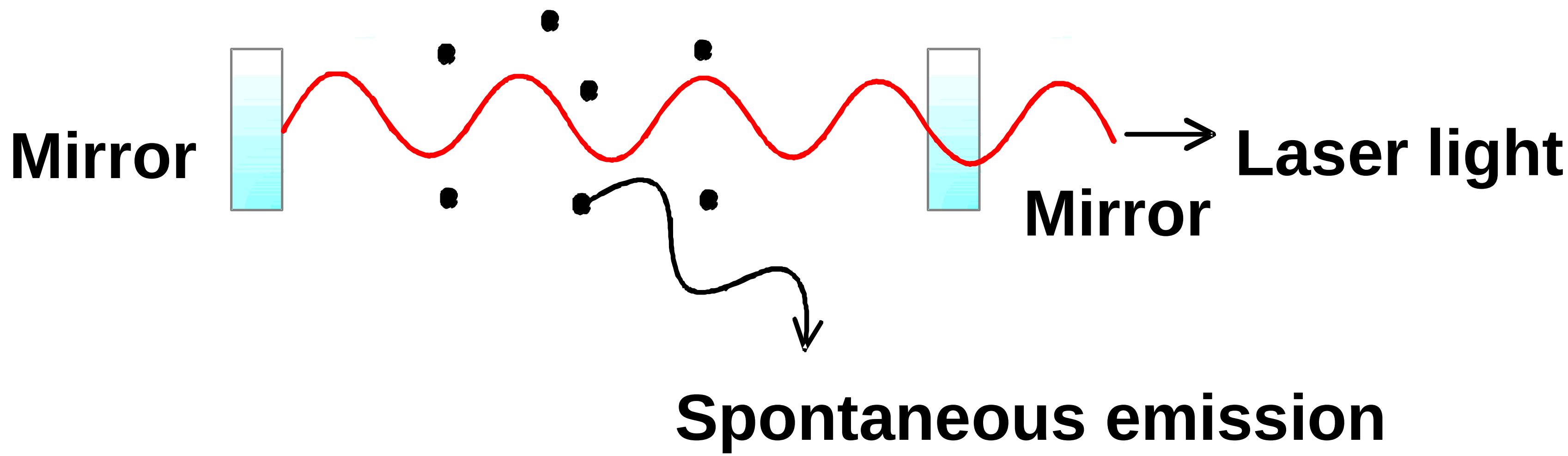
Discrete quantum states of the maser field (MPQ)

Determination of the Wigner function of a single photon (MPQ-ENS)

Generation of photon number states on demand (MPQ)

Scheme of a Laser

Laser cavity

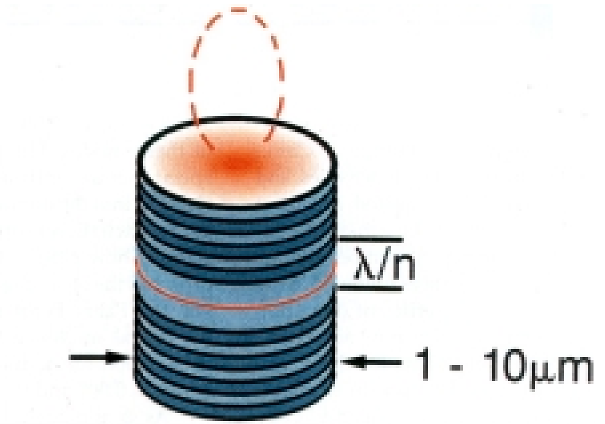


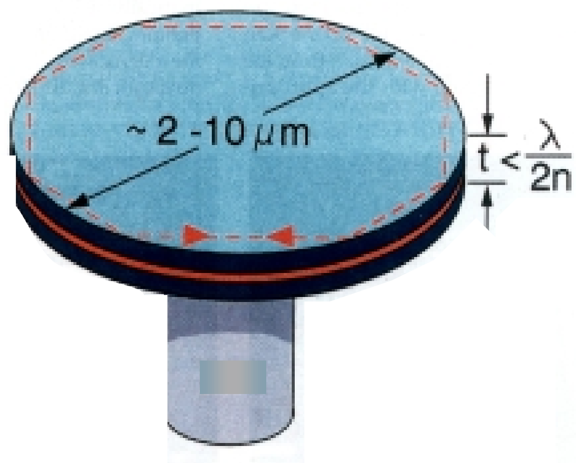
Stimulated emission causes coherent emission into cavity modes

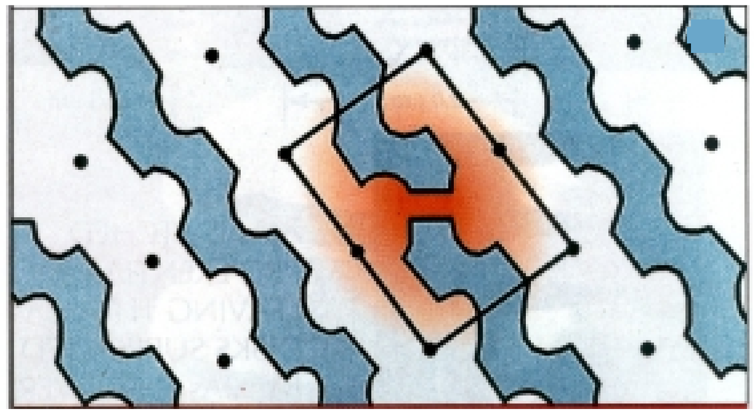
Spontaneous emission perturbs coherence and causes losses (spontaneous emission occurs in all directions)

Microlaser Arrangements

Cavity QED enhances efficiency of laser systems through control of spontaneous emission



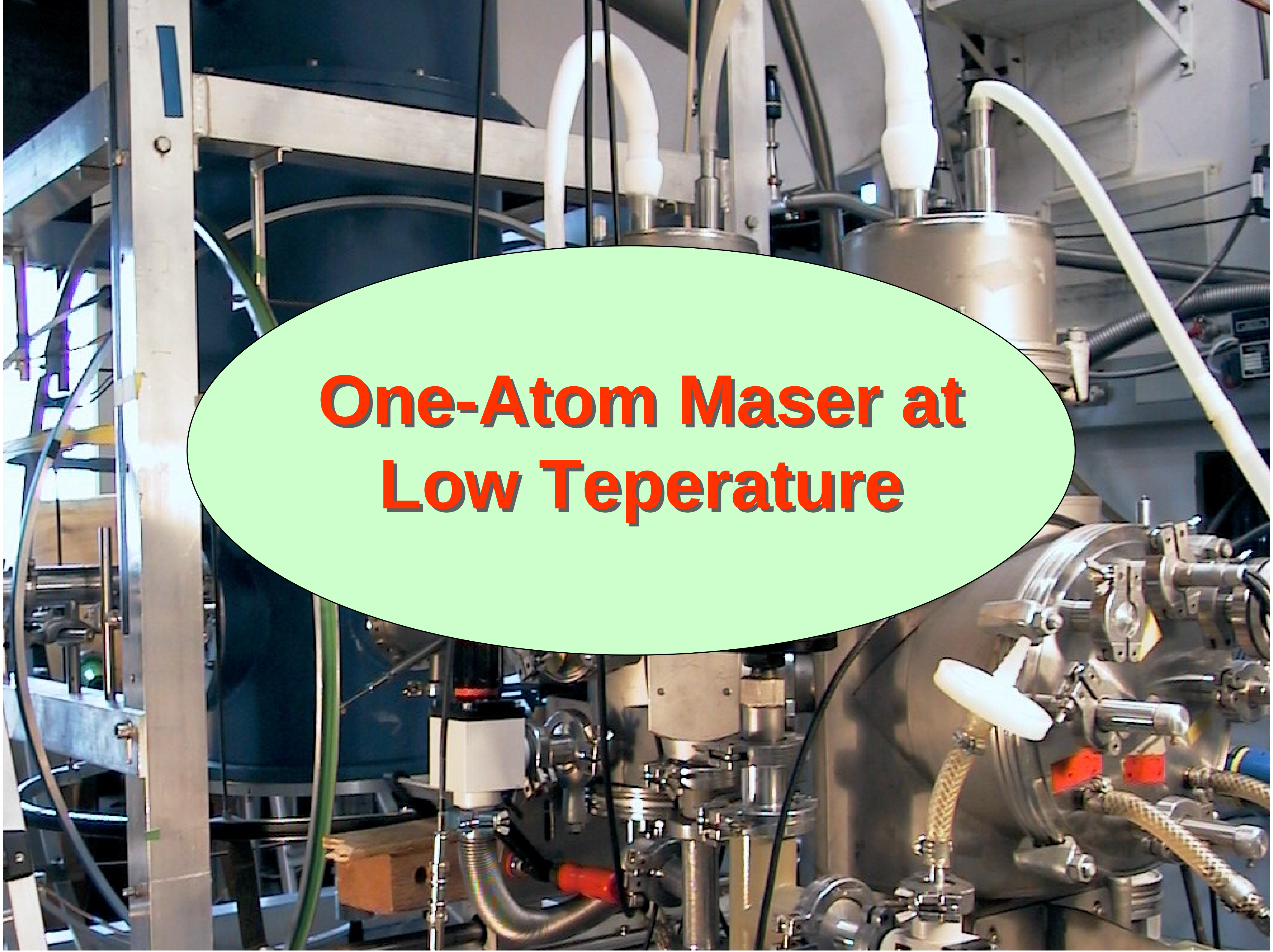




Microcavities

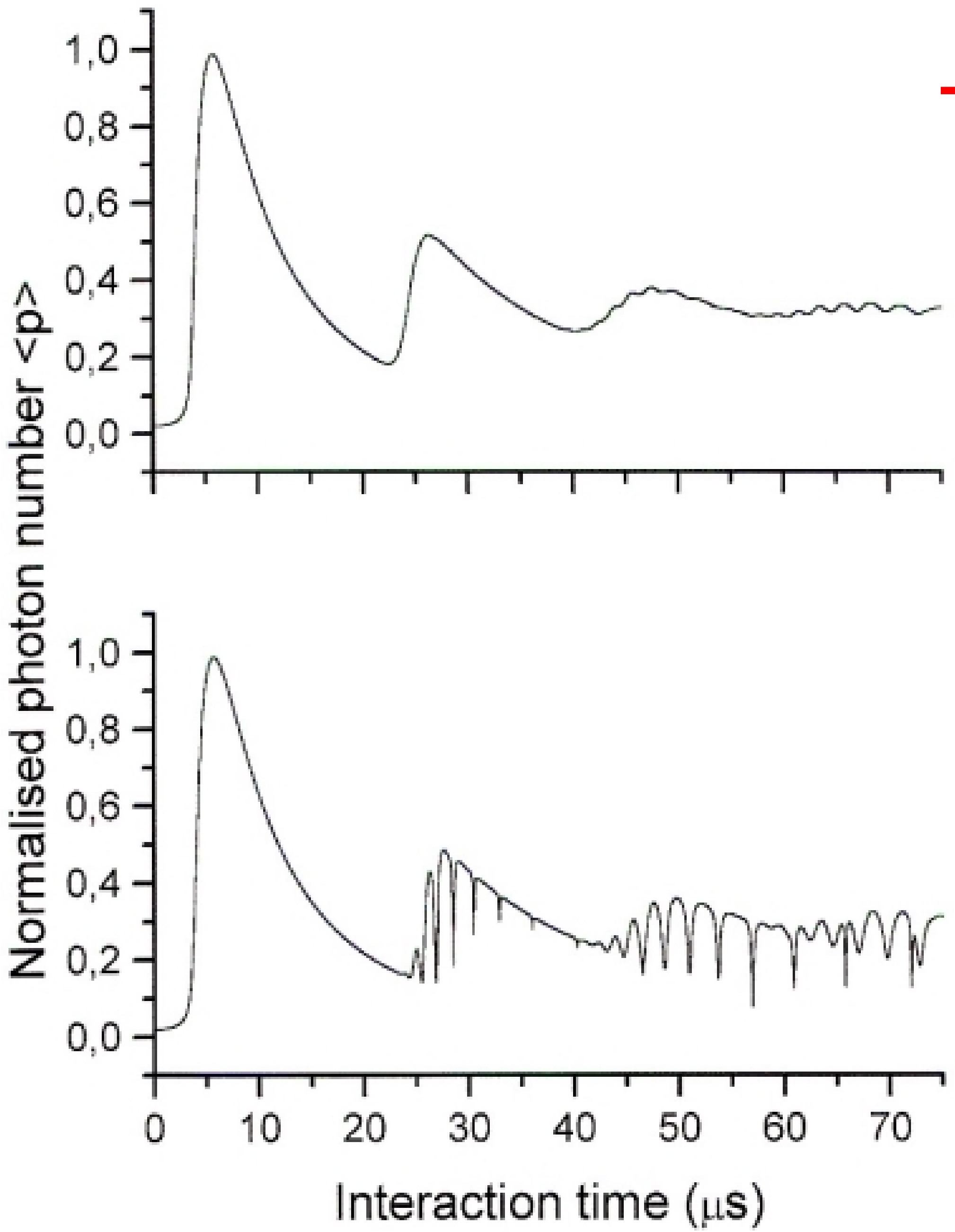
Whispering gallery modes

Photonic bandgap structure



One-Atom Maser at Low Teperature

Low Temperature Behaviour of the One-Atom-Maser



Thermal photon number = 0.1

$N_{ex} = 50$

$g = 39$ kHz

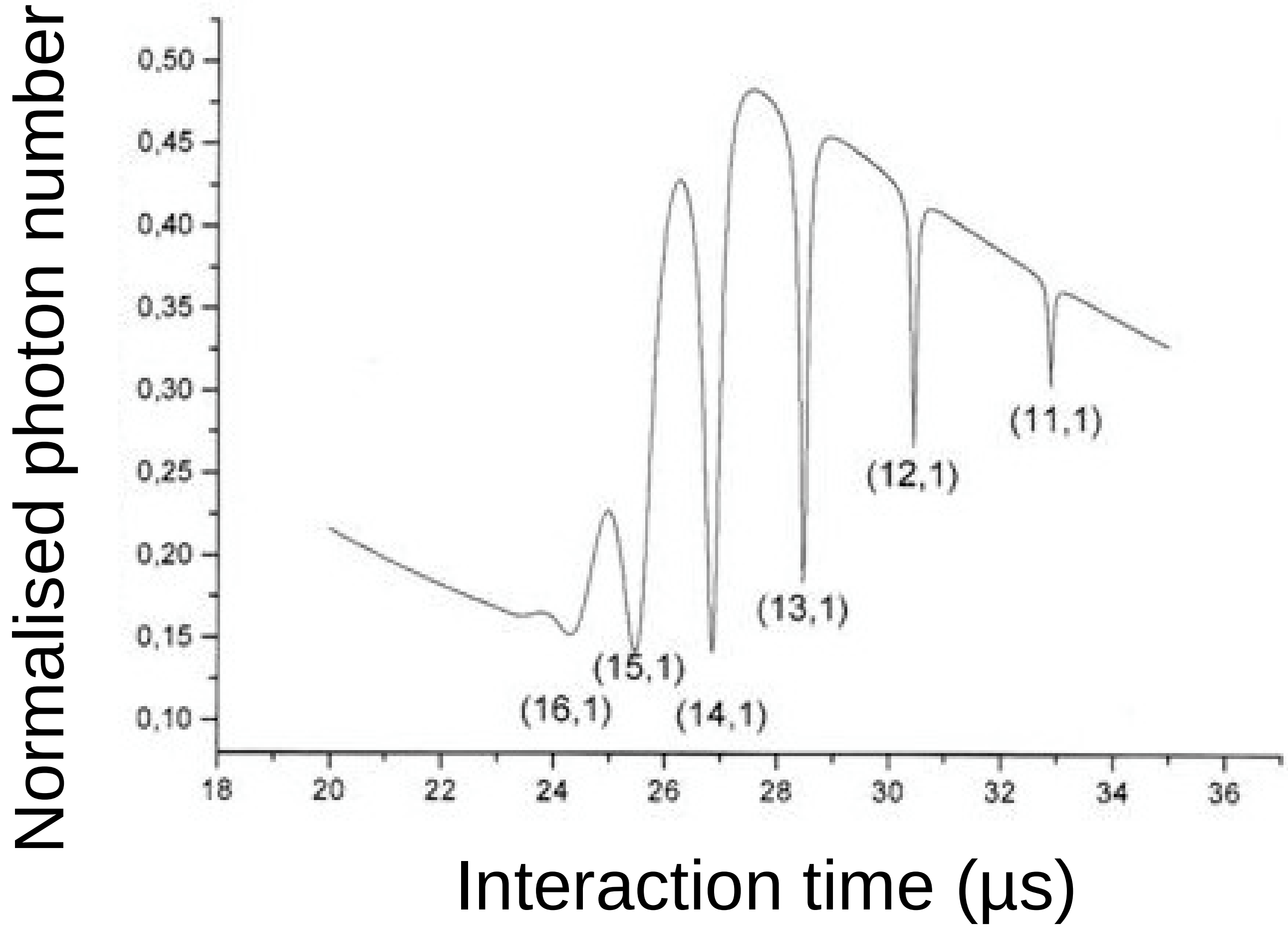
Thermal photon number = 10^{-4}

$N_{ex} = 50$

$g = 39$ kHz

P.Meystre, G.Rempe, H.Walther, Opt. Lett. 13, 1078 (1988)

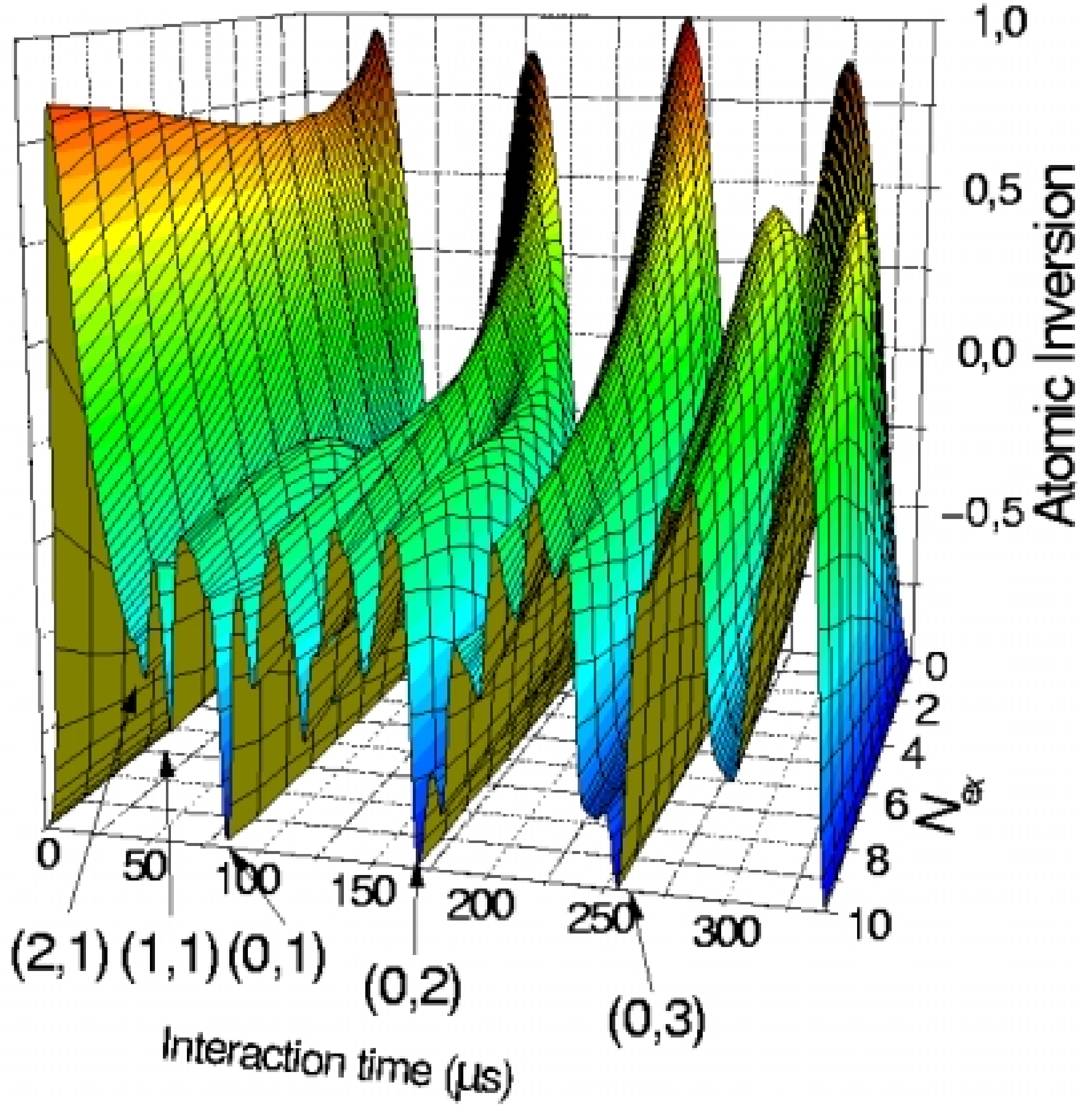
Low Temperature Behaviour of the One-Atom-Maser



Trapping states are characterised by the pair of numbers (n_q, k) that satisfies the relation:

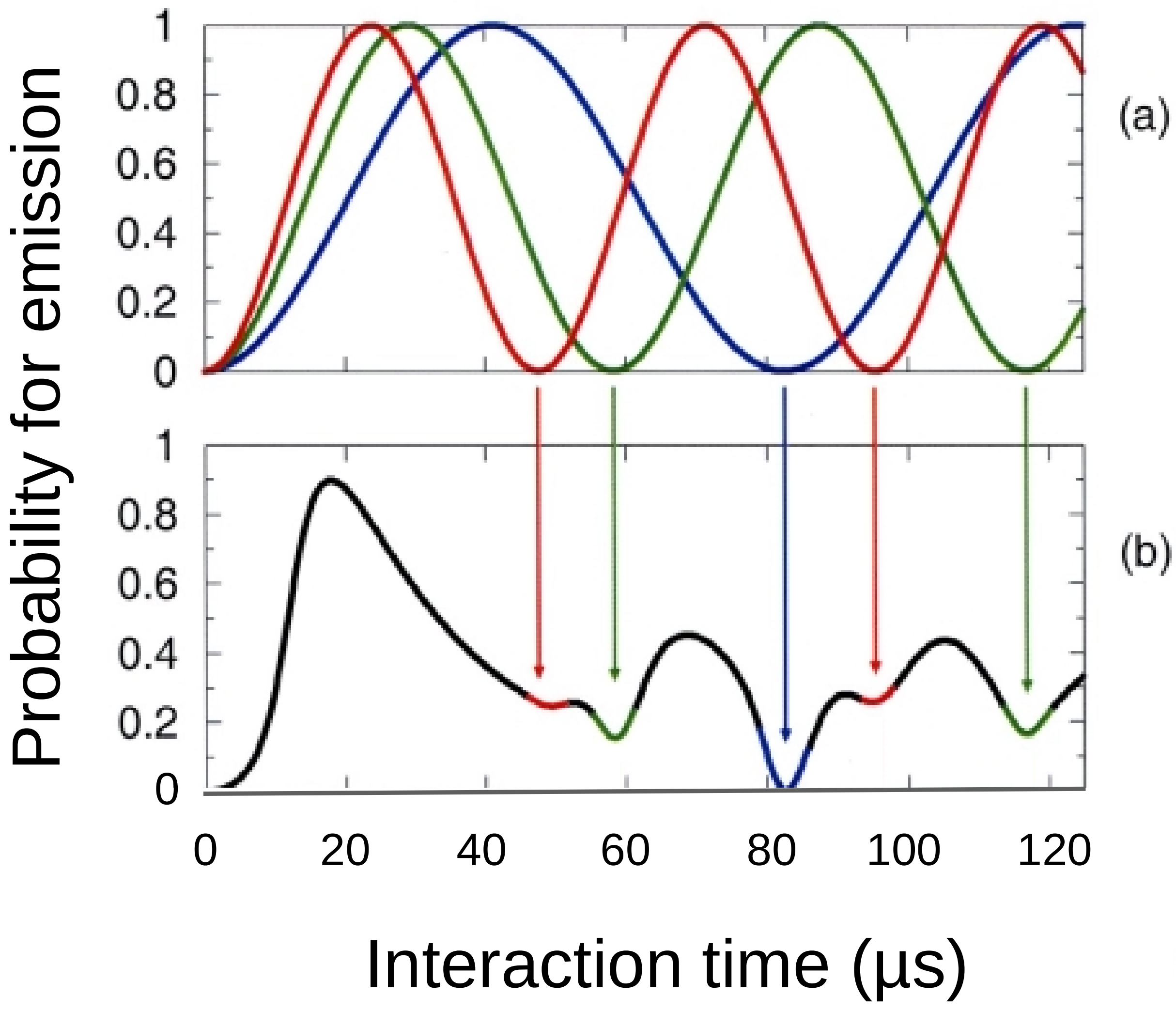
$$\sqrt{n_q+1}\, g t_{int} = k\pi$$

The Micromaser Pump Curve at Low Temperatures



Trapping states appear as valleys in the N_{ex} direction

Formation of Trapping States



Trapping state: **(2.1) (0.1) (1.2)**

N_{ex} = 5, n_{th} = 0 **(1.1) (2.2)**

Generation of Fock States

1) State reduction (dynamical process)
Nature **403**, 743-746 (2000)

2) Trapping states (steady state generation of Fock states)
Phys. Rev. Lett. **82**, 3795-3798 (1999)

3) Fock state generation on demand using trapping states
Phys. Rev. Lett. **86**, 3534-3537 (2001)

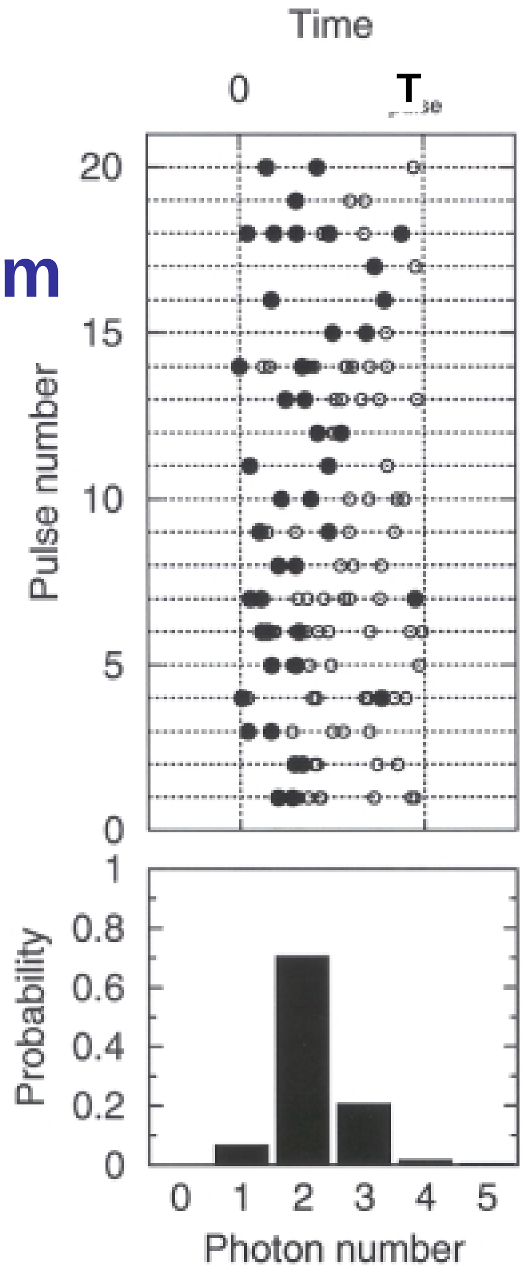
Pulsed excitation of Rydberg atoms

Interaction time tuned to a trapping state

When tuned to the (1.1) trapping state
one ground state atom and one photon
is produced per excitation pulse

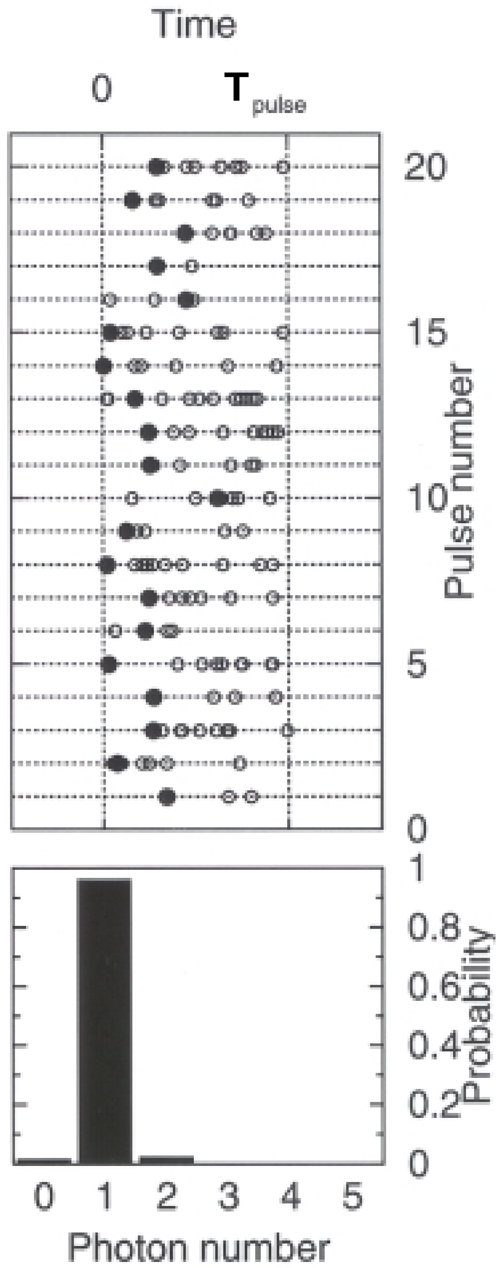
Photon-Fock-States on Demand

$t_{int} = 45$ µs deviates from trapping condition



$t_{int} = 58$ interaction time for the (1,1) trapping state

S. Brattke, B.T.H. Varcoe, H. Walther, Phys.Rev.Lett.86, 3534-3537 (2001)



New method for the determination of the Wigner function

P. Lougovski, E. Solano, Z.M. Zhang, H. Walther
H. Mack, W.P. Schleich

quant-ph/0206083

Wigner Function of a Single Photon State

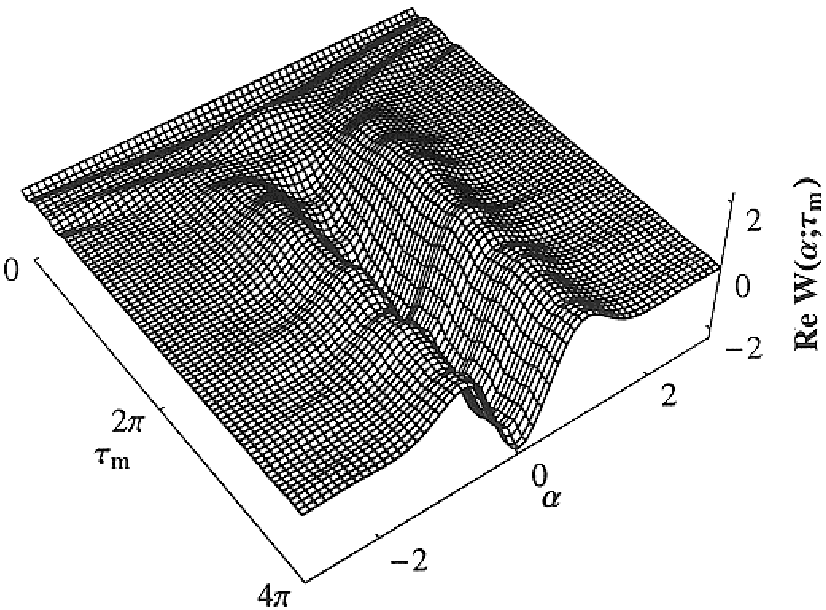
Determination of the Wigner Function

$P_g(t,\alpha)$ **Probability for an atom in the ground state $|g\rangle$**
α determined by displacement field

$$P_g(t,\alpha) = \frac{1}{2} - \frac{1}{2}\sum_{n=0}^{\infty} P_n(\alpha)\cos\left(2\sqrt{n+1}\;\Omega t\right)$$

Wigner-function obtained from the Fresnel transform of Rabi oscillations

$$W(\alpha) \simeq \frac{8}{\pi\sqrt{i}}\int_0^{\infty} d\tau\, e^{i\tau^2/\pi}\left[P_g(\tau,\alpha) - \frac{1}{2}\right]$$

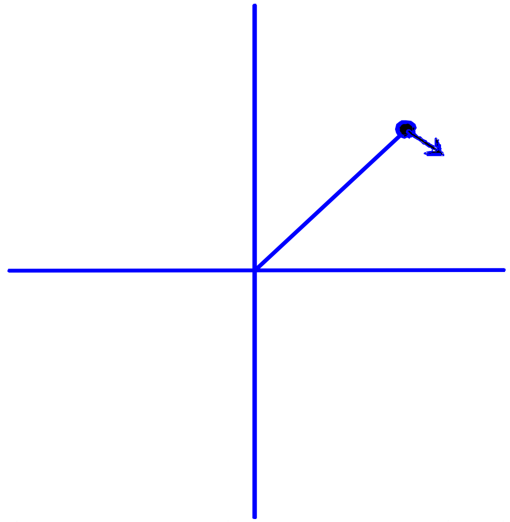


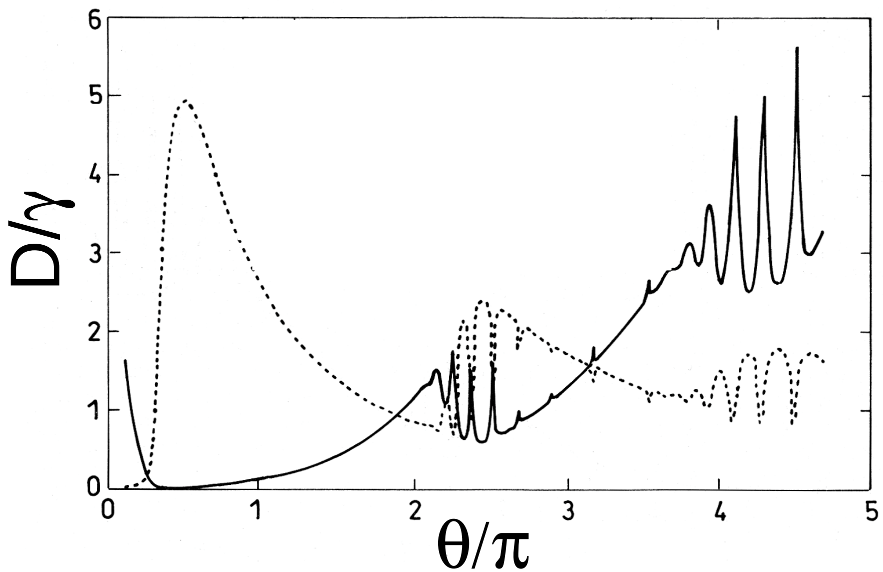
Rabi oscillations of a one-photon number state

W(0) = -1.9

Phase Diffusion of the Micromaser Field

Phase space representation:





Spectrum of the maser:

$$s(\omega) = \left| \int_0^\infty \langle E(t) \rangle \, e^{-i\omega t} \, dt \right|^2$$

$$s(\omega) = \frac{\langle E(0) \rangle}{(\omega - \omega_F)^2 + \frac{1}{4} D}$$

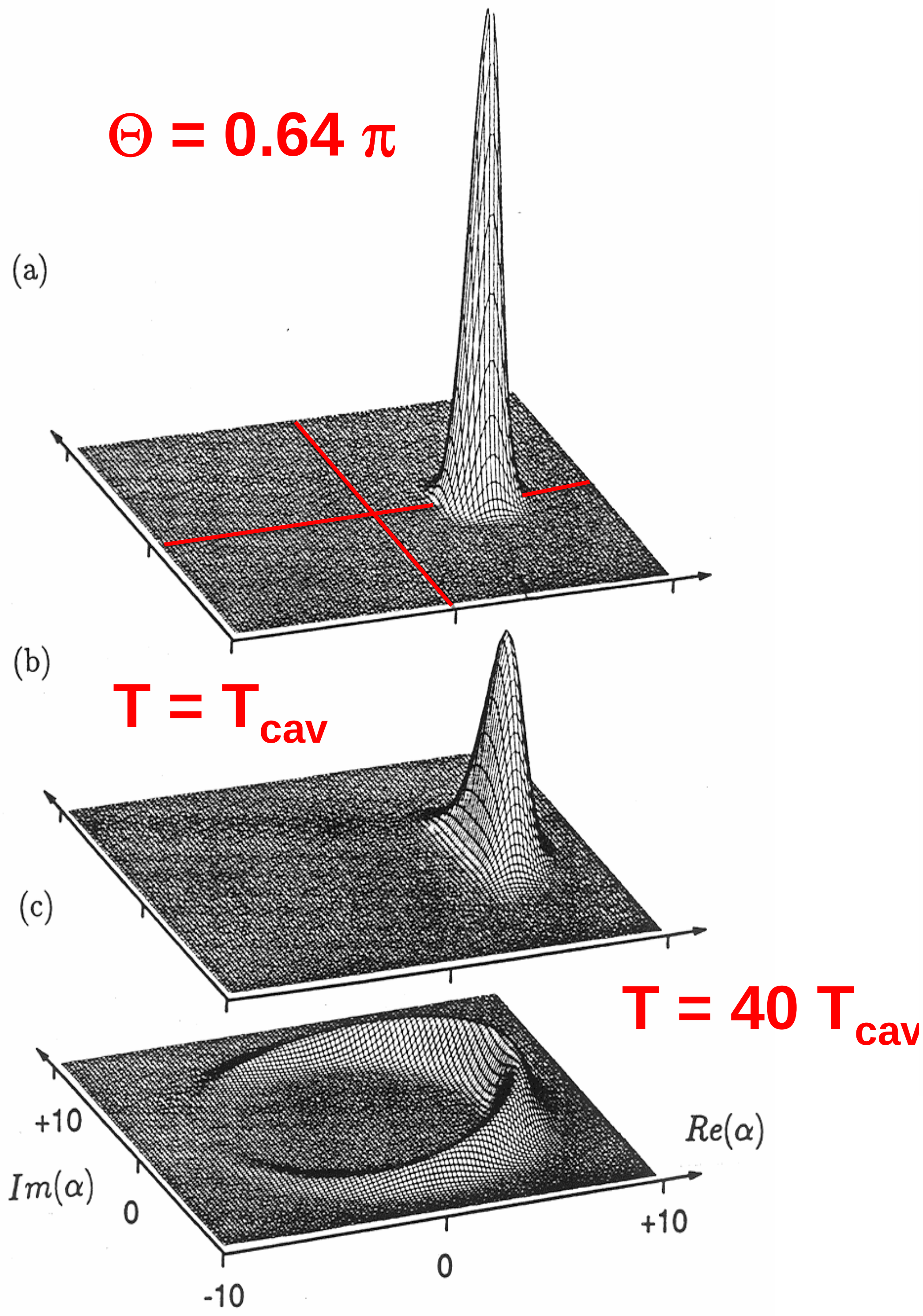
$$D \approx \frac{\alpha + \kappa (2 n_{th} + 1)}{4 \langle n \rangle}$$

$\alpha = \kappa \theta^2$ $\theta = g \, t_{int} \sqrt{N}$ pumping parameter

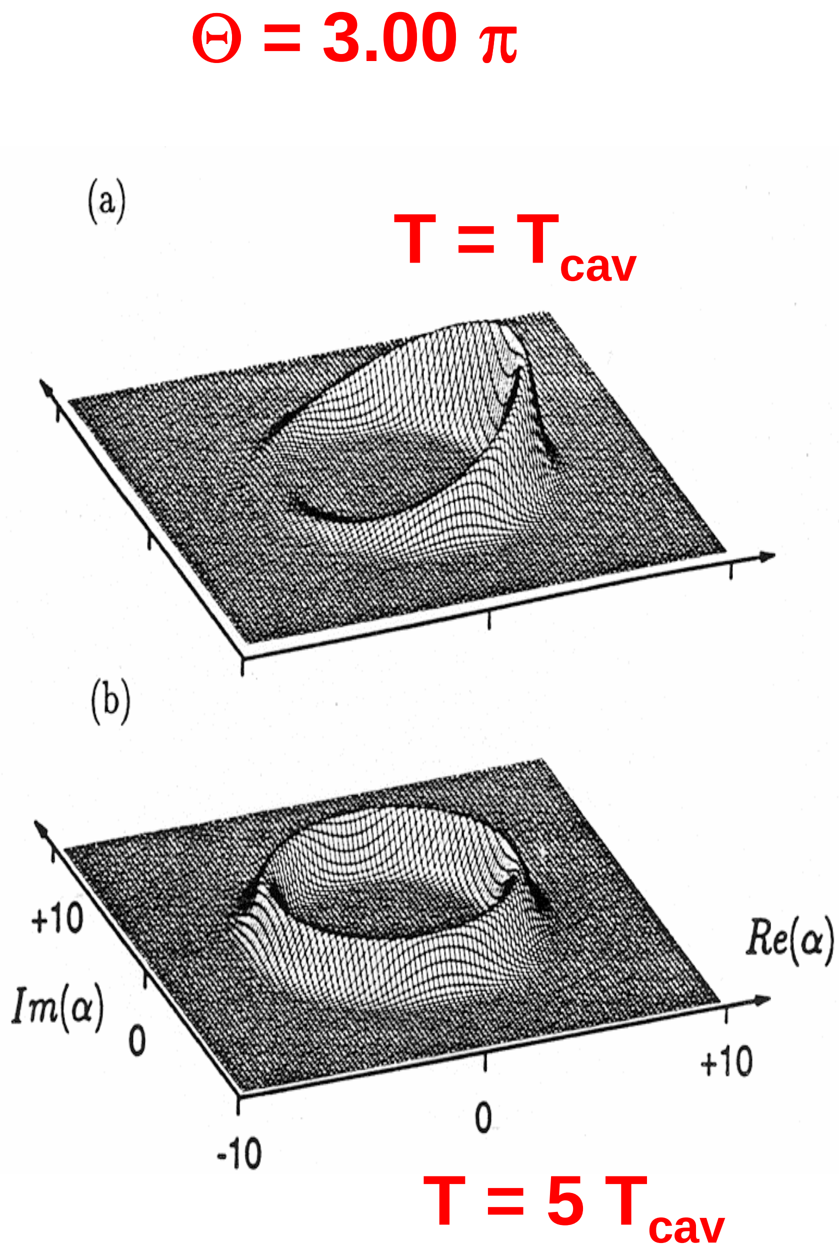
κ : cavity decay rate

n_{th}: thermal field

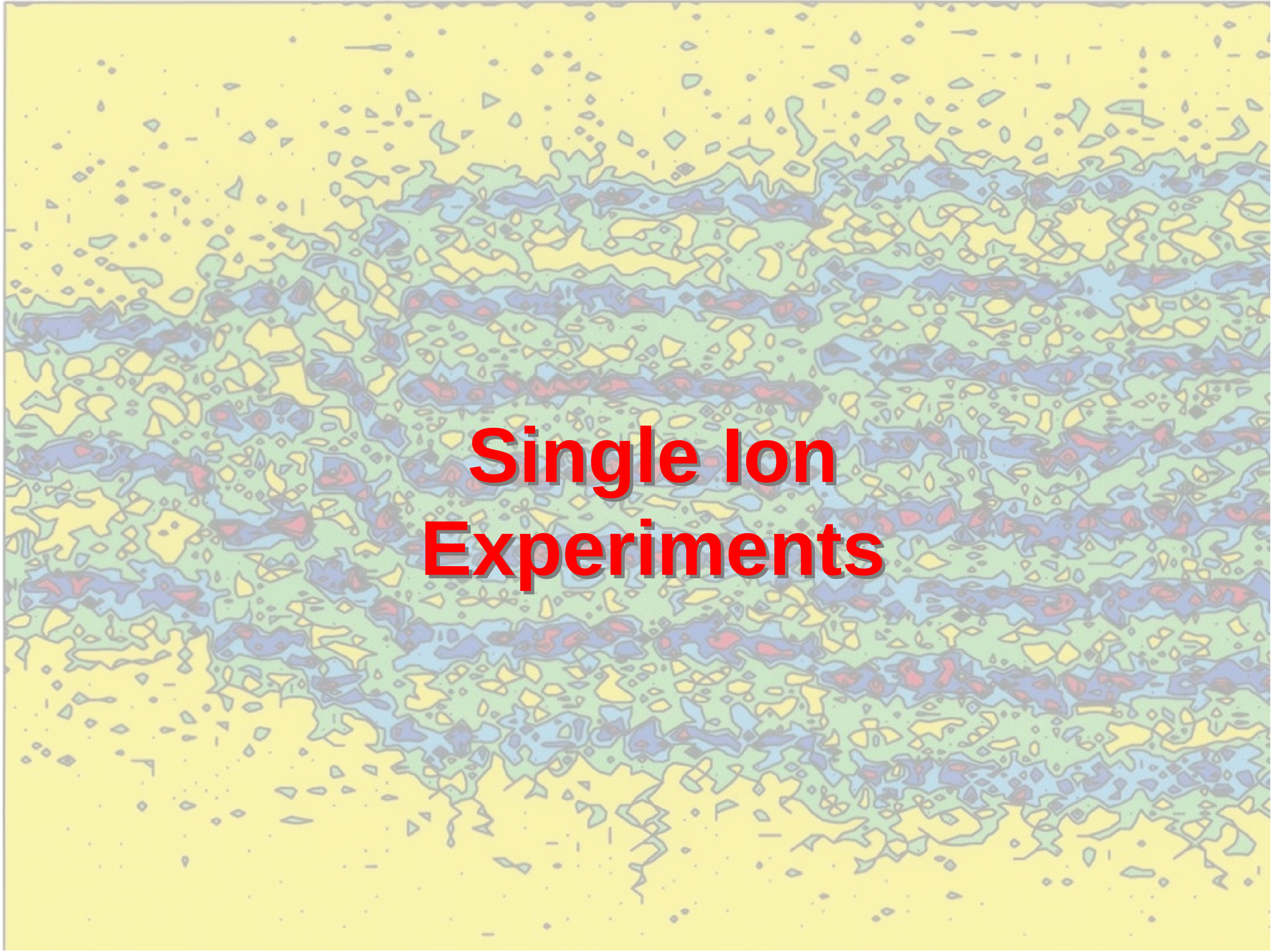
M.O.Scully, H.Walther, G.S.Agarwal, T. Quang, W. Schleich, Phys. Rev. A 44, 5992 (1992)



Θ = 0.64 π
(a)
(b)
T = T_cav
(c)
T = 40 T_cav
+10
Im(α)
0
-10
0
+10
Re(α)



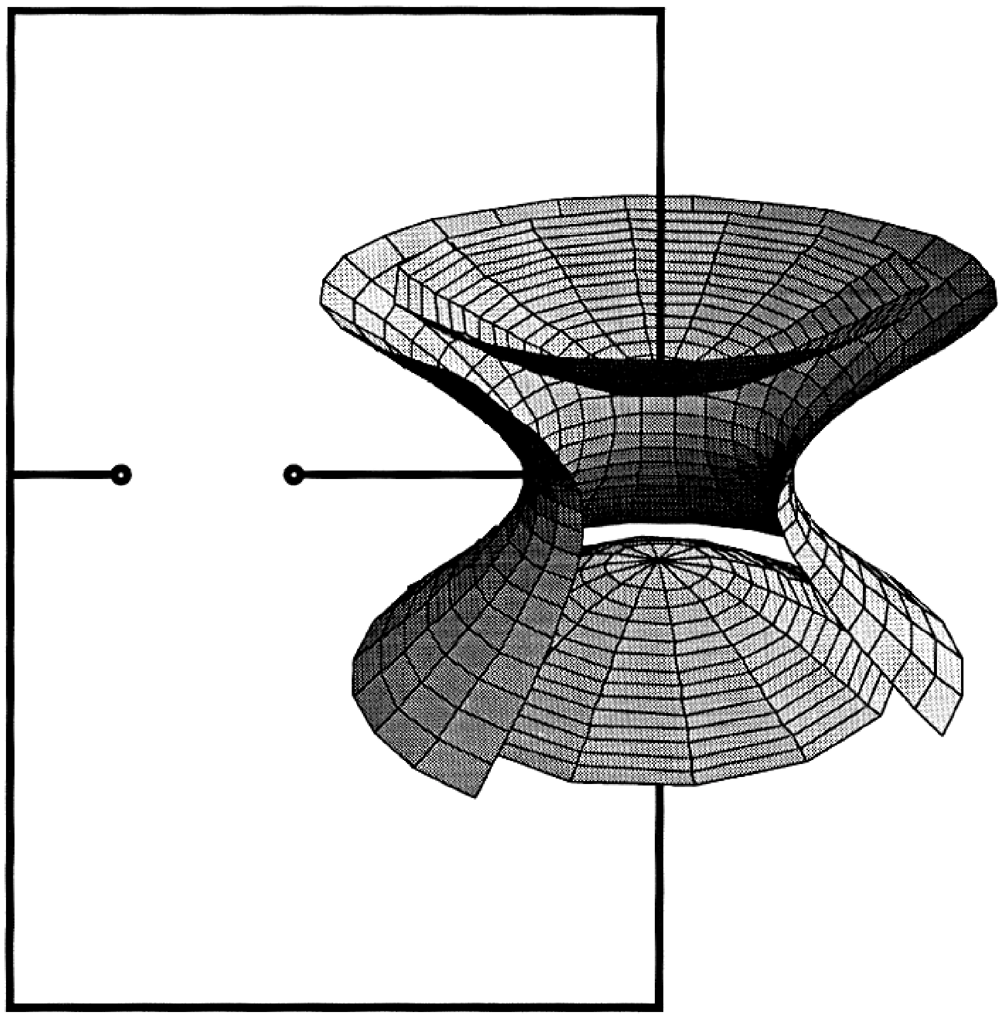
Θ = 3.00 π
(a)
T = T_cav
(b)
+10
Im(α)
0
-10
0
+10
Re(α)
T = 5 T_cav



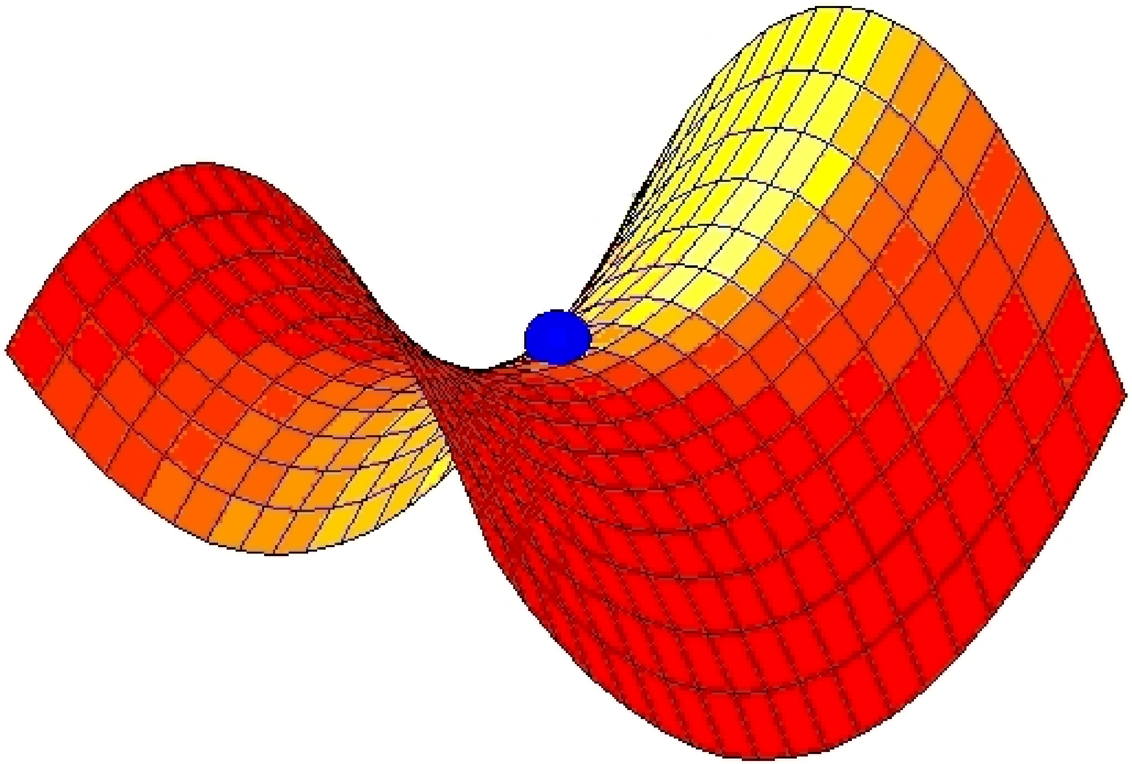
Single Ion Experiments

Wolfgang Paul 1955

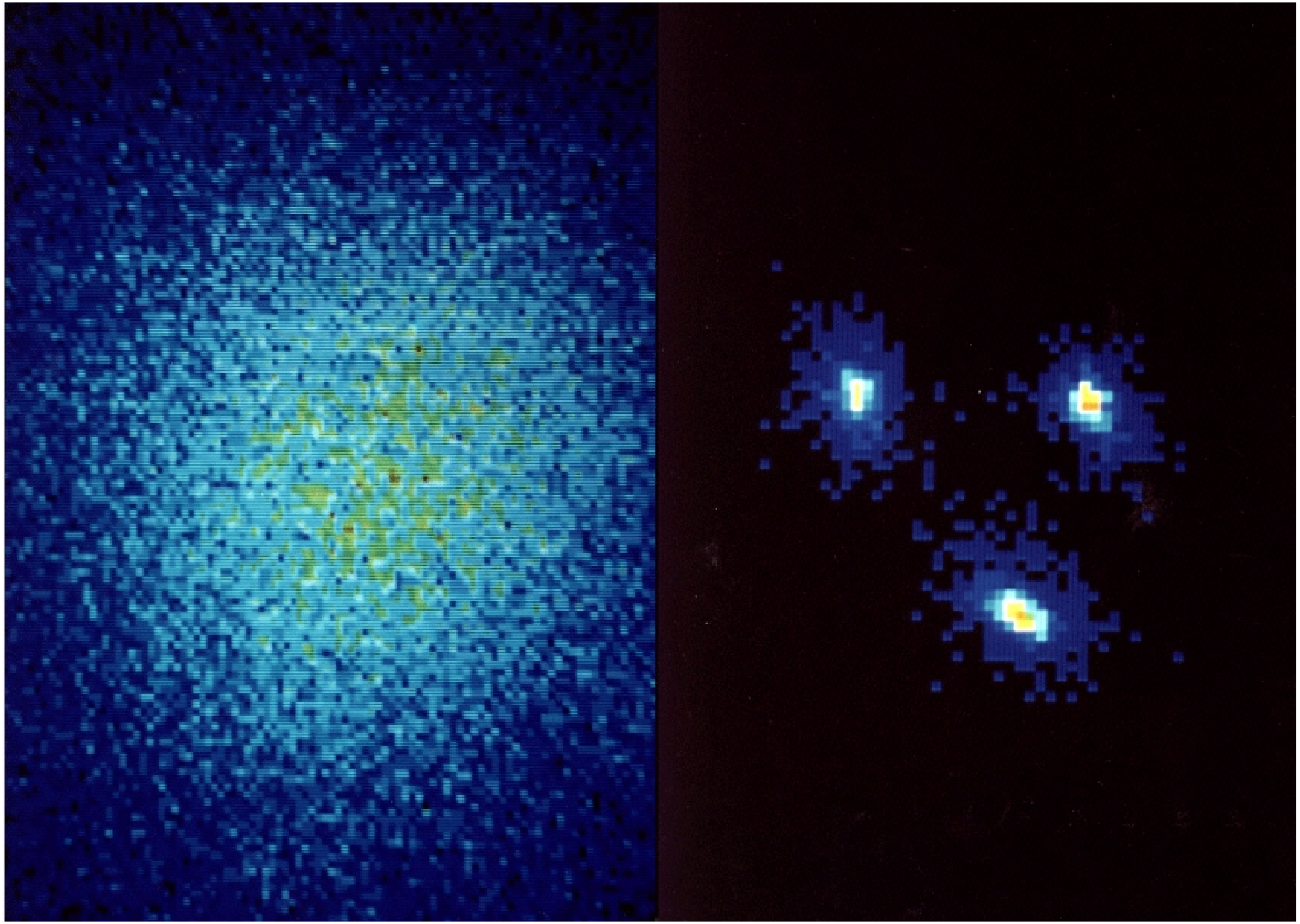
$U_0 + V_0 \cos \omega_{RF}$



Principle of the Paul trap

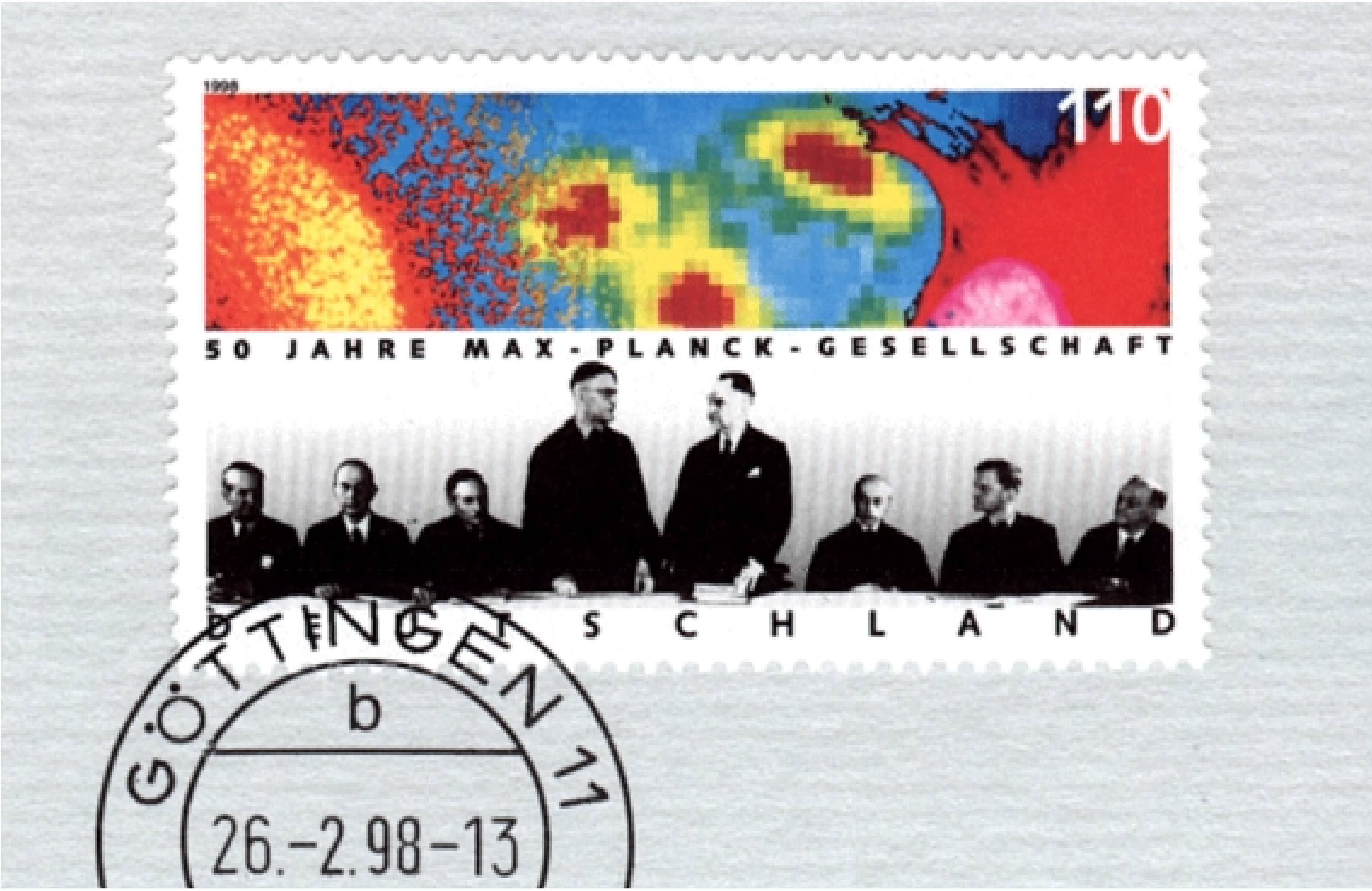


Magnesium Ions in a Paul-Trap

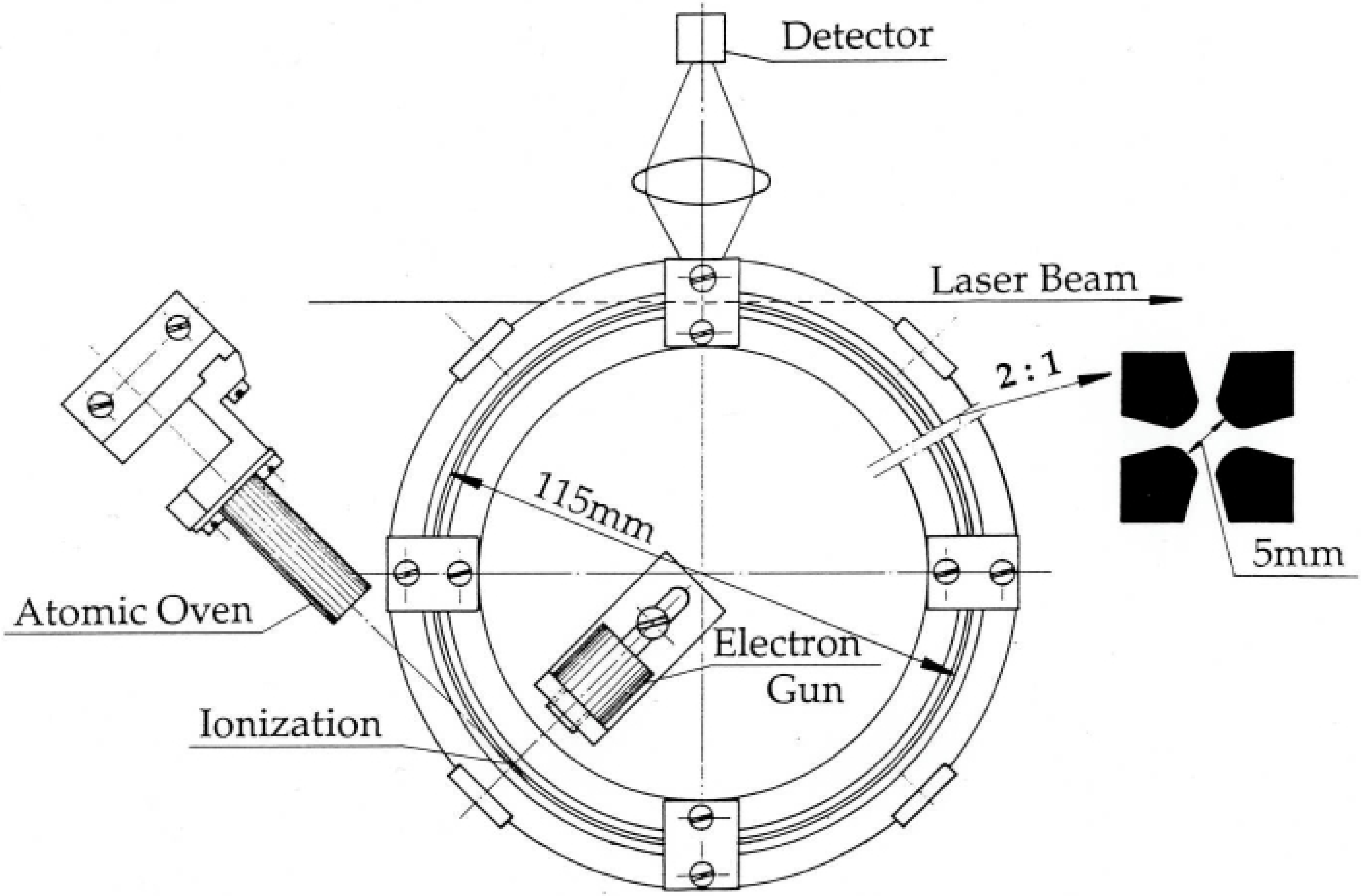



nature
INTERNATIONAL WEEKLY JOURNAL OF SCIENCE
Volume 334 No.6180
PHASE TRANSITIONS OF TRAPPED IONS

Stamp for the 50th Anniversary of the Max-Planck Society

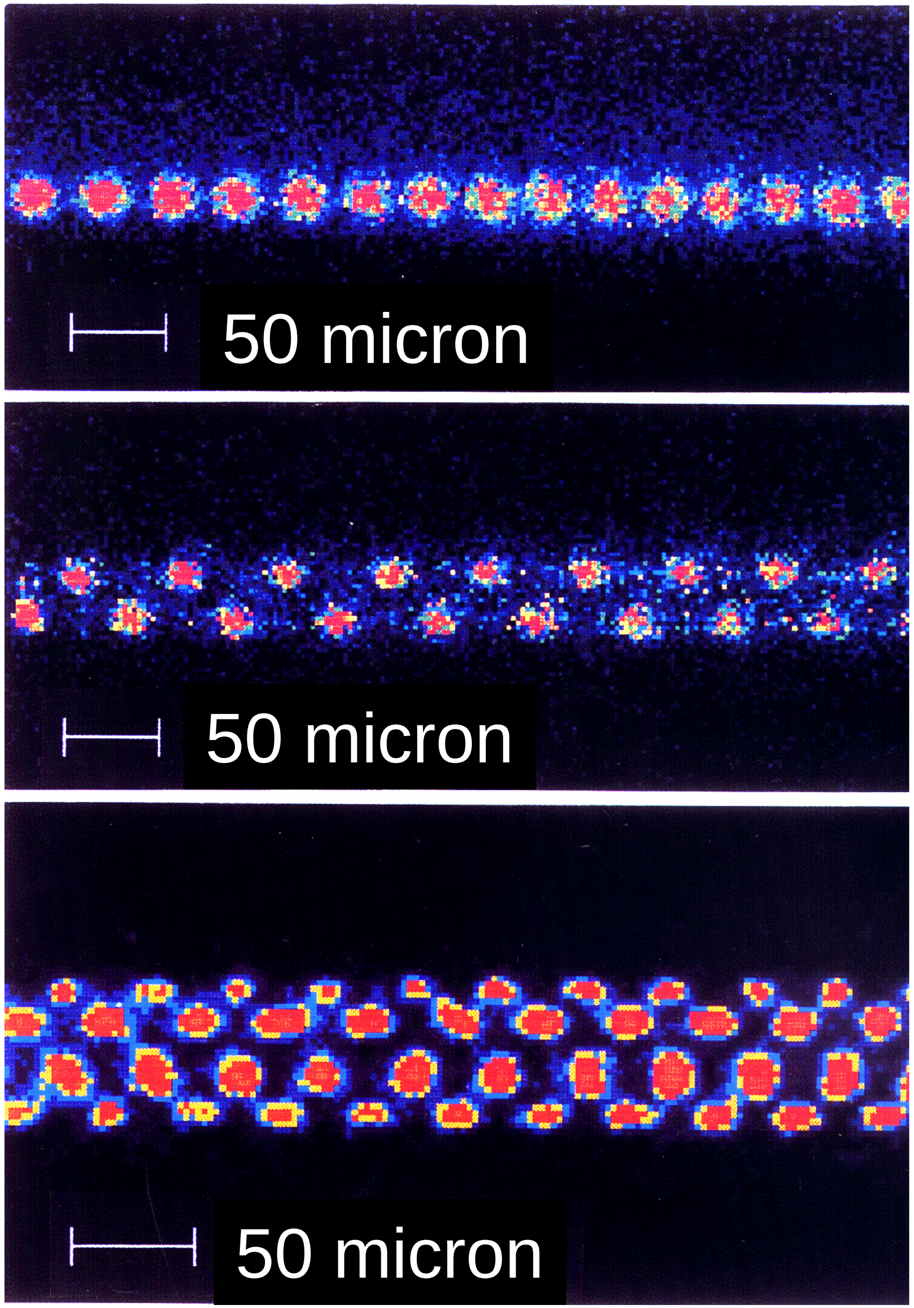


Scheme of the Ring-Trap



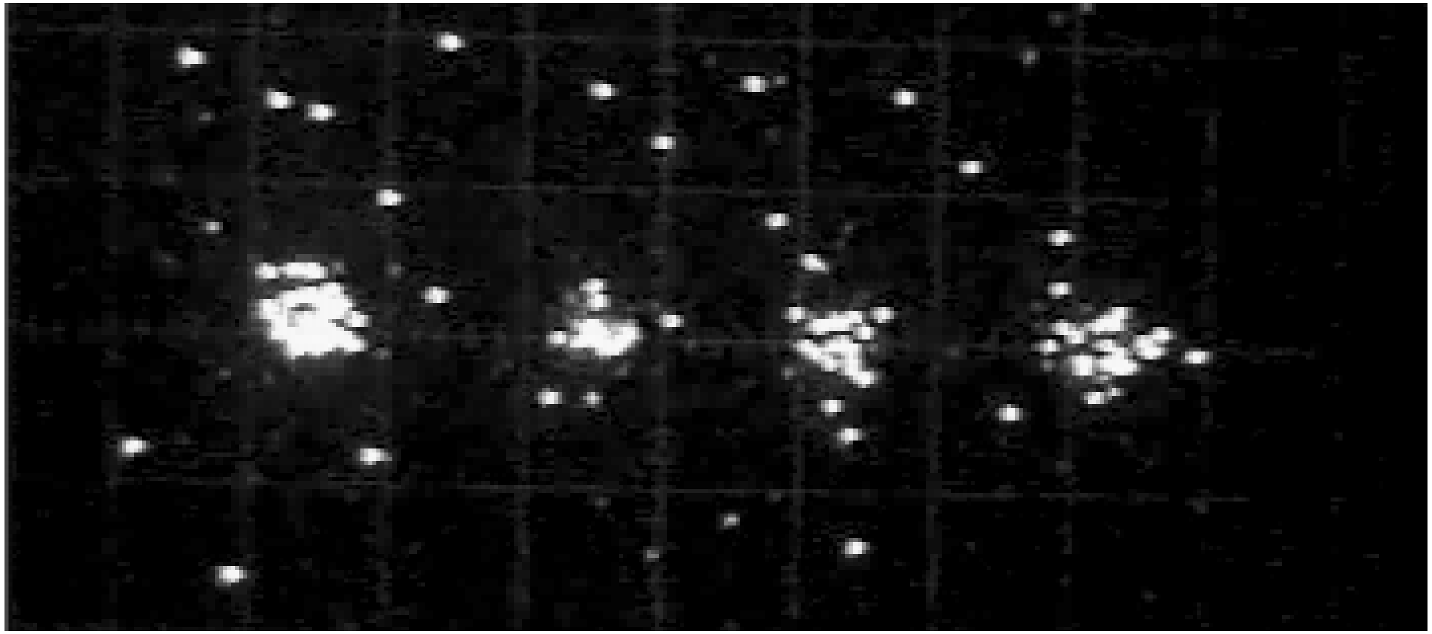
I. Waki, S. Kassner, G. Birkl, H. Walther, Phys. Rev. Lett. 68, 2007-2010 (1992)

Ordered Ion Structures in the Ring-Trap



G. Birkl, S. Kassner, H. Walther, Nature 357, 310 (1992)

Ion Chain



Quantum Computer

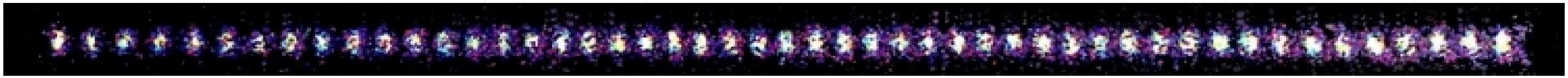
History: Feynman: simulation of quantum systems
Deutsch, Josza, Shor, Grover: considerable speedup
Bennett et al.: quantum cryptography

Classical Bit: A classical bit is represented by a voltage (one or zero)
0, 1

Quantum Bit (Q-Bit): Represented by a quantum object – **two level system** (spin-orientation, polarization, atomic or molecular states)
$|0\rangle, |1\rangle$

Superpositions are possible $|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$

→ **N classical bits represent one out of 2^N values**
N quantum bits can represent 2^N values simultaneously



Chain of 50 ions (1,125,899,906,842,624 numbers may be simultaneously processed.

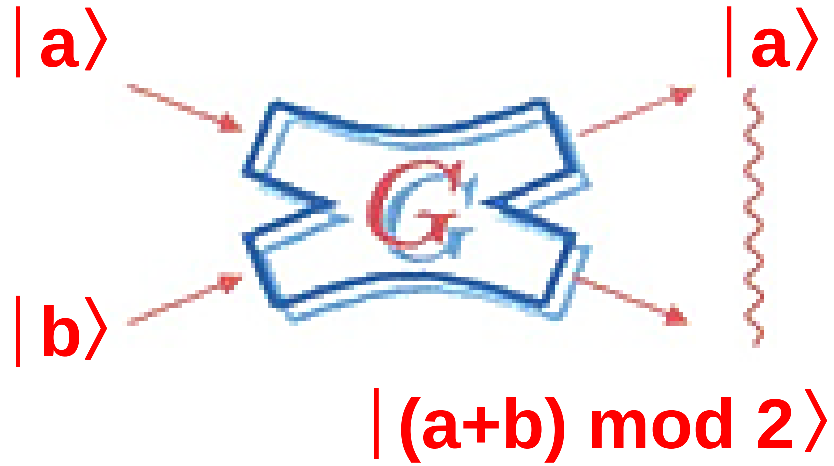
Quantum Logic

In order to produce logic operations strong interaction between parameters representing information is necessary.
Gates described by unitary transformations.

Controlled NOT is basic gate

b = target bit
a = control bit
a = zero: b is not changed
a = one: b is negated

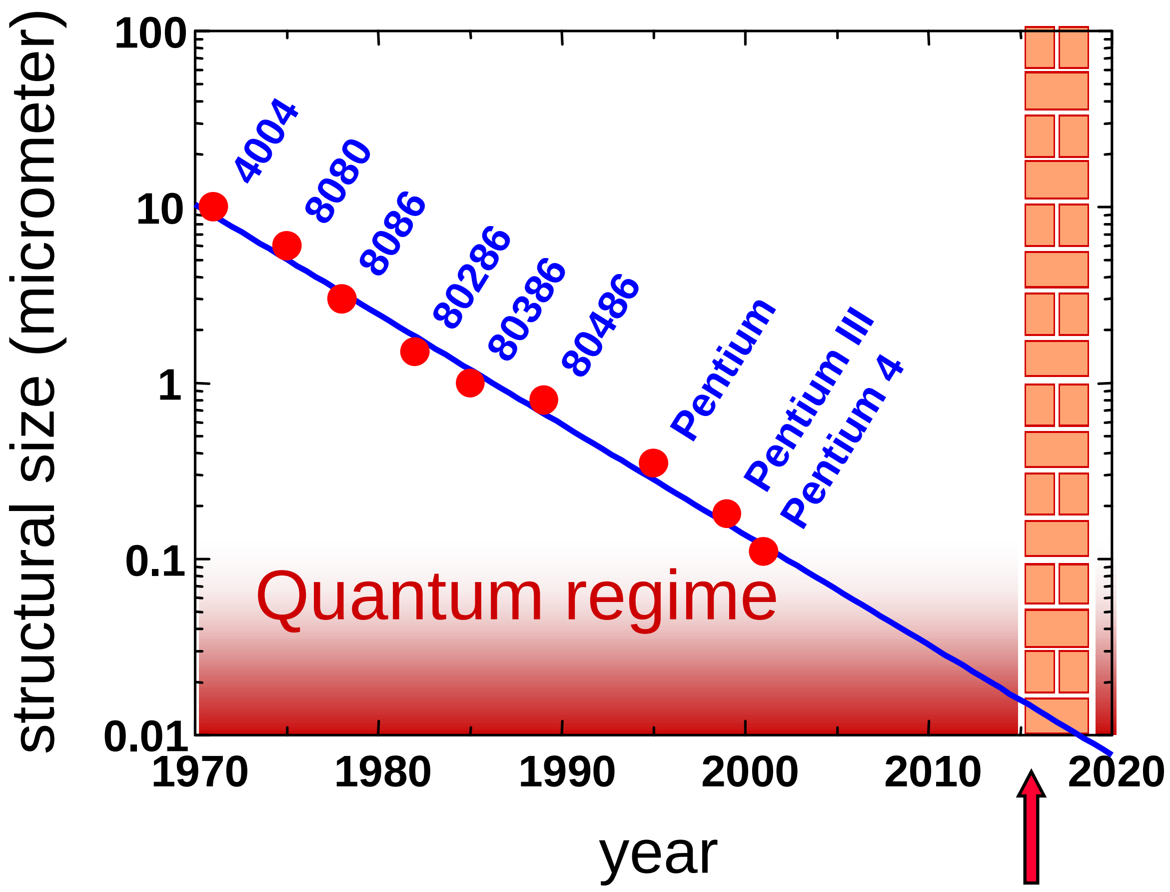
Controlled NOT



Controlled NOT operation changes a superposition into an entangled state

$$(|0\rangle + |1\rangle) \otimes |1\rangle \Rightarrow |0\rangle|1\rangle + |1\rangle|0\rangle$$

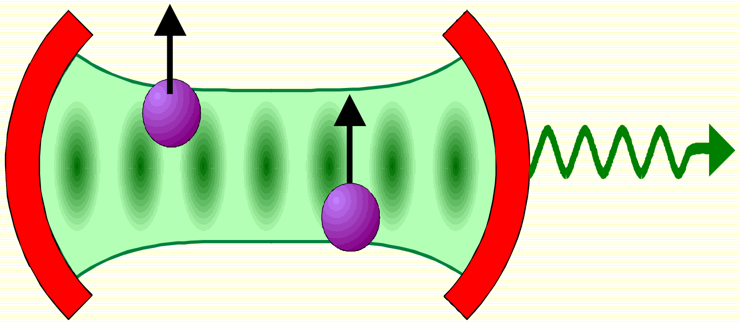
Development of Microelectronics - Moore´s Law



Single-ion Cavity Quantum Electrodynamics

Single-Ion Cavity QED

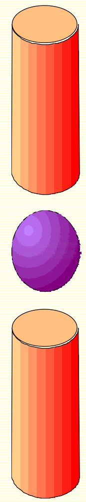
Single mode cavity QED



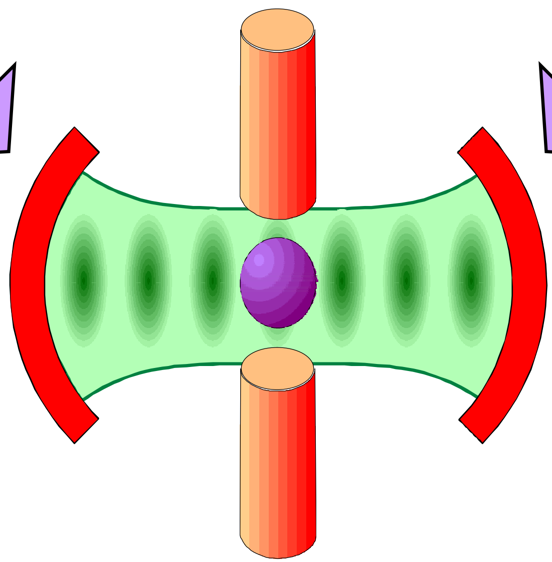
strong atom-field coupling

Single ion trapping

- **sub-wavelength position control**
- **unlimited observation time**



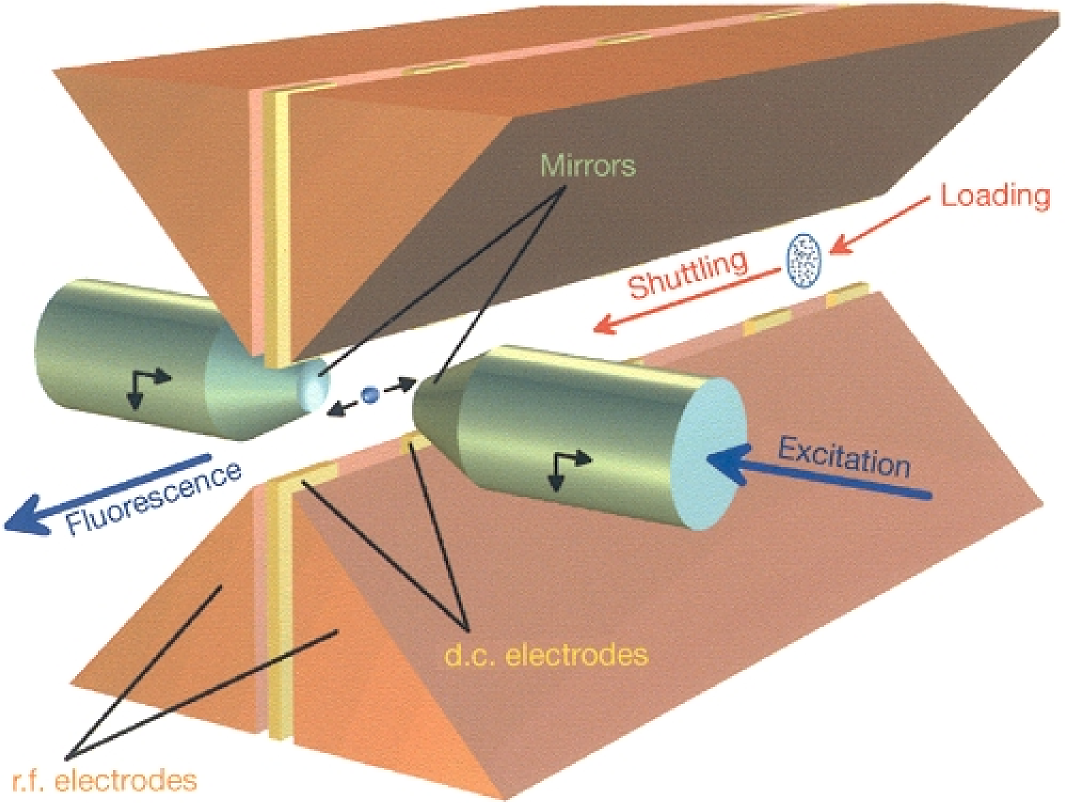
Combine the technologies:



- **deterministic ion-field interaction**
- **single-photon gun**
- **single-ion laser**

Setup: ion trap and optical cavity

How to place the ion between the mirrors?



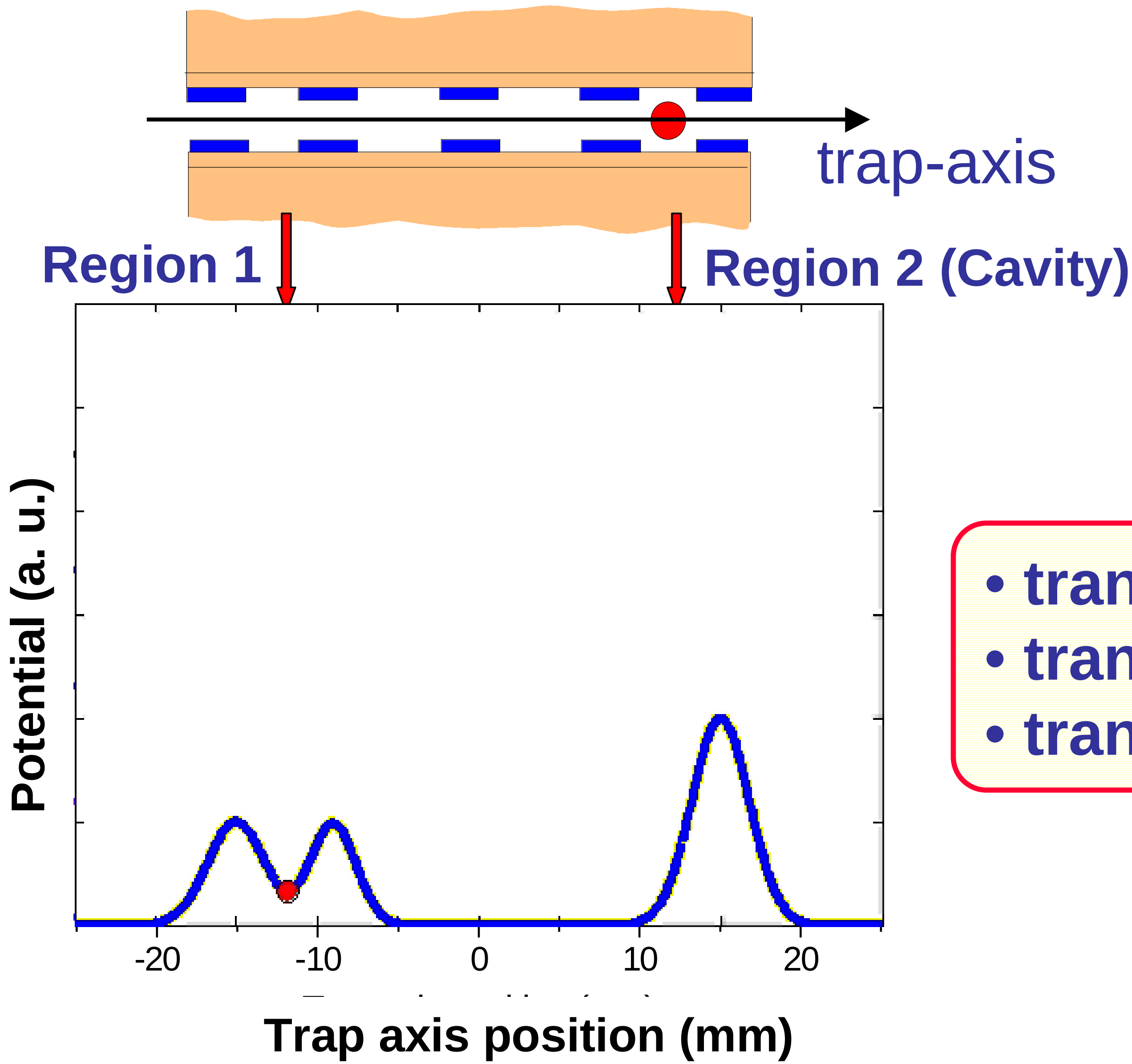
Nature 414,49 (2001)

Trap design:

- **Linear RF trap with open electrode configuration**
- **separate loading region**
- **Ion transfer by DC fields**

→ **no coating or charging of the dielectric mirrors even at small cavity length**

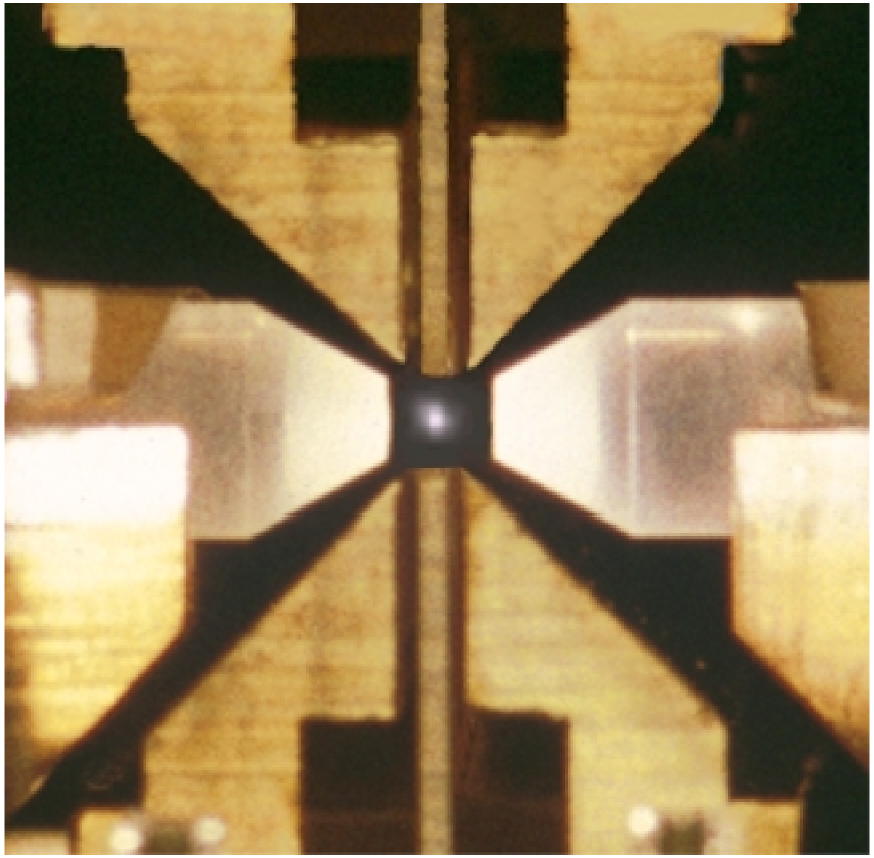
Ion Transfer from Loading Region to Cavity



axial ion position controlled by 5 DC-electrodes

- **transfer distance: 25 mm**
- **transfer time: 4 ms**
- **transfer efficiency: 50 %**

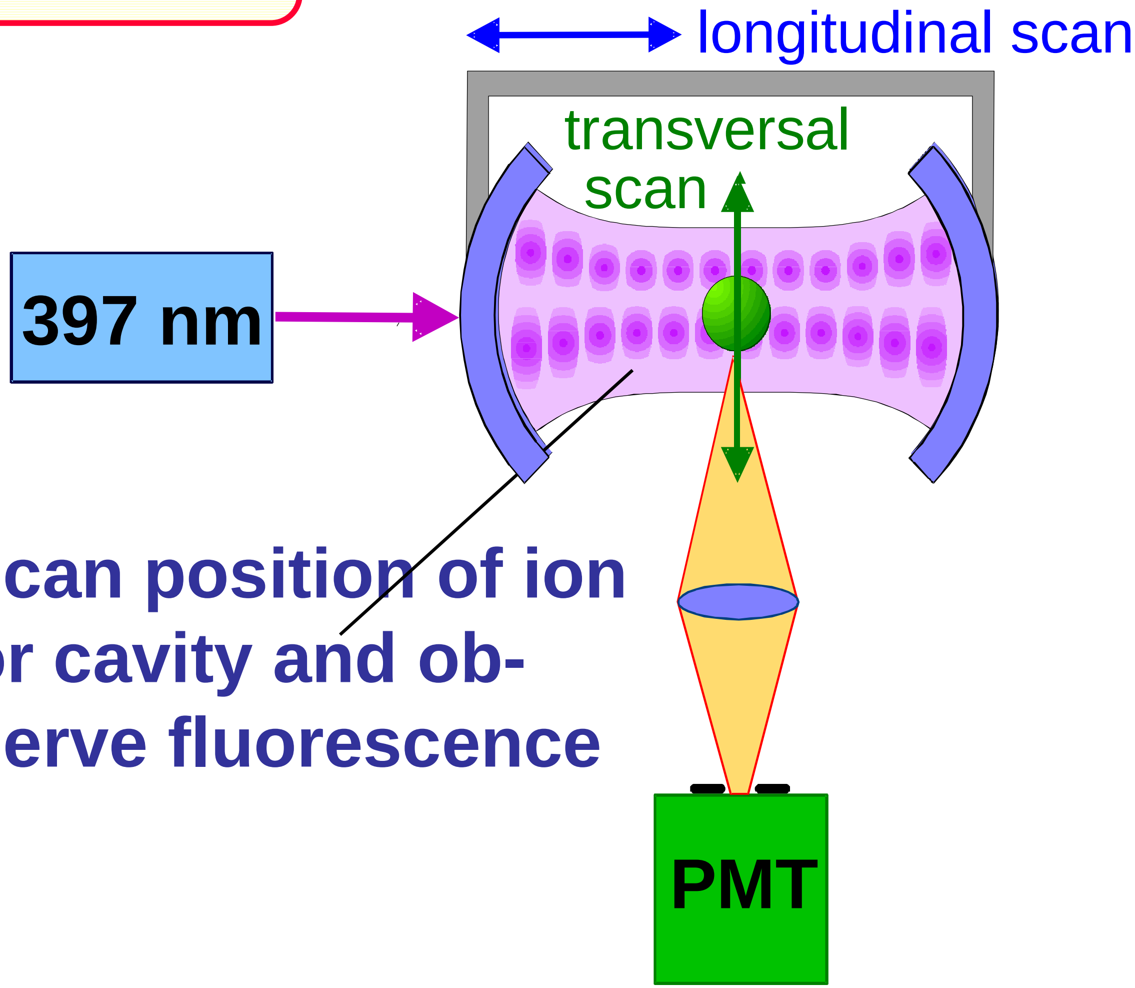
A Single Ion in a Cavity



Single-Ion Mode Mapping (SIMM)

single $^{40}Ca^{+}$ ion as a nanometric probe of the electromagnetic field:

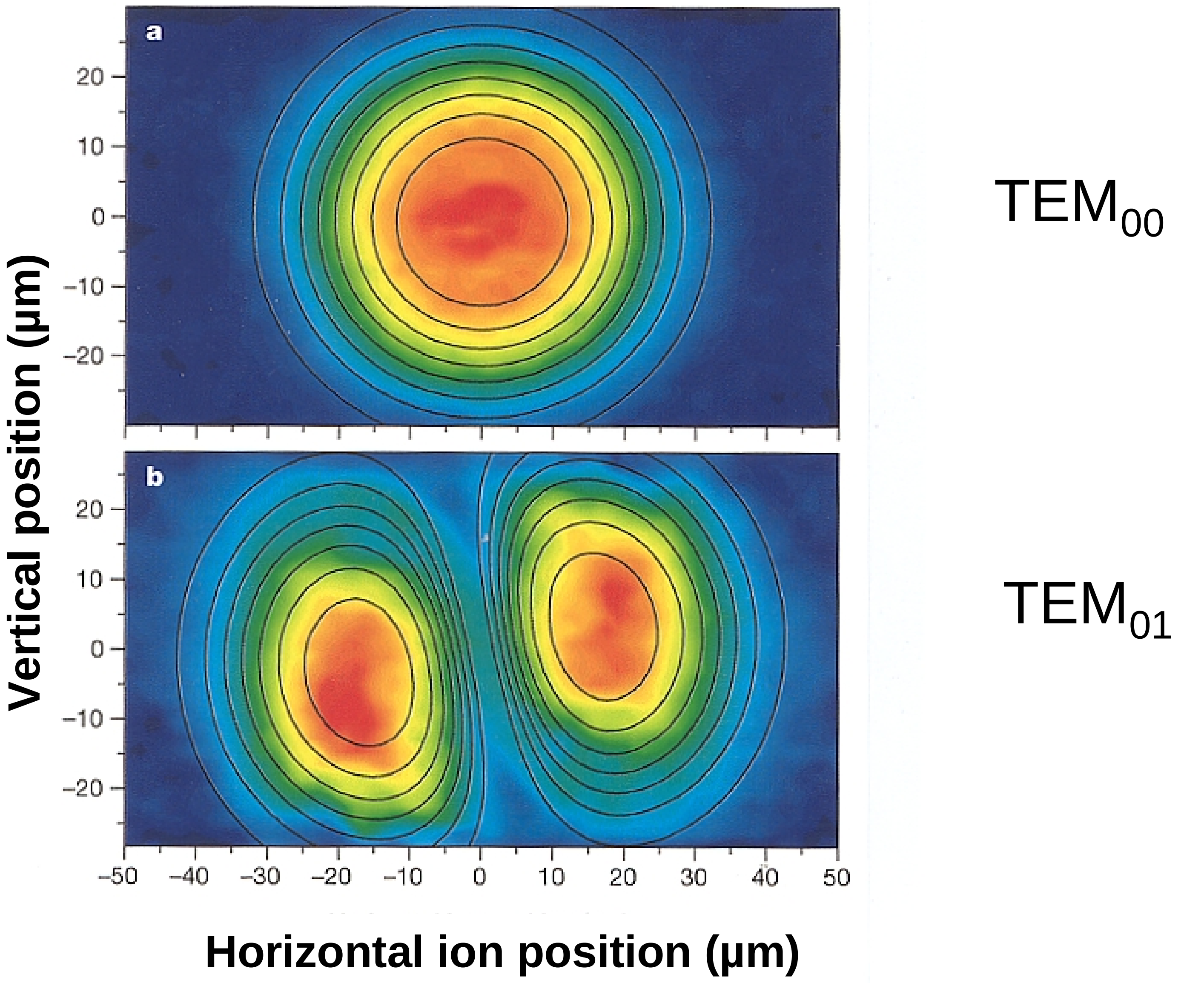
Test of the deterministic interaction of ion and cavity field



scan position of ion or cavity and observe fluorescence

- **resolution down to 10 nm**
- **first step towards single-ion cavity QED**

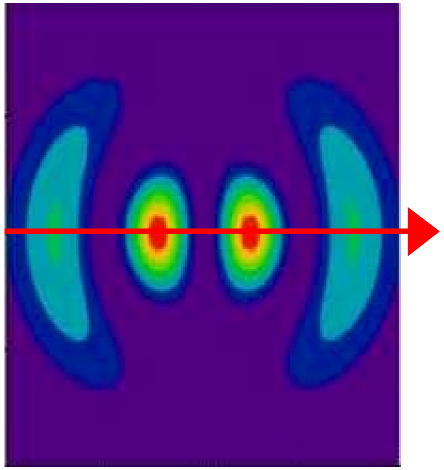
Two-Dimensional Images of the Cavity Field

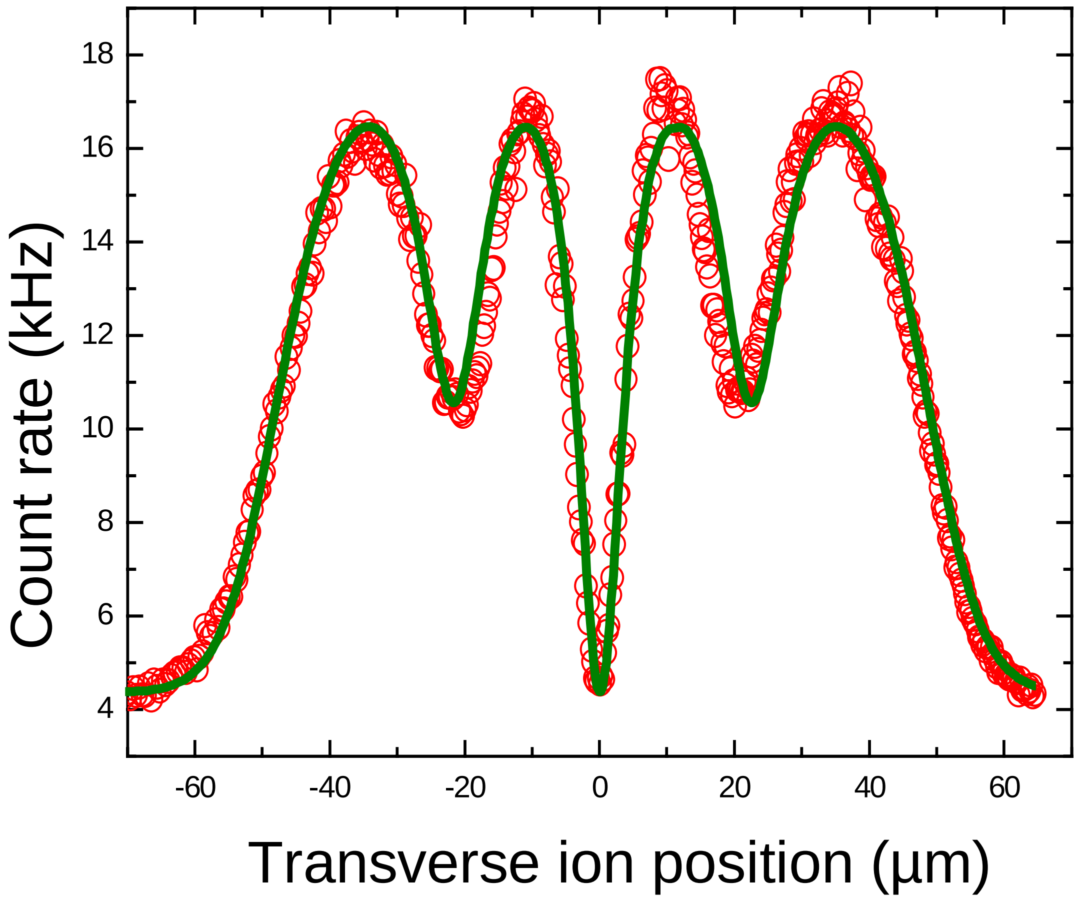


Higher-Order Gauss-Laguerre Modes

Example:

TEM_{11} Mode





Fit to fluorescence intensity includes:

- Saturation (up to 60 I_s inside cavity)
- Residual ion motion (thermal)

Longitudinal Cavity-Mode Mapping

Translation of the cavity along its axis:

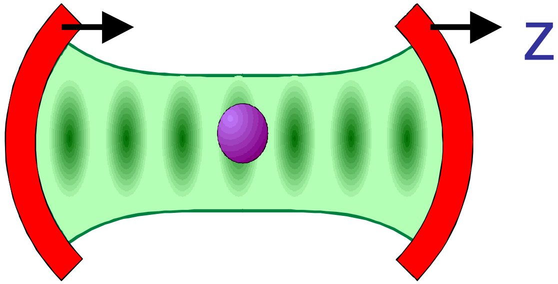
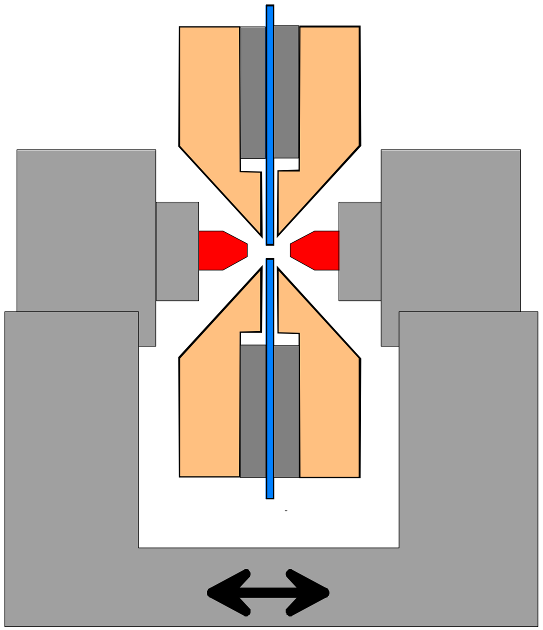
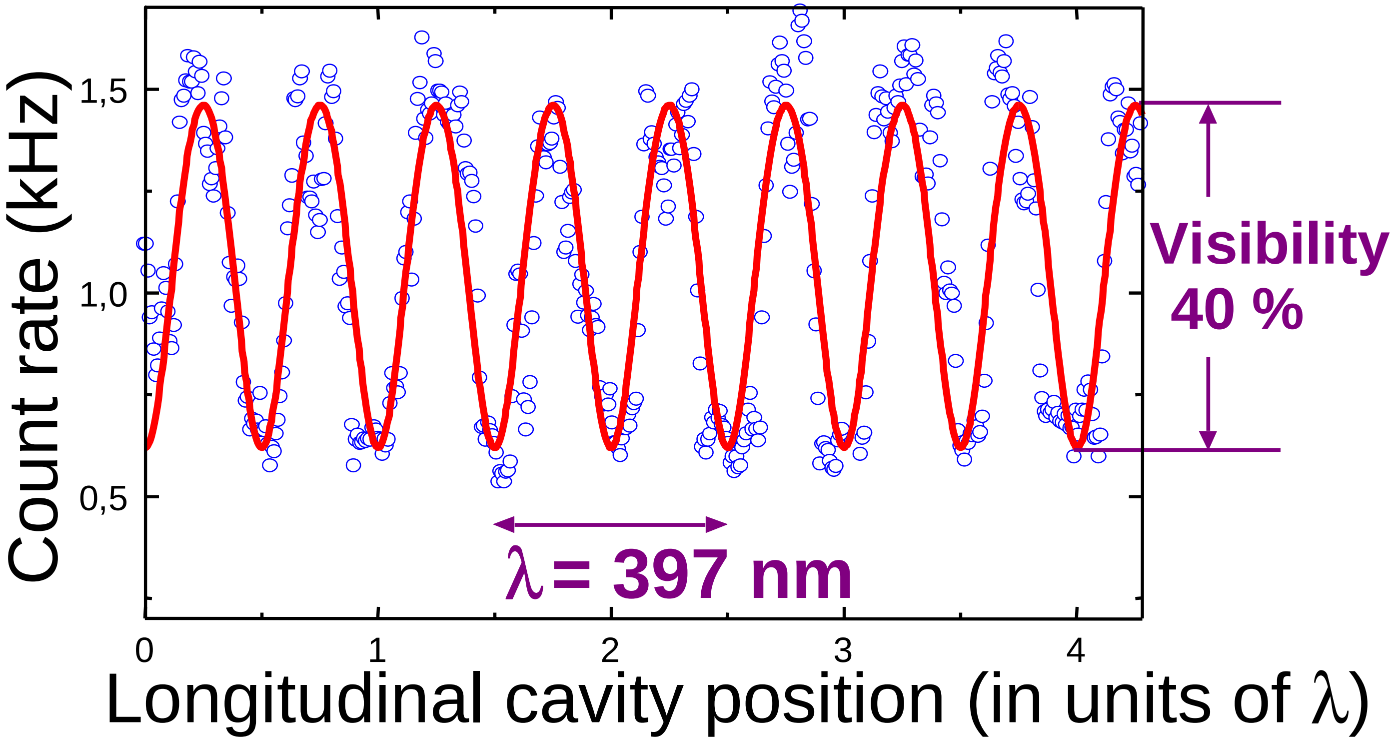


image of the standing wave structure

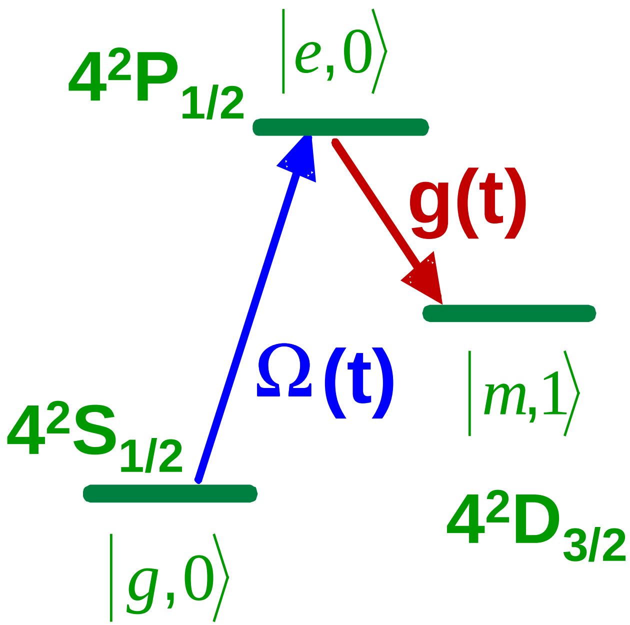




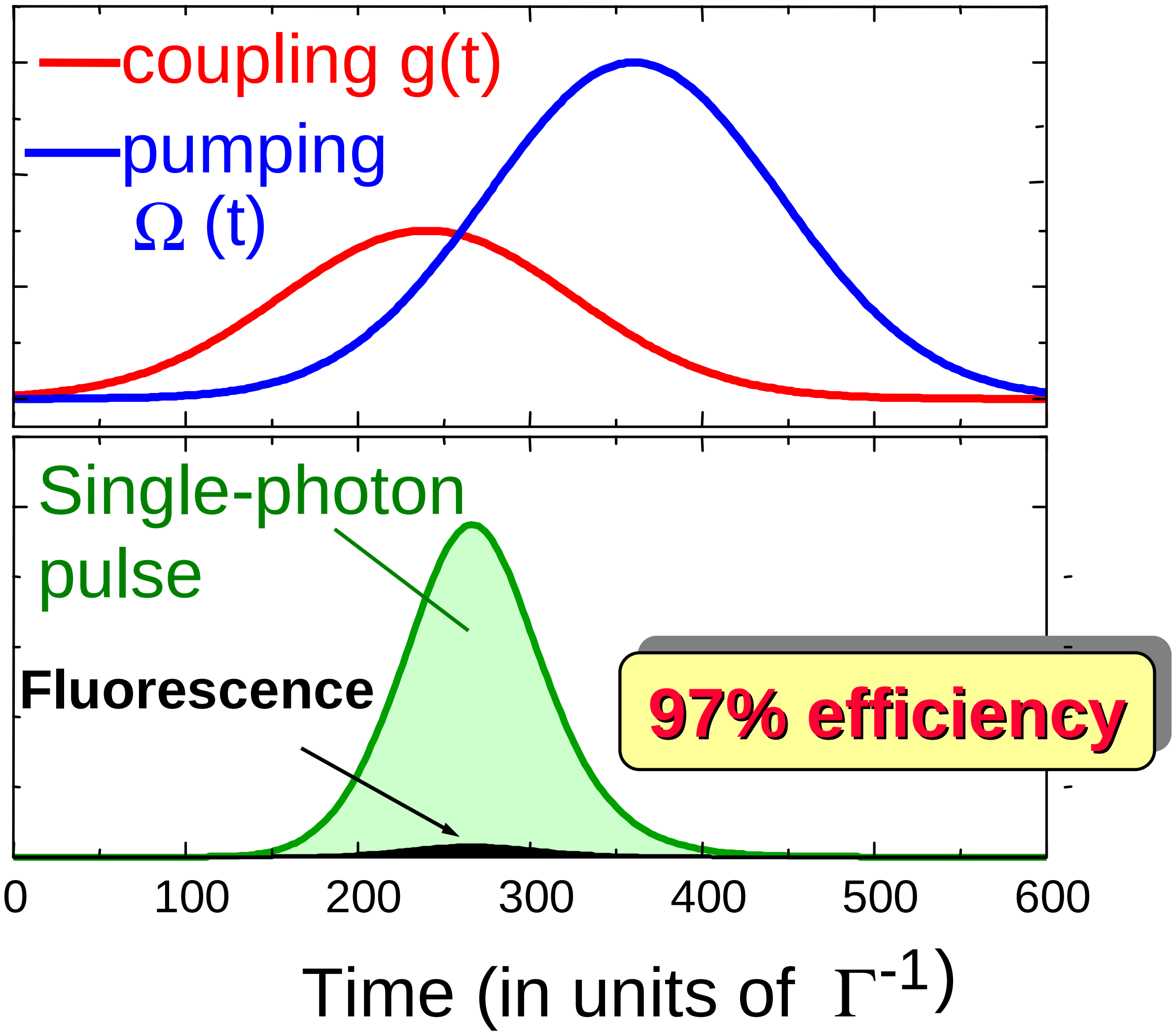
Resolution determined by wavefunction or residual motion of ion

Deterministic Single Photon Gun

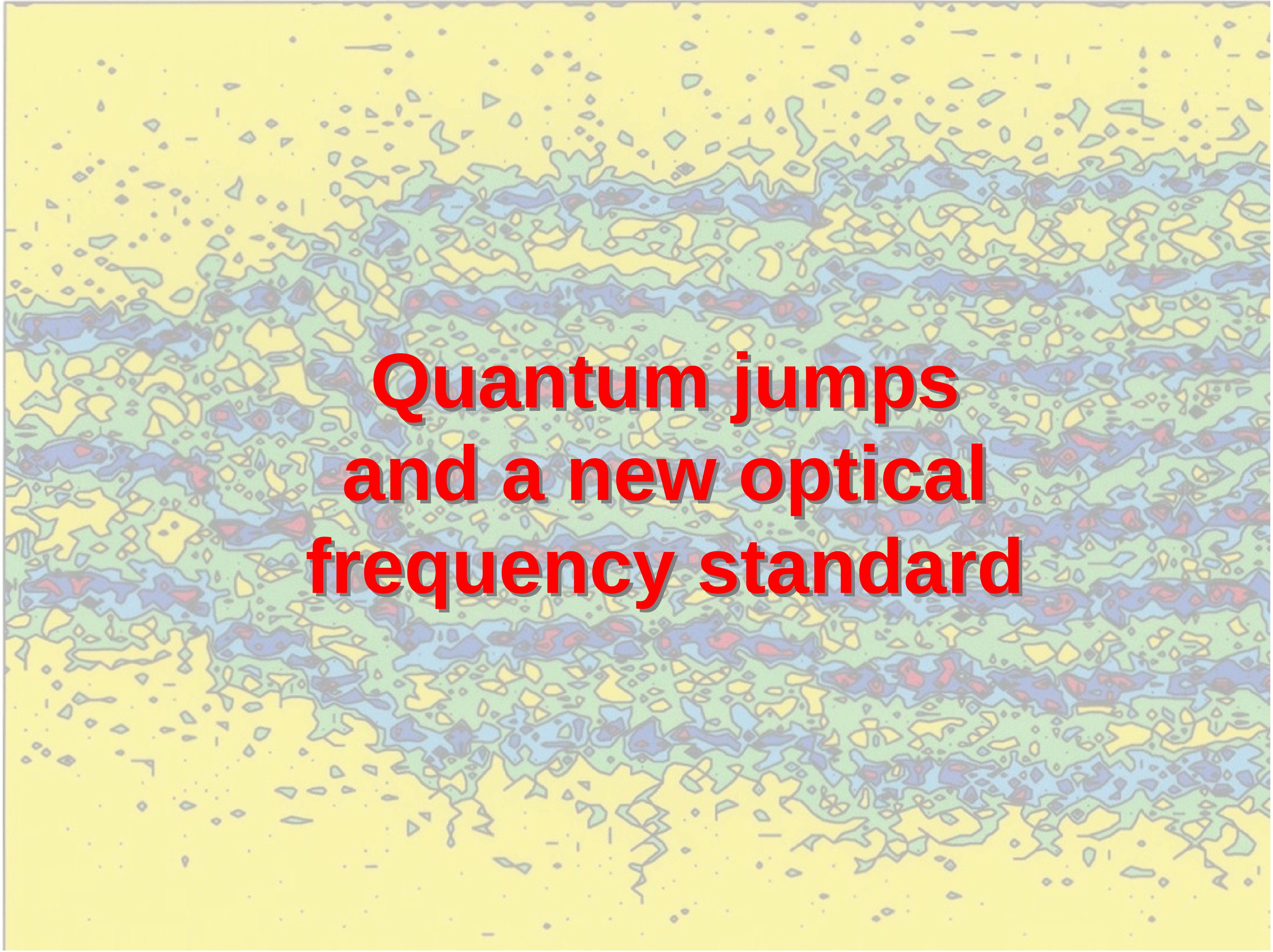
Method: adiabatic passage



Fourier-limited single photon pulse

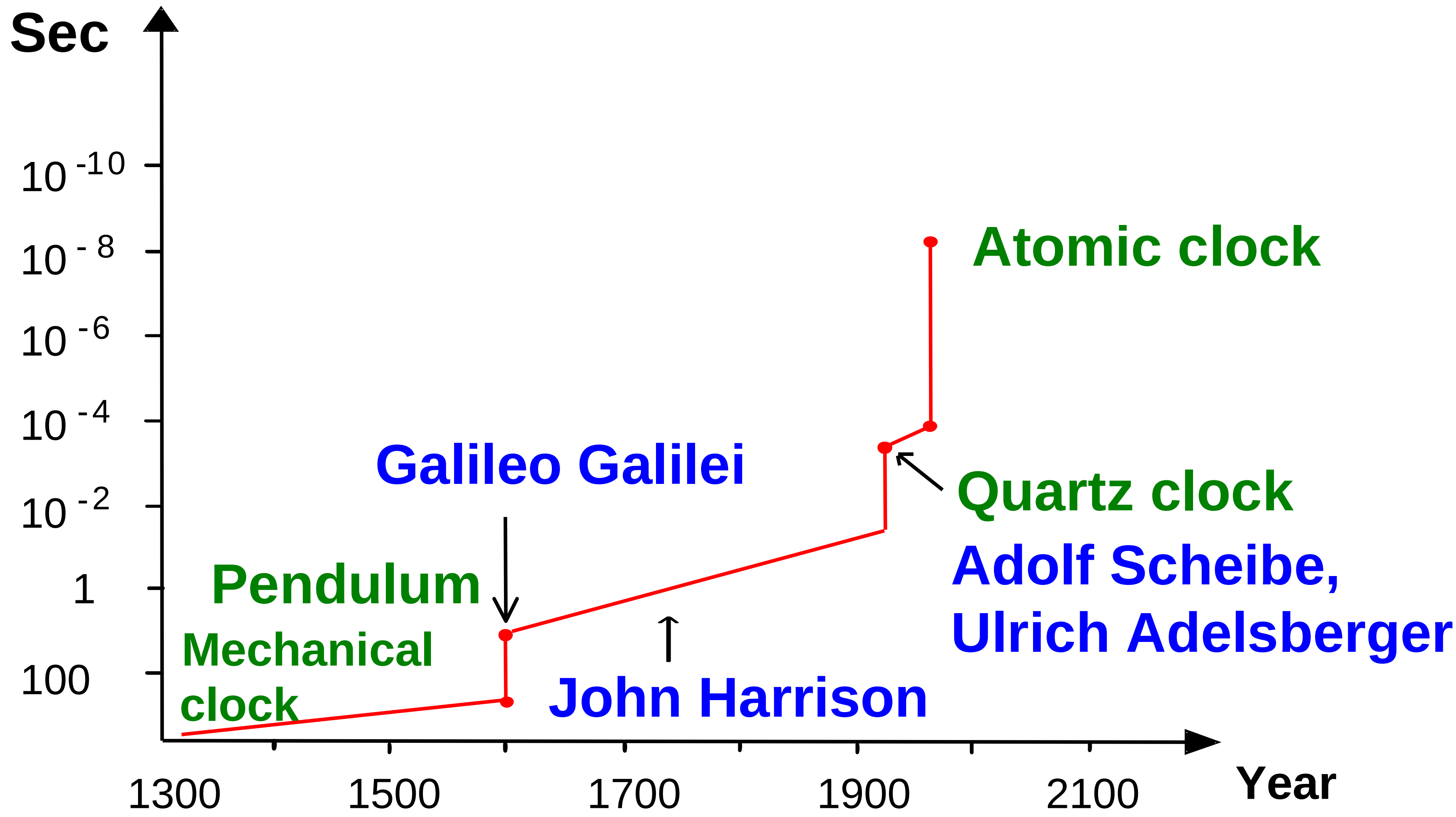


Quantum jumps and a new optical frequency standard



Accuracy of Time Measurement

Deviation per day



Accuracy of Present Day Clocks

		Accuracy
Mechanical clock	~1s/month	$3.8 \cdot 10^{-7}$
Quartz-clock	1s/30 years	$1 \cdot 10^{-9}$
Atomic-clock Cs-clock PTB Braunschweig	$1s/10^{6}$ years	$3 \cdot 10^{-14}$

Application of Atomic Clocks

Global positioning system

Integrated services digital network (ISDN)
(coding in multiplex operation)

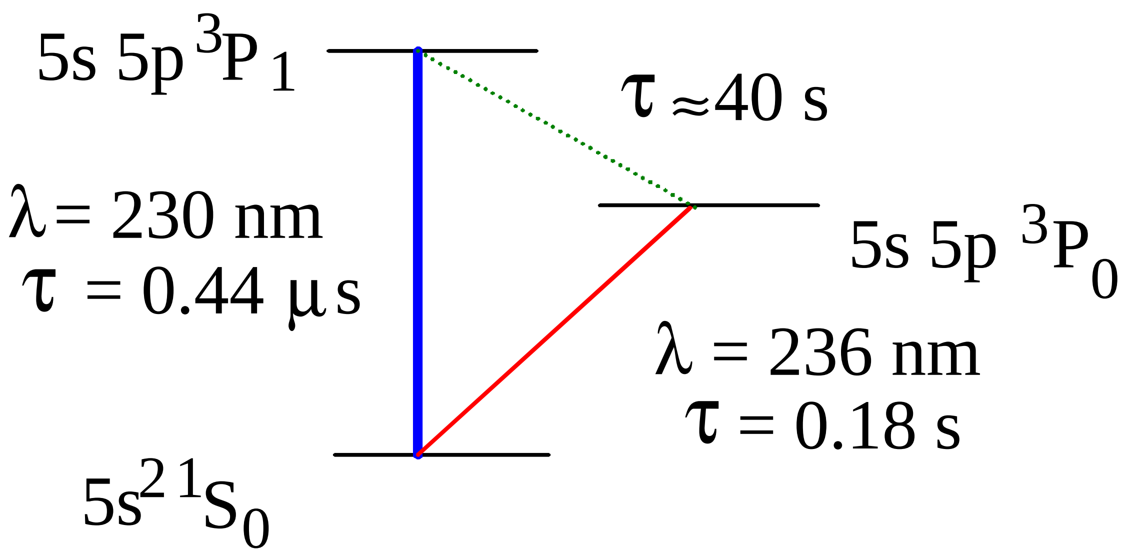
Long-baseline-interferometry in radio-astronomy

Precise measurement of fundamental constants and of phenomena of basic importance

- Test of a possible time variability of fundamental constants

In^+ Spectroscopy and Frequency Standard

Energy Levels of the In^+ - Ion



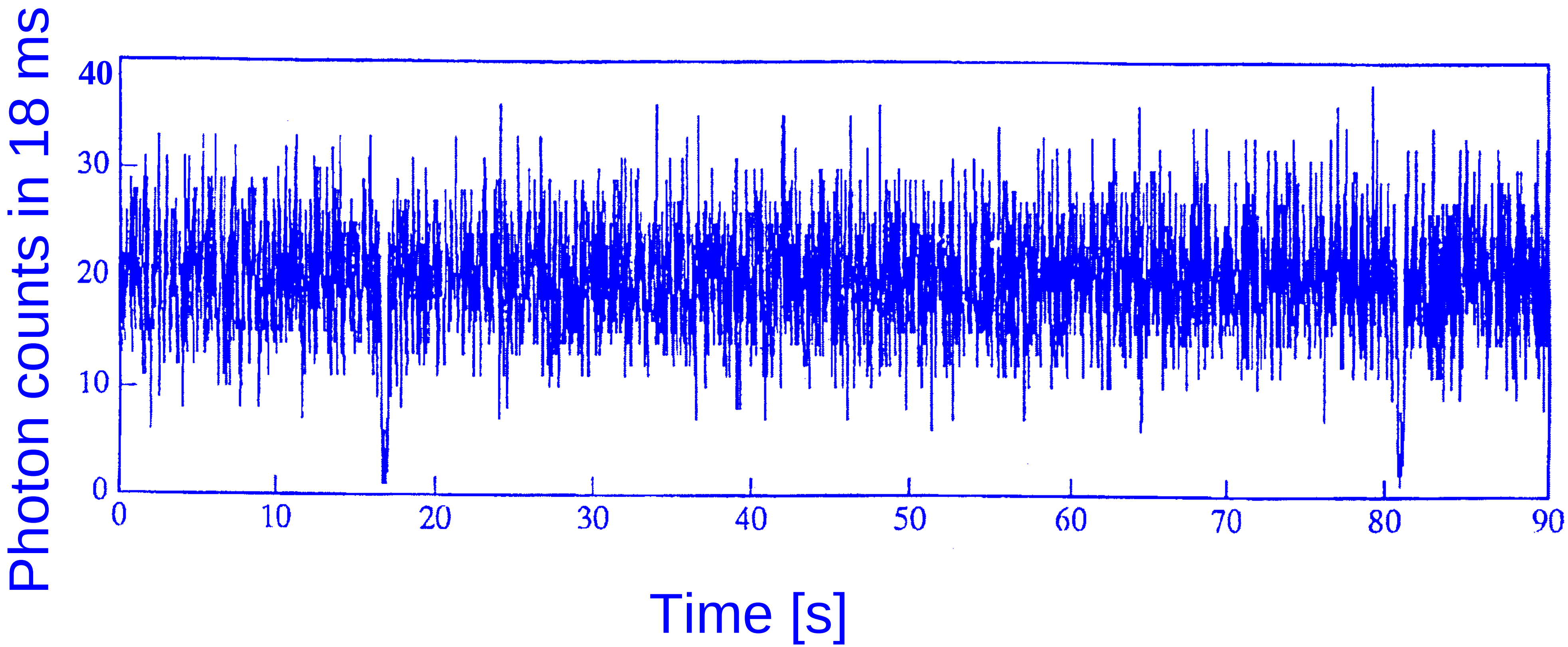
Perturbing effects

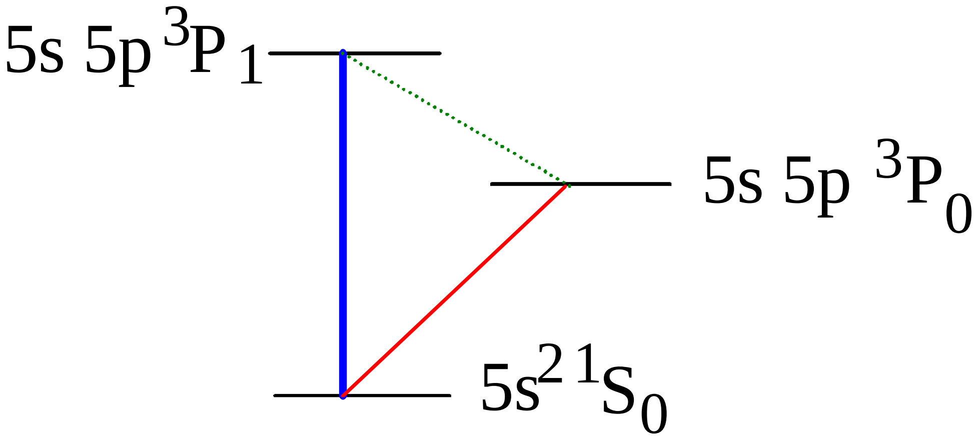
- **Zeeman splitting $2 \cdot 10^{-17}$**
- **Second order Doppler effect $\approx 10^{-18}$**
- **Quadratic Stark effect $\approx 10^{-19}$**
- **Residual gas collisions $\approx 10^{-17}$**

Other ions: Yb^+
Hg^+

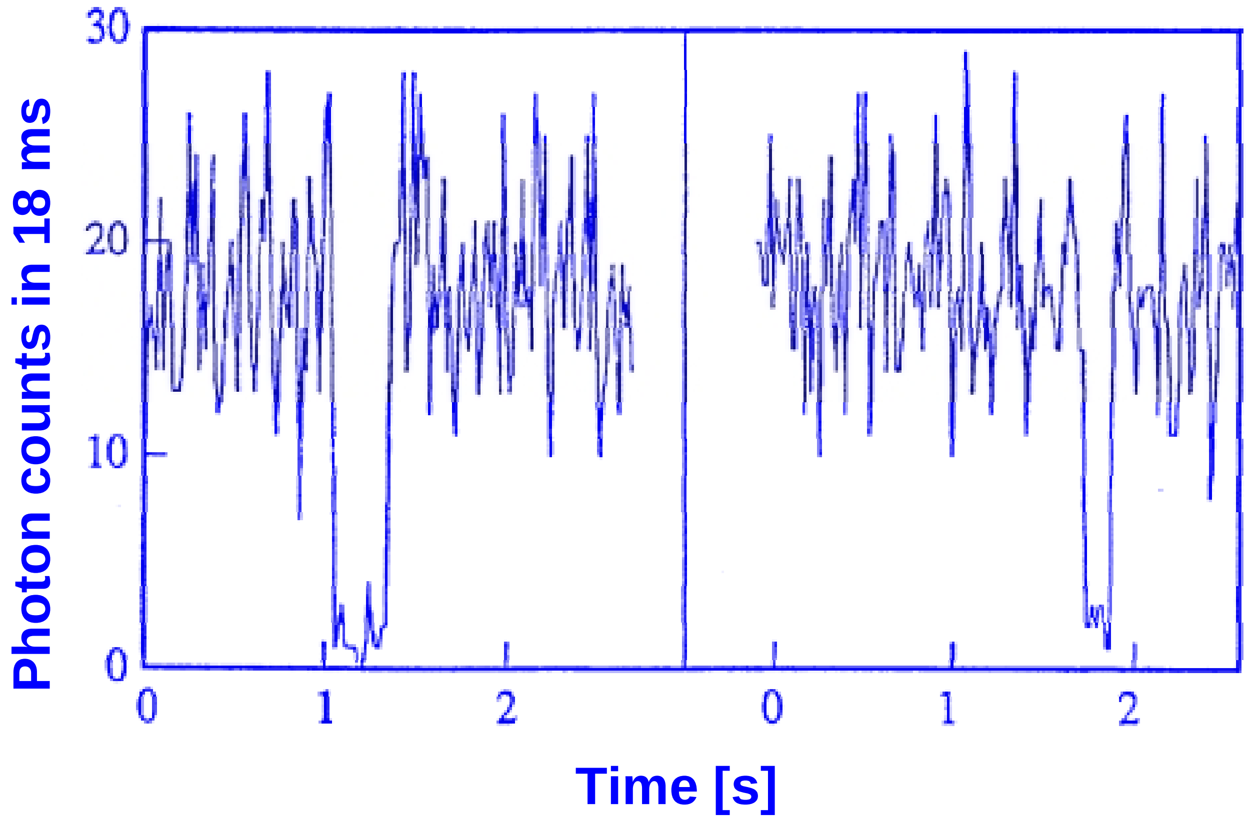
NIST, NPL, PTB

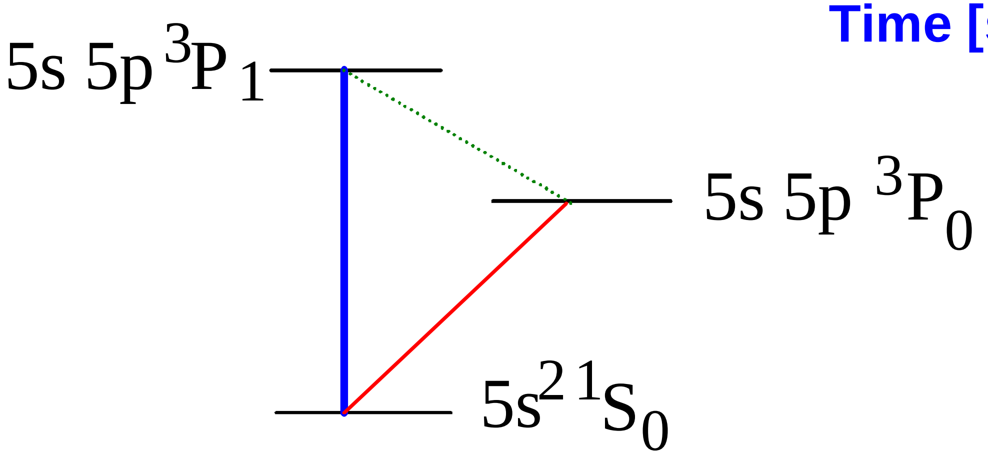
Quantum Jumps of the In^+ Ion





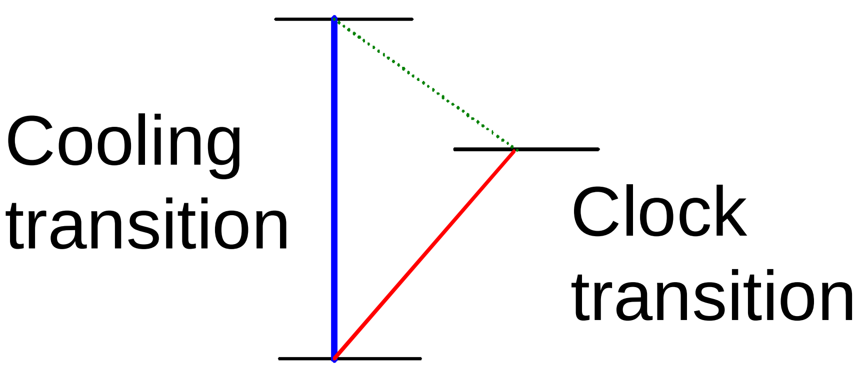
Quantum Jumps of the In^+ Ion

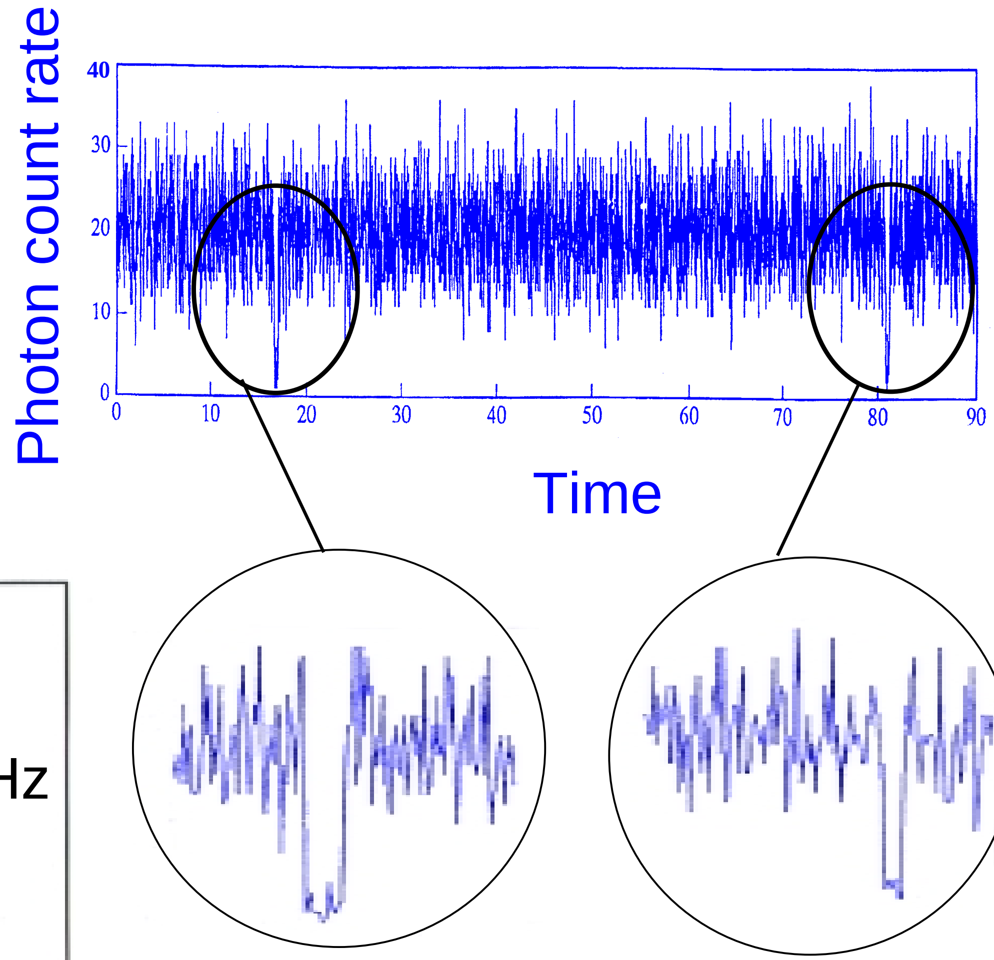


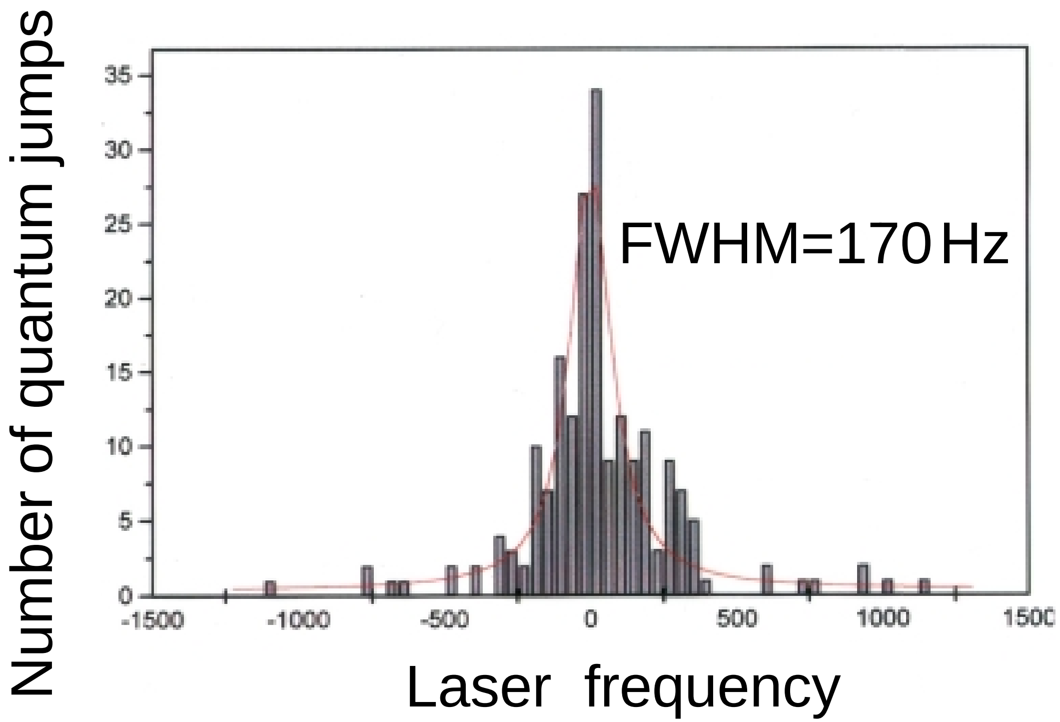


Quantum Jumps and Atomic Clock

Energy levels of In^{+}







Summary

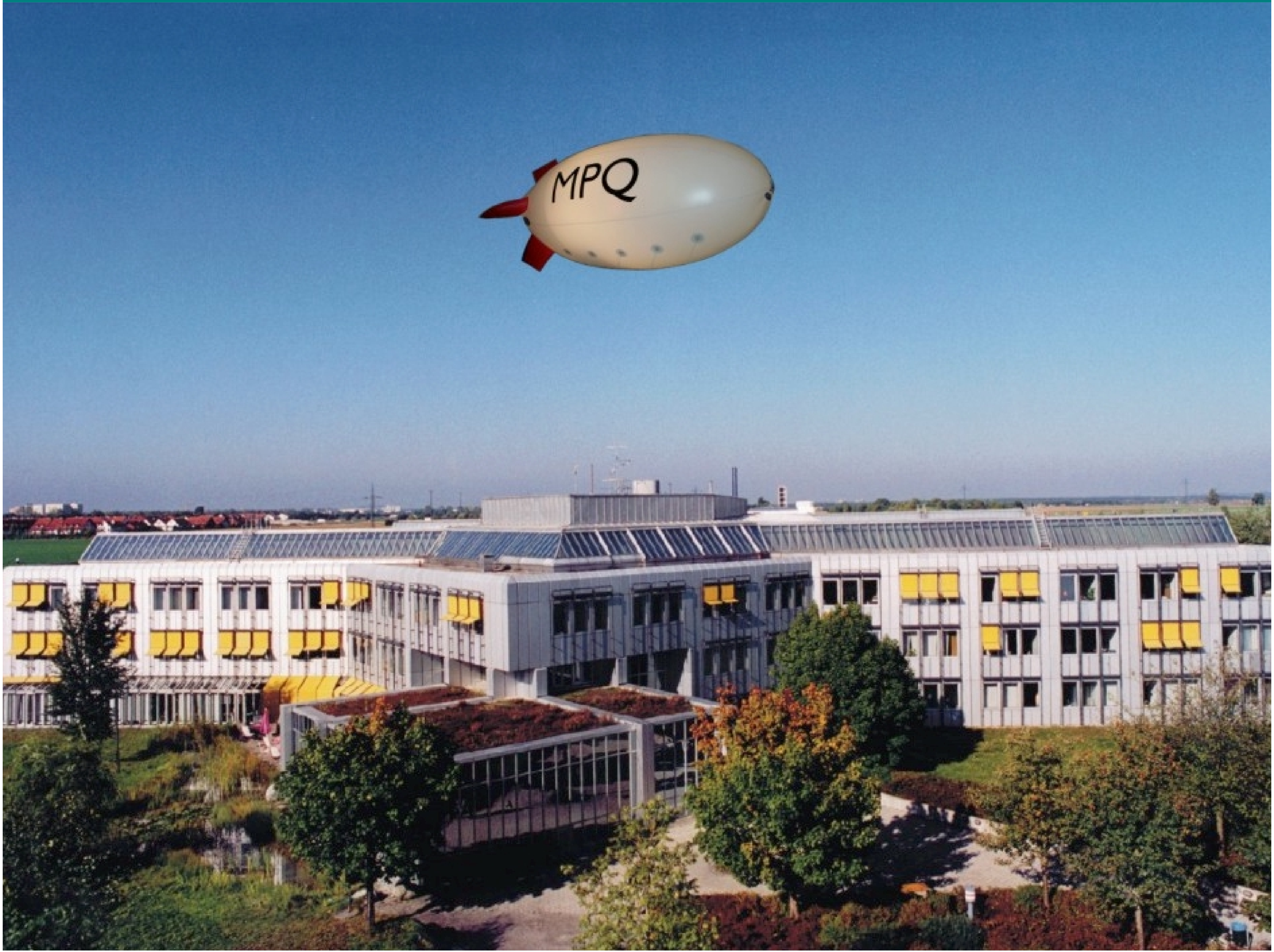
Cavity quantum electrodynamics with single atoms

One-atom maser or micromaser:

- source for number states of the radiation field
- photons on demand
- state reconstruction and phase diffusion of the maser field

Trapped ions:

- single ion as a nanoprobe of an optical field
- single photon sources and single ion laser
- realization of a new frequency standard


MPQ


MPQ

Strong Coupling Experiments

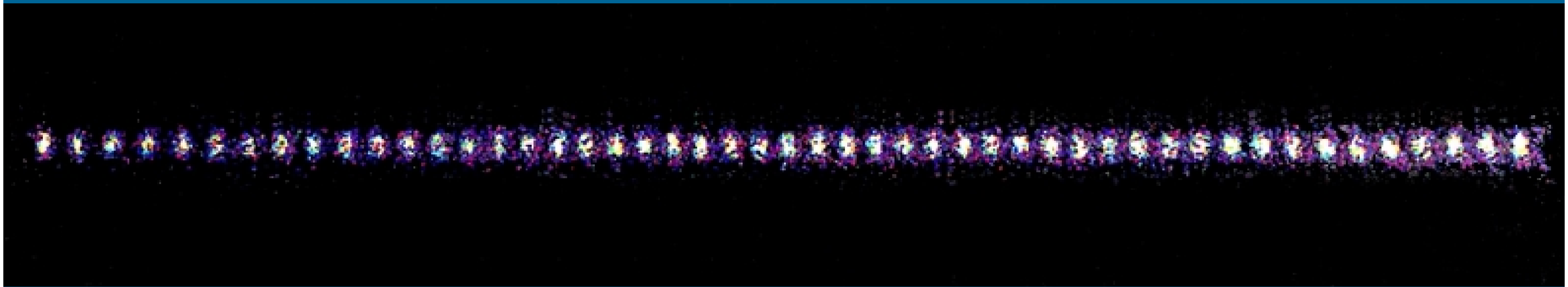
$g \gg (\kappa, \gamma)$

	$g/2\pi$	$\kappa/2\pi$	$\gamma/2\pi$	R_{th} (atoms/s)
Walther et al. 1985,1990	7 kHz	0.4 Hz	500 Hz	1.5
Haroche et al. 1994	48 kHz	400 Hz	5 Hz	$3 \cdot 10^4$
Kimble et al. 1994	7.2 MHz	0.6 MHz	5 MHz	$5 \cdot 10^6$
Rempe et al. 2000				
Feld et al. 1994	340 kHz	190 kHz	50 kHz	$8 \cdot 10^6$

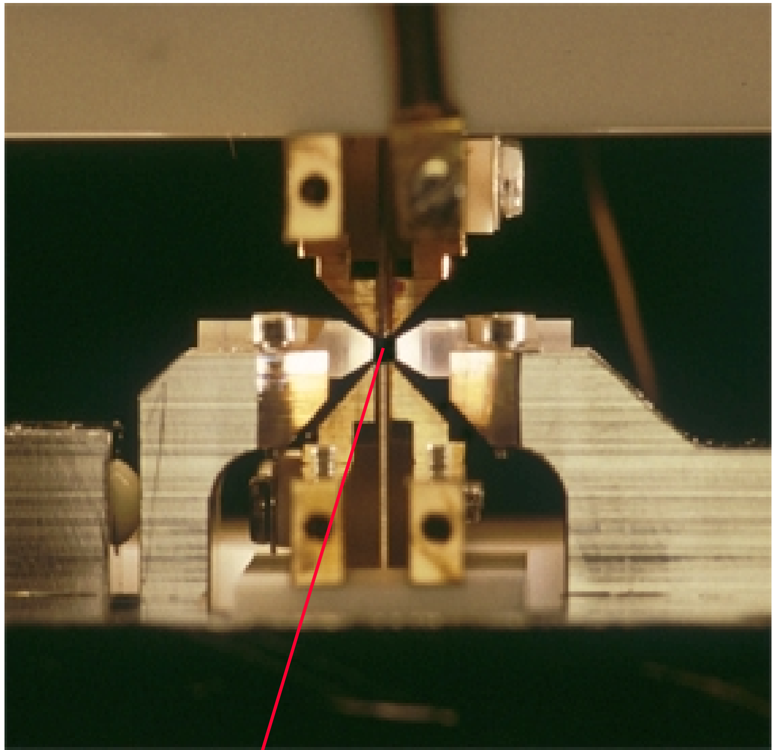
κ: decay rate of cavity field

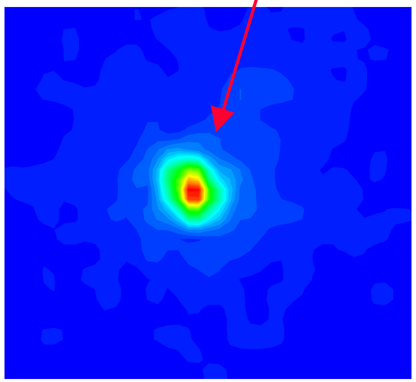
γ: spontaneous decay of atomic polarization

R_{th}: pumping rate at threshold



Single $^{40}Ca^{+}$ Ion in an Optical Cavity





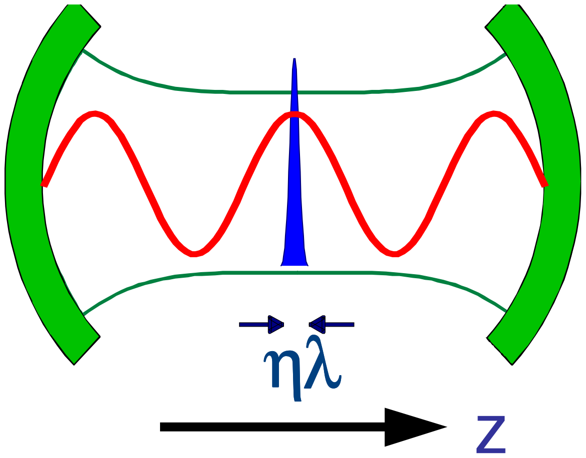
resonator:

length: $L = 1 \ldots 6$ mm

waist: $w_0 = 16 \ldots 24\ \mu m$

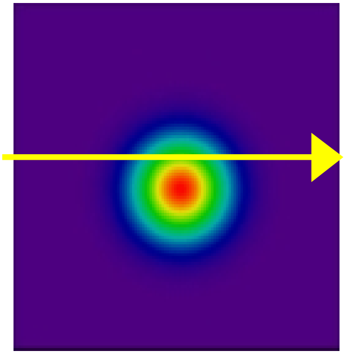
damping: $\kappa / 2\pi = 250 \ldots 4000$ kHz

coupling: $g/2\pi = 5.8 \ldots 2.7$ MHz

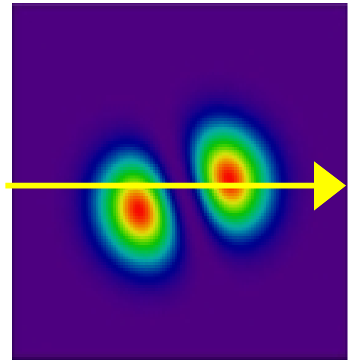


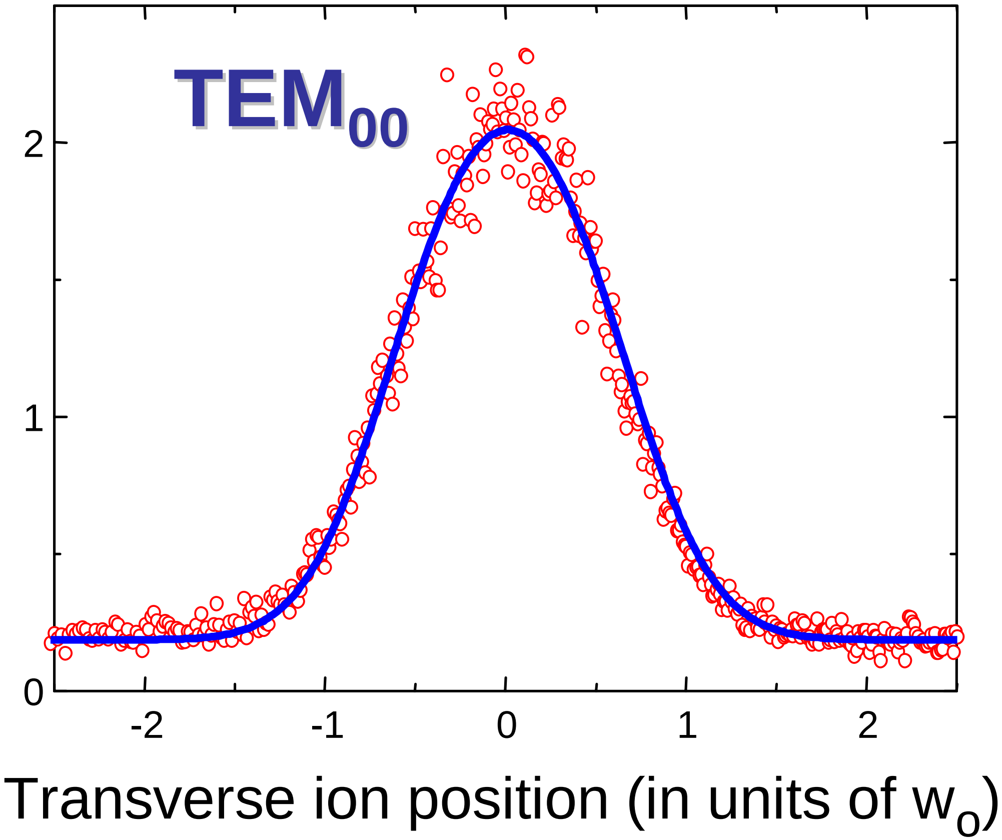
After compensation of RF-micromotion: localisation in z-direction $\sim \lambda/10$ (Lamb-Dicke regime)

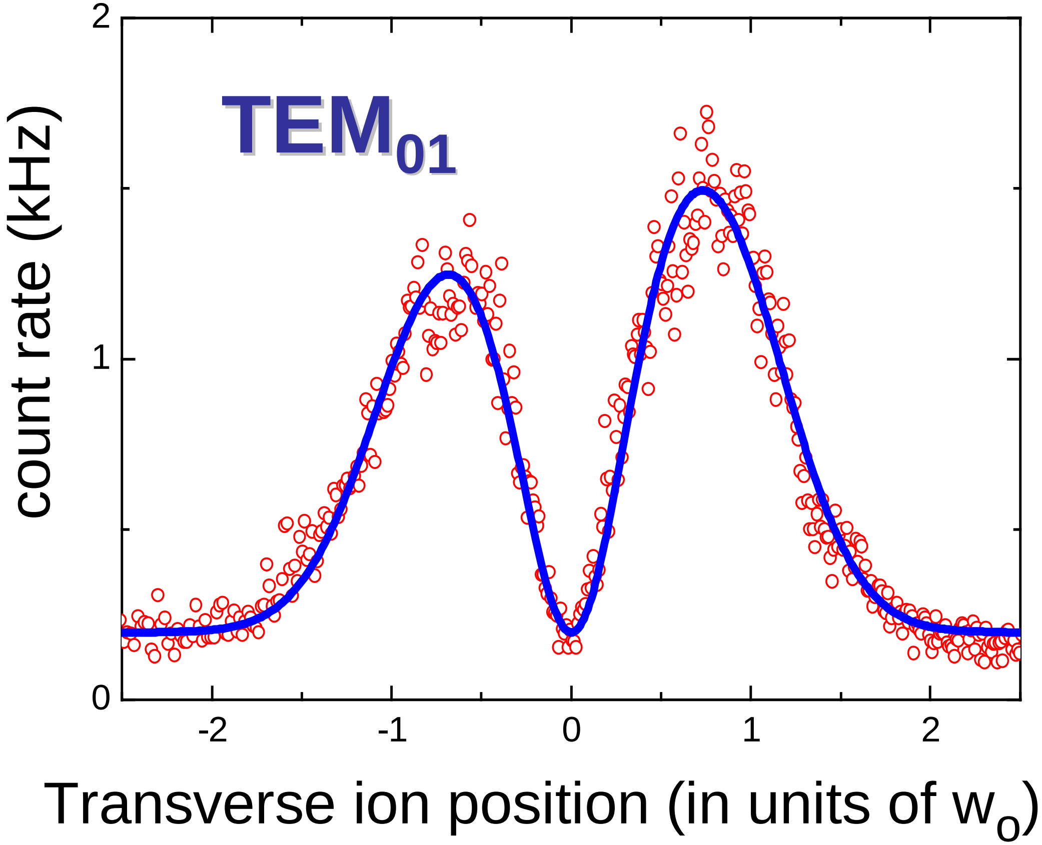
Transverse Scans of Hermite-Gauss-Modes



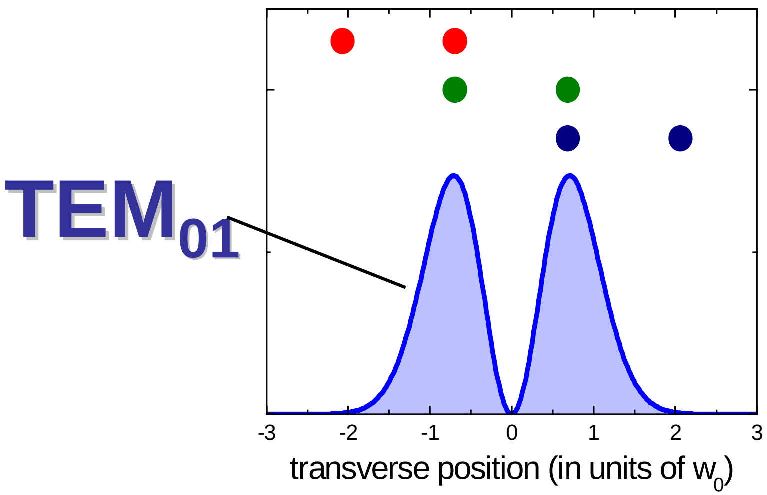
Axial trap frequency: $\omega_z/2\pi$=300 kHz
Transverse resolution: 170 nm
Cavity waist: W_0= 24µm



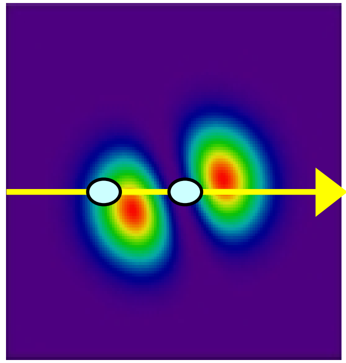


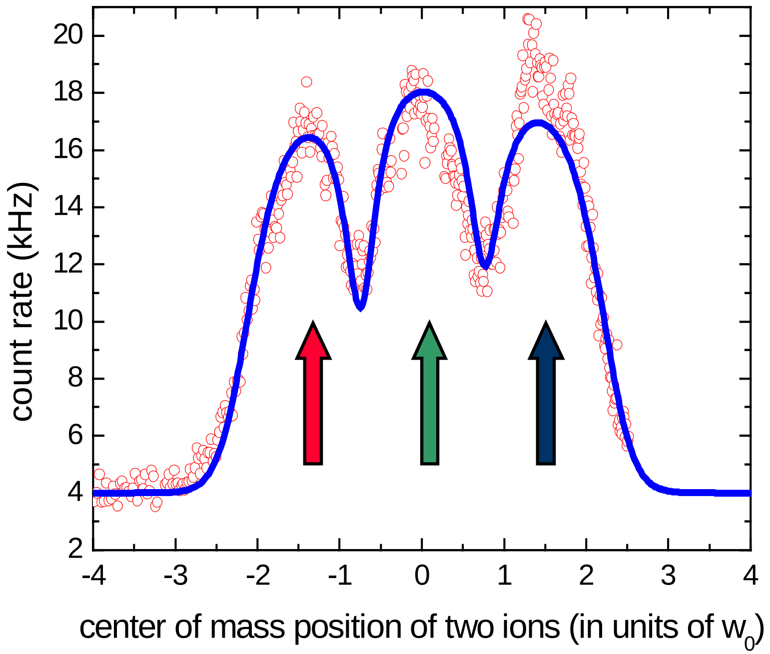


Two Ions in the Cavity Mode



a crystal of two Ca^+ ions is scanned transverse to the cavity axis:





ion separation $\Delta x = 33\ \mu m$

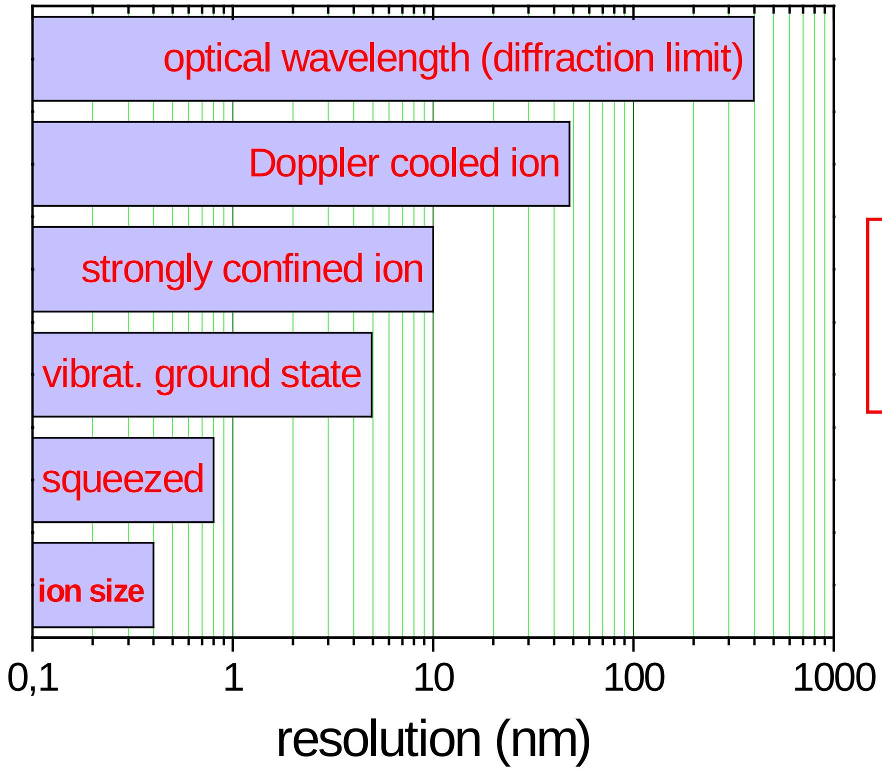
$\approx$ peak separation of TEM_{01} mode

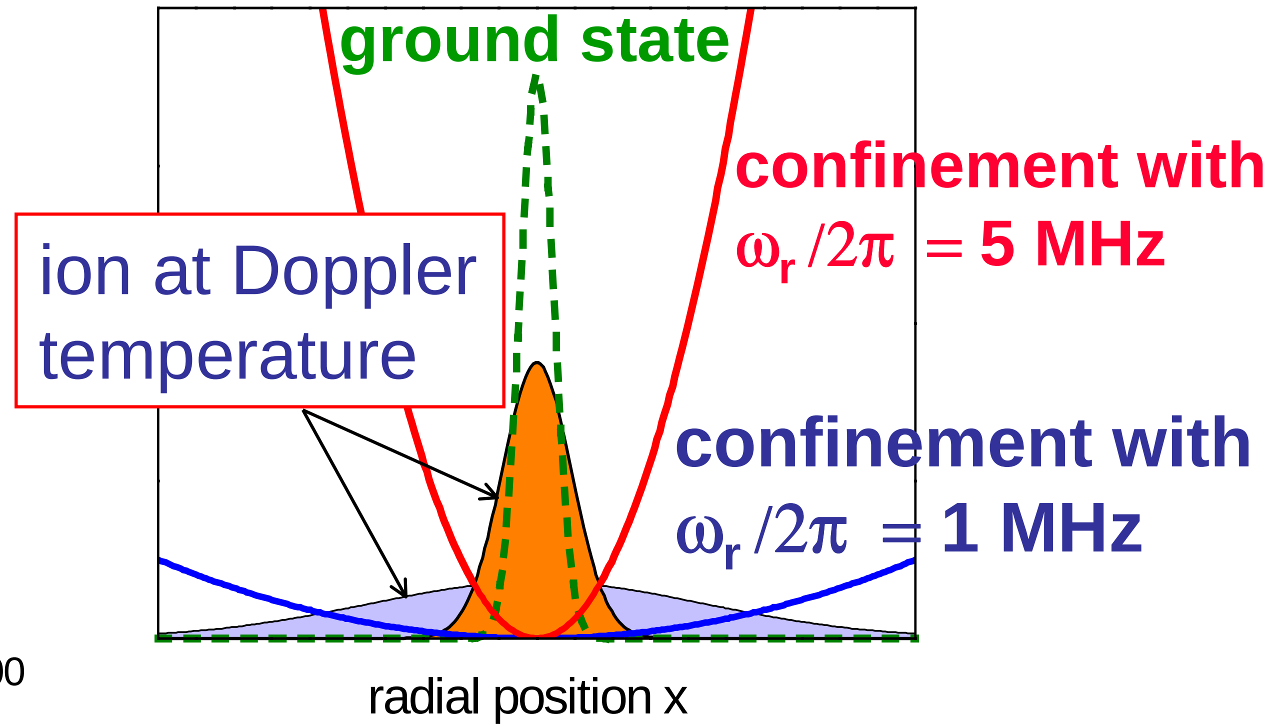
Applications:

- entanglement of two ions
- quantum state transfer
- two-bit quantum gate

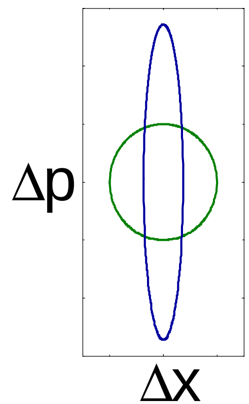
Cavity-mediated detuned Raman coupling leads to a fidelity in two-ion coupling of 93%

Resolution of Single Ion Mode Mapping





- resolution well below diffraction limit achieved
- sub-nm resolution feasible using:
  - strong confinement
  - ground state cooling
  - motional squeezing

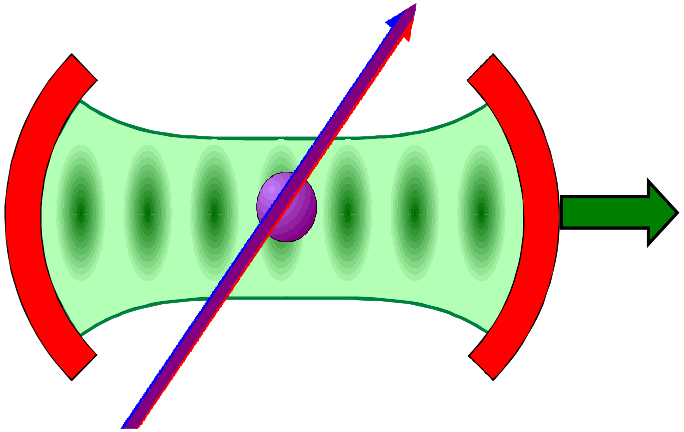


increased resolution by squeezing the ground state

Single-Ion Laser

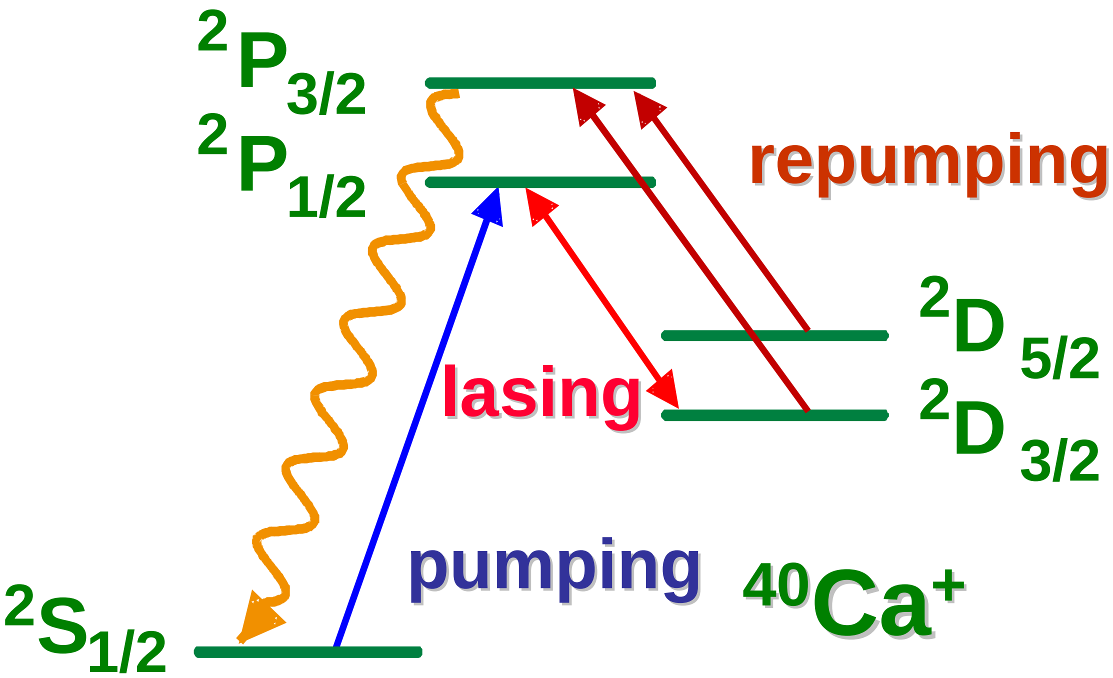
- single ion as gain medium
- ultralow-loss cavity (finesse ~ 300 000)
- continuous pumping / repumping
- strong atom-cavity coupling (L~1 mm)

$$g > \kappa, \gamma$$



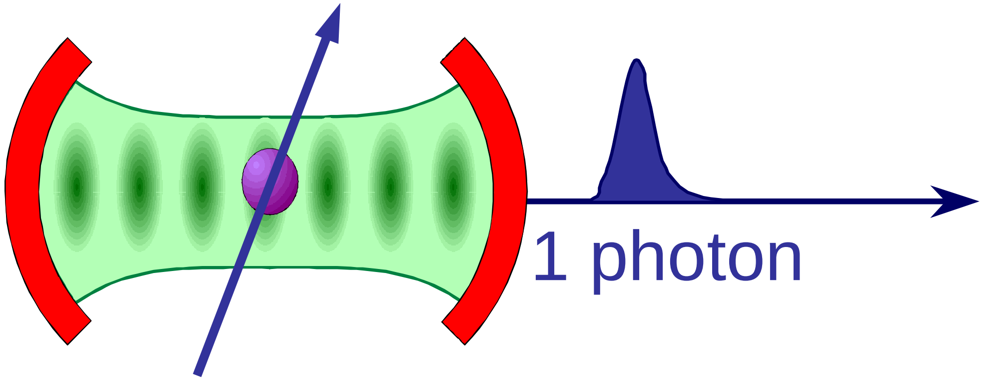
397 nm, 850 nm, 854 nm

cw source of
non-classical light



Deterministic Single Photon Gun

C. K. Law, H. J. Kimble, J. Mod. Opt. **44**, 2067 (97)

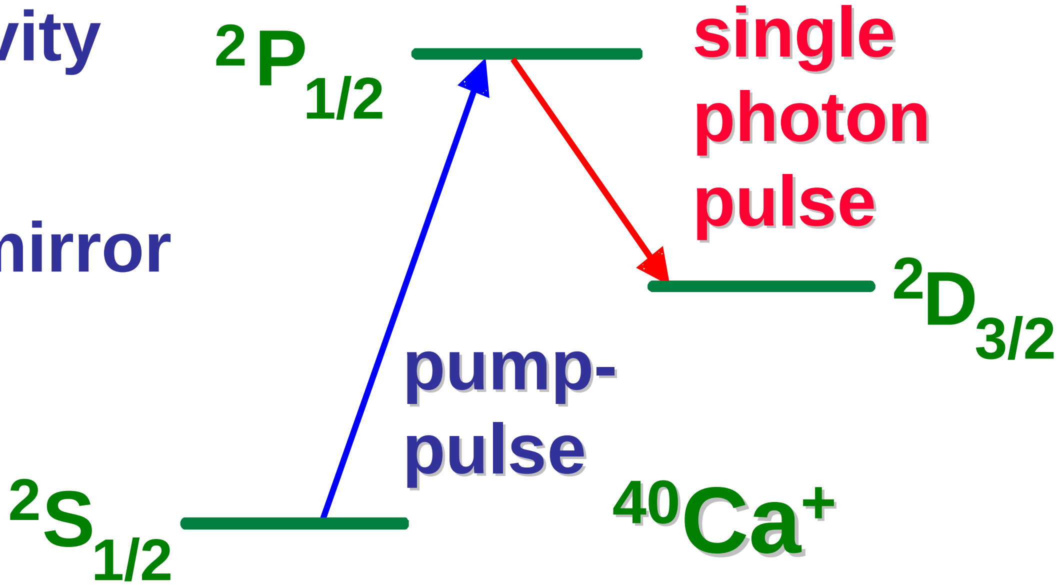


pulse with one single photon

- **Single ion at a node of the cavity**
- **external pump pulse**
- **cavity with one leaky output mirror**

$$\kappa > g$$

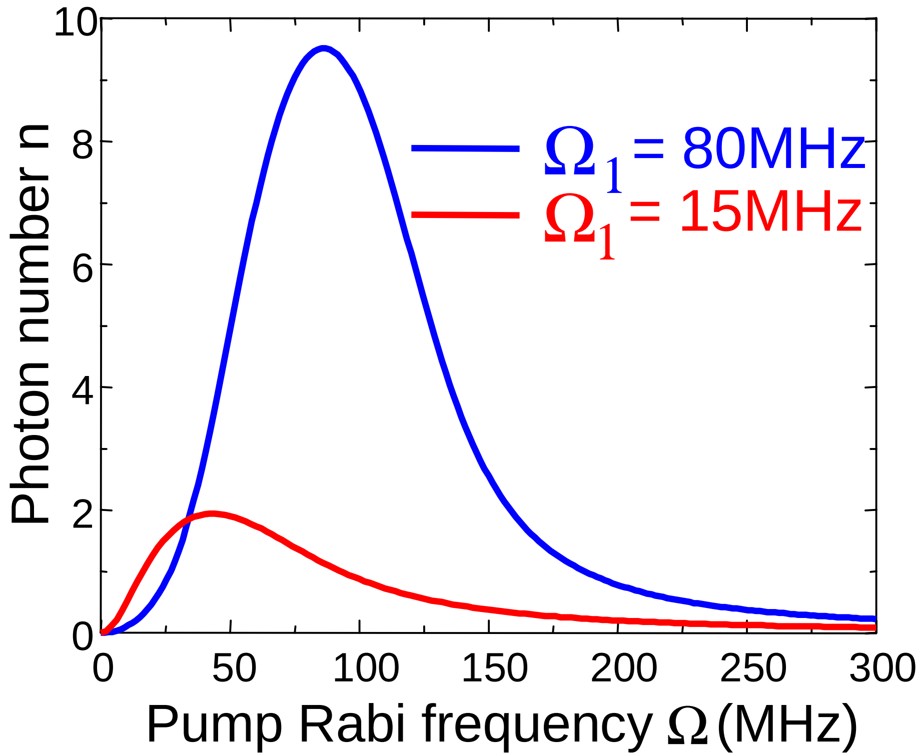
➡ **Single-photon pulse at pre-determined time**

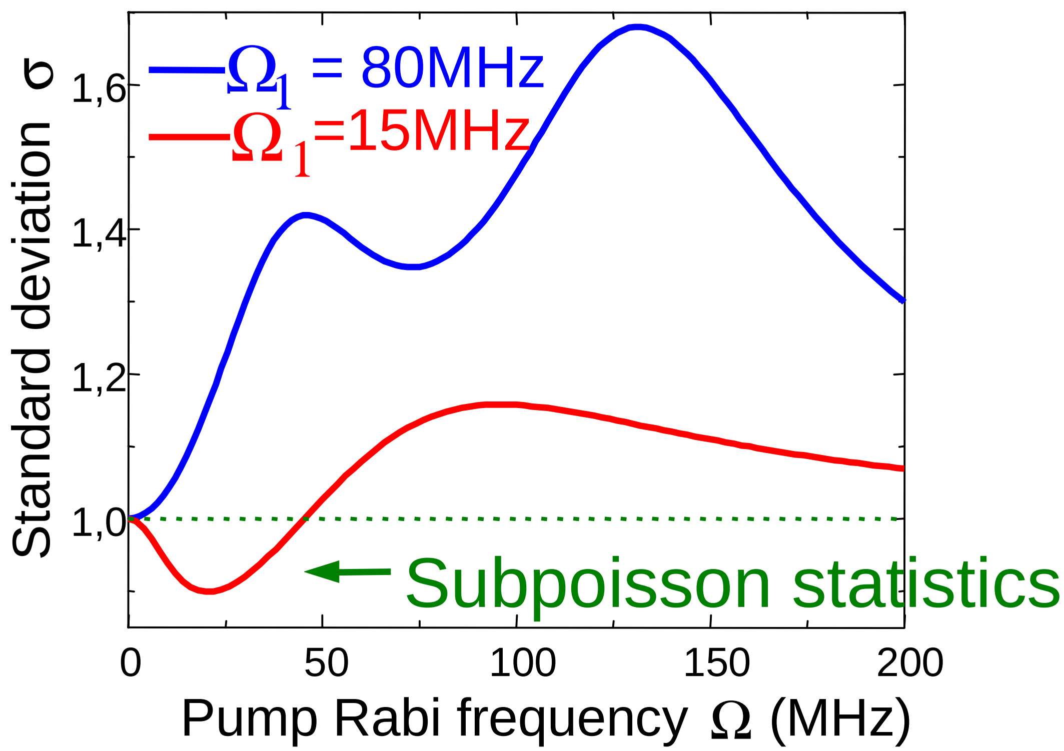


Single-Ion Laser

- stationary field of up to 10 photons in the cavity
- 10 MHz output rate
- non-classical characteristics

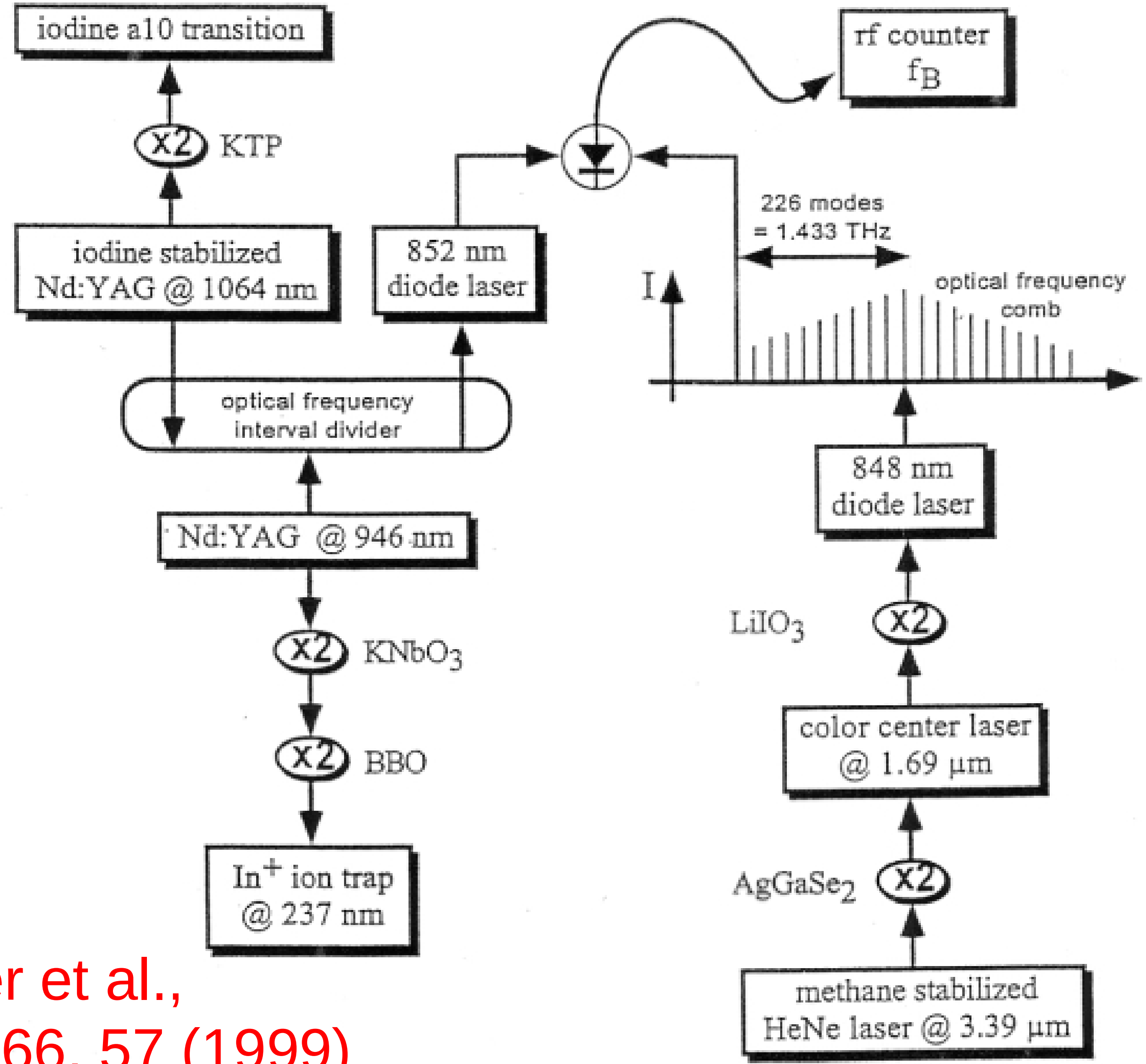
$g/2\pi$ = 2.3 MHz
$\kappa/2\pi$ = 0.08 MHz
$\gamma/2\pi$ =1.7 MHz





G. M. Meyer et al., Europhys. Lett. **37**, 317 (1997)

Optical Frequency Measurement



J. von Zanthier et al.,
Opt. Comm. 166, 57 (1999)