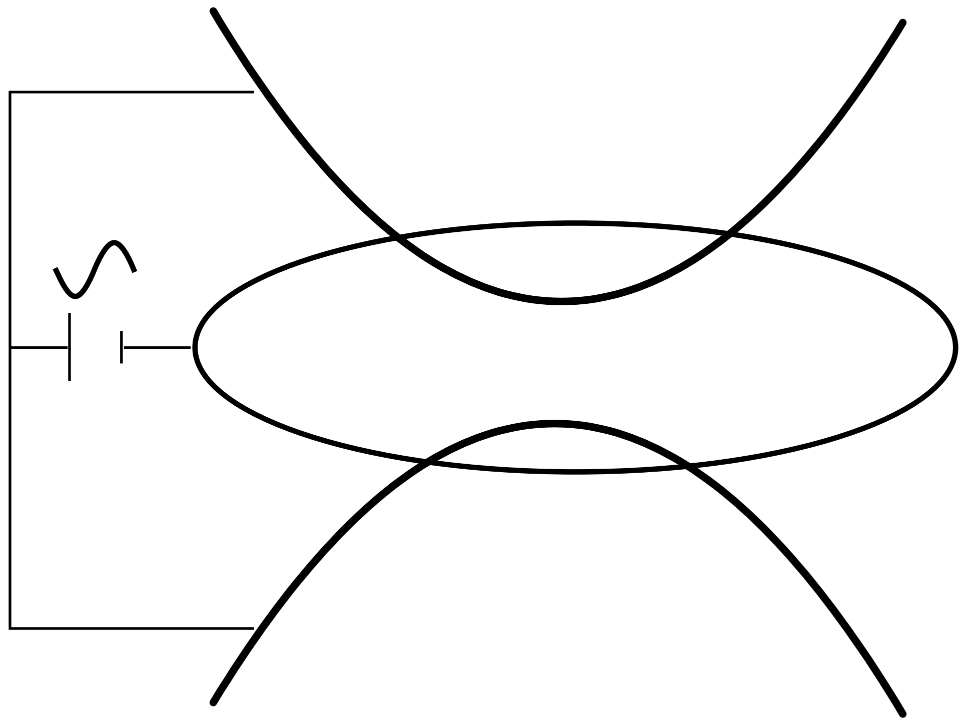
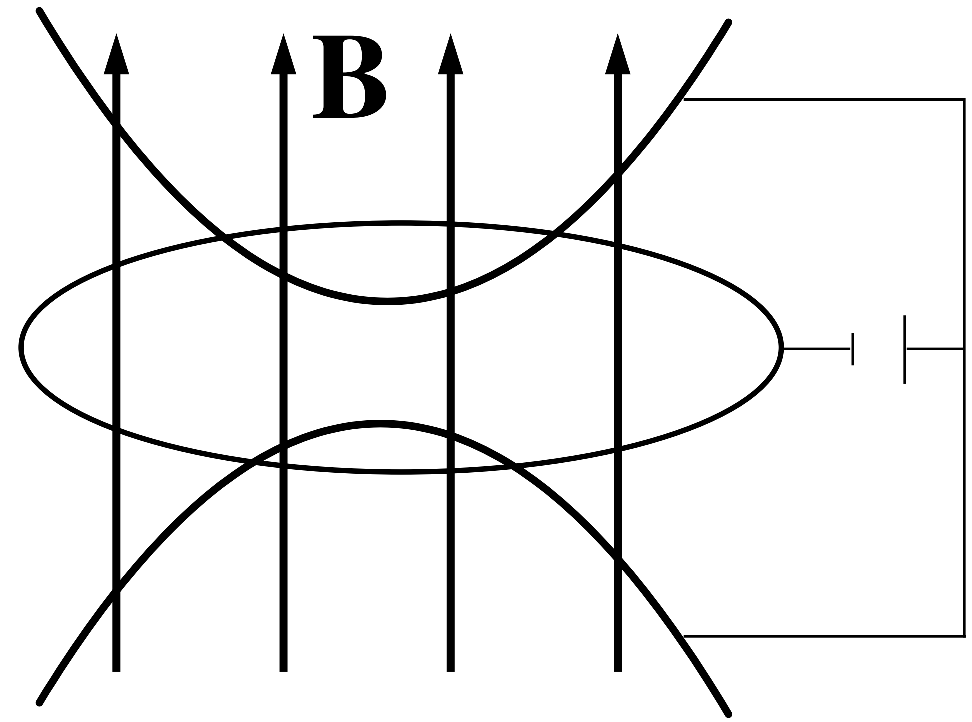
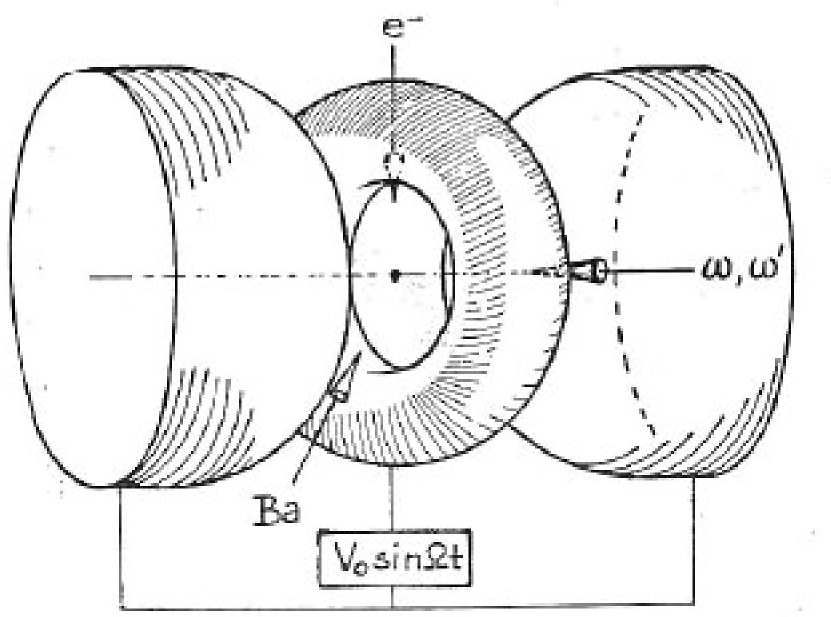
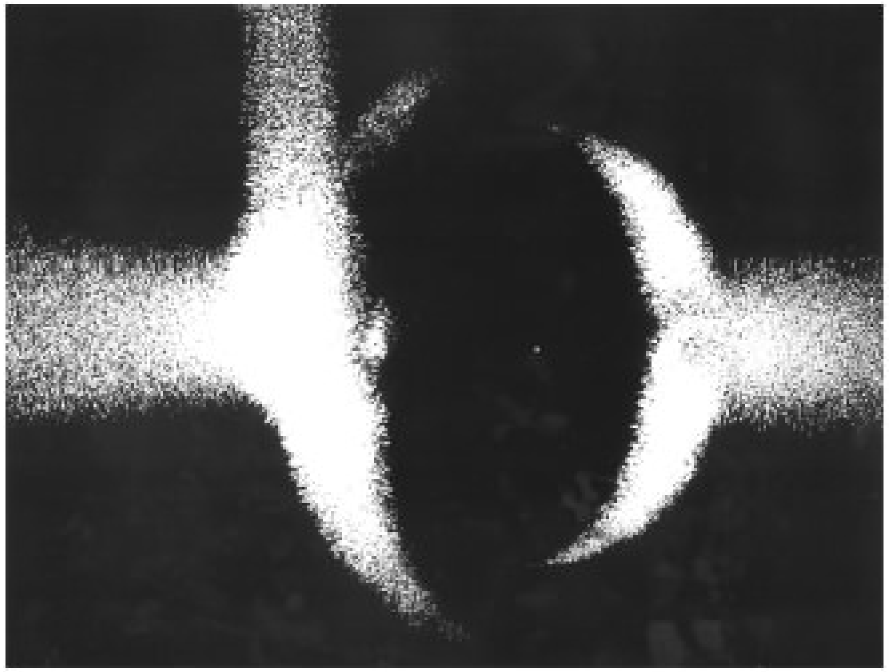
Ion Traps

Paul trap | **Penning trap**



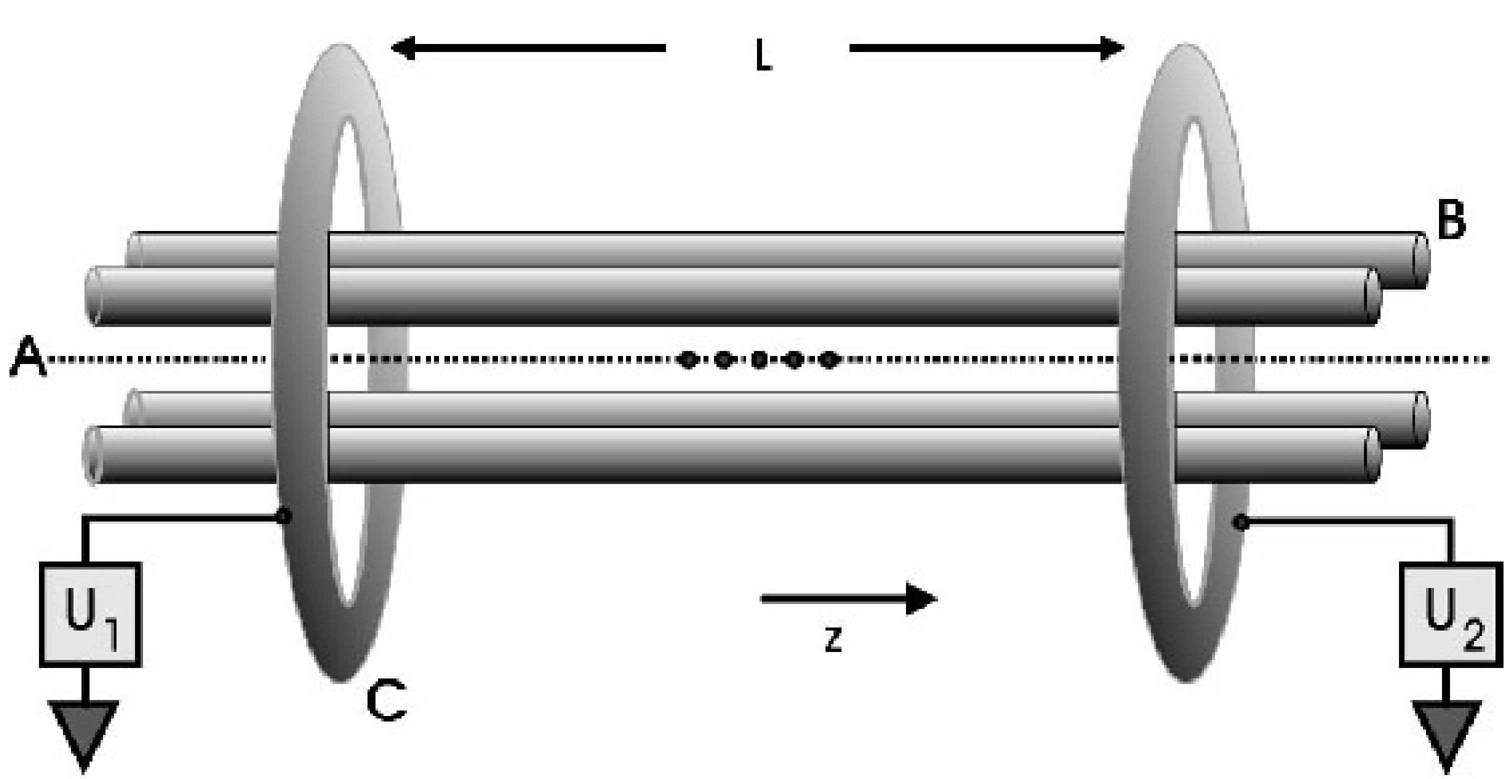


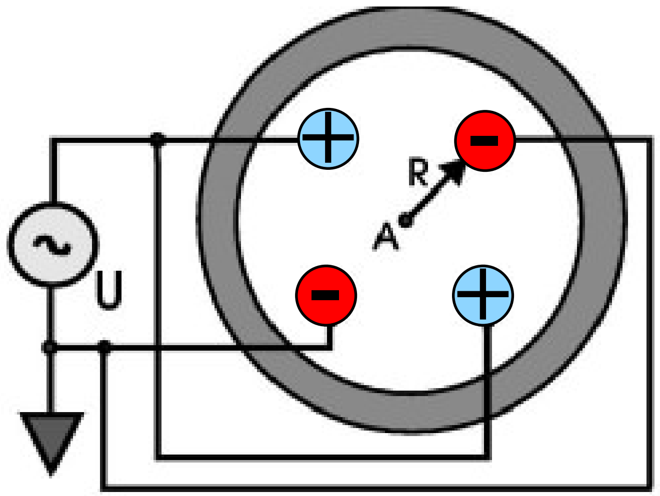




W. Neuhauser, M. Hohenstatt, P. E. Toschek, H.G. Dehmelt, Phys. Rev. A 22, 1137 (1980).

Linear Traps

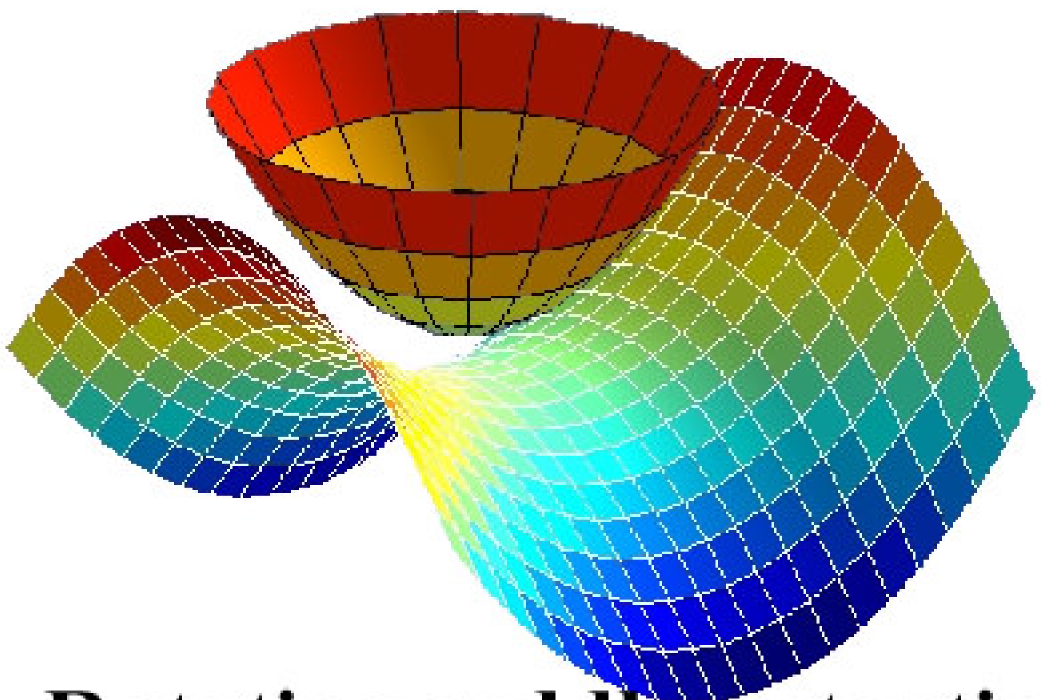




Quadrupole field

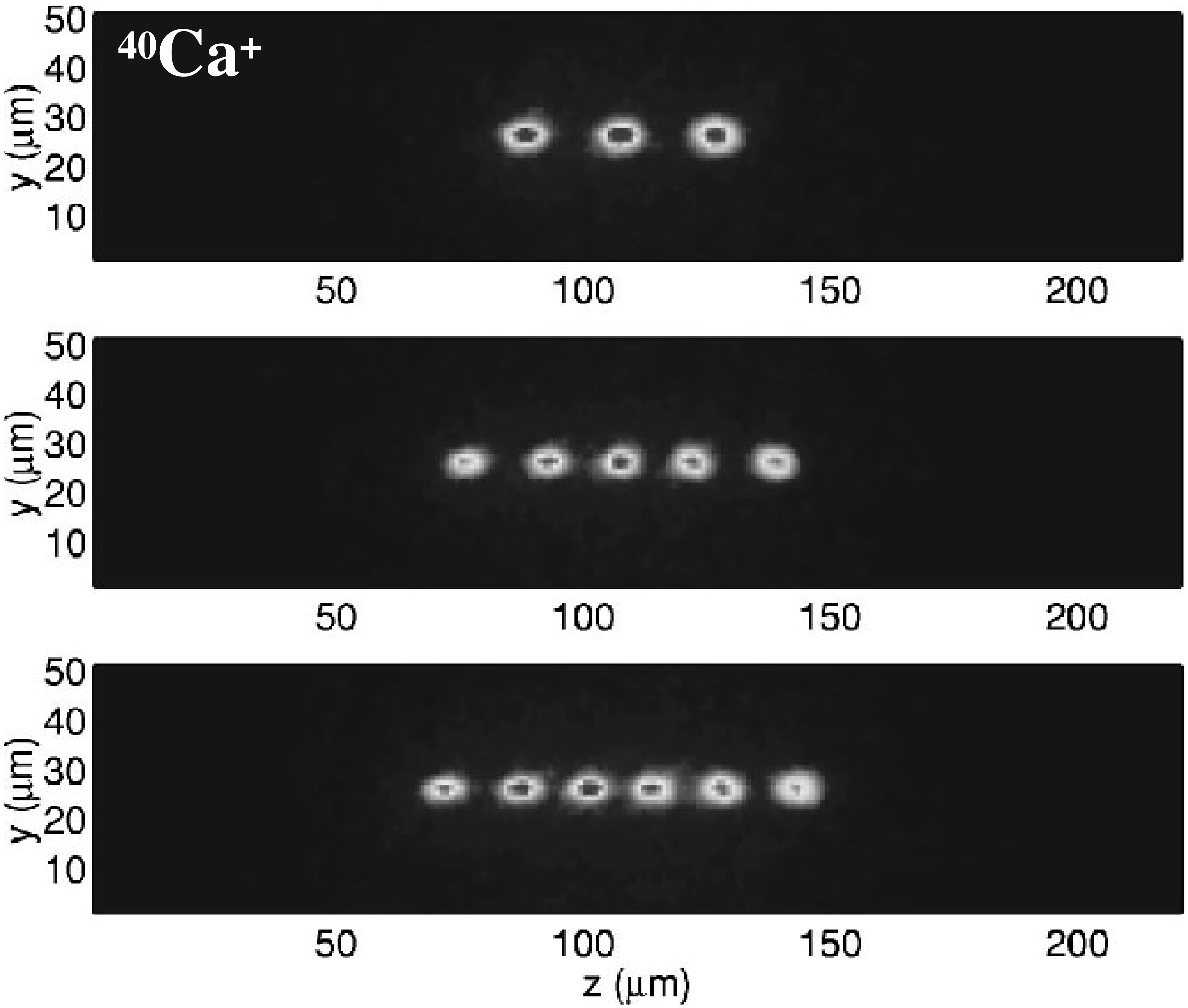
$$\Phi(x,y,t) = (U - V\cos\omega t)\frac{x^2 - y^2}{2r_0^2}$$

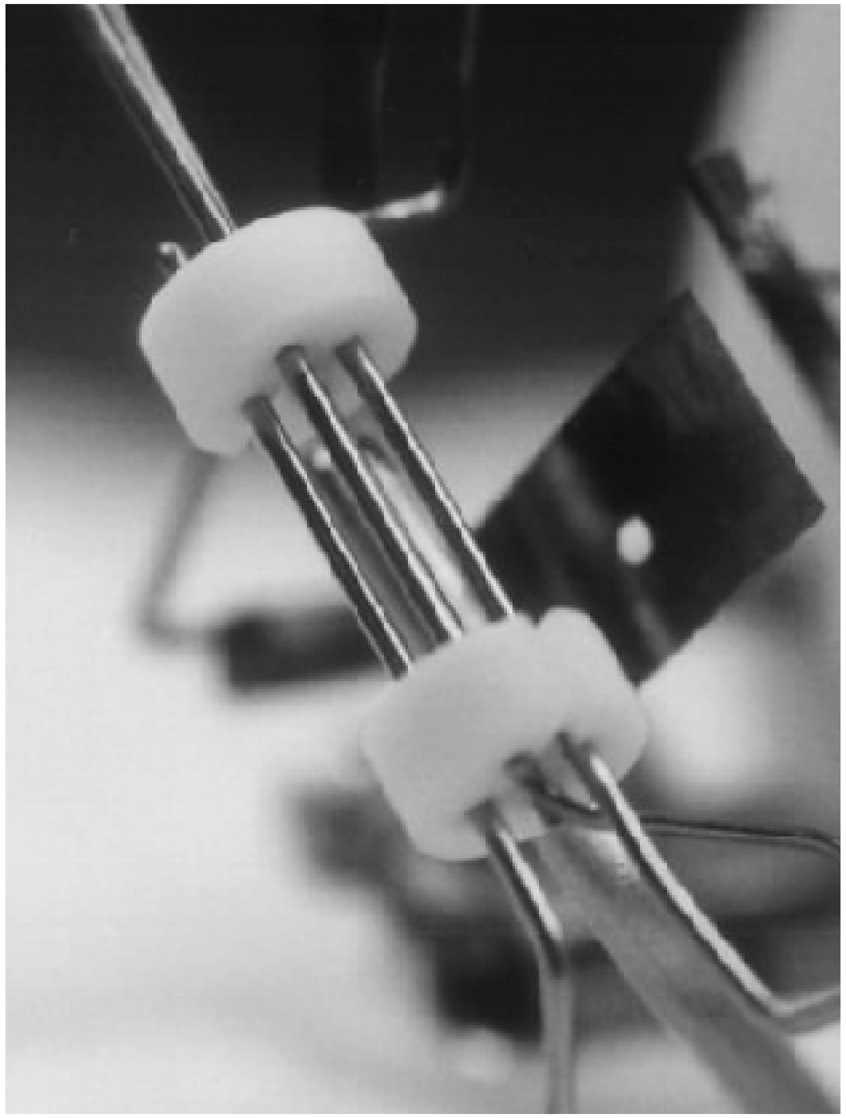
Time average



Rotating saddle potential

Trapped Ions

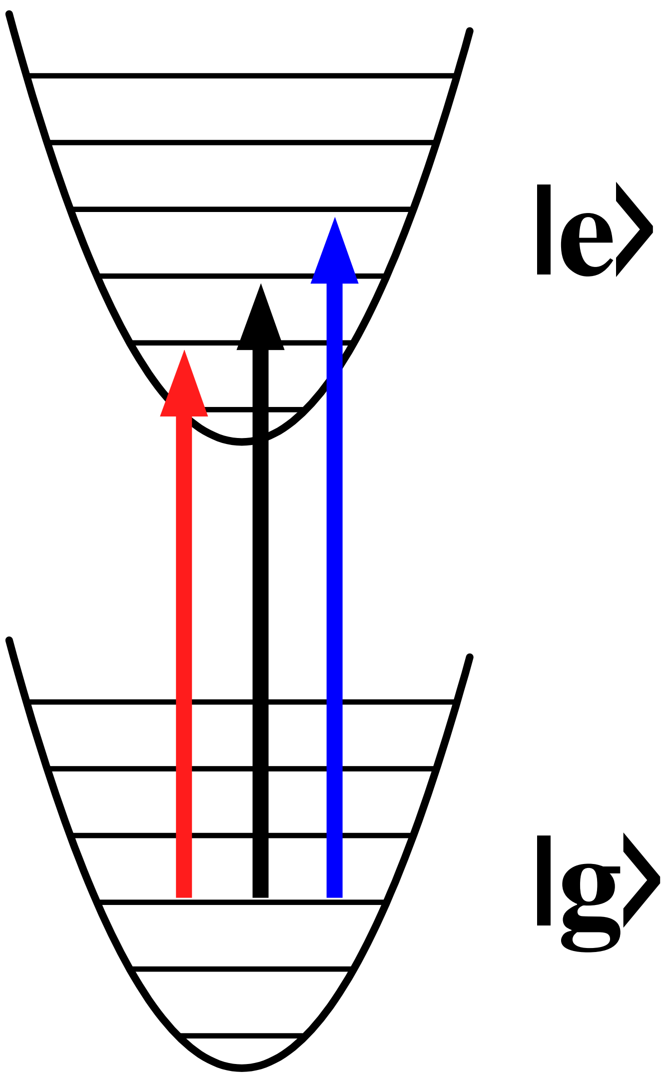




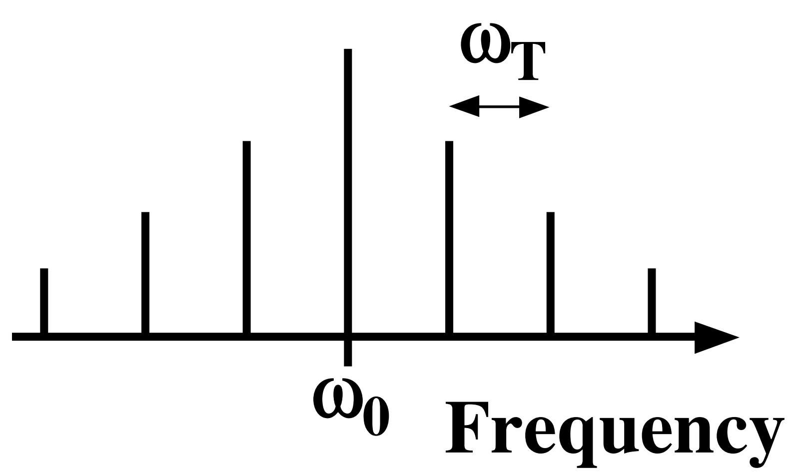
Motional States

Confinement potential

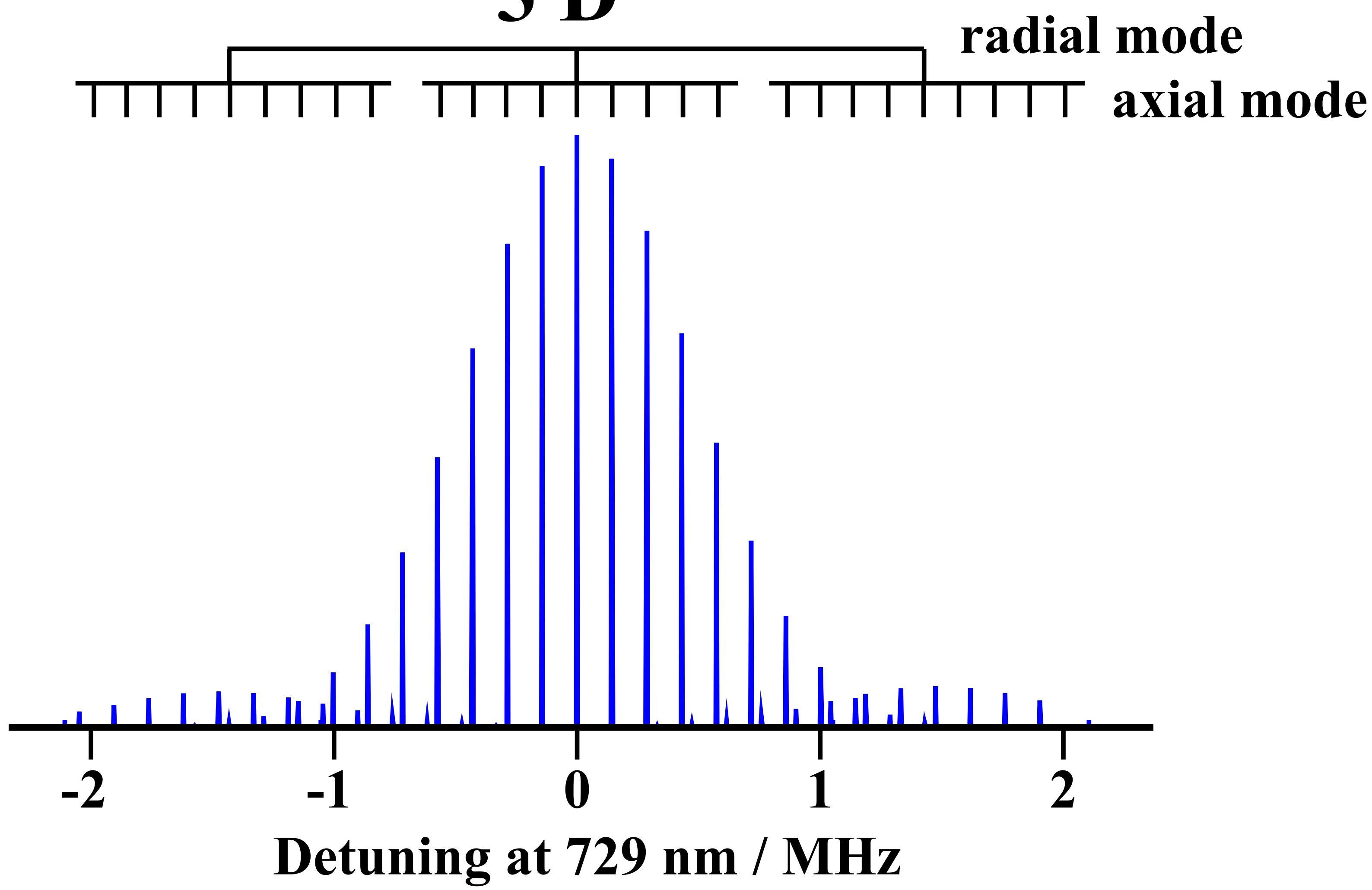
$$V(\vec{r}) = \omega_x^2 x^2 + \omega_y^2 y^2 + \omega_z^2 z^2$$



Single mode

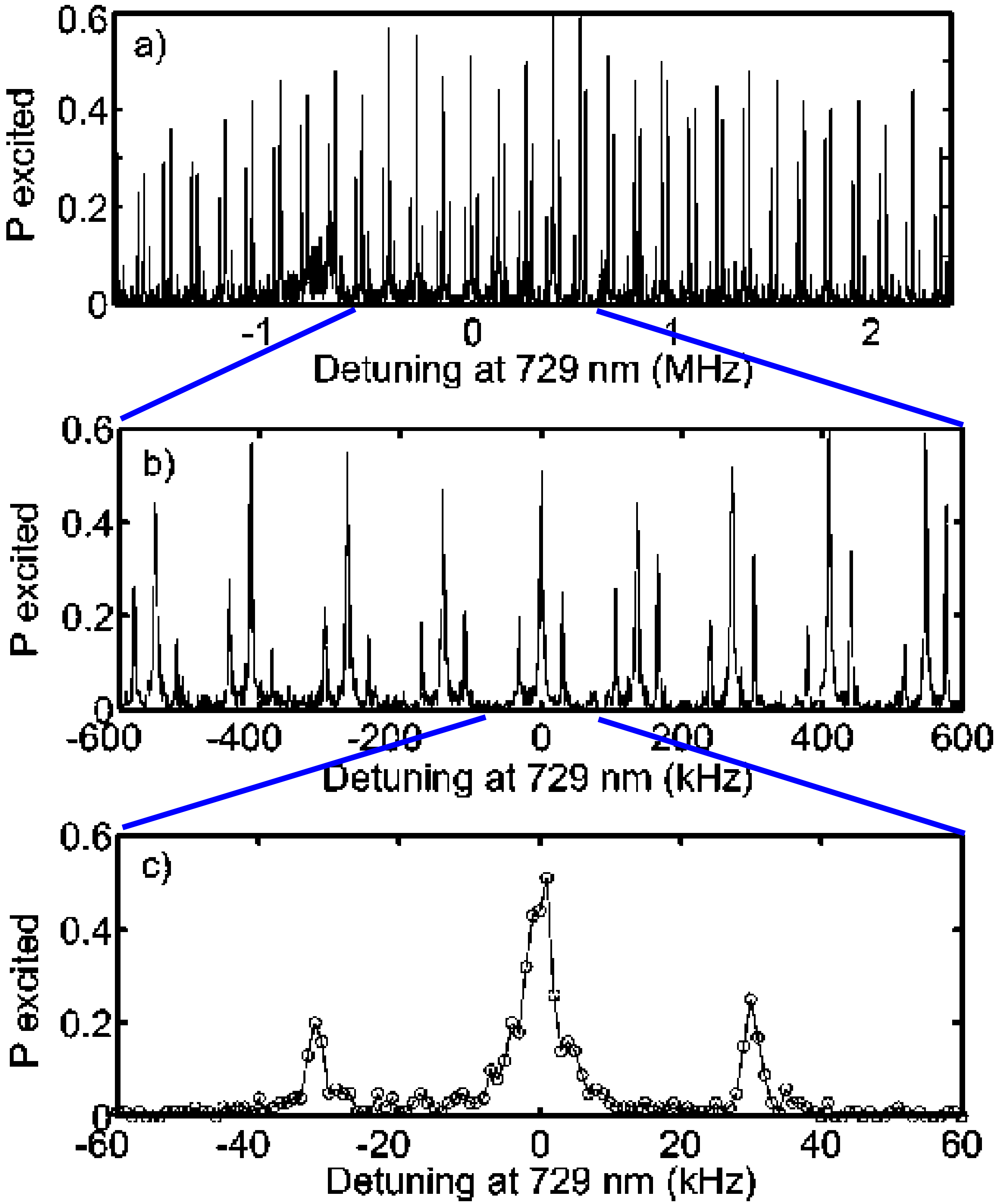


3 D



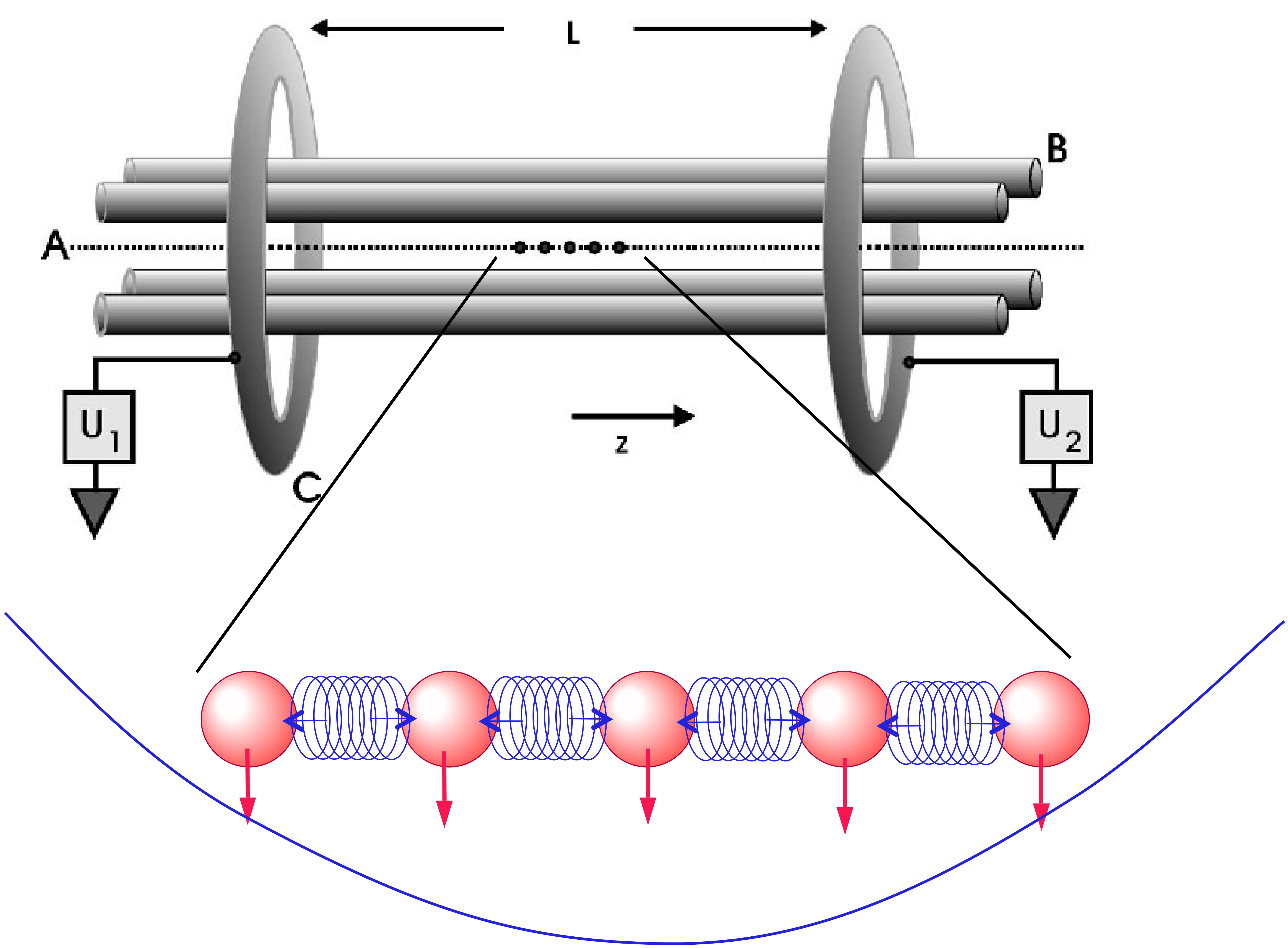
Sideband Spectrum

Ca$^+$

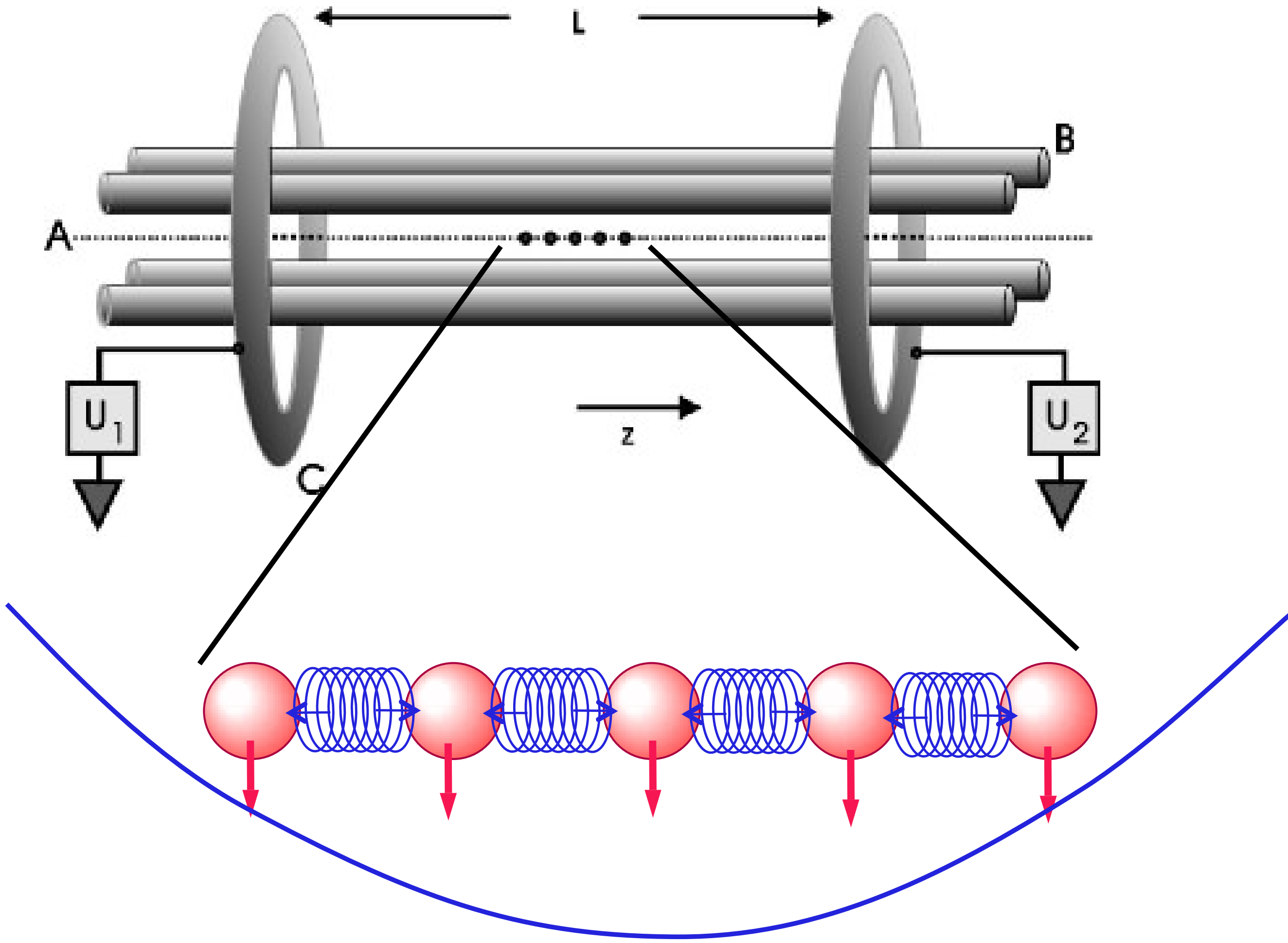


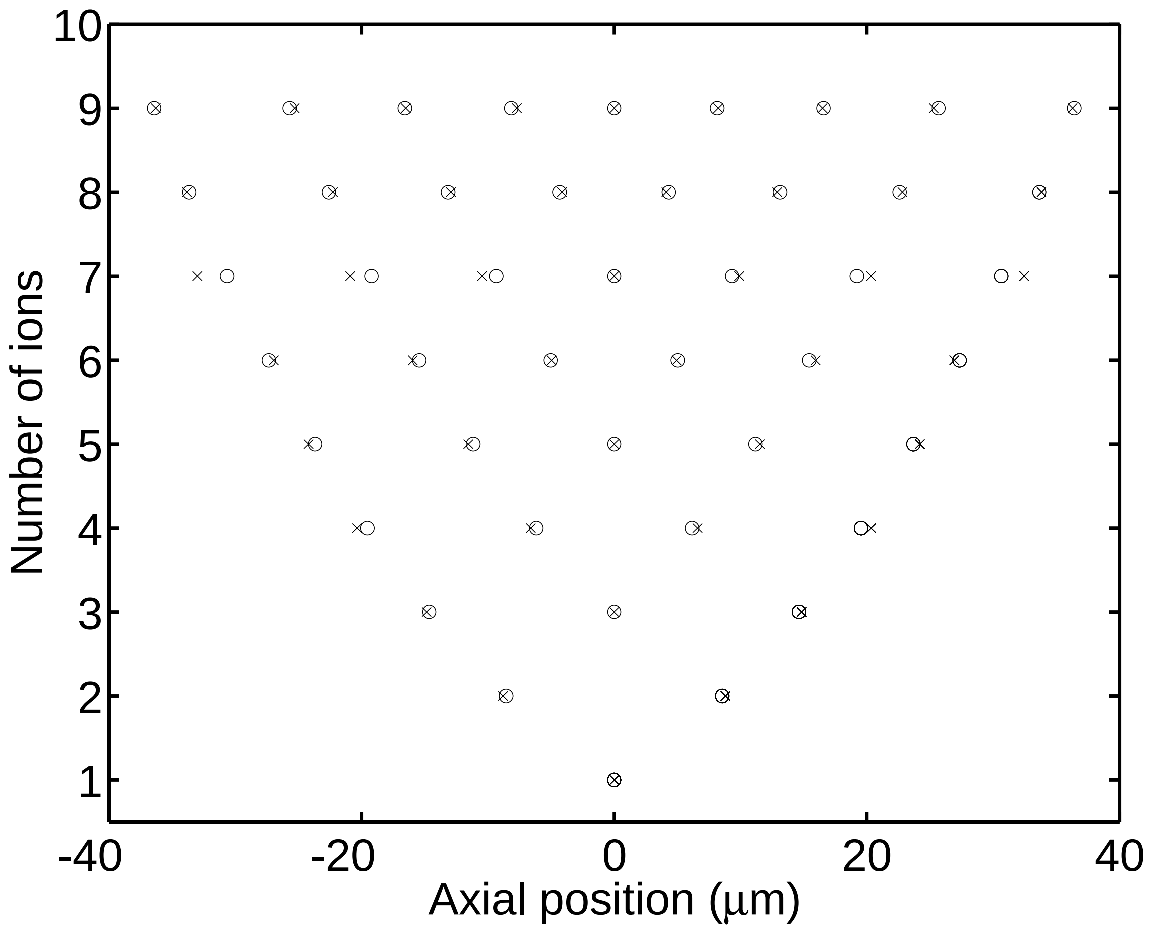
Nägerl et al., PRA 61, 023405 (2000).

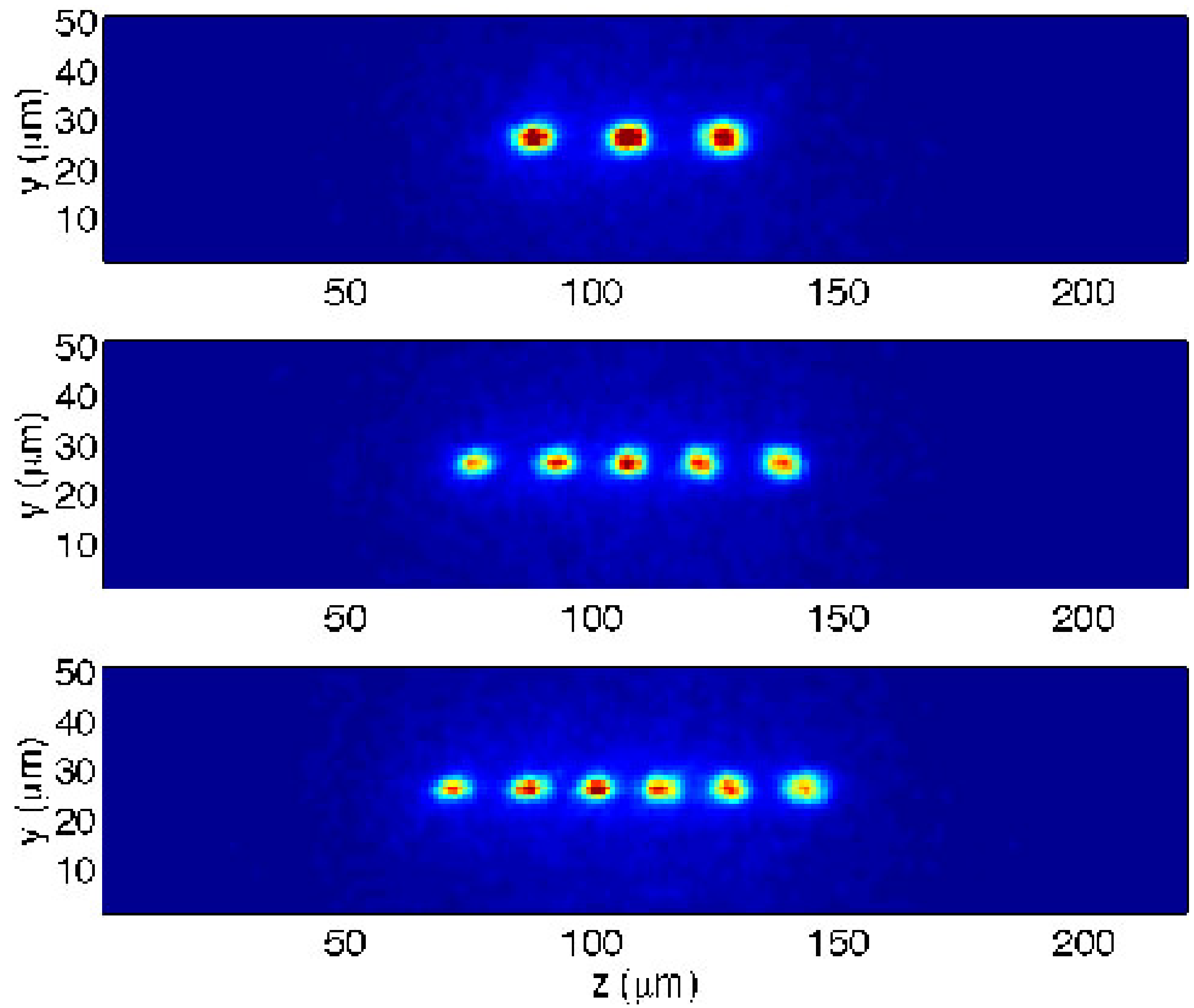
Multiple Ions



Multiple Ions

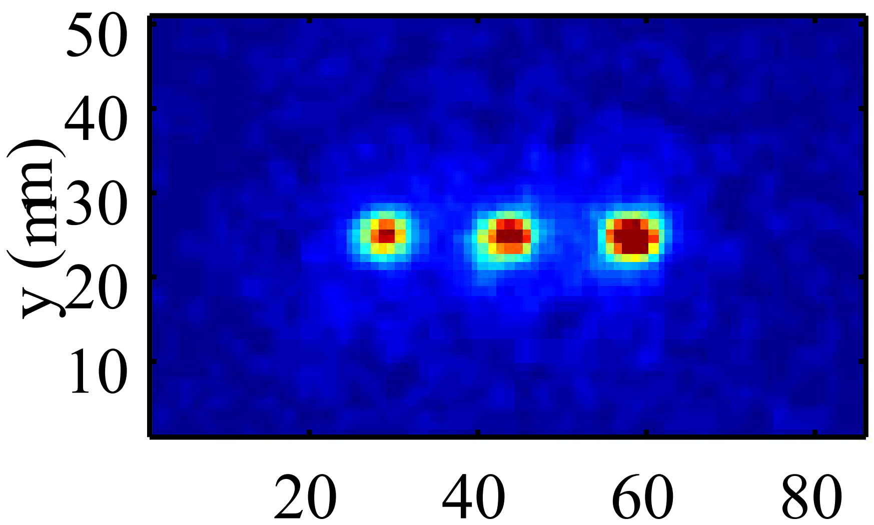




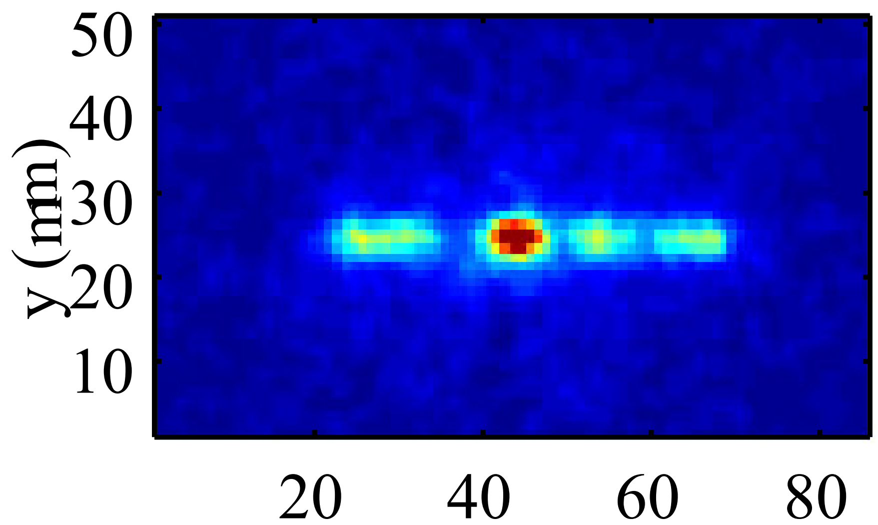


Collective Excitations

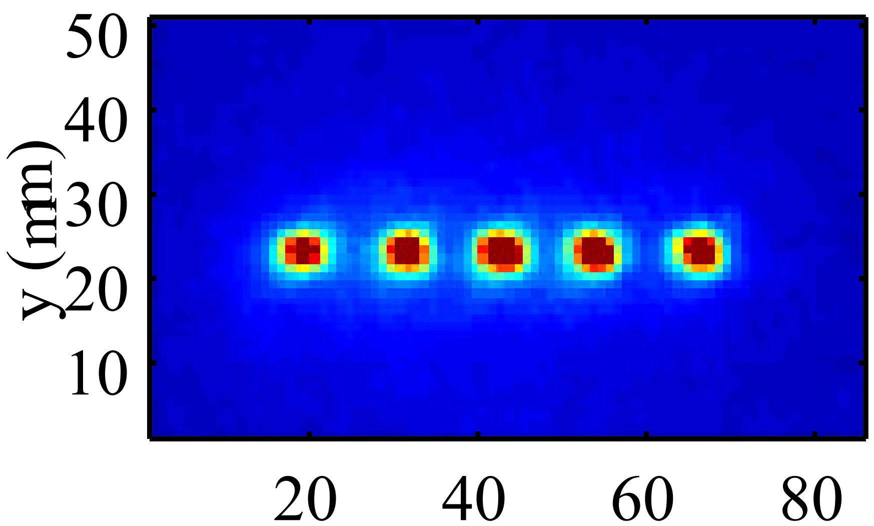
3 ions cold



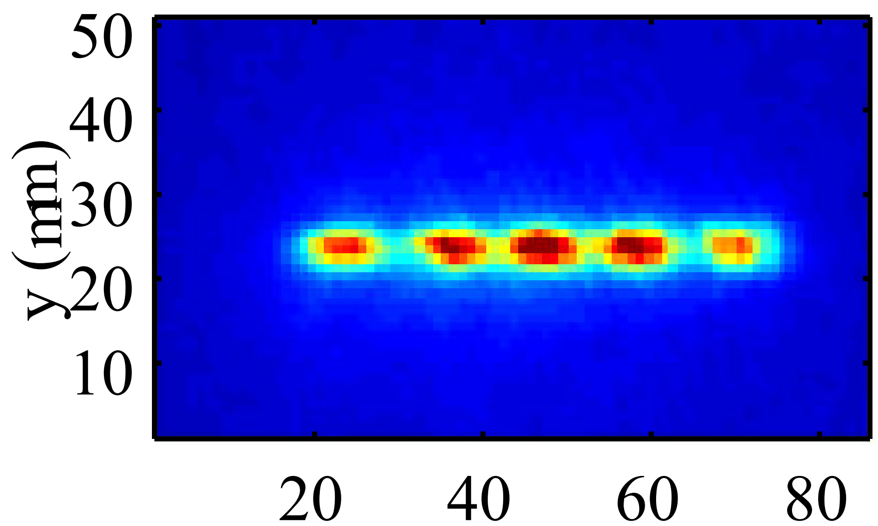
3 ions warm



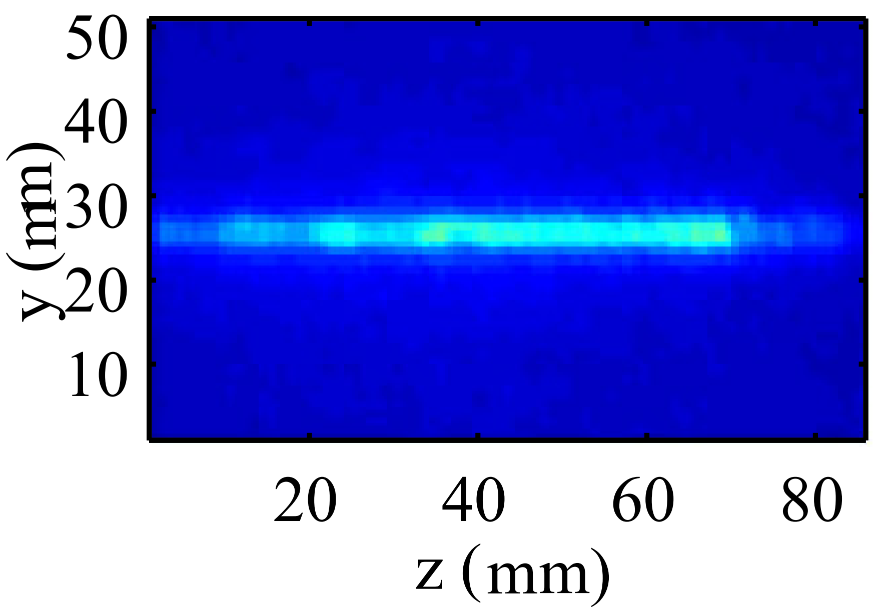
5 ions cold



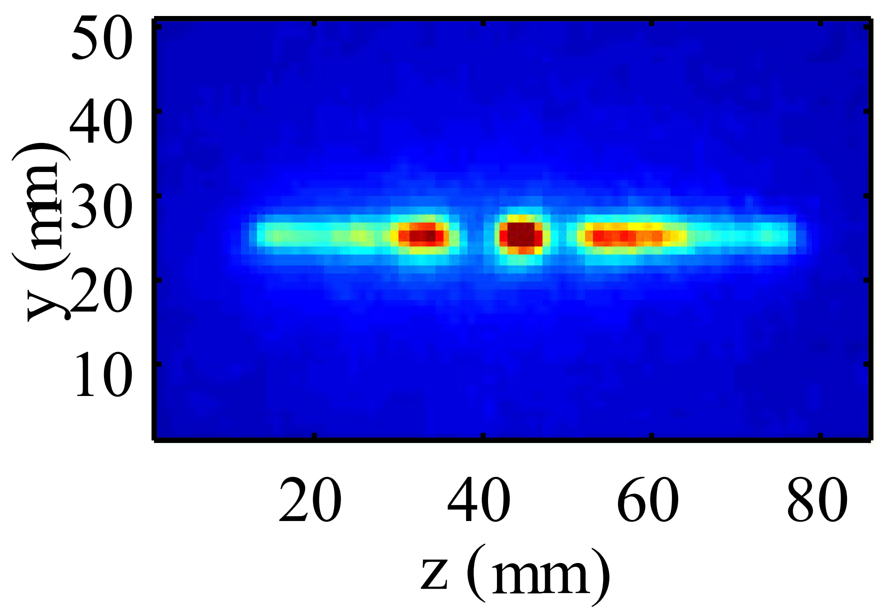
5 ions warm



5 ions very hot

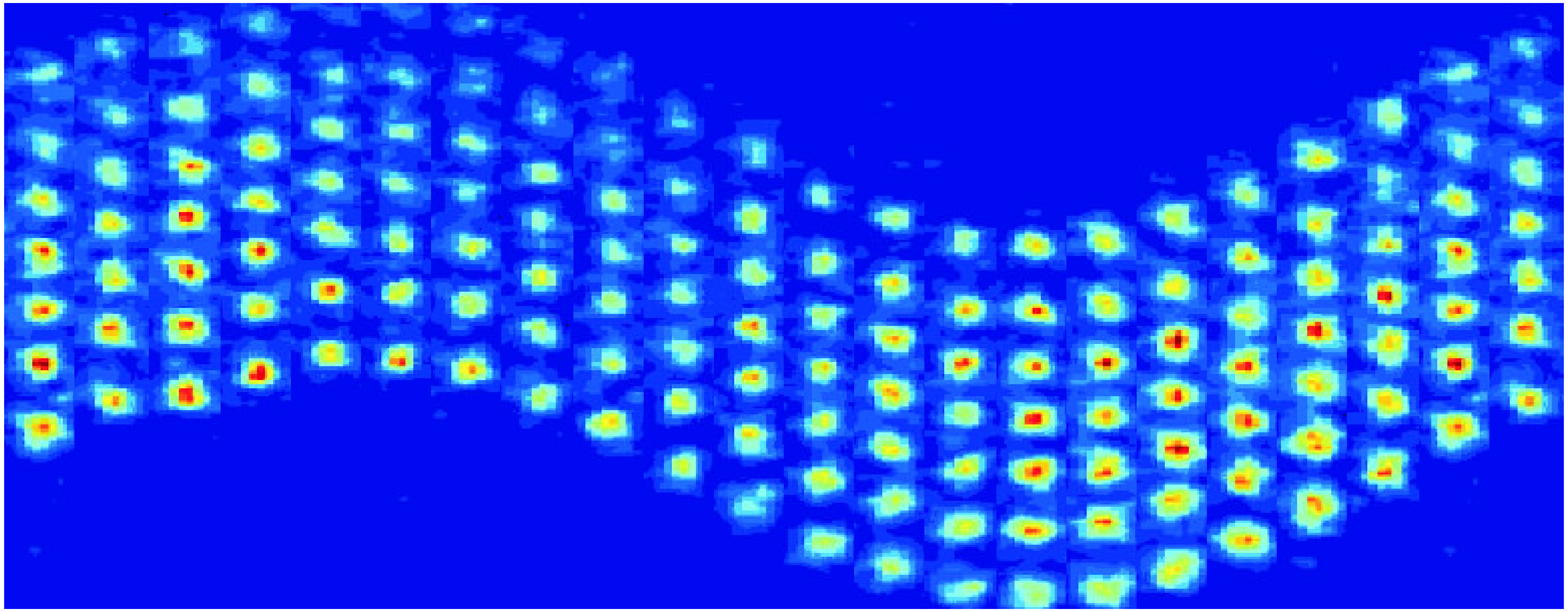


5 ions hot

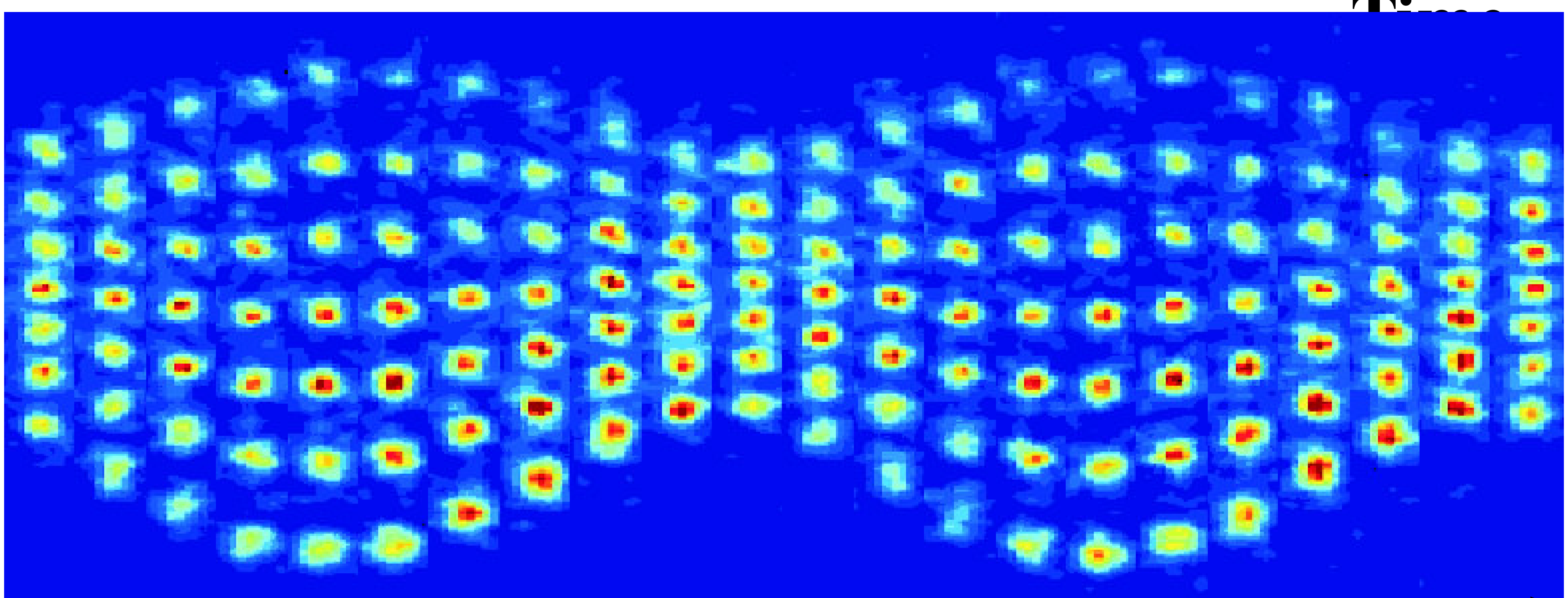


Collective Excitations

CM
106 kHz



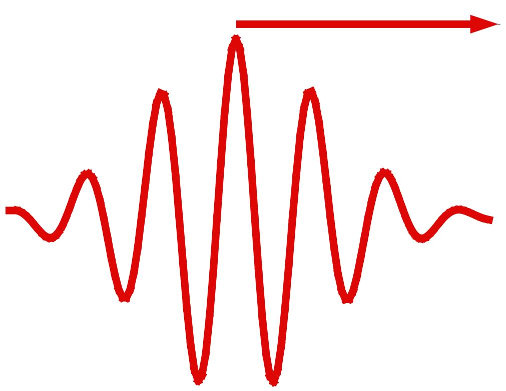
breathing
184 kHz



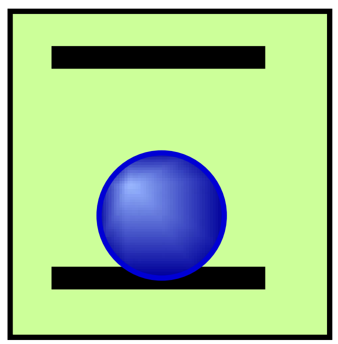
Time

Photon Momentum

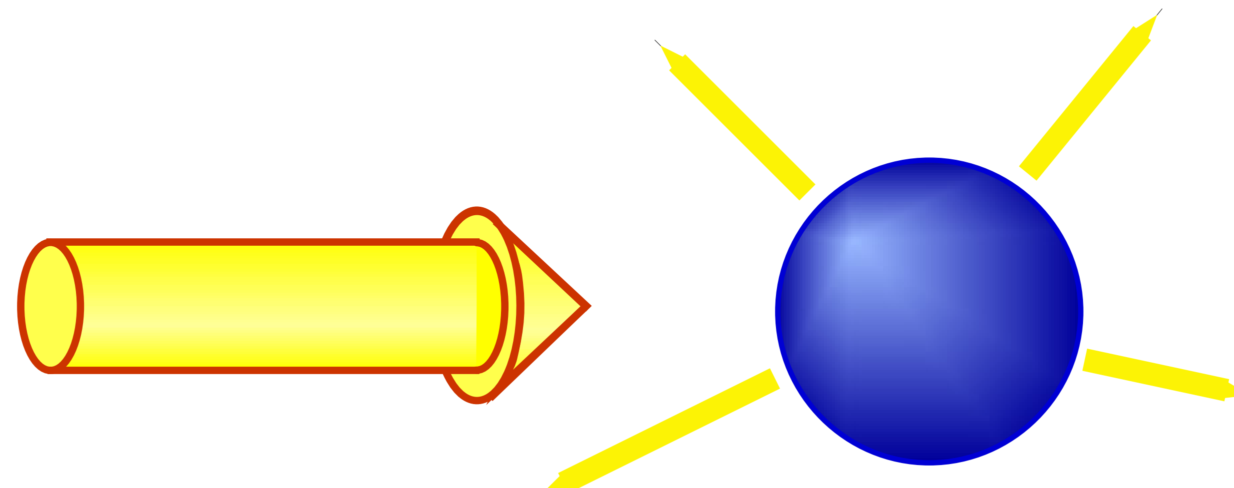
$E = \hbar\omega$
$p = \hbar k$



$E = 0$
$p = 0$



Experimental Situation

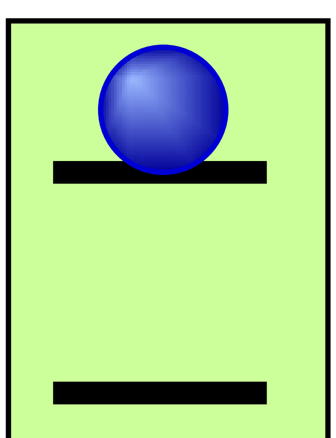


Absorption

Absorption is directional, Emission is isotropic ⇒ Force ↑↑ laserbeam, average force = 0

maximum effect: $n \leq 10^8$ cycles per second

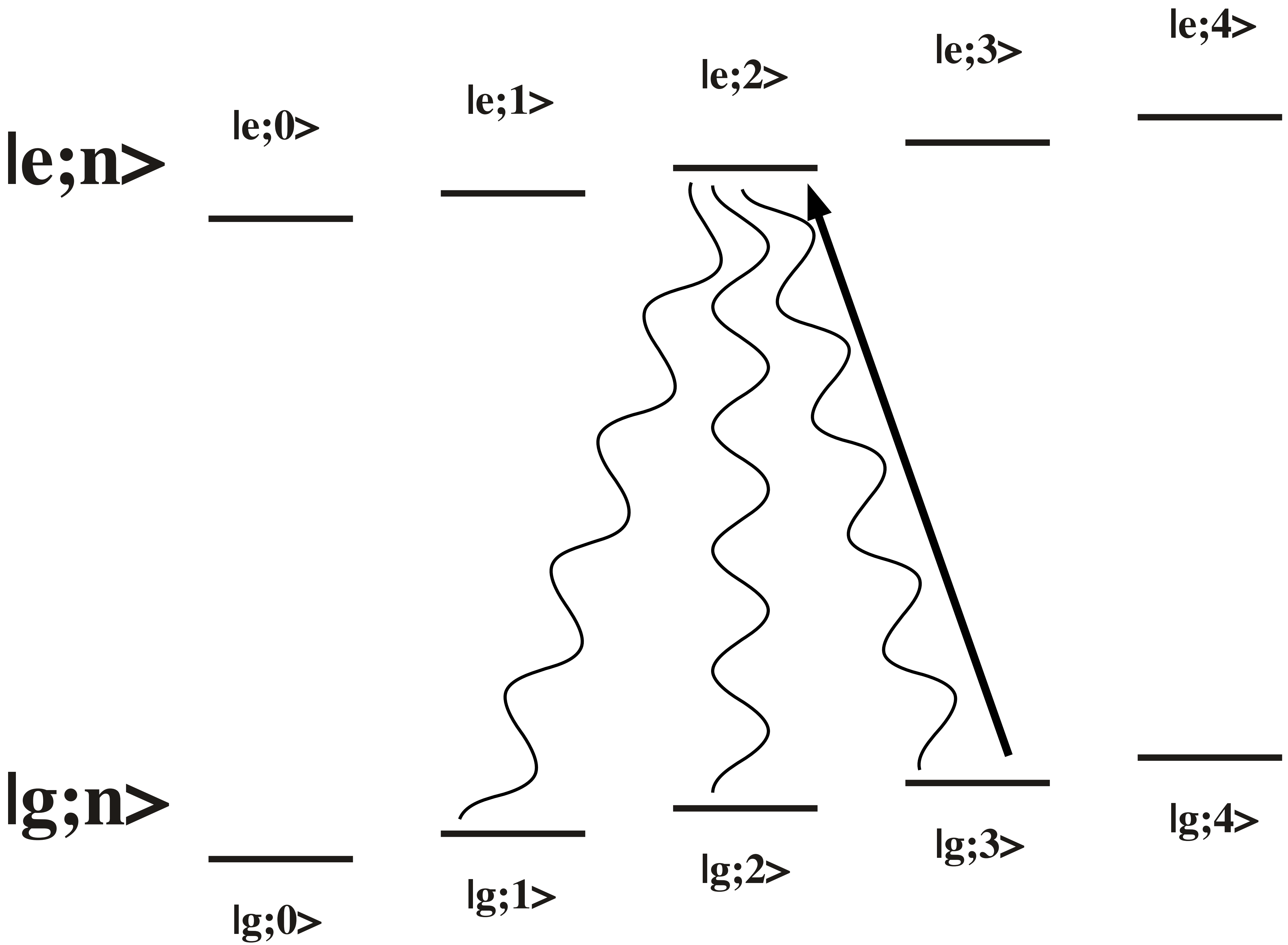
$E = \hbar\omega$
$p = \hbar k$



resulting accelaration =

$$\frac{n\,\hbar k}{\sec M_{atom}} = 1.7 \cdot 10^6 \frac{m}{\sec^2}$$

Sideband Cooling

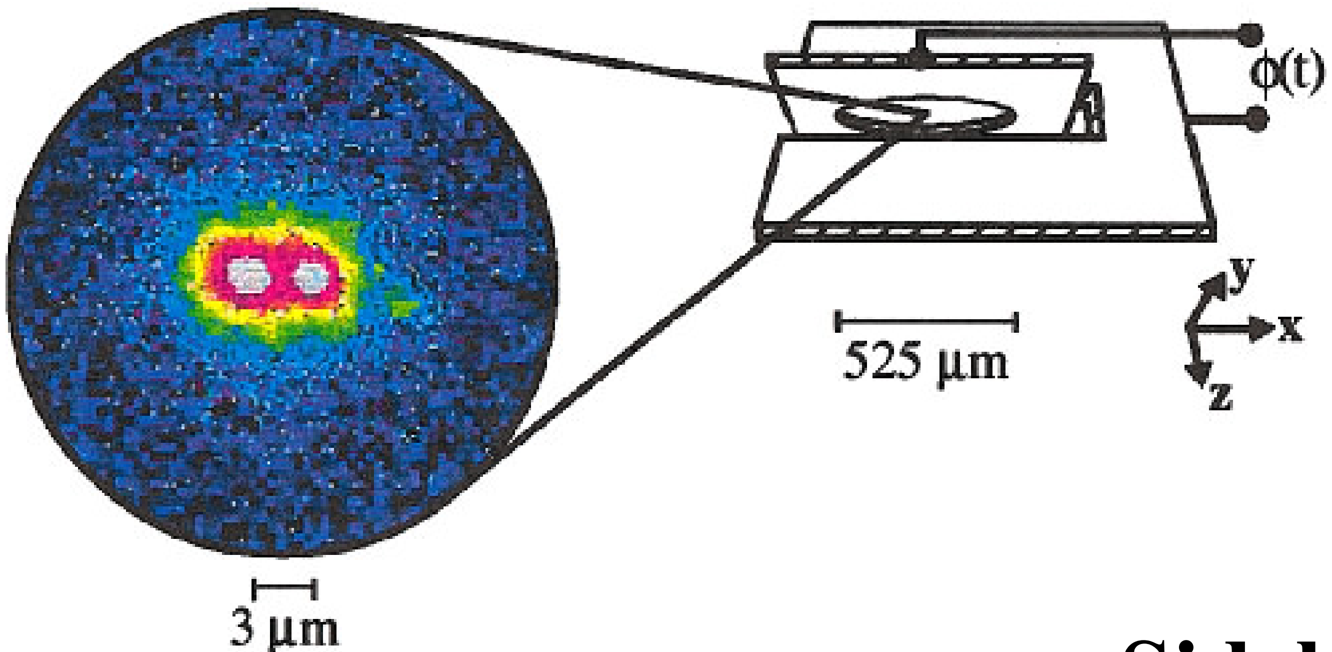


Use Raman pulses to eliminate Doppler broadening

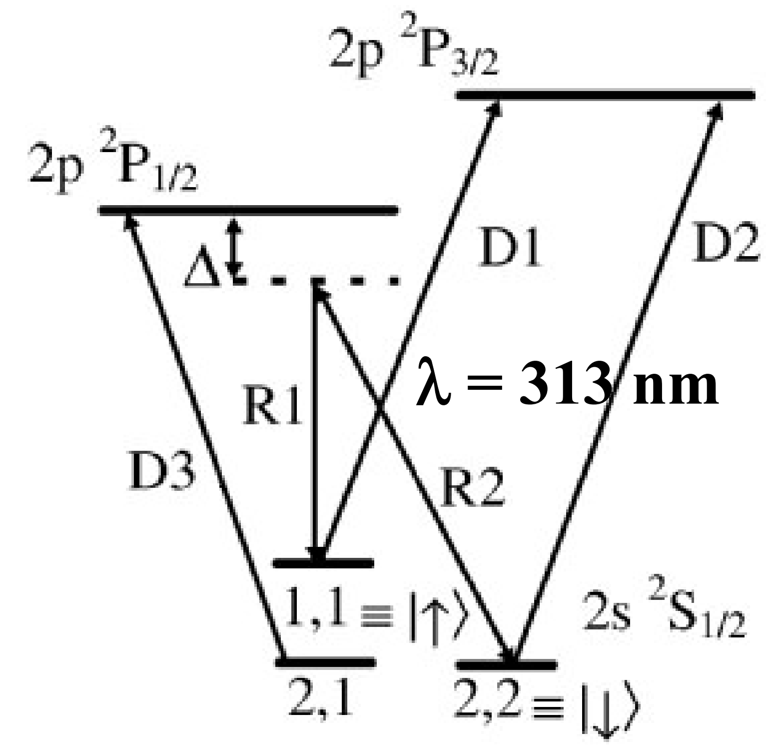
Sideband Cooling

$^9Be^+$

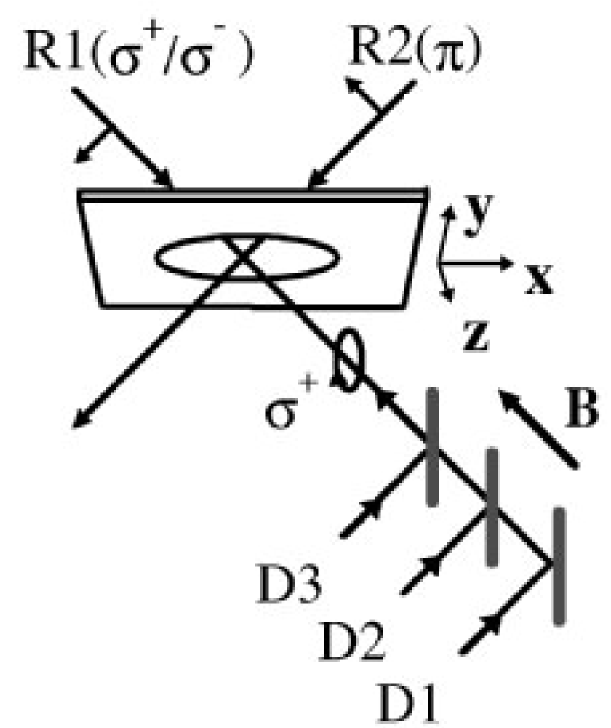
Microtrap : $(\omega_x, \omega_y, \omega_z)$ = (8.6, 17.6, 9.3) MHz



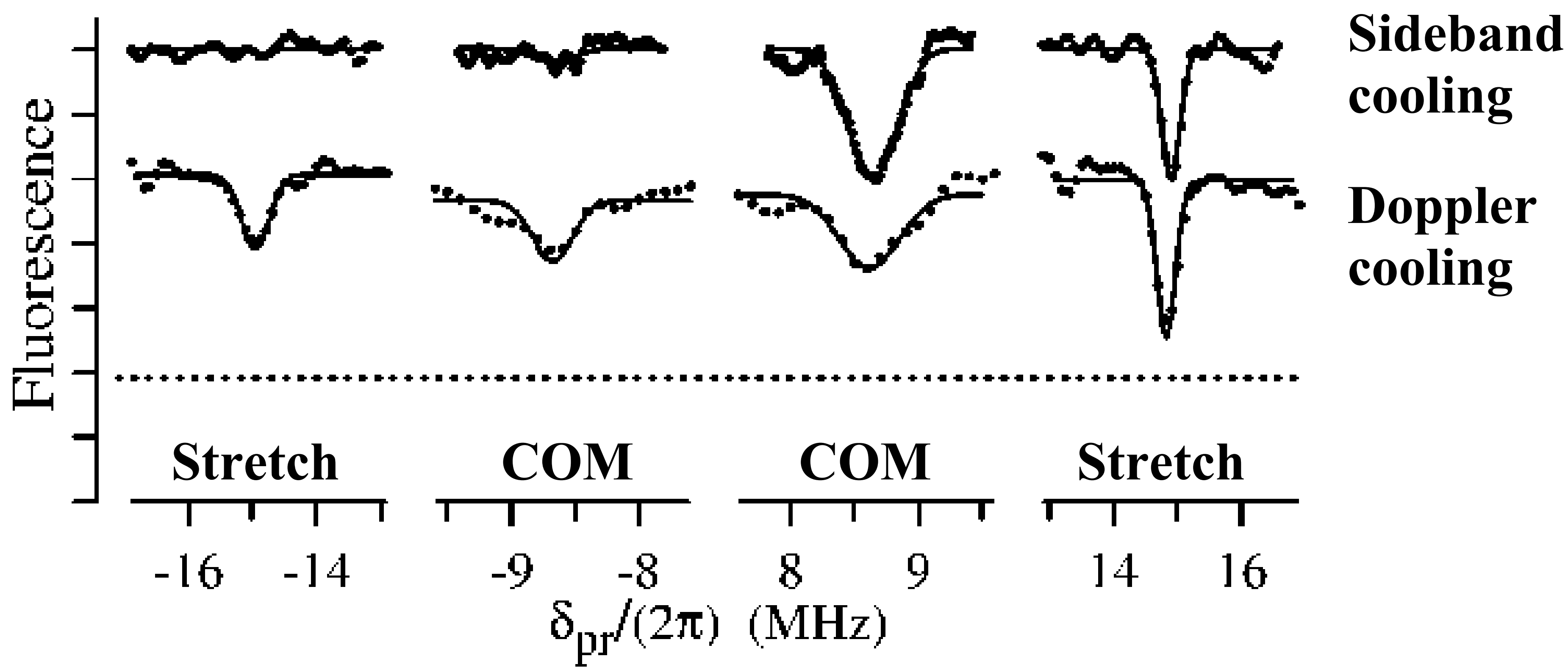
Transitions:



Cooling:

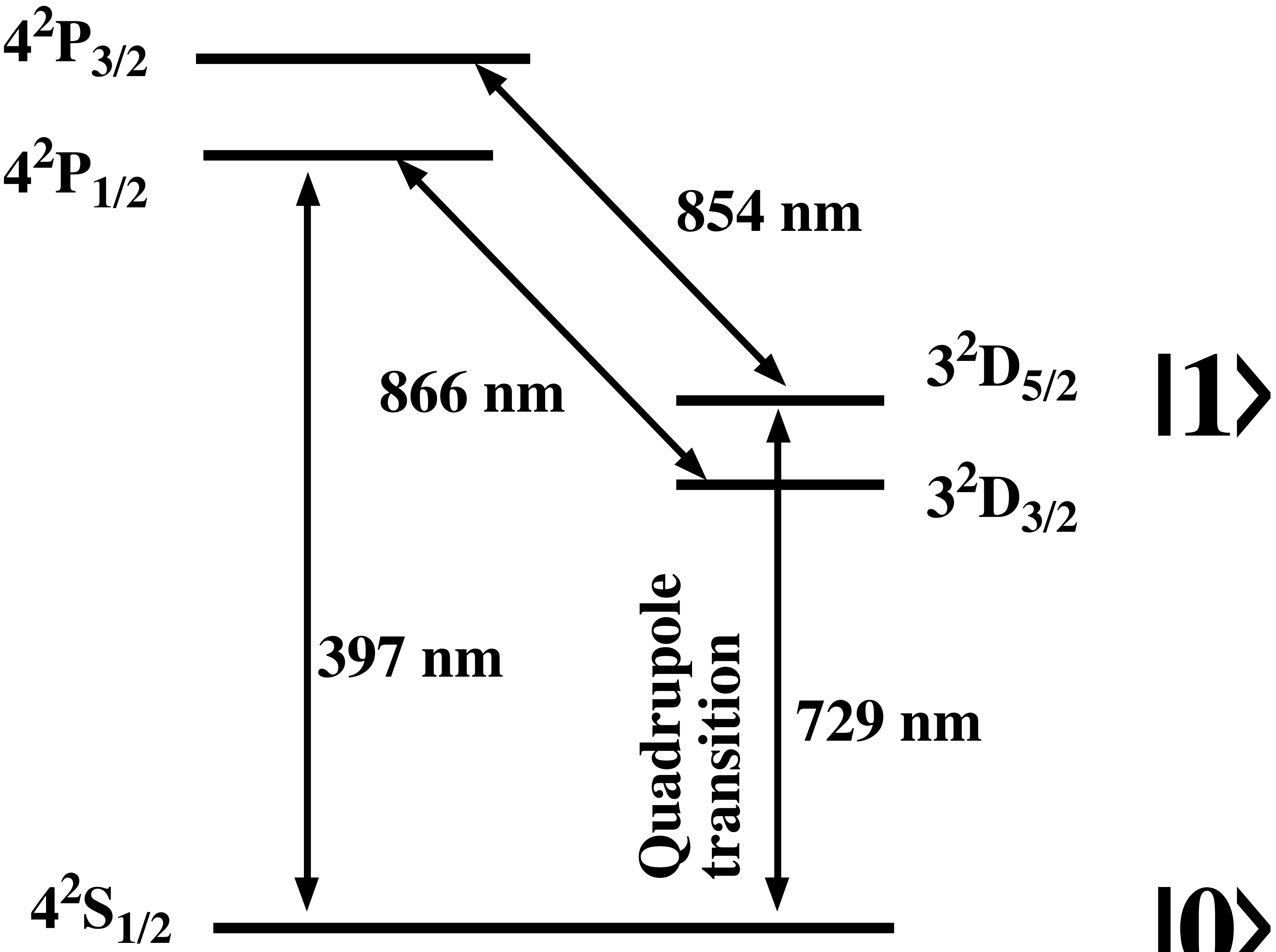


Sidebands:



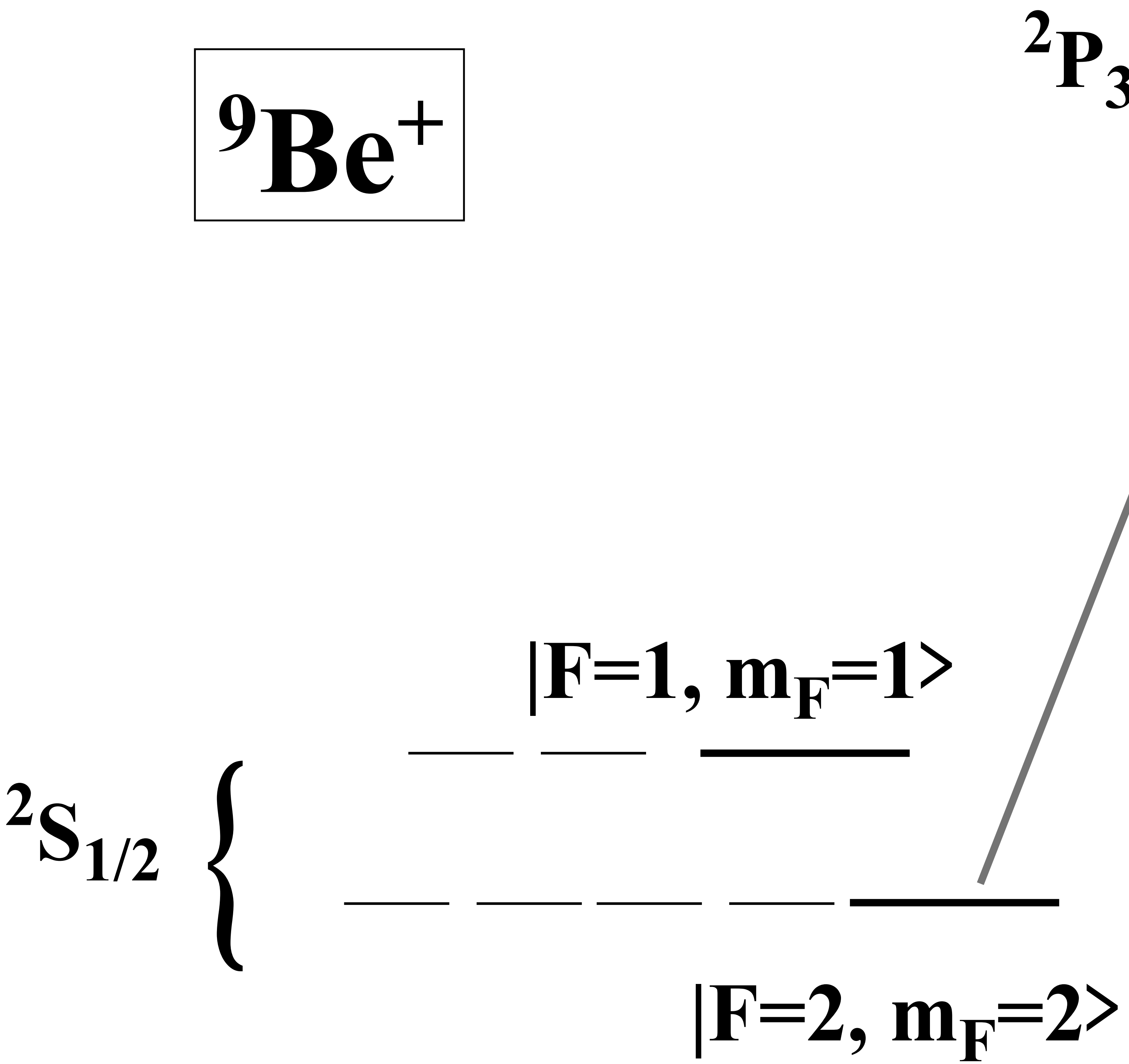
King et al., PRL 81, 1525 (1998).

Ca^+ Qubit



$4^2P_{3/2}$
$4^2P_{1/2}$
854 nm
866 nm
$3^2D_{5/2}$
$|1\rangle$
$3^2D_{3/2}$
397 nm
Quadrupole transition
729 nm
$4^2S_{1/2}$
$|0\rangle$

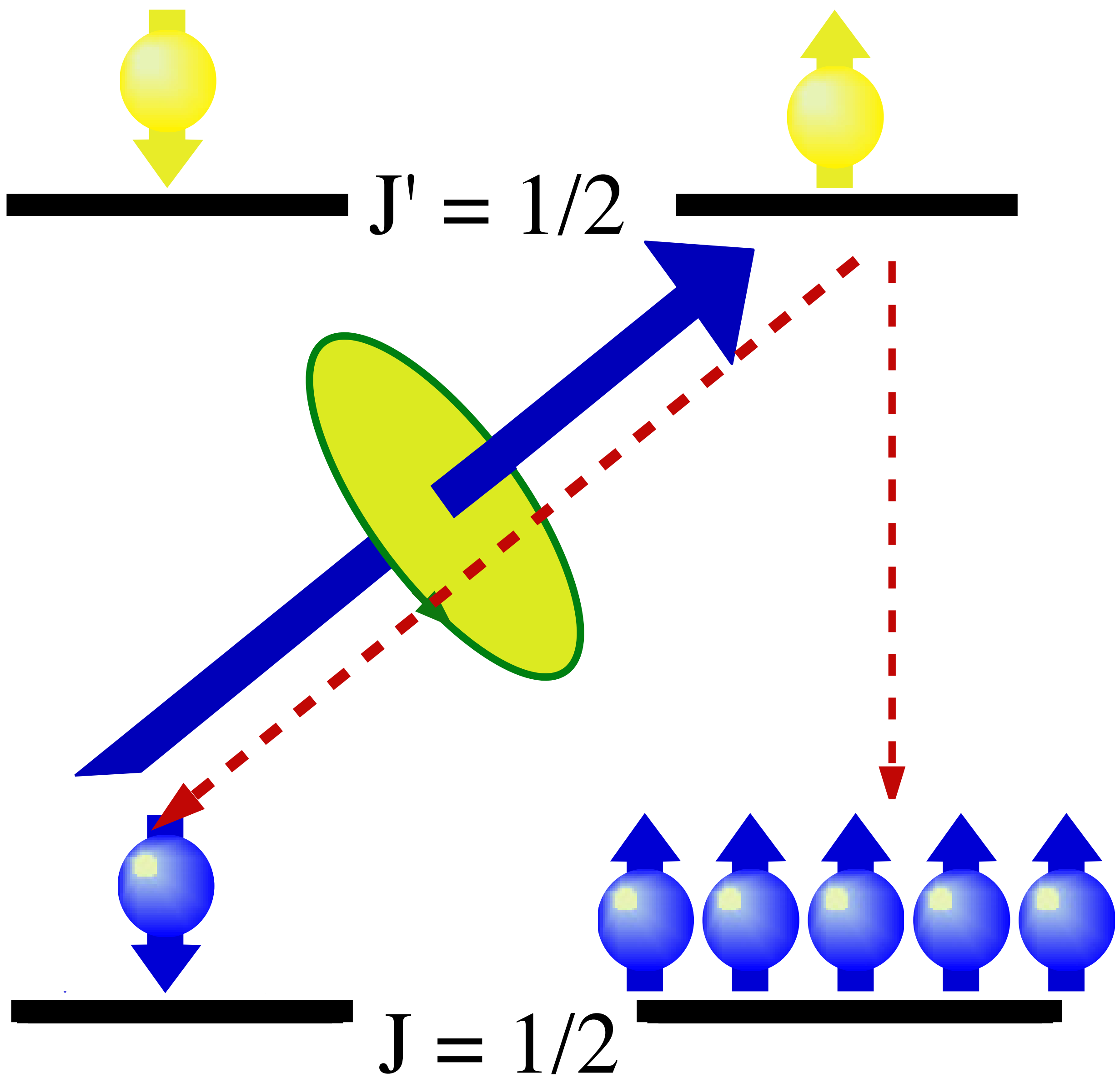
Be^+ Qubit



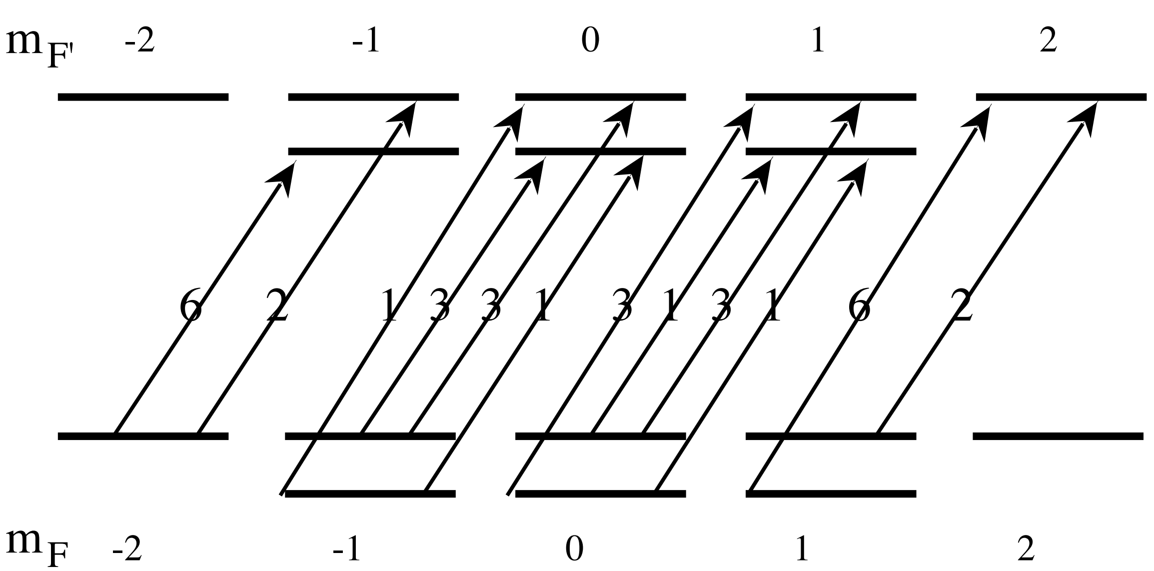
Optical Pumping

Principle:

A. Kastler, J. Phys. ***11***, *255 (1950)*

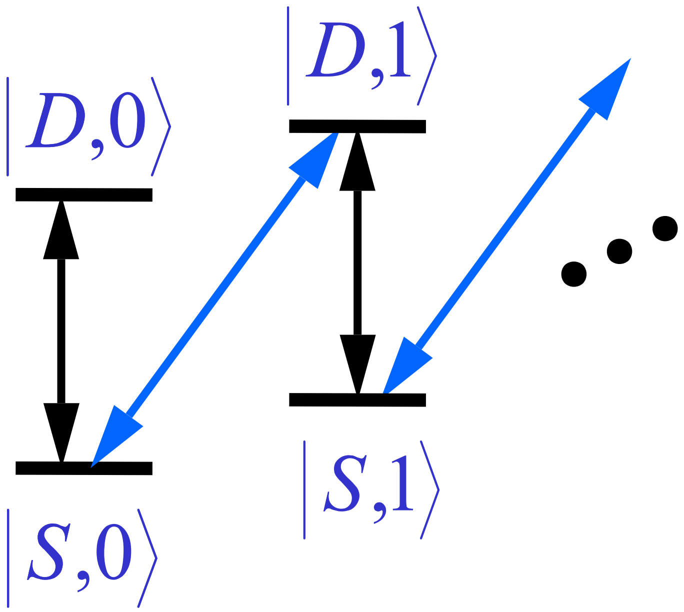


Multilevel system:



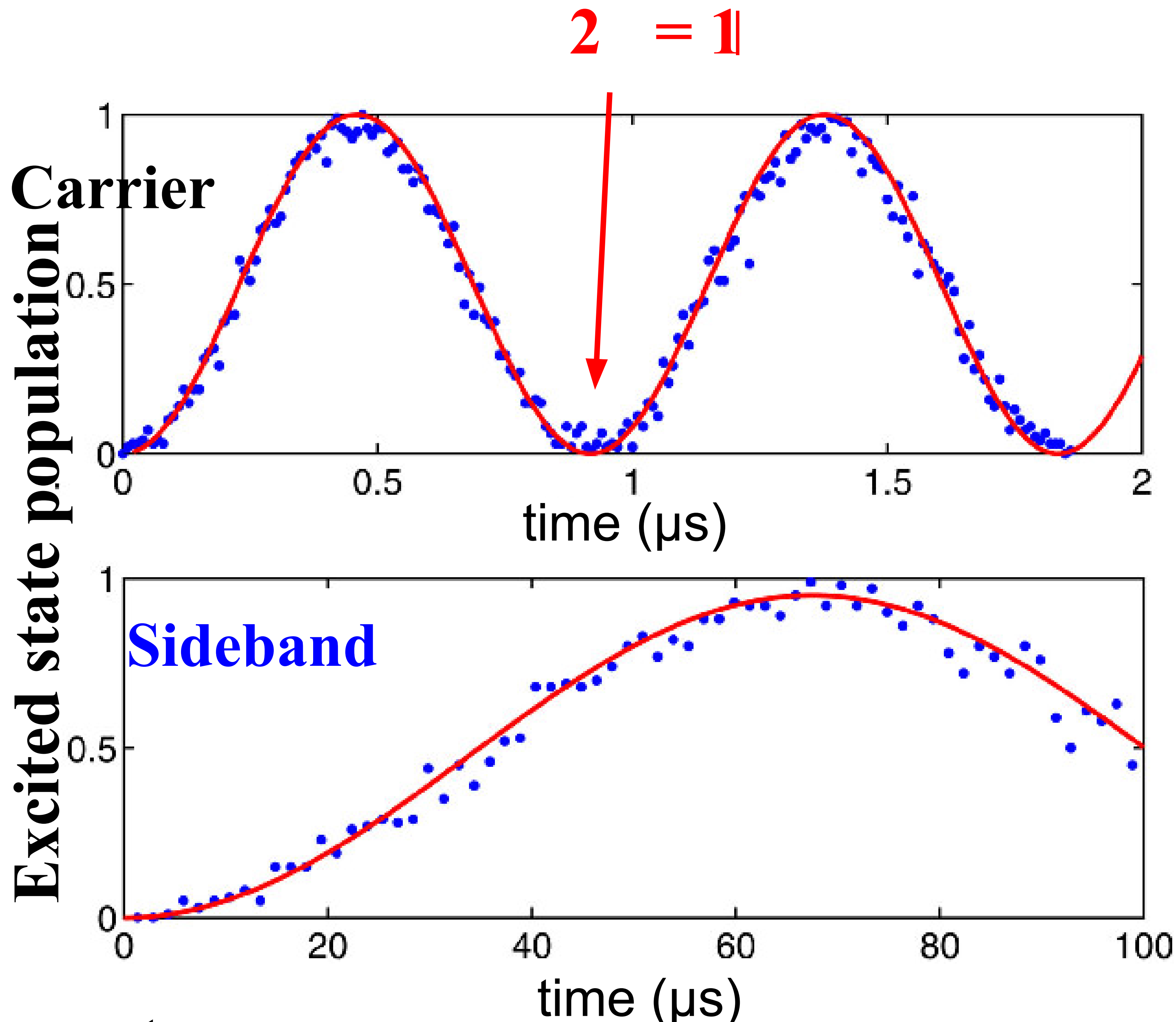
Two Qubit Gate

$^{40}Ca^+$



carrier and sideband
Rabi oscillations
with Rabi frequencies

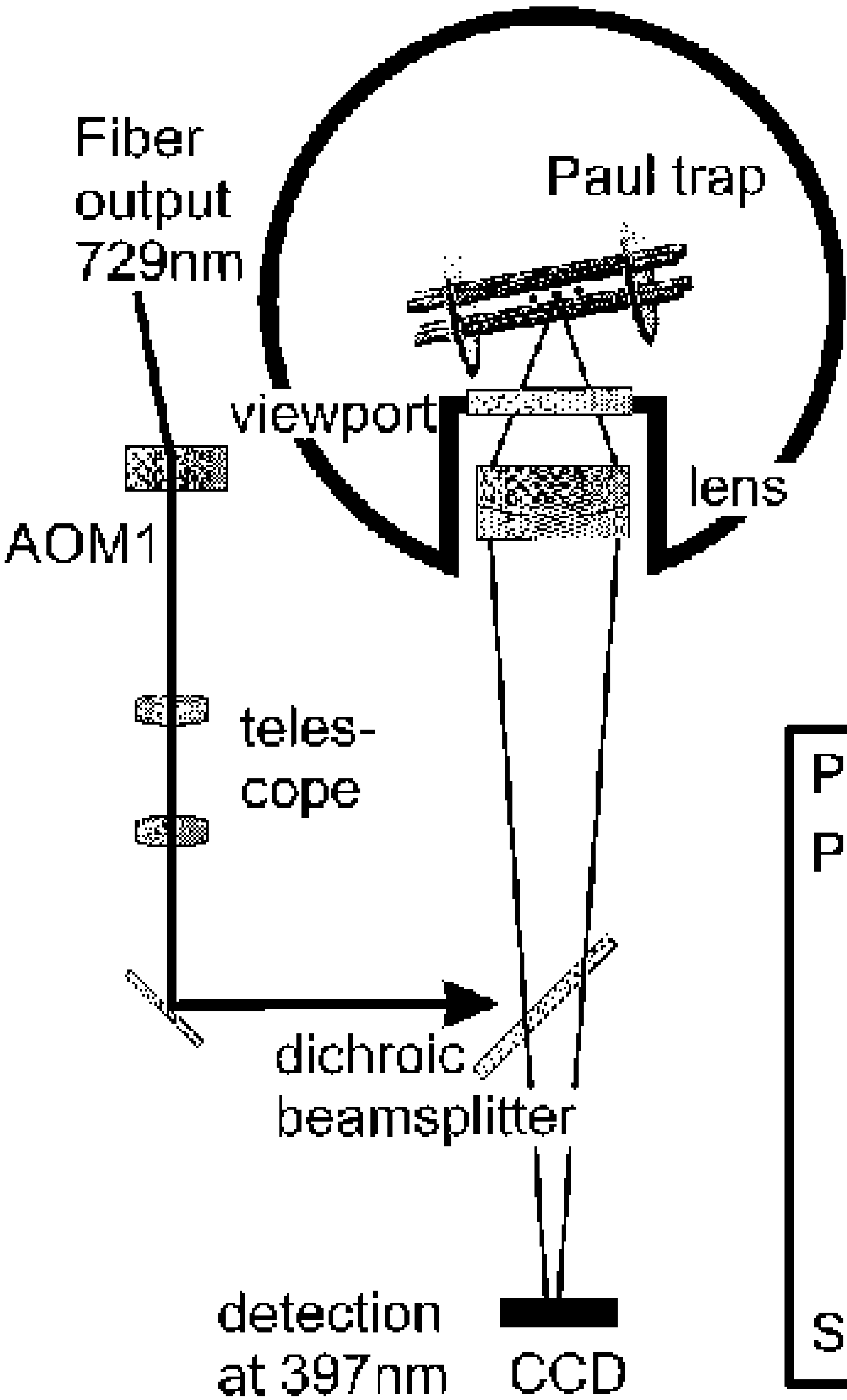
$$\Omega, \quad \eta\Omega\sqrt{n+1}$$

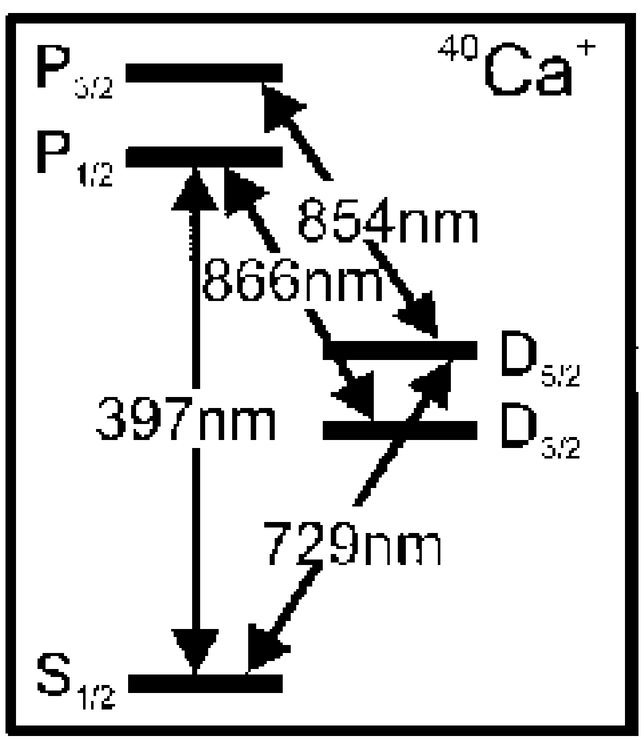


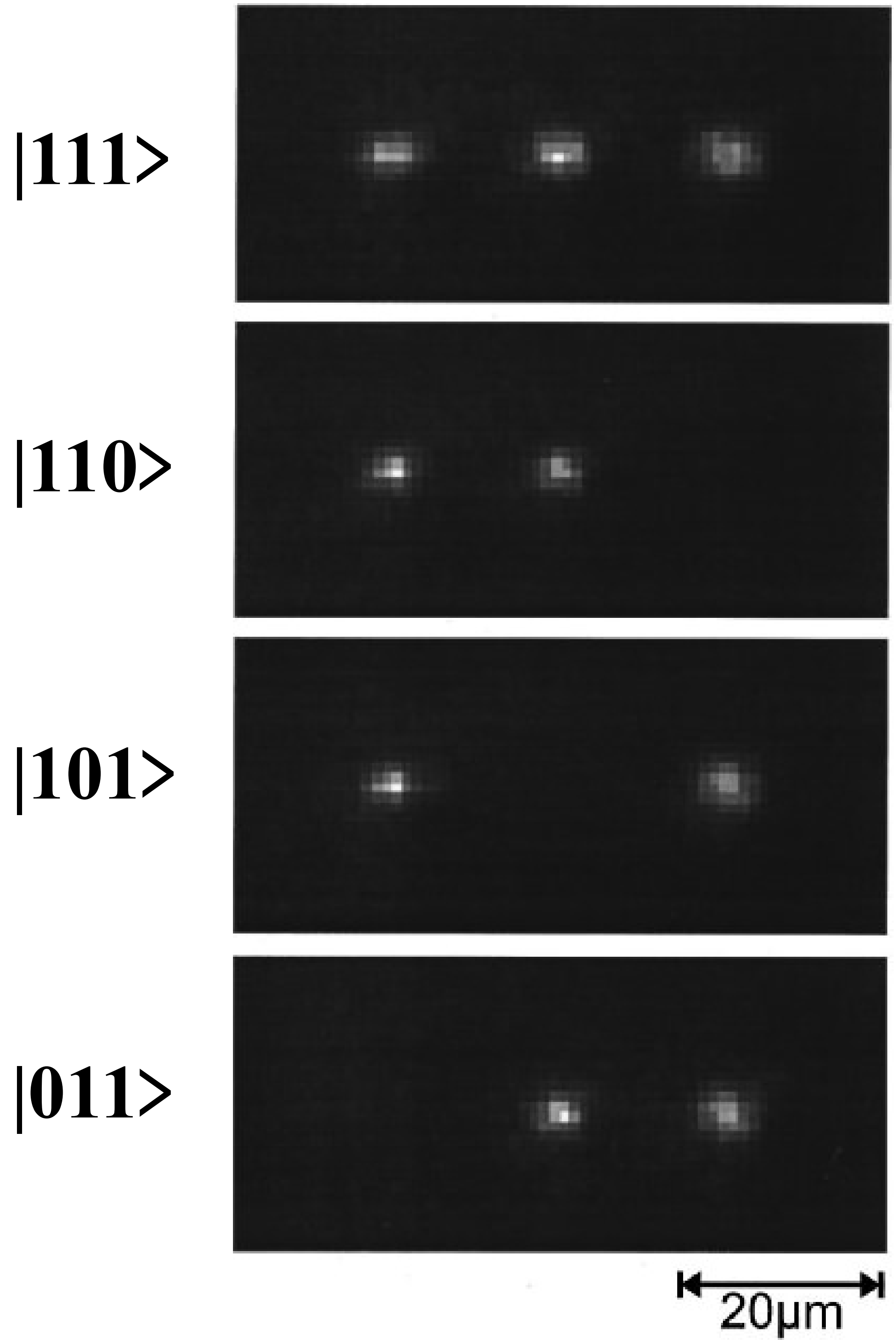
$\eta = kx_0$ Lamb-Dicke parameter

R. Blatt, Innsbruck

Addressing

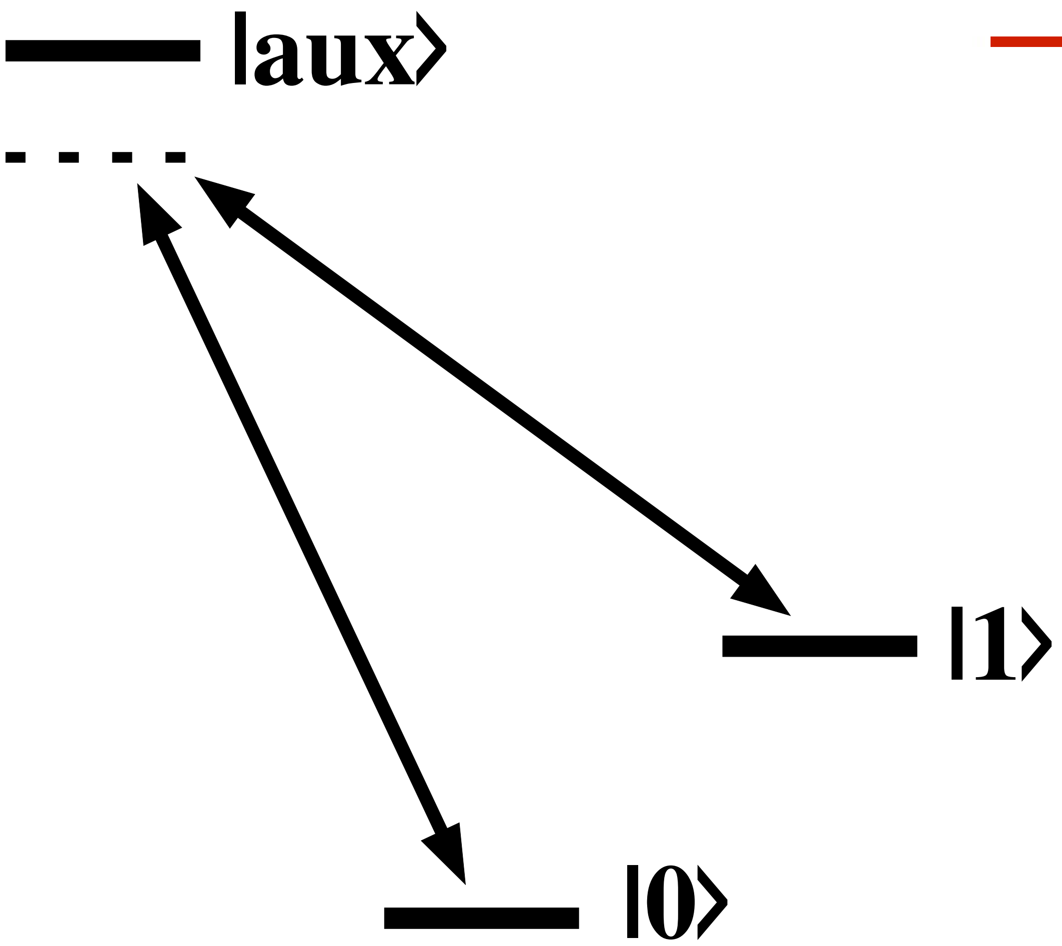


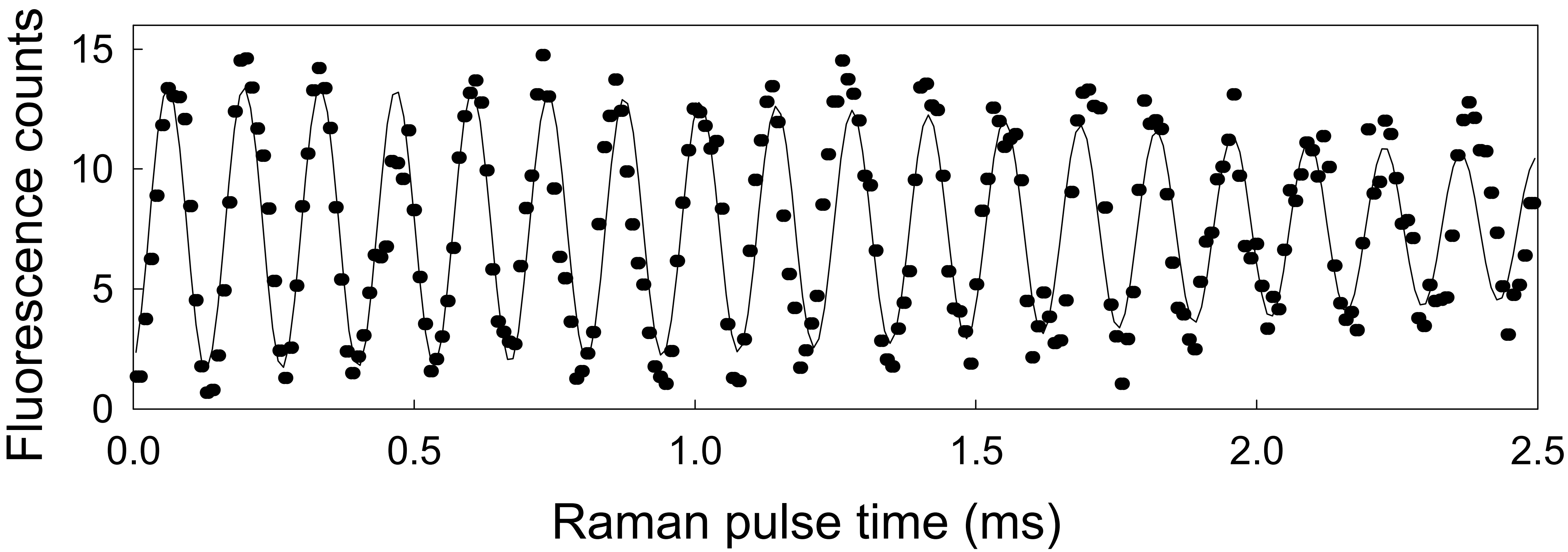




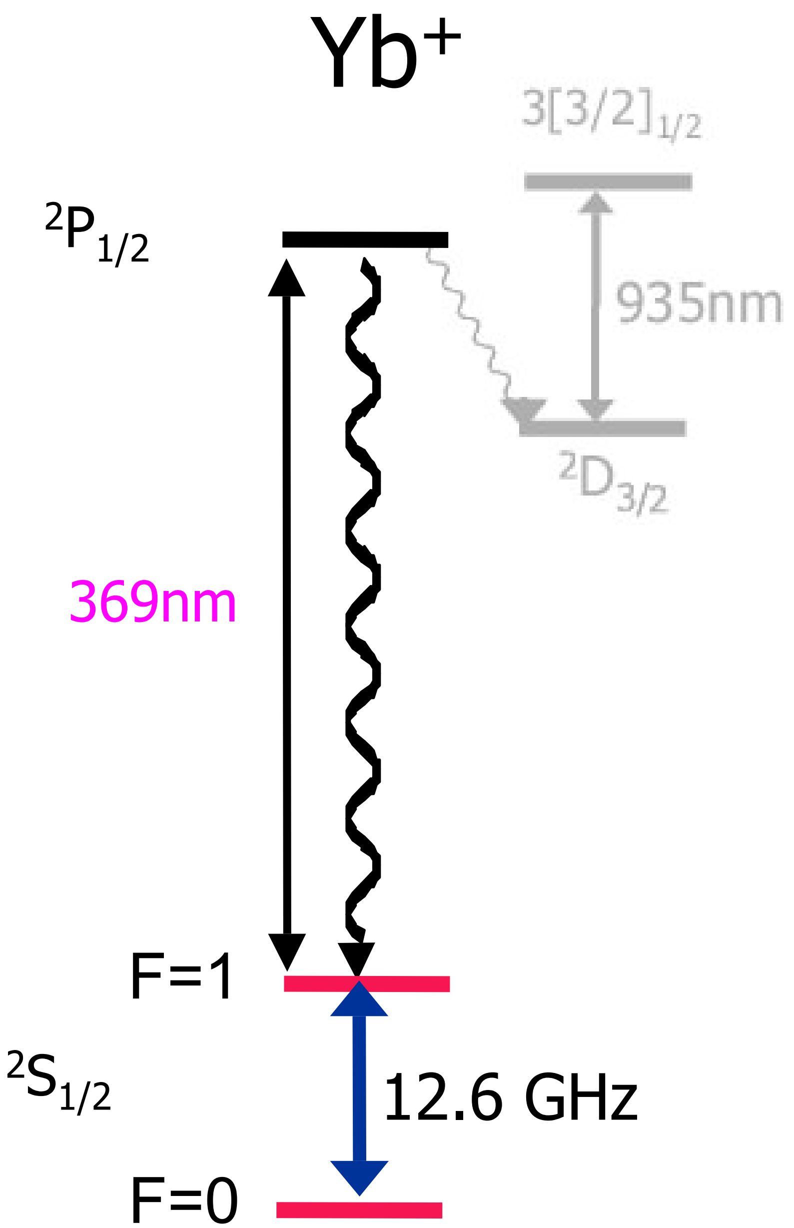
Nägerl et al., PRA <u>60</u>, 145 (1999).

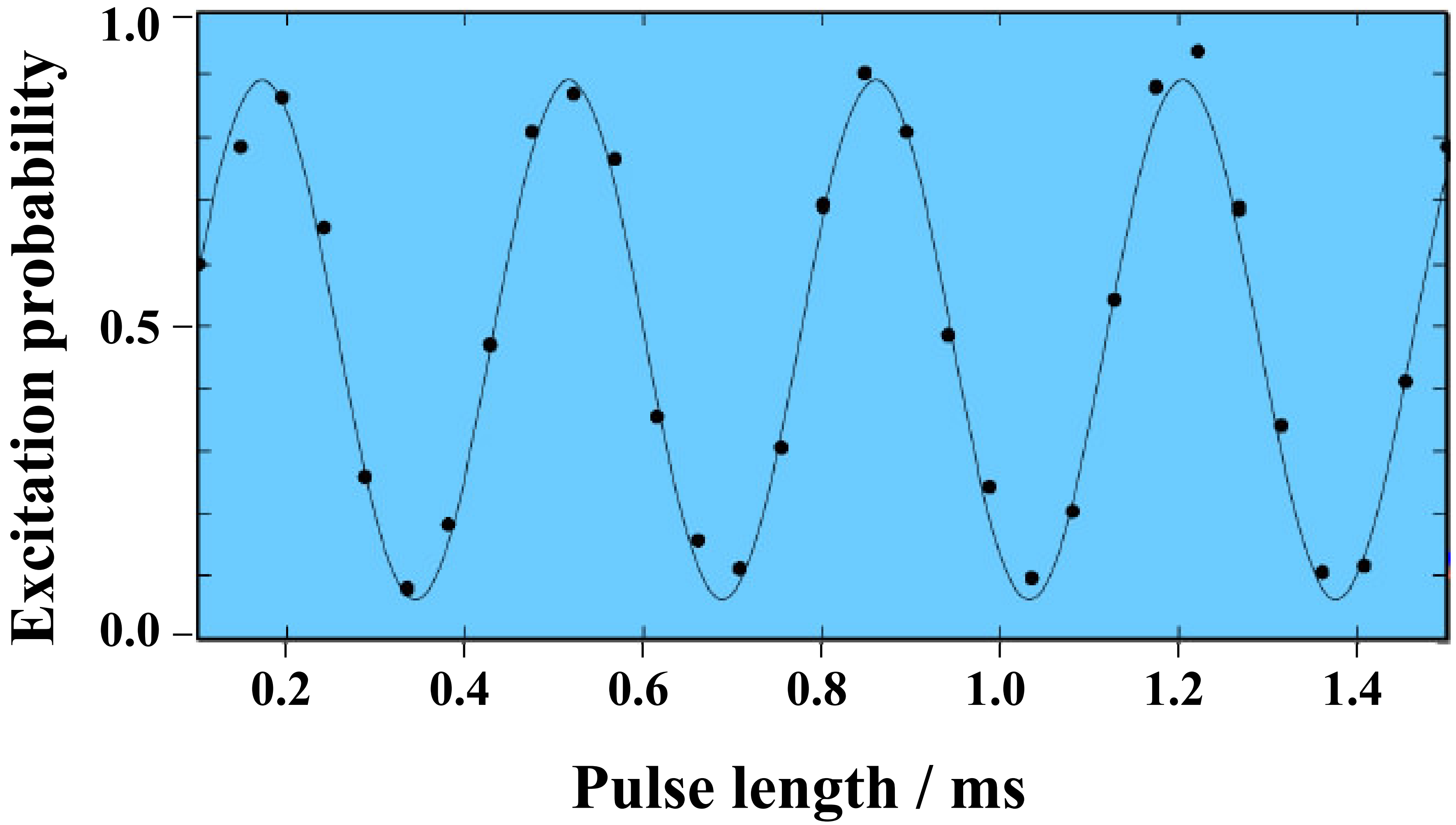
Raman Laser Pulse



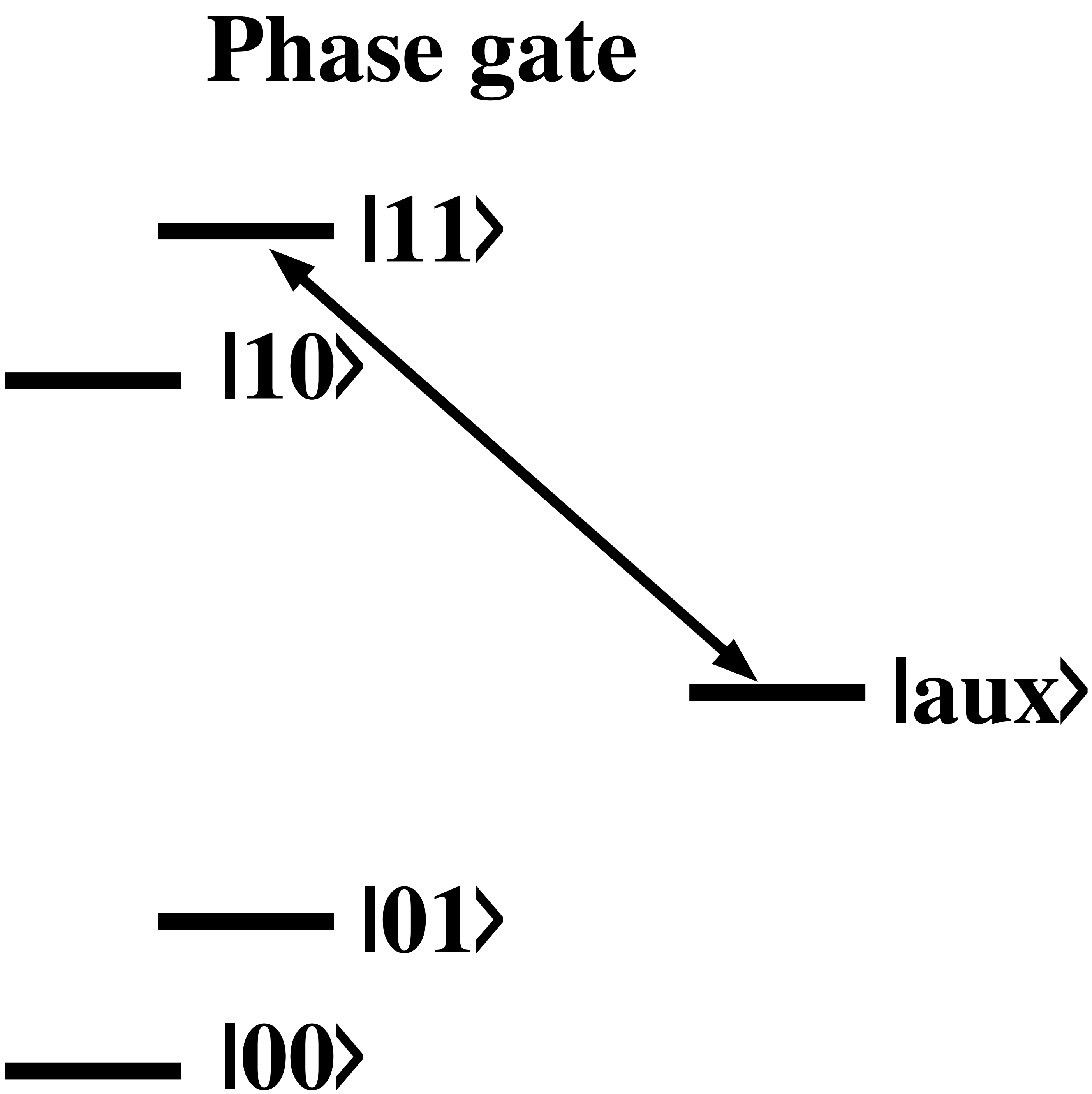


Microwave Pulse



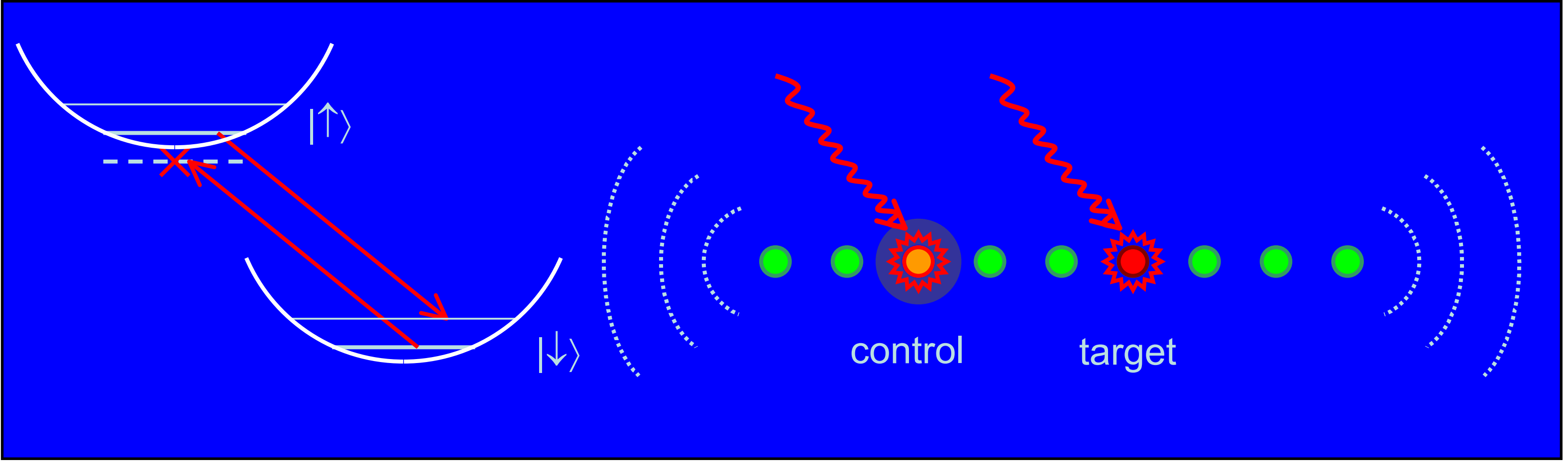


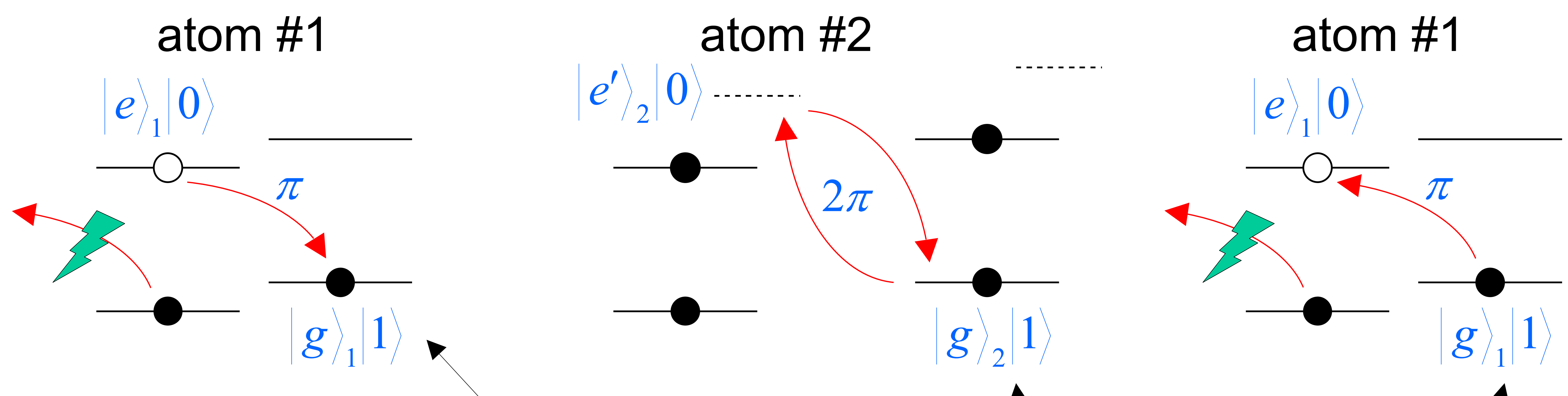
Two Qubit Gates



C Phase

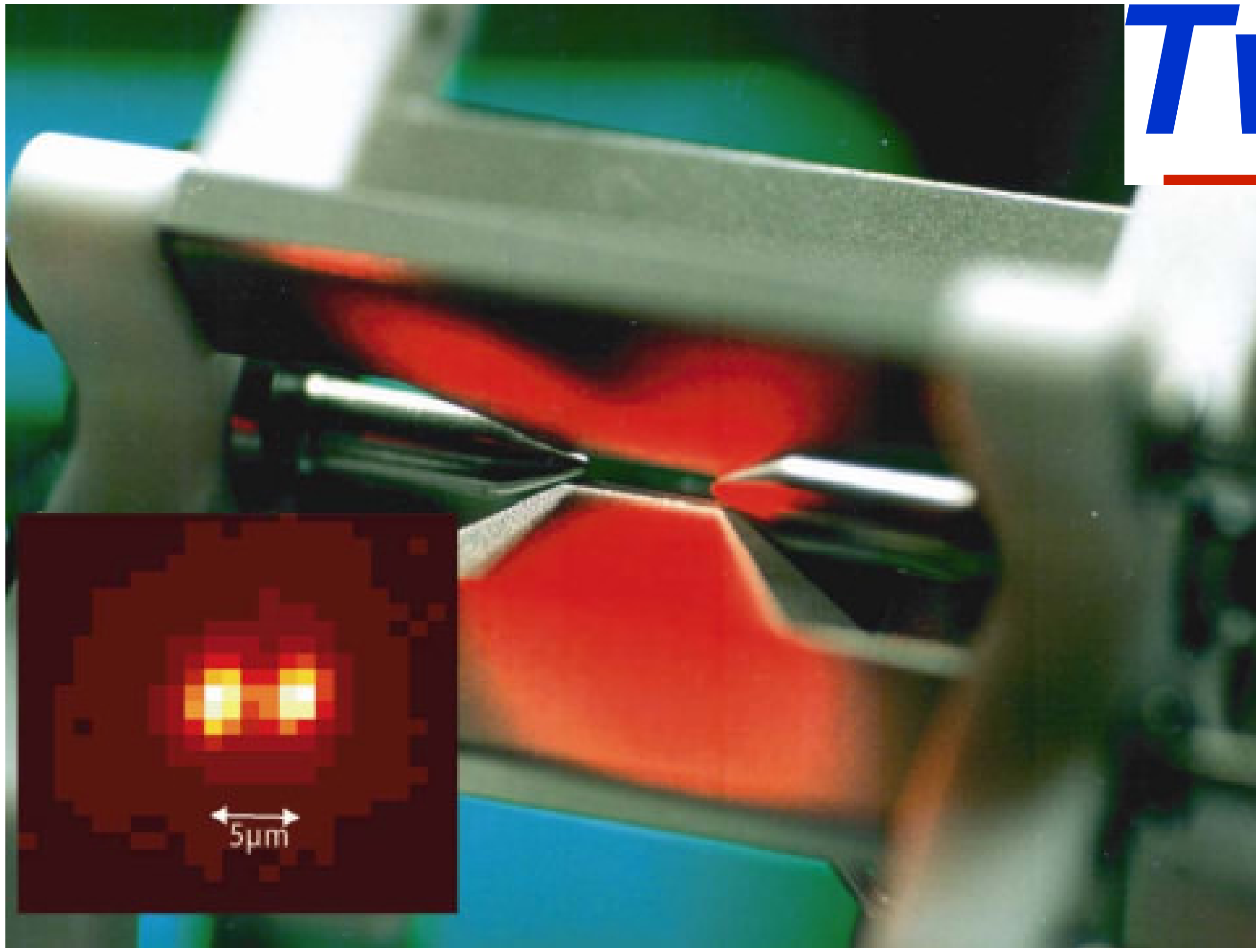
Cirac & Zoller, PRL 74, 4091 (1995)

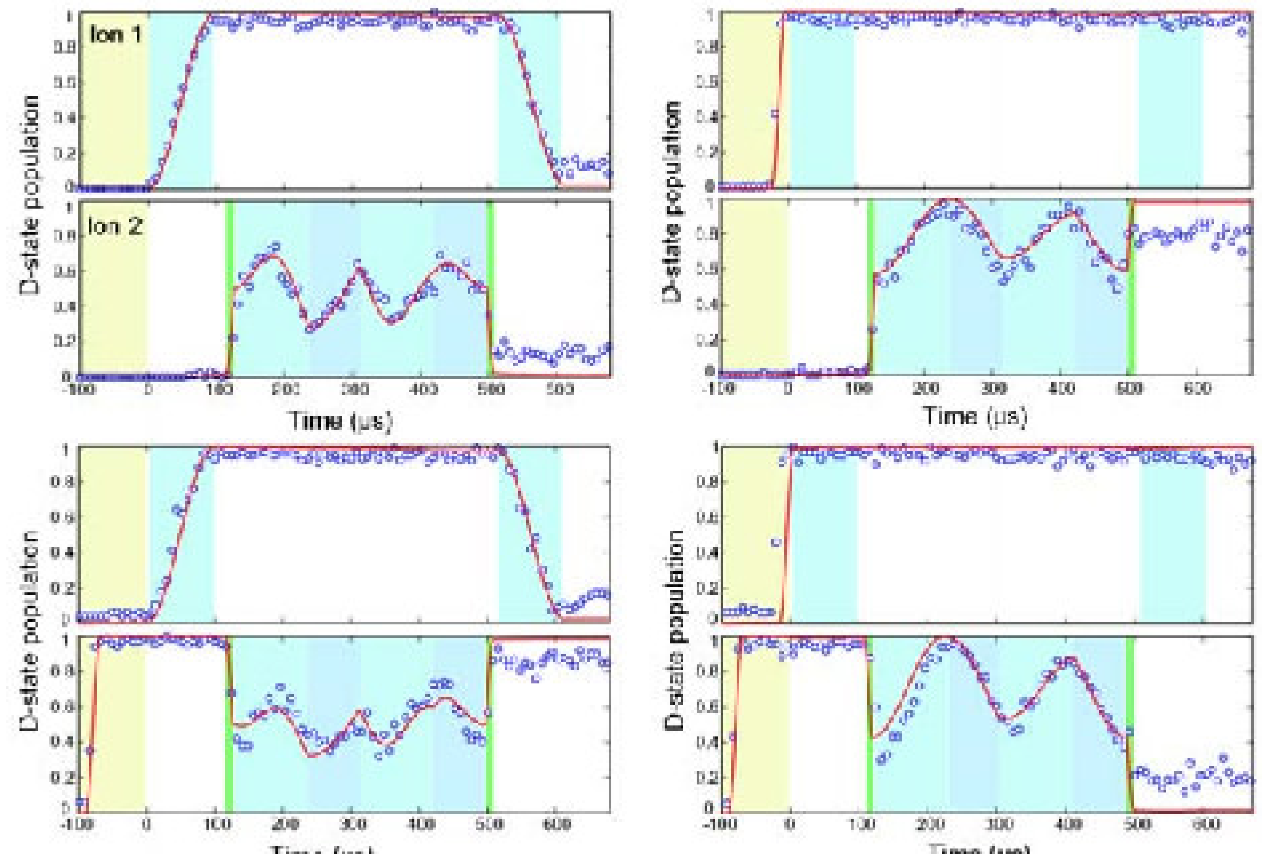


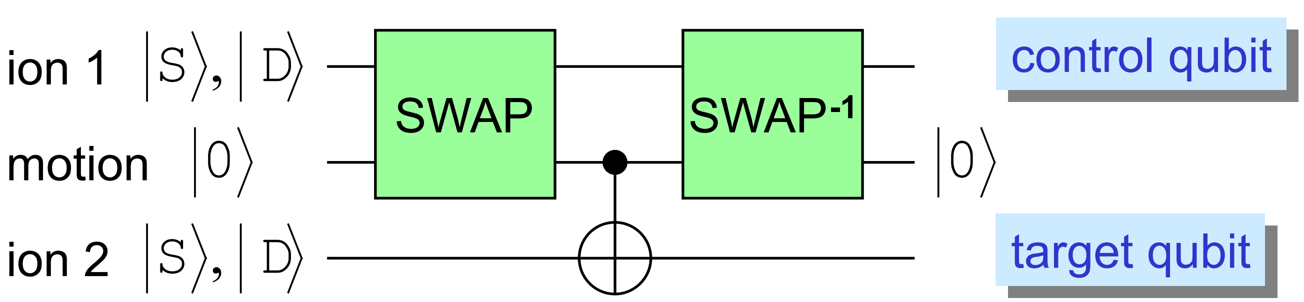


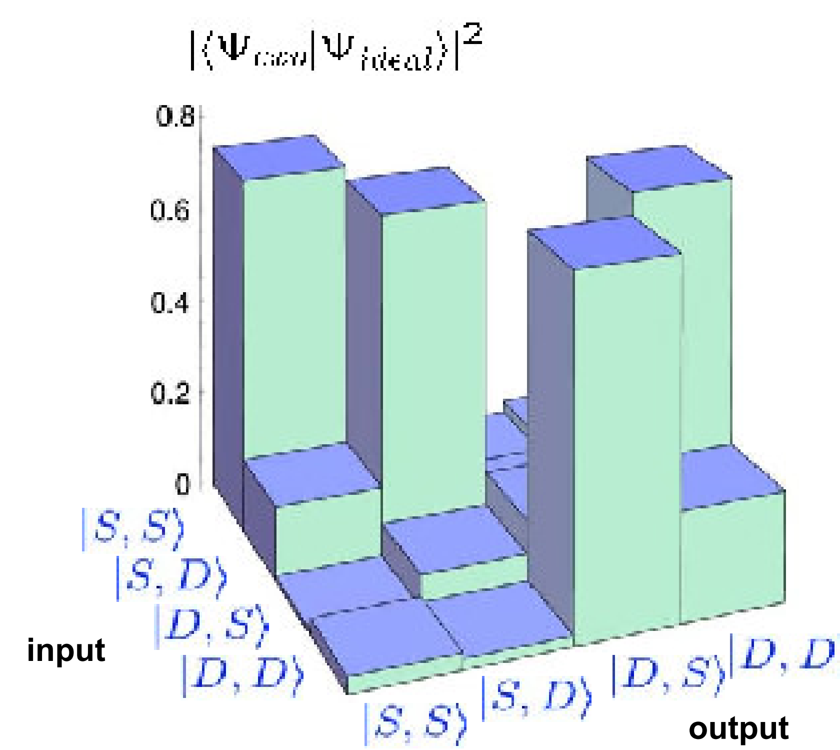
qubits	initialize	after 1st π-pulse lower sideband	after 2π-pulse to auxiliary state	after 2nd π-pulse lower sideband
00	$\|gg\rangle\|0\rangle$	$\|gg\rangle\|0\rangle$	$\|gg\rangle\|0\rangle$	$\|gg\rangle\|0\rangle$
10	$\|eg\rangle\|0\rangle$	$\|eg\rangle\|0\rangle$	$\|eg\rangle\|0\rangle$	$\|eg\rangle\|0\rangle$
01	$\|ge\rangle\|0\rangle$	$-i\|gg\rangle\|1\rangle$	$+i\|gg\rangle\|1\rangle$	$\|ge\rangle\|0\rangle$
11	$\|ee\rangle\|0\rangle$	$-i\|eg\rangle\|1\rangle$	$-i\|eg\rangle\|1\rangle$	$-\|ee\rangle\|0\rangle$

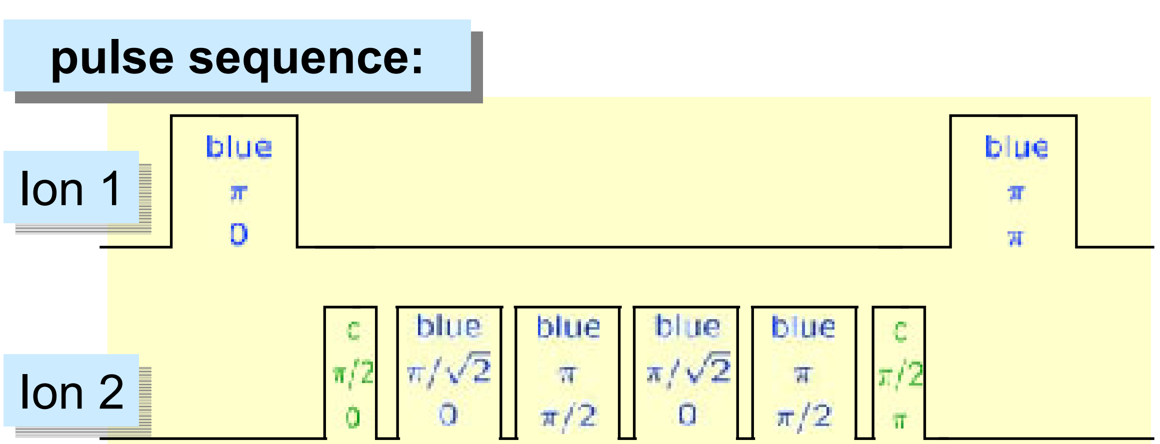
Two Qubit Gates





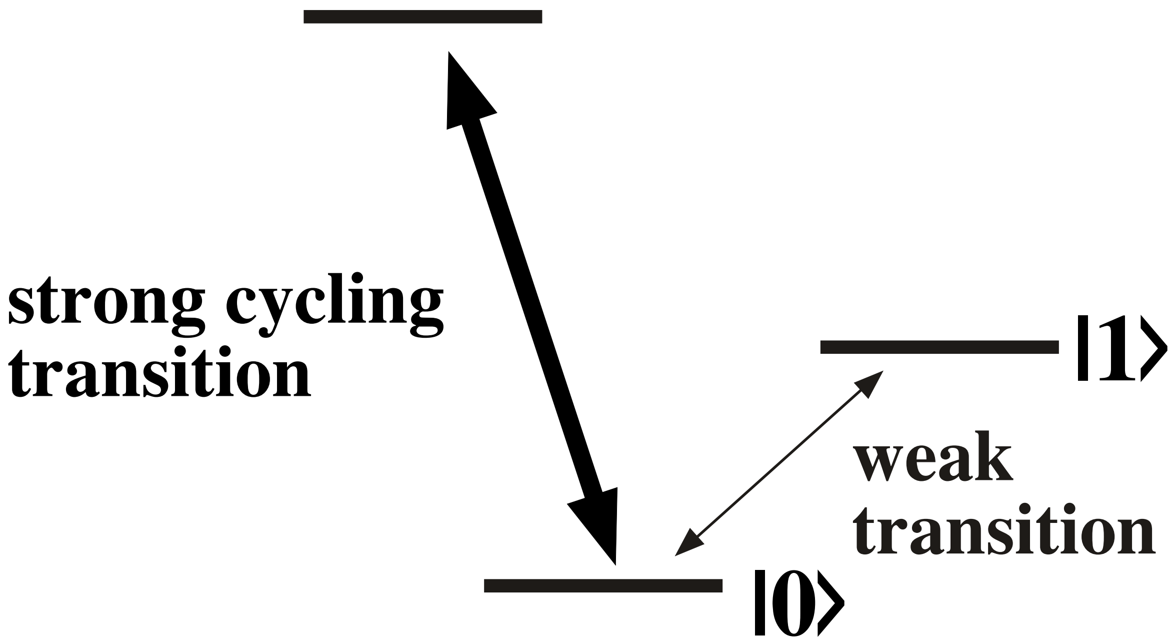




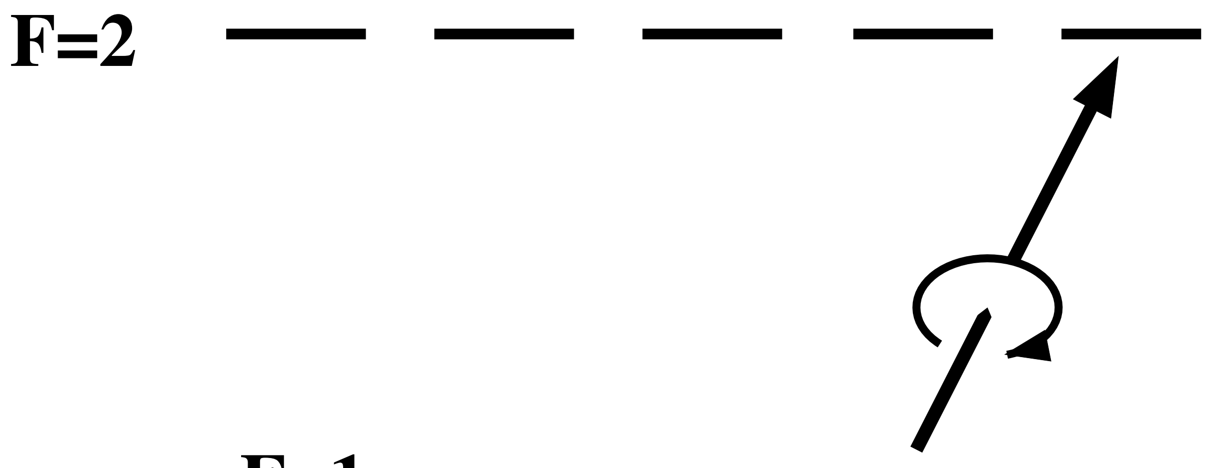


Schmidt-Kaler et al., Nature 422, 408 (2003)

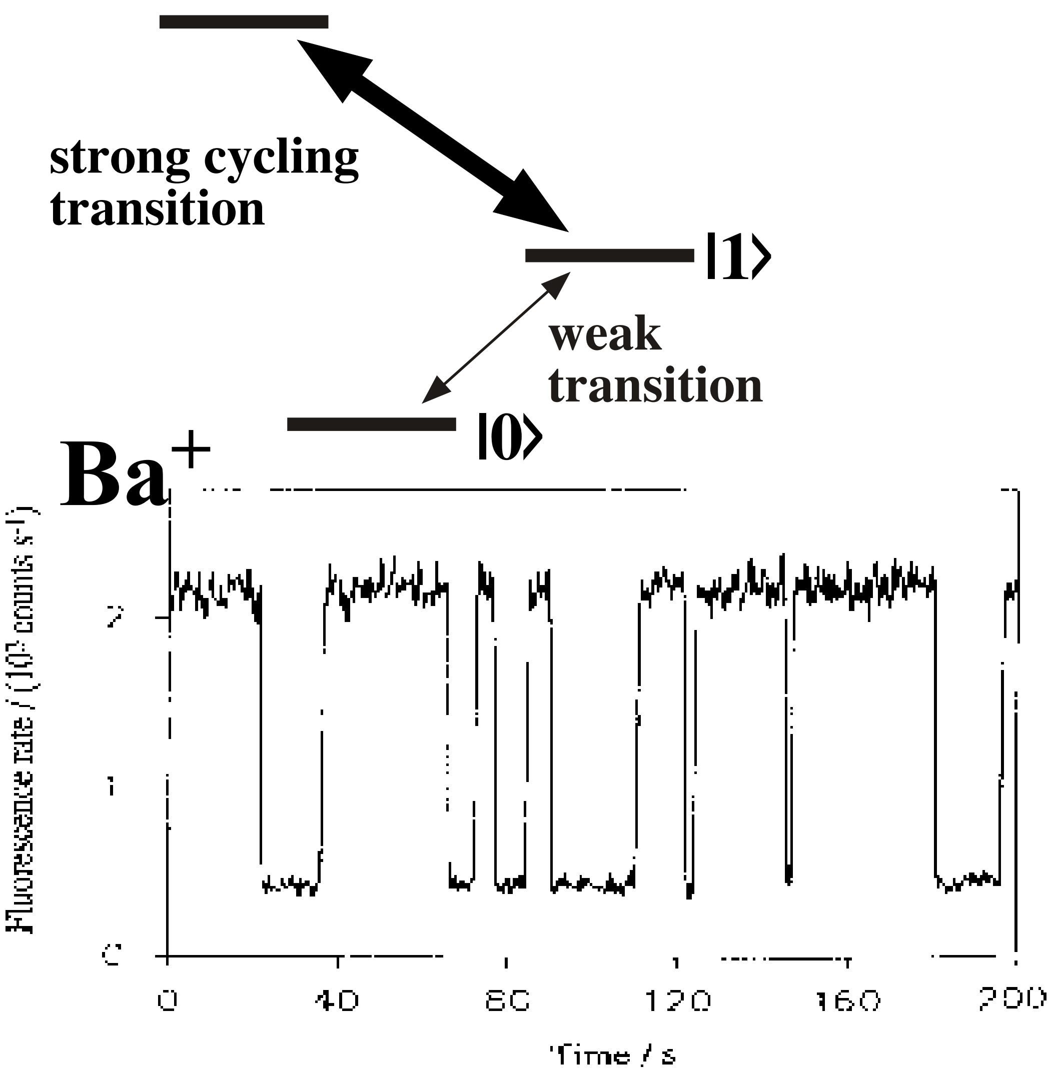
Readout

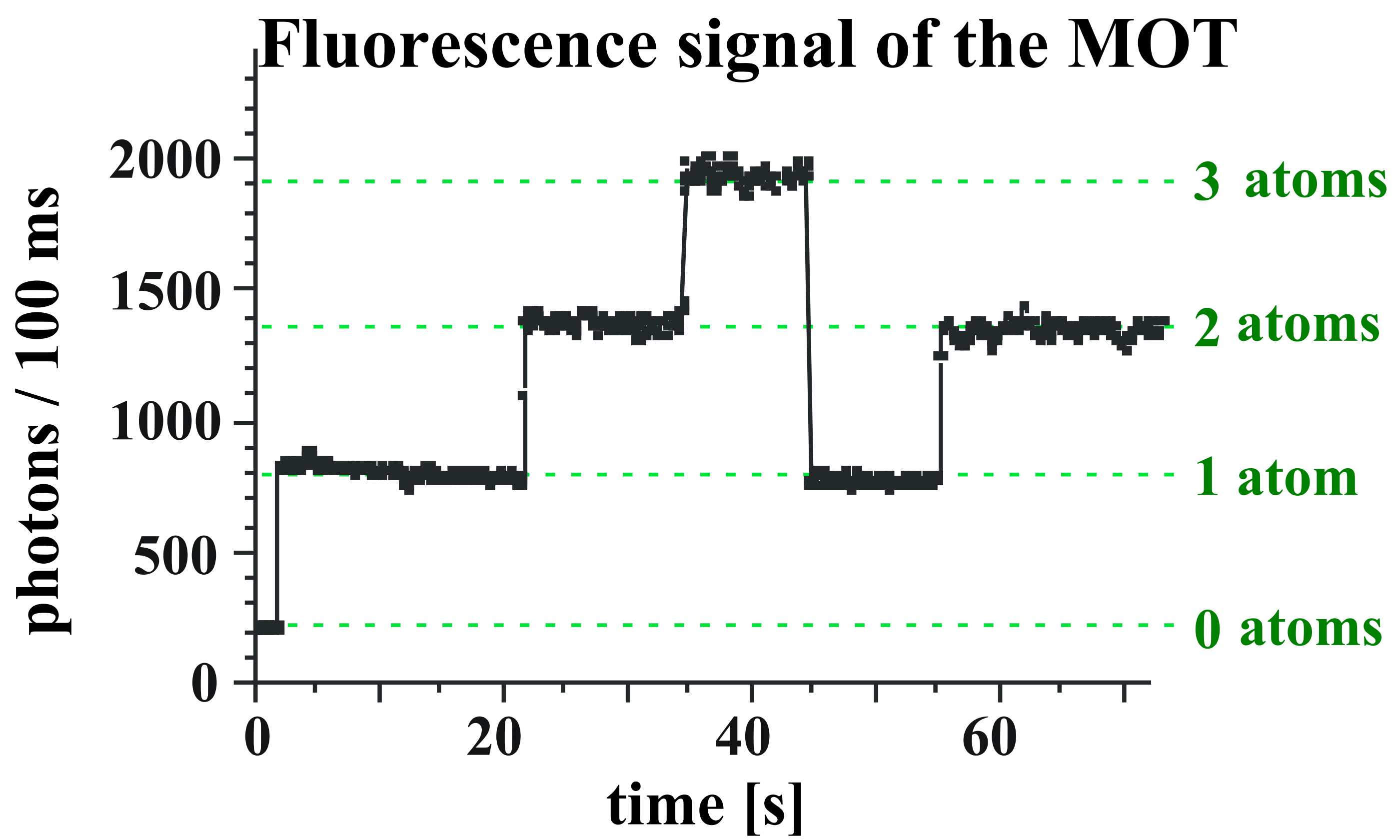


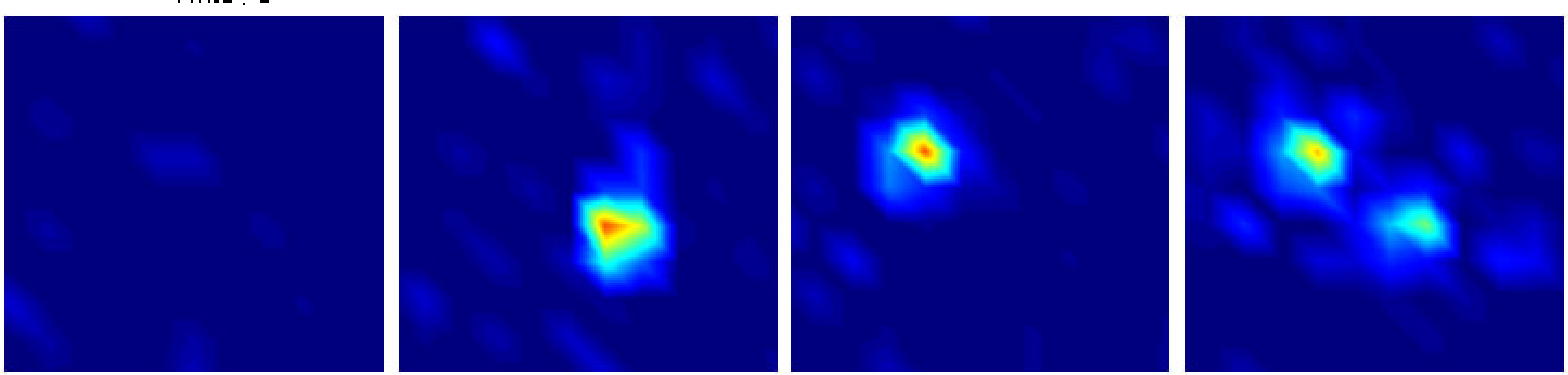
Cycling transition



Fluorescence of Single Ion







|00> |01> |10> |11>

5 Qubit Quantum Register

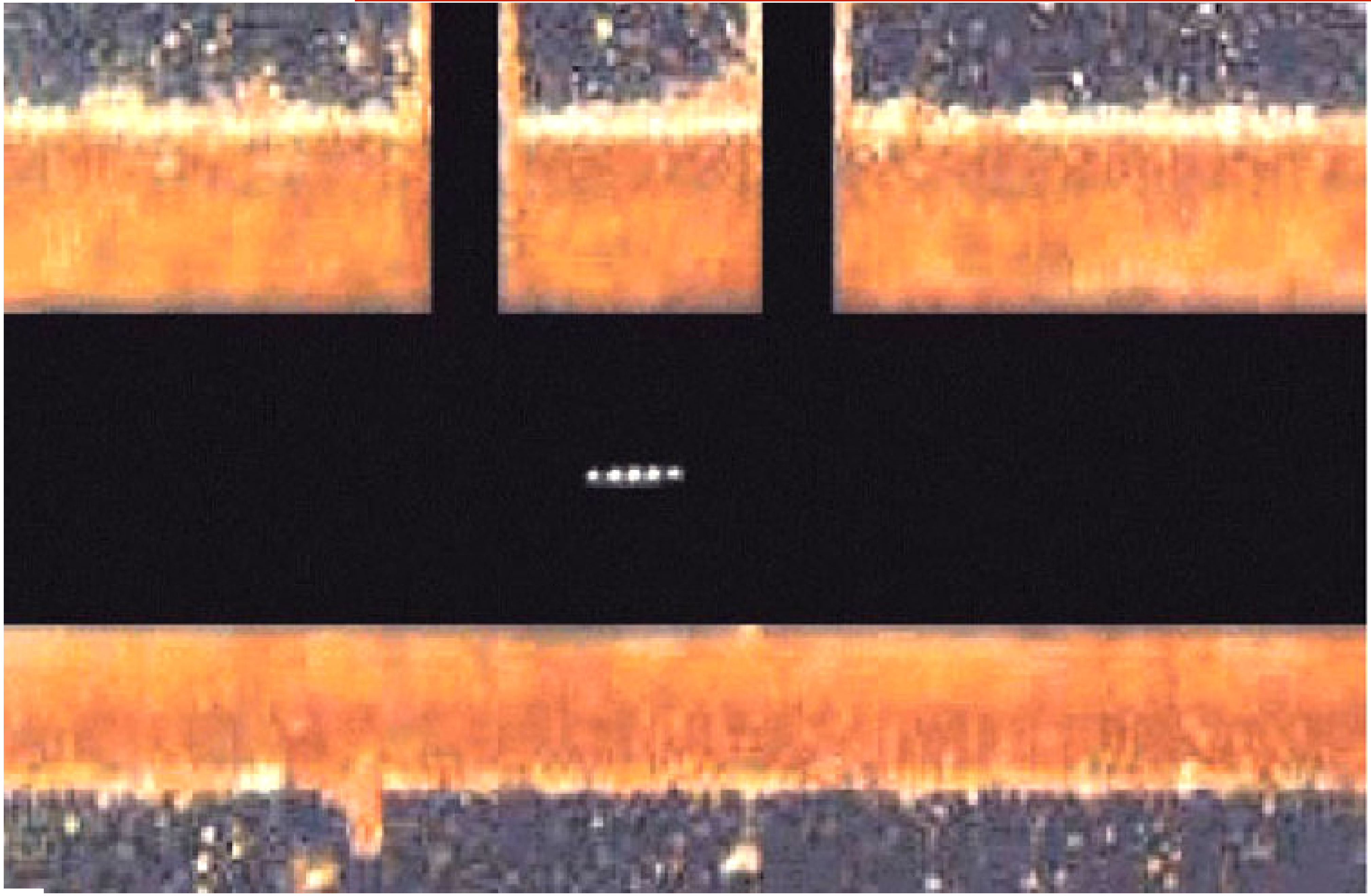
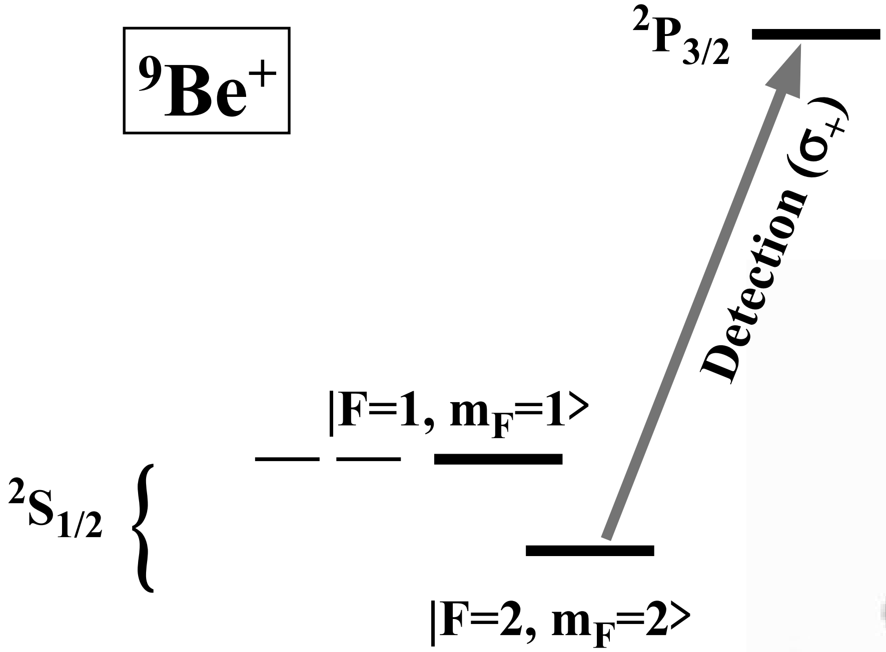


Figure 2 A crystal of five atomic beryllium ions (small white dots at centre) confined in a radio-frequency ion trap. The ions balance their mutual Coulomb repulsion with the confining force of electric fields generated from the surrounding electrodes (brown). The ions strongly fluoresce under the application of appropriate laser radiation near 313 nm. The horizontal electrode gap is about 0.2 mm and the ion–ion spacing is ~5 μm. (Image courtesy of NIST, Boulder.)

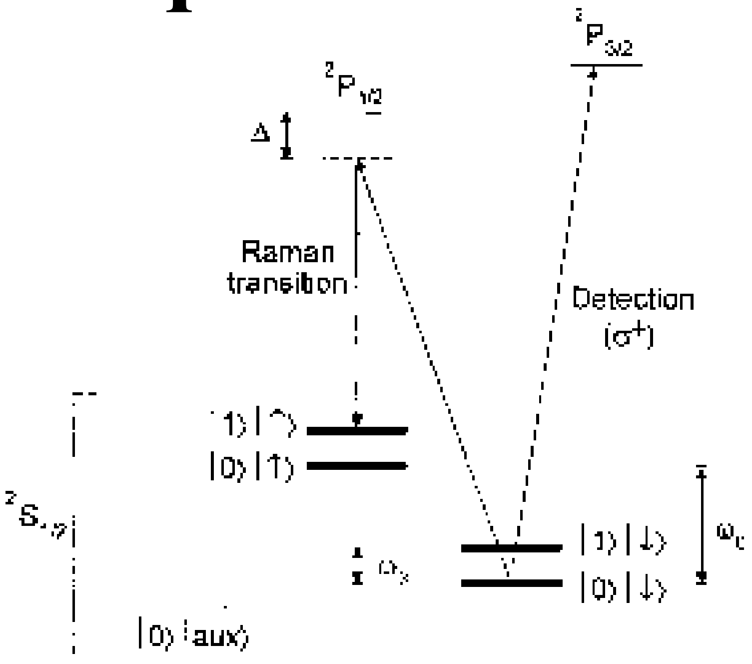
Exp. CNOT Gate on $^9Be^+$

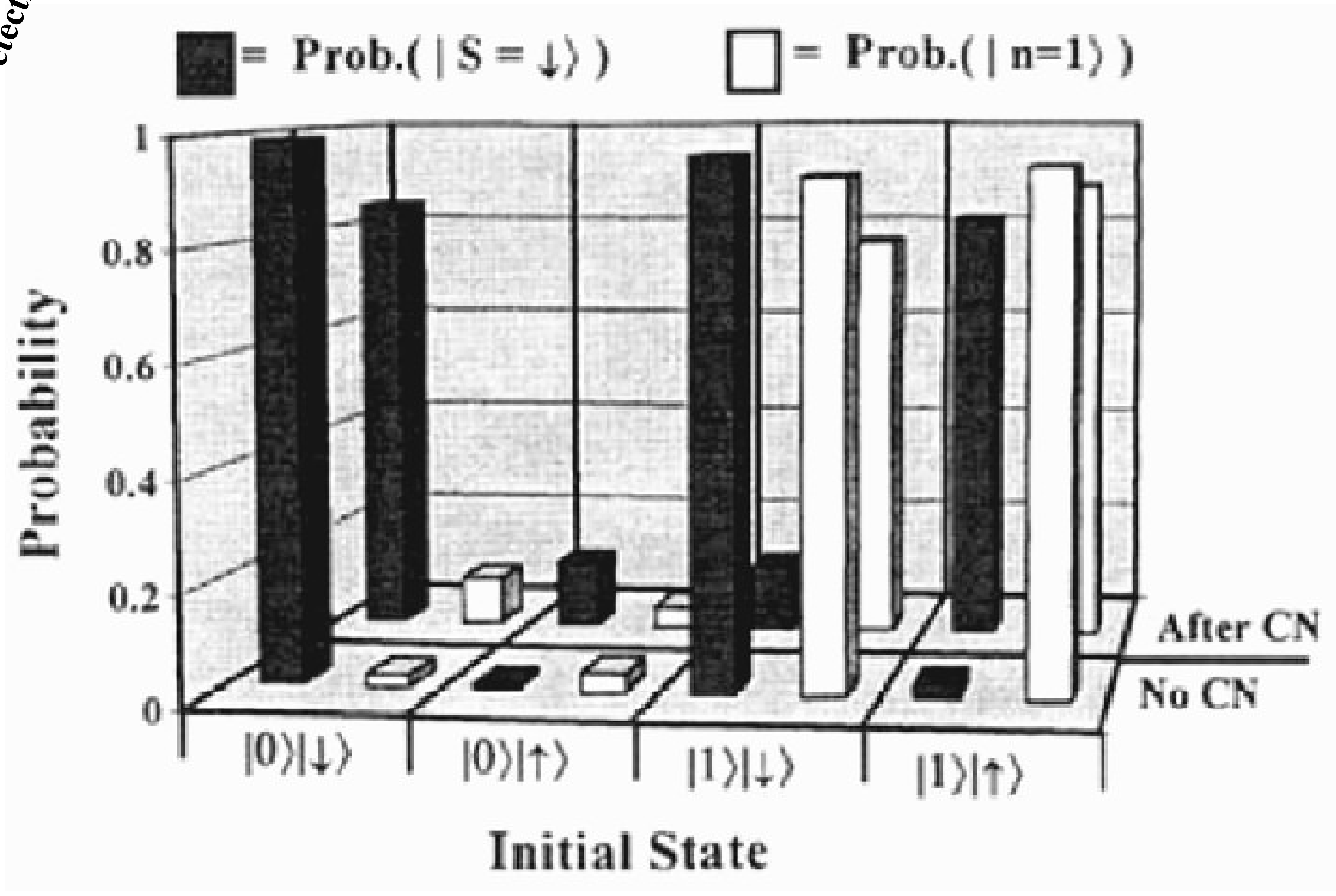
C. Monroe, D.M. Meekhof, B.E. King, W.M. Itano, and D.J. Wineland, 'Demonstration of a fundamental quantum logic gate', Phys. Rev. Lett. 75, 4714 (1995).

1 qubit

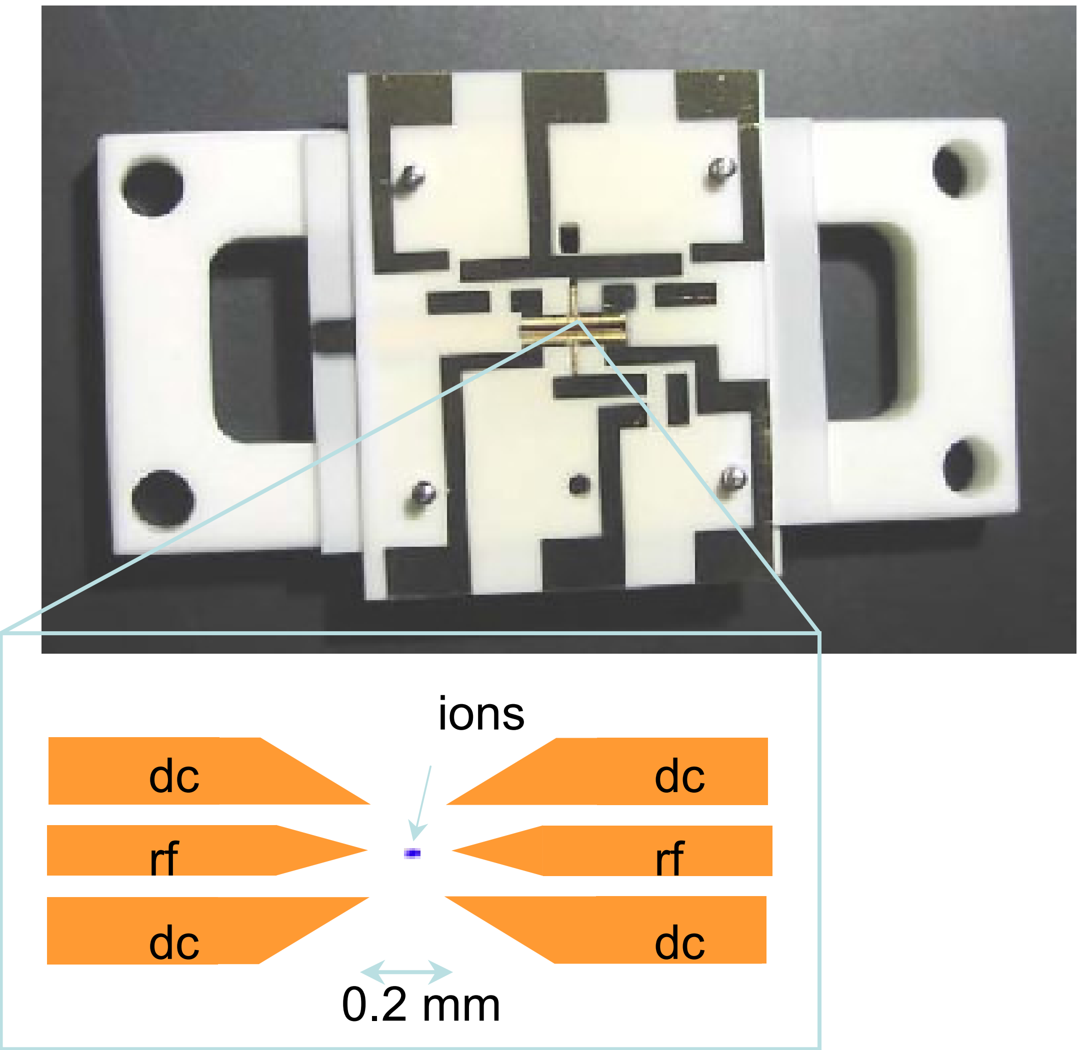


2 qubits



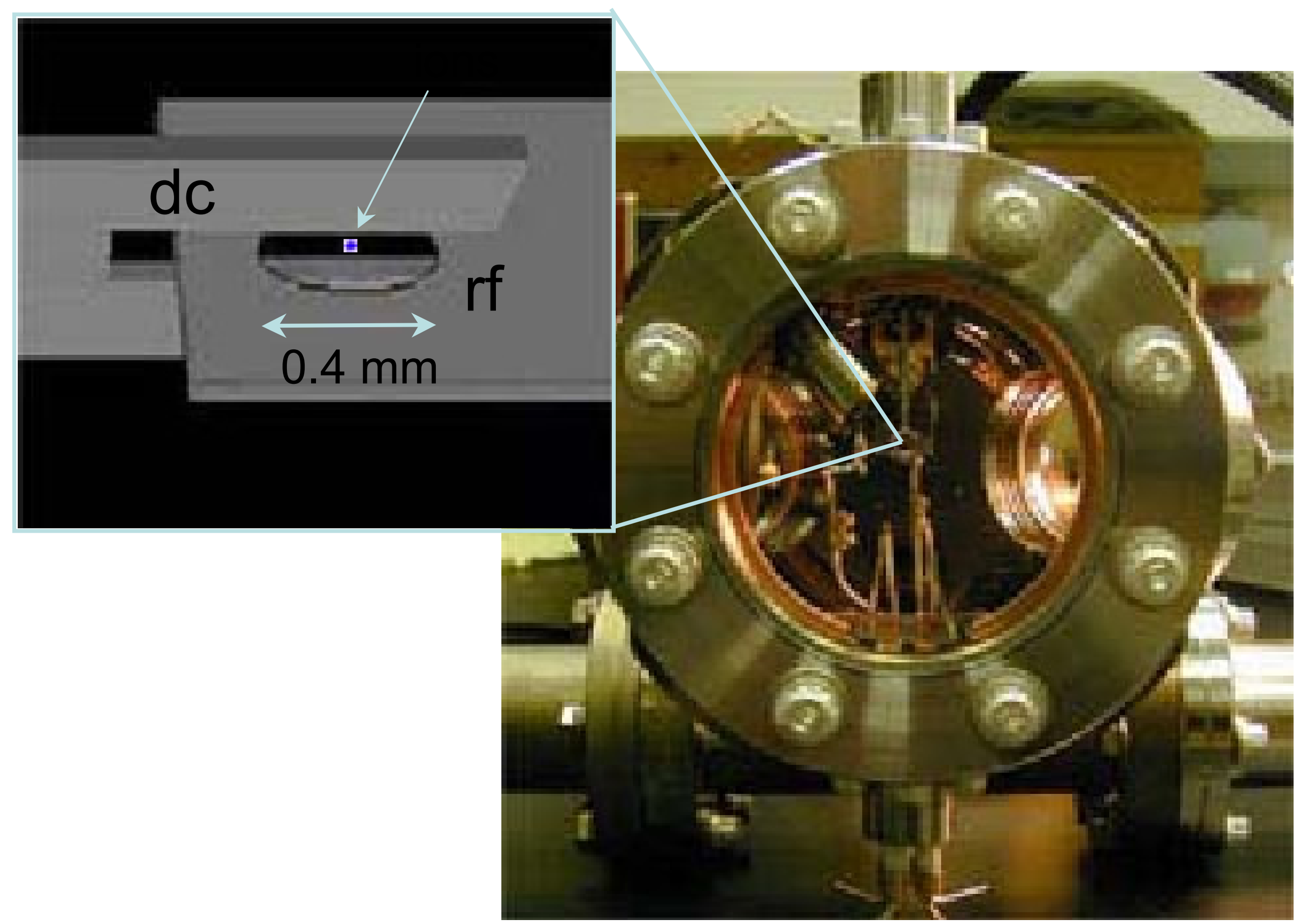


Miniature Traps



3-layer lithographic linear trap

- RF nodal line (ion string)
- static voltage compensation electrodes
- 200 micron size (strong confinement)

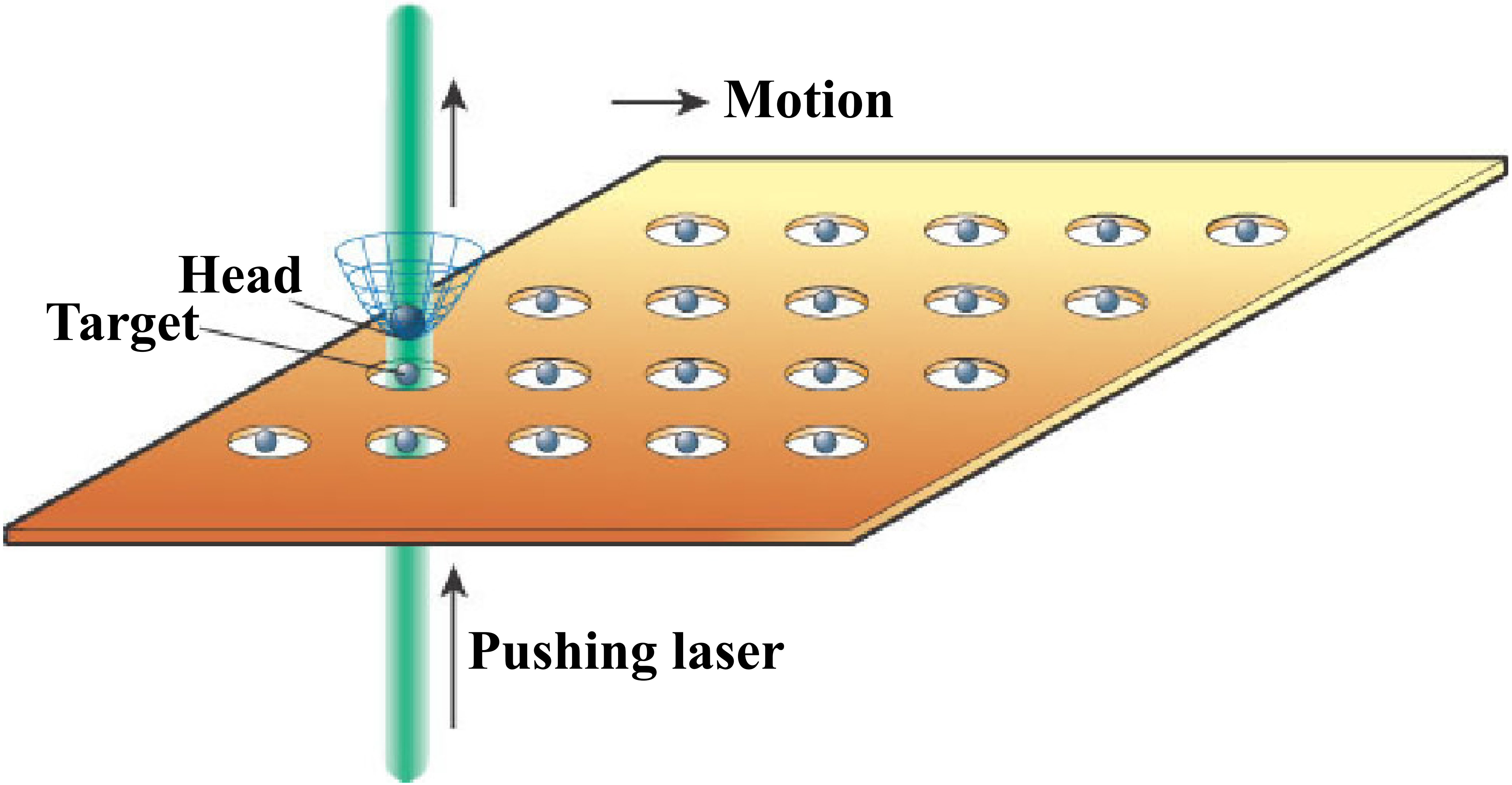


Ring-and-fork quadrupole trap

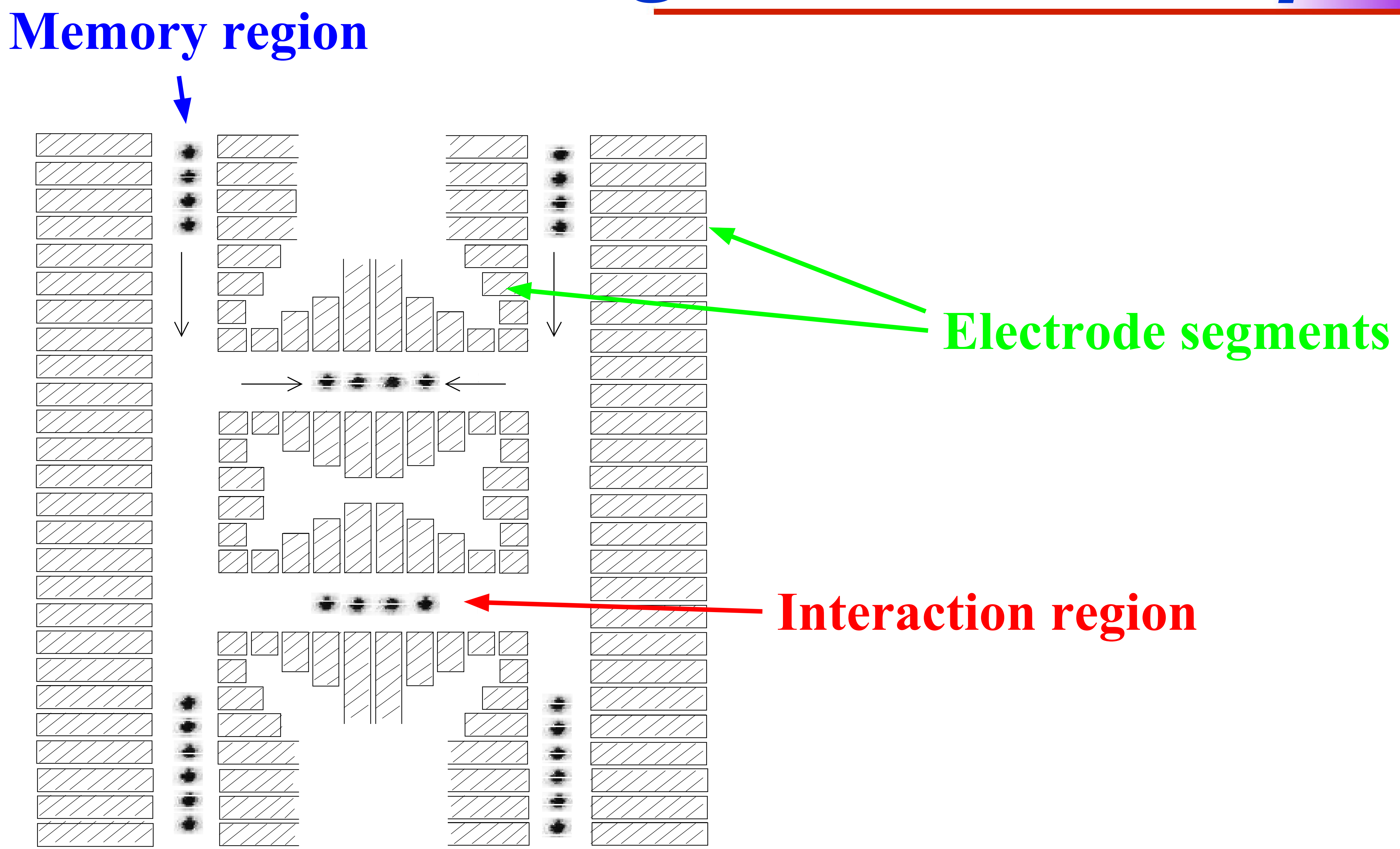
- easy to build and operate
- good optical access
- trapping few ions near RF null

Alternative Traps

J. I. Cirac and P. Zoller, Nature 404, 579–581 (2000).

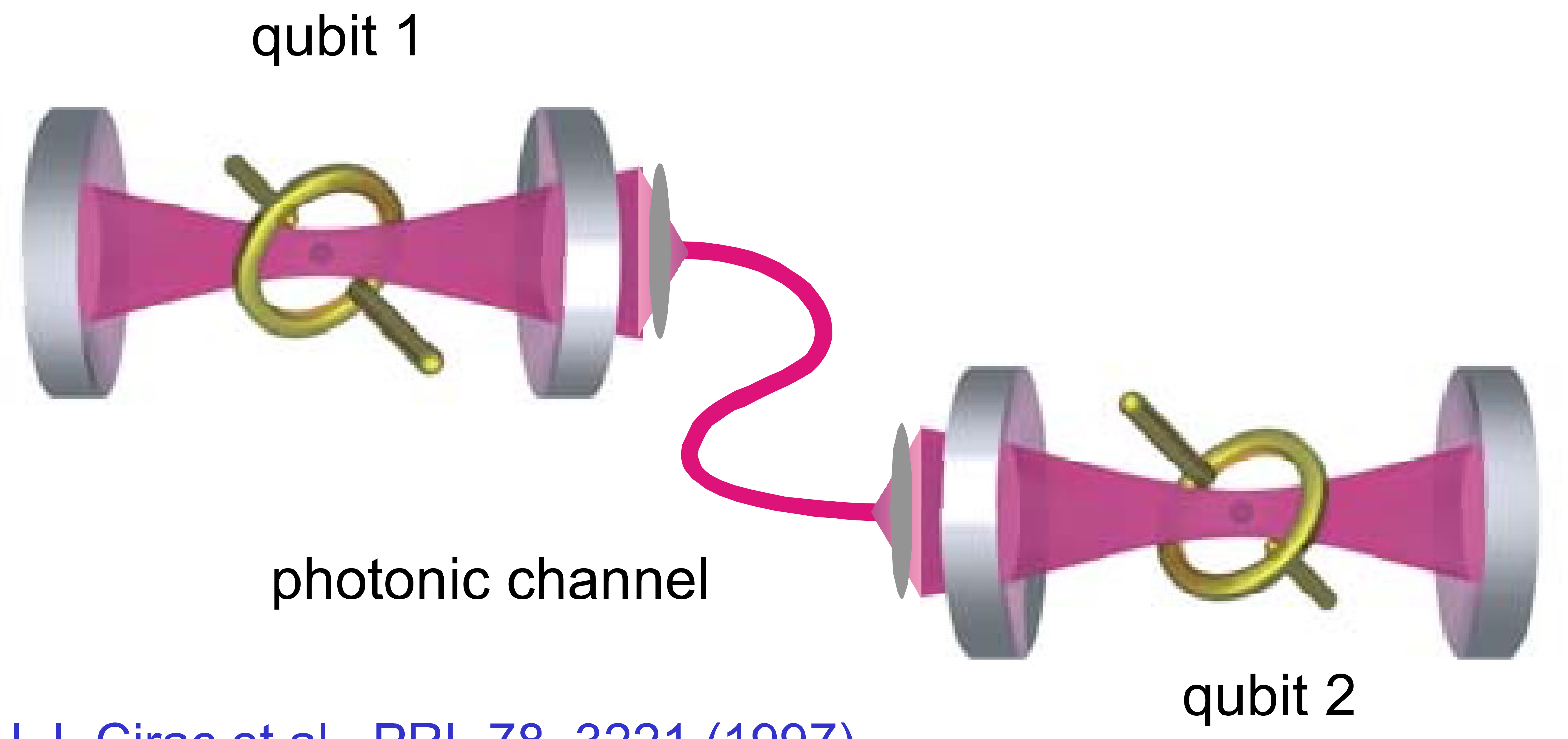


Segmented Traps



D. Kielpinski, C. Monroe, and D.J. Wineland,
'Architecture for a large-scale ion-trap quantum computer', Nature 417, 709 (2002).

Coupled Traps



J. I. Cirac et al., PRL 78, 3221 (1997)