Oxford Ion Trap QIPC Group

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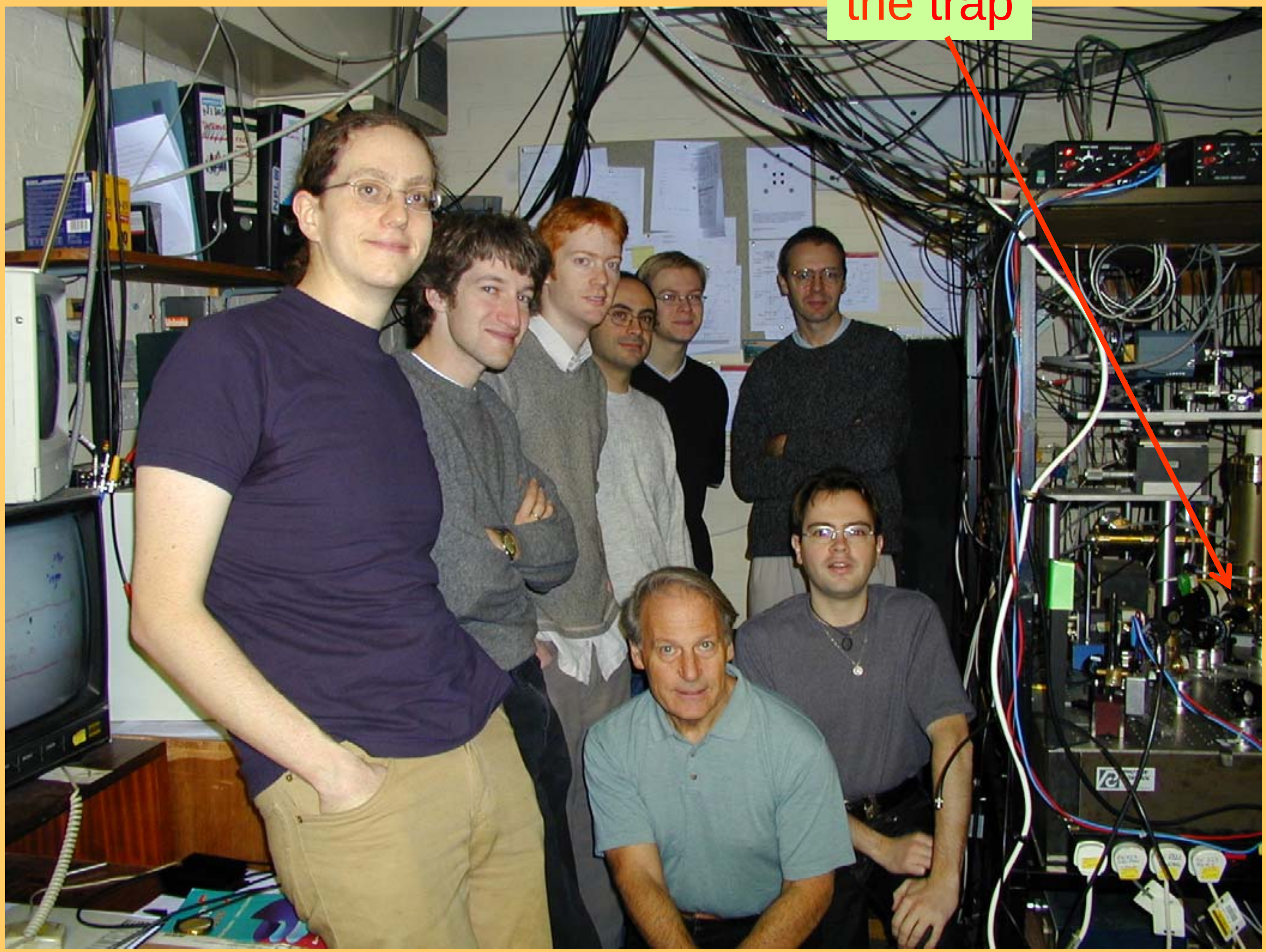
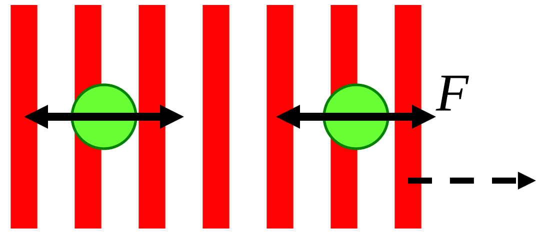


Summary

1. Some issues for phase gate by pushing ions
2. Designing traps for fast ion displacement
3. Experiments:
   1. Spin-state detection
   2. Rabi flopping of the qubit
   3. Cooling to near the ground state of motion

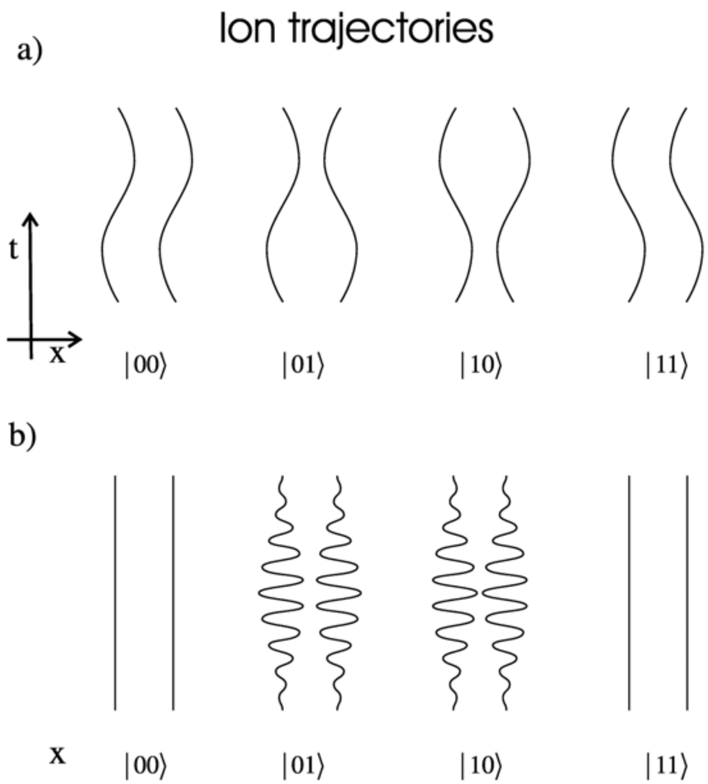
Push gate, wobble gate

Dipole force in moving standing wave:



Slow oscillation of force: "**push**"

Near-resonant oscillation of force: "**wobble**"



Aim:

phase gate: $\theta =$ 0 $\pi/2$ $\pi/2$ 0

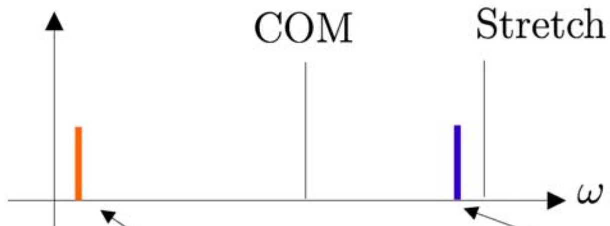
I. Cirac and P. Zoller Nature 404 p579 (2000)

D. Liebfried et.al. Nature 422 p412 (2003)

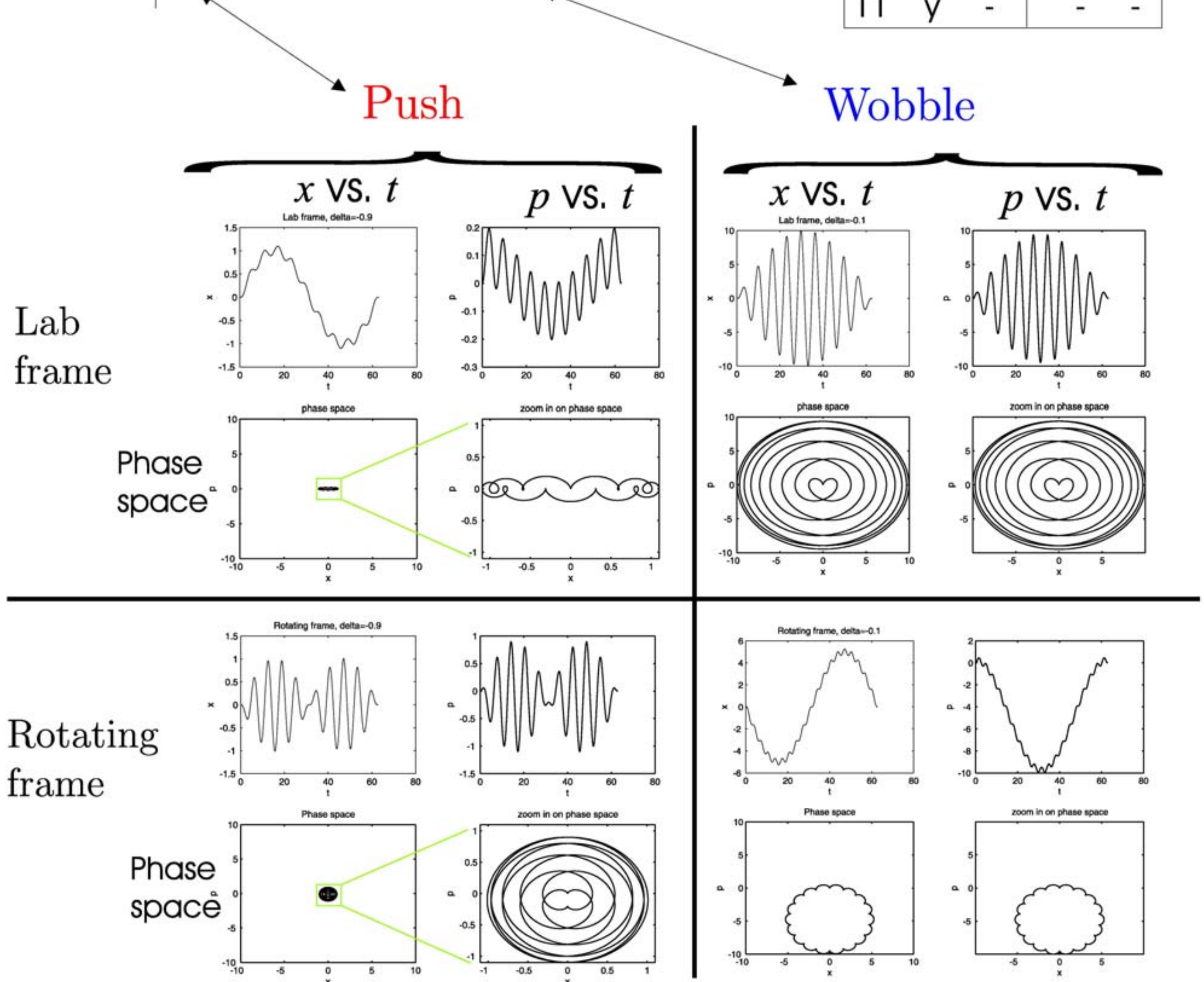
Phase gate:

$$\begin{pmatrix} 1 & & & \\ & 1 & & \\ & & 1 & \\ & & & -1 \end{pmatrix} \text{‘='} \begin{pmatrix} 1 & & & \\ & i & & \\ & & i & \\ & & & 1 \end{pmatrix}$$

Geometrical Argument



	Push		Wobble	
	COM	Str	COM	Str
00	y	-	-	-
01	-	y	-	y
10	-	y	-	y
11	y	-	-	-



Phase acquired
θ = area in phase space in rotating frame

Dynamical Argument: θ = exp(s_0^t –H dt/~)

Push: Coulomb interaction when ion pushed by distance x_F

$$\begin{array}{cccc} 00 & 01 & 10 & 11 \end{array}$$

$$\frac{q^2}{4\pi\epsilon_0}\left(\frac{1}{d},\ \frac{1}{d+x_F},\ \frac{1}{d-x_F},\ \frac{1}{d}\right)$$

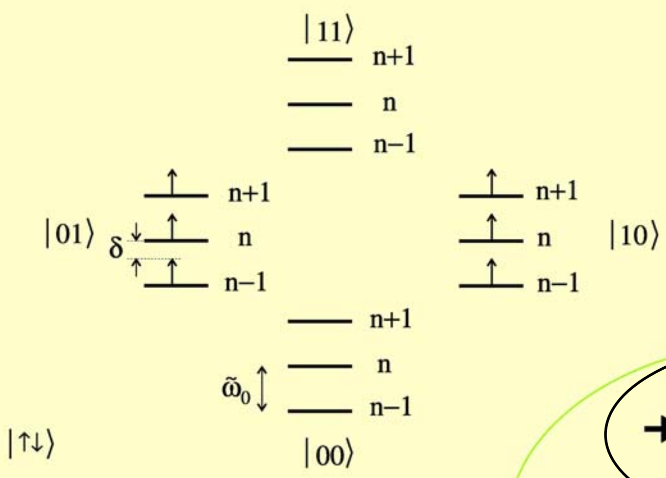
$$\simeq \frac{q^2}{4\pi\epsilon_0 d}\left(1,\ 1+\frac{x_F}{d}+\frac{x_F^2}{d^2},\ 1-\frac{x_F}{d}+\frac{x_F^2}{d^2},\ 1\right).$$

distance pushed

ion separation

Hence $\theta_{\mathrm{p}} \simeq \frac{q^2}{4\pi\epsilon_0 d}\frac{2x_F^2}{d^2}\frac{\tau}{\hbar}.$

Wobble: Raman transition causes light shift.



Rabi freq. $\Omega_D = \eta\ \Omega_{\mathrm{Raman}}$

level n shifted up by n-1
and down by n
➔ net effect ind. of n

➔ $\theta_{\mathrm{w}} = 2\frac{\Omega_D^2}{\delta}\tau.$

(Choose $\delta = 2\,\Omega_D$)

$$\theta_{\mathrm{p}} \simeq 16\sqrt{3}\,\frac{\Omega_D^2}{\omega_0}\tau.$$

c.f.

COM freq.

Fidelity

Photon Scattering

$$N \simeq \frac{\Omega^2}{2\Delta^2}\Gamma\tau_g = \frac{\Omega_D \Gamma \tau_g}{\eta_L \Delta}$$

Push

$$N \simeq \frac{\sqrt{3}\Gamma\omega_0}{8\eta_L\Delta\Omega_D} = \frac{\sqrt{3}\omega_0\Gamma}{4\eta_L^2\Omega_0^2}.$$

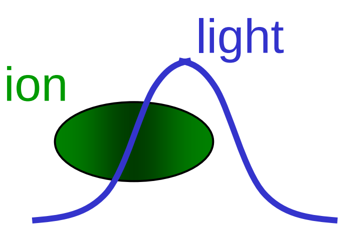
~1/intensity

Wobble

$$N \simeq \frac{\pi\Gamma}{\eta_L\Delta}$$

~1/detuning

Thermal



	Push	Wobble
Non-uniform force = deviation from Lamb-Dicke approx	$P \simeq 2\pi^2\eta_L^4\left(\frac{k_B T}{\hbar\omega_0}\right)^2$	$P = \eta_L^4(\pi^2/4)\bar{n}(\bar{n}+1)$
Coupling to other mode	—	$P \simeq 1.6\frac{\Omega_D^2}{\tilde{\omega}_0^2}(\bar{n}+1).$
Debye-Waller factor		$P = \eta_L^4(\pi^2/4)\,0.4\,\bar{n}(\bar{n}/2+1)$

The total thermal effect is similar for the two cases:

$$P \simeq (\bar{n}+1)\left(0.3\pi^2\eta_L^4\bar{n} + 1.6\frac{\Omega_D^2}{\tilde{\omega}_0^2}\right)$$

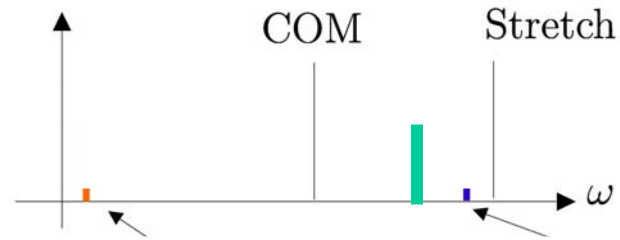
M. Sasura and A. M. Steane, PRA 65, 062318 (2003); A. Sorensen and K. Molmer, PRA 62, 022311 (2000)

Discussion

- Wobble uses resonance to displace ions further for a given force
  $\rightarrow$ requires less laser intensity (for given photon scattering N)

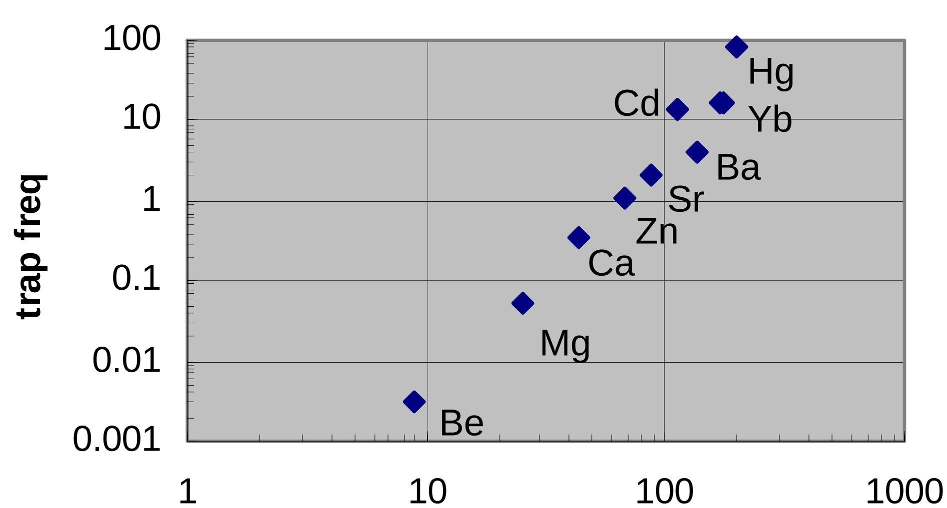
- Laser intensity noise typically falls with freq. $\Rightarrow$ better to oscillate the force.

- However, for a faster gate require δ not too small
  $\rightarrow$ adopt $\delta \simeq \omega_{\rm com}/2$
  i.e. intermediate between "push" and "wobble".



- Fine structure $\rightarrow$ limit on Δ

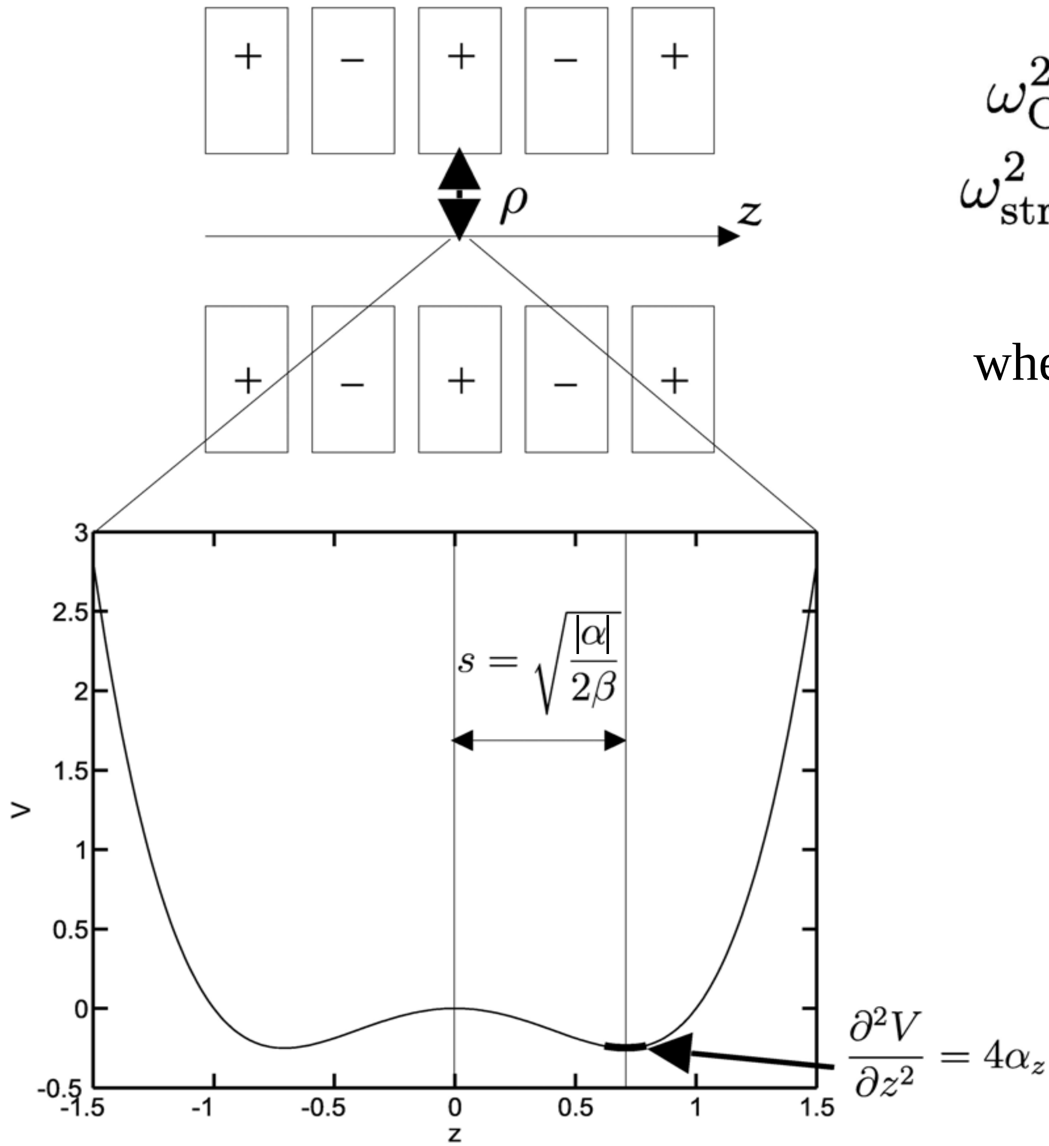
$$\rightarrow N_{\rm scattering} = \frac{2\sqrt{2}\pi\Gamma}{\eta\omega_{\rm fine}} = \frac{2(\lambda\Gamma)\sqrt{m\omega_z/\hbar}}{\omega_{\rm fine}}$$



but $\omega_{\rm fine} \sim m^2$ so speed $\omega_z \sim m^3 N^2 =$ mass^3 error^2

Designing traps for fast ion displacement

Bringing ions together



$$V = \alpha_z z^2 + \beta z^4$$

$$\omega^2_{\mathrm{COM}} = (2\alpha_z + 3\beta d^2) q/m$$
$$\omega^2_{\mathrm{stretch}} = \omega^2_{\mathrm{COM}}(1 + \tilde{\epsilon})$$

where d = separation of the ions, and

$$\tilde{\epsilon} = \frac{q^2}{\pi \epsilon_0 m \omega_{\mathrm{COM}} d^3}$$

) To maintain ω large when α_z goes through 0, require large β.

Electric Octopole Potential

Require large β at small α_z

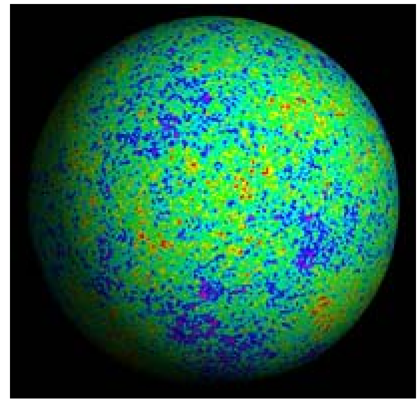
) increase voltages

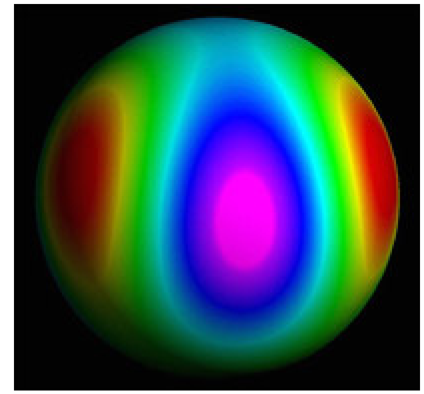
! get large $|\alpha_x|$, $|\alpha_y|$, ?

! can't confine the ions

) require $|\alpha_x|$, $|\alpha_y|$, $|\alpha_z|$ all small

but with large β





) Electric octopole trap

(small) d.c. quadrupole + octopole

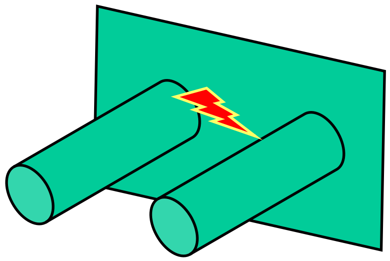
$$
\begin{aligned}
V(x,y,z,t) &\simeq \alpha\left(z^2 - \frac{1}{2}(x^2+y^2)\right) + \beta V_4(x,y,z) \\
&+ Q_{\mathrm{ac}} \cos(\Omega t)(x^2 - y^2)
\end{aligned}
$$

+ r.f. quadrupole for radial confinement

Geometric factors & electric field

$$
\begin{aligned}
V(x,y,z,t) &\simeq \alpha\left(z^2 - \frac{1}{2}(x^2+y^2)\right) + \beta V_4(x,y,z) \\
&+ Q_{\mathrm{ac}}\cos(\Omega t)(x^2-y^2)
\end{aligned}
$$

Assume limited by electrical breakdown, i.e. there is a maximum allowed electric field at an electrode surface.



Then:

Geometric factors γ, μ defined by

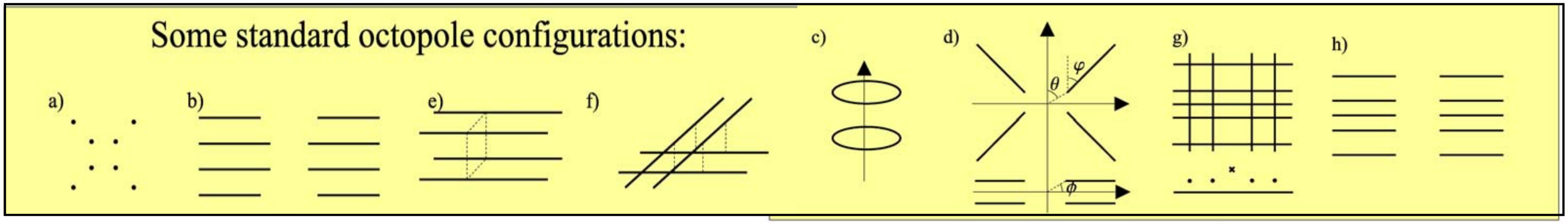
$$
\text{for } Q_{\mathrm{ac}} = 0, \quad \beta = \frac{\gamma E_{\max}}{\rho^3},
$$

$$
\text{for } \beta = 0, \quad Q_{\mathrm{ac}} = \frac{\mu E_{\max}}{\rho}.
$$

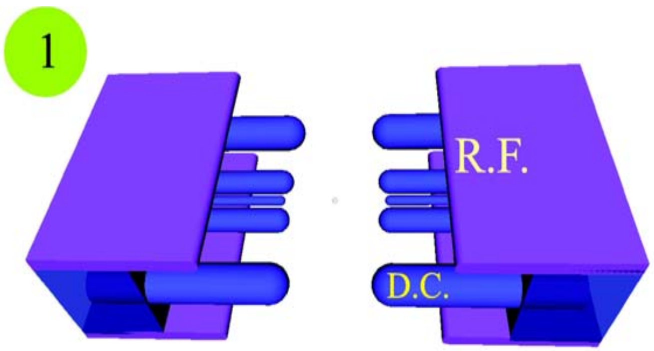
Maximum electric field

Distance to nearest surface

Example structures

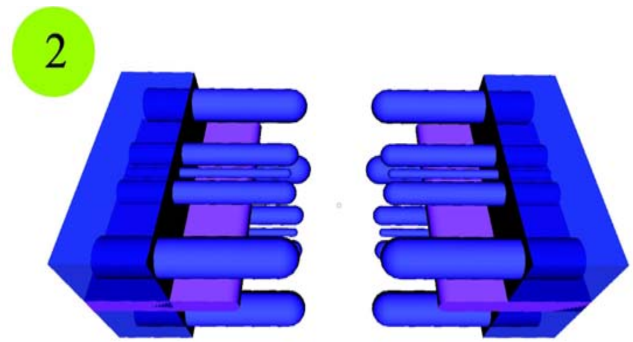


"Two hands"



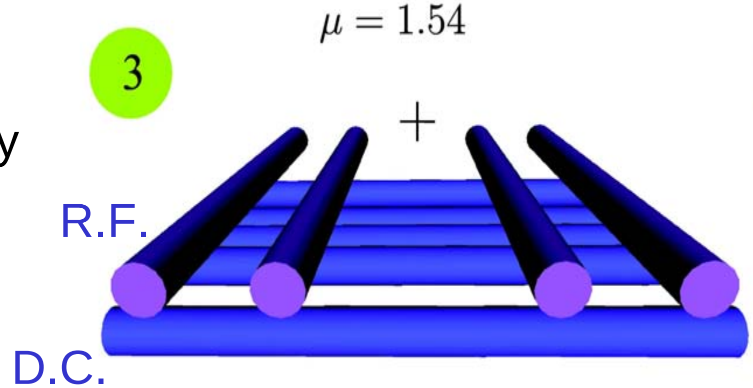
$\gamma = 0.027$
$\mu = 1.54$

"hands" inverted



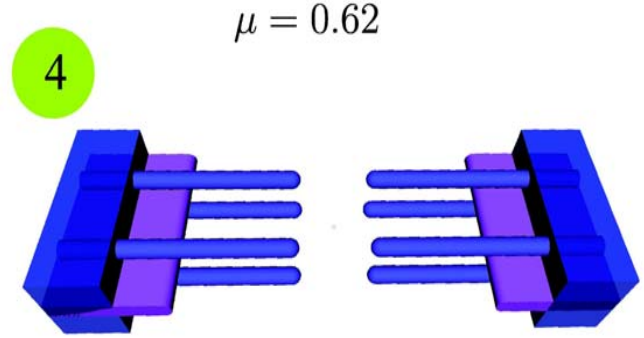
$\gamma = 0.0065$
$\mu = 0.62$

"Railway track"



$\gamma = 0.0064$
$\mu = 0.48$

Geometric octopole



$\gamma = 0.0033$
$\mu = 0.072$

Scaling with mass and ρ

$$\frac{\omega_{\rm COM}(\text{octopole})}{2\pi}[\text{MHz}] \simeq \frac{840}{\sqrt{A}}\frac{(\gamma E_{\max})^{3/10}}{\rho^{9/10}}.$$

$$\frac{\omega_{\rm radial}}{2\pi}[\text{MHz}] \simeq \frac{1105}{\sqrt{A}}\left(\frac{q_r\mu E_{\max}}{\rho}\right)^{1/2}$$

Ion	$\omega_0/2\pi$ (kHz)
^{9}Be	201.8
^{25}Mg	121.1
^{43}Ca	92.3
^{67}Zn	73.9
^{87}Sr	64.9
^{111}Cd	57.5
^{135}Ba	52.1
^{171}Yb	46.3
^{199}Hg	42.9

A = mass no. of ion, q_r = Mathieu q parameter
$E_{\max}$ in Vμm^{-1} ... in μm.

ρ sma... (octopole)
ρ larg... pole)

Define $\omega_0 = (\omega_{\rm radial}$ fo...
At $E_{\max} = 10^6$V/m, $q_r = 0.$...

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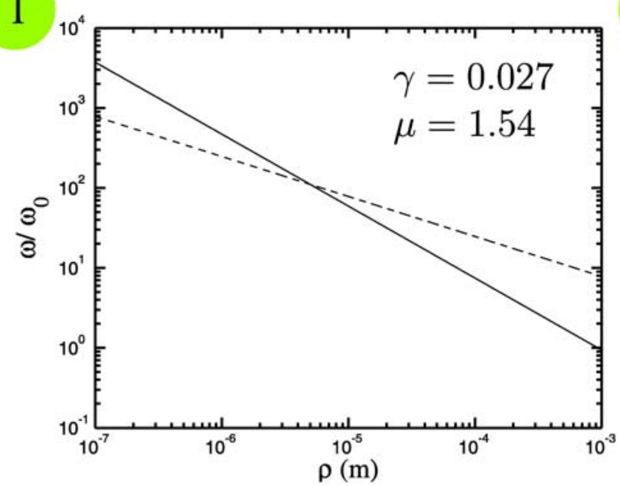
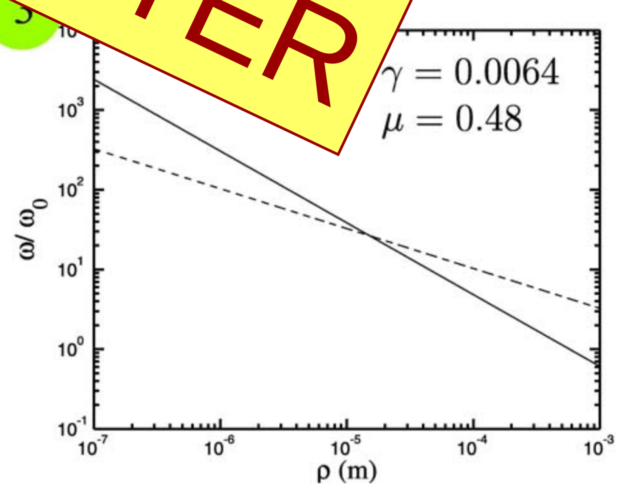
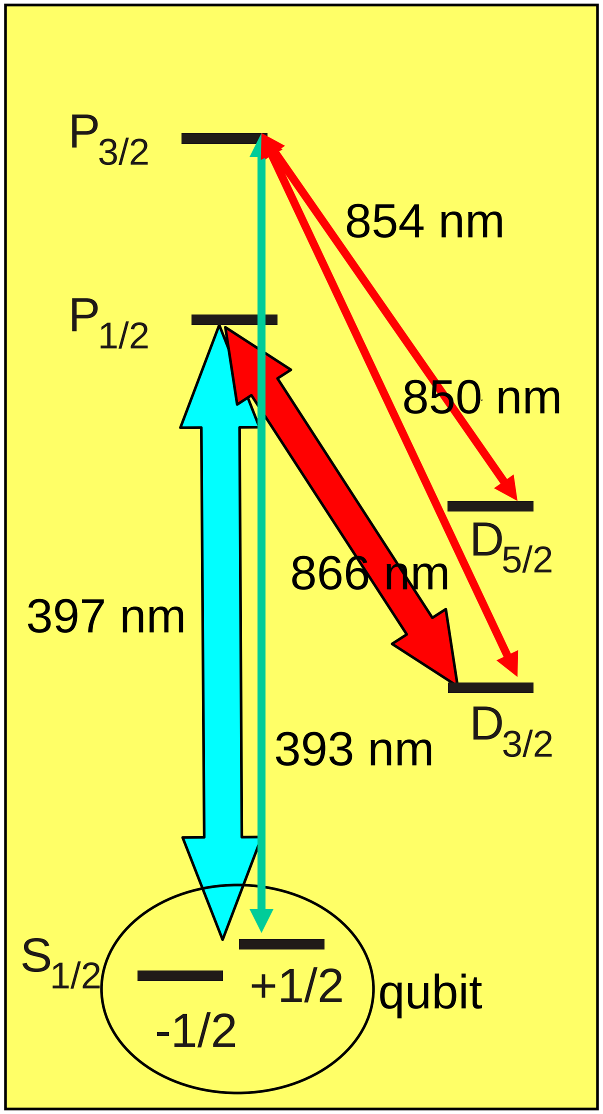


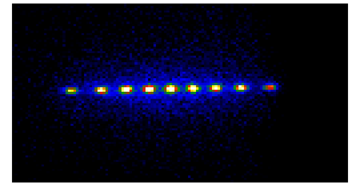
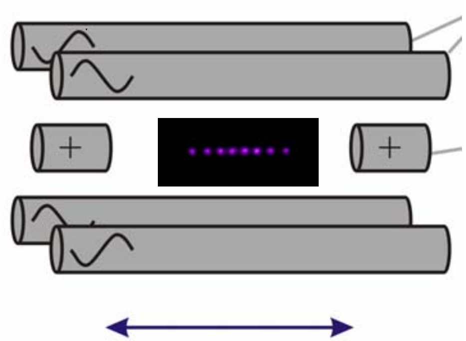
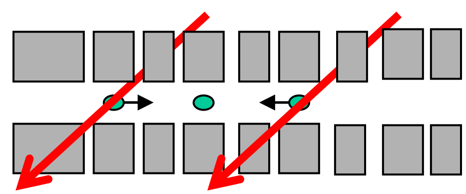


$\omega_{\rm COM}(\text{octopole})$ ———— $\omega_{\rm radial}$ - - - - - -

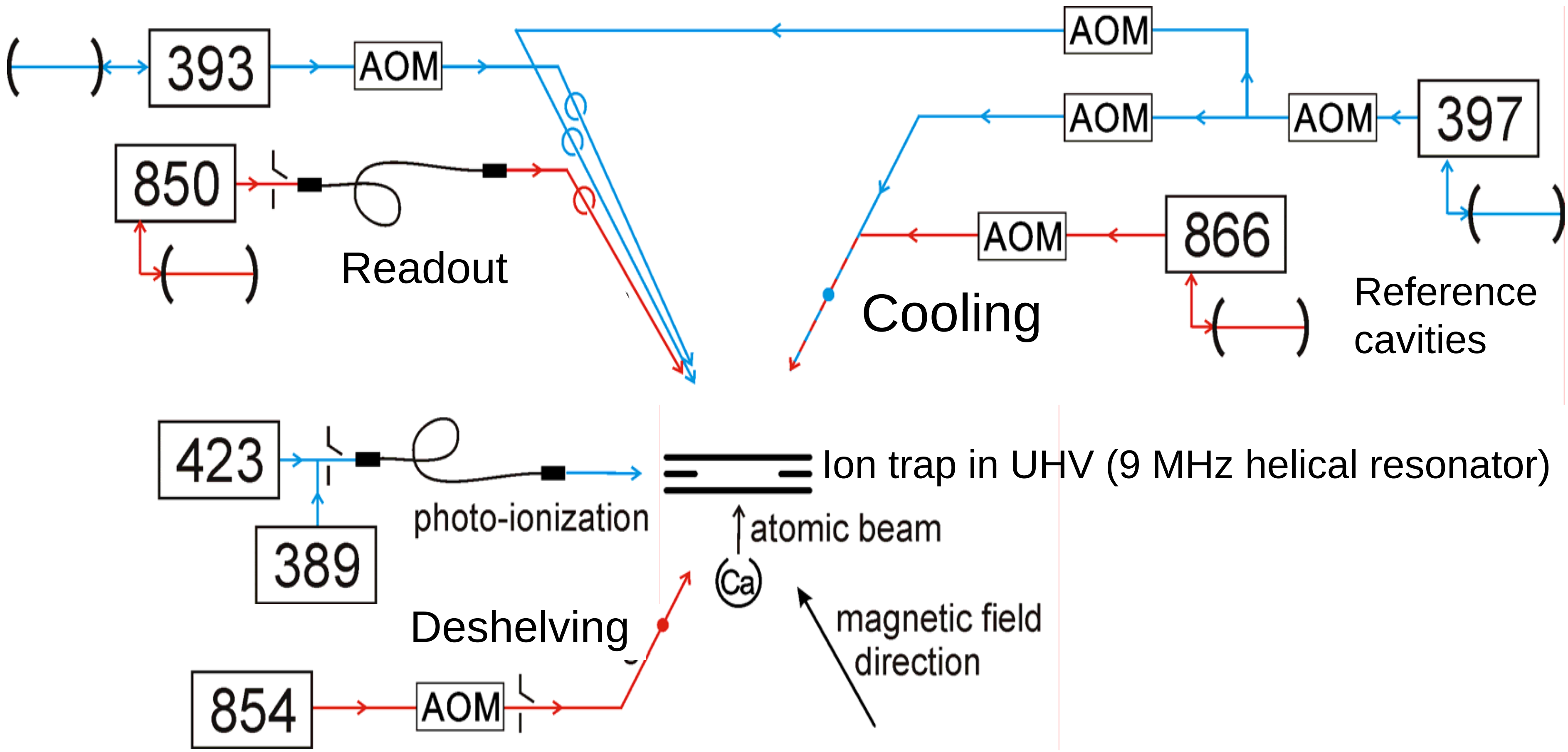
Experiments

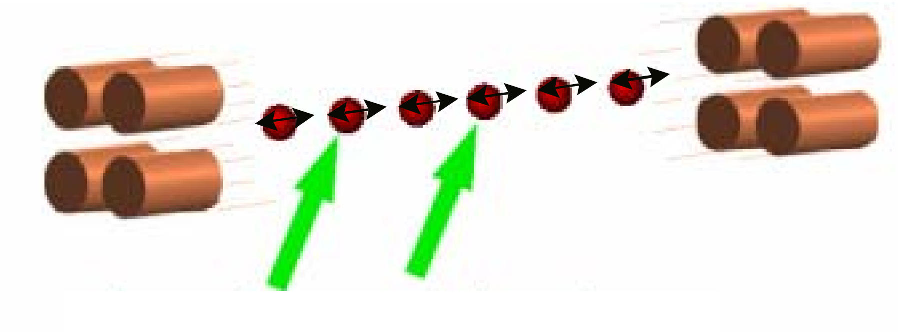
Physical system: Calcium ions in a trap

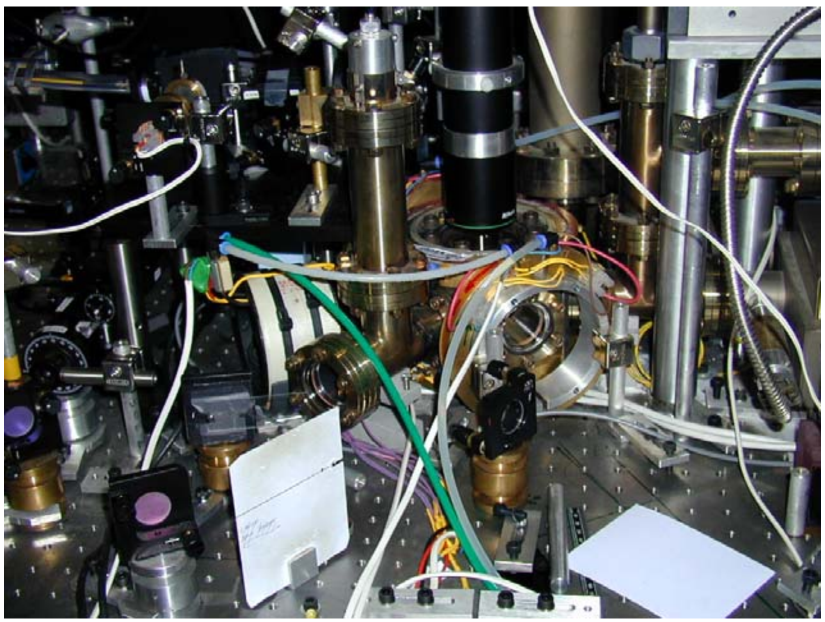


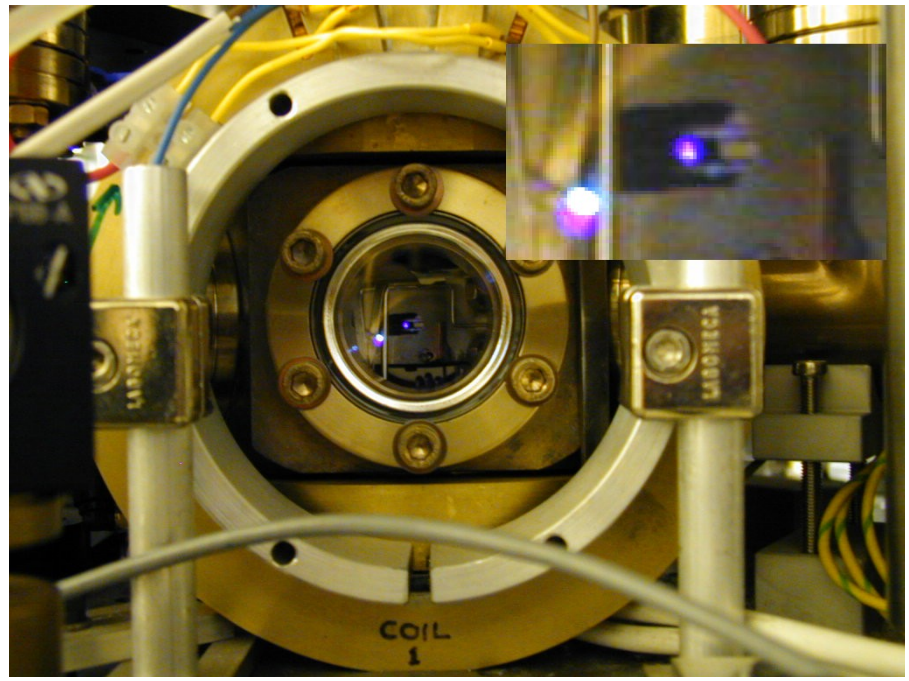
Present	Future
Ion: 40 Ca	43 Ca 
Qubit: M=+1/2, -1/2 spin state	Hyperfine levels
A single linear trap. ν_{ion} ~ 1 MHz 	Multiple traps 

Apparatus summary





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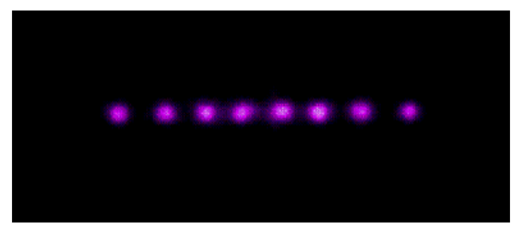
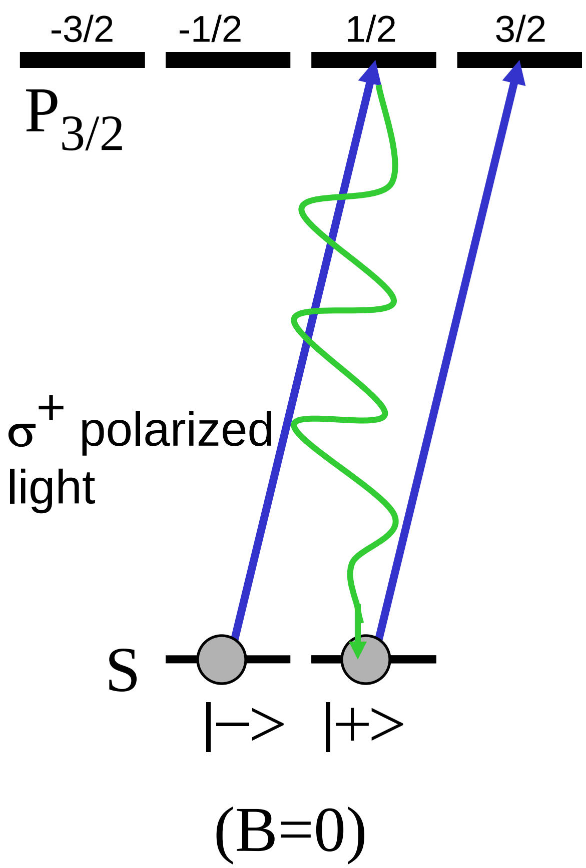


Spin-state detection (qubit readout)

Principle of spin detection

We want to detect: is the spin state |–> or |+> ?



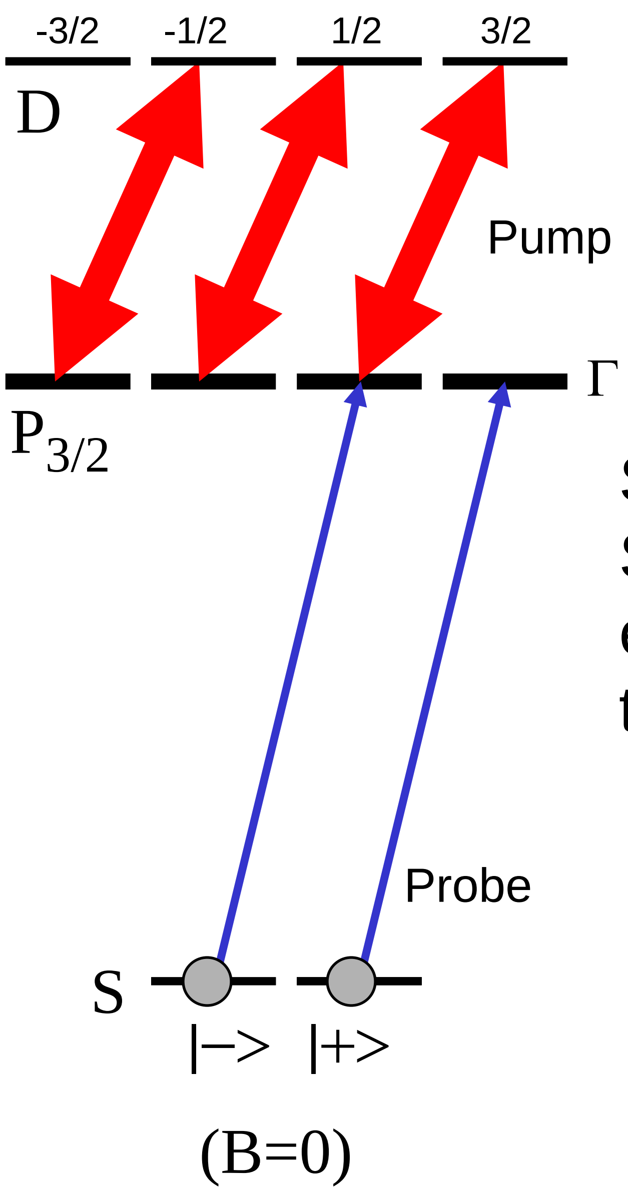
Cycling: $S_{1/2} \rightarrow P_{3/2}$?

but optical pumping → only ~1 photon.

Problem:
No matter what type of transition, fluorescence is always accompanied by optical pumping between |–> and |+>

→ Spin state is caused to relax before a detectable signal is obtained.

Principle of spin detection

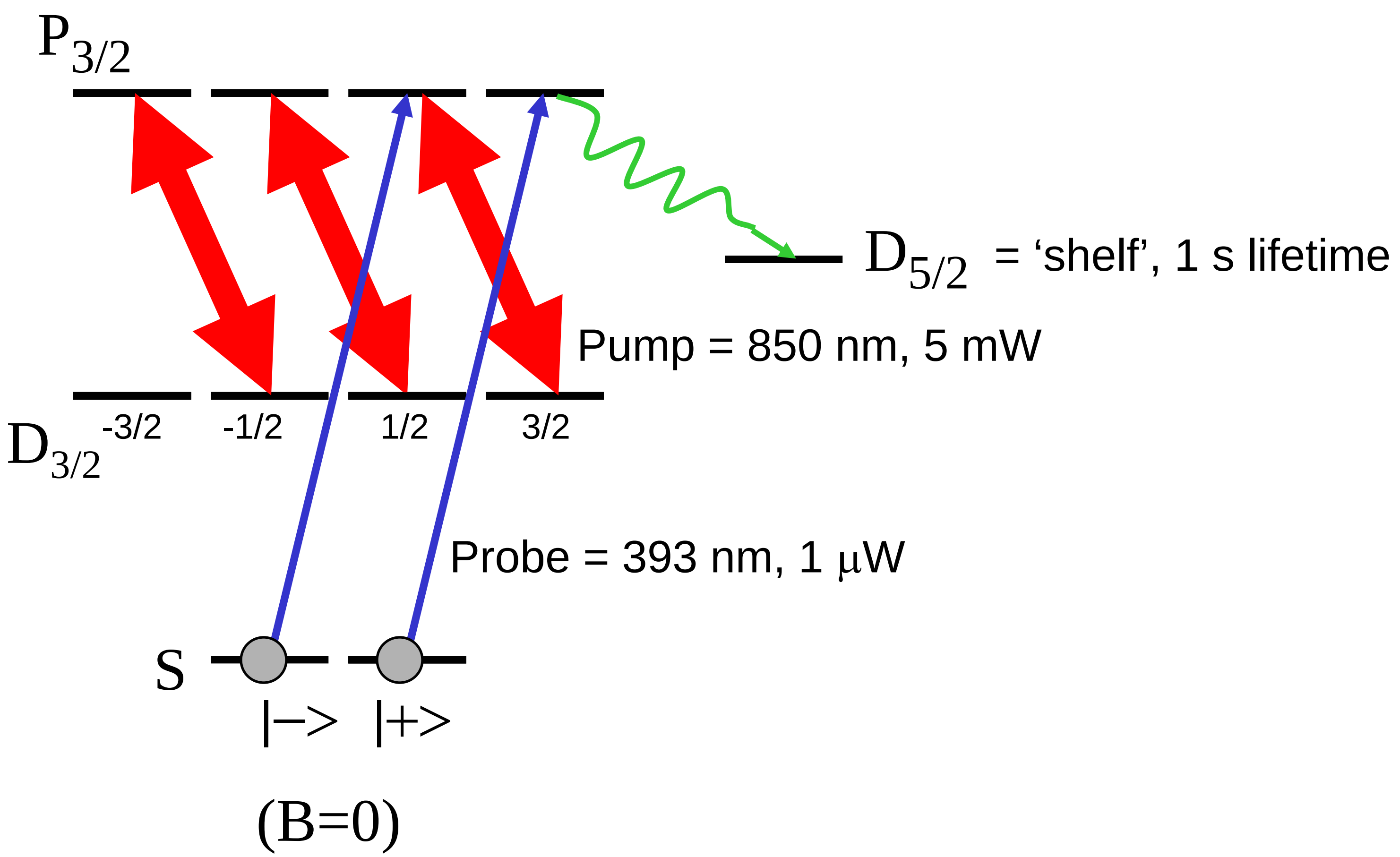


Solution:
Suppress the unwanted excitation by electromagnetically induced transparency (EIT).

Ratio wanted/unwanted excitation
$= (\Omega_{pump})^2 / \Gamma\,\gamma \quad >> 1$

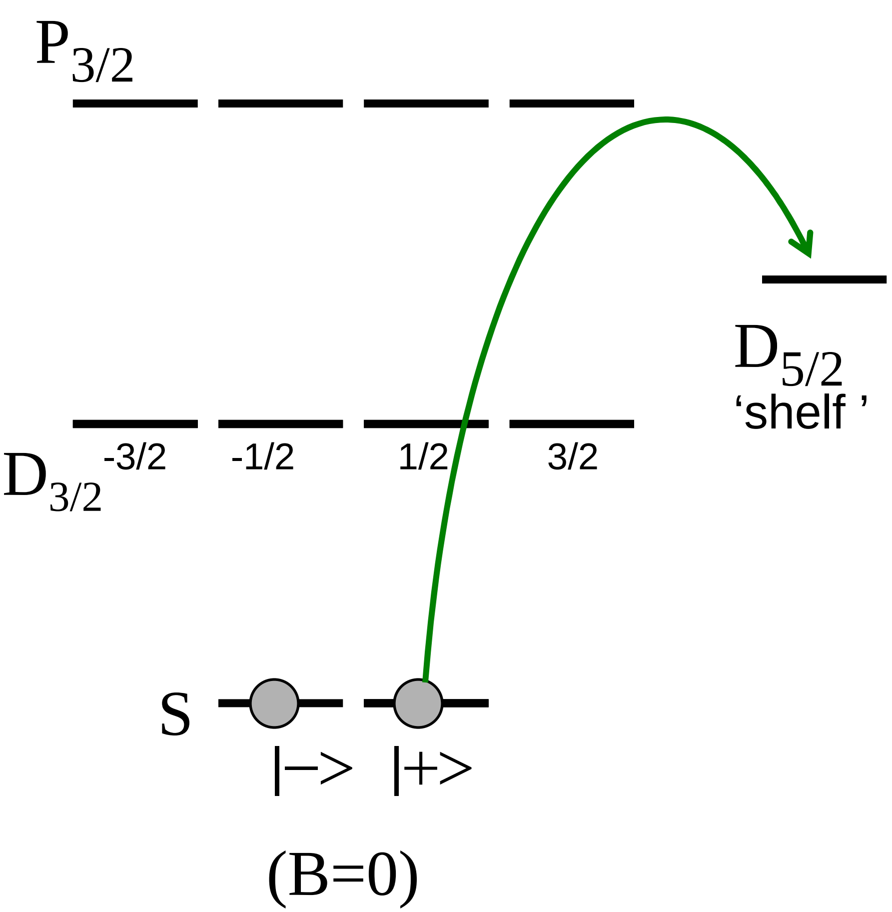
where $\gamma =$ laser linewidths + D linewidth

Experiment in calcium

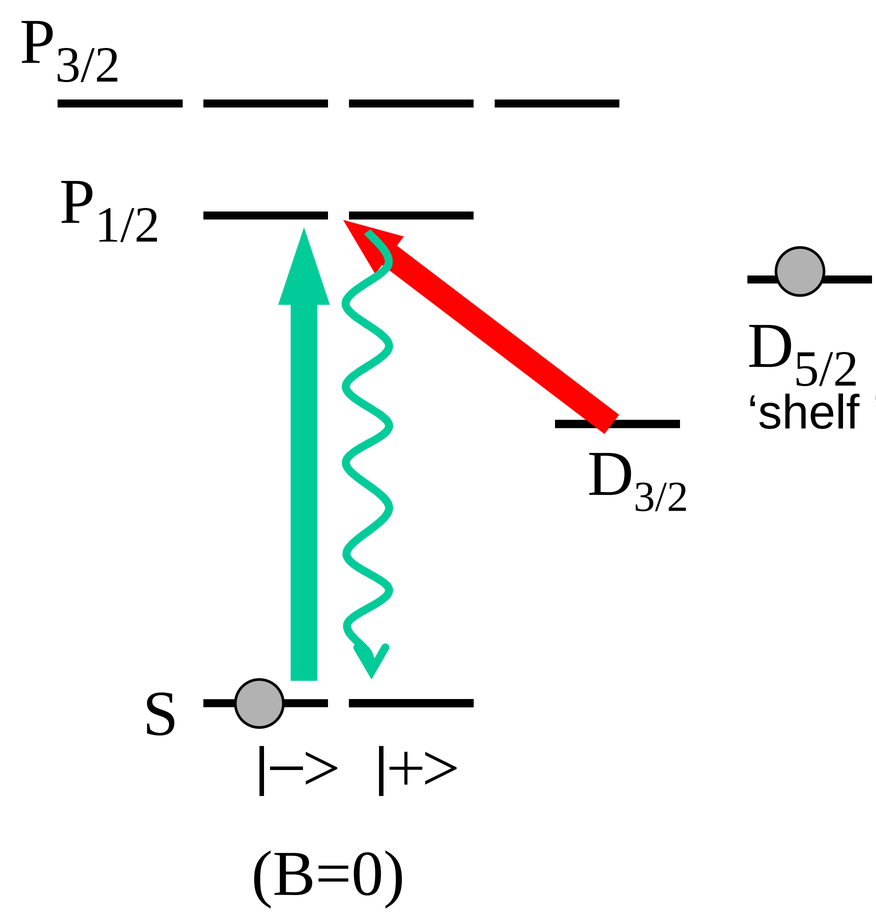


Experiment in calcium

First step: transfer to shelf, using EIT for selectivity.

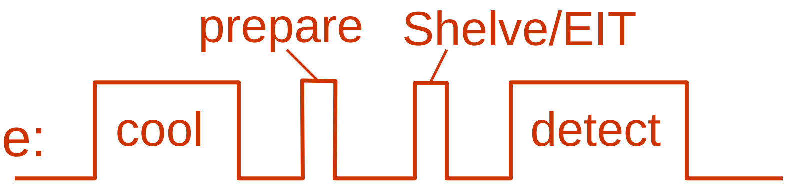


Second step: detect fluorescence using the cooling lasers.

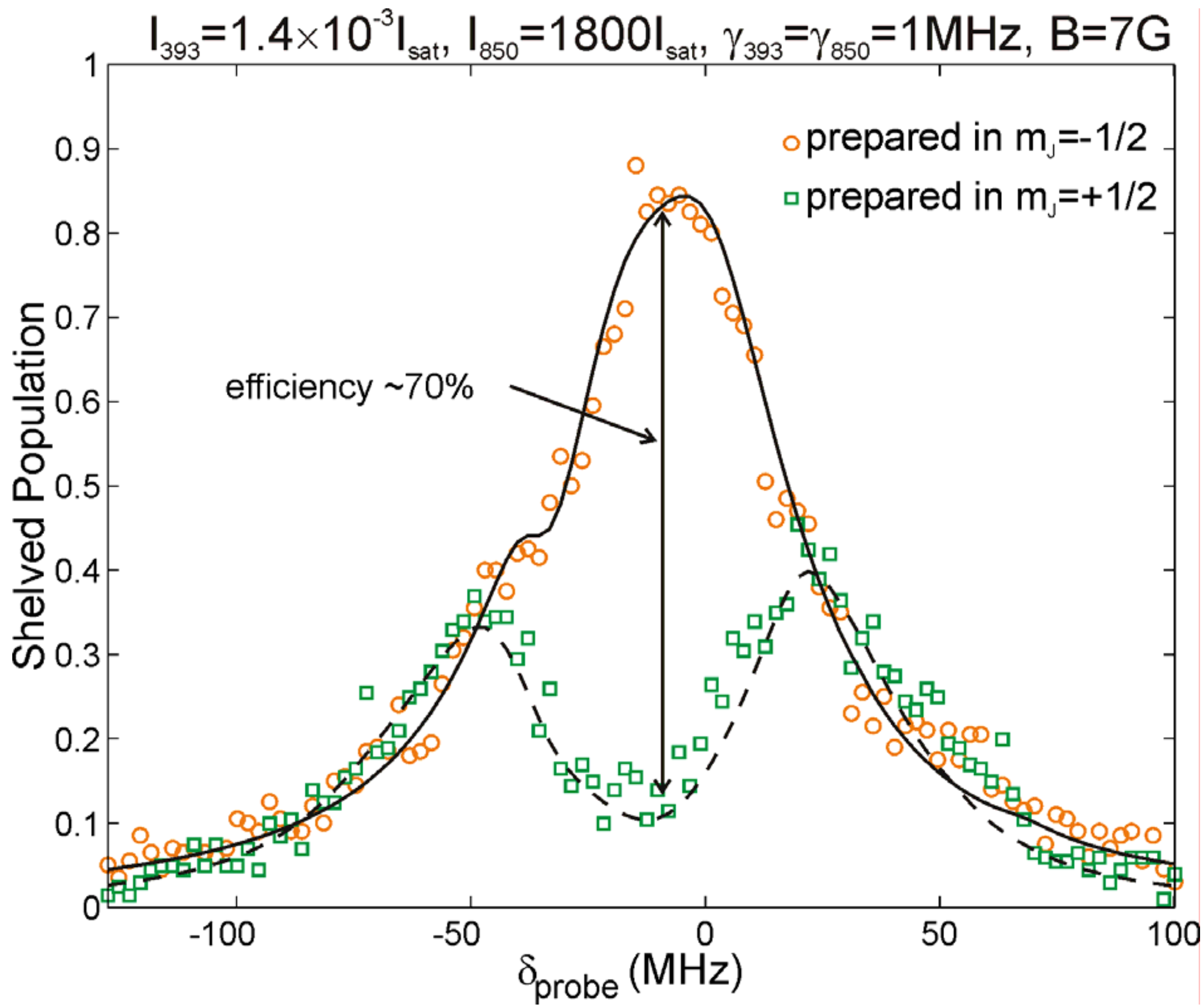


EIT spin state readout: results

Experimental sequence:

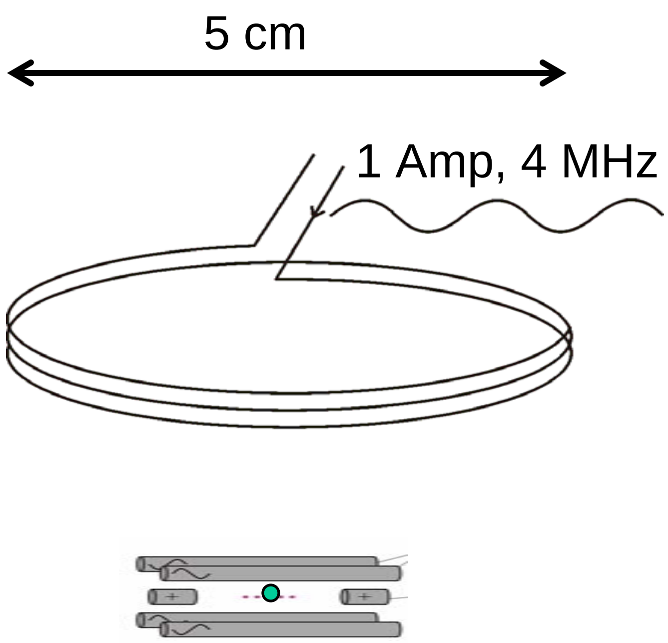


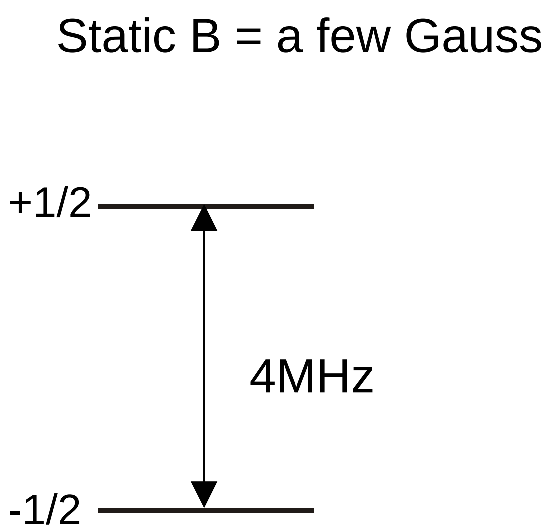
(Prepare –1/2 or +1/2 spin state by optical pumping.)



Rabi flopping of the qubit

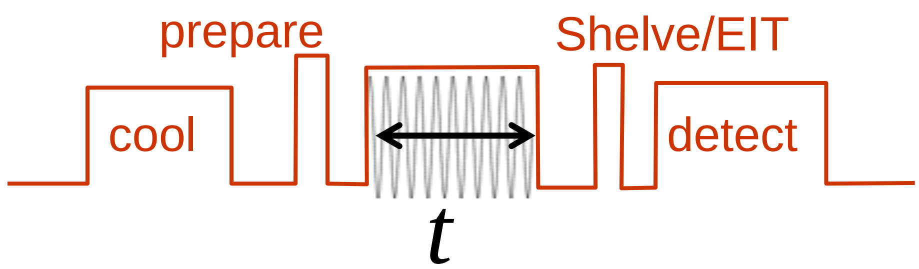
Magnetic resonance

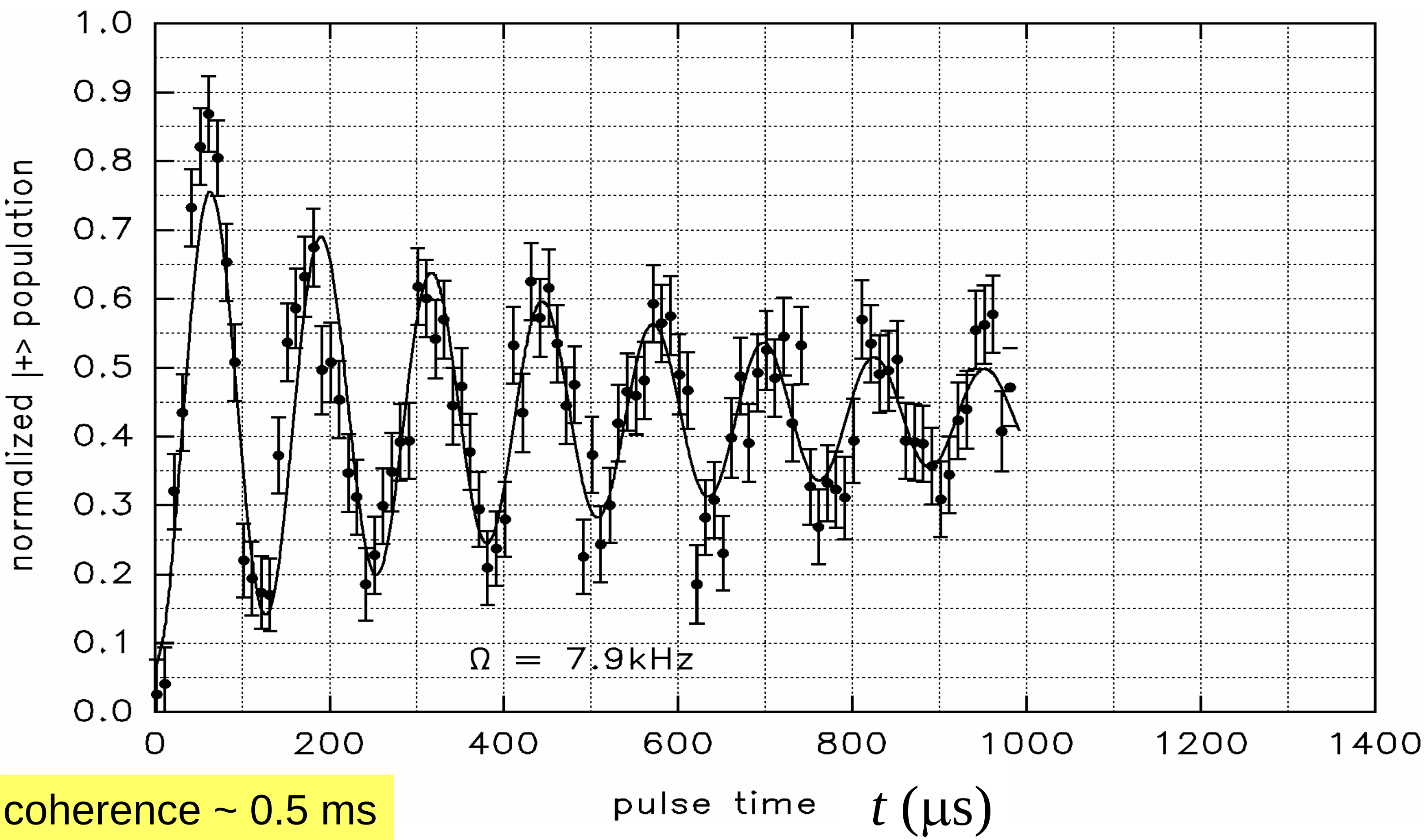




~10 mG magnetic field oscillating at the Larmor frequency drives Rabi oscillations of the spin state.

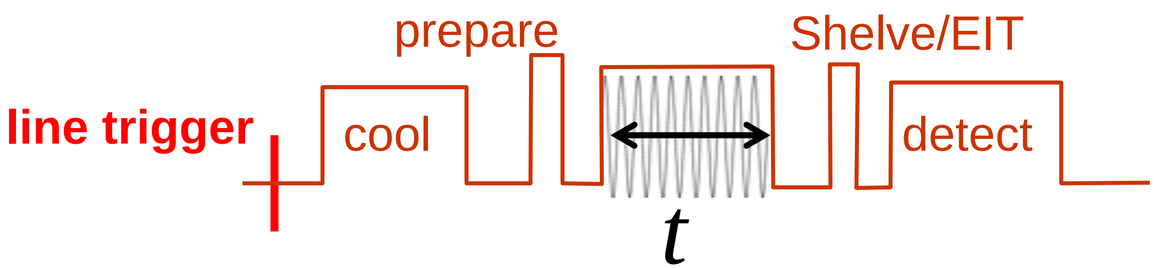
Rabi Oscillations

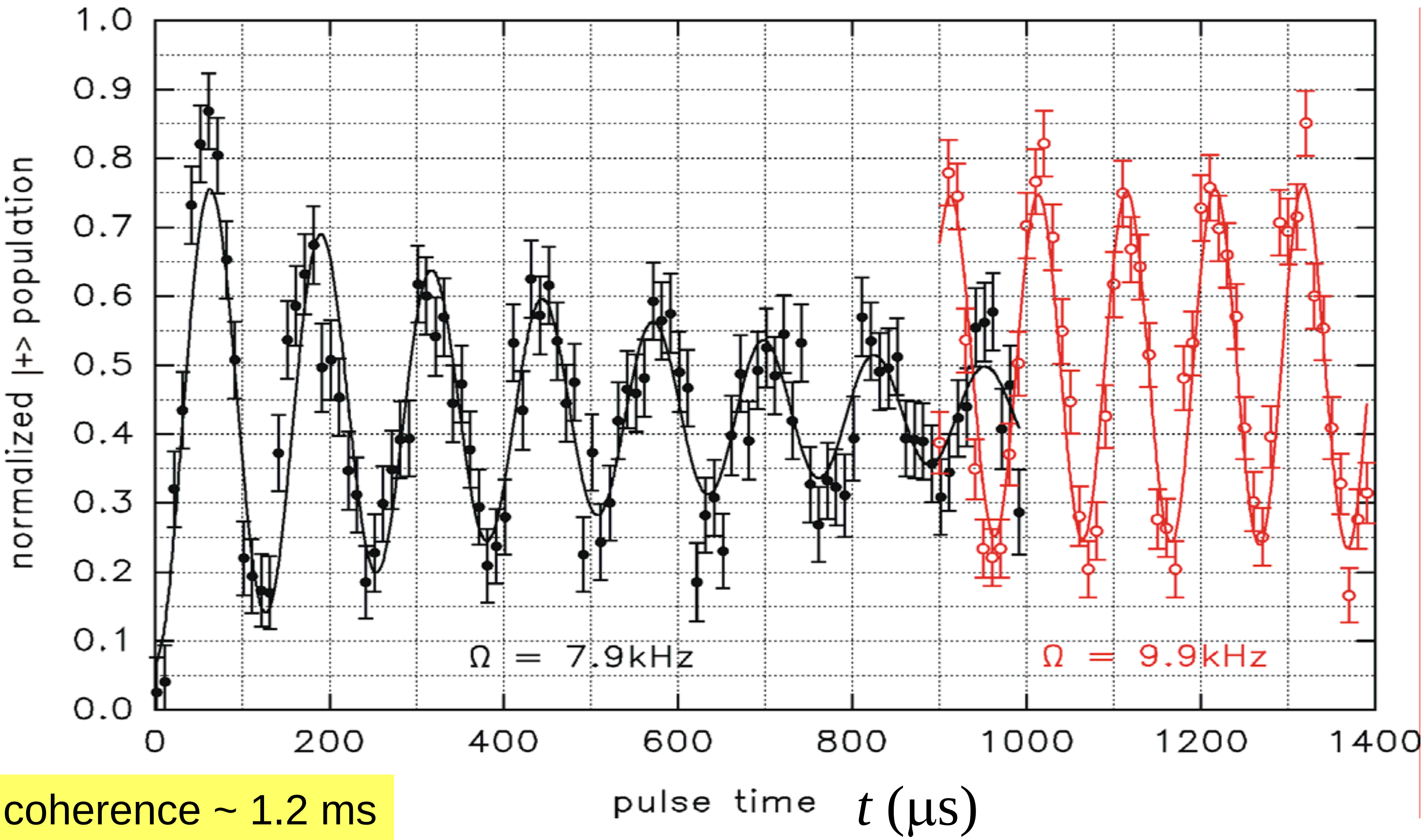




t coherence ~ 0.5 ms

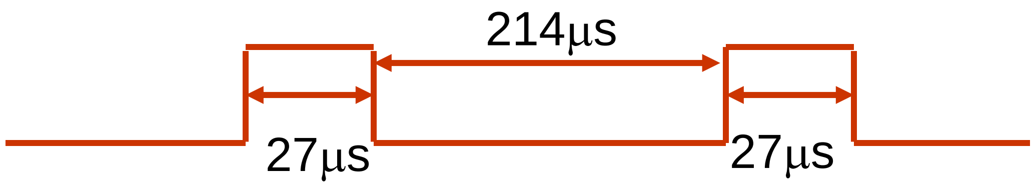
Rabi Oscillations with 50 Hz line trigger

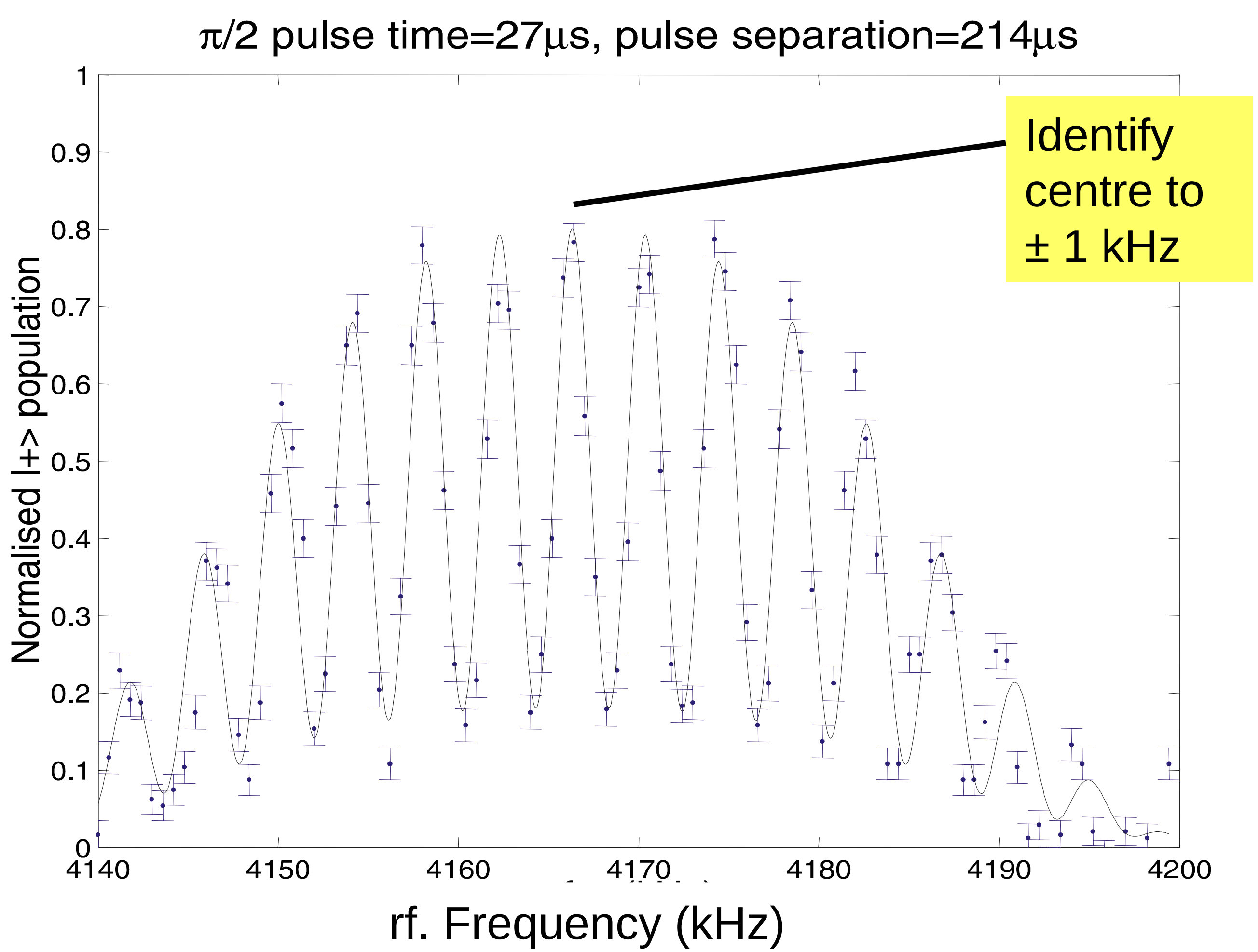




t coherence ~ 1.2 ms

Ramsey fringes





Cooling to near the ground state

Continuous Raman Sideband Cooling

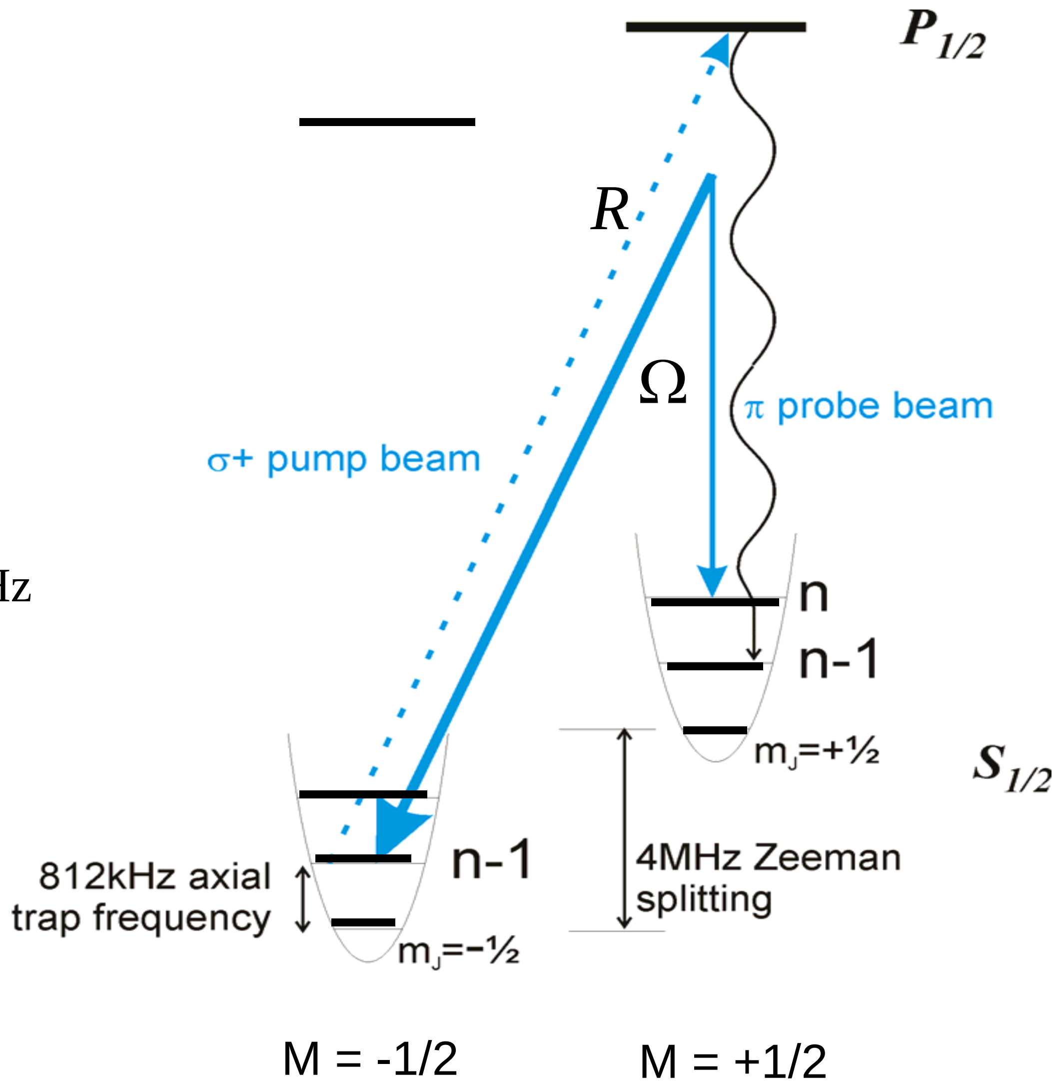
Typical values

Trap ν_z = 812 kHz

Lamb-Dicke $\eta = 0.2$

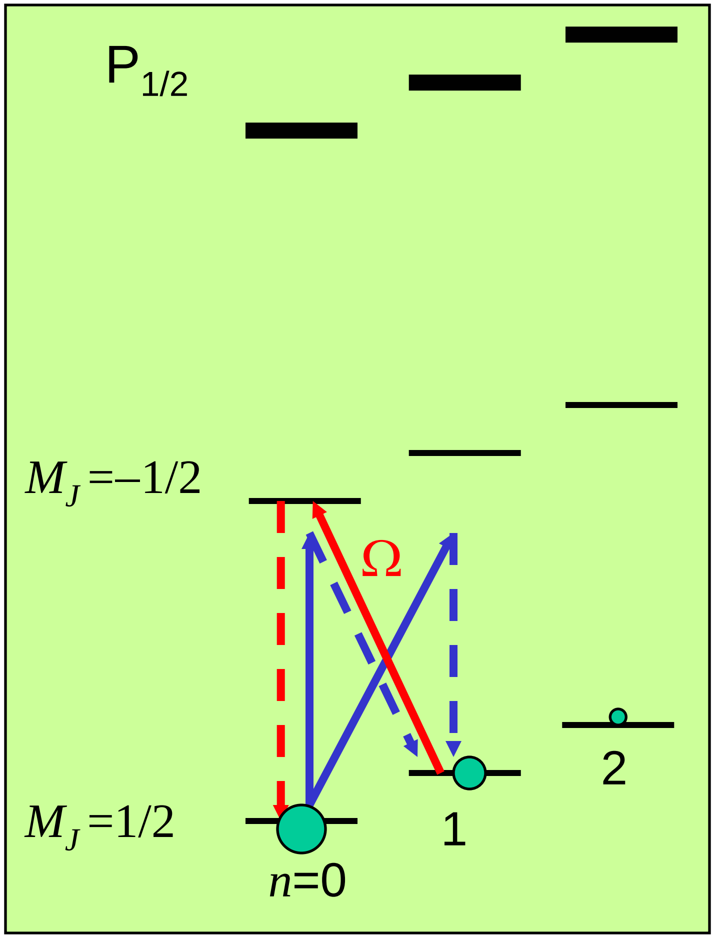
Raman $\Omega_{rsb} = 80$ kHz

Repumping $R = 100$ kHz

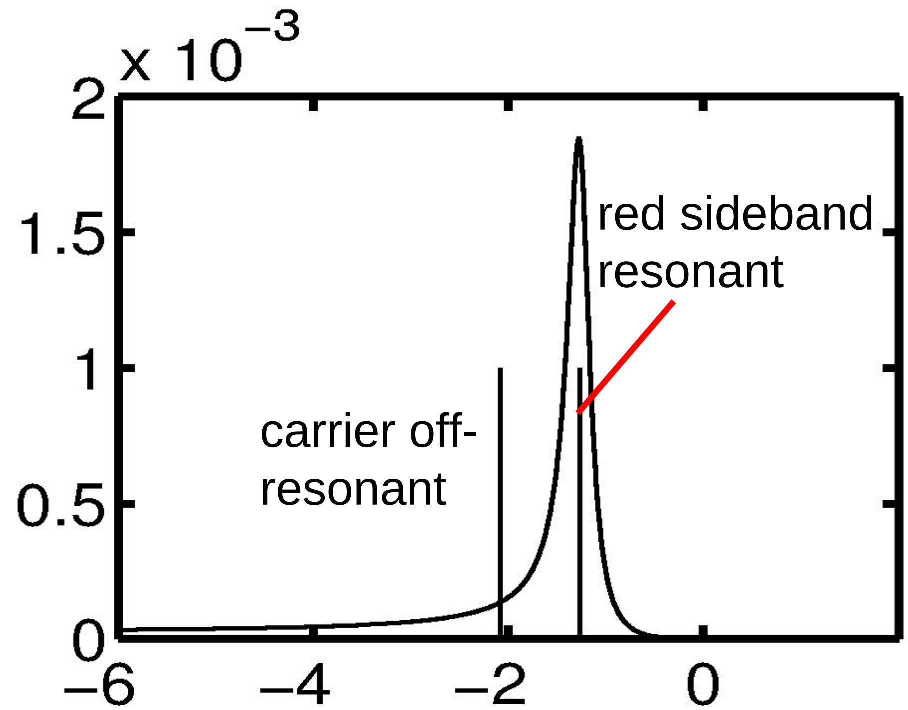


Lindberg & Javanainen, JOSAB **3**,1008 (1986)
G. Morigi et al. PRL **85**,4458 (2000)

Cooling rate and steady-state temperature



• Cooling rate (vib. quanta per second) is given by Rabi frequency on the red sideband Ω_{rsb}

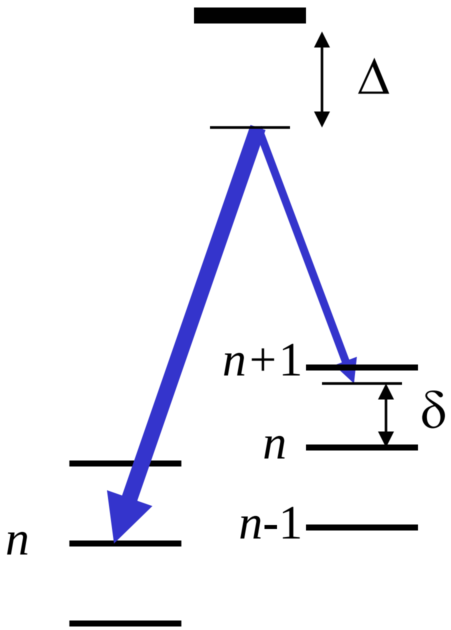


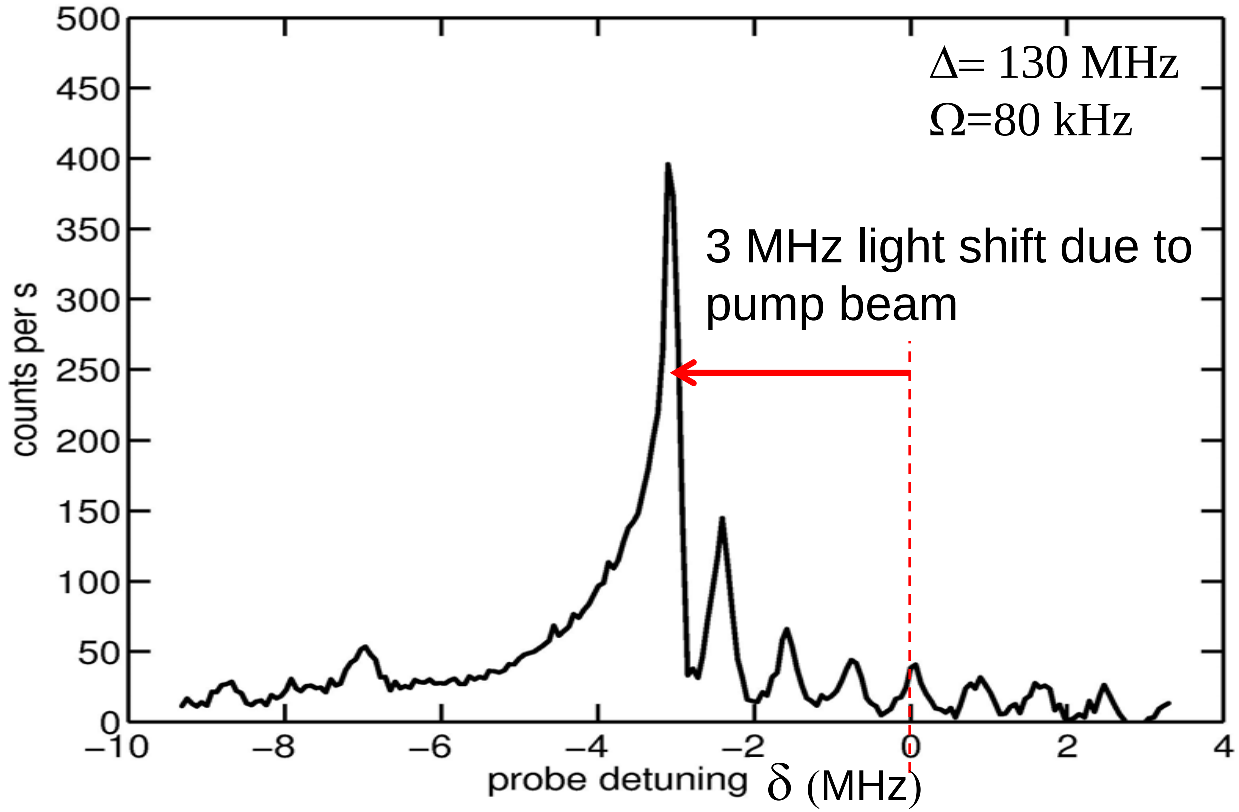
For our Raman + repumping process,

Linewidth $\Gamma = \max(R, \Omega_{rsb}) \sim 100$ kHz

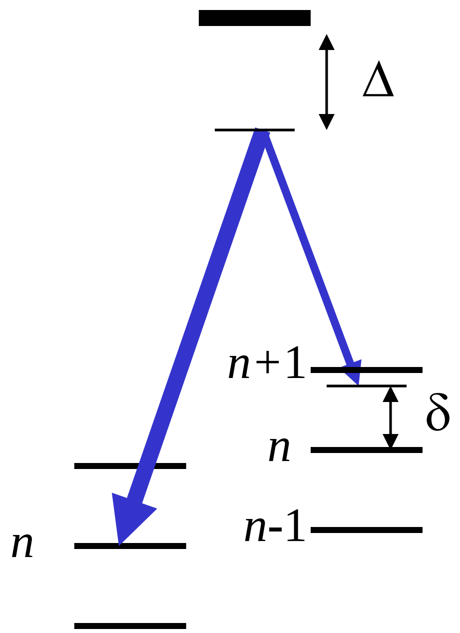
• So we expect $\langle n \rangle \sim (100/812)^2 \sim 0.01$

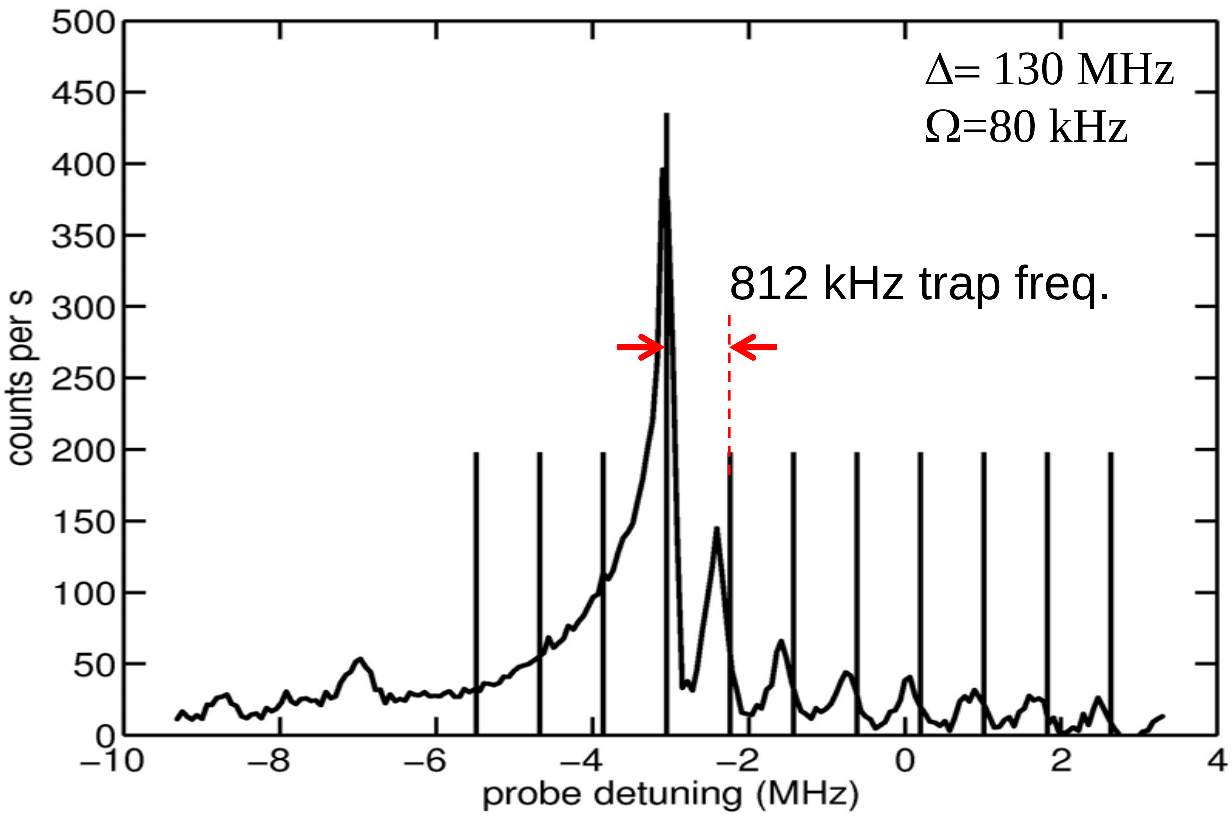
Sideband cooling – Results



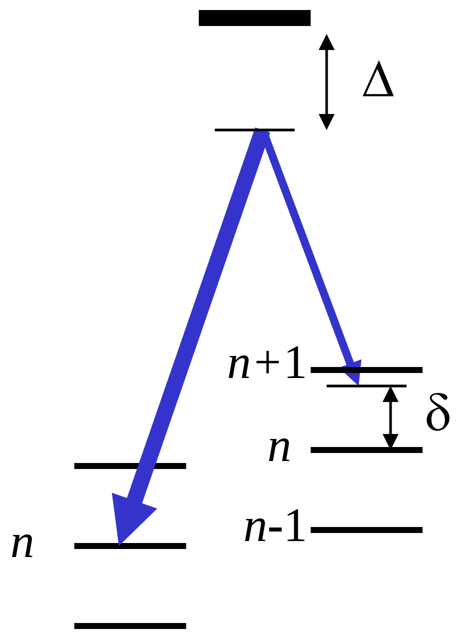


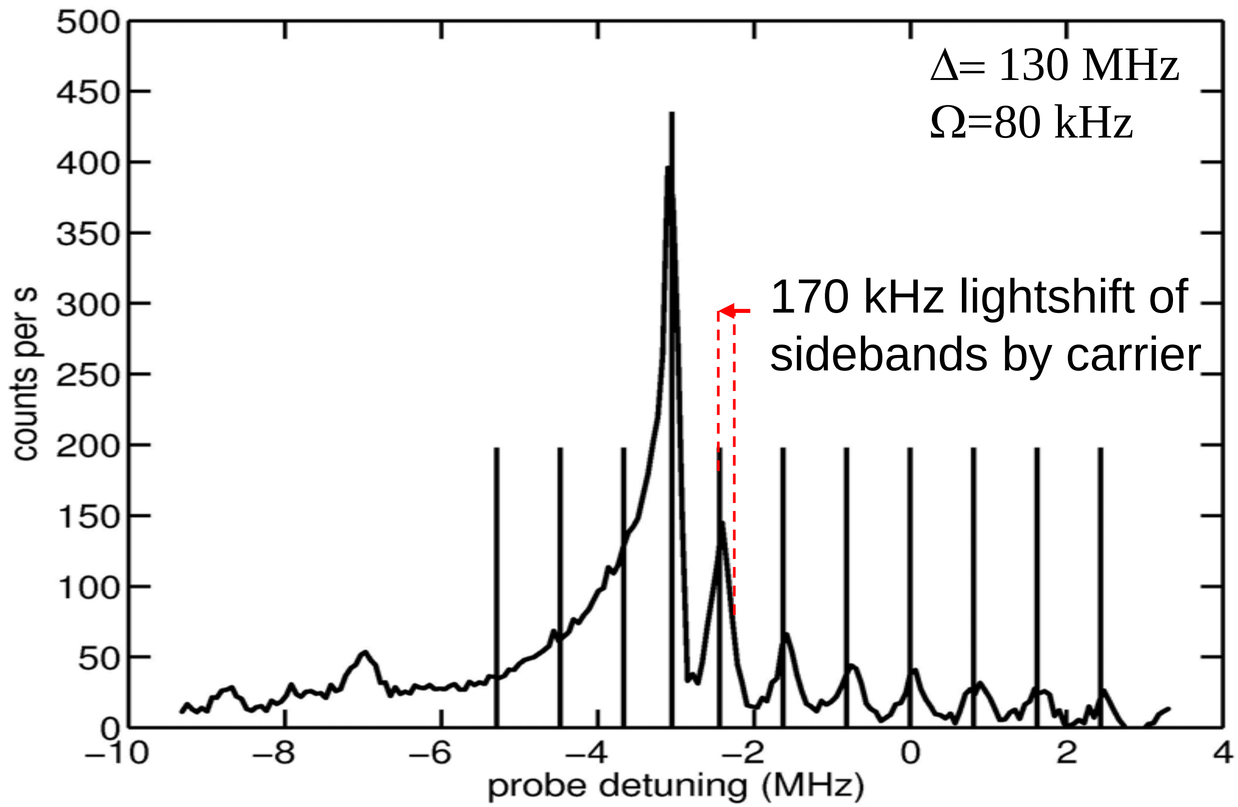
Sideband cooling – Results



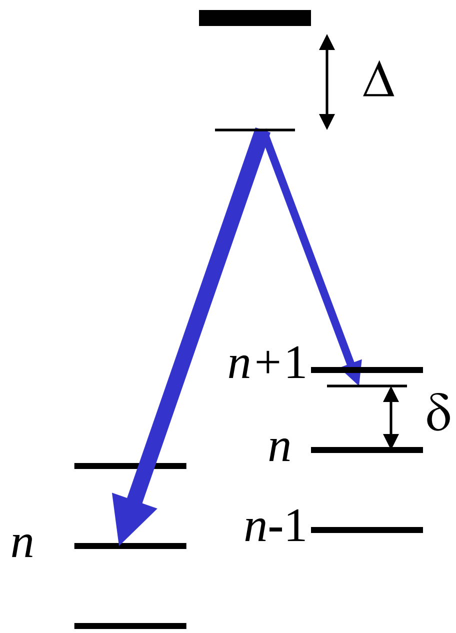


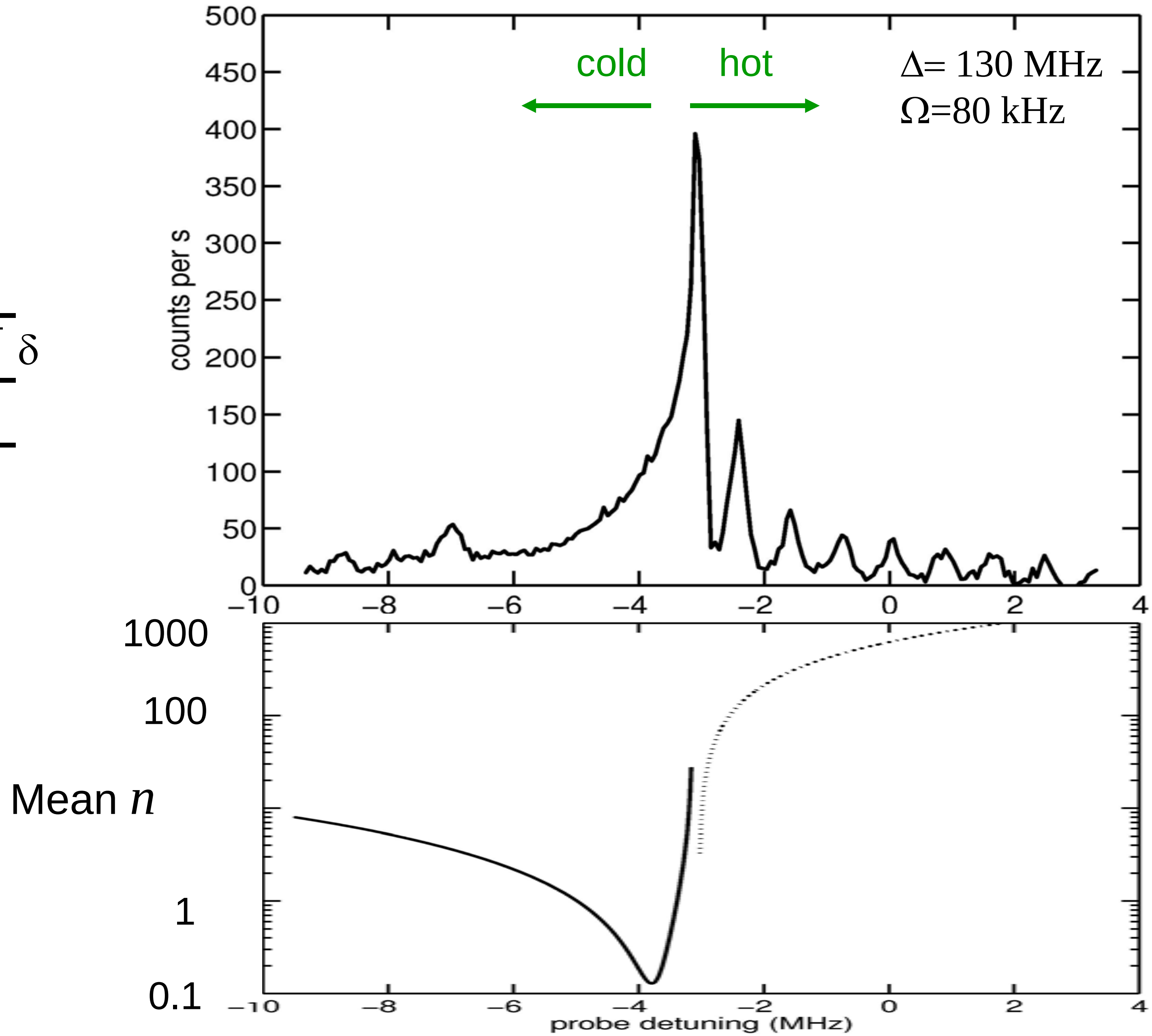
Sideband cooling – Results



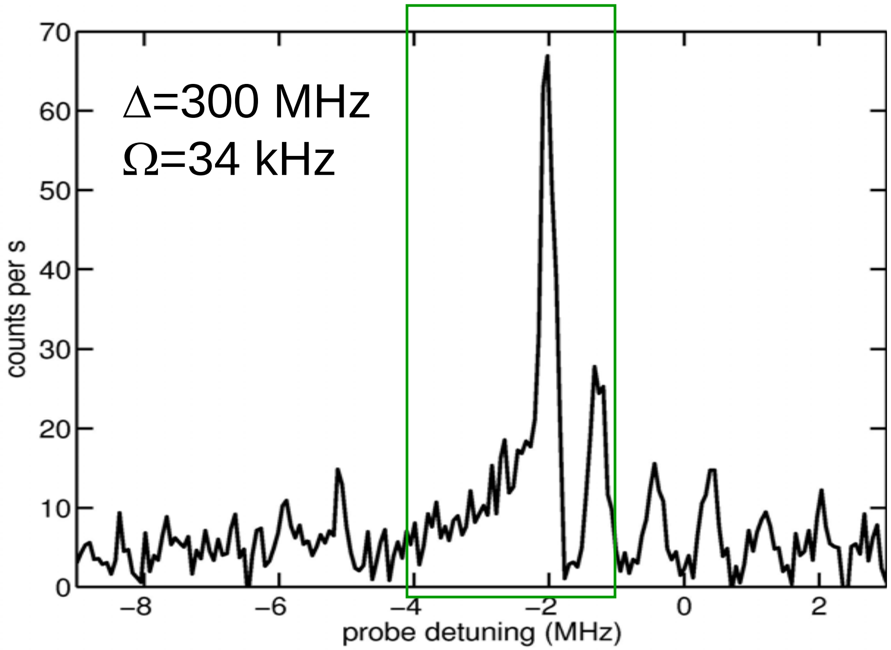


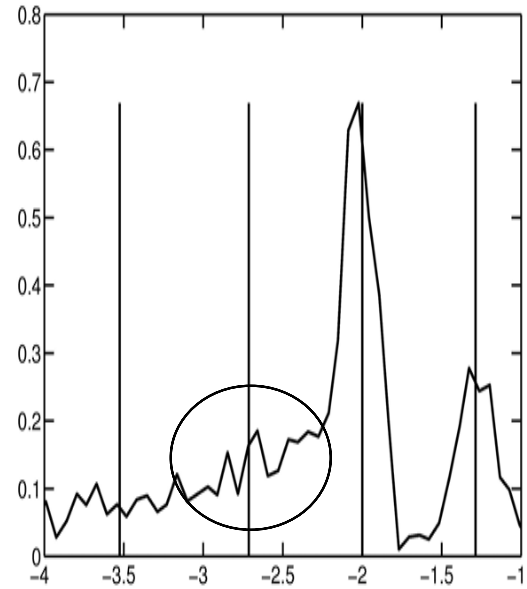
Interpretation

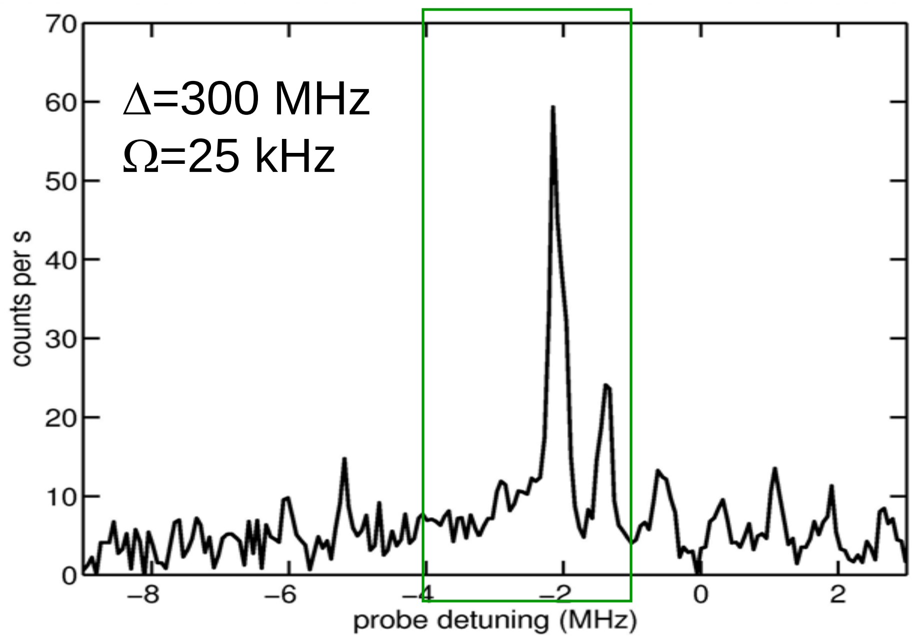


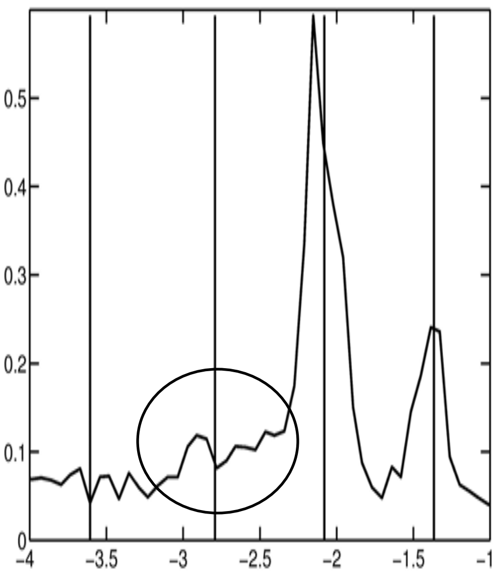


Upper bound on <n> and heating rate







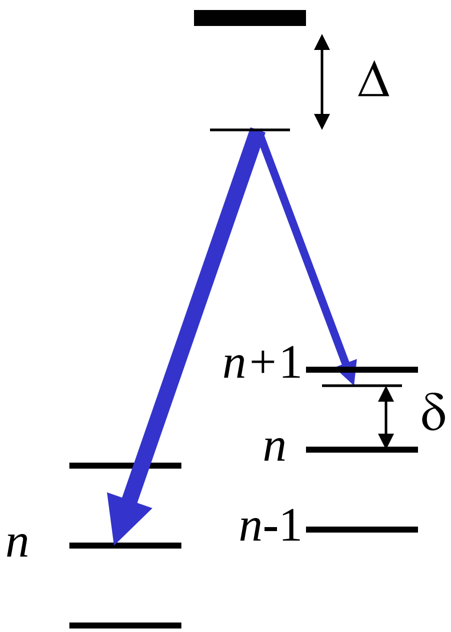


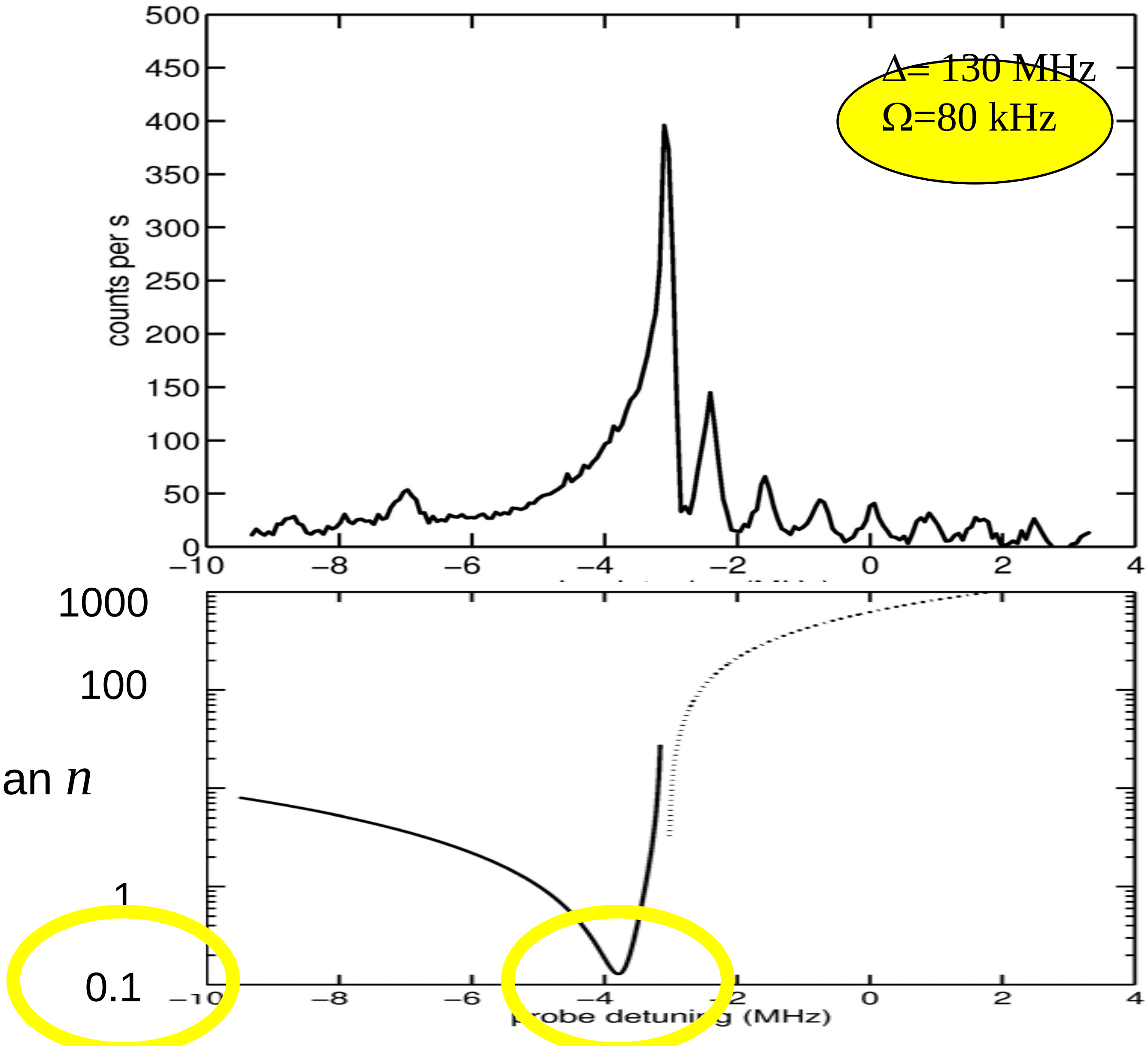
Data implies

$$\langle n \rangle < 0.5$$

$$\frac{dn}{dt} < 10 \text{ per ms}$$

→ Suggests the 1st exp. was cold





Sideband cooling conclusions

Data gives upper bound

$$\langle n \rangle < 0.5$$

$\Rightarrow$ Ground state population $P_0 > 0.7$

And indirect evidence for

$$\langle n \rangle \sim 0.1$$

$\Rightarrow$ Ground state population $P_0 \sim 0.9$

Conclusions

- A really thorough grasp of the pushing methods is needed to aim for fidelity 0.9999, and is also a good starting point for understanding faster methods.

- Electrode designs : we would welcome discussion of this.

- Experimentally, we have preparation, readout, single-bit rotation and cooling

→ next stage is to diagnose the temperature better, and then entanglement.