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Towards Quantum Phase Transitions of Small Ion Coulomb Crystals in Penning and RF Traps

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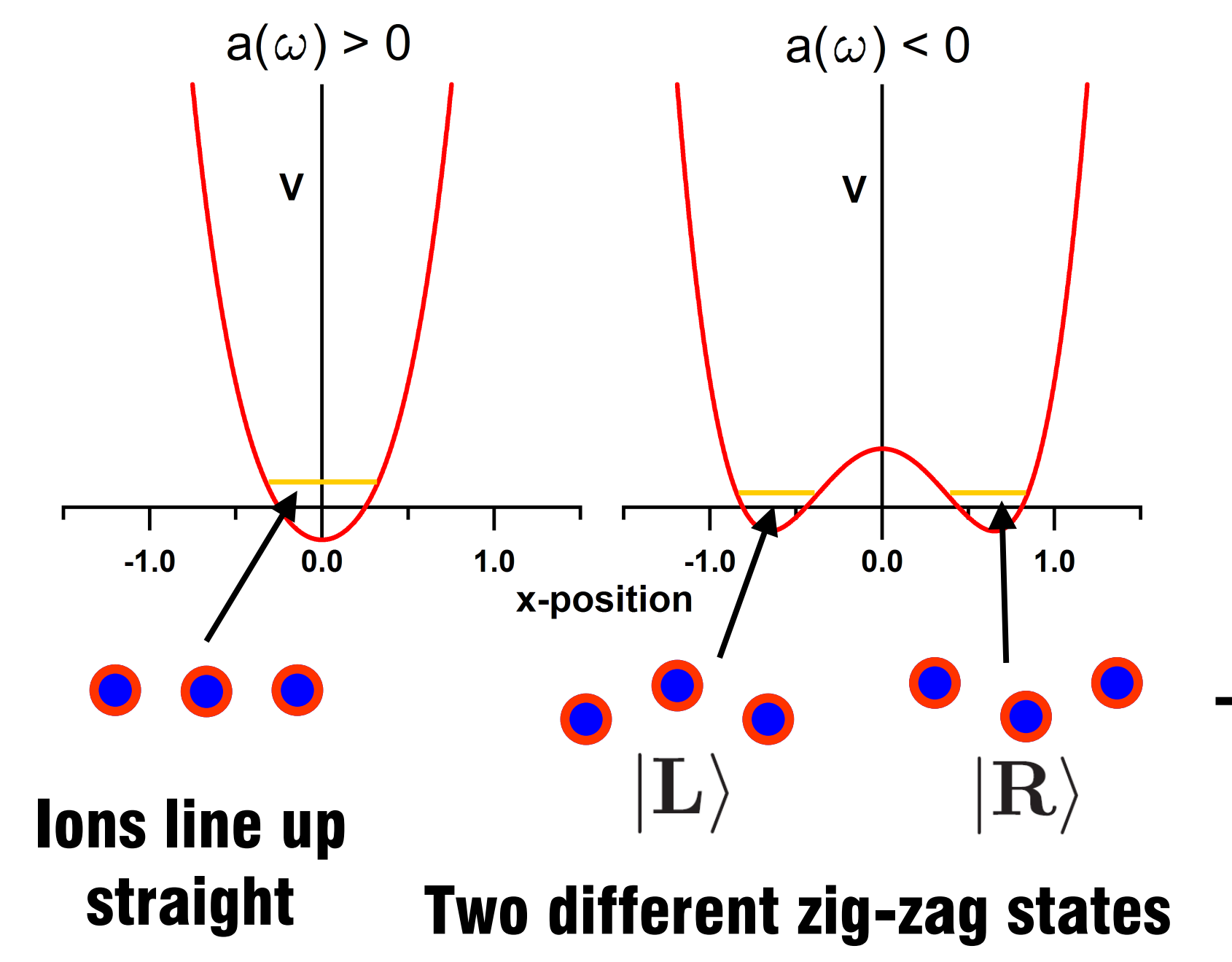
Tunnelling in a double well potential

Quantum tunnelling can be studied by accurate control of a double well potential of different depths [1]. This can be formed in both Paul and Penning traps. In a Penning trap the double well is in a rotating frame but does not suffer from micromotion.

$$V=\frac{1}{2}m\sum_{m=1}^{N}\left(\omega_x^2x_m^2+\omega_z^2z_m^2\right)+\frac{e^2}{4\pi\epsilon_0}\sum_{m=1}^{N}\sum_{n=m+1}^{N}\frac{1}{\sqrt{\left(x_m-x_n\right)^2+\left(z_m-z_n\right)^2}}$$

A Taylor expansion of the potential in a harmonic trap with coulomb repulsion between ions has the form of a quartic polynomial.

$$\tilde{V}=V\left(0\right)+\frac{1}{2}a\left(\omega\right)x^2+\frac{1}{4}b\left(\omega\right)x^4$$

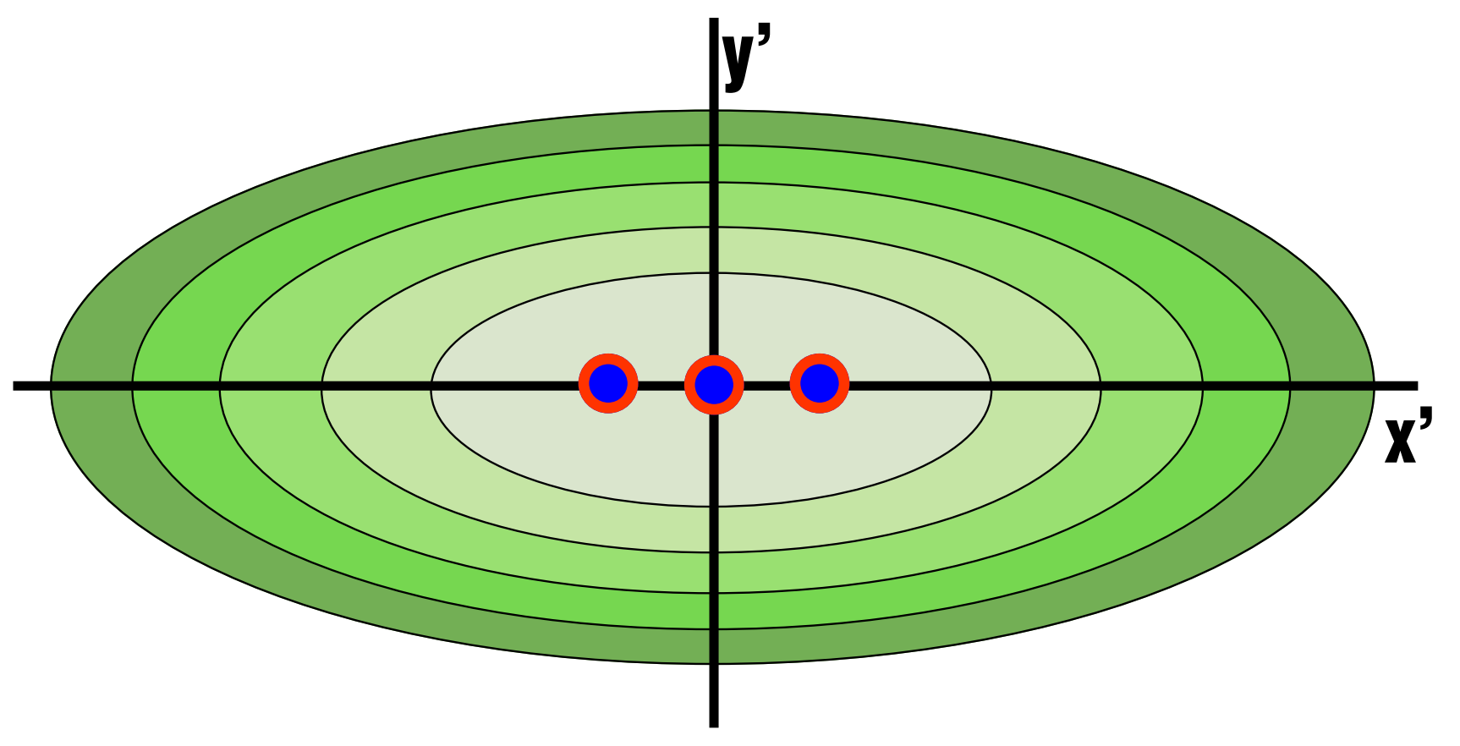


Ions line up straight

Two different zig-zag states

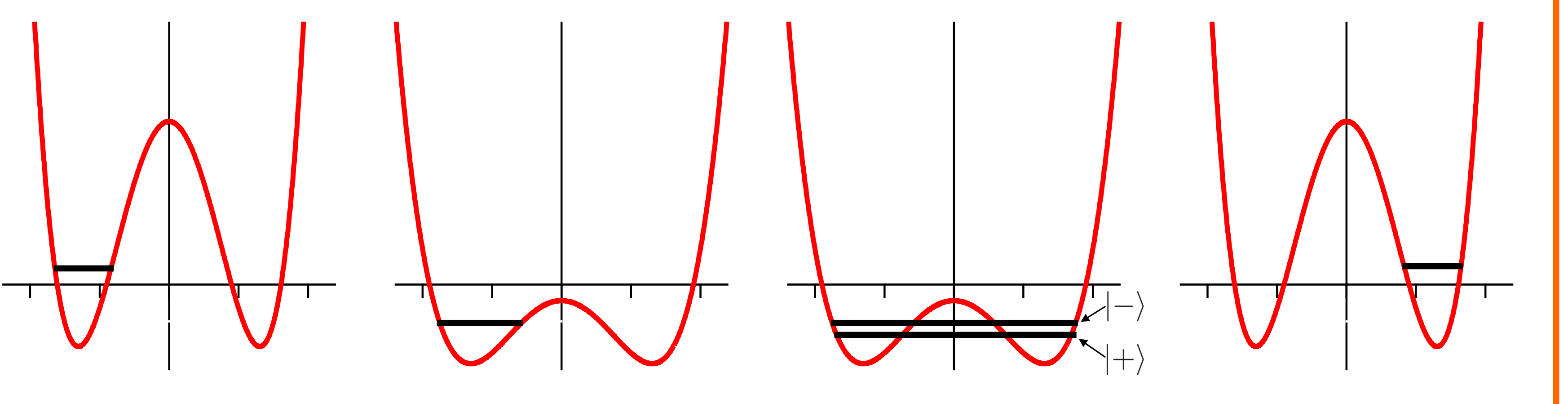
An RF voltage is applied to a Penning trap with quadrupole symmetry at half the cyclotron frequency. This squeezes the potential well in the rotating frame.

The ions line up as a crystal along the soft axis potential well.



Experimental procedure for tunnelling experiment:

By manipulating the RF perturbation the frequencies of the x' and y' directions can be altered and a zig-zag crystal formed.



(1) Prepare the system in the left state.

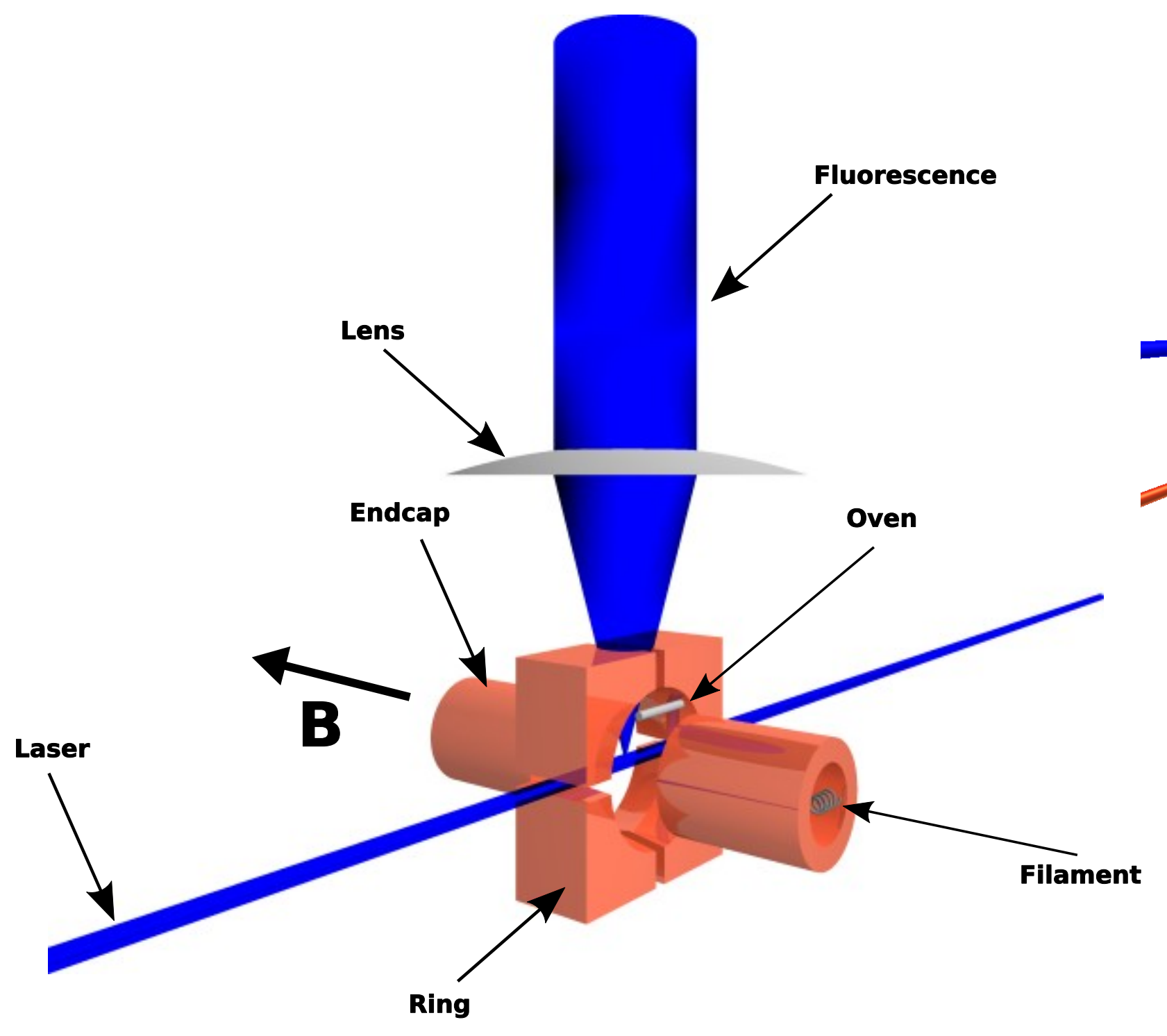
(2) Lower the potential barrier so only one state can exist in each side.

(3) The states can be written in a new basis $|+\rangle=|\mathrm{L}\rangle+|\mathrm{R}\rangle$ and $|-\rangle=|\mathrm{L}\rangle-|\mathrm{R}\rangle$. These states evolve (tunnel).

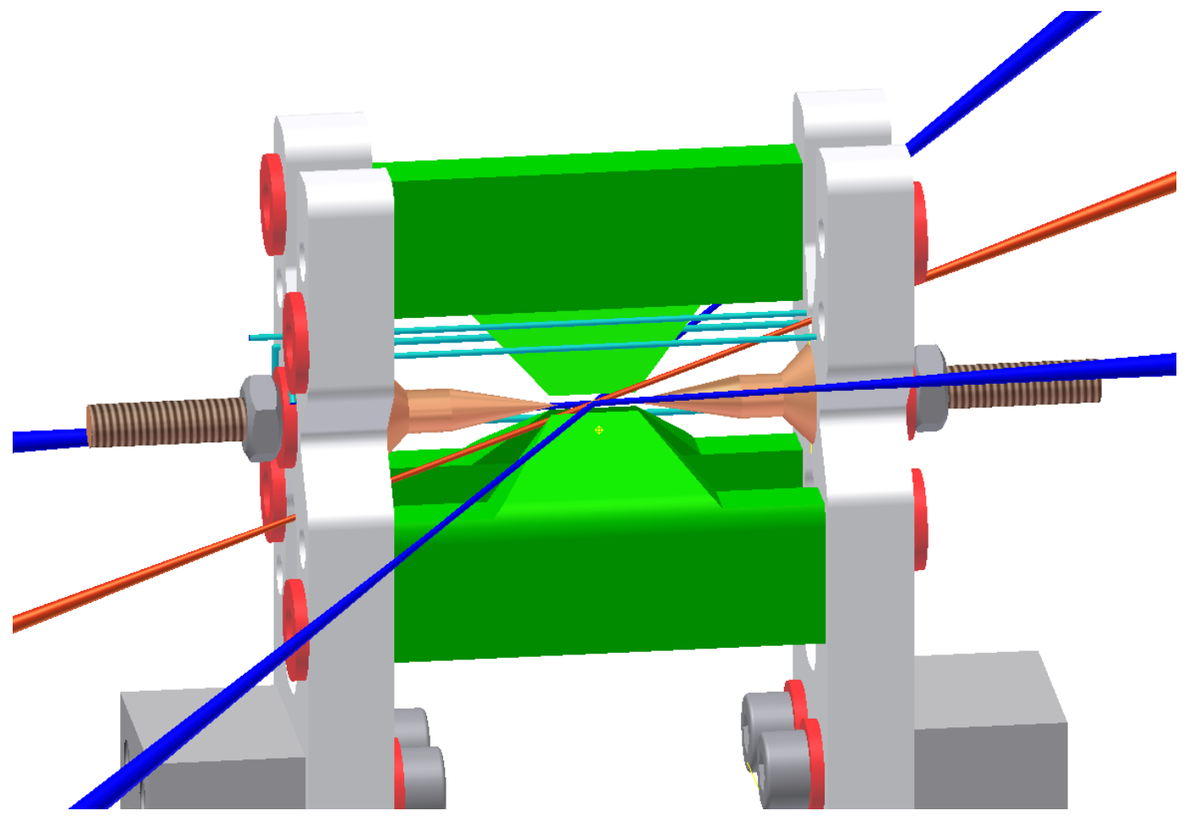
(4) Increase the barrier again and measure the final state the system ends up. Without tunnelling the system would always return to $|\mathrm{L}\rangle$.

Possible traps for implementation of tunnelling experiments:

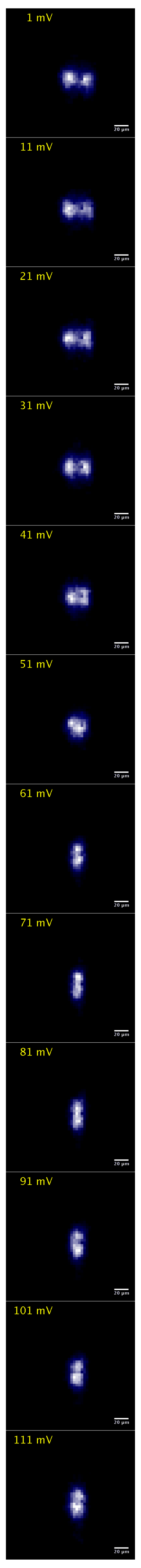
Crystal experiments in a Penning trap must be conducted in the rotating frame.



Linear Paul trap where degeneracy in the radial plane can be removed.



Applying a quadrupole field of the appropriate frequency [2] to the radial potential we can affect the cooling efficiency of a small crystal in a Penning trap and alter the crystal orientation [3].



Summary

- Penning and Paul traps could be an ideal system for studying double well dynamics.
- m_j states are no longer eigenstates in Penning traps due to the high magnetic field, inducing quantum jumps.
- Laser cooling in a Penning trap is more difficult, but can be done. The large Zeeman splitting gives an extra degree of freedom which may be advantageous in some sideband cooling schemes.

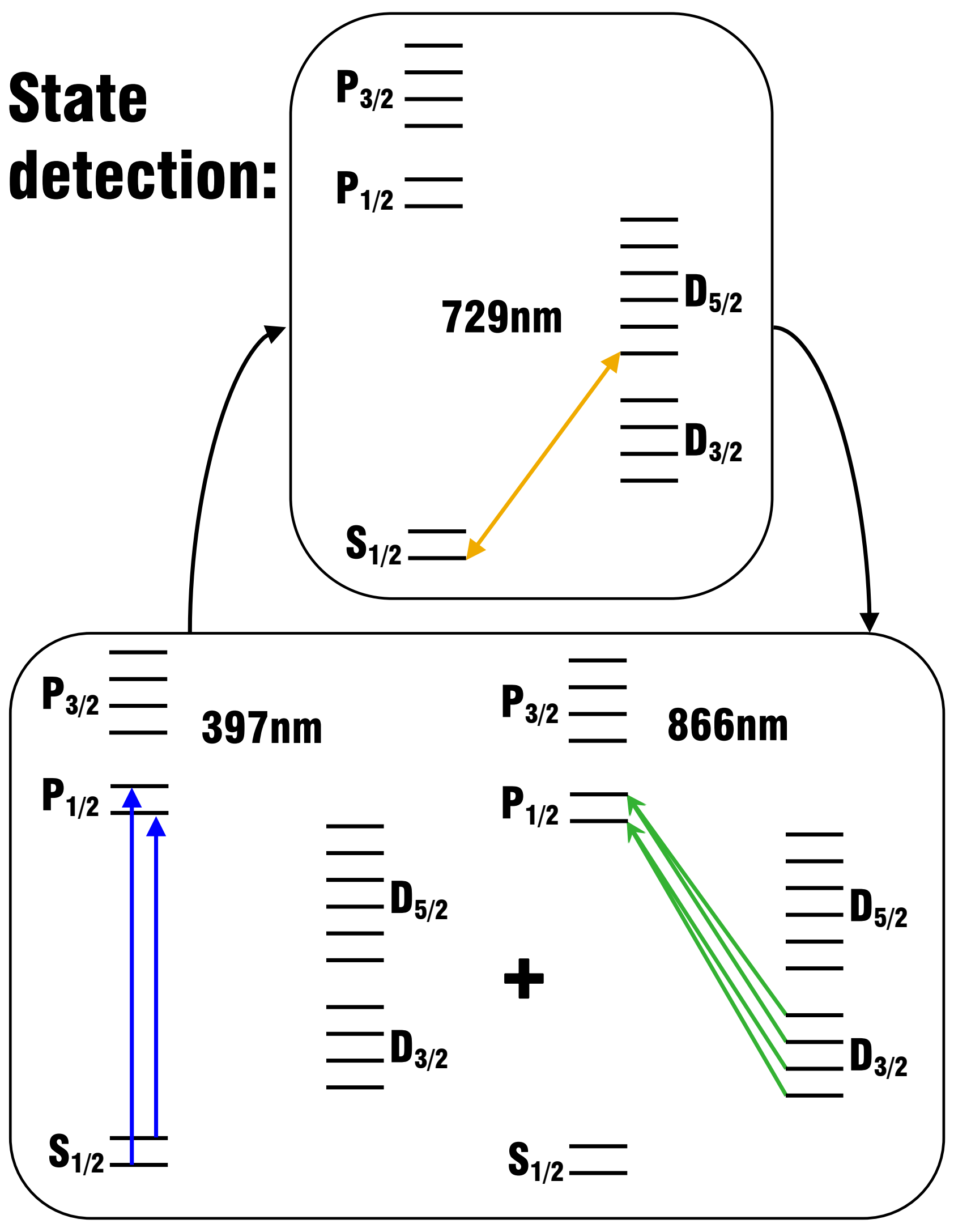
Future plans

- Implement a Penning trap repumping scheme using a high frequency EOM.
- Build a blade RF trap for initial tunnelling experiments.
- Perform experiments with double well potentials in Penning and Paul traps.

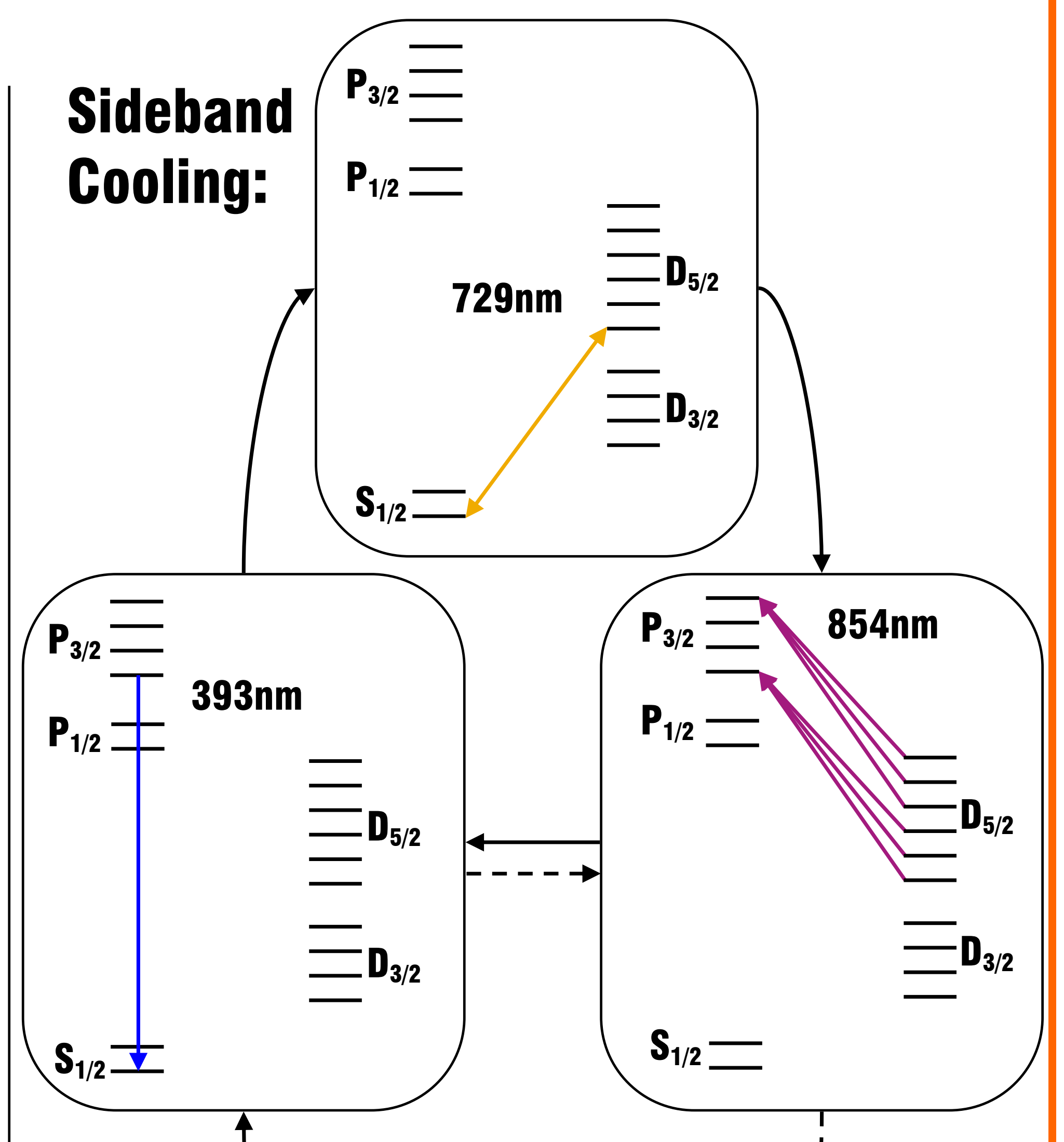
Laser repumping $^{40}Ca^+$: Penning trap vs Paul trap

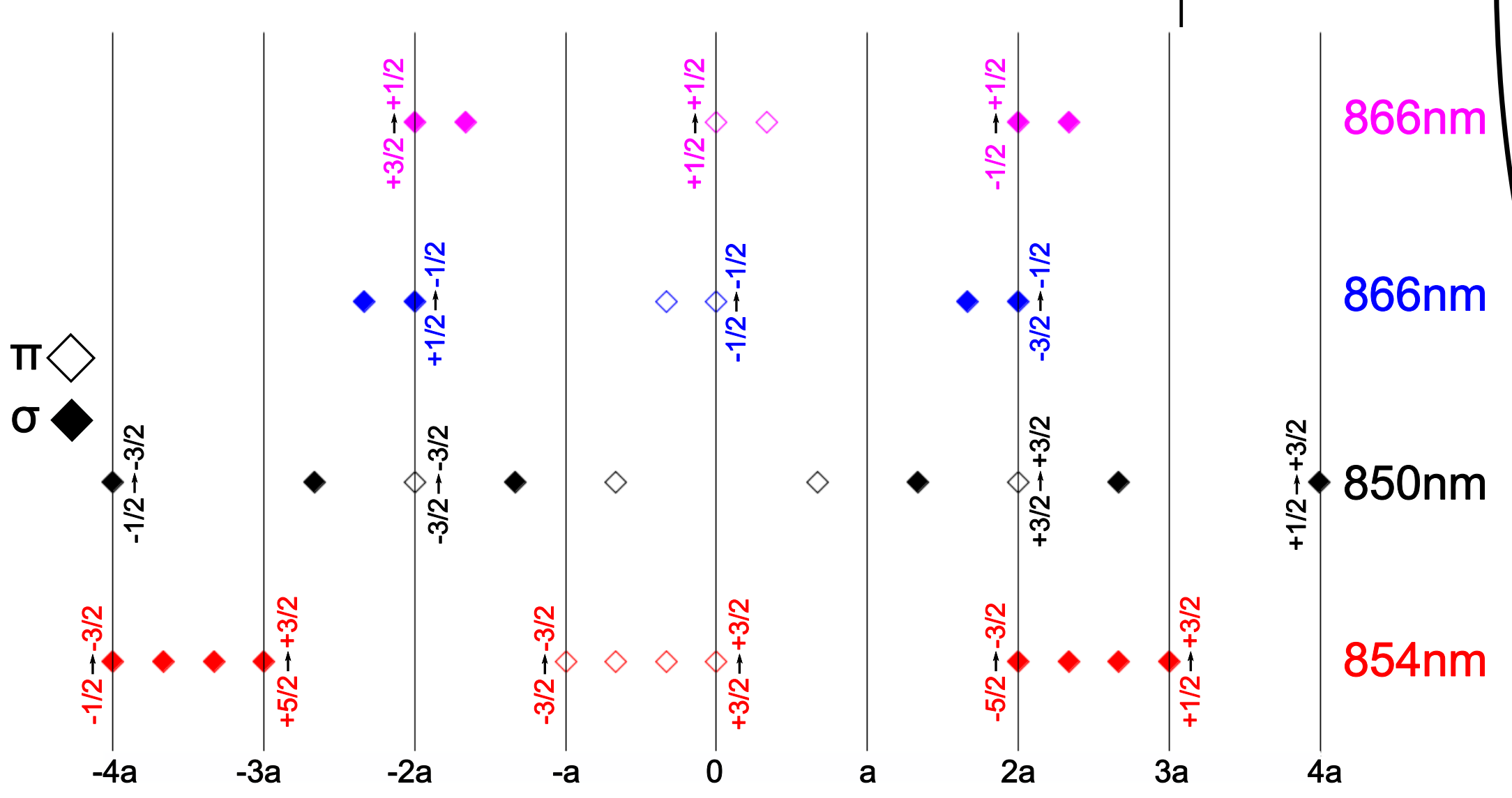
In a Penning trap, transitions are Zeeman split by several GHz. This requires several different laser frequencies, which we currently produce using several different diode lasers. In the near future we plan to use a high frequency fibre EOM to put sidebands on the repumper lasers.

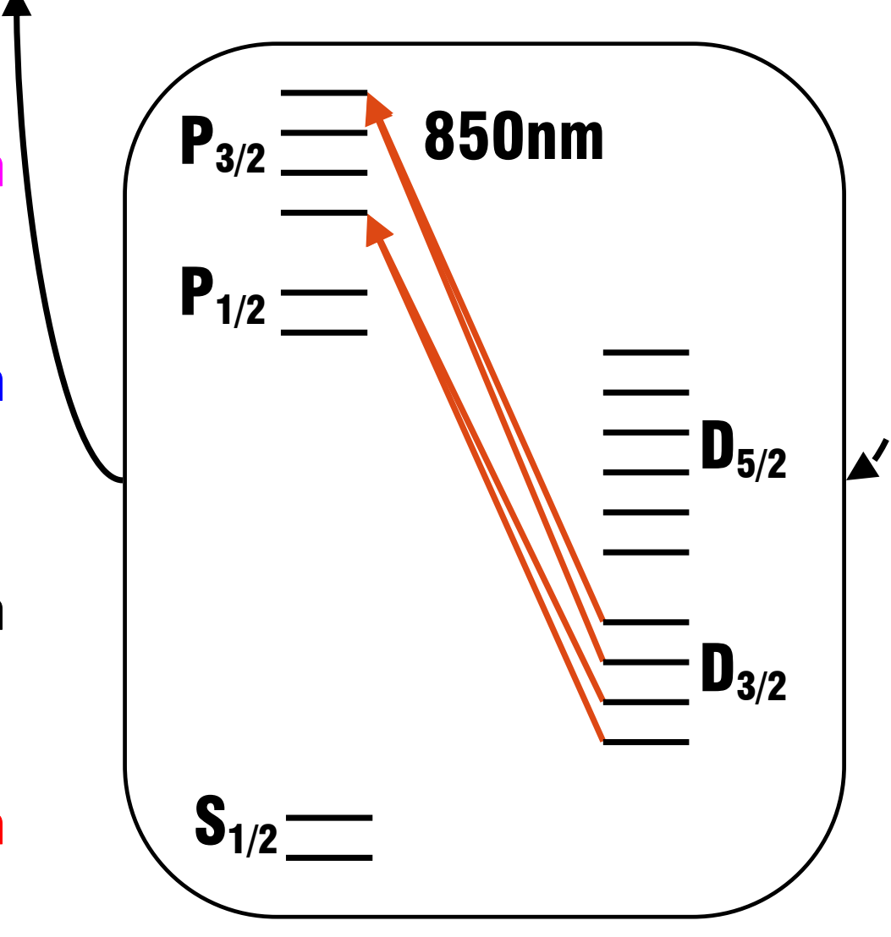
State detection:



Sideband Cooling:







Transition frequencies relative to laser carrier. a = 5.6 GHz / Tesla.

The large Zeeman splitting gives an extra degree of freedom in addition to laser polarisation and angle to choose certain transitions in preference to others.

It should be possible, by stimulating the appropriate 850 nm and 854 nm (and 729 nm) transitions, to create a completely closed loop for sideband cooling which is not possible in a similar system at low magnetic field.

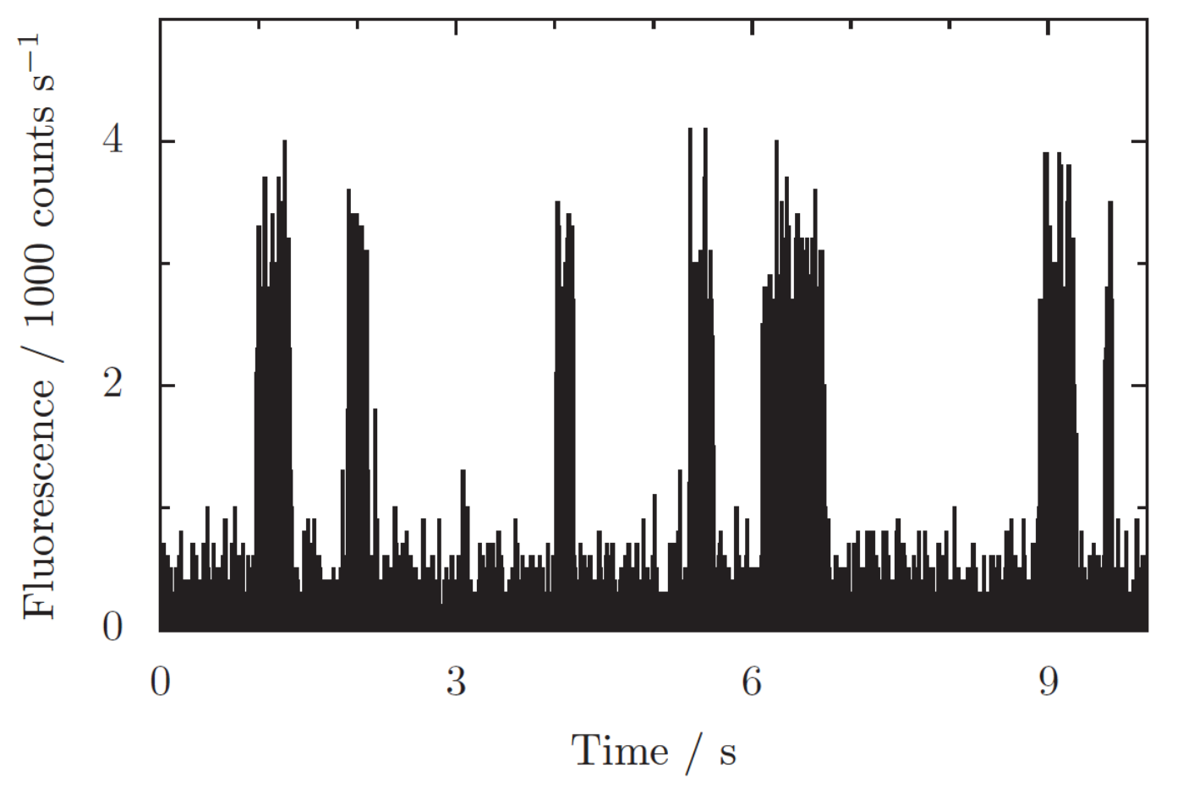
Quantum J-state mixing

With a single $^{40}Ca^+$ ion trapped we have investigated the statistics of quantum jumps in the presence of the large magnetic field of the Penning trap [4].

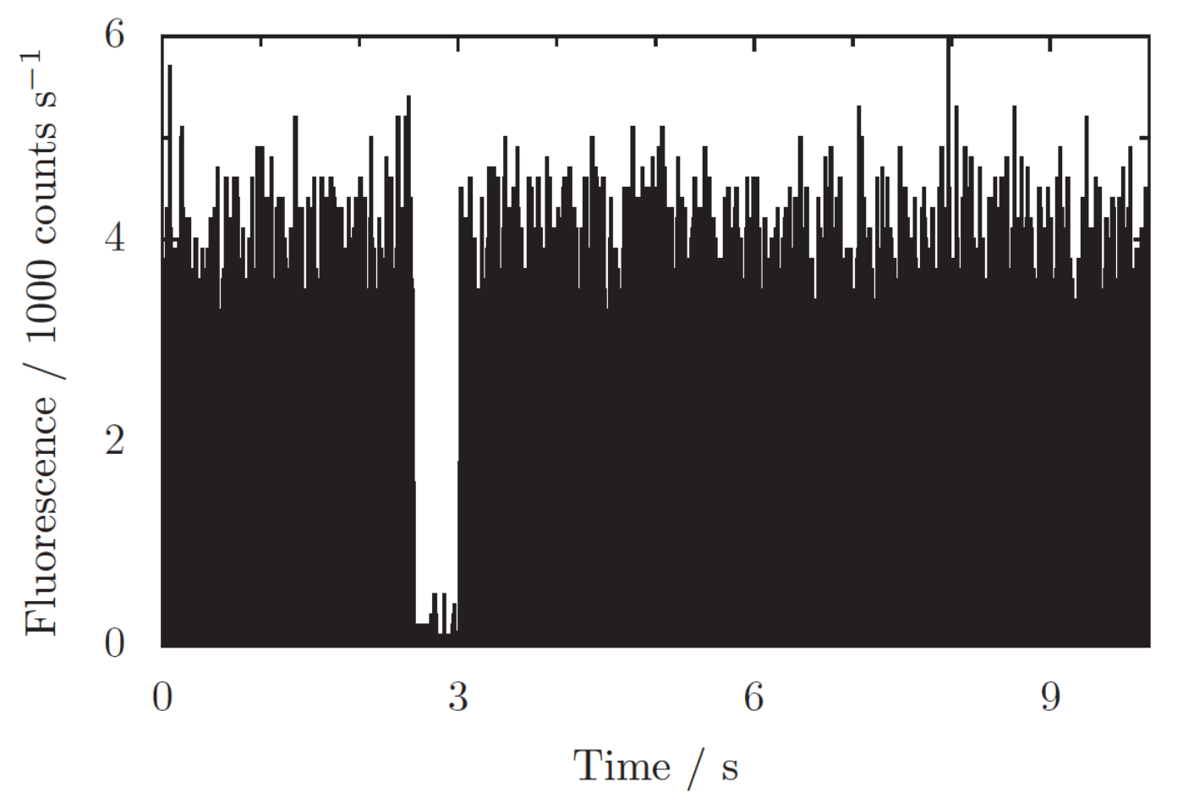
A magnetic field leads to mixing of states with different values of the *J* quantum number.

A small admixture of the D3/2 state in the D5/2 state makes forbidden P1/2 to D5/2 transition partially allowed, leading to quantum jumps. Electron shelving allows us to detect this small effect.

Quantum jumps in a Penning trap at 0.9T



Quantum jumps in a combined trap at 0.2T



$$\left|D^{m_J}_{\frac{5}{2}}\right\rangle'=\left|D^{m_J}_{\frac{5}{2}}\right\rangle+\delta_{D^{m_J}}\left|D^{m_J}_{\frac{3}{2}}\right\rangle$$

Using first order perturbation theory the rate of quantum jumps can be calculated.

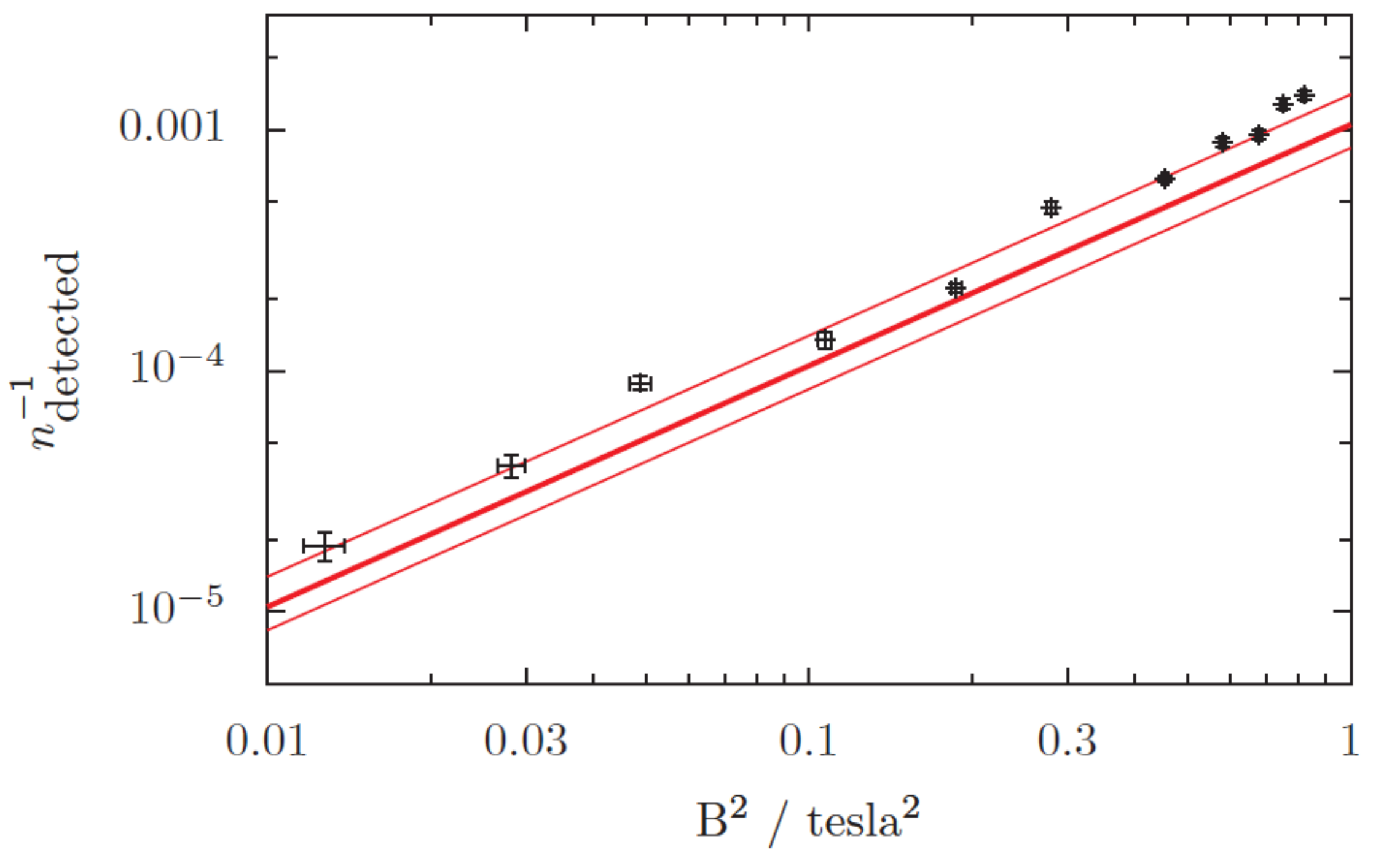
$$-\mu\cdot\mathbf{B}=-\mu_BB\left(L_z+2S_z\right)$$

$$\delta_{D^{m_J}}=\frac{\left\langle D^{m_J}_{\frac{3}{2}}\middle|-\mu\cdot\mathbf{B}\middle|D^{m_J}_{\frac{5}{2}}\right\rangle}{E\left(D_{\frac{5}{2}}\right)-E\left(D_{\frac{3}{2}}\right)}$$

$$\delta_{D\frac{3}{2}}=\frac{2}{5}\frac{\mu_BB}{\Delta E_D}$$

n is the average number of photons detected between quantum jumps.

$$\boxed{n^{-1}=4.2\times10^{-7}B^2}$$



The shelving rate increases with the square of the magnetic field.

References

[1] Double Well Potentials and Quantum Phase Transitions in Ion Traps, A. Retzker, R.C. Thompson D.M. Segal, and M.B. Plenio, Phys. Rev. Lett., 26, 260504 (2008).
[2] Axialization of Laser Cooled Magnesium Ions in a Penning Trap, H. F. Powell, D. M. Segal, and R. C. Thompson, Phys. Rev. Lett., 89, 93003 (2002).
[3] Two-ion Coulomb crystals of Ca+ in a Penning trap, D. R. Crick, H. Ohadi, I. Bhatti, R. C. Thompson, and D. M. Segal, Opt. Exps., 16, 2351 (2008).
[4] Magnetically induced electron shelving in a trapped Ca^+ ion, D. R. Crick, S. Donnellan, D. M. Segal and R.C. Thompson, Phys. Rev. A, 81, 052503 (2010).