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Coherent control of ground-state cooled ions in a Penning trap

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FQT
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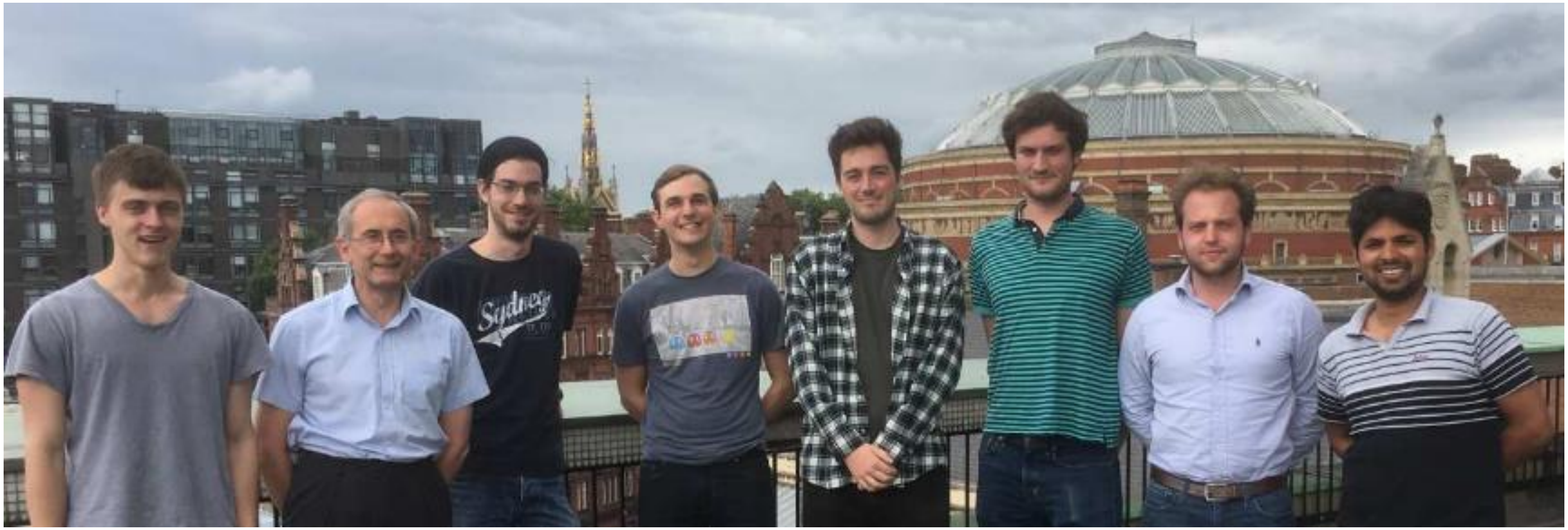
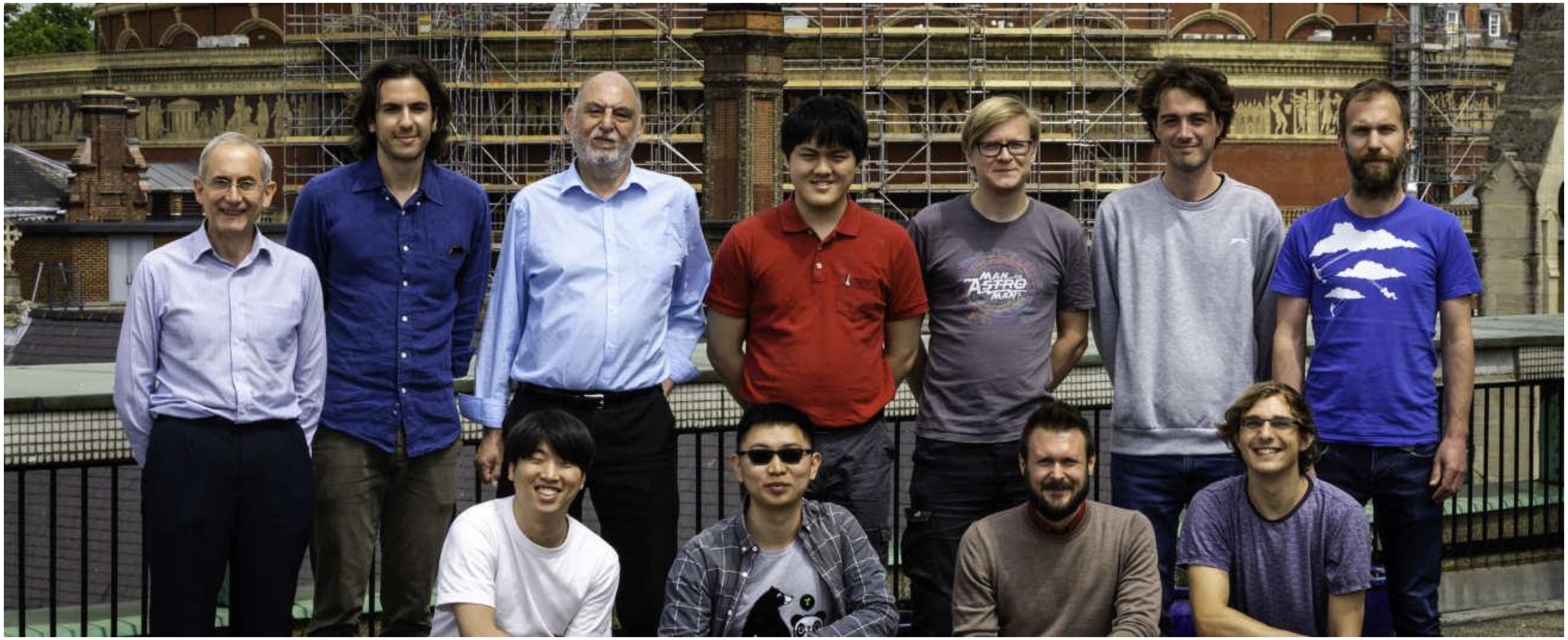
People involved in this work earlier



- *PhD students:* Ollie Corfield, Jake Lishman (theory), Manoj Joshi (Innsbruck), Vincent Jarlaud (Aarhus), Pavel Hrmo (Innsbruck)
- *Staff:* Richard Thompson, Florian Mintert (theory), Danny Segal (1960-2015)

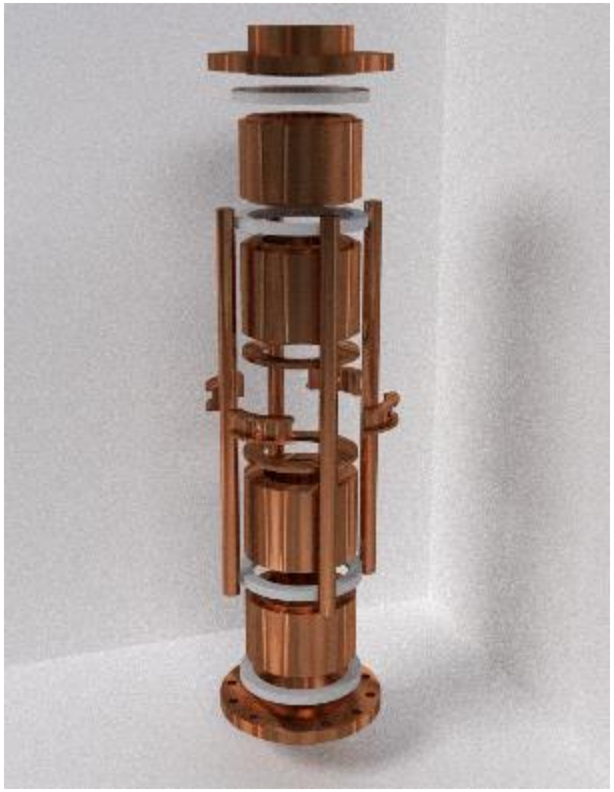
People involved in this work now



- *PhD students:* Ollie Corfield, Jake Lishman (theory), Chungsun Lee, Jacopo Mosca Toba
- *Postdocs*: Simon Webster, Johannes Heinrich, Mahdi Sameti (theory)
- *Staff:* Richard Thompson, Florian Mintert (theory)

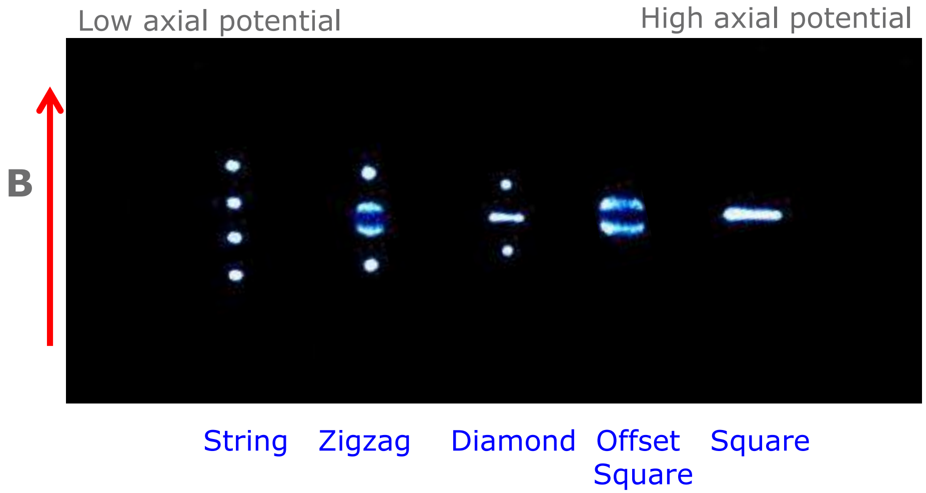
Outline of the talk

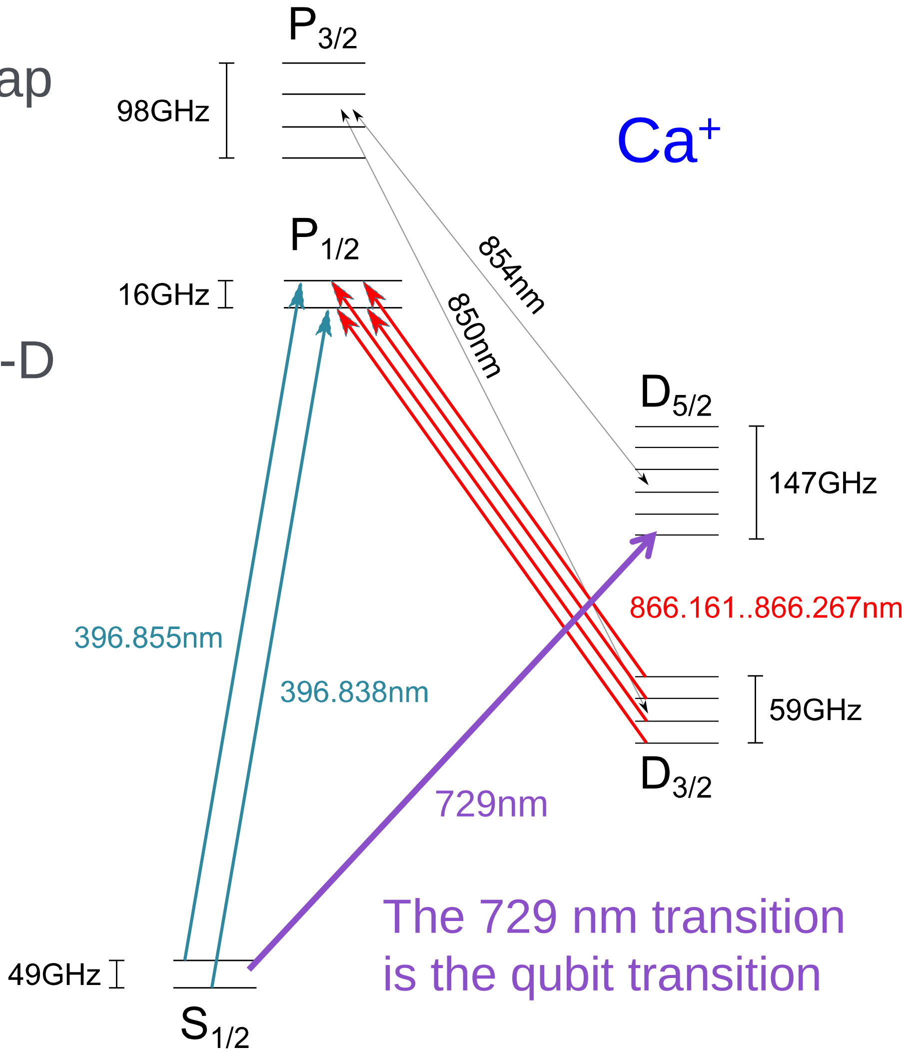
- Laser cooling in the Penning trap
- Effect of a large Lamb-Dicke parameter
- Sideband cooling of a single ion
    - Coherent operations on the single ion
- Sideband cooling of two-ion ‘crystals’
- Sideband cooling of the radial motion
- Outlook



Laser cooling of calcium in a Penning trap

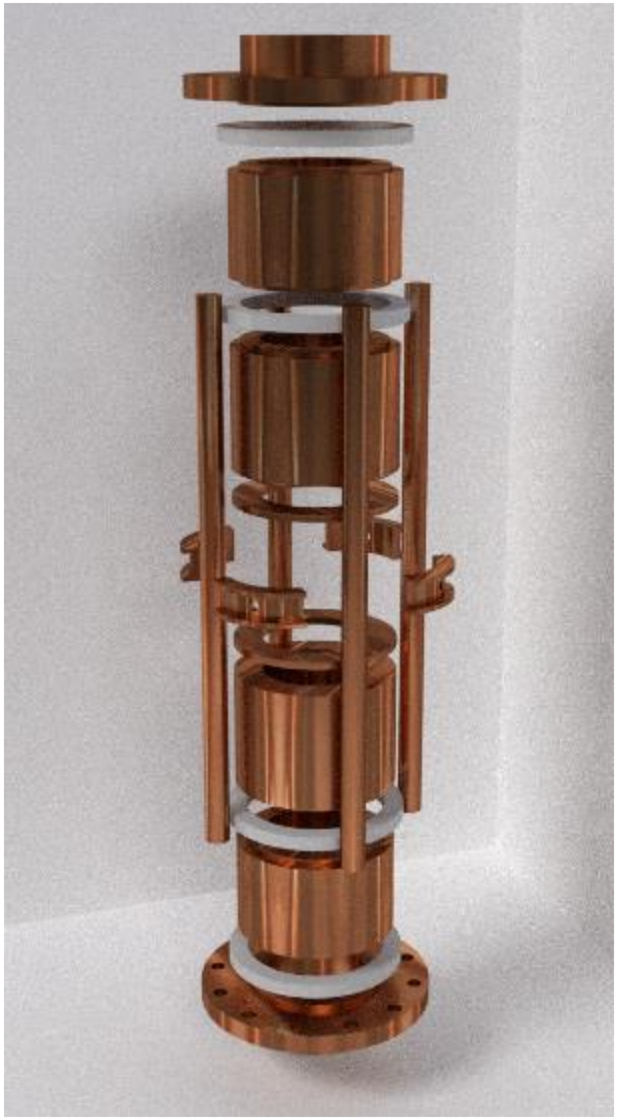
- In the magnetic field of the Penning trap we obtain large Zeeman splittings
- We require 10 laser frequencies (4 lasers) for Doppler cooling
- We can create and control 1, 2, and 3-D Coulomb crystals





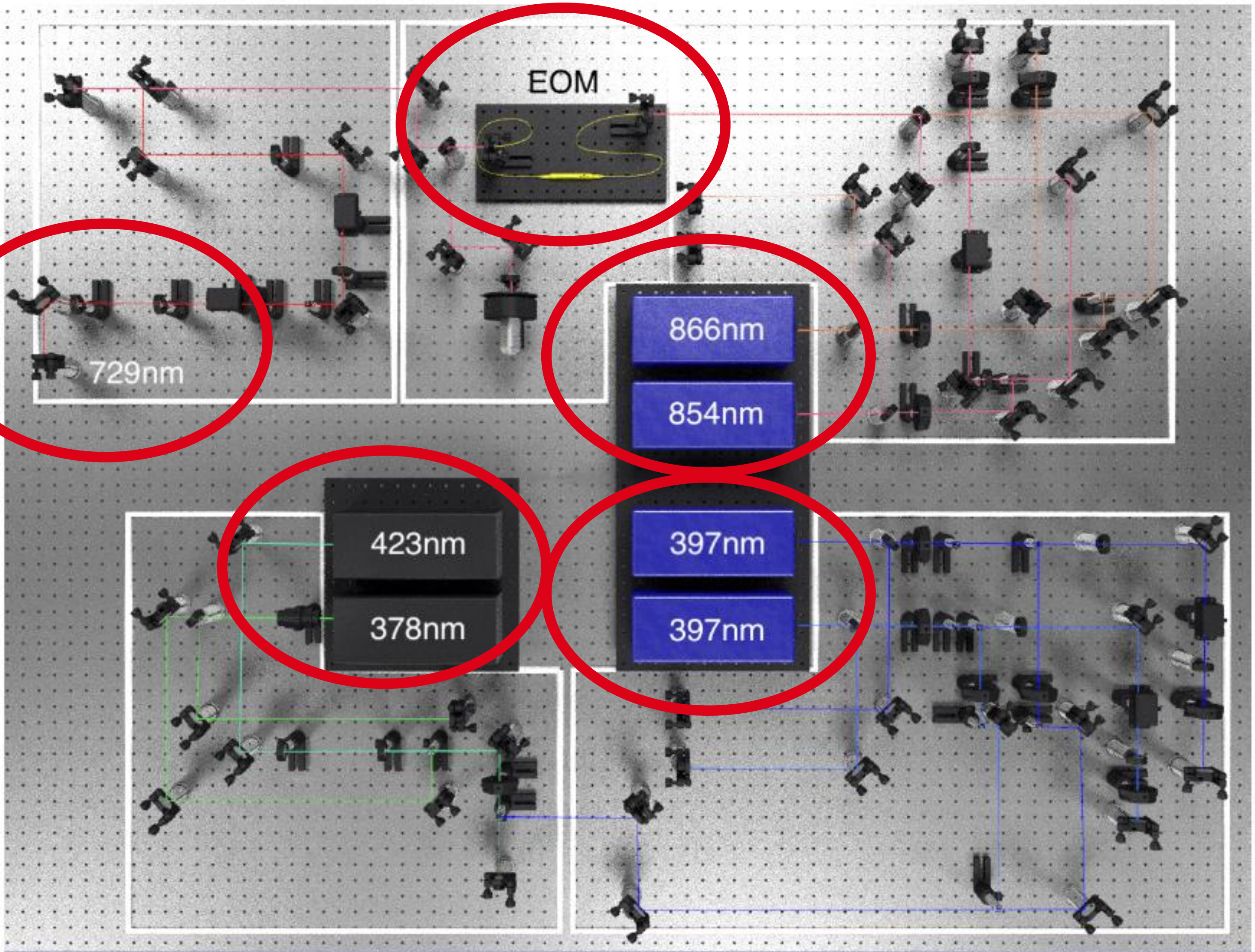
The 729 nm transition is the qubit transition

Imperial Penning trap (exploded view)



- Stack of cylindrical electrodes
- 1.89 T vertical magnetic field
- Internal diameter 21 mm
- Ring split into four segments for application of axialisation signal
- Axial and radial laser beams for cooling all degrees of freedom
- Fluorescence collected in the radial plane

Optical table



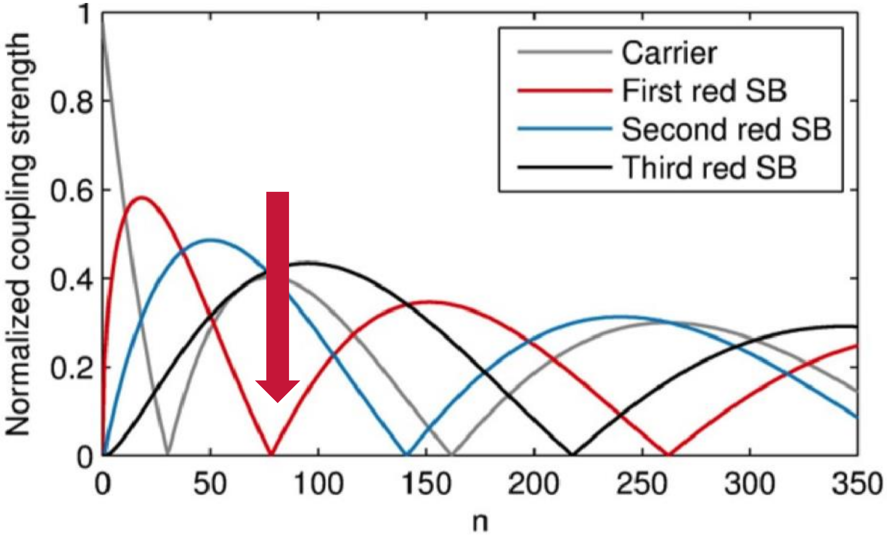
Lamb-Dicke parameter

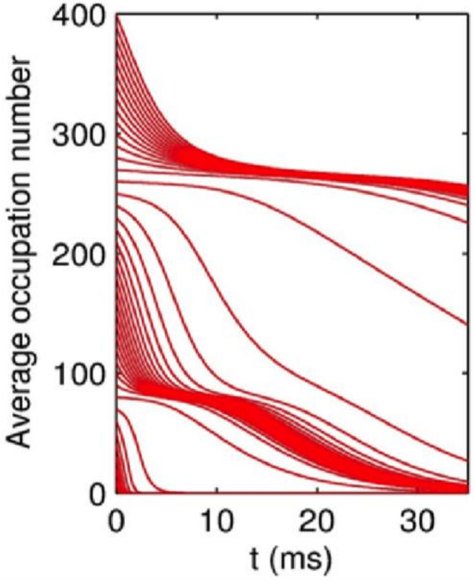
- Motion of the ion gives rise to sidebands on the optical transition
- The Lamb-Dicke parameter η is defined by

  $\eta = x_0 (2\pi/\lambda)$ [x_0 is the size of ground state wavefunction]
- The strength of each sideband depends on η
  - *Quantum equivalent to FM sidebands in classical frequency modulation*
- Typically in a Penning trap the L-D parameter is quite large: around 0.2 for our trap
  - Sidebands are stronger
  - There are more sidebands present
  - Nonlinear behaviour of sidebands affects gate fidelity
  - Off-resonant driving of sidebands affects fidelity of coherent operations
  - During Doppler cooling, ions can get trapped in high *n* motional states

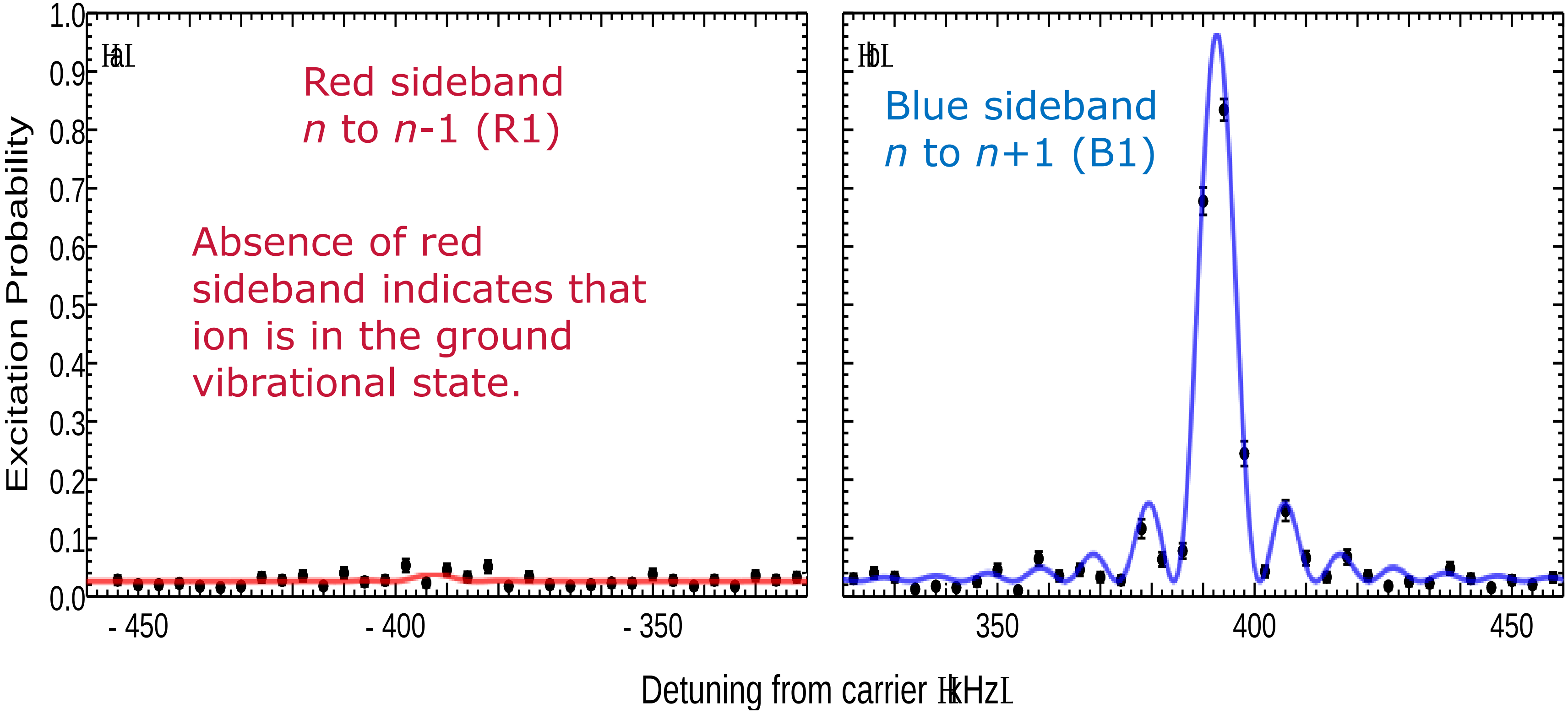
Clearing out the “trapped” motional states

- At the Doppler limit, ~ 20% of the population is above the first sideband minimum
- Cooling on the first red sideband (R1) will only be effective for *n*<80
- To pump this population we need to drive the 2^{nd} red sideband first
- Then drive the 1^{st} red sideband as normal





Axial sideband cooling with multiple stages



Red sideband
n to *n*-1 (R1)

Absence of red sideband indicates that ion is in the ground vibrational state.

Blue sideband
n to *n*+1 (B1)

Cooling sequence is R1 (10ms), R2 (5ms), R1 (5ms, reduced power)

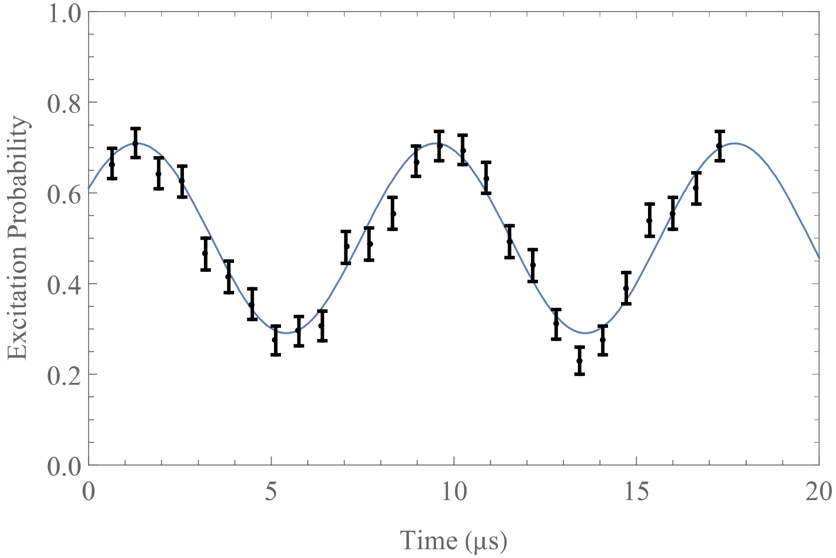
<*n*> ~ (R1 amplitude) / (B1 amplitude)

Motional ground state occupation is >98%; heating rate <1 phonon/s

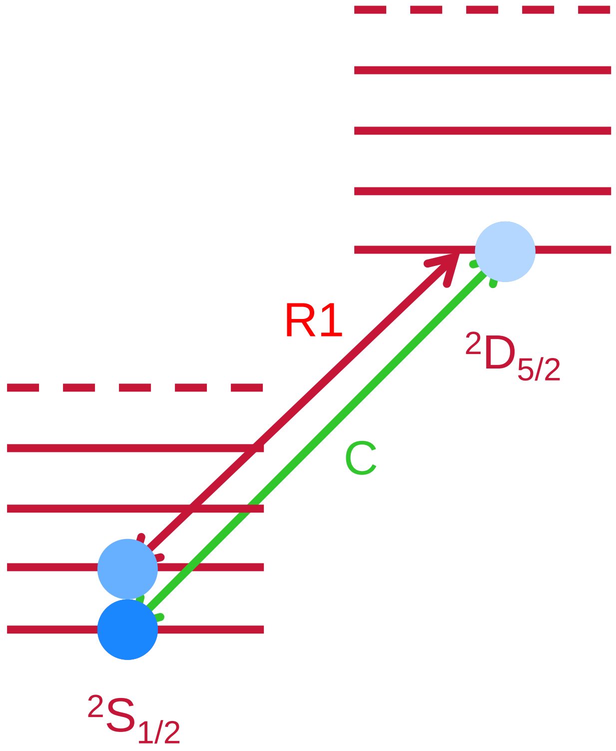
Goodwin *et al* PRL **116** 143002 (2016)

Coherent manipulation of motional states

- π/2 pulse on the carrier (C)
- π pulse on 1st red sideband (R1)
- Wait time *T*
- π pulse on 1st red sideband (R1)
- π/2 pulse on the carrier (C)
- Measure gound state population



Motional Ramsey fringes after 50ms wait time



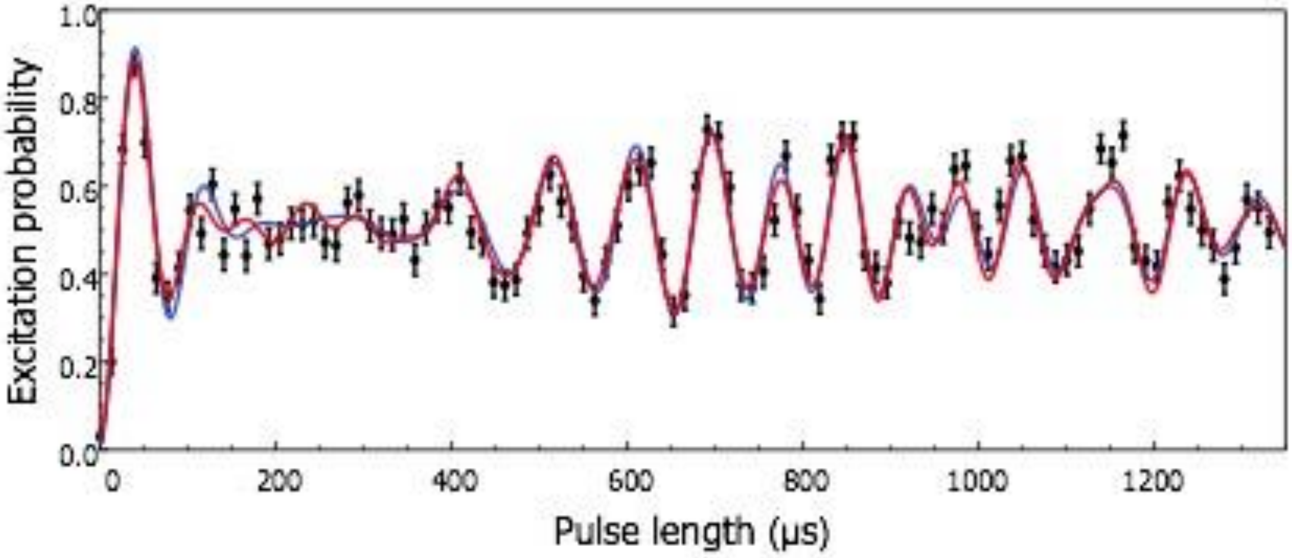
Motional coherence times up to ~1s observed

Bichromatic drive generating coherent state

- Simultaneous driving on the first Red and Blue sidebands (R1 and B1) is equivalent to the position operator $x \sim a + a^{+}$, generating after time t the displacement operator:

$$D(\alpha) = \exp(\alpha a - \alpha^{*} a^{+}) \quad \text{with} \quad |\alpha| = \eta\Omega t/z_0$$

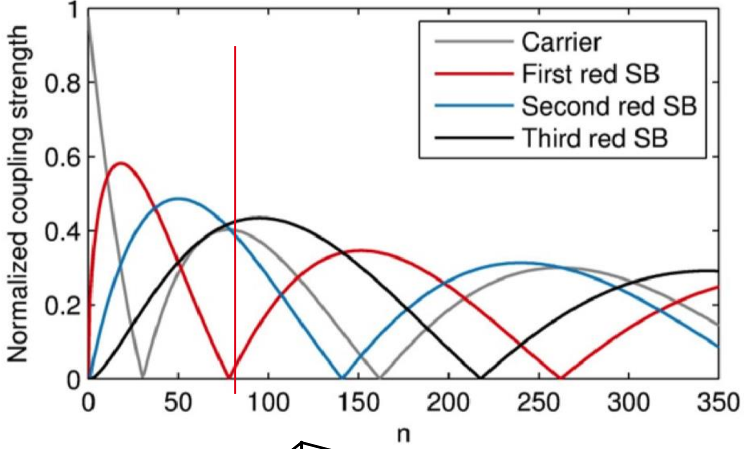
- So we can generate a coherent state using a bichromatic drive

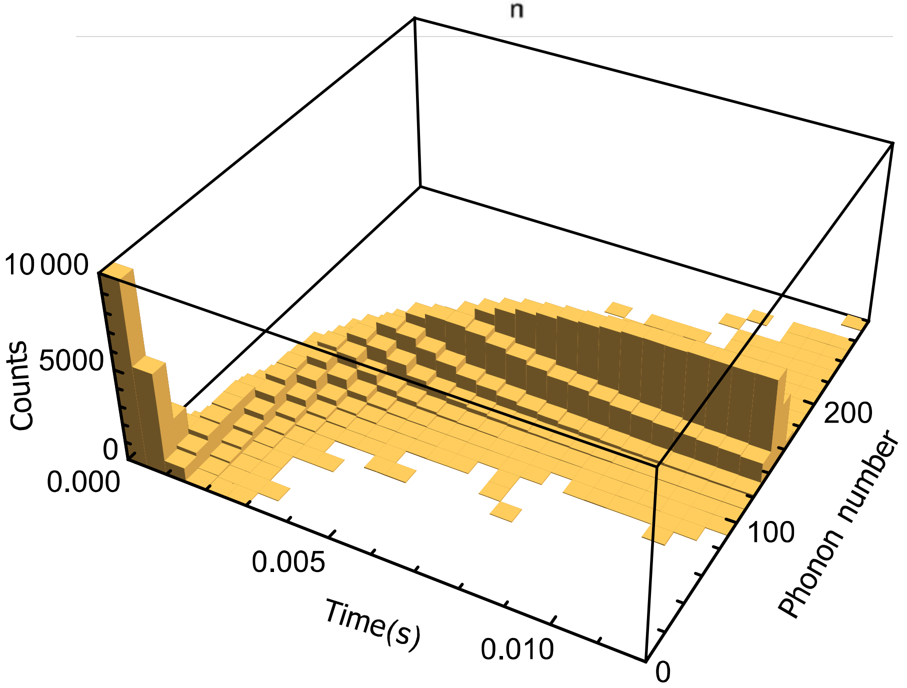


Rabi oscillations on B1 after a 150μs bichromatic pulse. The fitted value of α is 1.73

Sideband heating on the blue sideband

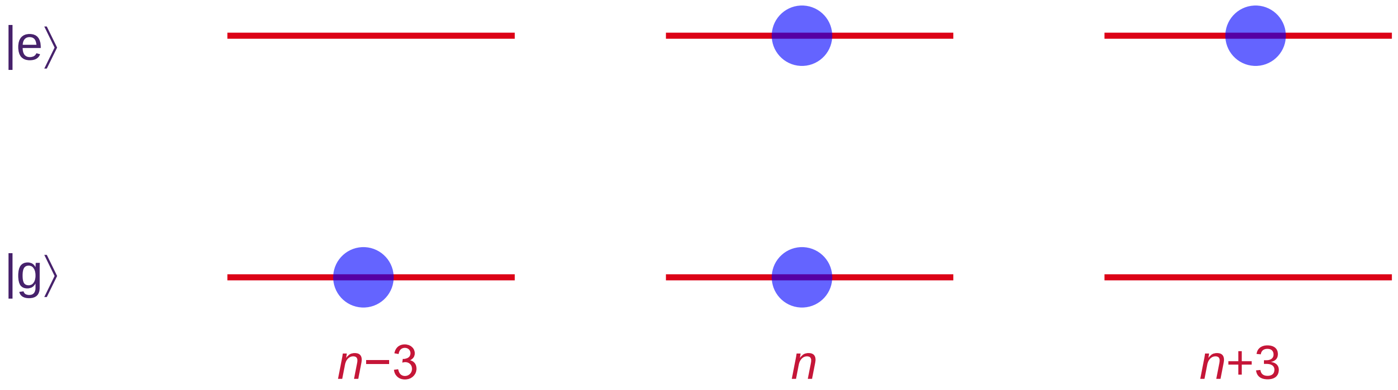
- Sideband cooling on R1 drives us towards *n*=0
- After cooling to the ground state, we can also drive the ion on B1 back towards ***higher*** *n* states
- This prepares an *incoherent* spread of population around the first minimum with Δ*n* ~ 10
- But we can still drive *coherent* operations after this process on the other sidebands





Joshi *et al* PRA **99** 013423 (2019)

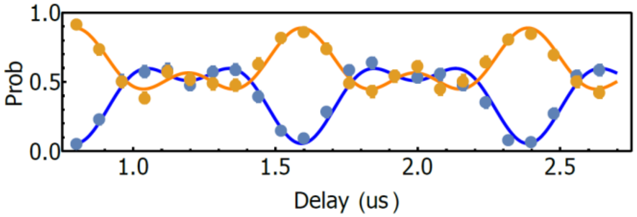
Preparation of superposition of high-*n* states



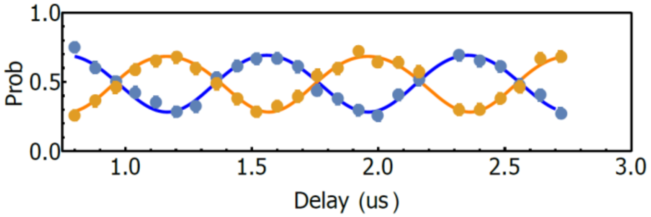
- A $\pi/2$ carrier pulse creates a coherent superposition of $|g,n\rangle$ and $|e,n\rangle$
- A $\pi/2$ B3 pulse then creates a coherent superposition of $|g,n\rangle$, $|g,n-3\rangle$, $|e,n\rangle$ and $|e,n+3\rangle$
- Period of free evolution T
- Probe the coherence with a second pair of pulses on B3 and carrier (with variable phases)
- Measured interference is (nearly) independent of n

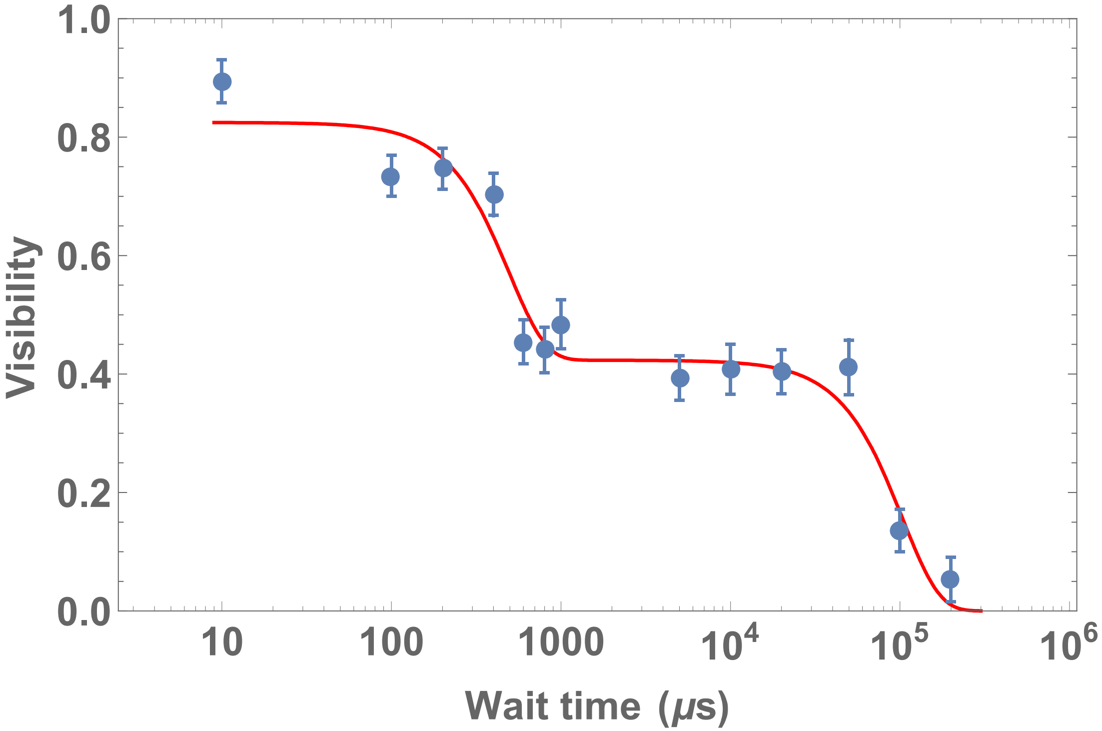
Coherence measurements

10 μs



10 ms

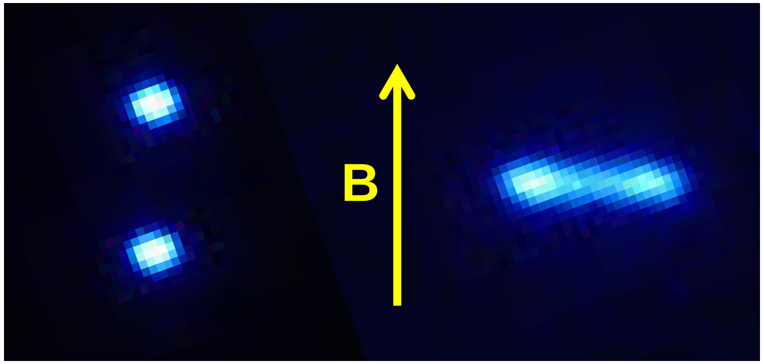




- At small *T* we see fringe visibility ~1
- After 1 ms the optical coherence is lost and the visibility drops to ~0.5
- Motional coherence is preserved out to ~100 ms for Δ*n*=3

Sideband cooling of 2-ion crystals

- Two ions can arrange themselves along the axis or in the radial plane
- In each case there are two axial oscillation modes
- Axial crystal:
  - Centre of Mass at ω_z
  - Breathing Mode at $\sqrt{3}\ \omega_z$
- Radial crystal:
  - Centre of Mass at ω_z
  - Rocking mode $< \omega_z$



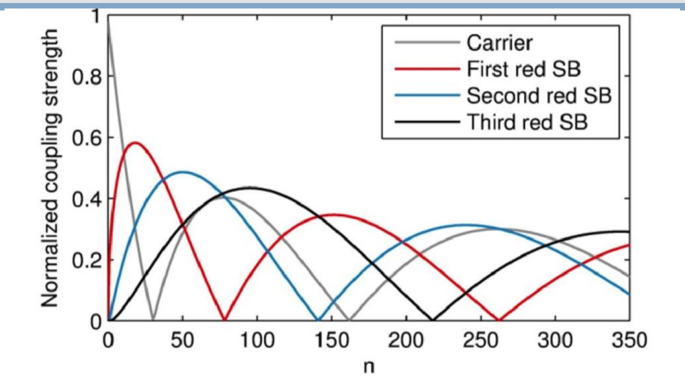
Axial crystal

Radial crystal

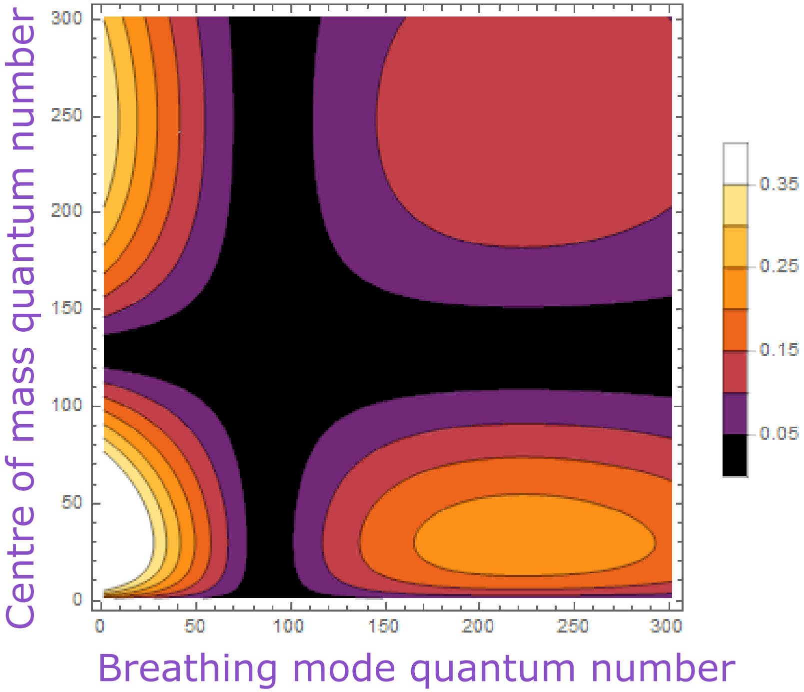
Note that the ions are imaged from the side and the radial crystal is rotating due to the magnetic field

Trapped motional states in 2D

- There are two independent axial modes
  - The strength of each sideband depends on ***both*** quantum numbers
- We have to use a combination of several different sidebands of each motion
- But there are still regions that are never pumped by pure centre of mass sidebands ***or*** pure breathing mode sidebands
  - We have to use “sidebands of sidebands” in the cooling sequence

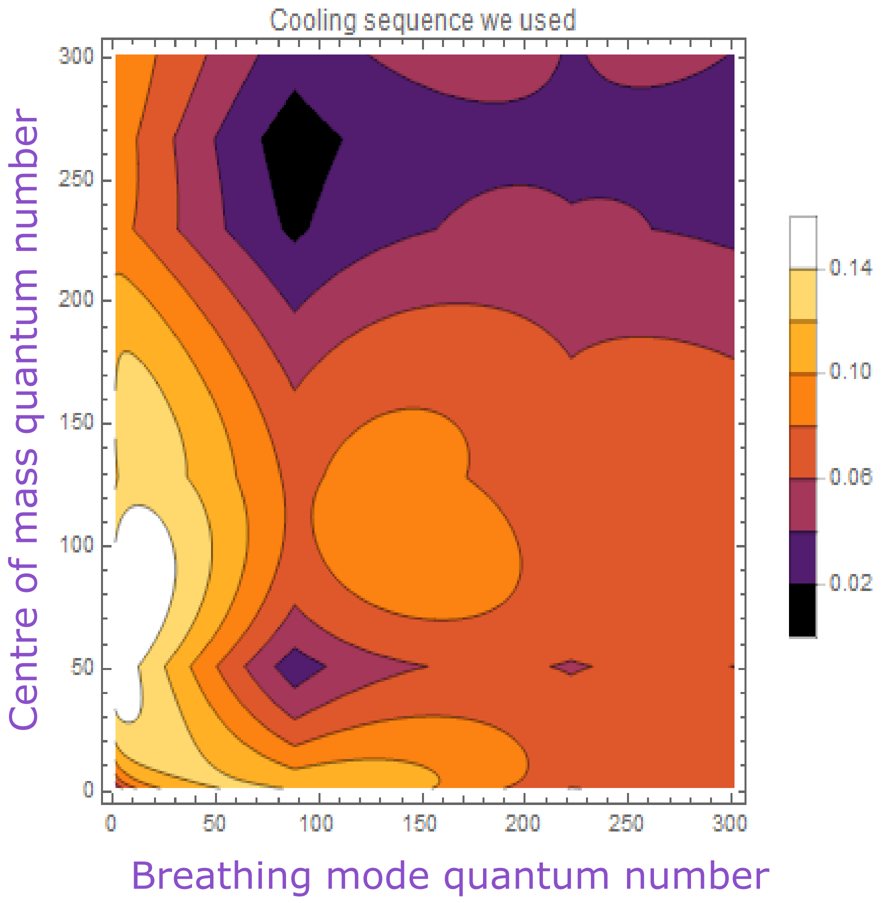


Amplitude of 1st Red sideband of COM

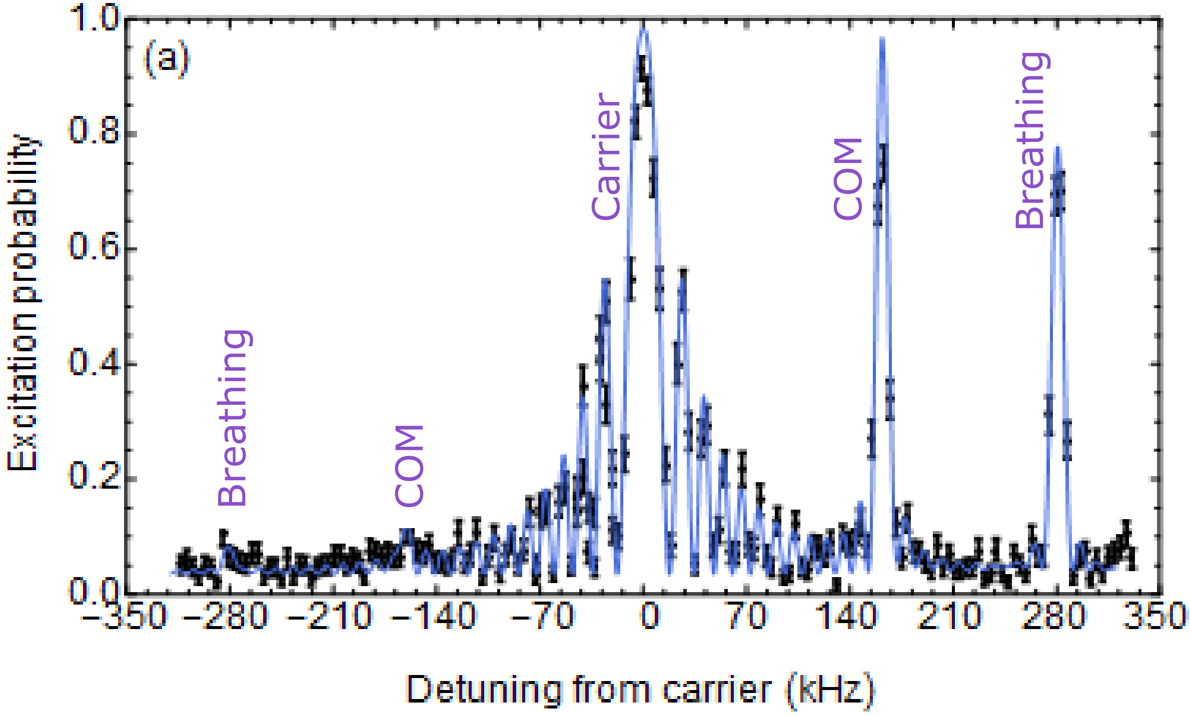


Cooling effect of the sequence of sidebands

- This shows the combined effect of a sequence of 5 different sidebands including one “sideband of a sideband”
- Every region of the plane is now addressed by at least one of the sidebands effectively
- We cycle through this sequence of sidebands many times to complete the cooling process



Sideband cooling of two ions in axial crystal

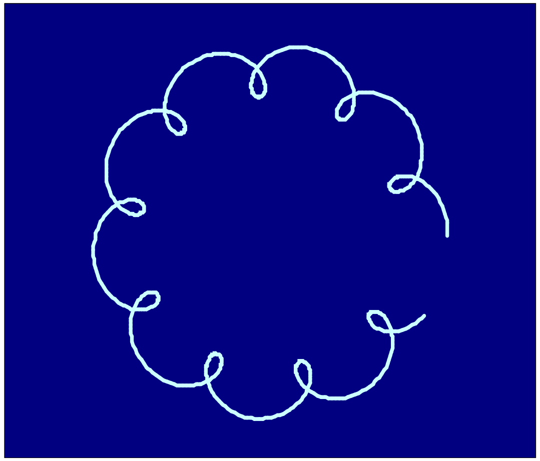


- We have cooled both modes of the two-ion axial crystal
  - COM at ω_z and breathing mode at $\sqrt{3}\,\omega_z$
- The final mean quantum numbers are $n_{COM}=0.3$ and $n_B=0.07$
  - Heating rates are also low

Stutter *et al* JMO **65** 549 (2018)

Radial motion of a single ion

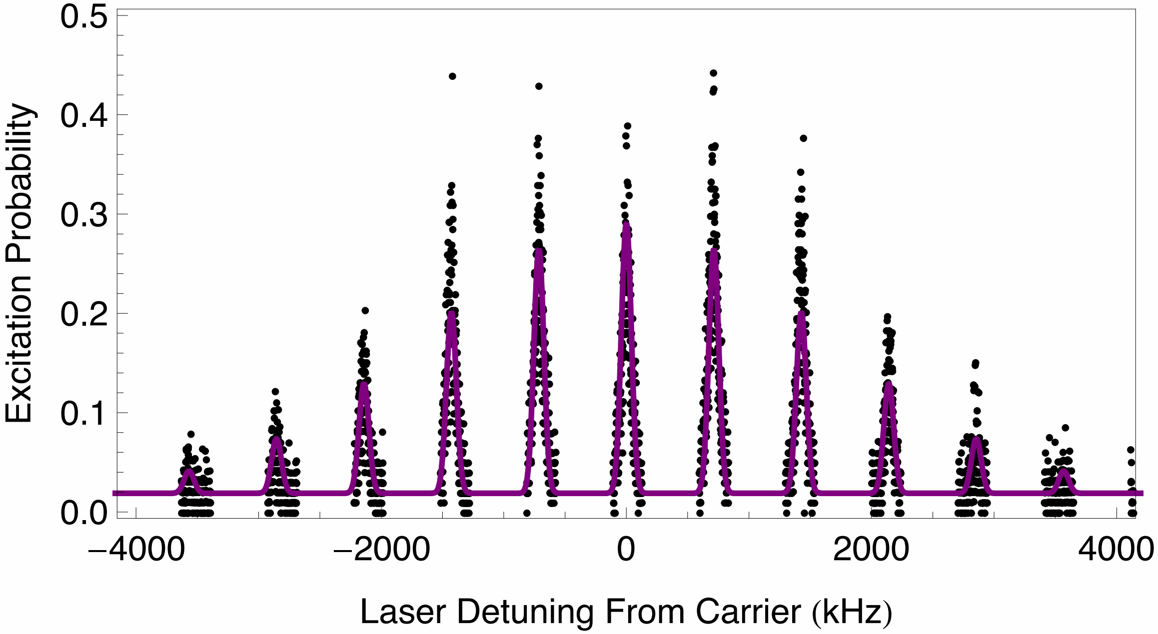
- The radial motion in the Penning trap has two modes
  - Cyclotron motion (fast) [700kHz]
  - Magnetron motion (slow) [10s of kHz]
- The sideband spectrum will show structure due to both motions
- We use the spectrum to measure the temperatures of the two modes directly from the velocity distribution
- We want to sideband cool both motions to the ground state



Radial motion in the Penning trap

Radial spectrum after Doppler cooling

- The (fast) cyclotron motion gives rise to sidebands
- The ~4 MHz FWHM corresponds to a cyclotron temperature of ~7 mK
- Each cyclotron sideband has structure due to the magnetron motion
  - but individual sidebands are not resolved here



The narrow width of the magnetron structure demonstrates that its "temperature" is very low (~40 μK)

See Mavadia et al
Phys. Rev. A ***89****, 032502*

Axialisation

- After Doppler cooling, the magnetron quantum number is too high for optical sideband cooling
- Axialisation is used in the mass spectrometry field to couple the magnetron motion to the cyclotron motion for cooling
- We have adapted it for use with optical sideband cooling
- The ion is driven by an oscillating radial quadrupole field at $\omega_c = eB/M$

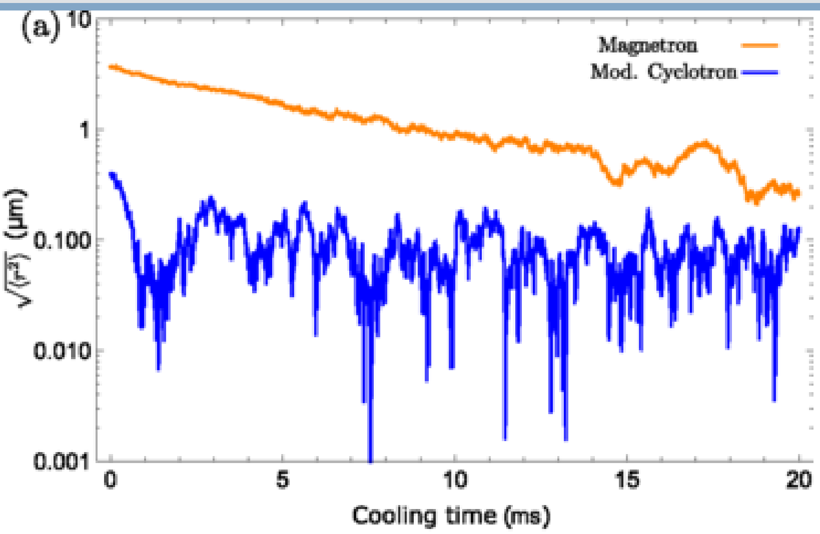
Classically:

The field creates a coupled oscillator system so there is a continuous transfer of energy between the two modes. Damping of both comes from the strong cyclotron cooling. Eventually $r_m \approx r_c$

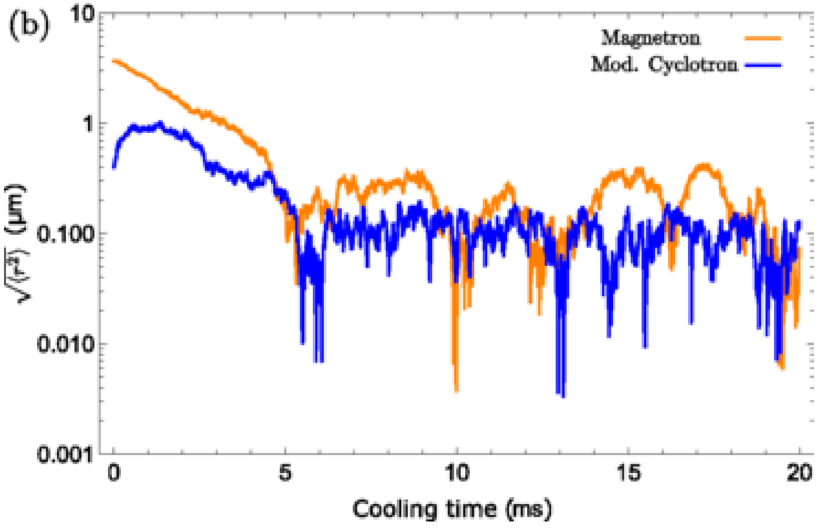
Quantum mechanically:

The field drives transitions where $\Delta n_m = -1$ and $\Delta n_c = +1$. The Doppler cooling continuously drives n_c to lower values. Eventually $n_m \approx n_c$

Effect of axialisation (simulation)



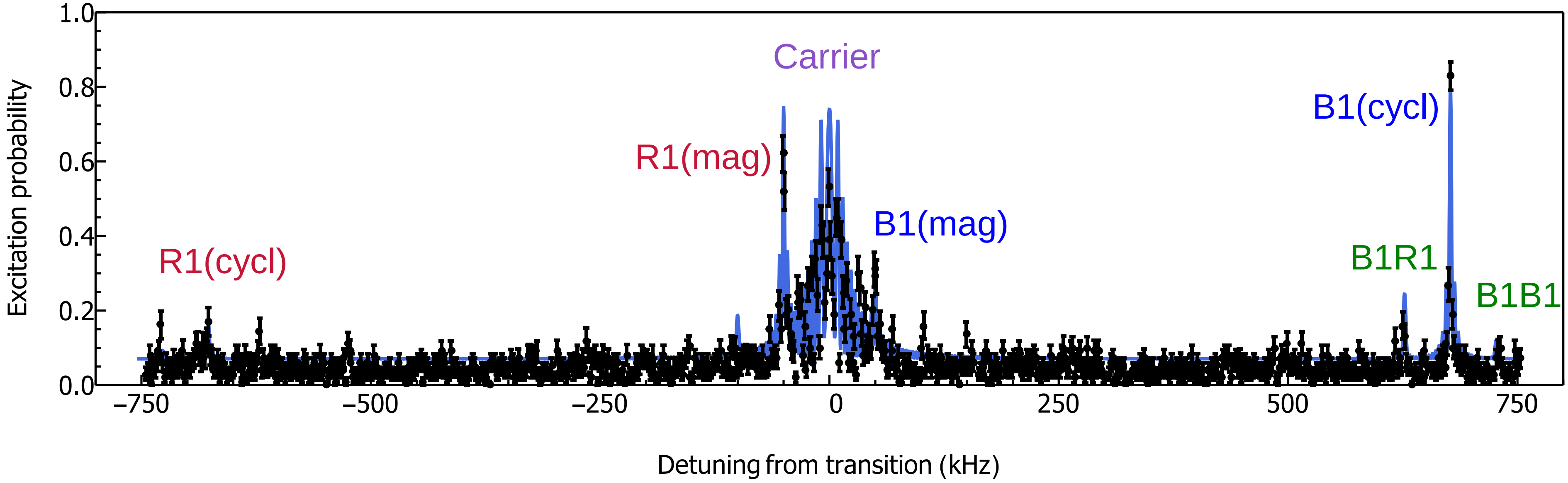
Without axialisation, the magnetron motion is cooled very slowly and the final quantum number is high.



With axialisation, the magnetron cools much quicker and the final quantum numbers for cyclotron and magnetron motions are roughly equal.

Now both modes can be sideband cooled, similar to the two ion crystal

Sideband cooled radial spectrum



- The carrier is very strong to bring out the other sidebands
- The asymmetry in cyclotron sidebands indicates $n_c=0.07\pm0.03$
- The (reversed) asymmetry in the magnetron sidebands indicates $n_m=0.40\pm0.06$
- Weak second-order sidebands can also be seen

Hrmo *et al* PRA **100** 043414 (2019)

For EQLIPS

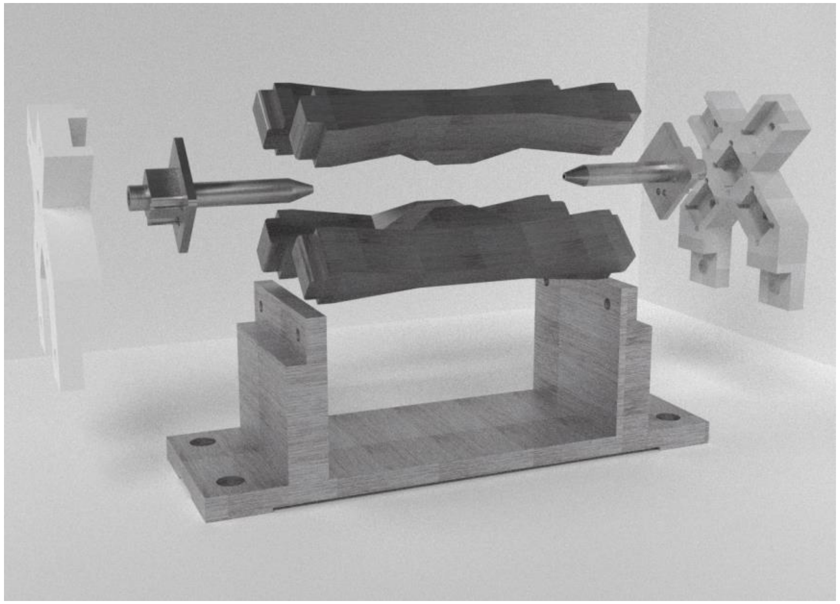
Our involvement in EQLIPS includes

- Faster cooling, especially of two-ion crystals
  - Further develop cooling with multiple sidebands
  - Apply optimal control techniques
- Creation of non-classical states of the motion of an ion
  - Already demonstrated the principle in earlier work with a bichromatic drive
- Demonstration of quantum logic technique with two ions
  - The ions communicate through their common state of motion
  - Detect a transition on the spectroscopy ion (e.g. $^{42}Ca^+$) by probing the logic ion (e.g. $^{40}Ca^+$) using motional sidebands on qubit transition

- What about Brexit?
  - OK if there a deal but situation is unclear if no deal

Summary

- We have cooled the axial motion of single ions and small Coulomb crystals to the ground state in a Penning trap
- Coherent processes can be observed even at high motional quantum numbers for single ions
- We have performed the first sideband cooling of the radial motion of an ion



New RF blade trap for the optimisation of 2-qubit gates using optimal control techniques

Thank you for your attention!