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

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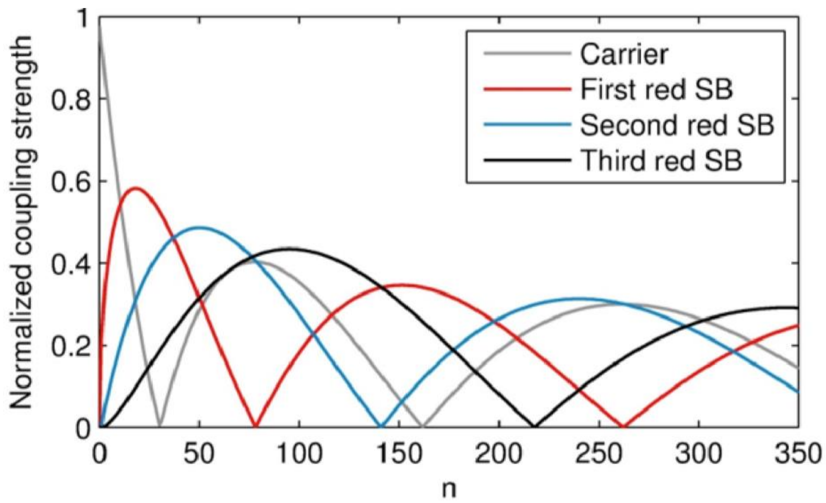
www.imperial.ac.uk/ion-trapping

People involved in this work

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

Outline of the talk

- Laser cooling in the Penning trap
- Effect of a large Lamb-Dicke parameter
- Sideband cooling of a single ion
  - Coherent superpositions of motional states
  - Coherent control with a bichromatic beam
  - Coherent manipulation of the motion in high-*n* states
- Sideband cooling of two-ion 'crystals'
- Sideband cooling of the radial motion
- Outlook



Strengths of motional sidebands as a function of *n* for Lamb-Dicke parameter η ~ 0.2

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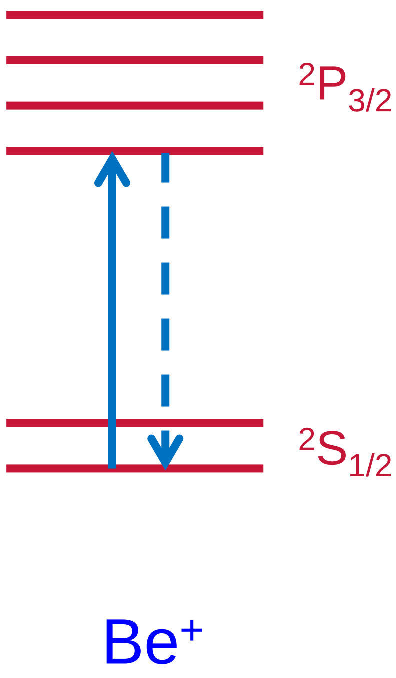
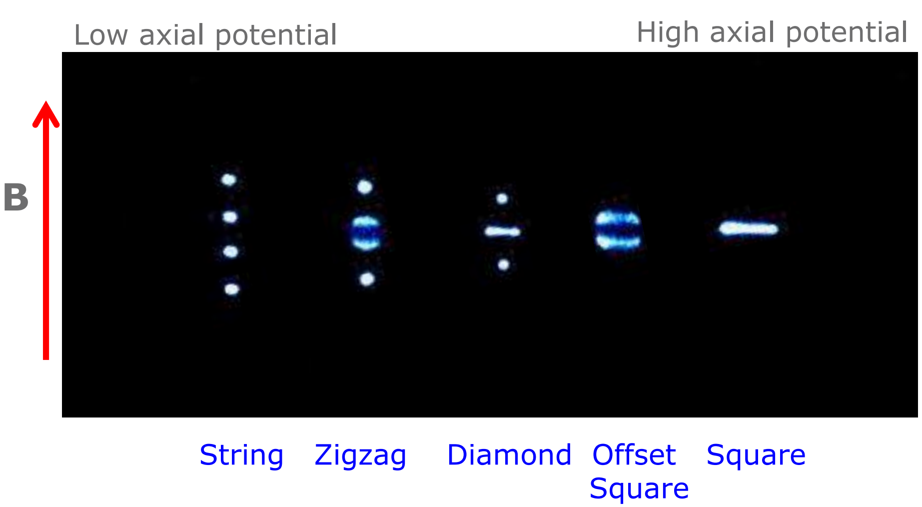
Laser cooling in the Penning trap

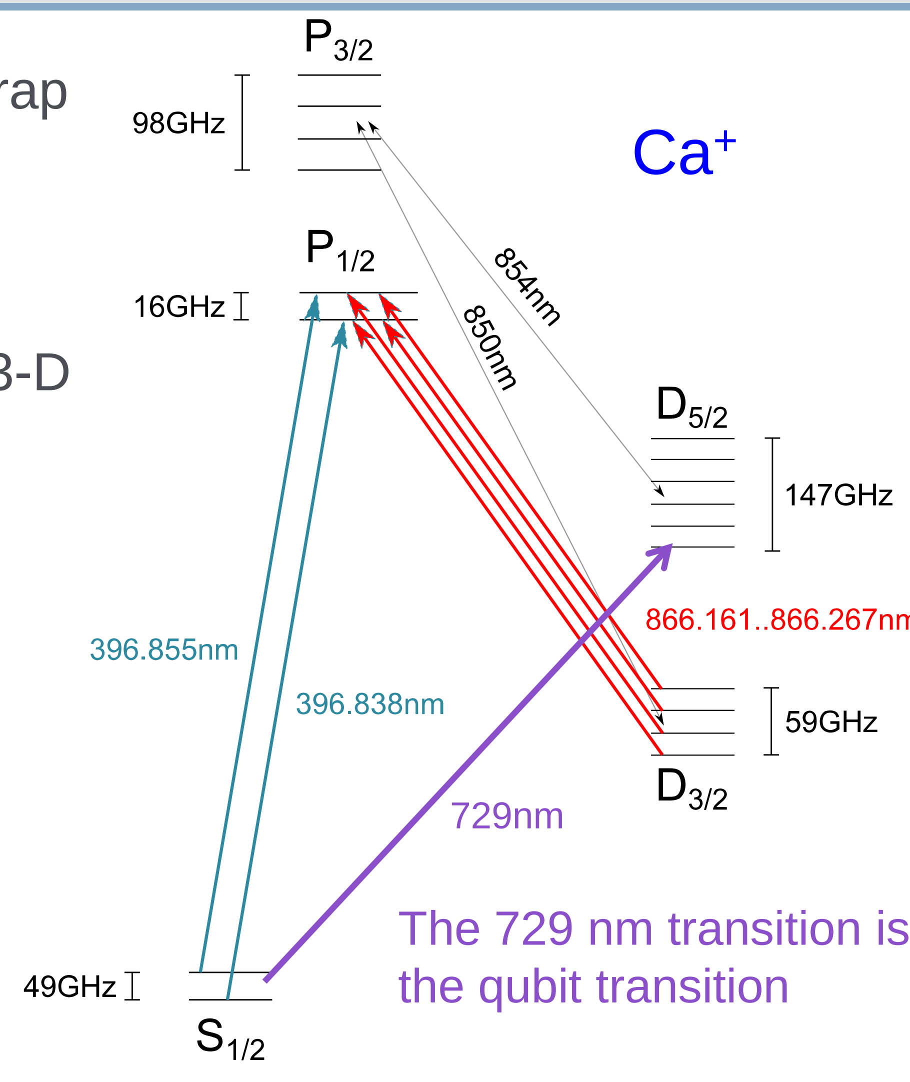
- Doppler cooling is basically the same in radiofrequency and Penning traps, but...
- Zeeman splitting of levels requires multiple laser frequencies for cooling
  - » Avoided in simple ions (Mg^+ and Be^+) by using optical pumping techniques
- Magnetron motion has negative energy and is hard to cool
  - » Needs laser beam offset from trap centre
  - » Or additional fields (rotating wall, axialisation)
- Oscillation frequencies are relatively low (<1MHz in our case)



Working with 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



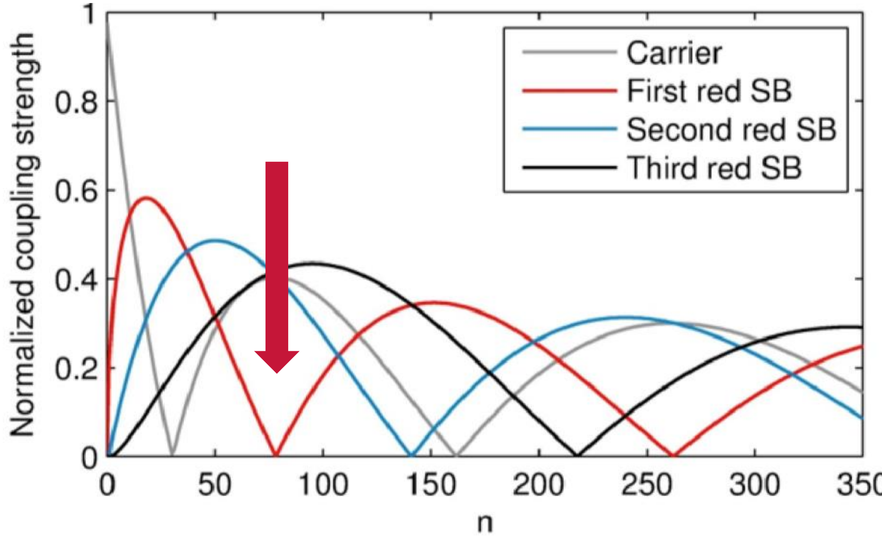


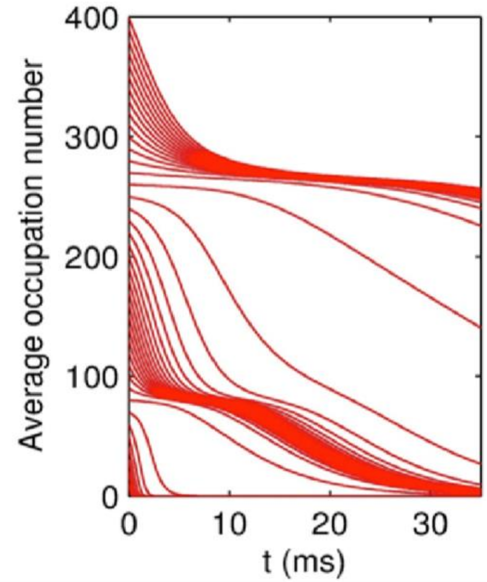
The 729 nm transition is the qubit transition

Sideband cooling: "trapped" motional states

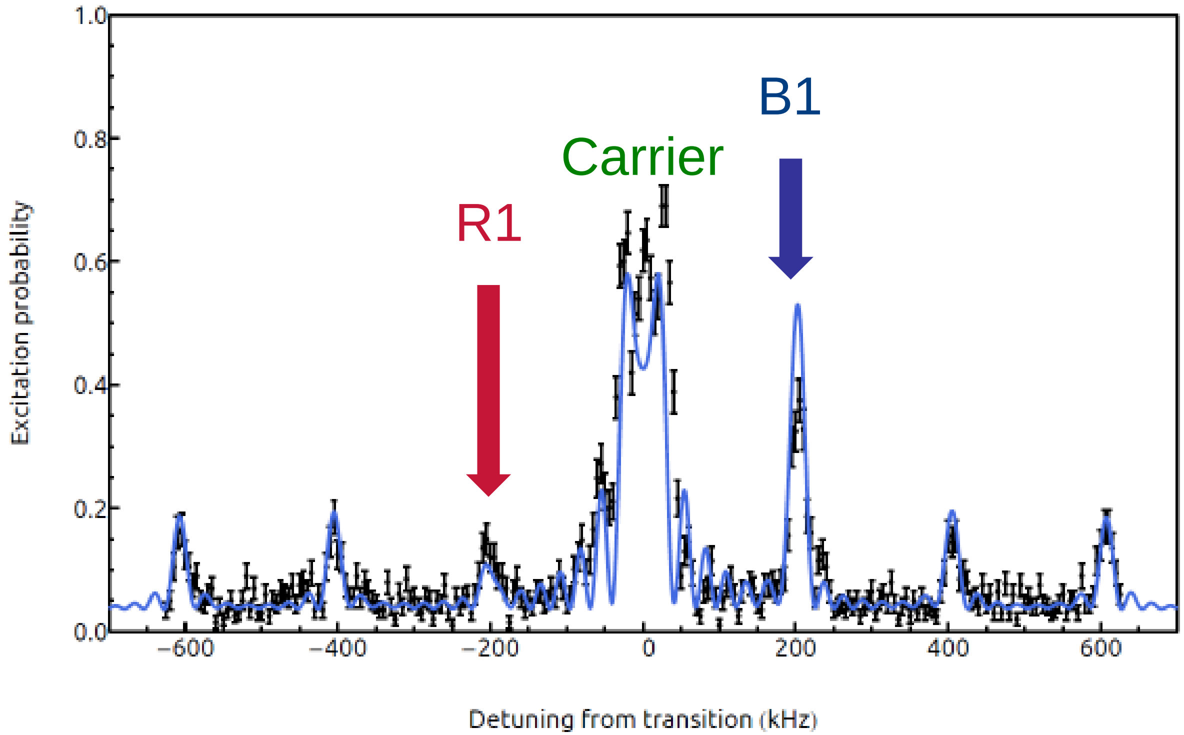
- The Lamb-Dicke parameter η determines the amplitude of the motional sidebands

  $\eta = x_0(2\pi/\lambda) \sim 0.2$ for our trap
  [x_0 is size of g.s. wavefunction]
- The strength of each motional sideband depends on η
  - *Quantum equivalent to sidebands in classical frequency modulation*
- For our low trap frequencies we expect the first red sideband to have zero amplitude around n=80
- Cooling on the first red sideband (R1) will only be effective for n<80
- Around 20% of the population is at n>80 at the Doppler limit (<n>=47)





Spectrum showing population in trapped state



- After sideband cooling on the first red sideband (R1):
  - much of the population is in n=0
    - » this gives the strong asymmetry between R1 and B1
  - but some is trapped around n=80
    - » This gives the higher order sidebands in the spectrum

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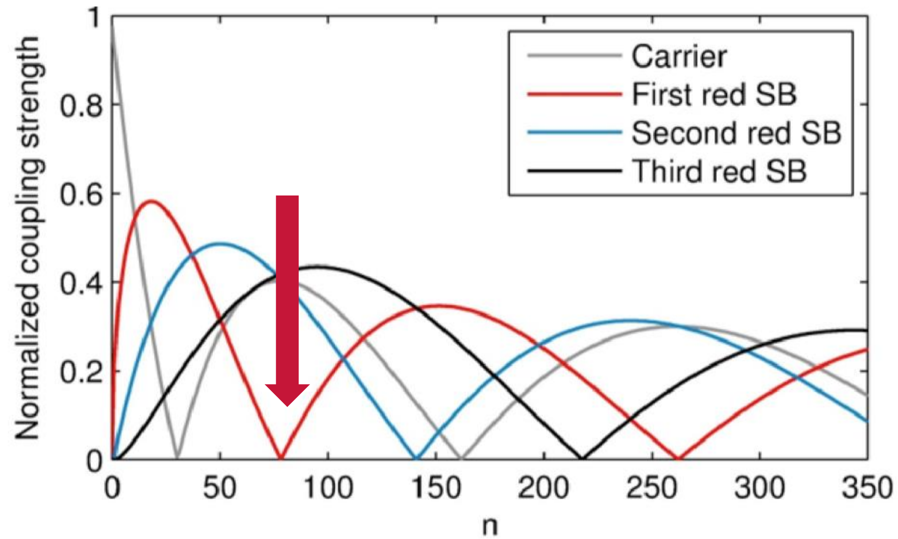
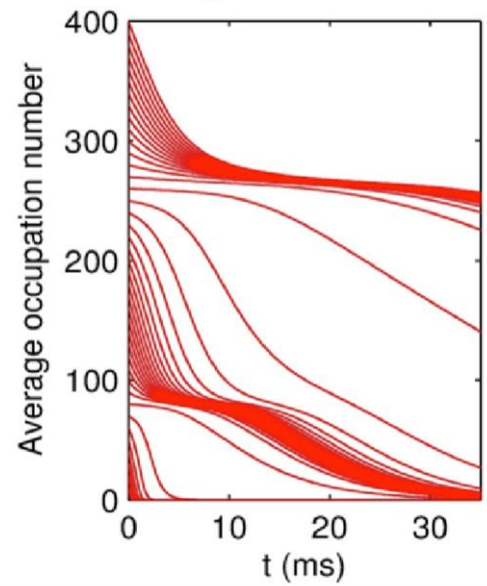
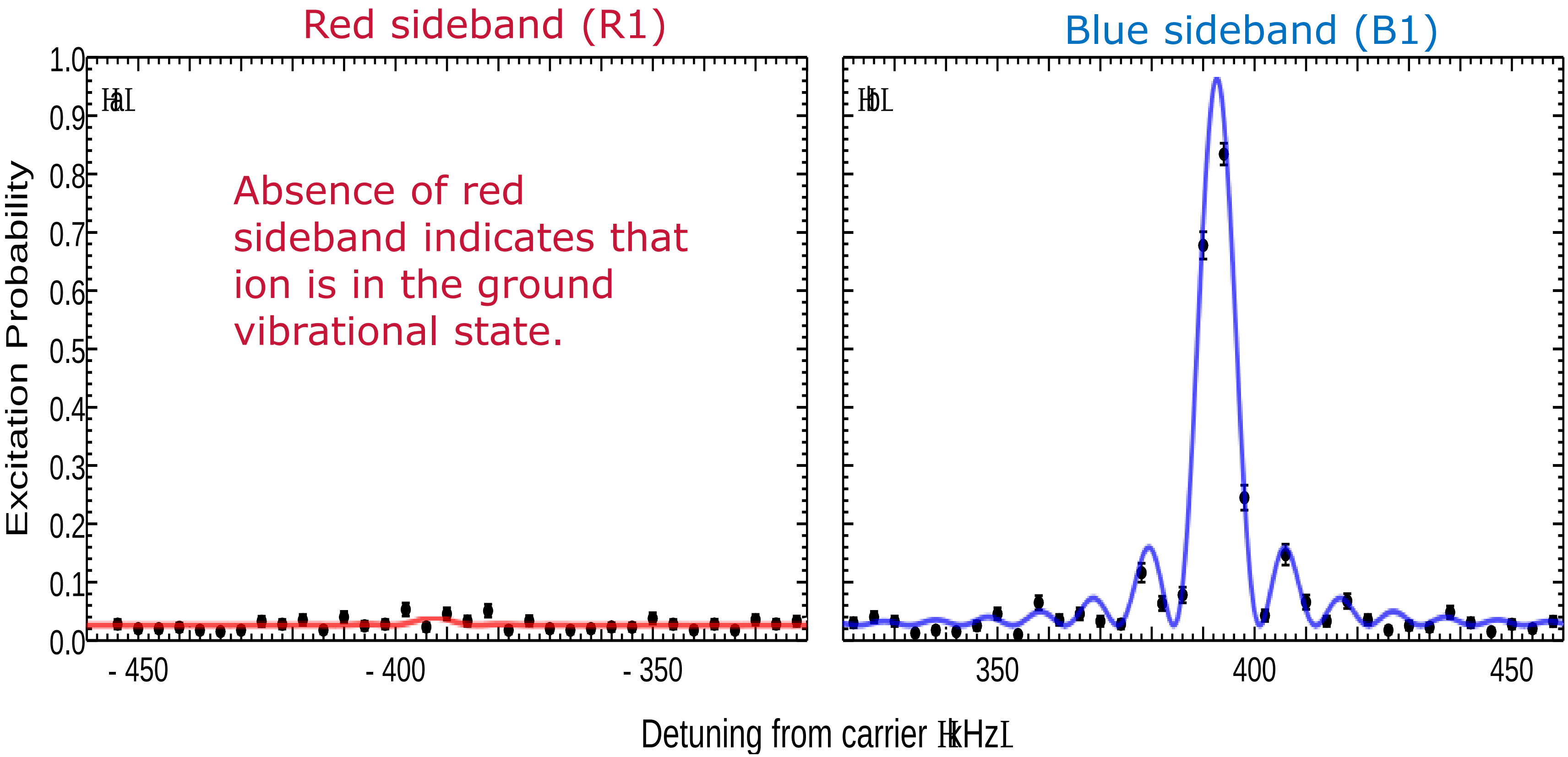
Clearing out the "trapped" motional states

- Cooling on the first red sideband (R1) will only be effective for $n<80$
- Around 20% of the population is at $n>80$ at the Doppler limit
- To pump this population we need to drive the 2nd red sideband (R2) first
    - R2 is strong right up to $n=140$ but does not give effective cooling at low n
- The procedure is then
    - R1 (10 ms)
    - R2 (5 ms)
    - R1 (5 ms) at reduced power





Axial sideband cooling with multiple stages



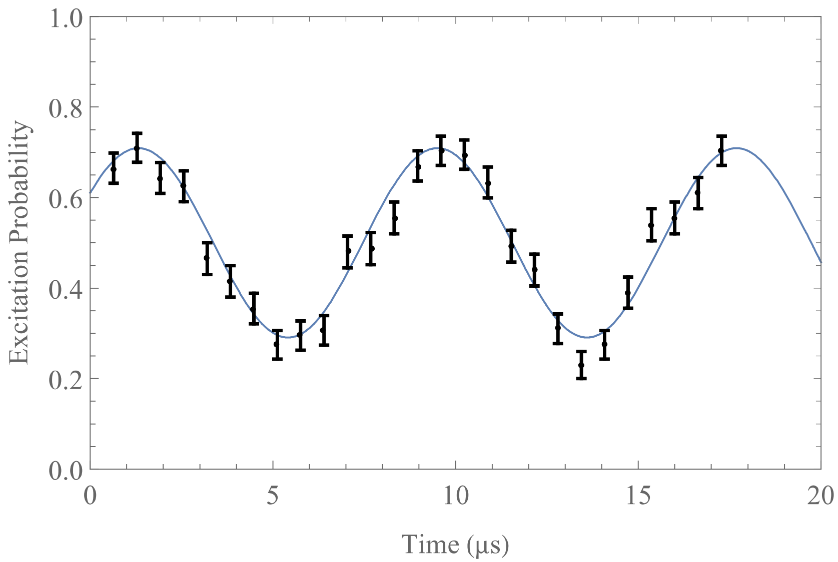
Cooling sequence is R1 (10ms), R2 (5ms), R1 (5ms, reduced power)

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

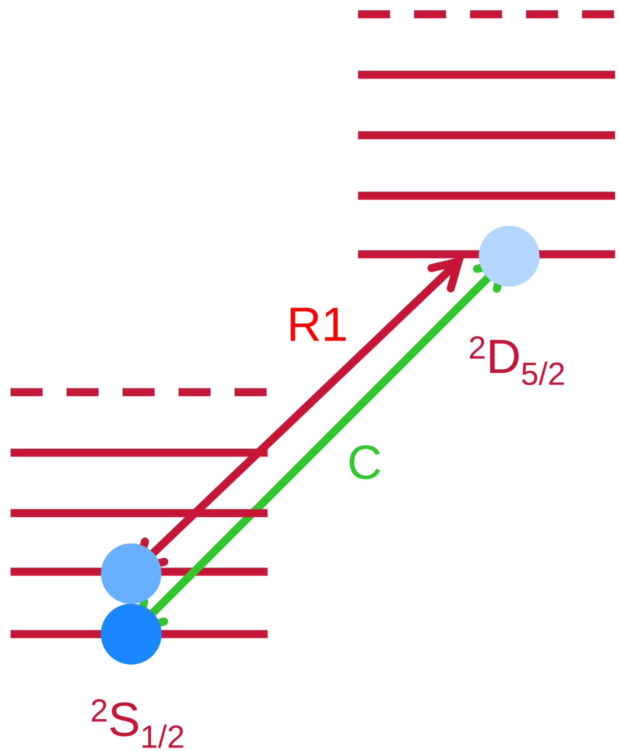
Motional ground state occupation is >98%; heating rate <1 phonon/s

Superpositions 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

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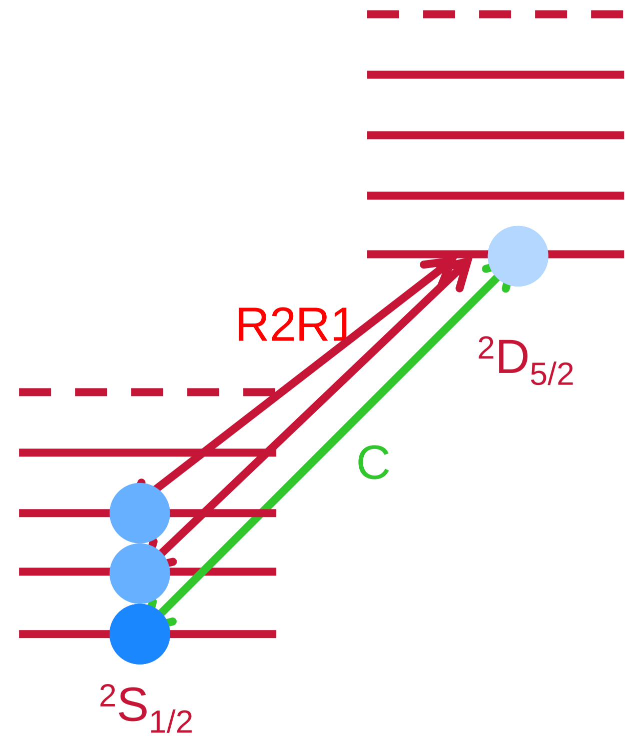
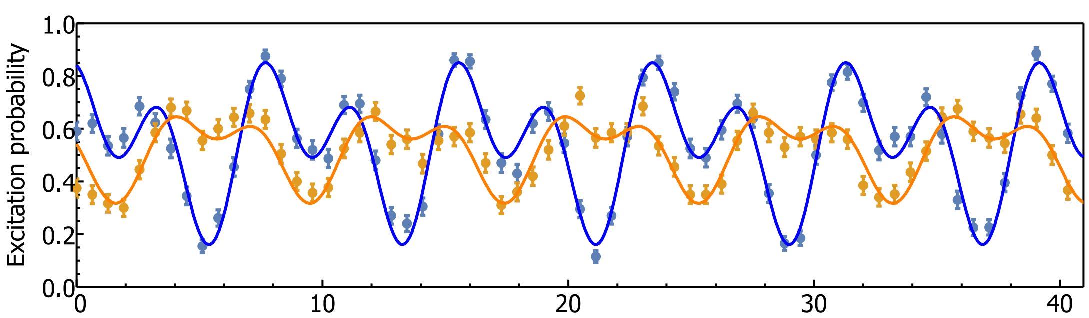
"Triple slit" using motional states

- "2/3 π" pulse on the carrier (C)
- π/2 pulse on 1st red sideband (R1)
- π pulse on 2nd red sideband (R2)
- Wait time *T*
- Reverse the pulse sequence
- Measure gound state population



Motional interference fringes after wait times *T*=0 (blue) and *T*=30ms (gold)



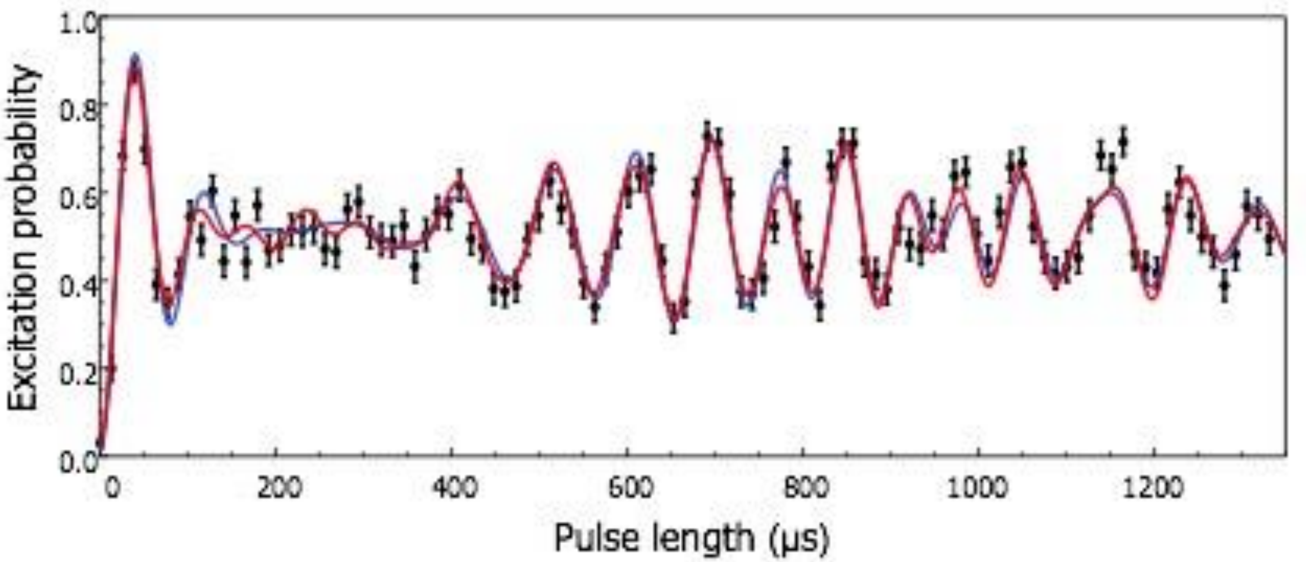
This is analogous to an optical triple slit and can be used to study higher order coherence (see Jake Lishman's poster)

Bichromatic drive

- 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

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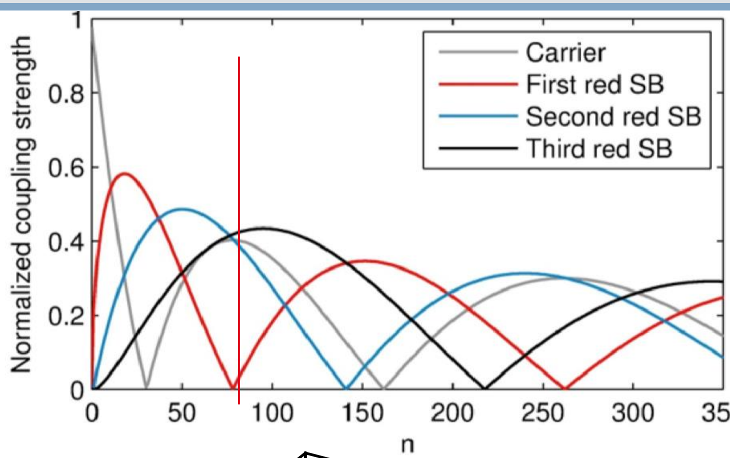
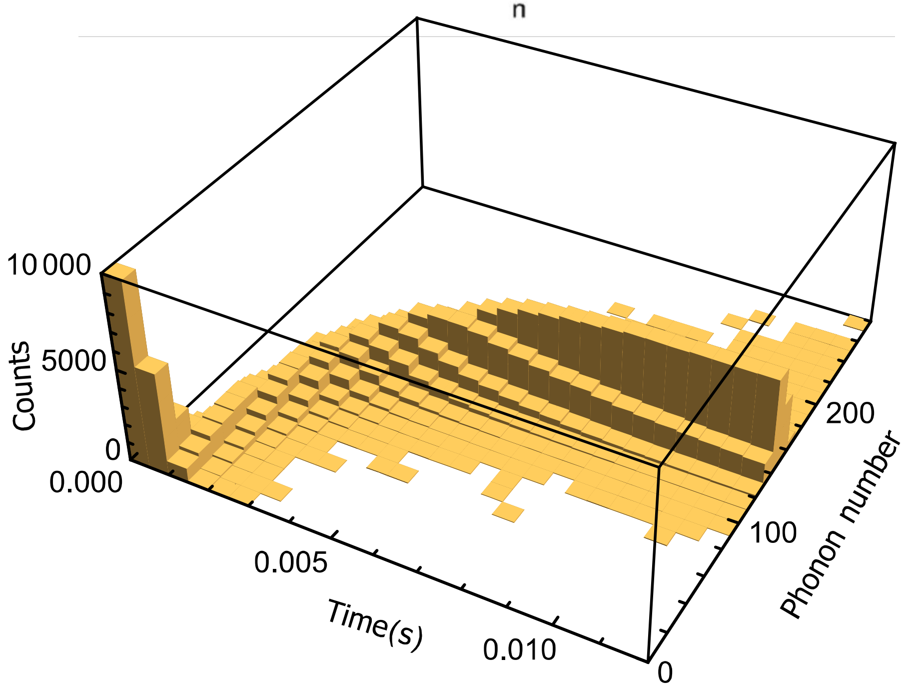
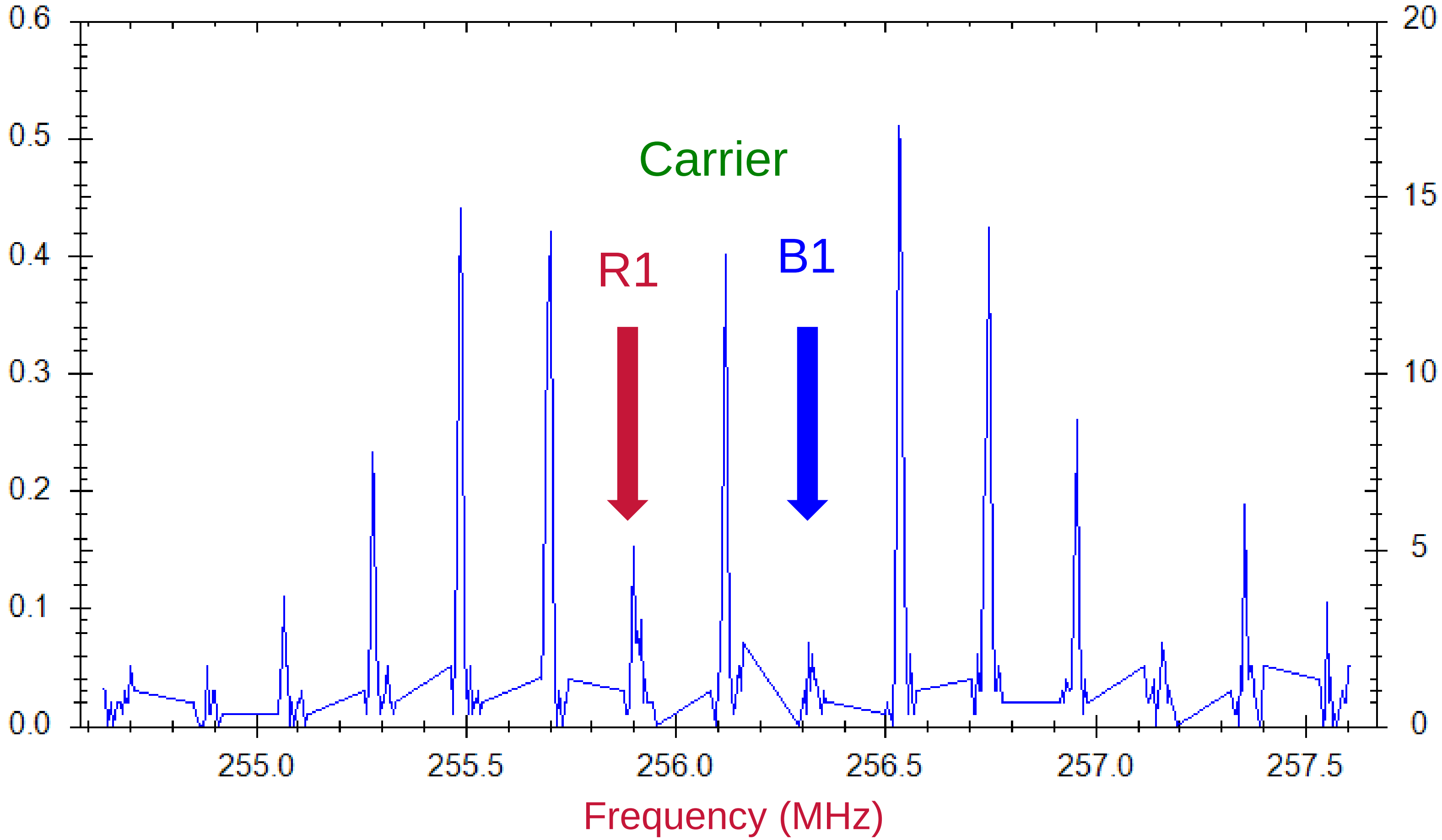
Sideband heating on the blue sideband

- 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 Δn ~ 10
- After sideband heating the spectrum shows a distinctive minimum for first order sidebands





Spectrum of ions in the trapped state



- Here we have driven the ion on B1 after sideband cooling in order to drive the population into the first minimum at n=80

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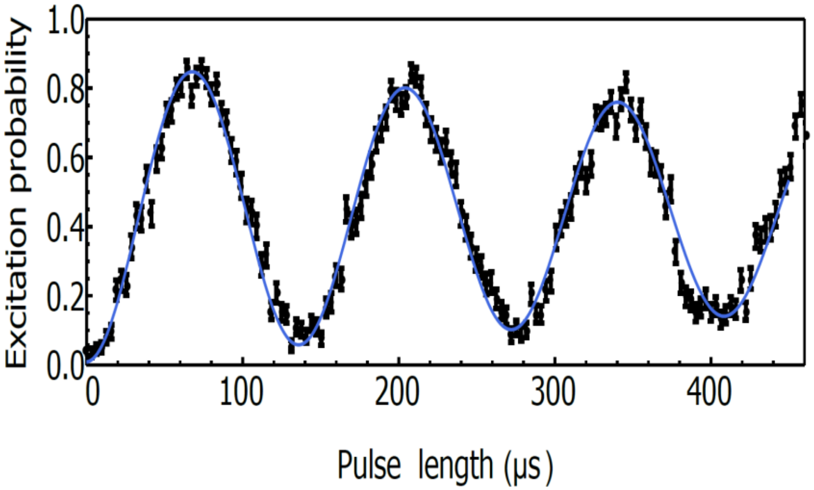
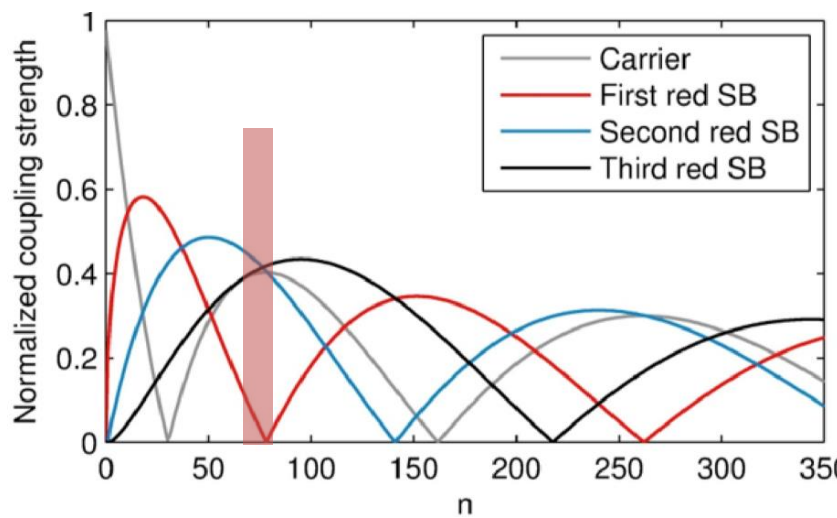
Coherence in highly excited motional states

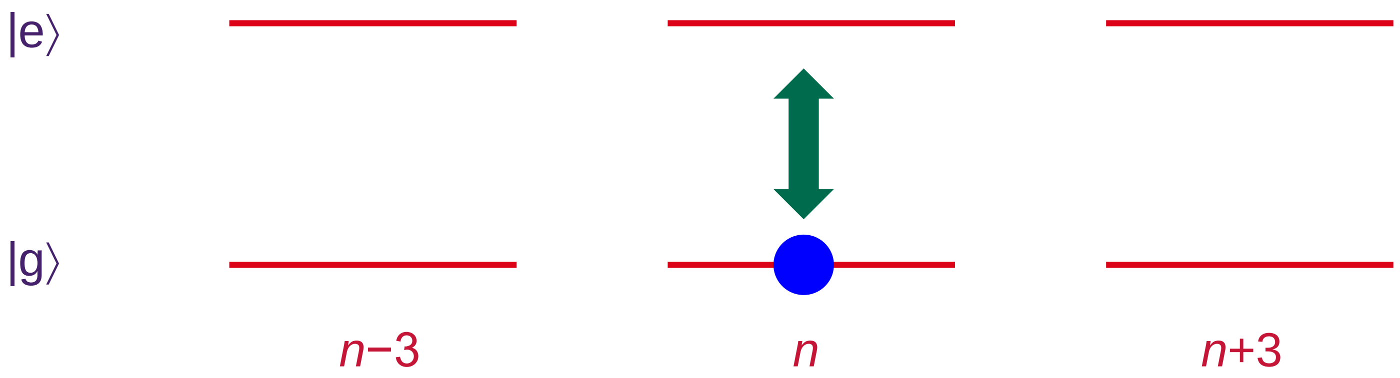
- After sideband heating the population is centred in a narrow range of *n* around a minimum
- The strengths of the other sidebands are often fairly constant across the distribution
- Therefore we see coherent behaviour
- We can study the optical and motional coherence for high *n* states by using π/2 pulses to create coherent superpositions of states
- The interference persists because the other sideband strengths are fairly constant across the range of *n* we populate



Rabi oscillations on 4th red sideband around *n*=280

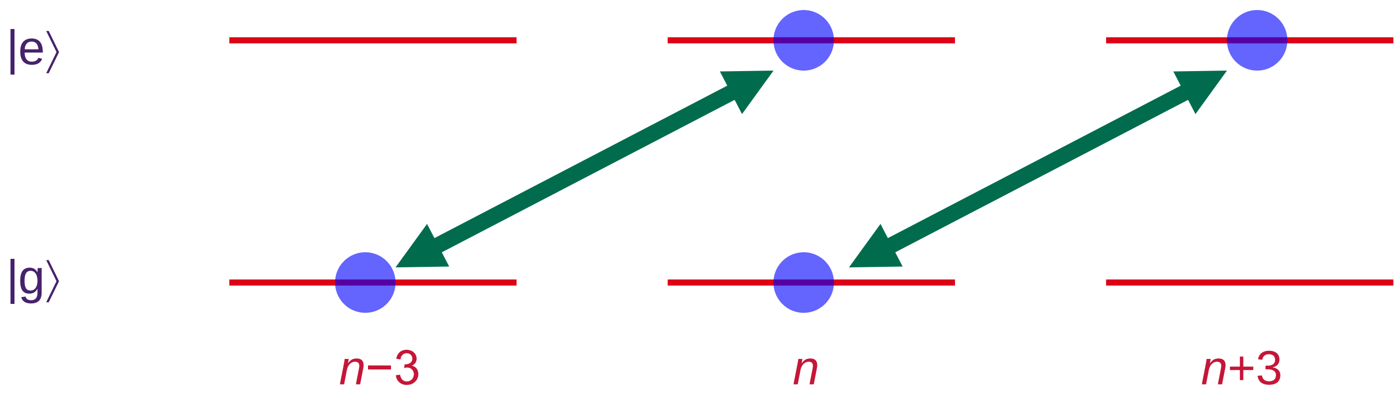


Preparation of superposition of high-*n* states



- A π/2 carrier pulse creates a coherent superposition of |g,*n*⟩ and |e,*n*⟩

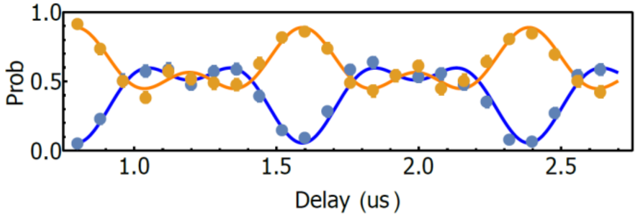
Preparation of superposition of high-*n* states



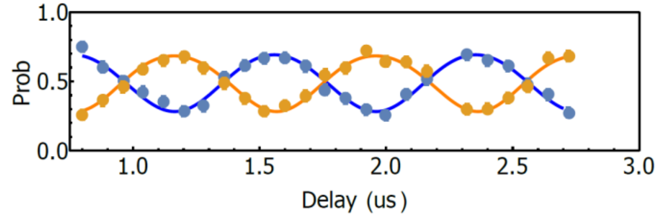
- A π/2 carrier pulse creates a coherent superposition of |g,*n*⟩ and |e,*n*⟩
- A π/2 B3 pulse then creates a coherent superposition of |g,*n*⟩, |g,*n*−3⟩, |e,*n*⟩ and |e,*n*+3⟩
- Period of free evolution *T*
- Probe the coherence with a second pair of pulses on B3 and carrier (with variable phases)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

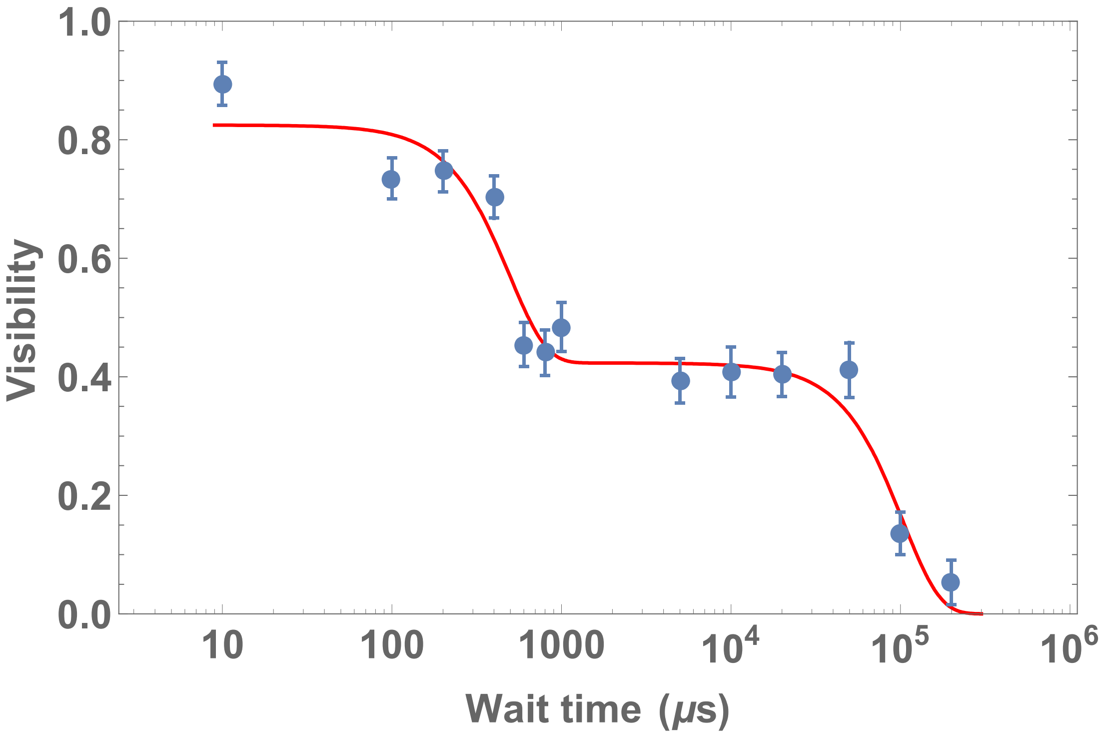
Coherence measurements

10 μs



10 ms

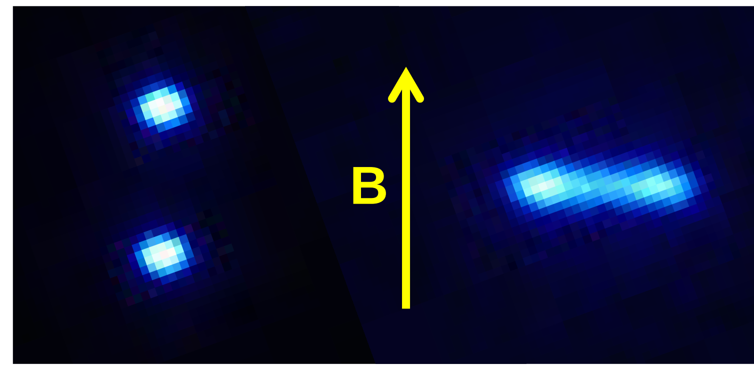




- At small *T* we see fringe visibility ~1
- After 1 ms the optical coherence is lost and the visibility drops to ~0.5
- Motional coherence is preserved out to ~100 ms for Δ*n*=3

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 between $\sqrt{(\omega_z^2 - \omega_1^2)}$ and ω_z depending on ion separation (where $\omega_1 = \sqrt{(\omega_c^2/4 - \omega_z^2/2)}$ is the effective radial trapping frequency)

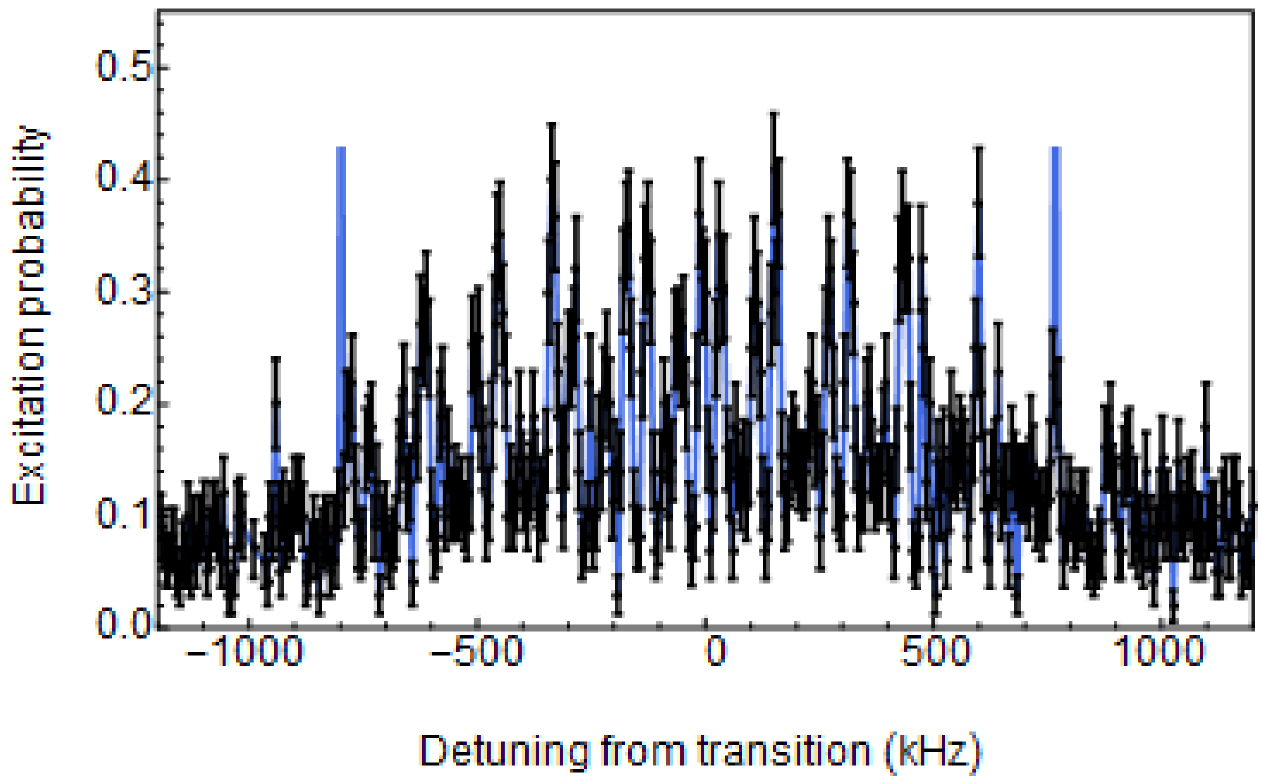


Axial crystal

Radial crystal

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

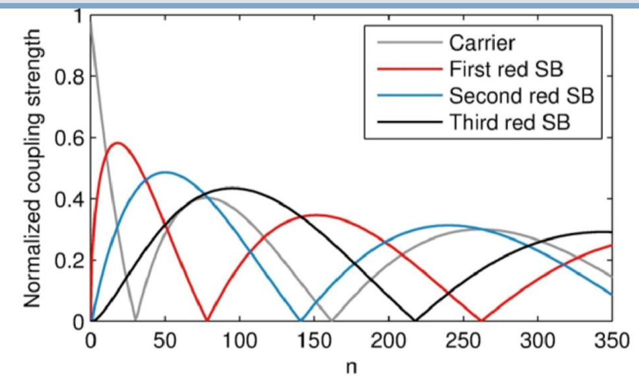
Two-ion axial crystal after Doppler cooling



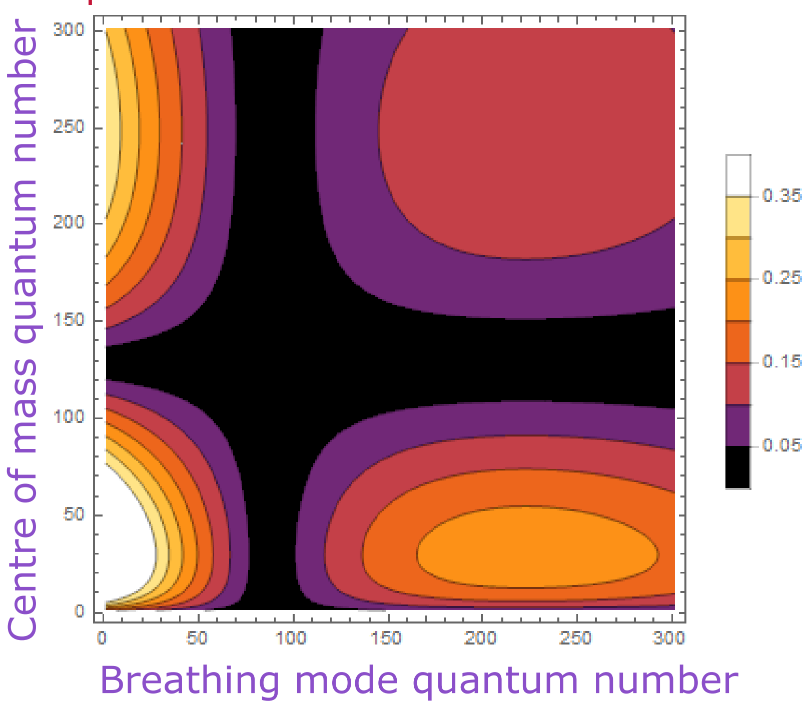
- The spectrum is complicated because each sideband of one motion has a complete set of sidebands due to the other motion
- The overall width corresponds to the Doppler limit of ~ 0.5 mK

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



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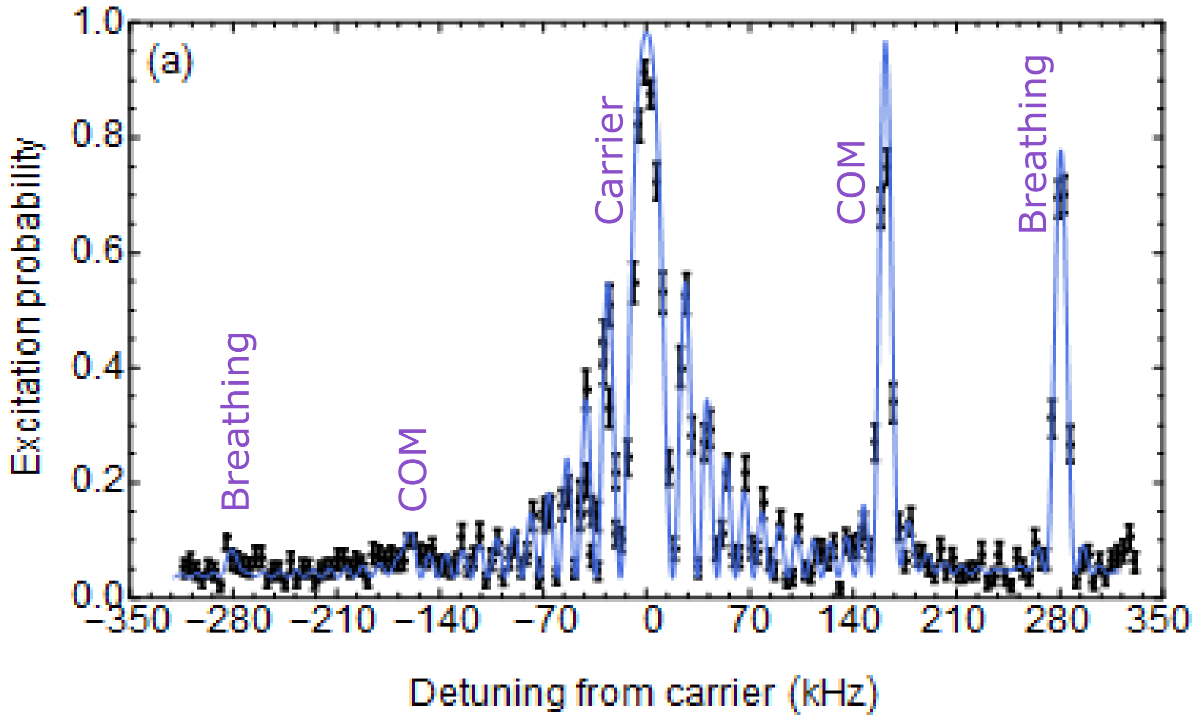
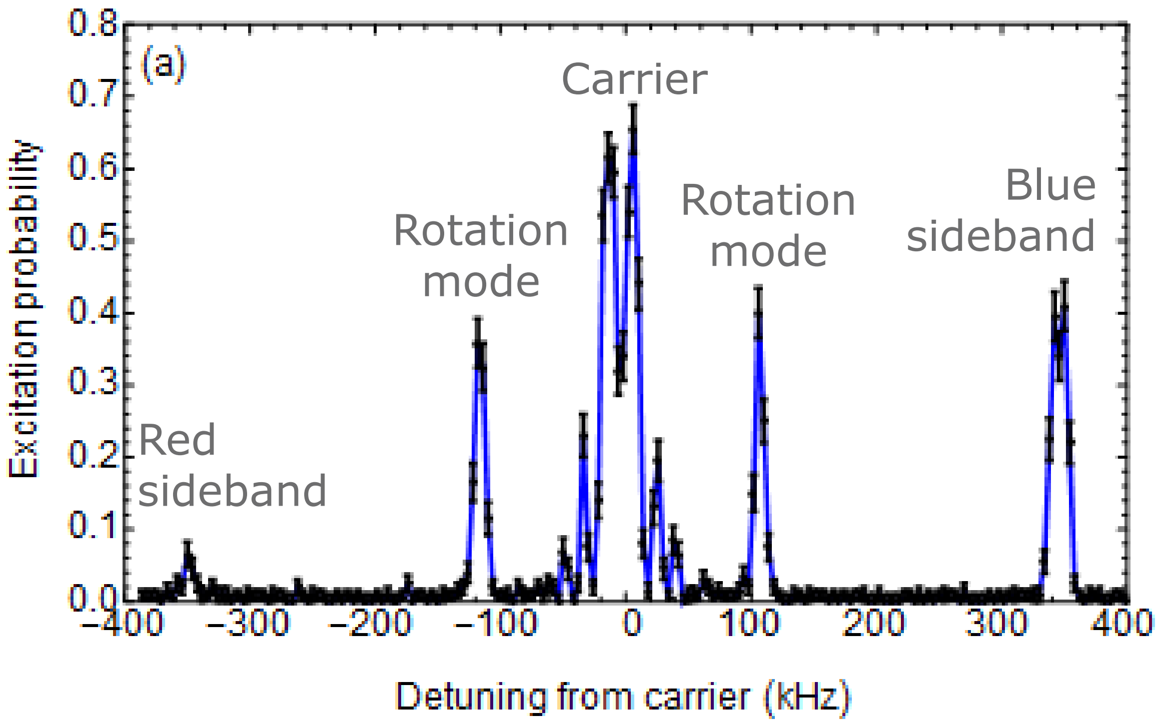
Sideband cooling of two ions in axial crystal



- 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

https://arxiv.org/abs/1705.08518

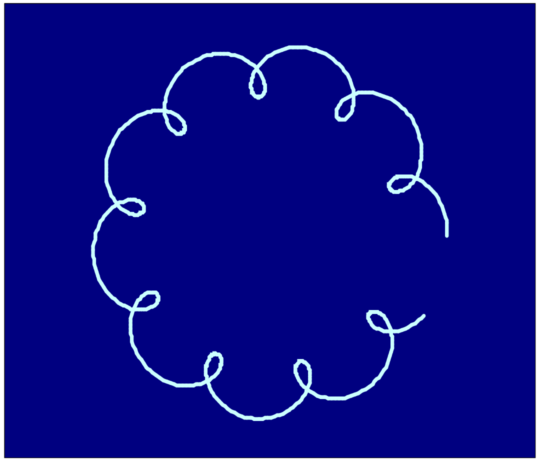
Axial sideband cooling of two-ion radial crystal



- The ions are both in the radial plane
- We see artifacts due to the rotational motion in the radial plane
- The two axial modes frequencies cannot be resolved in this plot
  - This makes the cooling process more straightforward as both cool together
- We also have cooling results for up to 10-ion radial crystals

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



Radial motion in the Penning trap

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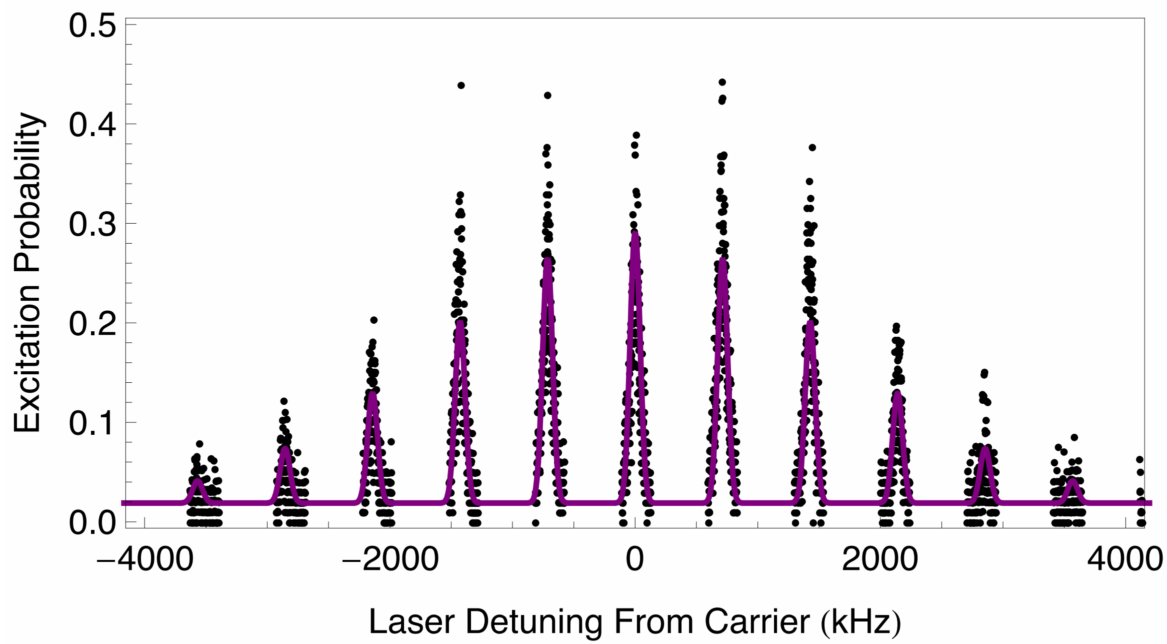
Radial spectrum at low potential

- 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*

Problems for radial cooling

- Need to cool two modes at the same time
  - We have gained experience of this with ion crystals
- The magnetron sidebands are unresolved
  - Increase trap voltage to raise magnetron frequency
- The magnetron energy is negative
  - Cool on the ***blue*** sidebands of magnetron motion, not ***red***
- The initial quantum number of magnetron motion is very large (n up to 1000 in some cases after Doppler cooling)
  - Use the axialisation technique to couple to cyclotron motion

Axialisation

- This technique 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 $n_m = -1$ and $n_c = +1$. The Doppler cooling continuously drives n_c to lower values. Eventually $n_m \approx n_c$

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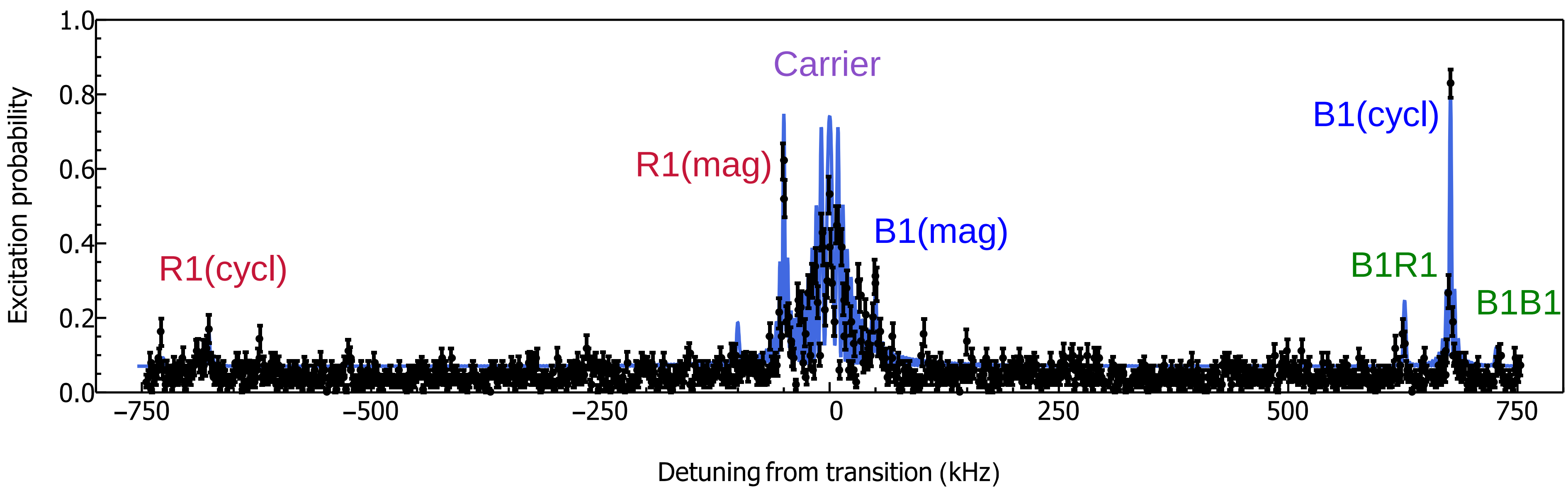
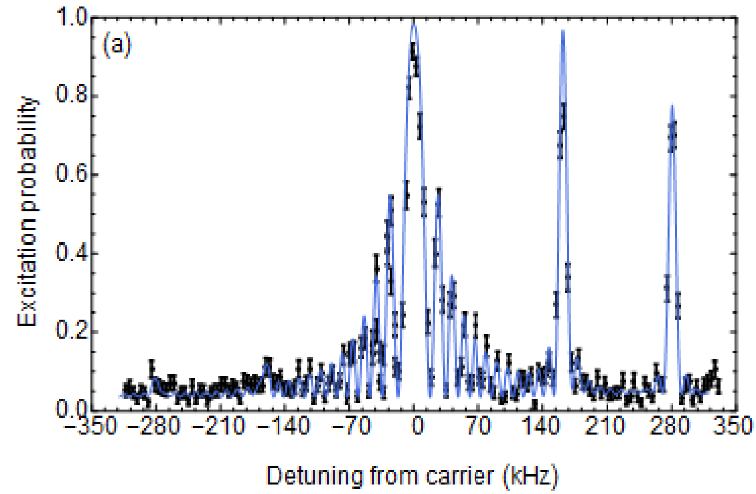
Sideband cooled radial spectrum

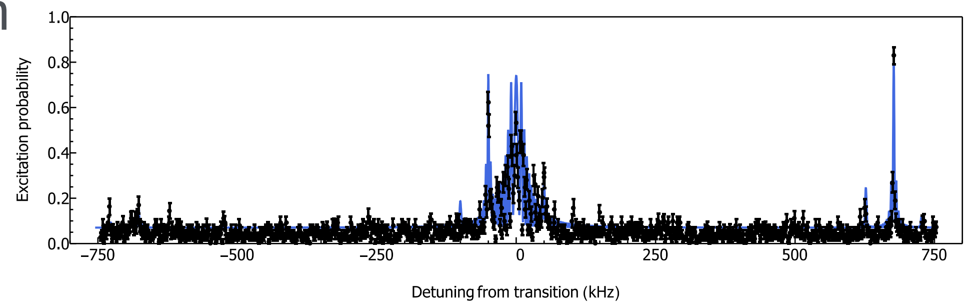


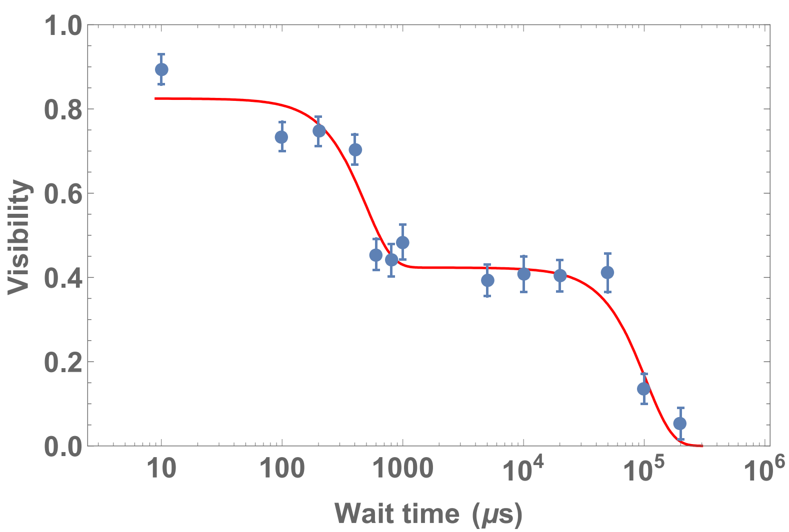
- The carrier is very strong to bring out the other sidebands
- The asymmetry in cyclotron sidebands indicates n_c=0.07±0.03
- The (reversed) asymmetry in the magnetron sidebands indicates n_m=0.40±0.06
- Weak second-order sidebands can also be seen

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

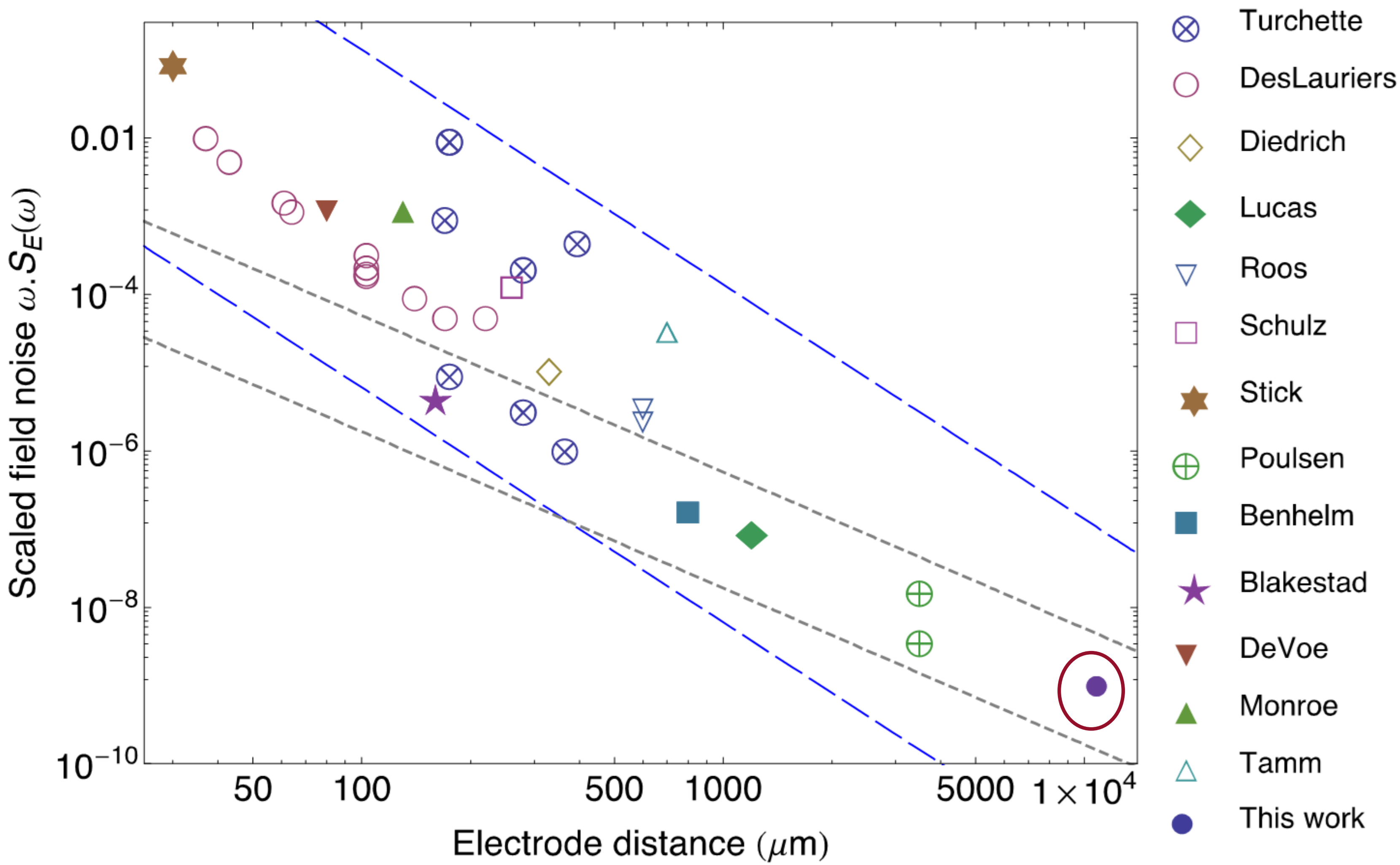




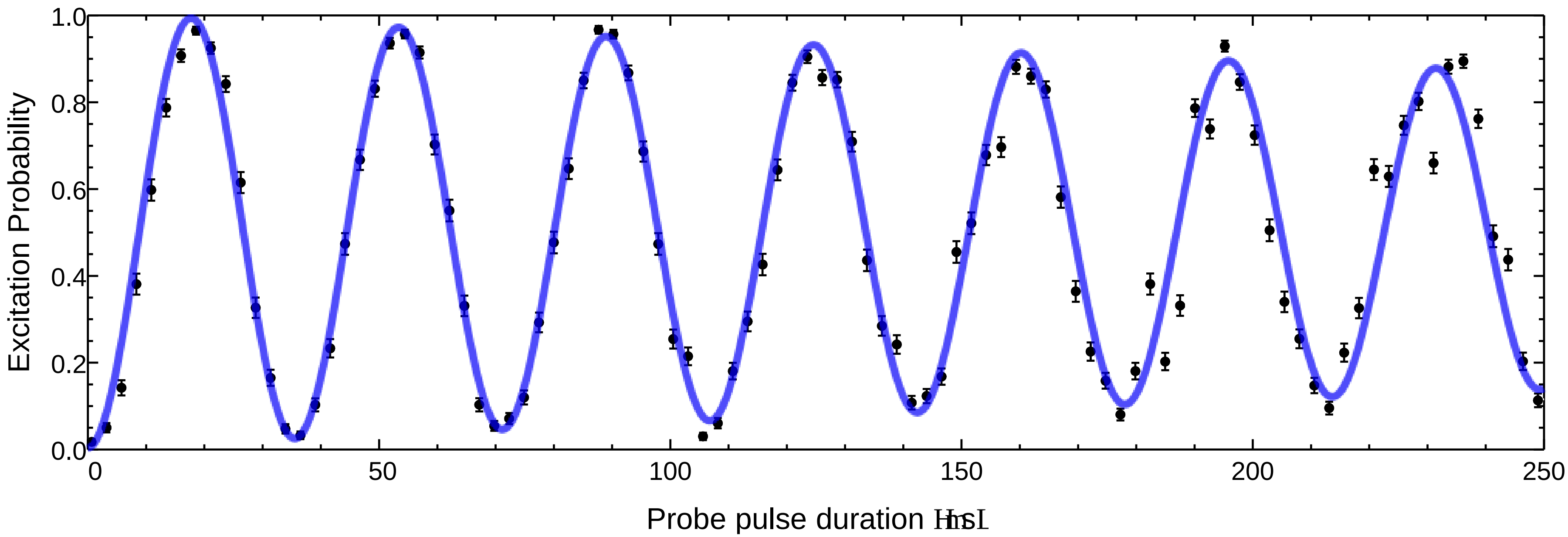


Thank you for your attention!

Heating rate comparison



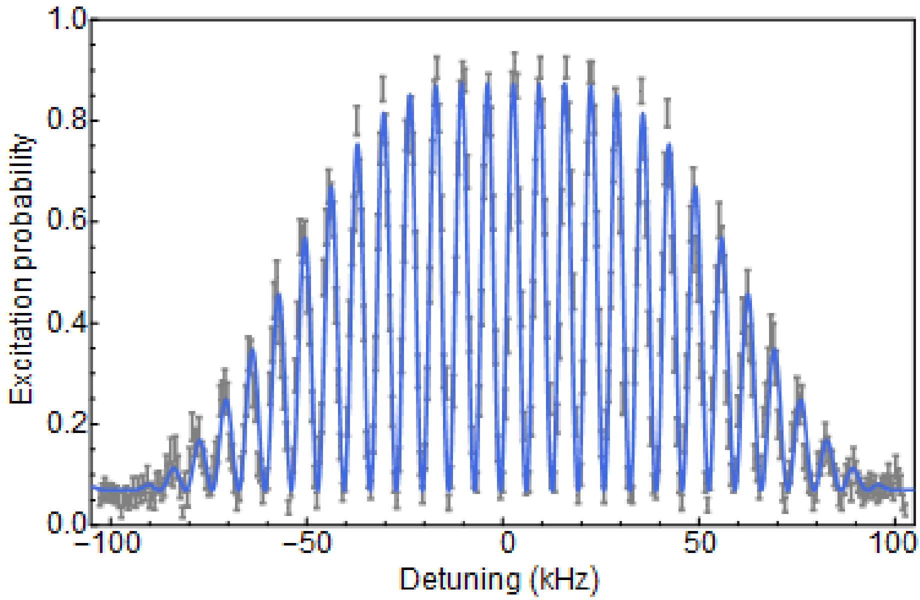
Rabi oscillations



- We can see Rabi oscillations for ground-state cooled ions
  - The carrier Rabi frequency is up to 60 kHz and the coherence time is ~0.8 ms
- Spin-echo techniques can be used to increase coherence time to a few ms

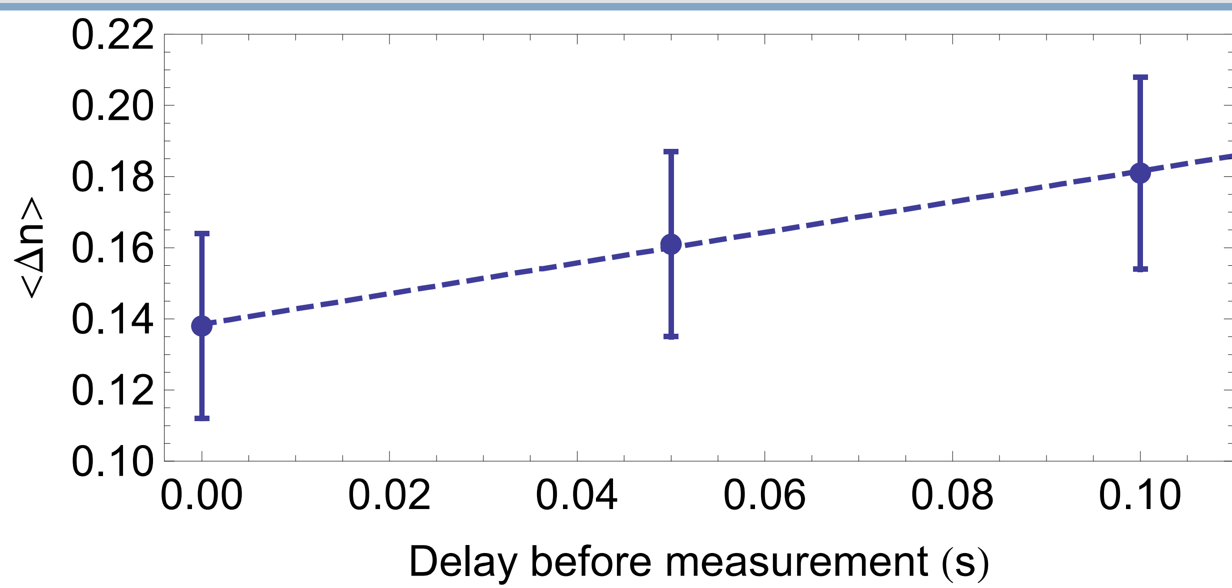
Ramsey interference with two-ion crystal

Ramsey interference pattern after 140μs delay between two π/2 pulses



- The observation of Ramsey fringes confirms coherent behaviour of the system

Heating rate results



This heating rate was taken at an axial frequency of 200 kHz

- The heating rate averages at around **0.4 phonons/second** and is roughly independent of frequency
  - Probably limited by technical noise
- The heating rate is expected to be low because
  - The trap is very large (radius 10 mm)
  - The trapping fields are static and there is no micromotion

Goodwin *et al. PRL* 2016

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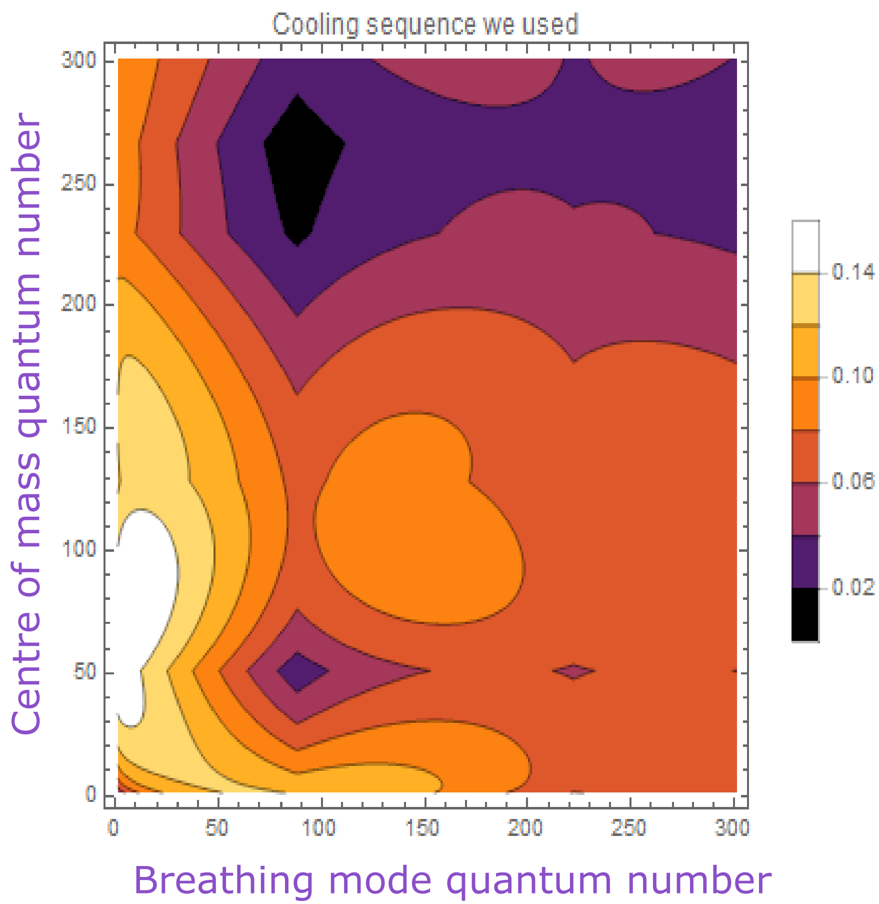
Cooling effect of the sequence of sidebands

- 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



Proportion of population above mimimum

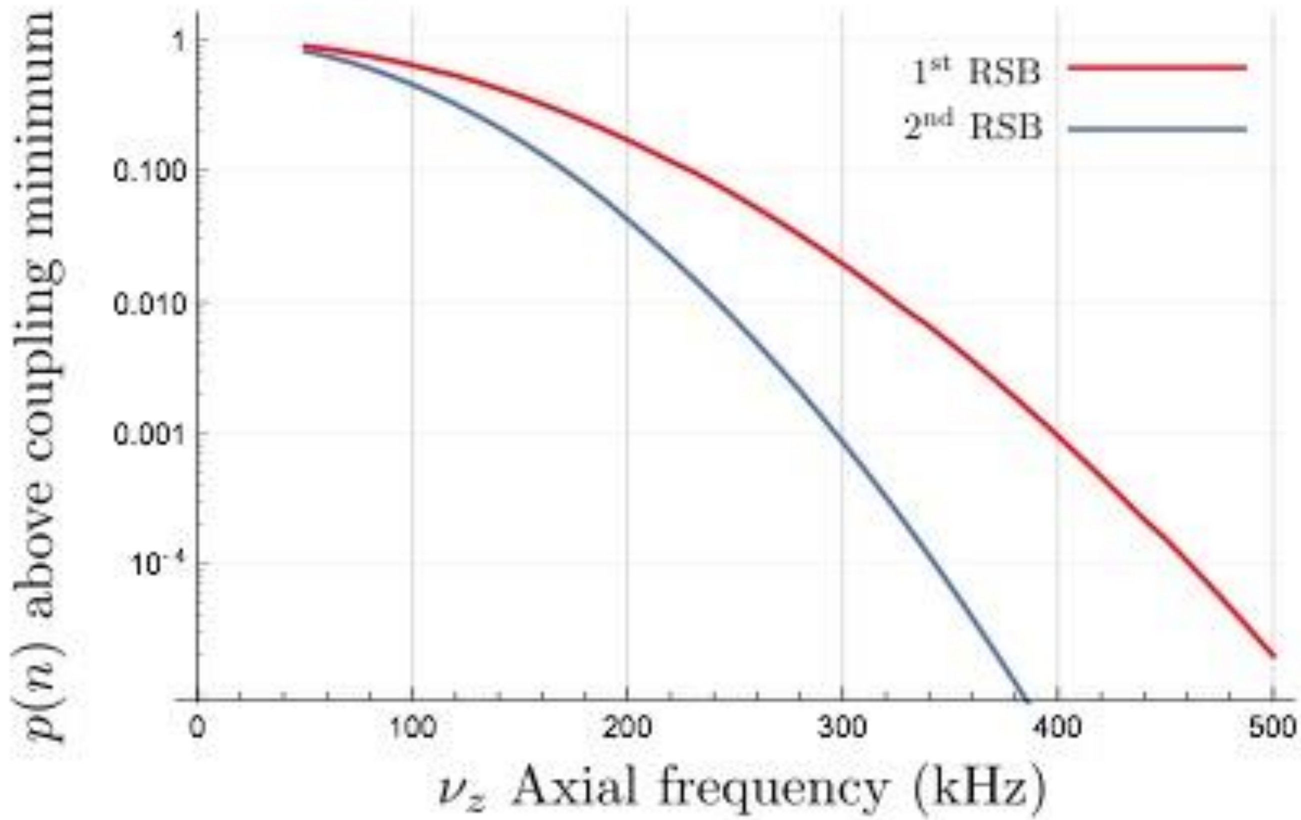
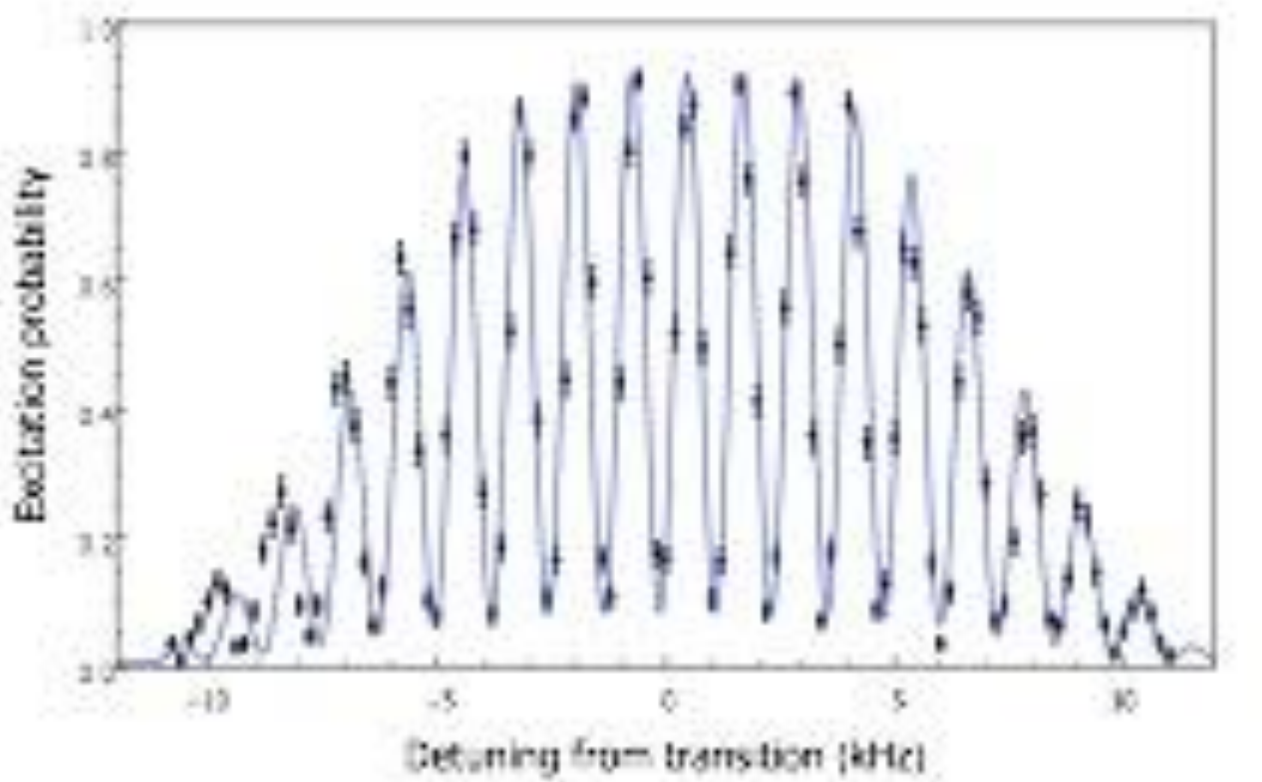


Figure 6.4: Plot showing fraction of population at the Doppler limit that lies above the the lowest coupling minima of the first two red sidebands as a function of the trapping frequency.

Ramsey fringes



$$T_w = 700\mu s \;,\; \Omega_0/2\pi = 3.2 \text{ kHz}$$