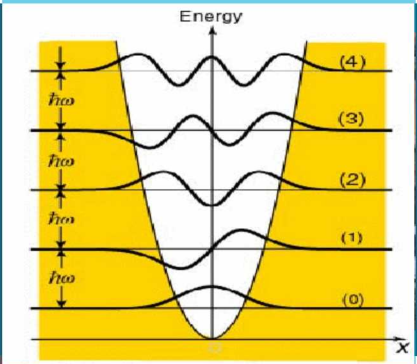
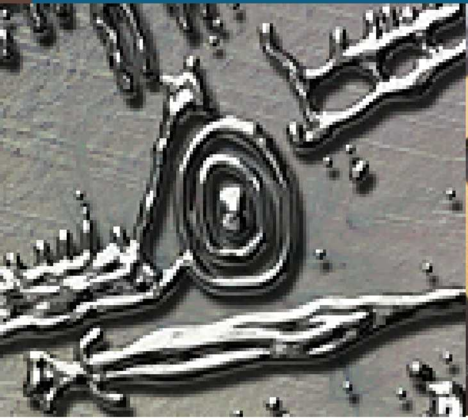
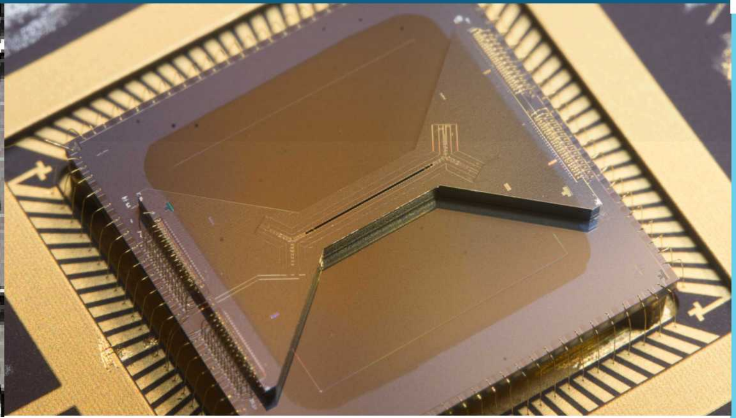
SAND2019-5648C

Sideband Cooling of Ytterbium







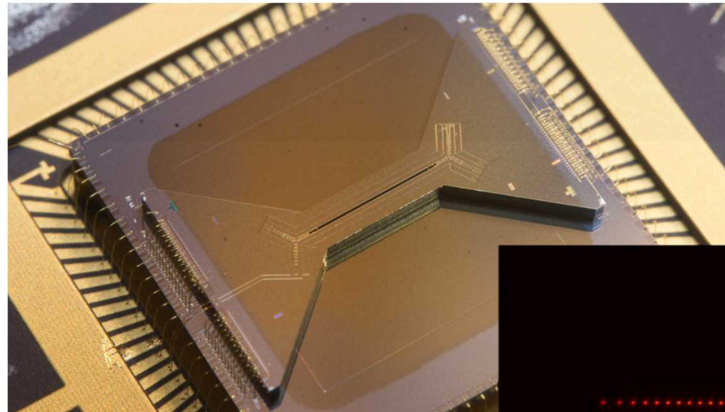
Brandon Ruzic, Melissa Revelle, and Peter Maunz

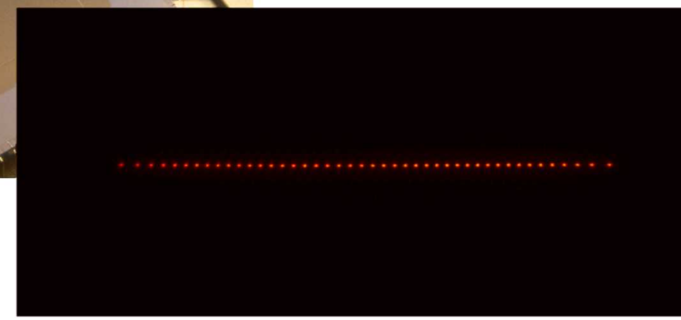
Sandia National Laboratories, Albuquerque, New Mexico 87123

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

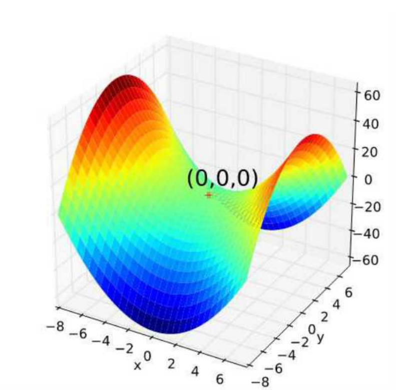
Ion Chains

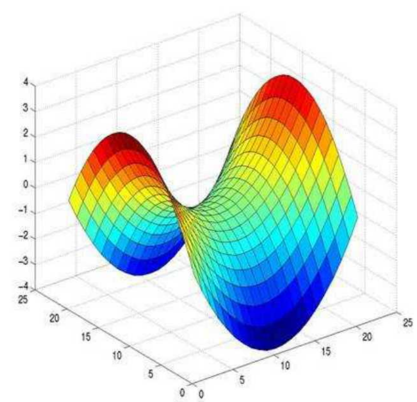
- A 2D array of electrodes on this surface can trap a linear chain of ions along the slot





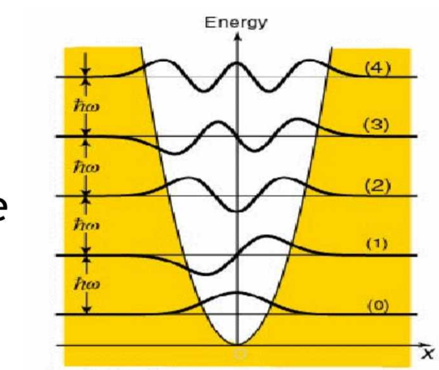
- A/C electric fields create an oscillating saddle potential, which can trap an ion near the saddle point





- The result is a fairly harmonic static potential

- Multiple ions in the same trap push each other apart and move in collective normal modes of motion

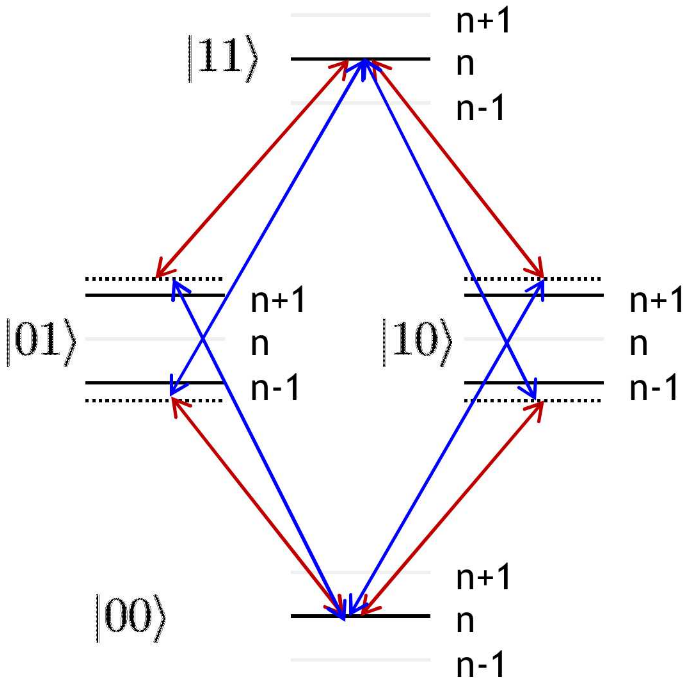


Two-qubit Entangling Gate

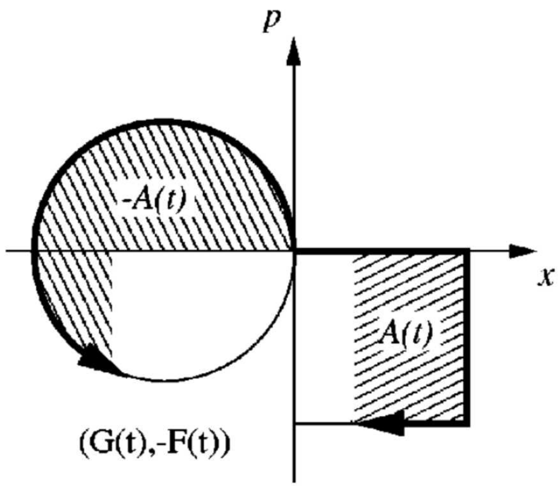
- An essential ingredient for many quantum applications is a 2-qubit entangling gate

$$|00\rangle \rightarrow |00\rangle + |11\rangle$$

Molmer-Sorensen Gate



- The Molmer-Sorensen gate can entangle the spins of two ions
  - Two tones of a laser (red and blue) off-resonantly drive two motional sideband transitions simultaneously



- For a fast gate, the bi-chromatic light field strongly couples the ions' spin and motion

- Ideally, the gate leaves the spin and motion uncoupled (and the motional state unchanged) by closing the loop in phase space.

Gate Errors from Heating

- High-fidelity gates require the ions' motional degrees of freedom to be kept at ultracold temperatures

- Lamb-Dicke Approximation
  - When an ion's excursion in the trap is on the order of the laser wavelength, the complete decoupling of spin and motion breaks down

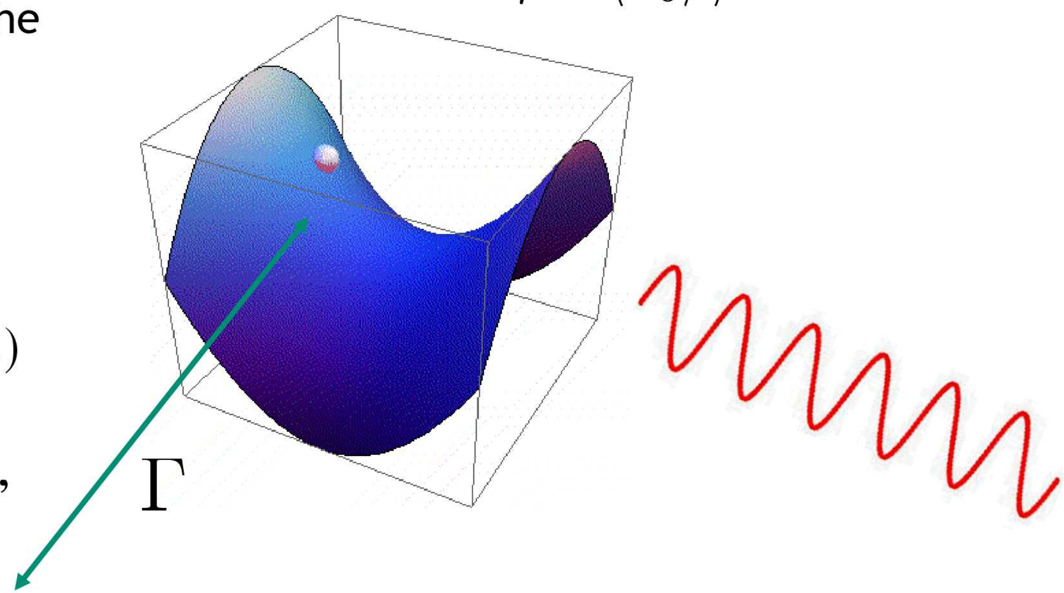
$$F = 1 - \frac{\pi^2 N(N-1)}{8} \eta^4 \, \mathrm{Var}(n)$$

$$\tau_{opt} = \frac{\pi}{2\tilde{\Omega}} (1 + \eta^2(2\bar{n} + 1)),$$

- Heating From the Environment
  - An ion cannot be completely isolated from the environment
  - The gate fidelity can be ruined before this heating takes the ion out of the Lamb-Dicke limit

Lamb-Dicke Parameter

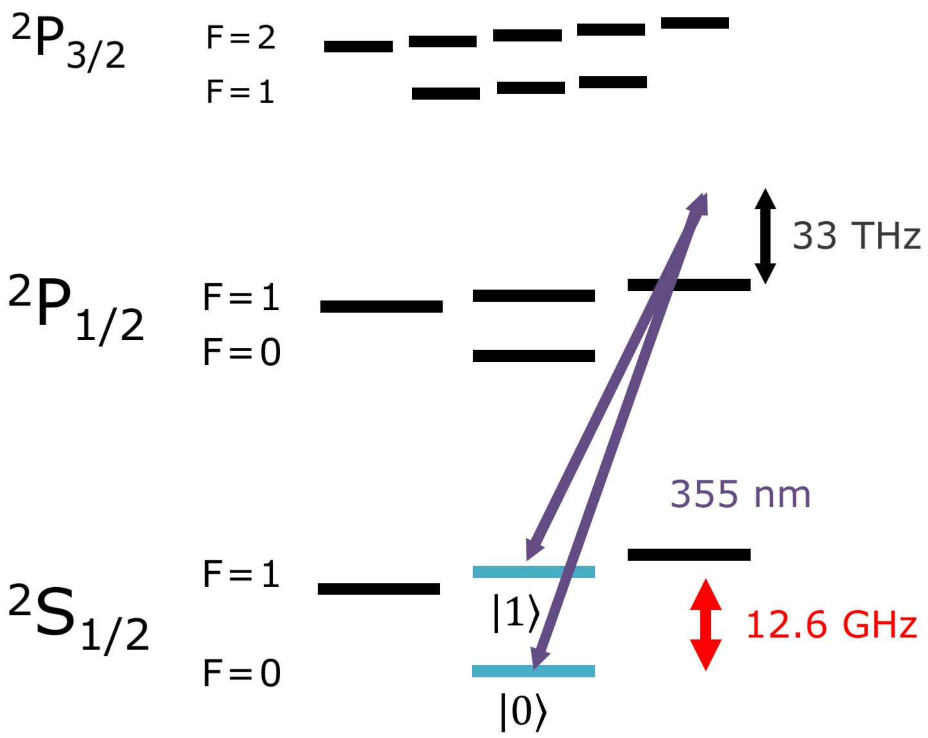
$$\eta = \langle x_0 \rangle / 2\pi\lambda$$



$$F = \frac{1}{\sqrt{1 + N \frac{\Gamma(1 + 2n_{th})}{4K} \tau}}.$$

Sideband Cooling of $^{171}Yb^+$

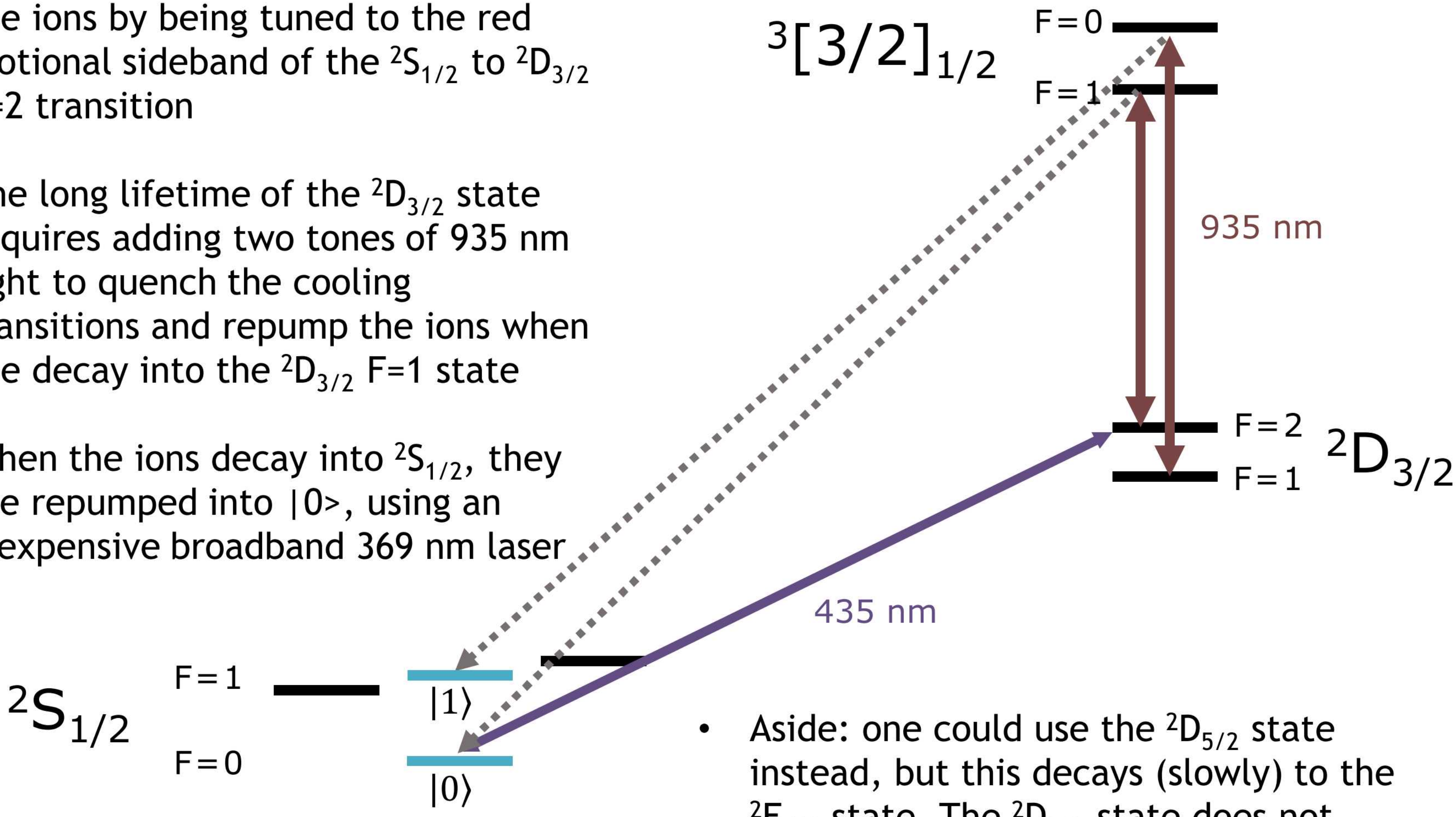
- Two tones of a narrow linewidth 355 nm Raman laser can cool the ions by being tuned to the red motional sideband of the qubit transition



- This can achieve excellent cooling rates of 60 quanta / second
- Problems
  - The 355 nm laser is very expensive
  - It's is hard to set up – hard to align, etc.
  - This same laser is also used for Raman gates
- We'd like to find a simple alternative that's able to achieve the same cooling rate

Sideband Cooling of $^{171}Yb^+$

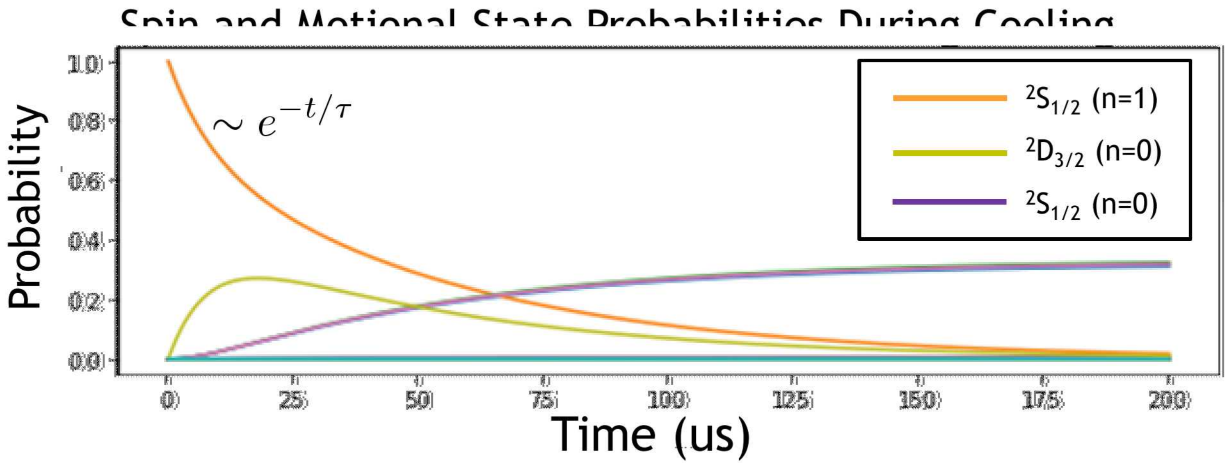
- Alternatively, a 435 nm laser can cool the ions by being tuned to the red motional sideband of the $^2S_{1/2}$ to $^2D_{3/2}$ F=2 transition
- The long lifetime of the $^2D_{3/2}$ state requires adding two tones of 935 nm light to quench the cooling transitions and repump the ions when the decay into the $^2D_{3/2}$ F=1 state
- When the ions decay into $^2S_{1/2}$, they are repumped into |0>, using an inexpensive broadband 369 nm laser



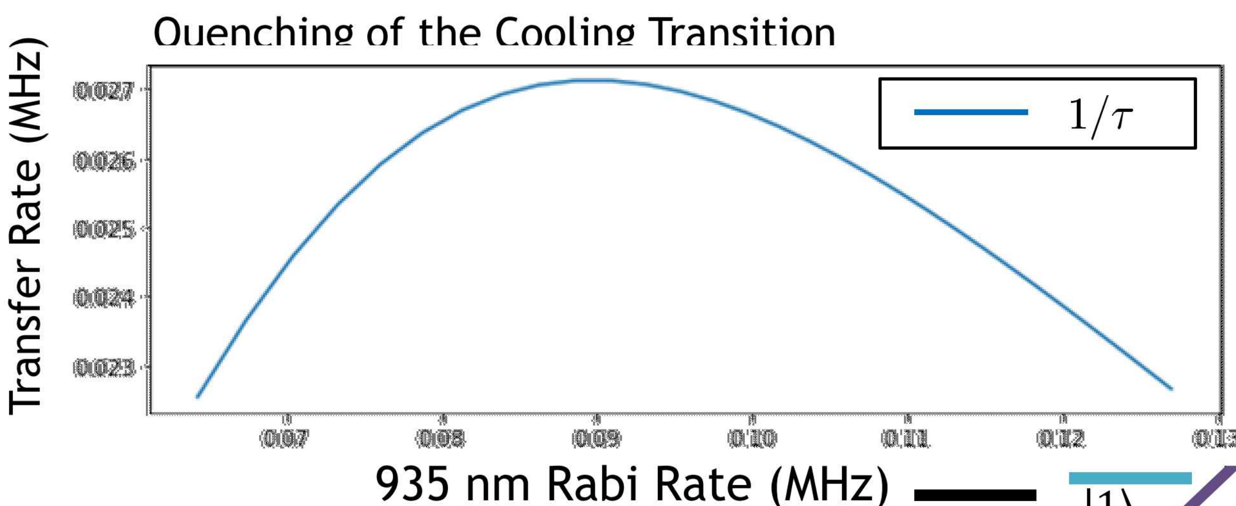
- Aside: one could use the $^2D_{5/2}$ state instead, but this decays (slowly) to the $^2F_{7/2}$ state. The $^2D_{3/2}$ state does not.

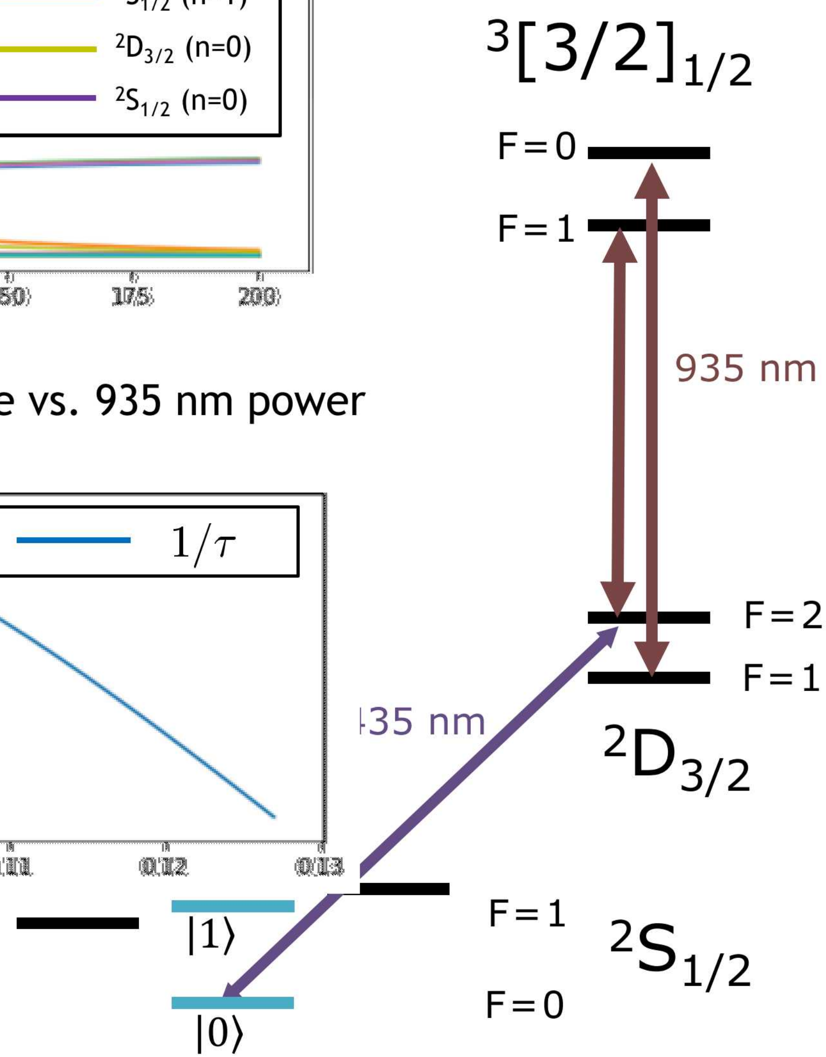
$^2D_{3/2}$ Sideband Cooling Simulation

- We've numerically simulated this new cooling scheme

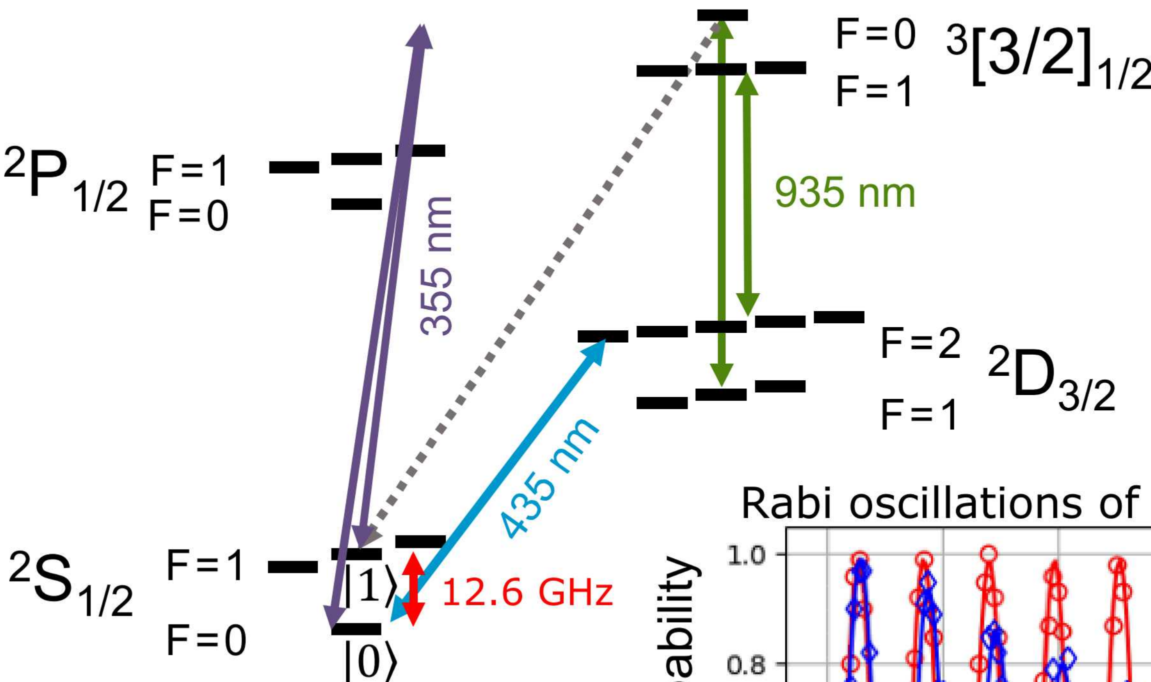


- We've identified a peak in the cooling rate vs. 935 nm power

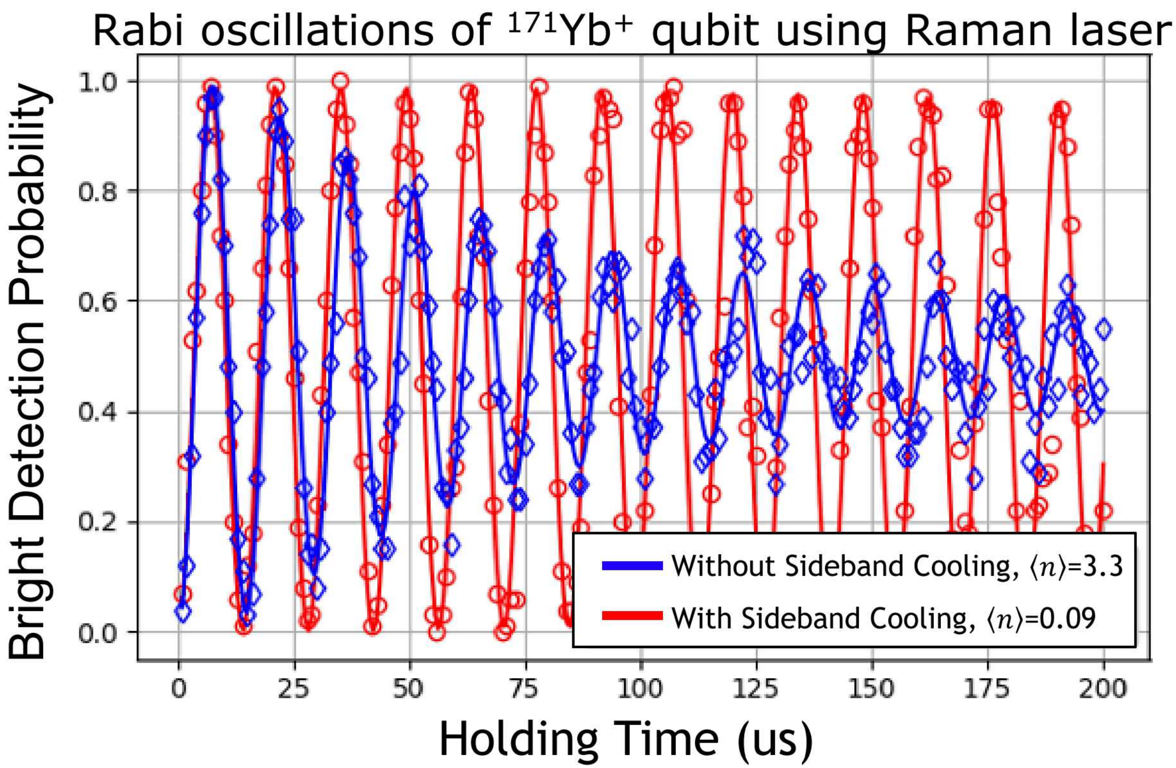




Successful $^2D_{3/2}$ Sideband Cooling

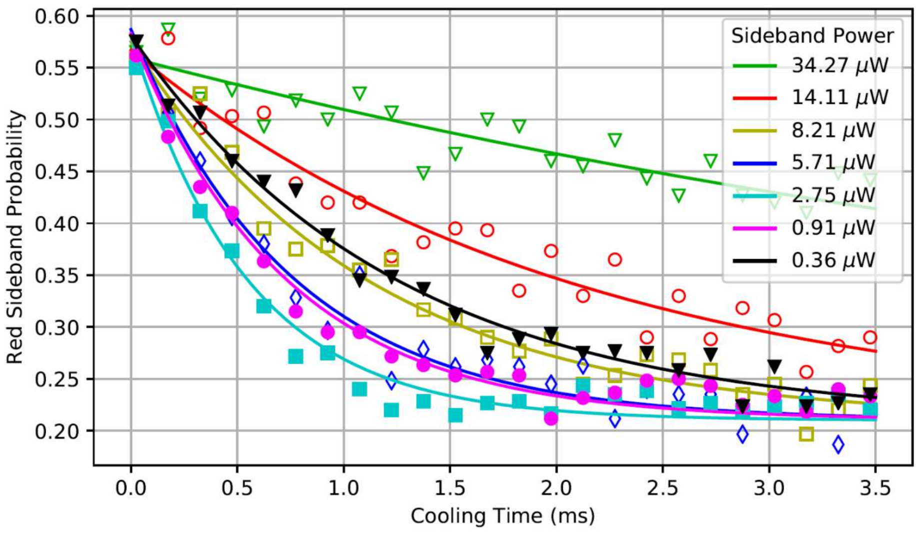


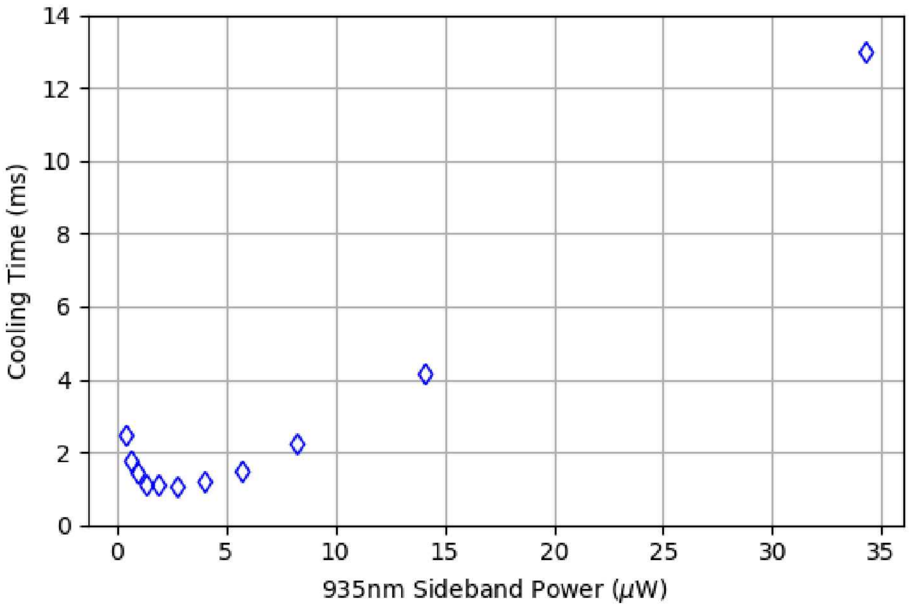
- We've successfully tested the $^2D_{3/2}$ cooling scheme
- We drove Raman qubit transitions using 355 nm light before and after cooling
- We saw a much longer coherence time after cooling
- The cooling rate was comparable to using the qubit lasers to Doppler cool



Measurement of Peak Cooling Rate

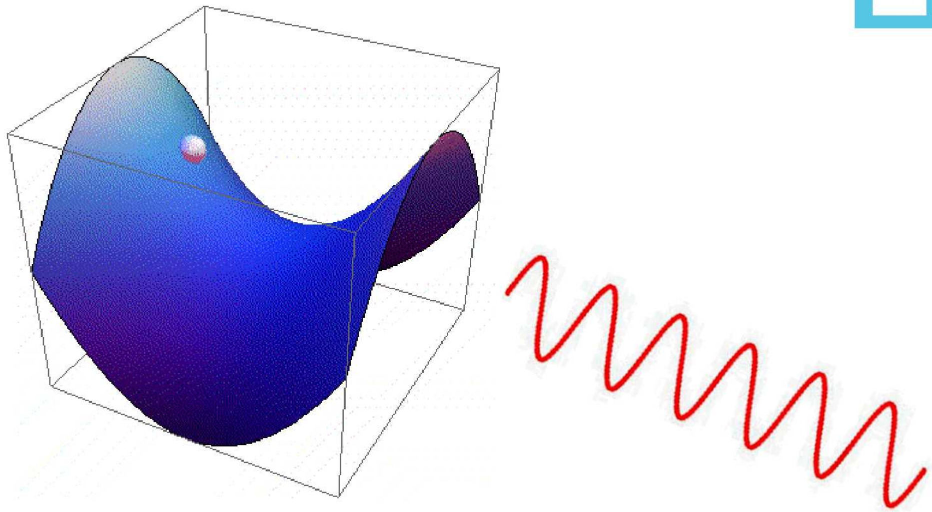
- We've confirmed our prediction that the cooling rate has a non-monotonic dependence on the 935nm power
- Higher powers can broaden the 435nm transition and decrease the cooling efficiency
- The 935nm sideband power must be optimized for the beam polarization and power in the 435nm beam
- Cooling times of less than 1 ms are easily achievable using about 2mW of 435nm light

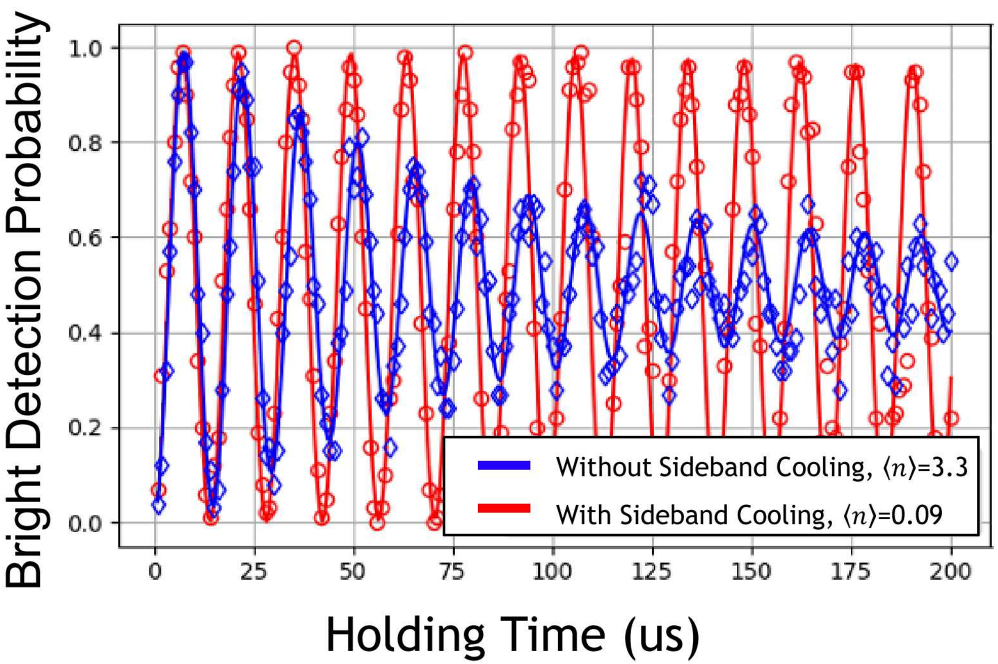




Summary

- Ion chains are a promising platform for quantum applications
- High-fidelity quantum gates require that the ions' motional degrees of freedom are cooled to ultracold temperatures
- Using the qubit laser system to cool $^{171}Yb^{+}$ is expensive, challenging, and occupies the qubit lasers
- We developed and demonstrated a convenient sideband cooling technique that uses the $^{2}D_{3/2}$ level
- We achieved a comparable cooling rate to using the qubit laser system for cooling
- We analyzed the effects of quenching the cooling transition and optimized the cooling rate vs. 935 nm power





Theory
Brandon Ruzic

Experiment
Melissa Revelle
Peter Maunz

Collaborators
Kevin Young
Dan Lobser
Craig Hogle

Thanks!