



Harvard-MIT Center for Ultracold Atoms

Quantum Information

Ultracold Collisions/Chemistry

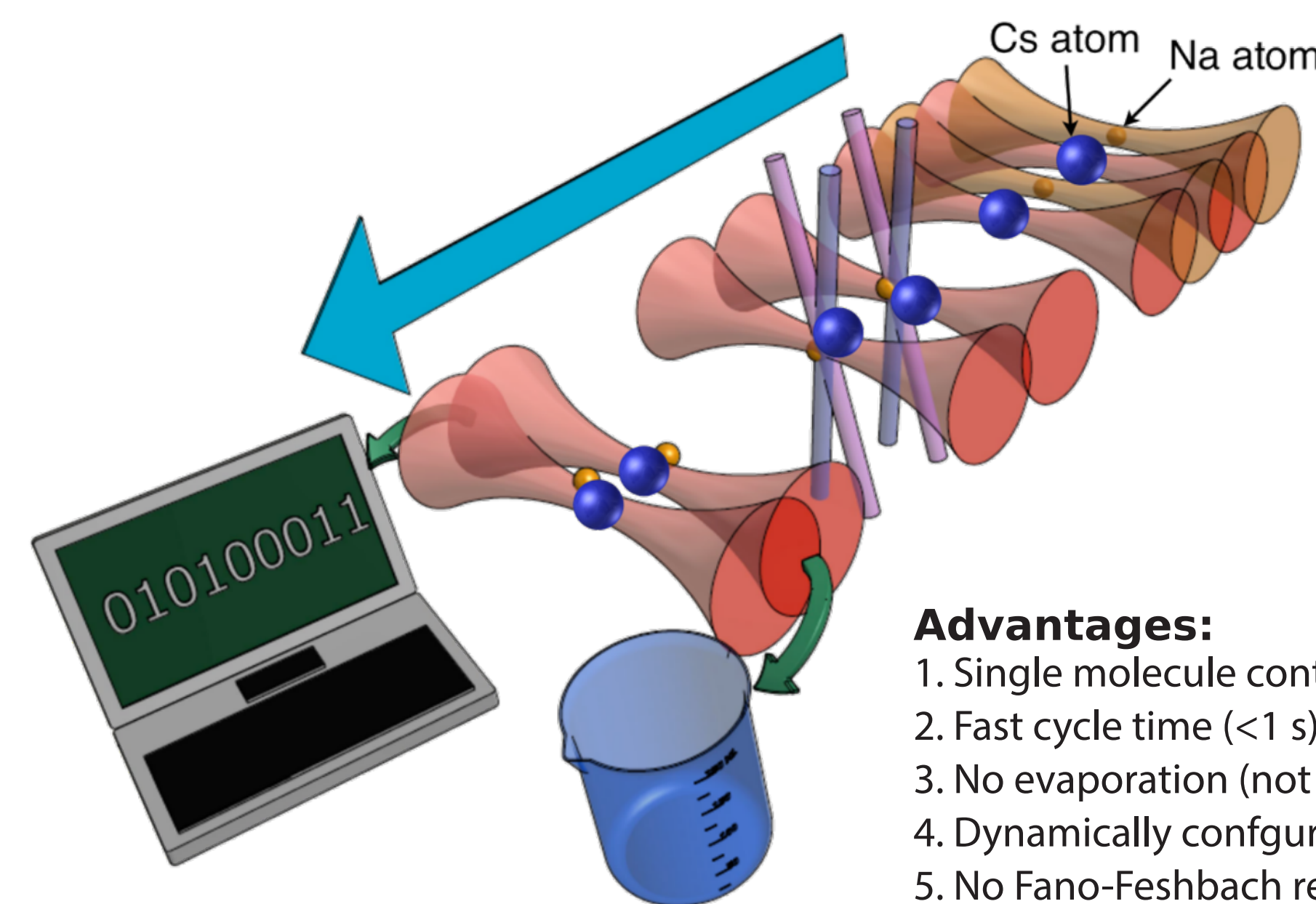
Quantum Simulation

P. Rabl, et al., Phys. Rev. Lett. 97, 33003 (2006).

K.-K. Ni et al., Nature 464, 1324 (2010).

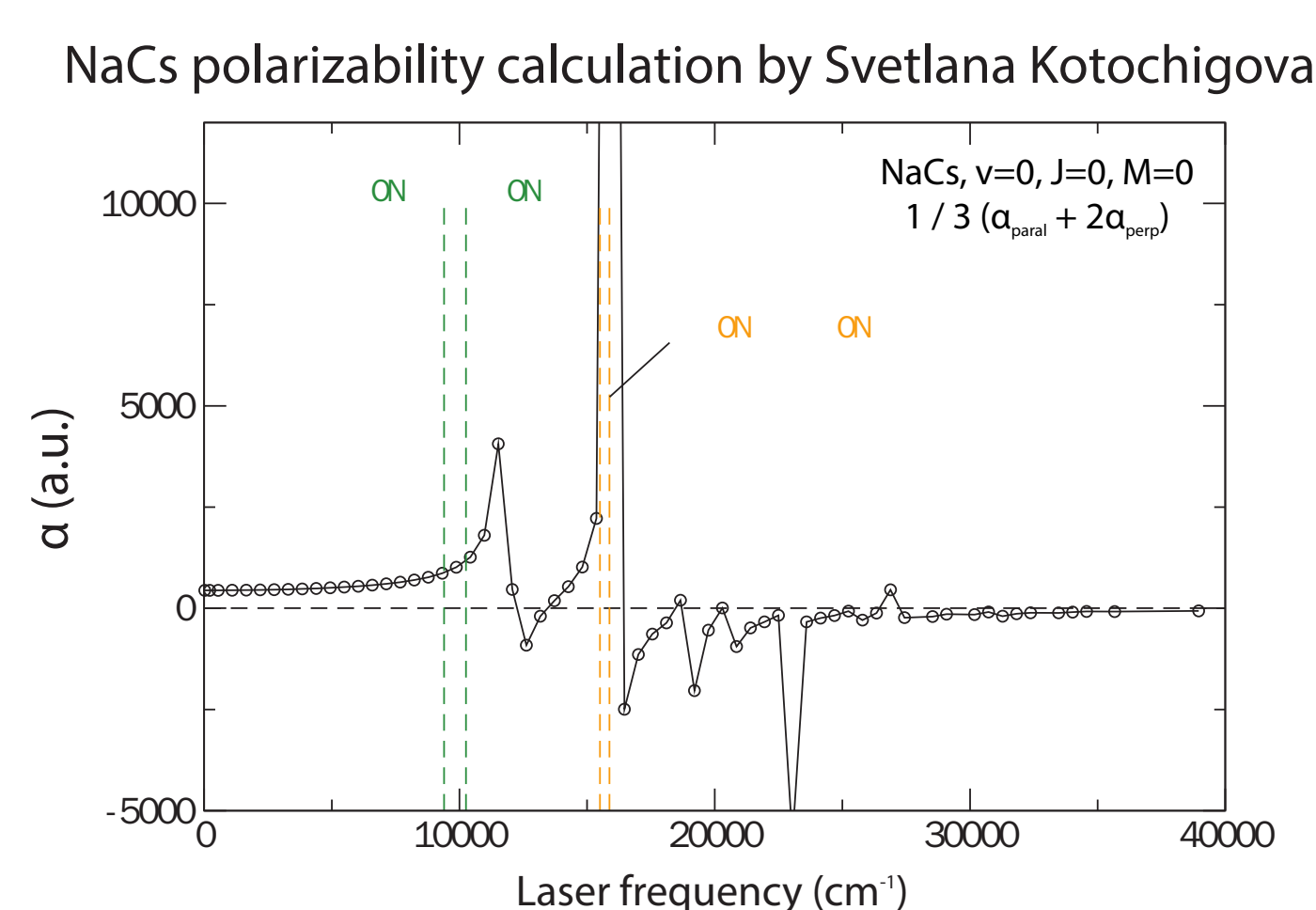
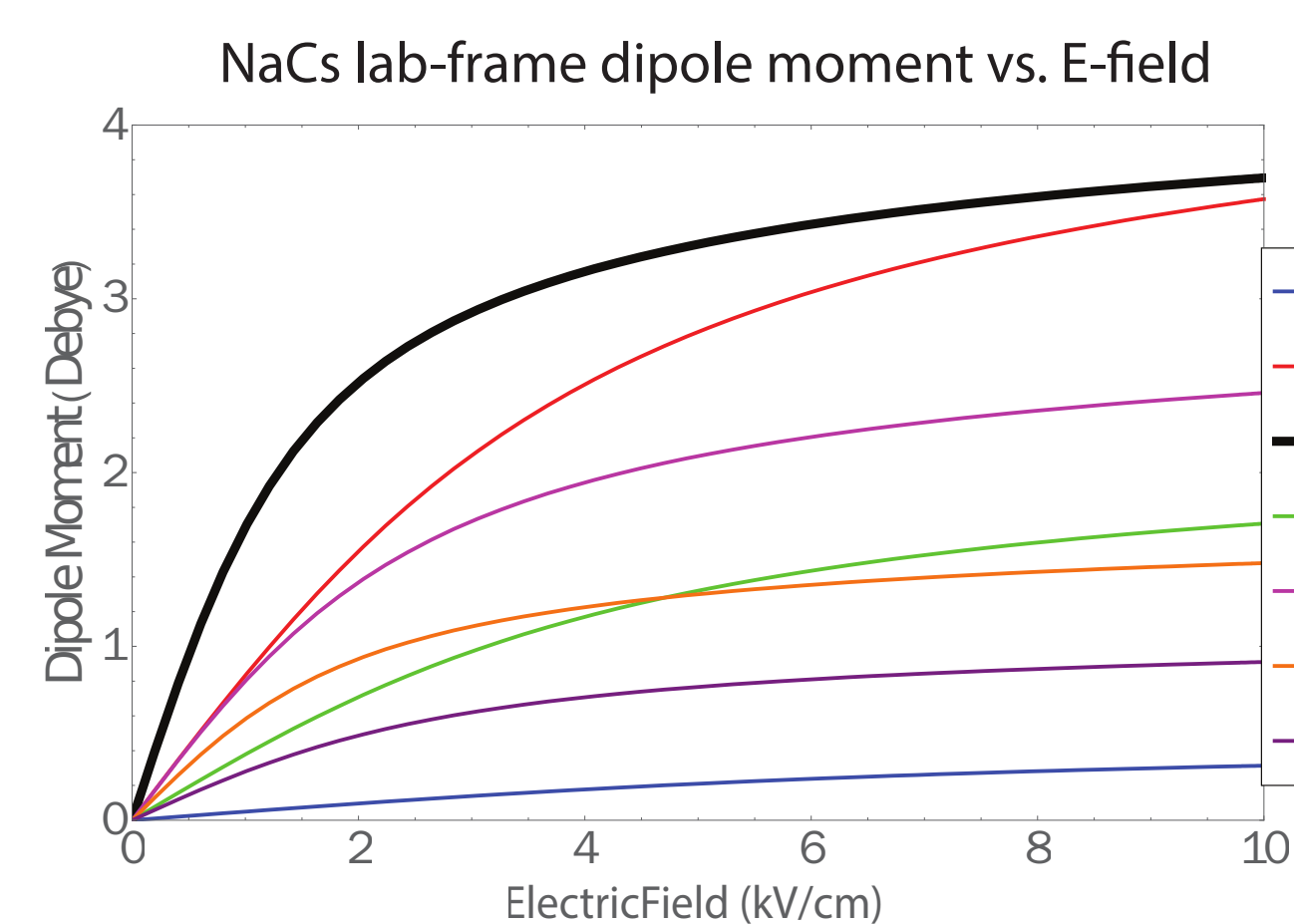
A. Micheli, G. K. Brennen, and P. Zoller, Nat. Phys. 2, 341 (2006).

We aim to assemble and trap individual ultracold polar molecules in optical tweezers from laser-cooled atoms



### Advantages:

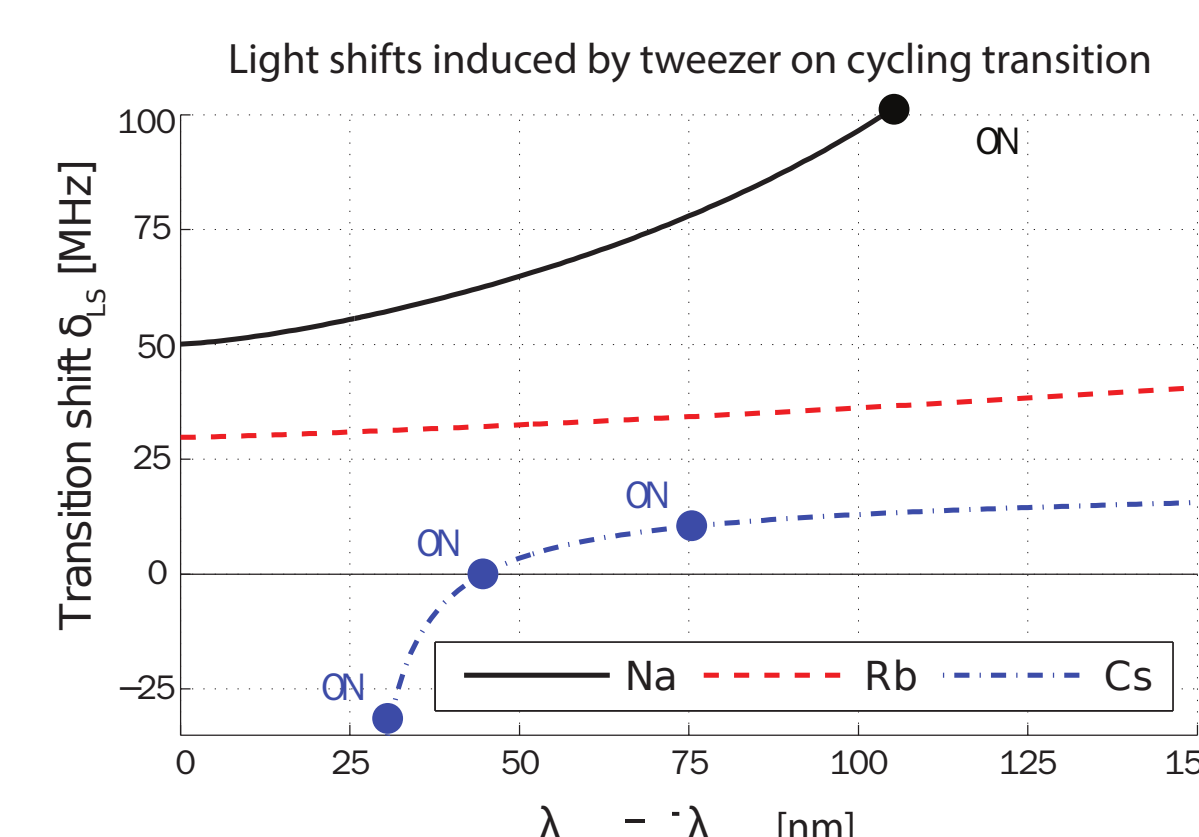
1. Single molecule control
2. Fast cycle time ( $< 1$  s), small vacuum chamber
3. No evaporation (not dependent on dual-species atomic collisions)
4. Dynamically configurable trapping geometry
5. No Fano-Feshbach resonance required (relaxes B-feld control)
6. No atomic three body losses



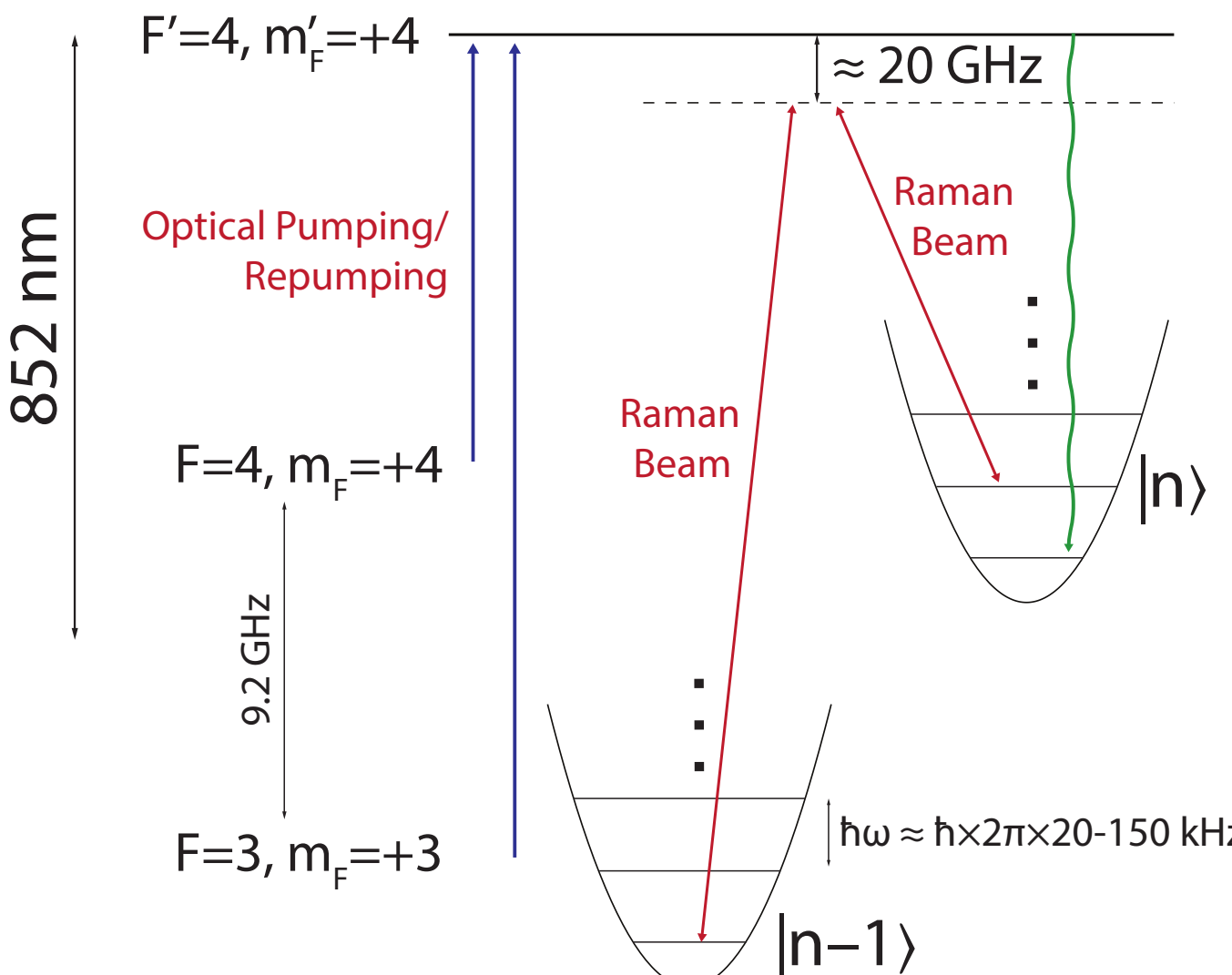
The schematic diagram illustrates the experimental setup for the quantum simulation. It features an EMCCD Camera for atomic fluorescence detection. Dipole trapping beams, filtered by a dichroic mirror, are used to trap the atoms. The setup includes a superchromatic filter (589 - 1000 nm) and a NA 0.55 objective lens. The atoms are trapped in a MOT (Magneto-Optical Trap) within a UHV (Ultra-High Vacuum) glass cell, which is also equipped with electric field plates. An inset shows the trapping potential with radial frequency  $\omega_{\text{radial}} = 2\pi \times 100-200 \text{ kHz}$  and axial frequency  $\omega_{\text{axial}} = 2\pi \times 20-30 \text{ kHz}$ . A 2D fluorescence image on the right shows the distribution of Na and Cs atoms, with axes  $x(\mu\text{m})$  and  $y(\mu\text{m})$ .

AC Stark shifts can prevent atom loading, as is the case with Na atoms in tweezers at convenient wavelengths.

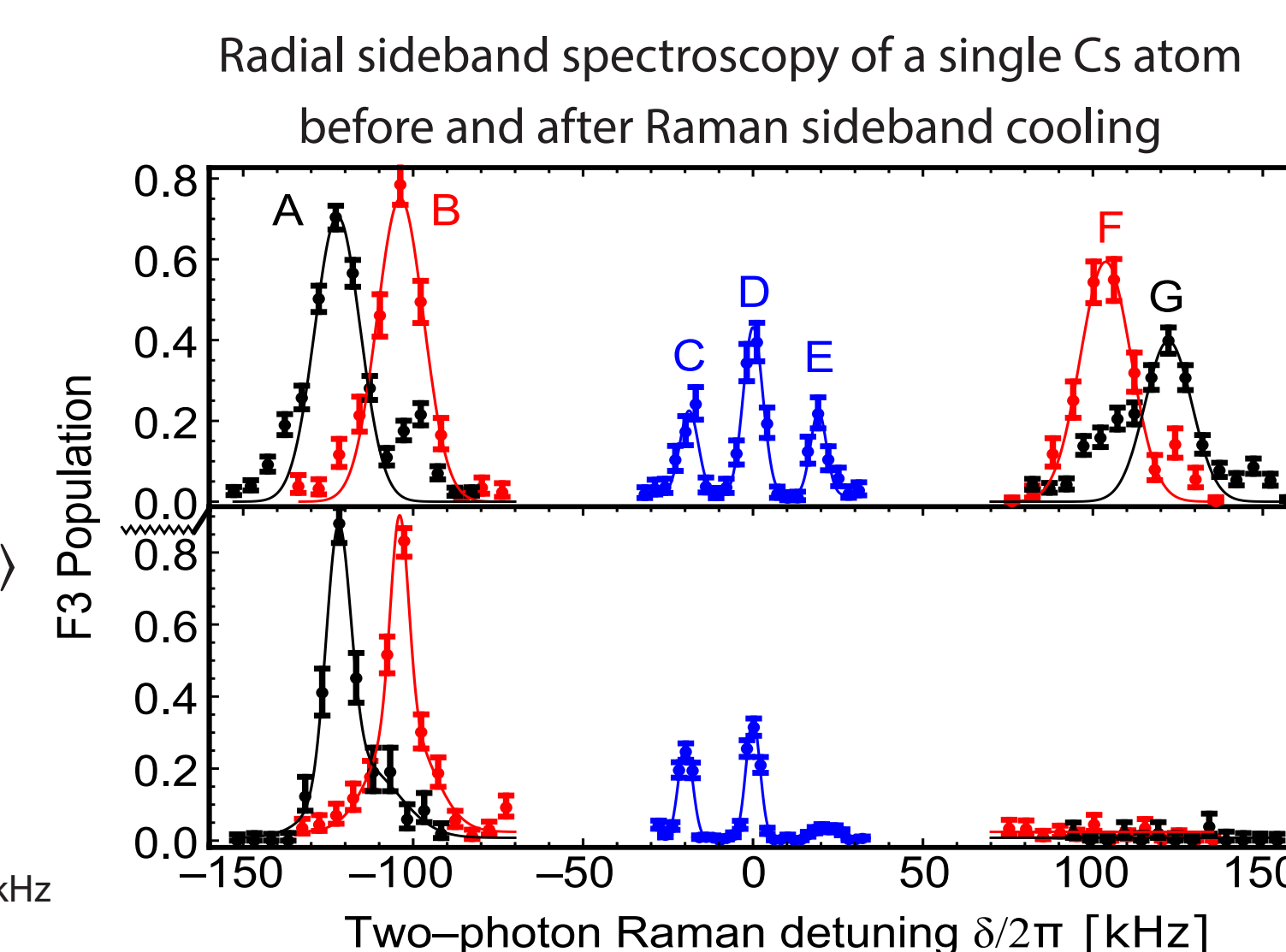
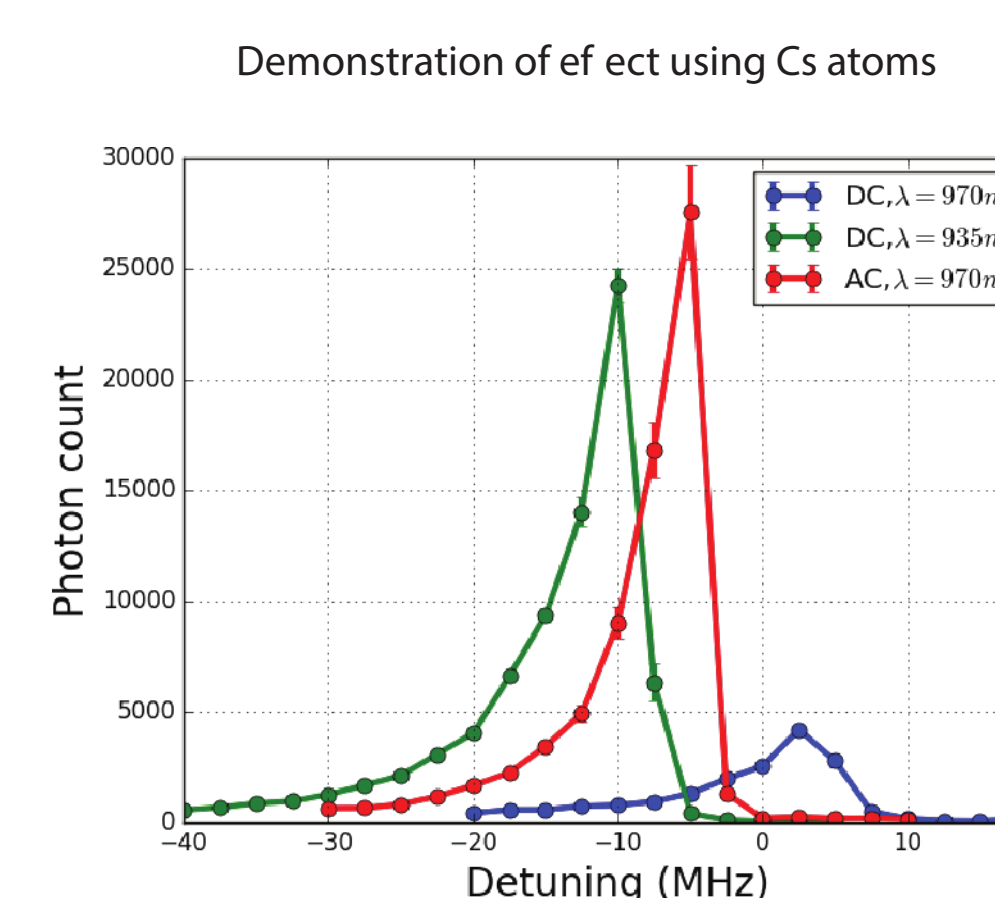
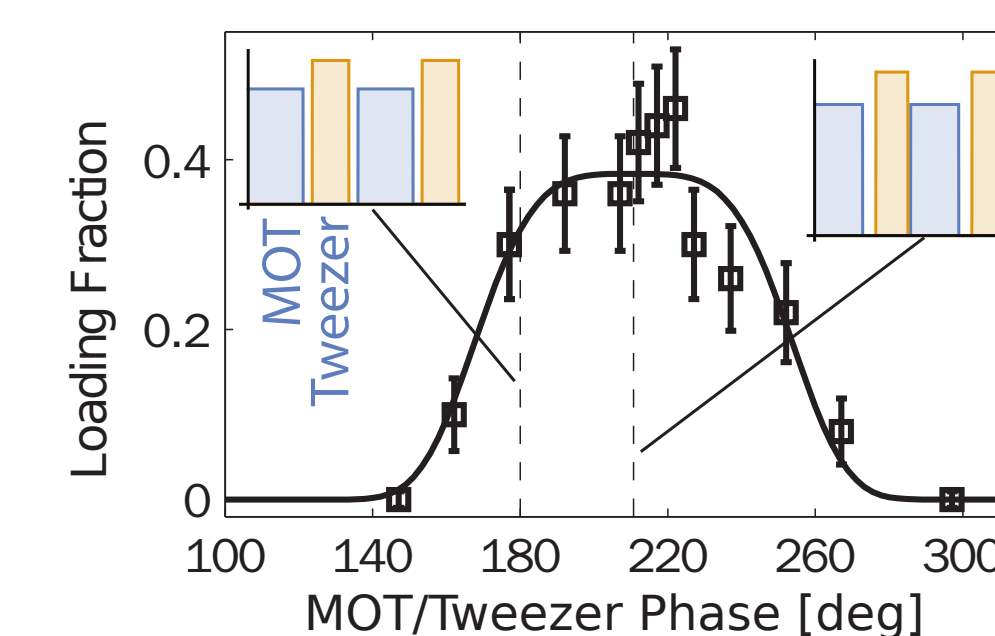
Our solution: rapidly modulate the intensity of the MOT, cooling, imaging, and tweezer beams. Light shifts are effectively eliminated, and Na atoms can be loaded.



## Raman sideband cooling scheme for Cs



- Raman sideband ground state cooling for neutral atoms
  - » Demonstrated for single Rb atoms in tight tweezer traps
  - » A. Kaufman, B. Lester, and C. Regal, PRX 2, 041014 (2012)
  - » J. D. Thompson et al., PRL 110, 133001 (2013)



- Initially cool using polarization gradient cooling in tweezer
  - » Can cool single Cs atom to 15  $\mu$ K in 3 ms
- Follow with pulsed Raman sideband cooling (RSC)
  - » Alternate cooling beams between three axes.
  - » Use Blackman shape Raman pulse to reduce off-resonance coupling to carrier and heating sidebands.
  - » Sweep Raman pulse time to address different vibrational states with different matrix elements.
  - » Achieve 3D ground state with probability 84.1%

Figure 3 displays four plots showing the survival probability (Y-axis, ranging from 0.0 to 0.5) versus the detuning (MHz) (X-axis) for different experimental conditions. The plots are arranged in a 2x2 grid.

- Top-left plot:** Radial sideband (no RSC). The X-axis ranges from -0.2 to 1.0 MHz. The plot shows a series of peaks. The main peak is labeled "Carrier" (black arrow) at approximately 0.0 MHz. Other peaks are labeled "Cooling 1" (green arrow) at approximately 0.4 MHz and "Cooling 2" (blue arrow) at approximately 0.8 MHz.
- Top-right plot:** Axial sideband (no RSC). The X-axis ranges from -0.1 to 0.4 MHz. The plot shows a series of peaks. The main peak is labeled "Carrier" (black arrow) at approximately 0.0 MHz. Other peaks are labeled "Heating 1" (red arrow) at approximately -0.05 MHz, "Cooling 1" (green arrow) at approximately 0.1 MHz, and "Cooling 2" (blue arrow) at approximately 0.2 MHz.
- Bottom-left plot:** Axial sideband (with RSC). The X-axis ranges from -0.2 to 1.0 MHz. The plot shows a series of peaks. The main peak is labeled "Carrier (overdriven)" (black arrow) at approximately 0.0 MHz. Other peaks are labeled "Cooling 1" (green arrow) at approximately 0.4 MHz and "Cooling 2" (blue arrow) at approximately 0.8 MHz.
- Bottom-right plot:** Axial sideband (with RSC). The X-axis ranges from -0.05 to 0.15 MHz. The plot shows a series of peaks. The main peak is labeled "Carrier" (black arrow) at approximately 0.0 MHz. Other peaks are labeled "Heating 1" (red arrow) at approximately -0.05 MHz, "Cooling 1" (green arrow) at approximately 0.05 MHz, and "Cooling 2" (blue arrow) at approximately 0.10 MHz.

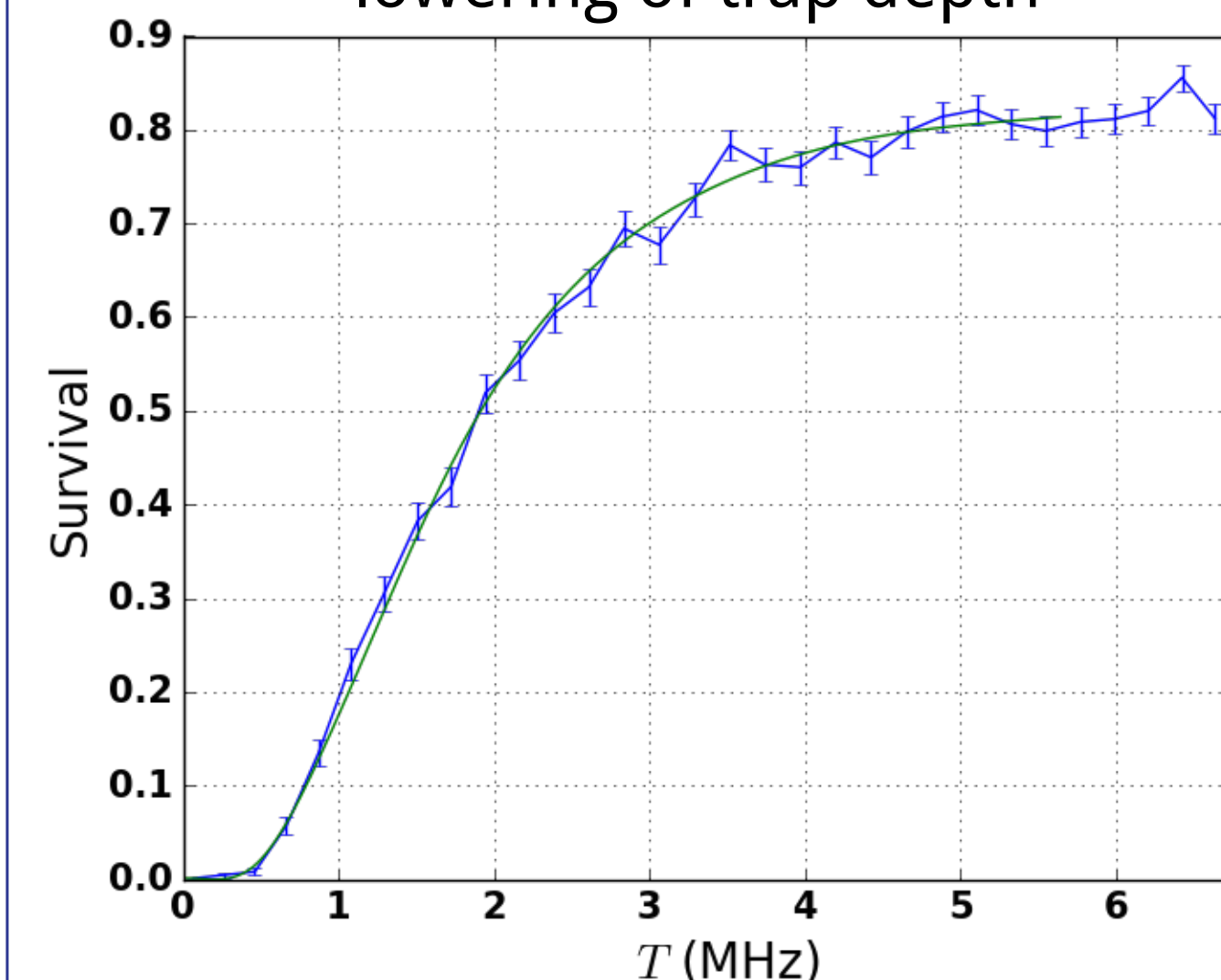
Normal sideband thermometry relies on  $|\langle n | e^{ikr} | n-1 \rangle| \propto \sqrt{n}$

This is only valid when  $\eta \ll 1$  ( $\eta \equiv [\omega_{\text{recoil}}/\omega_{\text{trap}}]^{1/2}$ ).

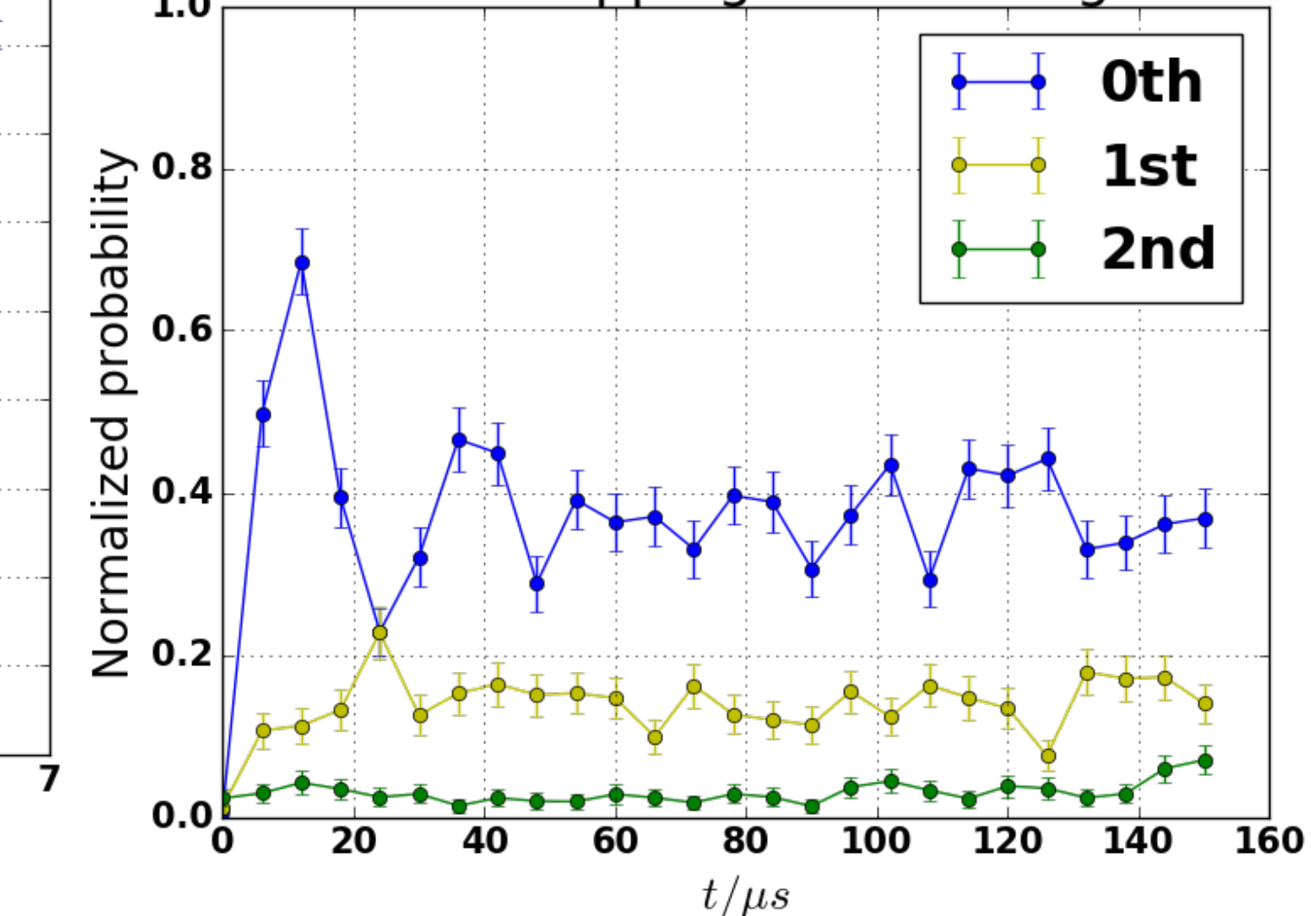
which is not the case for sodium.

For sodium, we have  $\eta_{axial} = 0.46$ ,  $\eta_{radial} = 0.35$

## Survival after adiabatic lowering of trap depth



### Rabi flopping with cooling



## Optimizing and simulating RSC sequence

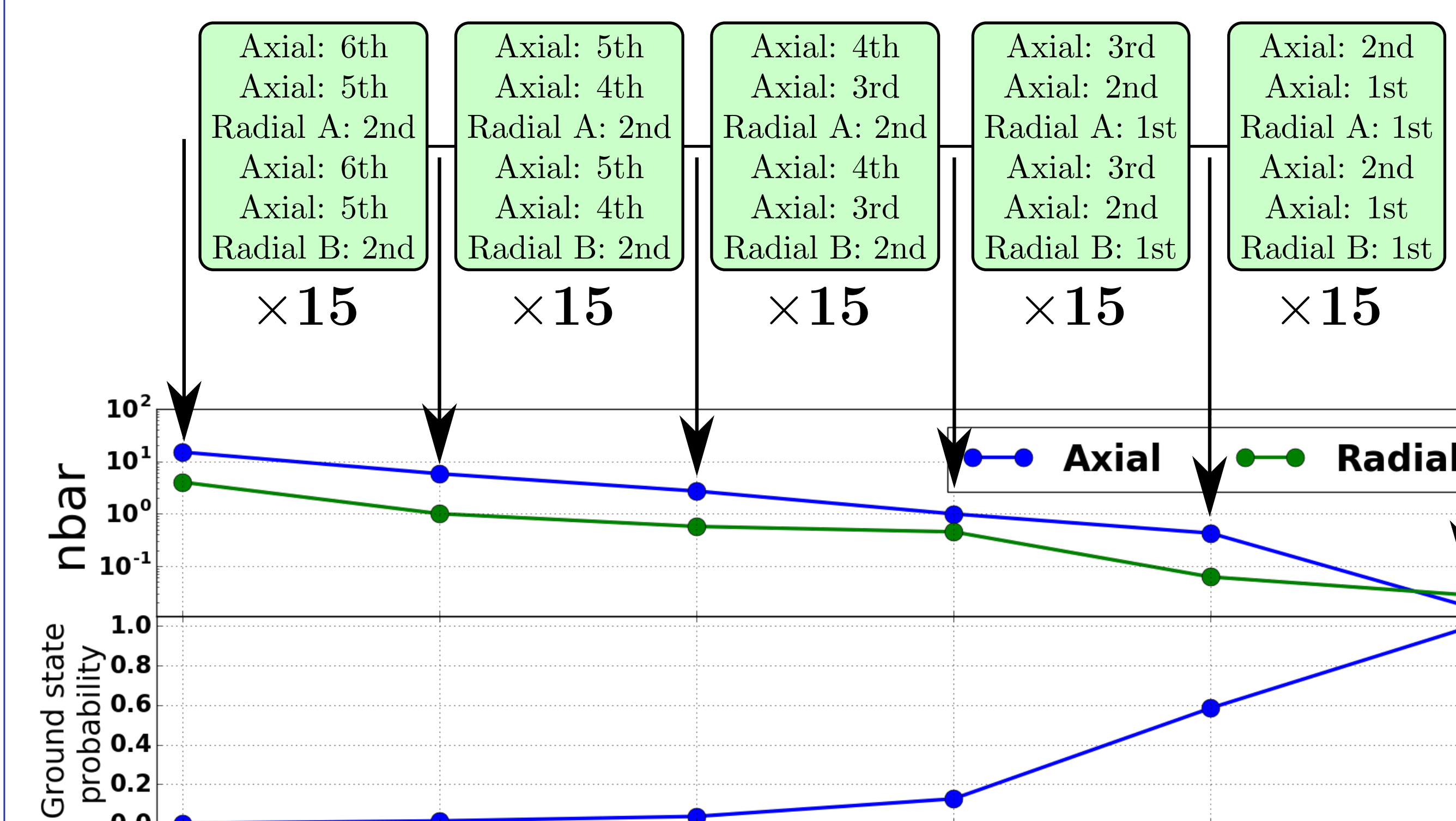
### Known challenges for RSC of Na compared to Cs (or Rb)

2. Larger  $\eta$  causing more heating during optical pumping

We use simulation to help cooling sequence optimization

### Simulation of a typical RSC sequence

The axis and order of sidebands in the cooling sequence.  
Each group of pulses is repeated the specified number of times before continuing to the next group.



Preliminary simulation shows that the high initial temperature and the high recoil aren't fundamental problems. In an ideal system, the atom can be cooled to the 3D ground state with > 99% probability with 360 Raman cooling pulses.

**Imperfections to be taken into account in the simulation:**

- » Dark state fidelity
- » Off resonance Raman coupling
- » Off resonance scattering from the Raman beams