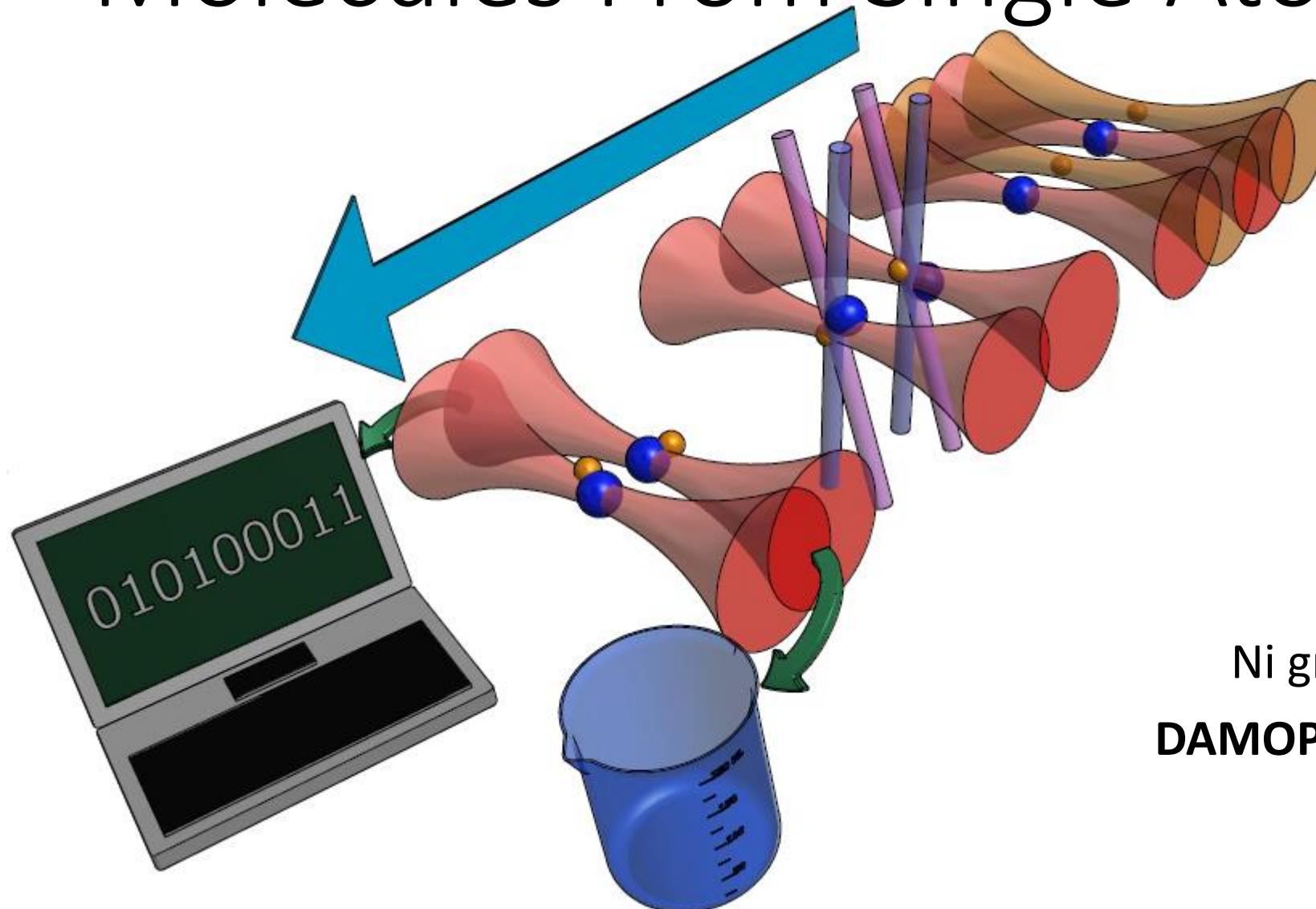


# Assembling Ultracold Polar Molecules From Single Atoms



Lee Liu

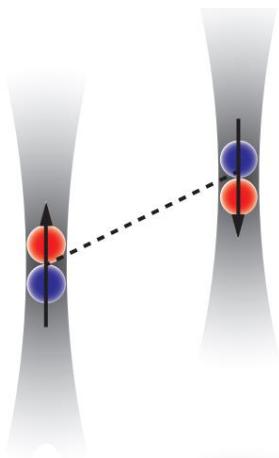
Ni group, CUA Harvard

**DAMOP May 23-27, 2016**

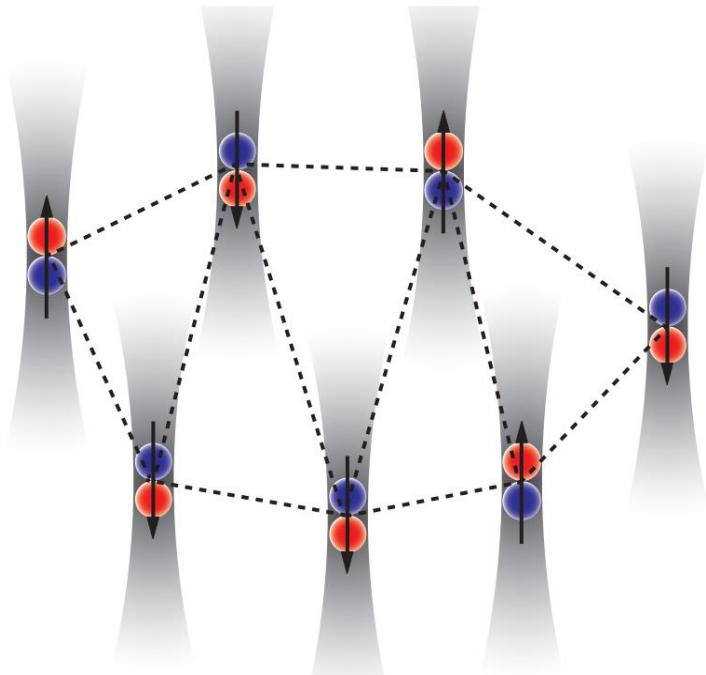
# Molecules with Individual Control



# Molecules with Individual Control



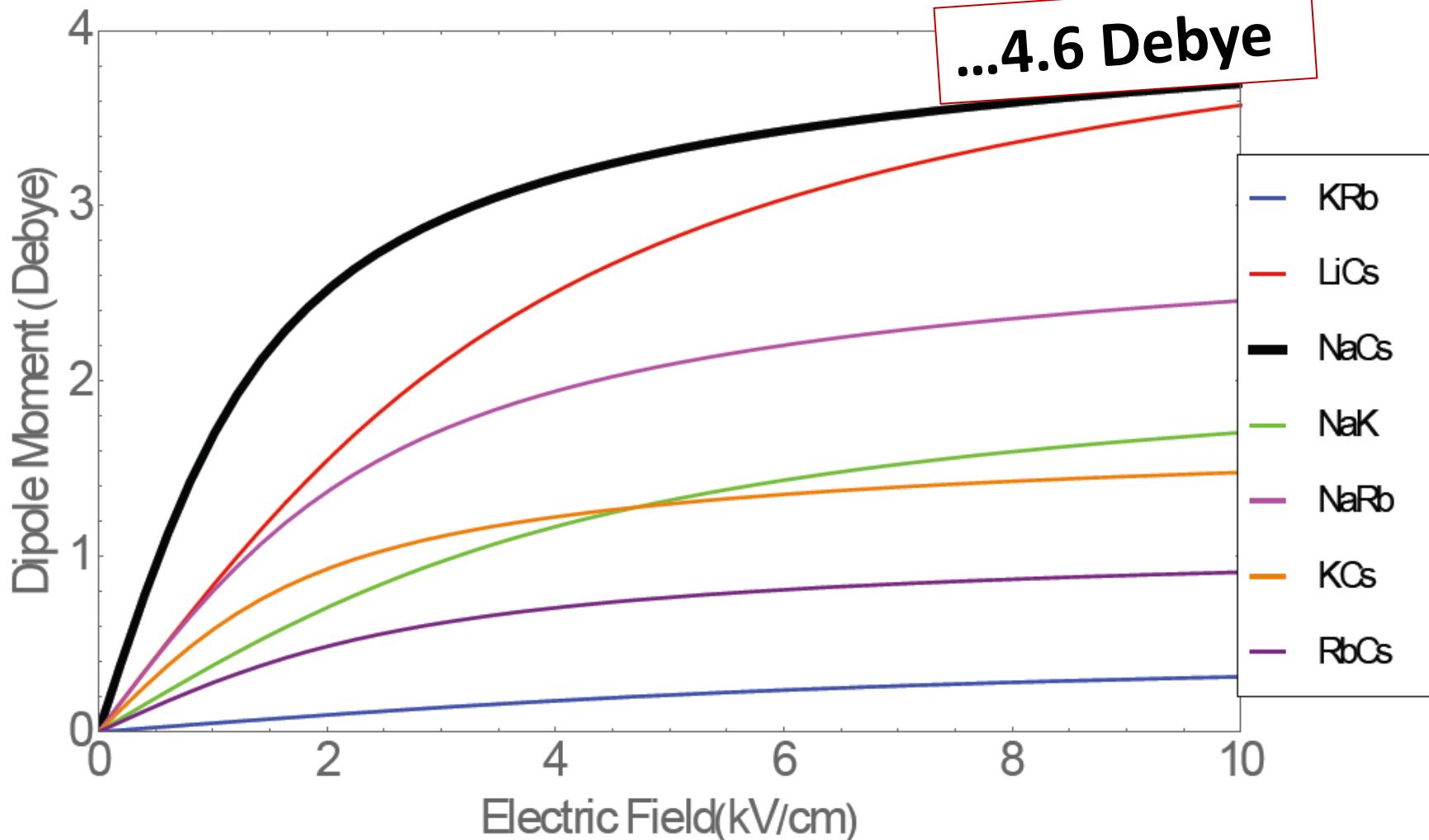
# Molecules with Individual Control



- Dipole-Dipole Interaction
  - Long-range
  - Anisotropic
  - Highly tunable
- Long-lived states
- Our approach will yield full control over every molecule

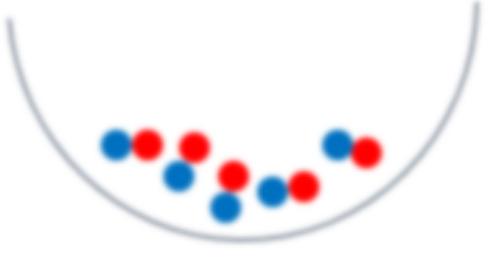
# Sodium Cesium (NaCs)

NaCs Lab-Frame Dipole Moment vs. E-Field



# Our Approach

## Quantum Gas



See, eg.

KRb (2008)

K –K Ni,...,J Ye,  
Science **322**, 231

RbCs (2014)

T Takekoshi,...,H -C Nägerl,  
PRL **113**, 205301

PK Molony,...,SL Cornish,  
PRL **113**, 255301

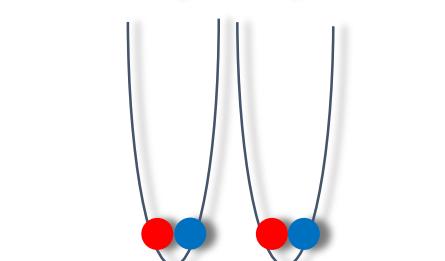
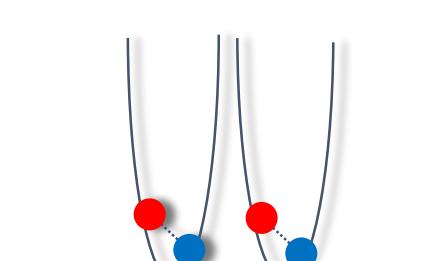
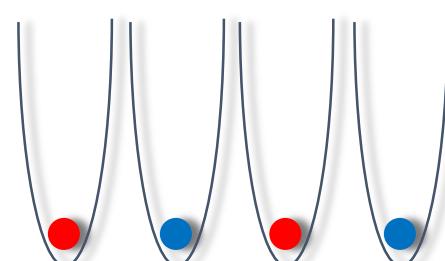
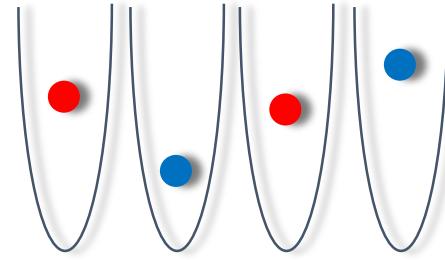
NaK (2015)

JW Park,...,MW Zwierlein,  
PRL **114**, 205302

NaRb (2016)

M Guo,...,D Wang,  
PRL **116**, 205303

## Single atom



Trap

Cool

Weakly bound  
molecules

Ground state  
molecules

# Our Approach

## Quantum Gas



See, e.g.

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K –K Ni,...,J Ye,  
Science **322**, 231

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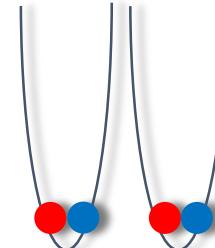
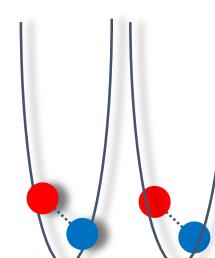
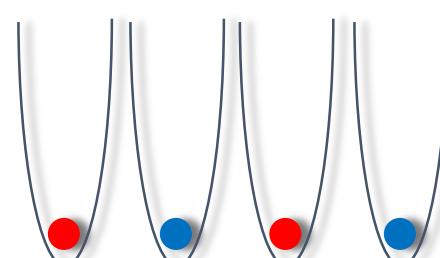
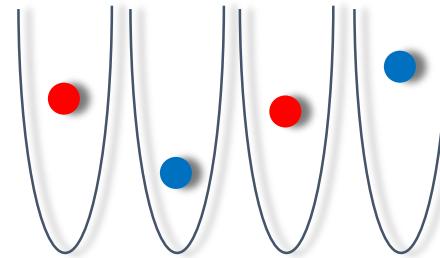
## Single atom

Trap ✓✓

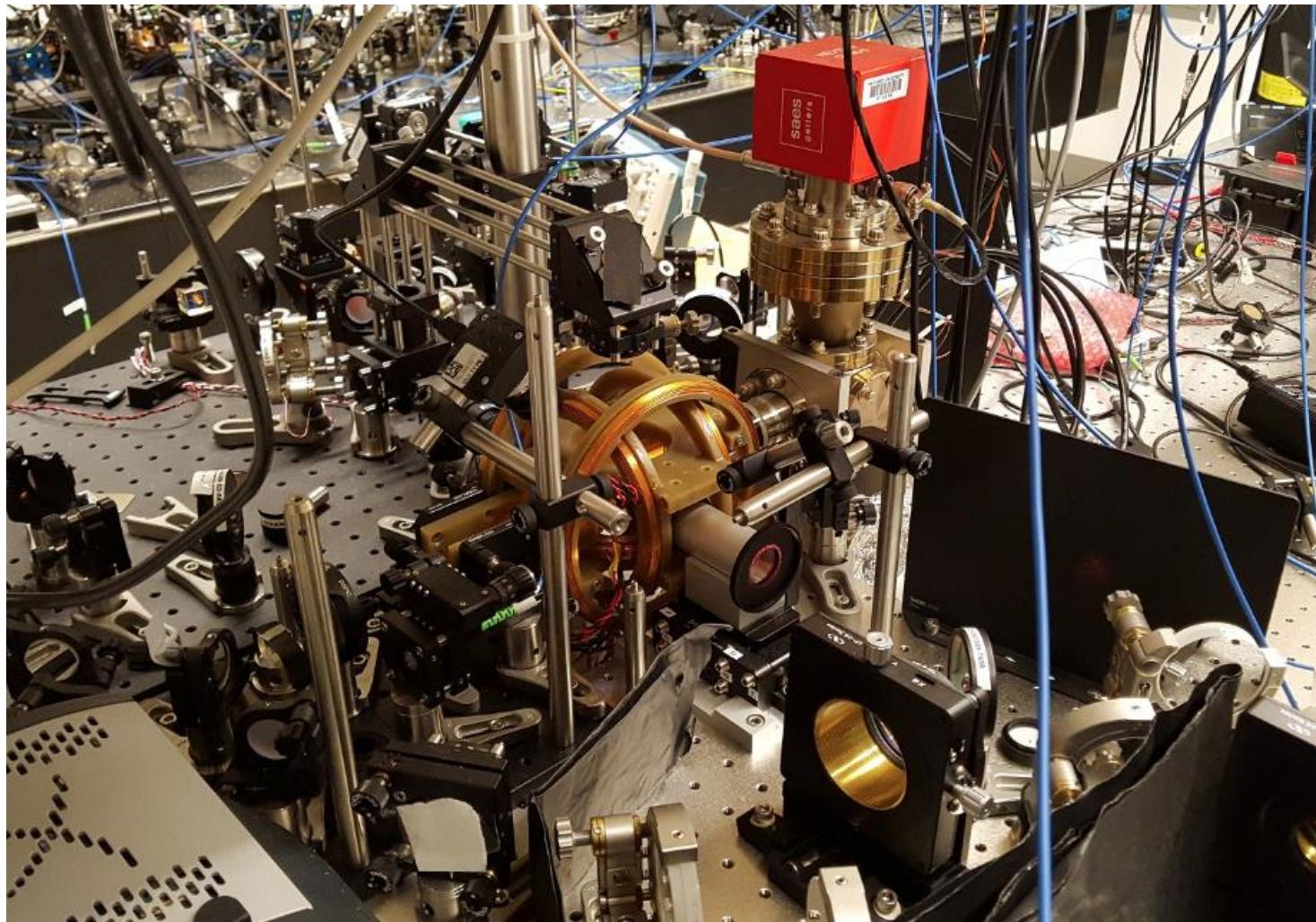
Cool ✓

Weakly bound  
molecules

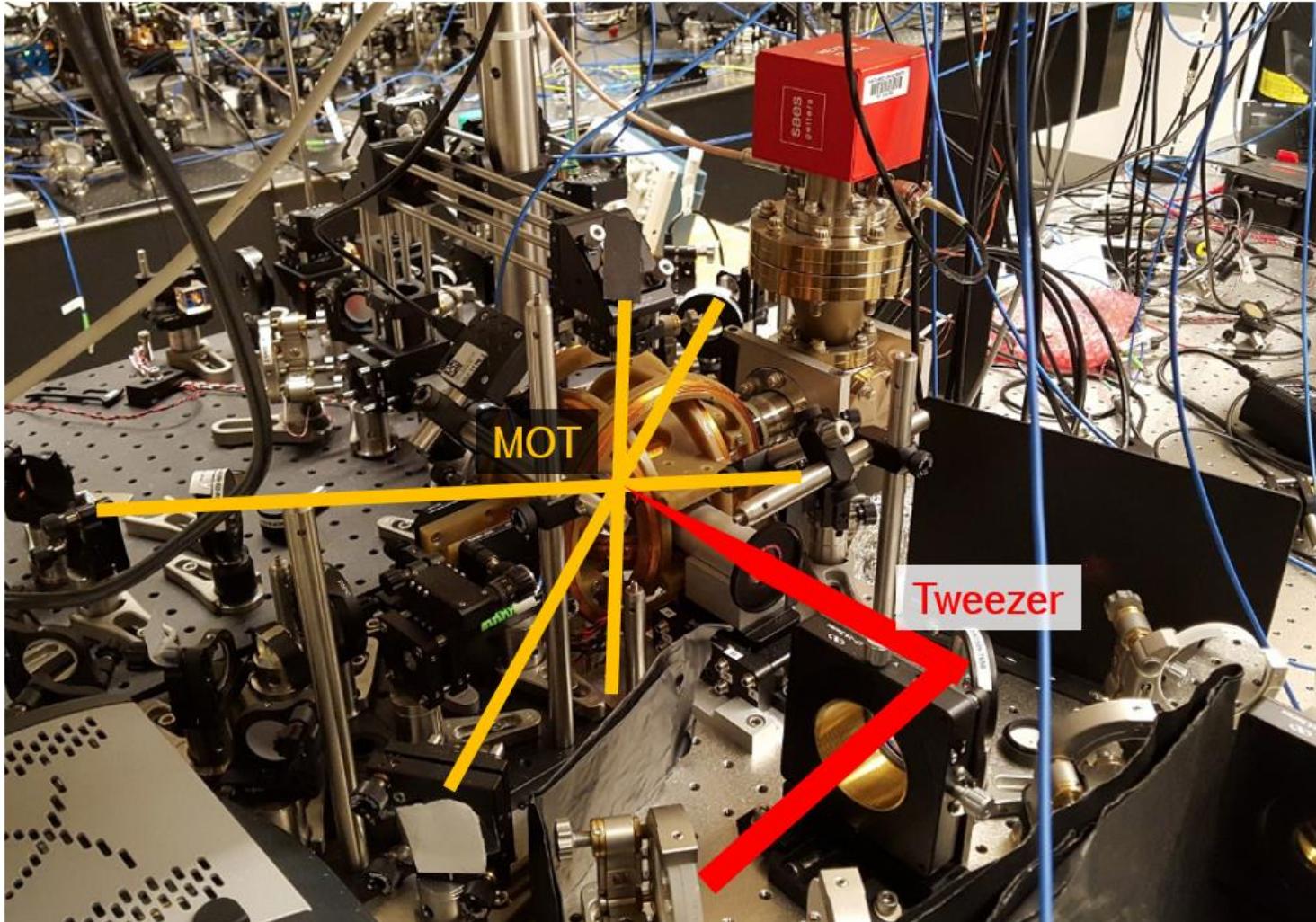
Ground state  
molecules



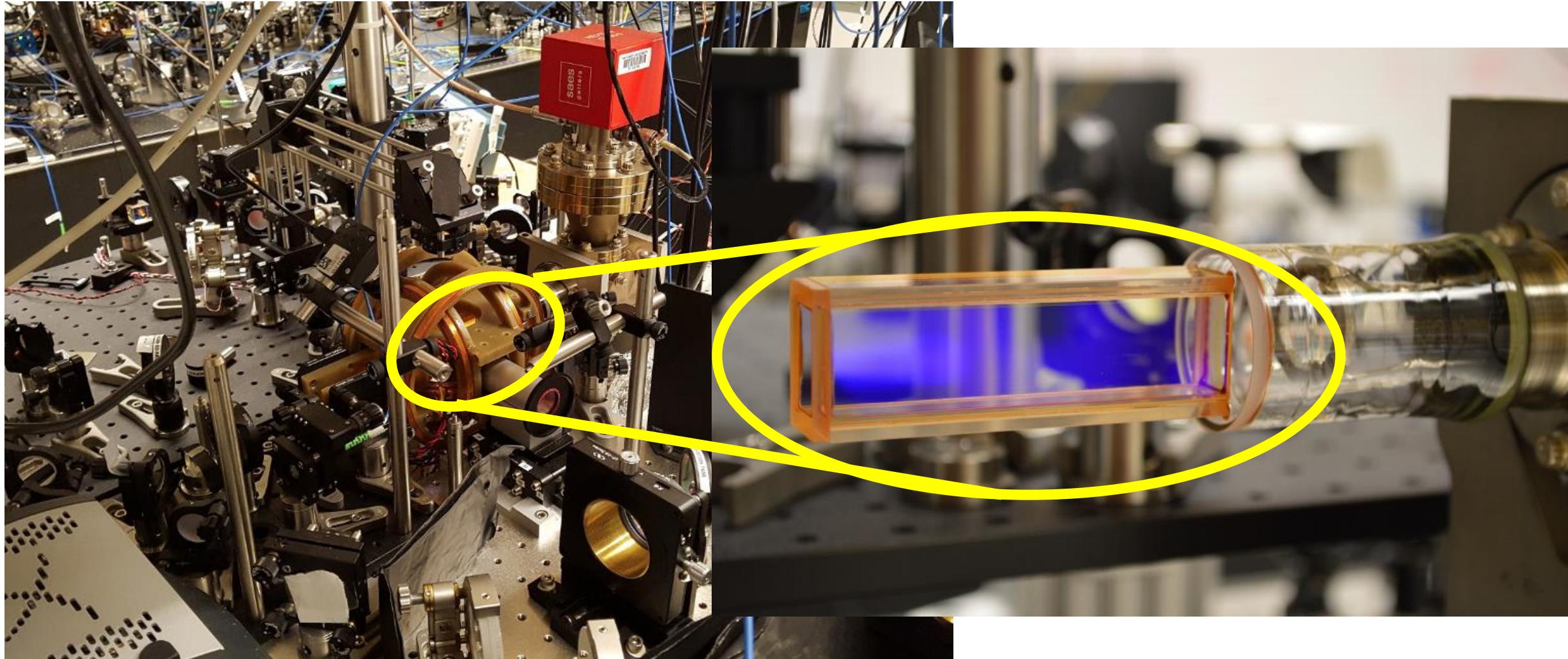
# Apparatus

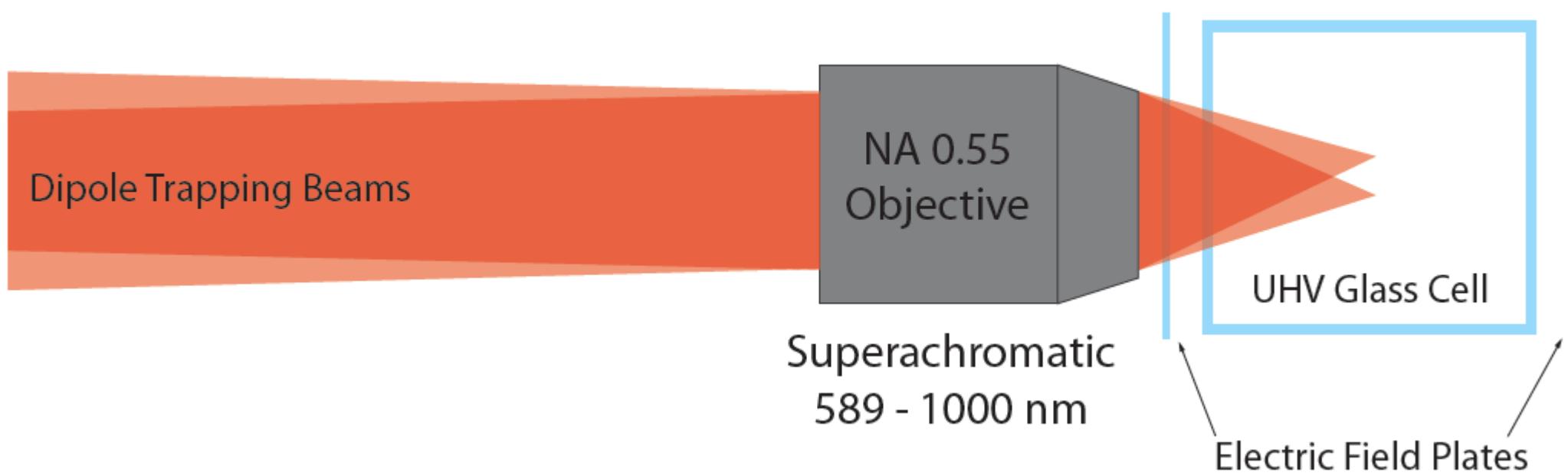


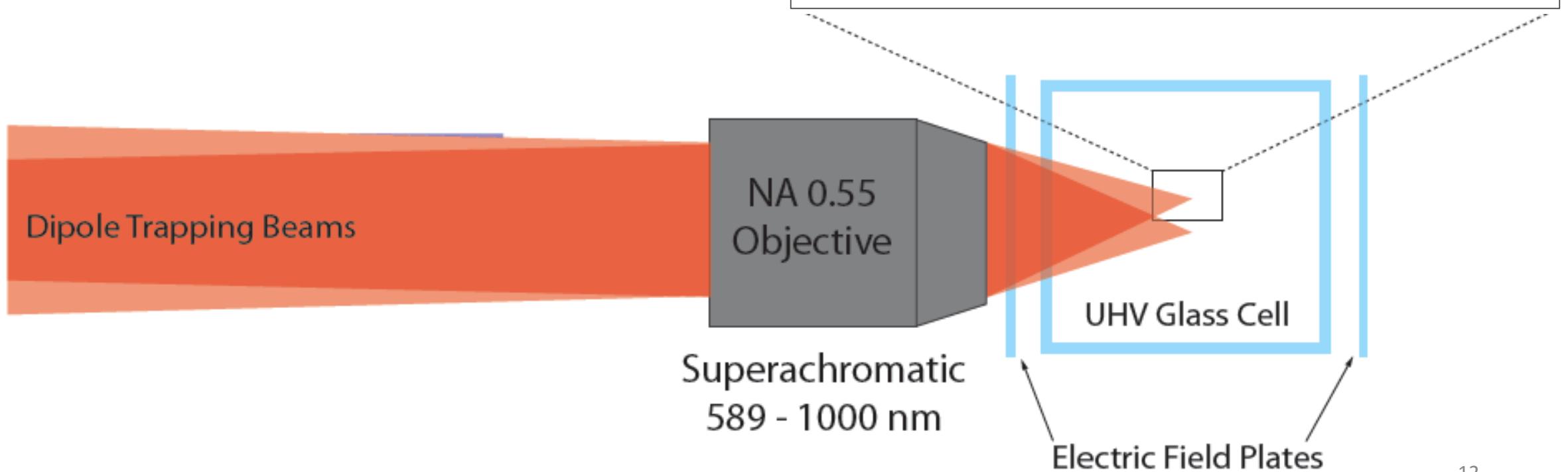
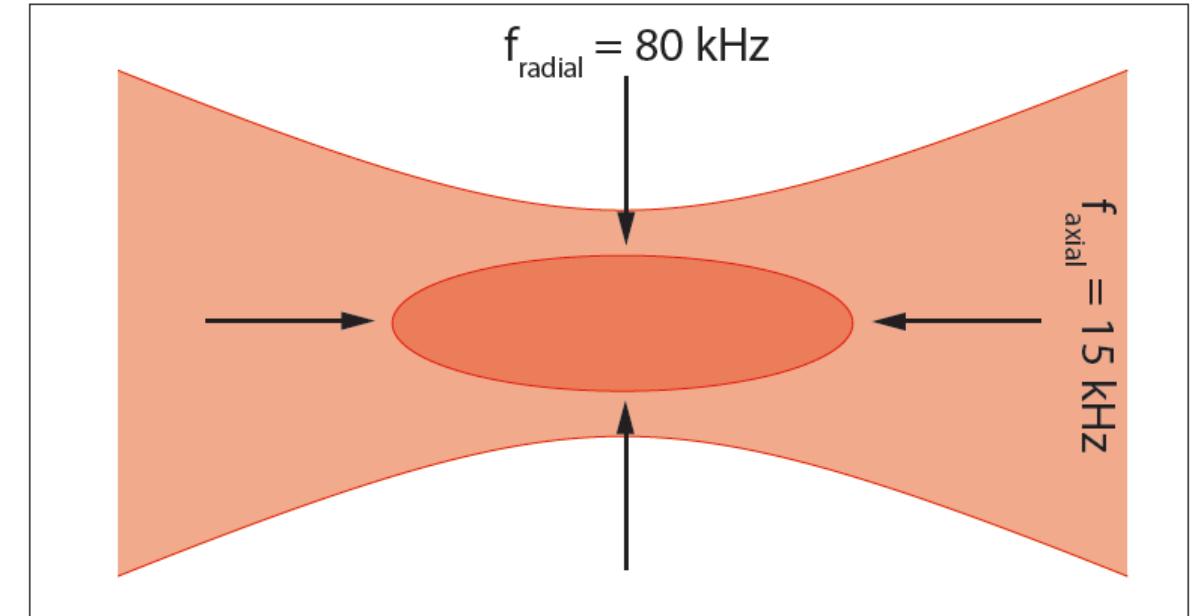
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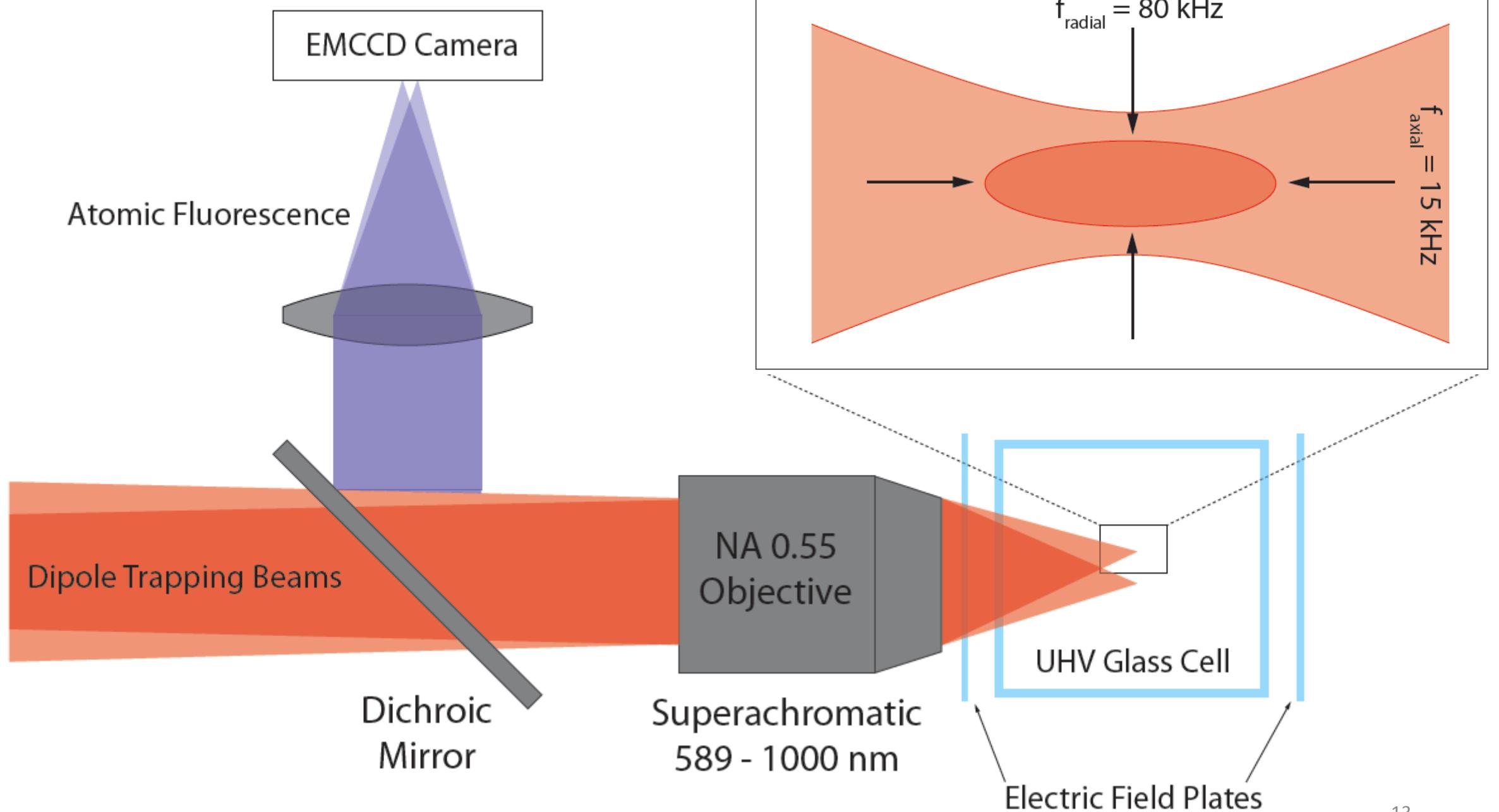


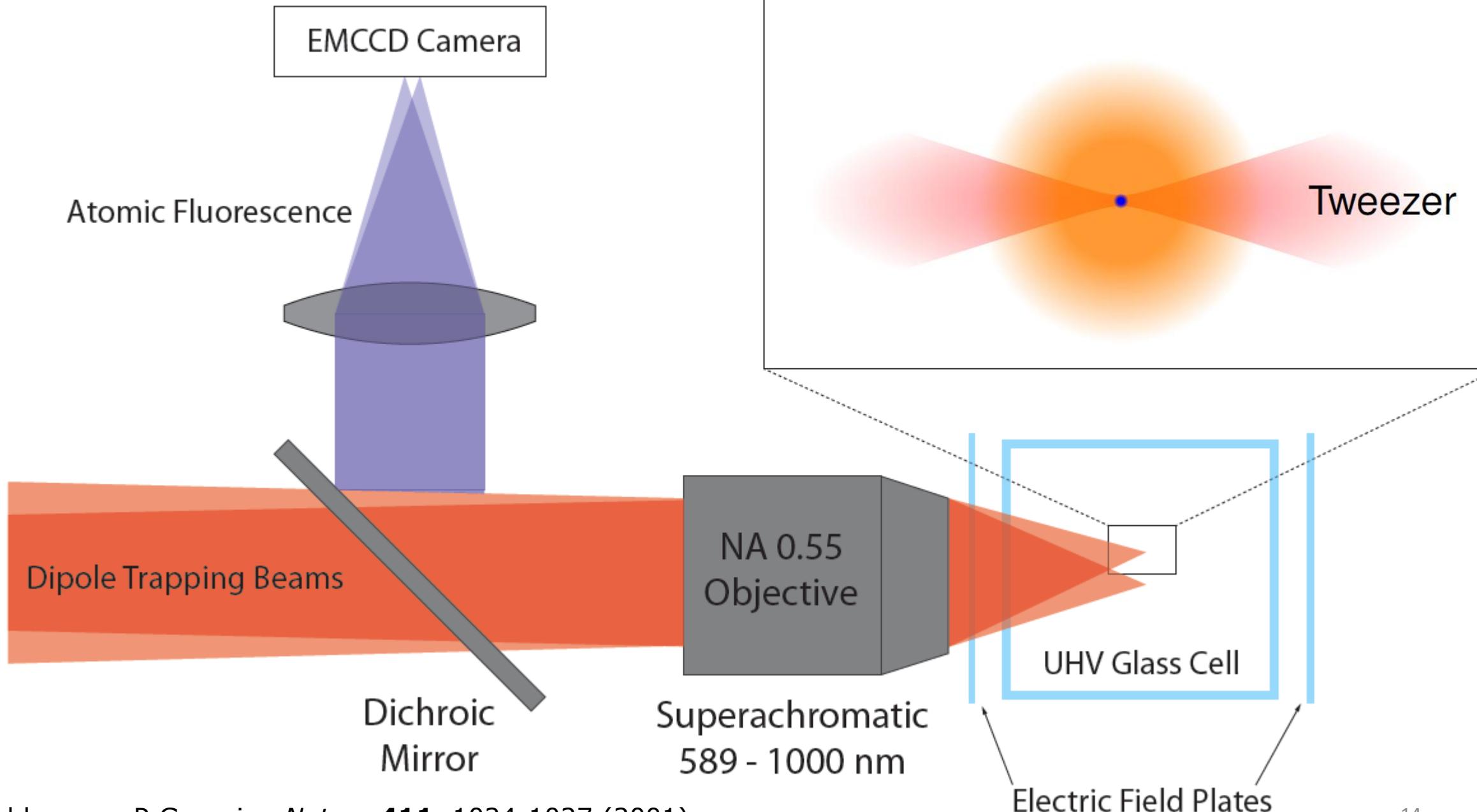
# Apparatus

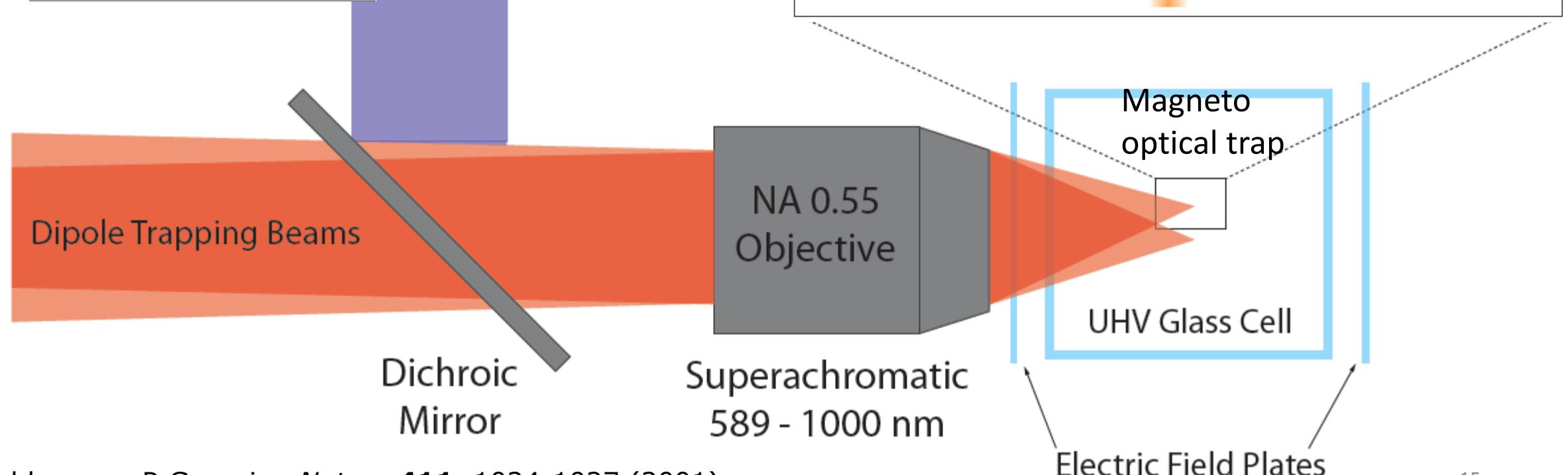
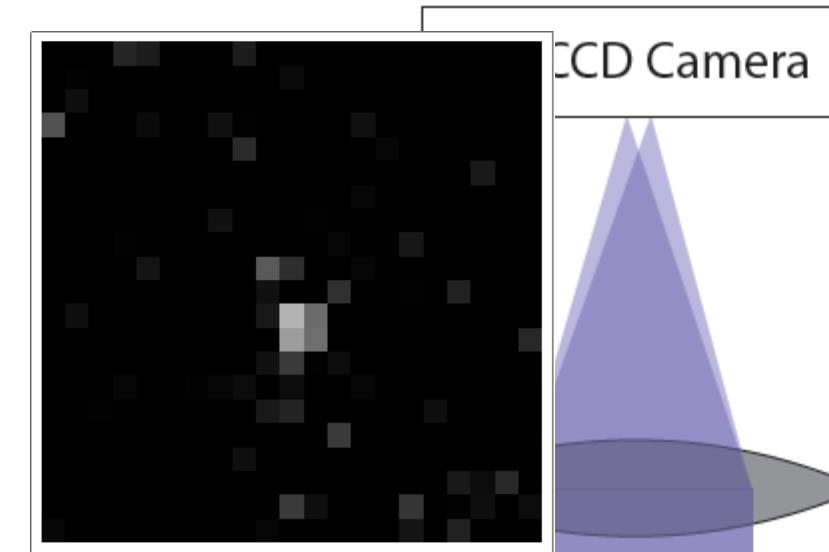


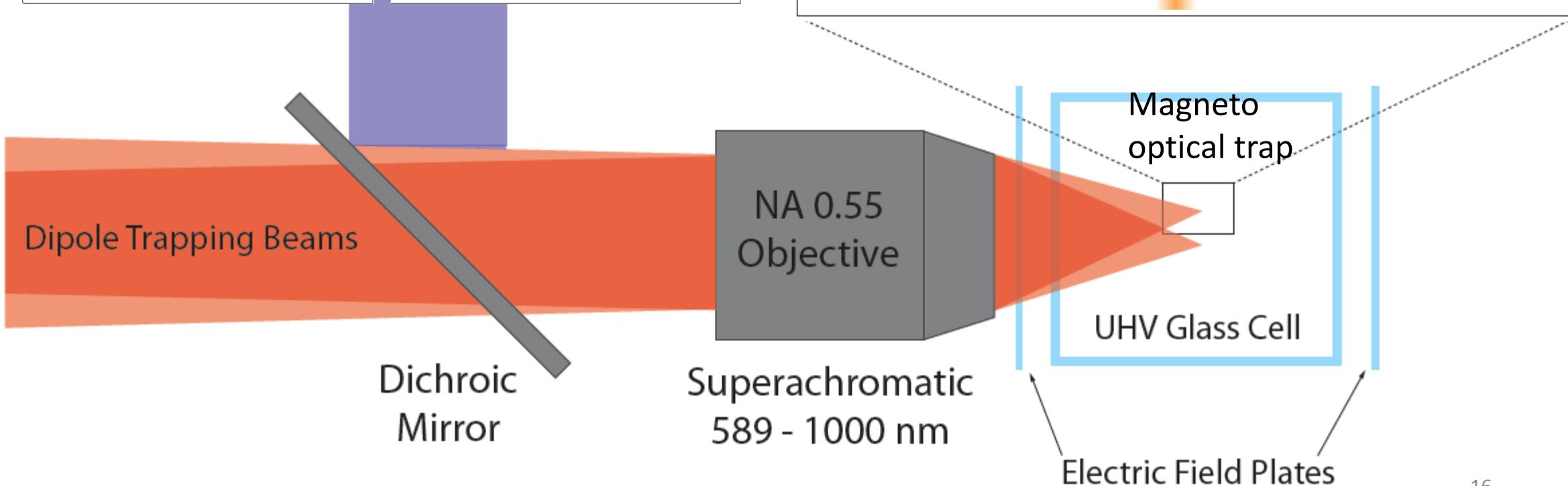
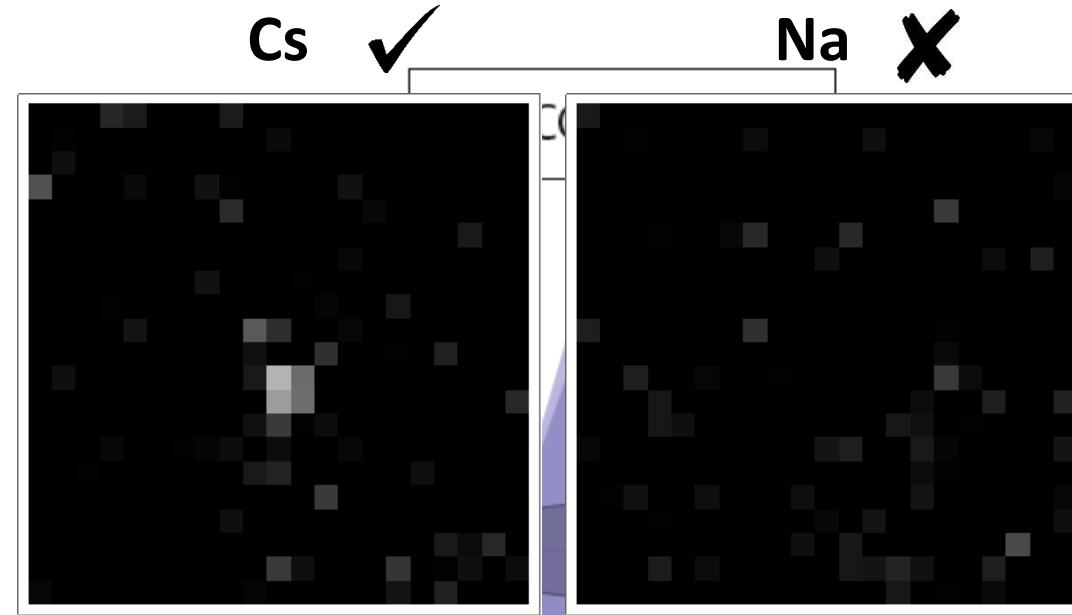


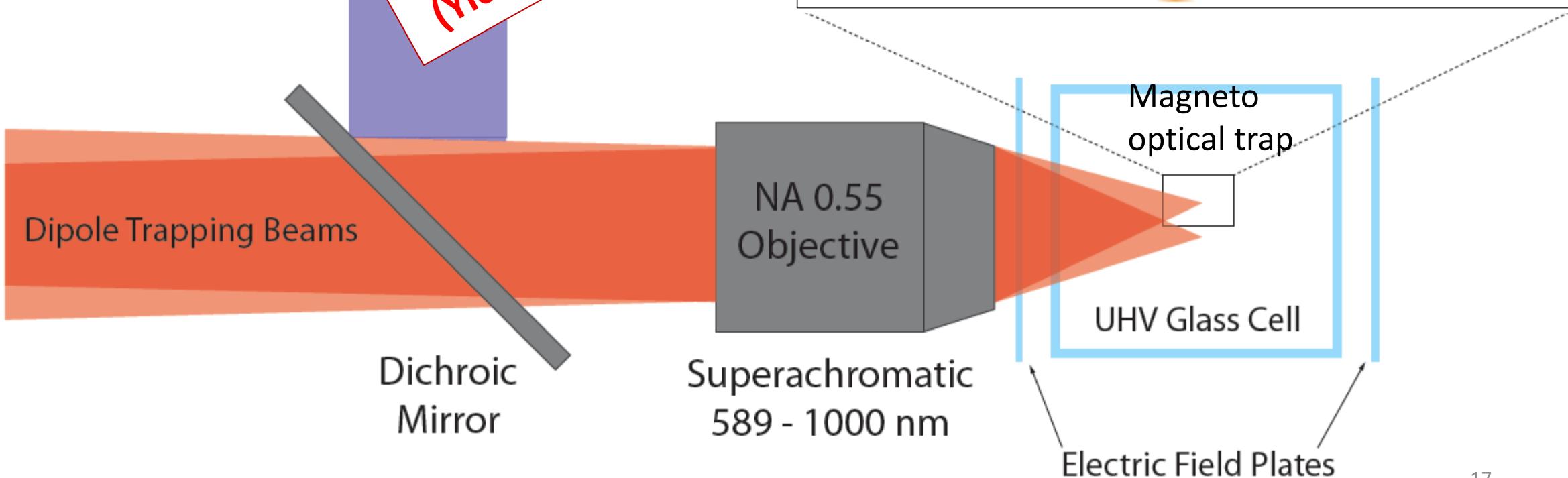
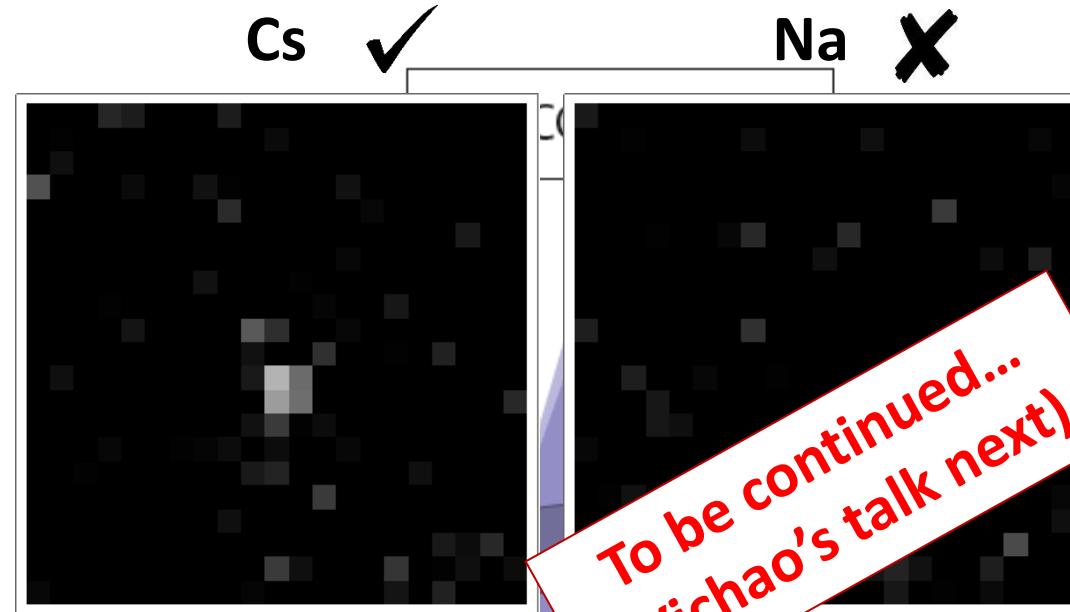












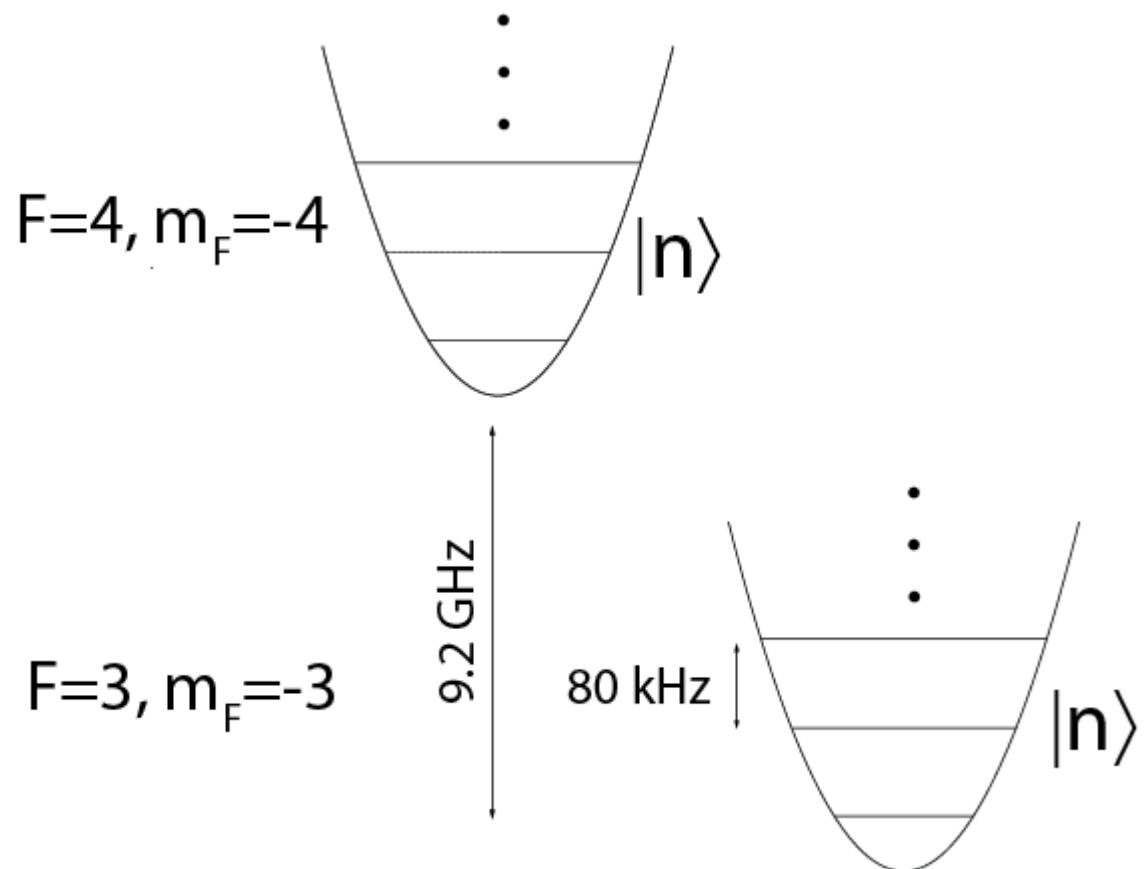
# Cooling to Motional Ground State (Cesium)

In neutral atom tweezers:

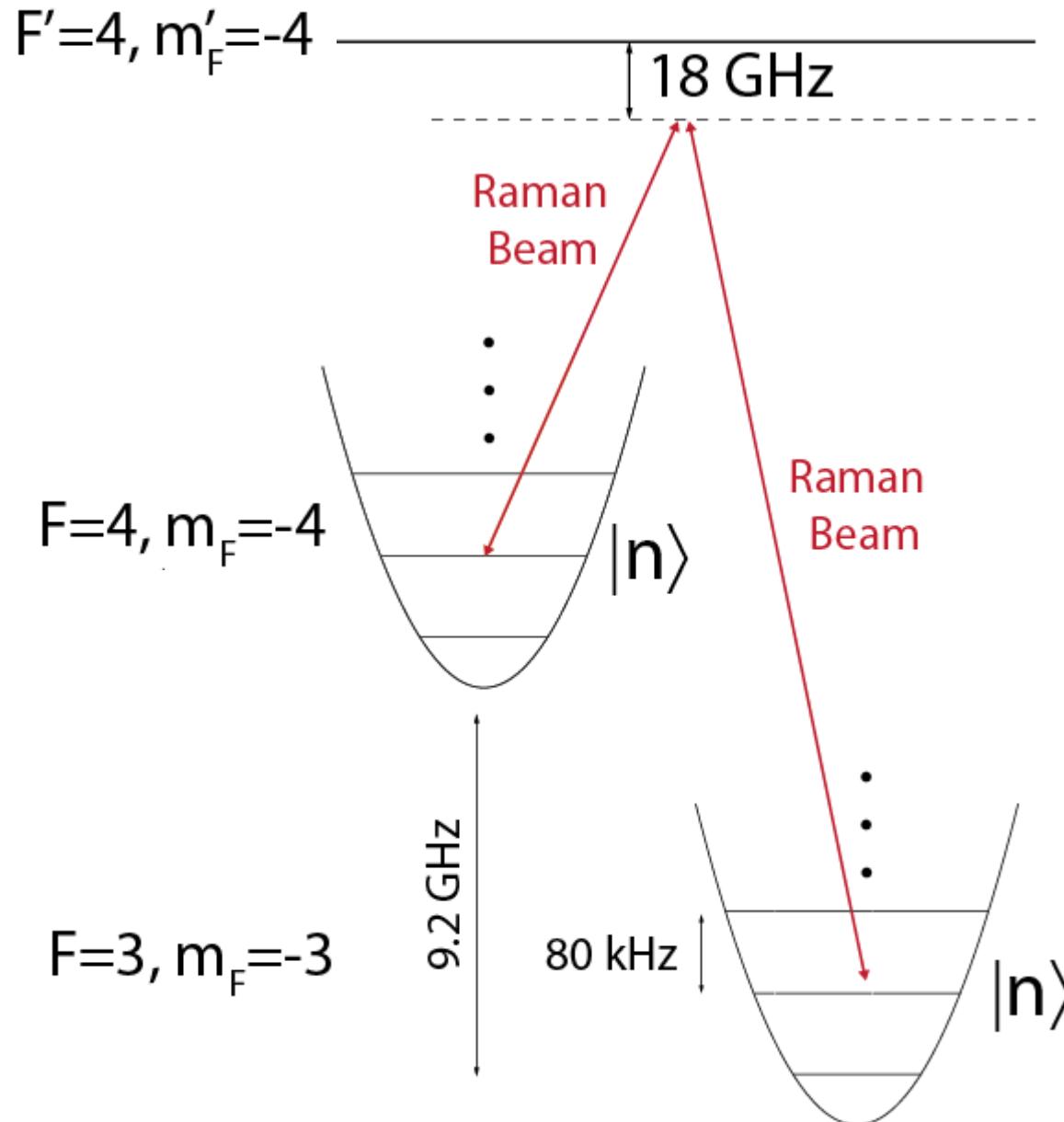
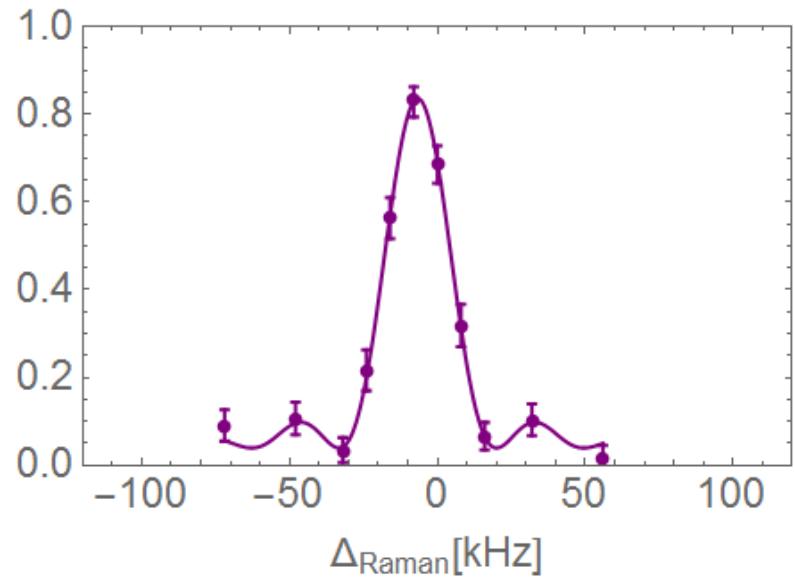
AM Kaufman,...,CA Regal PRX **2**, 041014 (2012)

JD Thompson,...,MD Lukin PRL **110**, 133001 (2013)

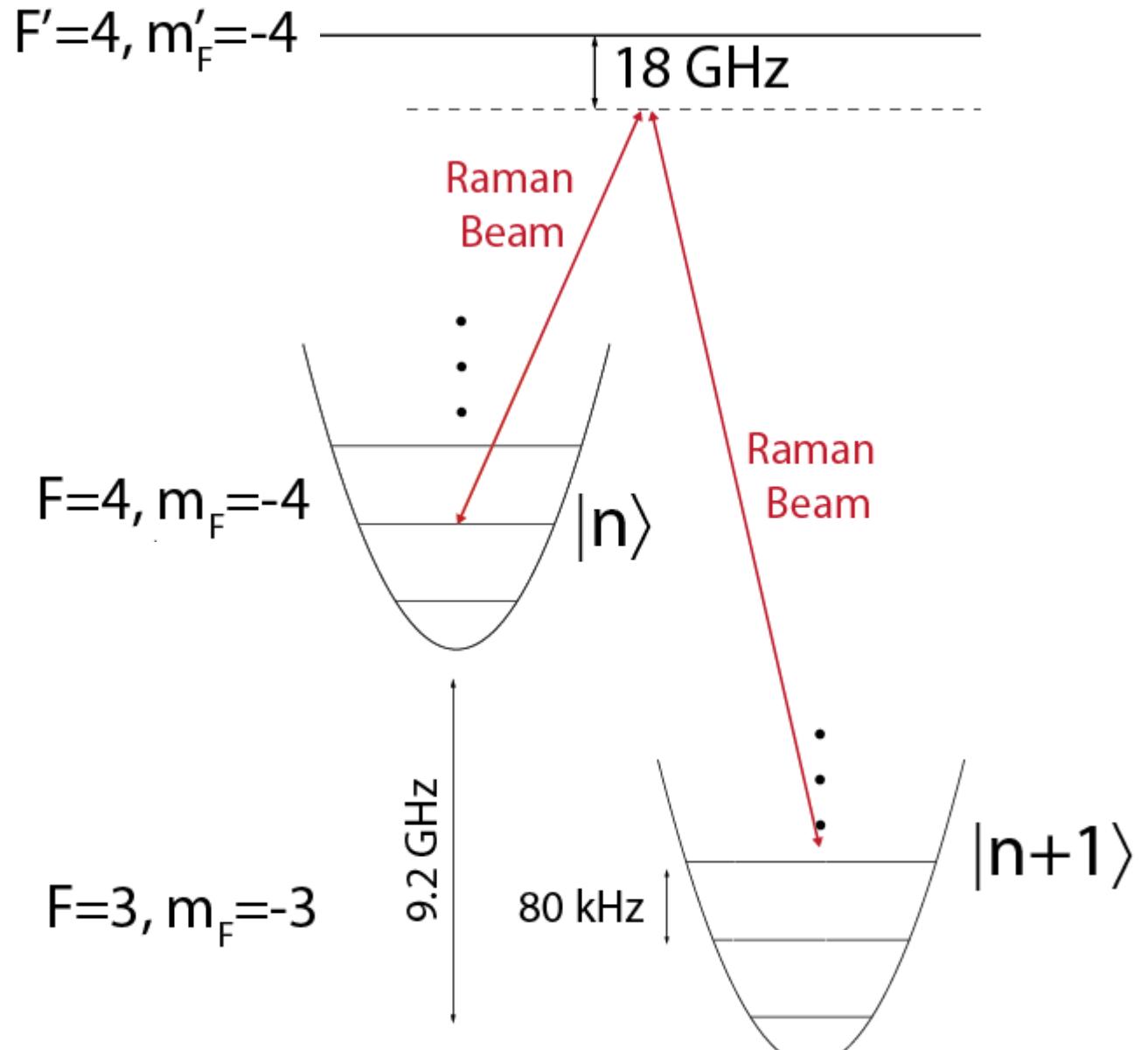
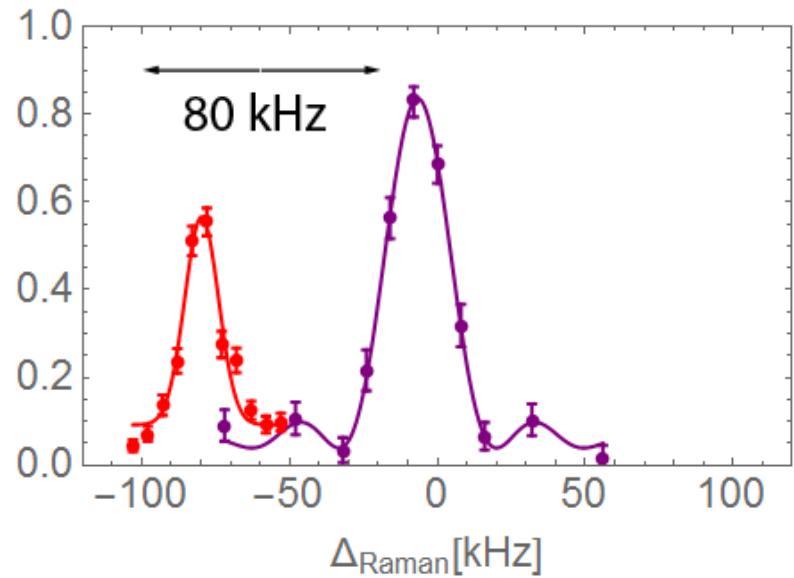
# Raman Sideband Spectroscopy



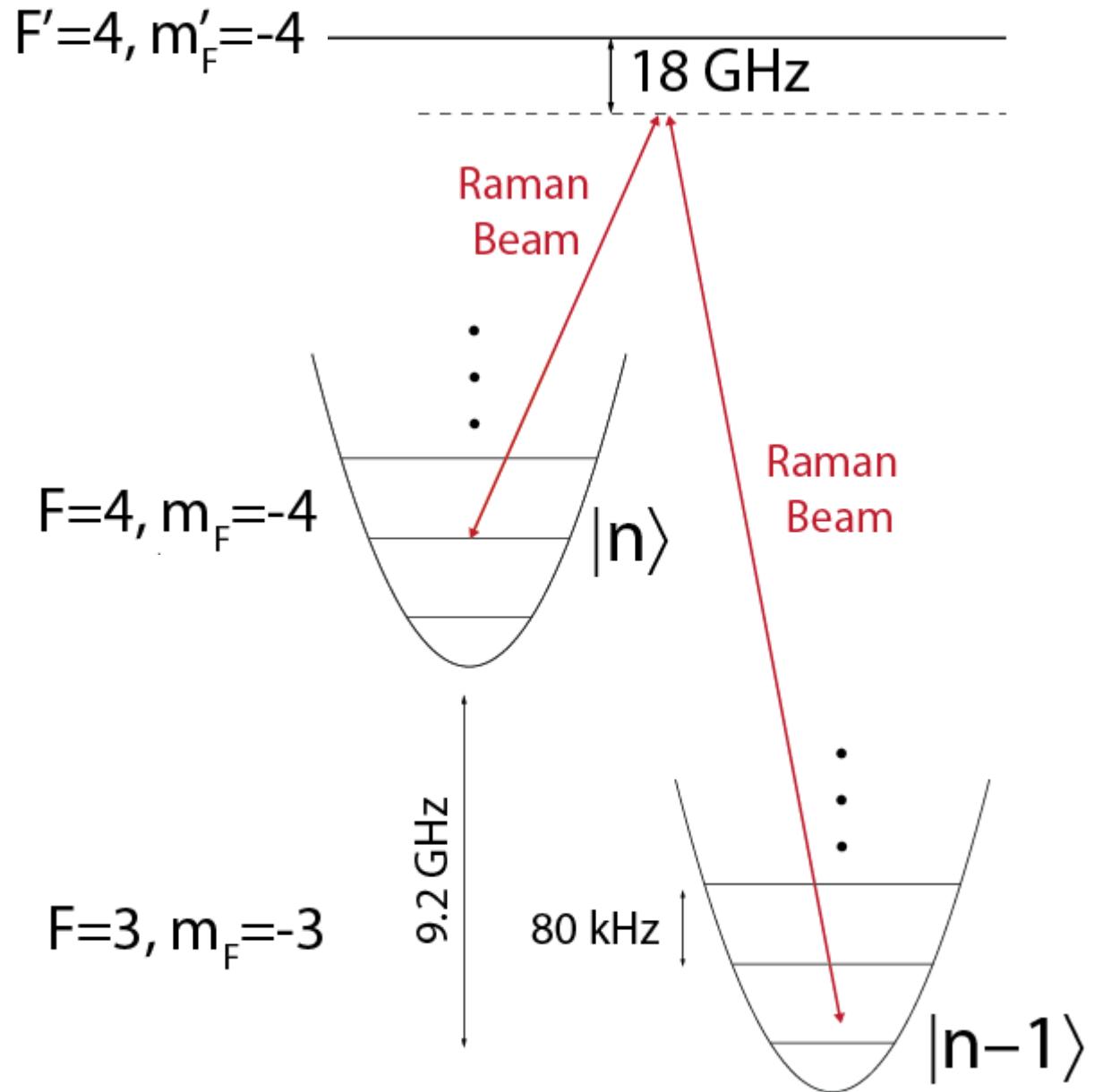
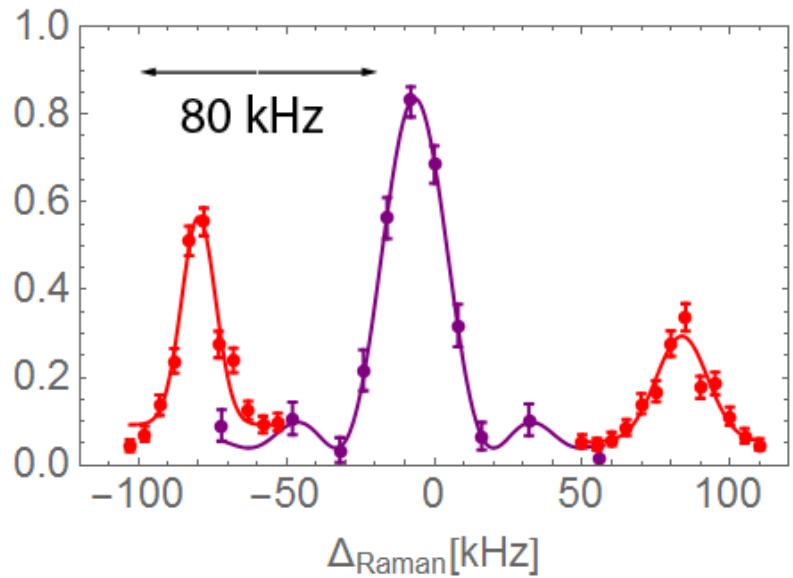
# Raman Sideband Spectroscopy



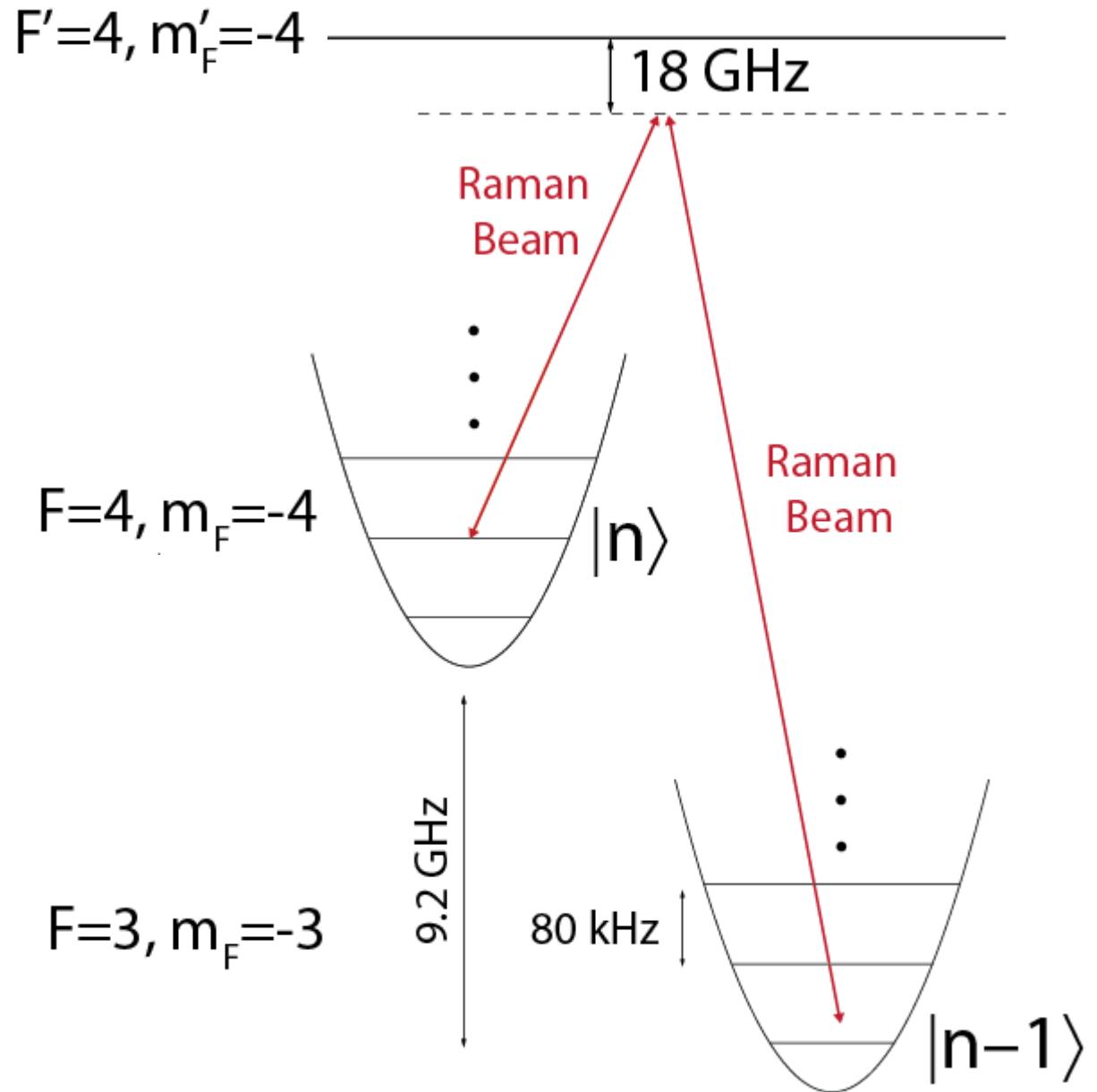
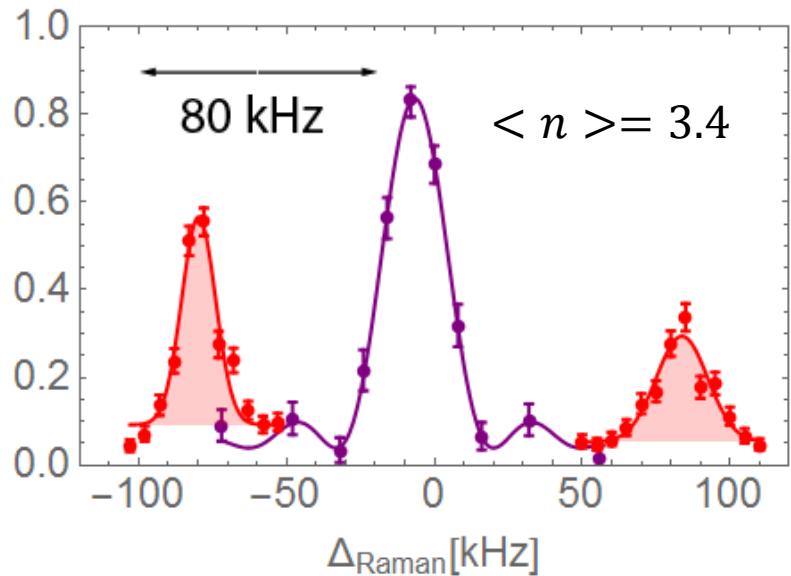
# Raman Sideband Spectroscopy



# Raman Sideband Spectroscopy



# Raman Sideband Spectroscopy

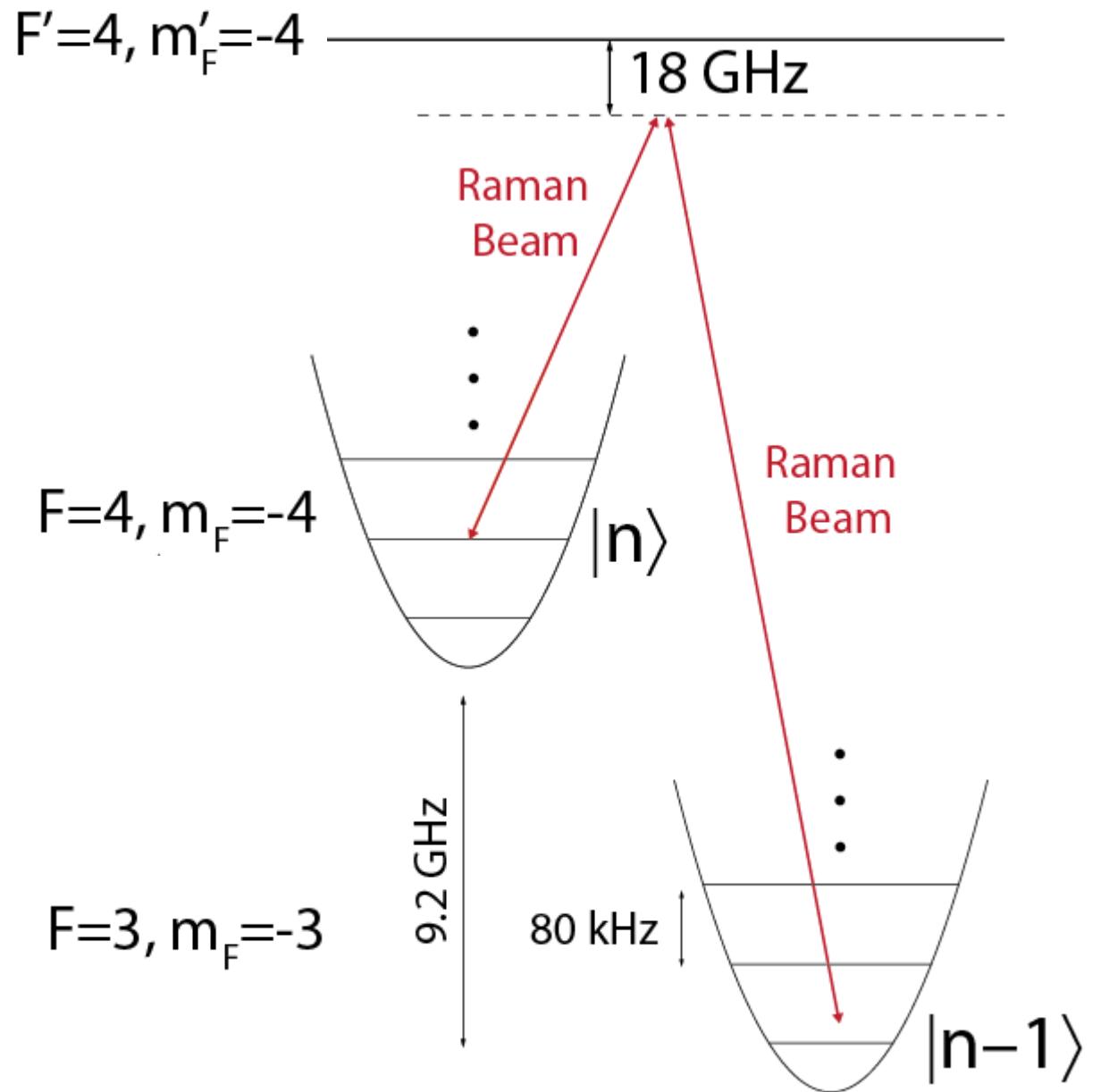
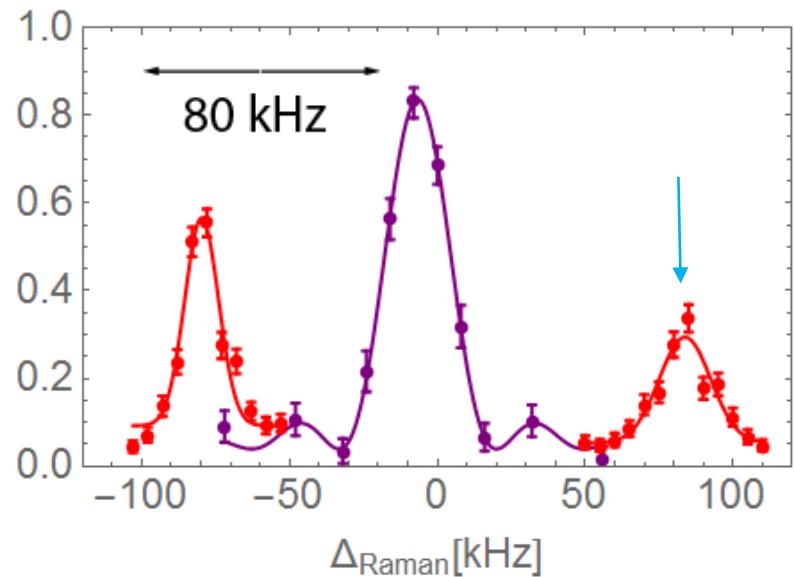


# Raman Sideband Cooling

In neutral atom tweezers:

AM Kaufman,...,CA Regal PRX **2**, 041014 (2012)

JD Thompson,...,MD Lukin PRL **110**, 133001 (2013)

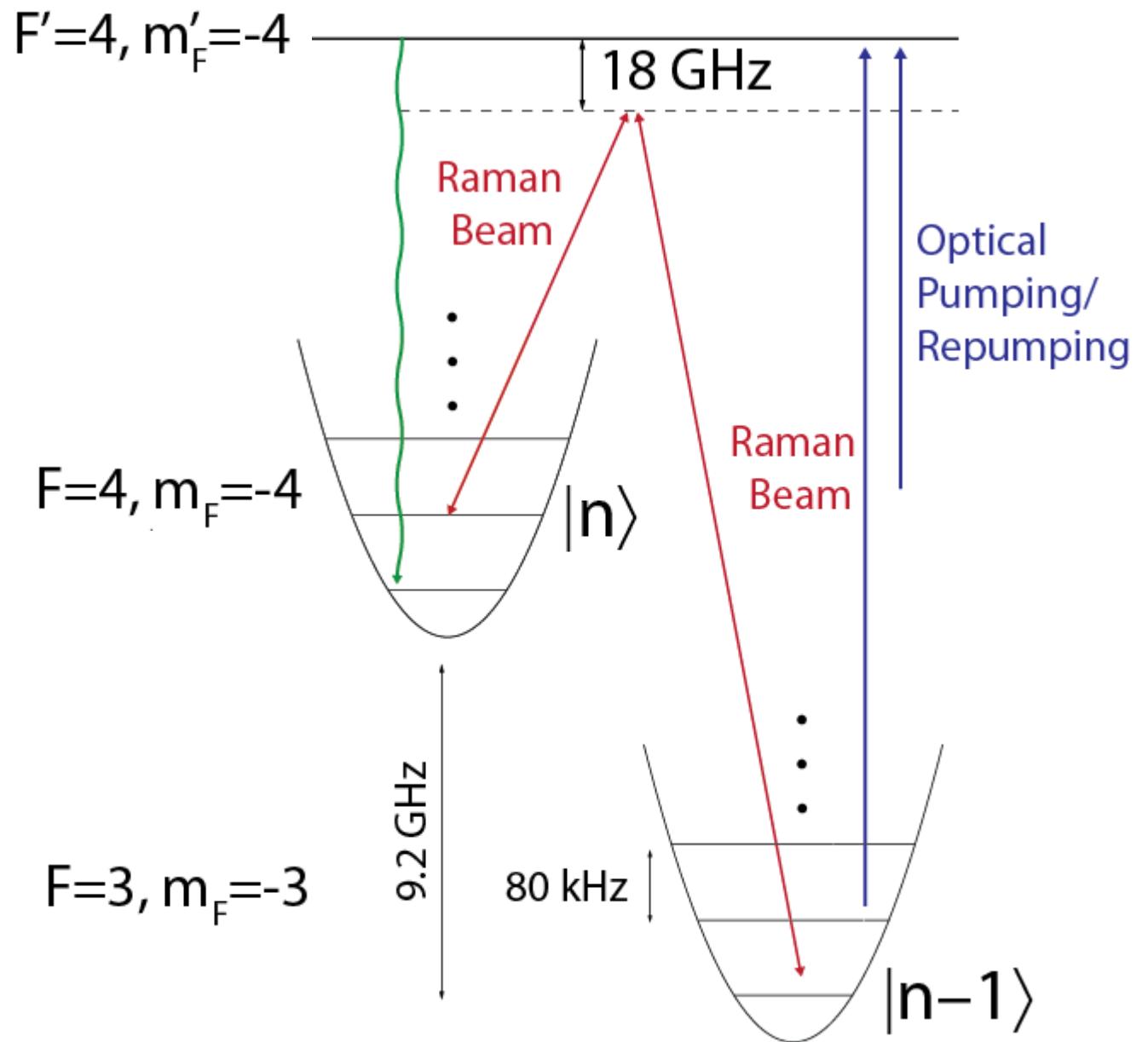
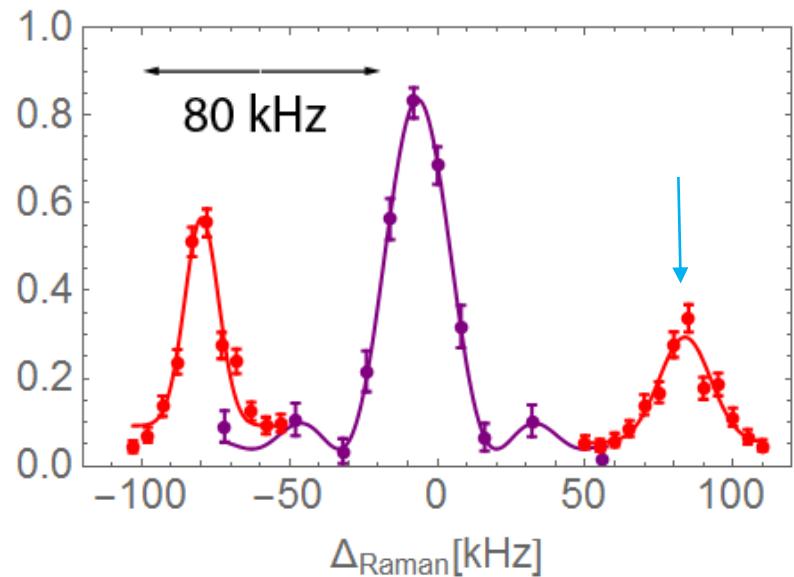


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In neutral atom tweezers:

AM Kaufman,...,CA Regal PRX **2**, 041014 (2012)

JD Thompson,...,MD Lukin PRL **110**, 133001 (2013)

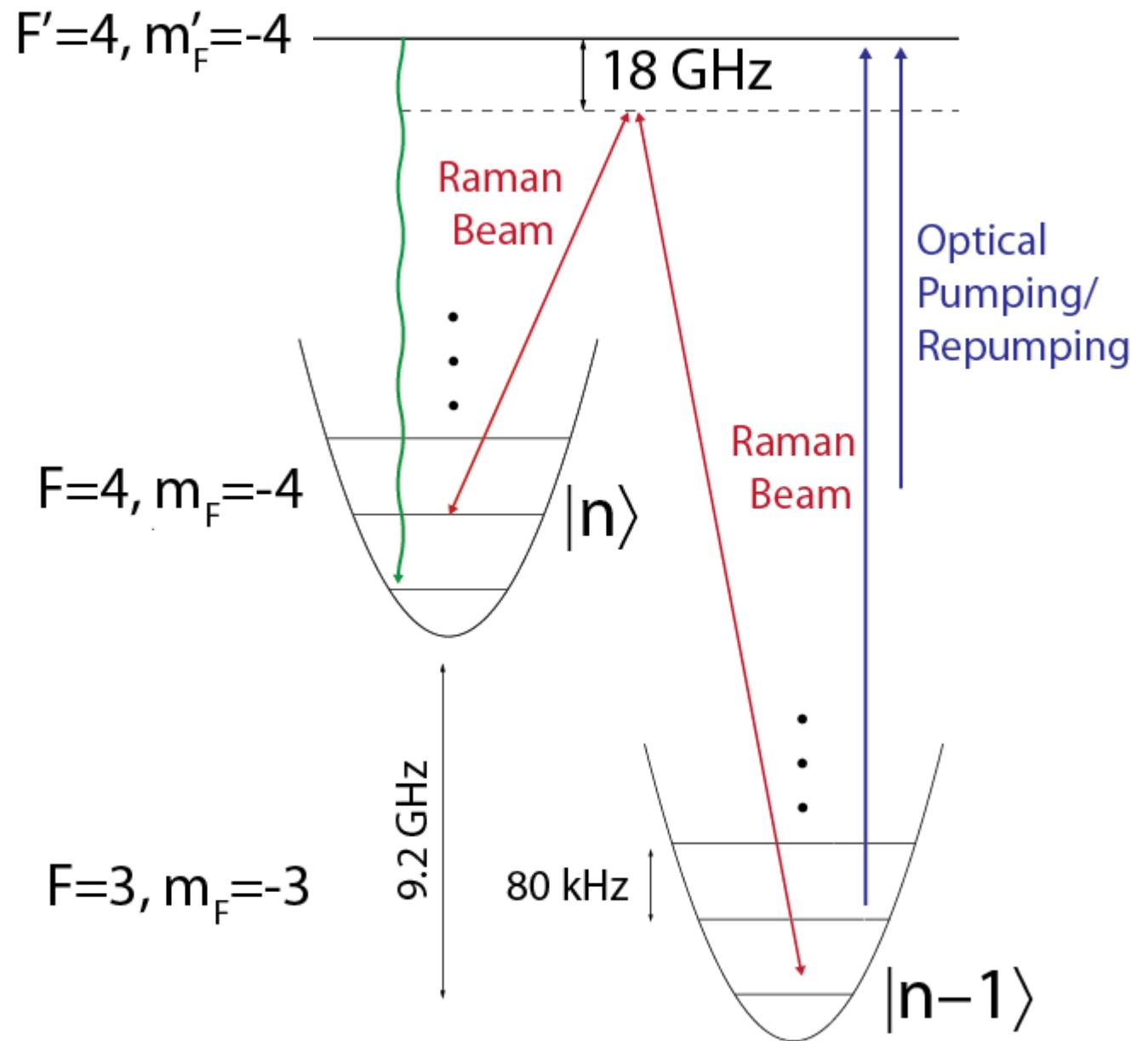
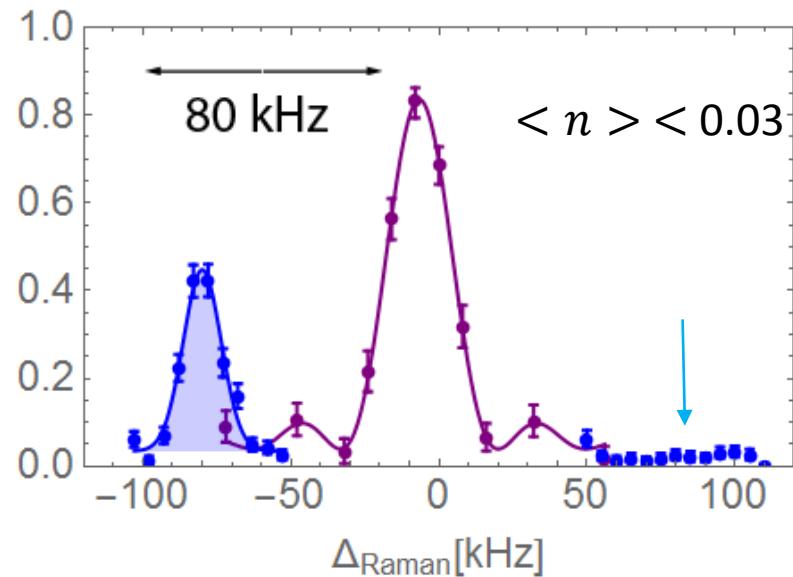


# Raman Sideband Cooling

In neutral atom tweezers:

AM Kaufman,...,CA Regal PRX **2**, 041014 (2012)

JD Thompson,...,MD Lukin PRL **110**, 133001 (2013)

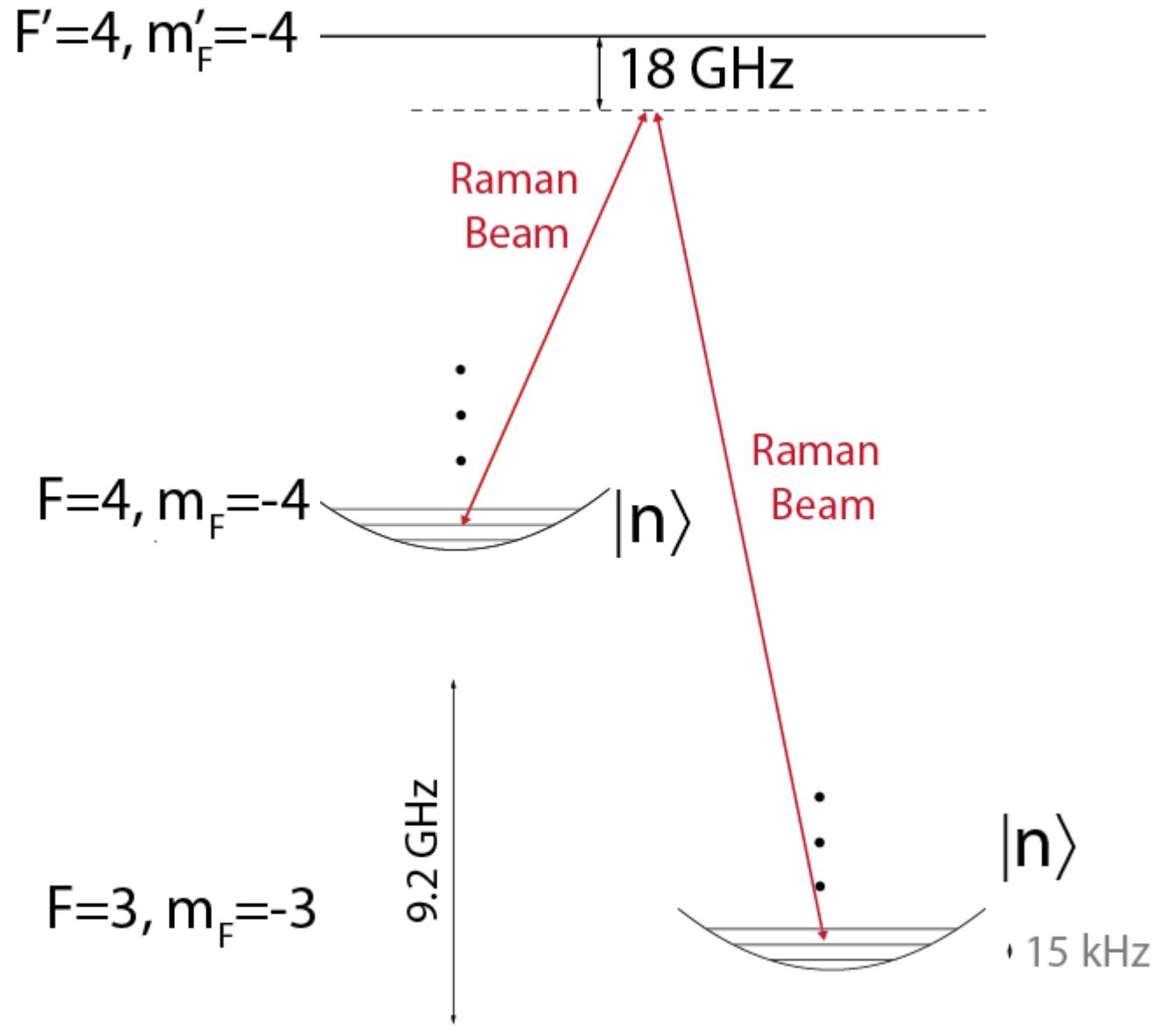
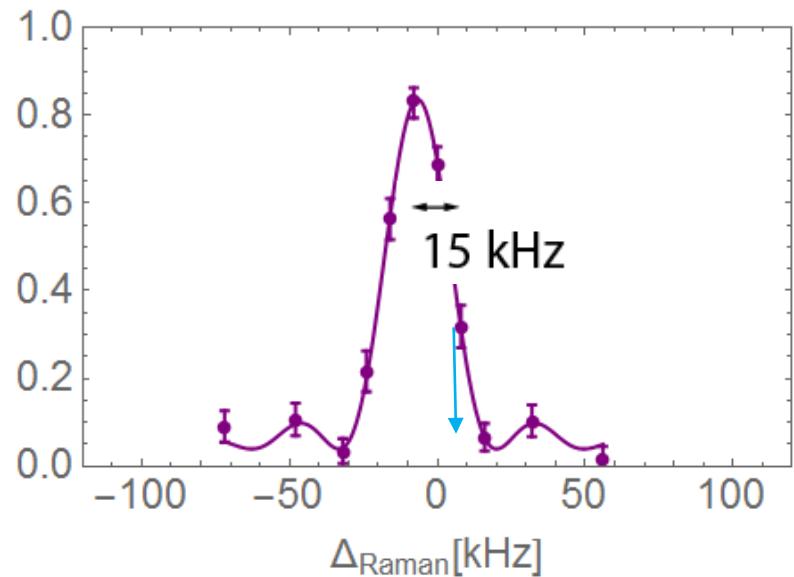


# Raman Sideband Cooling (Axial)

In neutral atom tweezers:

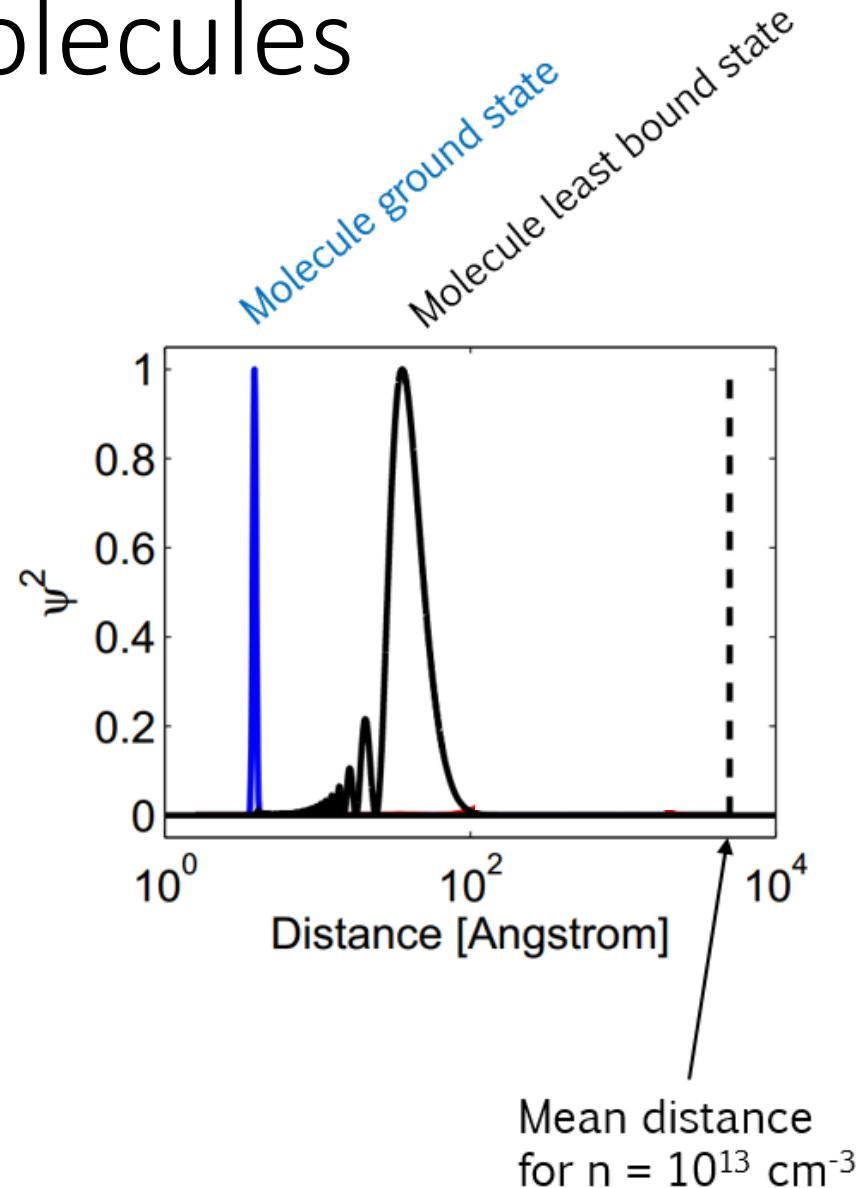
AM Kaufman,...,CA Regal PRX **2**, 041014 (2012)

JD Thompson,...,MD Lukin PRL **110**, 133001 (2013)

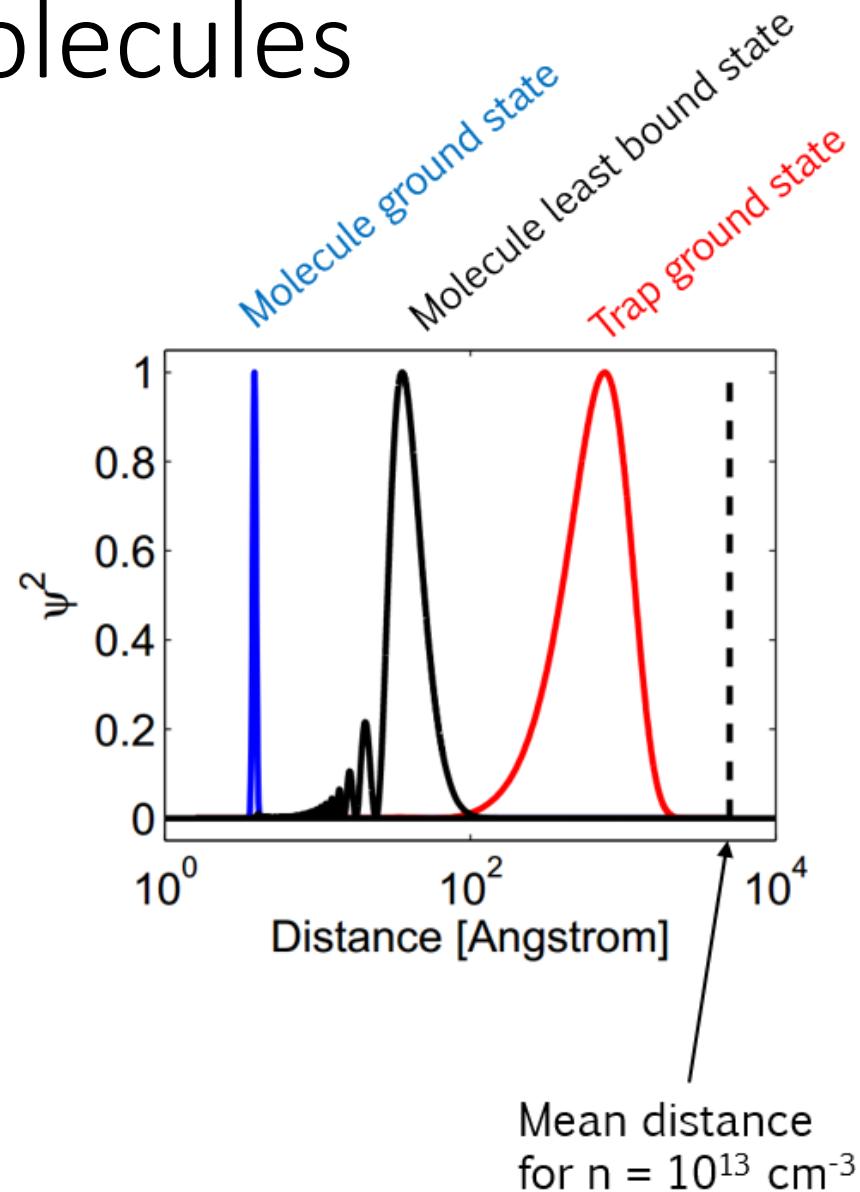


# Making molecules

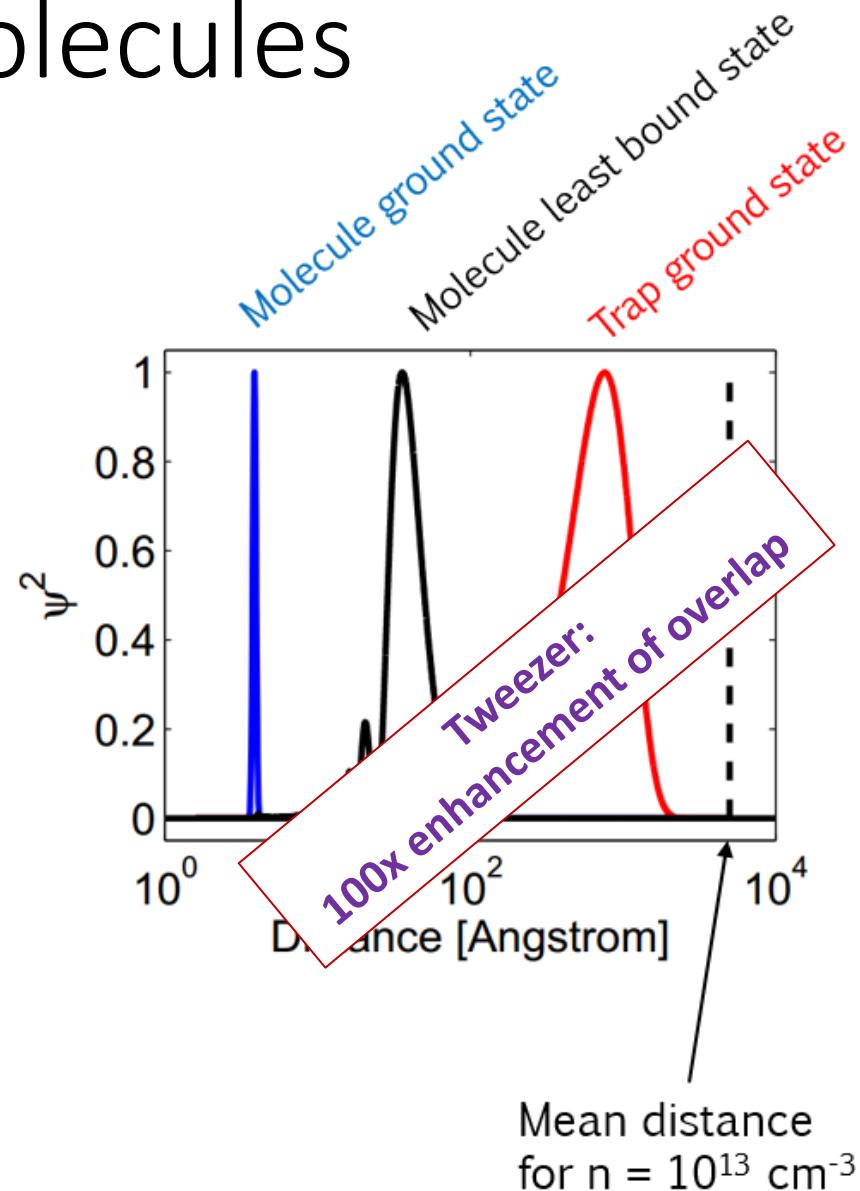
# Atoms to Molecules



# Atoms to Molecules



# Atoms to Molecules



# Thank you!

PI: Kang-Kuen Ni

Goal: Reconfigurable array of ultracold  
polar NaCs molecules

NaCs

Nick Hutzler  
Lee Liu

Yichao Yu  
Jessie Zhang

We have achieved loading of Cs and Na

KRb

Yu Liu  
Ming-guang Hu  
Andrei Gheorghe

Axial sideband cooling of Cs in progress

Undergrads

William Tobias  
Jason Rosenberg

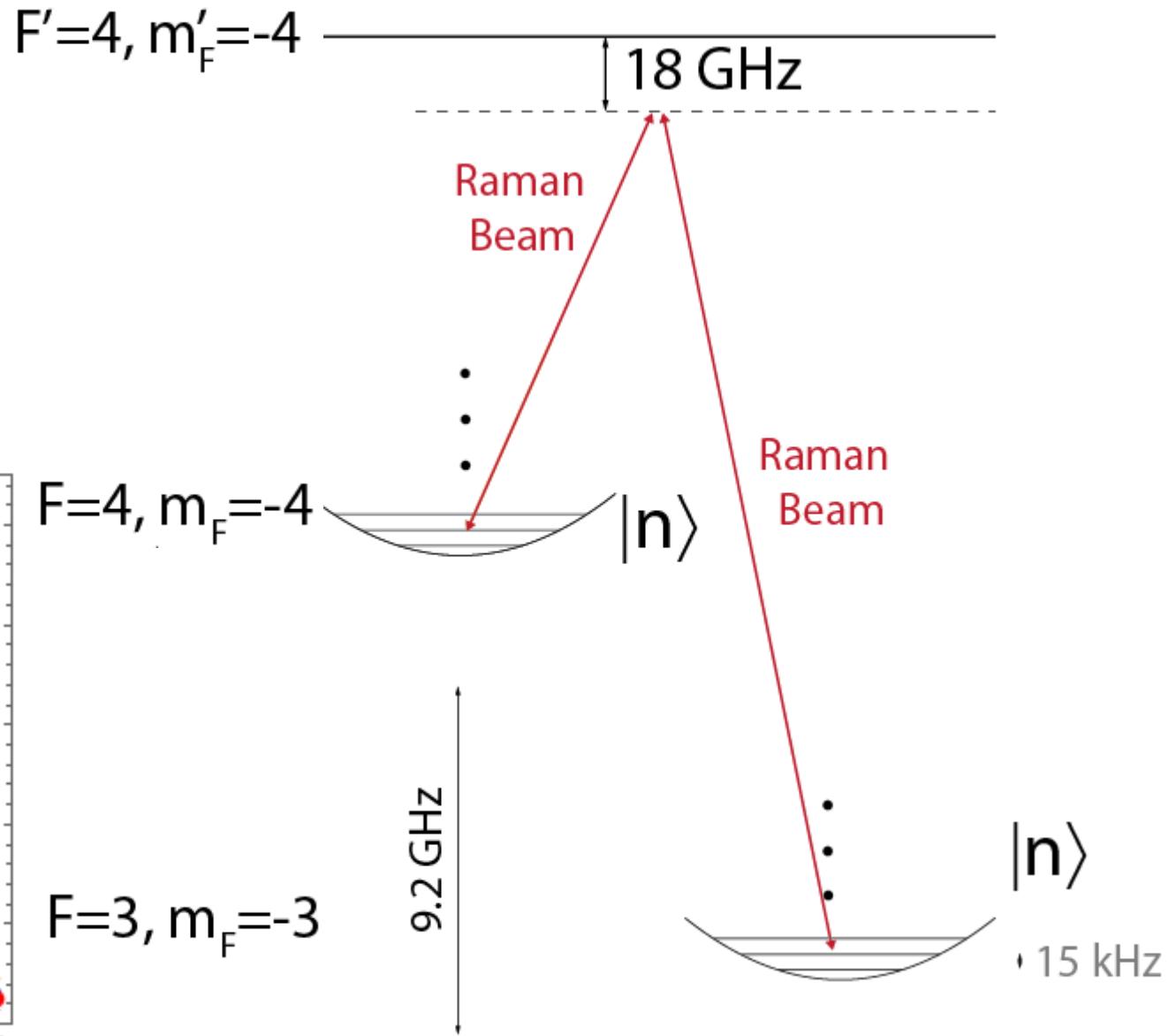
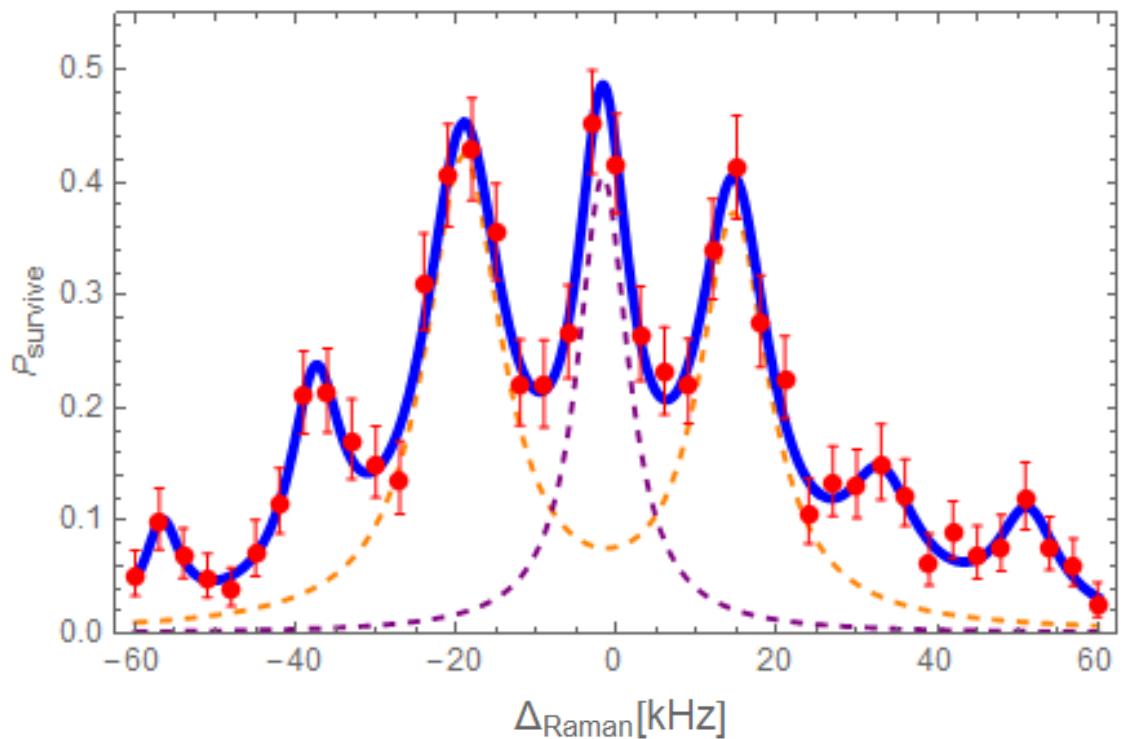
Calculations show association in tweezer  
is feasible

# Raman Sideband Cooling (Axial)

In neutral atom tweezers:

AM Kaufman,...,CA Regal PRX **2**, 041014 (2012)

JD Thompson,...,MD Lukin PRL **110**, 133001 (2013)

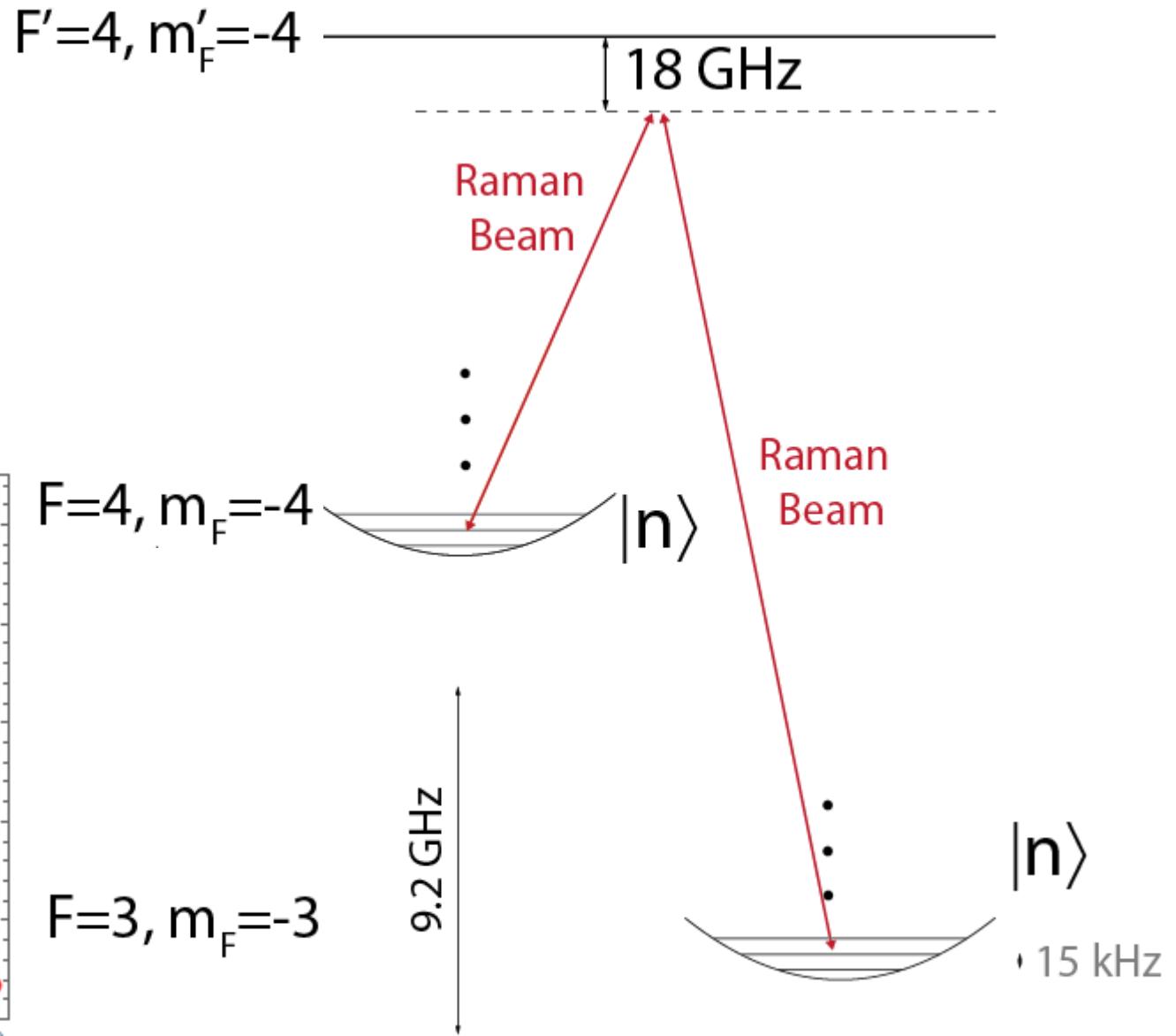
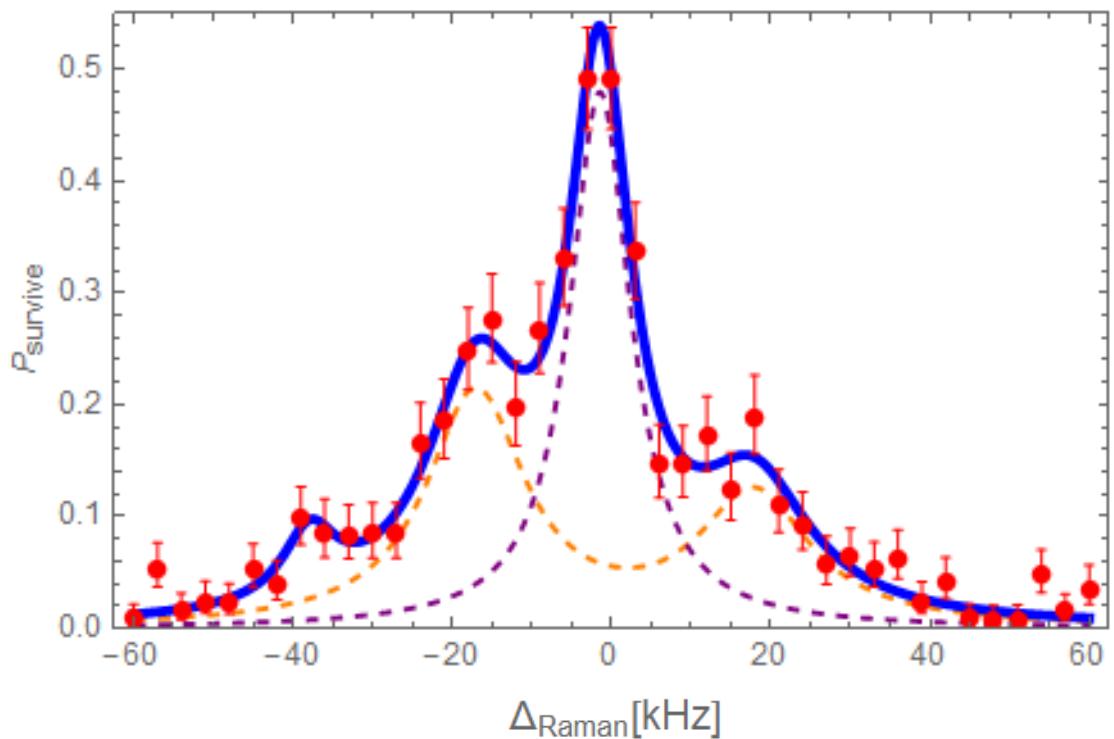


# Raman Sideband Cooling (Axial)

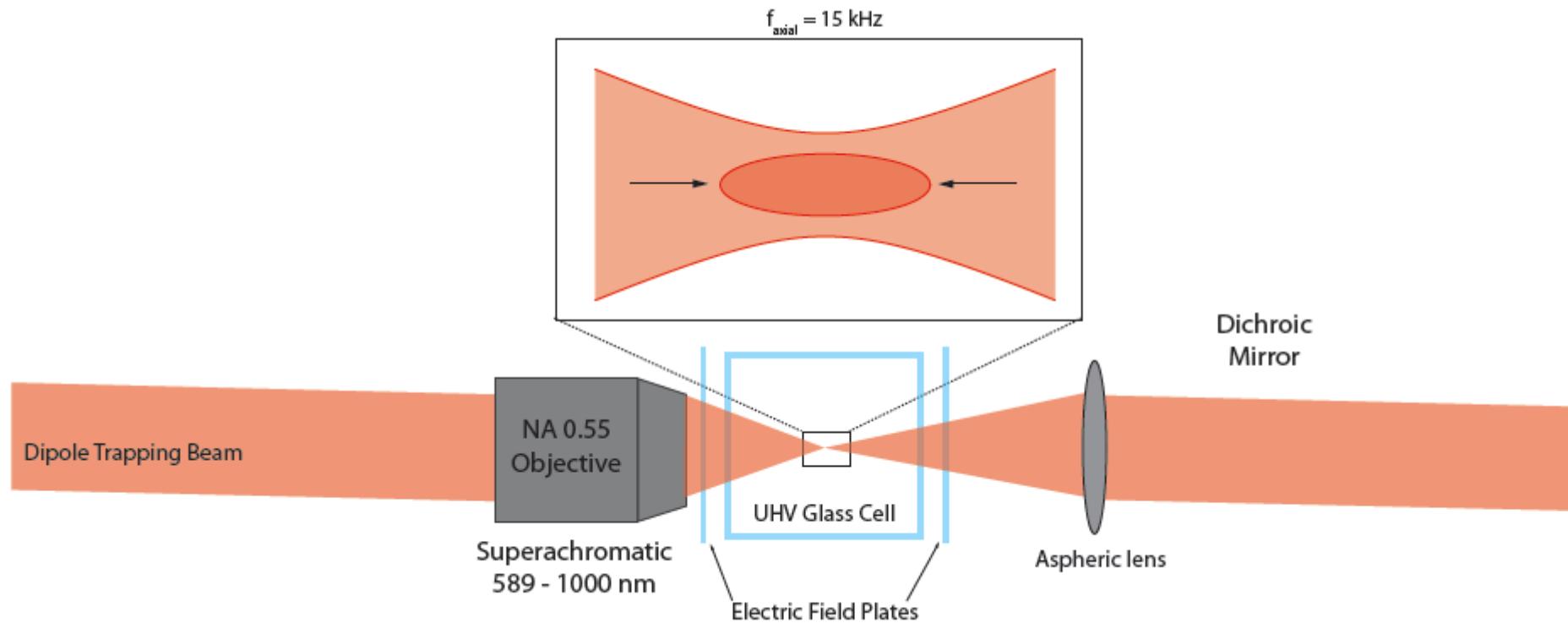
In neutral atom tweezers:

AM Kaufman,...,CA Regal PRX **2**, 041014 (2012)

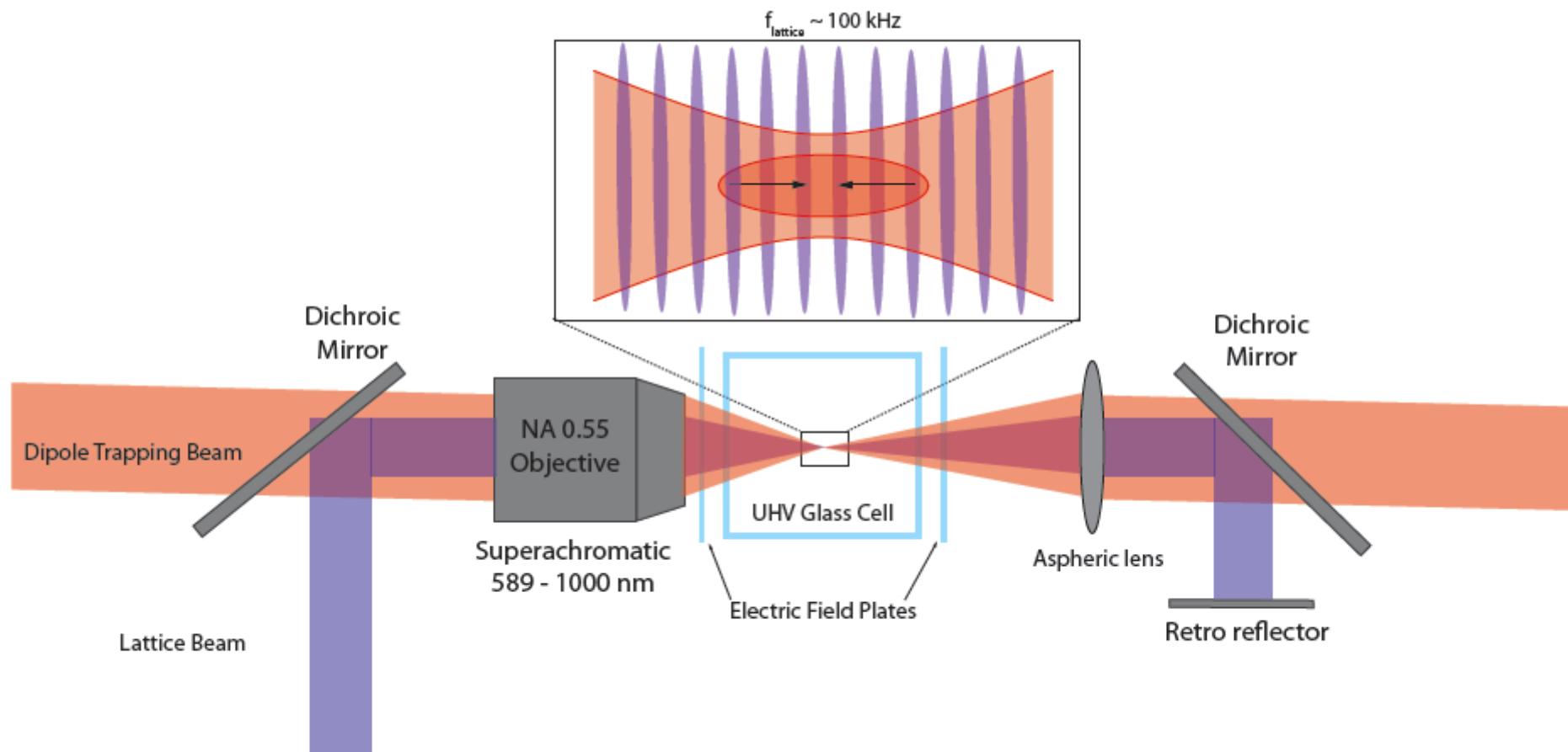
JD Thompson,...,MD Lukin PRL **110**, 133001 (2013)



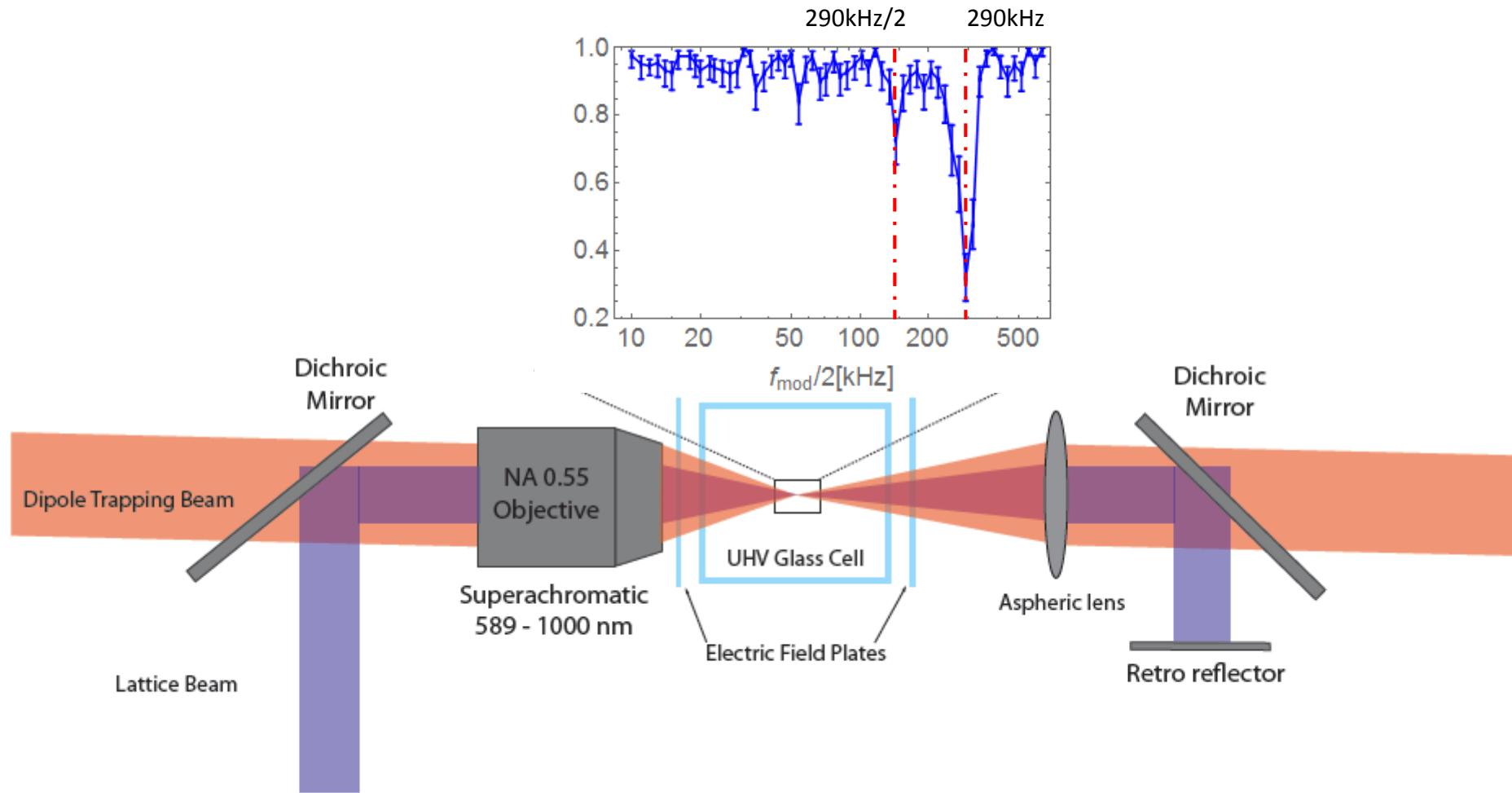
# 1-D Axial lattice



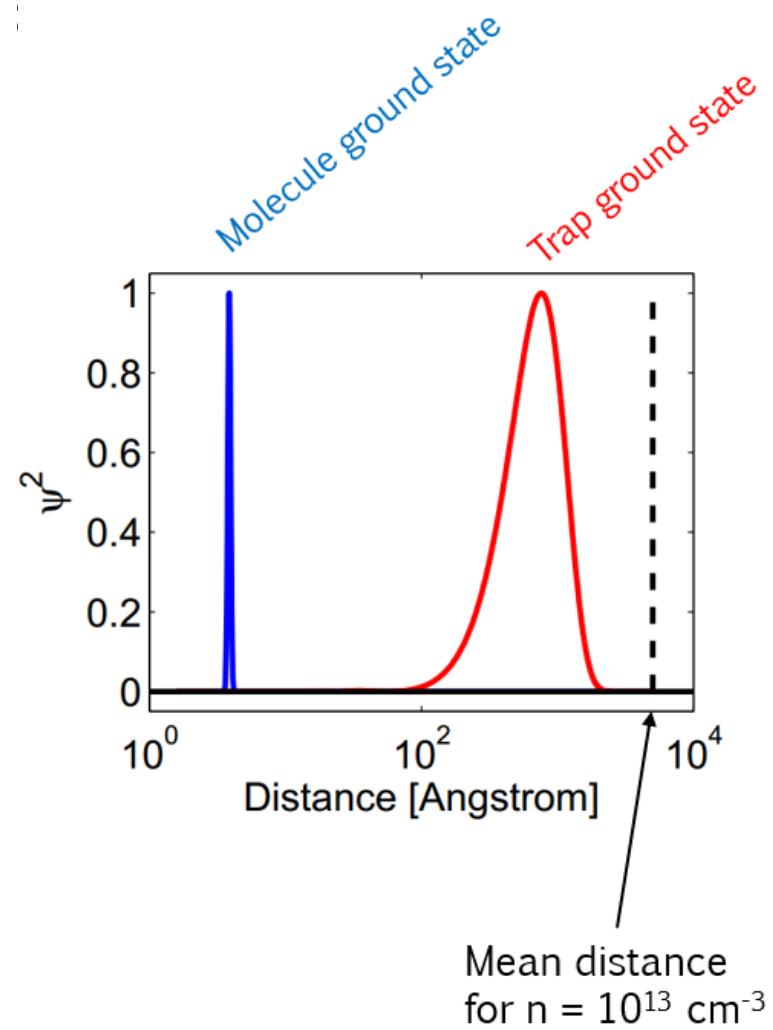
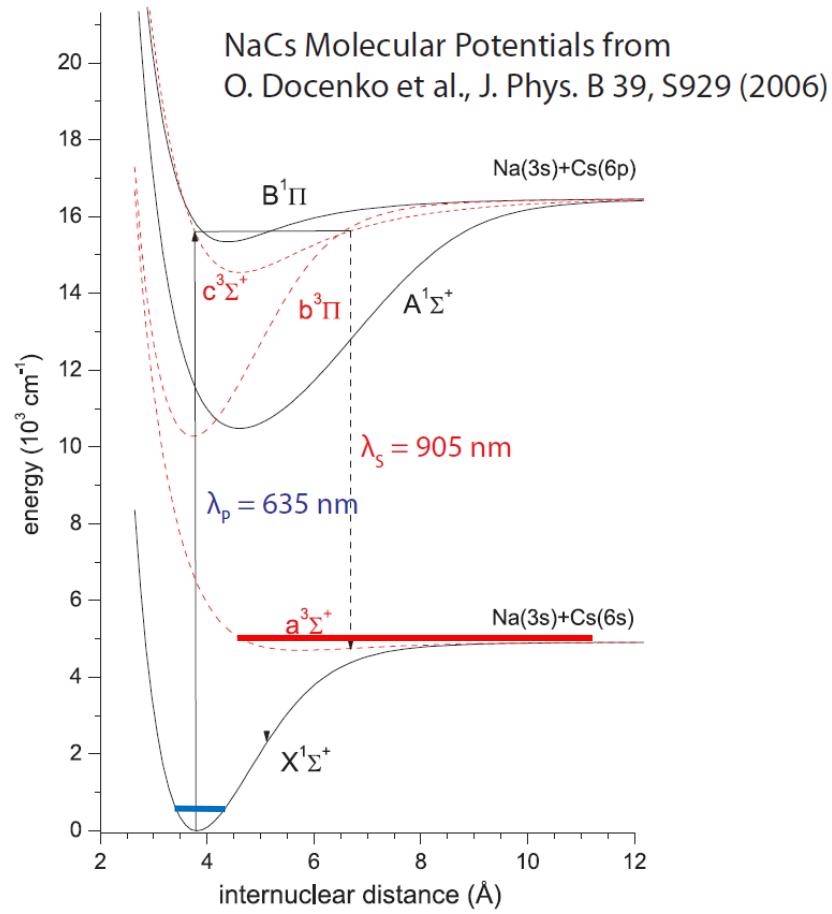
# 1-D Axial lattice



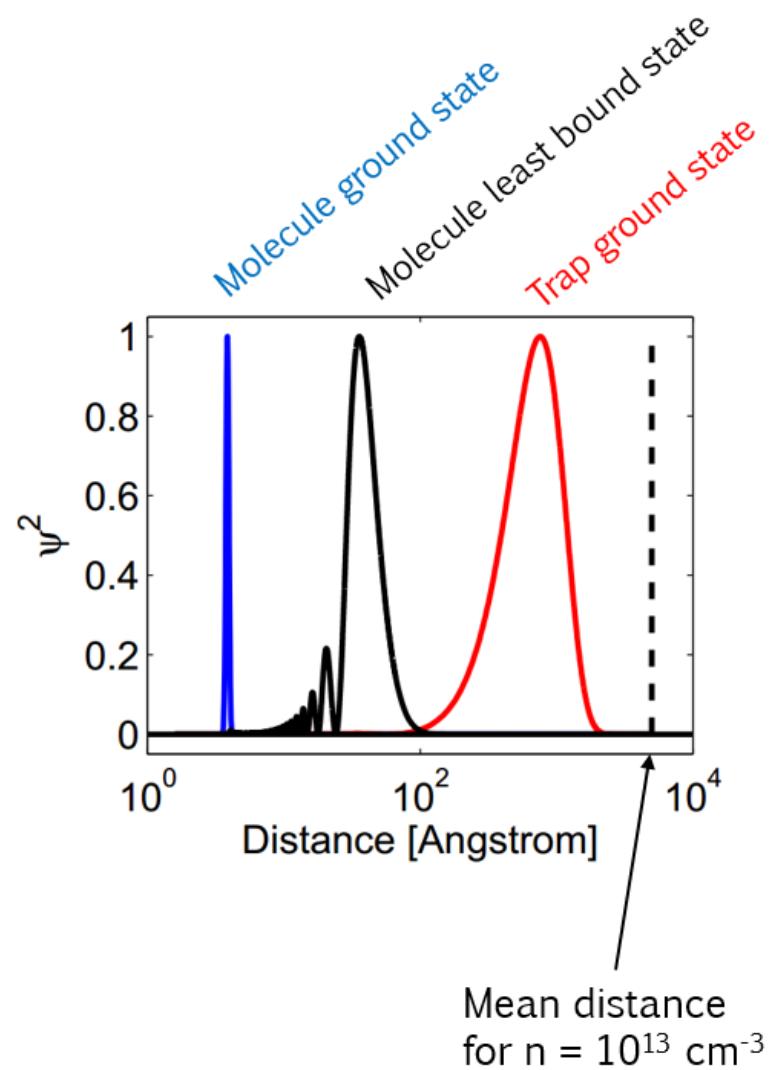
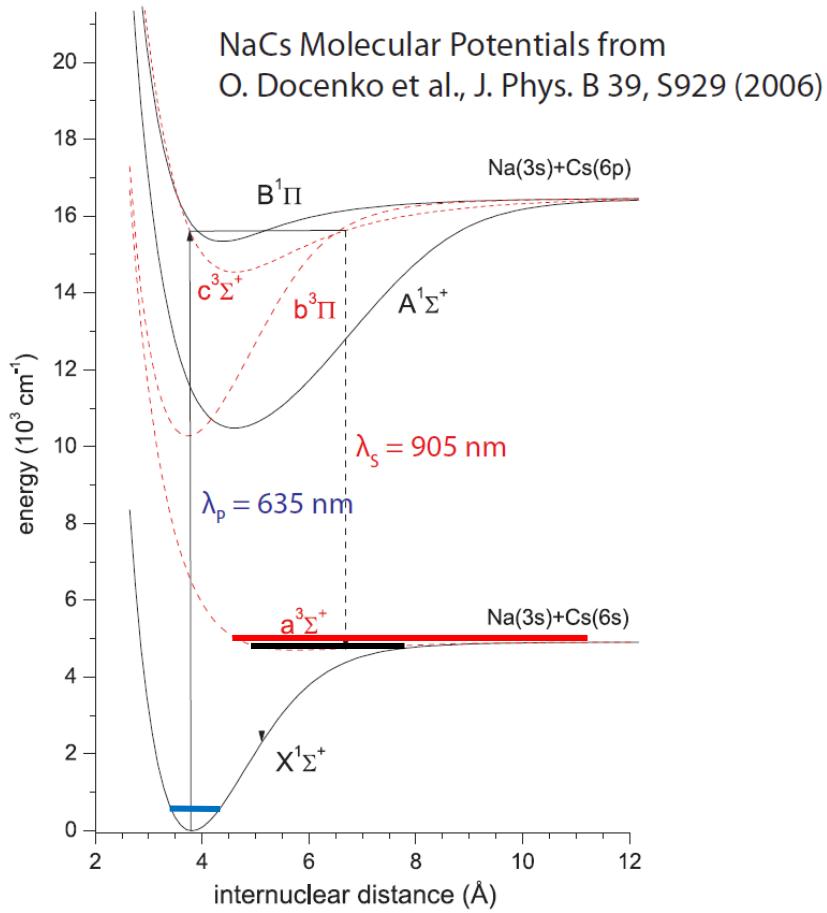
# 1-D Axial lattice



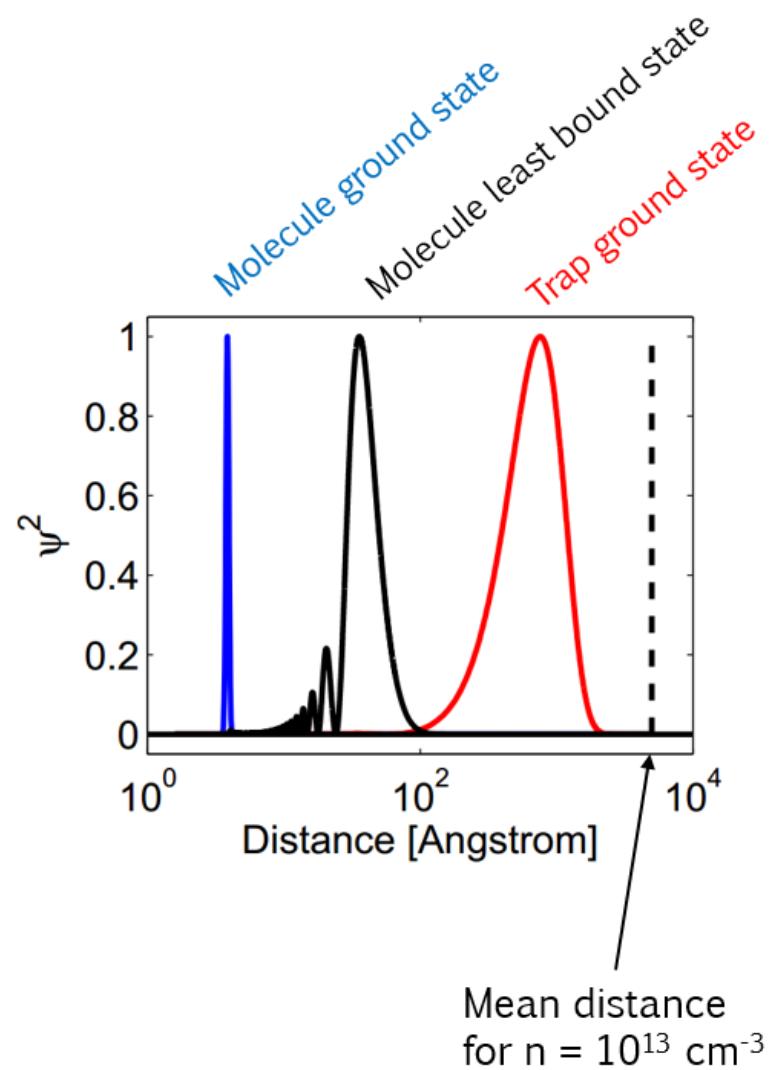
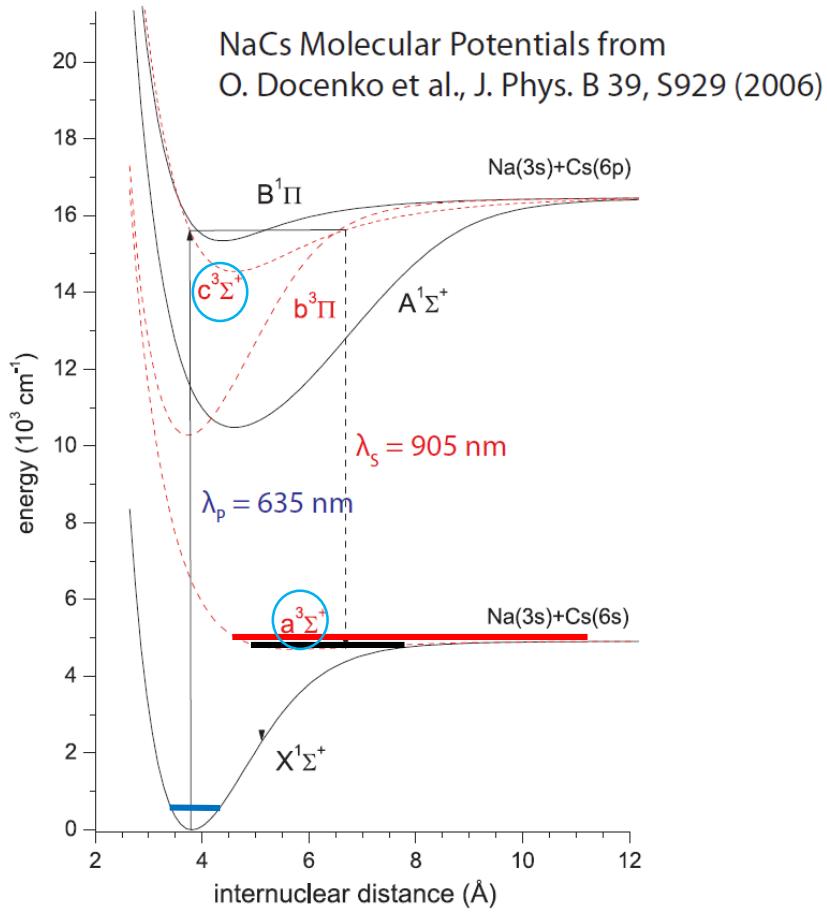
# Atoms to Molecules



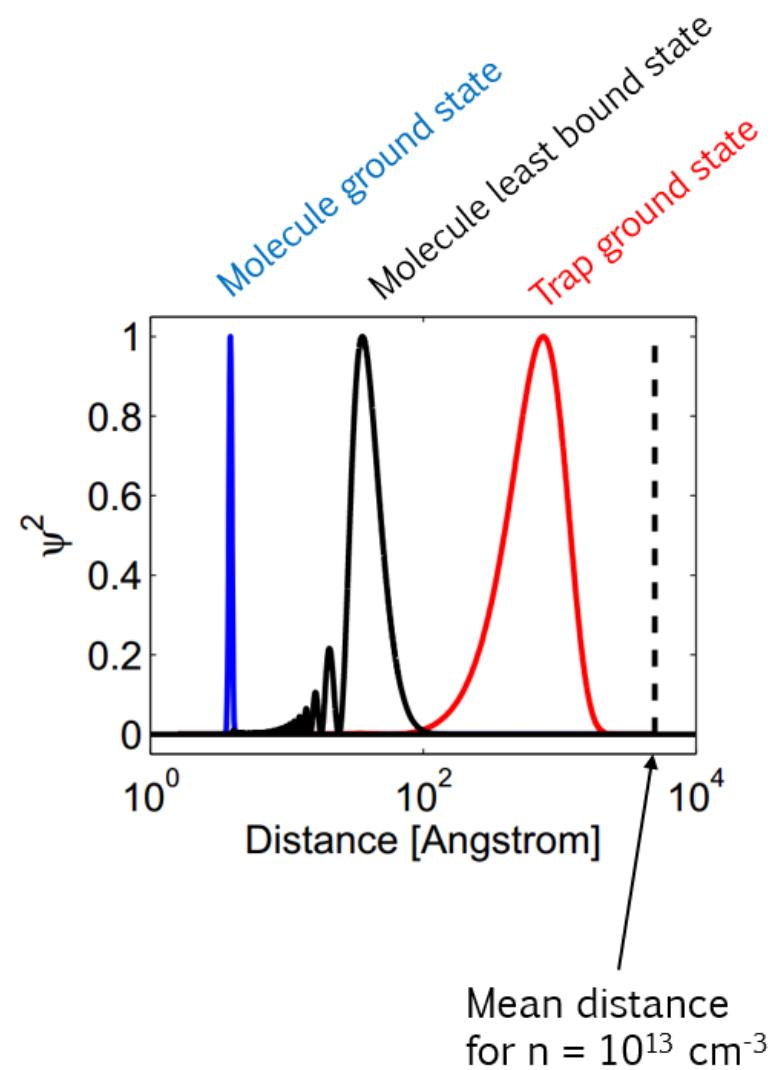
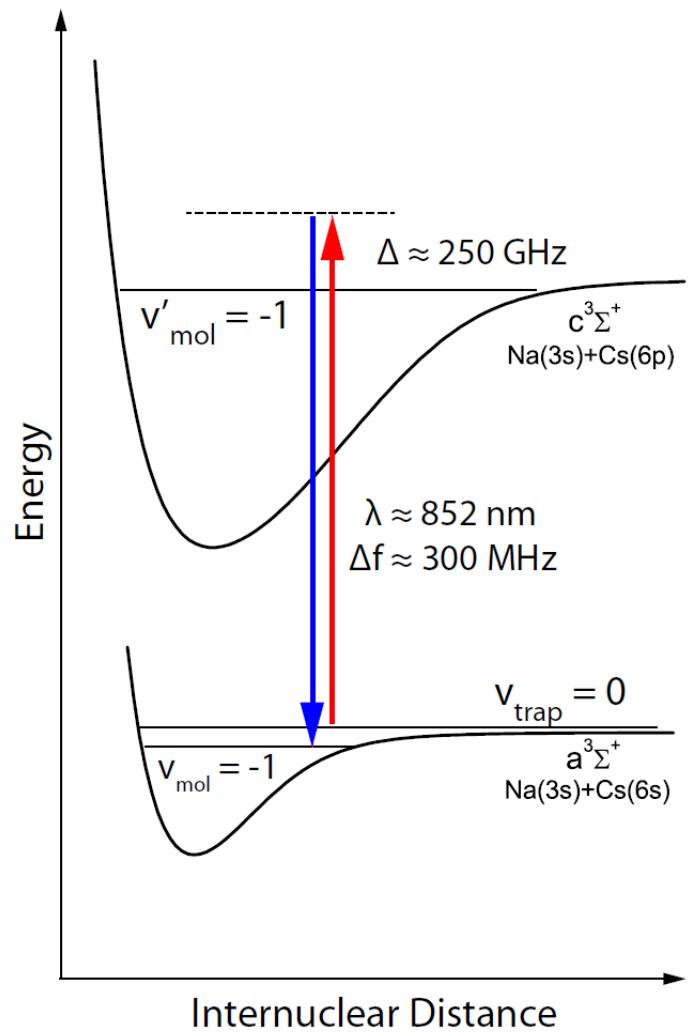
# Atoms to Molecules



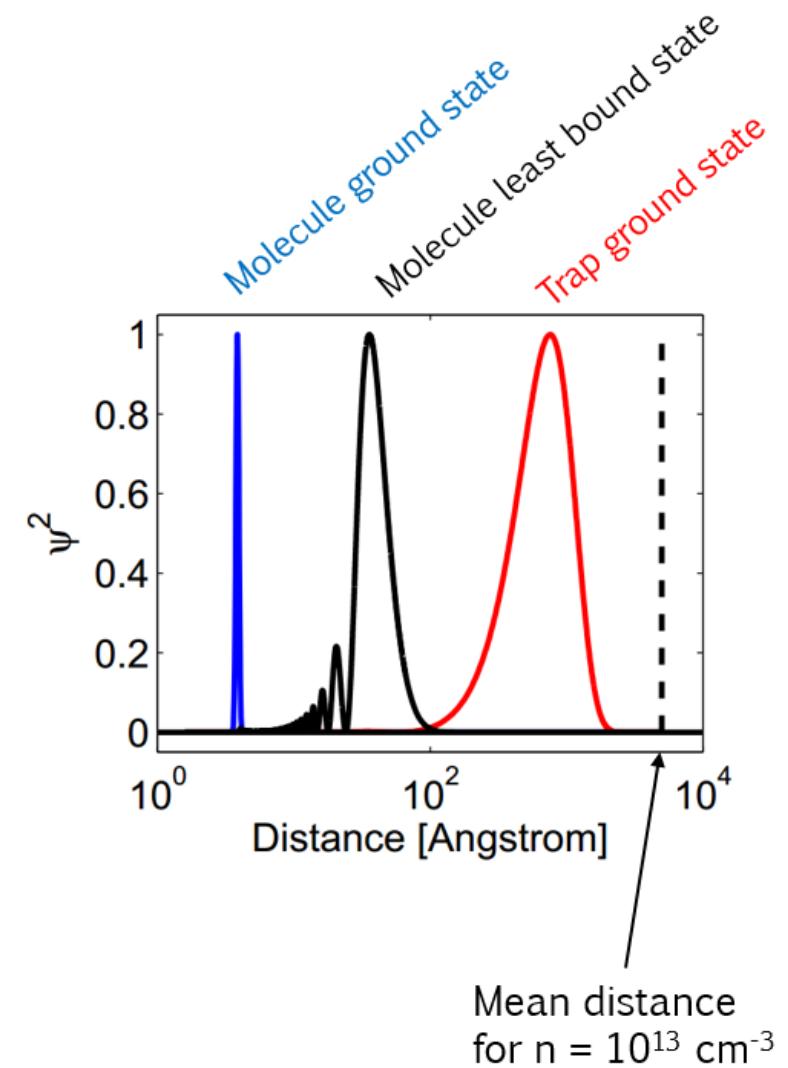
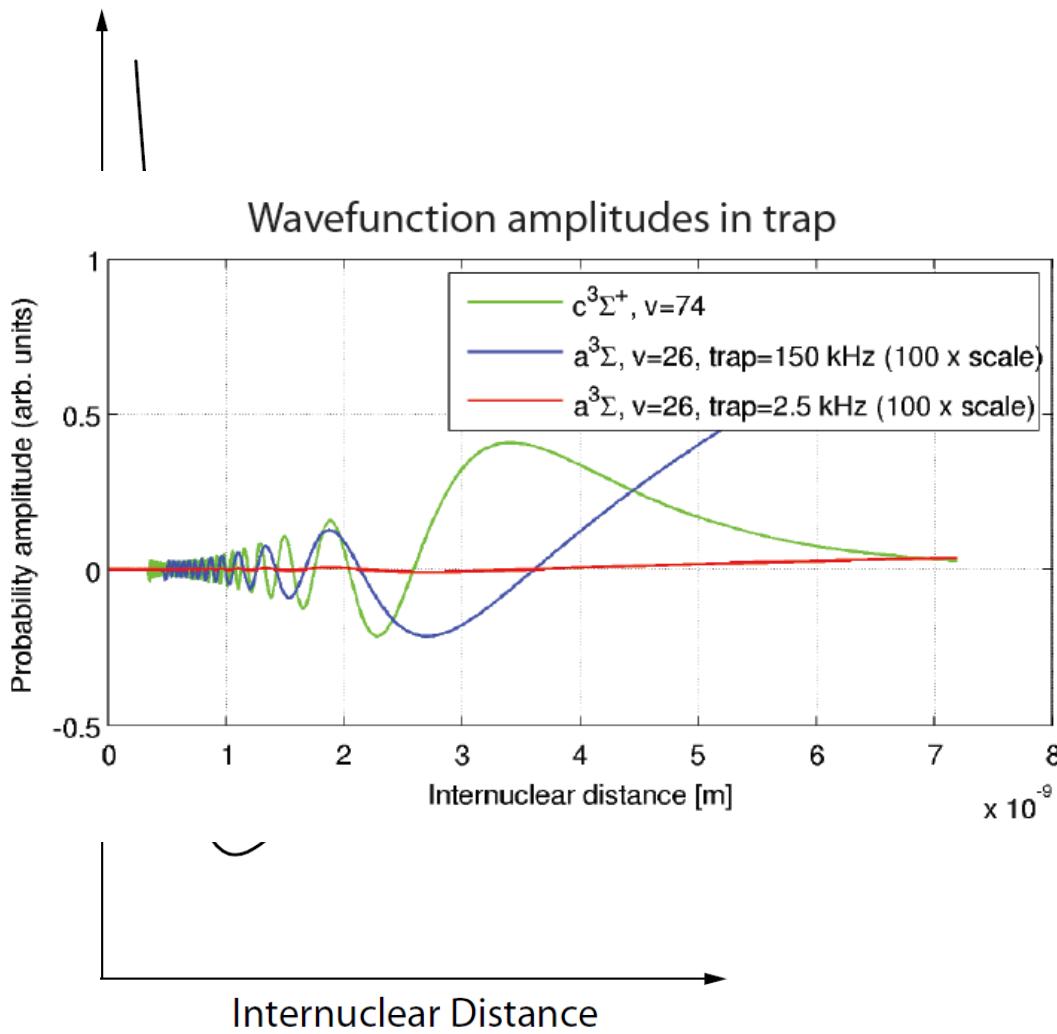
# Atoms to Molecules



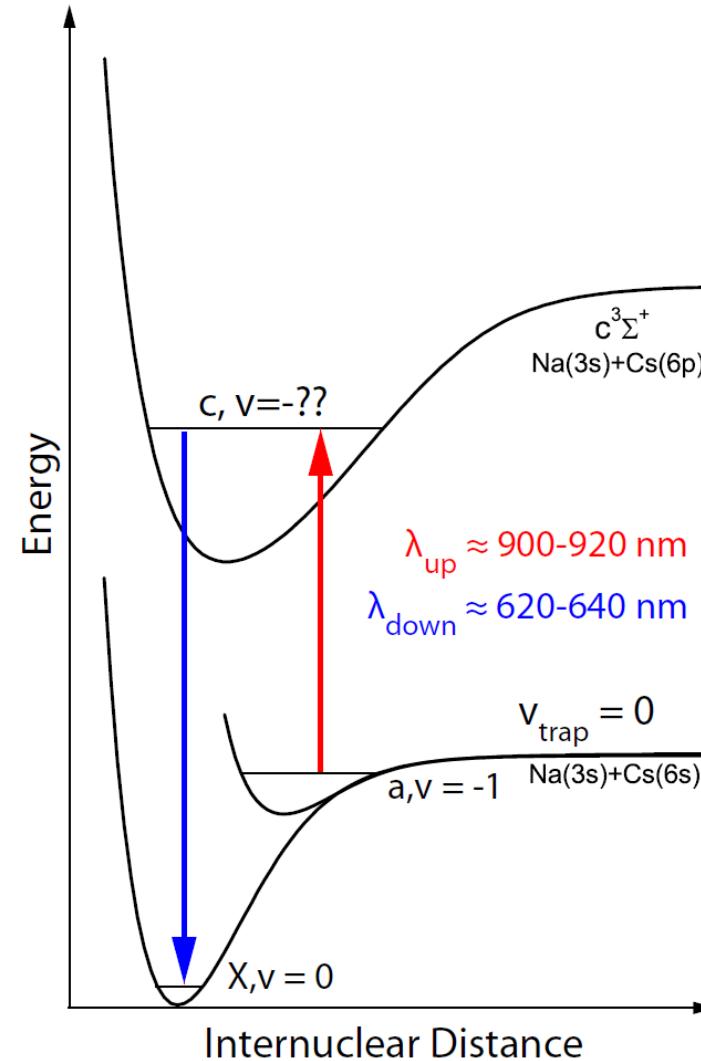
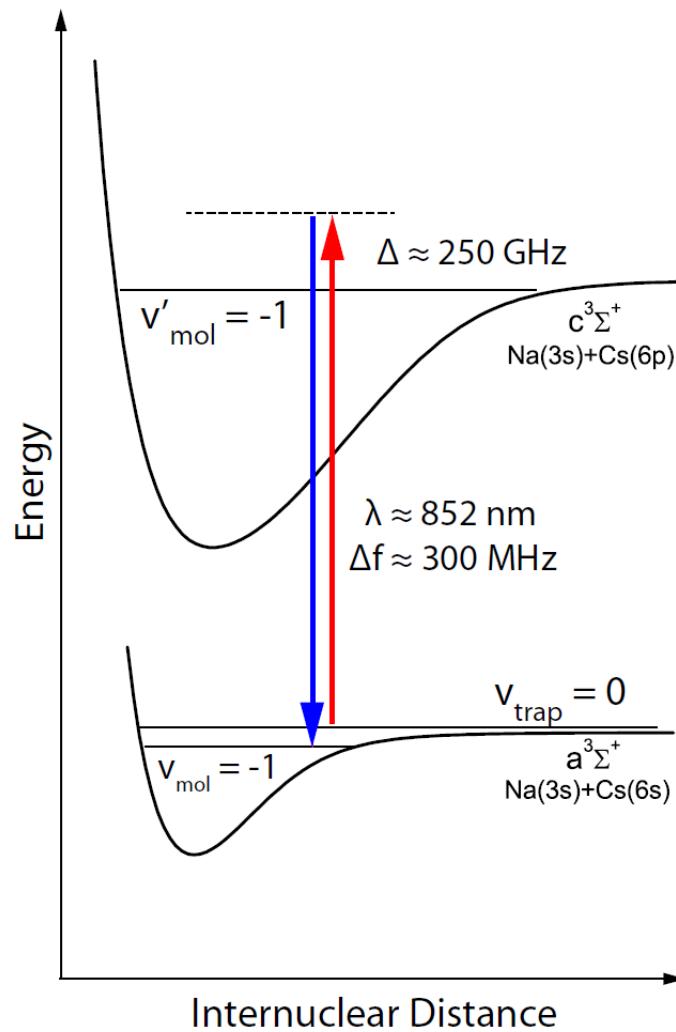
# Atoms to Molecules



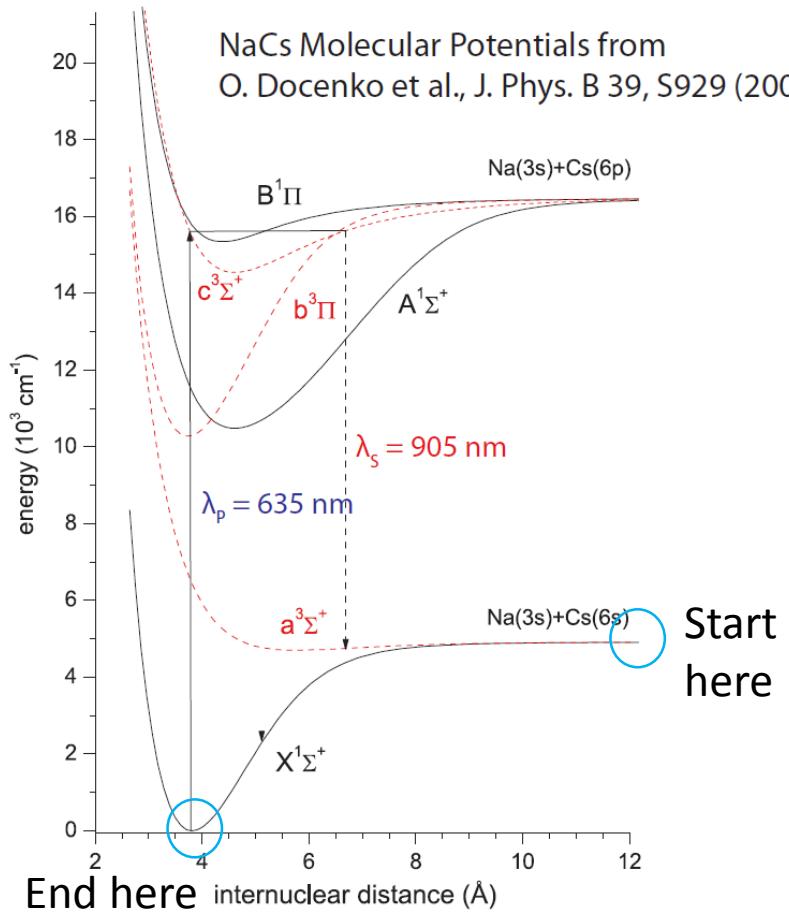
# Atoms to Molecules



# Ground state molecules

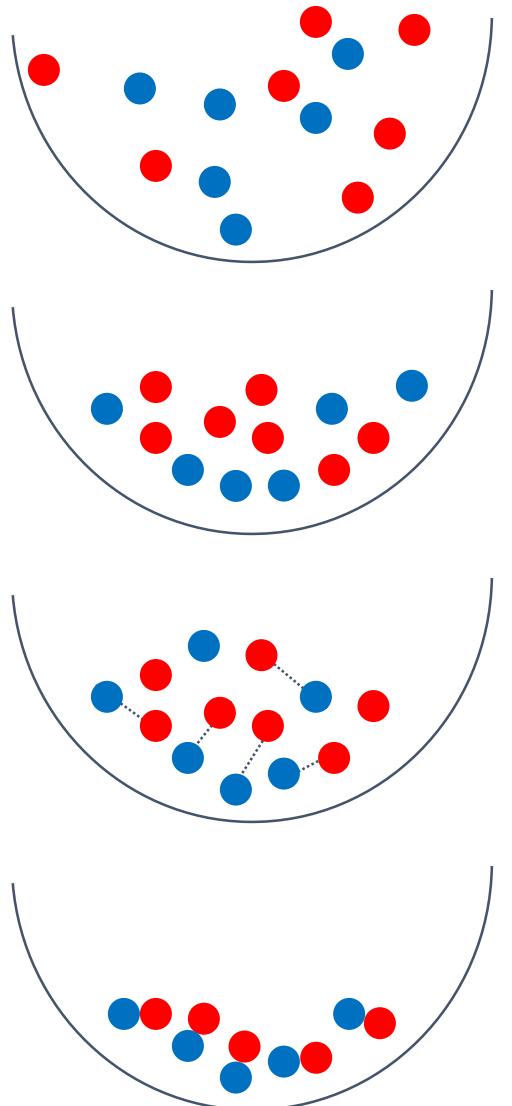


# Atoms to Molecules

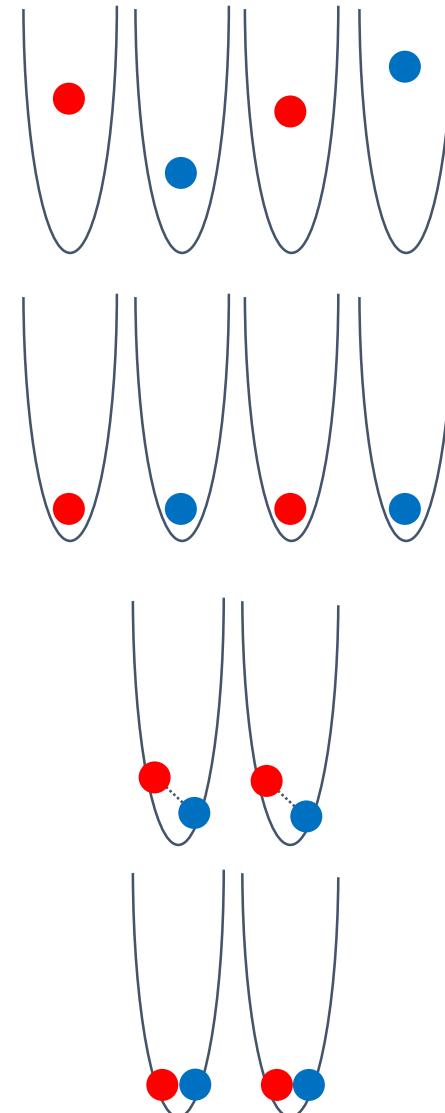


# Our Approach

Quantum gas

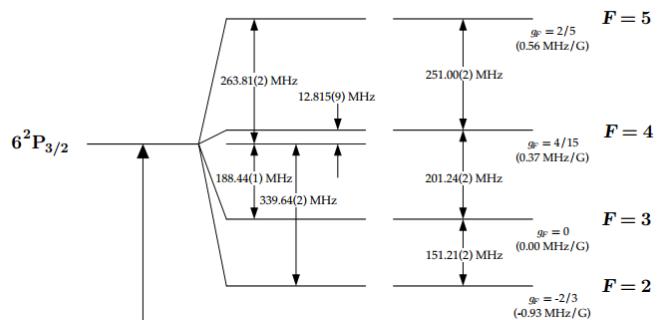


Single atom

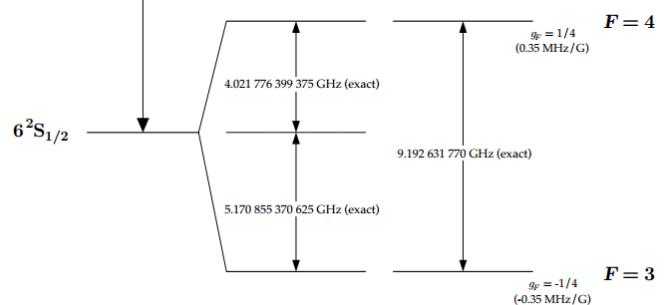


Trap  
↓  
Cool  
↓  
Weakly bound molecules  
↓  
Ground state molecules

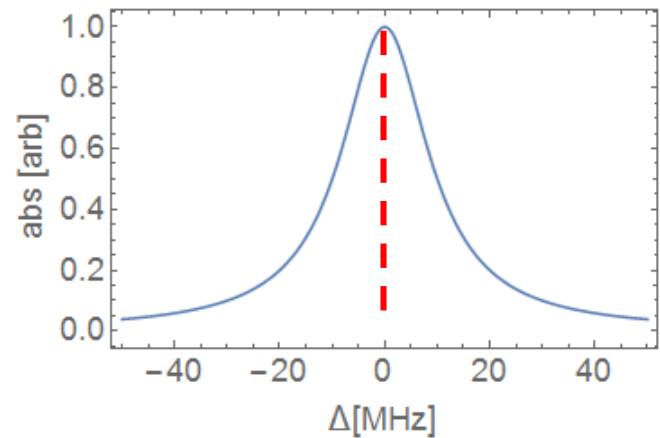
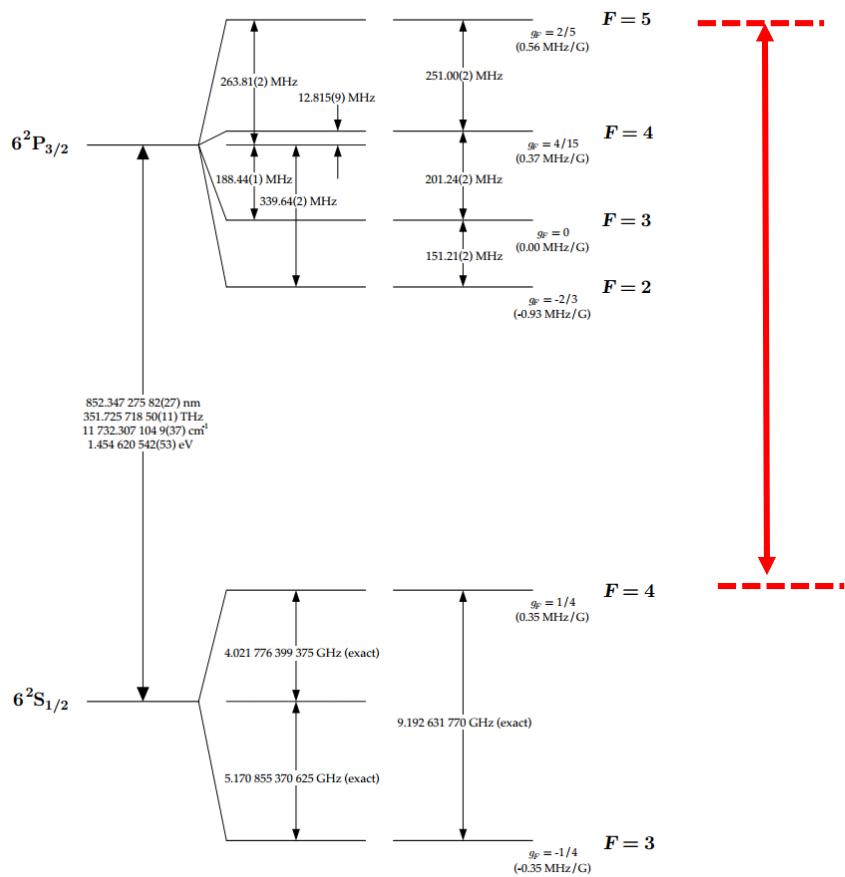
# Light Shifts (Cesium)



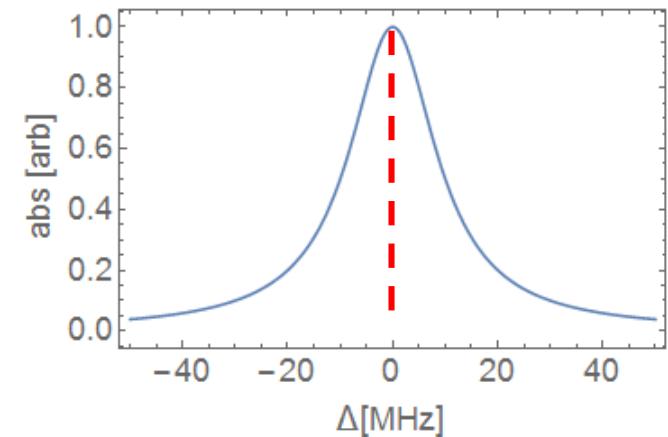
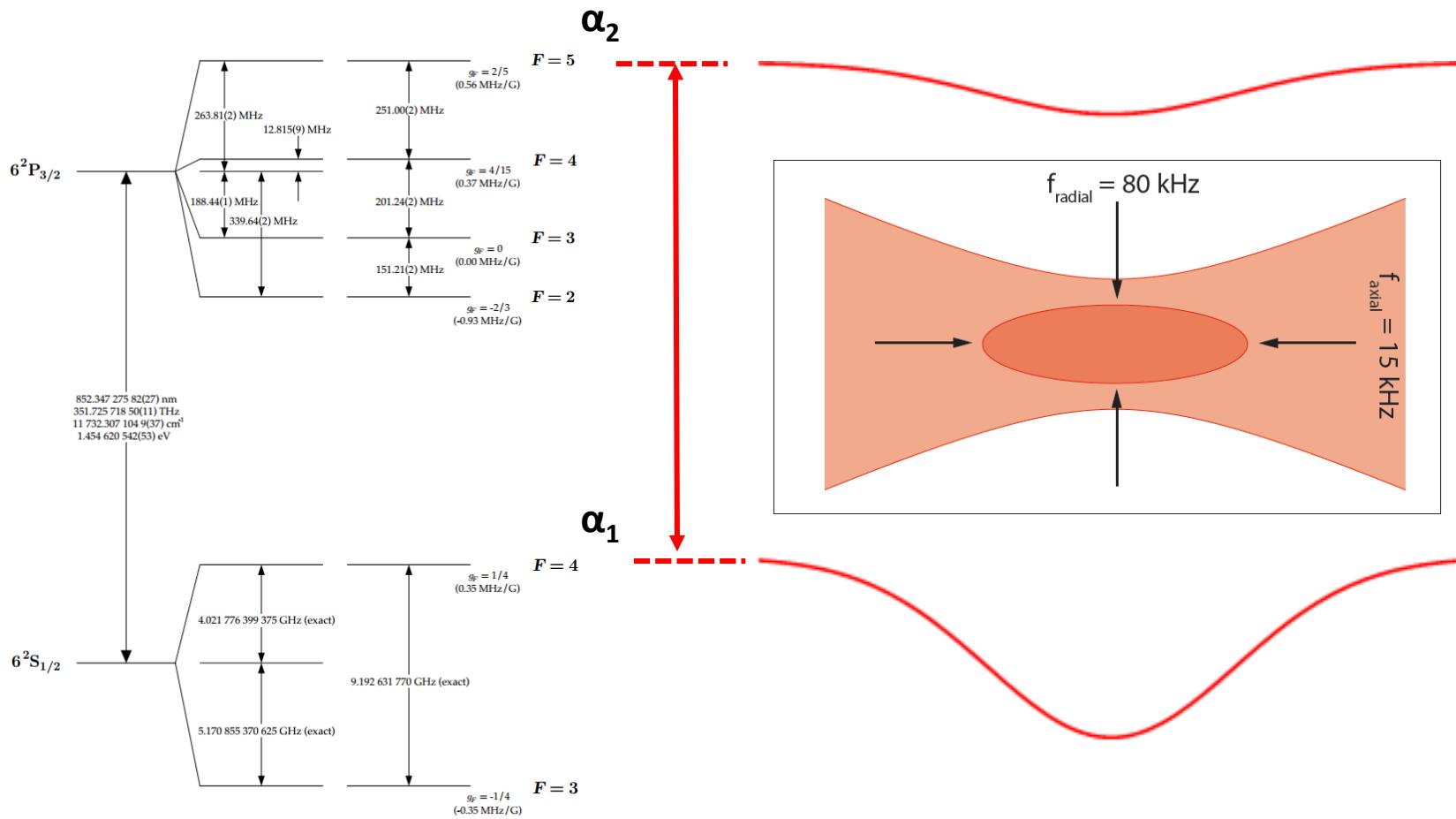
852.347 275 82(27) nm  
351.725 718 50(11) THz  
11.732.307 104 9(37) cm<sup>-1</sup>  
1.454 620 542(53) eV



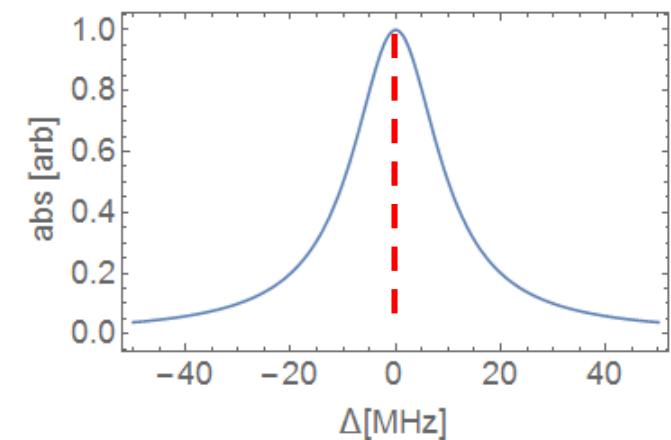
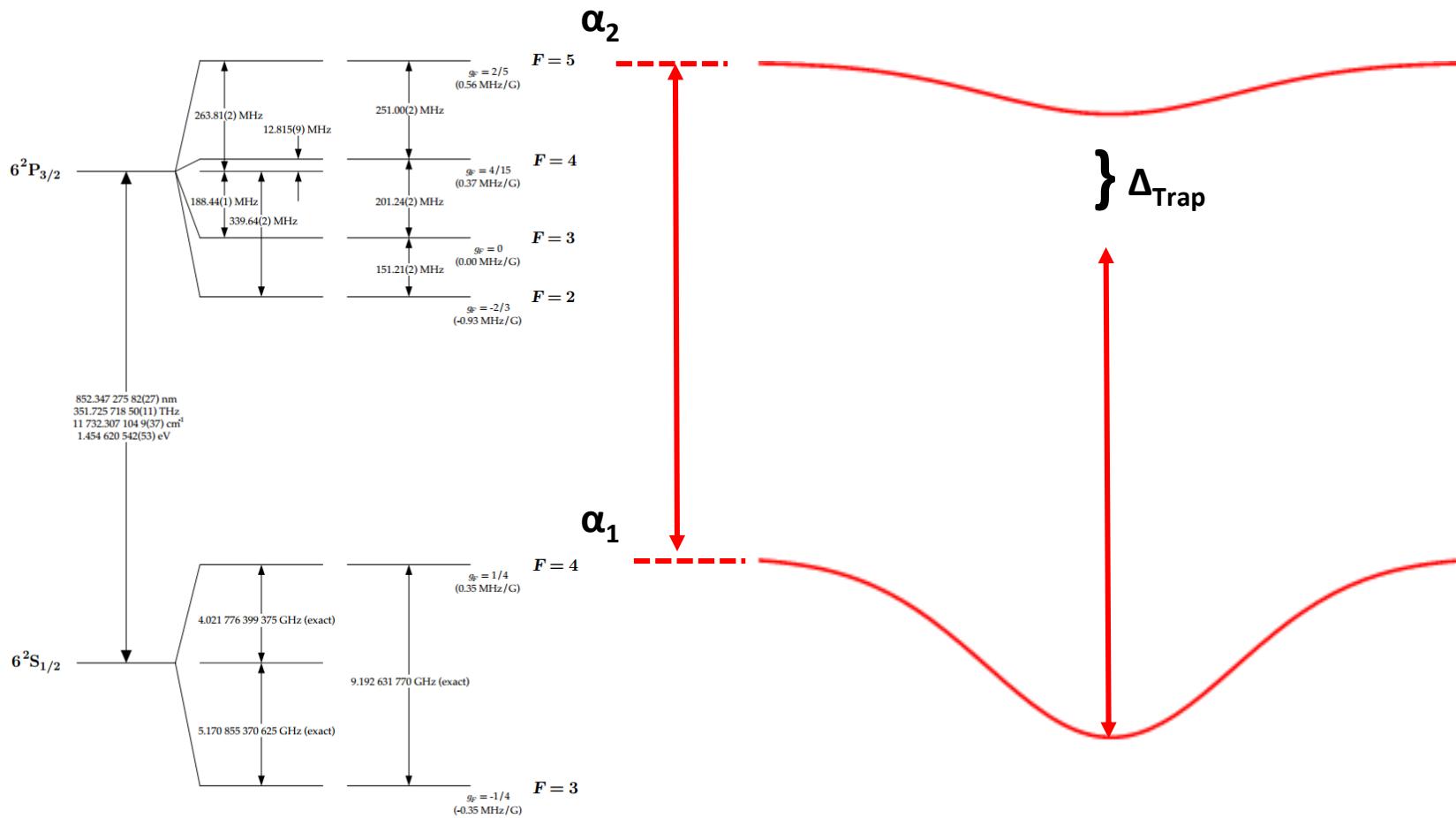
# Light Shifts (Cesium)



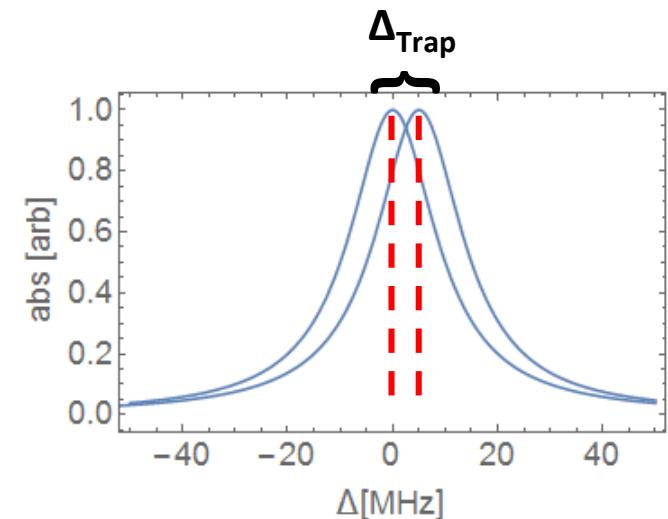
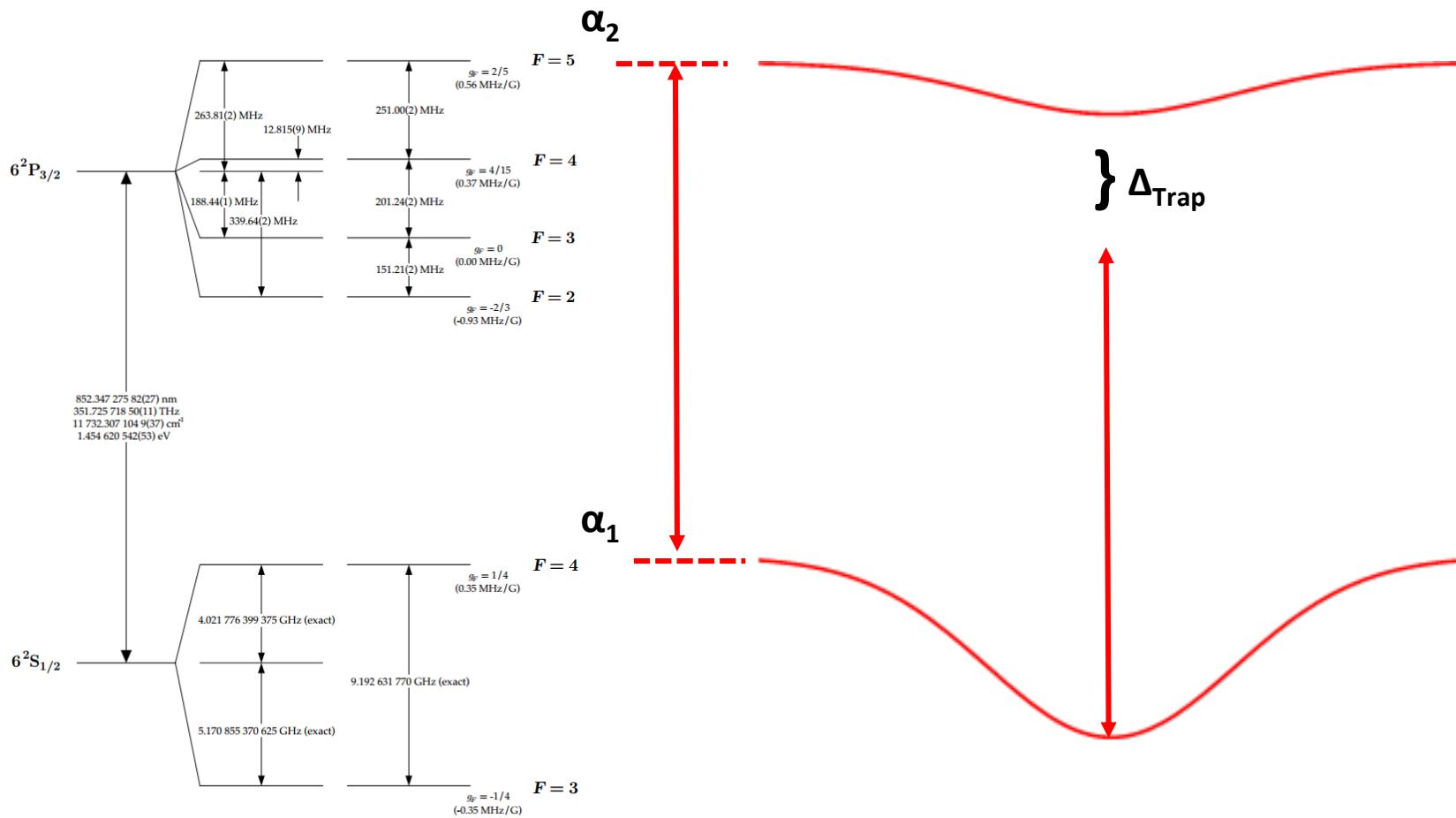
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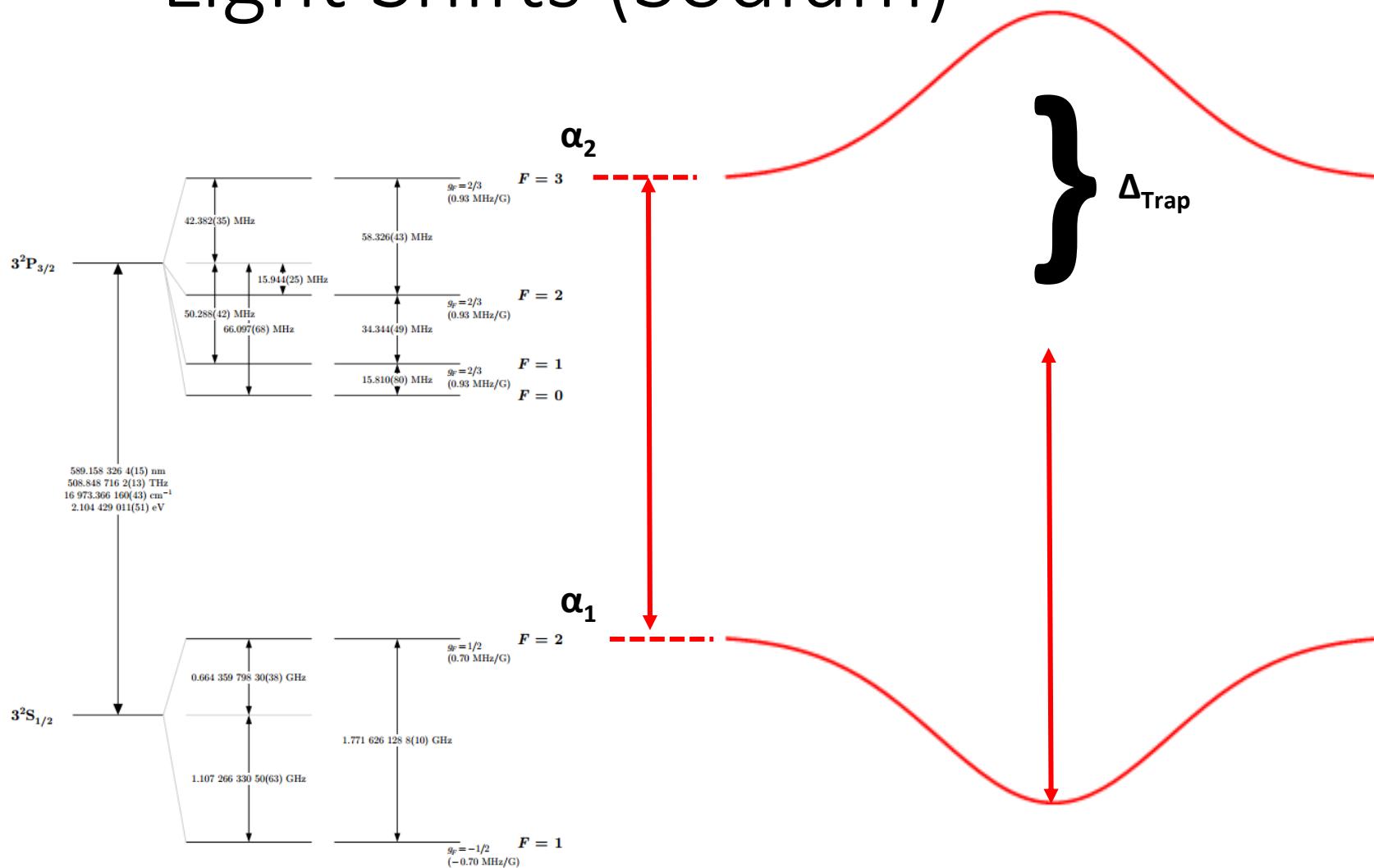
# Light Shifts (Cesium)



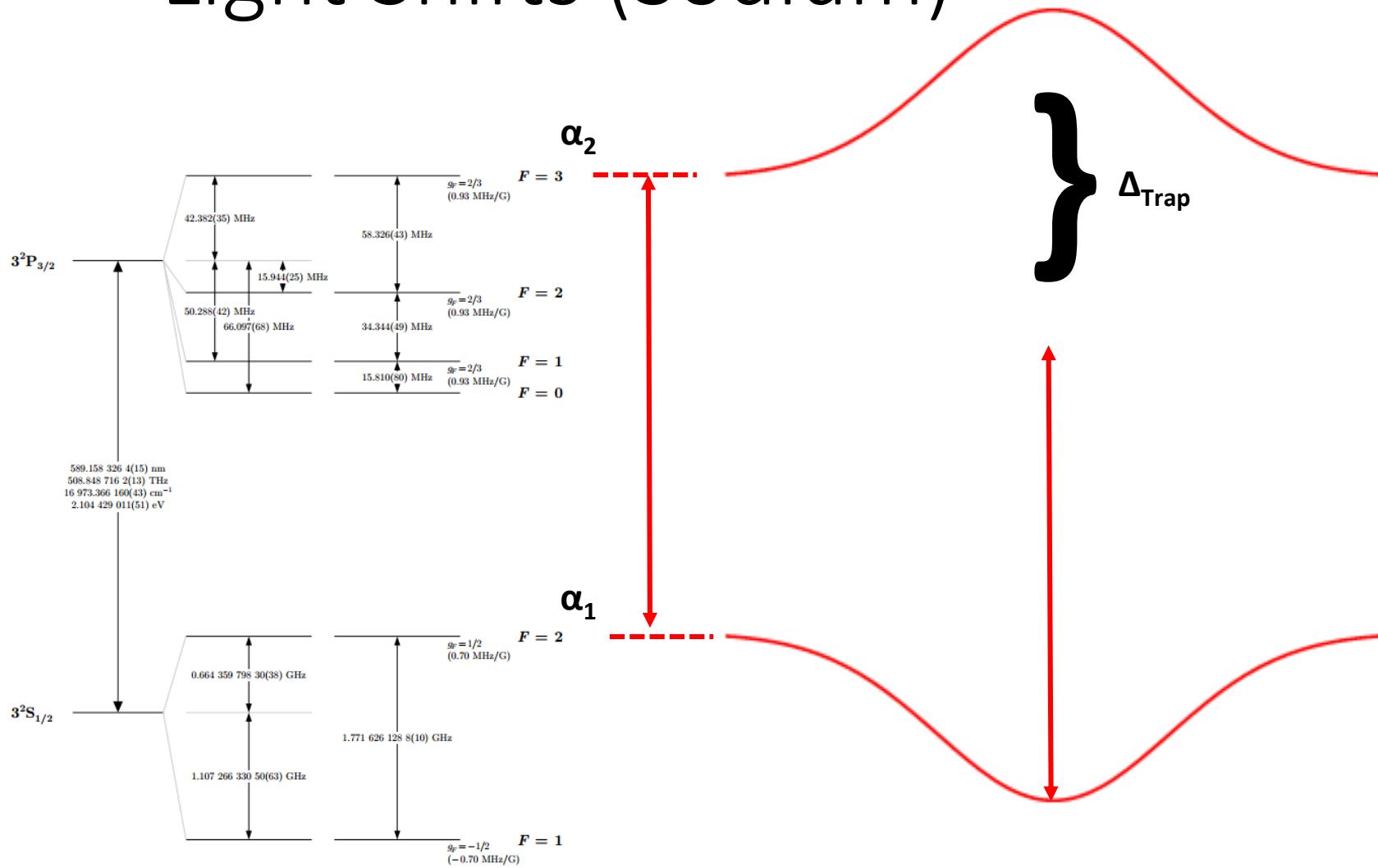
# Light Shifts (Cesium)



# Light Shifts (Sodium)

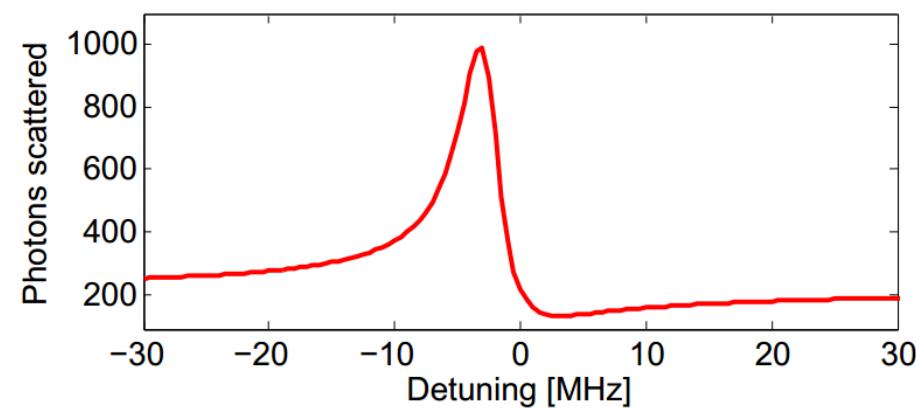
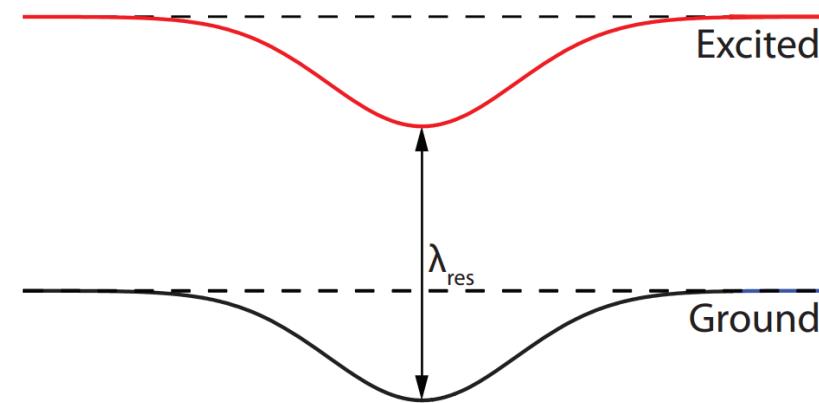


# Light Shifts (Sodium)



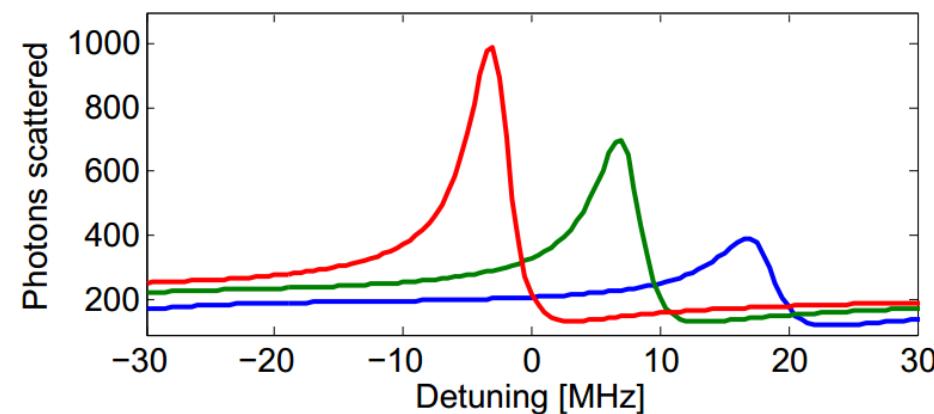
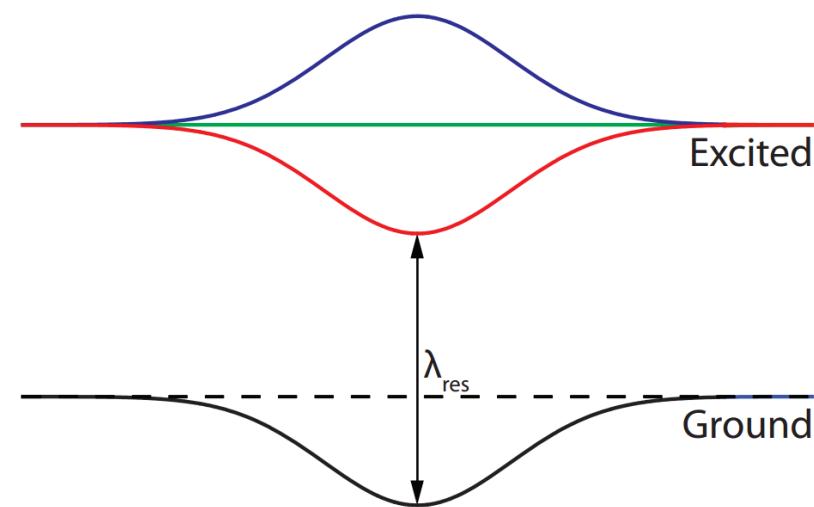
# Light Shifts (Summary)

- Tweezer shifts levels



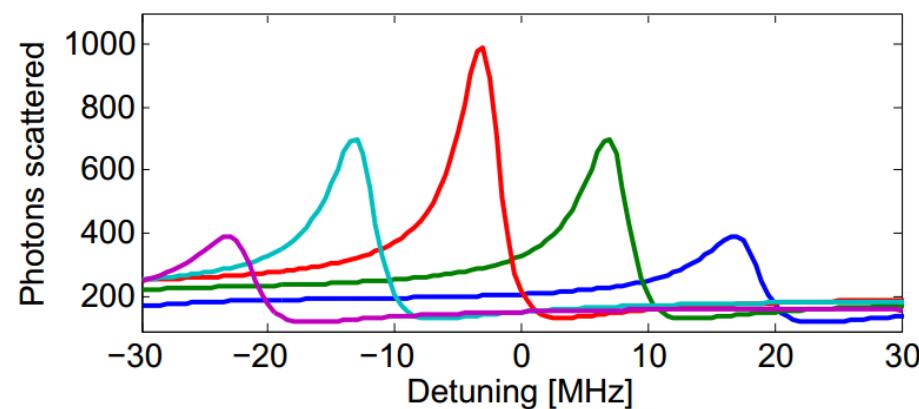
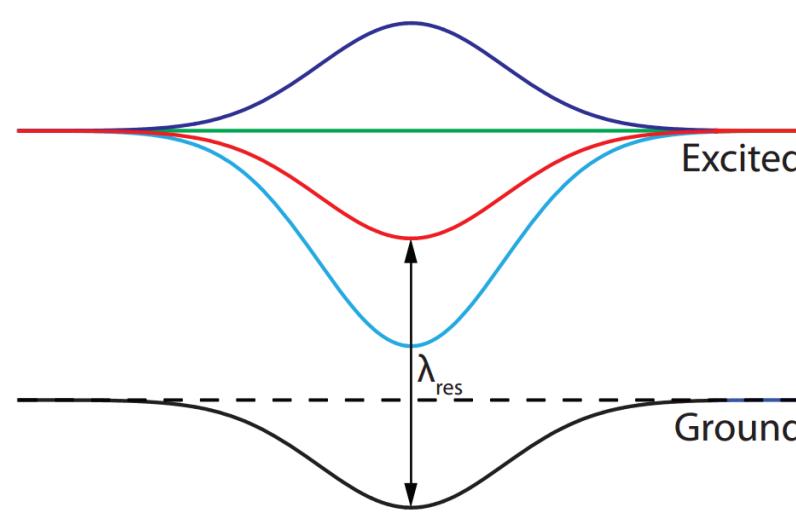
# Light Shifts (Summary)

- Tweezer shifts levels
- Shifts resonance, and gives rise to fluctuating dipole force heating



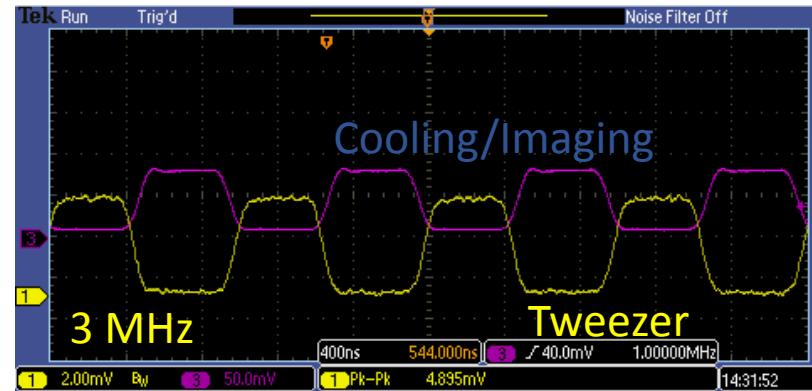
# Light Shifts (Summary)

- Tweezer shifts levels
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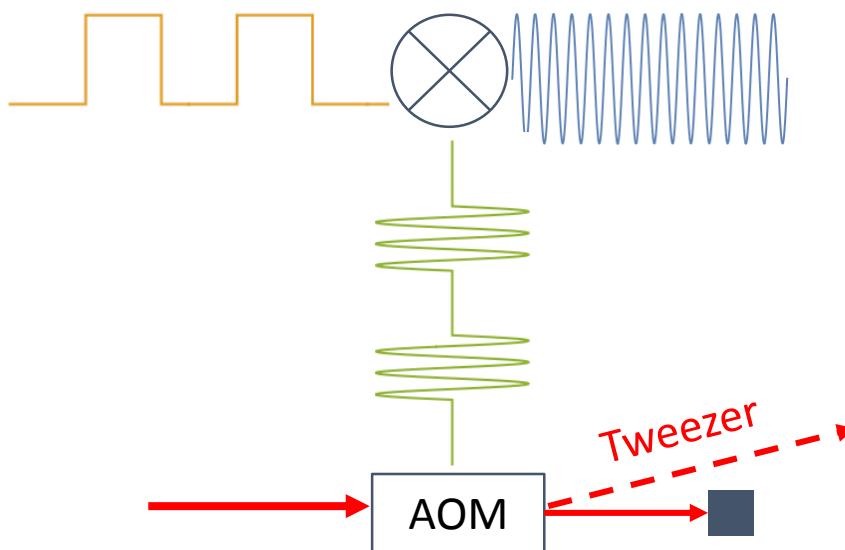
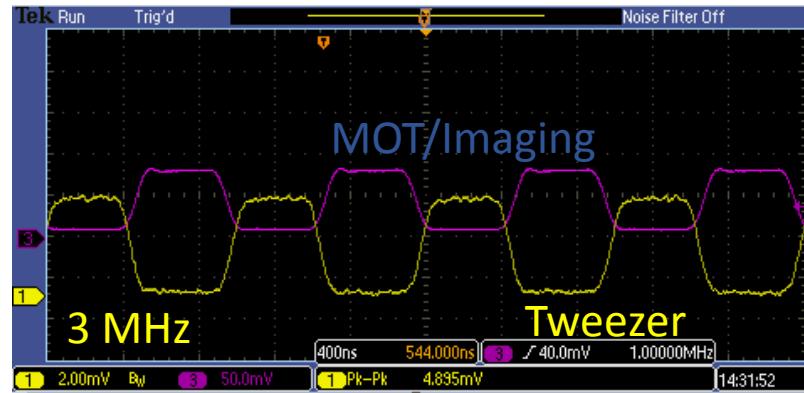
# Fast switching

- Alternate tweezer,  
MOT/imaging much  
faster than trap  
frequency



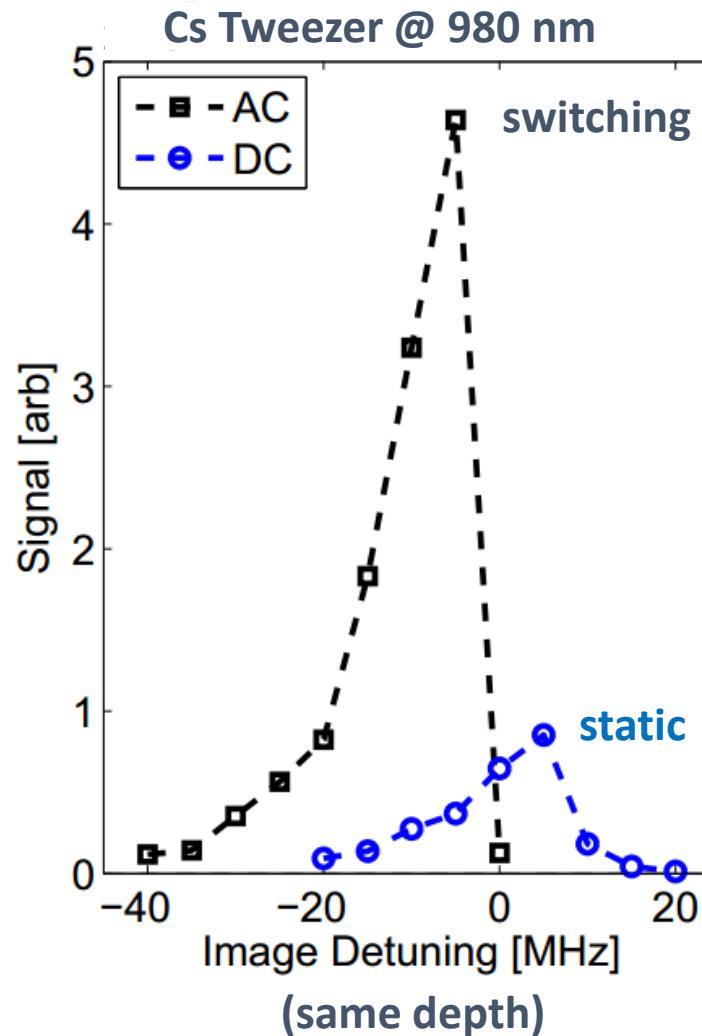
# Fast switching

- Alternate tweezer, MOT/imaging much faster than trap frequency
- Mix square wave with RF and send to AOM
- “AC Tweezer”
- MOT, molasses can still work with switching



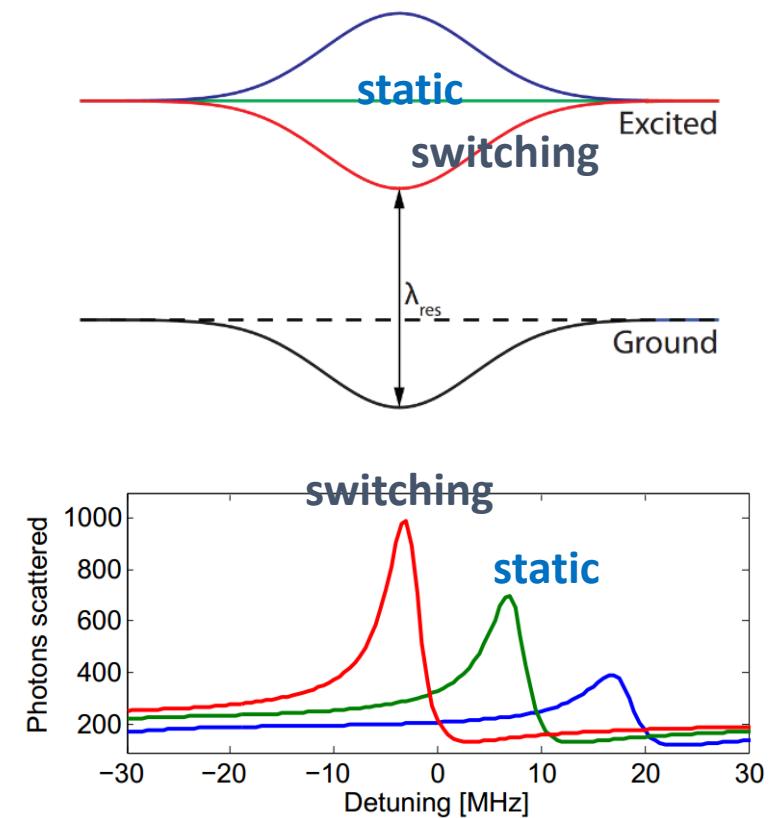
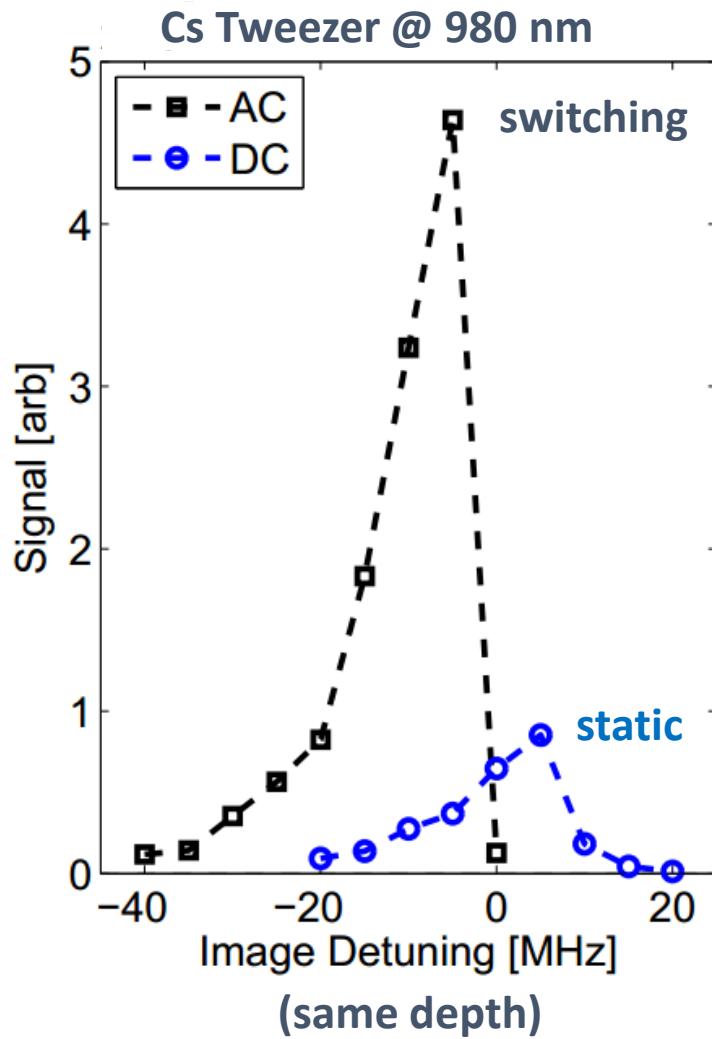
# Atom never sees light shift

- Looks like a magic wavelength trap
  - No resonance shift
  - No fluctuating dipole heating
- Enables loading when otherwise prevented
- Not wavelength dependent

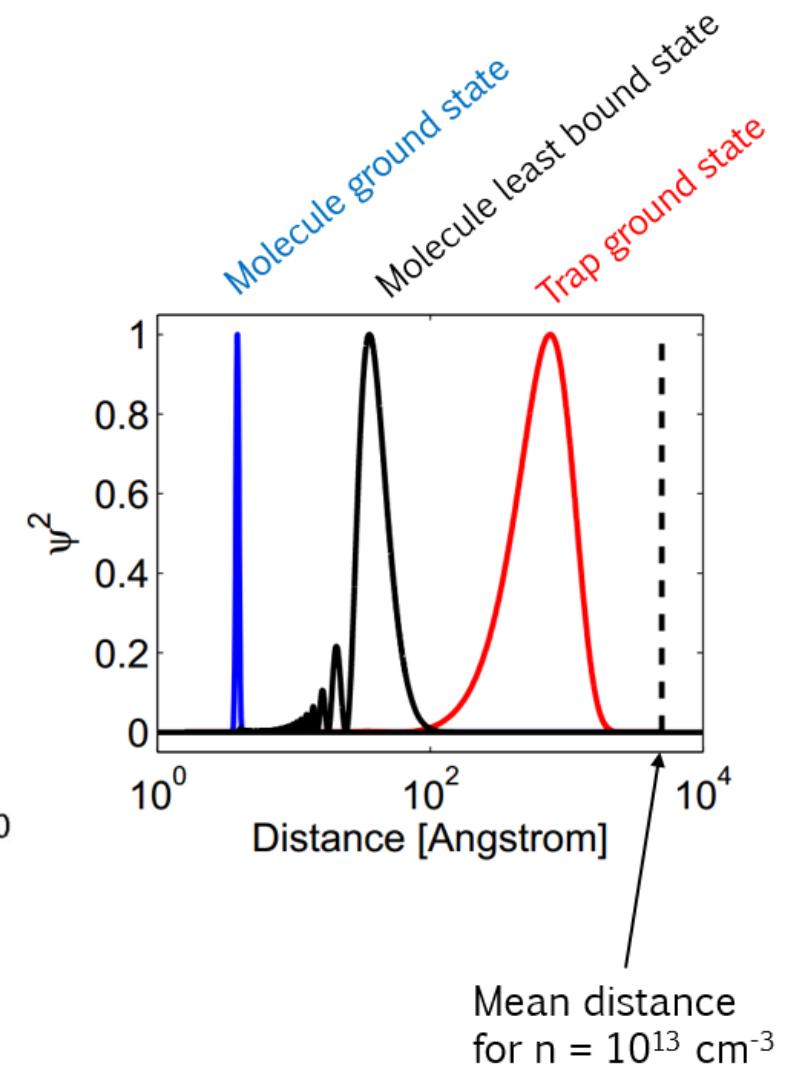
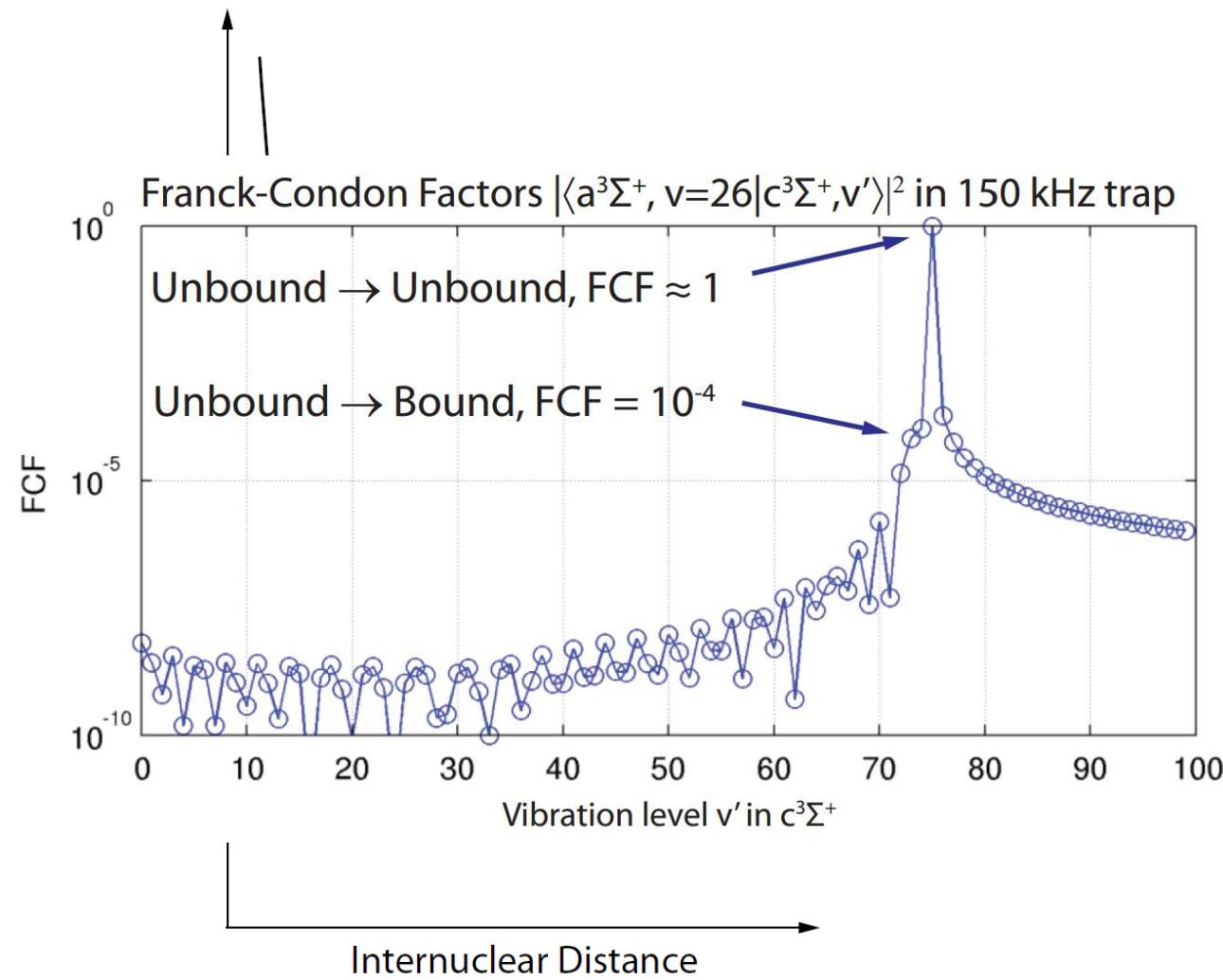


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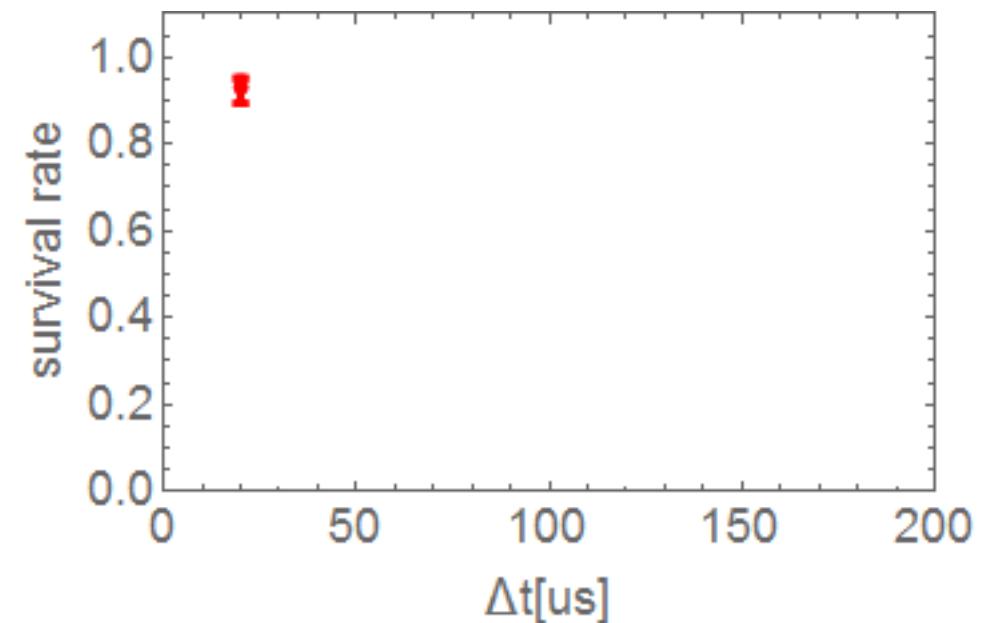
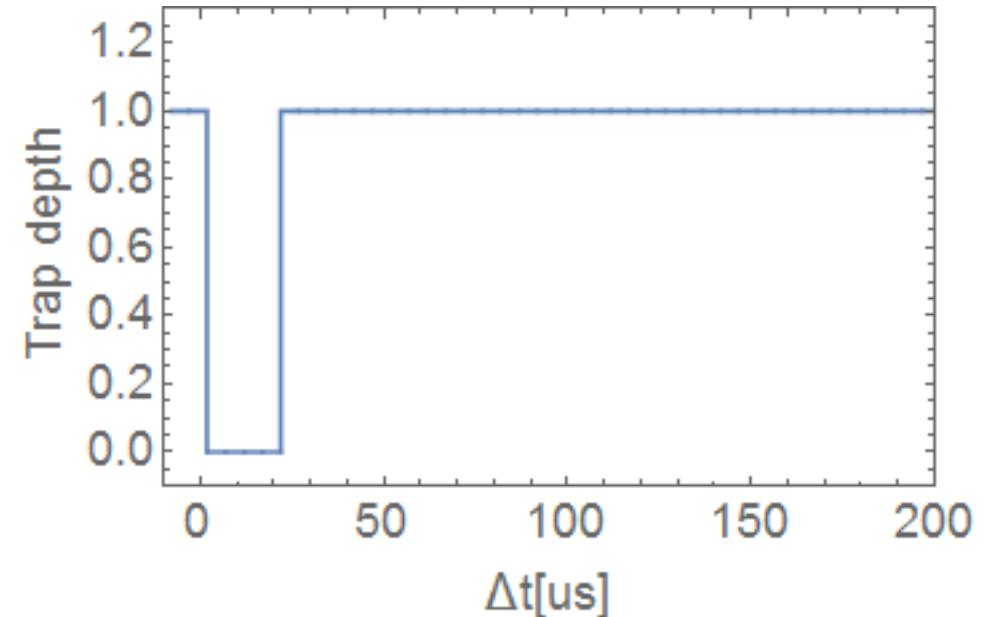


# Atoms to Molecules



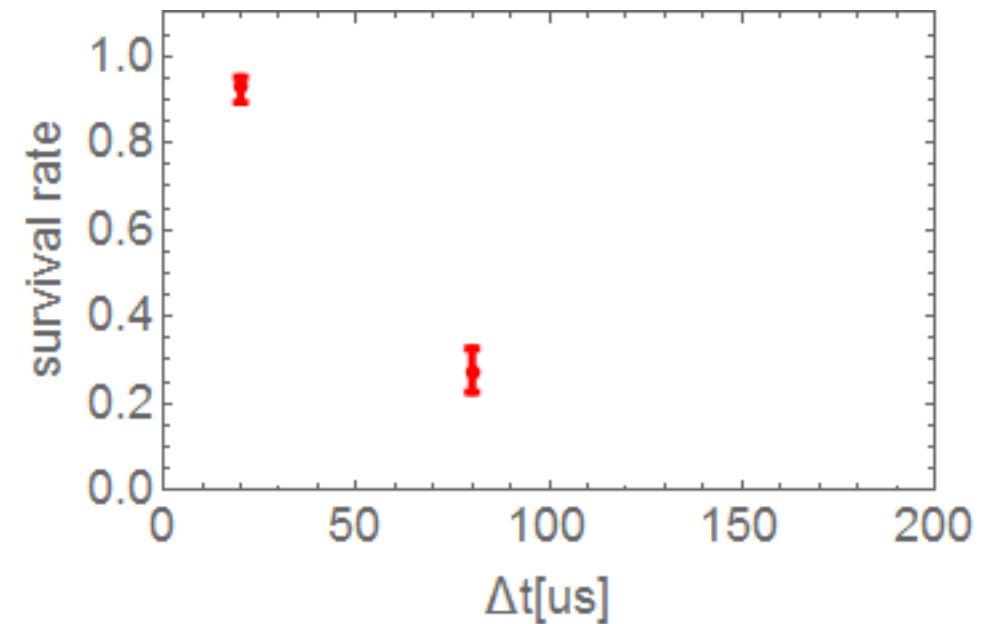
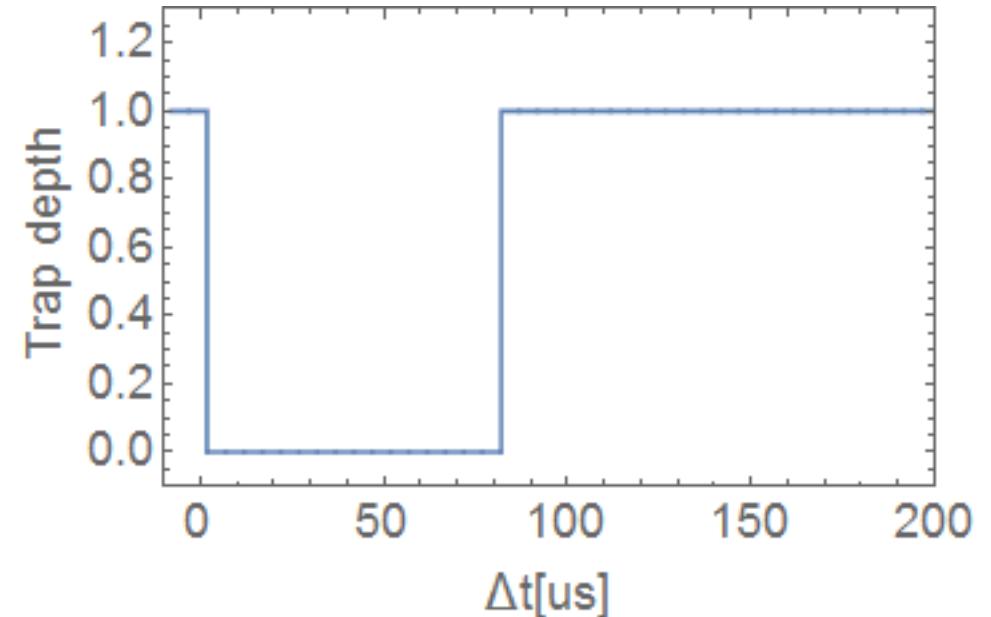
# Thermometry (coarse)

- “release and recapture”



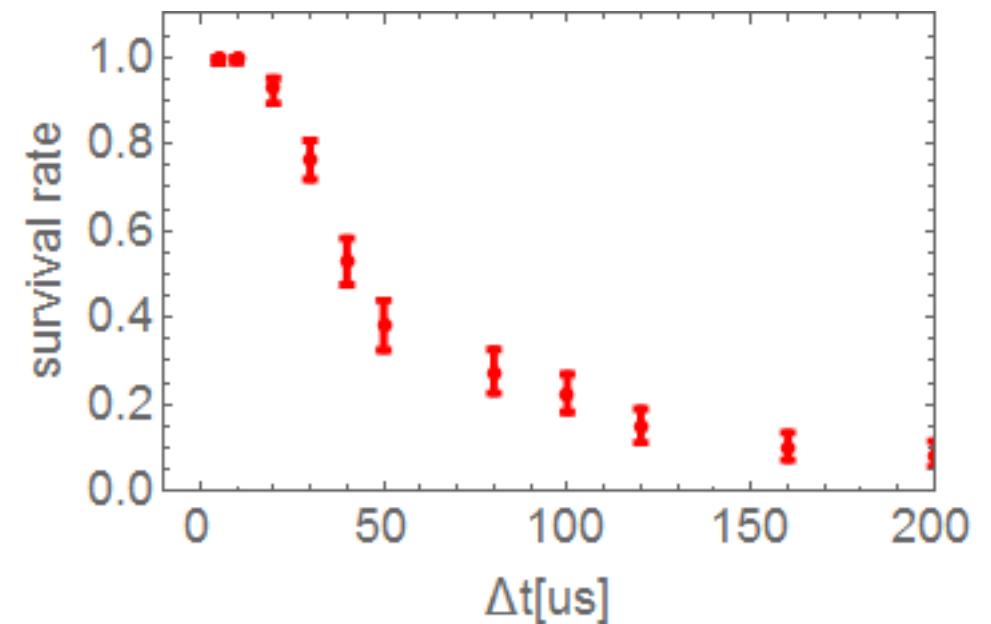
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- “release and recapture”



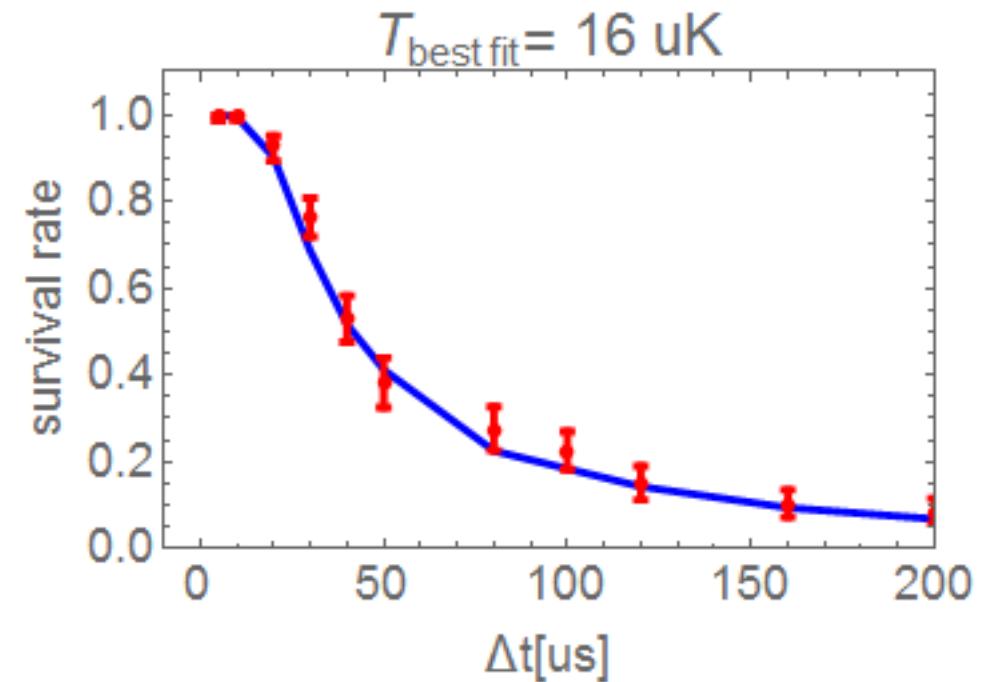
# Thermometry (coarse)

- “release and recapture”



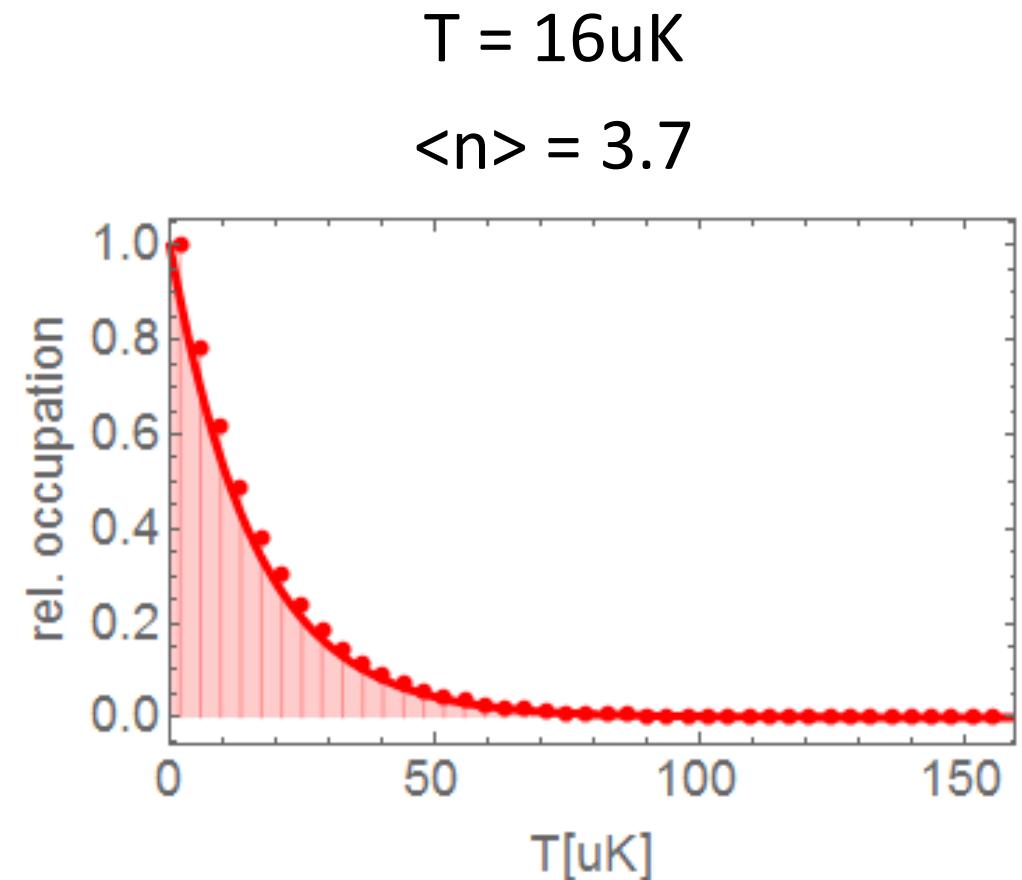
# Thermometry (coarse)

- “release and recapture”
- Classical monte carlo fit



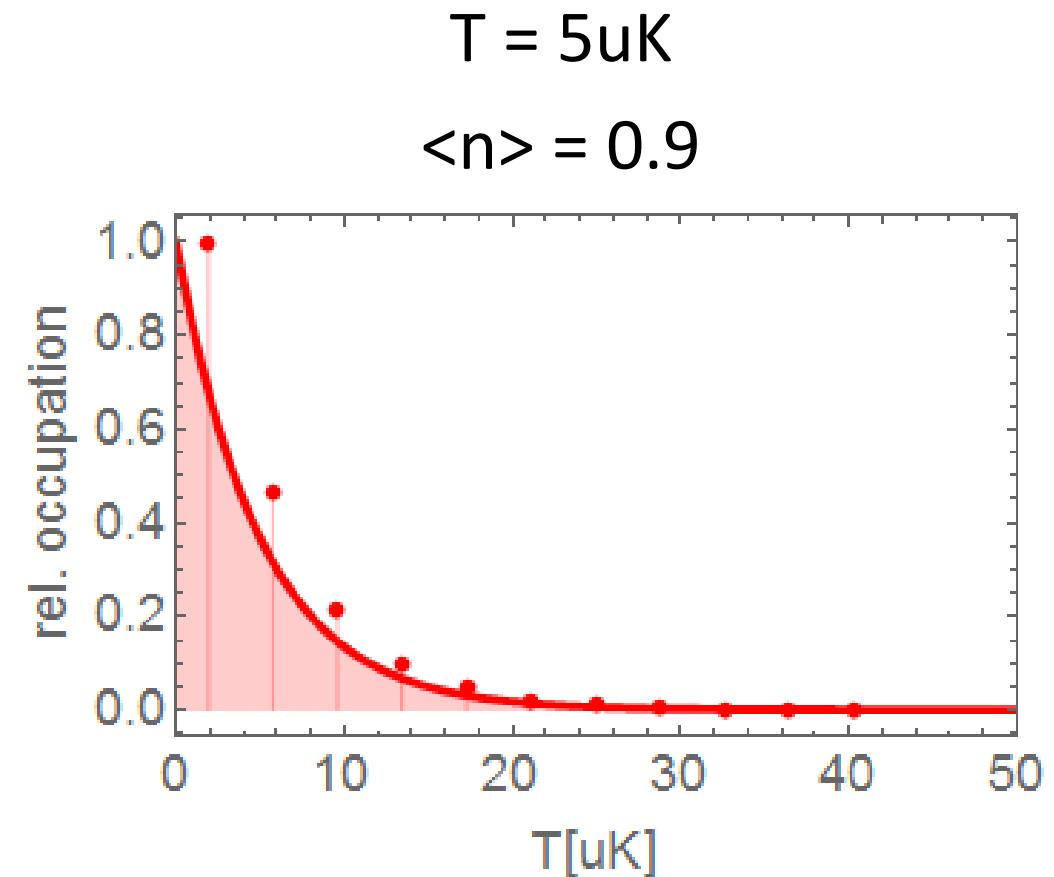
# Thermometry (coarse)

- “release and recapture”
- Classical monte carlo fit
- Saturation behaviour
  - Classical:  $e^{-n}/\langle n \rangle$
  - Quantum:  $\langle n \rangle^n / (\langle n \rangle + 1)^{n+1}$



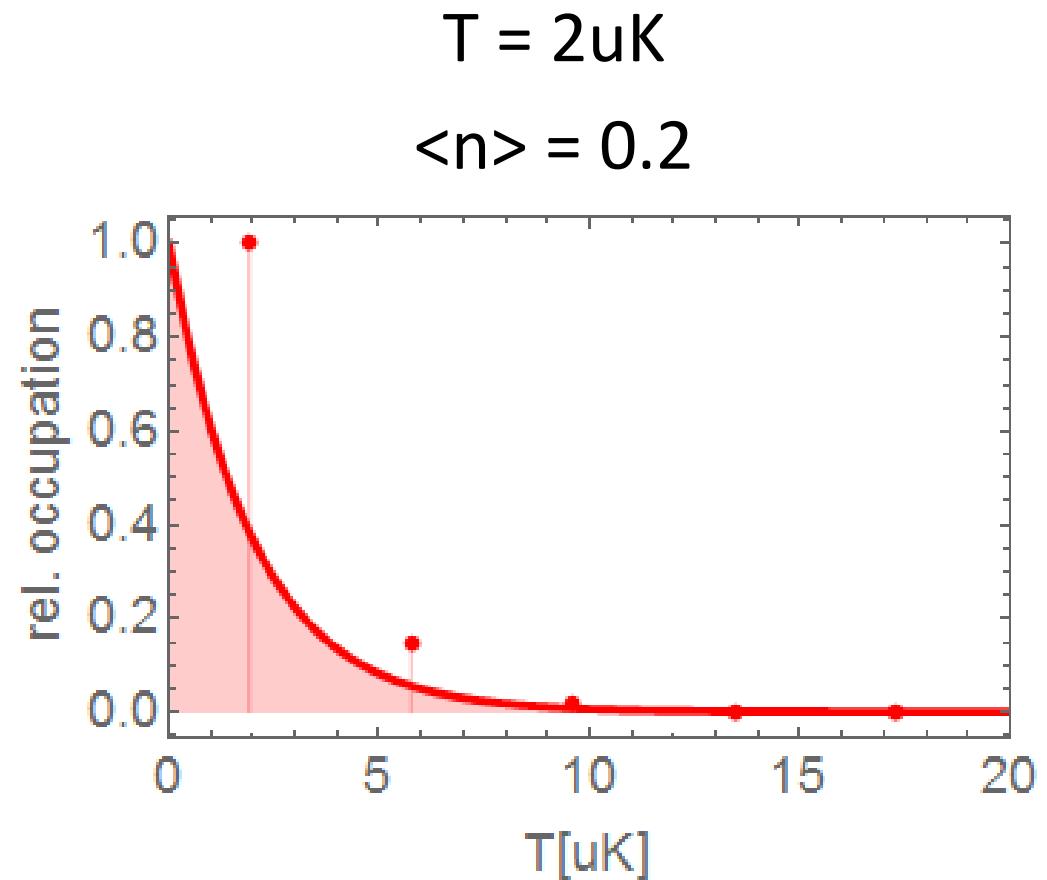
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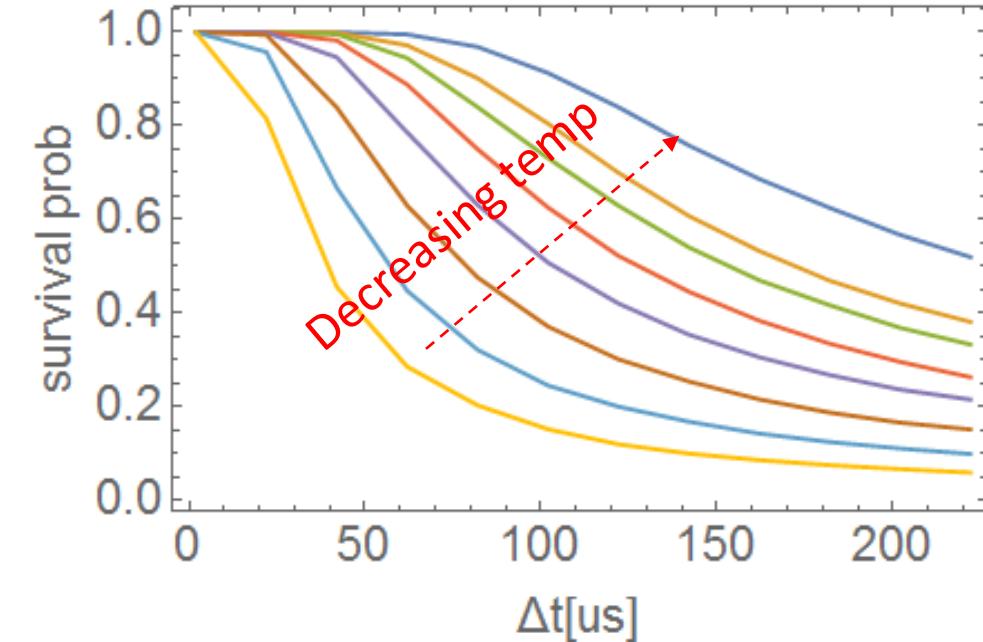
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# Thermometry (coarse)

- “release and recapture”      Classical:
- Classical monte carlo fit
- Saturation behaviour
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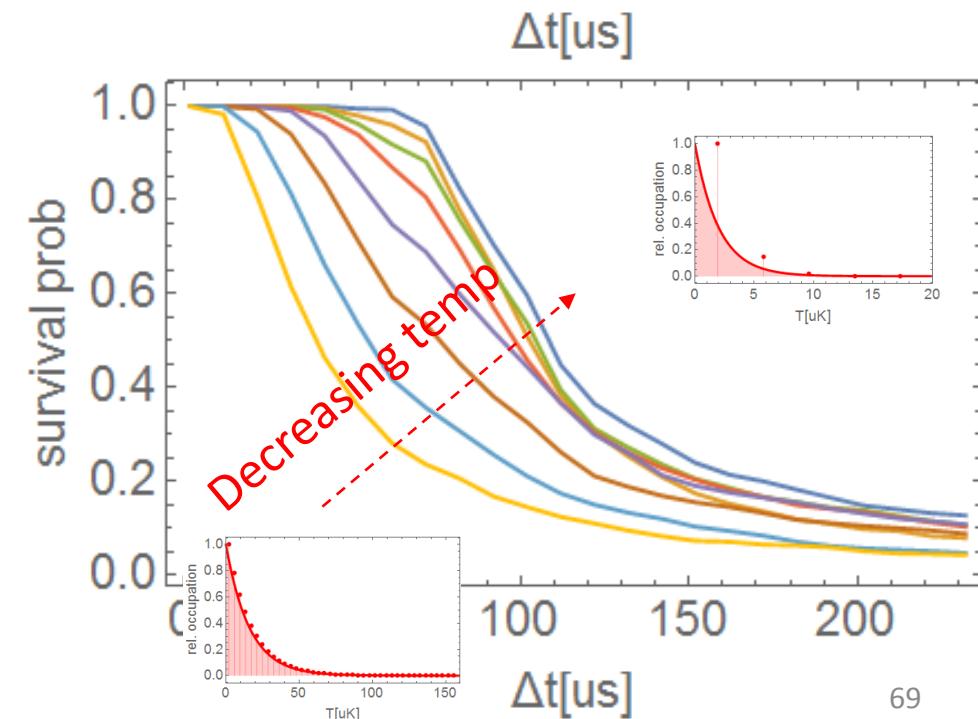
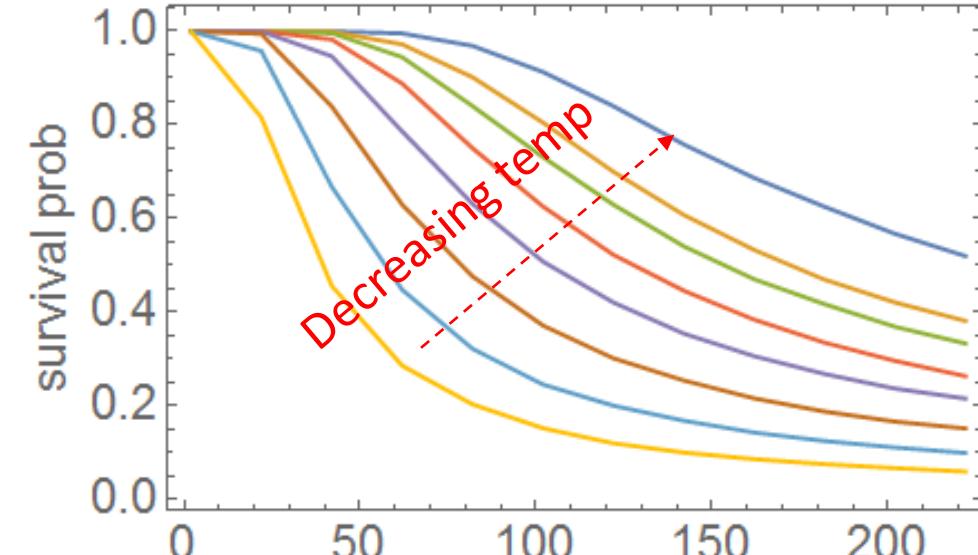


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- “release and recapture”
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  - Quantum:  $\langle n \rangle^n / (\langle n \rangle + 1)^{n+1}$

Classical:

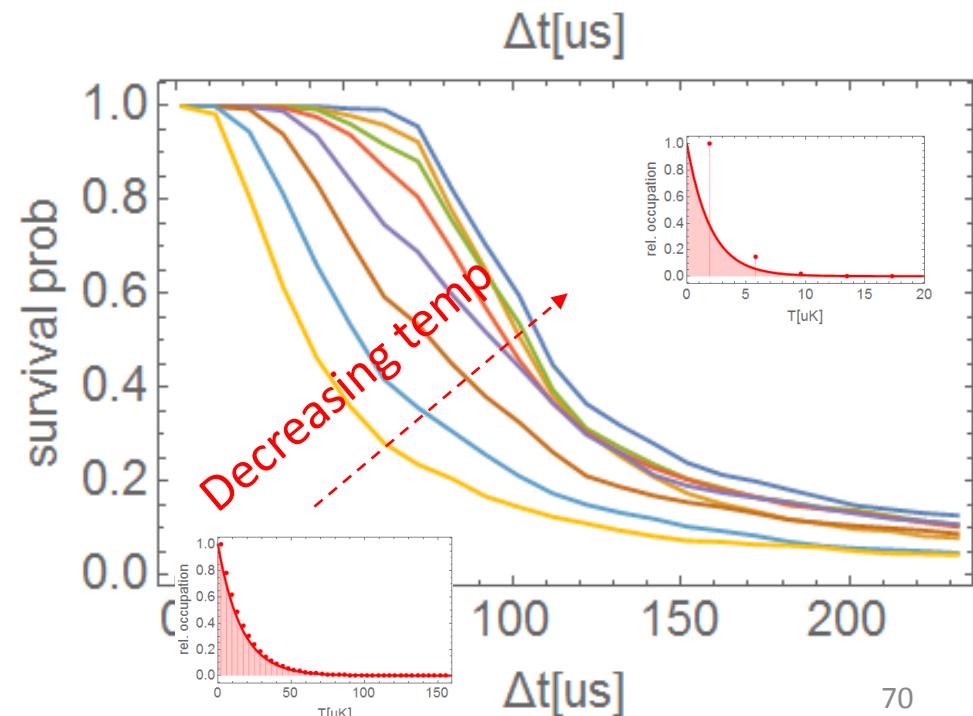
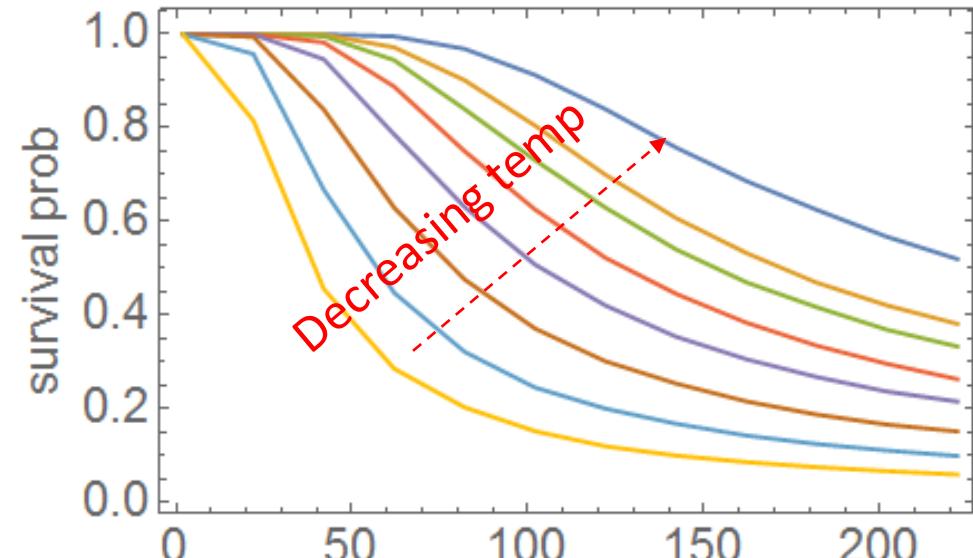
Quantum:



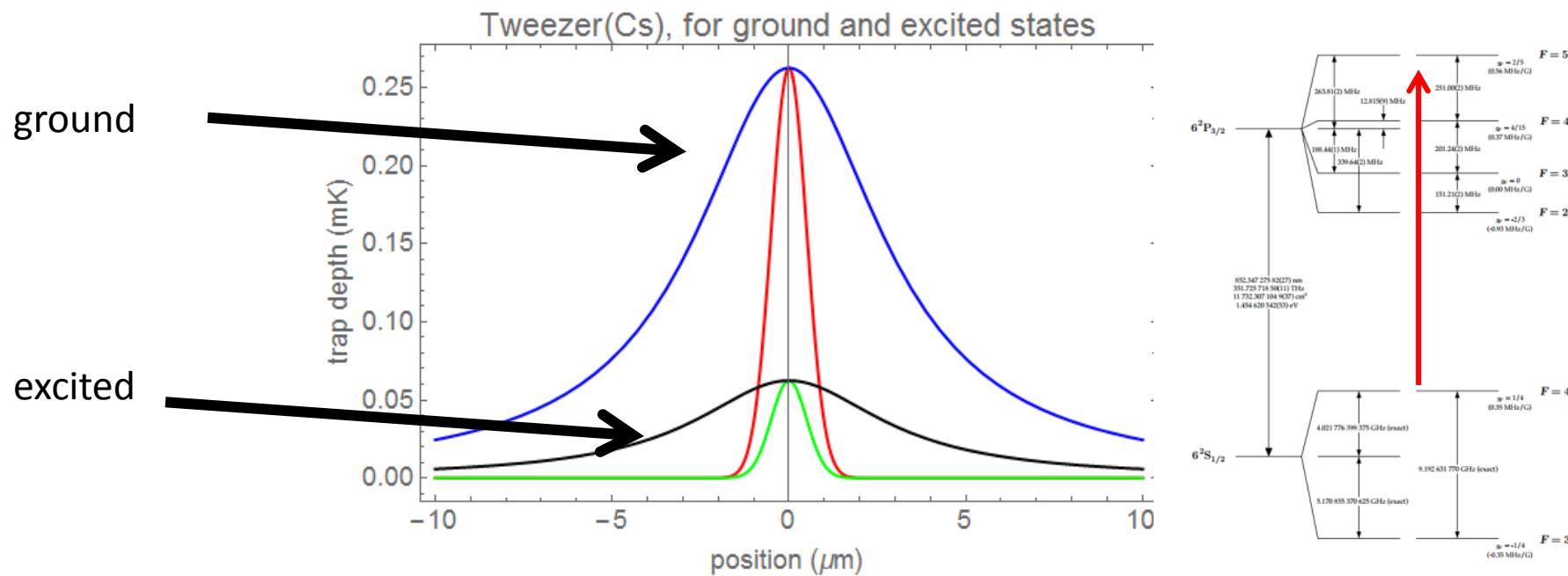
# Thermometry (coarse)

- “release and recapture”      Classical:
- Classical monte carlo fit
- Saturation behaviour
  - Classical:  $e^{-n}/\langle n \rangle$
  - Quantum:  $\langle n \rangle^n / (\langle n \rangle + 1)^{n+1}$
- 2 models diverge  
 $\langle n \rangle \sim 0.8$  (5uK)
  - Optimization signal saturates  
 $\langle n \rangle \sim 0.03$  (1uK)

Quantum:



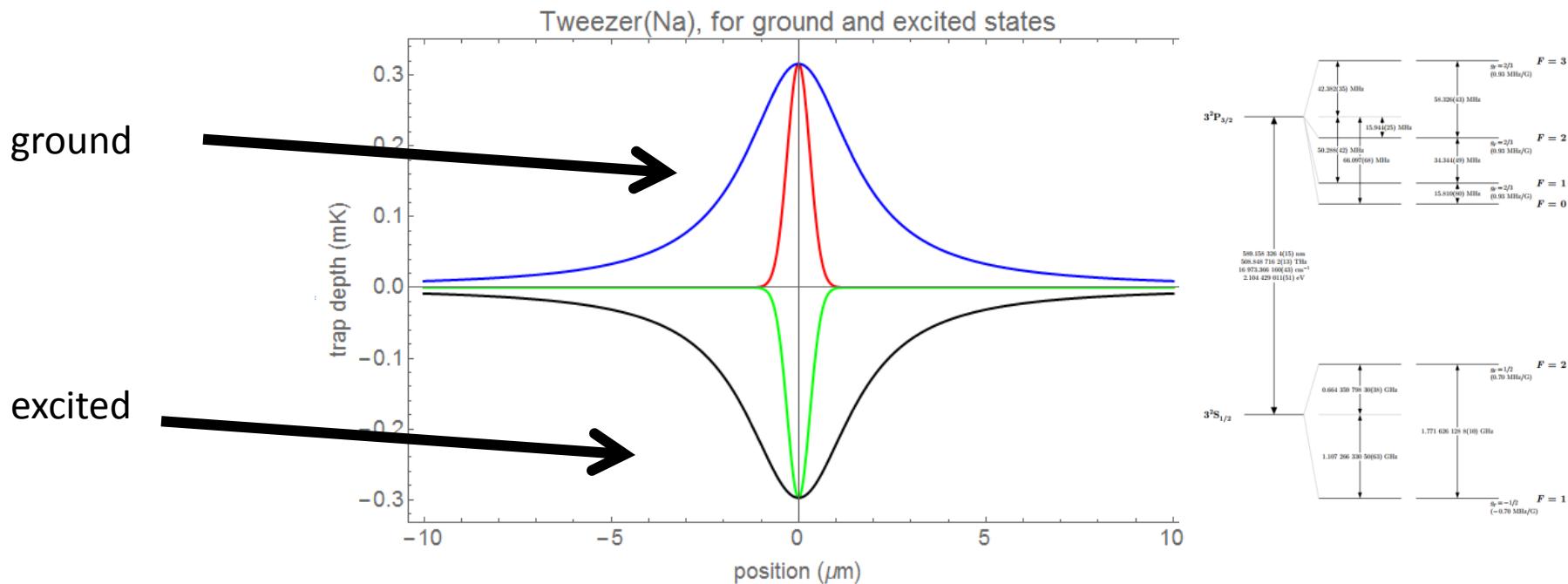
# Cs tweezer (980 nm)



- small lightshift/trap depth 16 MHz/ 1mK
- well separated excited state hyperfine structure ~200 MHz
- Doppler temp: 125 uK
- Linewidth: 5 MHz

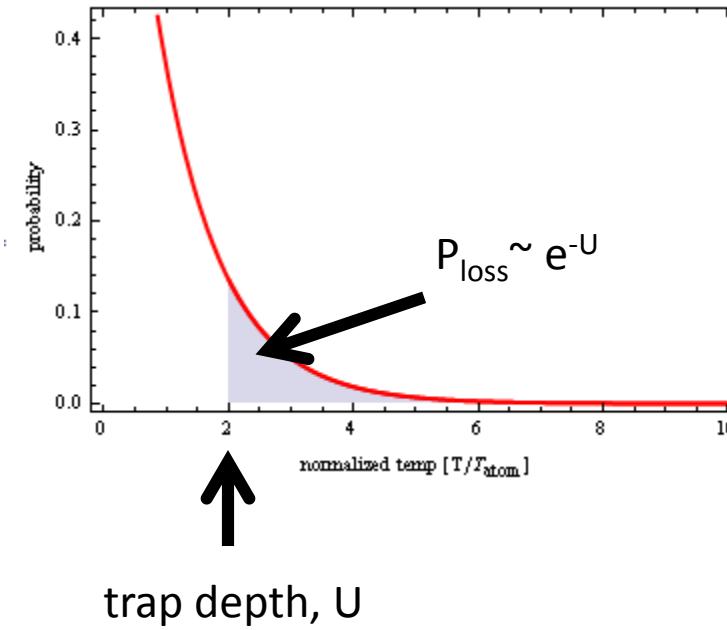
600 uK trap, 5 MHz light shift

# Na tweezer (660 nm)



- BIG lightshift/trap depth 40 MHz/ 1mK
- DENSE excited state hyperfine structure ~60 MHz
- Doppler temp: 235 uK (500 uK ~ 1mK in our setup)
- Linewidth: 10 MHz
- narrow range of permissible trap depths.
- excited state is highly anti-trapped

# Trap depth



Probability of kicking atom out is  $P_{\text{loss}} \sim e^{-U}$

$$N \sim 10^4$$

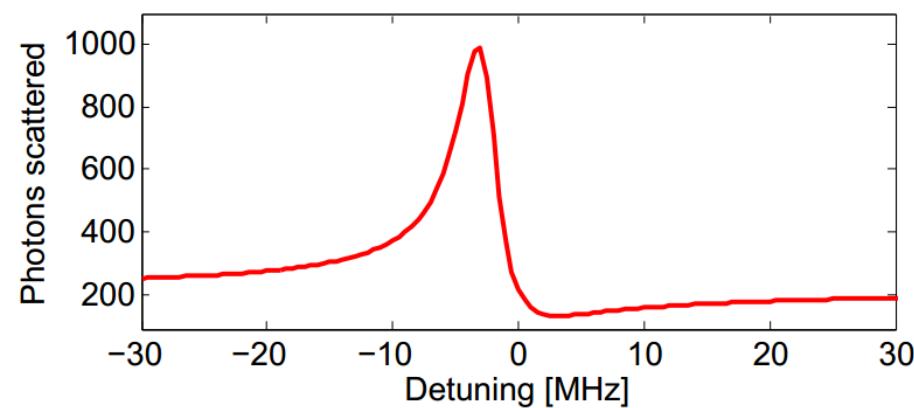
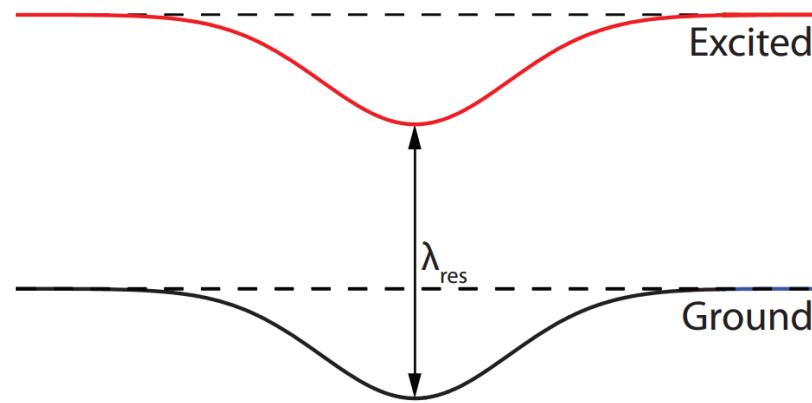
$$N P_{\text{loss}} < 1 \rightarrow U \sim 10$$

Need a very deep trap  $\rightarrow$  need to decouple imaging and loading

$\rightarrow$  "live loading" out of the question

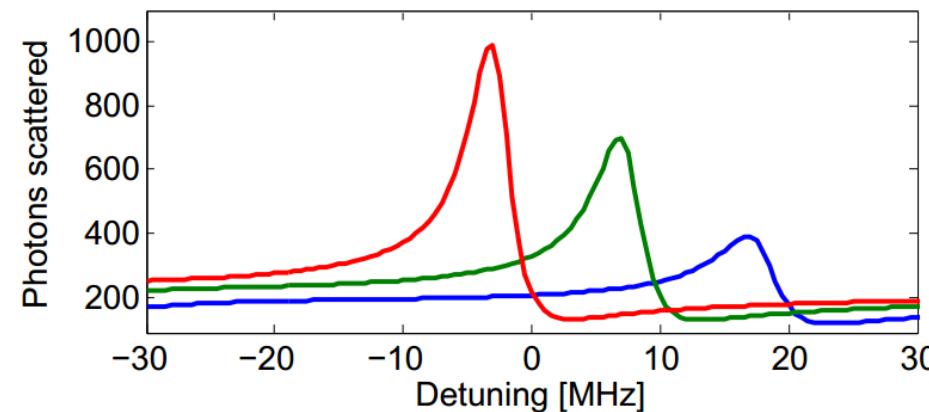
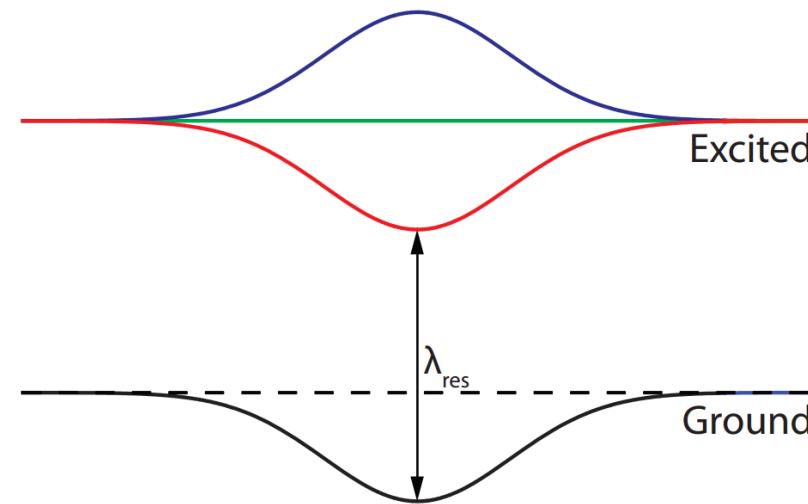
# Light Shifts

- Tweezer shifts levels



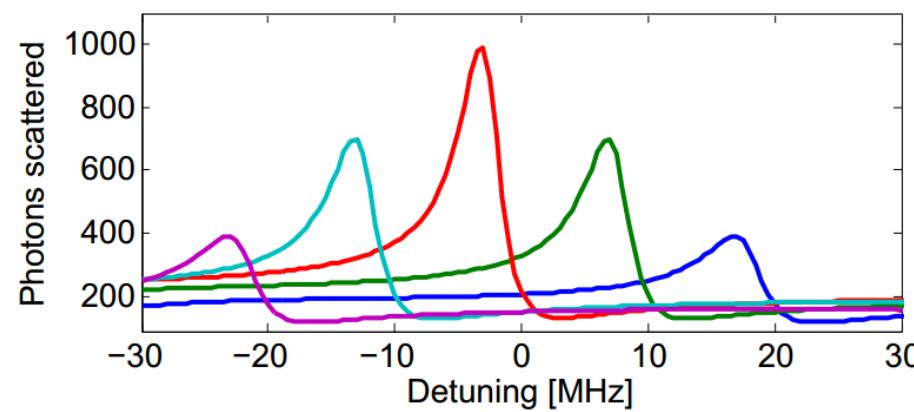
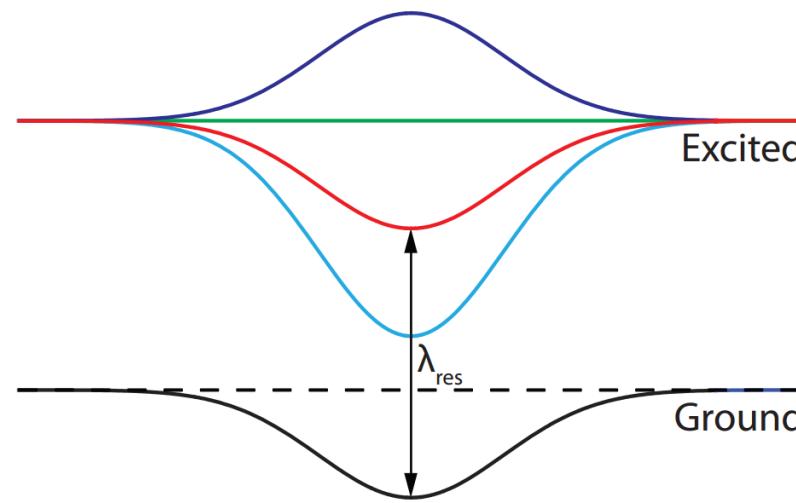
# Light Shifts

- Tweezer shifts levels
- Shifts resonance, and gives rise to fluctuating dipole force heating

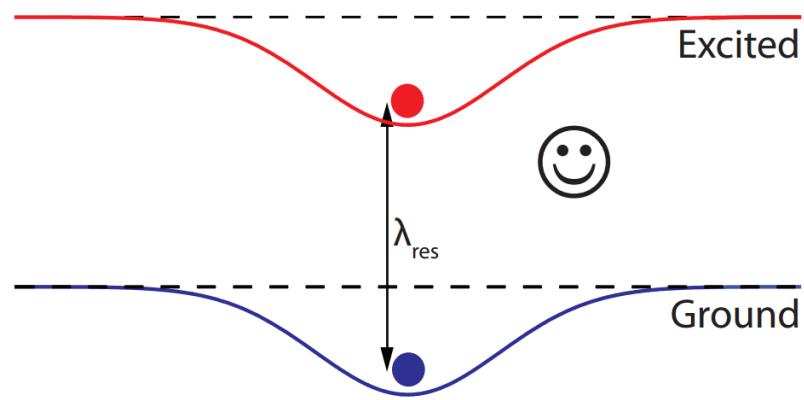


# Light Shifts

- Tweezer shifts levels
- Shifts resonance, and gives rise to fluctuating dipole force heating

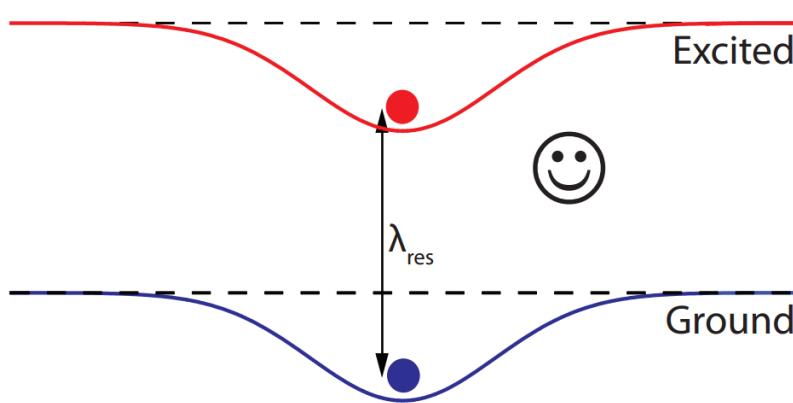


# Loading and Light Shifts

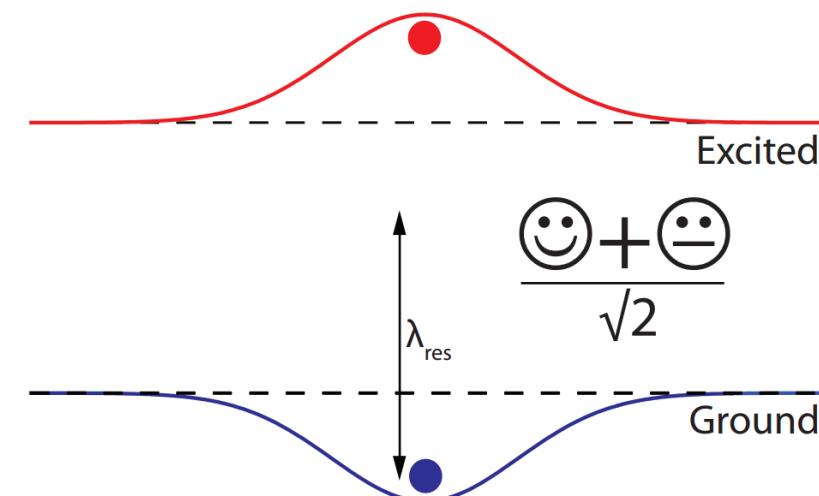


Example: Cs

# Loading and Light Shifts

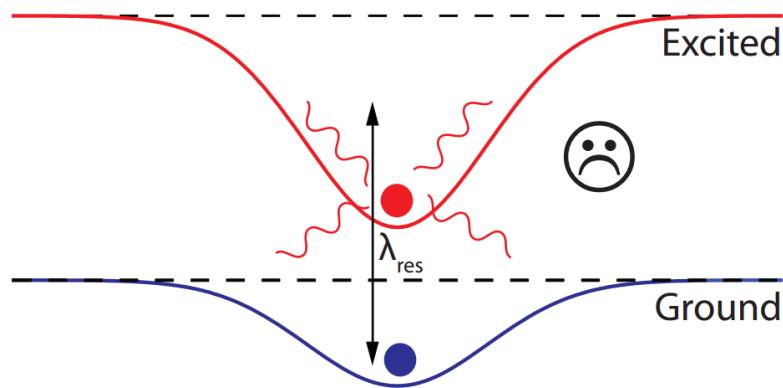


Example: Cs

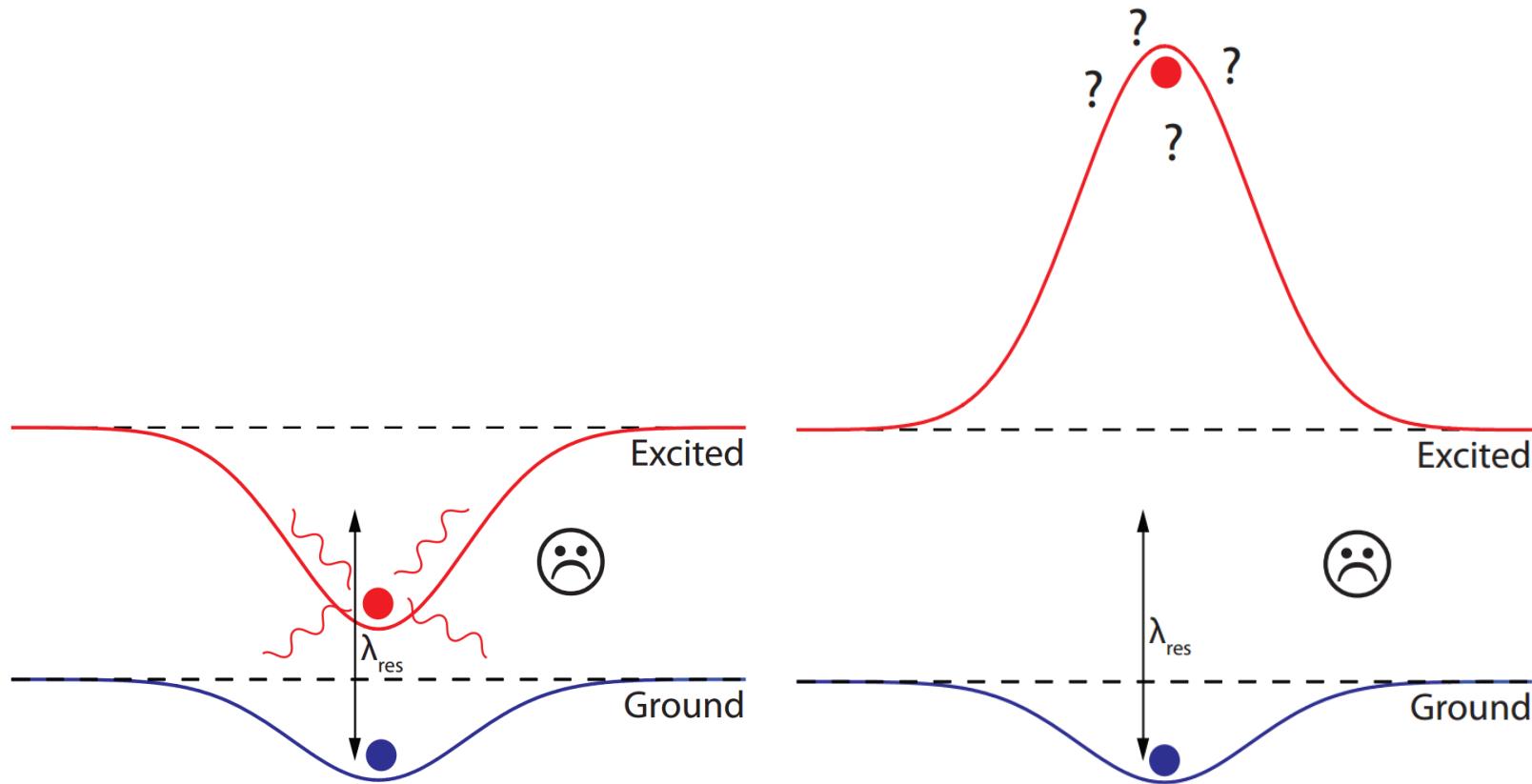


Example: Rb

# Loading and Light Shifts

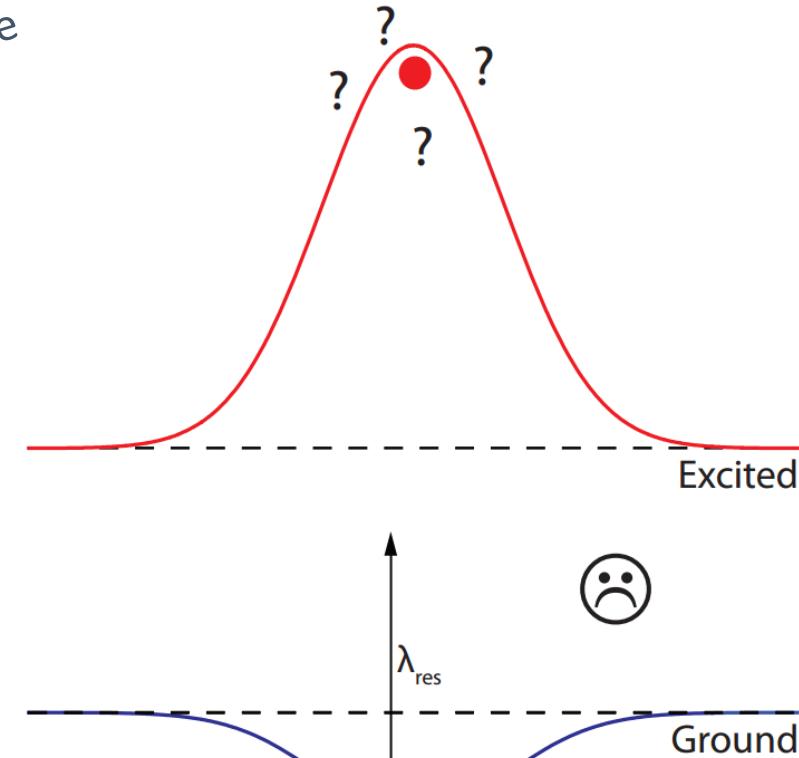
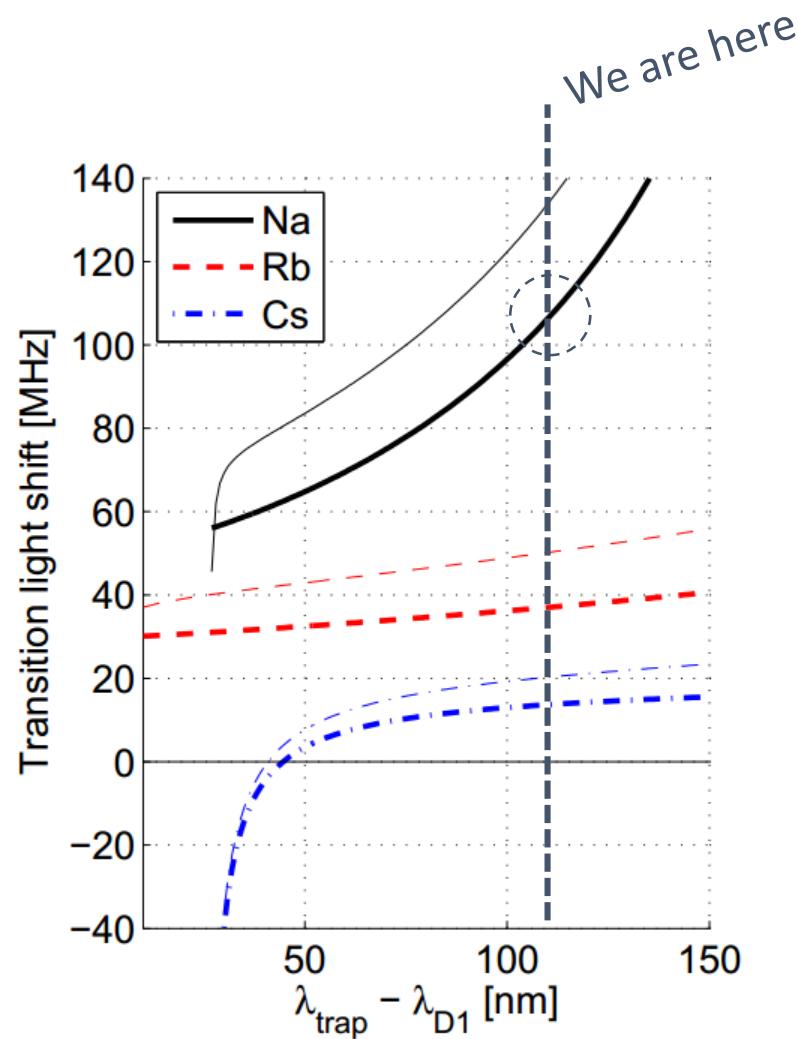


# Loading and Light Shifts



Example: Na

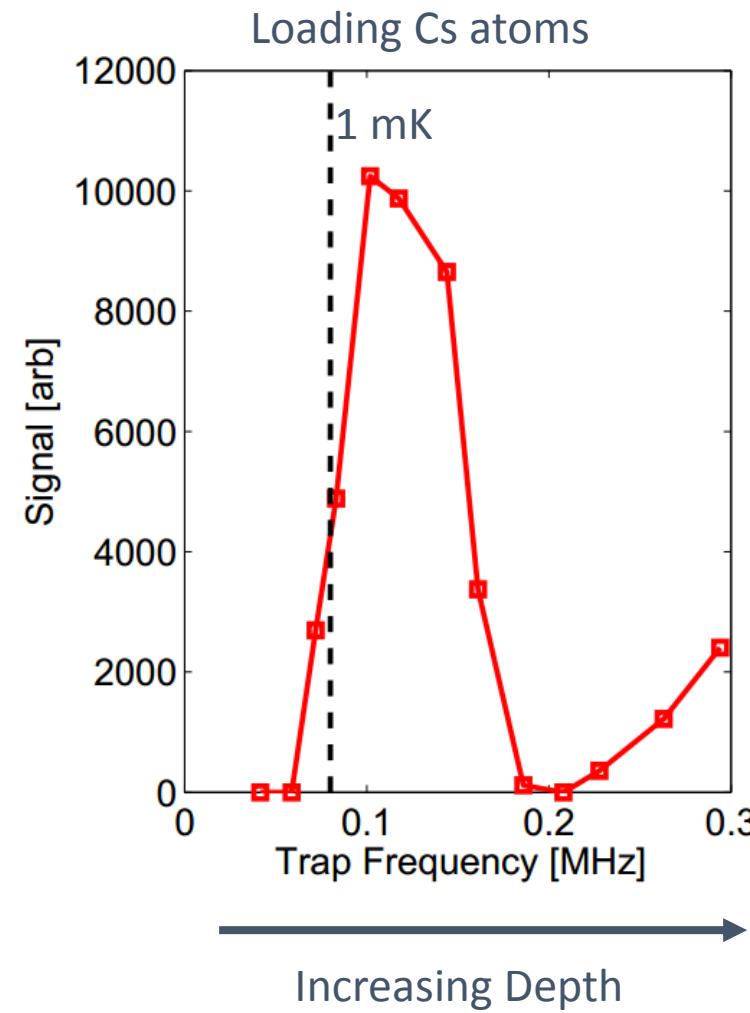
# Loading and Light Shifts



Example: Na

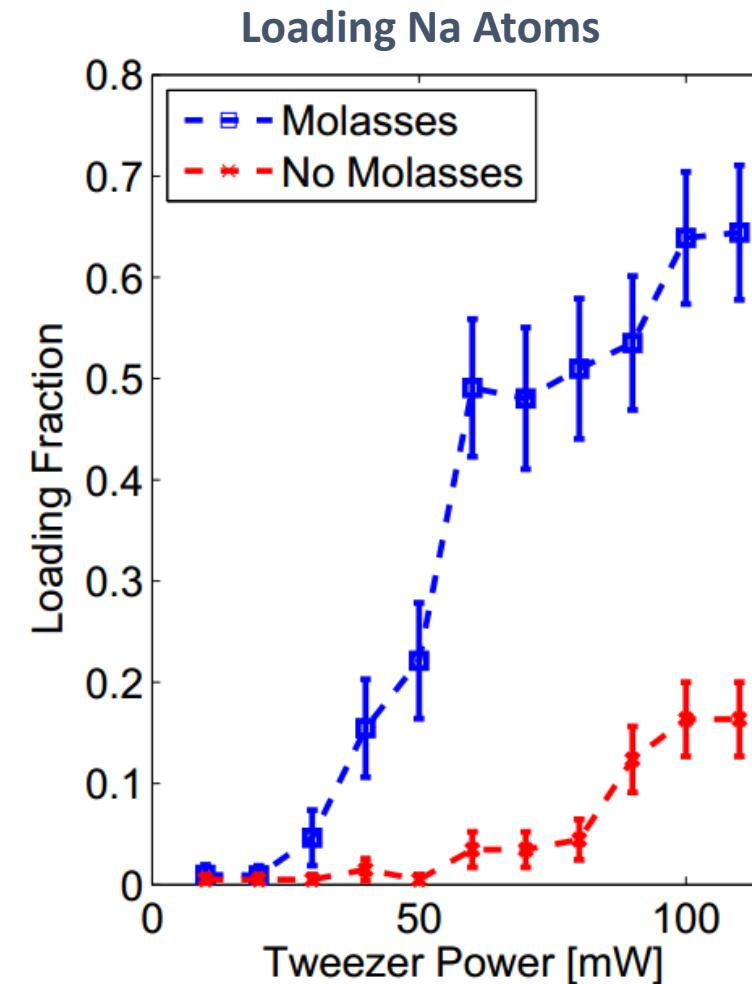
# Modulation Frequency Requirements

- Greater than  $2 \times f_{\text{trap}}$
- Less than  $1/2\pi\tau_{\text{rad}}$
- Generally easy to satisfy, even for tweezers/lattices



# Loading Sodium from Molasses

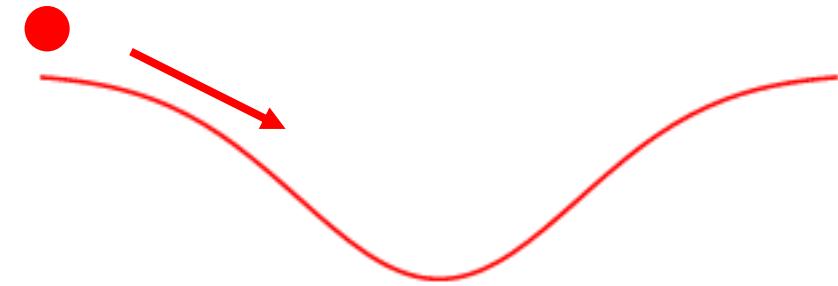
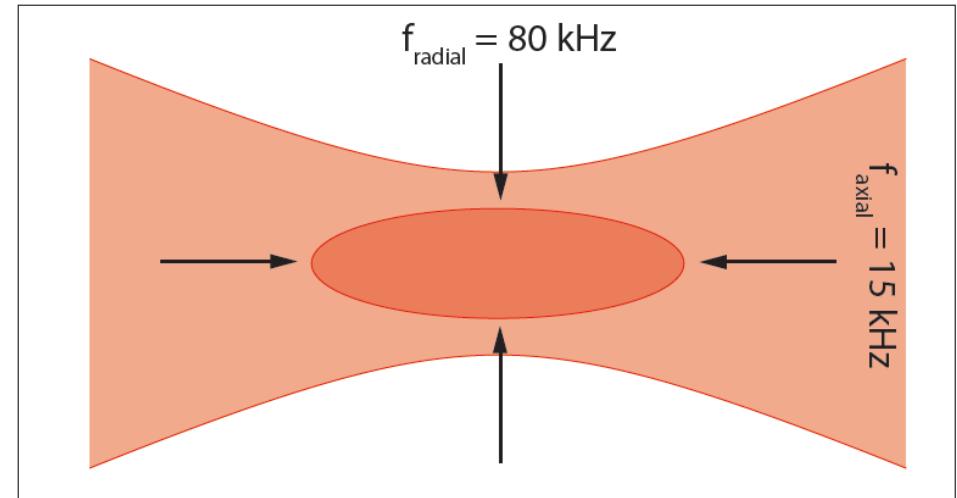
- Loading from molasses reduces tweezer power requirements
- We can now load single atoms of Na into our tweezer



# Loading Cesium

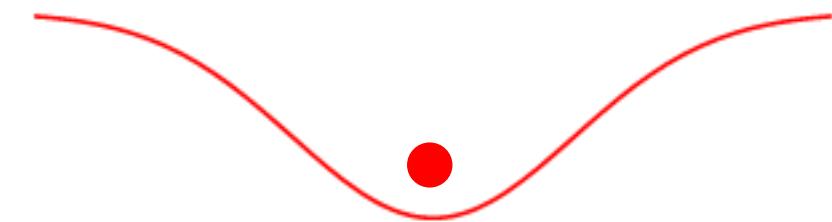
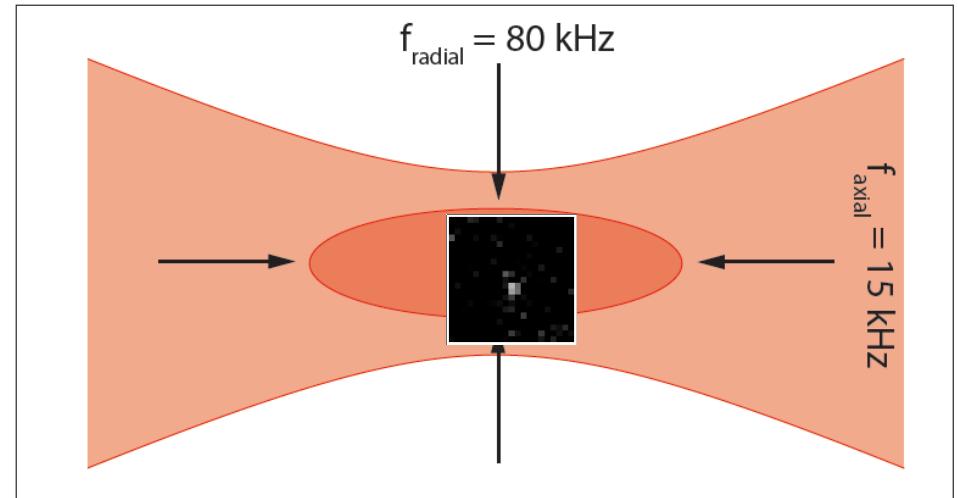
# Loading

Diffraction limited trap



# Loading

Diffraction limited trap

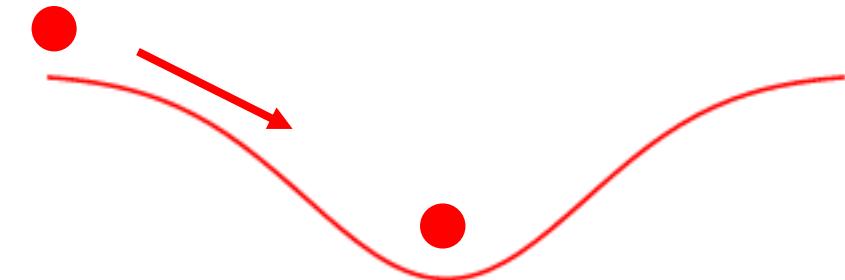
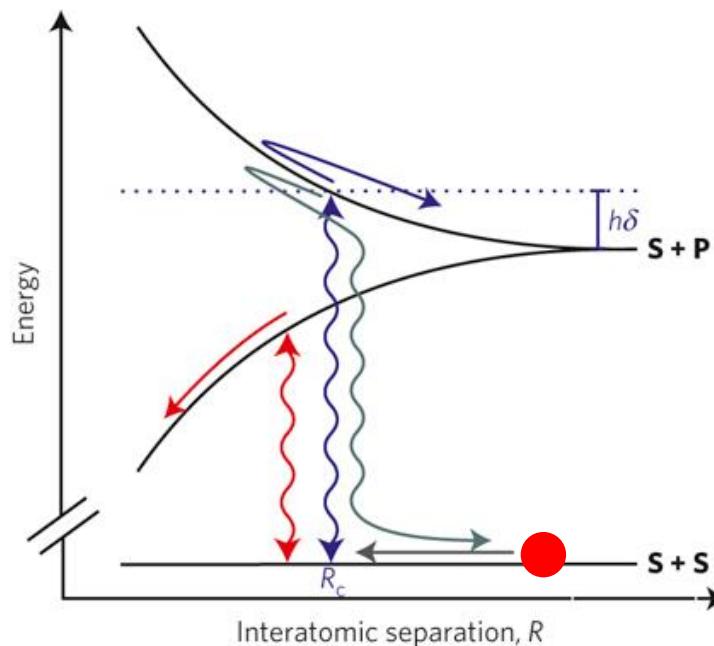
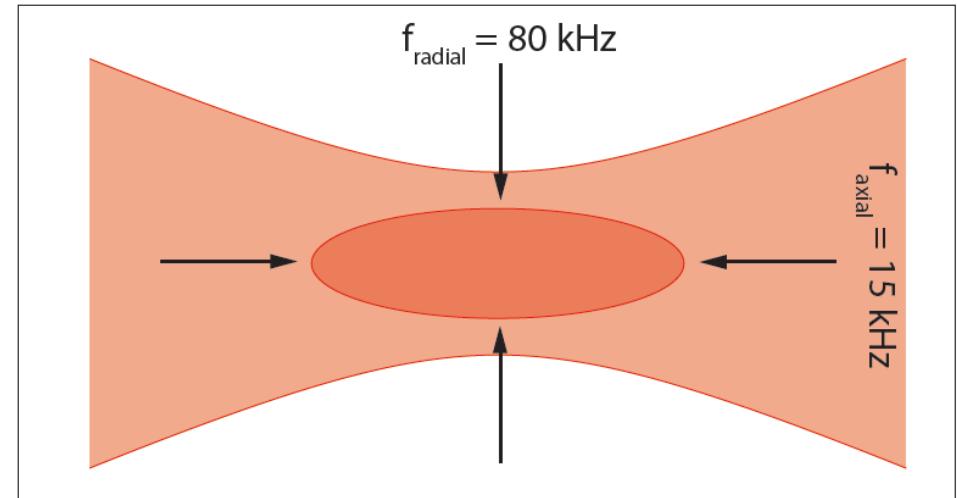


# Loading

Diffraction limited trap

+

Light assisted collisions



# Loading

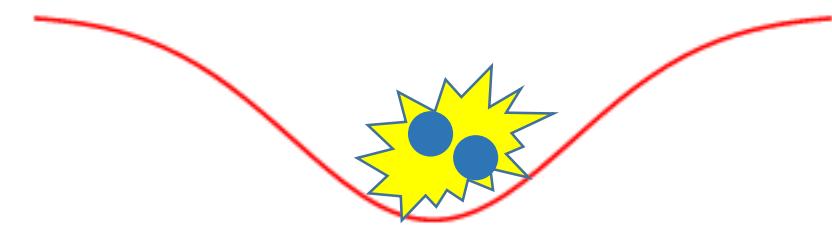
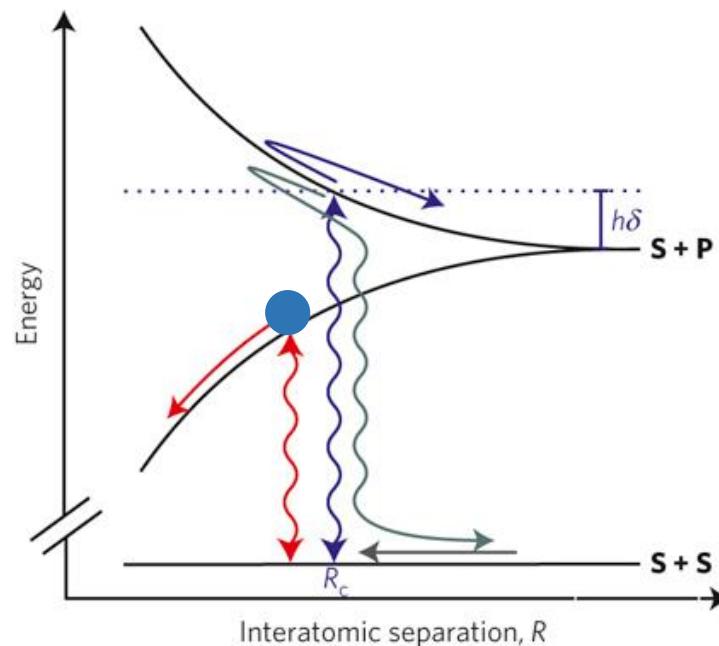
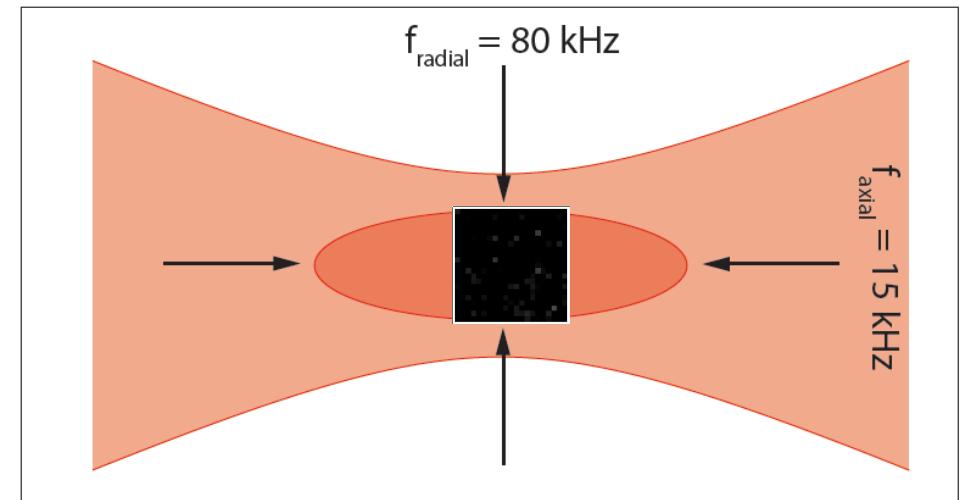
Diffraction limited trap

+

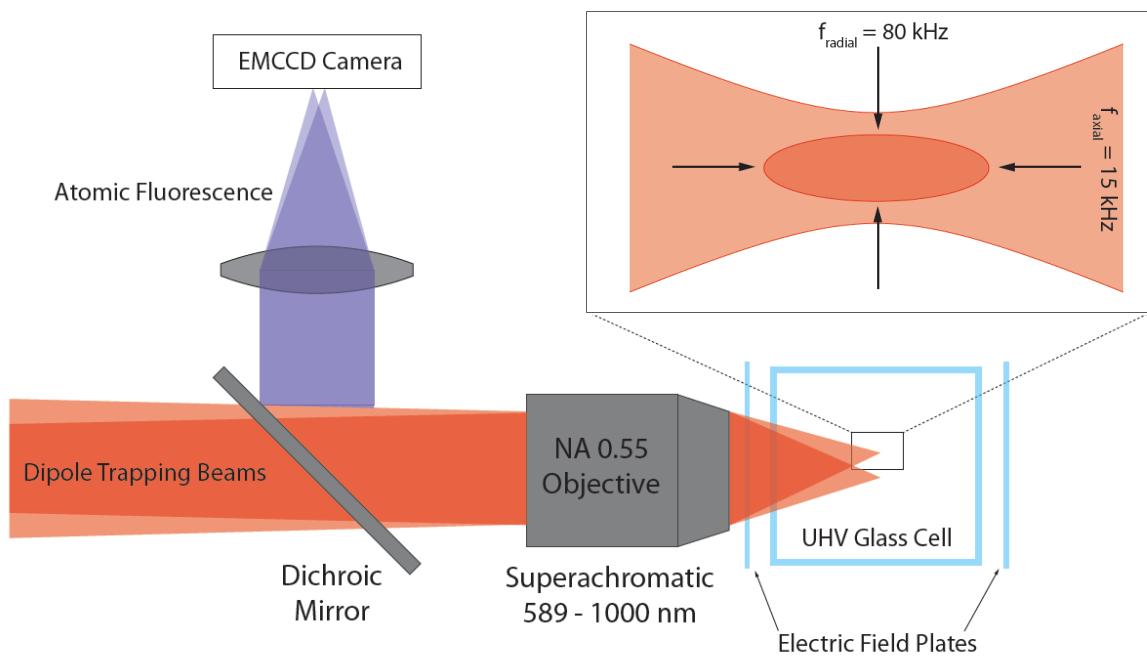
Light assisted collisions

=

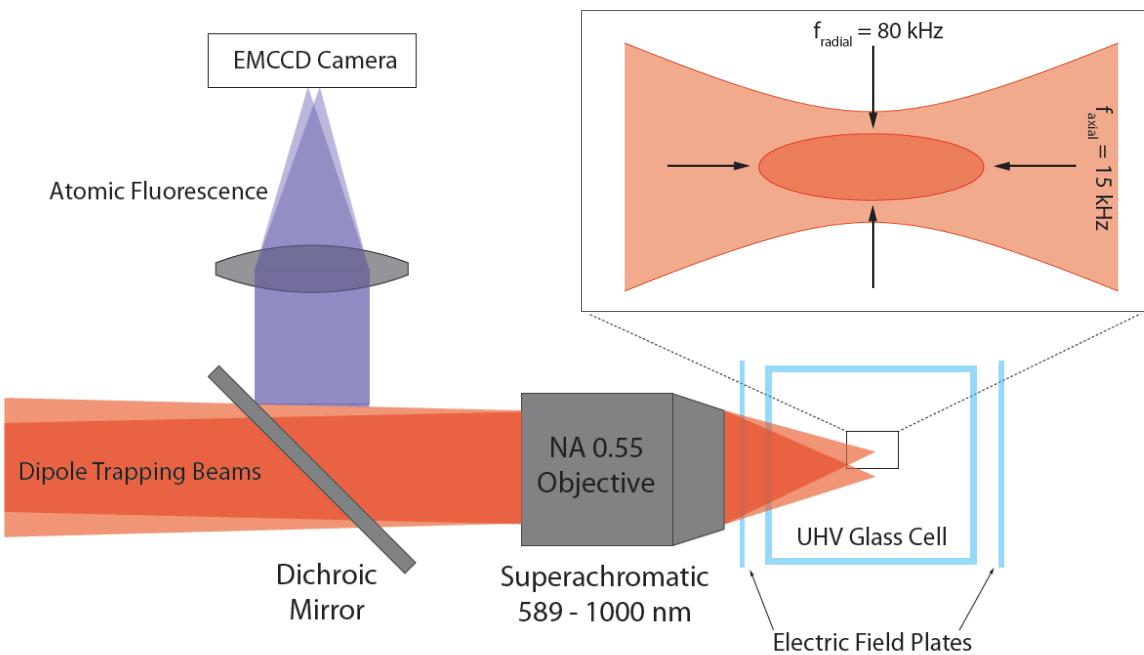
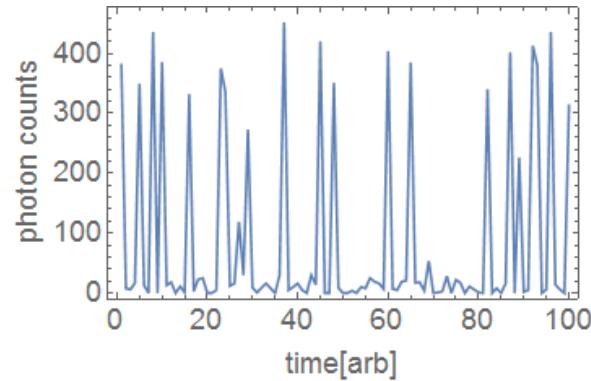
Collisional Blockade



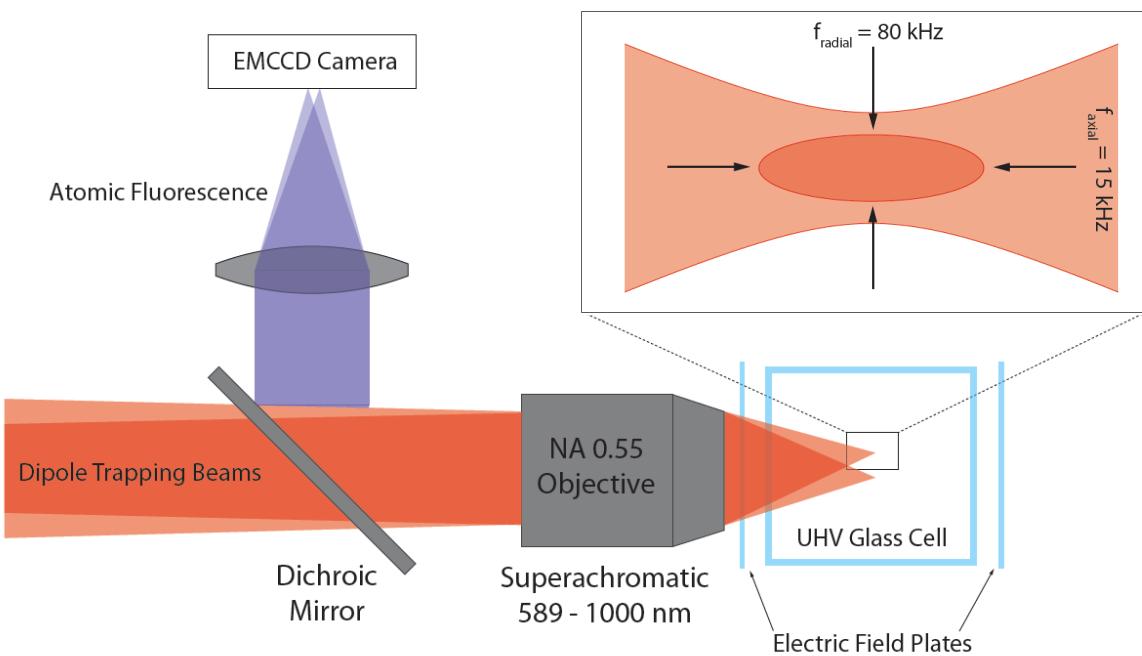
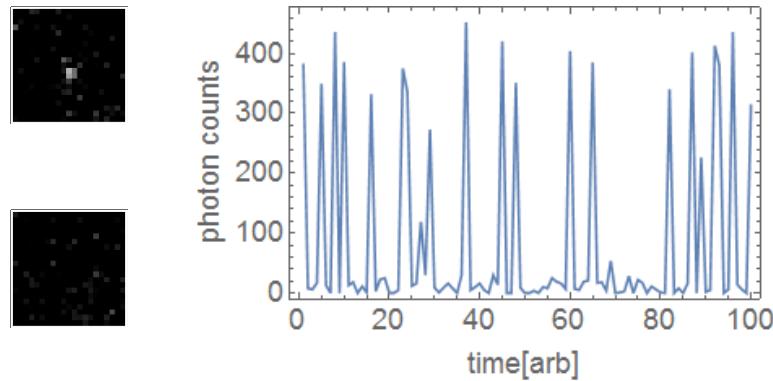
# Imaging/detection



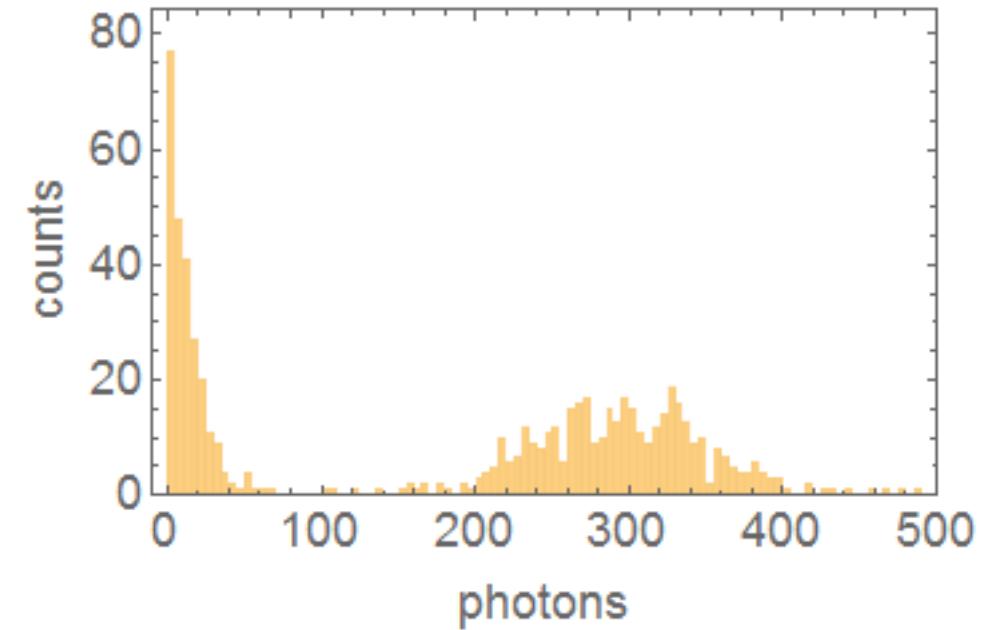
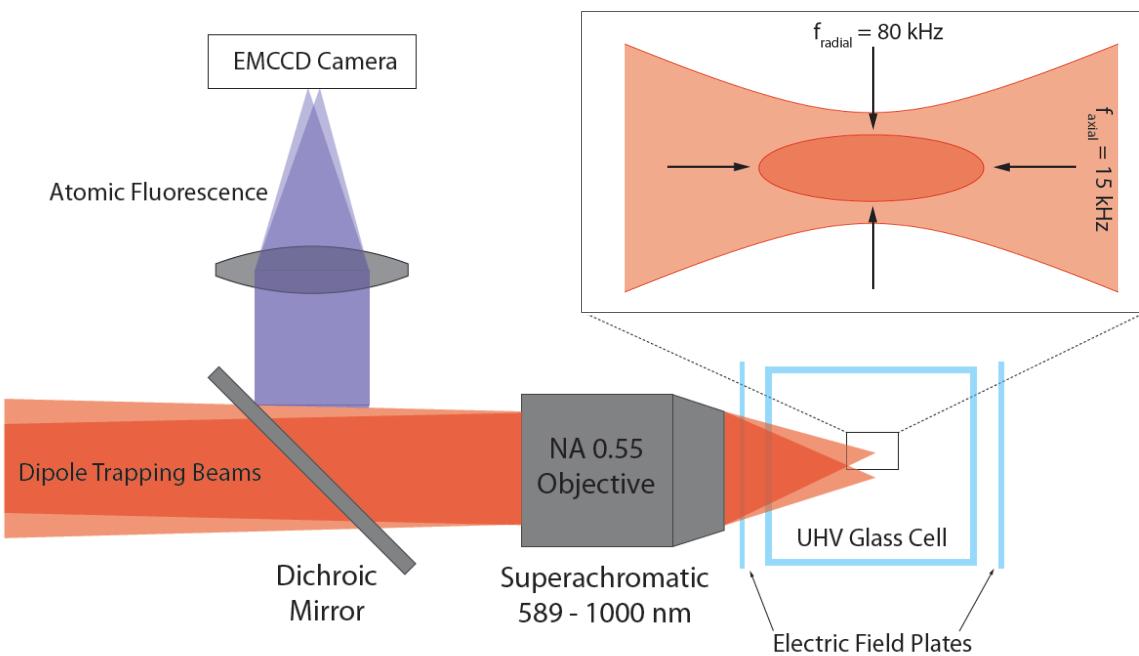
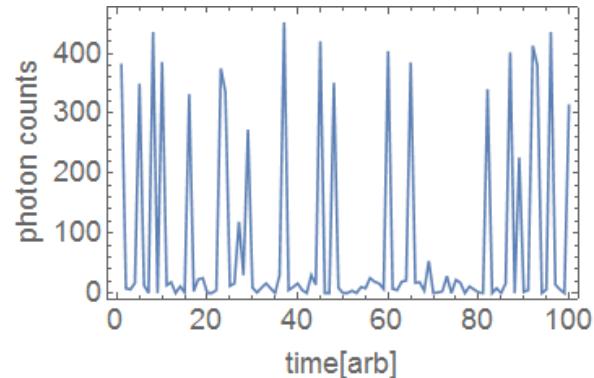
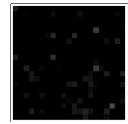
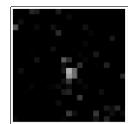
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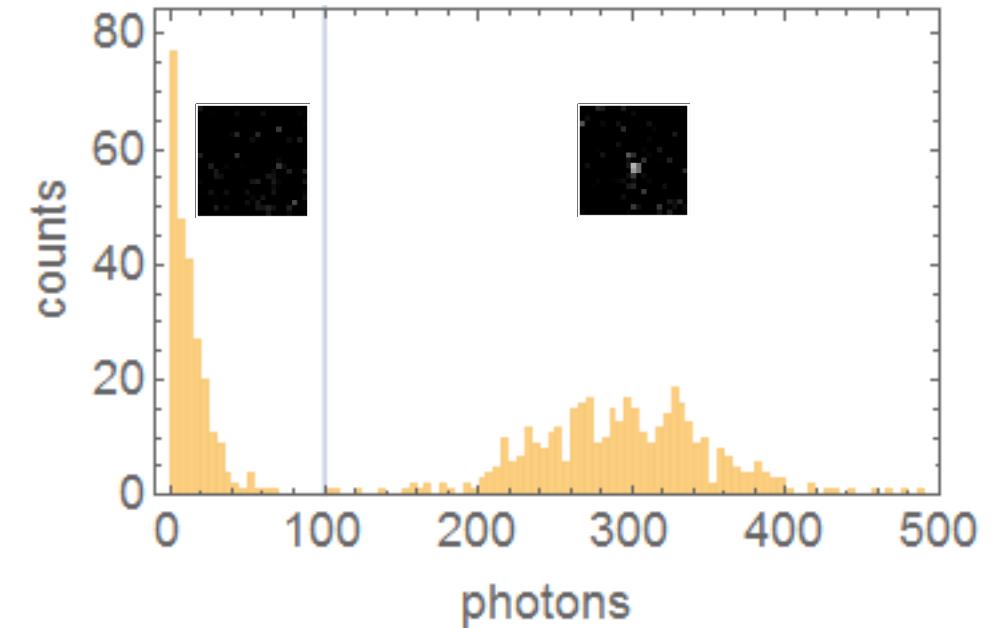
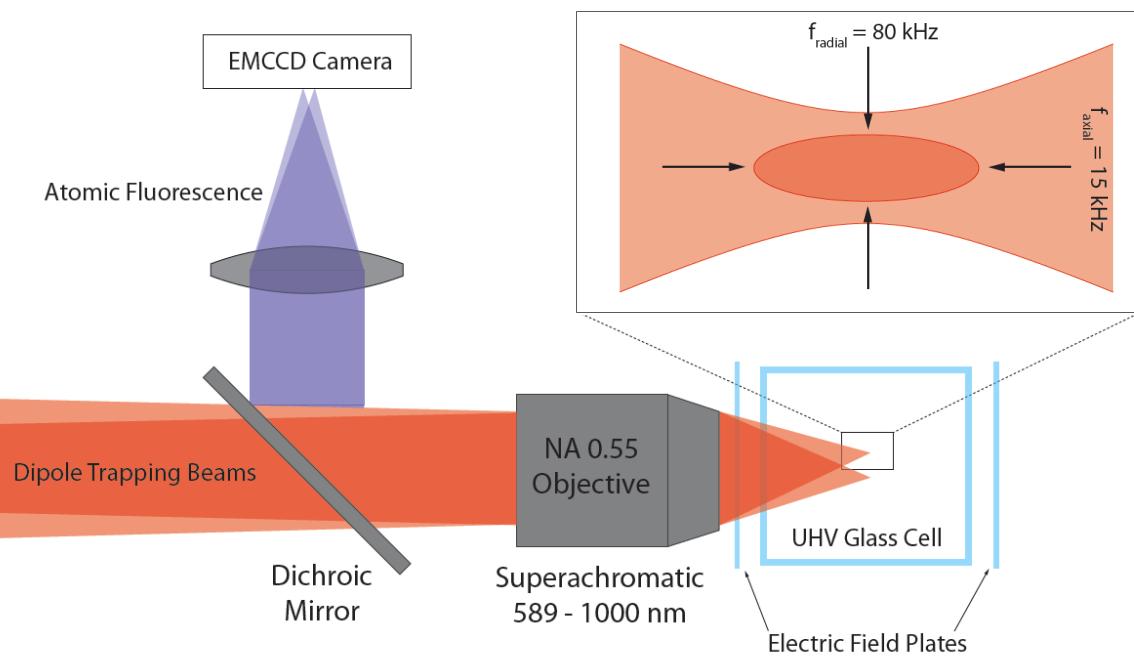
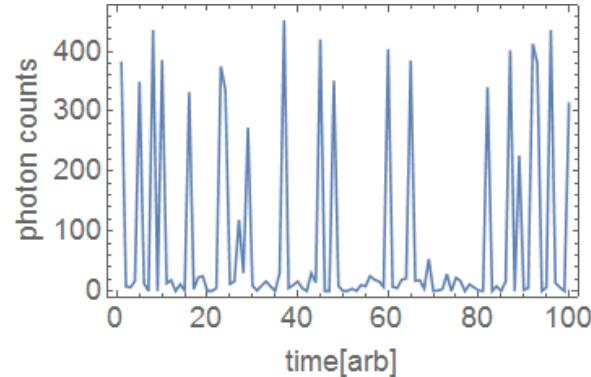
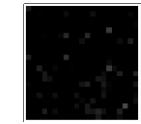
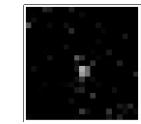
# Imaging/detection



# Imaging/detection



# Imaging/detection



99.999% fidelity