

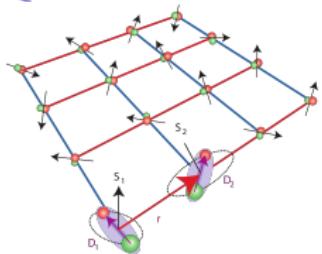
# Building Single Molecules from Single Atoms

Yichao Yu

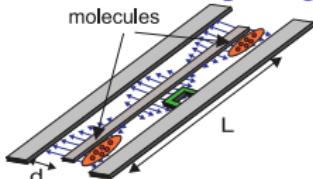
Ni Group/Harvard

Jul. 2020

## Quantum Simulation



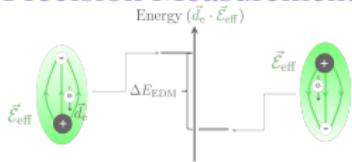
## Quantum Computing



PRL. 97, 33003 (2006)

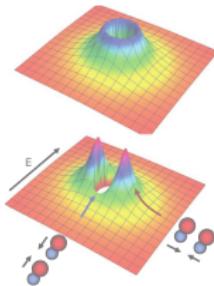
Nat. Phys. 2, 341 (2006)

## Precision Measurement



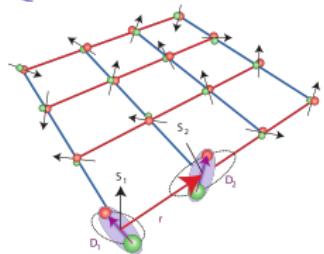
Science 343, p. 269-272 (2014)

## Quantum Chemistry



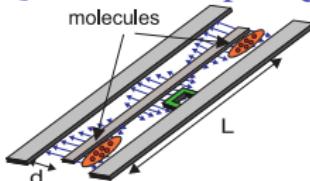
Nature 464, 1324 (2010)

## Quantum Simulation



Nat. Phys. 2, 341 (2006)

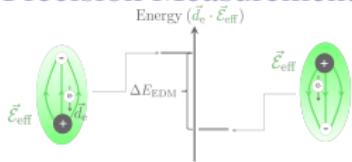
## Quantum Computing



PRL. 97, 33003 (2006)

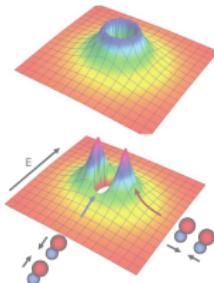
- Full quantum control
- Entanglement
- ...

## Precision Measurement



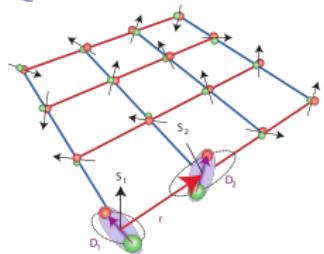
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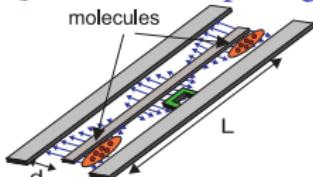
Nature 464, 1324 (2010)

## Quantum Simulation



Nat. Phys. 2, 341 (2006)

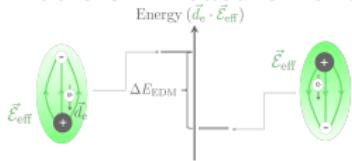
## Quantum Computing



PRL. 97, 33003 (2006)

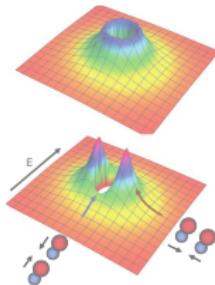
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Science 343, p. 269-272 (2014)

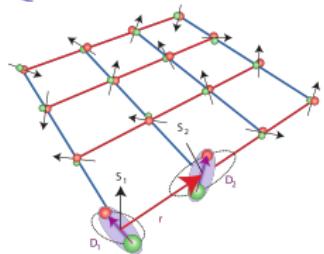
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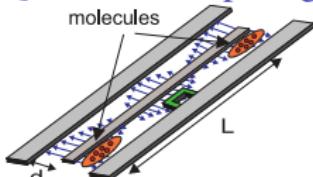
## New Approach?

## Quantum Simulation



Nat. Phys. 2, 341 (2006)

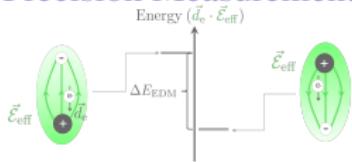
## Quantum Computing



PRL. 97, 33003 (2006)

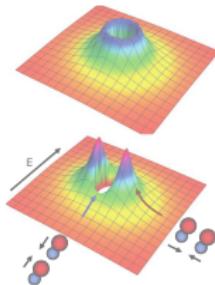
- Full quantum control
- Entanglement
- ...

## Precision Measurement



Science 343, p. 269-272 (2014)

## Quantum Chemistry



Nature 464, 1324 (2010)

## New Approach!

# Entanglement

# Single particle control

# Entanglement

i.e. interaction

Single particle control

**Entanglement**

i.e. interaction

Single particle control

**Dipolar molecules**

## Dipolar molecules

- Strong and tunable interaction  
( $\approx k\text{Hz}$  at  $\approx \mu\text{m}$  distance)
  - ▶ Fast gate operations
  - ▶ Long coherence time
- Rich internal structure  
(Electronic, vibrational,  
rotational, hyperfine, etc.)

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# Single particle control

## Optical tweezers

# Entanglement

i.e. interaction

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## Optical tweezers

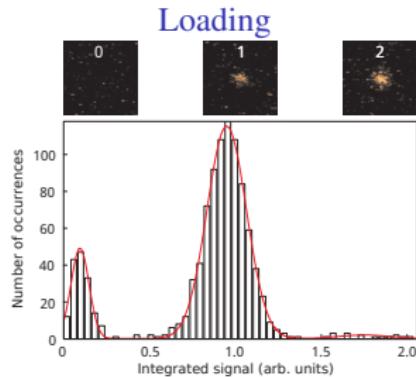
- Single site resolution



# Entanglement

i.e. interaction

## Dipolar molecules



Nat. Phys. 6, 951 (2010)

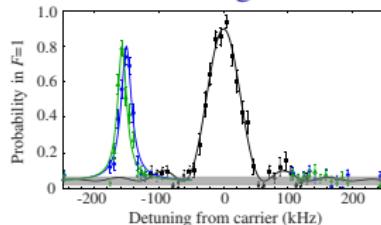
# Single particle control

## Optical tweezers

- Single site resolution

- ...

### Cooling



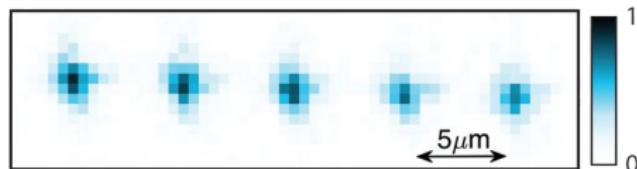
PRX. 2, 041014 (2012)

### Rearranging



# Ultracold molecule in tweezers

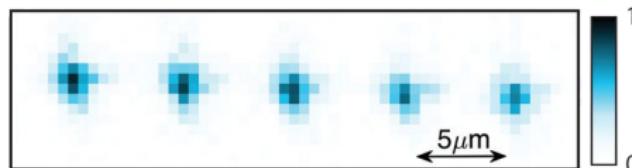
## Direct cooling



Science 365, 1156 (2019)

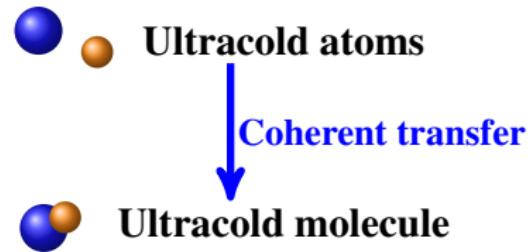
# Ultracold molecule in tweezers

## Direct cooling



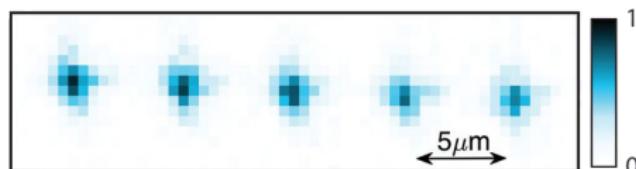
Science 365, 1156 (2019)

## Assembly



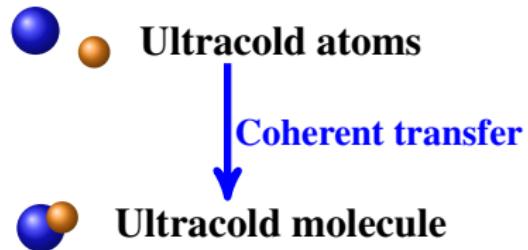
# Ultracold molecule in tweezers

## Direct cooling



Science 365, 1156 (2019)

## Assembly

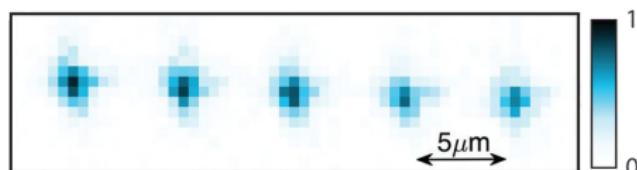


## Challenges

- Temperature in tweezers
- Quantum control

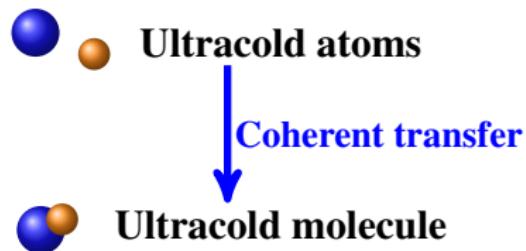
# Ultracold molecule in tweezers

## Direct cooling



Science 365, 1156 (2019)

## Assembly



## Challenges

- Temperature in tweezer
- Quantum control
- Creating molecules
- Maintain coherence

# Outline

## 1 Experiment overview

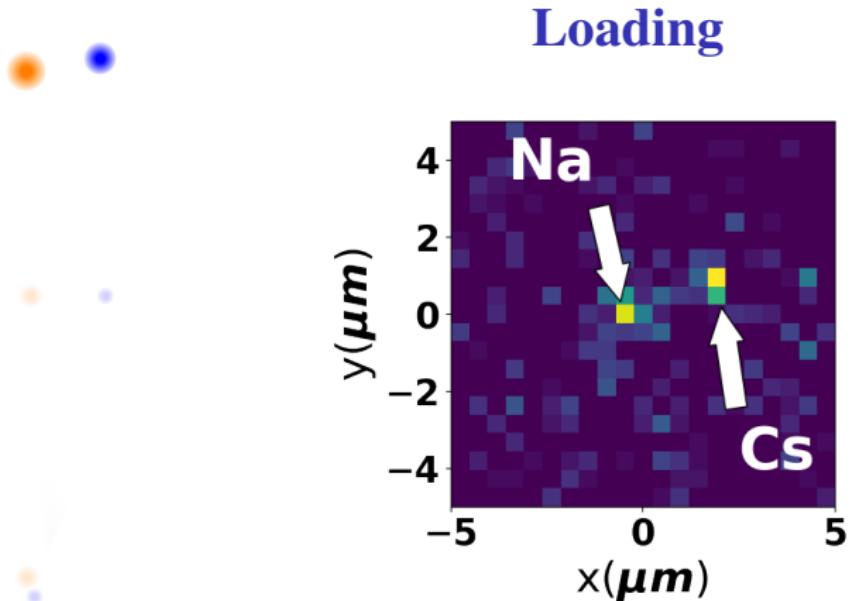
## 2 Atom state control

- Raman sideband cooling of Na atoms

## 3 Optical molecule creation

## 4 Conclusion

## Experiment overview

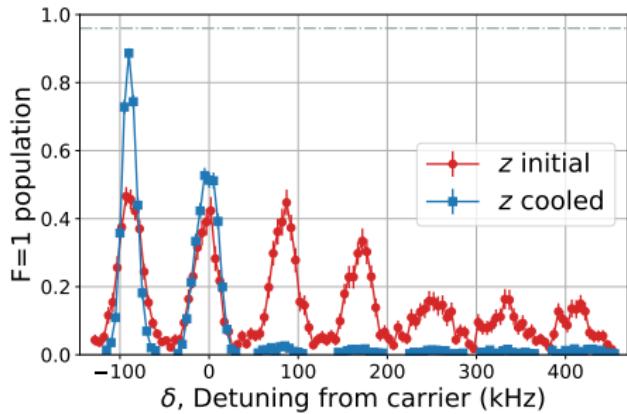


Loading probability per site: 60%  
Post select on initial and final state.

# Experiment overview



## Cooling



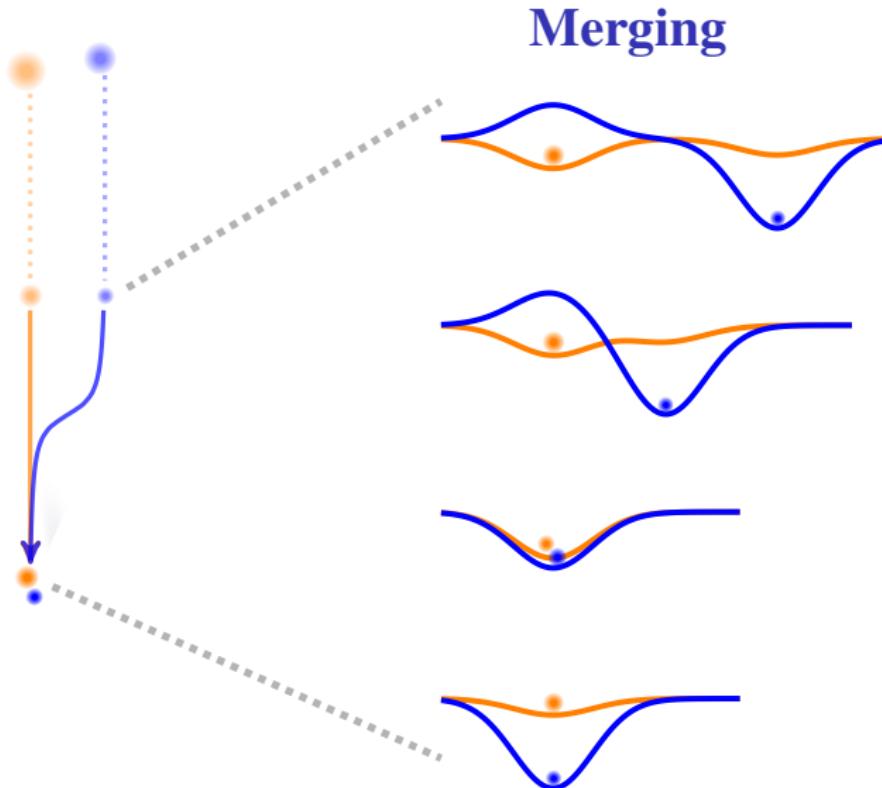
Cs: 96% ground state<sup>1</sup>

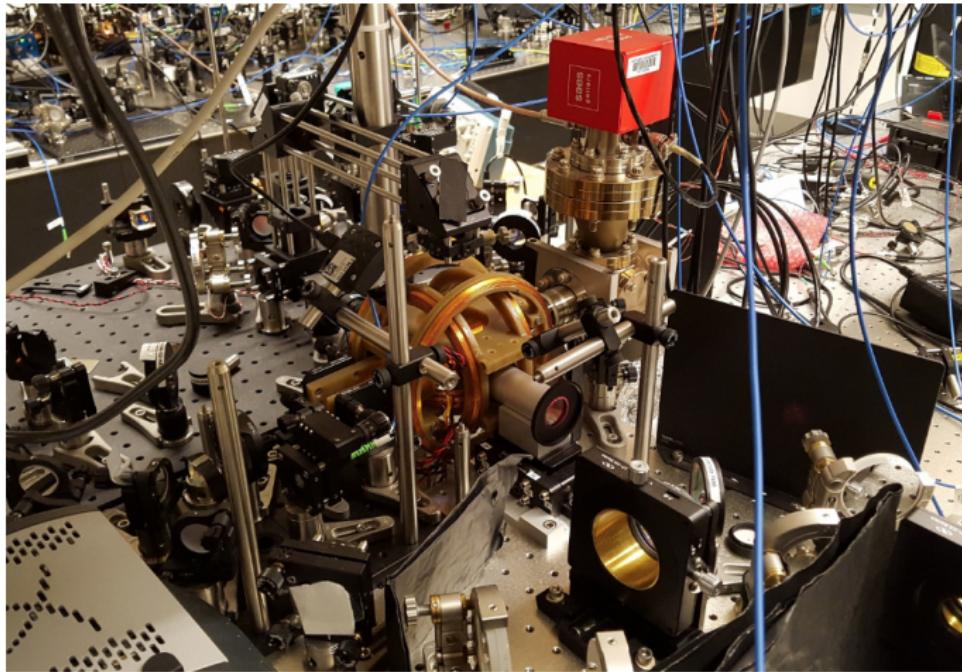
Na: 94% ground state<sup>2</sup>

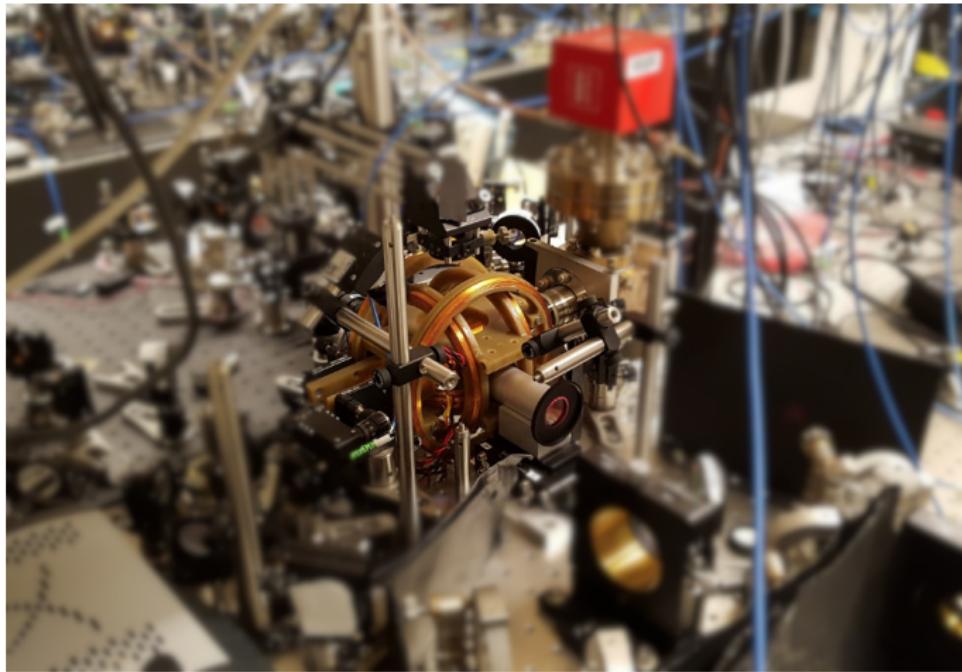
<sup>1</sup>Phys. Rev. X 9, 021039

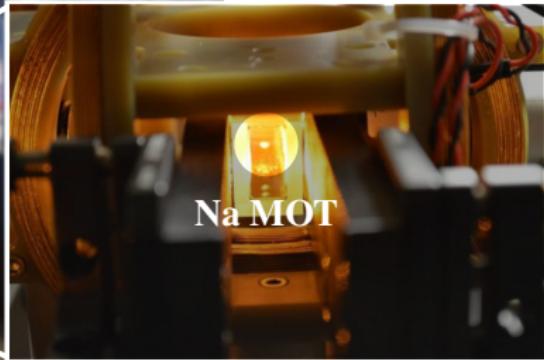
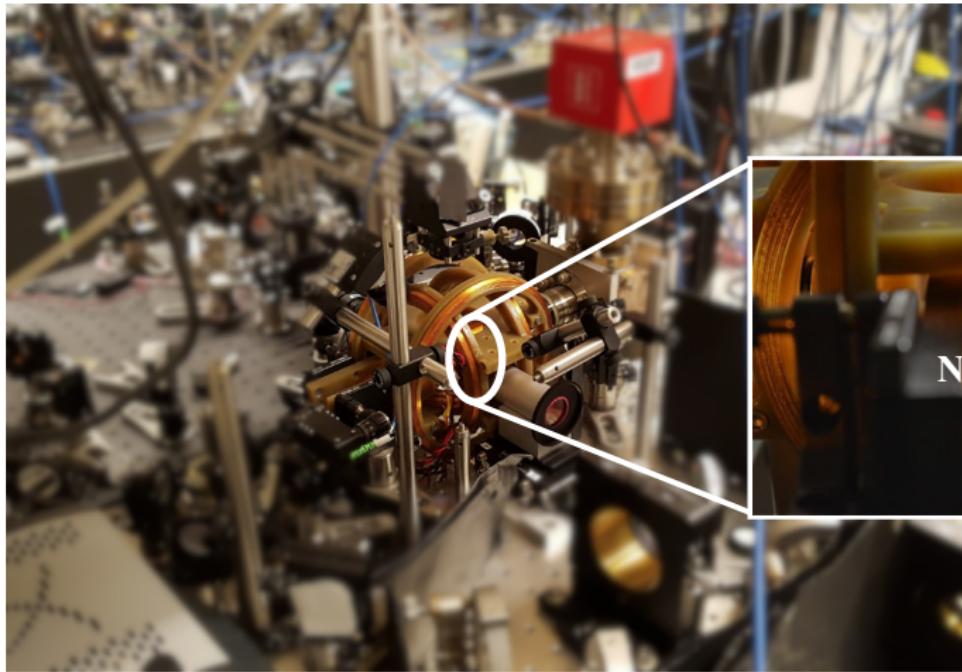
<sup>2</sup>Phys. Rev. A 97, 063423

## Experiment overview

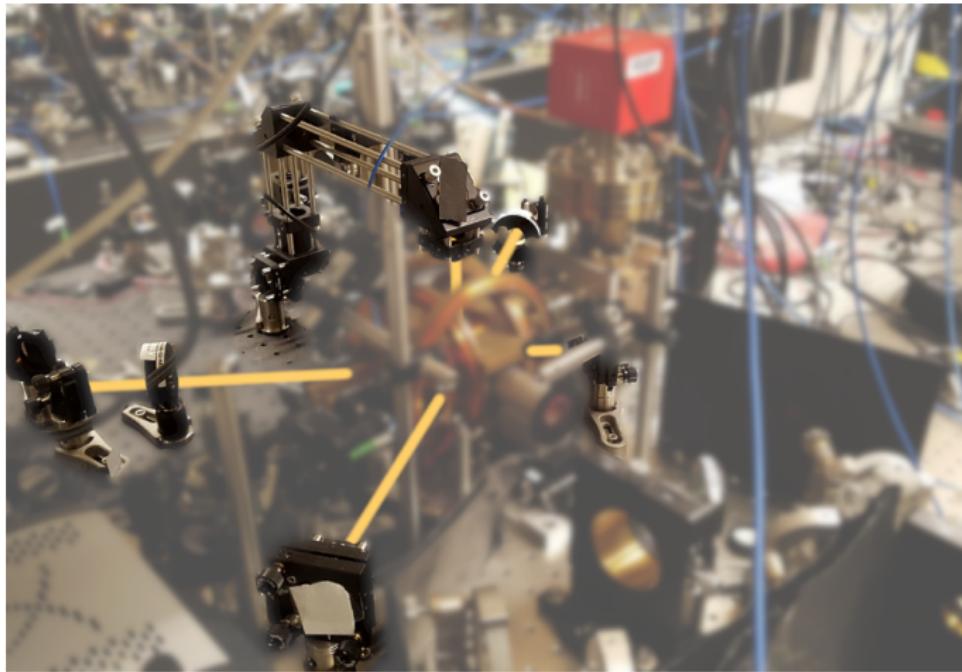




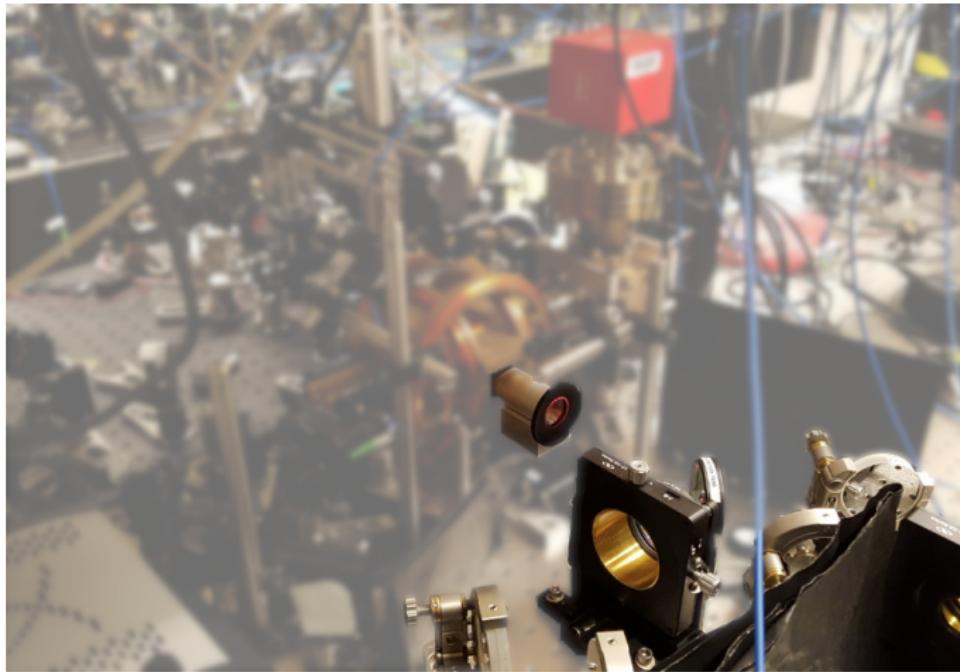




## MOT beam path



## Tweezer beam path



# Outline

## 1 Experiment overview

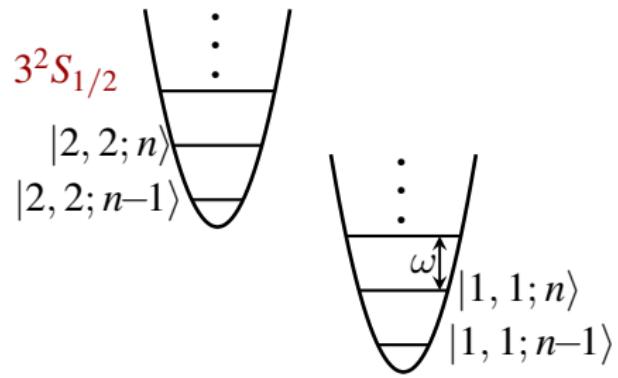
## 2 Atom state control

- Raman sideband cooling of Na atoms

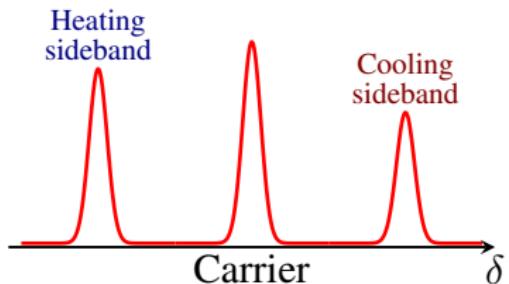
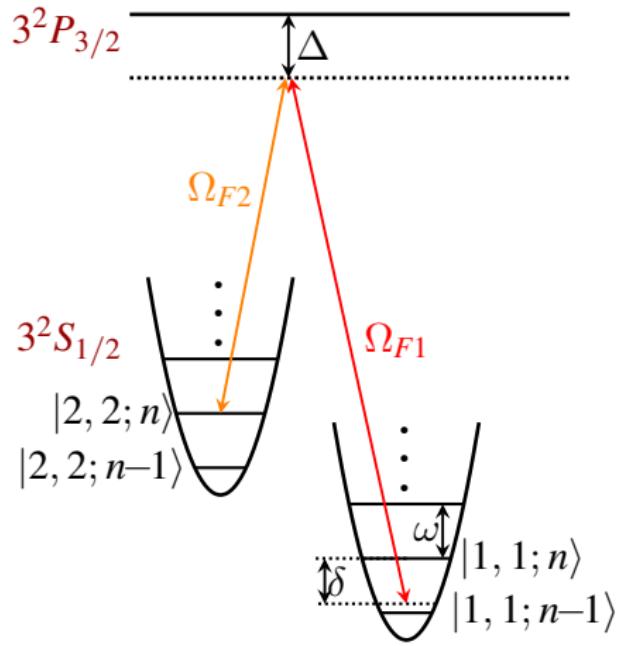
## 3 Optical molecule creation

## 4 Conclusion

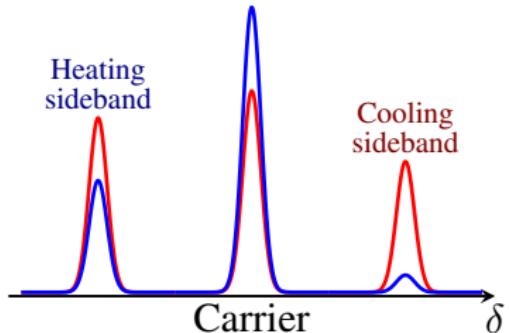
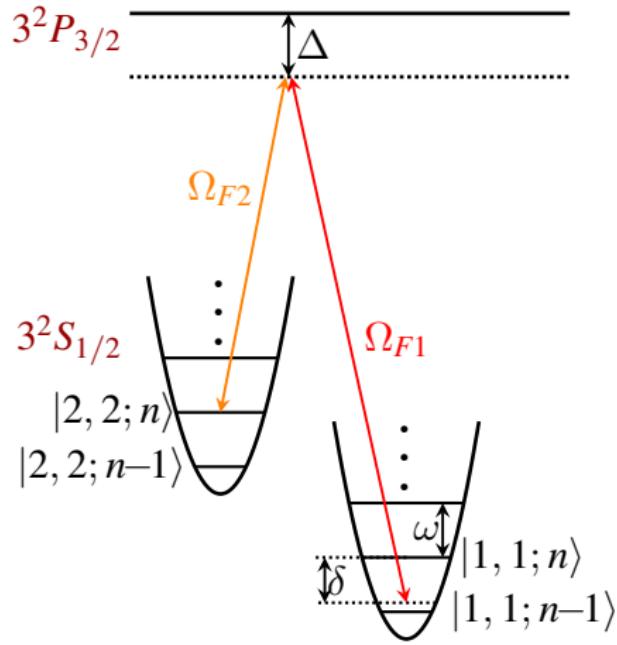
# Raman sideband cooling



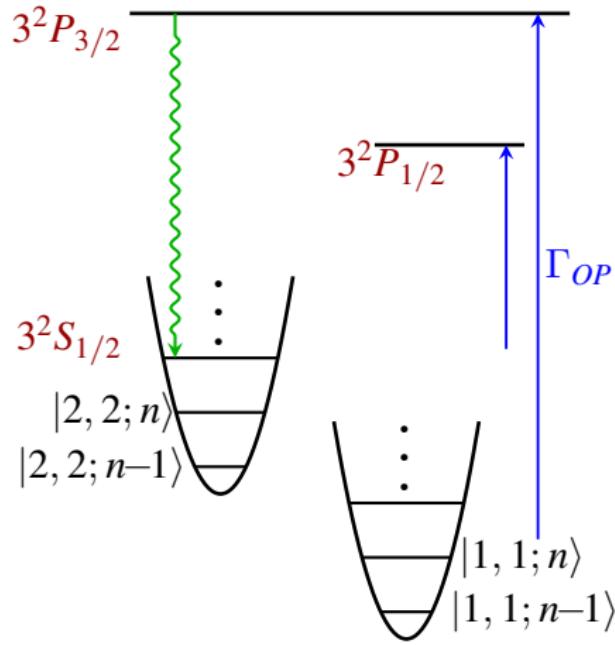
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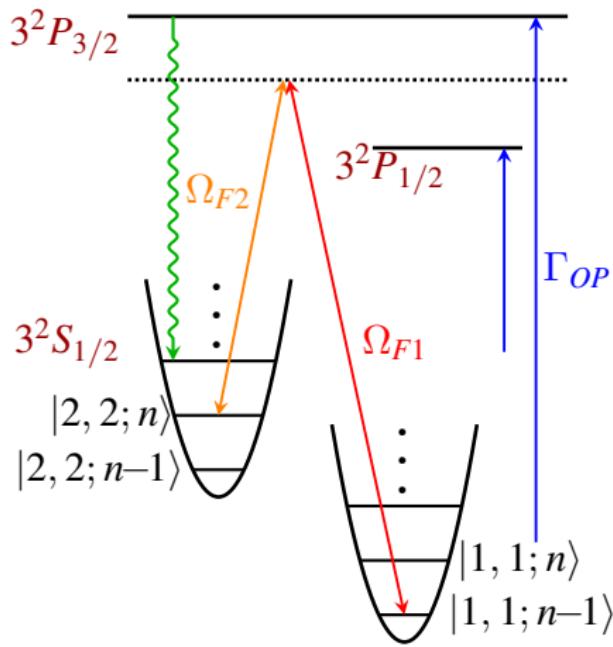
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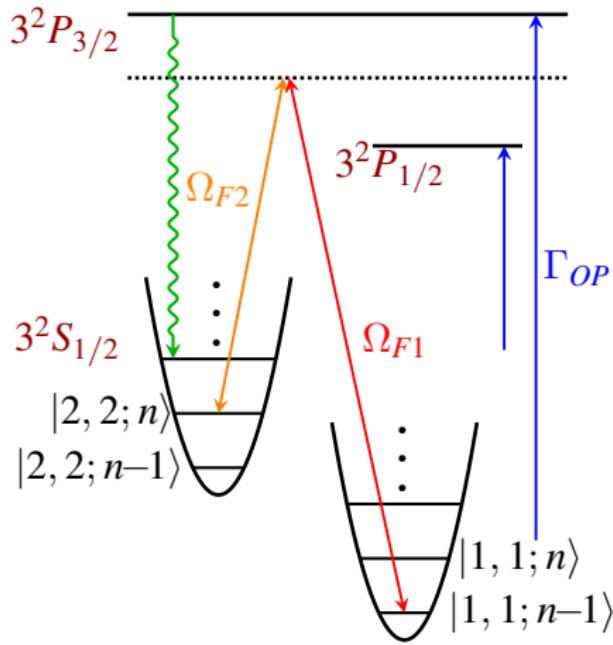
# Raman sideband cooling

## Lamb Dicke parameter

$$\eta \equiv kz_0 = \frac{2\pi z_0}{\lambda} = \sqrt{\frac{\omega_{recoil}}{\omega_{trap}}}$$



# Raman sideband cooling

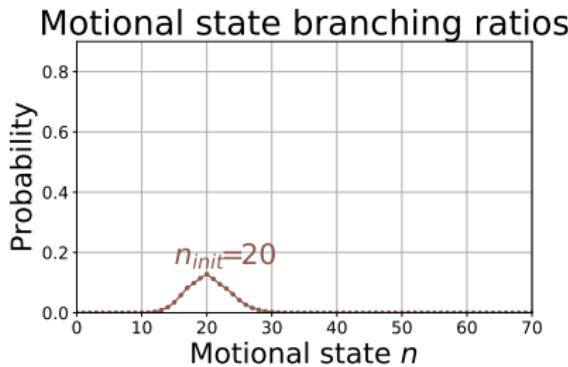


## Lamb Dicke parameter

$$\eta \equiv kz_0 = \frac{2\pi z_0}{\lambda} = \sqrt{\frac{\omega_{recoil}}{\omega_{trap}}}$$

$$\eta_{Na}^{OP} = 0.55$$

## Raman sideband cooling



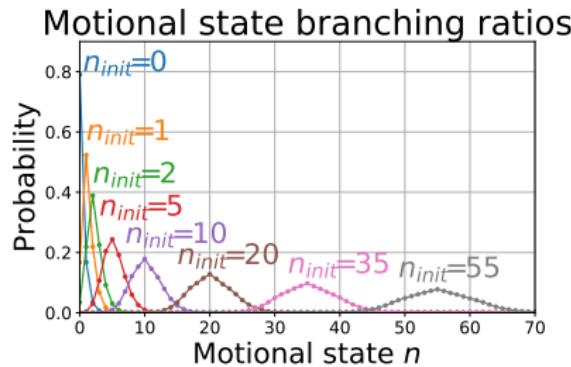
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- Motional state branching
- Coupling “dead zone”

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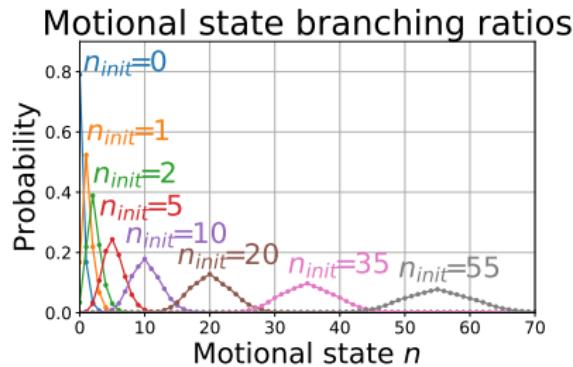
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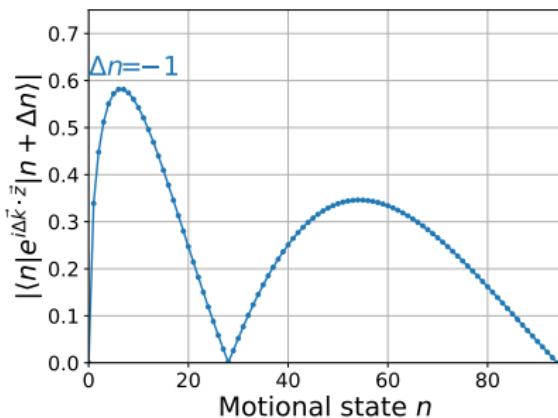


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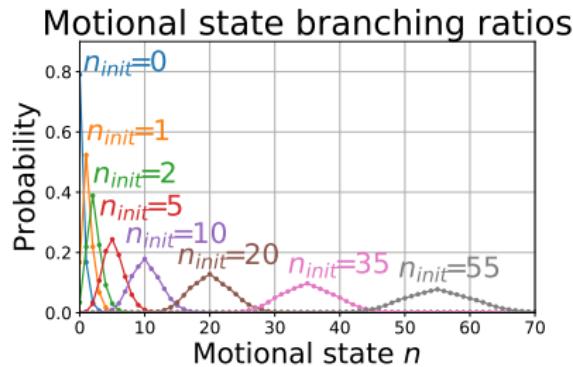
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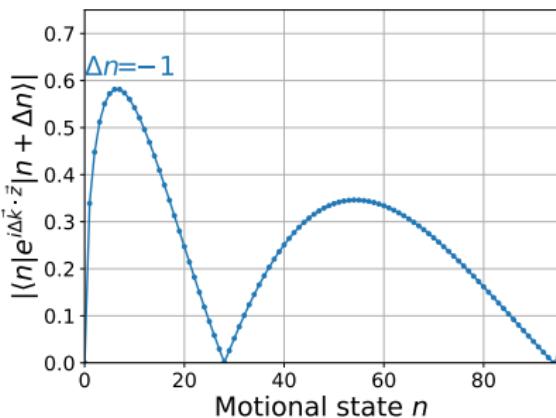


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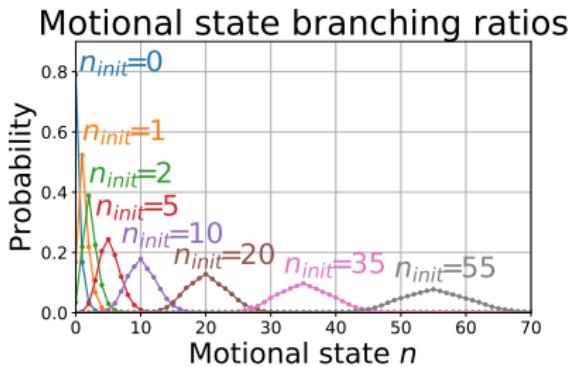
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## Solution

Use higher order sidebands.

# Raman sideband cooling

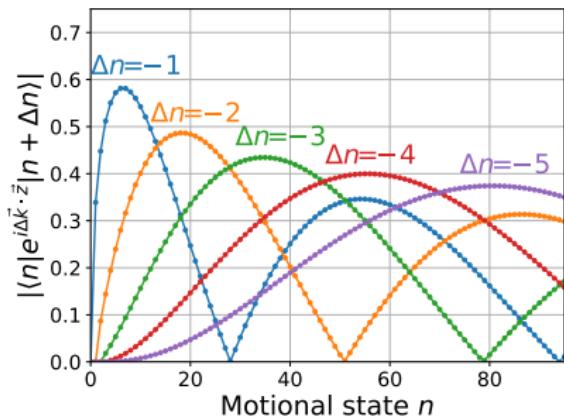


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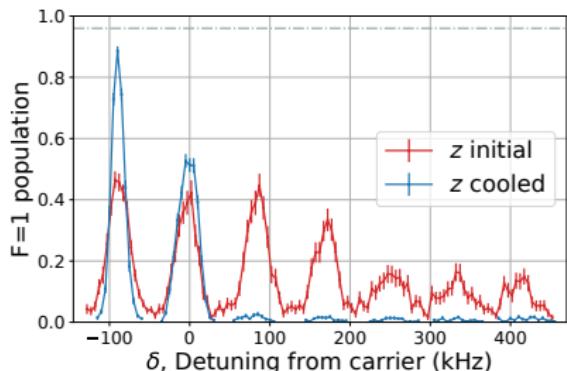


## Solution

Use higher order sidebands.

## Raman sideband cooling

Axial sideband spectrum

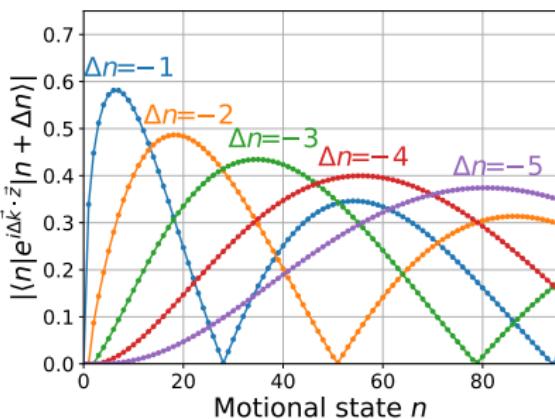


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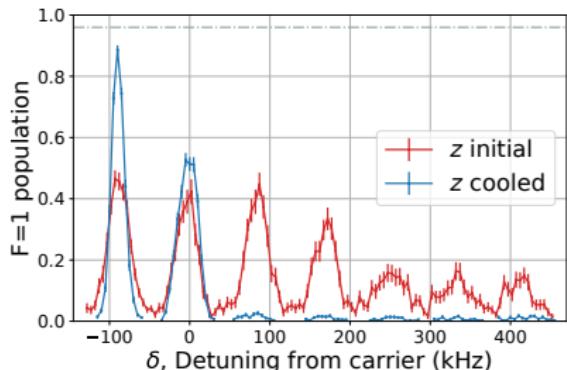


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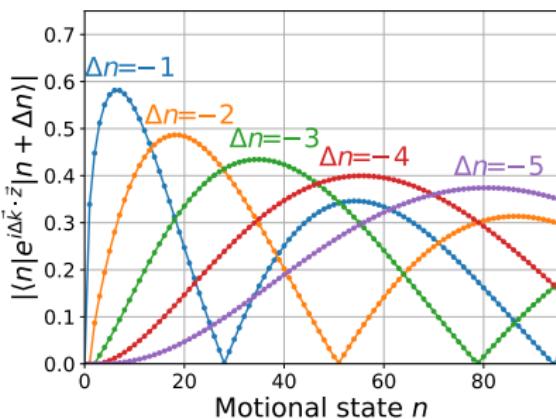


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## Solution

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3D ground state: 93.5(7)%

# Outline

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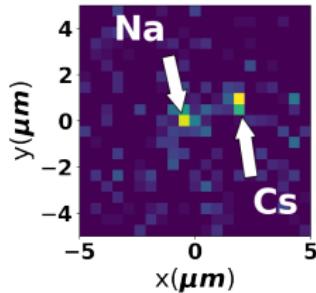
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## 4 Conclusion

## Loading

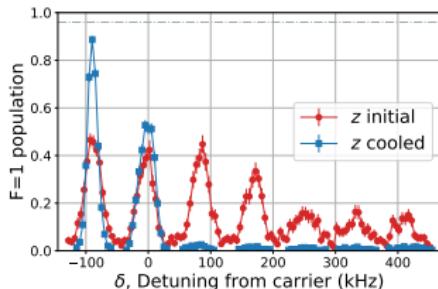


NJP. 19, 023007 (2017)

## Merging

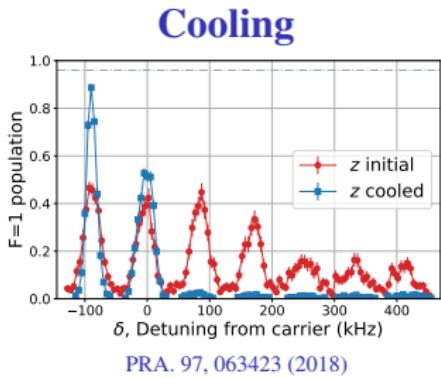
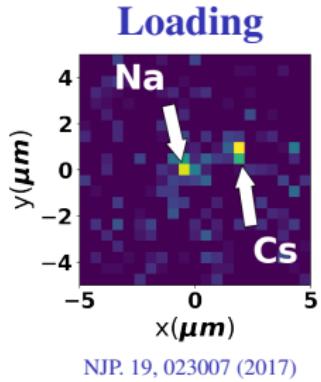


## Cooling

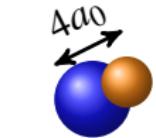
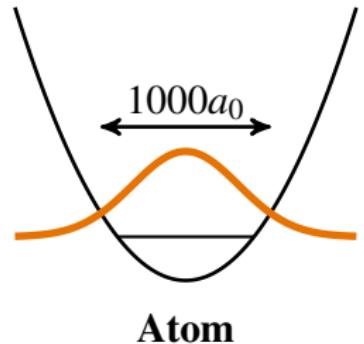


PRA. 97, 063423 (2018)

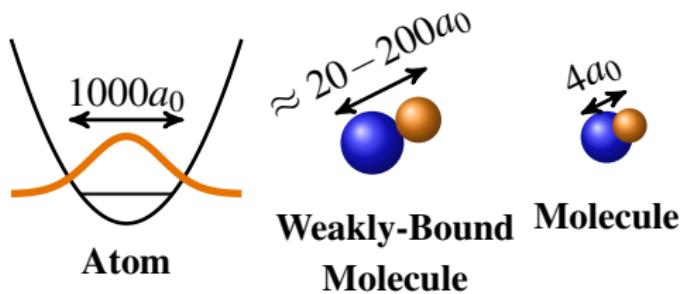
PRX. 9, 021039 (2019)

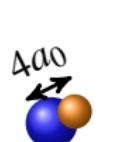
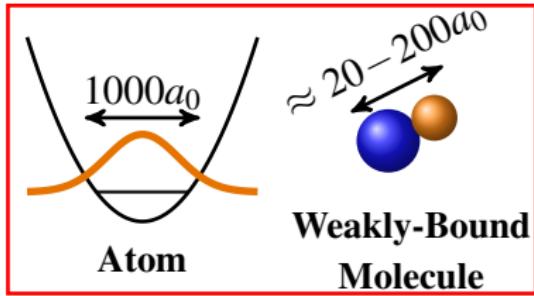


**Merging**

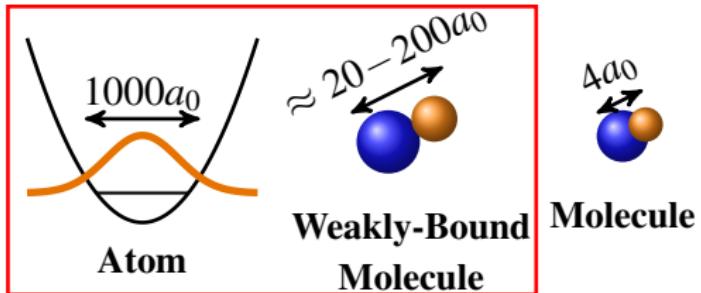


**Molecule**

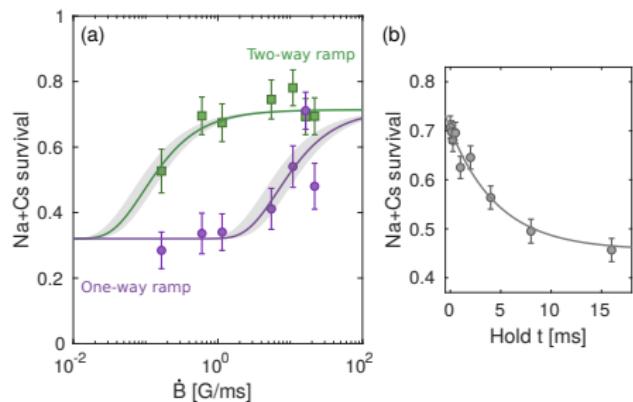




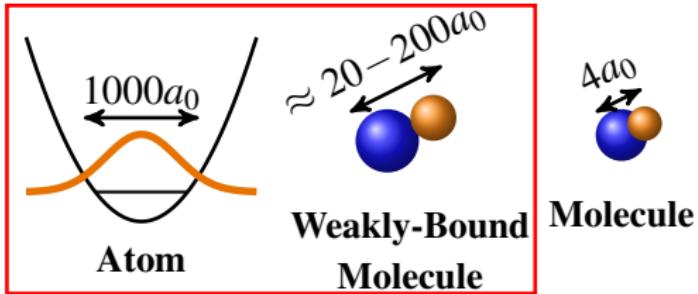
Molecule



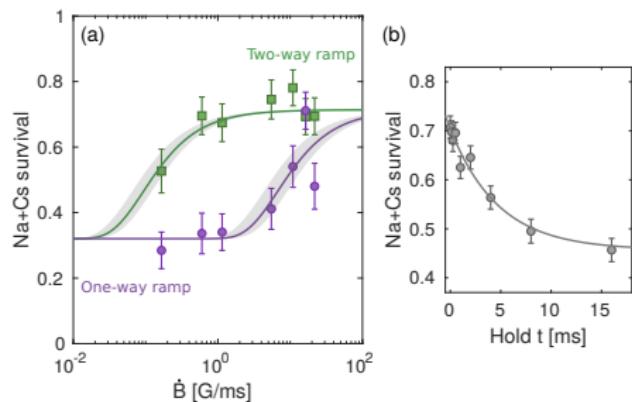
## Feshbach molecule



PRL. 124, 253401 (2020)

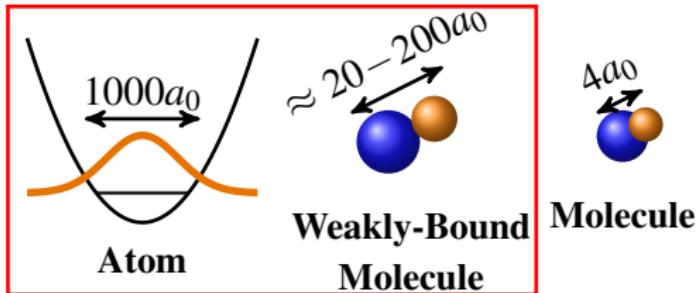


## Feshbach molecule



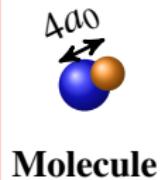
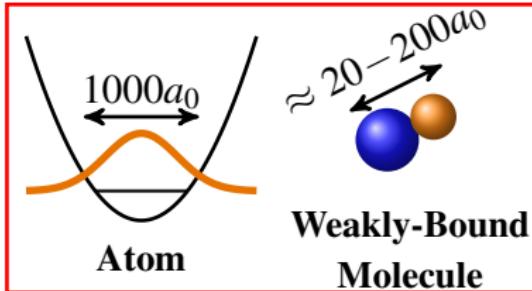
- Requires Feshbach resonance
- Usually large magnetic field

PRL. 124, 253401 (2020)



## Optical transfer

- More general
- Faster

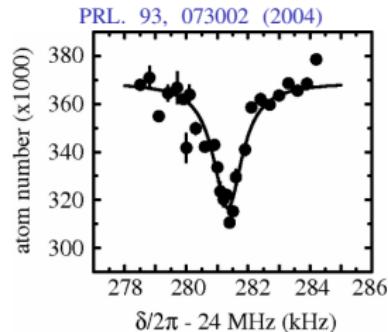


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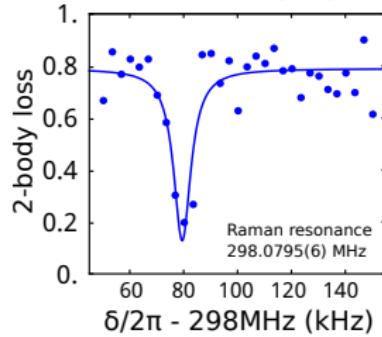
## Previous results

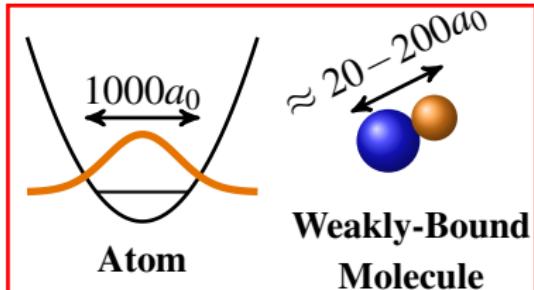
Rb<sub>2</sub> Science 287, p. 1016-1019 (2000)



Sr<sub>2</sub> PRL. 109, 115302 (2012)

NaCs PRX. 9, 021039 (2019)





## Optical transfer

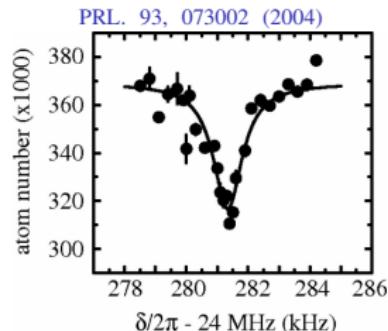
- More general
- Faster

### Limitations so far

- Incoherent due to scattering
- Rely on narrow line optical transition

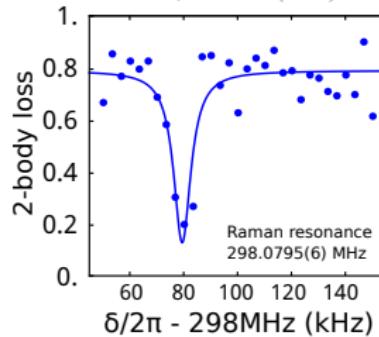
## Previous results

$\text{Rb}_2$  Science 287, p. 1016-1019 (2000)

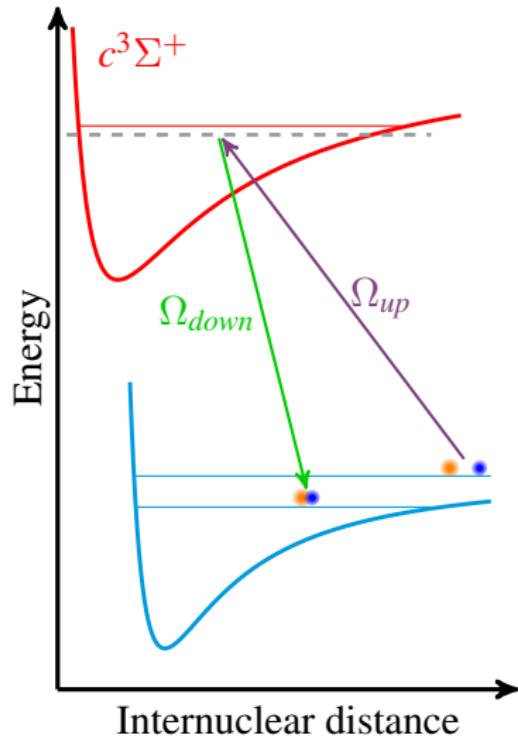


$\text{Sr}_2$  PRL. 109, 115302 (2012)

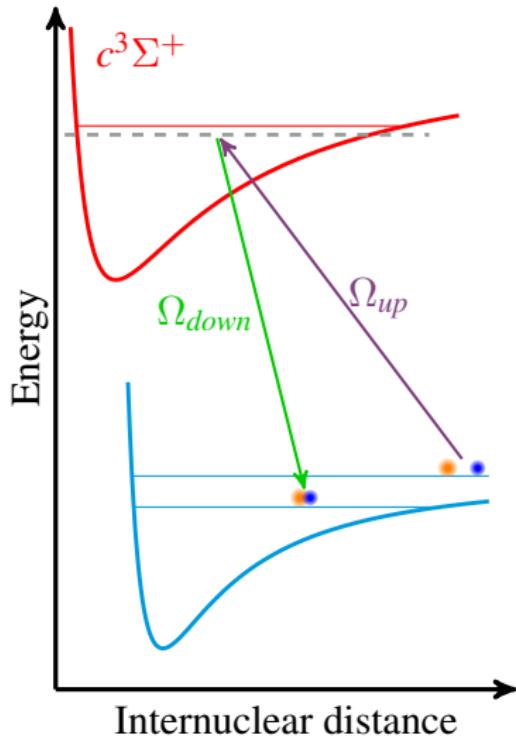
$\text{NaCs}$  PRX. 9, 021039 (2019)



# Raman transfer



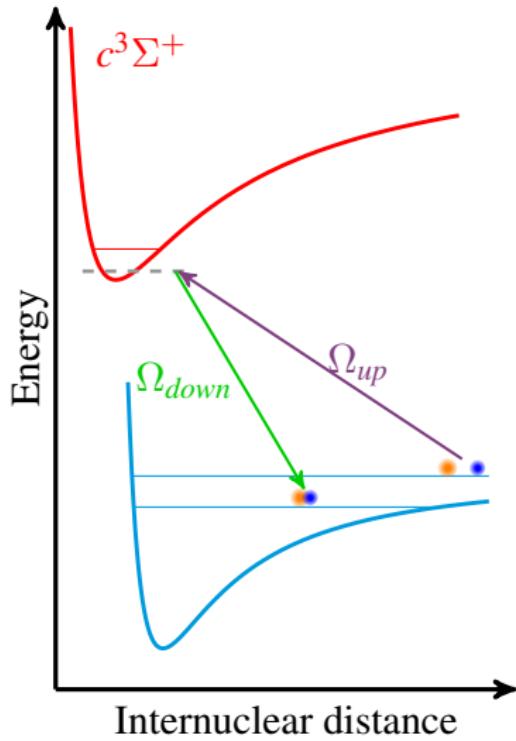
## Raman transfer



## Near threshold states

- Stronger coupling ( $\Omega_{up}$  and  $\Omega_{down}$ )
- Closely spaced
- Fast scattering

# Raman transfer



## Near threshold states

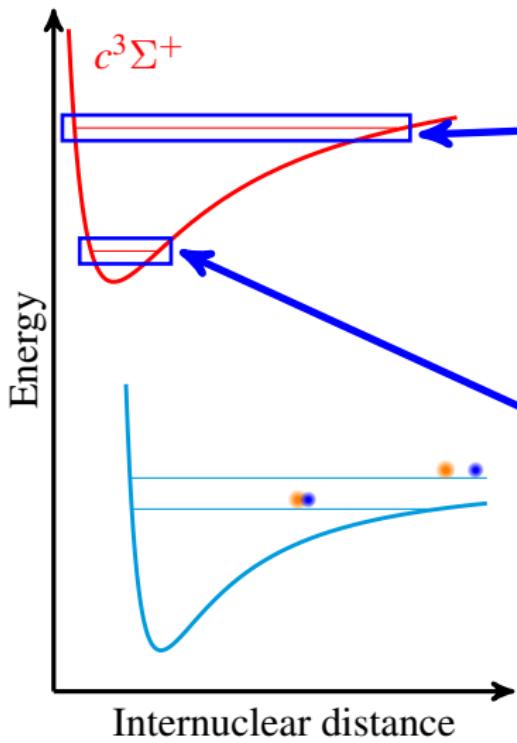
- Stronger coupling ( $\Omega_{up}$  and  $\Omega_{down}$ )
- Closely spaced
- Fast scattering

## Deeply bound states

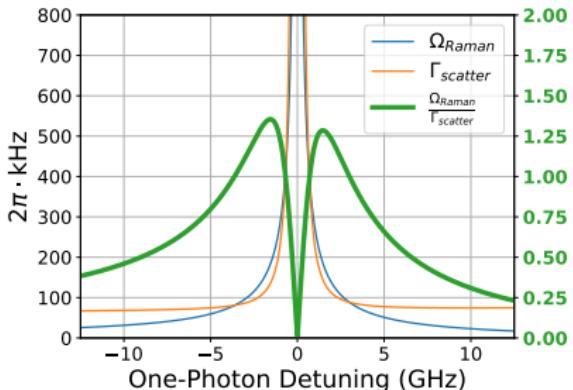
- Weaker coupling
- Sparsely spaced
- Allow larger detuning
- Slower scattering

arXiv:1701.03121(2017)

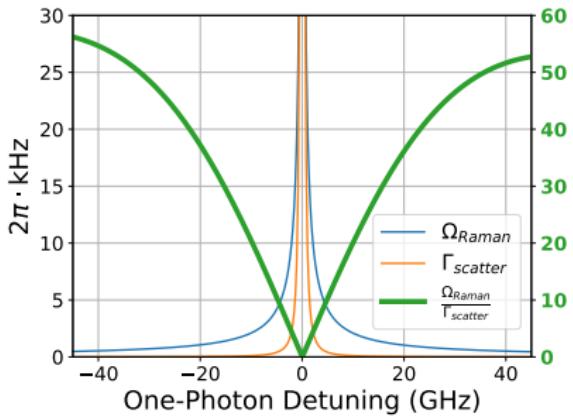
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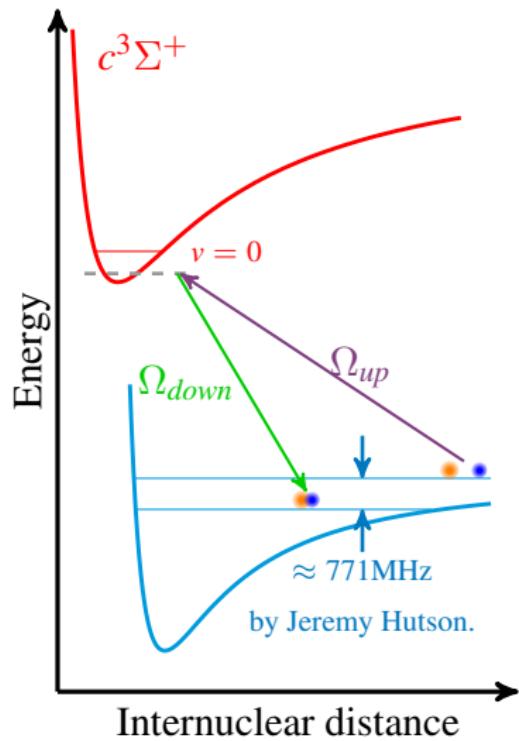
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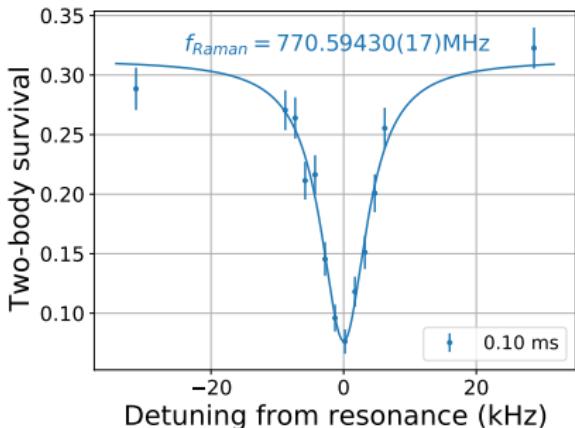
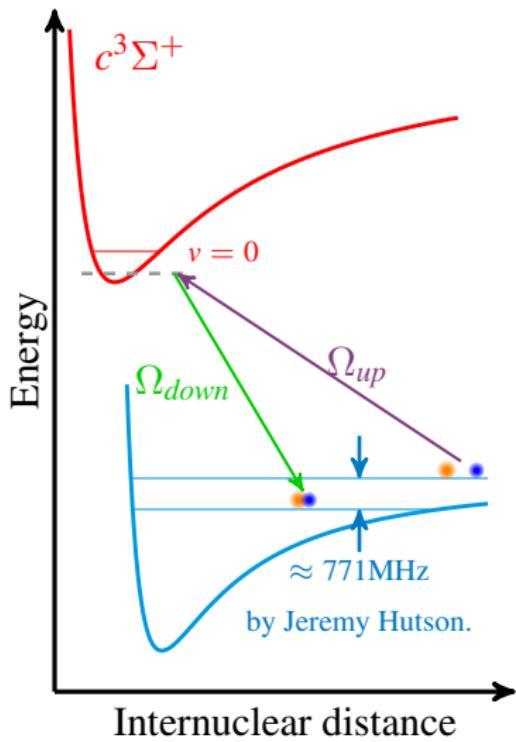
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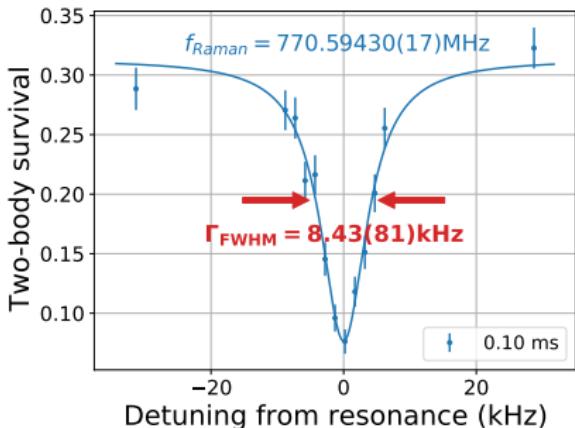
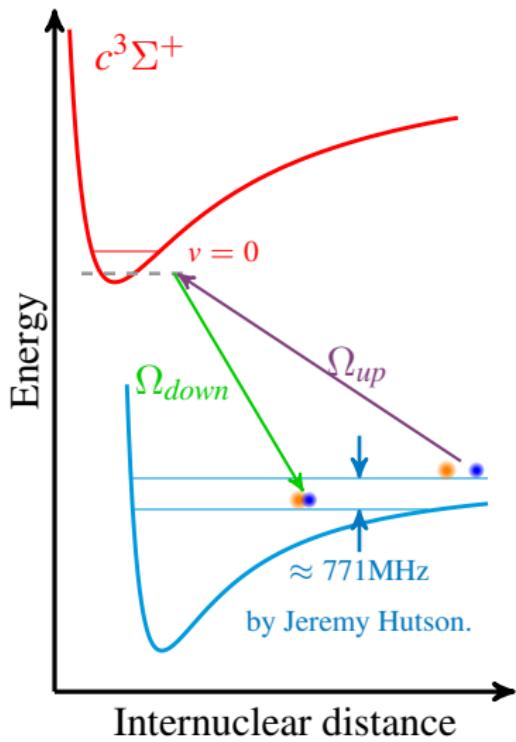
# Experiment



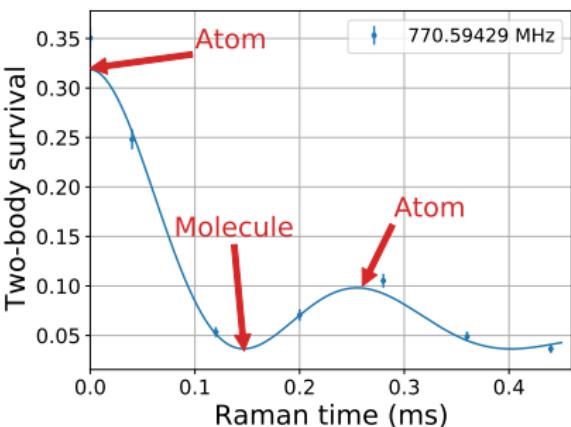
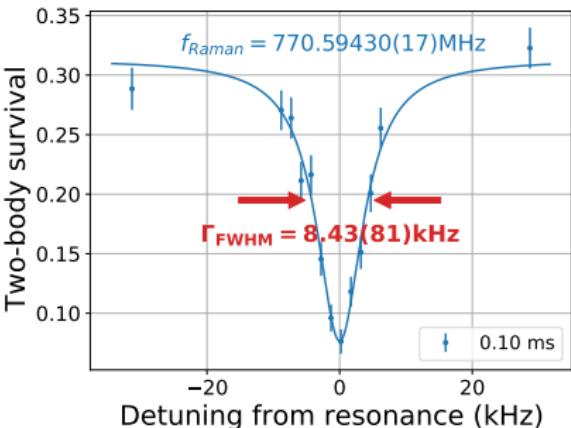
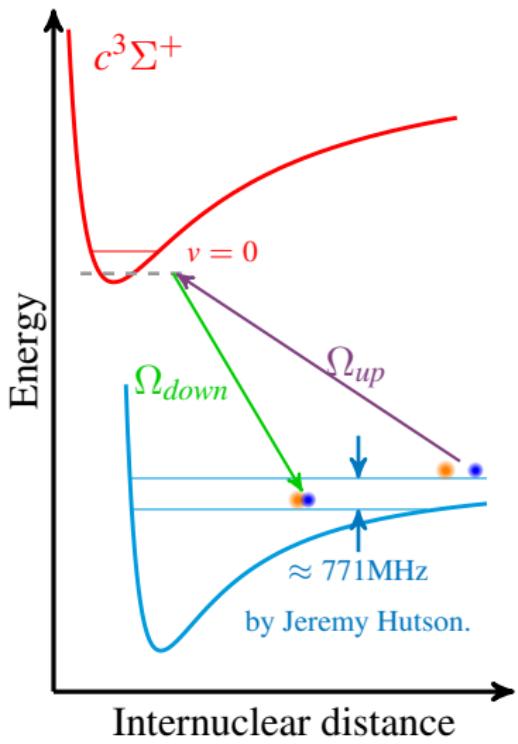
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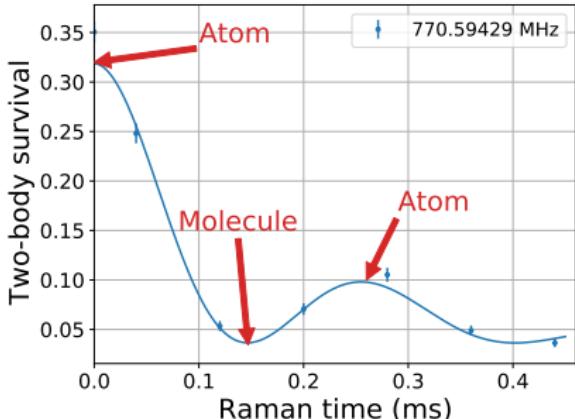
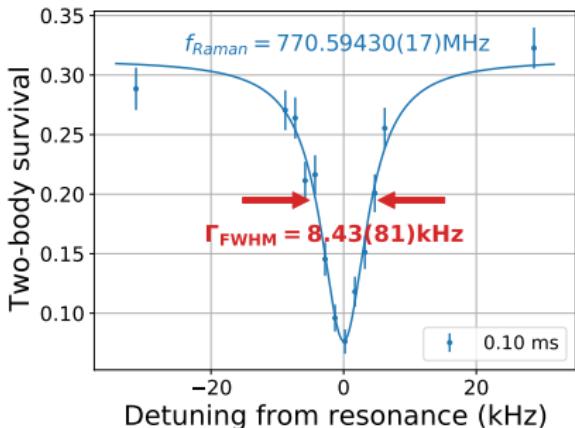
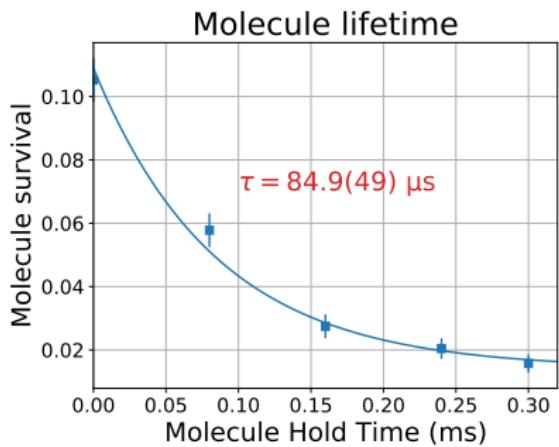


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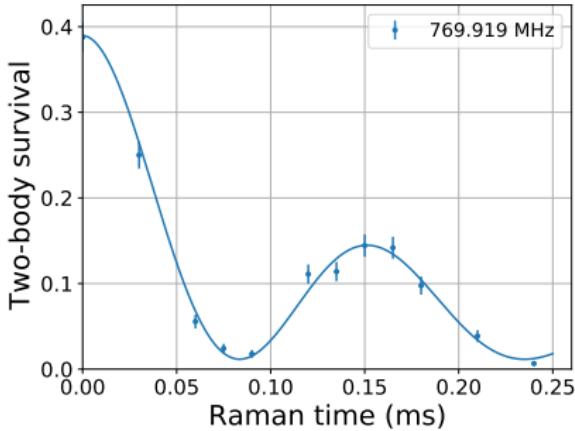
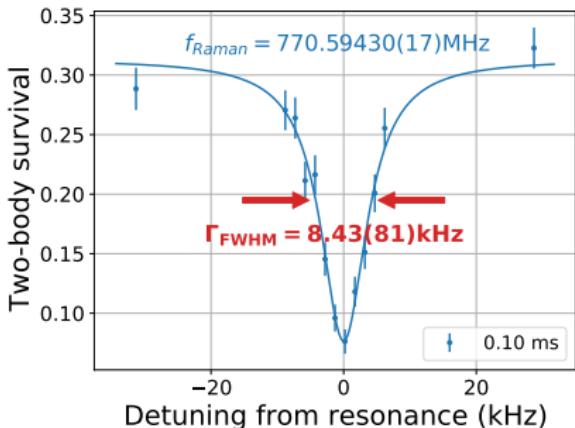
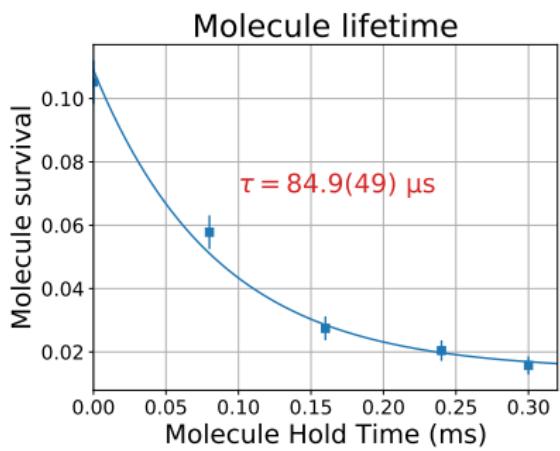
# Experiment

- Transferred 50% of ground state atom to molecule.
- Improving signal
- Single molecule spin state
- > 50% of molecule in motional ground state.



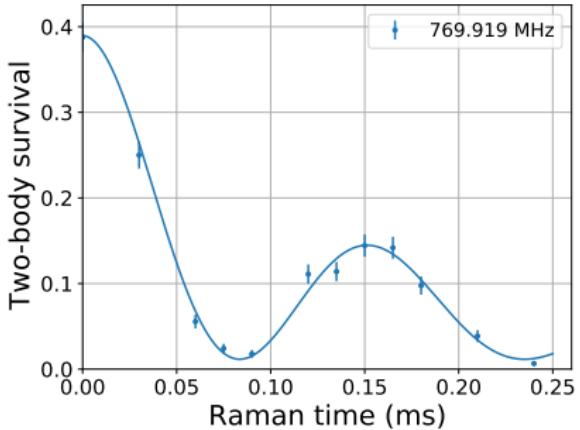
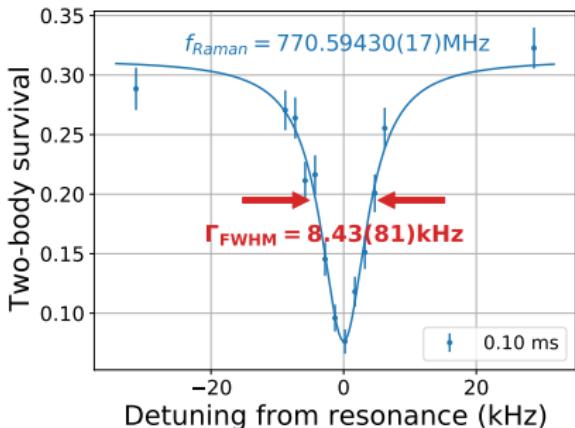
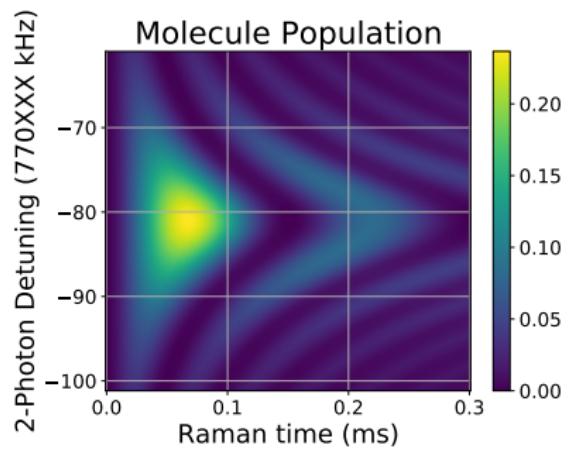
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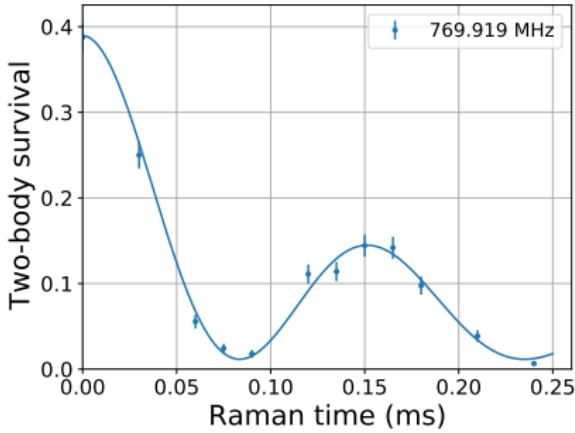
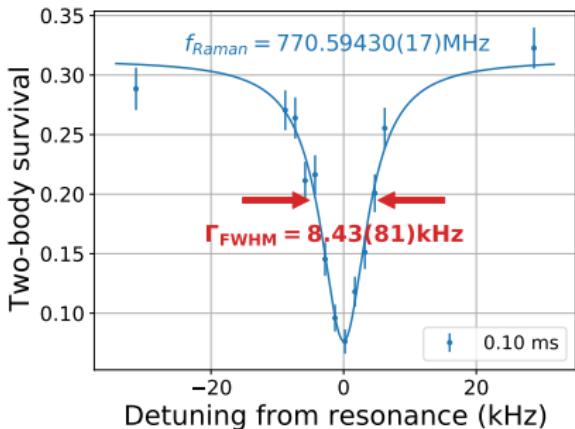
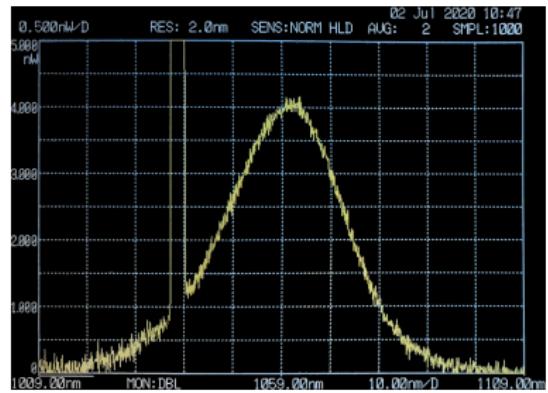
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- Transferred 65% of ground state atom to molecule.
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- > 50% of molecule in motional ground state.



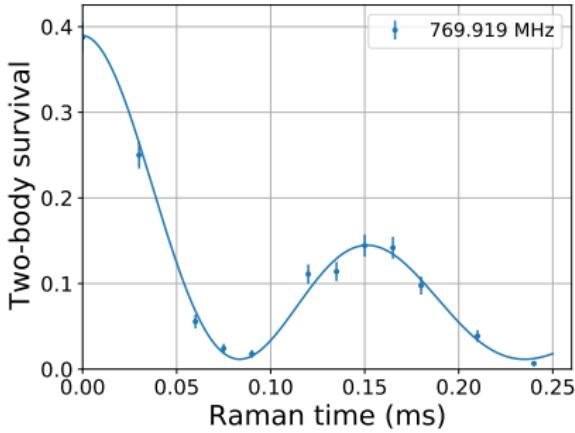
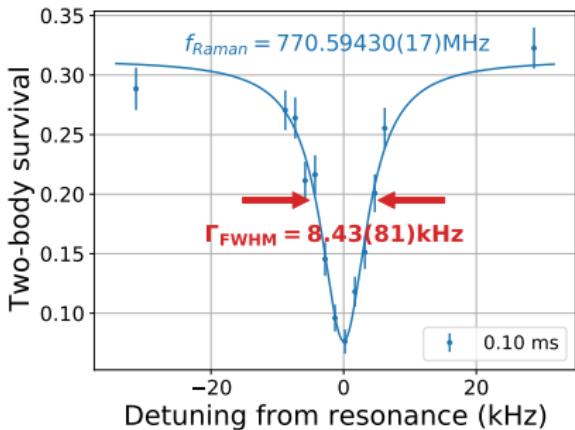
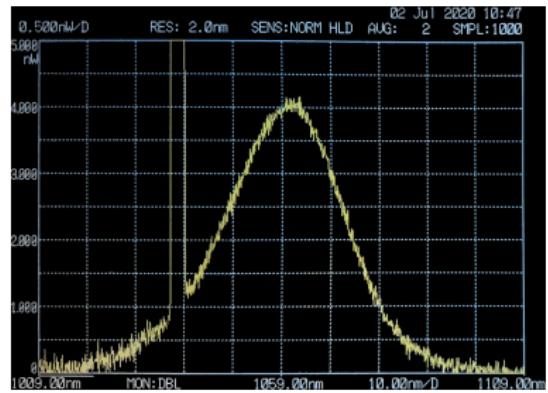
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## Conclusion and outlook

- Full quantum control of atoms in optical tweezers
- Coherent all-optical creation of single molecule
- Improve molecule lifetime and signal contrast
- Feshbach molecule ( $\tau = 4.7(7)$  ms)

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# Conclusion and outlook

## Experiment

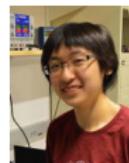


Kang-Kuen Ni

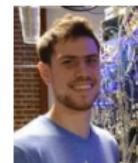
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Kenneth  
Wang



Jessie  
Zhang



Lewis  
Picard



William  
Cairncross



Lee Liu  
Postdoc @JILA



Jonathan Hood  
Asstn Prof @Purdue



Nick Hutzler  
Asstn Prof @Caltech

## Theory



Jeremy Hutson



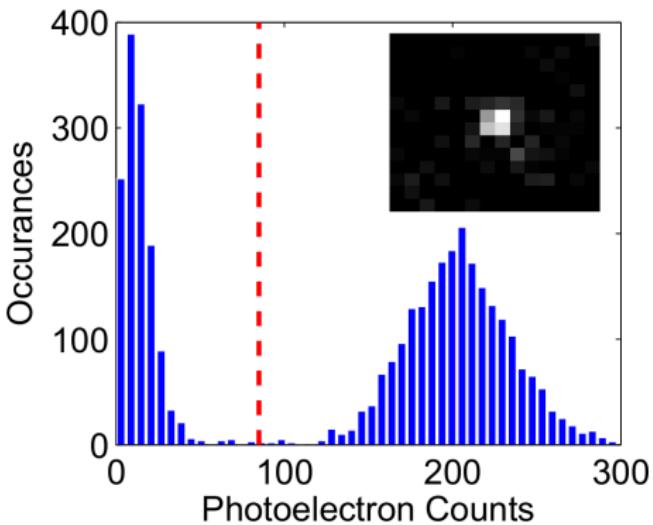


# Single Atom in Tweezer

- Previously done with Rb
- Works for Cs
- Doesn't work for Na

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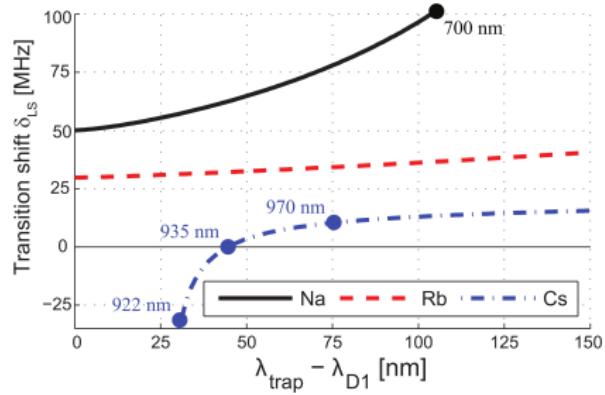
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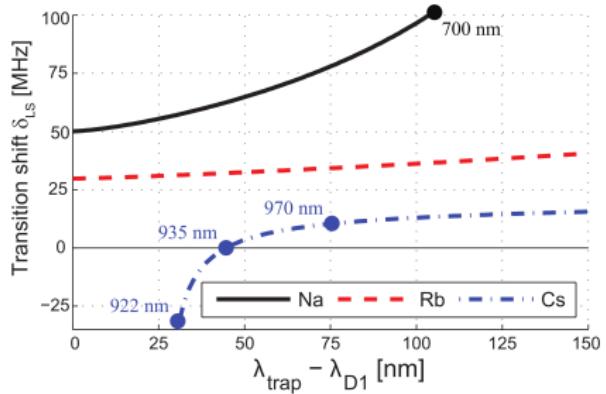
## Issues with Na

- Low vapor pressure
- Broad linewidth
- Low mass
- Small hyperfine structure

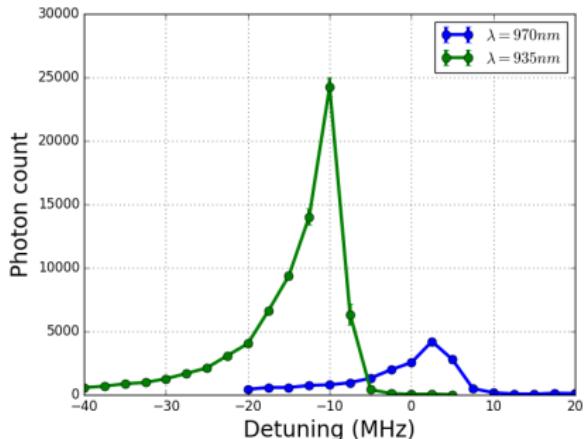
# Real Issue with Na: Light Shift



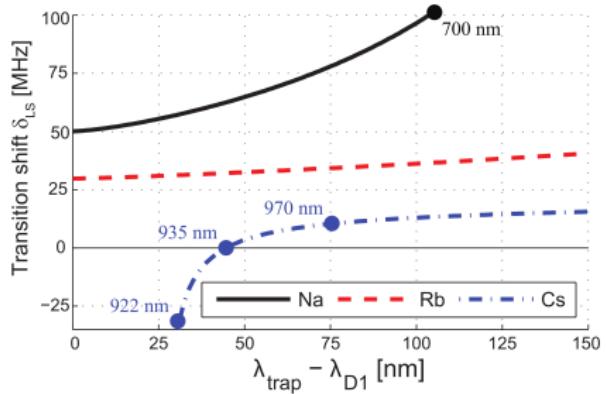
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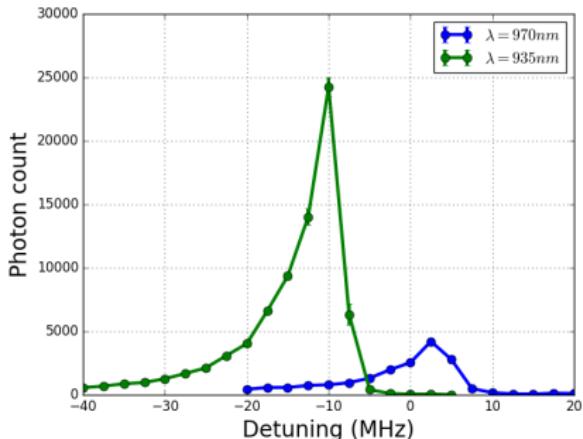
## Cs single atom imaging



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## Cs single atom imaging



- Low imaging signal
- No cooling in tweezer

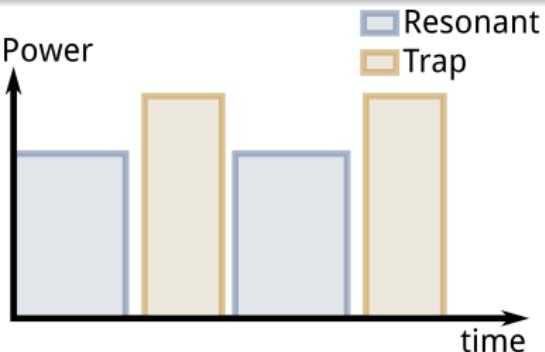
# Real Issue with Na: Light Shift

## Trap modulation

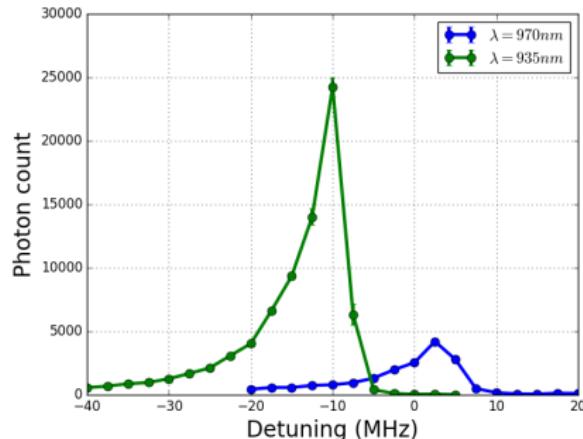
Alternate between trap and resonant (cooling and imaging) light at 2.5 MHz

$$f_{trap} = 100 \sim 500 \text{ kHz}$$

$$\Gamma = 2\pi \times 10 \text{ MHz}$$



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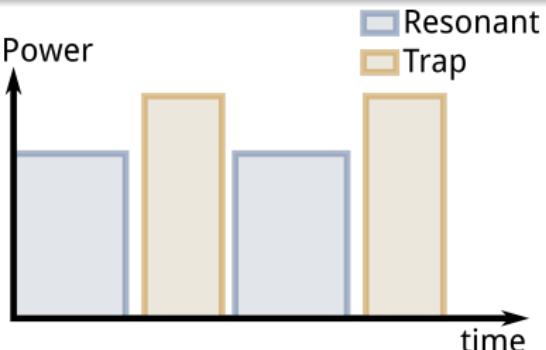
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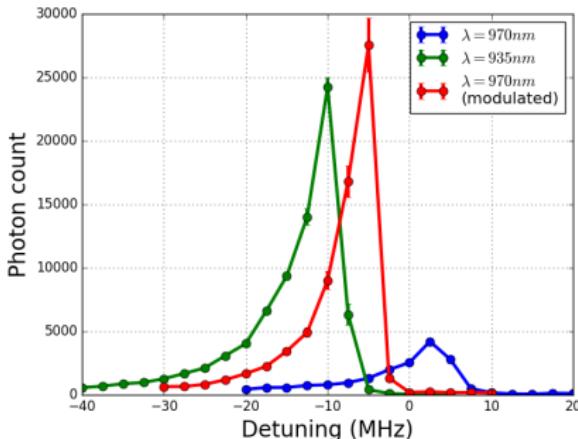
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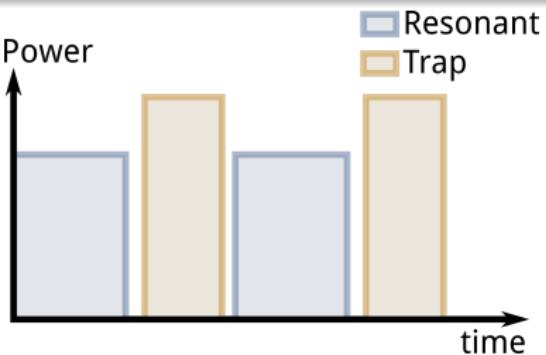
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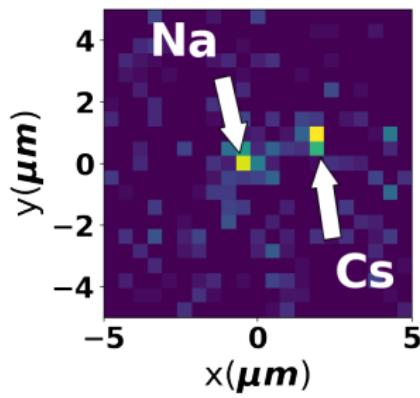
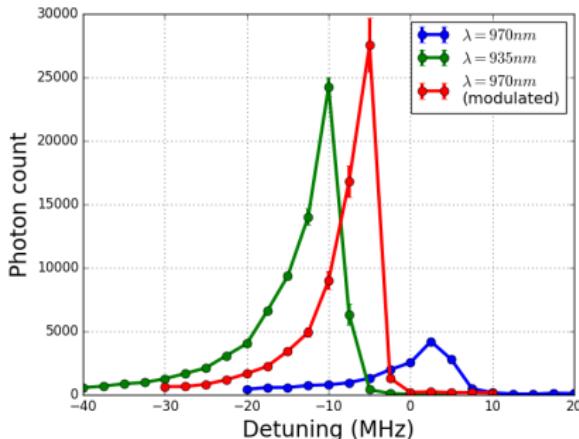
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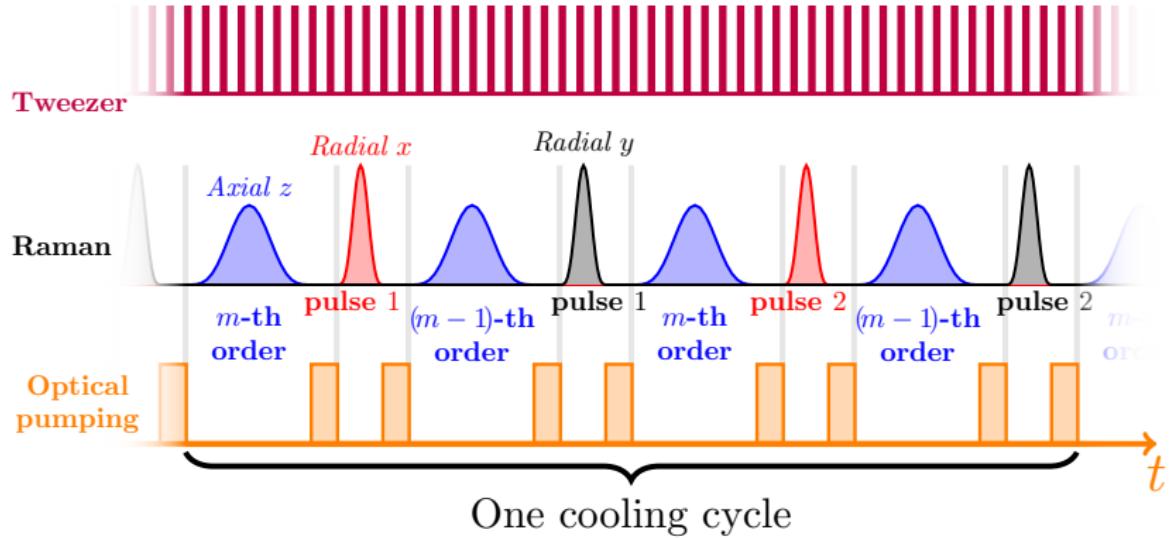
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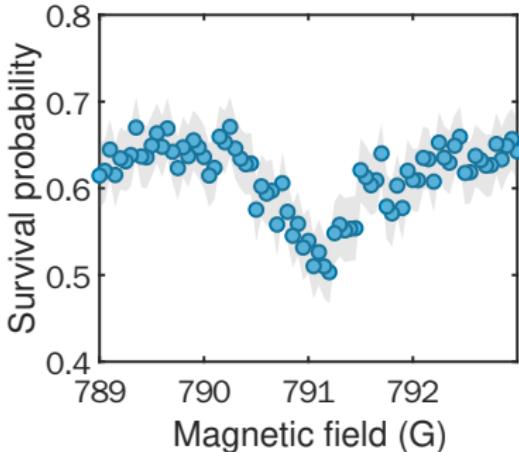
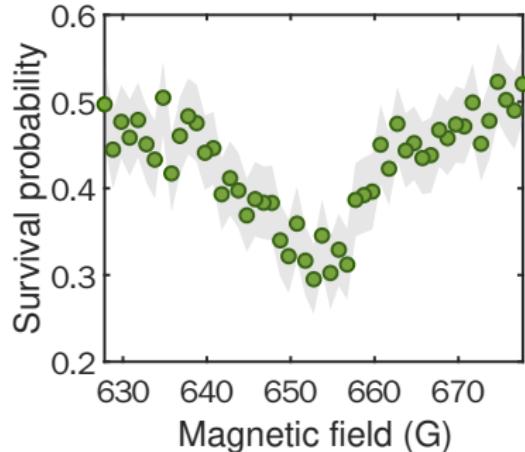
# Na Raman sideband cooling sequence



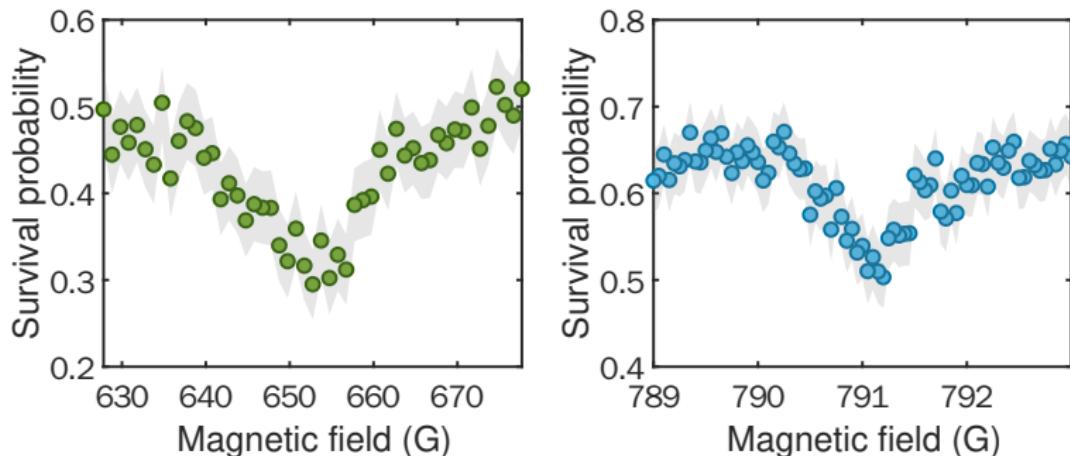
## Na (1, -1) Cs (3, -3) Feshbach resonance



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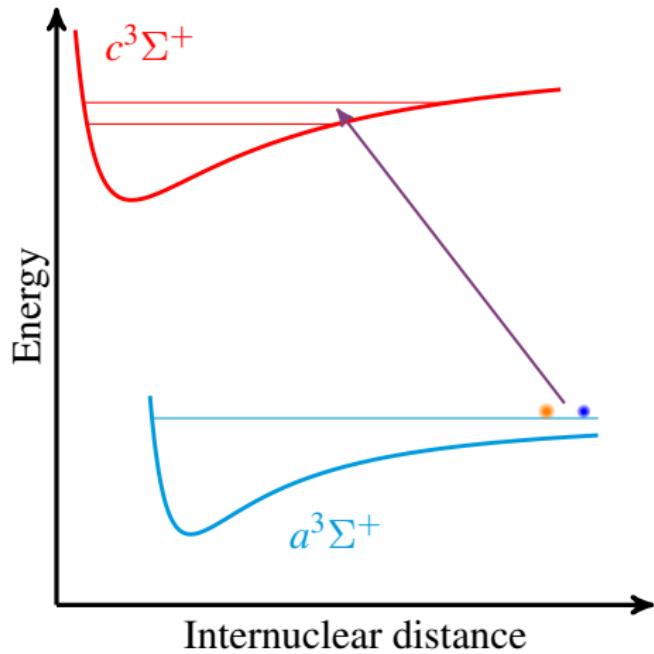
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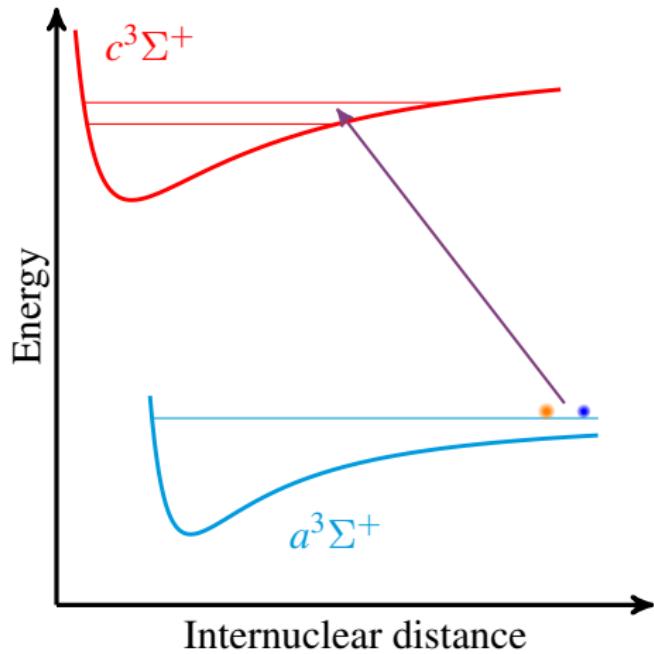
	<i>s</i> -wave	<i>p</i> -wave
Predicted (based on interaction shift) <sup>1</sup>	663 G	799 G
Measured	652(3) G	791.2(2) G

<sup>1</sup>In collaboration with Bo Gao

# Photoassociation (PA) Spectroscopy



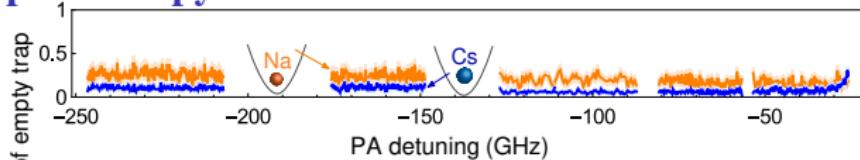
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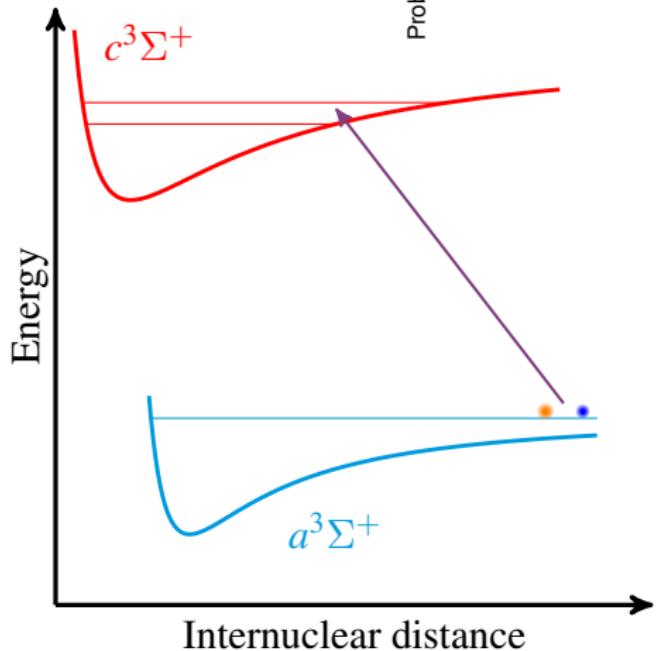
## Single Atom PA

- Clean initial state
- Narrow excitation laser
- Final state detection

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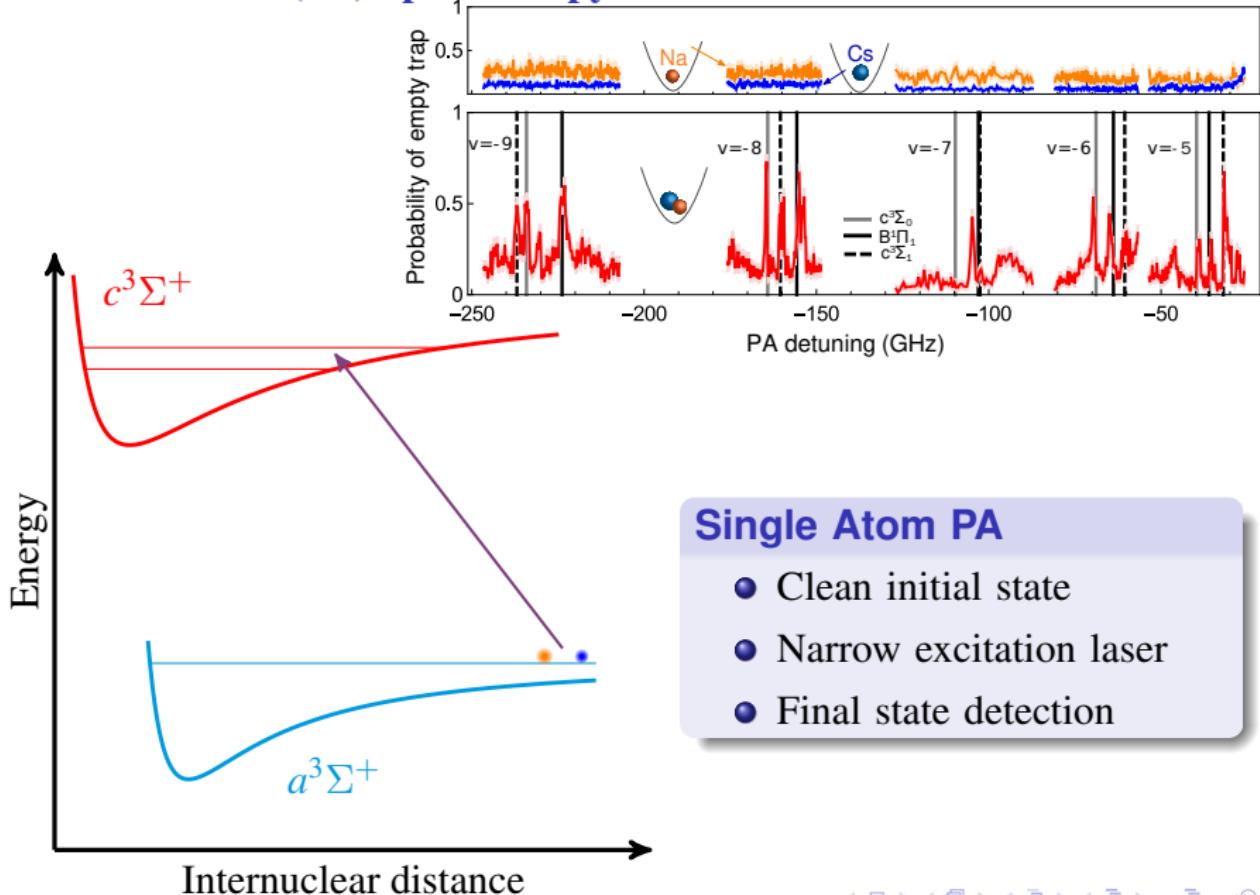
Probability of empty trap



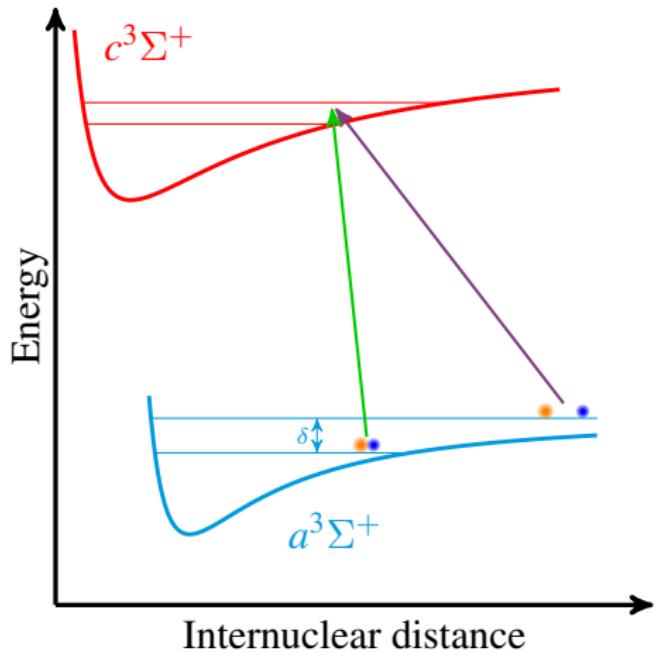
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# Photoassociation (PA) Spectroscopy



# Electromagnetically Induced Transparency (EIT) Spectroscopy



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