SAND2016-10821C

Sandia National Laboratories

Interacting single atom interferometers

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SAND2016-8869 C

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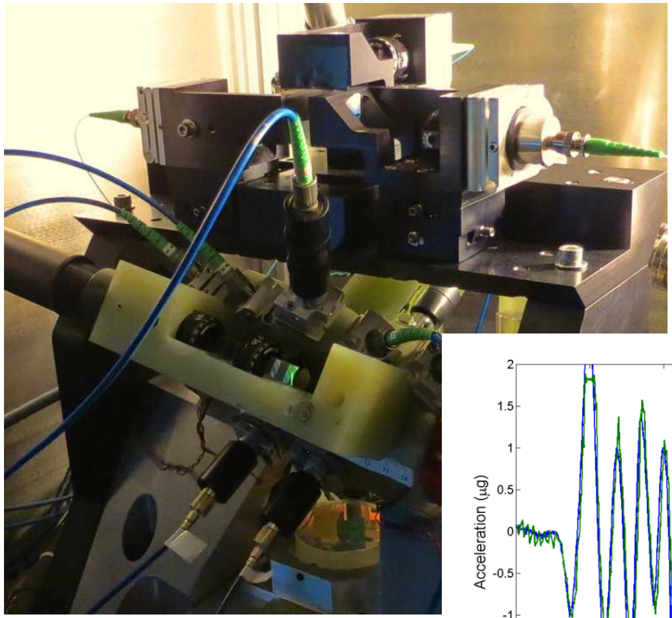
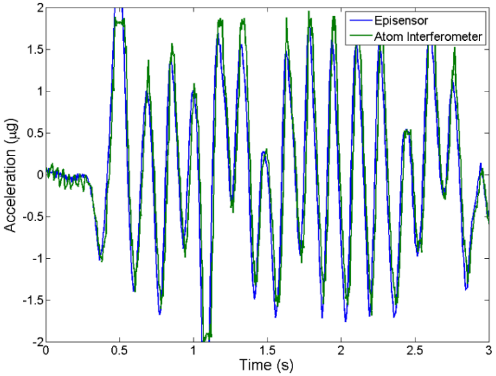
Interactions

Sandia AI Gyro/Accel



Accel. signal



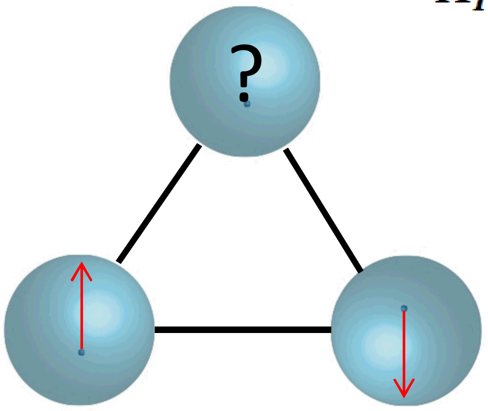
Applications

- Atom interferometer inertial sensors
  - Accelerometers
  - Gyroscopes
- Clocks
- Magnetometers
- Quantum information
  - improved sensors
  - quantum computation
  - quantum simulation

$$H_P = \sum_{i=1}^{N} \tilde{h}_i \sigma_z^{(i)} + \sum_{i,j=1}^{N} \tilde{J}_{ij} \sigma_z^{(i)} \otimes \sigma_z^{(j)}$$

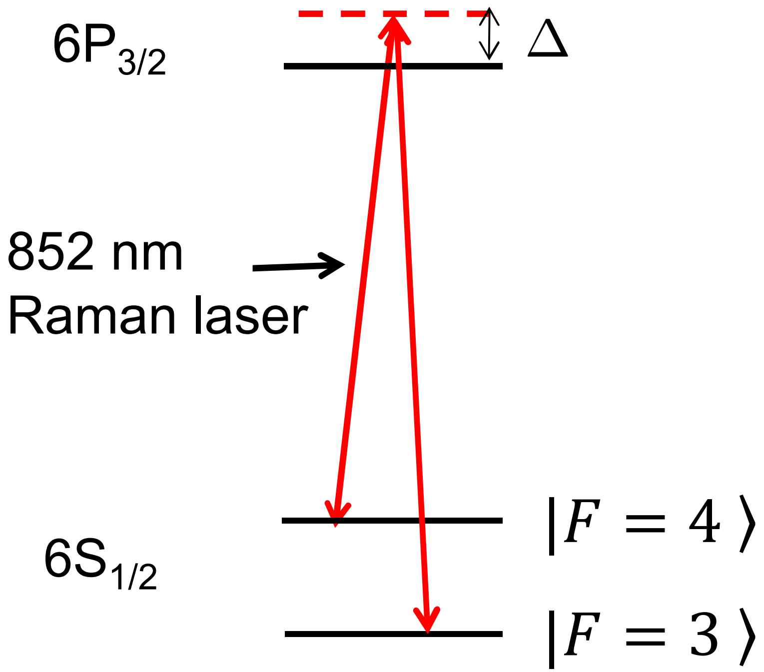
Generic Ising model
& beyond?

Achieve exquisite control of interactions



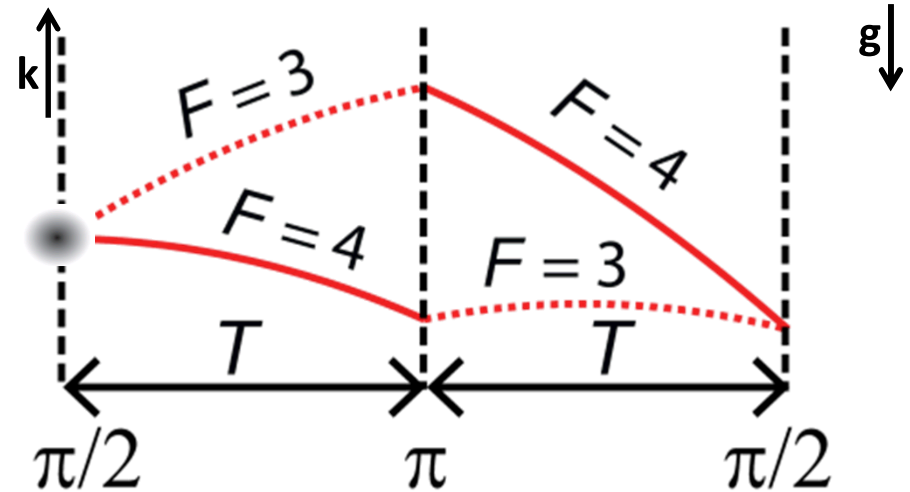
Frustrated magnetism

Light-pulse atom interferometers



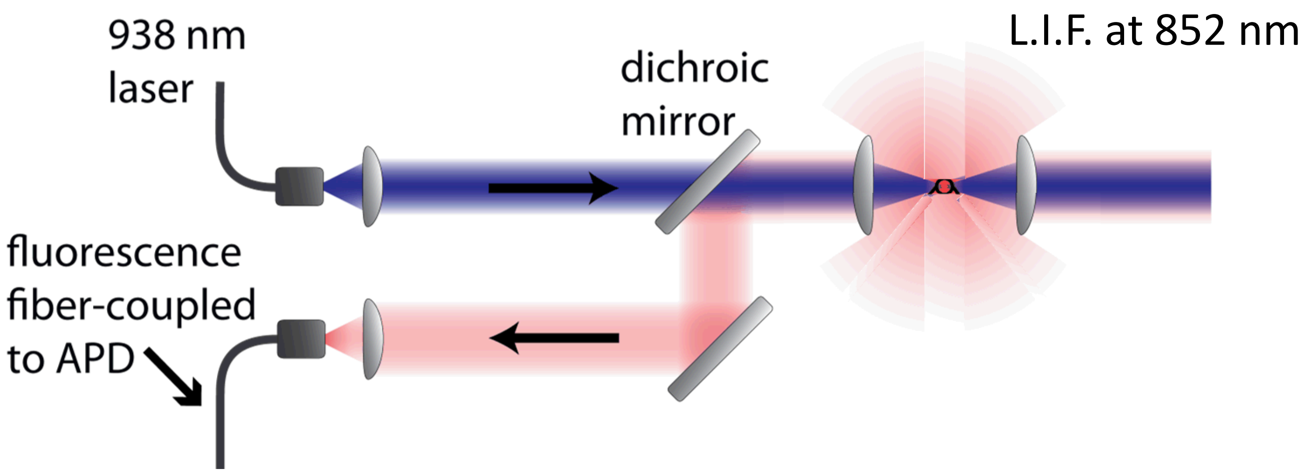
stimulated Raman transition

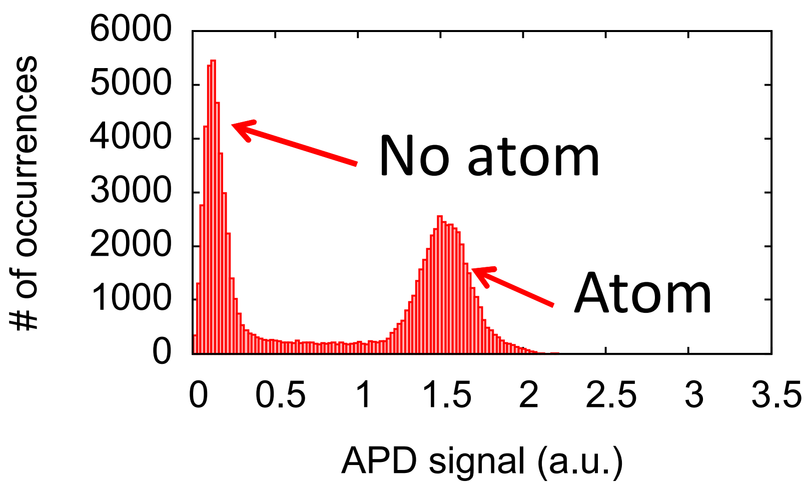
wavepacket trajectory



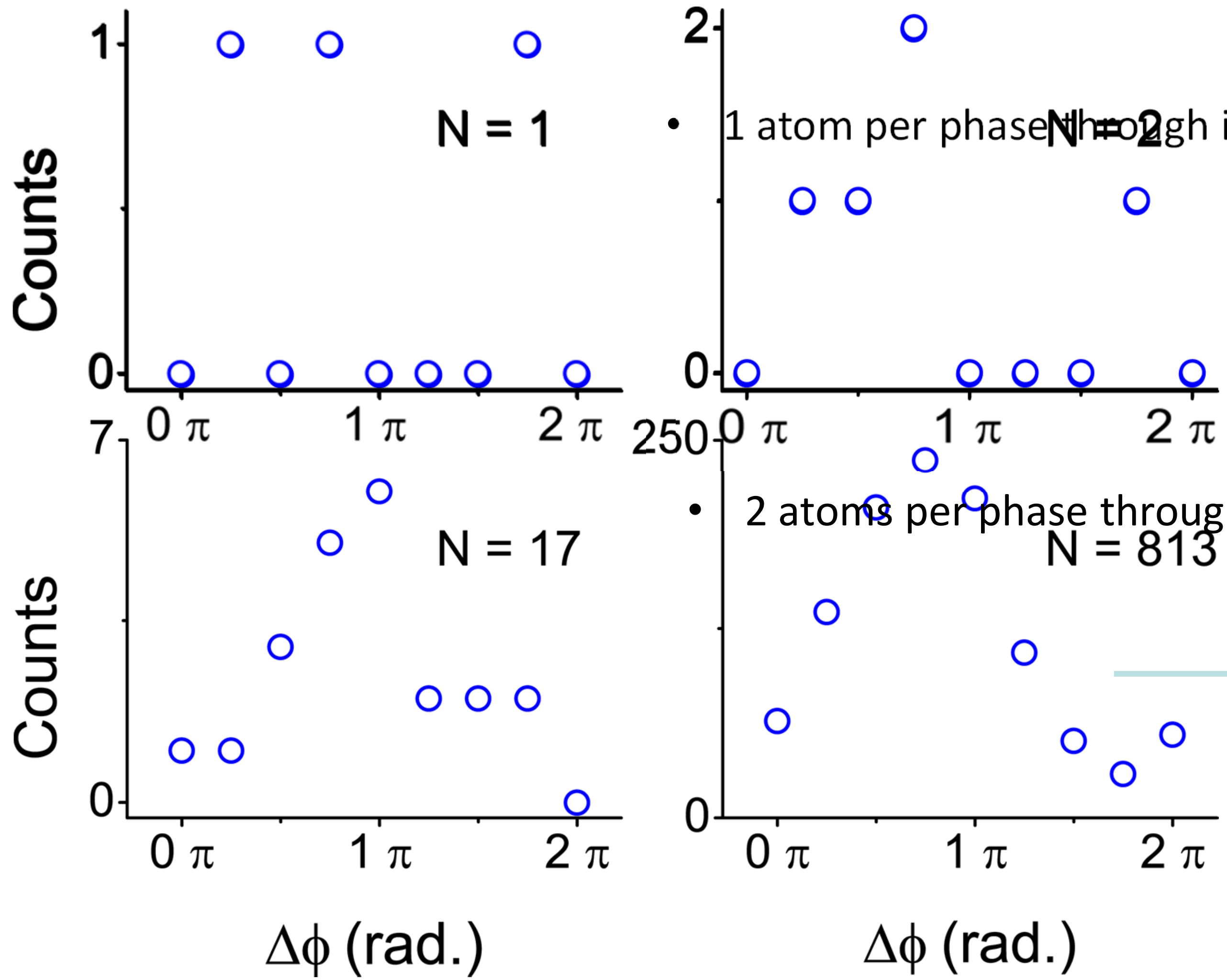
$\Delta\phi = \mathbf{k} \bullet \mathbf{g}\, T^2$

Free-space matterwave interference with a single atom





Building fringe one atom at a time



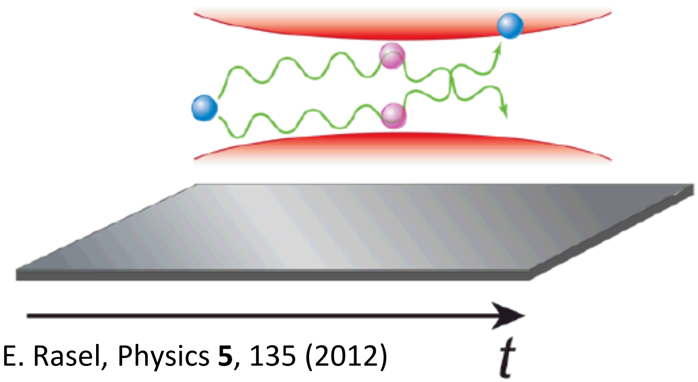
- 1 atom per phase through interferometer.
- 2 atoms per phase through interferometer.

7,317 atoms

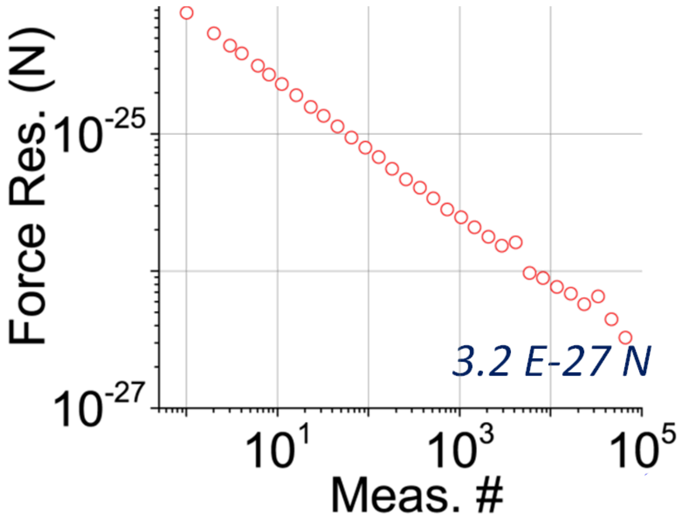
Parazzoli, et al., “Observation of free-space single-atom matterwave interference”, Phys. Rev. Lett. **109**, 230401 (2012)

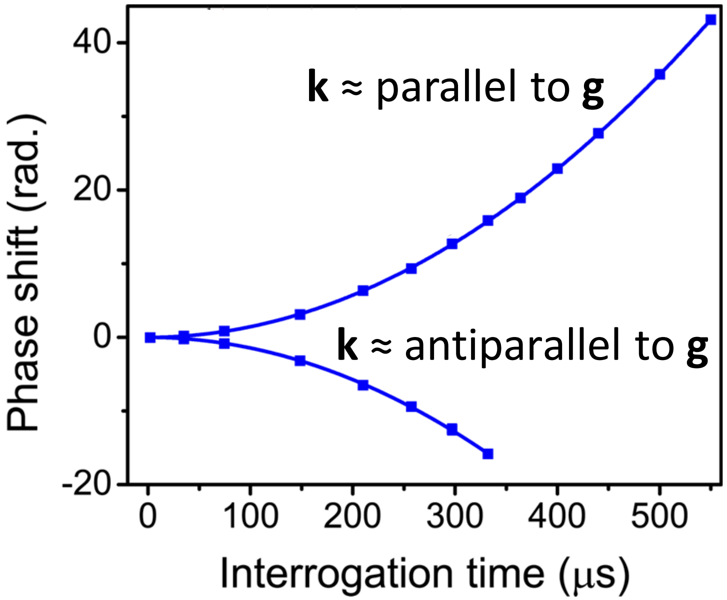
Force resolution of a single atom interferometer

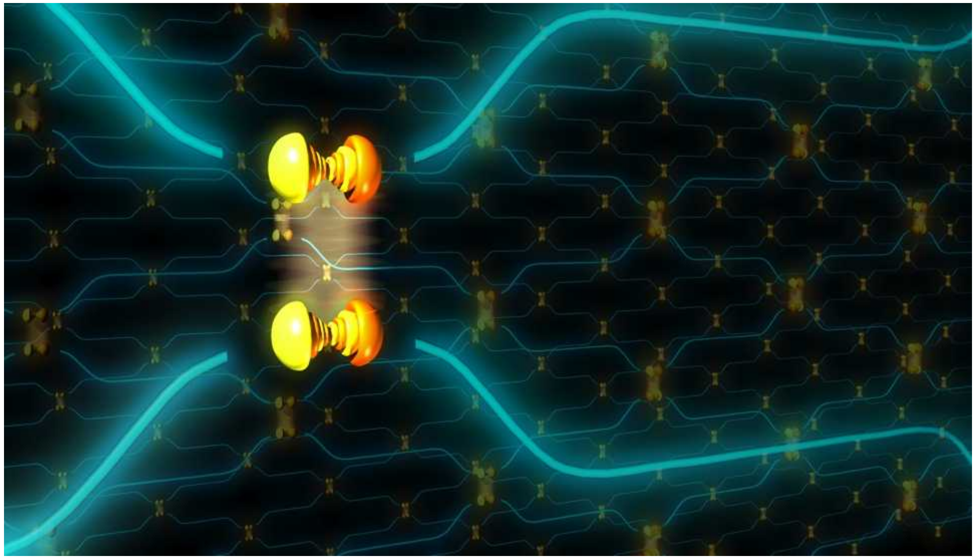
Parazzoli, et al., Phys. Rev. Lett. **109**, 230401 (2012)



E. Rasel, Physics **5**, 135 (2012)

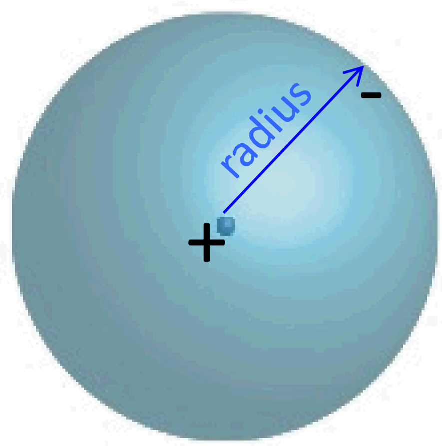






Interaction between *neutral* atoms

Valence electron in Rydberg state

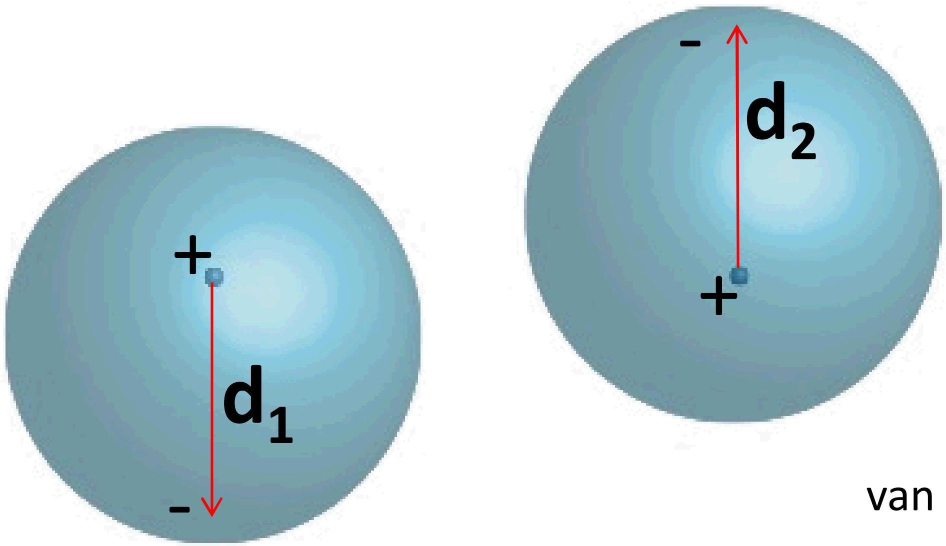


orbital radius α n^2

Wavefunction symmetric in zero electric field

- Interaction between ground state atoms is small ~ 100 Hz
- Excite valence electron to Rydberg state—nearly ionized
- Atom becomes highly polarizable—strong interactions
- Even the presence of another atom can cause a massive response >> 10 MHz

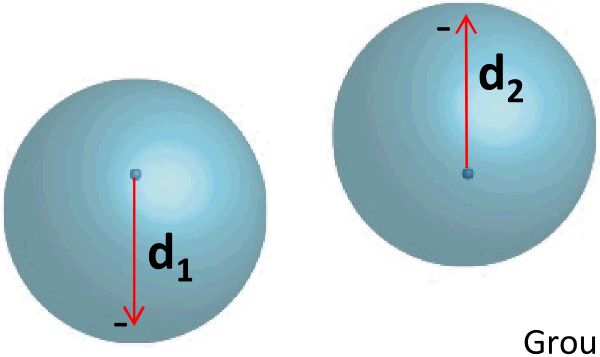
Interaction between *neutral* atoms



van der Waals interaction

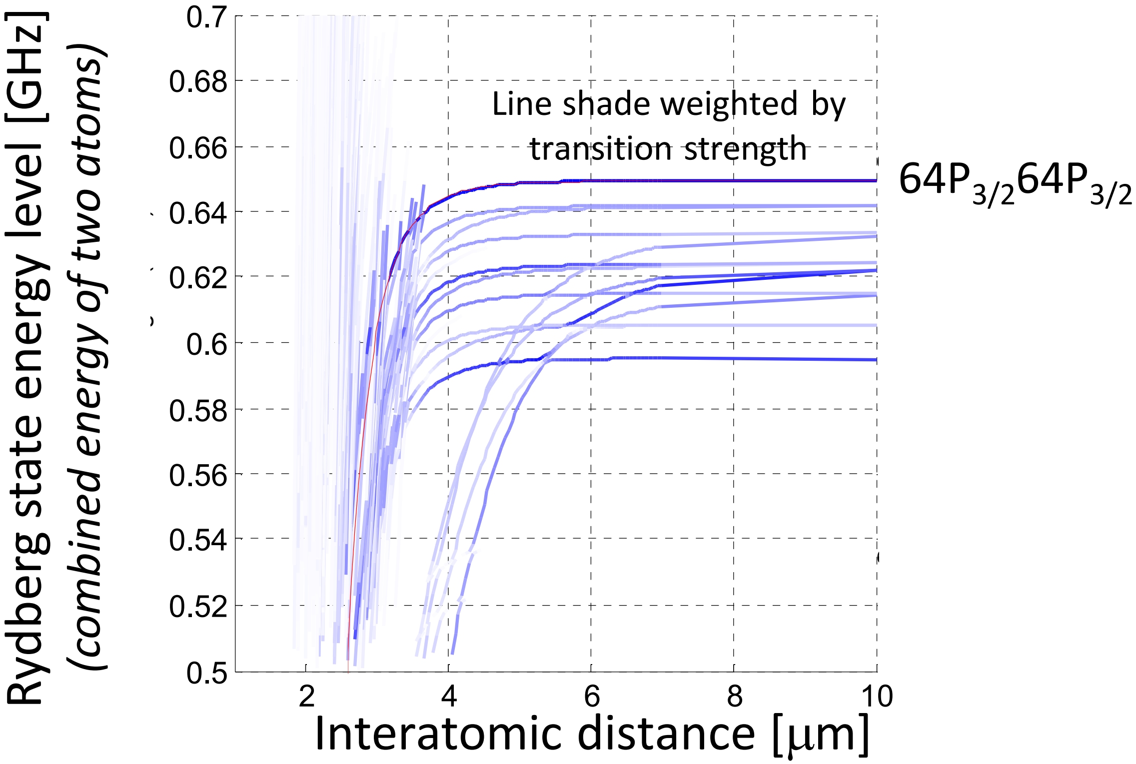
- Interaction between ground state atoms is small ~ 100 Hz
- Excite valence electron to Rydberg state—nearly ionized
- Atom becomes highly polarizable—strong interactions
- Even the presence of another atom can cause a massive response >> 10 MHz

Interaction between *neutral* atoms

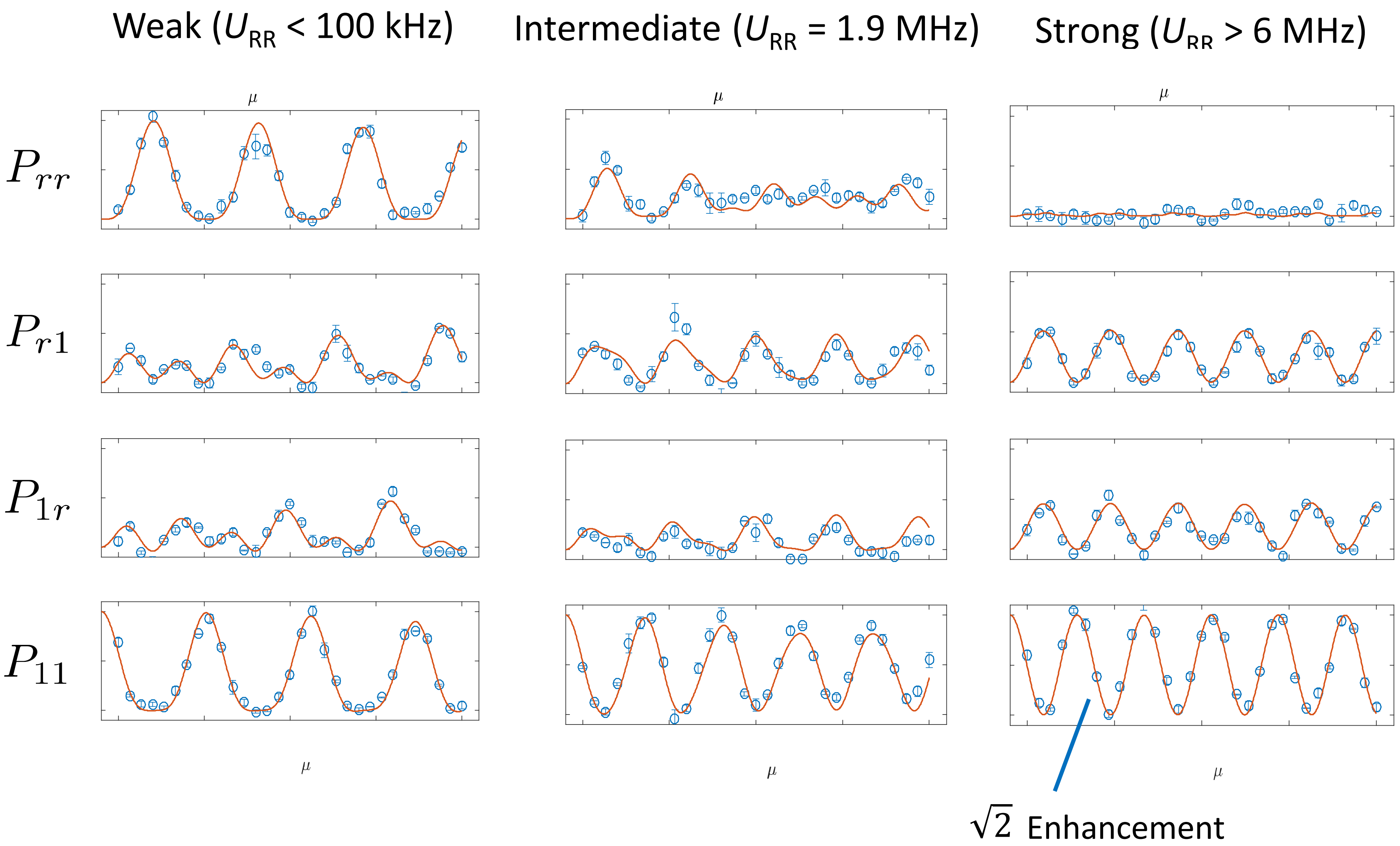


Entanglement demonstrations
- Madison: Phys. Rev. Lett. 104, 010503 (2010)
- Paris: Phys. Rev. Lett. 104, 010502 (2010)

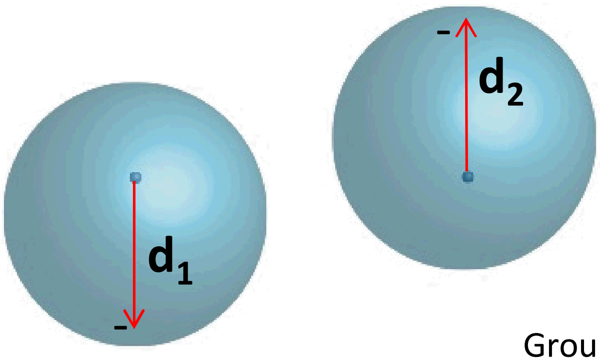
Ground to 64P3/2, x-polarized, B=4.8 G, E = 6.4 V/m



Rydberg blockade—direct excitation



Interaction between *neutral* atoms



Entanglement demonstrations
- Madison: Phys. Rev. Lett. 104, 010503 (2010)
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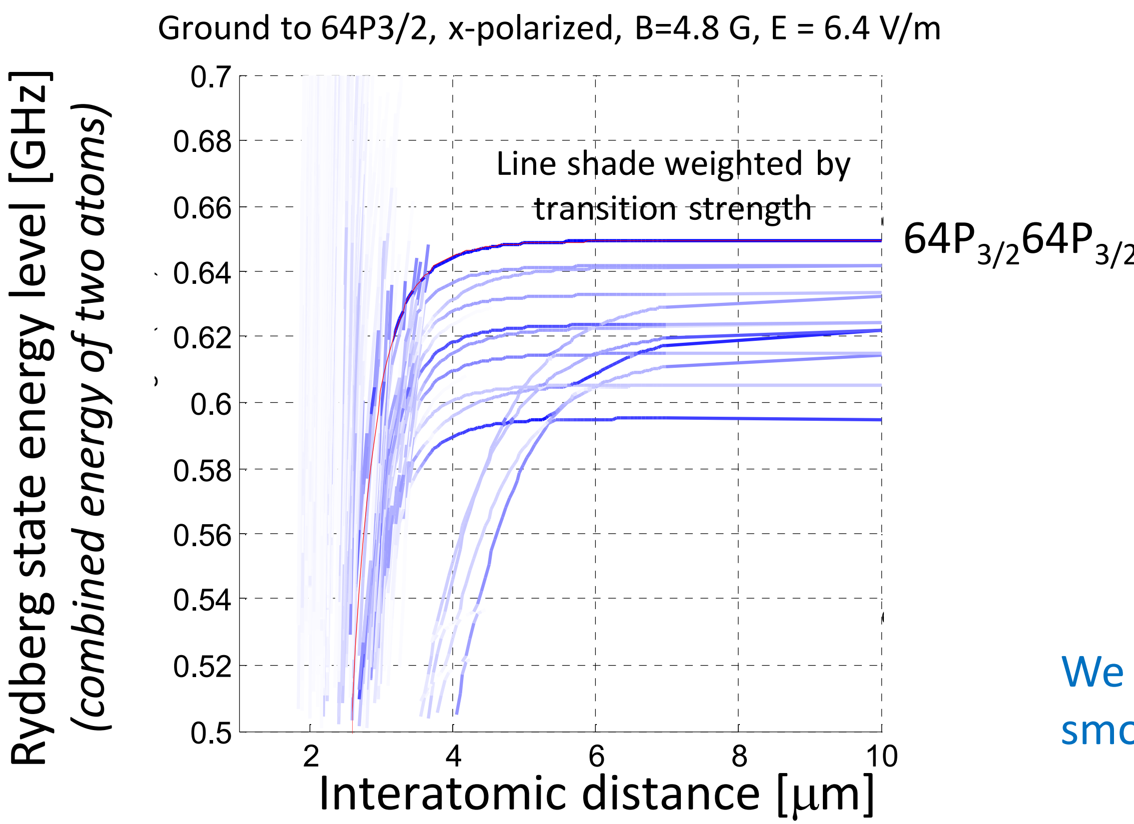
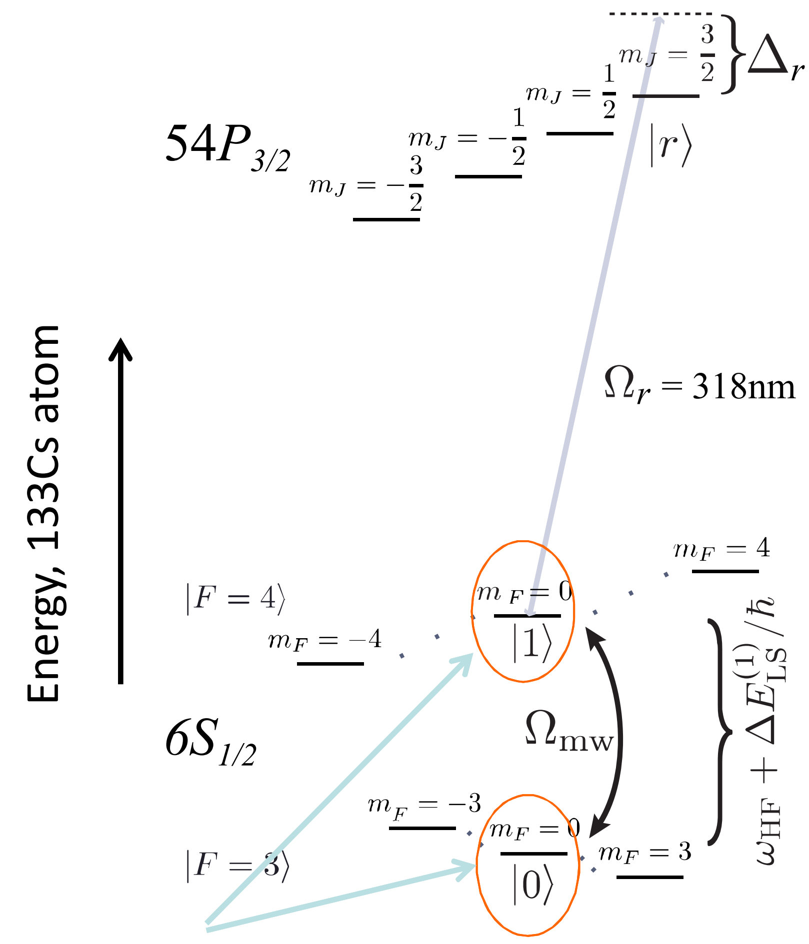
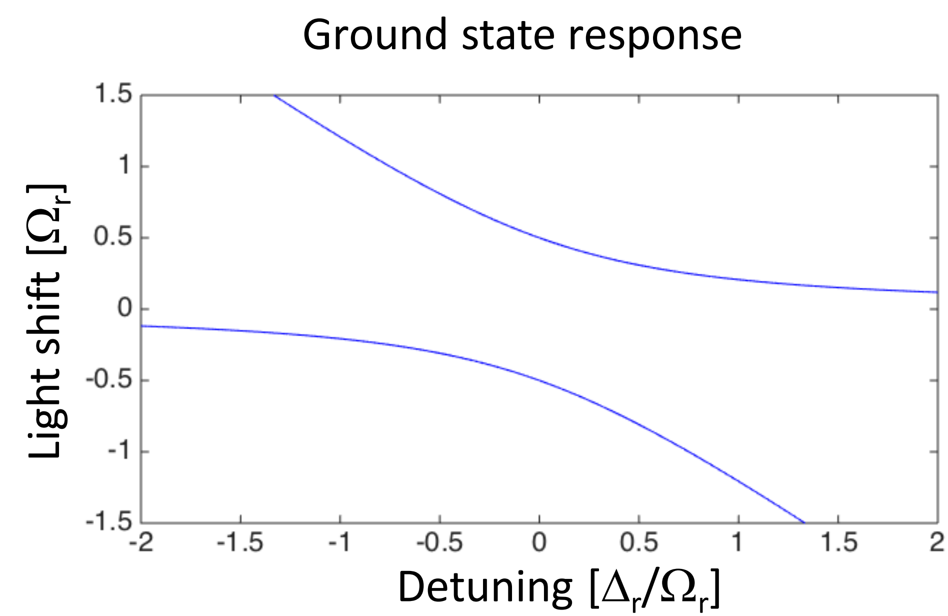


We want something smooth and tunable

Rydberg-dressed states



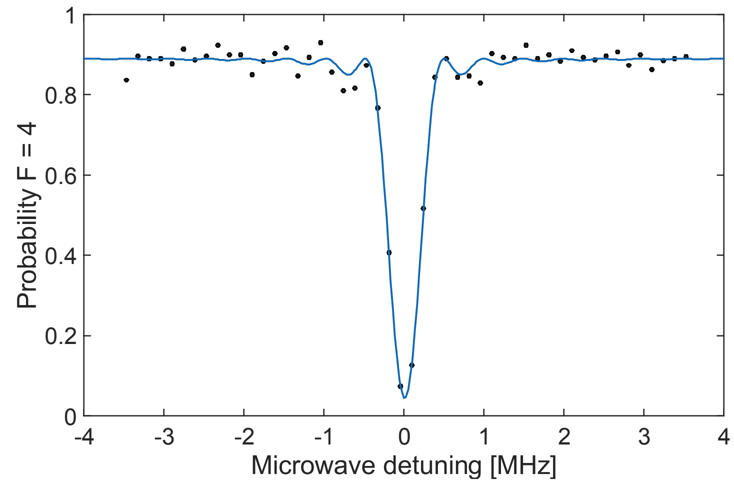
Single atom picture



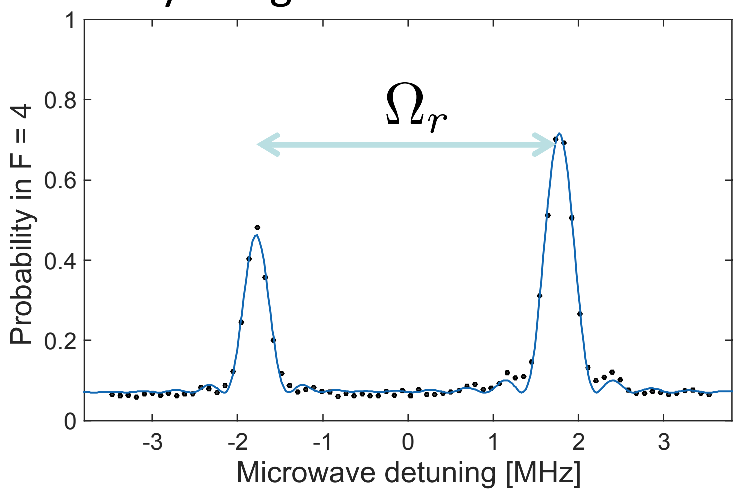
- Controllable with laser intensity and detuning—on demand
- Transfers blockade effect to ground state manifold
- Blockade changes light shift
- i.e. "J" = change in light shift due to dipole-dipole interaction

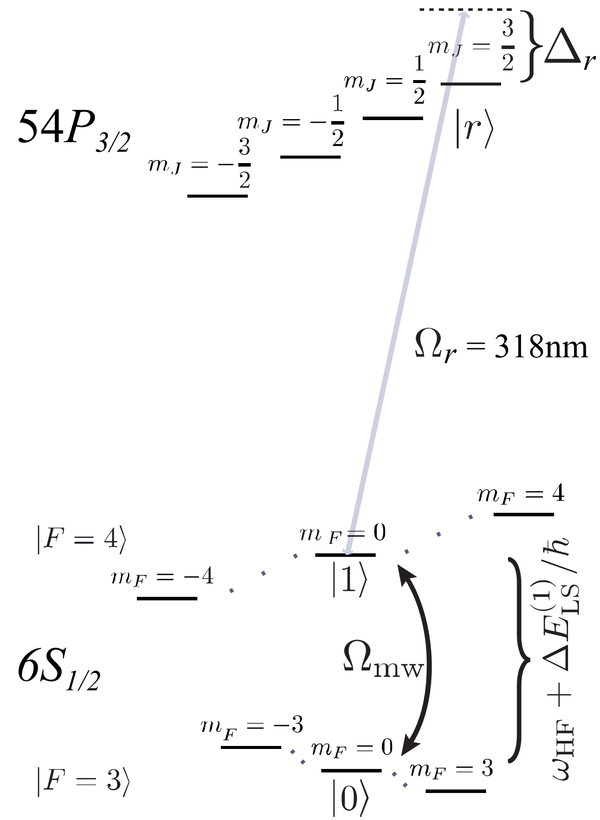
Rydberg-dressed states

Bare atom



Rydberg-Dressed F=4 state

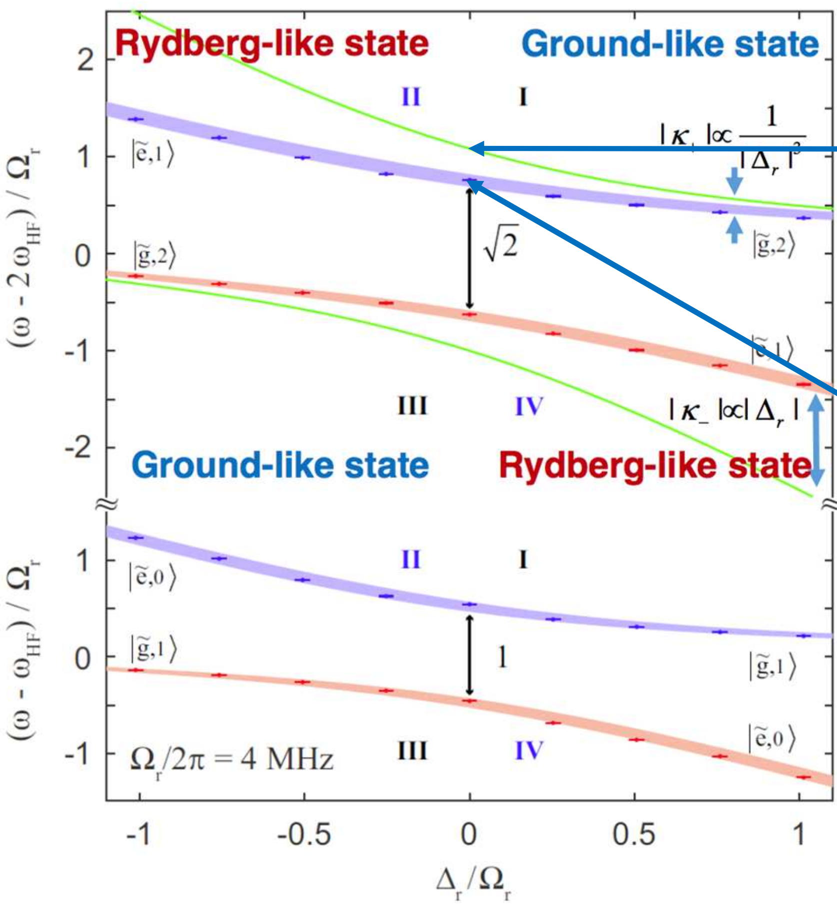




What about multiple atoms?

Jaynes-Cummings Ladder

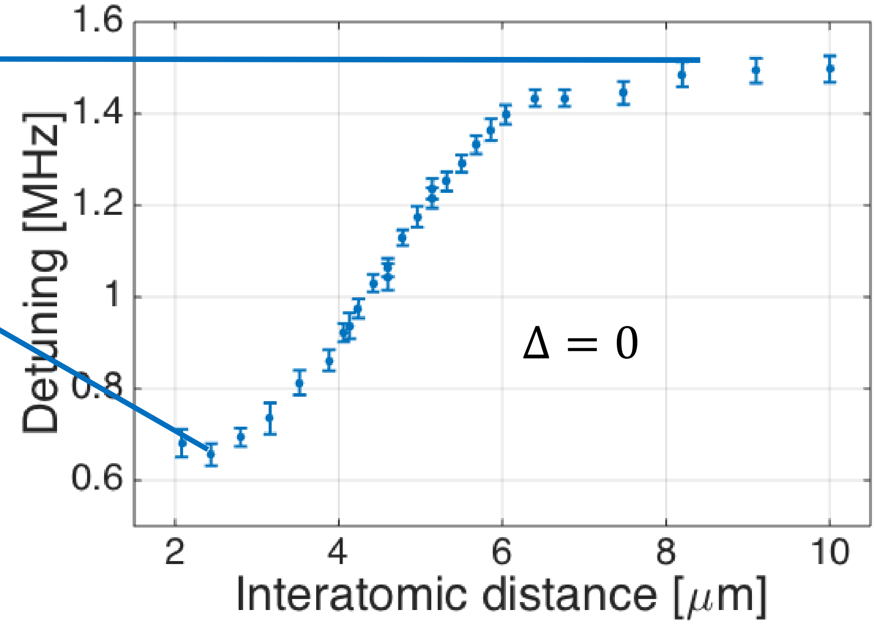
Autler-Towns Spectrum



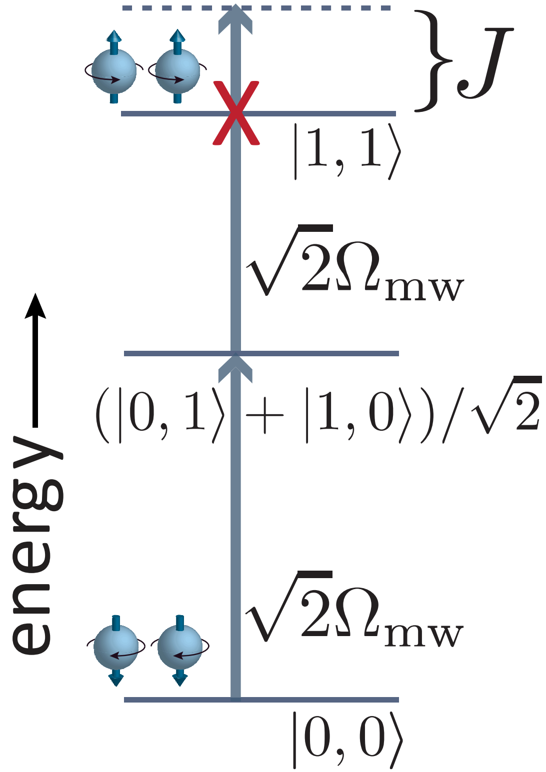
Publication in progress

Spatial dependence

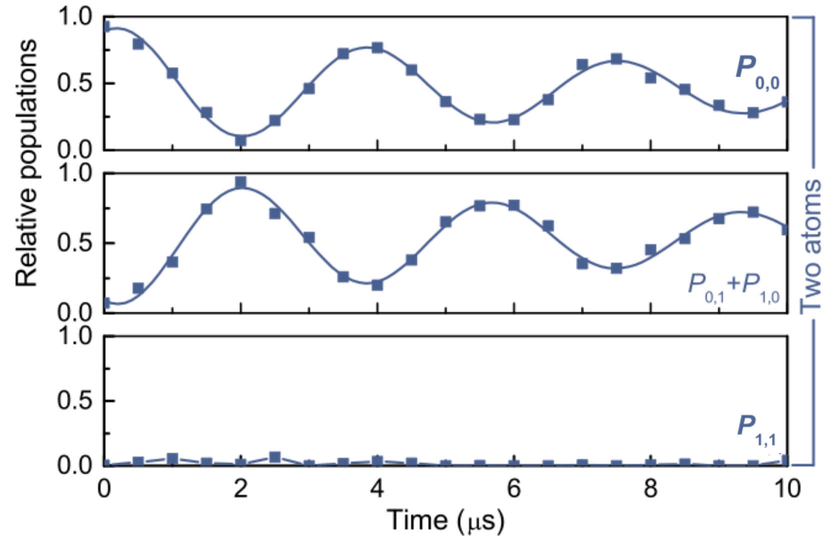
Light shift of Rydberg-dressed state

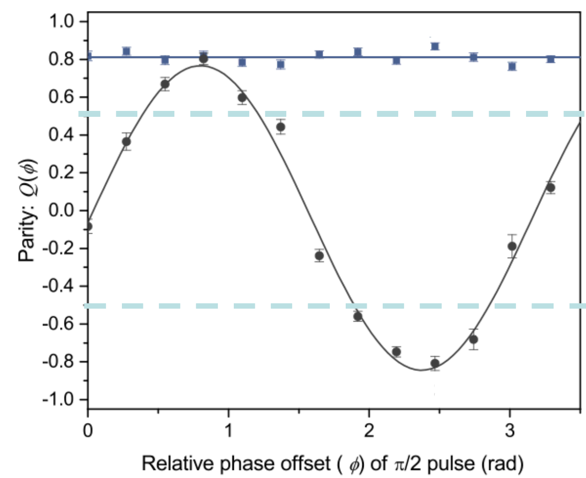


Ground state, *Spin-flip* blockade



Rabi oscillations

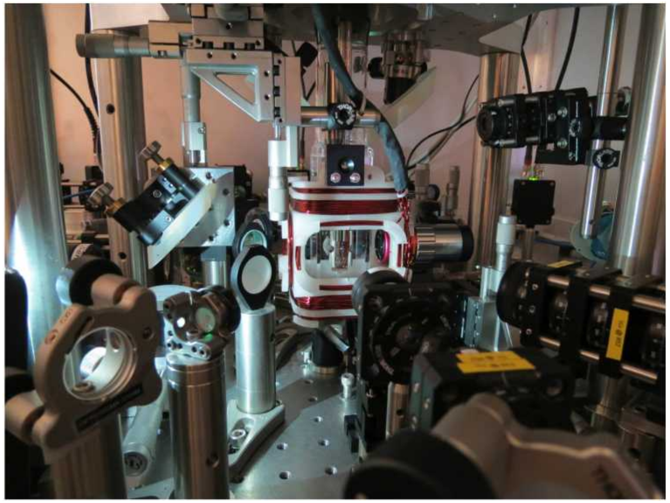


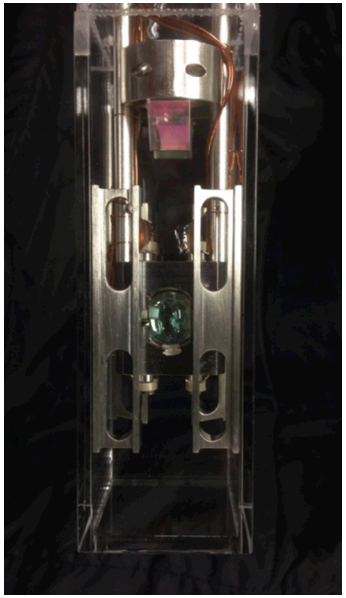


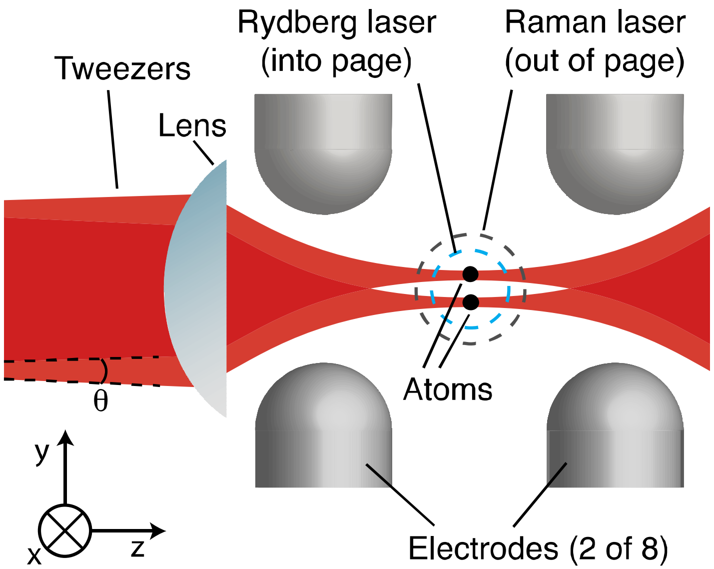
Parity

Fidelity: 81%*
60% deterministic

Apparatus

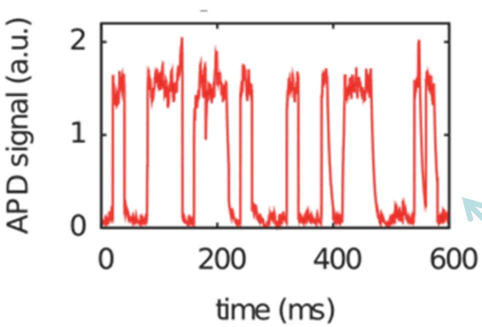


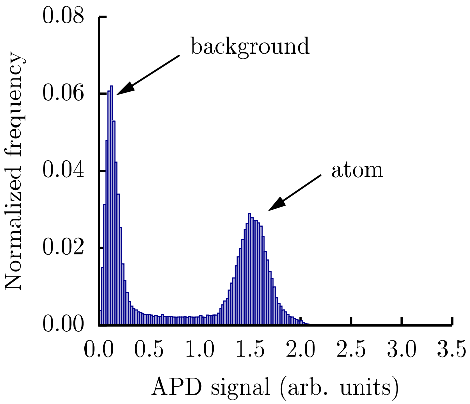


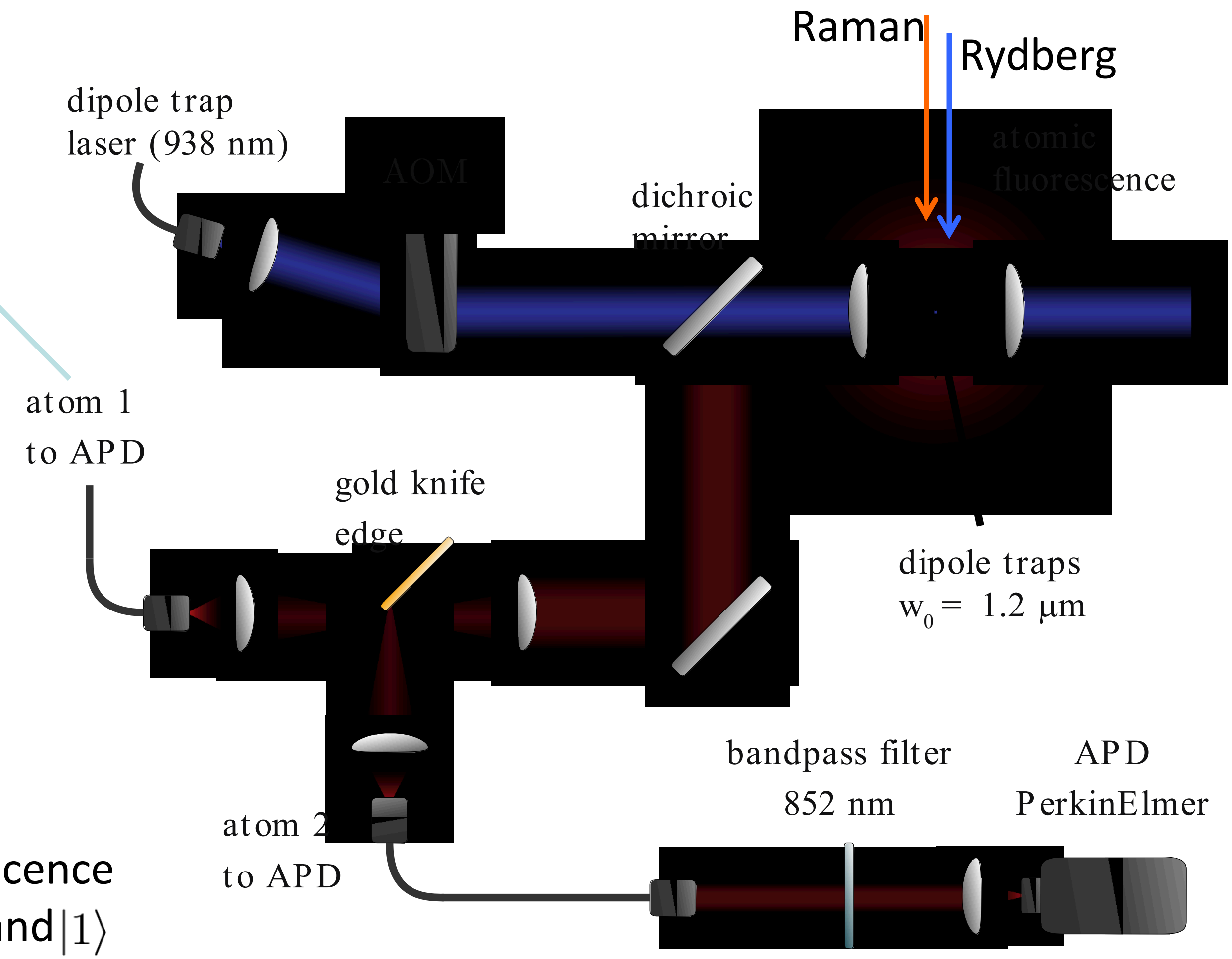

Tweezers
Rydberg laser
(into page)
Raman laser
(out of page)
Lens
Atoms
θ
y
x
z
Electrodes (2 of 8)

Single atom control of 2 atoms

Sandia National Laboratories

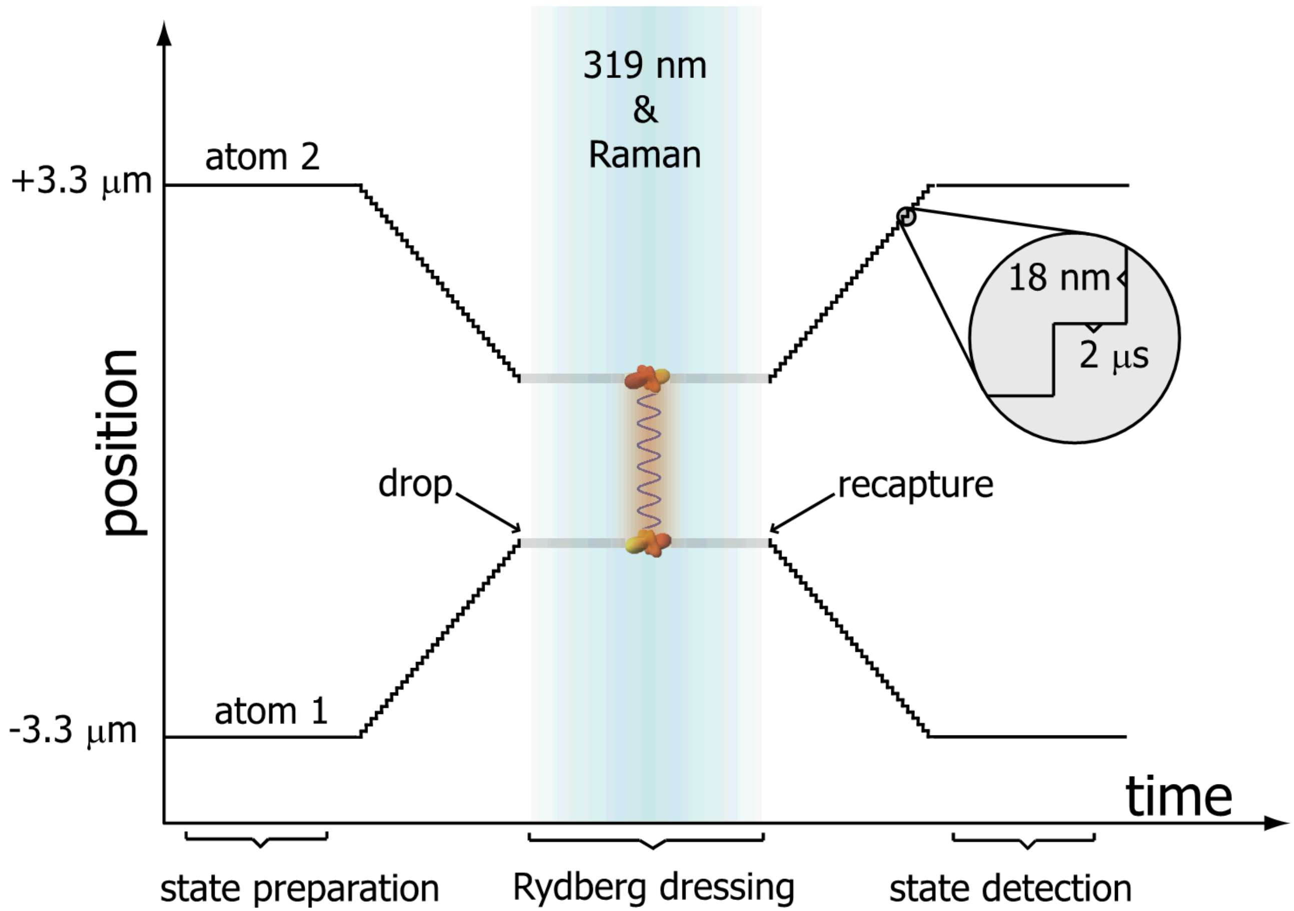






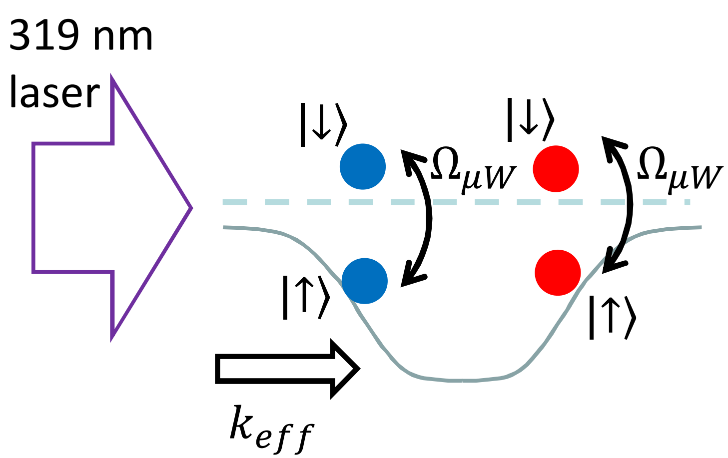
- State-dependent fluorescence
- Directly detect both $|0\rangle$ and $|1\rangle$
- Distinguishable from loss
- FPGA control: Reuse atoms
- Data rate ≈ 10 s^{-1} for two atoms

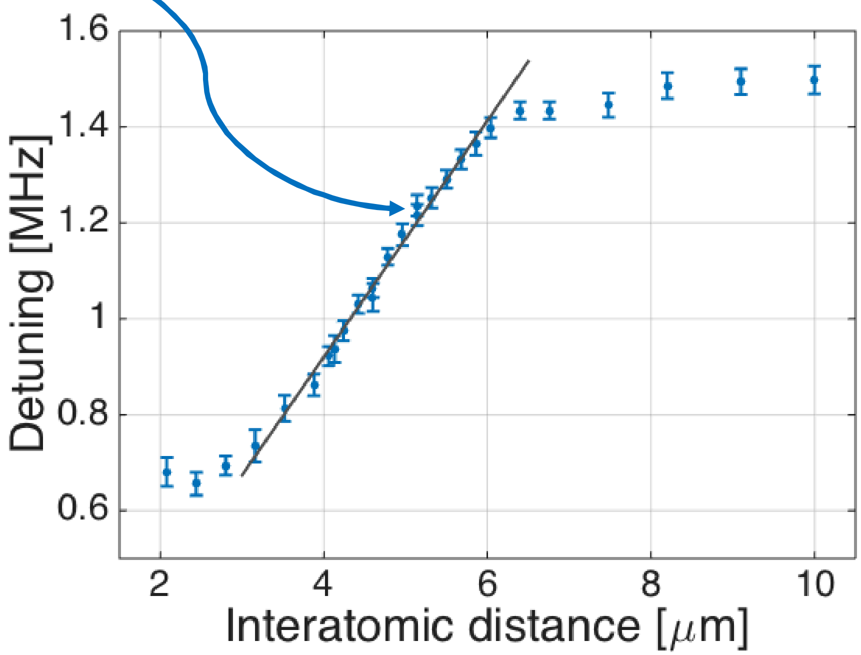
Dynamic atom positioning



Interacting interferometers

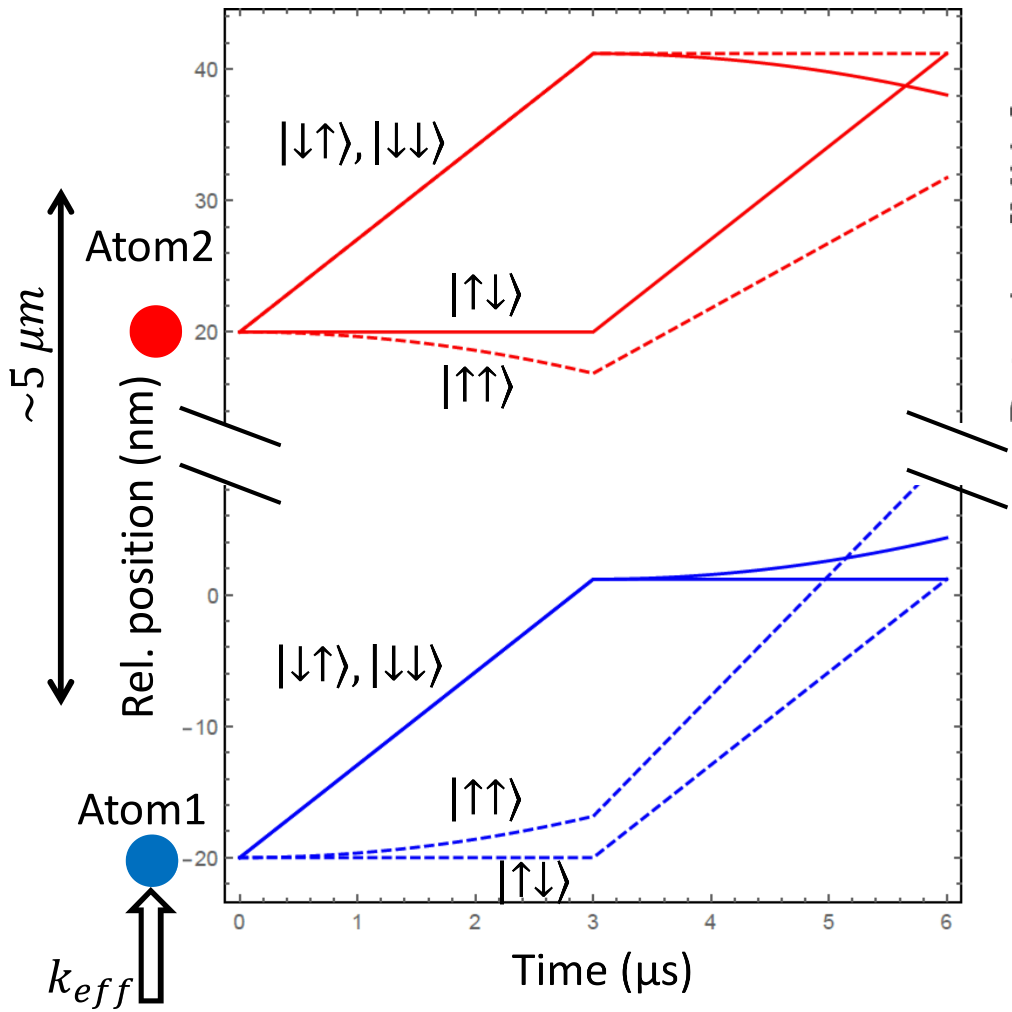
State-dependent force = 740+/- 45 m/s^2

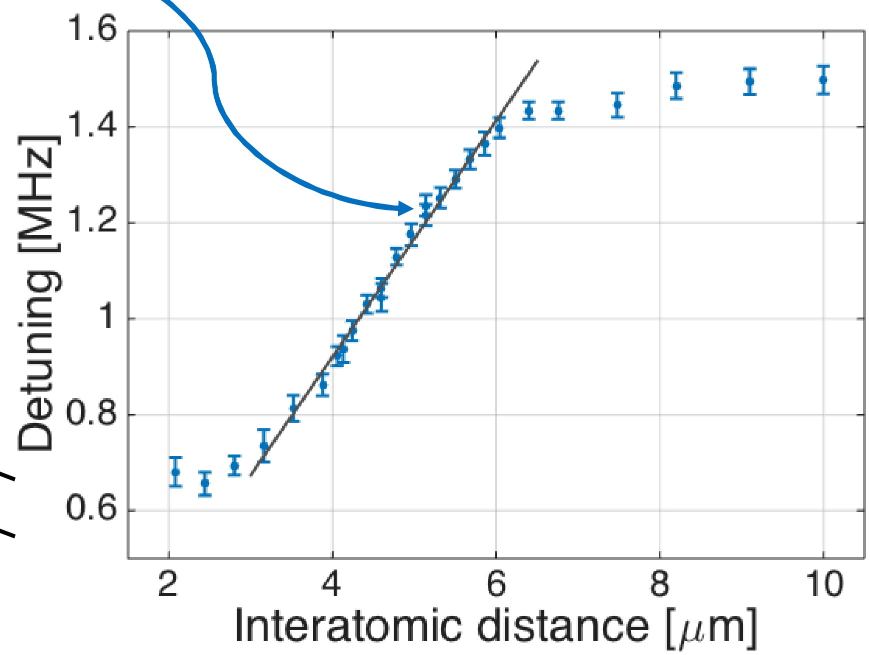




Interacting interferometers

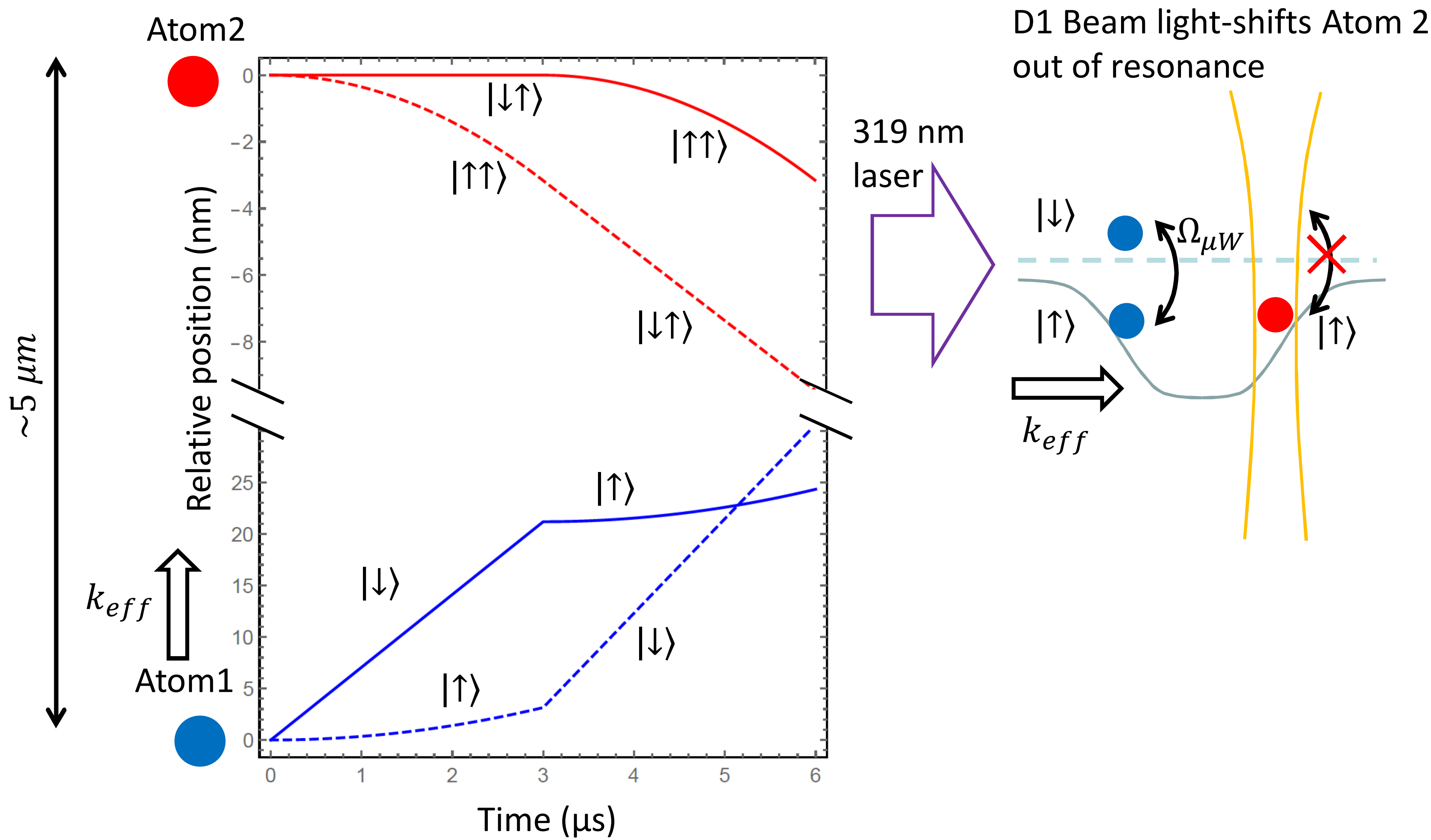
State-dependent force = 739+/- 45 m/s^2



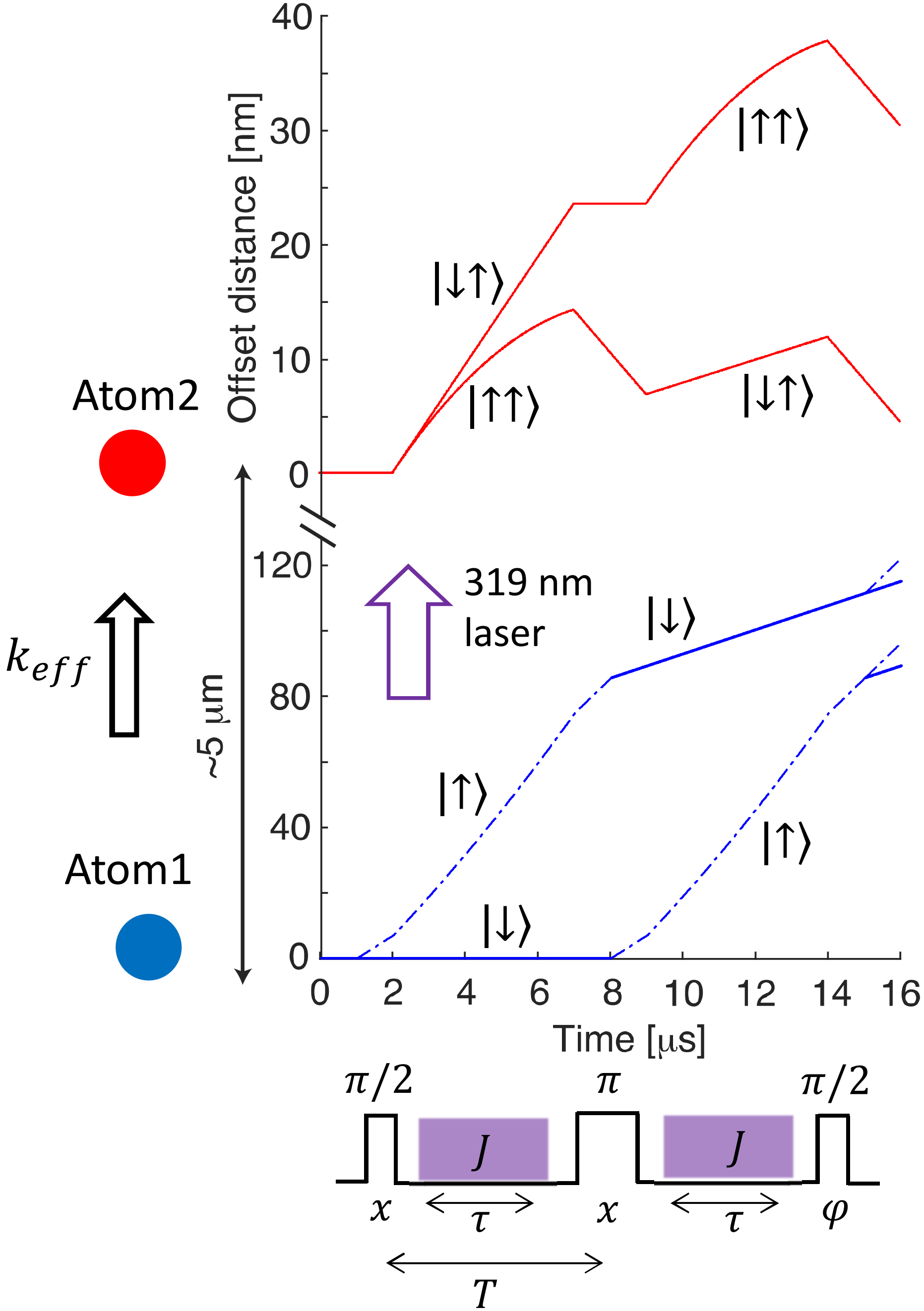


Each interferometer in a superposition of 4 possible scenarios

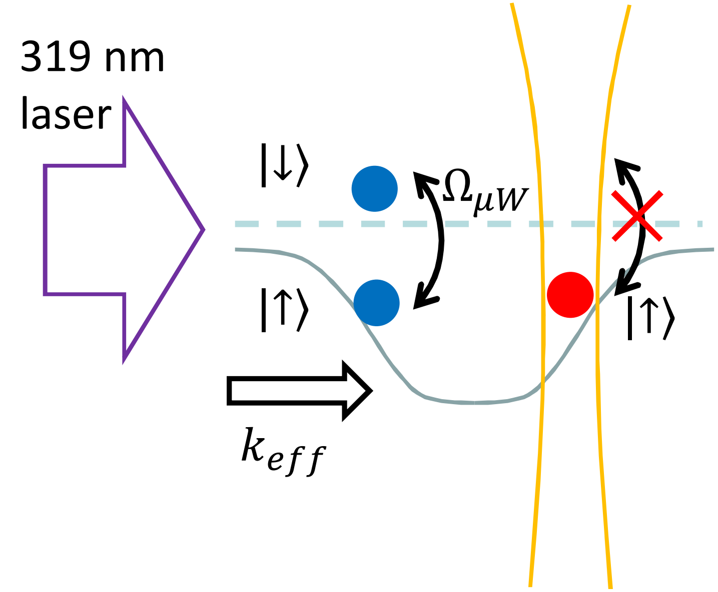
Interferometry of interacting atoms—simplified



Interferometry of interacting atoms—simplified



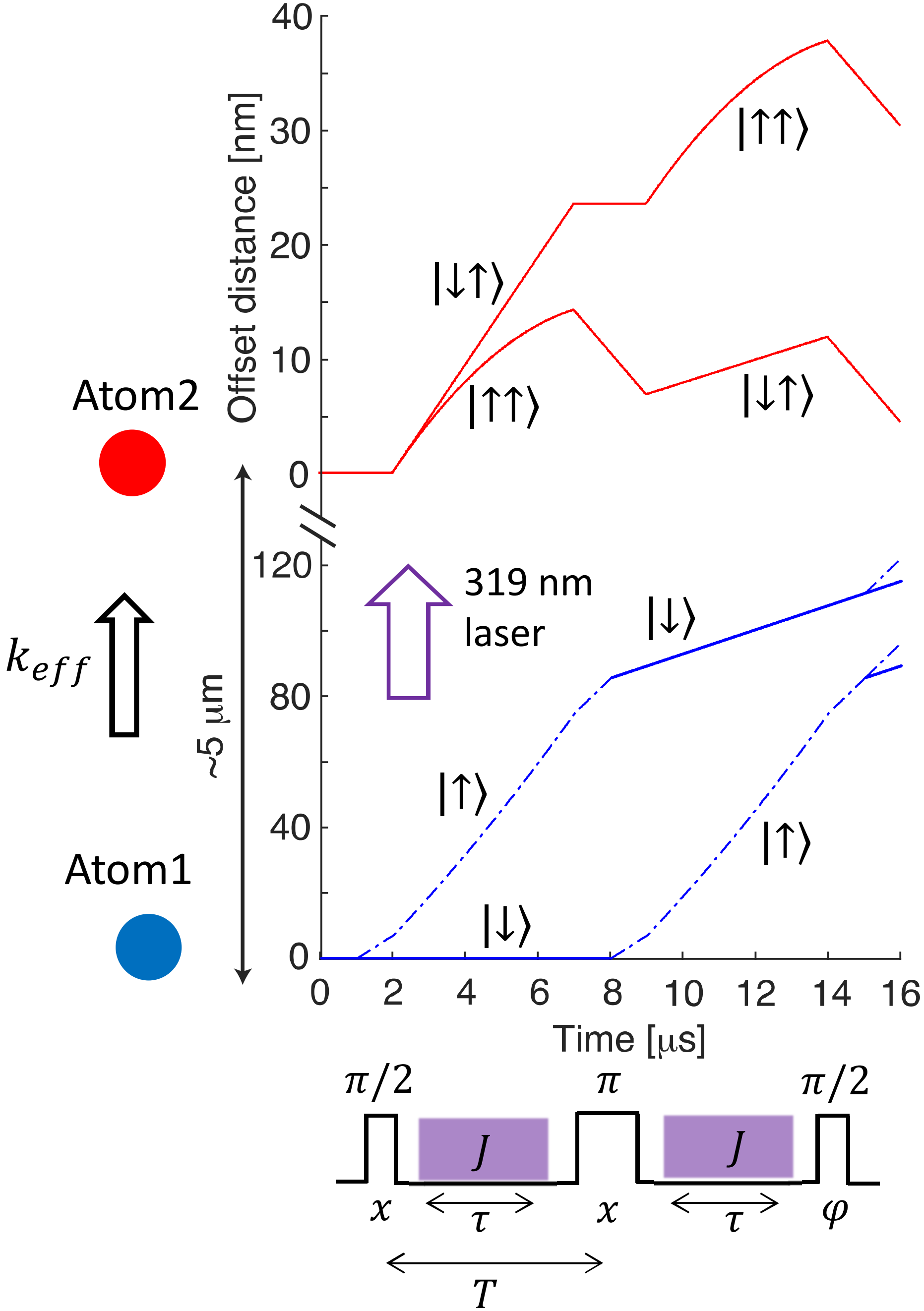
D1 Beam light-shifts Atom 2 out of resonance



$$\phi(k_{eff}) = \alpha k_{eff} a \tau T + \beta \frac{3ma^2\tau^2 T}{2h} + \ldots$$

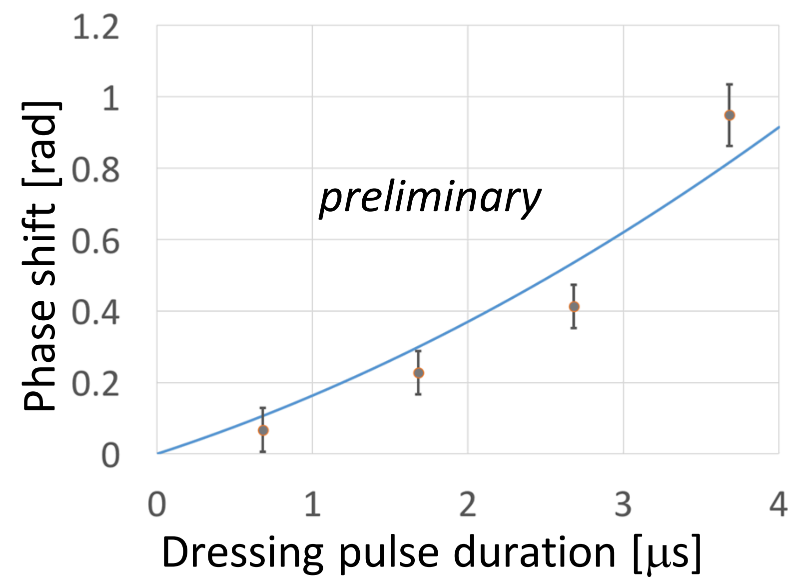
K. Bongs, R. Launay, and M. Kasevich, Appl. Phys. B., 84,599 (2006)

Interferometry of interacting atoms—simplified

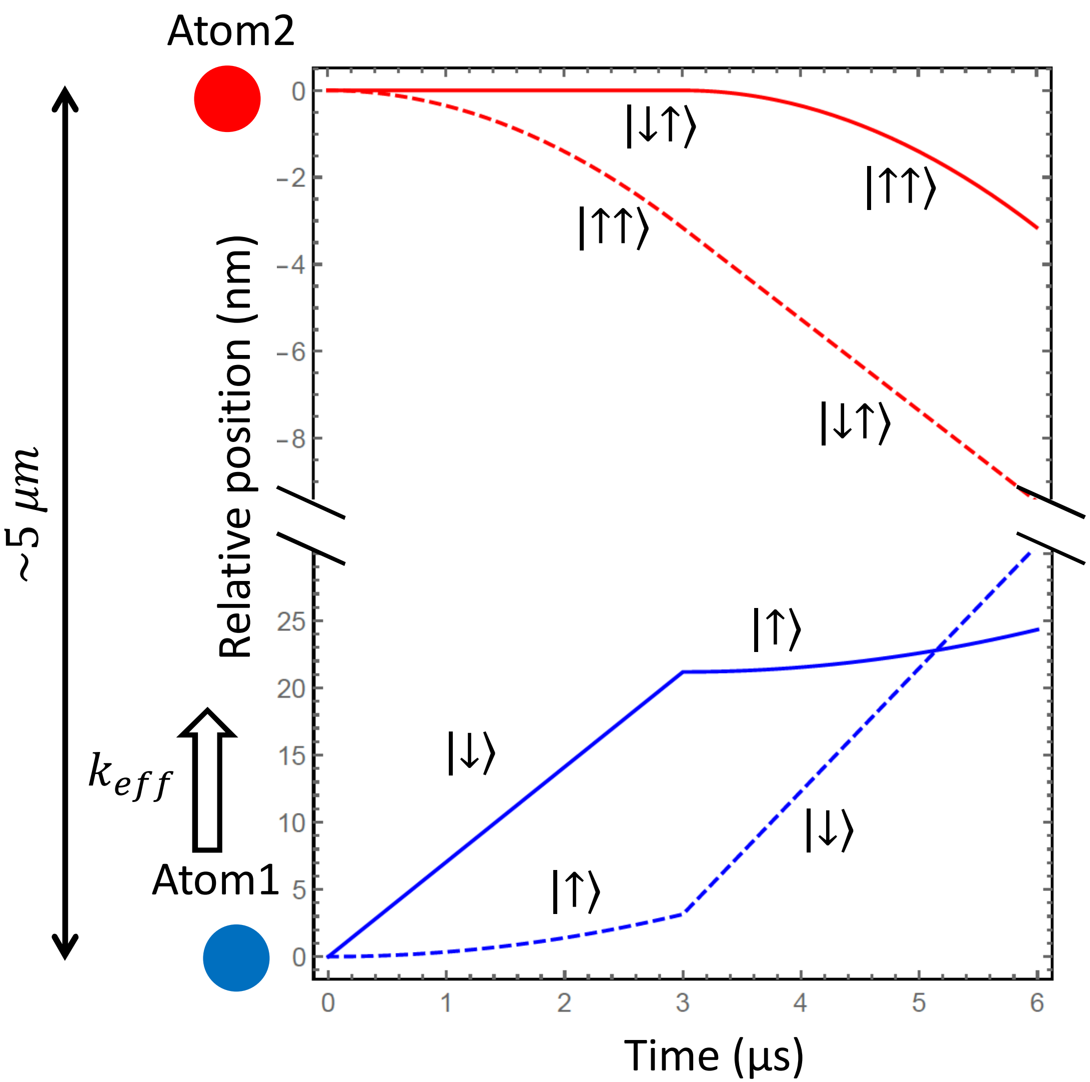


$$\phi(k_{eff}) = \alpha k_{eff} a T^{\,2} + \beta \frac{3ma^2T^3}{2h} + \ldots$$

$$\Delta\phi \equiv \phi(+k_{eff}) - \phi(-k_{eff})$$



Interferometry of interacting atoms—simplified



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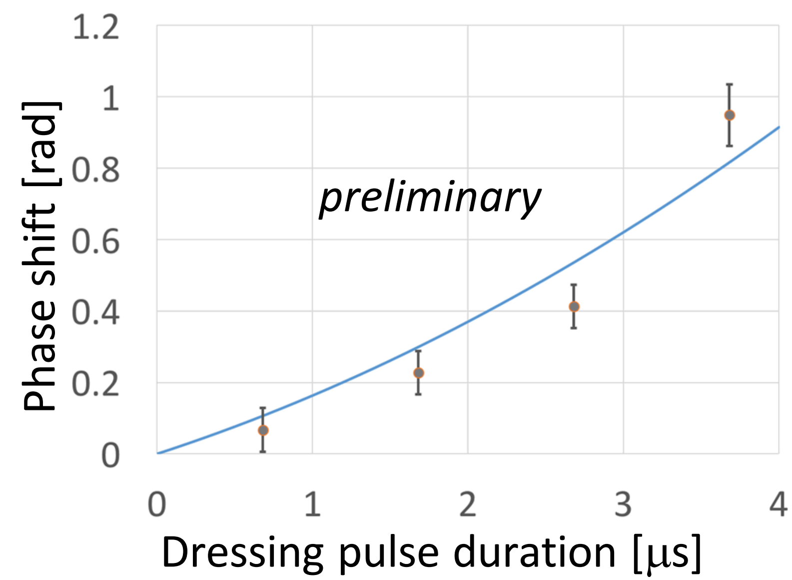

Interacting interferometers

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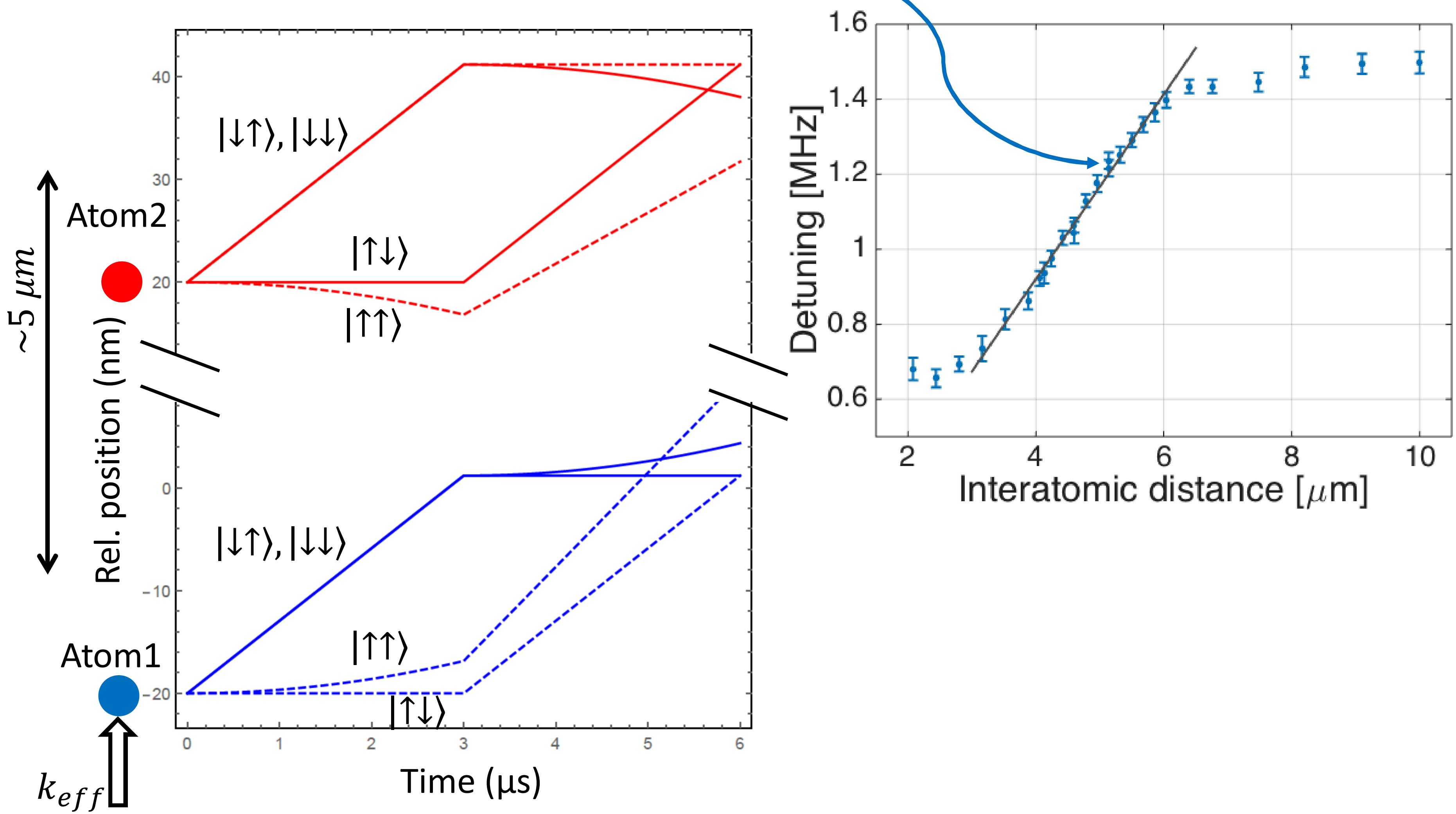
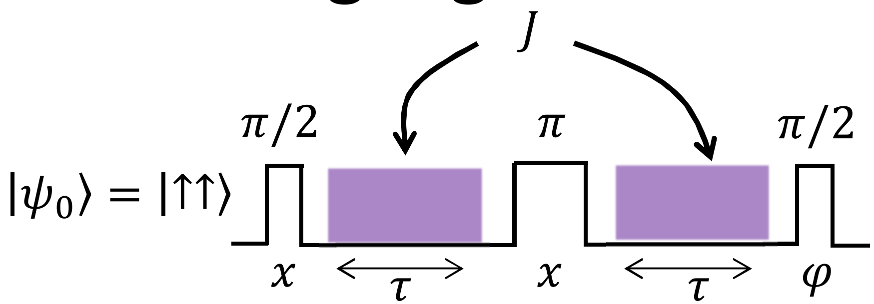
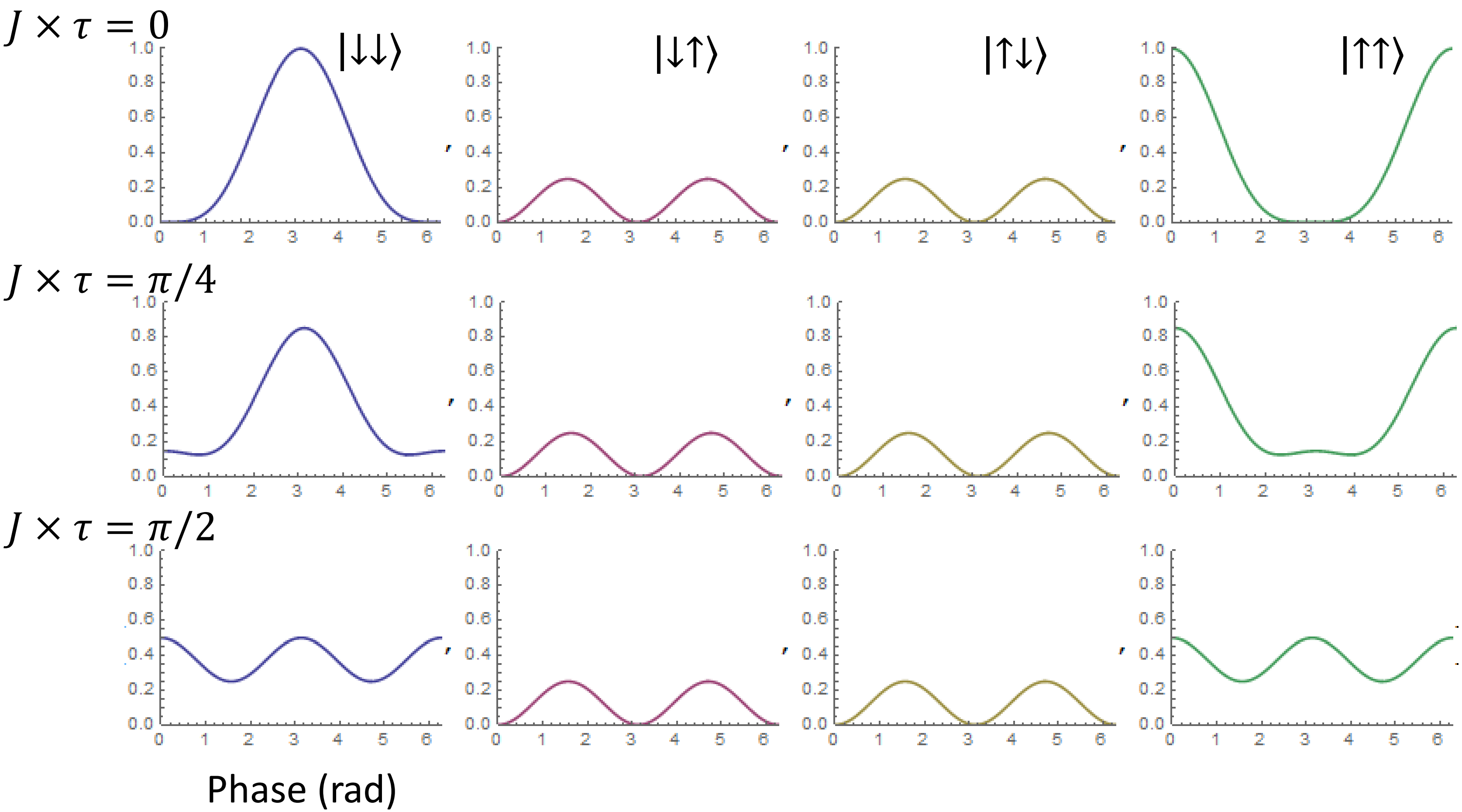


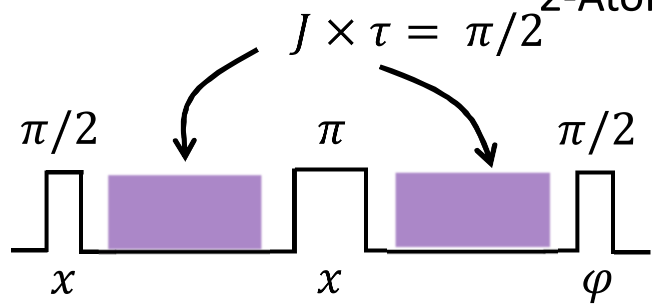
Entangling interferometer

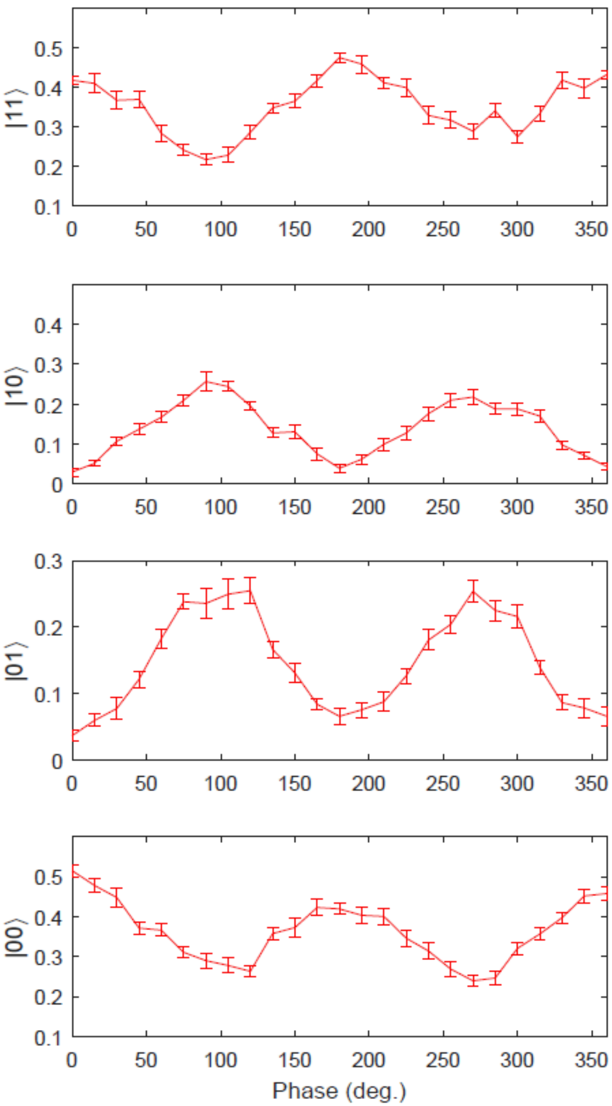




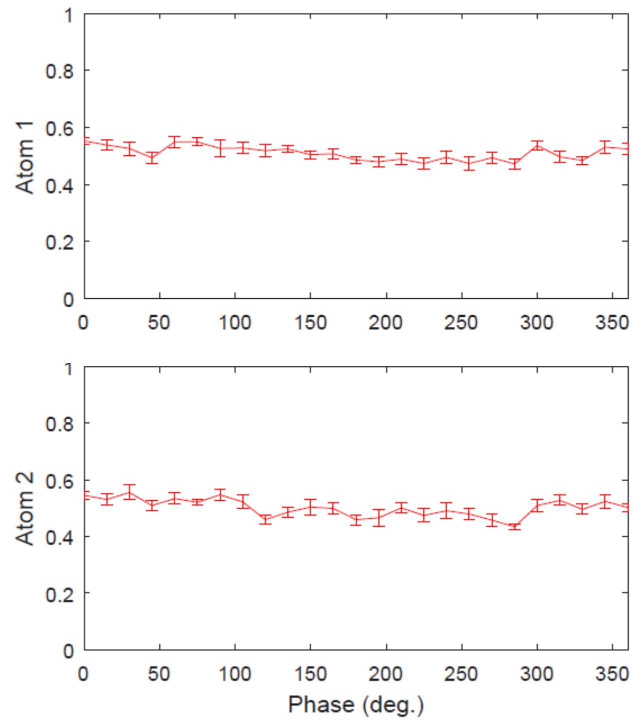
Entangling interferometer

2-Atom basis





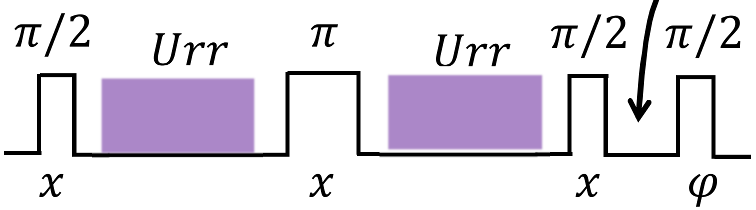
1-Atom basis



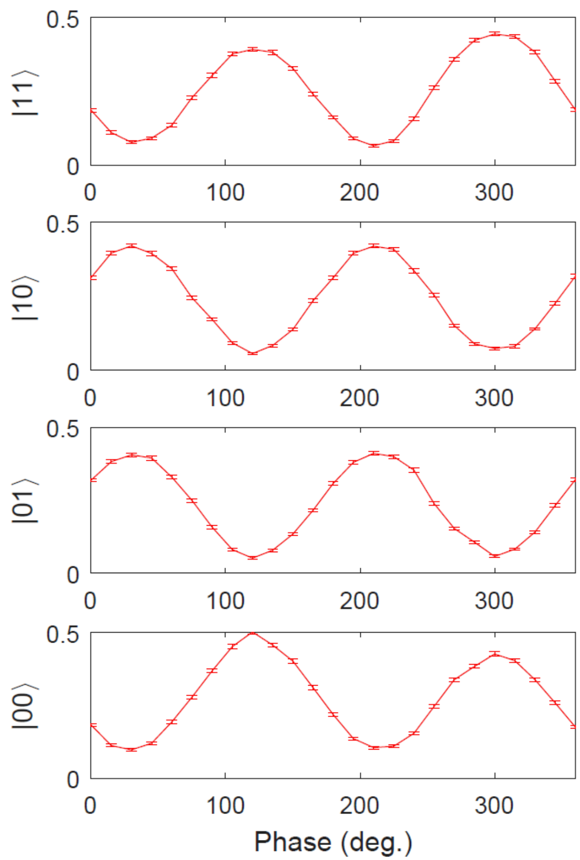
Before final π/2 Pulse:

$$|\psi\rangle = \frac{|\uparrow\downarrow\rangle + |\downarrow\uparrow\rangle}{\sqrt{2}}$$

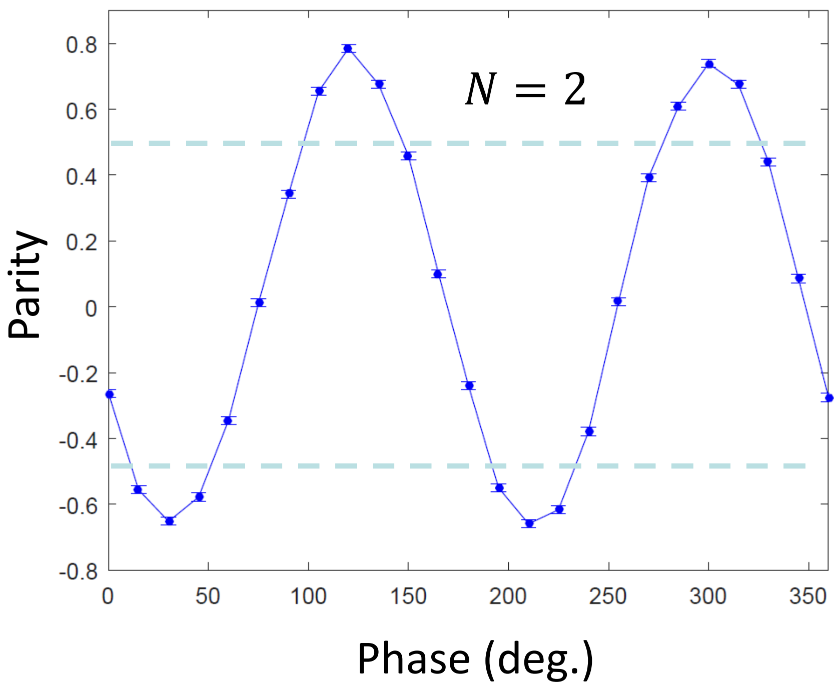
Parity measurement of cat target state



$$|\psi\rangle = \frac{|\uparrow\uparrow\rangle + |\downarrow\downarrow\rangle}{\sqrt{2}}$$

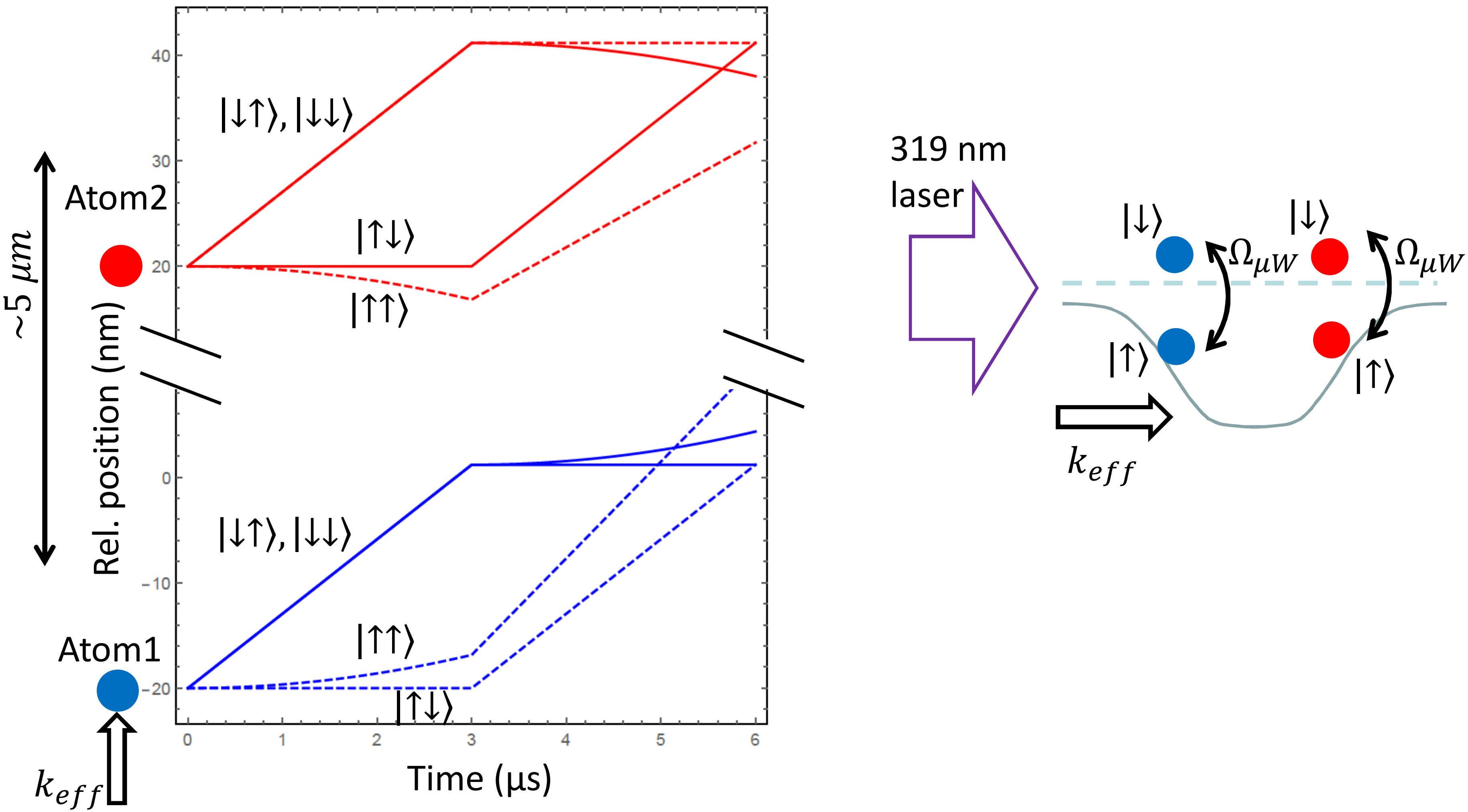


$$\langle \hat{\Pi} \rangle \propto \sin N\varphi$$

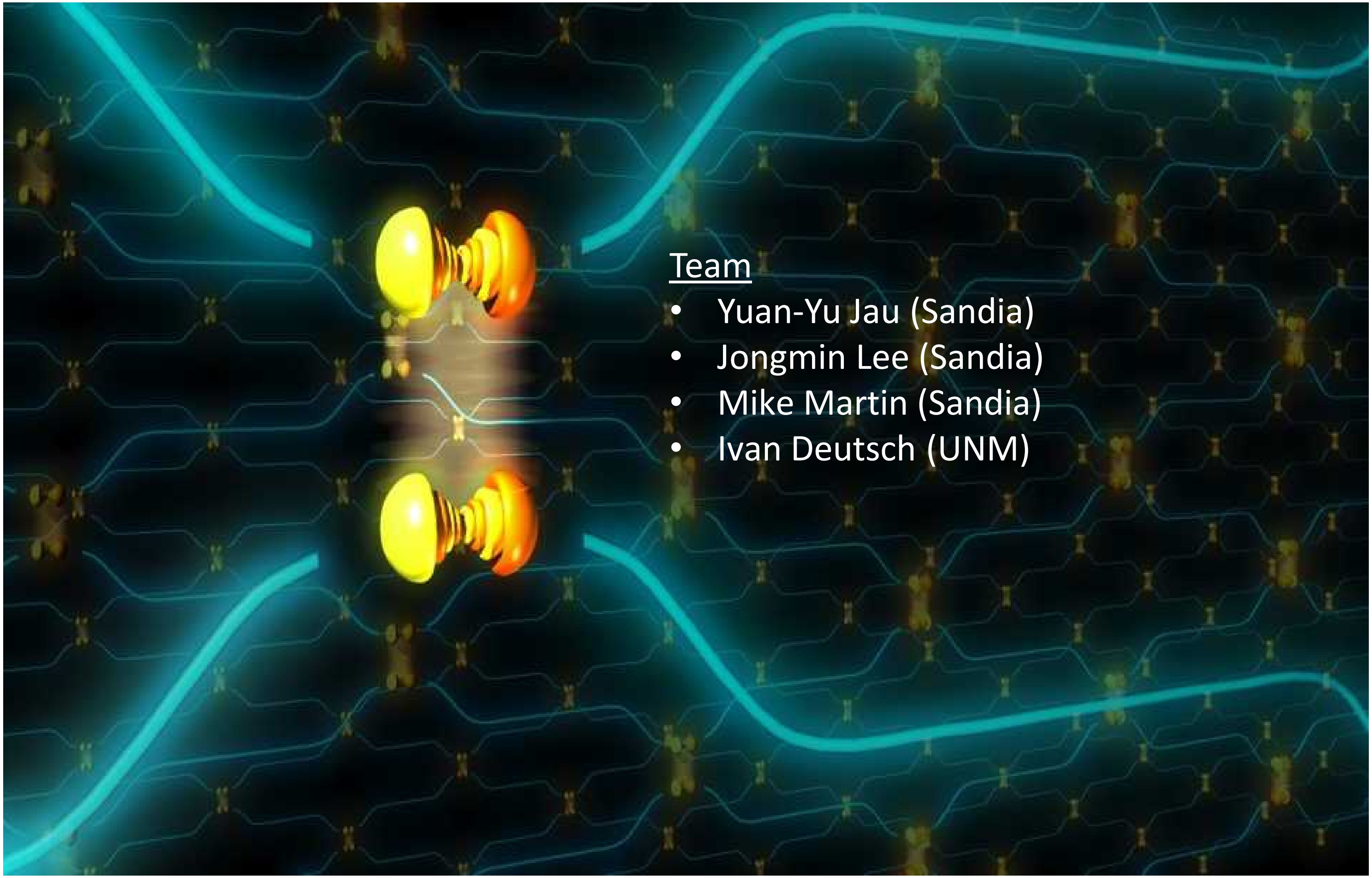


J. J. Bollinger *et al.*, "Optimal frequency measurements with maximally correlated states." Phys. Rev. A **54**(6) (1996).

Interacting interferometers



Thank you



Team

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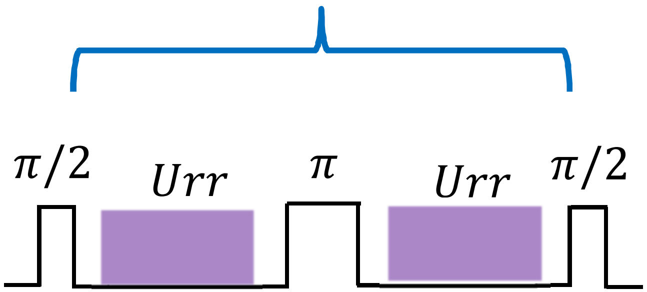
Scaling to N atoms

$$\hat{H}_{\text{eff}} = Urr \times (\hat{S}_z)^2$$



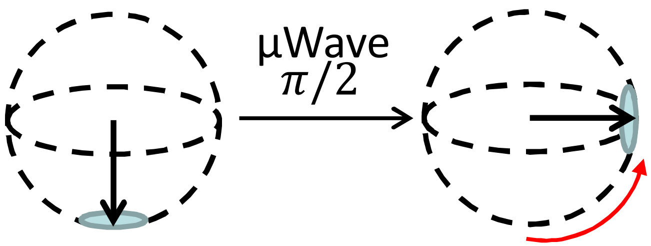
- $\hat{S}_z$ is the collective S_z spin operator for the pseudospin $N/2$ system.
- For N atoms all within a blockade radius, an N-atom cat state forms at $J \times \tau = \pi/2$

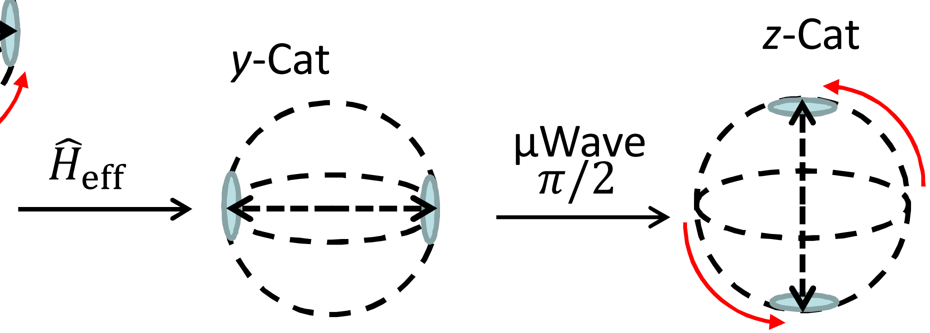
(2-atom case)

$$\frac{|\uparrow\downarrow\rangle + |\uparrow\downarrow\rangle}{\sqrt{2}}$$

(2-atom case)

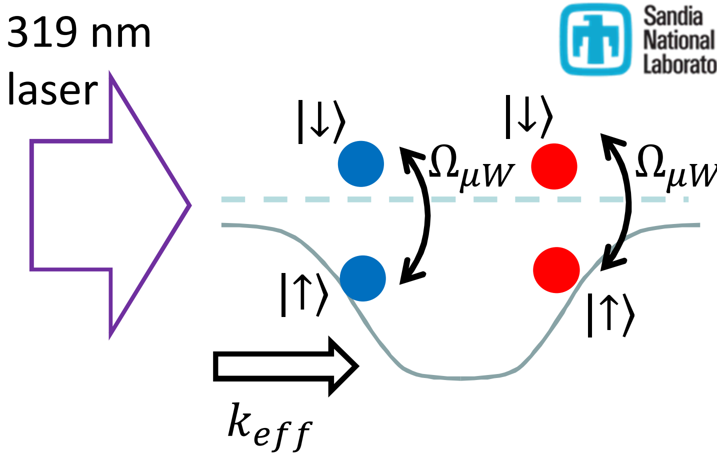
$$\frac{|\uparrow\uparrow\rangle + |\downarrow\downarrow\rangle}{\sqrt{2}}$$

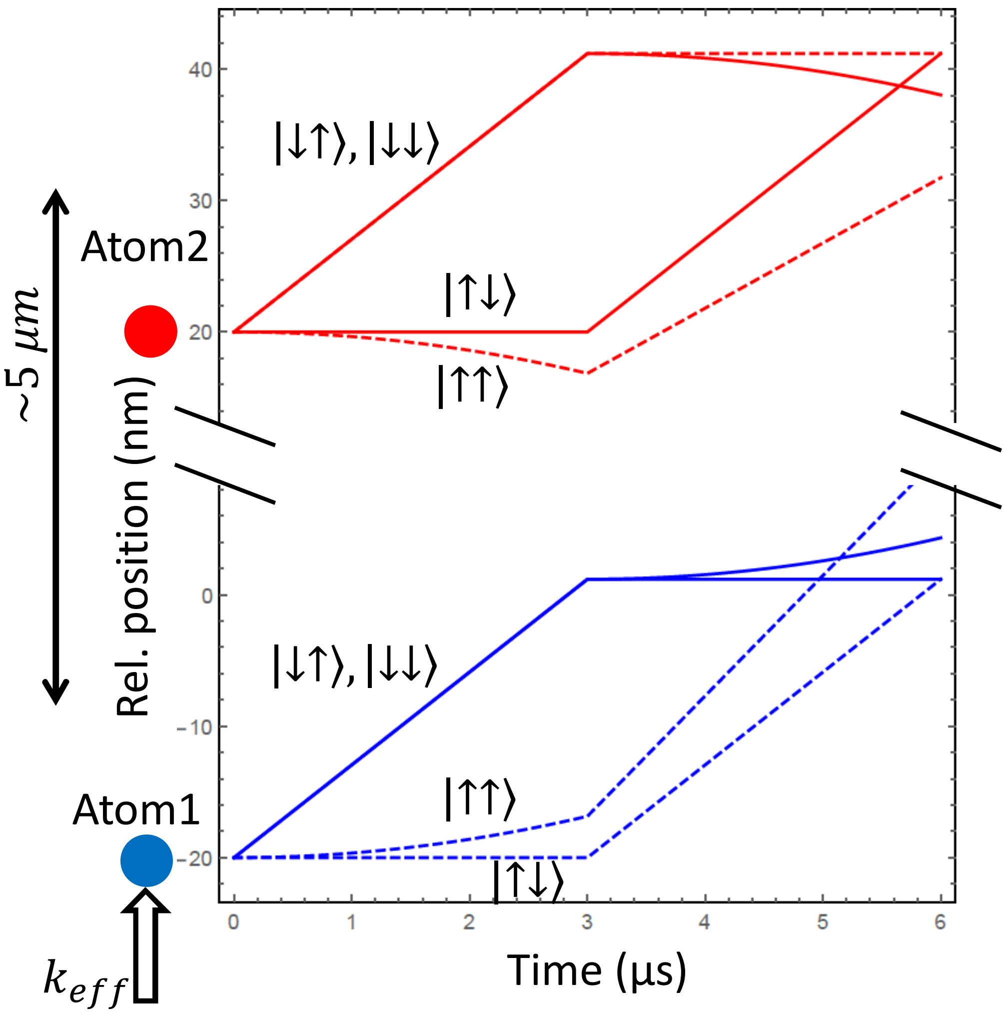


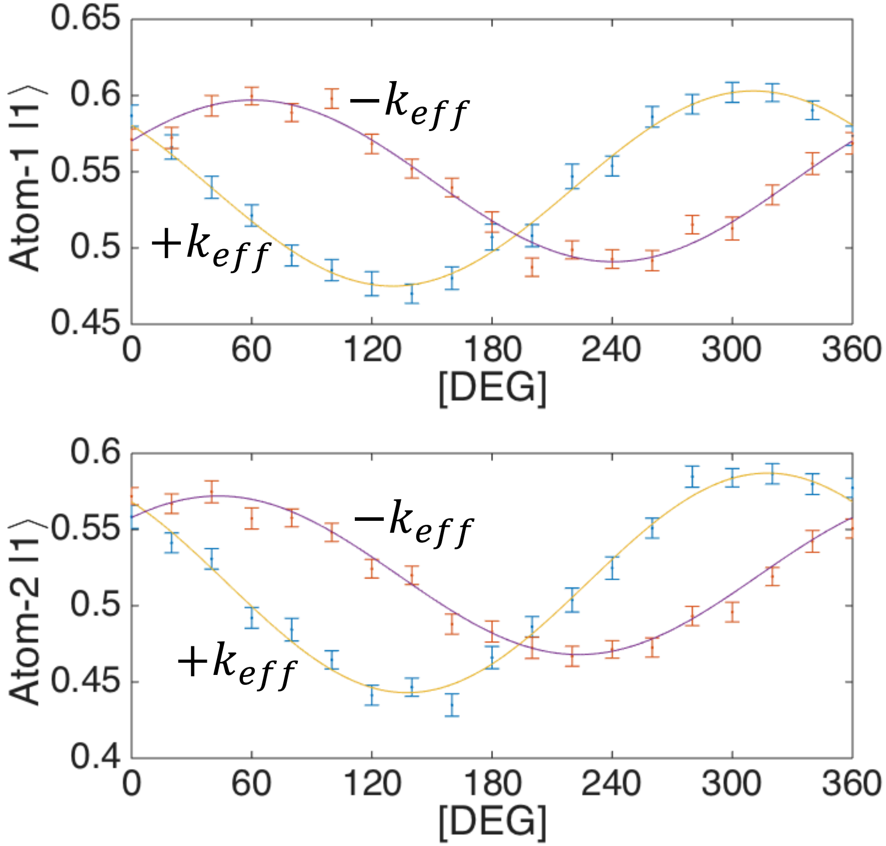


Molmer and Sorensen, "Multiparticle Entanglement of Hot Trapped Ions, PRL **82**(9) (1999).

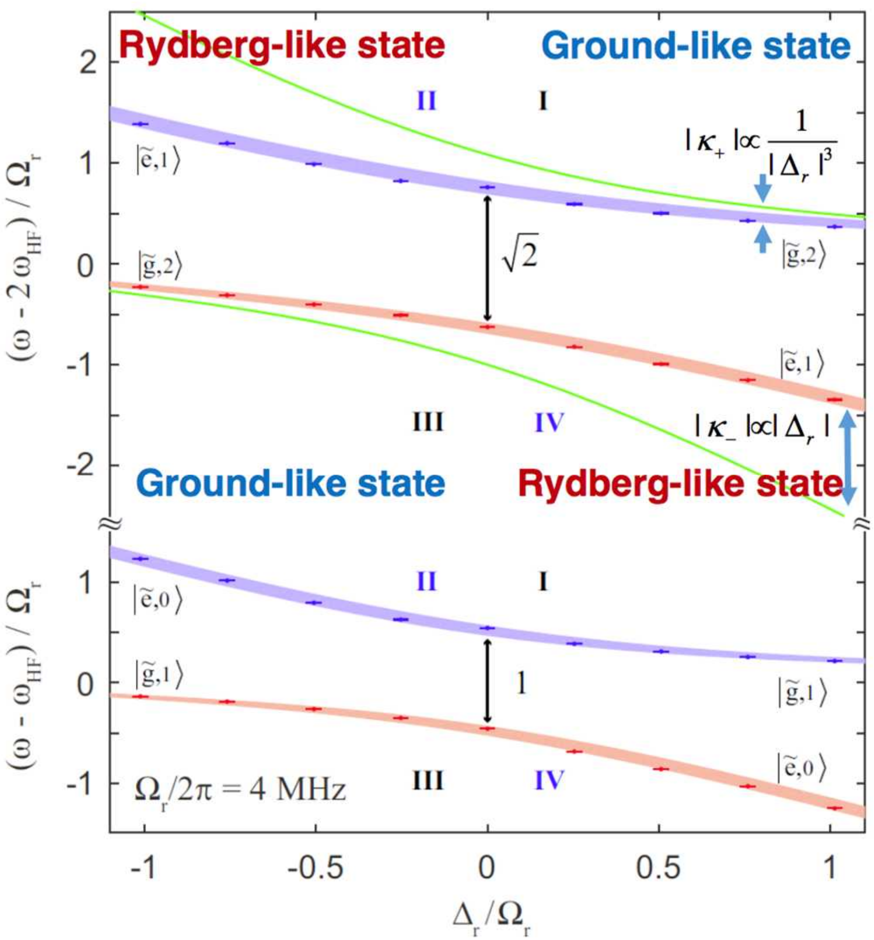
Interacting interferometers







Jaynes-Cummings ladder with Rydberg-dressed atoms



Publication in progress

Autler-Townes Spectrum

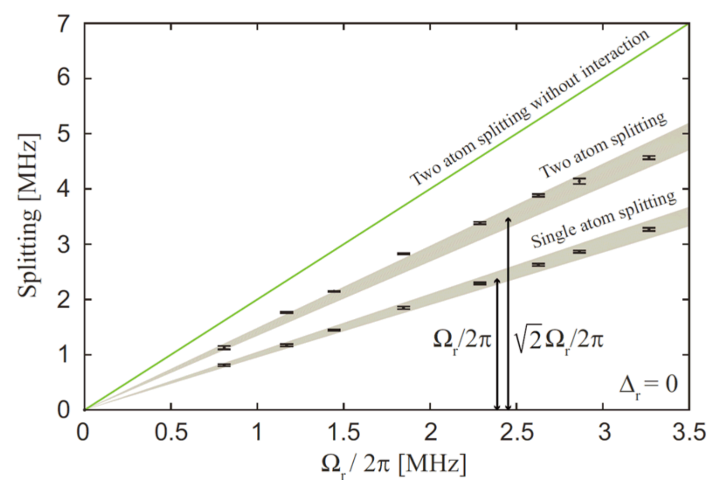
$$\kappa_+ = E_{2,+} - 2E_{1,+} = \langle \tilde{g},2 | \hat{H} | \tilde{g},2\rangle - 2\langle \tilde{g},1 | \hat{H} | \tilde{g},1\rangle$$

$$\kappa_+ = E_{2,+} - 2E_{1,+} = \langle \tilde{e},1 | \hat{H} | \tilde{e},1\rangle - 2\langle \tilde{e},0 | \hat{H} | \tilde{e},0\rangle$$

$$\kappa_\pm = \frac{\hbar}{2}\left(\Delta_r \pm \text{sign}(\Delta_r)\left[\sqrt{2\Omega_r^2 + \Delta_r^2} - 2\sqrt{\Omega_r^2 + \Delta_r^2}\right]\right)$$

$\sqrt{N}$ scaling with number of atoms

Autler-Townes splitting at resonance



See also: Mϕlmer, PRL **100,** 170504 (2008)

Rydberg-dressed interaction, J

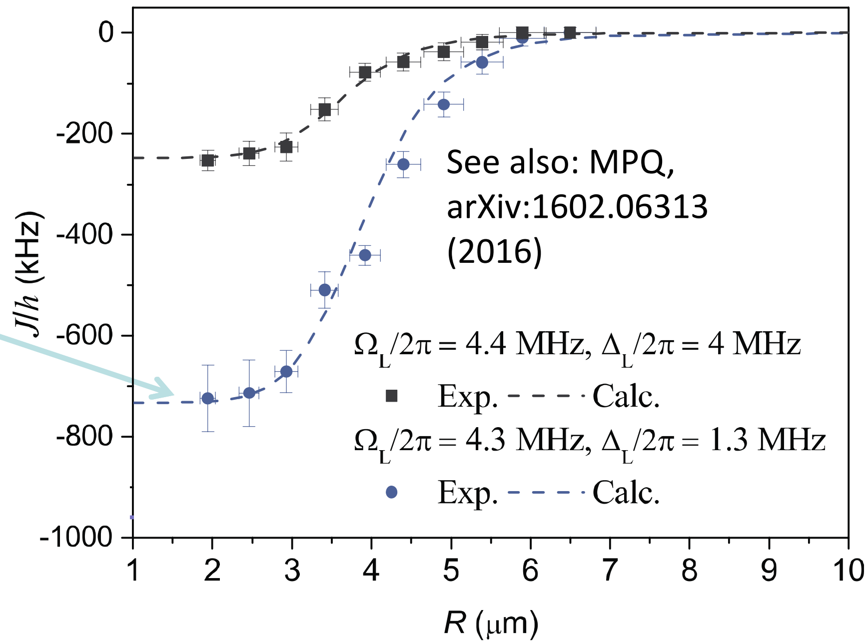
J = change in light shift due to interaction

Interaction >> Ω_r
J saturates

Soft core potential—

low sensitivity to atom motion.

Jau, et al., Nat. Phys. (2016)



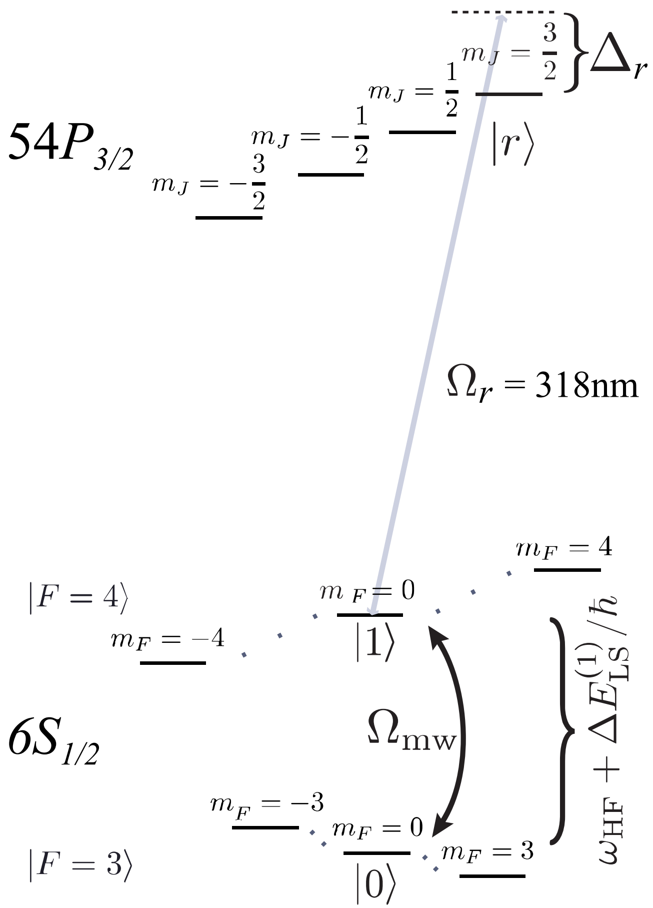
Can be either attractive or repulsive

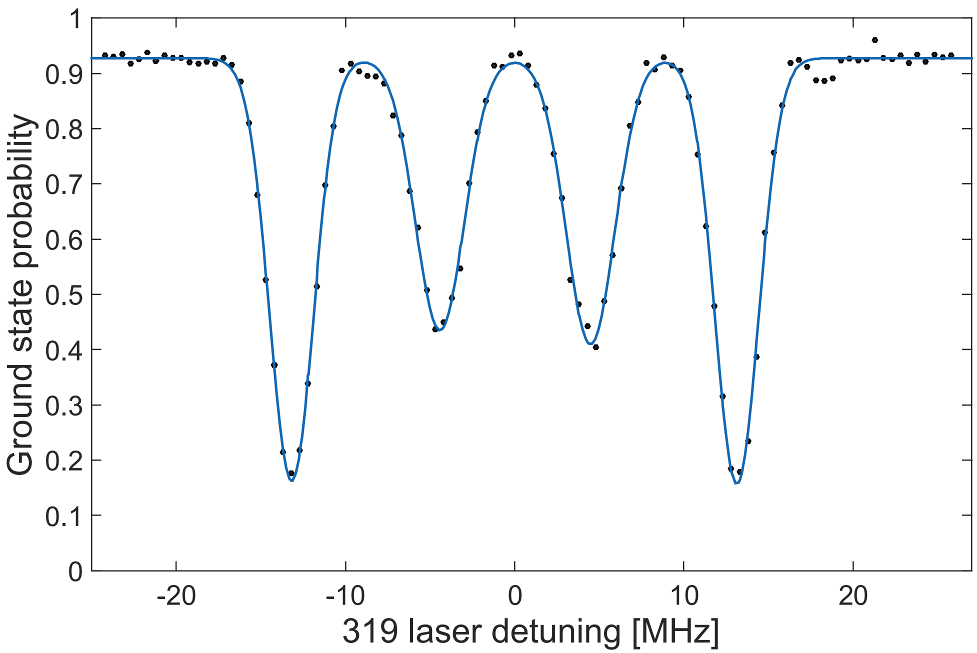
Work near resonance to maximize J

For $\Delta = 0$: $J_{max} \approx 0.29 * \Omega$
For $\Delta = 10\ \Omega$: $J_{max} \approx 10^{-4} * \Omega$

I. Bouchoule, K. Mølmer, Phys. Rev. A 65, 041803 (2002); J. Johnson, S. Rolston, Phys. Rev. A 82, 033412 (2010).

Rydberg state spectrum

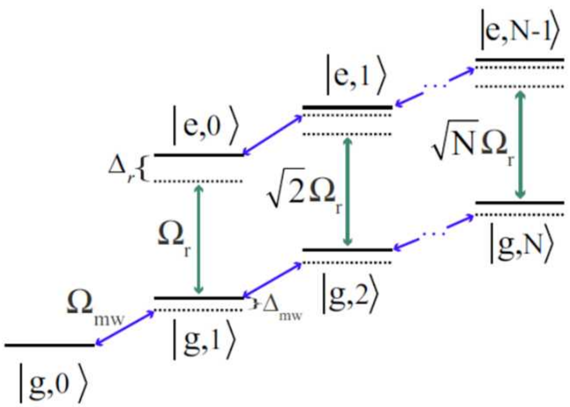




Jaynes-Cummings ladder with Rydberg-dressed atoms

Sandia National Laboratories

Bare State atoms

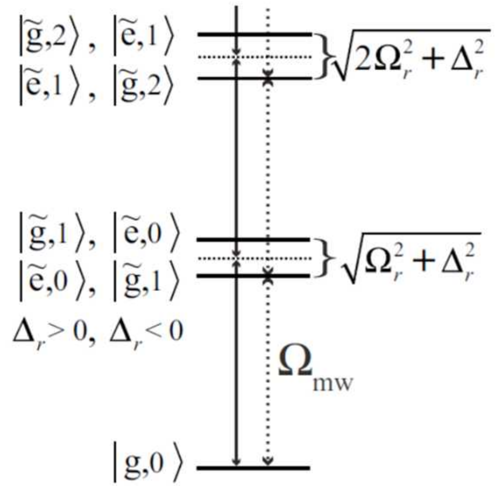


$$| g,n\rangle \equiv \left\{|0\rangle^{\otimes N-n} |1\rangle^{\otimes n}\right\}_{sym}$$

$$| e,n\rangle \equiv \left\{|0\rangle^{\otimes N-n-1} |1\rangle^{\otimes n} |r\rangle\right\}_{sym}$$

Bare state atoms, symmetrically coupled with a perfect Rydberg Blockade

Dressed state atoms



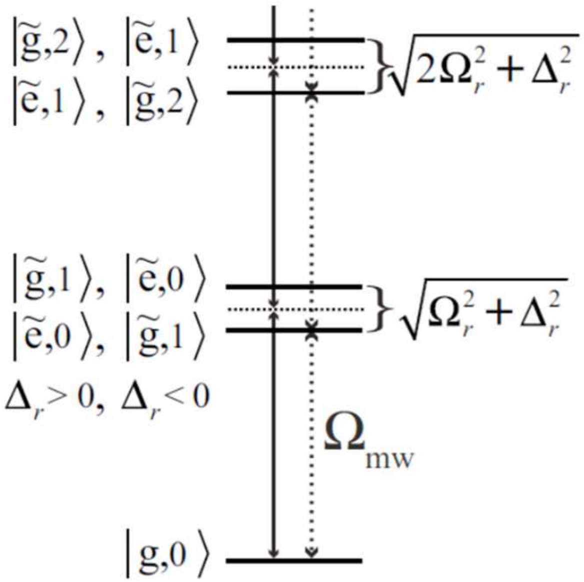
$$| \tilde{g},n\rangle \equiv \cos(\theta_n / 2) | g,n\rangle + \sin(\theta_n / 2) | e,n-1\rangle$$

$$| \tilde{e},n-1\rangle \equiv \cos(\theta_n / 2) | e,n-1\rangle - \sin(\theta_n / 2) | g,n\rangle$$

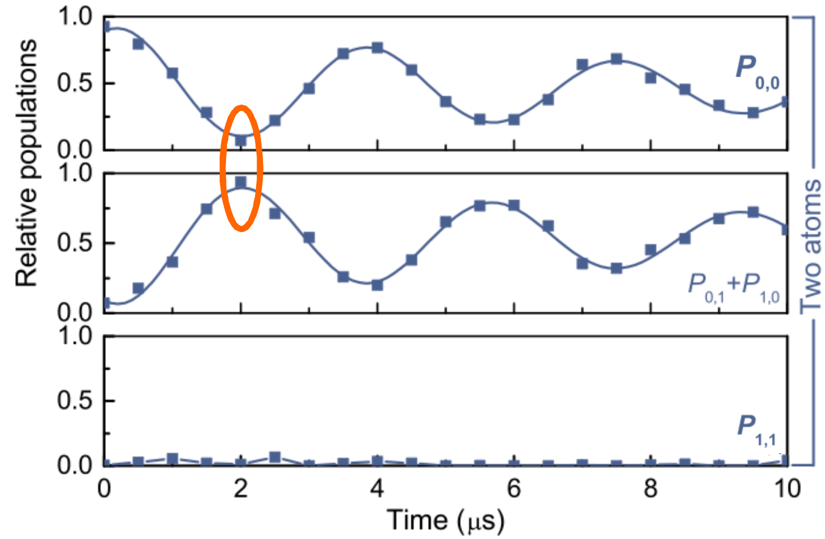
$$\tan(\theta_n) = \sqrt{n}\Omega_r / \Delta_r$$

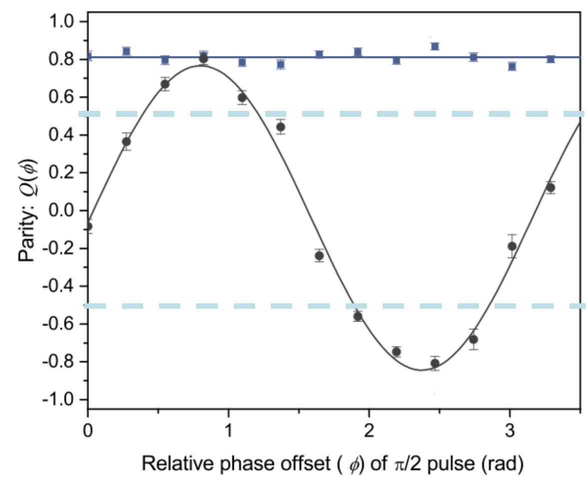
Dressed state is an admixture state with a ground state and a Rydberg state.

Ground state, *Spin-flip* blockade



Rabi oscillations





Parity

Fidelity: 81%*
60% deterministic

Jaynes-Cummings ladder with Rydberg-dressed atoms

	Cavity QED	Symmetric Atomic Ensemble
Two-level system	2-level atom, $\{\lvert g\rangle, \lvert e\rangle\}$	Presence or absence of Rydberg excitation
Bosonic mode	$\lvert n\rangle = n$ photons in cavity mode	$\lvert n\rangle = n$ atoms in logical-$\lvert 1\rangle$
Vacuum	$\lvert 0\rangle$ =no photons in cavity mode	$\lvert 0\rangle^{\otimes N}$ =all atoms in logical-$\lvert 0\rangle$
Bare states	$\lvert g\rangle \otimes \lvert n\rangle, \lvert e\rangle \otimes \lvert n\rangle$	Sym.$(\lvert 0\rangle^{\otimes N-n}\lvert 1\rangle^{\otimes n})$, Sym.$(\lvert 0\rangle^{\otimes N-n}\lvert 1\rangle^{\otimes n-1}\lvert r\rangle)$
Dressed states	$\alpha\lvert g,n\rangle \pm \beta\lvert e,n-1\rangle$	Sym.$(\lvert 0\rangle^{\otimes N-n}\lvert 1\rangle^{\otimes n-1}[\alpha\lvert 1\rangle \pm \beta\lvert r\rangle)$
Frequency scales	boson= ω_c, 2-level= ω_{eg}, Rabi= g	boson= E_{HF}, 2-level= $E_{HF} - \Delta_r$, Rabi= Ω_r
Qubit control	Rabi oscillations on 2-level atom	Rabi oscillations on collective Rydberg excitation
Boson control	Field driving cavity mode	Rabi oscillations between clock states

Cavity QED

$$\hat{H}_{JC} = \hbar\omega_{eg}\hat{\sigma}_+\hat{\sigma}_- + \hbar\omega_c\hat{a}^\dagger\hat{a} + \hbar g(\hat{a}^\dagger\hat{\sigma}_- + \hat{a}\hat{\sigma}_+)$$

$$\updownarrow \quad g = \frac{\Omega_r}{2}$$

Symmetric atomic ensemble (Rydberg atom)

$$\hat{H} = \sum_{n=0}^{N}\left\{\begin{array}{l} n\hbar\omega_{HF}\lvert g,n\rangle\langle g,n\rvert + (n\hbar\omega_{HF} - \hbar\Delta_r)\lvert e,n-1\rangle\langle e,n-1\rvert \\ +\dfrac{\sqrt{n}\hbar\Omega_r}{2}(\lvert e,n-1\rangle\langle g,n\rvert + \lvert g,n\rangle\langle e,n-1\rvert) \end{array}\right\}$$