SAND2015-5002C

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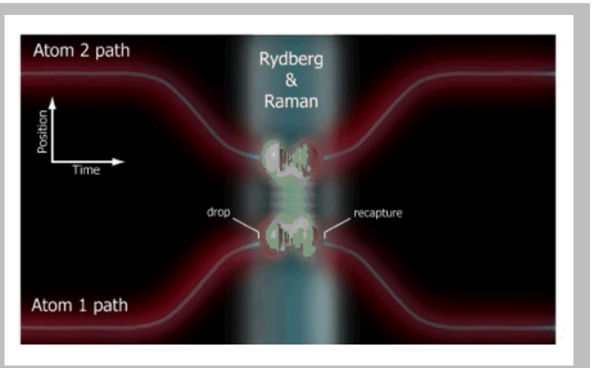
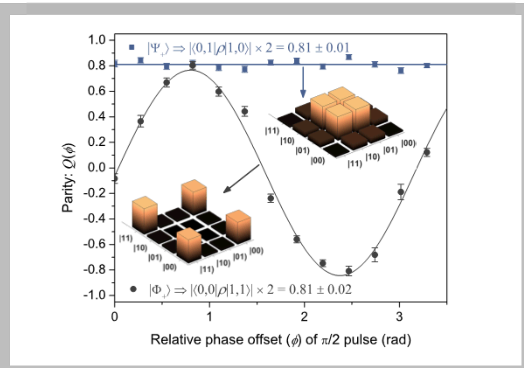
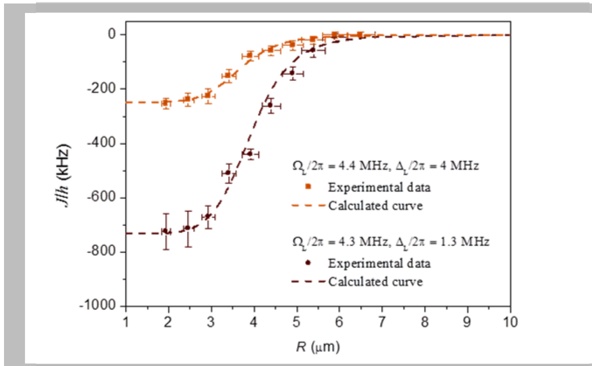






Rydberg-dressed spin-flip blockade

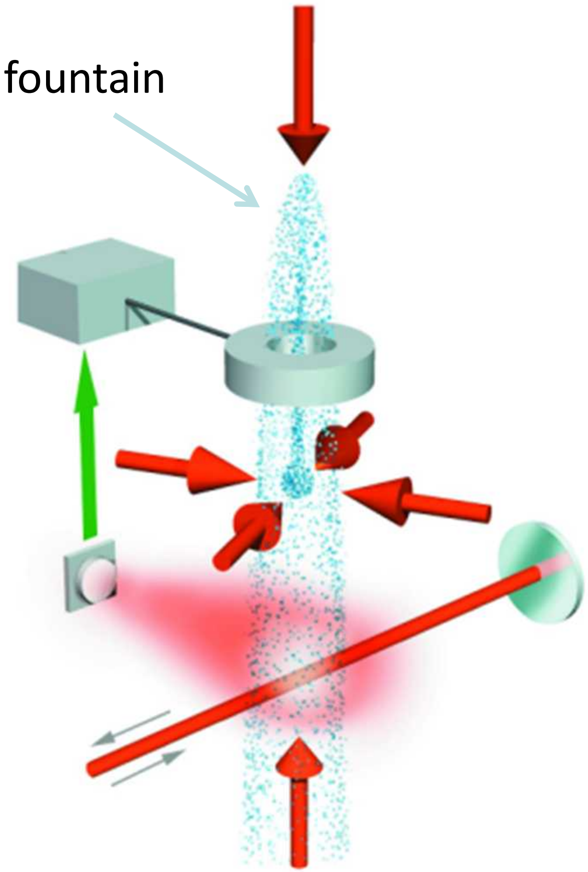
Grant Biedermann

UNM CQuIC

U.S. DEPARTMENT OF ENERGY NNSA National Nuclear Security Administration LDRD

Quantum-Coherence

Qubit fountain



Atomic fountain principle

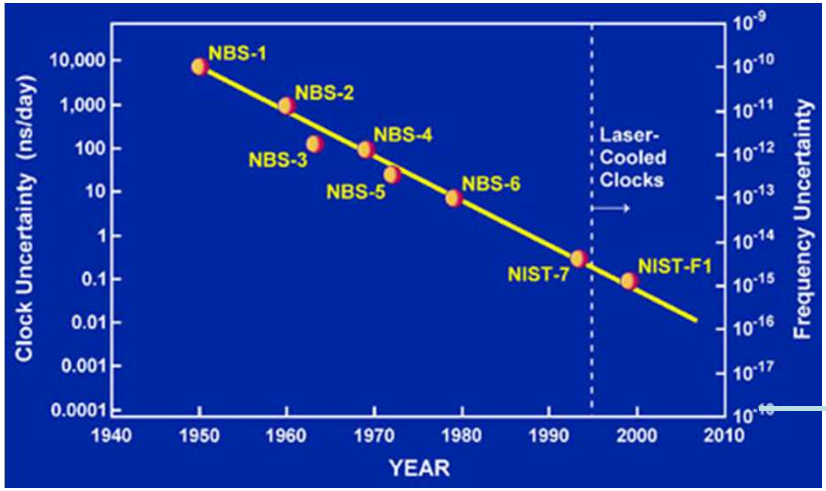
http://smsc.cnes.fr/PHARAO/GP_instrument.htm

Outstanding quantum coherence in neutral atoms enables precision metrology and quantum information

- Example: atomic clocks

$$\left|6^2 S_{1/2}; F=3, M_F=0\right\rangle \leftrightarrow \left|6^2 S_{1/2}; F=4, M_F=0\right\rangle$$

$$\left|0\right\rangle \leftrightarrow \left|1\right\rangle$$

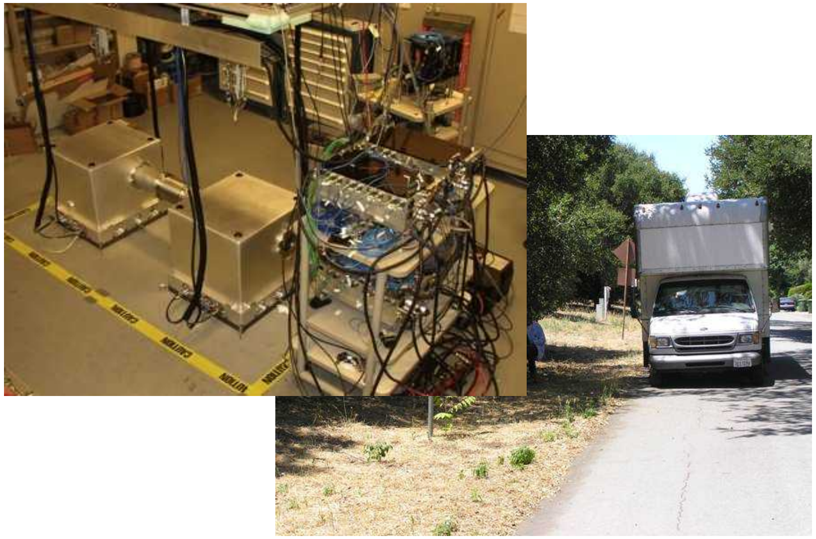


Optical clocks

http://www.nist.gov

Atom interferometer inertial sensors

Stanford gravity gradiometer

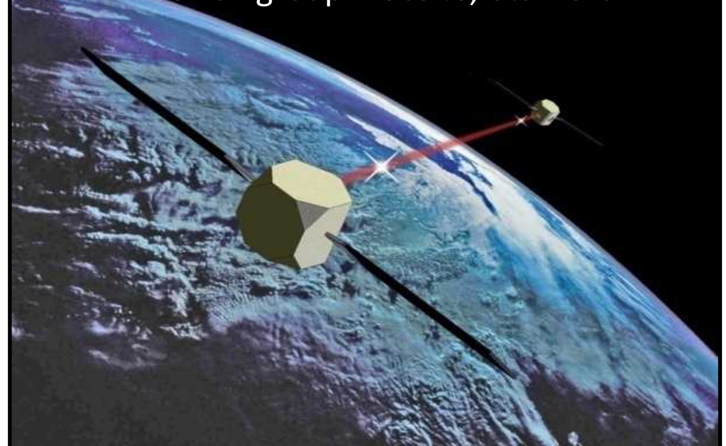


100 m drop tower, Bremen

10 m tower, Stanford

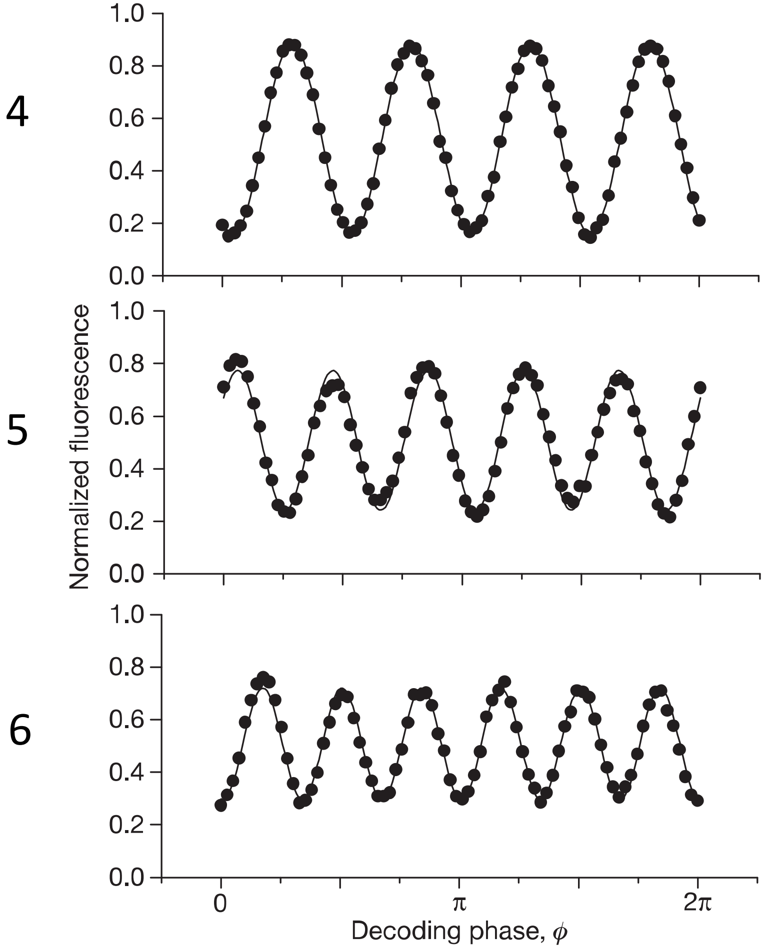
Gyro/Accel Sandia

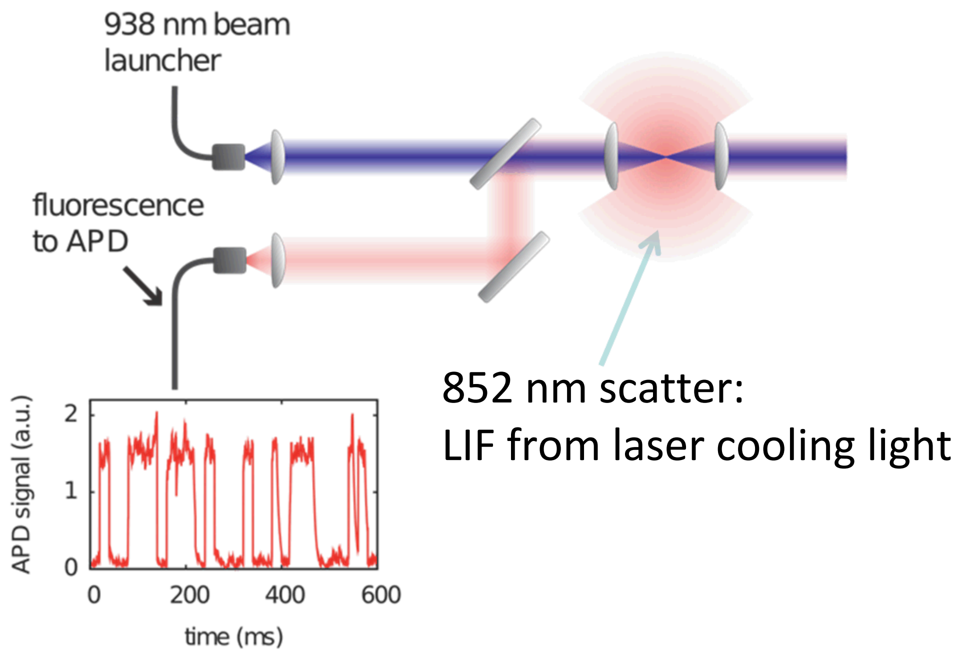
Gravitational Wave Detector concept
Kasevich group website, Stanford



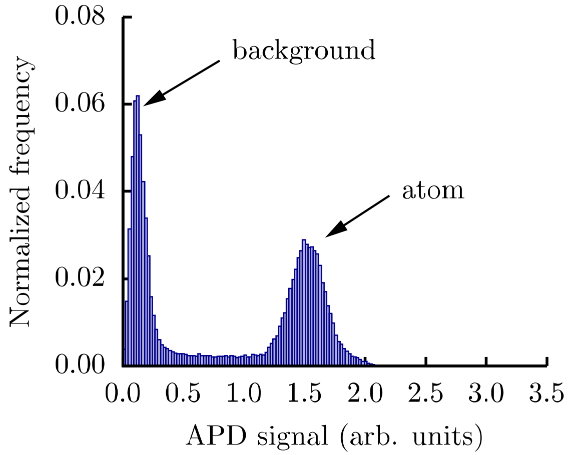
Entangled states for metrology

Cat states with ions [1]



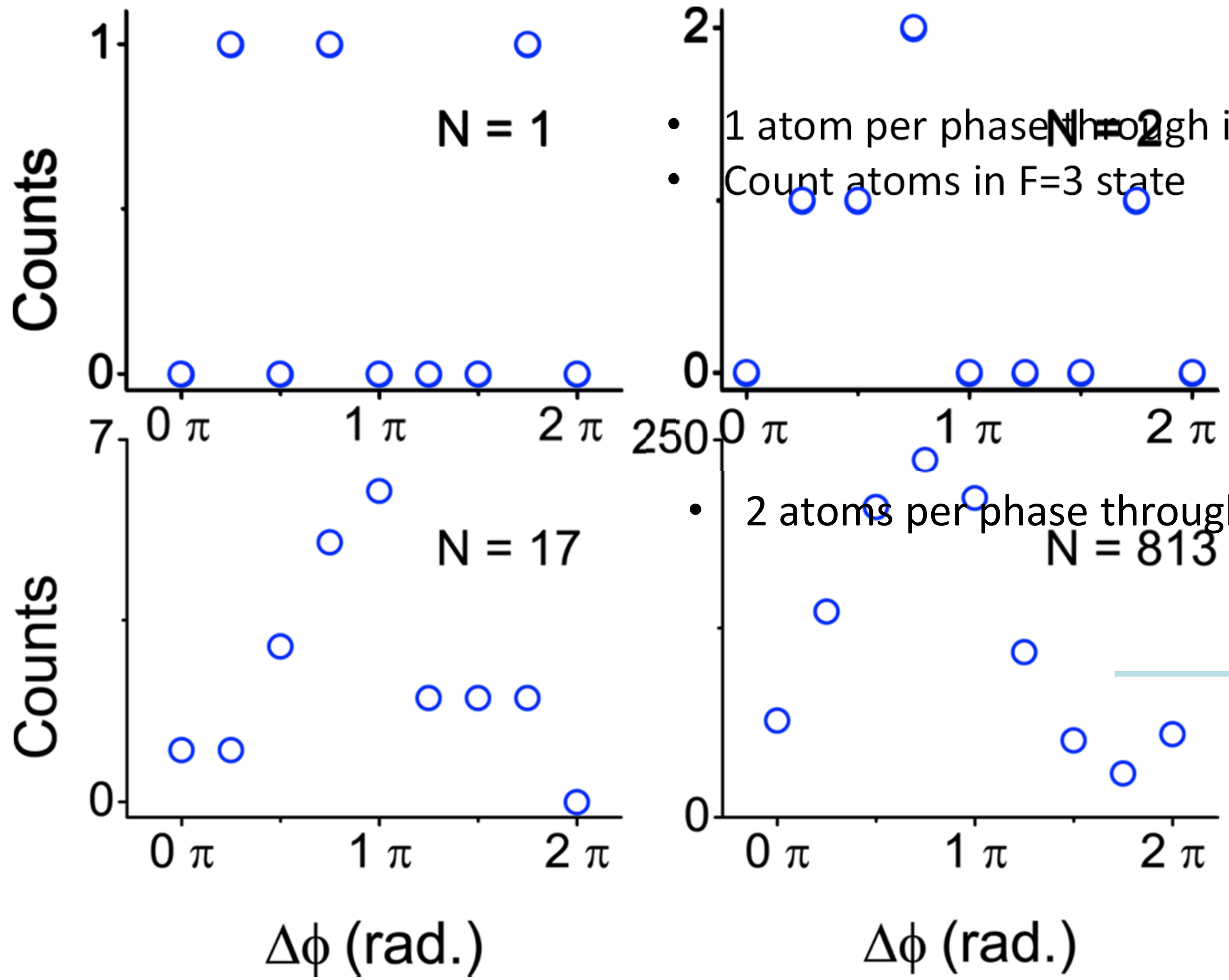


Micron-scale: inherently low power



[1] Leibfried, et al., "Creation of a six-atom 'Schrödinger cat' state", *Nature* **438**, 639 (2005)

Building a fringe, one atom at a time



- 1 atom per phase through interferometer.
- Count atoms in F=3 state

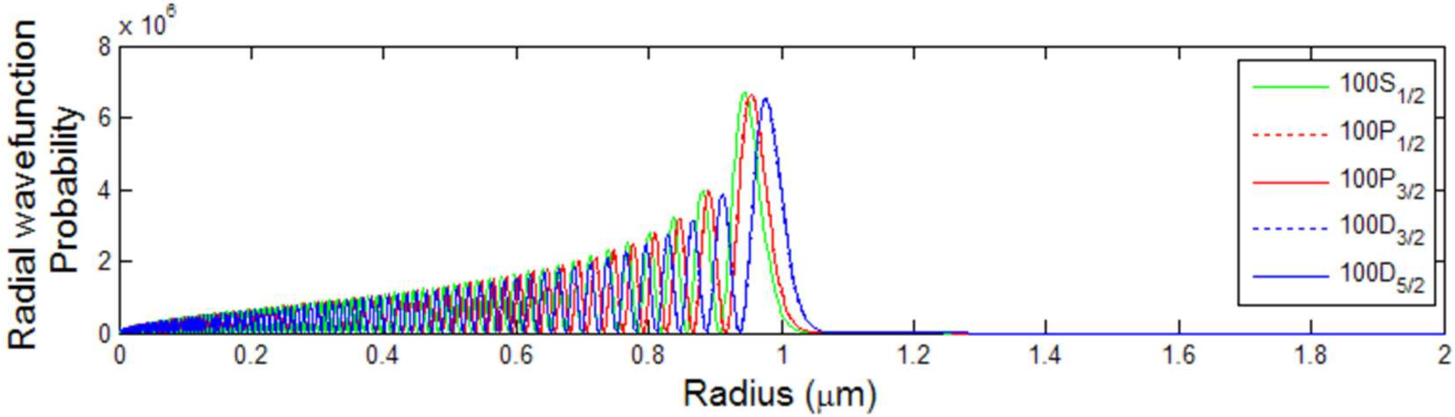
- 2 atoms per phase through interferometer.

7,317 atoms

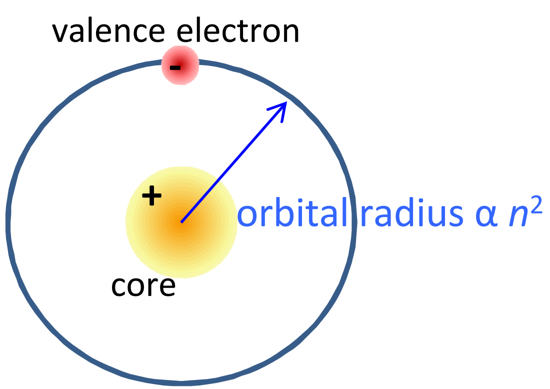
Parazzoli, et al., "Observation of free-space single-atom matterwave interference", Phys. Rev. Lett. **109**, 230401 (2012)

Rydberg state mediated interaction

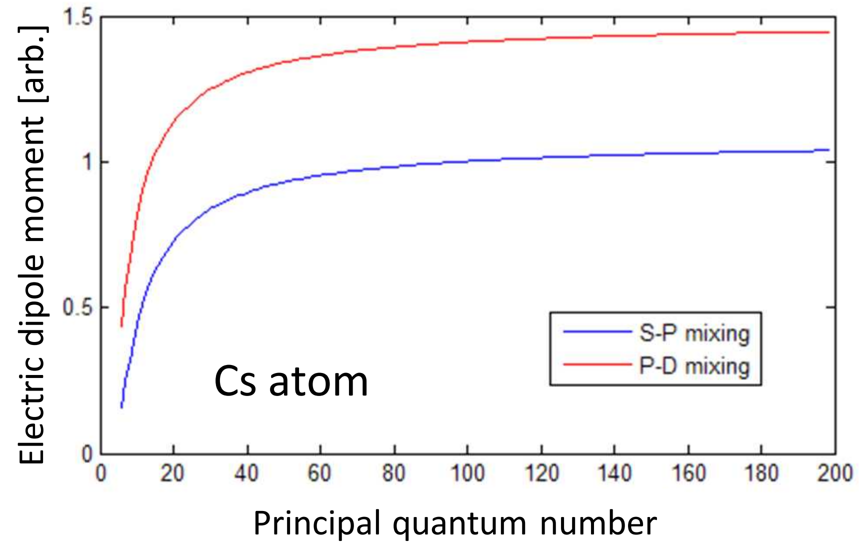
An example of the radial wavefunctions of a Cs atom at n = 100:



A Rydberg atom can have a strong electric dipole moment.

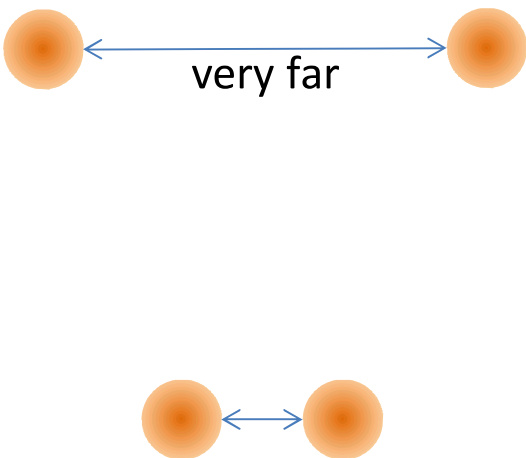


A classical picture of an atom

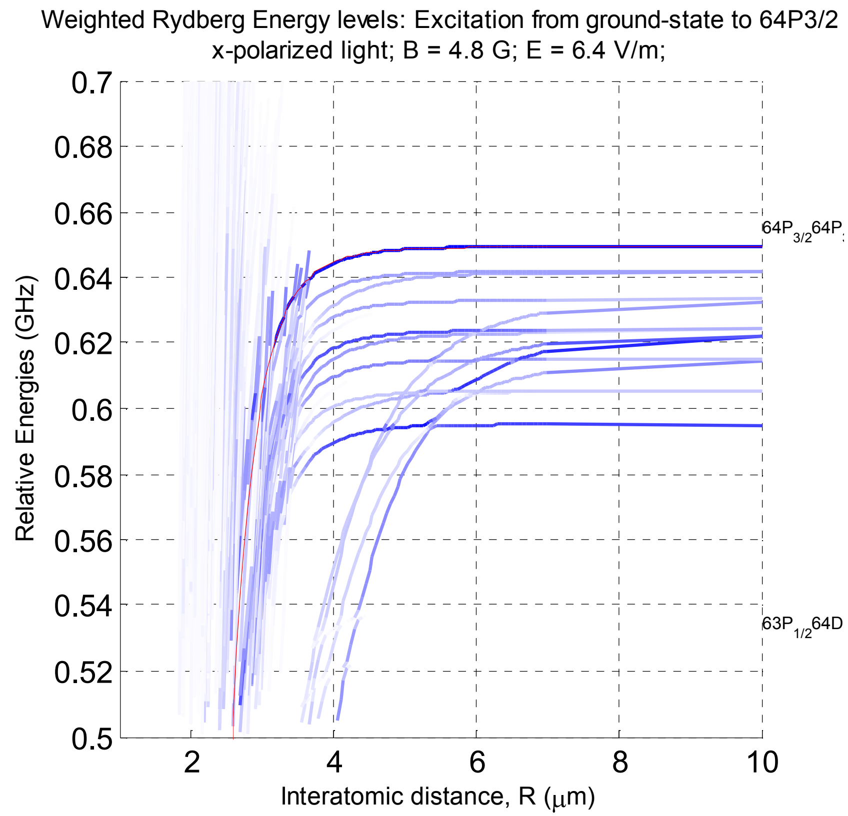


Electric dipole-dipole interaction

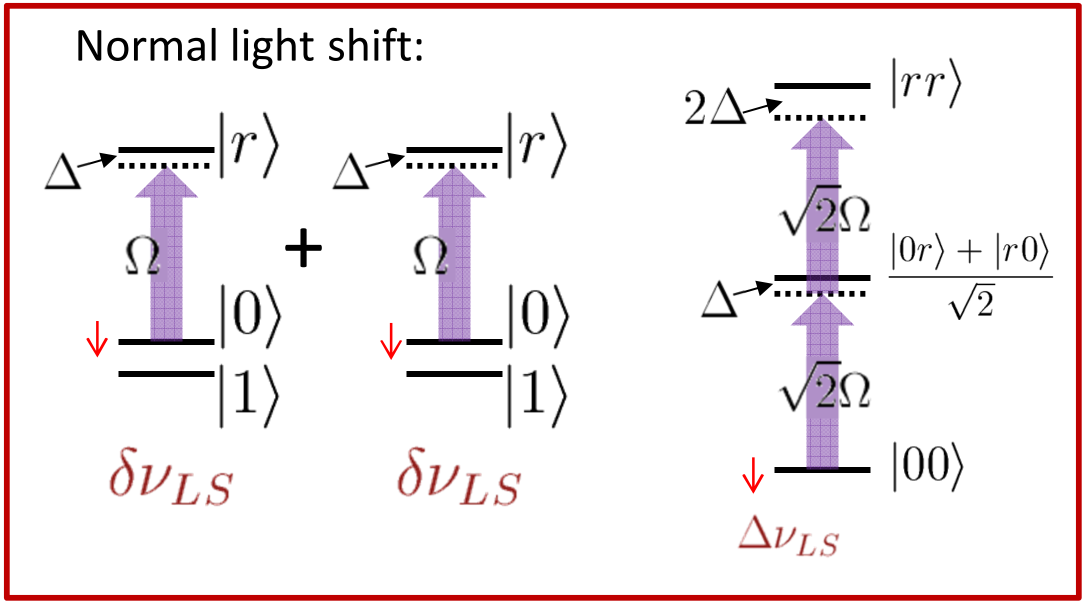
$$H_{\text{atoms}} = \sum_i H_0^{(i)} + \frac{1}{4\pi\varepsilon_0 r^3} \sum_{i \neq j} \left(\mathbf{D}^{(i)} \cdot \mathbf{D}^{(j)} - 3\mathbf{D}^{(i)} \cdot \hat{\mathbf{r}}\hat{\mathbf{r}} \cdot \mathbf{D}^{(j)} \right)$$

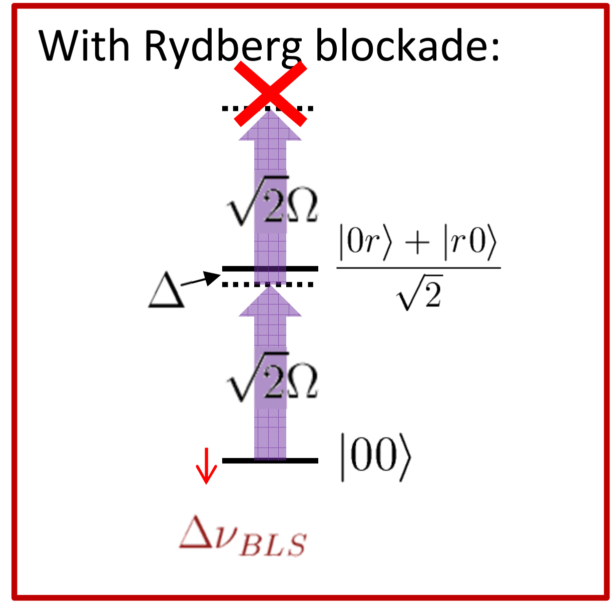


close enough (< 10 μm)



Interaction between two Rydberg-dressed atoms





$$H_{BLS} = H_{LS} + H_{int} = \begin{bmatrix} 2\delta\nu_{LS} & 0 & 0 & 0 \\ 0 & \delta\nu_{LS} & 0 & 0 \\ 0 & 0 & \delta\nu_{LS} & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} + \begin{bmatrix} J & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \text{for} \begin{bmatrix} |00\rangle \\ |01\rangle \\ |10\rangle \\ |11\rangle \end{bmatrix}$$

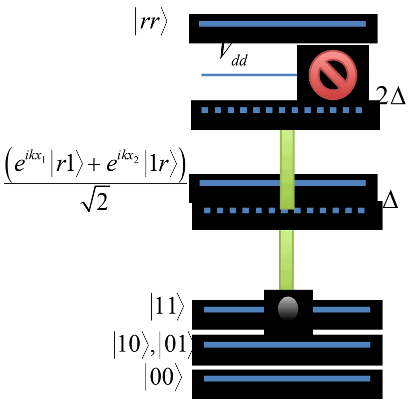
$$J = \Delta\nu_{BLS} - \Delta\nu_{LS} = \frac{\Omega^4}{8\Delta^3} - \frac{3\Omega^6}{16\Delta^5} + \frac{35\Omega^8}{128\Delta^7} - \cdots$$

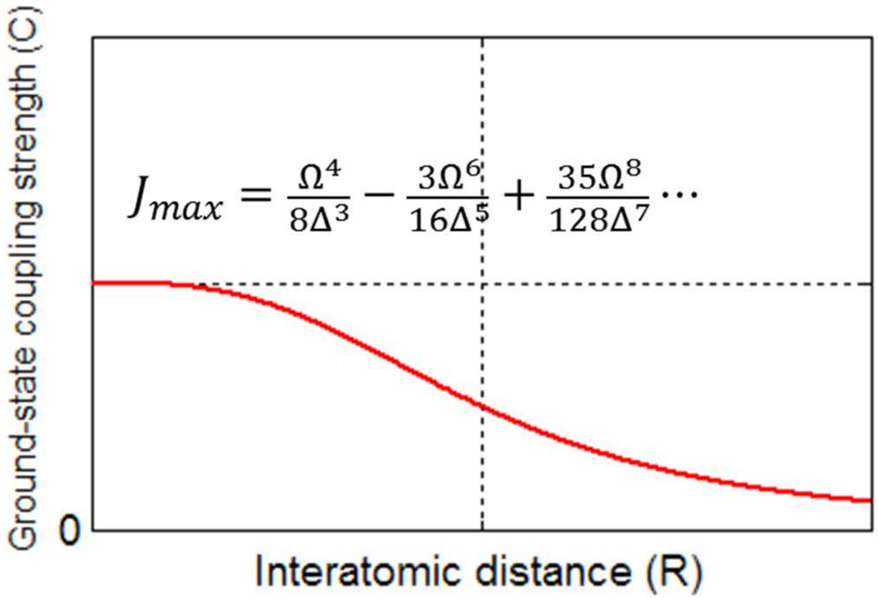
$$H_{int} = \frac{J}{4}(\sigma_z^{(1)} + 1)(\sigma_z^{(2)} + 1)$$

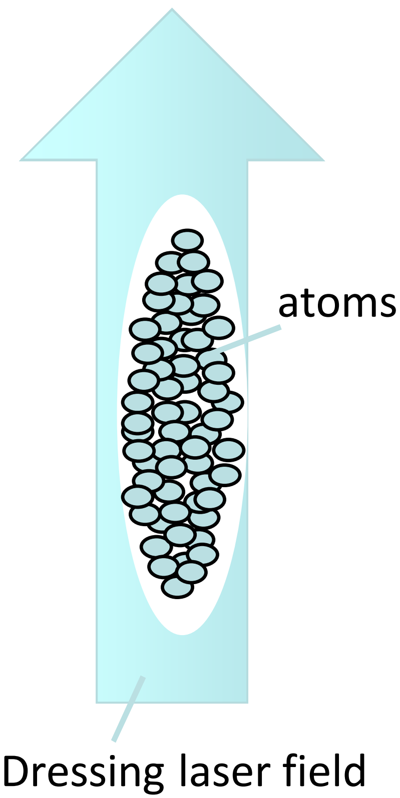
Rydberg-dressed interactions

Tunable interaction strength (J), low sensitivity to atom motion, and effectively strong ground-state interactions.

$$H_{int} = \sum_{ij} \frac{J_{ij}}{4} (\sigma_z^{(i)} + 1)(\sigma_z^{(j)} + 1)$$



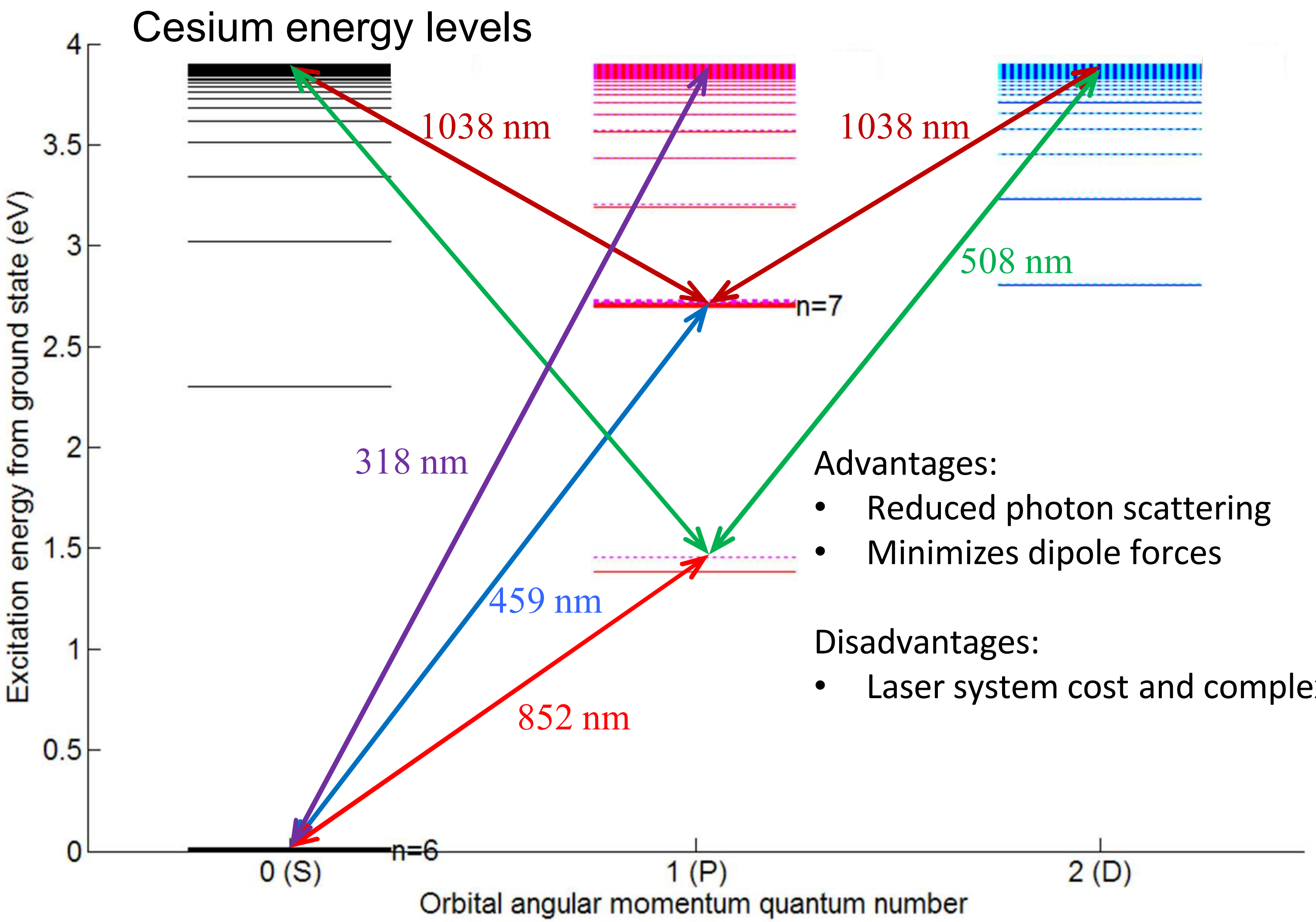




I. Bouchoule, K. Mølmer, Phys. Rev. A 65, 041803 (2002).
J. Johnson, S. Rolston, Phys. Rev. A 82, 033412 (2010).

Favors small detuning

Optimizing for long-term relationships



Advantages:

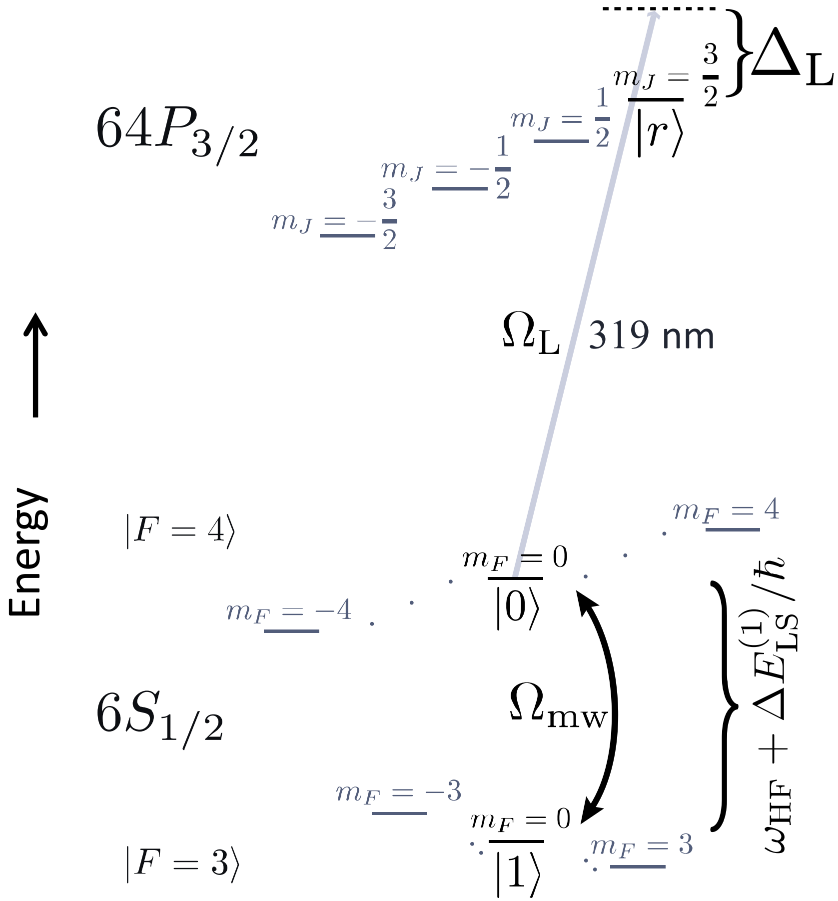
- Reduced photon scattering
- Minimizes dipole forces

Disadvantages:

- Laser system cost and complexity

Published: Phys. Rev. A 89, 033416 (2014)

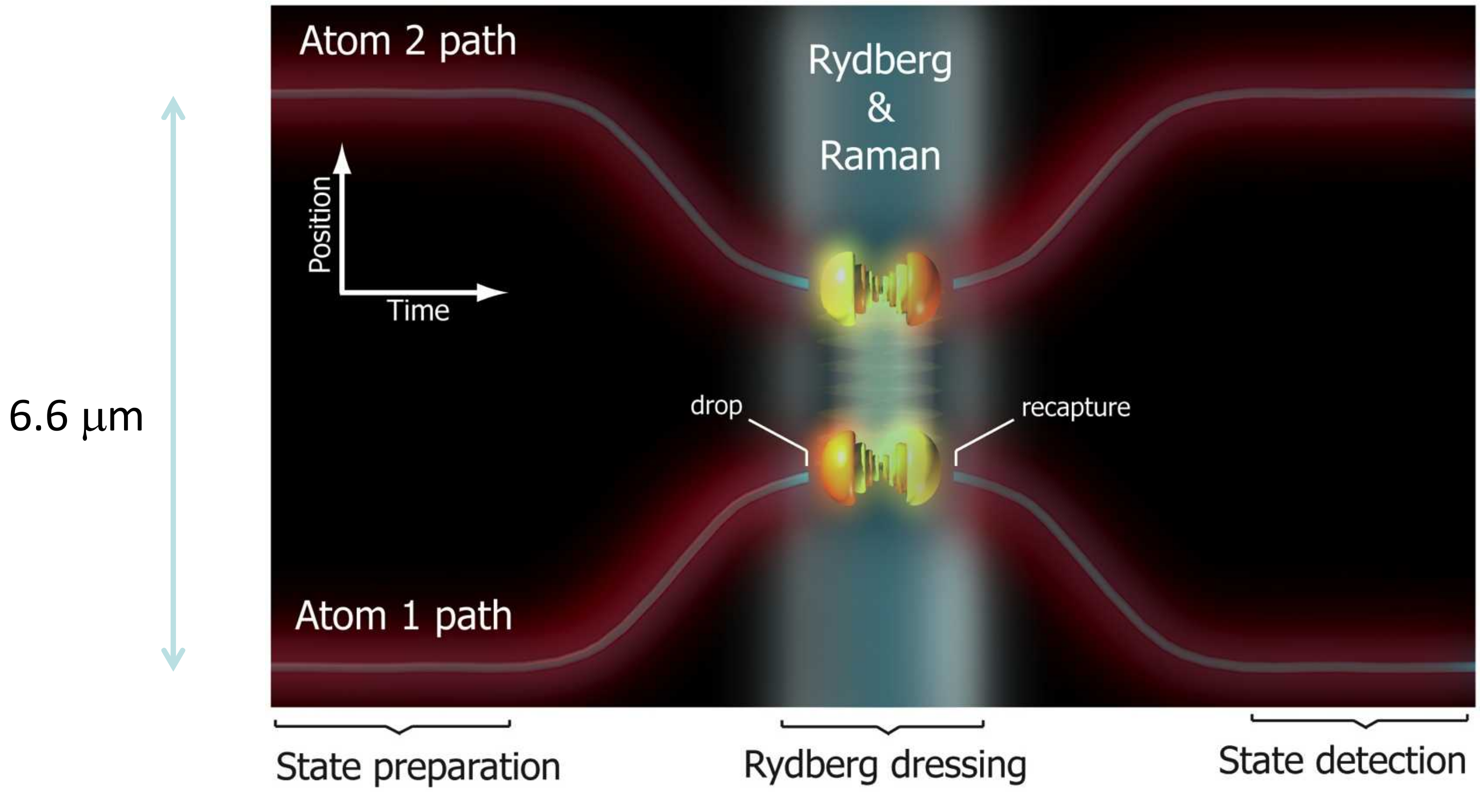
Rydberg-dressed ground state interaction



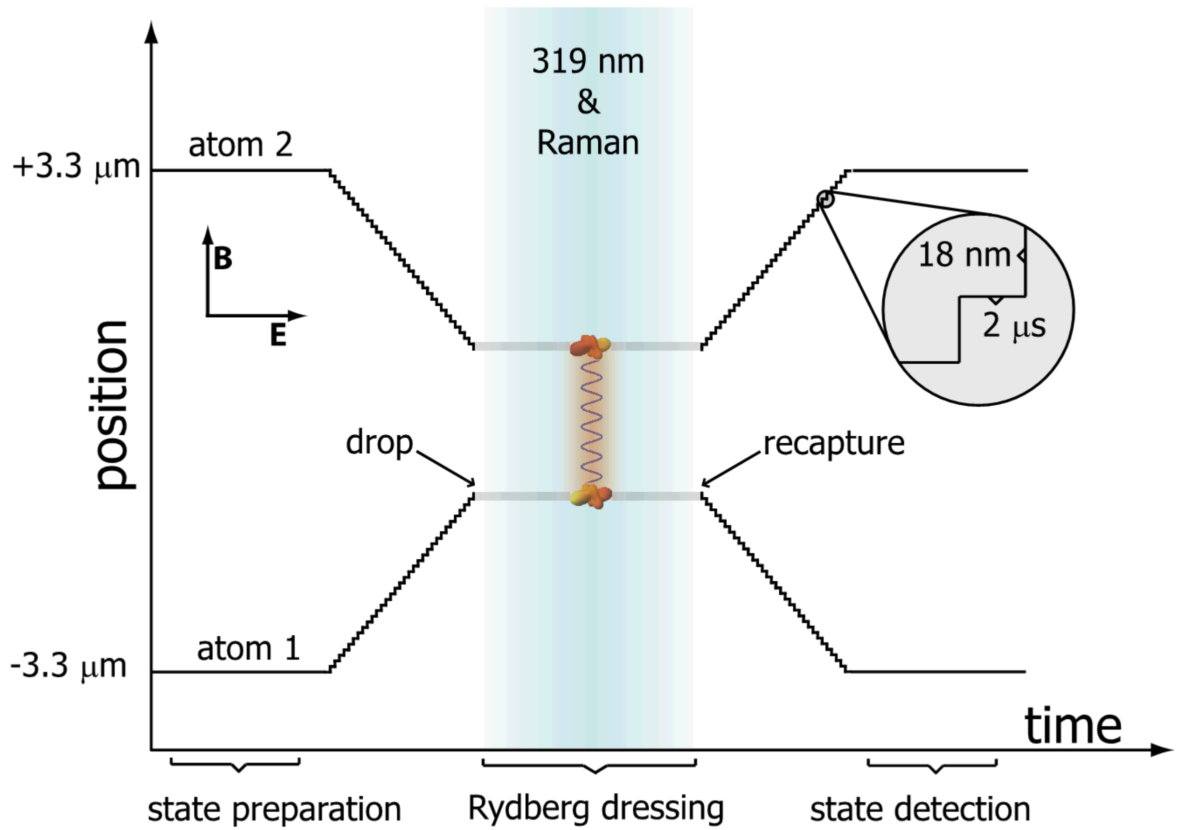
Single atom picture

- Interaction range increases as principal quantum number *n* increases
- However, oscillator strength decreases as *n* increases—making Ω_L smaller and thus *J*
- Target smallest *n* that your optical resolution can accommodate
- Solution—*dynamic postioning*

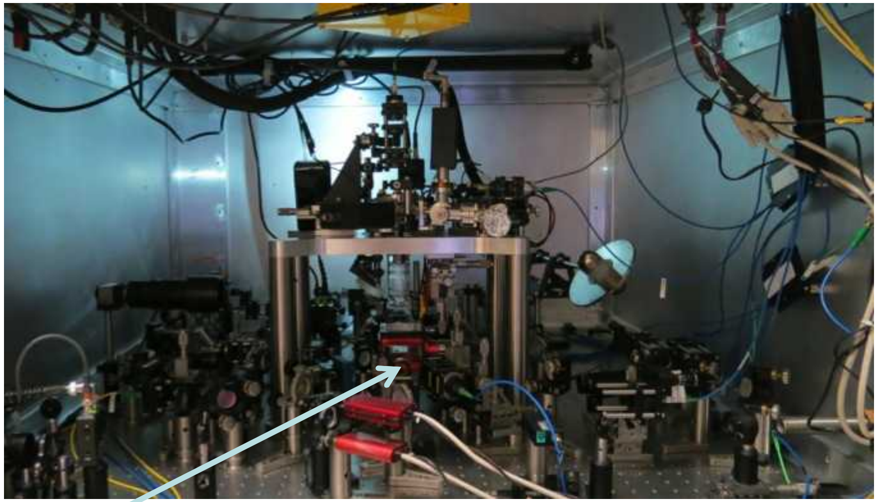
Dynamic atom positioning

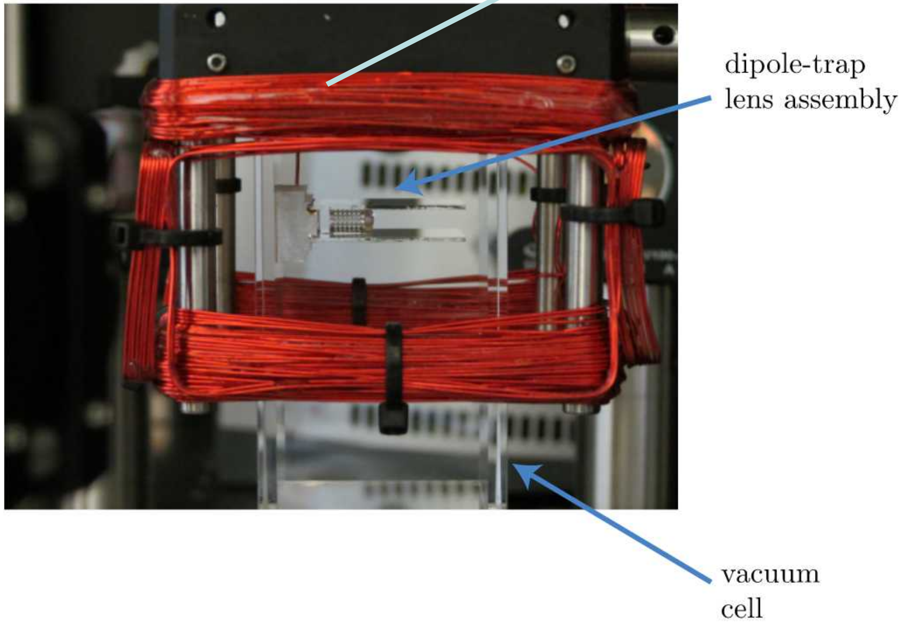


Dynamic atom positioning

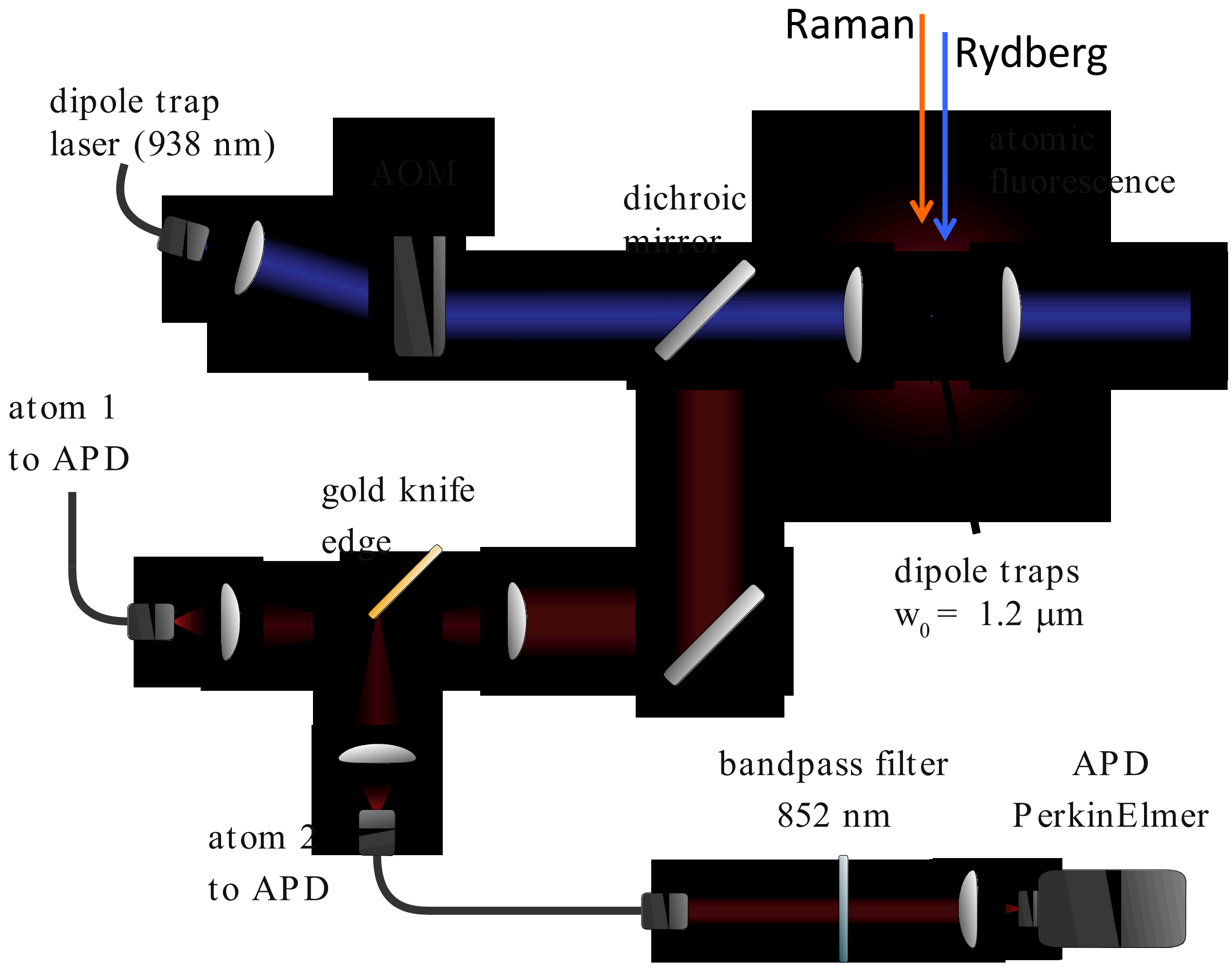


Apparatus

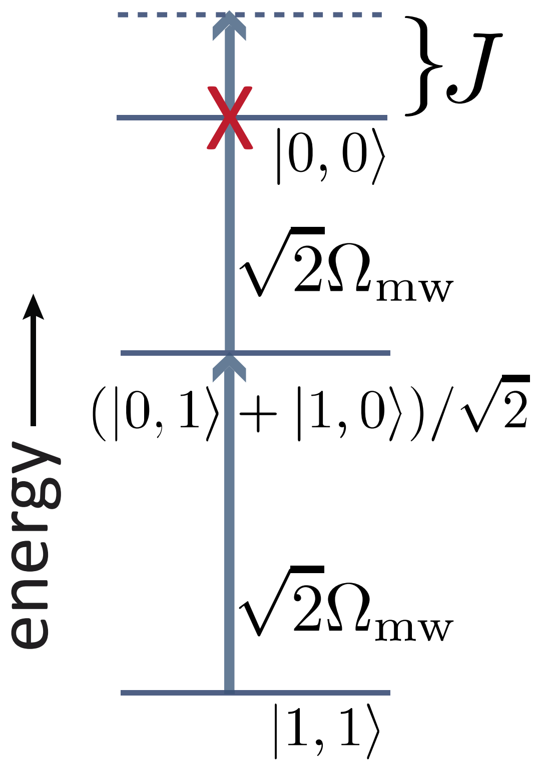


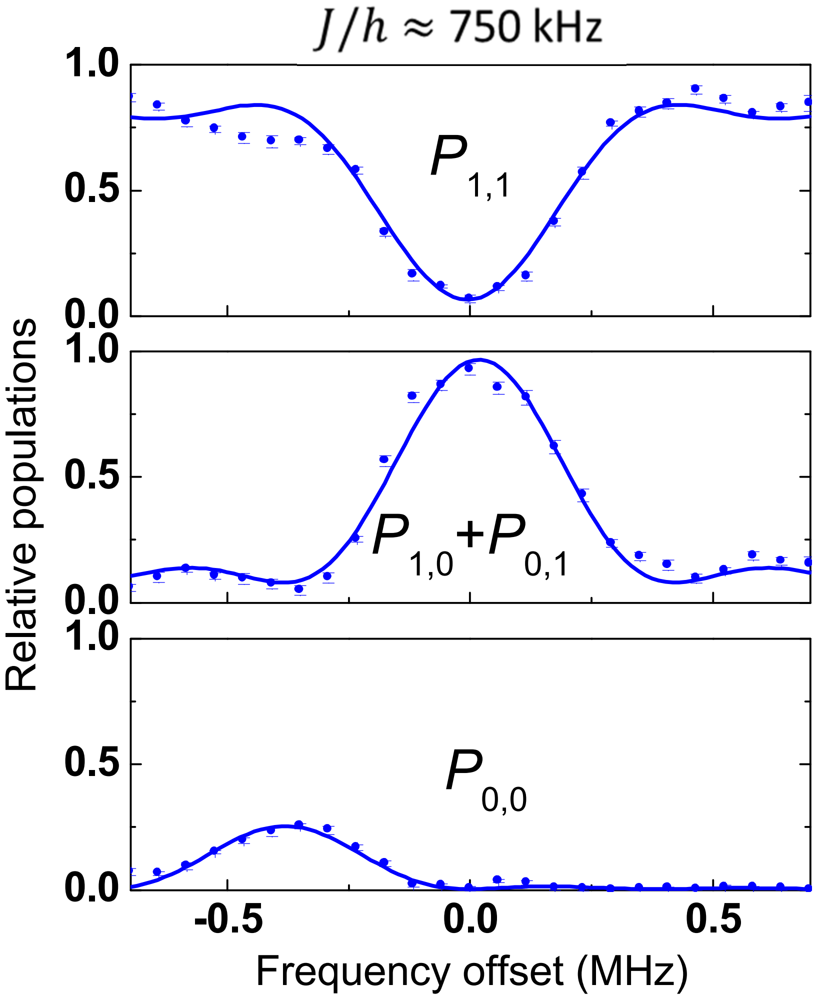


Experiment schematic



Two-qubit microwave resonances





J vs. R

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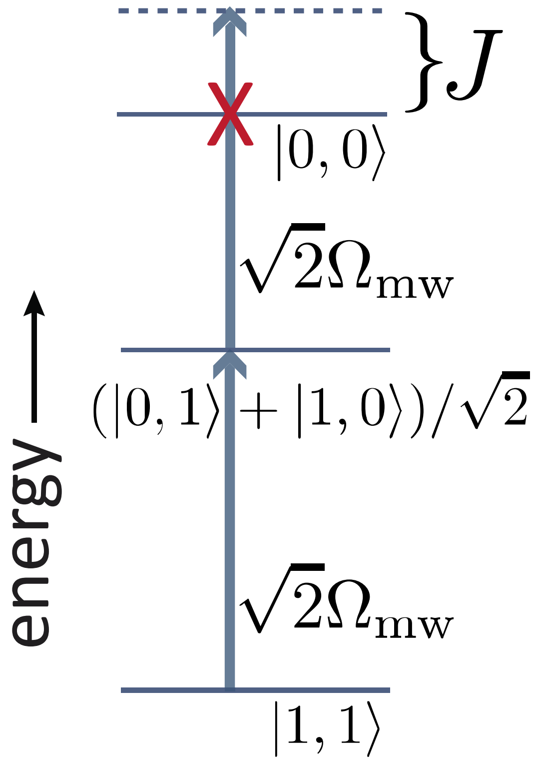
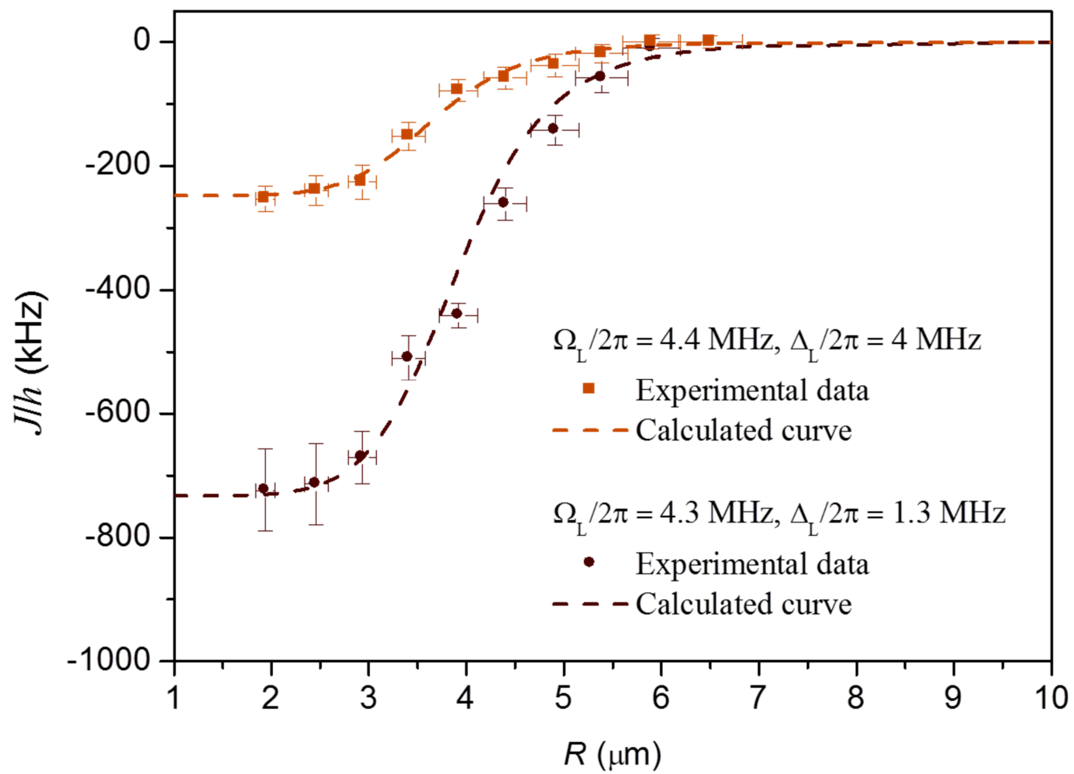
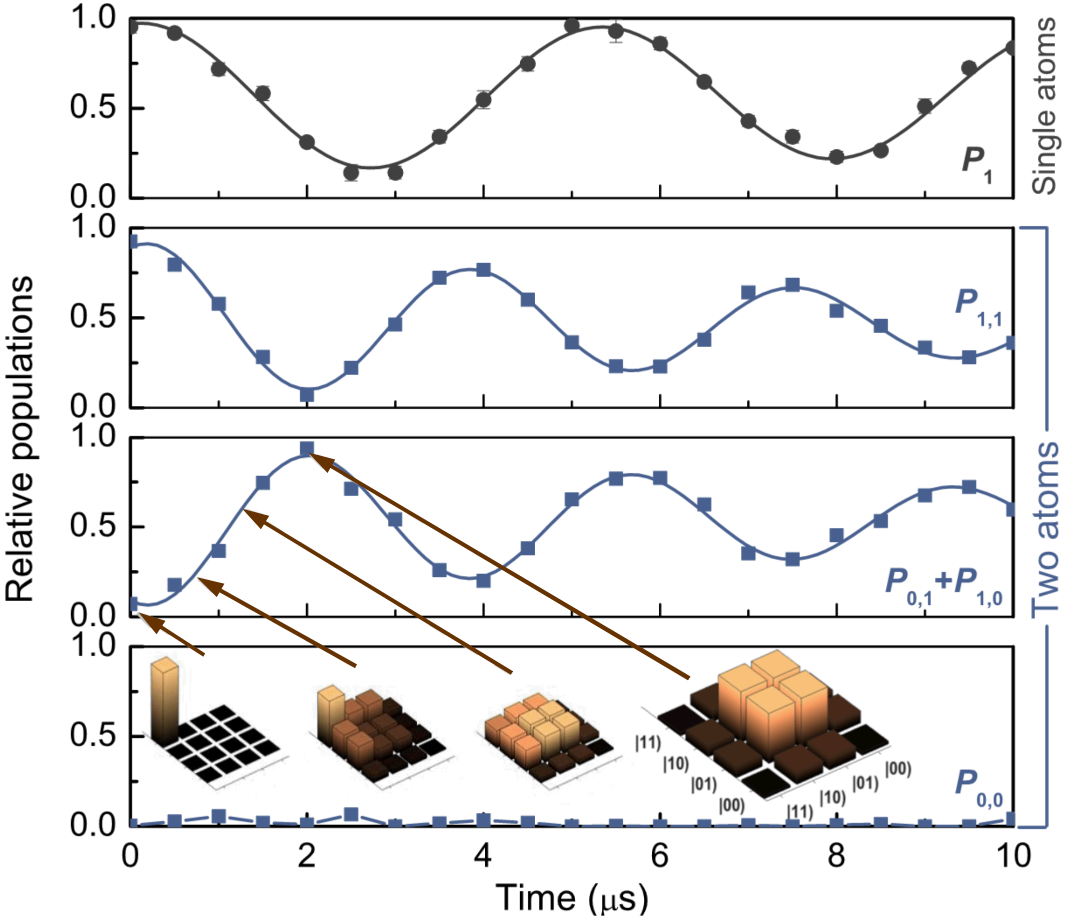
Direct measurement of two-qubit interaction strength J as a function of two-atom separation with two conditions.





Producing Bell-state entanglement

Initial state is $|1\rangle$ or $|11\rangle$, then apply 318-nm and Raman lasers
Experimental data with $J/h \approx 750$ kHz



Single-atom Rabi oscillation: $|1\rangle \leftrightarrow |0\rangle$

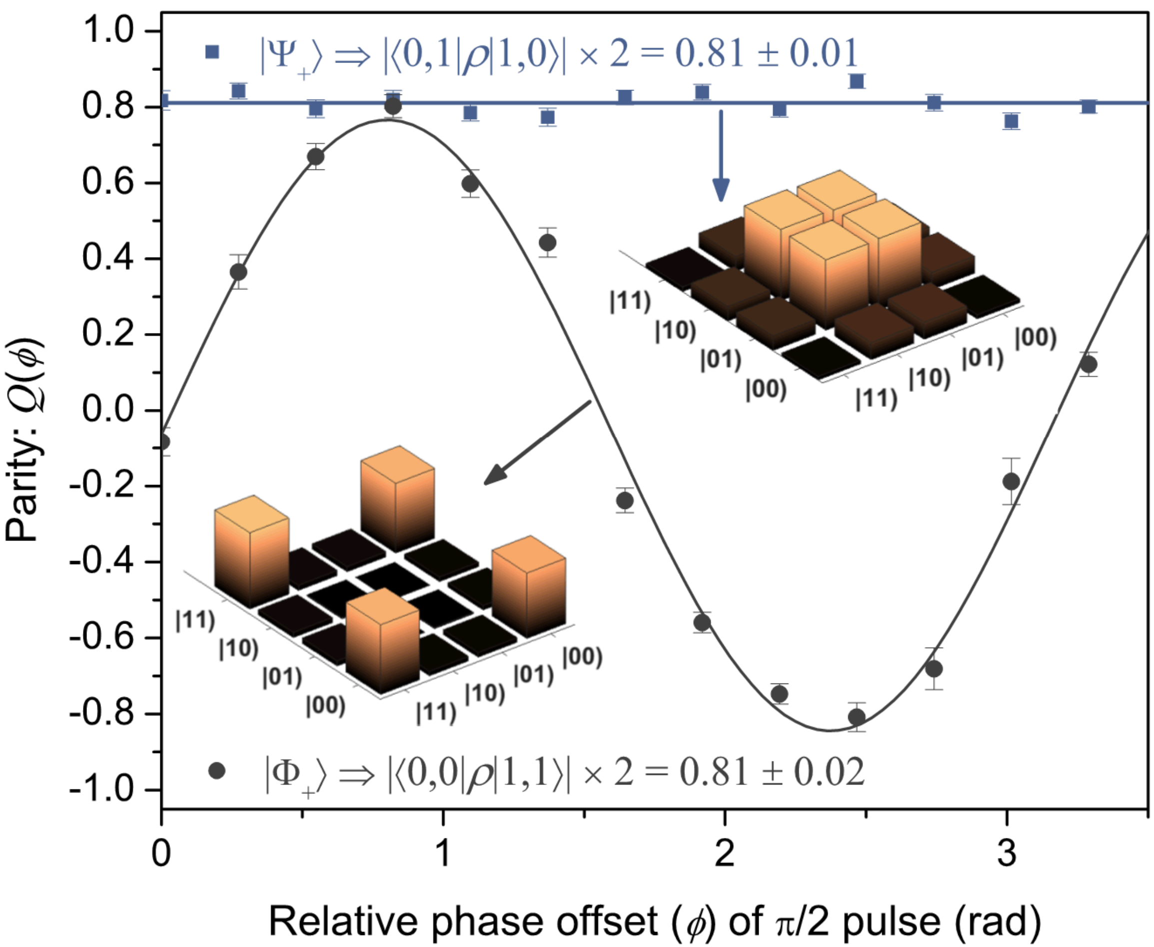
Two-atom Rabi oscillation: $|11\rangle \leftrightarrow (|10\rangle + |01\rangle)/\sqrt{2}$

- $\sqrt{2}$ times faster
- No significant population being transferred to $|00\rangle$
- Bell state $|\Psi_+\rangle$ is produced at $t = \pi/\sqrt{2}\Omega_{mw}$

Process occurs entirely and directly in the ground state

Entanglement Fidelity ≥ 81%

Verify the entanglement via parity measurements



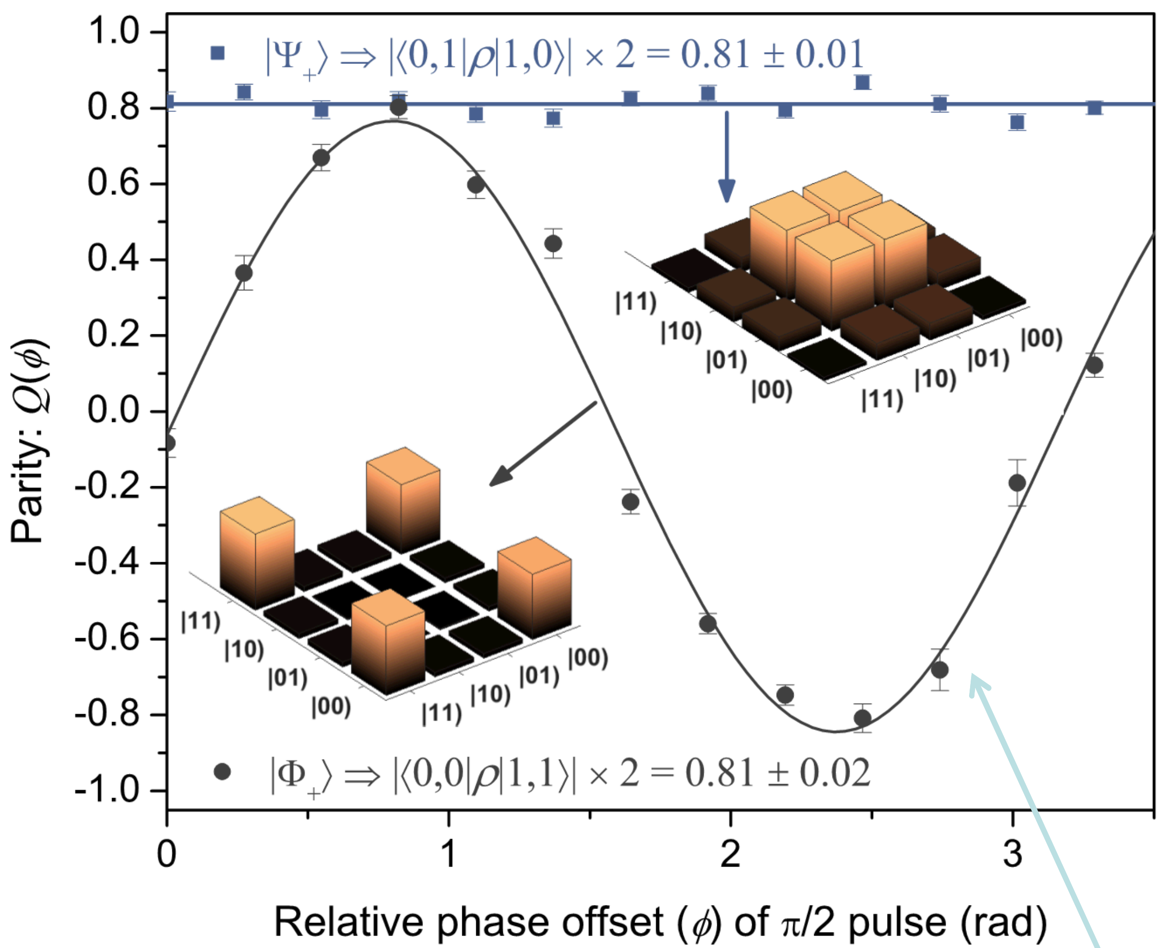
Prepare two Cs atoms in Bell state $|\Psi_+\rangle$ or $|\Phi_+\rangle$

Apply a global $\pi/2$ rotation with a given phase

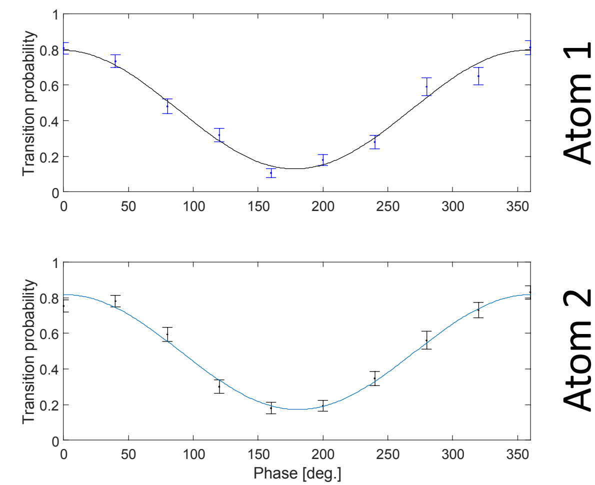
Perform parity measurement $Q = P_{11} + P_{00} - (P_{01} + P_{10})$

Obtain the two-qubit entanglement fidelity F, where $Q \leq F \leq 1$.

Application to metrology

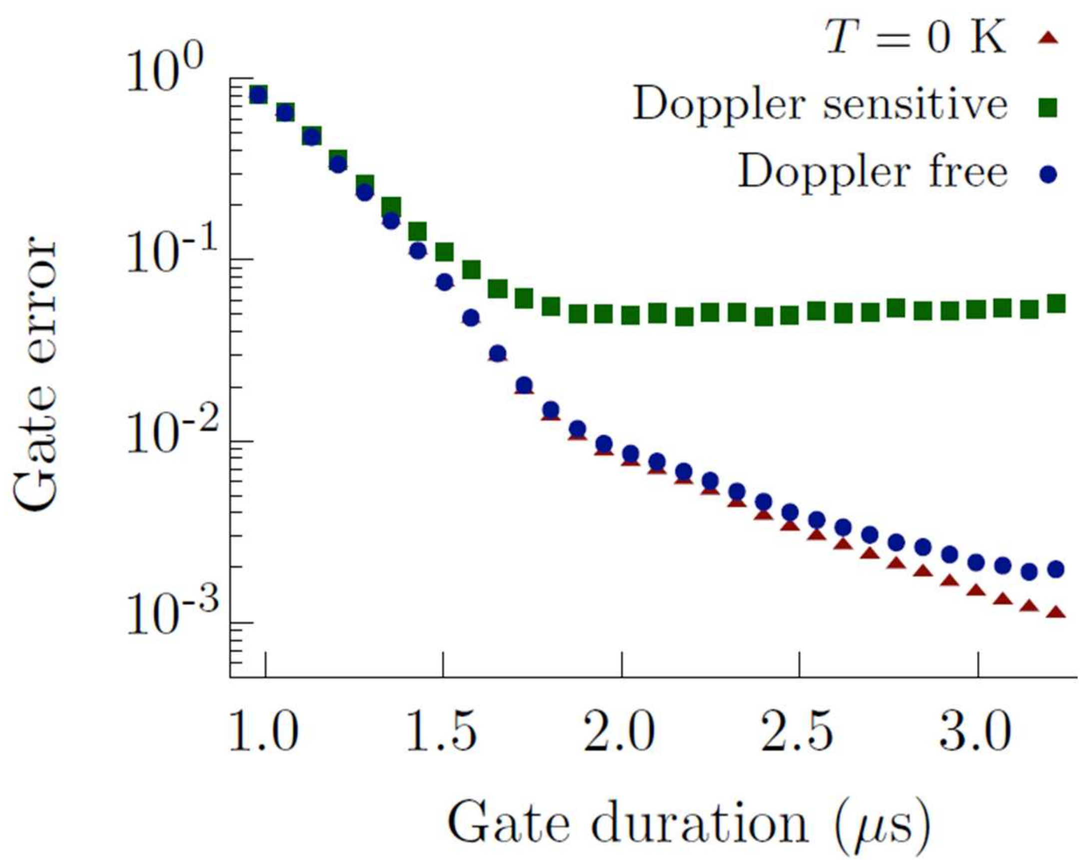


2-atom interferometer



Cat state 2x response to phase

Simulated CPHASE gate fidelities



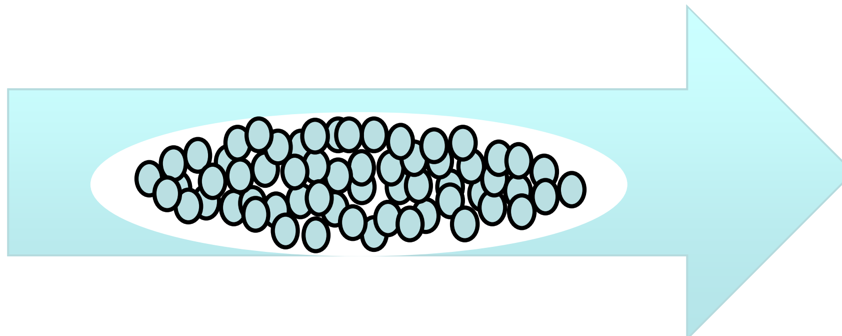
$\Omega = 0 \rightarrow 3$ MHz
$\Delta/2\pi = 6 \rightarrow 0$ MHz
$\Gamma = 3.7$ kHz
$T = 16\ \mu$K

- Motional errors set a high floor on error for the original scheme.
- The Doppler-free scheme is limited by the much smaller photon scattering rate.
- Entanglement fidelity expected to be even larger

Published: Phys. Rev. A 91, 012337 (2015) SUGGESTION

Quantum Control of Ensembles

Symmetrically couple ensemble of atoms localized with Rydberg blockade radius



Optimal Control $|\psi\rangle_0 \rightarrow |\psi\rangle_{target}$

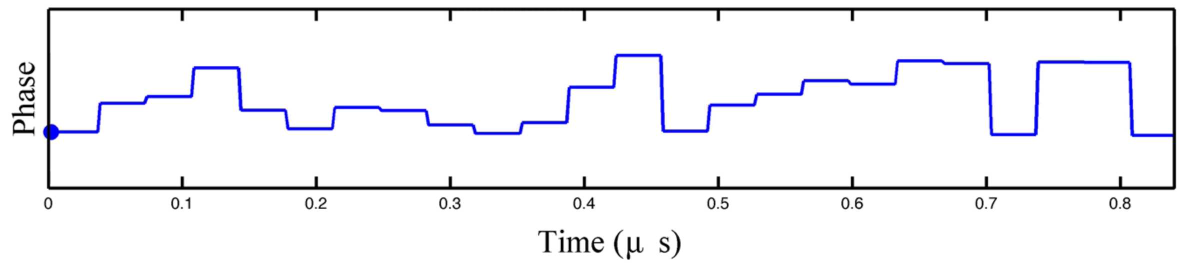
$$H\underbrace{\left[\phi(t)\right]}_{Control}$$

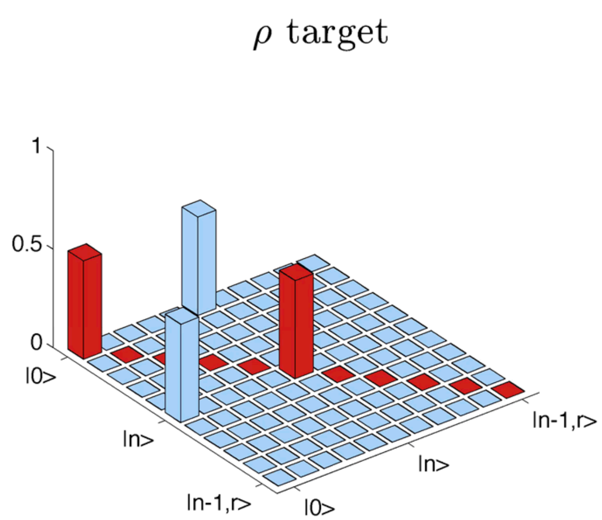
<u>For *n* atoms</u>

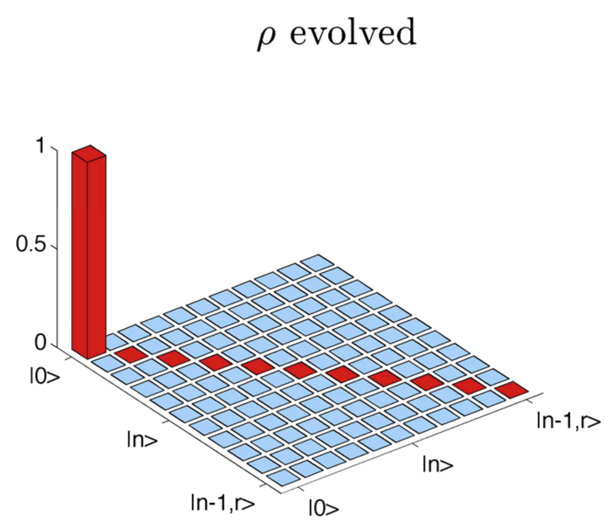
$$H = \sum_n \left[\frac{\Omega_{\mu w}}{2} \left(e^{i\phi(t)} |0\rangle\langle 1| + e^{-i\phi(t)} |1\rangle\langle 0| \right)^{(n)} + \frac{\Omega_R}{2} \left(|1\rangle\langle r| + |r\rangle\langle 1| \right)^{(n)} + \Delta |r\rangle\langle r|^{(n)} \right]$$

$$+ V_{dd} \sum_{n \neq m} |r\rangle\langle r|^{(n)} |r\rangle\langle r|^{(m)}$$

Example: A 5-atom "Cat State"







$$|\psi_{cat}\rangle = \frac{1}{\sqrt{2}}\left(|0\rangle|0\rangle|0\rangle|0\rangle|0\rangle + |1\rangle|1\rangle|1\rangle|1\rangle|1\rangle\right)$$

$$|\psi(t)\rangle$$

Summary

- We have demonstrated an effective ground-state interaction of J/h ~ 1 MHz via the Rydberg dressing technique
- Possible uses include many-body physics, quantum simulation/computation, and metrology.
- We experimentally show neutral atom entanglement with a fidelity of ≥ 81 ± 2%
- With two-atom survival probability is about 74 % and about 10 s^{-1} data rate, we produce 6 entangled pairs per second
- Multi-atom entanglement can be achieved based on a similar approach
- Universal quantum gate control can be realized with individual addressing of the trap atoms
- The parity quantity is immediately useful for enhanced metrology
- We are investigating atom interferometry with cat states and N > 2

Team members

- Aaron Hankin (Sandia, currently at NIST)
- Yuan-Yu Jau (Sandia)
- Jongmin Lee (Sandia)
- Bob Keating (UNM)
- Ivan Deutsch (UNM)

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