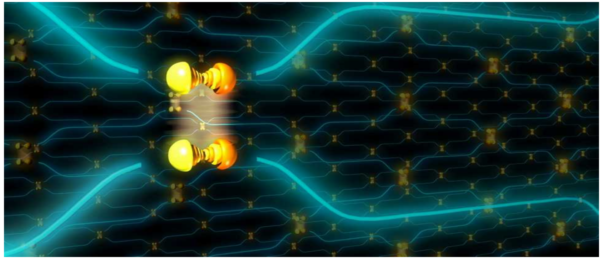
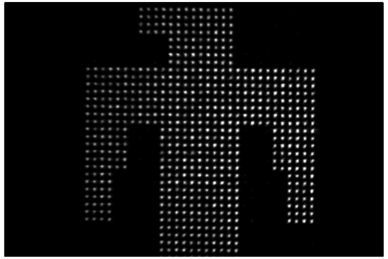
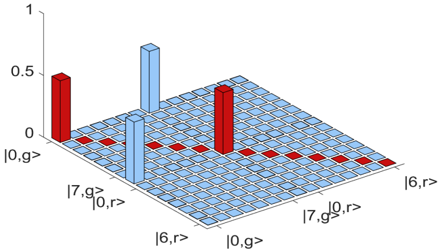
SAND2018-2244C







Team members
- Michael Martin (Sandia)
- Yuan-Yu Jau (Sandia)
- Jongmin Lee (Sandia)
- Ivan Deutsch (UNM)

Entangling atomic spins with a strong Rydberg-dressed interaction

Grant Biedermann

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

LDRD Laboratory Directed Research and Development

This work was supported by the Laboratory Directed Research and Development program at Sandia National Laboratories

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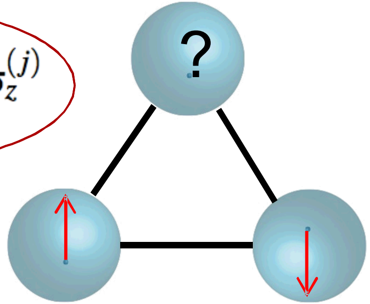
Outline

- Introduction to Rydberg-dressed atoms and the Sandia Rydberg atom experiment
- Rydberg dressed physics and entangling gates
- Study of a controlled-phase (CPHASE) gate
- Extension to trap arrays

Motivation

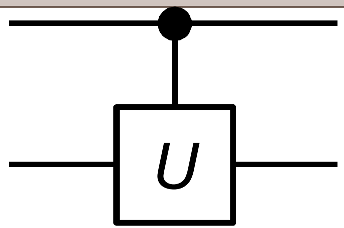
Quantum simulation

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

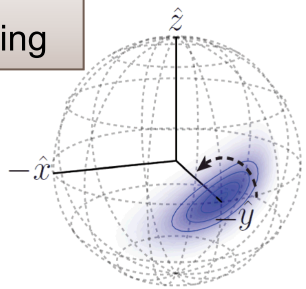


Frustrated magnetism

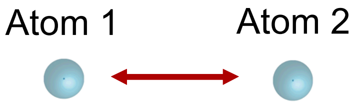
Pairwise entangling gates between two neutral atoms



Large-scale/rapid entanglement for sensing

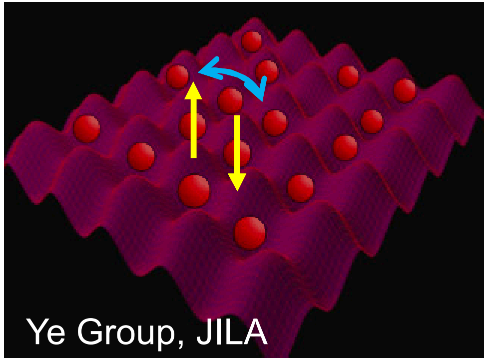


Interaction between *neutral* atoms



$$U = \frac{4\pi a\hbar^2}{m} \times \bar{n}$$

$$J_{ex} \propto J^2 / U$$



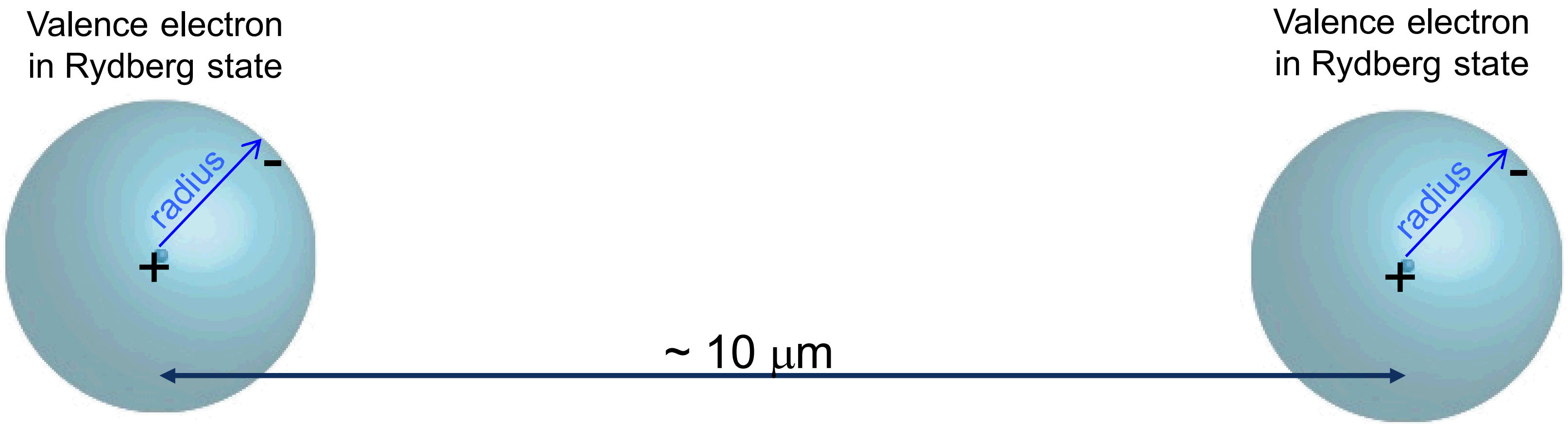
- Interaction between ground state atoms is small ~100 Hz
  - Thermal energy scales too large (*e.g.*, QSIM)
  - Long gate times (*e.g.*, QIP)

One solution: use Rydberg states

S. Trotzky *et al.*, Science **319**, 295-299 (2008)

I. Bloch, J. Dalibard, and S. Nascimbène, Nat. Phys. **8**, 267-276 (2012)

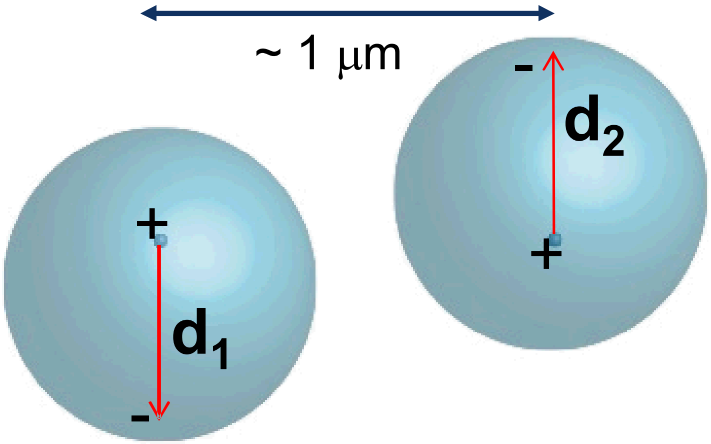
Interaction between *neutral* atoms



orbital radius α n^2

- Excite valence electron to Rydberg state—nearly ionized
- Atom becomes highly polarizable—strong interactions

Interaction between *neutral* atoms



van der Waals interaction

Parameter scaling

van der Waals
$U \propto n^{11}$

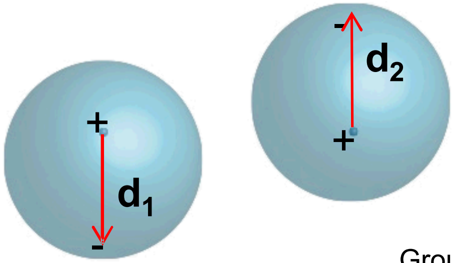
Lifetime
$\tau \propto n^3$

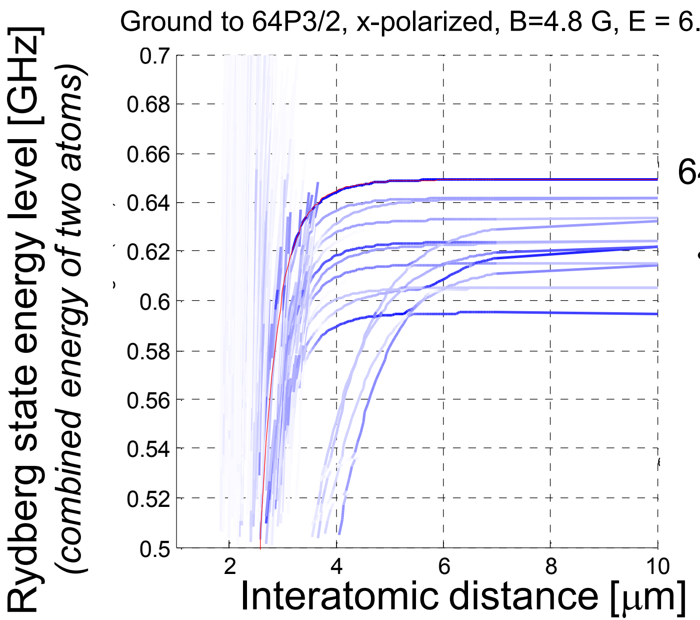
DC polarizability
$\alpha(0) \propto n^7$

- Even the presence of another atom can cause a massive response >> 10 MHz
- Induced Electric Dipole-Dipole Interaction $\propto 1/r^6$

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

Rydberg blockade—the nitty gritty



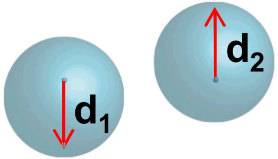


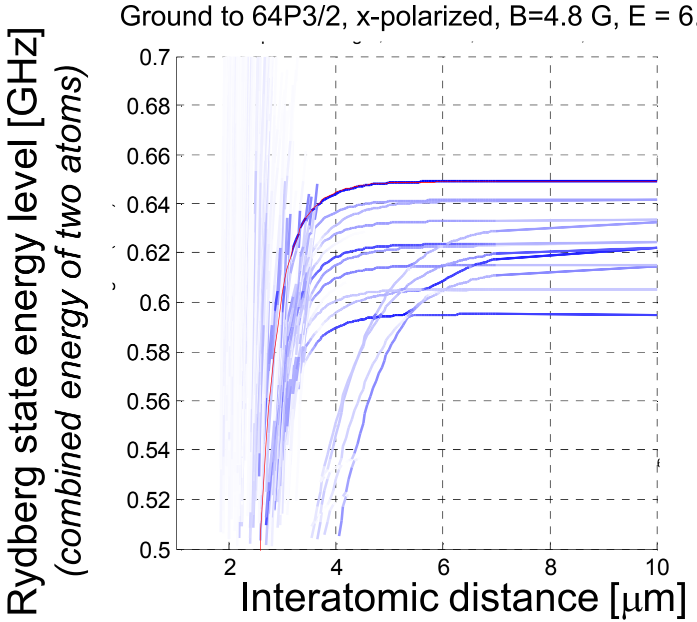
$64P_{3/2}64P_{3/2}$

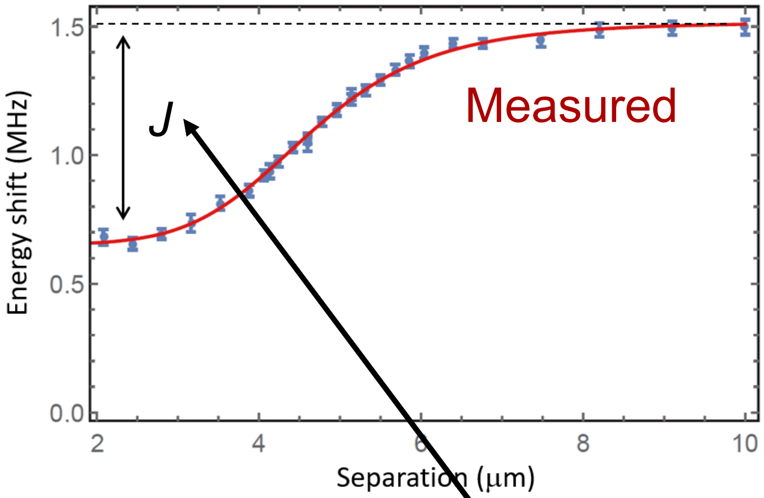
- Line shade weighted by transition strength

We want something smooth and tunable

Direct Rydberg → Rydberg-Dressed

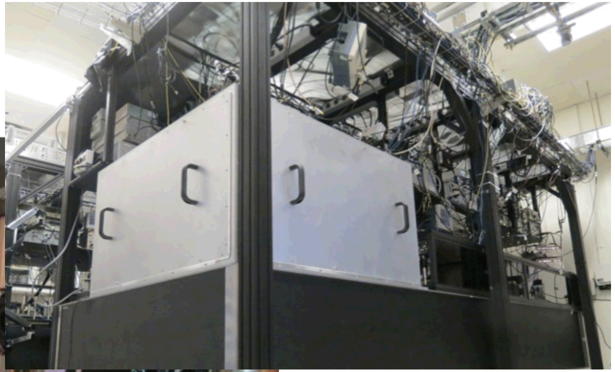


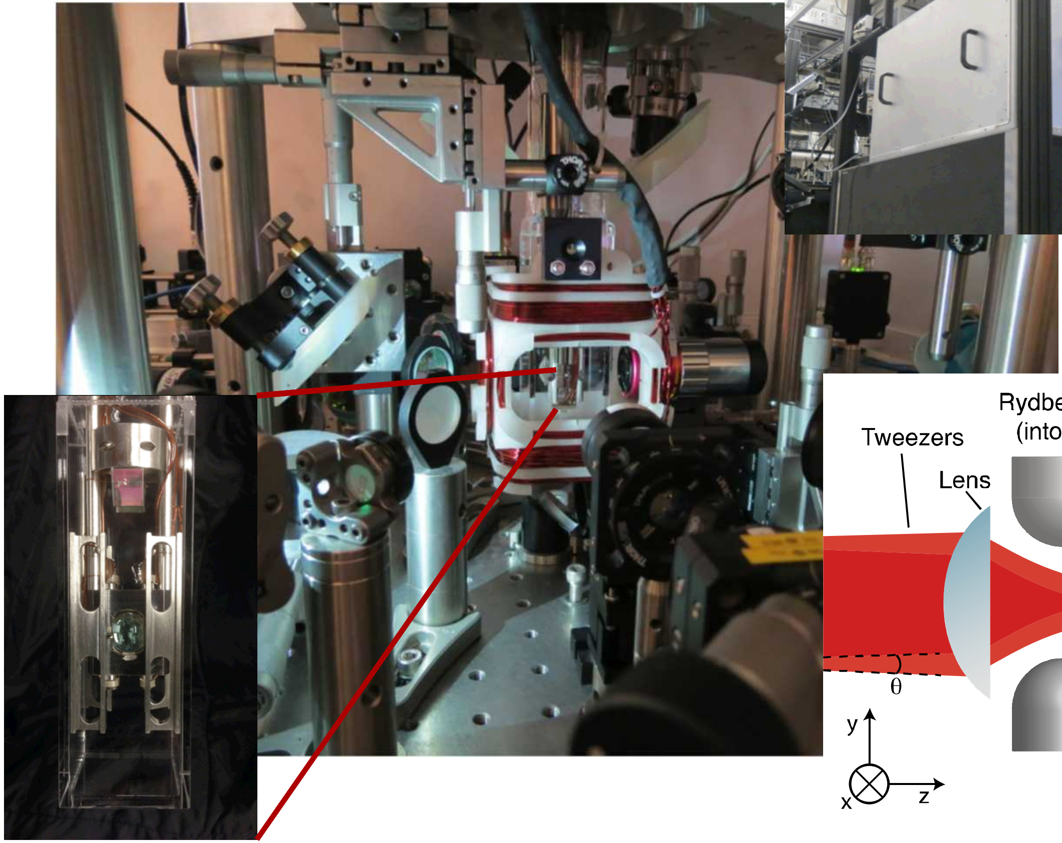


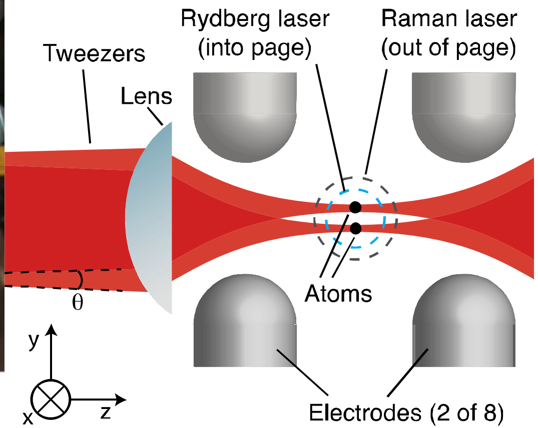


$$H_P = \sum_{i=1}^{N} \tilde{h}_i \sigma_z^{(i)} + \sum_{i,j=1}^{N} \tilde{J}_{ij} \sigma_z^{(i)} \otimes \sigma_z^{(j)}$$

Rydberg experiment

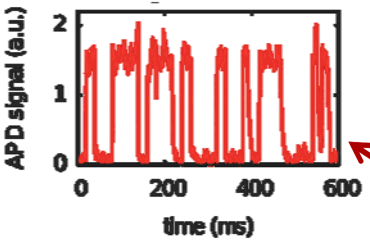


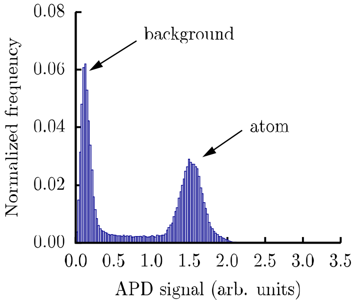


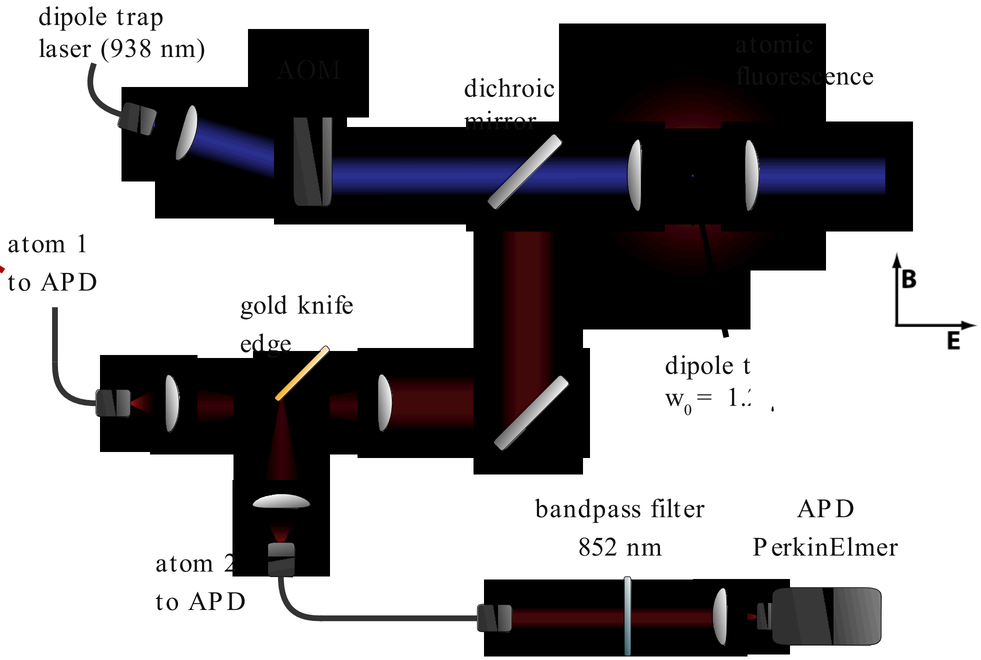


Phys. Rev. A **89**, 033416 (2014); Phys. Rev. A. **95**, 041801(R) (2017)

Single atom control of 2 atoms

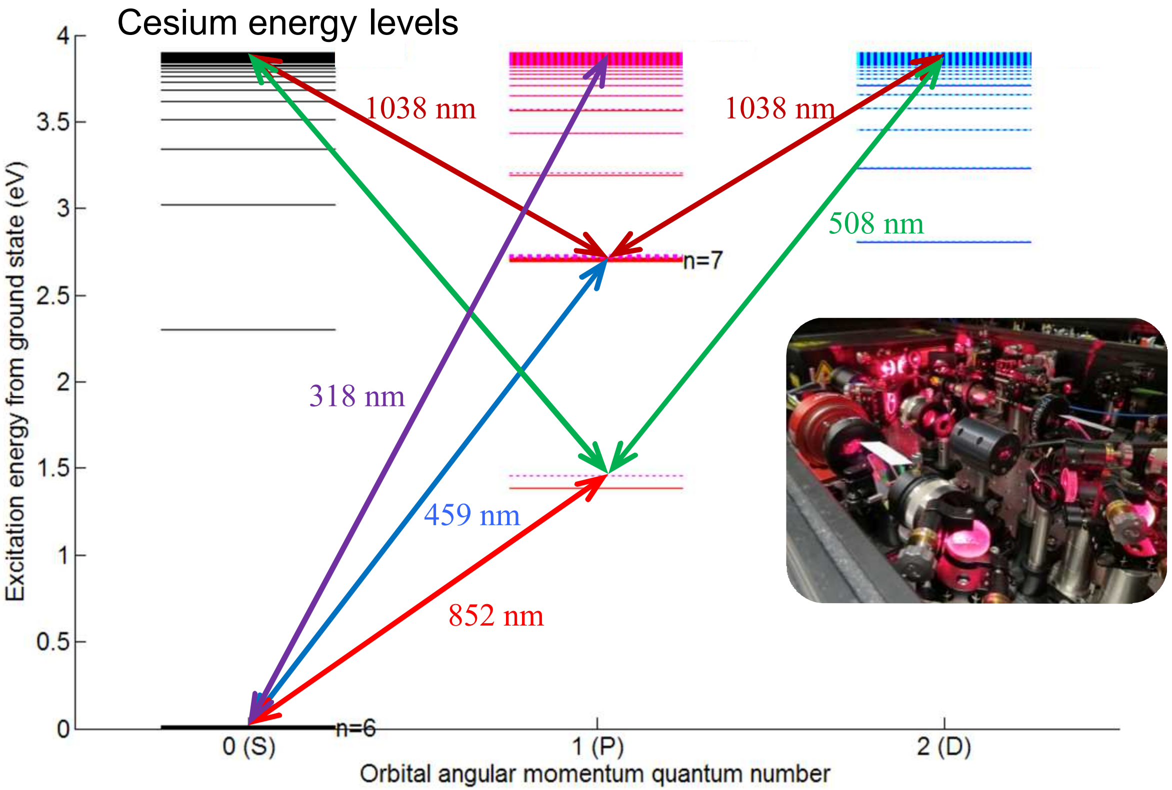




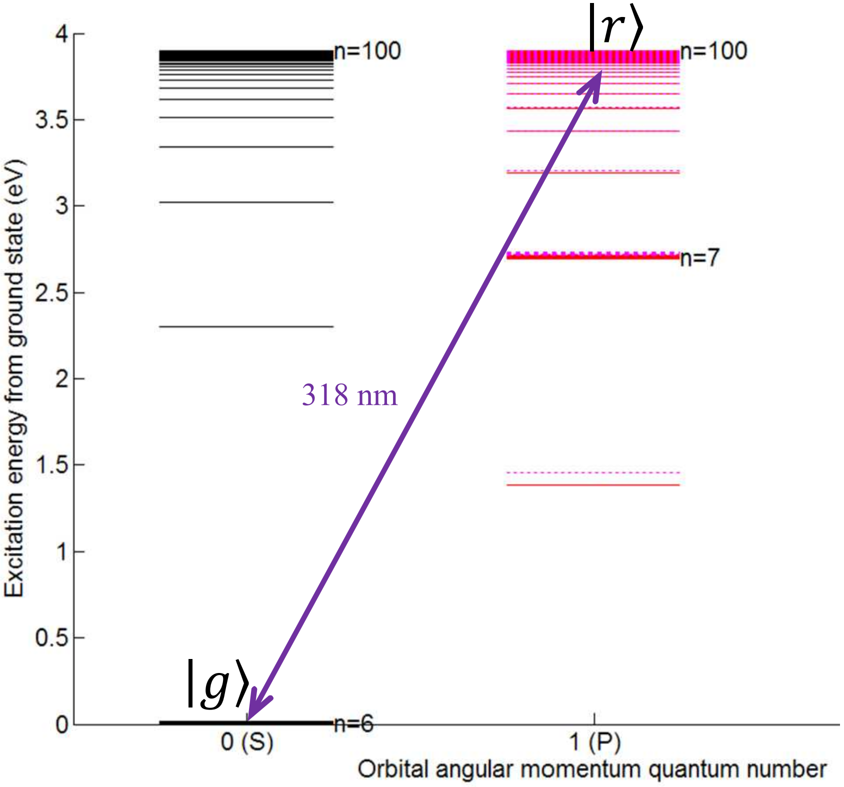


- Optical tweezers
- Trap single Cs atoms
- Laser cooling to load traps
- AOM deflection controls trap position
- Photon counters for detection

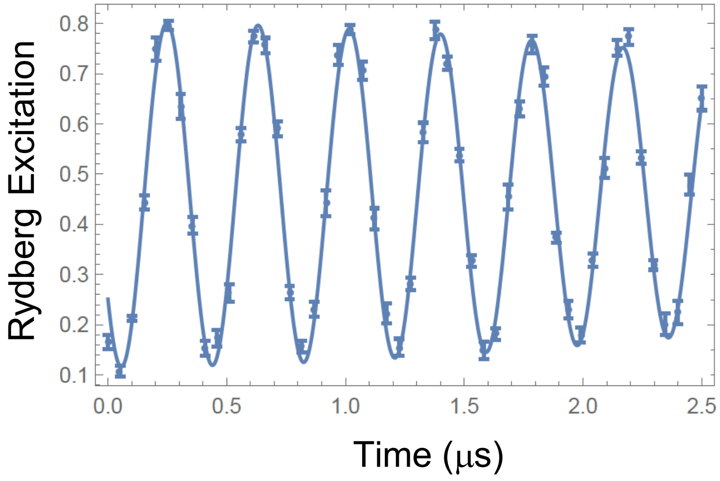
Rydberg excitation laser

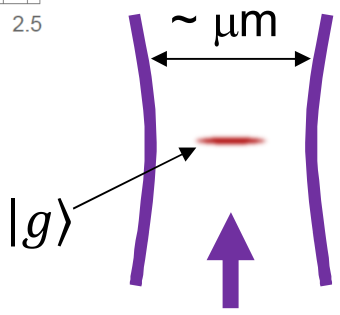


Direct excitation 318 nm Rydberg Rabi flopping



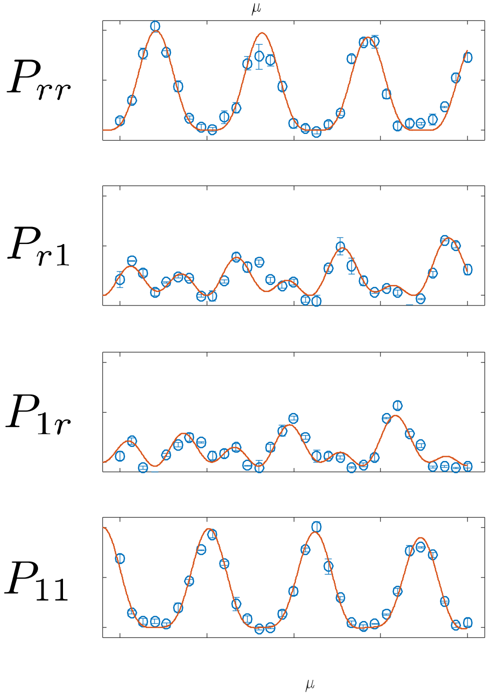
Direct excitation, measured through loss

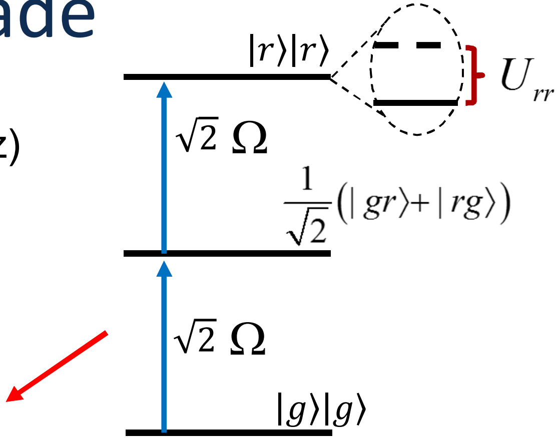


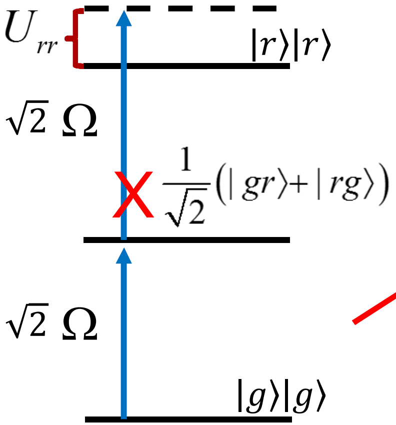


Rydberg blockade

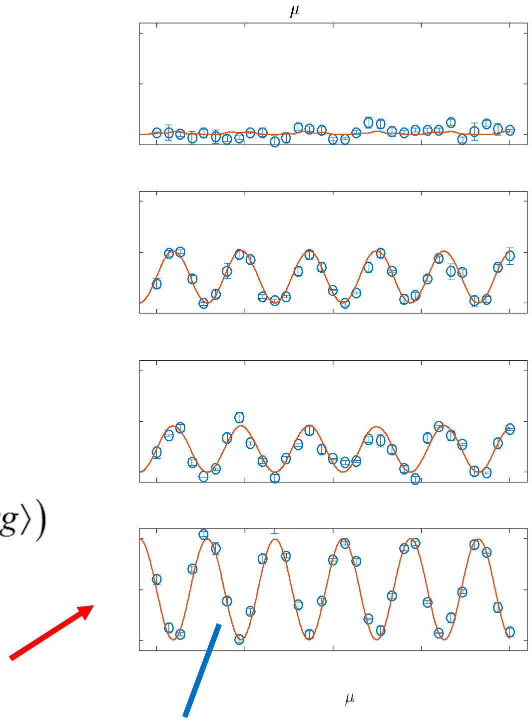
Weak (U_{RR} < 100 kHz)





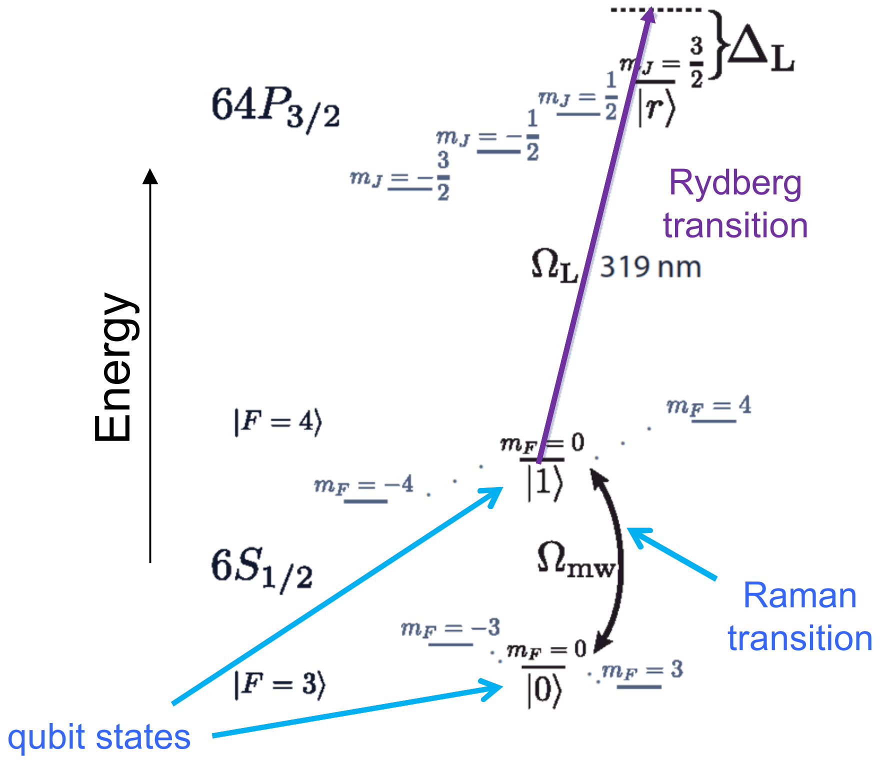


Strong (U_{RR} > 6 MHz)



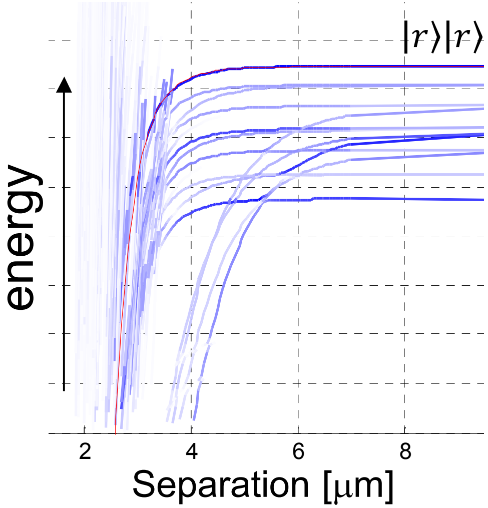
$\sqrt{2}$ Enhancement

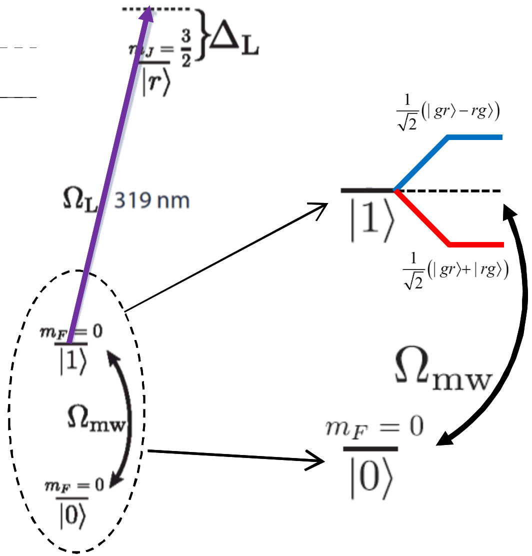
Creating Rydberg-Dressed states

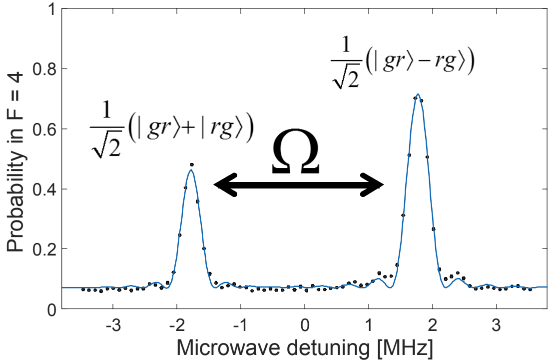


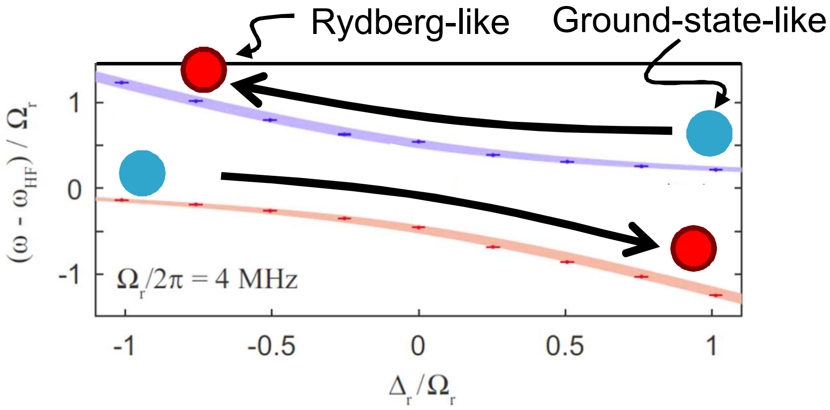
- 1-S scale coherence time. Neutral atoms define the SI second!
- Form the basis of sensors and clocks that use measurements of **~10^6** atoms.

1-atom Rydberg-dressed states

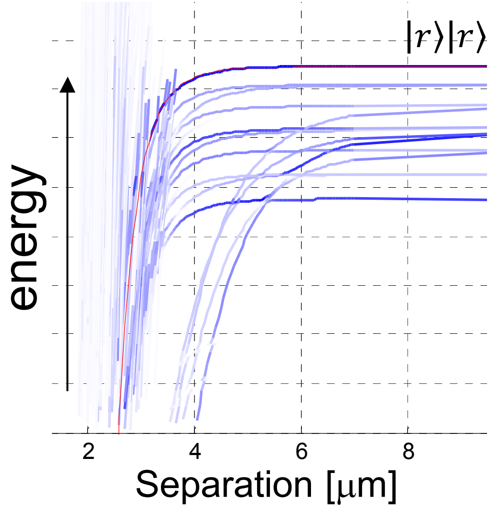


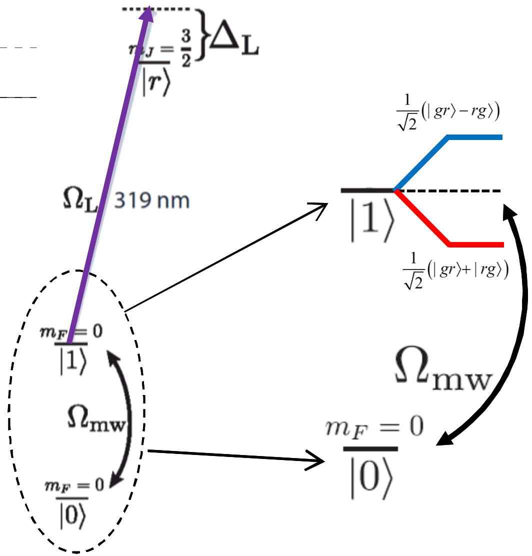


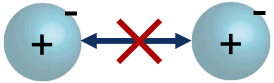


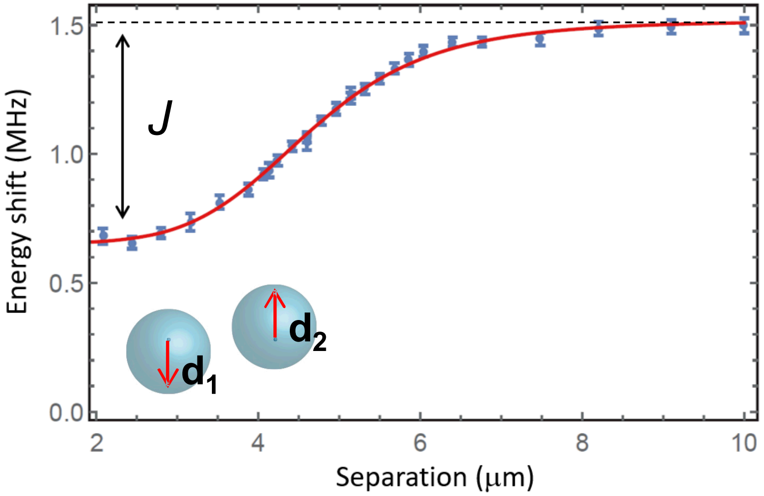


Rydberg-Dressed interaction



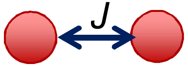






Rydberg-dressed interactions

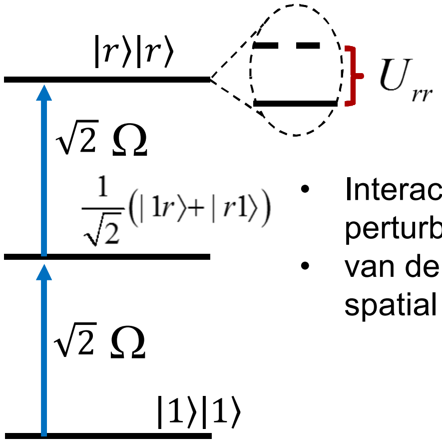
$U_{rr} \ll \Omega_r$ (atoms far apart)



$U_{rr} \gg \Omega_r$ (atoms close)

$$|\psi\rangle = \alpha\,|1\rangle + \beta\,|r\rangle$$

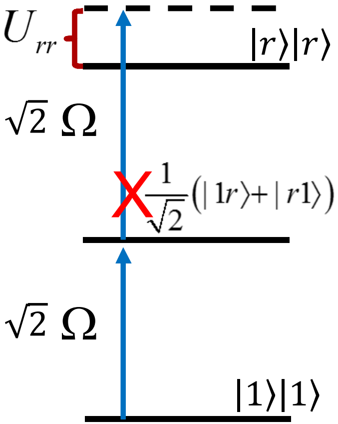
$$J \rightarrow |\beta|^4 \times U_{rr}$$



- Interaction is perturbative
- van der Waals spatial dependence

$$|\psi\rangle = \alpha'\,|11\rangle + \frac{\beta'}{\sqrt{2}}(|1r\rangle + |r1\rangle)$$

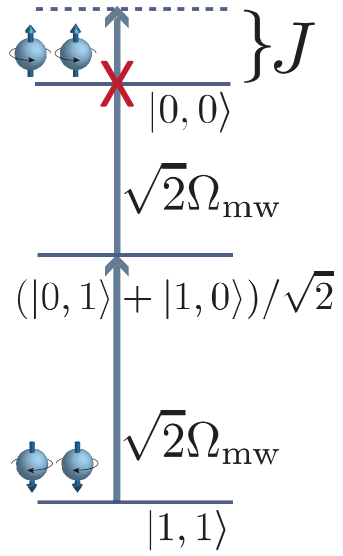
$$J \sim \Omega$$

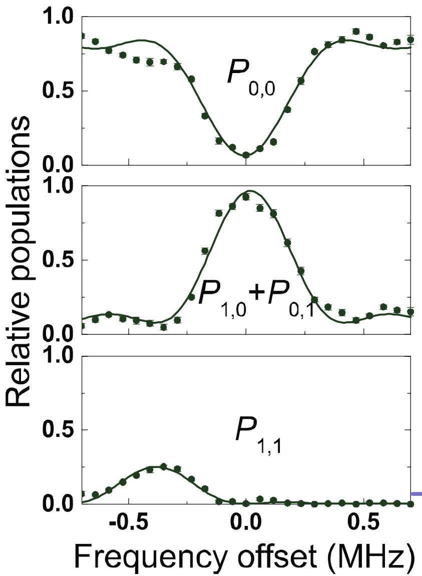


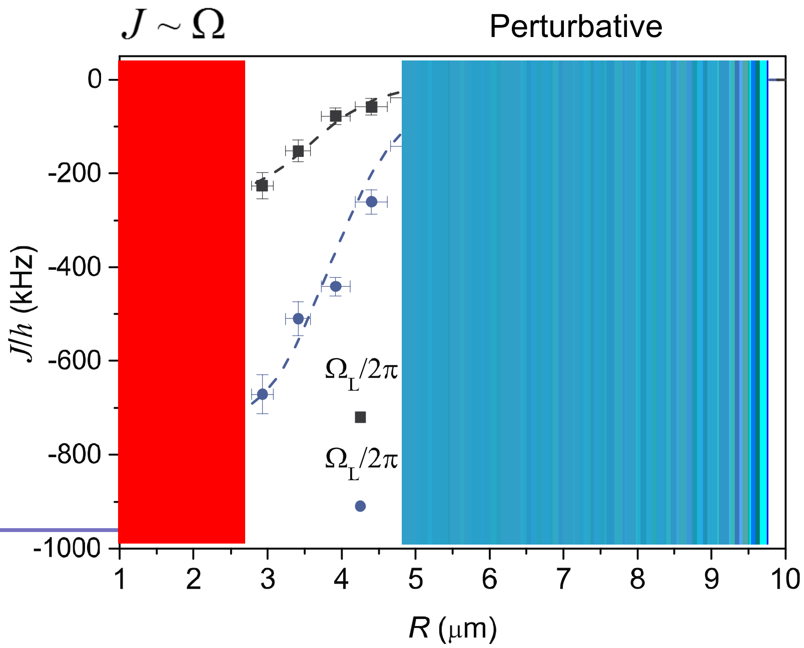
- Interaction non-perturbative
- Blockade truncates Hilbert space for light shift Hamiltonian

Observing blockade on hyperfine qubit

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

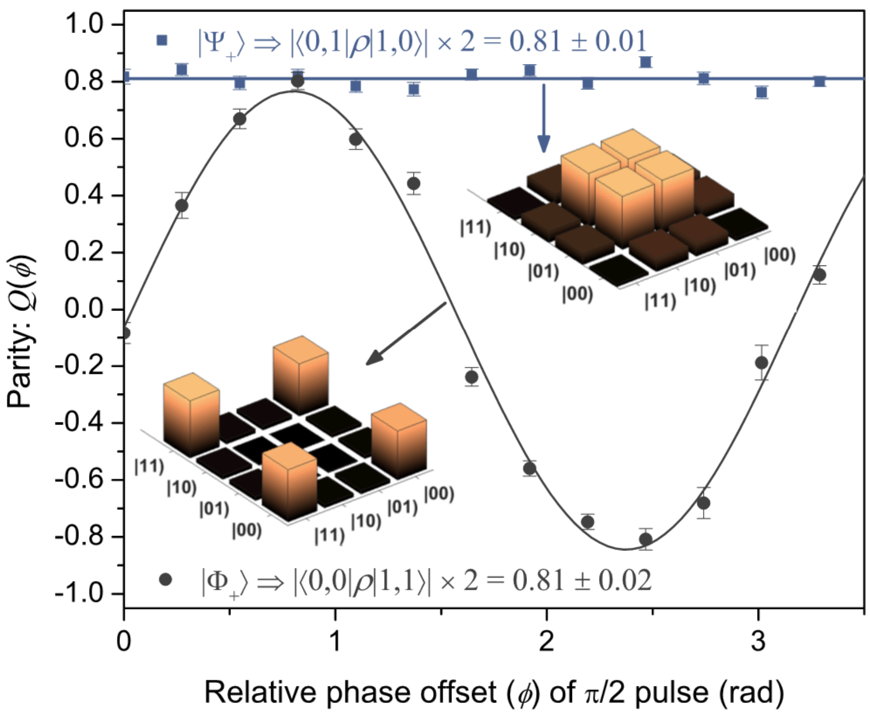


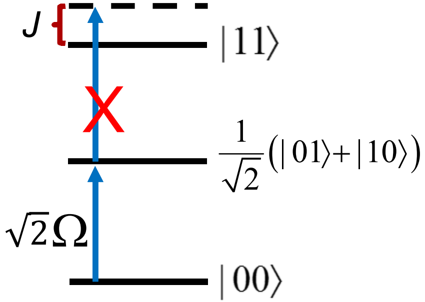




Spin-flip blockade

Verify the entanglement via parity measurements



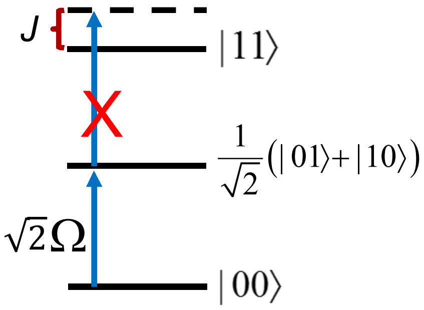


1. Prepare Bell state
2. Apply global π/2 with given phase
3. Measure parity Q
4. Obtain bound on fidelity =0.81(2)

Y.-Y. Jau, et al., Nature Phys. **12**, 71-74 (2016)

Spin-flip blockade vs. CPHASE

Blockade



- Conditional π phase shift can be used to generate controlled-Z and CNOT gates via direct excitation

Controlled Phase (CPHASE)

- Use nonlinear Hamiltonian:

$$\hat{H}_{DD} = J\,|11\rangle\langle 11|$$

(+ single-atom light shift terms)

- States acquire nonlinear phase shift:

$$|\psi_0\rangle = \frac{1}{2}\big(|0\rangle+|1\rangle\big)\otimes\big(|0\rangle+|1\rangle\big)$$

$$\rightarrow \frac{1}{2}\big(|00\rangle+|10\rangle+|01\rangle+e^{i\phi}\,|11\rangle\big)$$

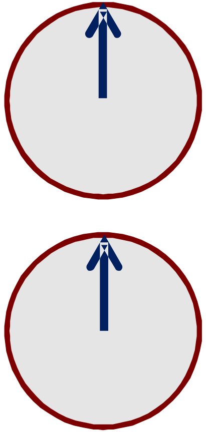
- π phase shift as a special case can be used to generate controlled-Z and CNOT gates between hyperfine qubits.
- Nonlinear Hamiltonians for larger systems

Generating Entanglement

$$\hat{H}_{DD} = J\,|11\rangle\langle 11|$$

Laser ONF

Phase:

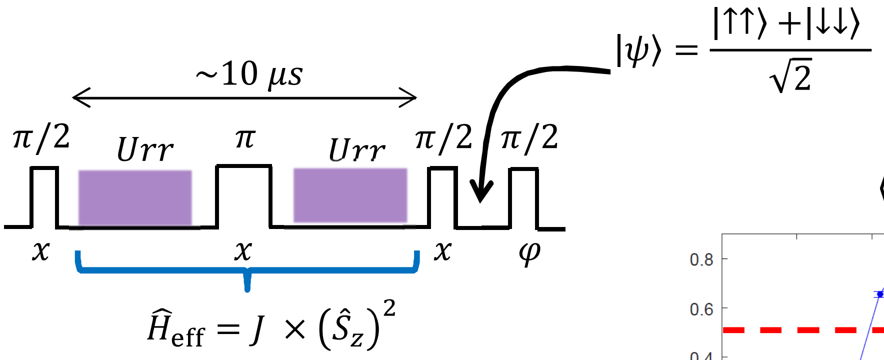


$|11\rangle$

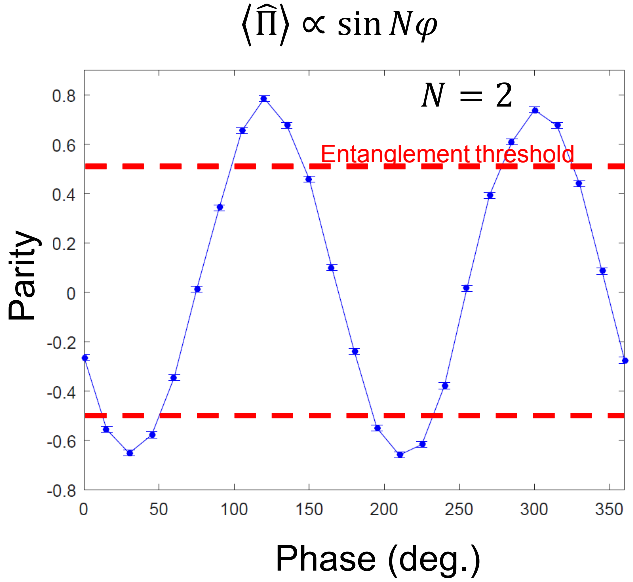
$|01\rangle\ |10\rangle$

and $|00\rangle$

Dressed CPHASE gate



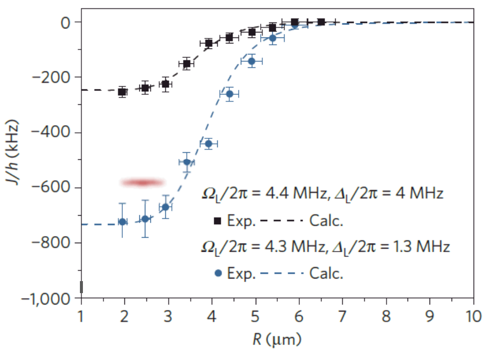
- Single-atom effects removed by echo pulse

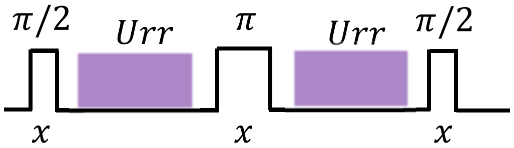


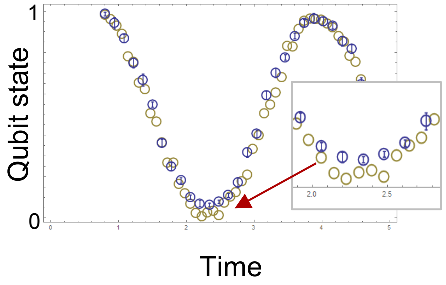
J. J. Bollinger *et al.*, "Optimal frequency measurements with maximally correlated states." Phys. Rev. A **54**(6) (1996).

Potential limitations

- Thermal, shot-to-shot, position spread
  - Measured position spread, currently limiting at the 3% level
  - "Fine structure" in dressed Rydberg potential still a possible limitation
- Doppler noise
  - Motion-dependent single-atom light shift
  - Mitigated by echo to <0.1%
- State purity
  - Implemented extra state purification
  - >97% purity demonstrated
- Rydberg laser phase and amplitude noise
  - Characterized for current operating parameters: contributes <1%

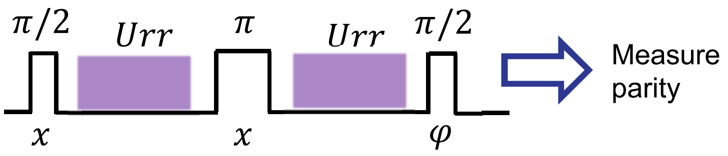






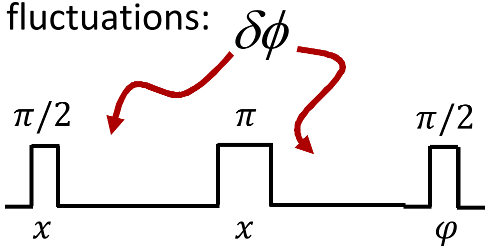
Local oscillator noise

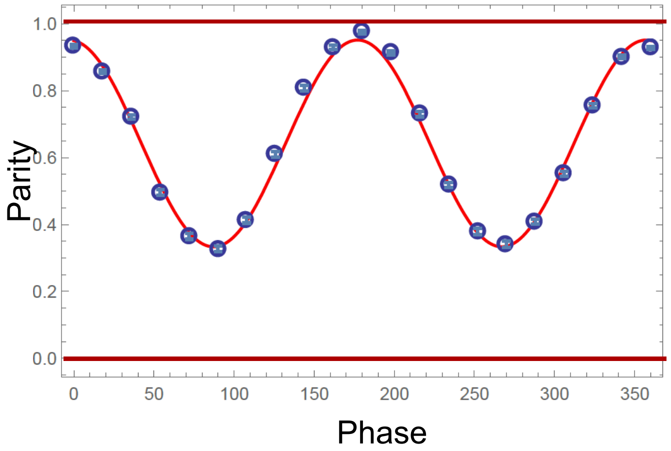
- Sequence to test qubit rotation operations:



- Expect sine wave with peak-to-peak amplitude of 1

- Measured results consistent with 0.5 rad RMS phase fluctuations:



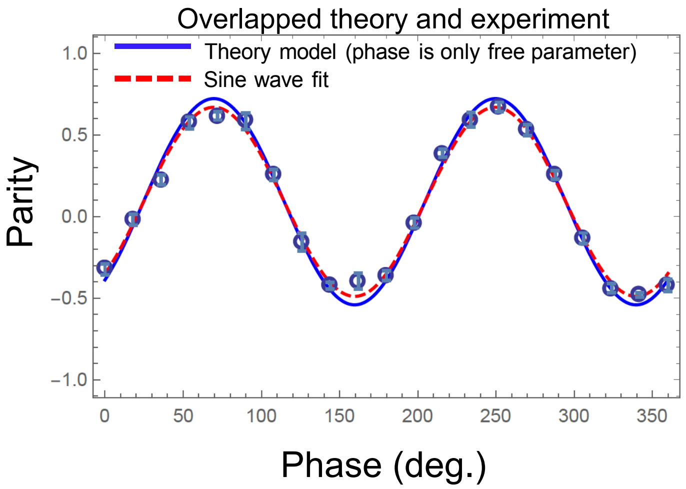


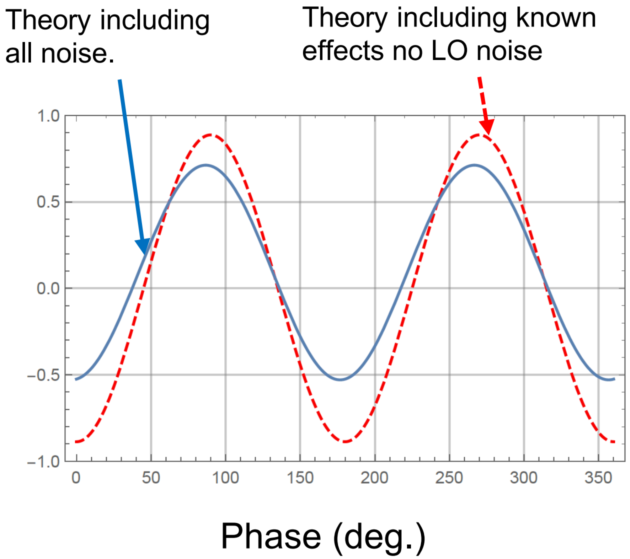
- Potential sources: Raman Laser linewidth and near-resonant amplified spontaneous emission pedestal

CPHASE limitations

- Calculated the effect of :
  - Atomic position spread
  - Atomic velocity distribution
  - Effective local oscillator phase noise

Theory model with measured noise parameters matches data.



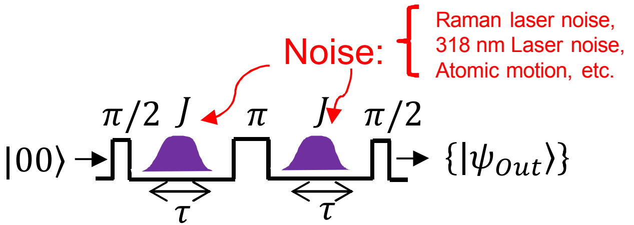


Error budget for CPHASE gate

Error budget: informing an experimental strategy

- Trace over external parameters to calculate effect on state fidelity, using measured parameters.

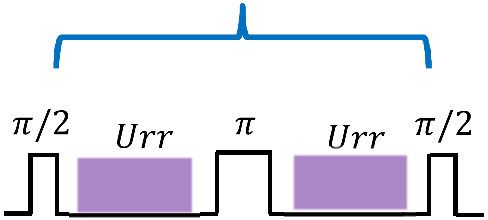
Fidelity = $\langle \psi_{tar} | \rho_{out} | \psi_{tar} \rangle$



Effect	Fidelity reduction	Mitigation
LO noise	10% ±0.1%(stat.) ±2%(sys.)	Clean Raman laser/μWave cavity
State purity	<3%	Clean Raman laser/μWave cavity
Atomic position spread	3%±0.5%	Increase blockade radius, increase confinement
Wave-packet overlap	<0.1%	Sideband cooling to ground state
Atomic velocity spread	<0.1%	Sideband cooling to ground state
318 nm Laser frequency noise	0.2%±0.1%	Pre-stabilized seed lasers, different detuning, dynamical decoupling
Spontaneous emission	0.4%±0.2%	Higher principal quantum #
318 nm laser amplitude noise	<0.1%	Install "noise eater" on laser

Scaling to N atoms

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

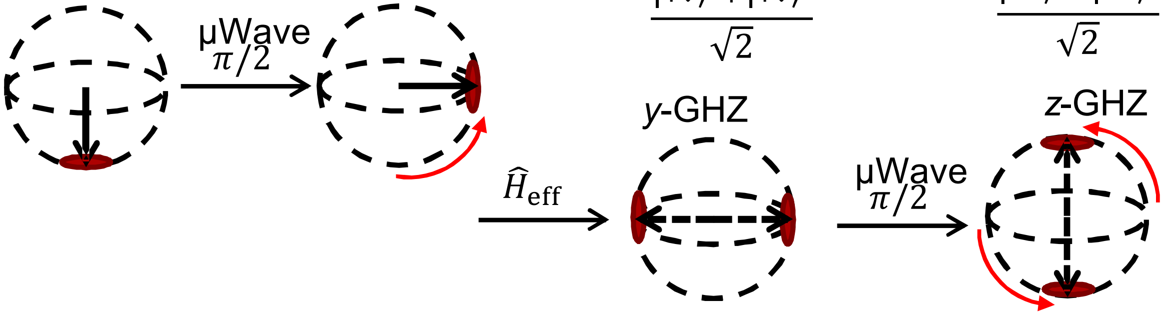


- $\hat{S}_z$ is the collective S_z spin operator for the pseudospin $N/2$ system.

- For N atoms all within a blockade radius, an N-atom cat state forms at $J \times \tau = \pi/2$

(2-atom case) $\frac{|\uparrow\downarrow\rangle + |\uparrow\downarrow\rangle}{\sqrt{2}}$

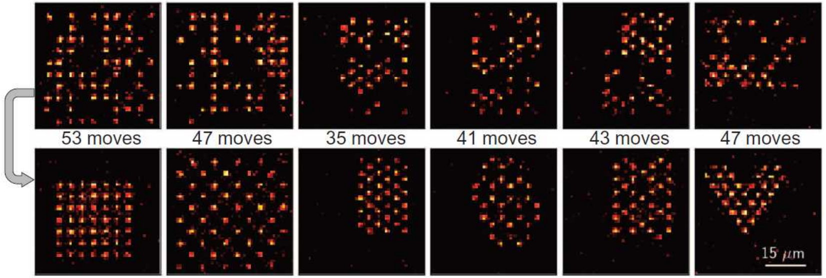
(2-atom case) $\frac{|\uparrow\uparrow\rangle + |\downarrow\downarrow\rangle}{\sqrt{2}}$



Defect-free neutral atom arrays

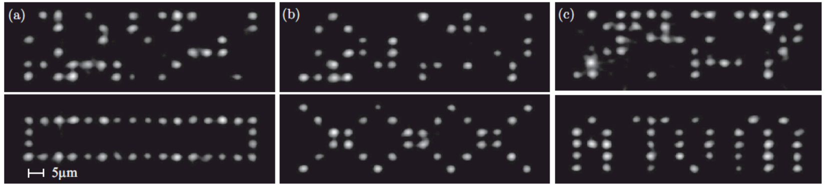
Lukin group, Harvard[1]

Browaeys group, Institut d'Optique (France)[2]



- There has been a revolution in creating defect free, controllable arrays of neutral atoms.
- 1D and 2D arrays demonstrated. 3D arrays are imminent.
- This capability makes scaling to a many qubit simulator a possibility.

Ahn Group, KAIST (South Korea)[3]

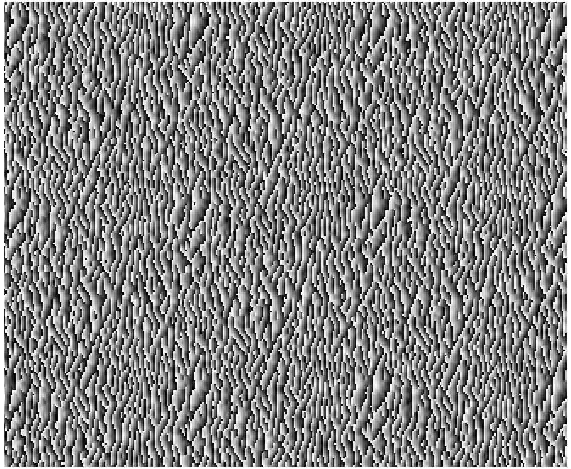


1. M. Endres et al., Science 354, 1024 (2016)
2. D. Barredo et al., Science 354, 1021 (2016)
3. W. Lee et al., Phys. Rev. A **95**, 053424 (2017)

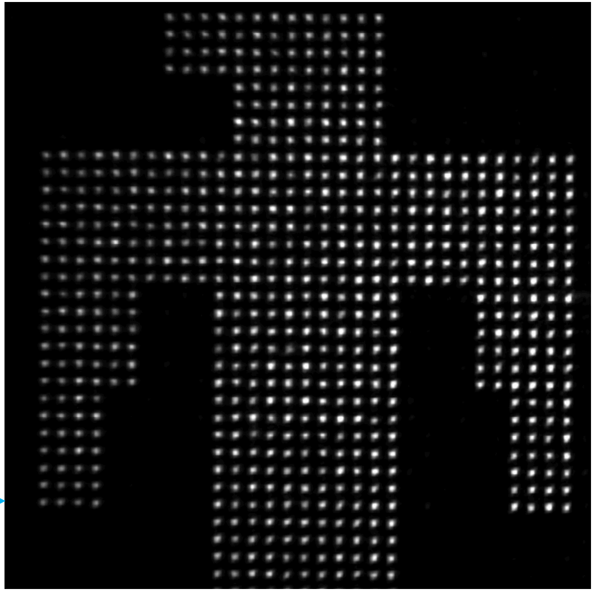
Generation and control of >500 of individual traps

Gerchberg-Saxton algorithm
With GPU compute acceleration
(~50 Hz hologram calculation)

Phase to SLM

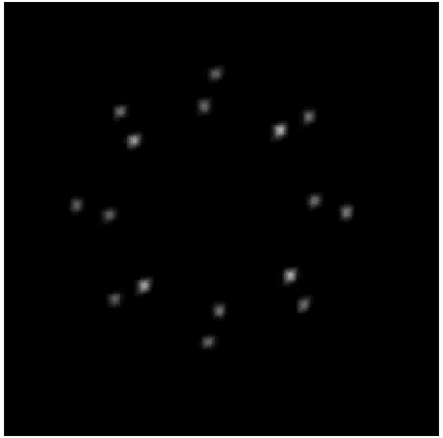


Intensity profile (measured)

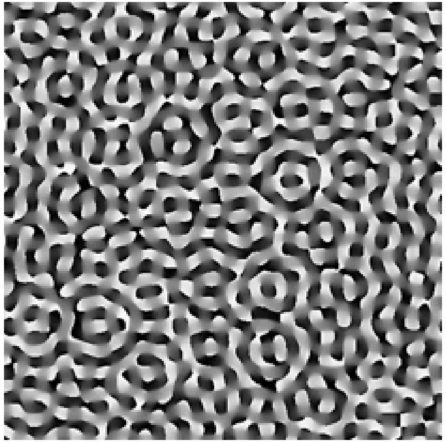


Dynamic control of hologram-generated traps

30 fps, real time

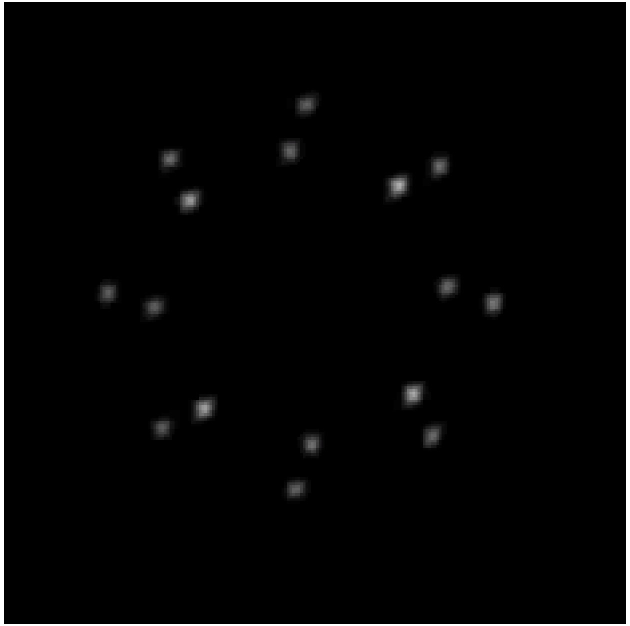


Phase hologram



Dynamic control of hologram-generated traps

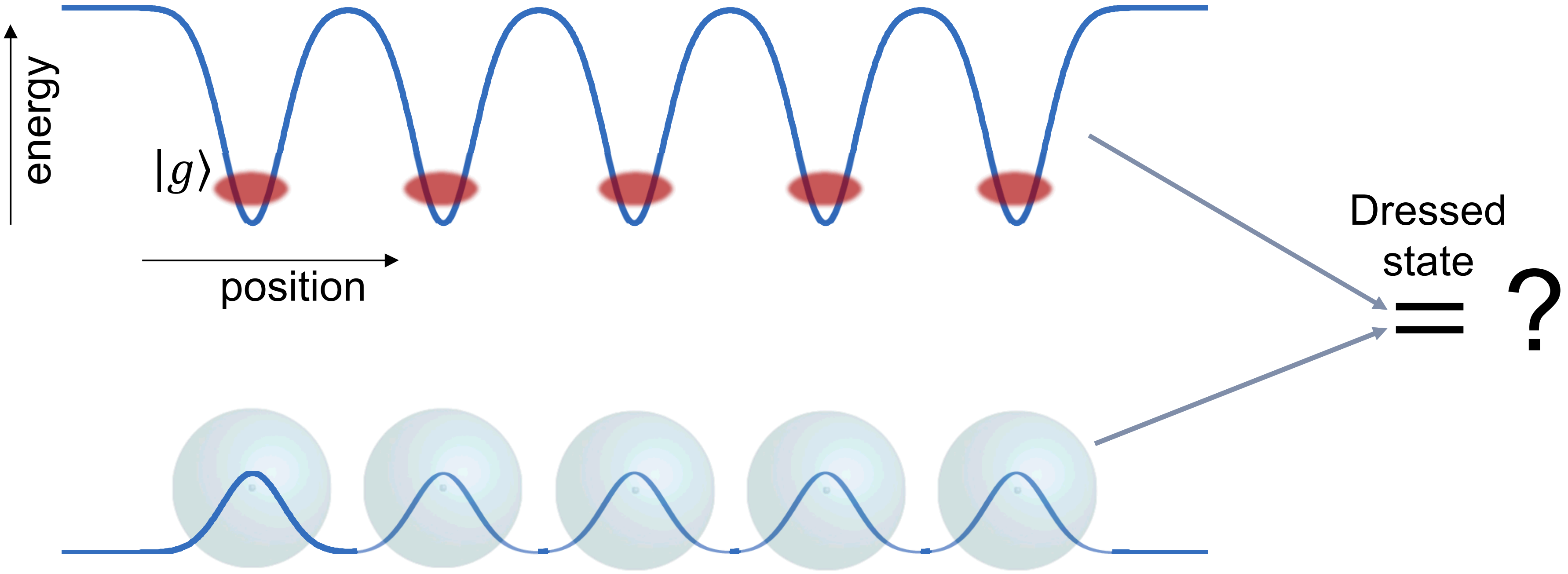
500 fps



-Optimize techniques for calculating hologram with as little phase discontinuity between frames as possible.

Trapping Rydberg-Dressed atoms

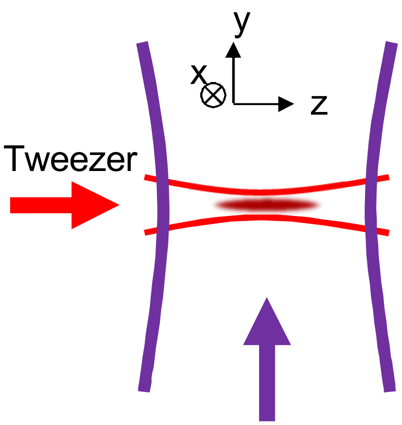
Ground state atoms in optical tweezers: Attractive potential

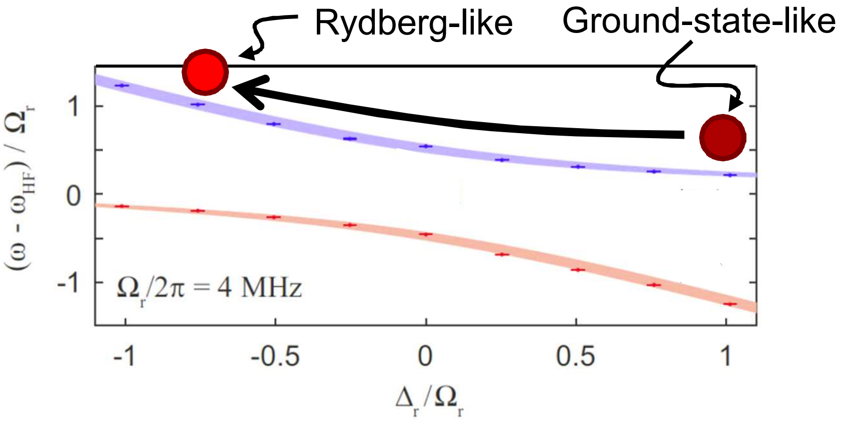


Rydberg state atoms in optical tweezers: Repulsive potential

Preparing a trapped, dressed-state

- Sweep Rydberg laser frequency and amplitude to prepare dressed, trapped final state.

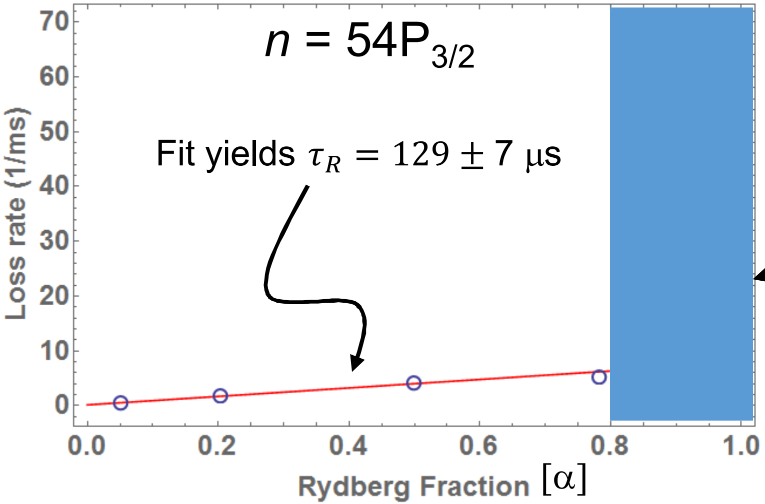




Test lifetime of dressed state in trap

Long-lived & trapped, Rydberg-dressed states

- loss rate depends linearly on Rydberg admixture
- consistent with theoretical Rydberg state lifetime of 121 μs



Trap distortion allows atoms to stay trapped by shifting distribution away from dressing beam, leading to lower actual Rydberg fraction than depicted in this region.

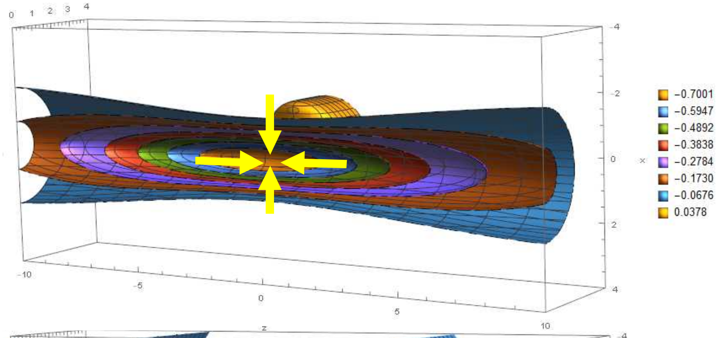
Combined potential

$\alpha \to 1$

$\alpha = 0$

Equipotential surfaces for the blue sideband for different dressing conditions.

Sandia National Laboratories



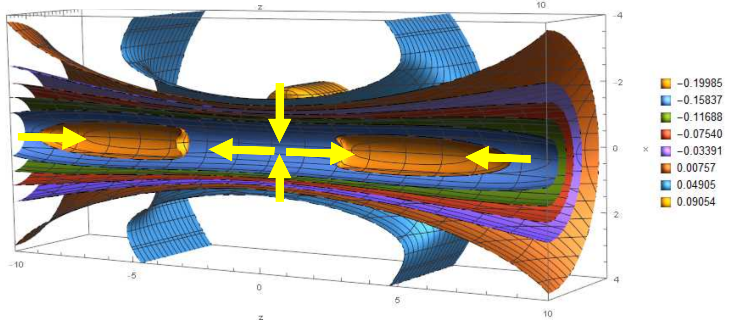
Rydberg Rabi freq. $\Omega_R = 2.2$ MHz

Bare trap depth $U_0 = 5$ MHz

$\Delta/\Omega_R = 0$

50% Rydberg admixture at trap center

Center is stable minimum.



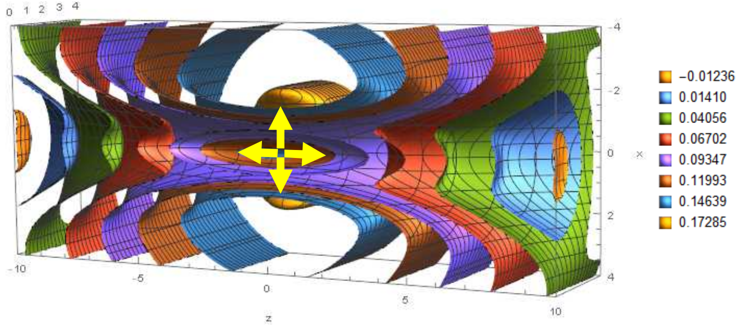
Rydberg Rabi freq. $\Omega_R = 2.2$ MHz

Bare trap depth $U_0 = 5$ MHz

$\Delta/\Omega_R = -1.75$

93% Rydberg admixture at trap center

Center is not stable minimum.
Trap closed.



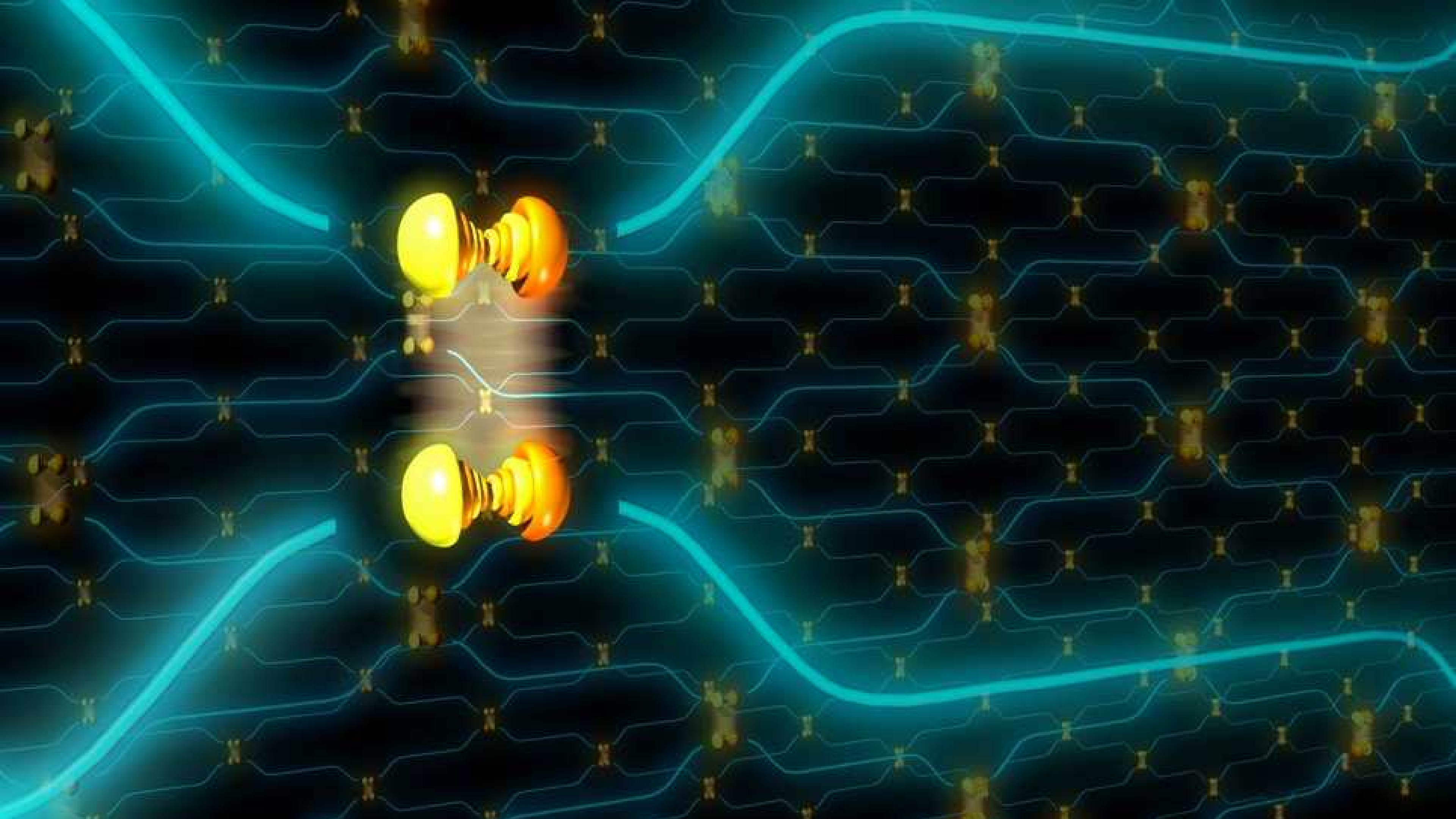
Rydberg Rabi freq. $\Omega_R = 2.2$ MHz

Bare trap depth $U_0 = 5$ MHz

$\Delta/\Omega_R = -2.5$

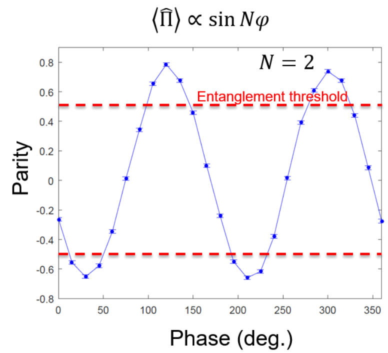
96% Rydberg admixture at trap center

Center is not stable minimum.
Trap open.

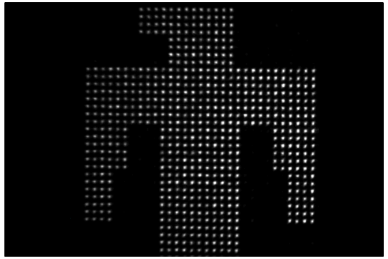


Recap

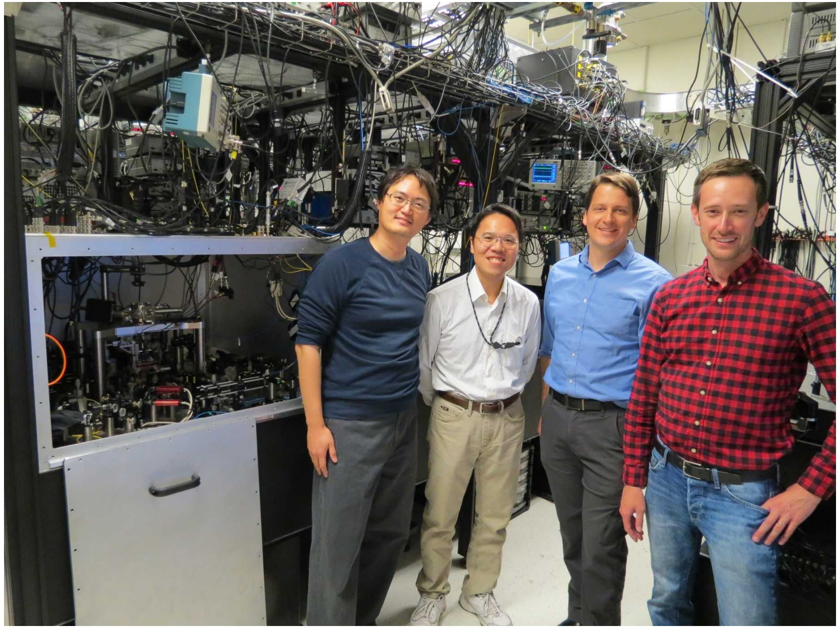
- Demonstrated both spin-flip and CPHASE gates between two Rydberg-dressed hyperfine qubits.
  - CPHASE functionality will permit useful quantum operations between atoms.
  - Tracking down systematic effects!



- Single-photon Rydberg dressing opens up possibilities for large-scale entanglement and quantum simulation.
  - Work towards larger systems is ongoing.



Sandia Rydberg Team



Sandia mountains viewed from the Rio Grande near Albuquerque, New Mexico

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