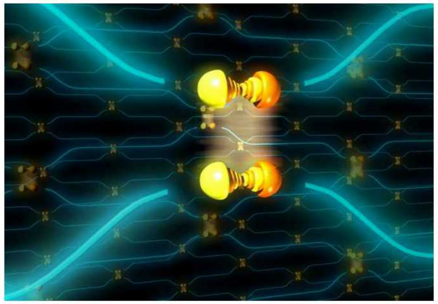
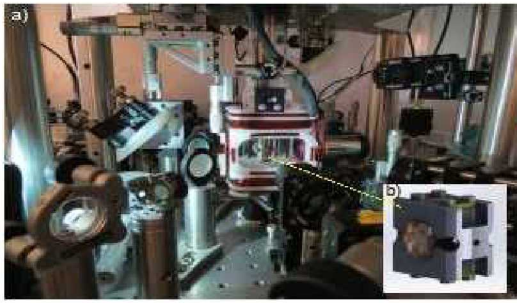
SAND2018-4886PE

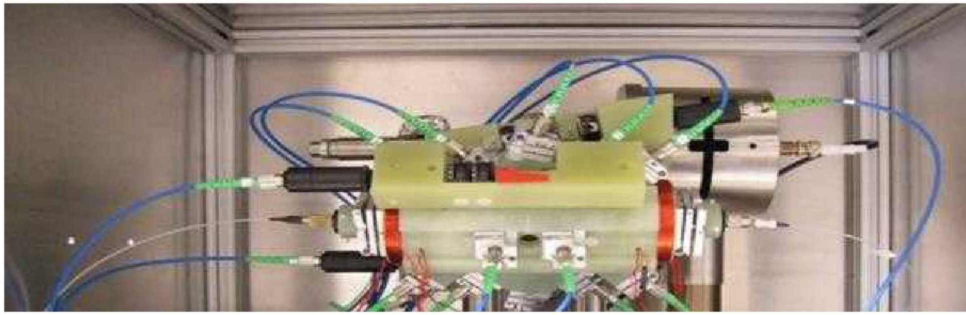
Collaborating with CQuIC

Grant Biedermann

University of New Mexico
May 7, 2018







UNM CQuIC

LDRD
Laboratory Directed Research and Development

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

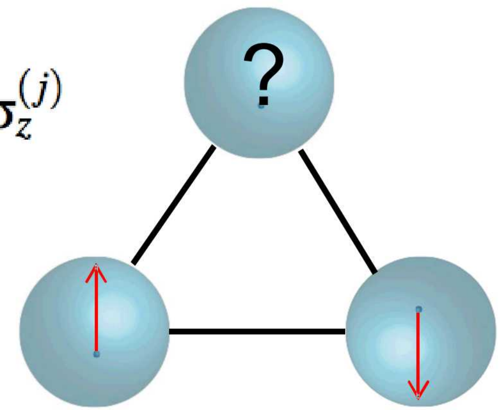
U.S. DEPARTMENT OF ENERGY   NNSA National Nuclear Security Administration

SAND2018-XXXXX

Applications

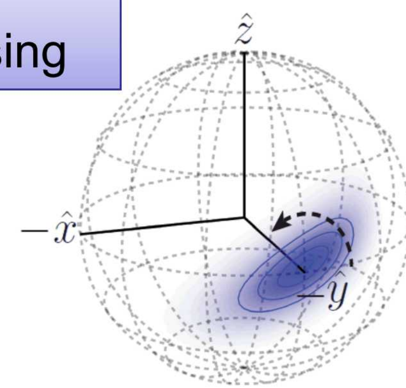
Quantum simulation

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



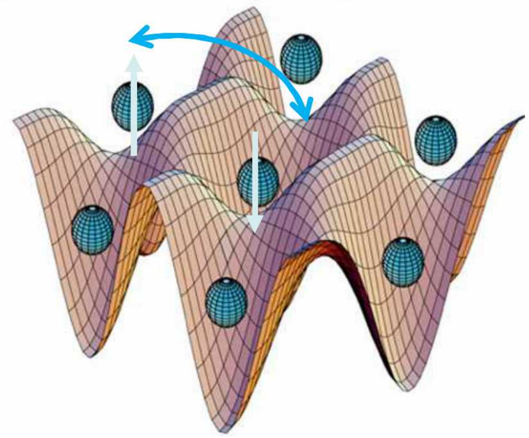
Frustrated magnetism

arge-scale/rapid
ntanglement for sensing



Interaction between *neutral* atoms

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



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

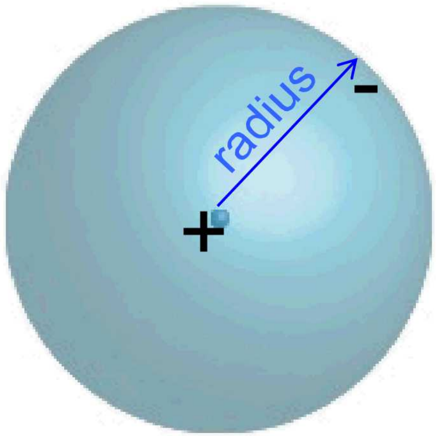
One solution: use Rydberg states

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

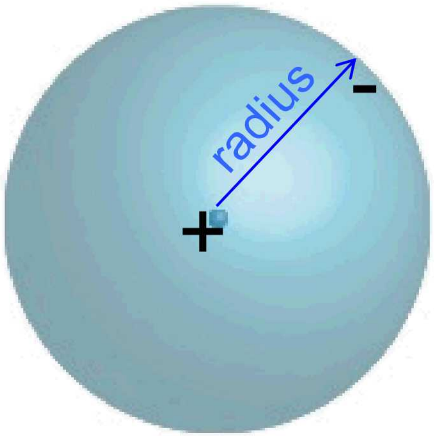
I. Bloch, J. Dalibard, and S. Nascimbène, Nat. Phys. **8**, 267-276 (2012)

Interaction between *neutral* atoms

Valence electron in Rydberg state



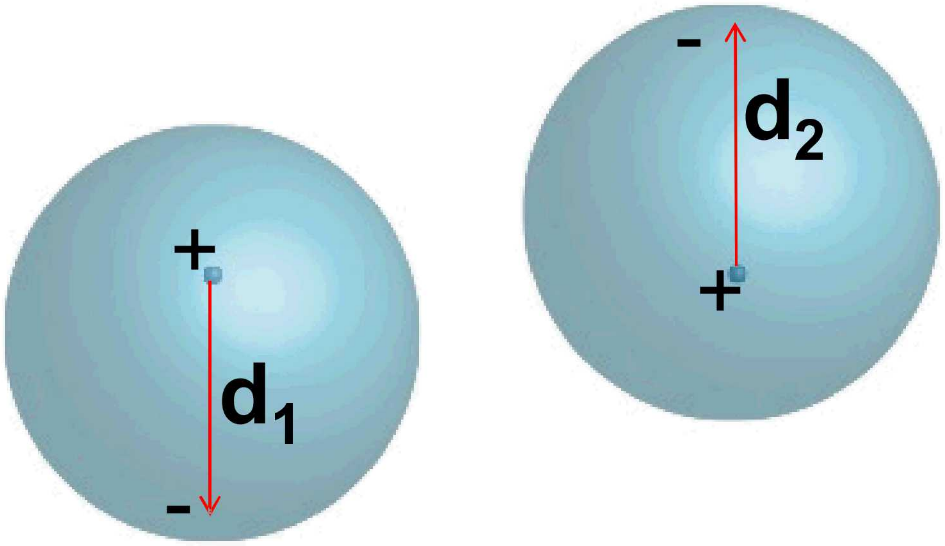
Valence electron in Rydberg state



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

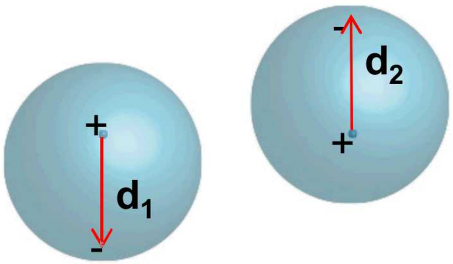
$\alpha(0) \propto n^7$

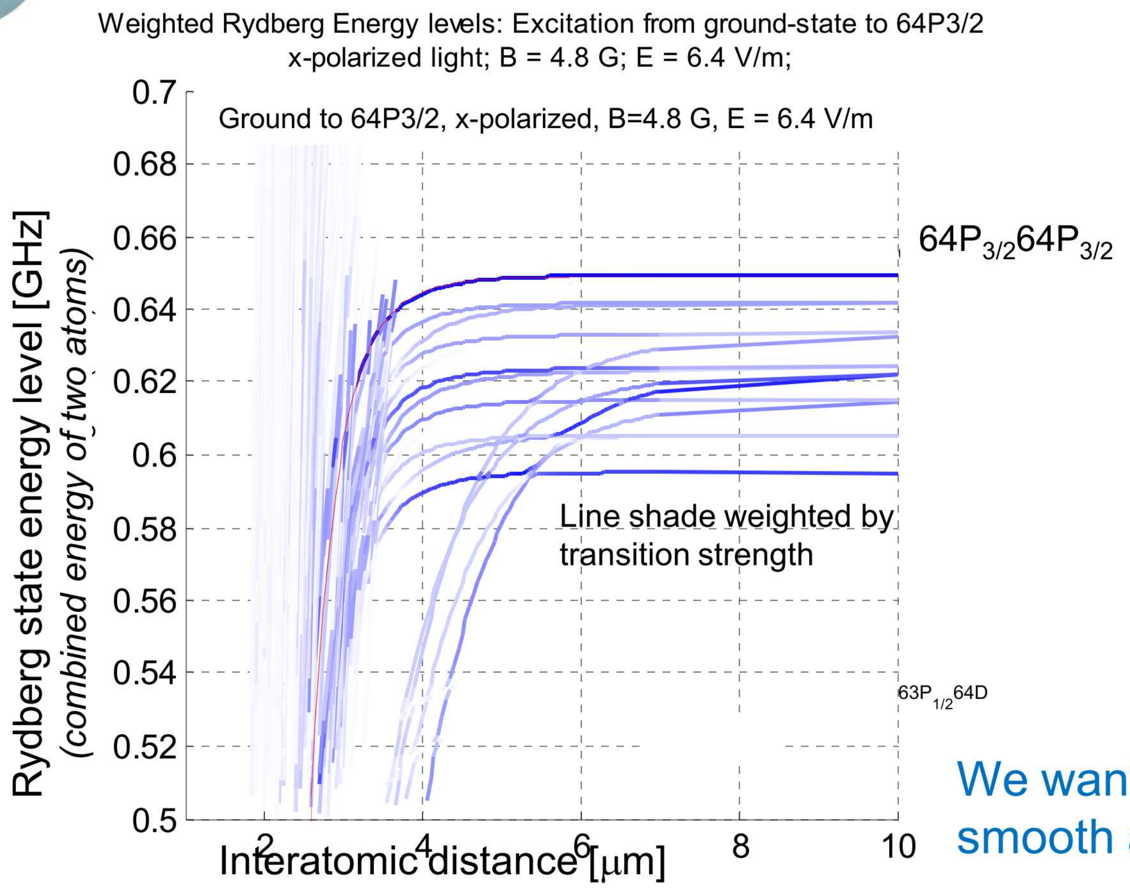
- Even the presence of another atom can cause a massive response >> 10 MHz
- Induced Electric Dipole-Dipole Interaction $\propto 1/r^6$

Entanglement demonstrations

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

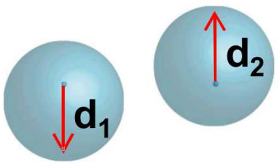
Rydberg blockade—the nitty gritty

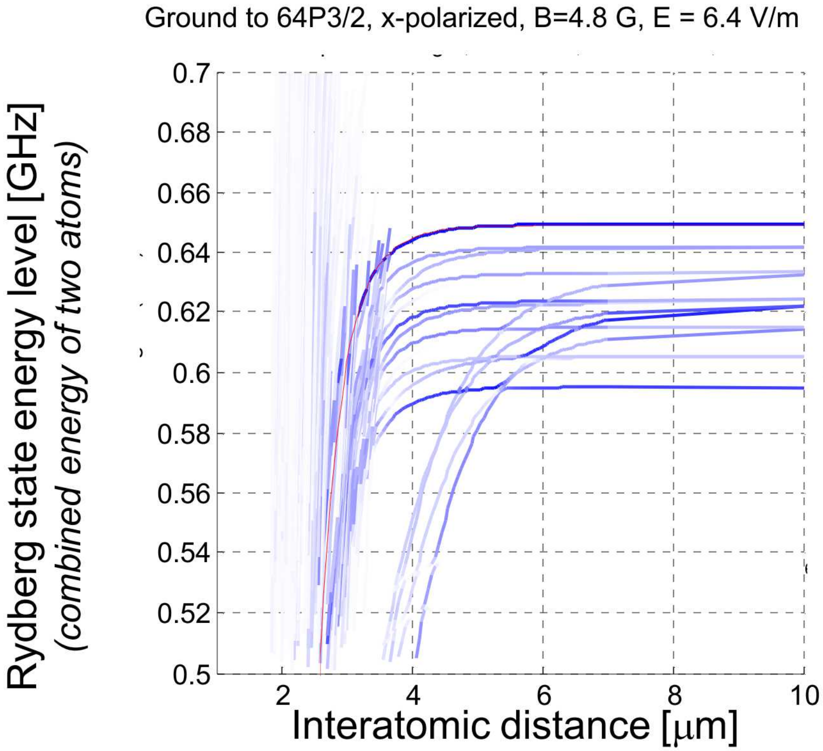


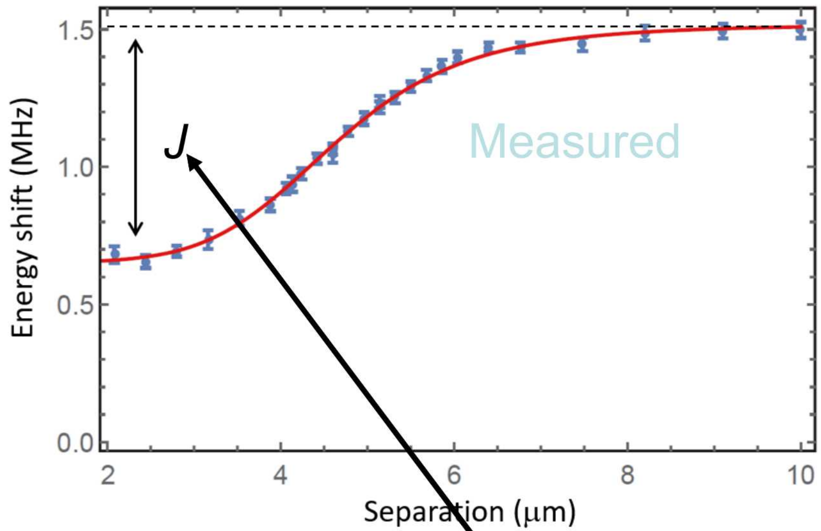


We want something smooth and tunable

Direct Rydberg → Rydberg-Dressed

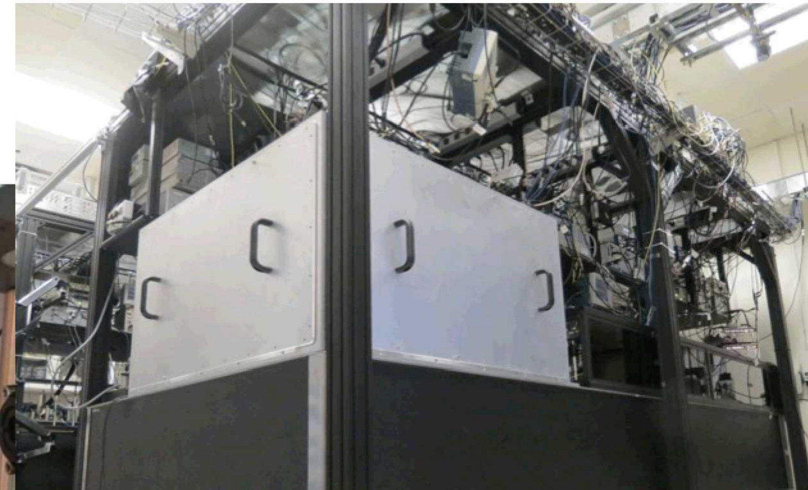


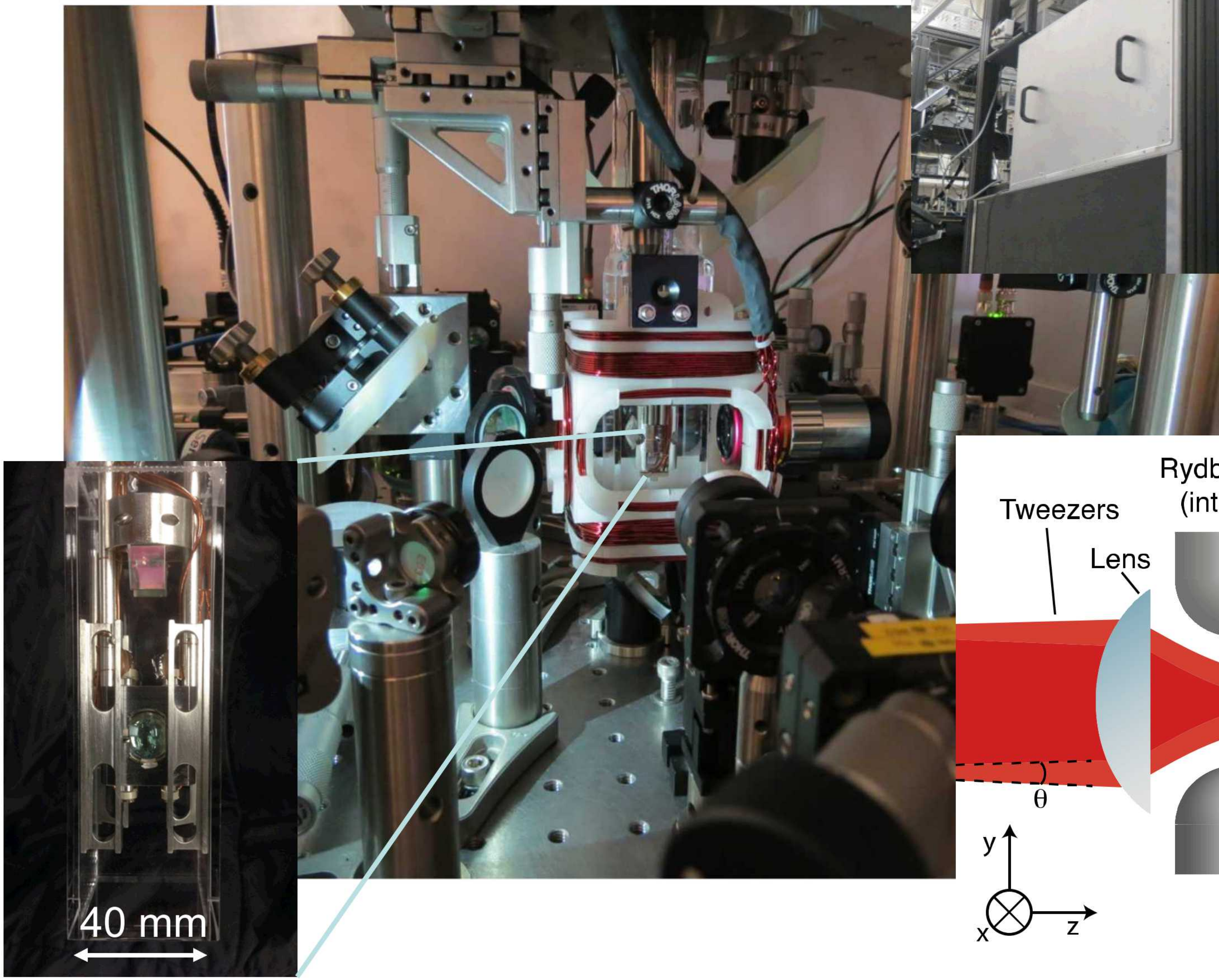


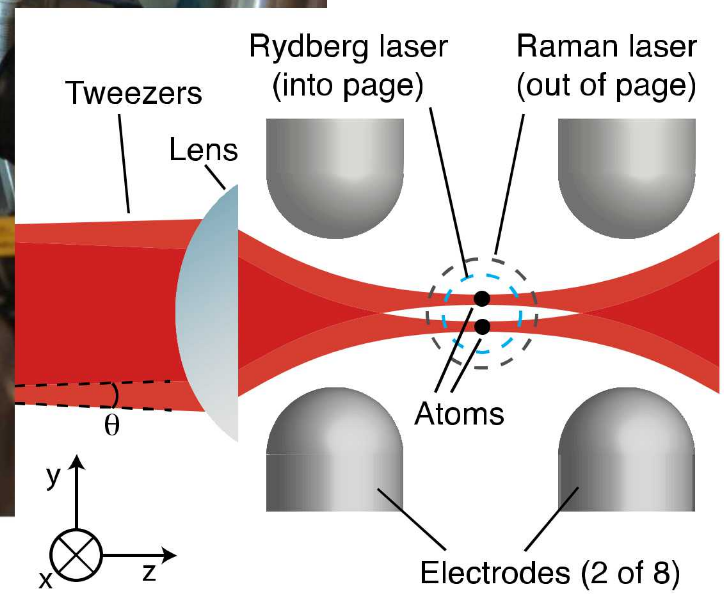


$$H_P = \sum_{i=1}^{N} \tilde{h}_i \sigma_z^{(i)} + \sum_{i,j=1}^{N} \tilde{J}_{ij} \sigma_z^{(i)} \otimes \sigma_z^{(j)}$$

Apparatus

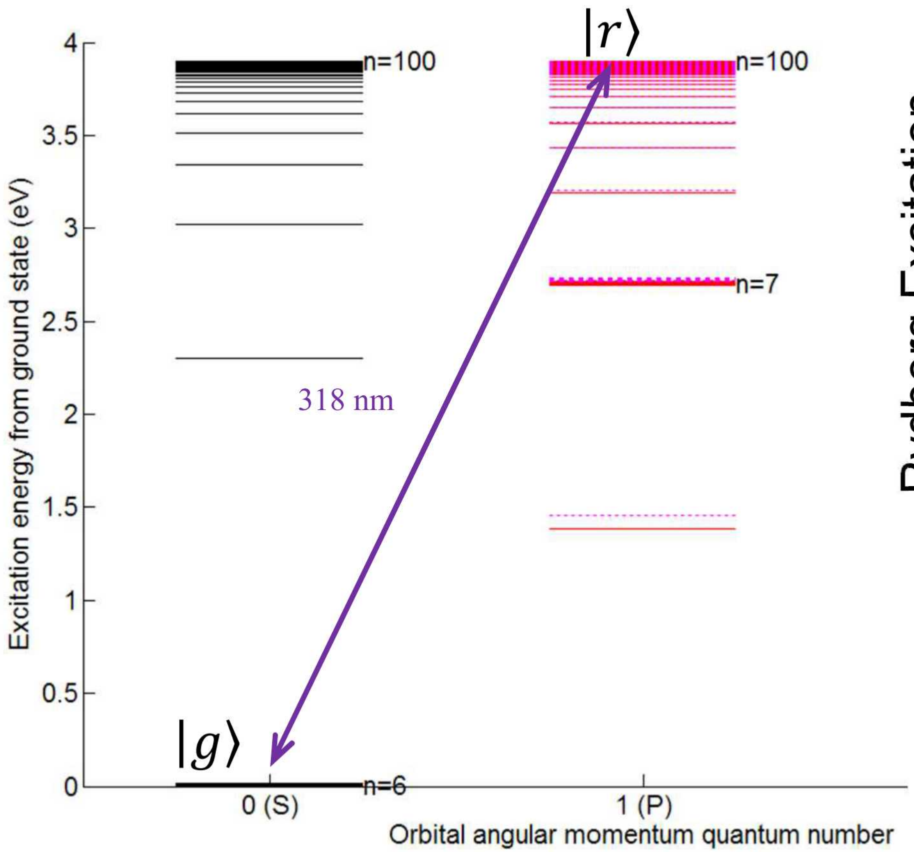


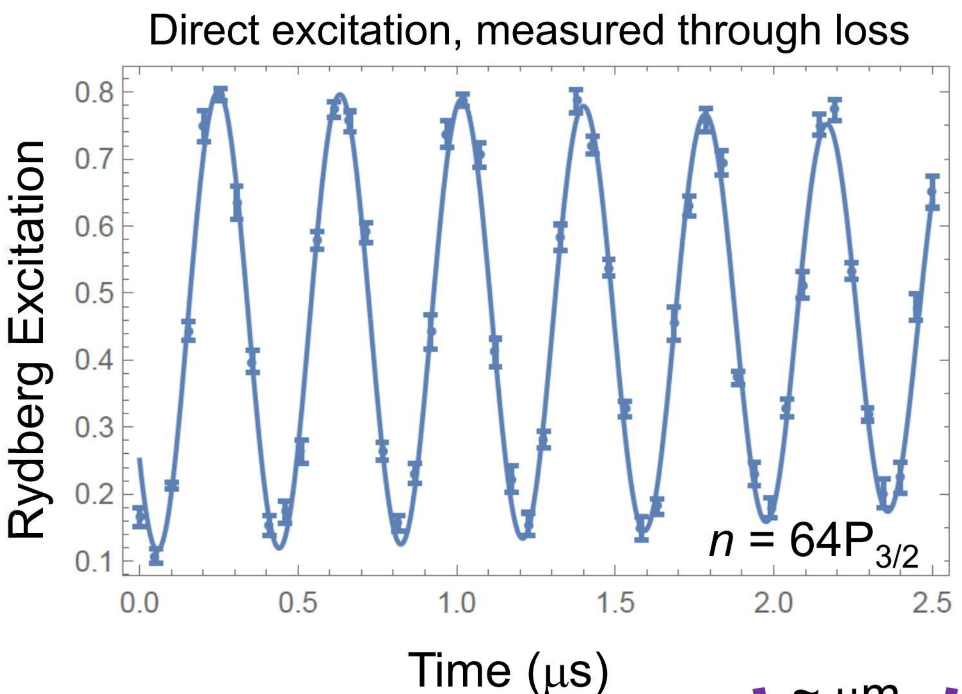


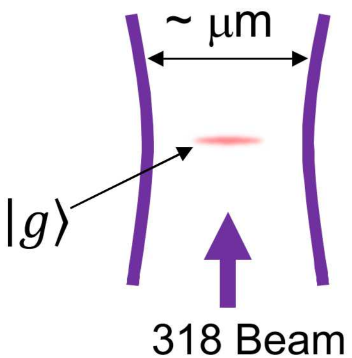


J. Lee, G.B., I.D., *et al.*,Phys. Rev. A. **95**, 041801(R), (2017)

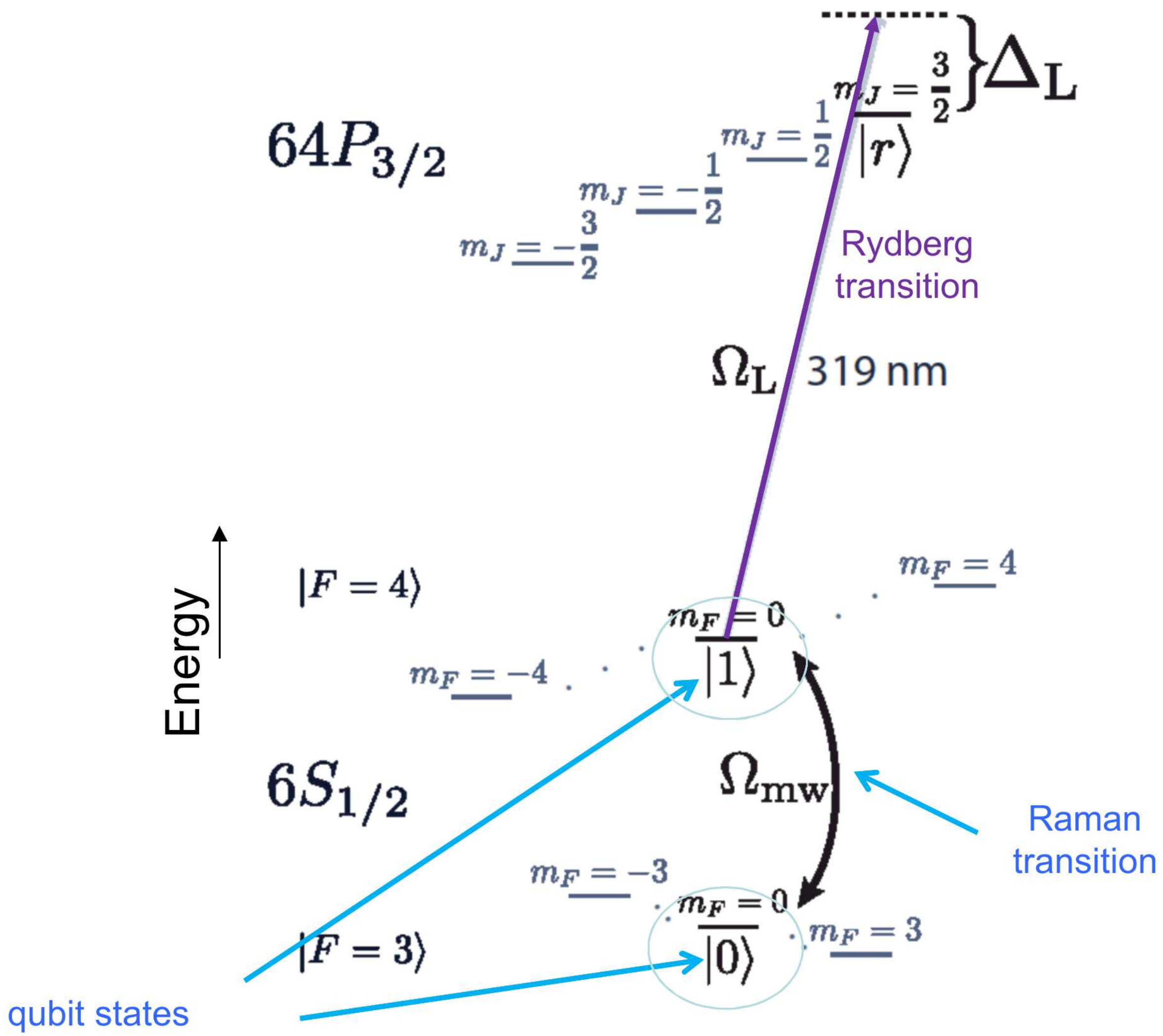
Rydberg Rabi flopping with 318 nm laser



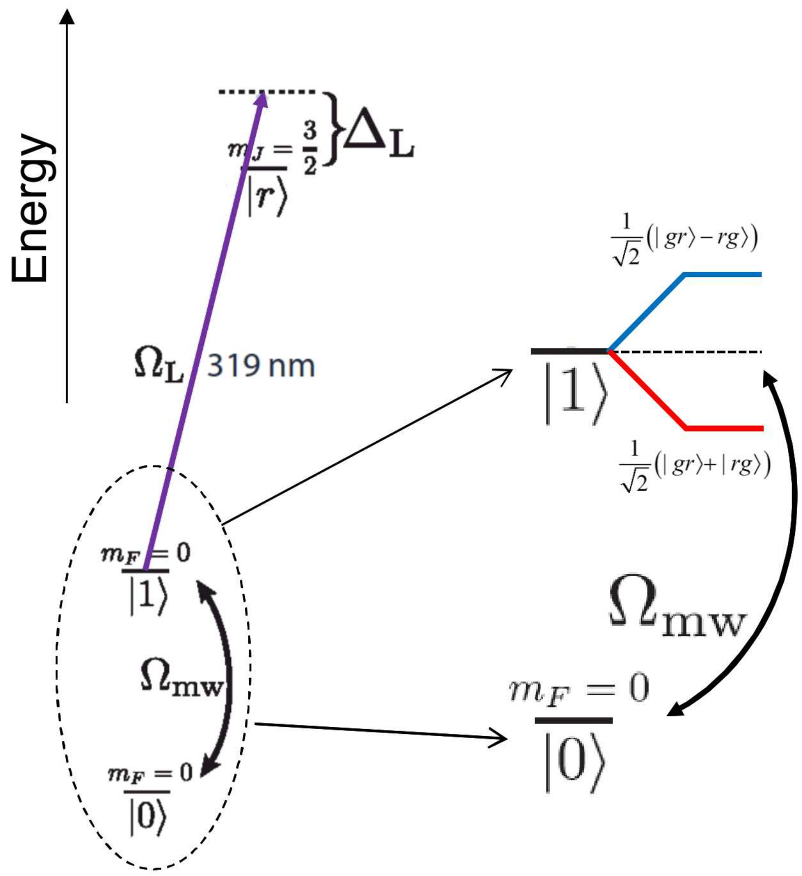




Creating Rydberg-Dressed states



Creating Rydberg-Dressed states

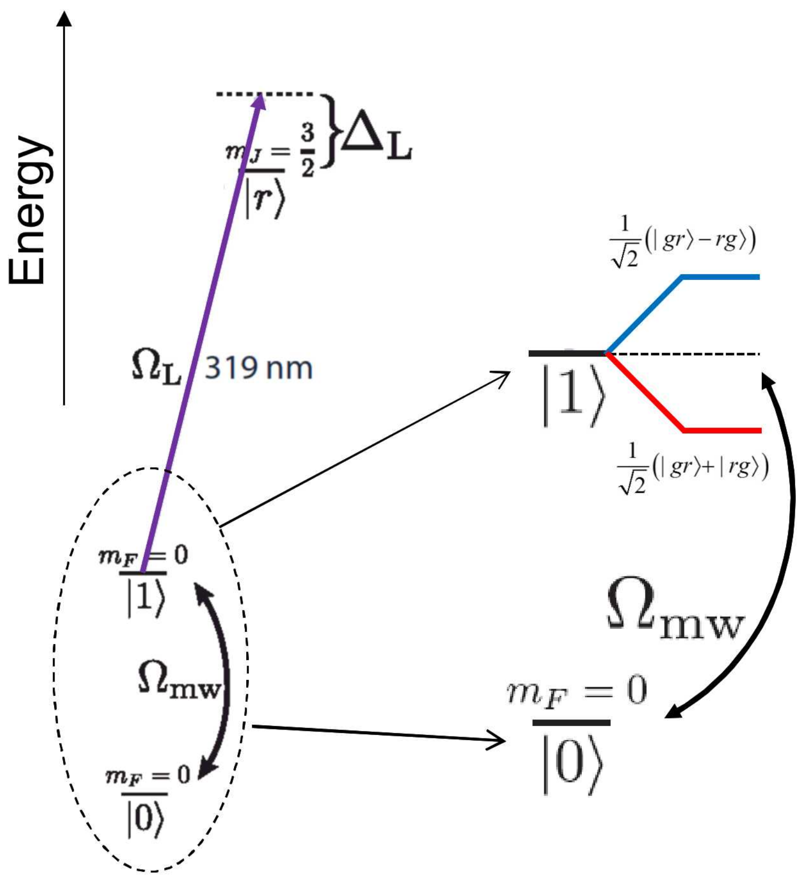


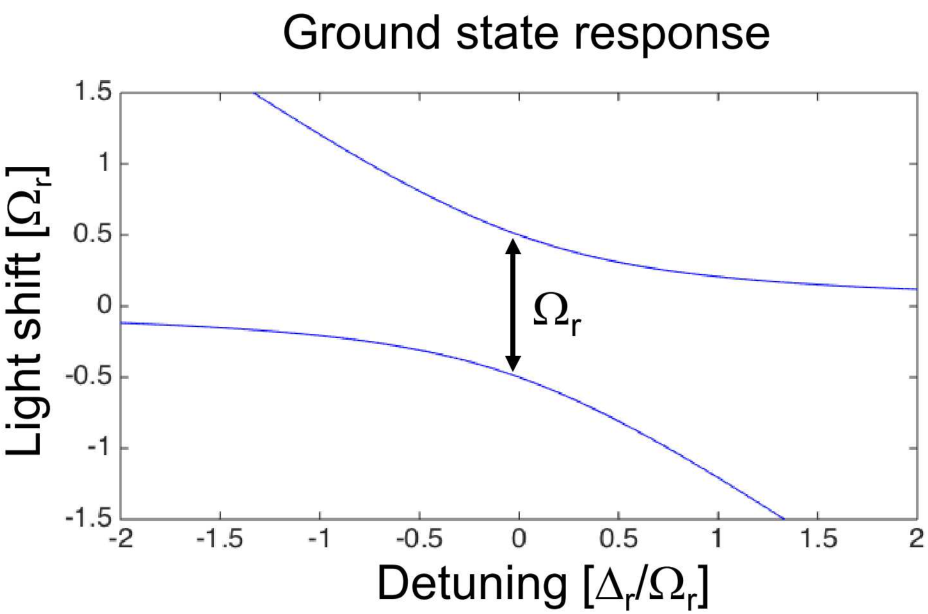
Light-shift Hamiltonian

$$H = \frac{\hbar}{2}\begin{pmatrix} -2\Delta_L & \Omega_L \\ \Omega_L & 0 \end{pmatrix}$$

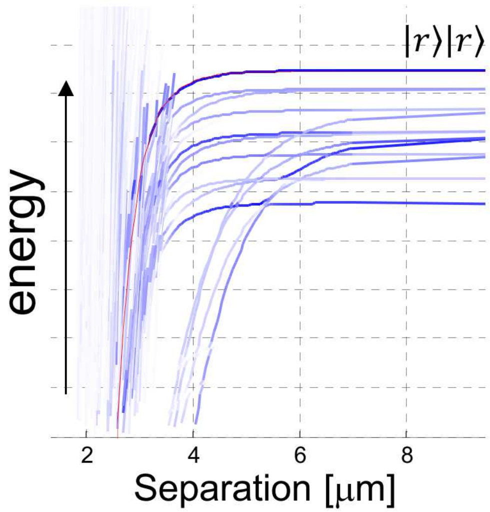
$$\Delta = \frac{\hbar\, \Omega_L^2}{4\, \Delta_L}$$

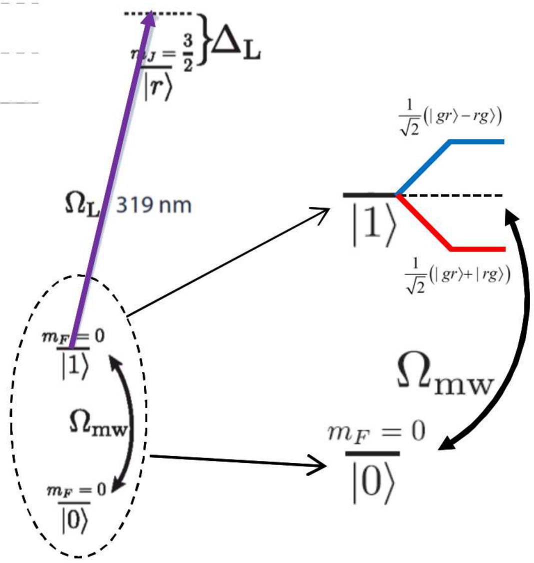
Creating Rydberg-Dressed states

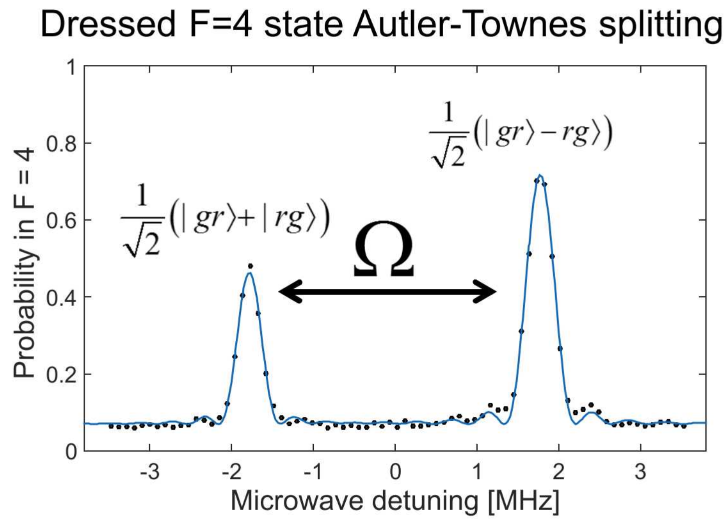


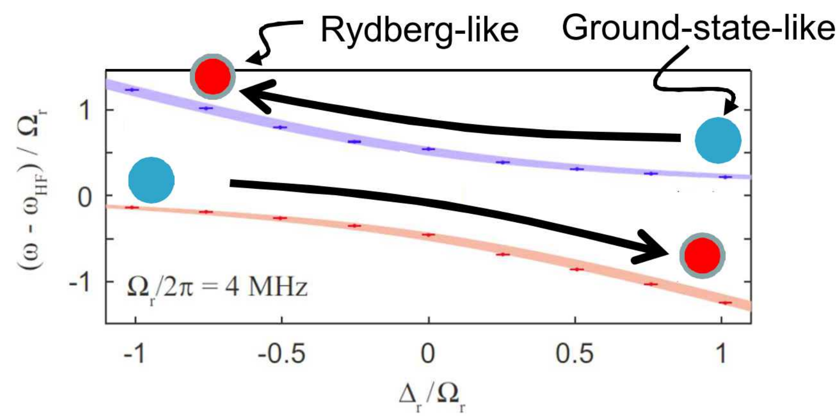


1-atom Rydberg-dressed states

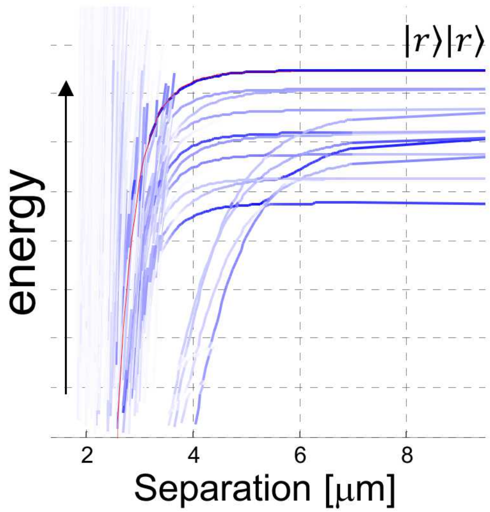


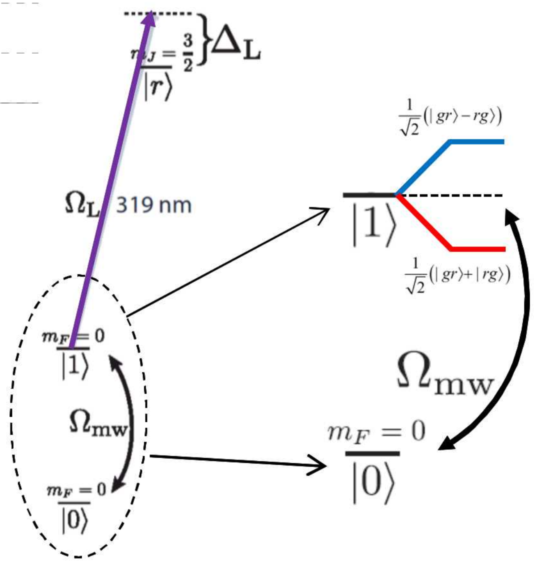


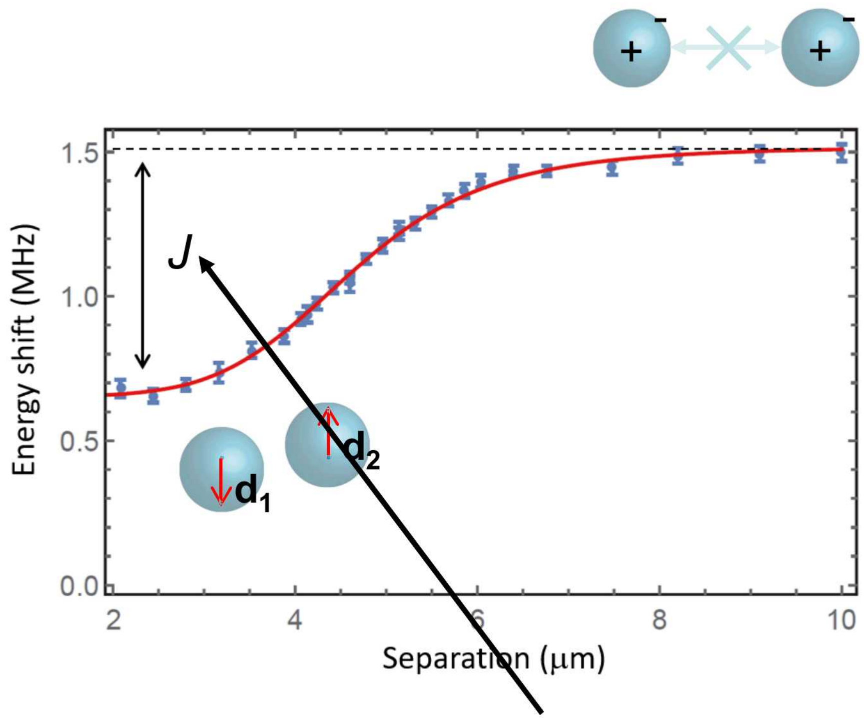




Rydberg-Dressed interaction

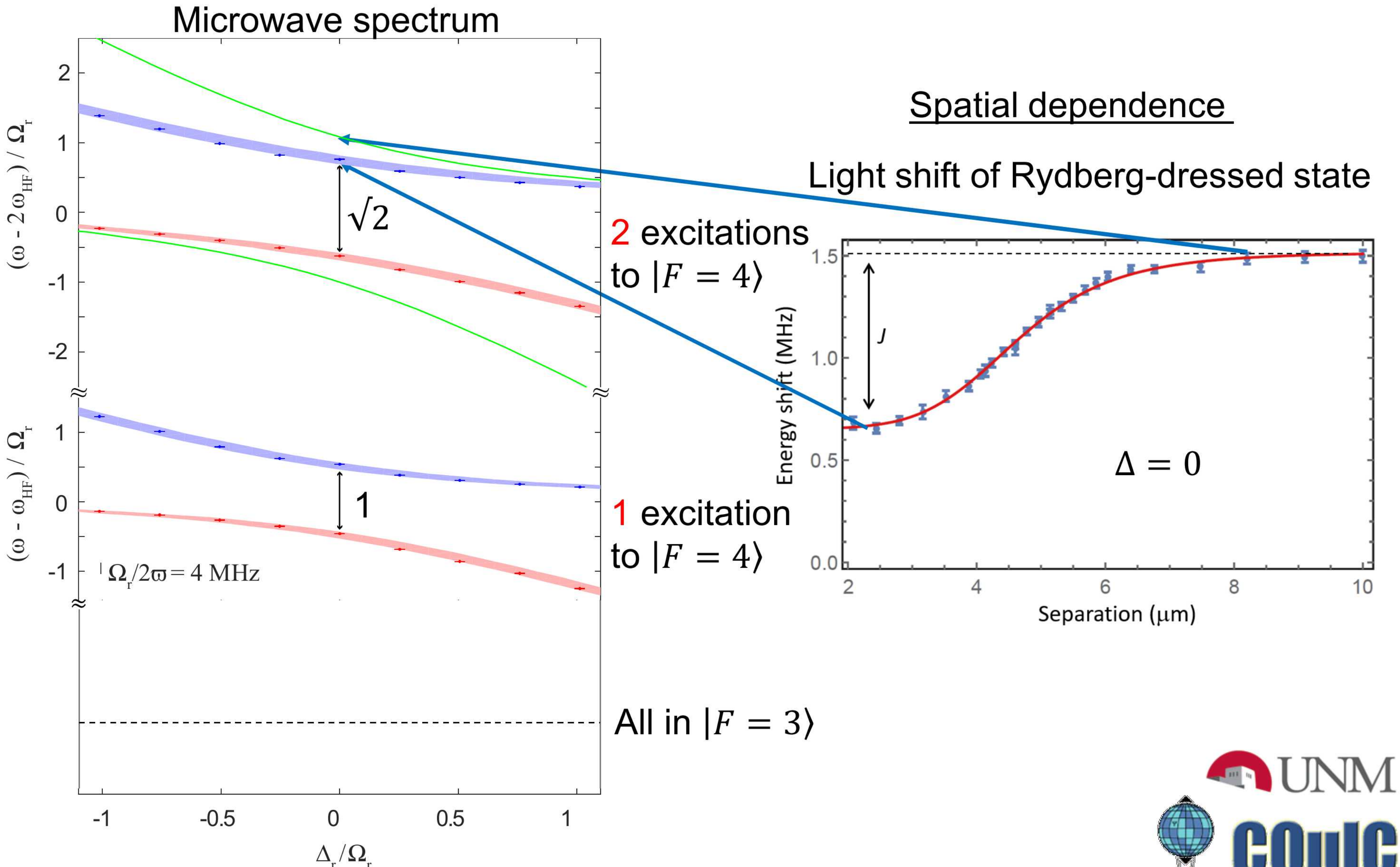






$$H_P = \sum_{i=1}^{N} \tilde{h}_i \sigma_z^{(i)} + \sum_{i,j=1}^{N} \tilde{J}_{ij} \sigma_z^{(i)} \otimes \sigma_z^{(j)}$$

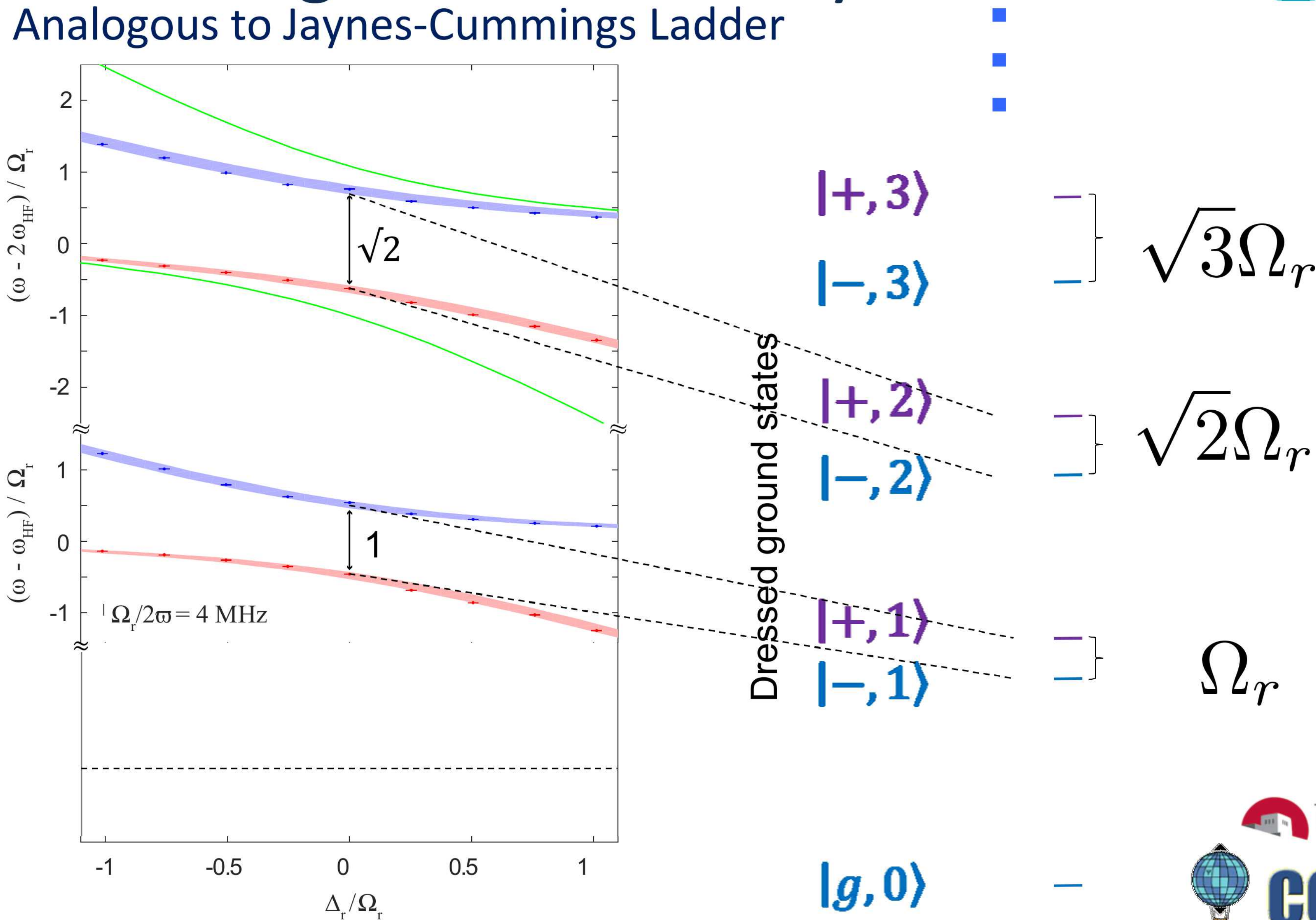
2-atom Rydberg-dressed states



J. Lee, G.B., I.D., *et al.*,Phys. Rev. A. **95**, 041801(R), (2017)

Extending to N atoms—symmetric

Analogous to Jaynes-Cummings Ladder

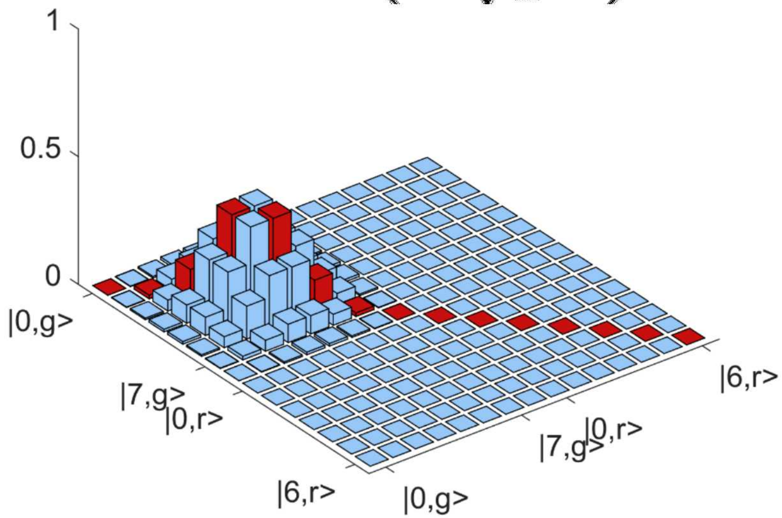


Sample Control Task

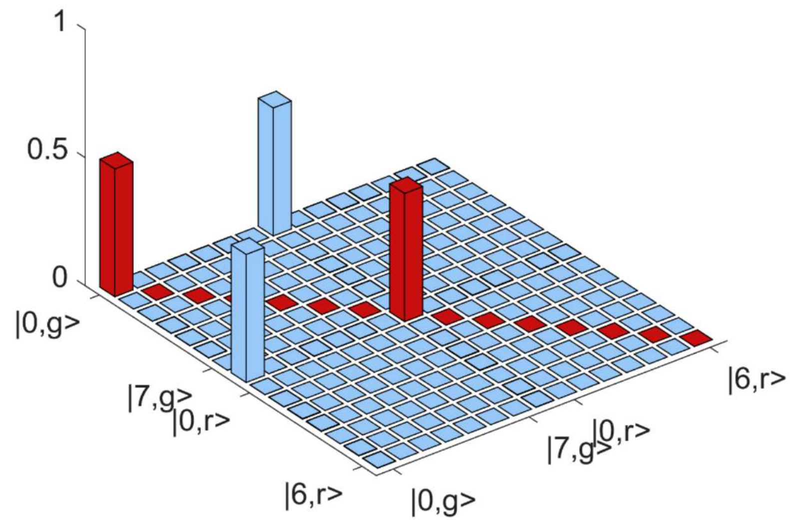
- Create a 7-atom cat state:

$$2\pi * \Omega_r = 5 \text{ MHz}$$
$$2\pi * \delta_r = -2.5 \text{ MHz}$$
$$2\pi * \kappa \approx 600 \text{ kHz}$$

$$\rho_{in} = \left(\frac{|0\rangle + |1\rangle}{\sqrt{2}}\right)^{\otimes 7}$$



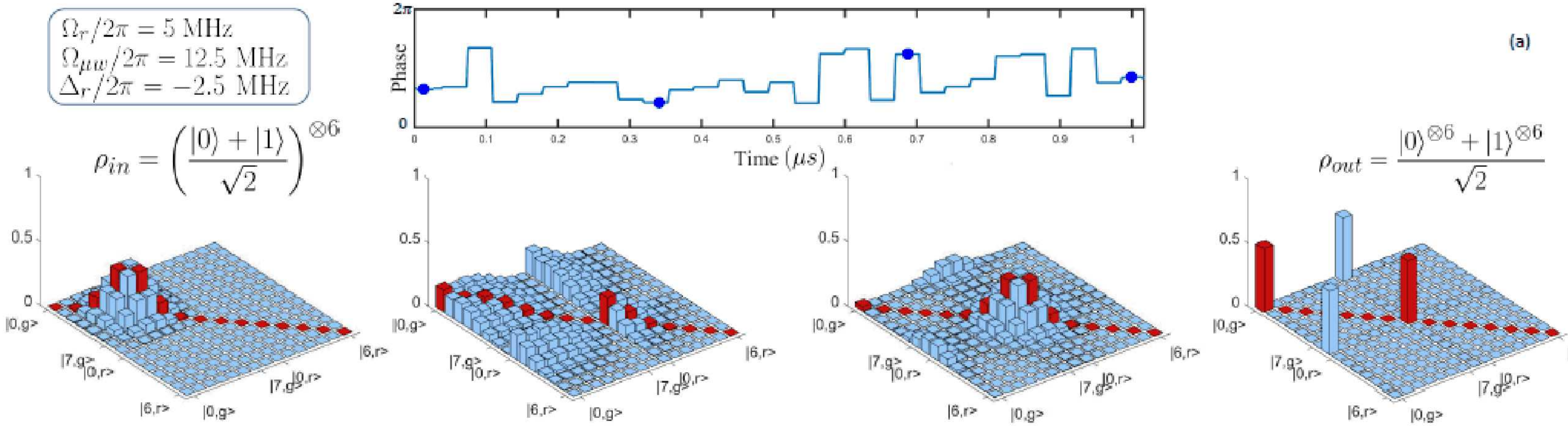
$$\rho_{out} = \frac{|0\rangle^{\otimes 7} + |1\rangle^{\otimes 7}}{\sqrt{2}}$$



- Find the sequence of microwave phases that does this with maximum fidelity

Arbitrary control

T. Keating *et al.*, Phys. Rev. Lett **117**, 213601 (2016)



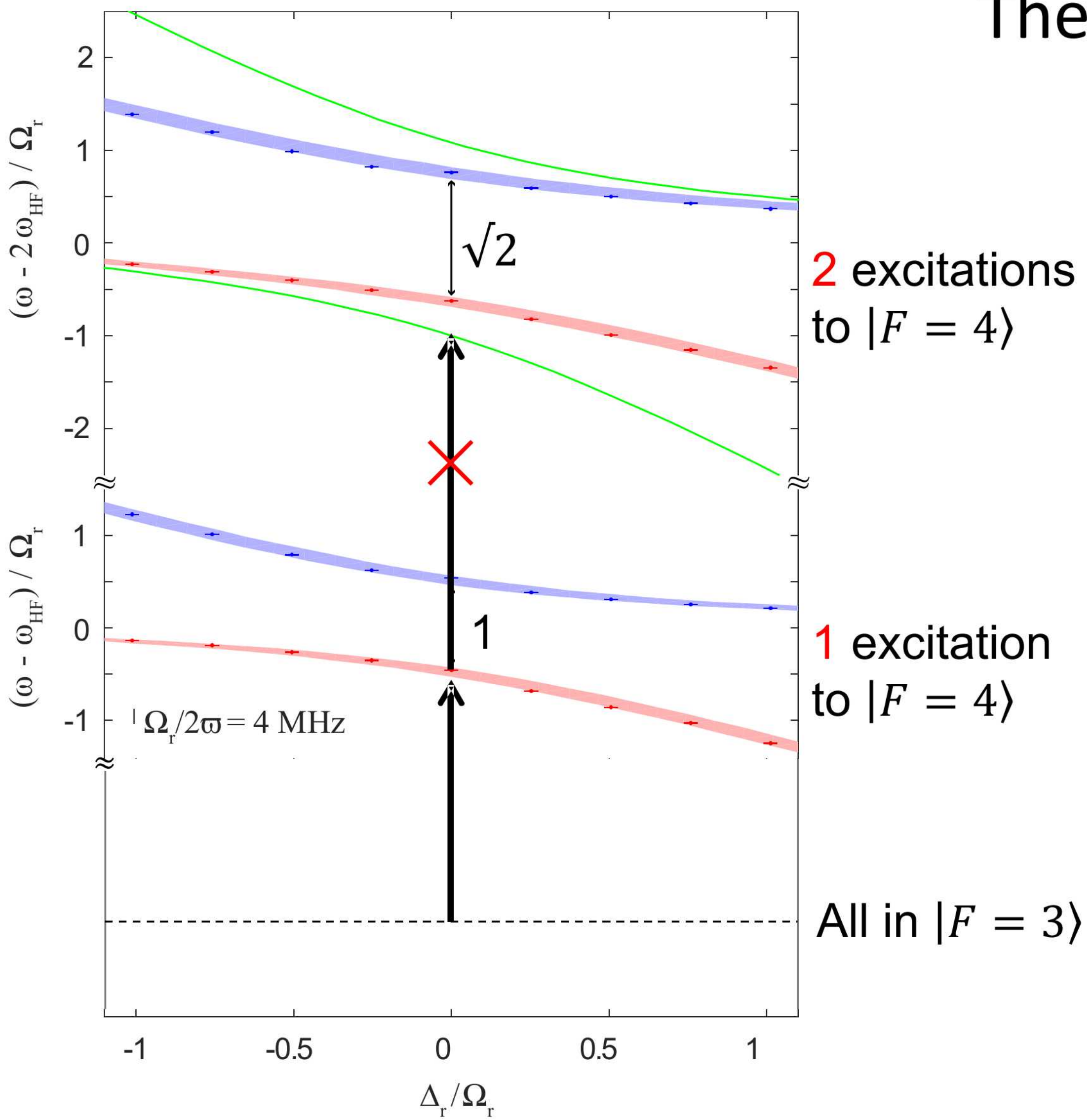
$$\hat{H}_c[\phi_{\mu w}(t)] = \frac{\hbar\Omega_{\mu w}}{2}\sum_{i=1}^{N}\left(e^{-i\phi_{\mu w}(t)}|1\rangle_i\langle 0| + e^{+i\phi_{\mu w}(t)}|0\rangle_i\langle 1|\right) = \hbar\Omega_{\mu w}(\cos[\phi_{\mu w}(t)]\hat{J}_x + \sin[\phi_{\mu w}(t)]\hat{J}_y)$$

control
$\phi_{\mu w}(t)$

The nonlinearity of the JCM, together with externally applied fields makes the system fully controllable on the symmetric Dicke space; we can generate an arbitrary superposition state.

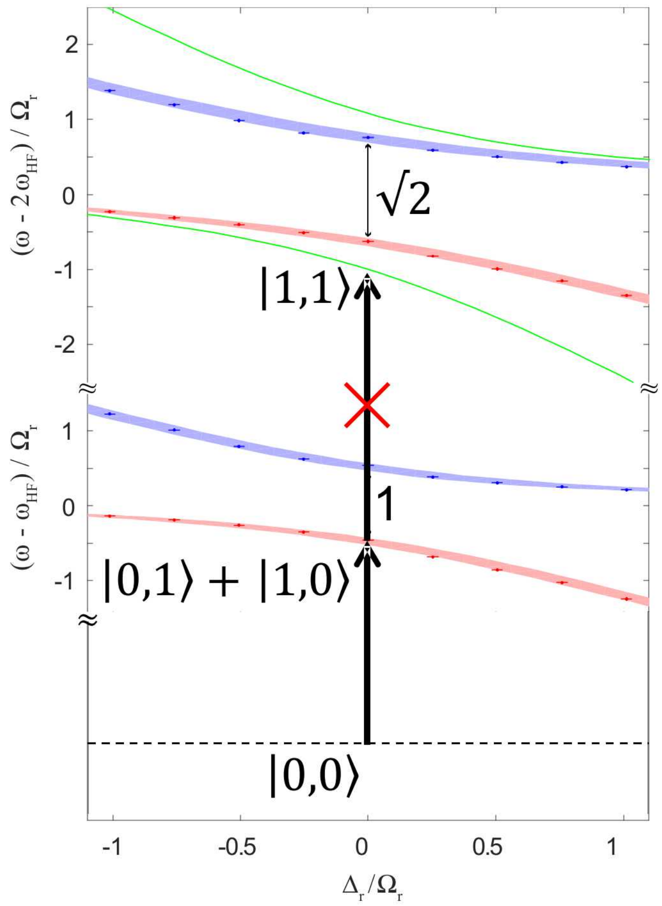
Creating entanglement with a single step

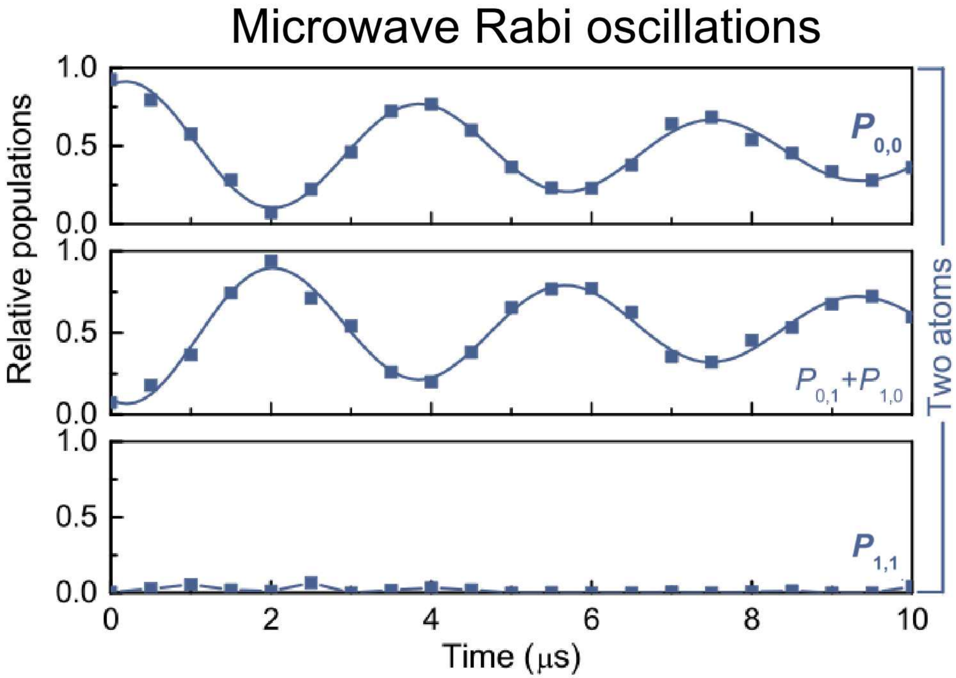
The “spin-flip blockade”



Creating entanglement with a single step

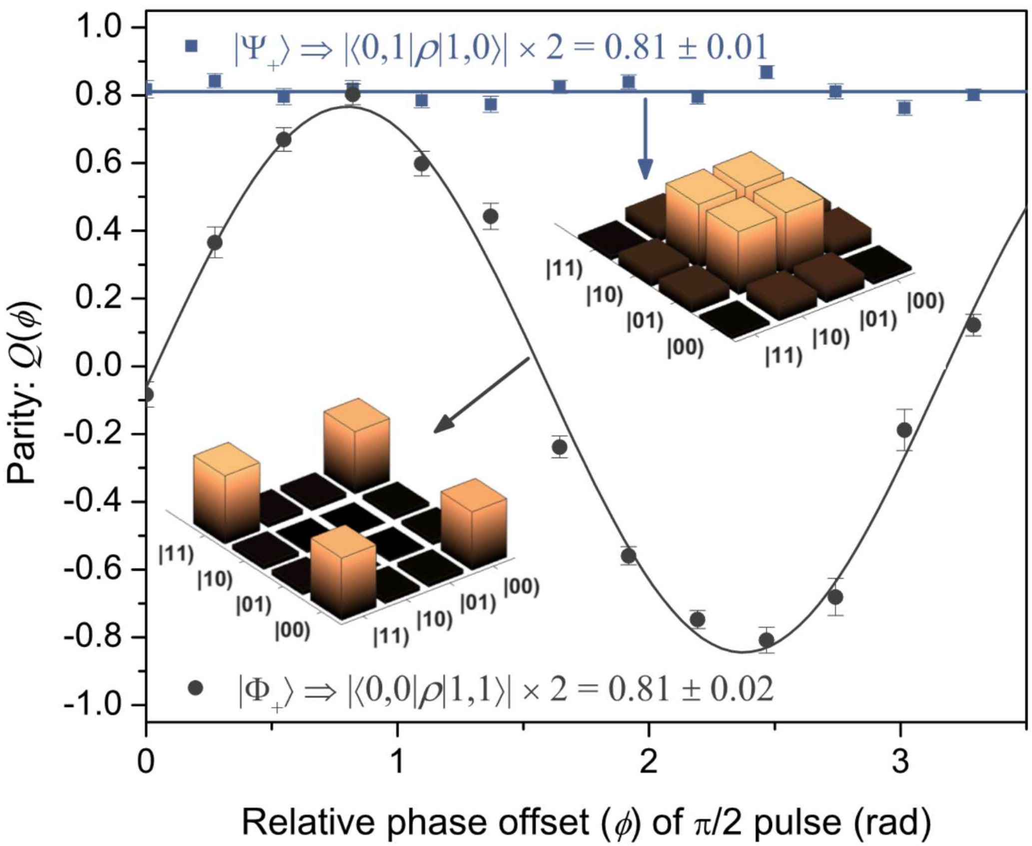
The "spin-flip blockade"





Spin-flip blockade

Verify the entanglement via parity measurements



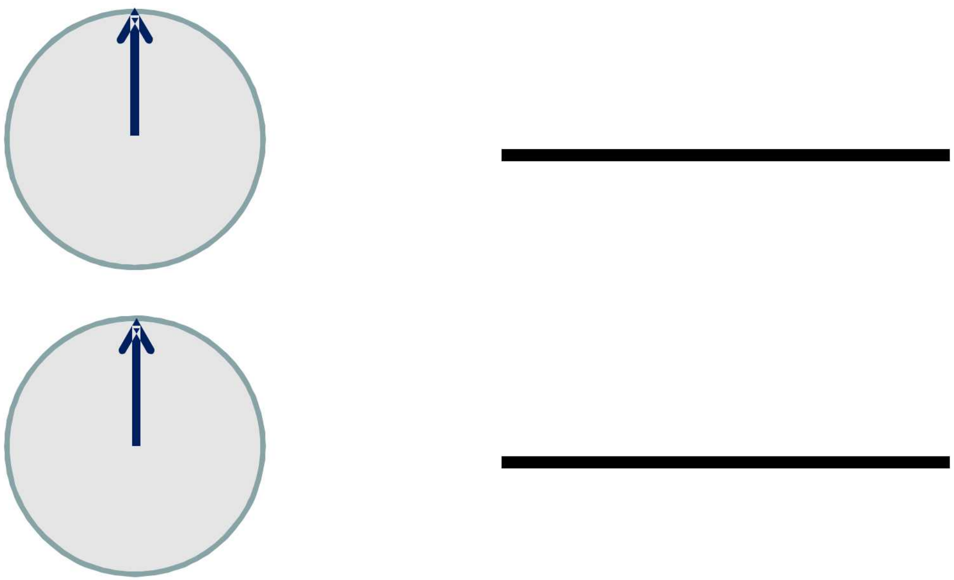
1. Prepare Bell state
2. Apply global $\pi/2$ with given phase
3. Measure parity Q
4. Obtain bound on fidelity =0.81(2)

Generating Entanglement

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

Phase:

Laser ON OFF

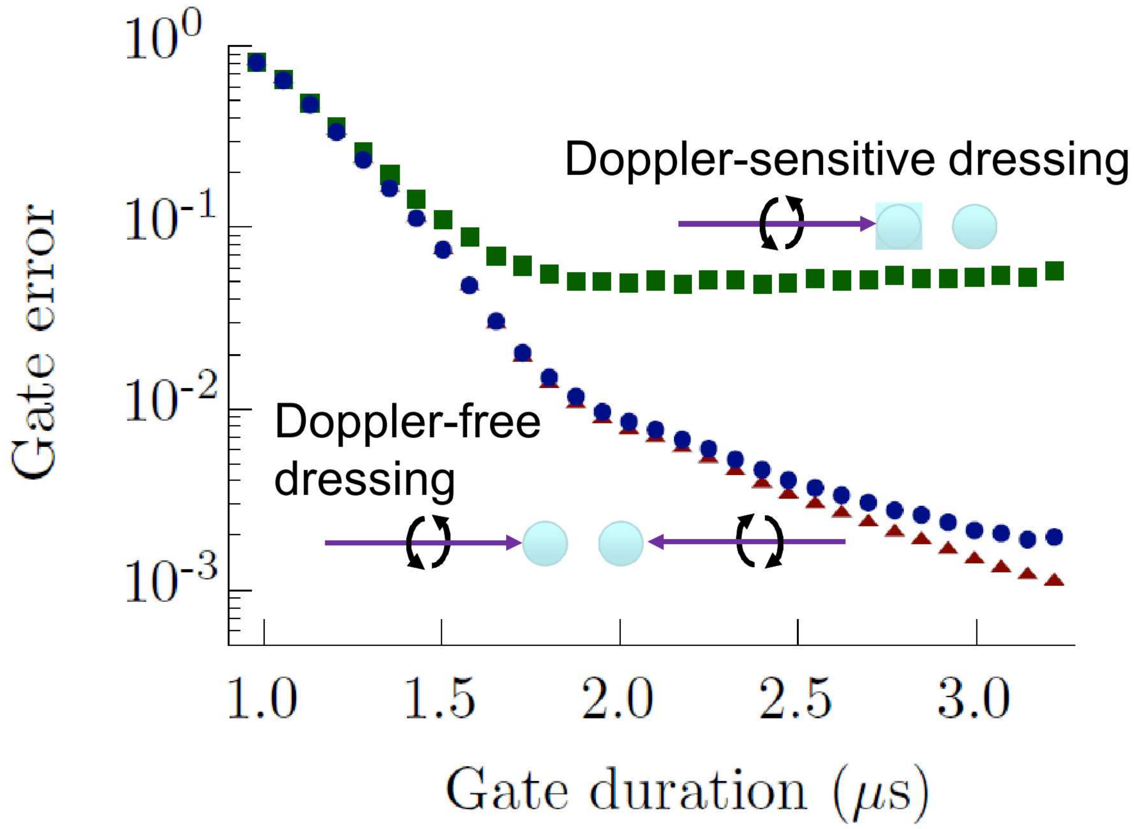


$|11\rangle$

$|01\rangle\ |10\rangle$

and $|00\rangle$

Simulated CPHASE gate fidelities

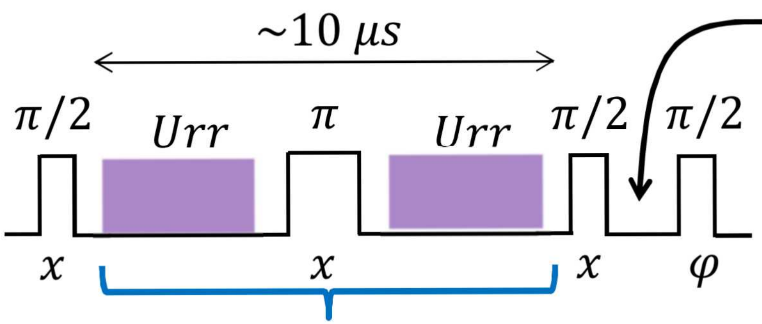


$\Omega = 0 \rightarrow 3$ MHz
$\Delta/2\pi = 6 \rightarrow 0$ MHz
$\Gamma = 3.7$ kHz
$T = 16\ \mu$K

- Motional errors set a high floor on error for the single-beam scheme.
- The Doppler-free scheme is limited by the much smaller photon scattering rate.

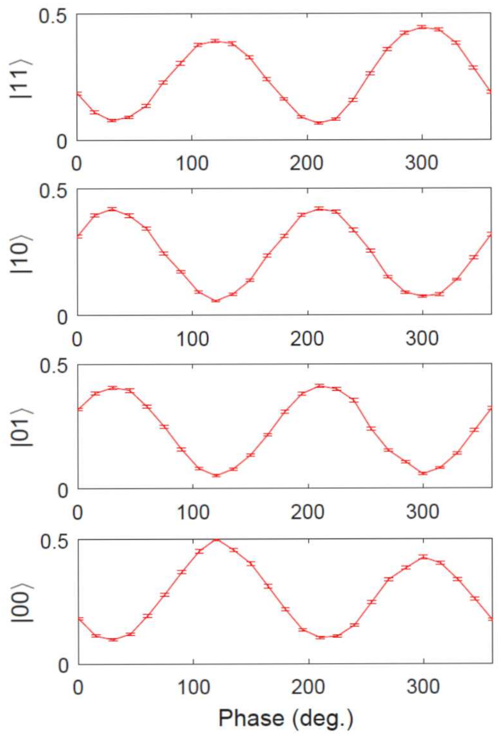
T. Keating, G.B., I.D., et al., Phys. Rev. A 91, 012337 (2015)

Dressed CPHASE gate

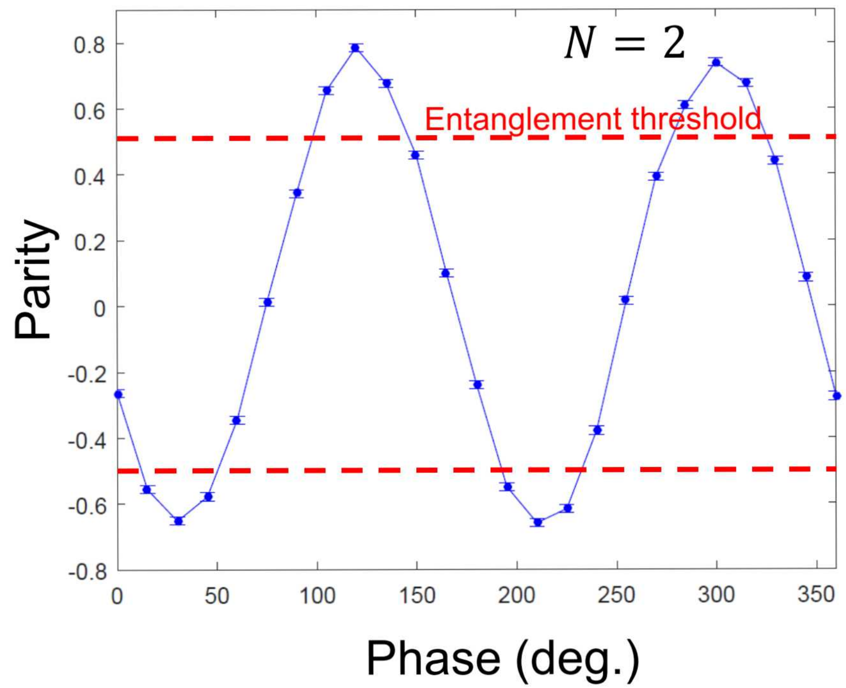


$$|\psi\rangle = \frac{|\uparrow\uparrow\rangle + |\downarrow\downarrow\rangle}{\sqrt{2}}$$

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



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

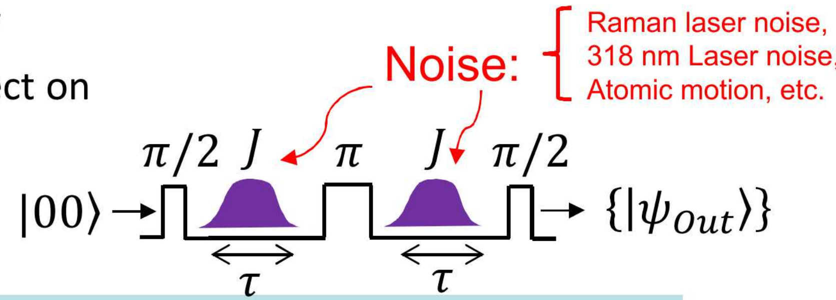


Error budget for CPHASE gate

Error budget: informing an experimental strategy

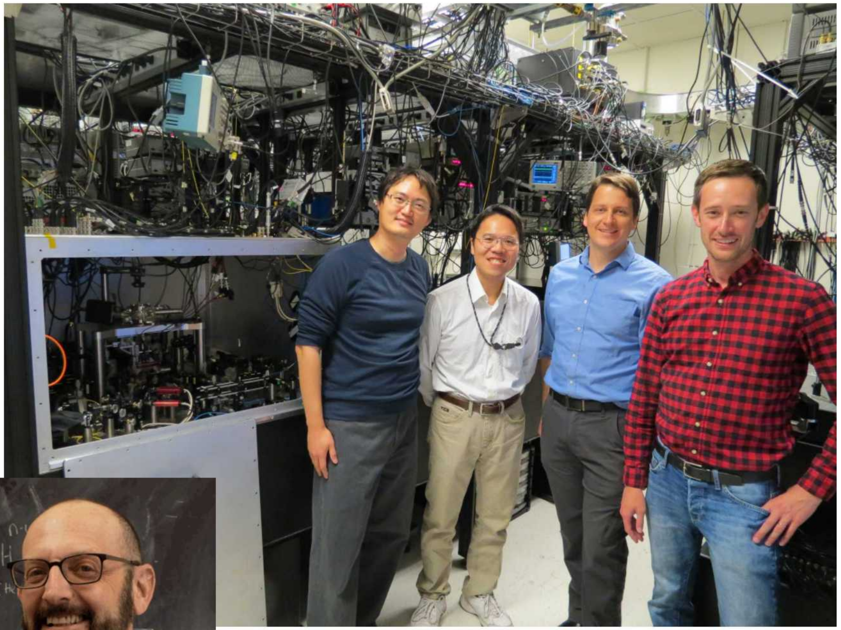
- Trace over external parameters to calculate effect on state fidelity, using measured parameters.

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%	**Sideband cooling to ground state**
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**

CQuIC-Sandia Team

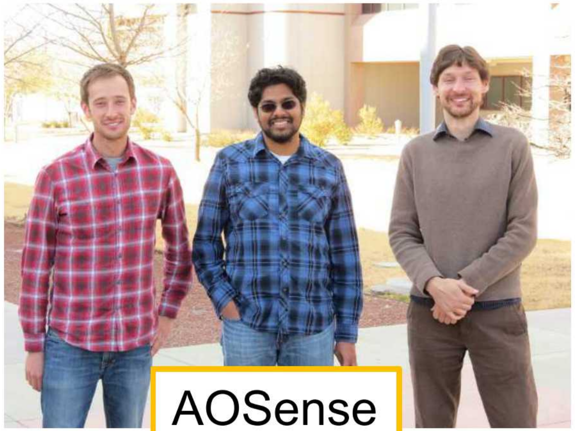


J. Lee, Y-Y. Jau, M. Martin, G. B.

I.Deutsch (UNM)

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

Previous CQuIC members



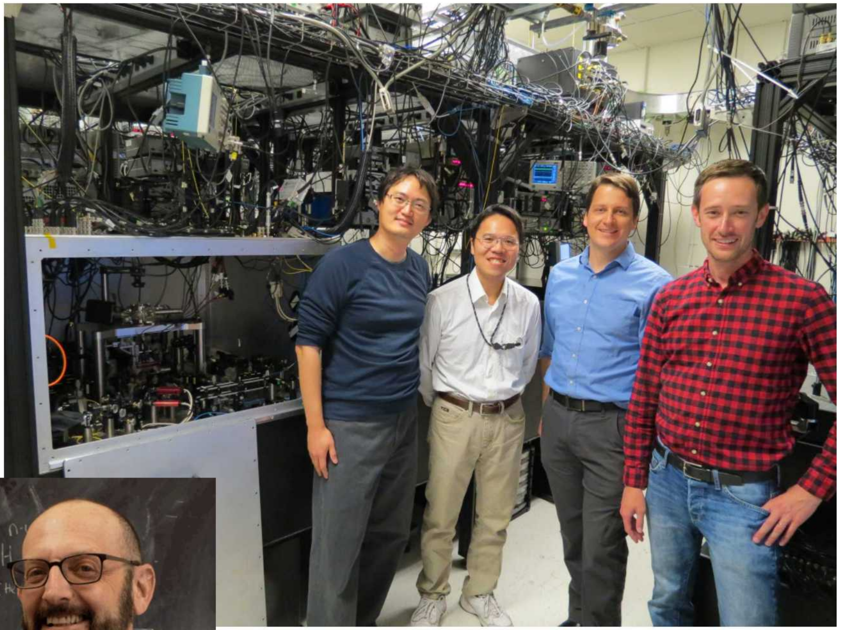
AOSense

G. B., A. Rakholia, H. McGuinness

NIST

L. Parazzoli, G. B., A. Hankin, A. Ferdinand, J. Chou, G. Burns

CQuIC-Sandia Team



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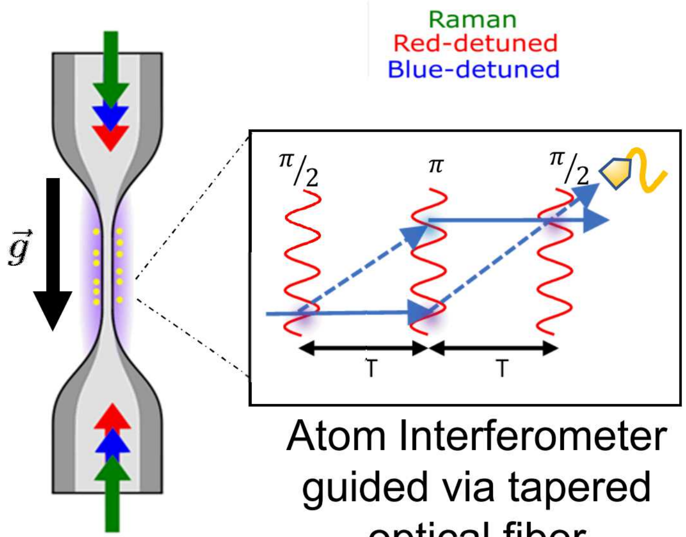
Sandia mountains viewed from the Rio Grande near Albuquerque, New Mexico

Current CQuIC members

J. Bainbridge (UNM)

A. Orozco (UNM)



Atom Interferometer guided via tapered optical fiber