SAND2016-5290C

Sandia National Laboratories

Entanglement and the Jaynes-Cummings model with Rydberg-dressed atoms

Team members

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

Grant Biedermann

Albuquerque, New Mexico

UNM CQuIC

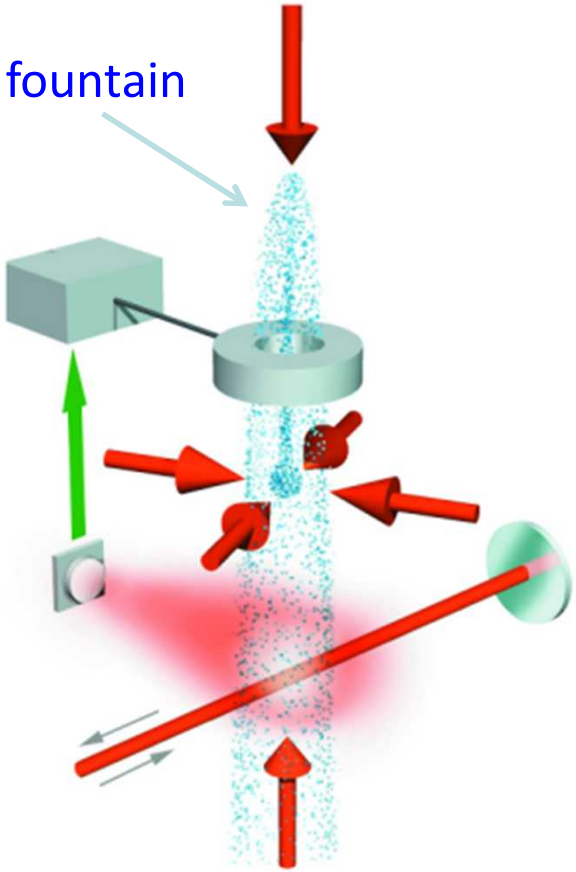
U.S. DEPARTMENT OF ENERGY NNSA LORD

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

Precision metrology with Alkali atoms

Sandia National Laboratories

Qubit fountain



Atomic fountain principle

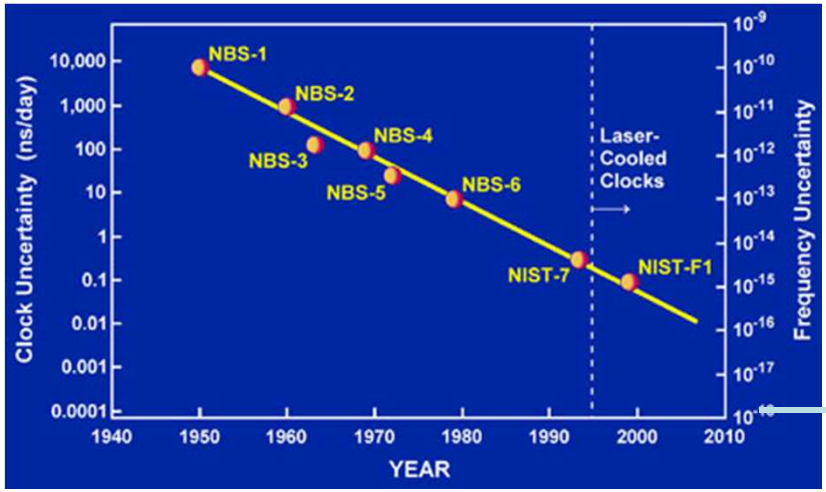
http://smsc.cnes.fr/PHARAO/GP_instrument.htm

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

- Example: atomic clocks

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

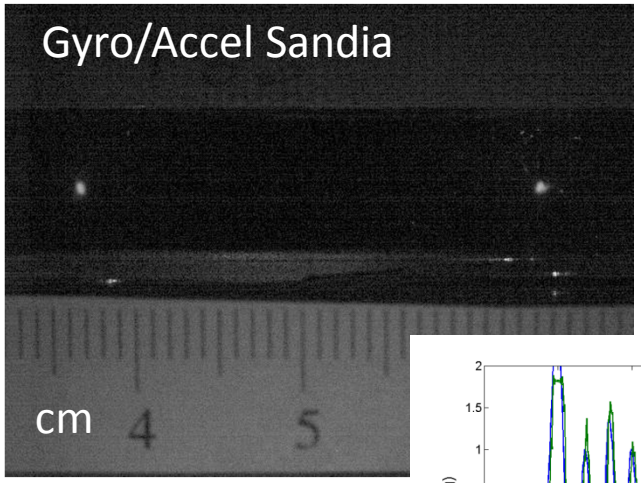
$$\left|0\right\rangle \leftrightarrow \left|1\right\rangle$$



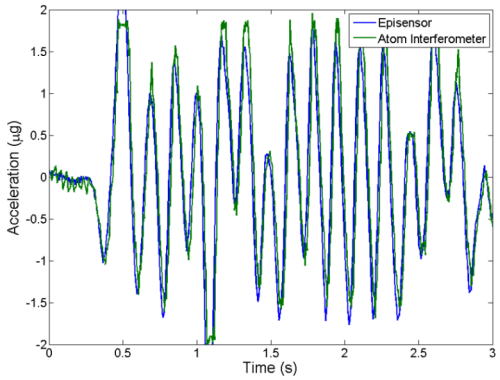
Optical clocks

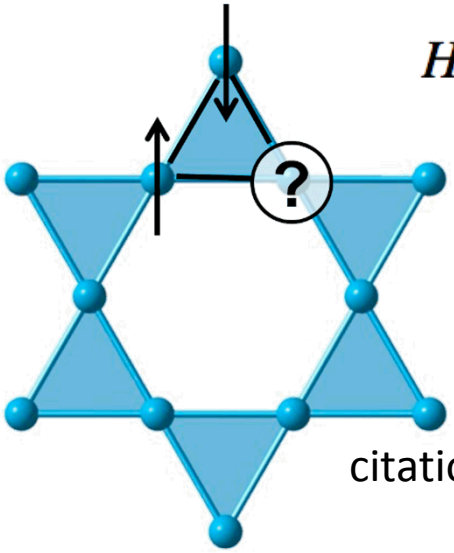
http://www.nist.gov

Applications



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





citation

Frustrated magnetism

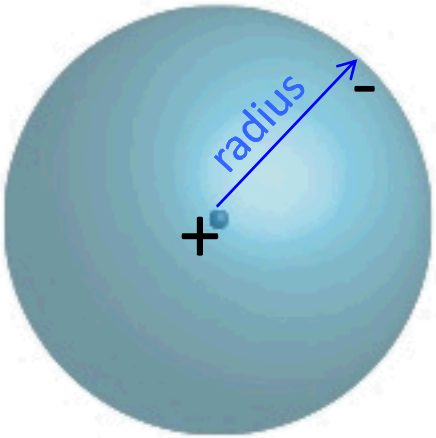
$$H_P = \sum_{i=1}^{N} \tilde{h}_i \sigma_z^{(i)} + \sum_{i,j=1}^{N} \tilde{J}_{ij} \sigma_z^{(i)} \otimes \sigma_z^{(j)}$$

Generic Ising model

& beyond?

Interaction between *neutral* atoms

Valence electron in
Rydberg state

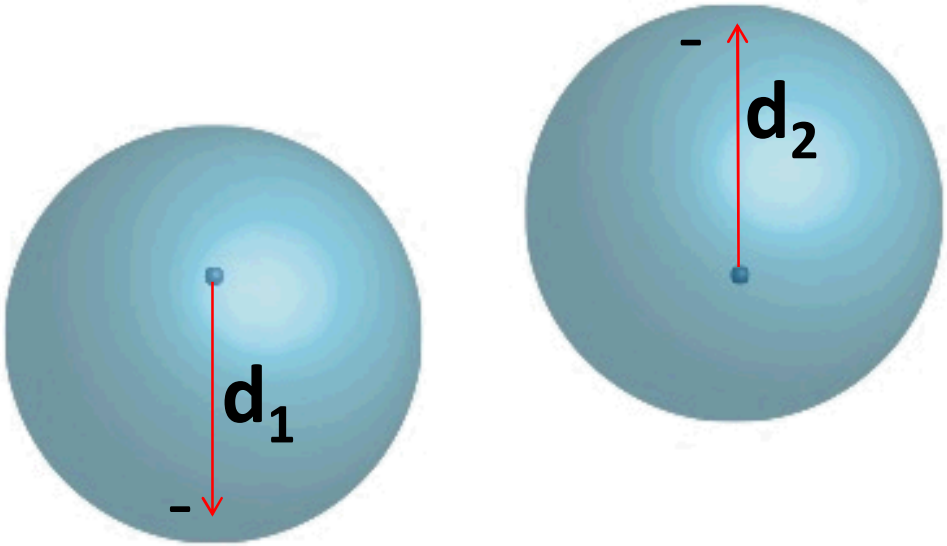


orbital radius $\alpha\ n^2$

Wavefunction symmetric in zero electric field

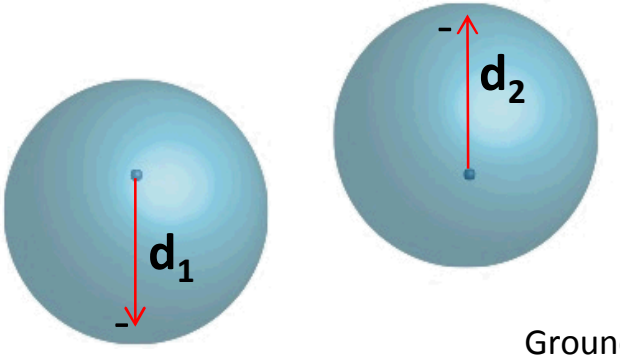
- Interaction between ground state atoms is small ~ 100 Hz
- Excite valence electron to Rydberg state—nearly ionized
- Atom becomes highly polarizable—strong interactions
- Even the presence of another atom can cause a massive response > 10 MHz

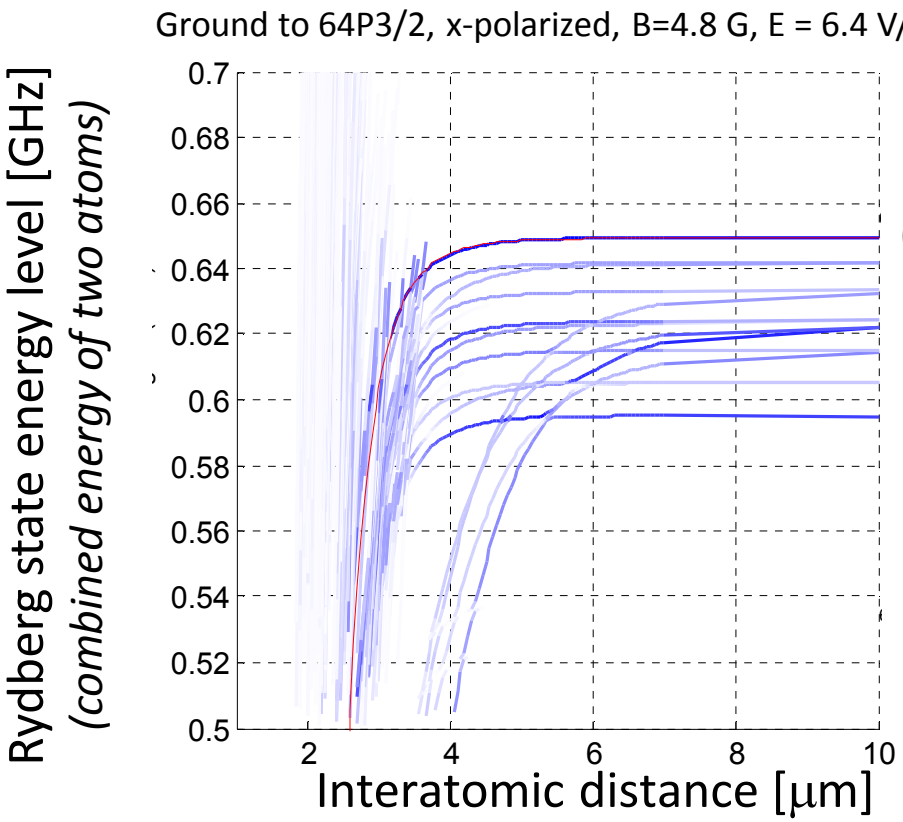
Interaction between *neutral* atoms



- 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



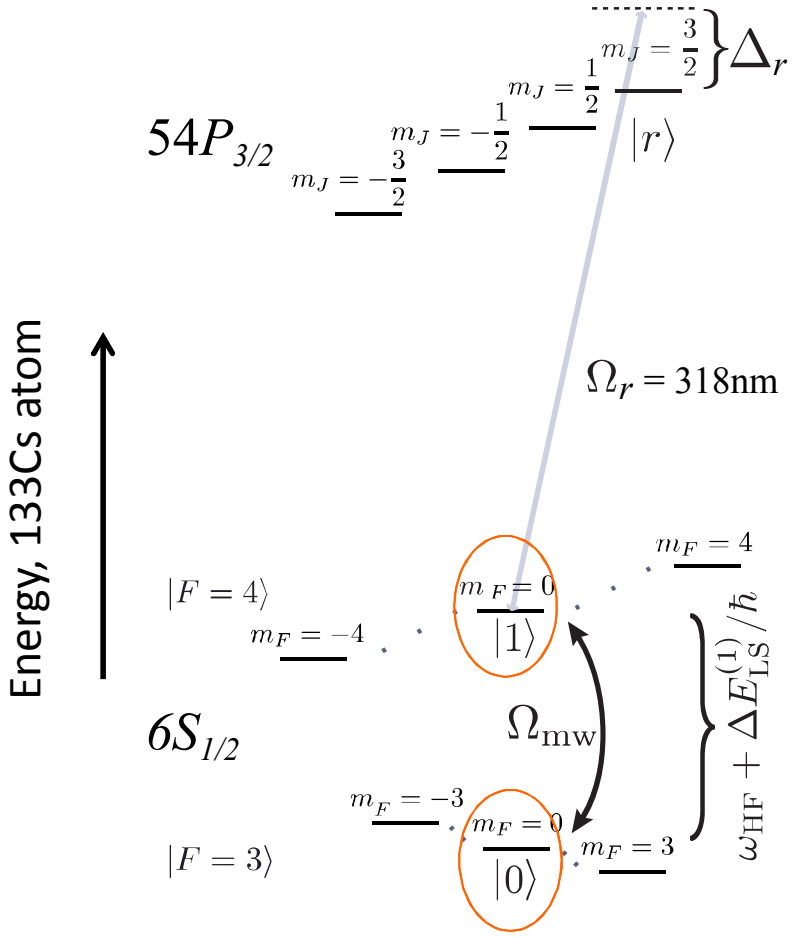


$64P_{3/2}64P_{3/2}$

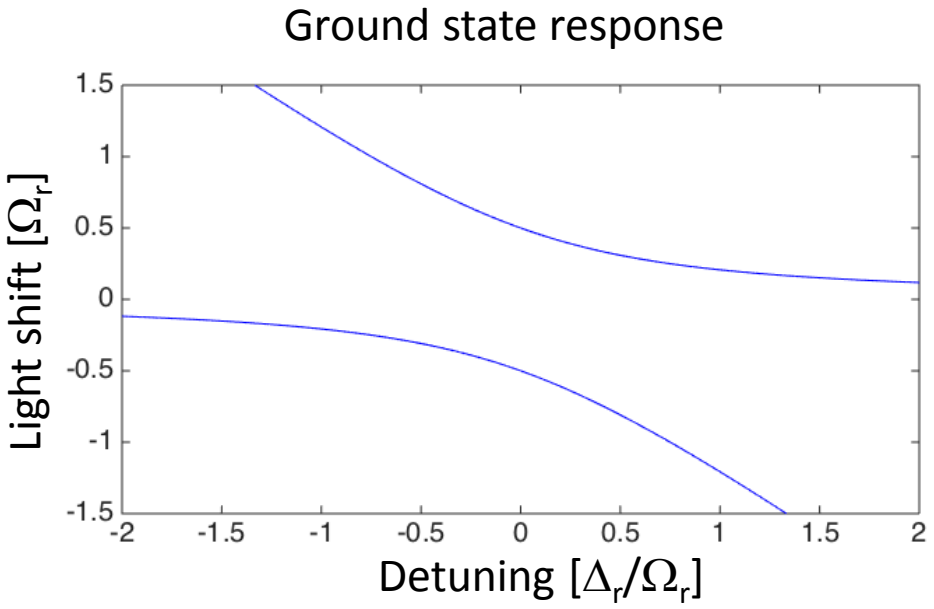
Line shade weighted by transition strength

However… we want something tunable

Rydberg-dressed states



Single atom picture



- Controllable with laser intensity and detuning—on demand
- 2 atom case—Rydberg blockade affects light shift
- Transfers blockade effect to ground state manifold

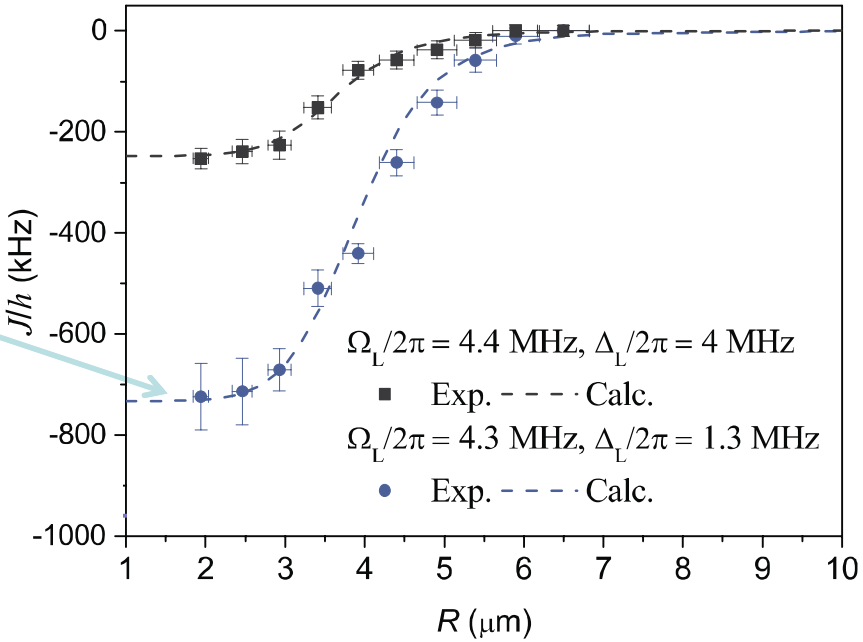
Rydberg-dressed interaction, *J*

J = change in light shift due to interaction

Interaction >> Ω_r
J saturates

Soft core potential—

low sensitivity to atom motion.

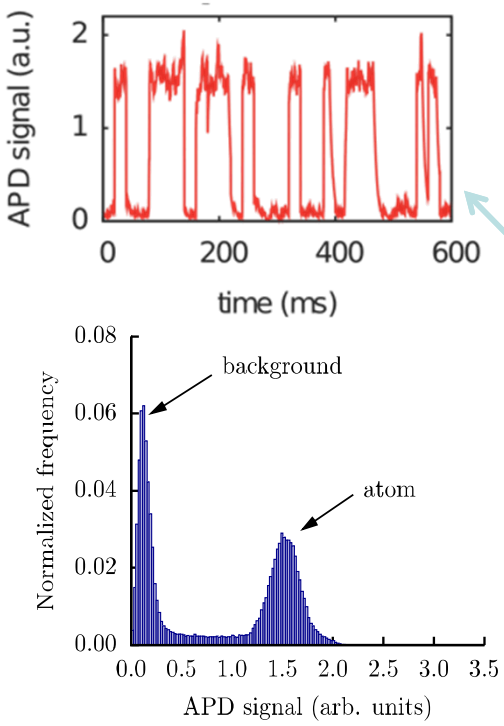


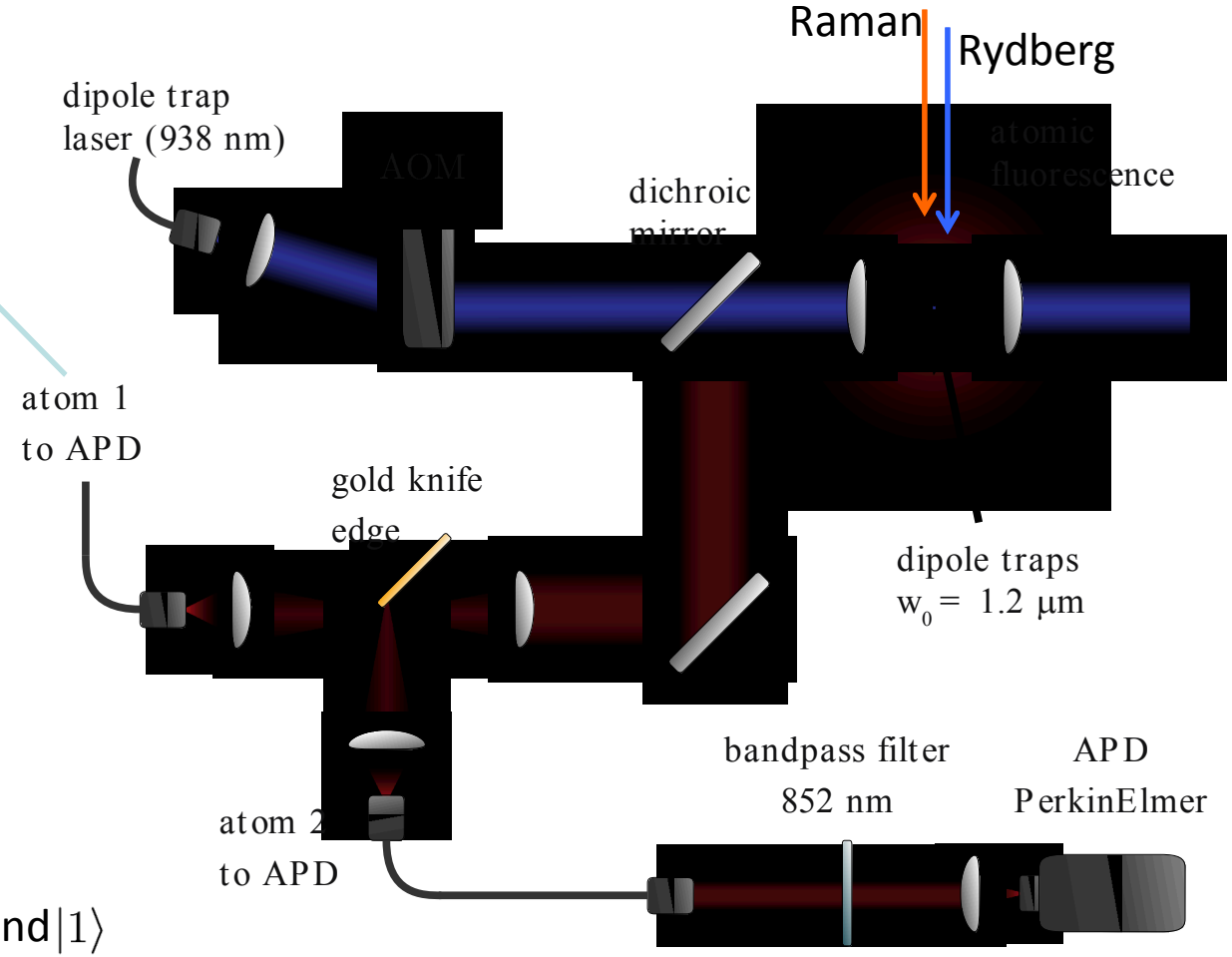
Can be either attractive or repulsive

Work near resonance to maximize *J*

For $\Delta = 0$: $J_{max} \approx 0.59*\Omega$
For $\Delta = 10\ \Omega$: $J_{max} \approx 0.0001*\Omega$

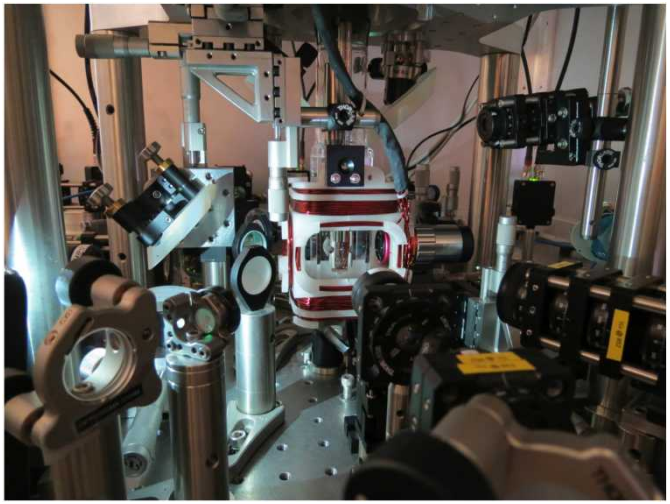
Single atom control of 2 atoms

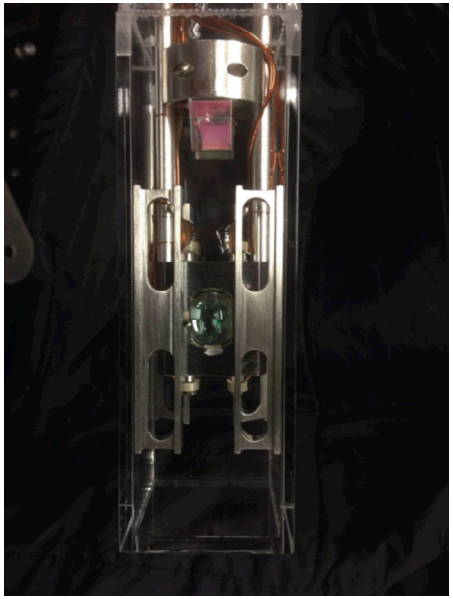


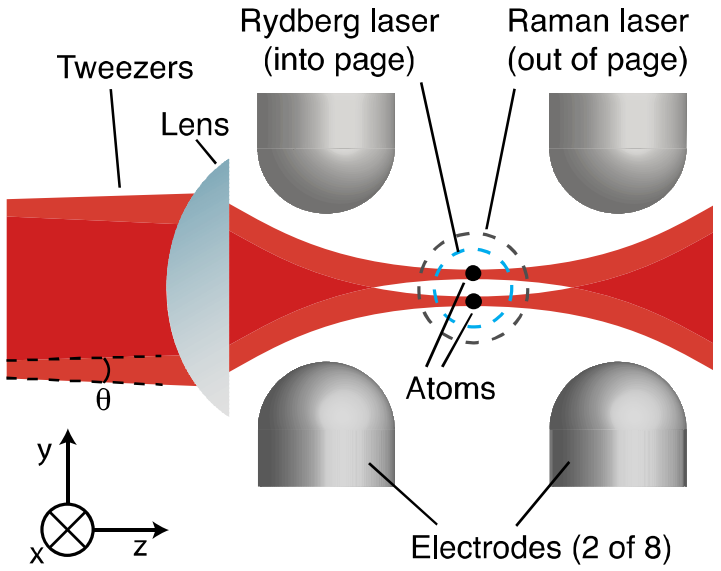


- Directly detect both $|0\rangle$ and $|1\rangle$
- Distinguishable from loss
- FPGA control: Reuse atoms
- Data rate ≈ 10 s^{-1} for two atoms

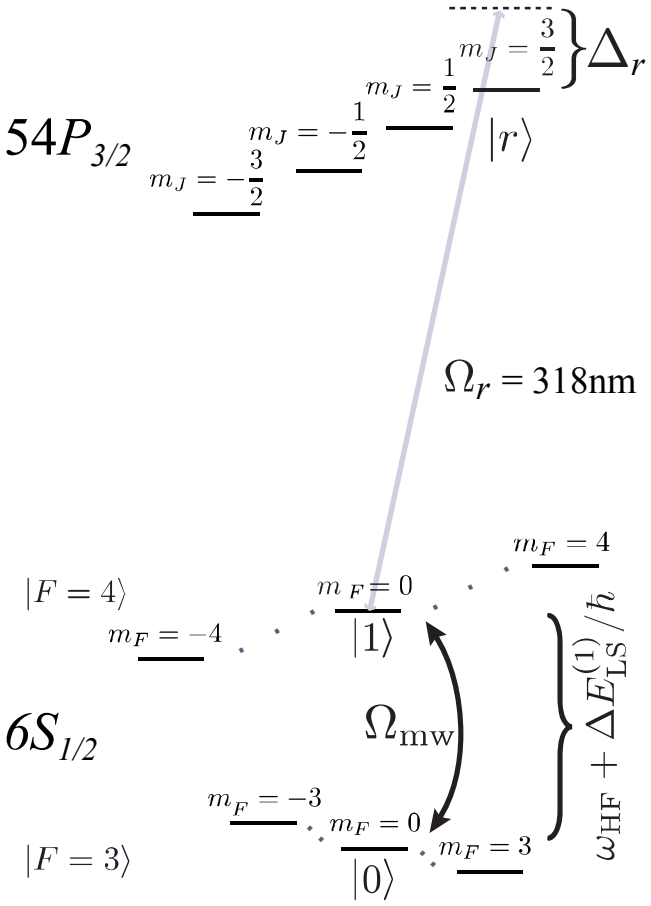
Apparatus

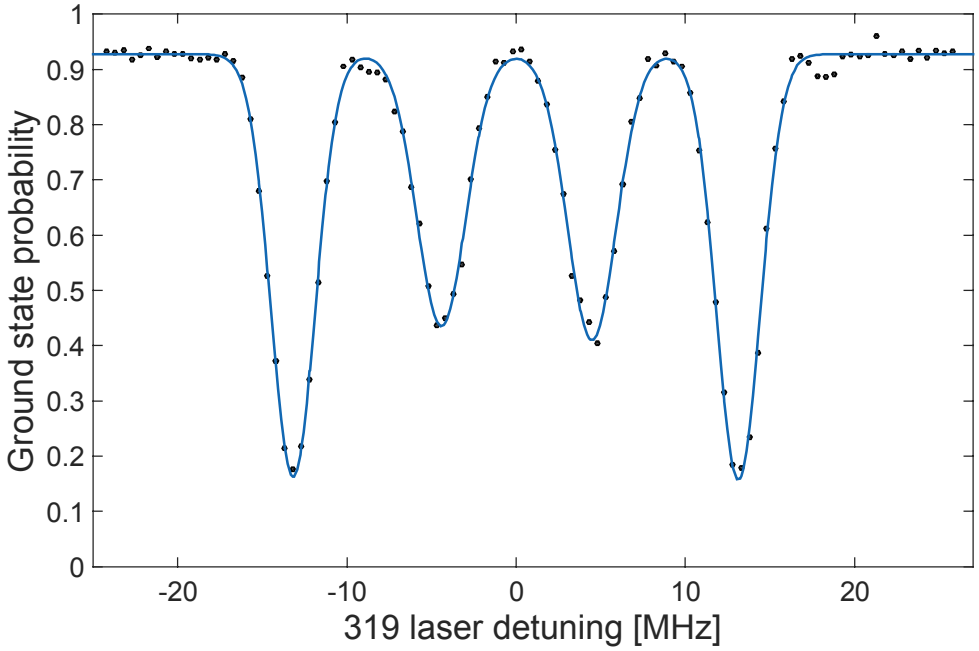





Tweezers
Lens
Rydberg laser
(into page)
Raman laser
(out of page)
θ
Atoms
y
x
z
Electrodes (2 of 8)

Rydberg state spectrum





Rydberg blockade—direct excitation

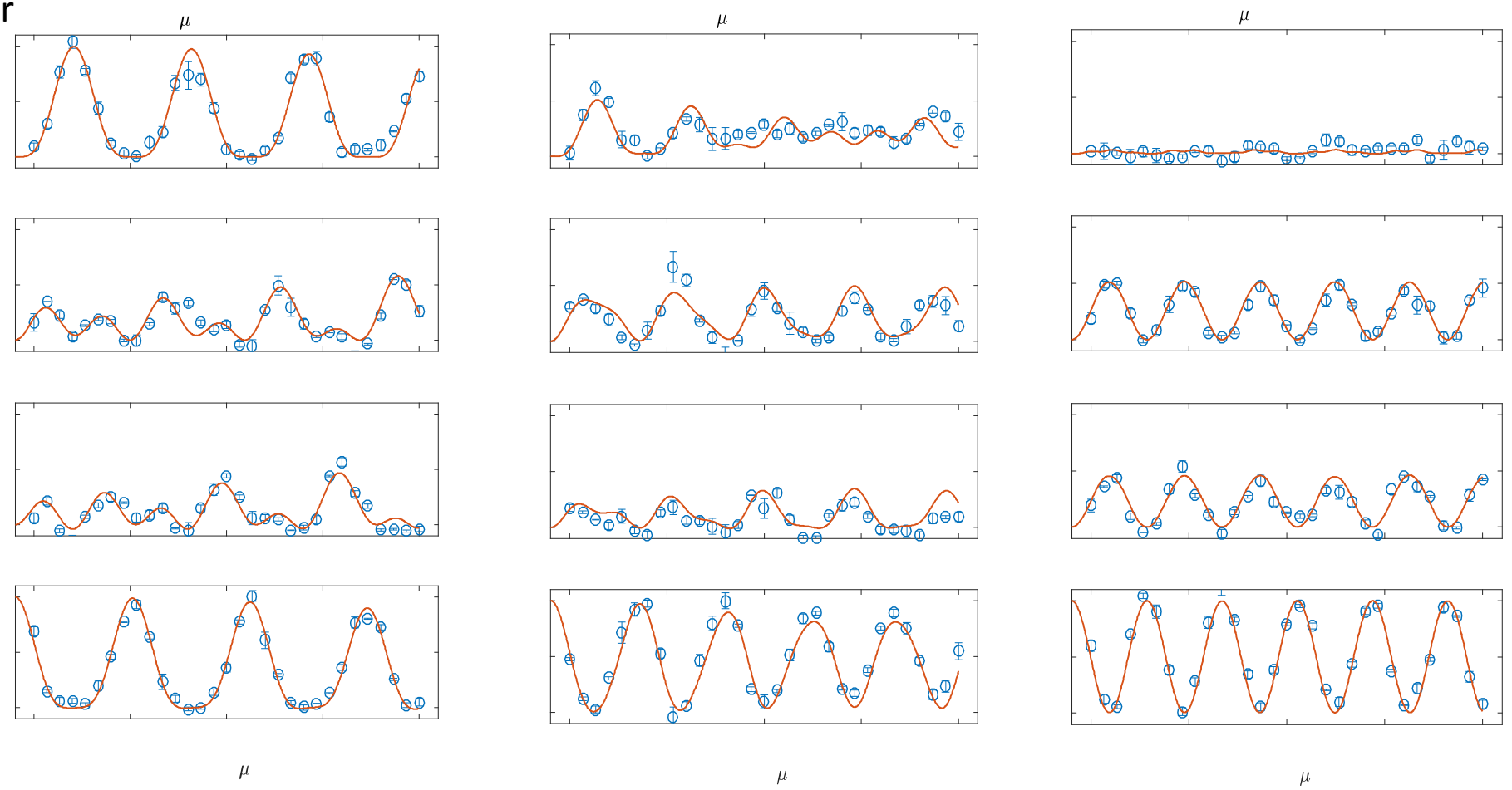
Sandia National Laboratories

Weak (U_{RR} < 100 kHz)

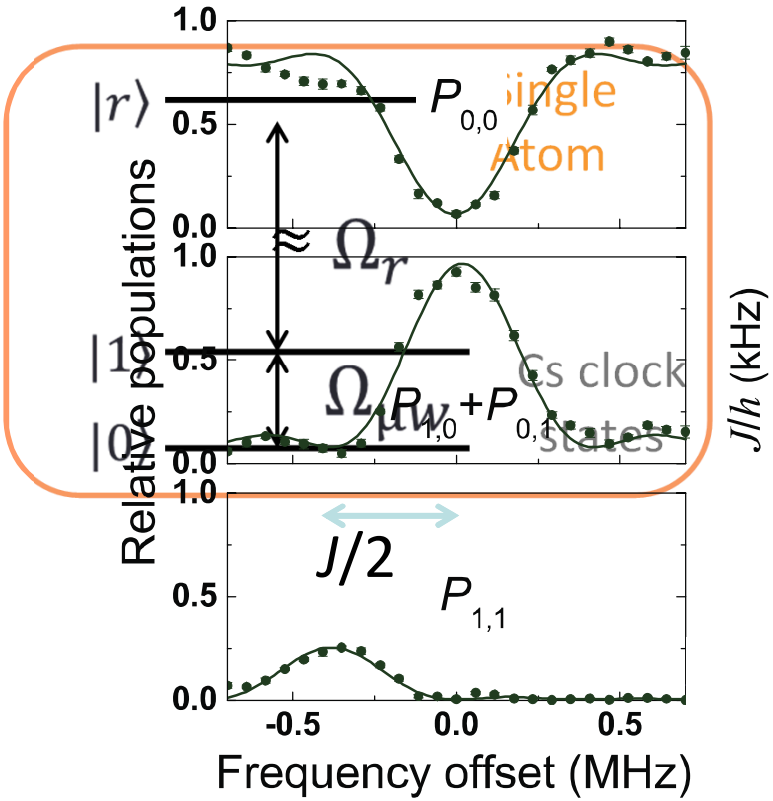
Intermediate (U_{RR} = 1.9 MHz)

Strong (U_{RR} > 6 MHz)

1->r

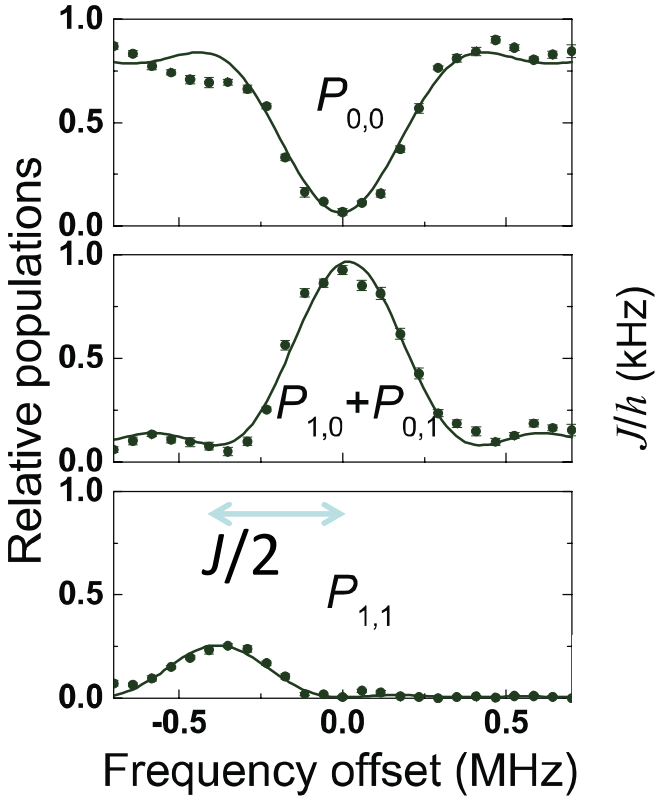


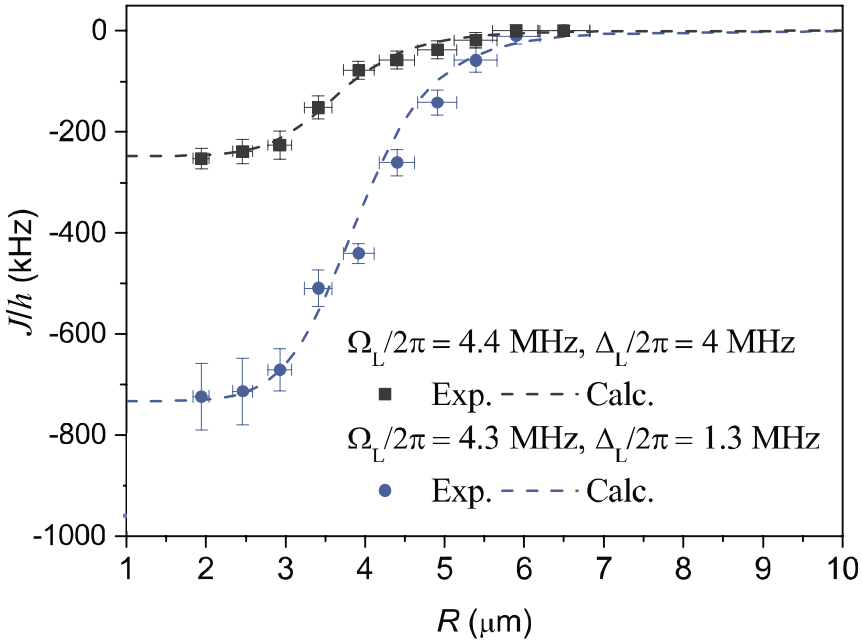
Ground state, *Spin-flip* blockade



J vs. *R*

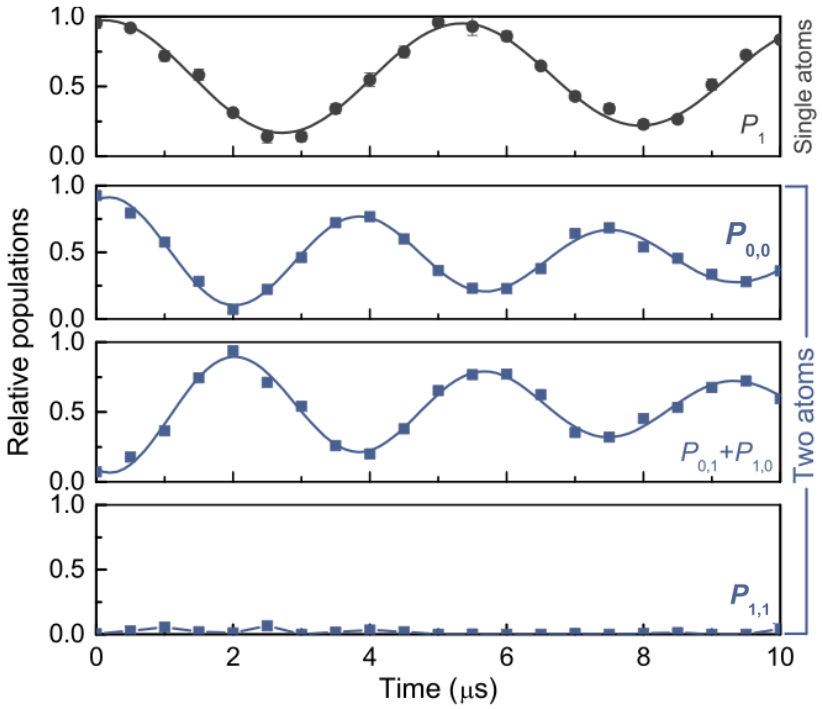
Direct measurement of two-qubit interaction strength *J* as a function of two-atom separation with two conditions.

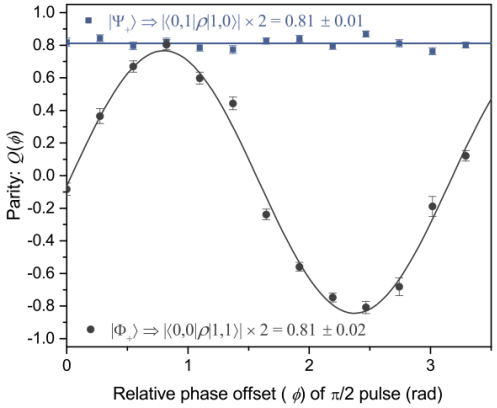


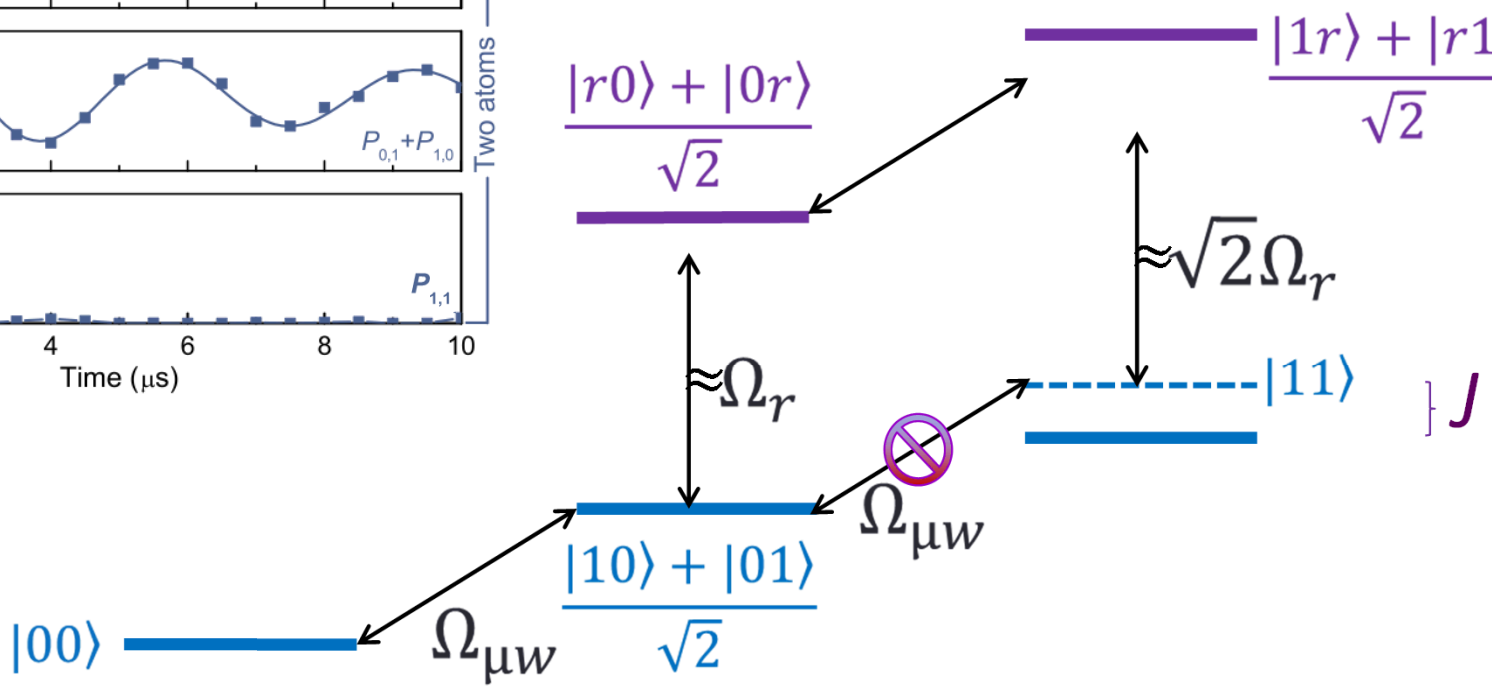


Jau, et al., Nature Phys. (2016)

Ground state, *Spin-flip* blockade







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

Extending to *N* atoms—symmetric

Sandia National Laboratories

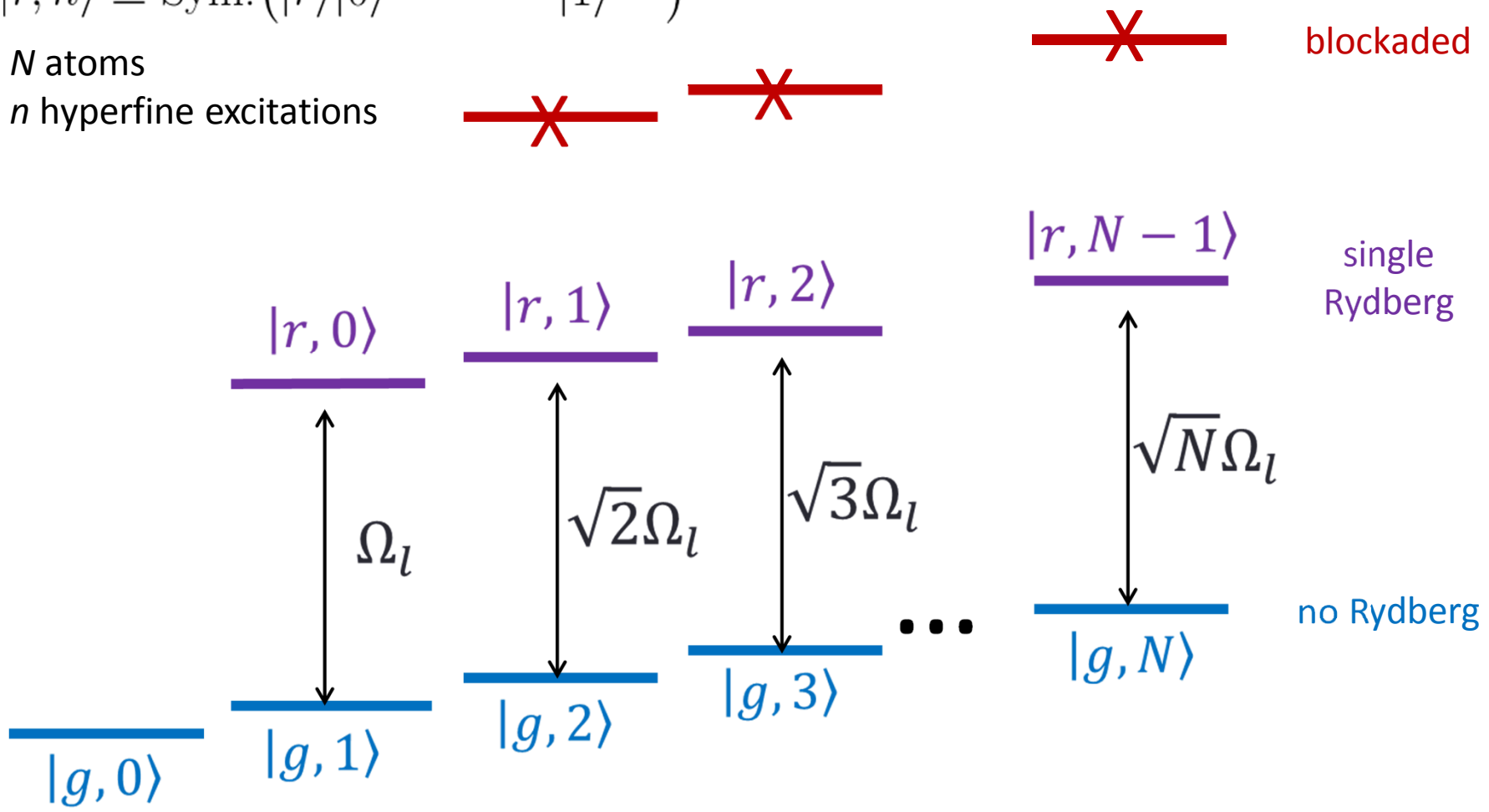
notation

$$|g,n\rangle \equiv \mathrm{Sym.}\left(|0\rangle^{\otimes N-n}|1\rangle^{\otimes n}\right)$$

$$|r,n\rangle \equiv \mathrm{Sym.}\left(|r\rangle|0\rangle^{\otimes N-n-1}|1\rangle^{\otimes n}\right)$$

N atoms

n hyperfine excitations



Extending to *N* atoms—symmetric

Sandia National Laboratories

notation

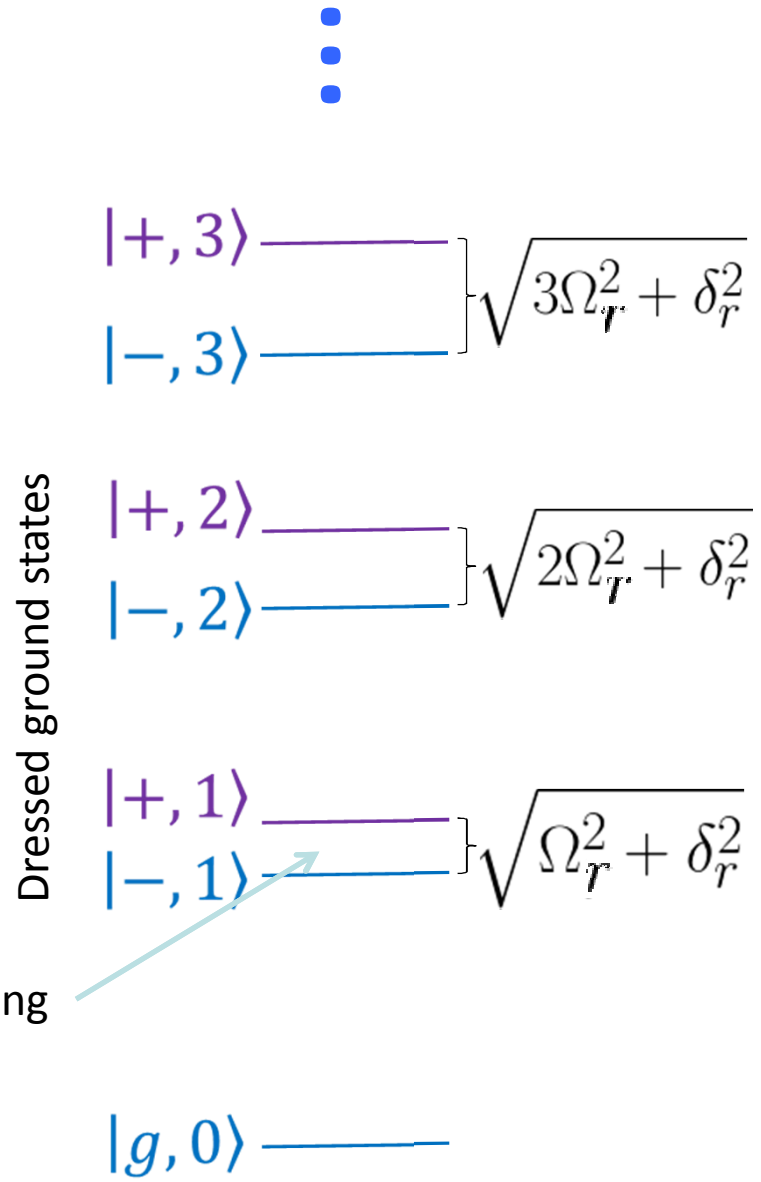
$$|g,n\rangle \equiv \mathrm{Sym.}\left(|0\rangle^{\otimes N-n}|1\rangle^{\otimes n}\right)$$

$$|r,n\rangle \equiv \mathrm{Sym.}\left(|r\rangle|0\rangle^{\otimes N-n-1}|1\rangle^{\otimes n}\right)$$

N atoms

n hyperfine excitations

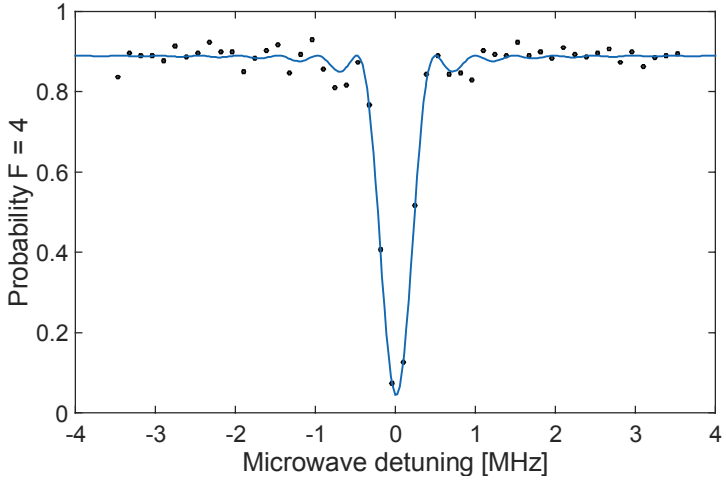
- Consider only ground states
- Isomorphic to Jaynes-Cummings model of a single atom in an optical cavity

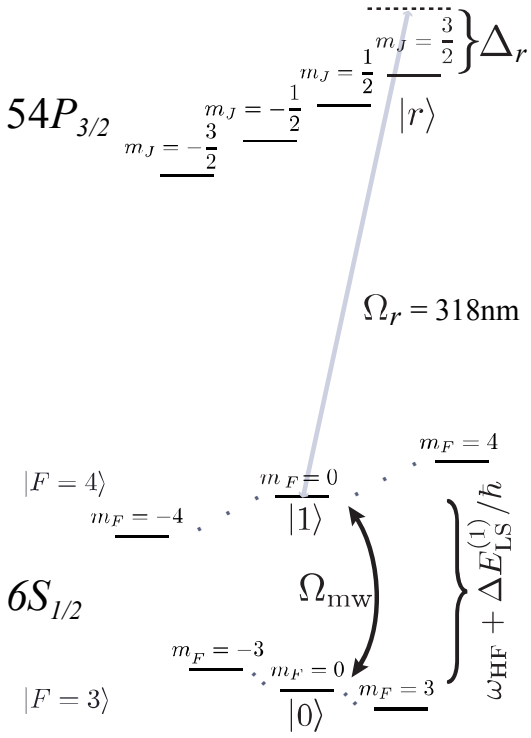


Rydberg-dressed states

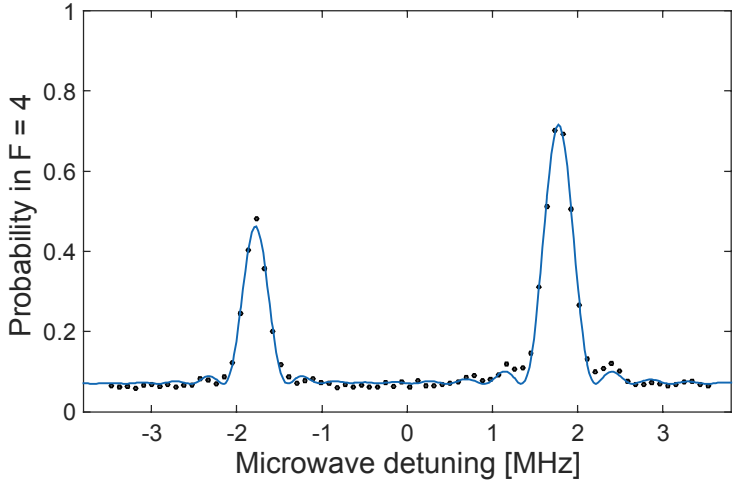
Sandia National Laboratories

Bare atom

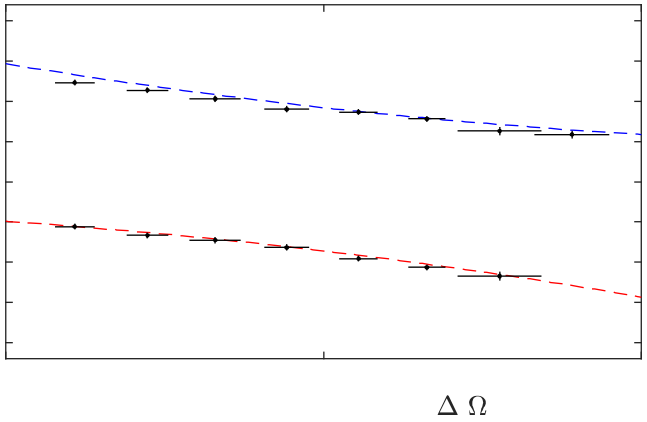




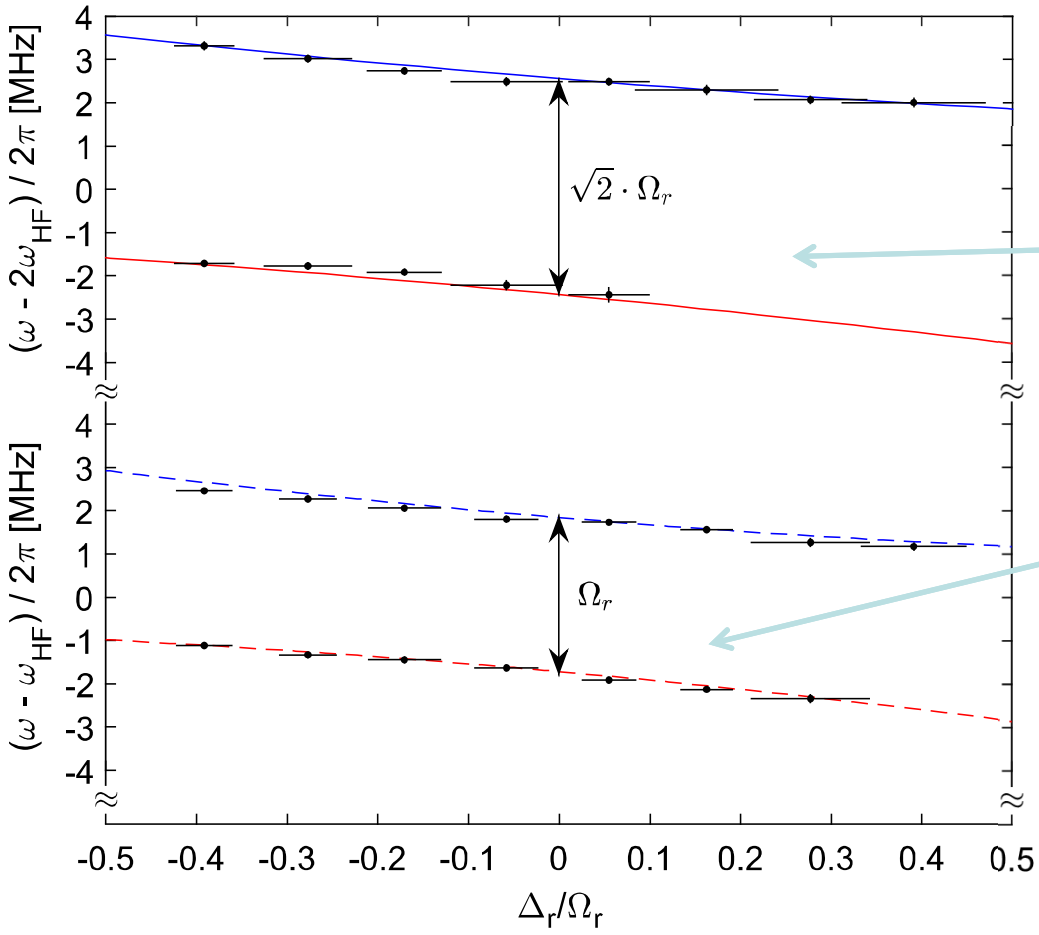
Dressed F=4 state



Autler-Townes splitting



Rydberg-dressed states under blockade



$|+,2\rangle$

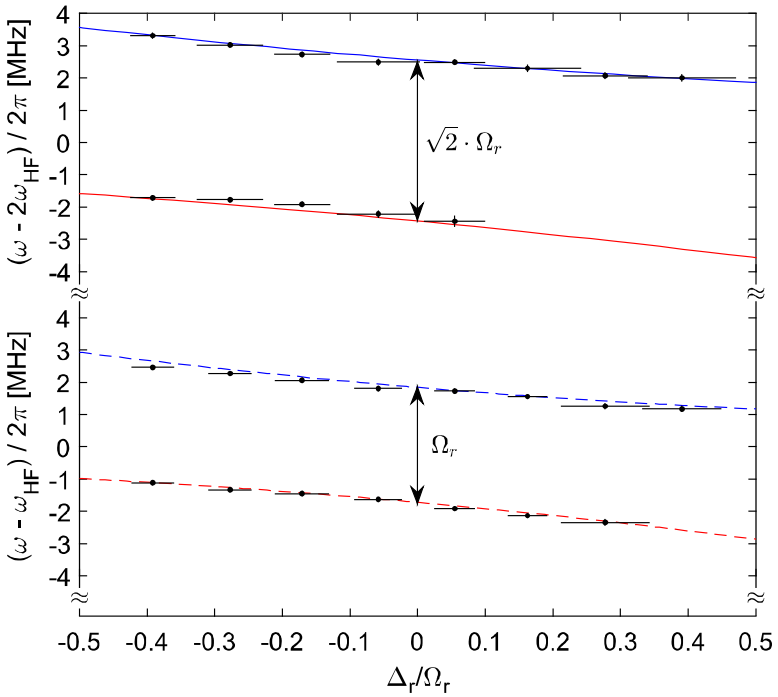
$|-,2\rangle$ $\sqrt{2\Omega_r^2 + \delta_r^2}$

$|+,1\rangle$

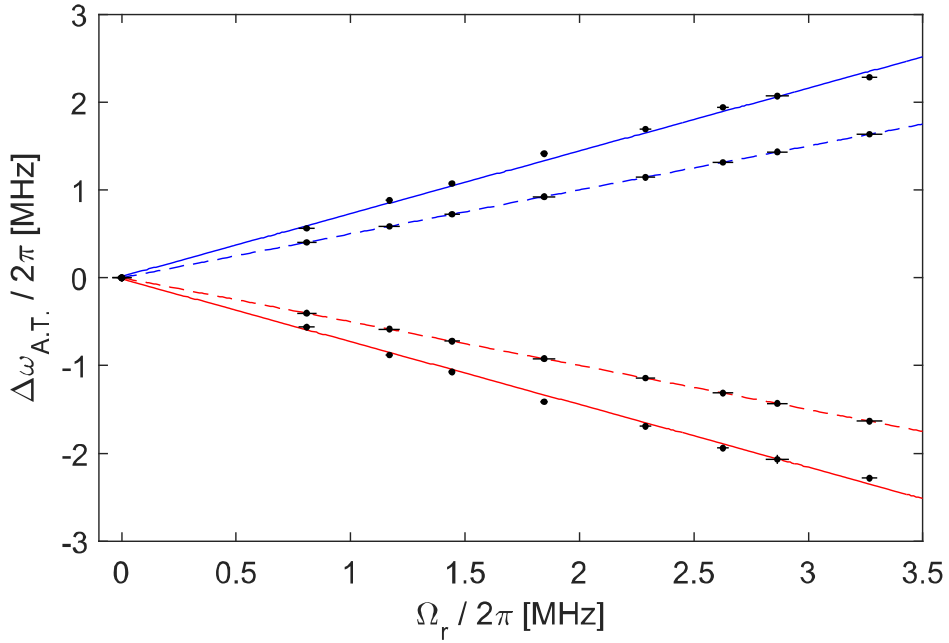
$|-,1\rangle$ $\sqrt{\Omega_r^2 + \delta_r^2}$

$|g,0\rangle$

Rydberg-dressed interactions—the big picture



Δ dependence

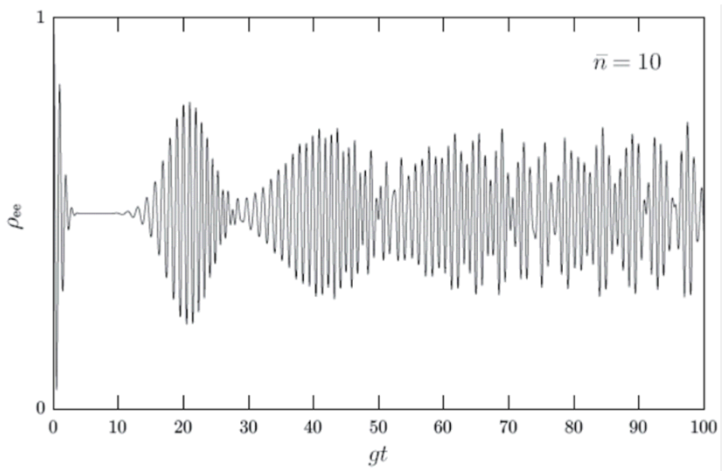


Ω dependence

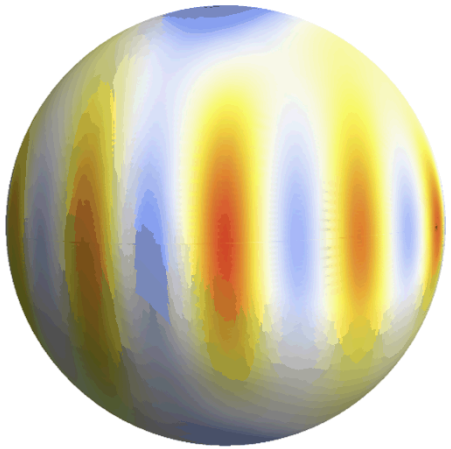
- Choose sign of interaction
- Design time-dependent interaction
- Opens new doors for adiabatic approach to entanglement, Gates, and quantum simulation— Phys. Rev. A 91, 012337 (2015)

Controlling the System

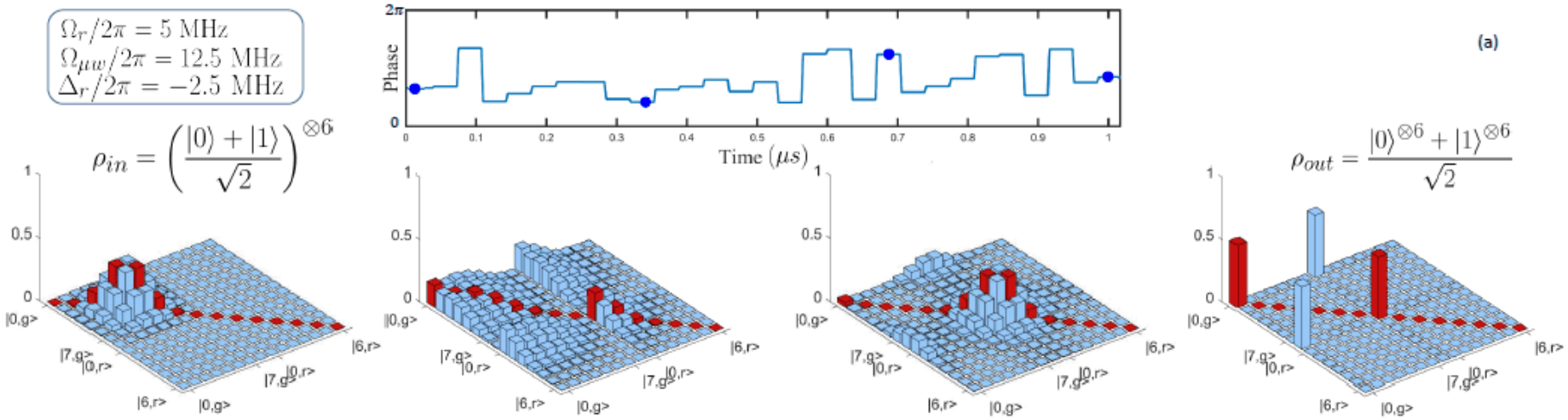
- Port over entanglement protocols from other JC platforms
  - Collective spin squeezing: Tomáš Opatrný and Klaus Mølmer. *Phys. Rev. A* **86**, 023845 (2012)
  - Collapse and revival: I. I. Beterov *et al. Phys. Rev. A* **90**, 043413 (2014)



from D.A. Steck, *Quantum and Atom Optics*



Arbitrary control



The nonlinearity of the JCM, together with externally applied fields makes the system fully controllable on the whole Hilbert space, i.e., we can generate an arbitrary superposition state.

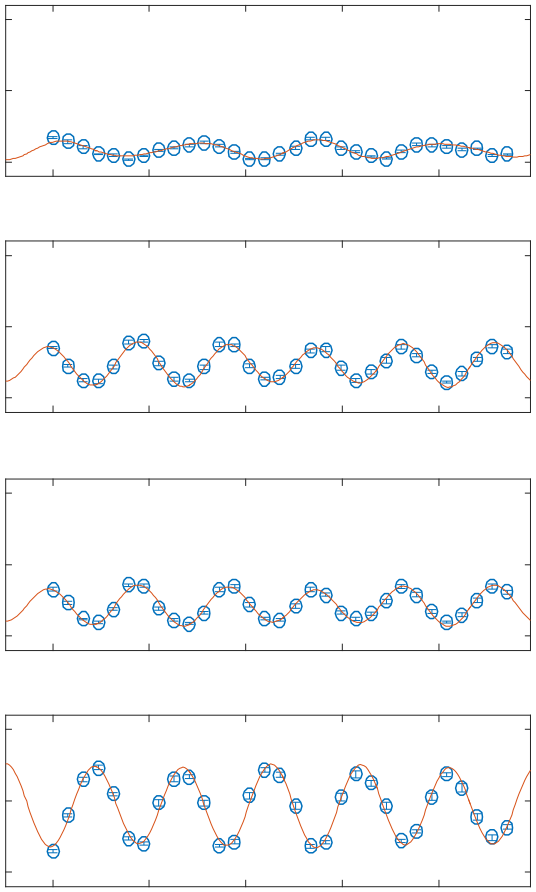
Thank you!

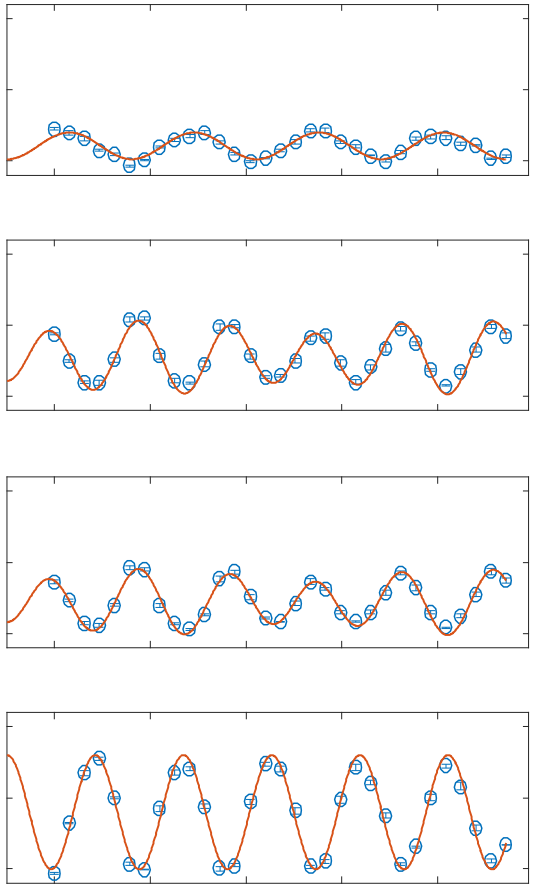
Sandia National Laboratories

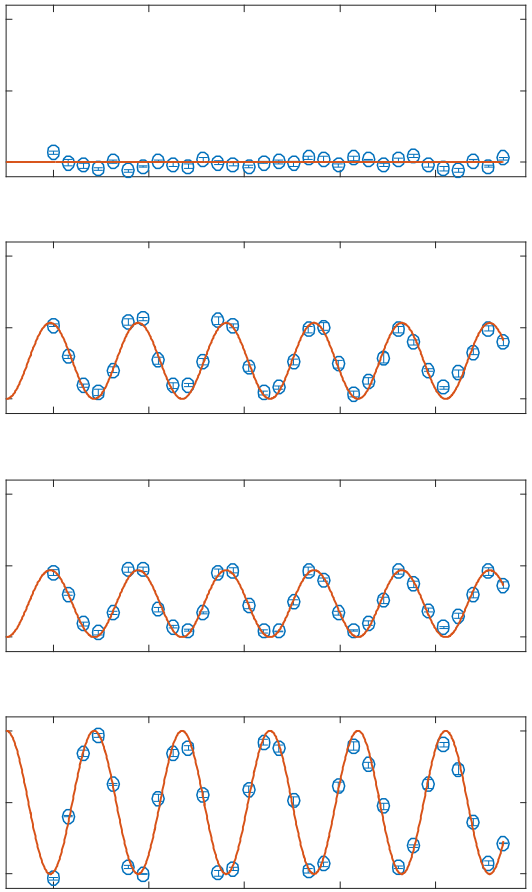
Raw data and fit

Correct for state detection errors

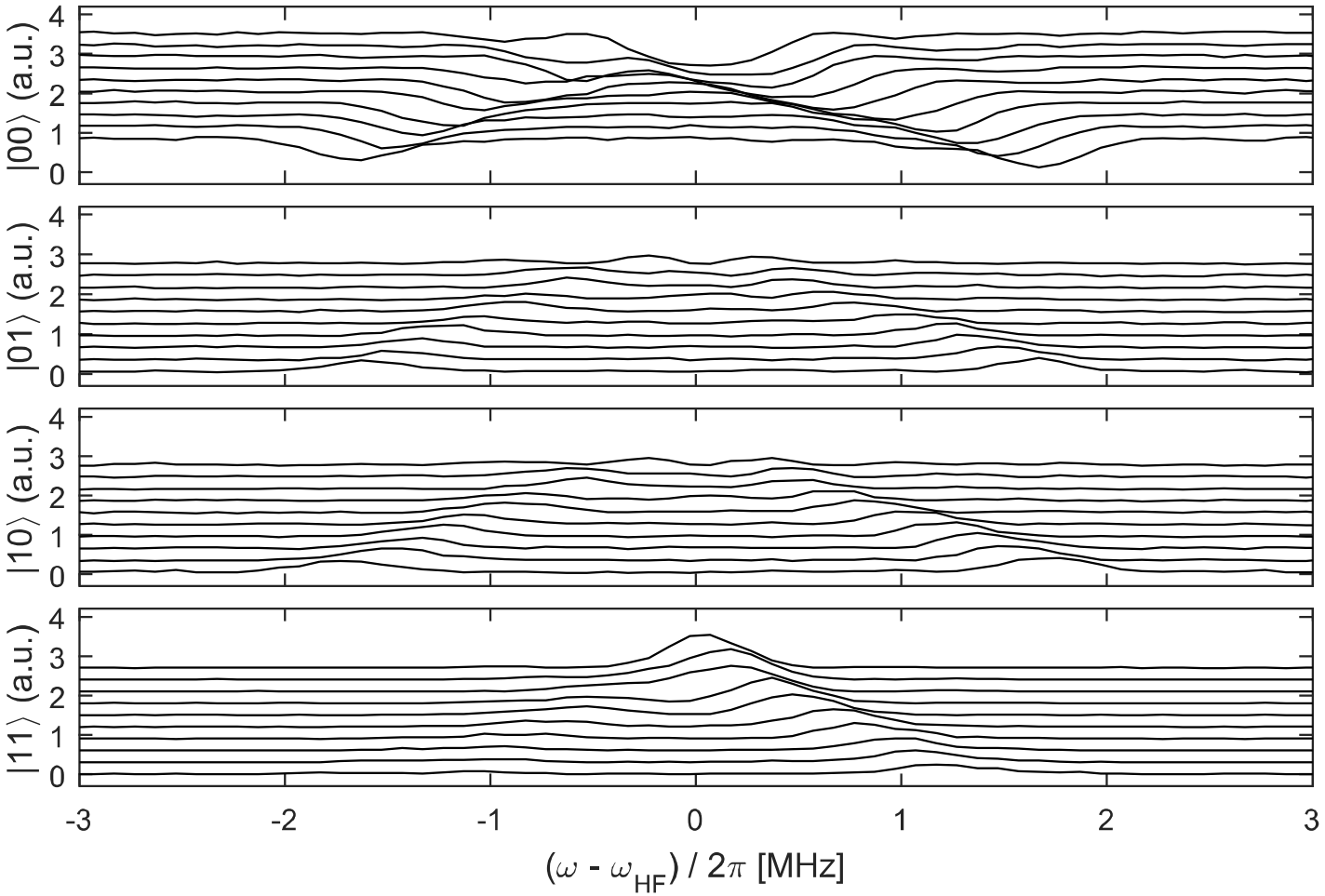
Remove contributions from all non two-atom loading



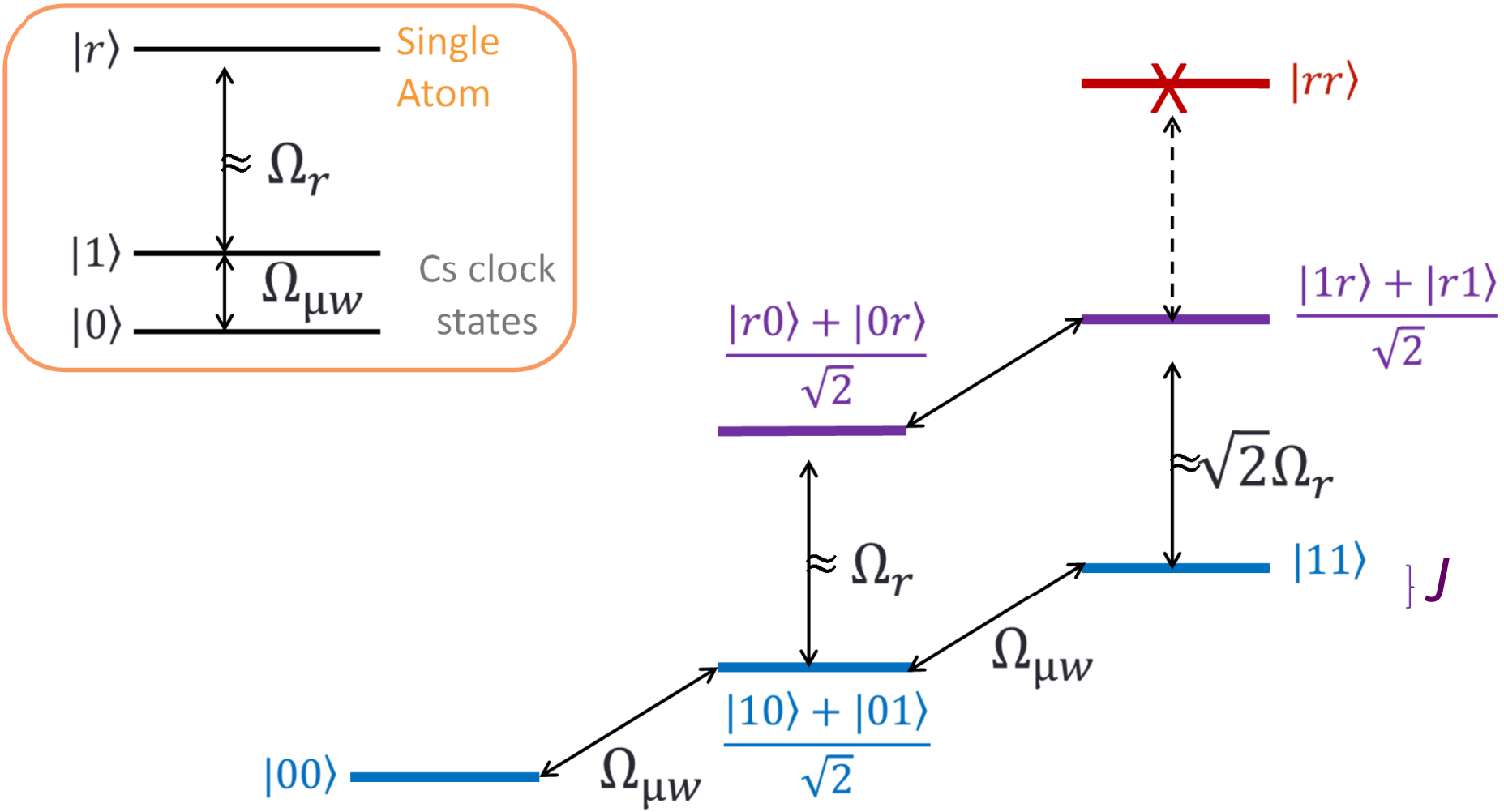




$\sqrt{N}$ dependence



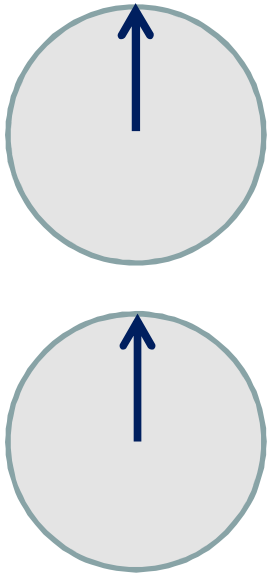
Generating Entanglement



Generating Entanglement

Sandia National Laboratories

Phase:



Laser ON

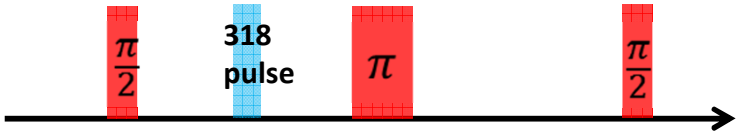
$$U = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix} = \text{CPHASE}$$

$|11\rangle$

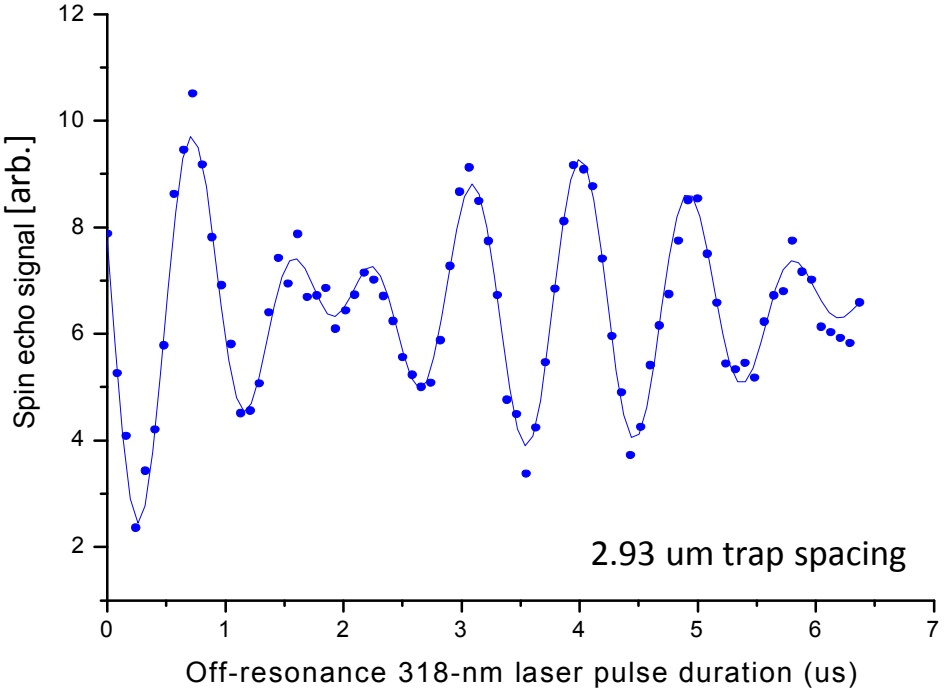
$|01\rangle$ $|10\rangle$ and $|00\rangle$

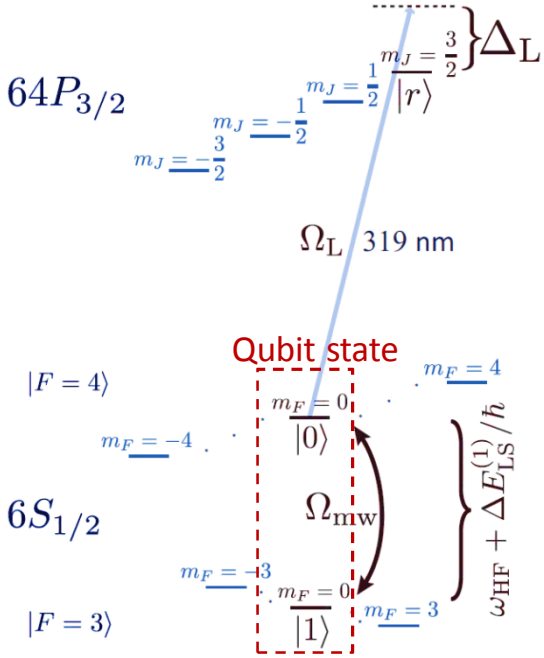
Rydberg-dressed Ramsey dynamics

Microwave transition is via Raman laser

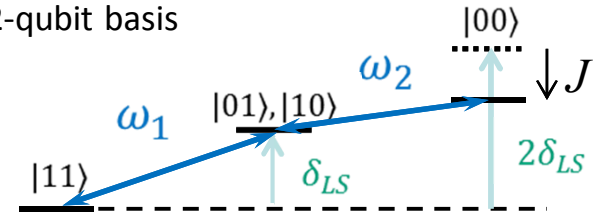


318-nm laser dressed spin echo sequence



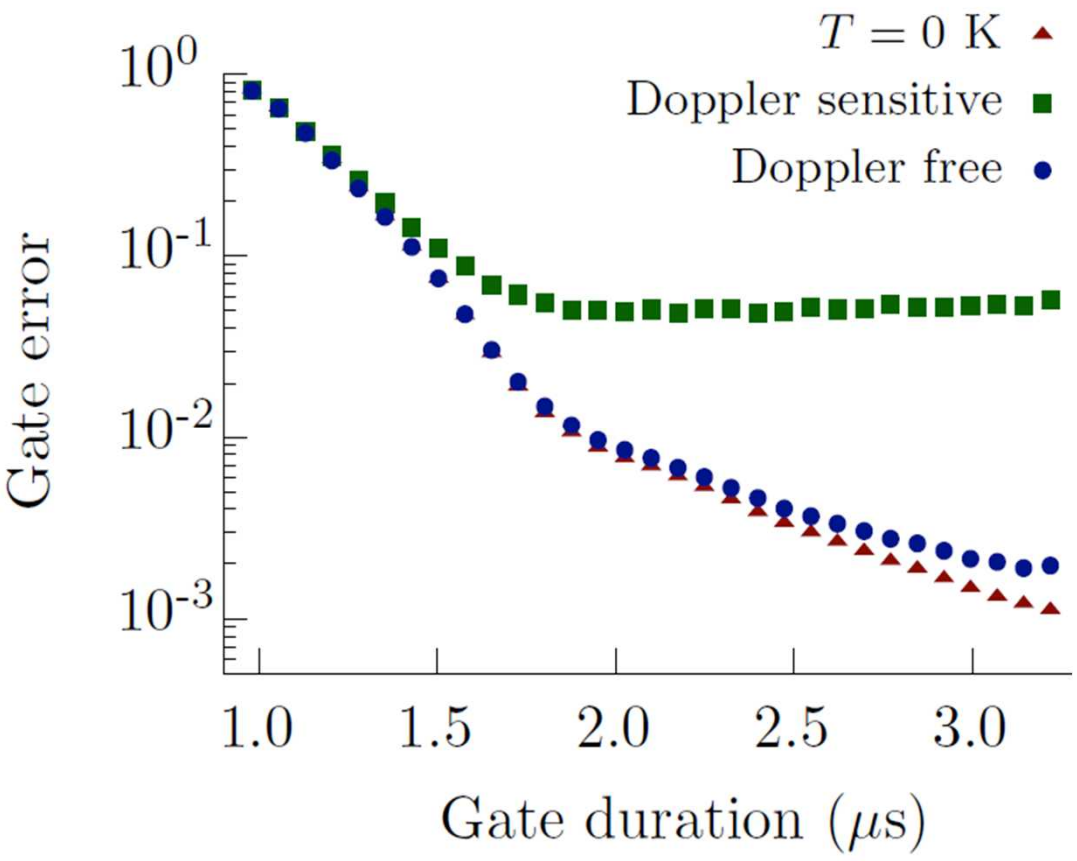


2-qubit basis



A frequency beat note is generated if $\omega_1 \neq \omega_2$

Simulated CPHASE gate fidelities



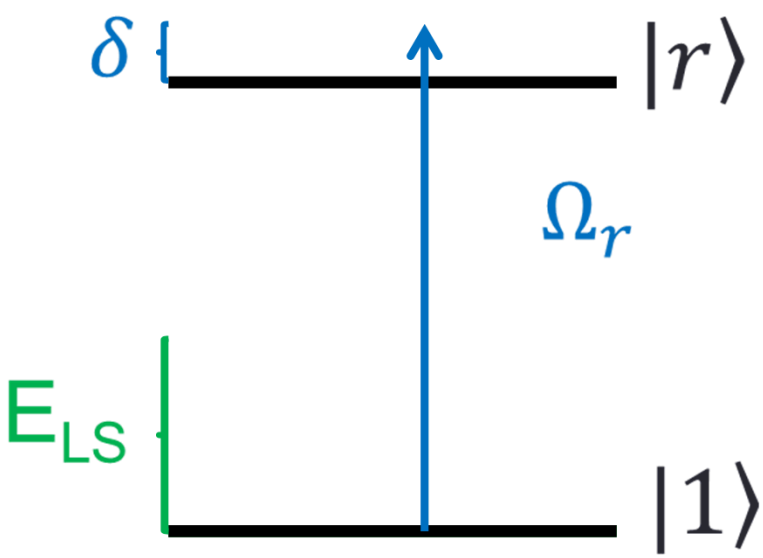
$\Omega = 0 \rightarrow 3$ MHz
$\Delta/2\pi = 6 \rightarrow 0$ MHz
$\Gamma = 3.7$ kHz
$T = 16\ \mu$K

- 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.

Phys. Rev. A 91, 012337 (2015)

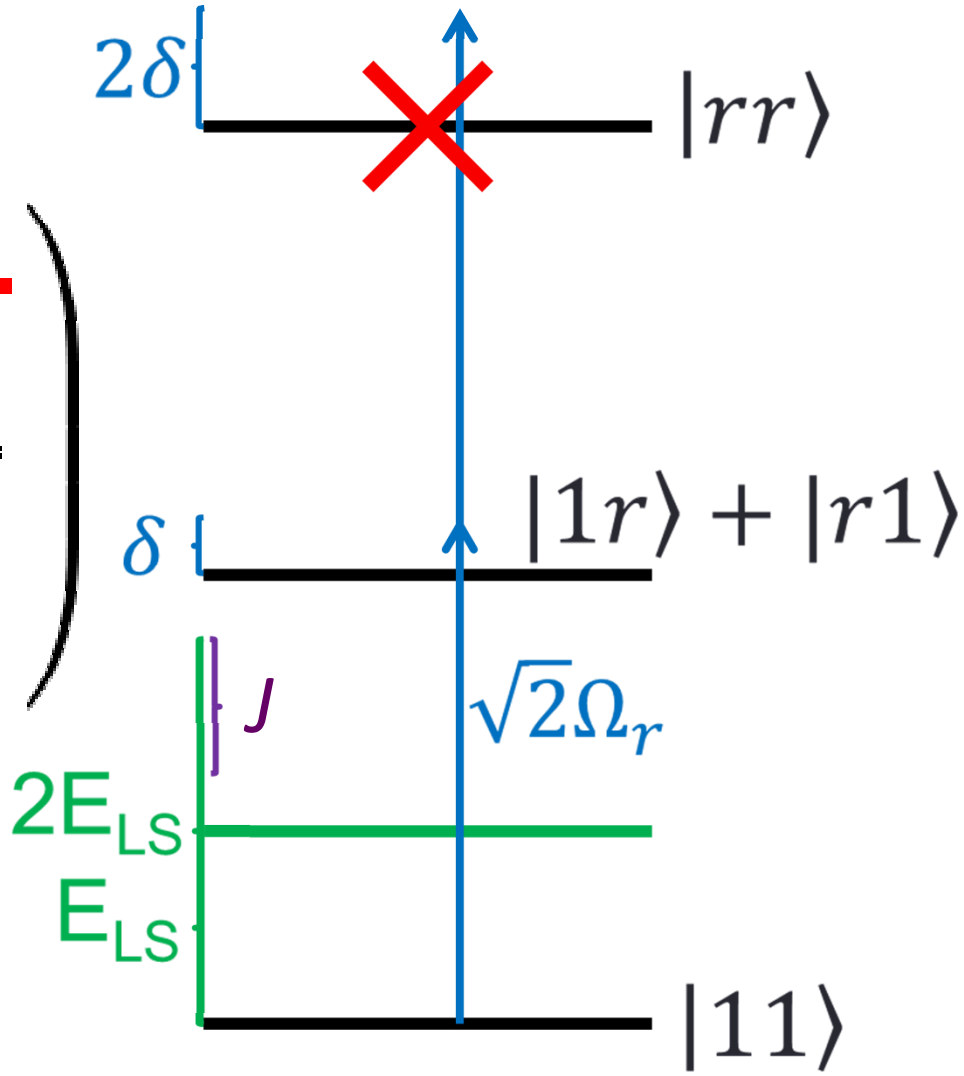
Rydberg-dressed states

$$H^{(1)} = \begin{pmatrix} -\delta_r & \frac{\Omega_r}{2} \\ \frac{\Omega_r}{2} & 0 \end{pmatrix}$$



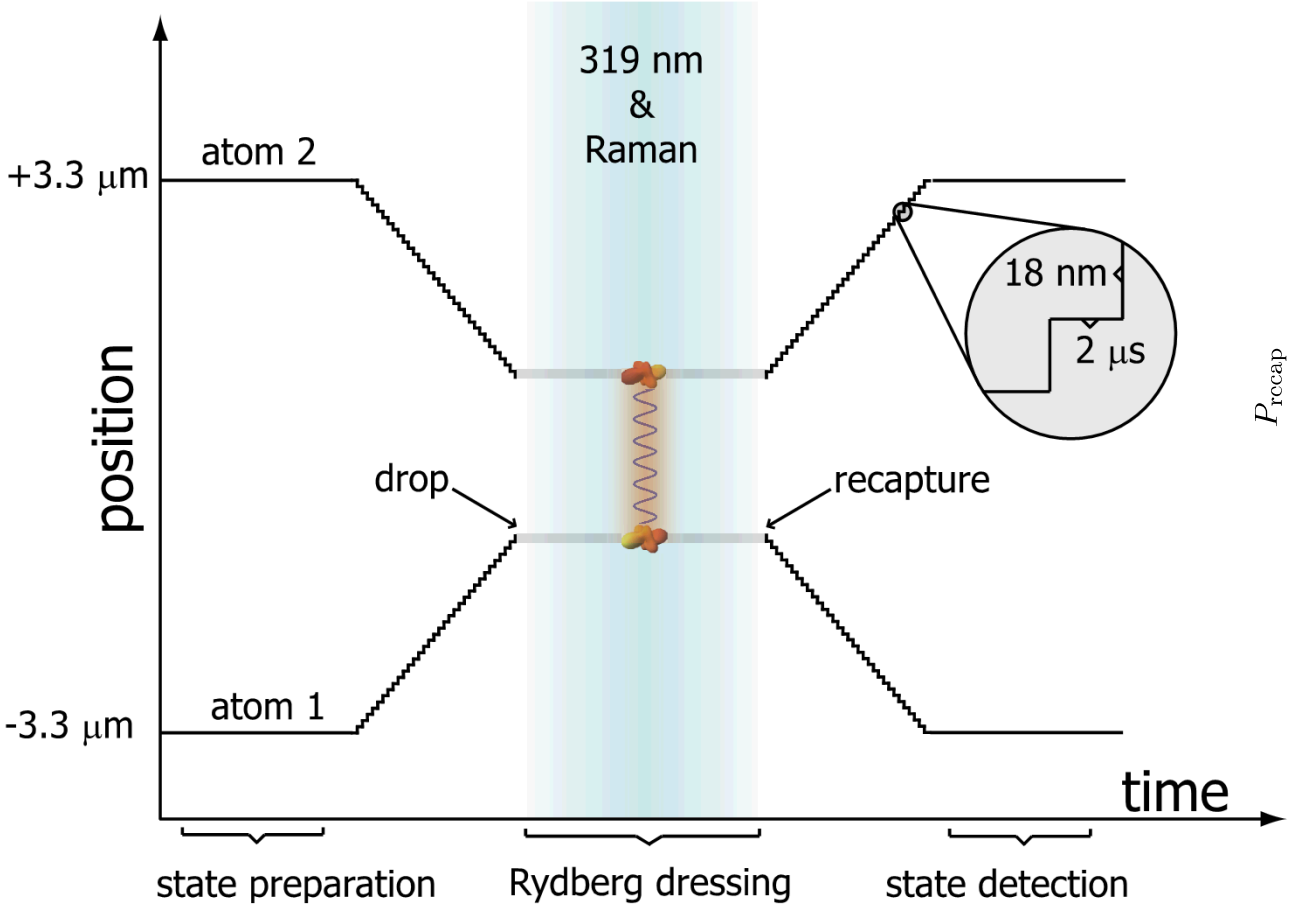
Rydberg-dressed states

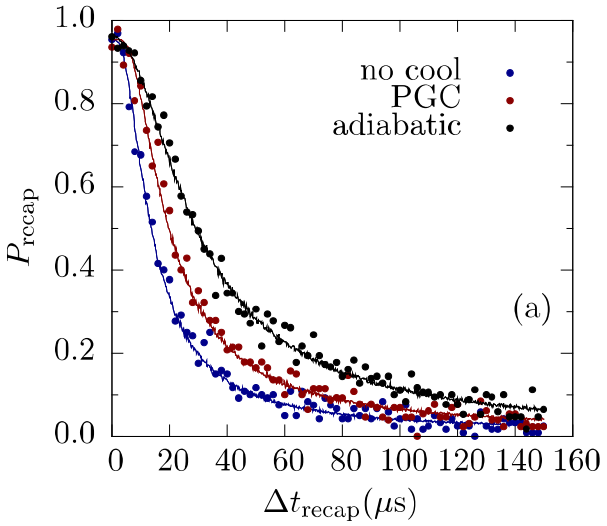
$$H^{(2)} = \begin{pmatrix} V_{dd} & \frac{\Omega_r}{\sqrt{2}} & 0 \\ \frac{\Omega_r}{\sqrt{2}} & -\delta_r & \frac{\Omega_r}{\sqrt{2}} \\ 0 & \frac{\Omega_r}{\sqrt{2}} & 0 \end{pmatrix}$$



$$\kappa = E_{LS}^{(2)} - 2E_{LS}^{(1)}$$

Dynamic atom positioning

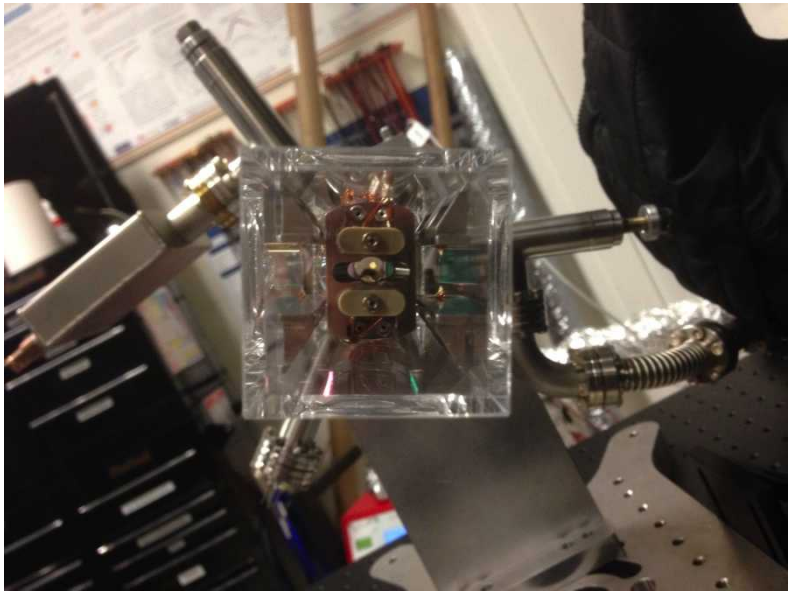




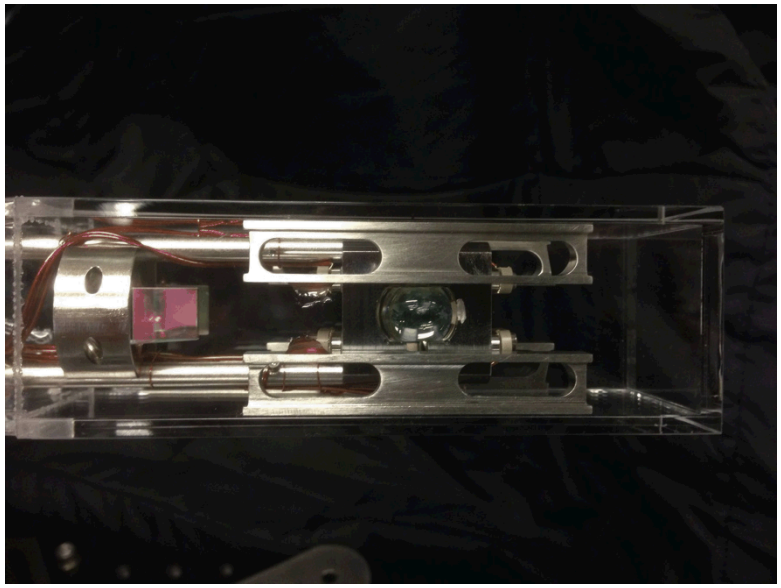
Drop and recapture

Apparatus—new configuration

Sandia National Laboratories



End view



Side view