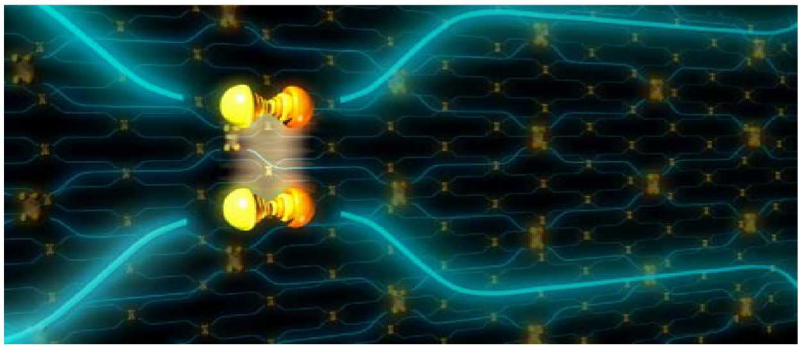
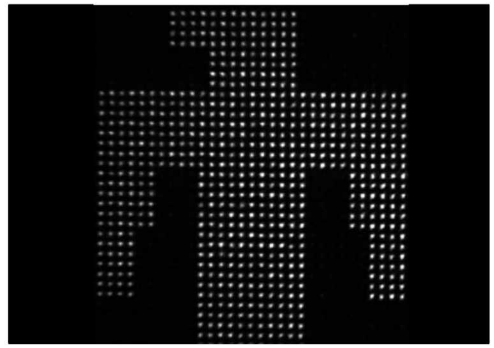
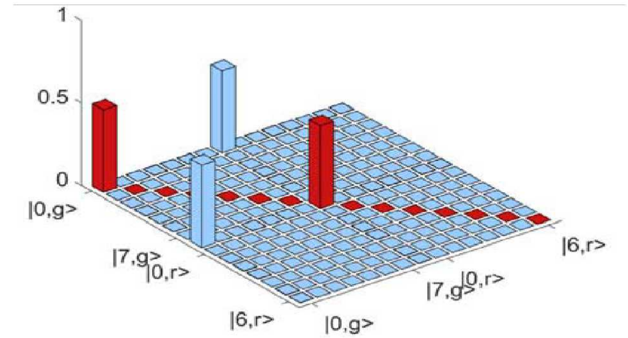
SAND2018-4373PE

Exceptional service in the national interest

Sandia National Laboratories







Optical manipulation of neutral atoms for quantum information science

Michael J. Martin

Team members
- **Grant W. Biedermann**
- Yuan-Yu Jau (Sandia)
- Jongmin Lee (Sandia)
- Ivan Deutsch (UNM)

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

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International, Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

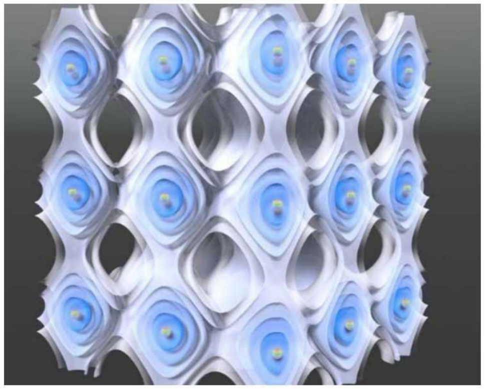
SAND2018-XXXX PE

Outline

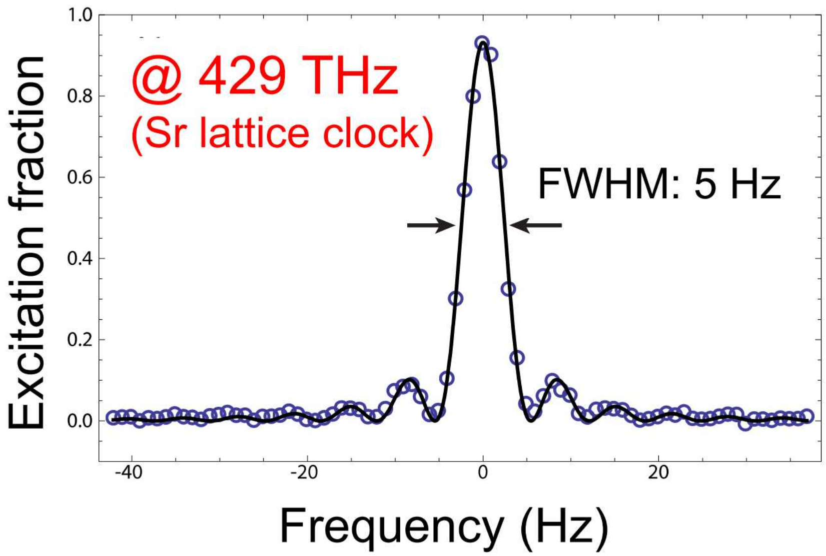
- Introduction to Rydberg atoms and the Sandia Rydberg atom experiment
- Rydberg dressed physics and entangling gates.
- Study of a controlled-phase (CPHASE) gate.
- Holography for trap arrays.

Neutral atom technology

- Trap, cool, manipulate 1 to >10^9 quantum particles.
- New phases of matter (*e.g.,* BEC).
- Incredibly precise measuring tools (root N).

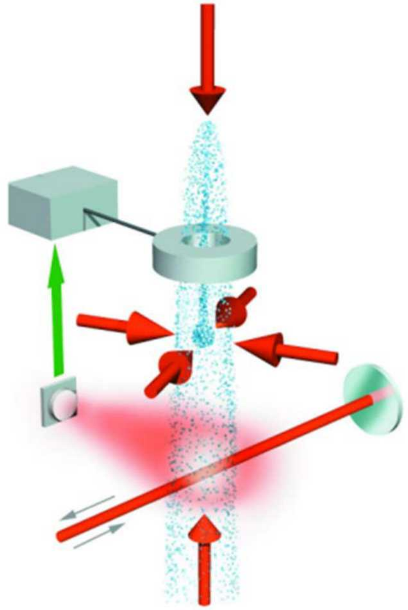


Credit: Brad Baxley, JILA



MJM, PhD Thesis, JILA

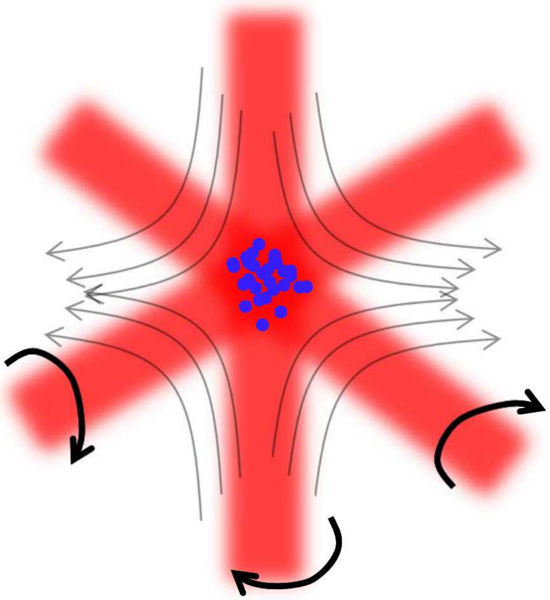
- Timekeeping, gravimetry, magnetometry, etc.



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

Neutral atom tools

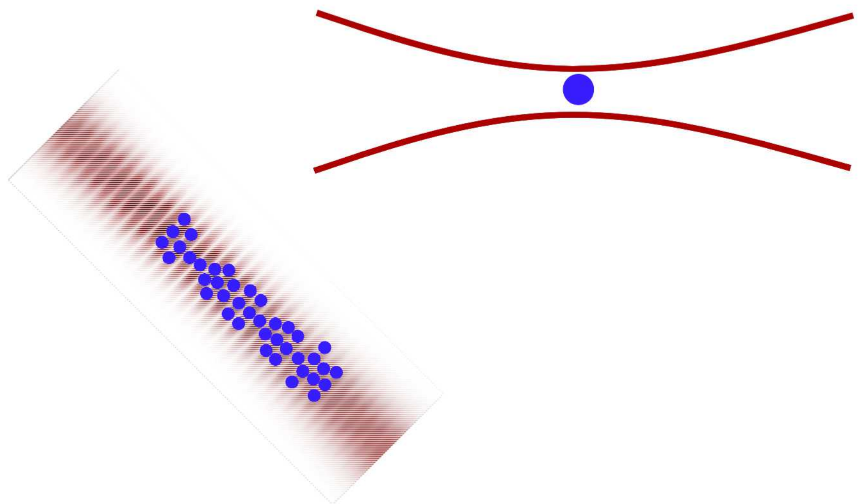
Magneto-optical trap (MOT)



- Trapping and cooling at the μK level via scattering laser light

Optical dipole traps

- Laser induces a polarization in atom that results in conservative trap potential.



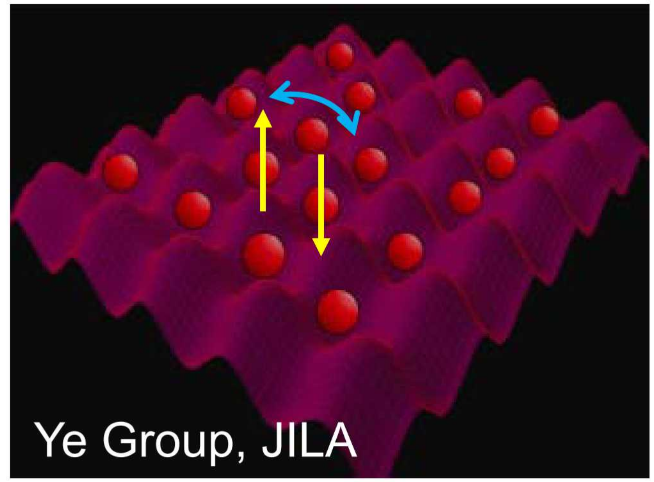
Interaction between *neutral* atoms

Atom 1 Atom 2

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

S-wave cold collisions

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



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

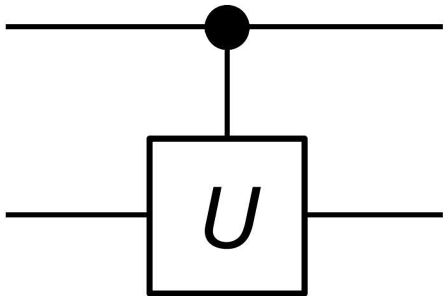
One solution: use Rydberg states

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

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

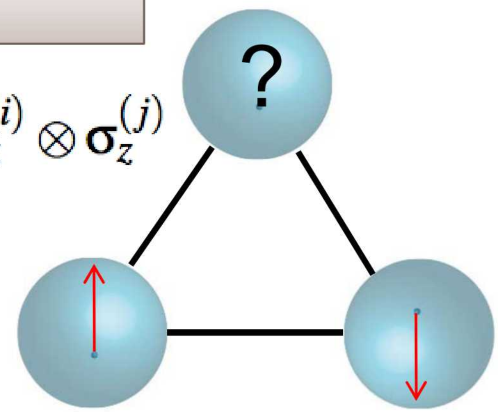
Applications

Pairwise entangling gates between two neutral atoms



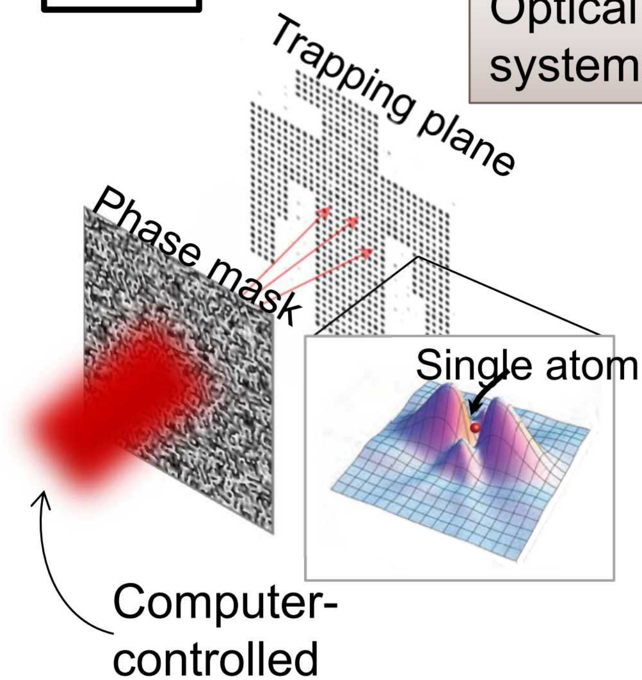
Quantum simulation

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

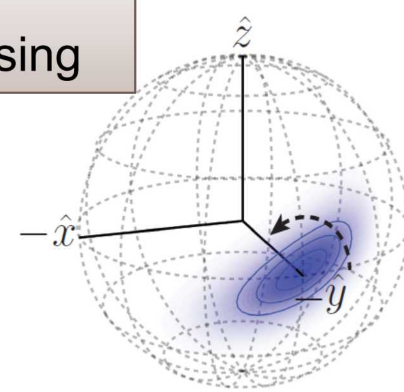


Frustrated magnetism

Optical control of atomic systems

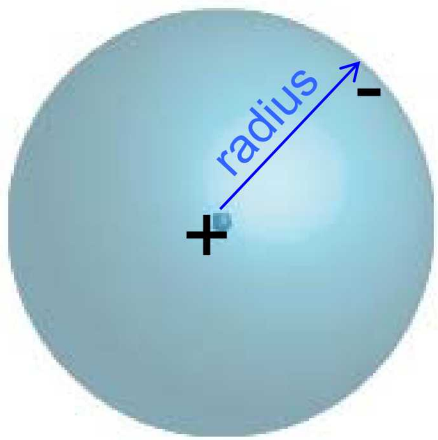


Large-scale/rapid entanglement for sensing



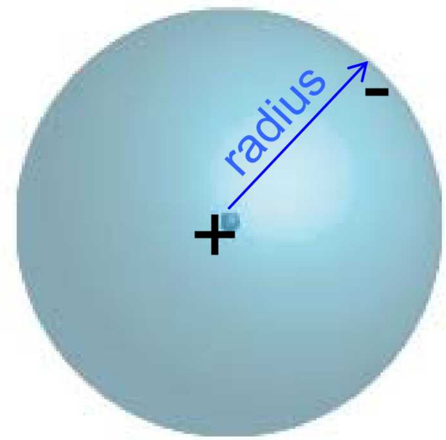
Interaction between *neutral* atoms

Valence electron
in Rydberg state



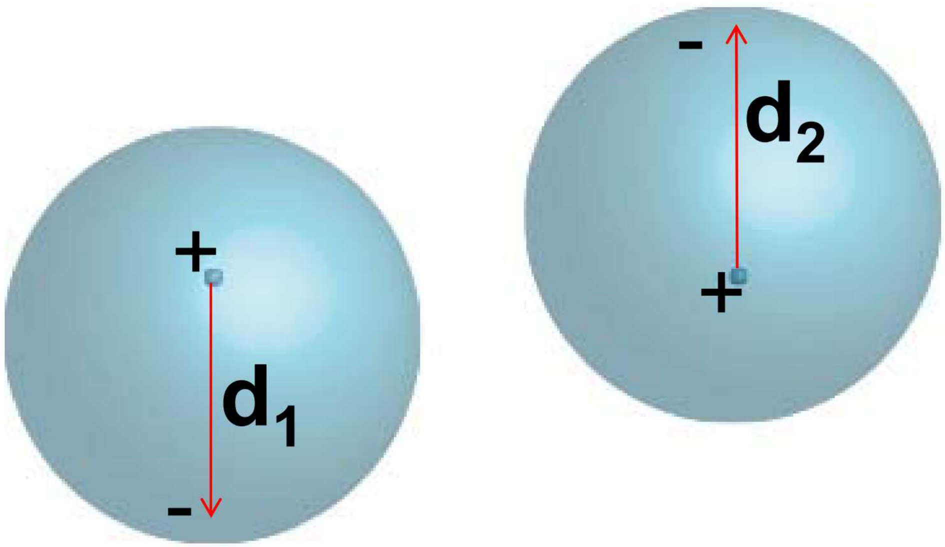
orbital radius α n^2

Valence electron
in Rydberg state



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

Interaction between *neutral* atoms



van der Waals interaction

<u>Parameter scaling</u>

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

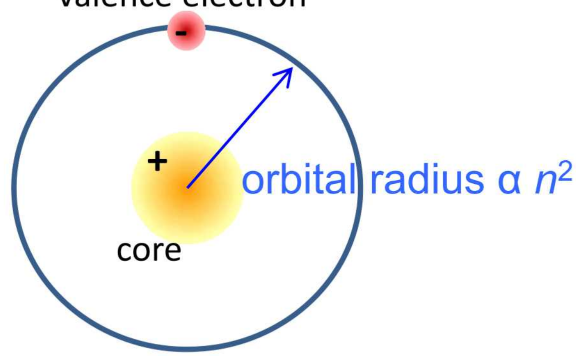
Lifetime
$\tau \propto n^{3}$

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 $\propto 1/r^6$

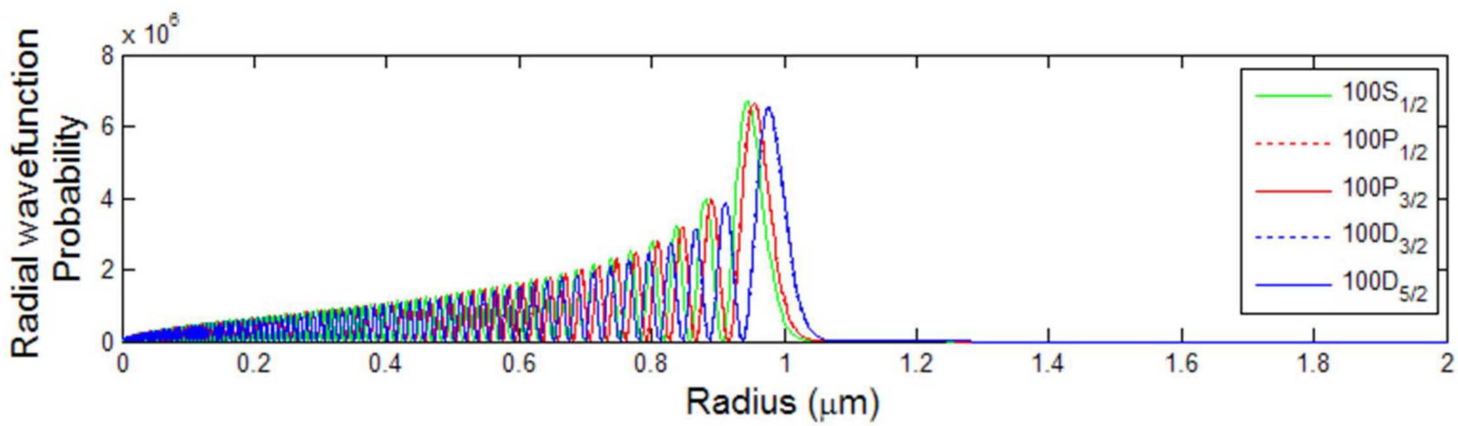
Entanglement demonstrations
- Madison: Phys. Rev. Lett. 104, 010503 (2010)
- Paris: Phys. Rev. Lett. 104, 010502 (2010)

Rydberg state mediated interaction

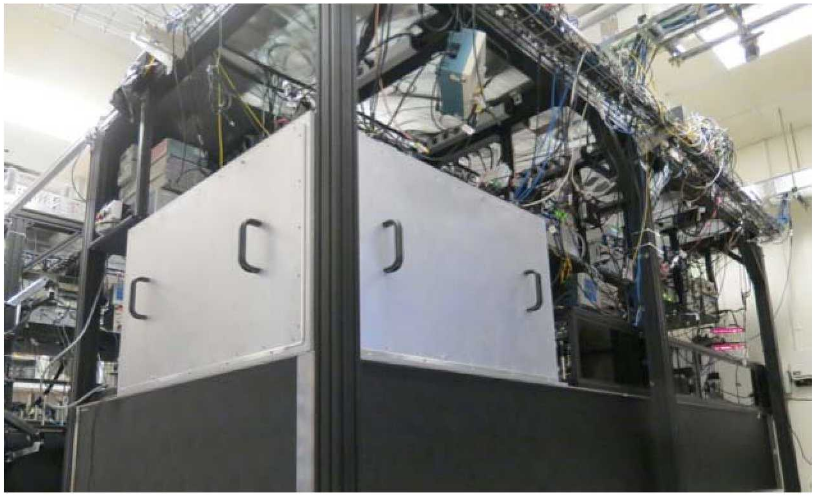


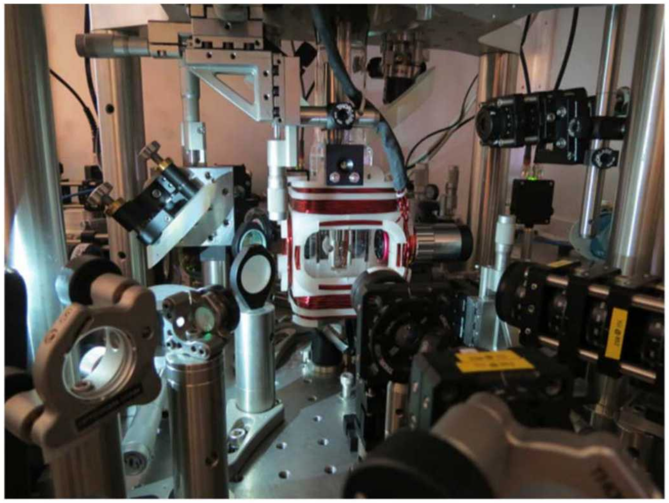
A classical picture of an atom

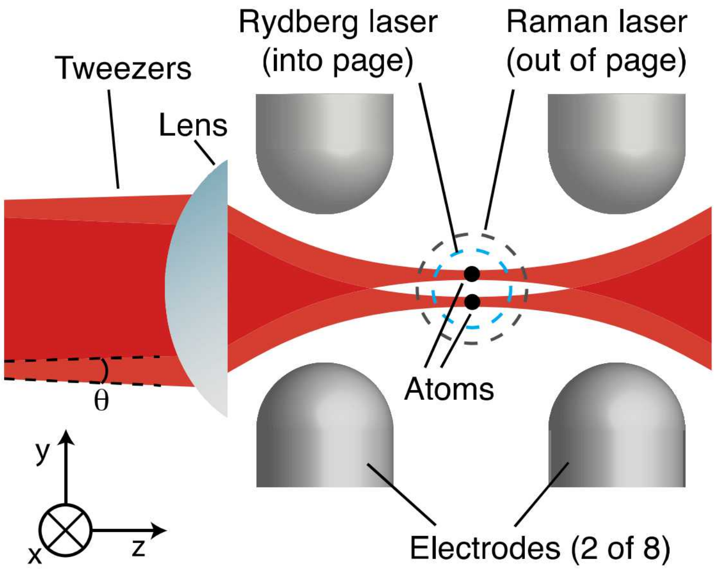
An example of the radial wavefunctions of a Cs atom at n = 100:



Apparatus

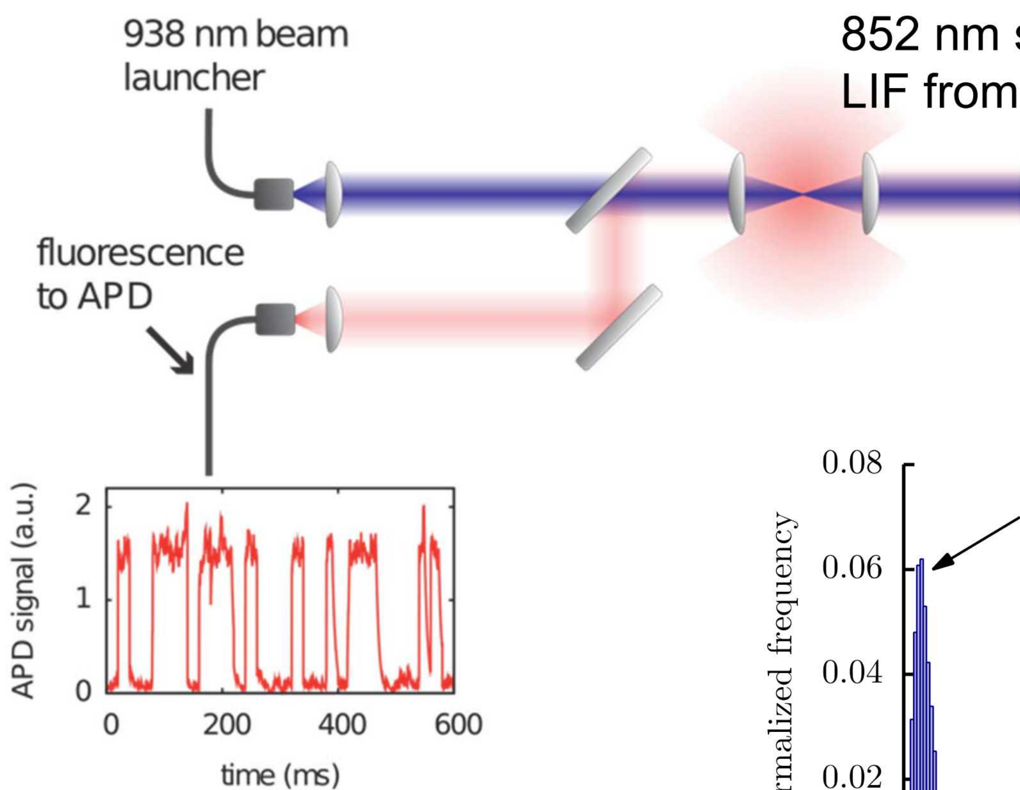


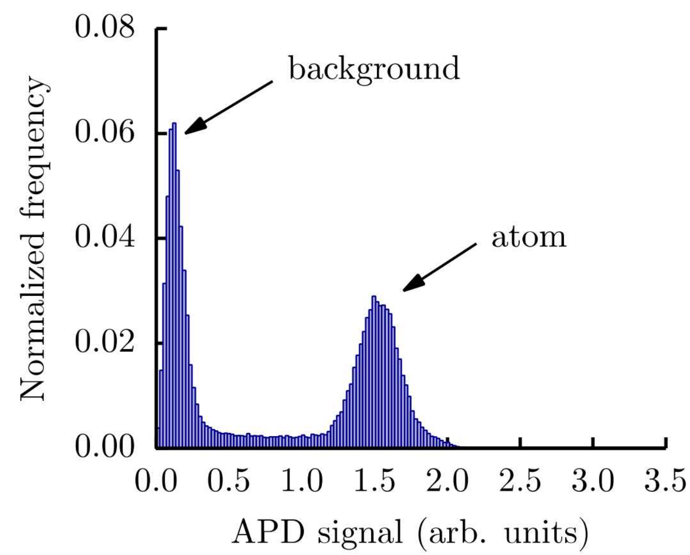



Rydberg laser
(into page)
Raman laser
(out of page)
Tweezers
Lens
θ
Atoms
y
x
z
Electrodes (2 of 8)

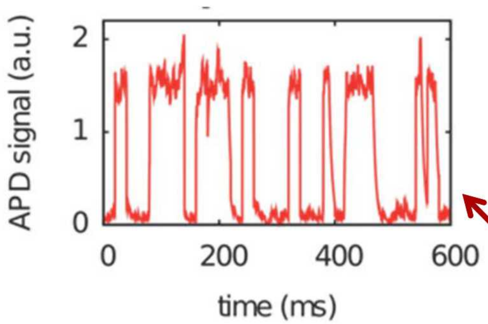
Single atom control

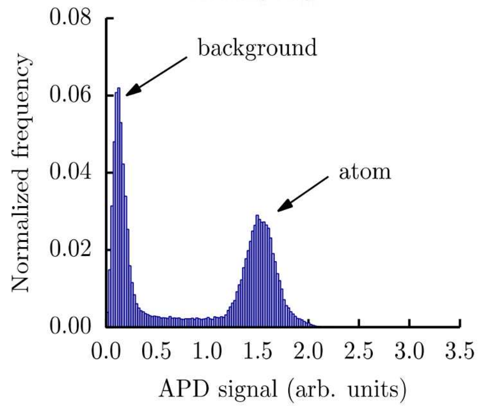
852 nm scatter:
LIF from laser cooling light

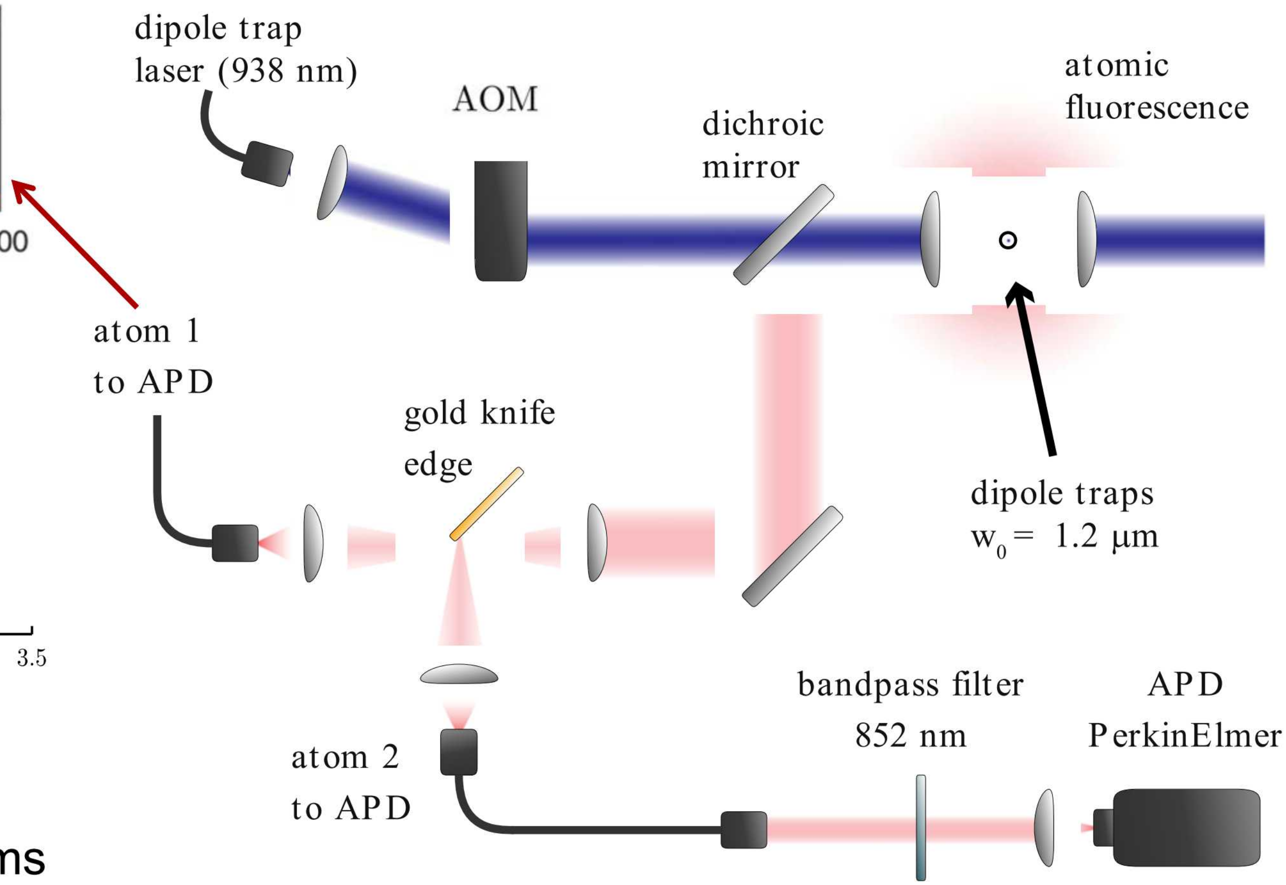




Single atom control of 2 atoms

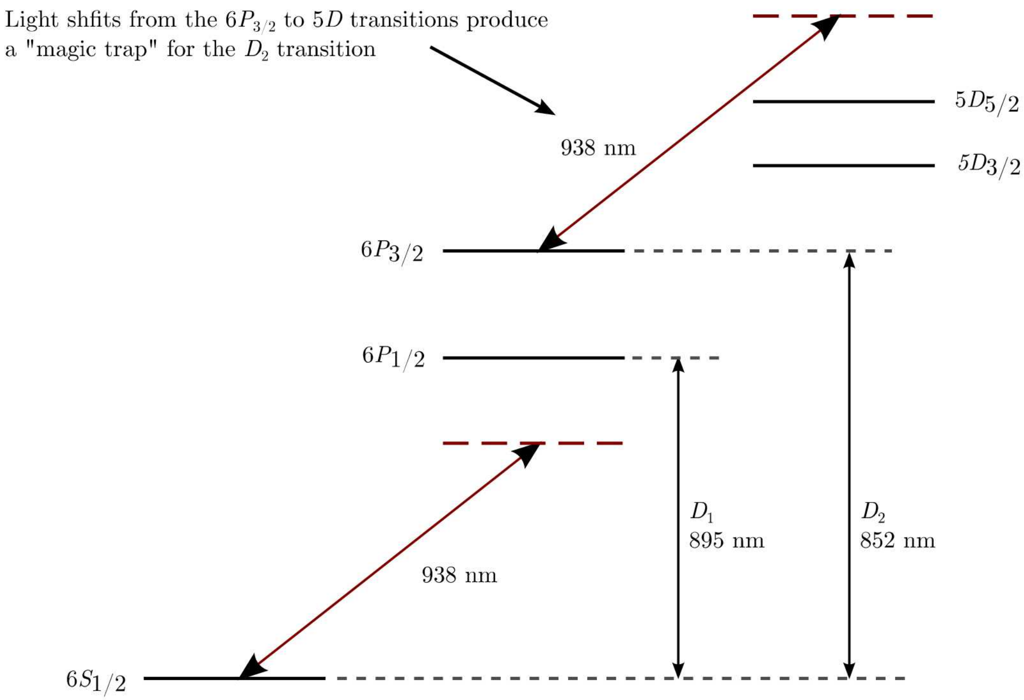


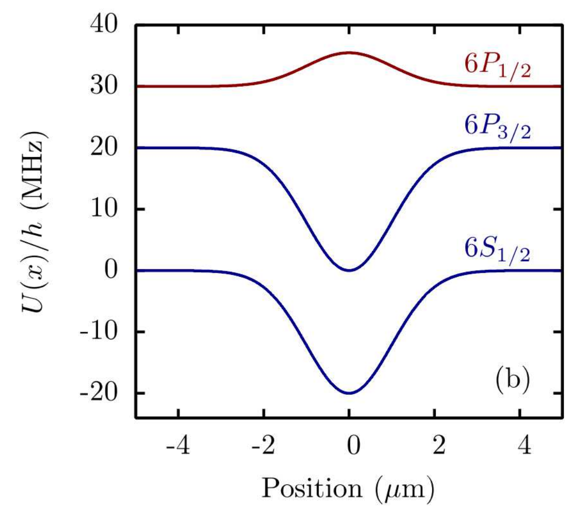




- Optical tweezers
- Trap single Cs atoms
- Laser cooling to load traps
- AOM deflection controls trap position
- Photon counters for detection

A note about our optical tweezers

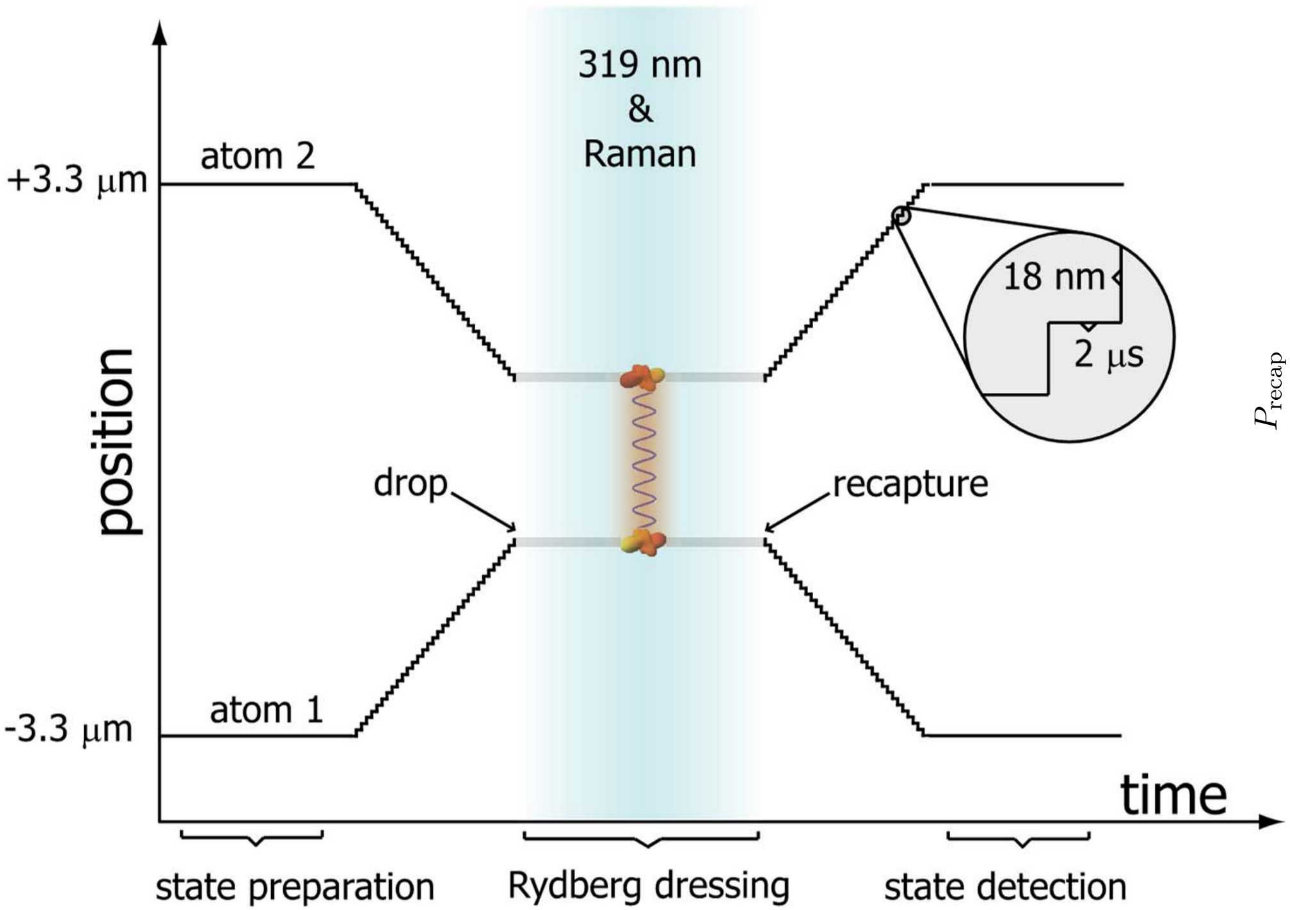


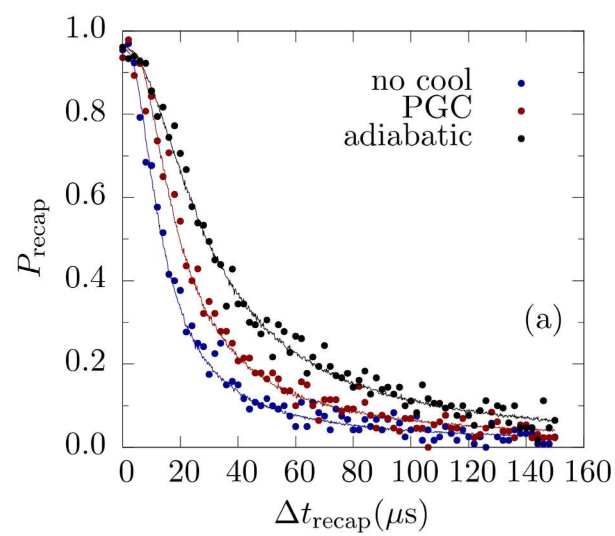


Why 938 nm? It's magic for the cooling transition.

- ≈ 5 mW, 43 nm red
- focused to ≈ 1 μm
- gives ≈ 20 MHz or ≈ 1 mK

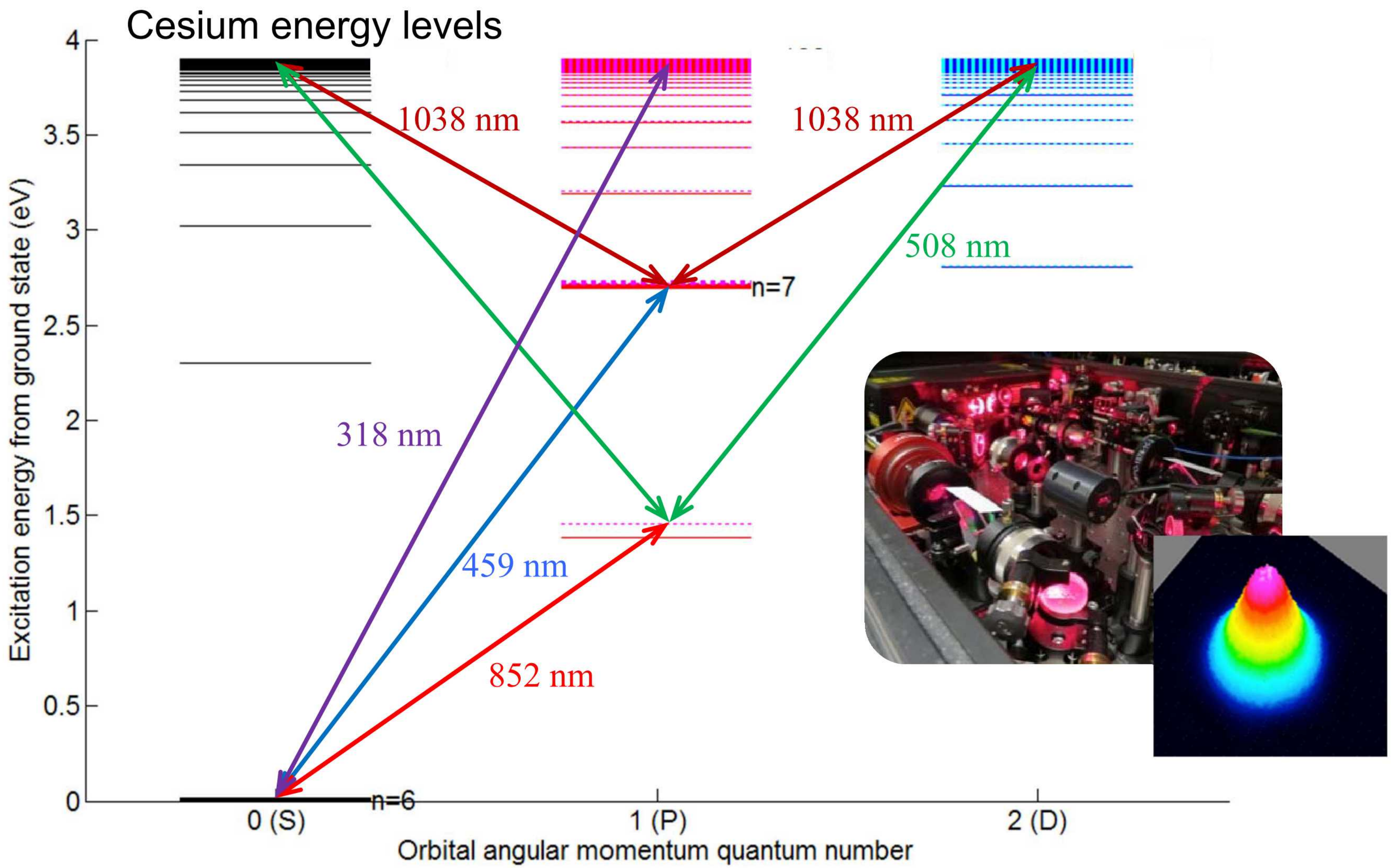
Dynamic atom positioning



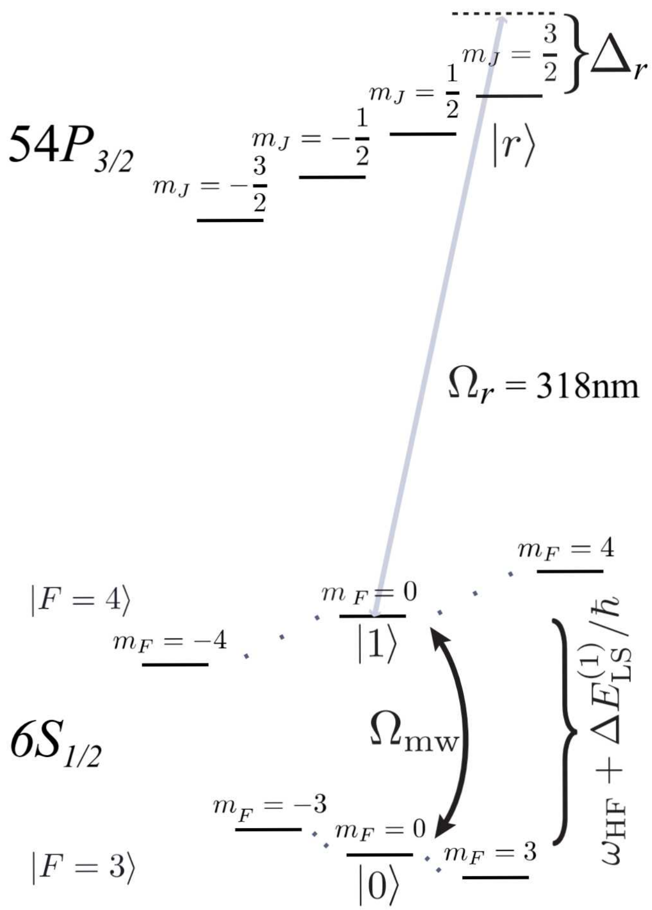


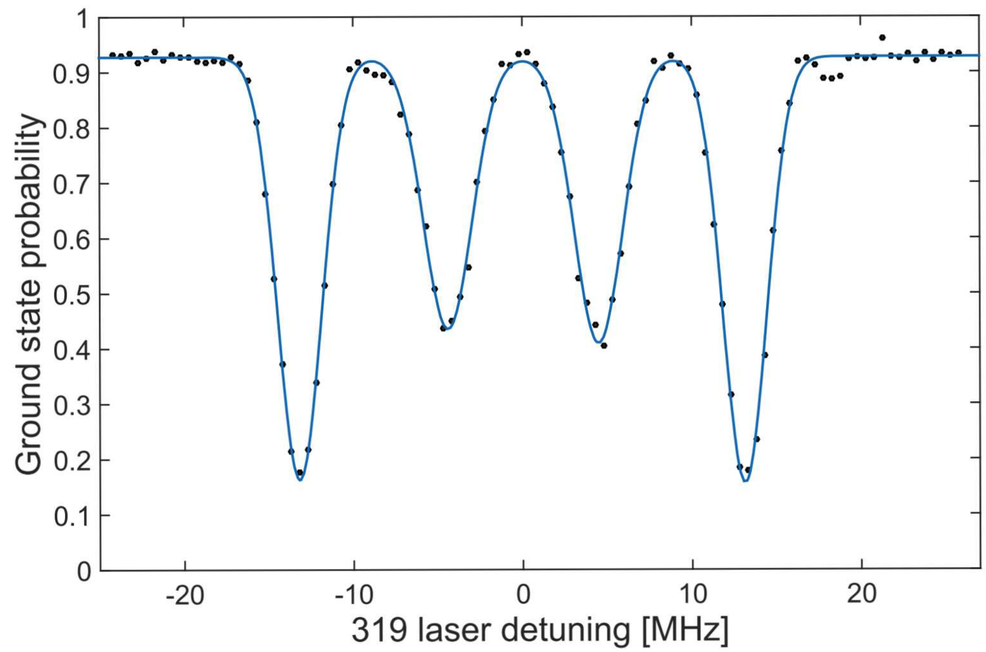
Drop and recapture

Rydberg excitation laser

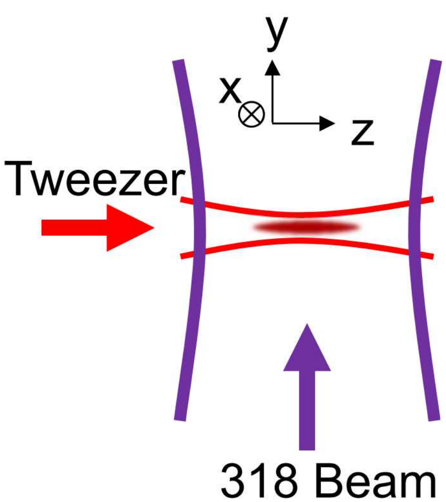


Rydberg state spectrum

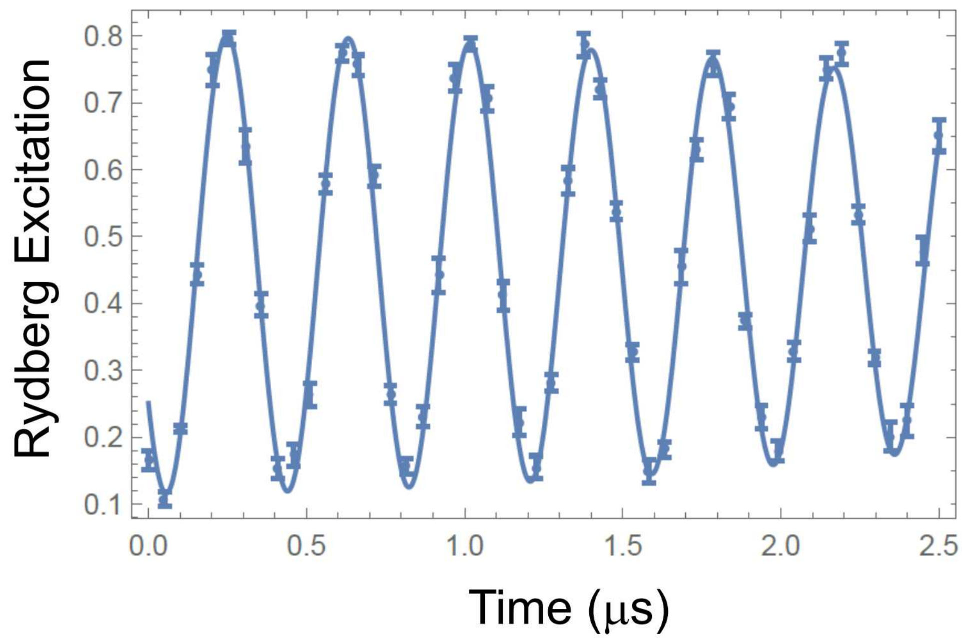


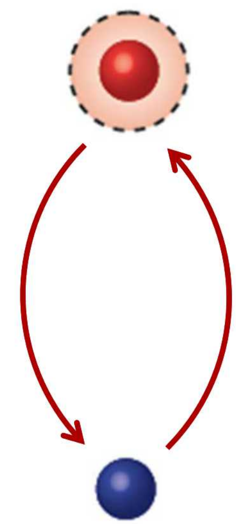


Direct excitation 318 nm Rydberg Rabi flopping

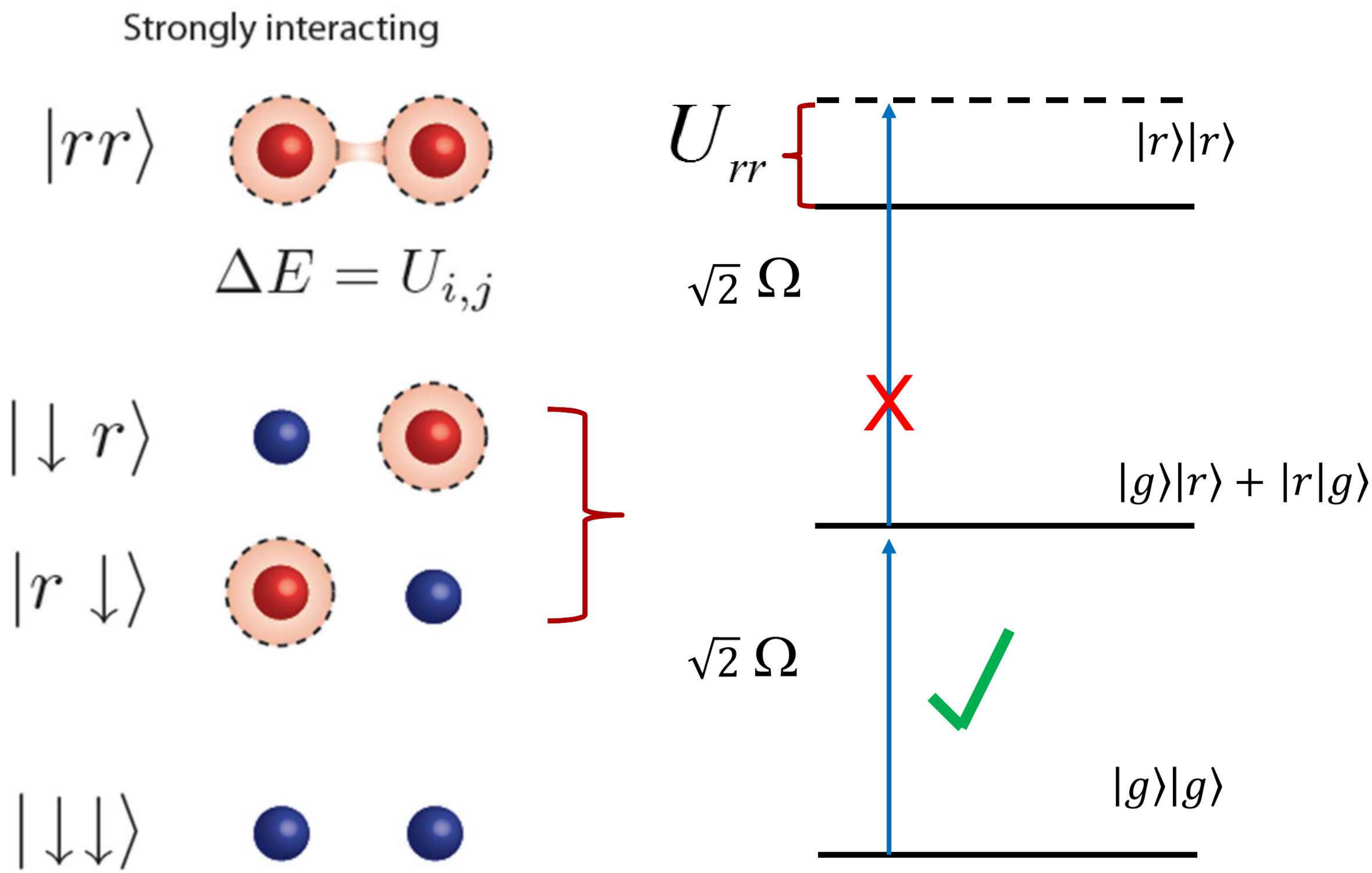


Direct excitation, measured through loss

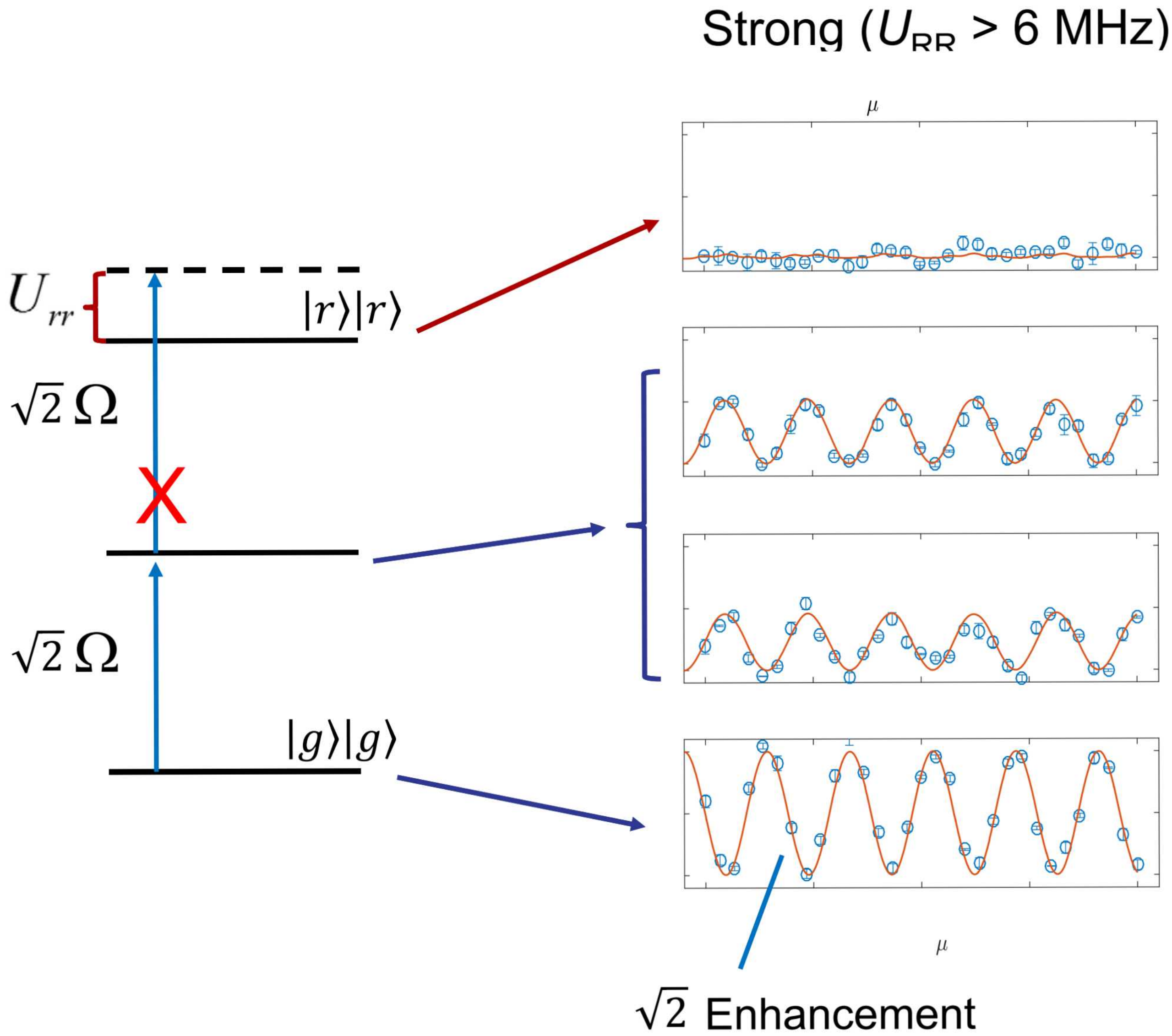




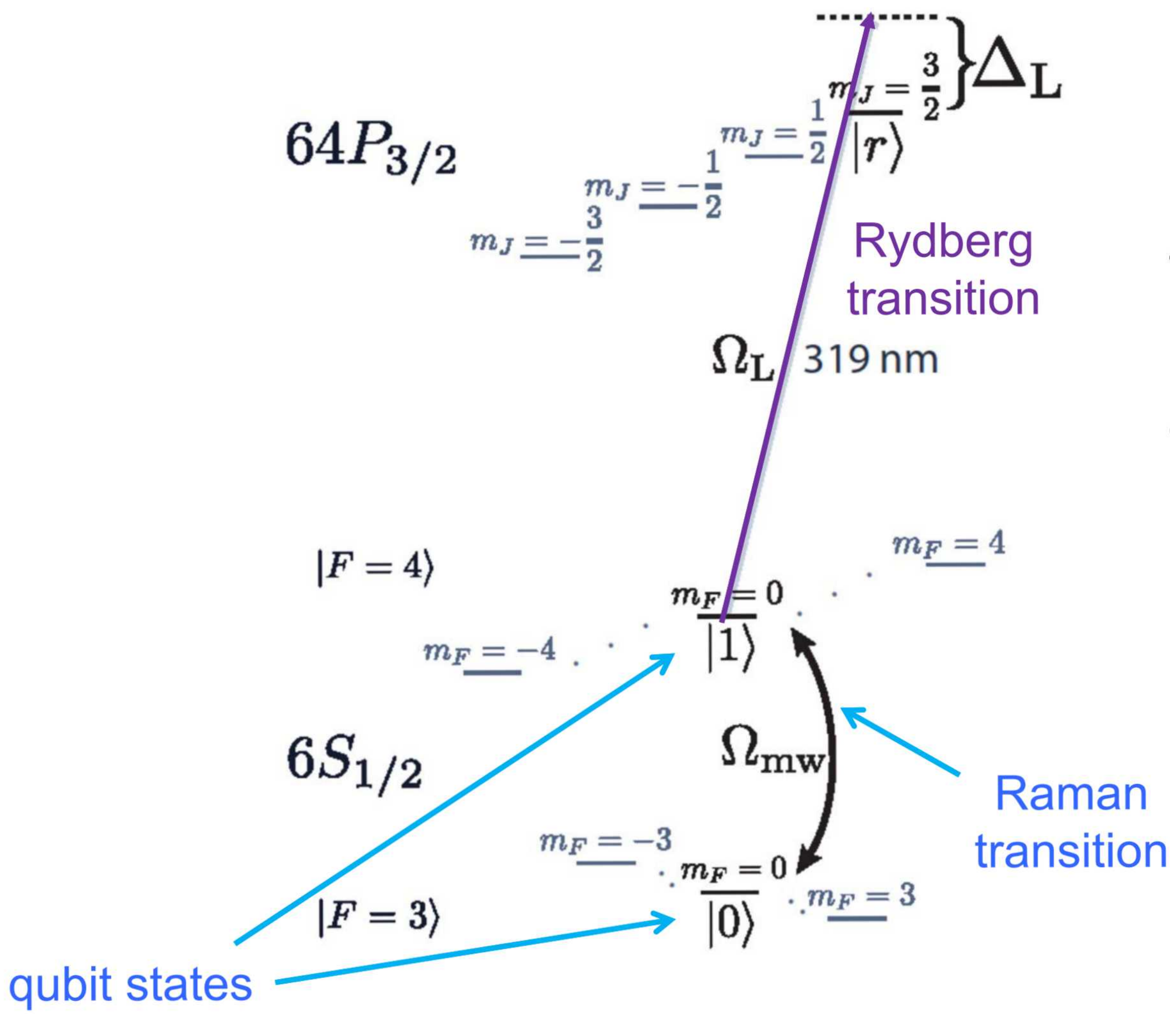
Two-atom picture



Two-atom Rydberg blockade



Level diagram



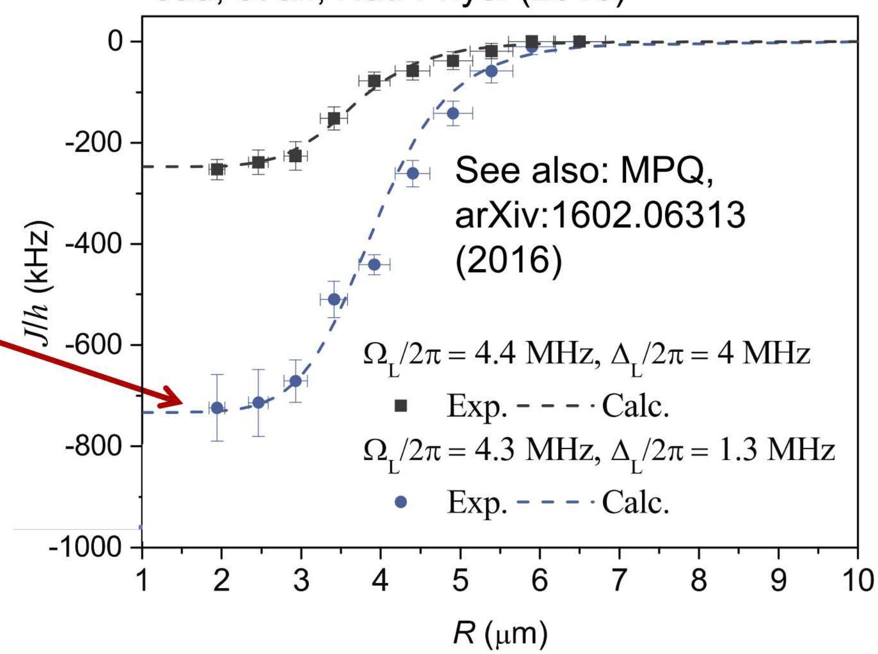
- 1-S scale coherence time. Neutral atoms define the SI second!
- Form the basis of sensors and clocks that utilize measurements of **~10^6** atoms.

Rydberg-dressed interaction
First measurement

Smooth and tunable!

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

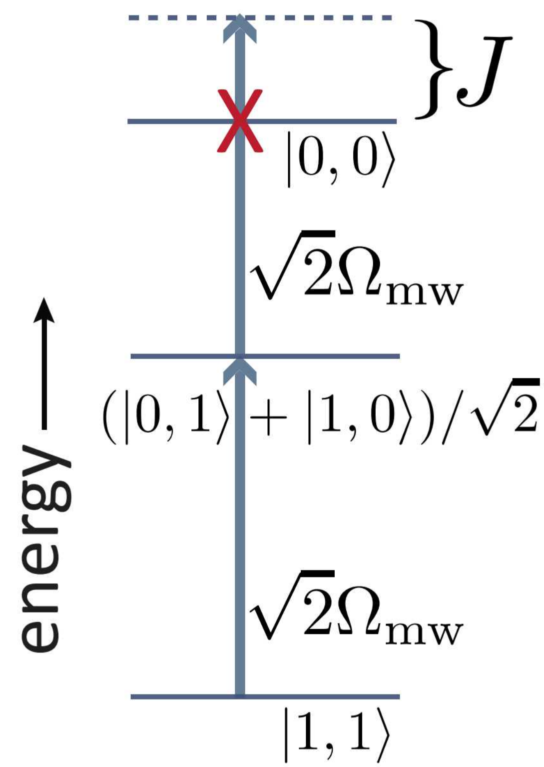
Interaction >> Ω_r
J saturates

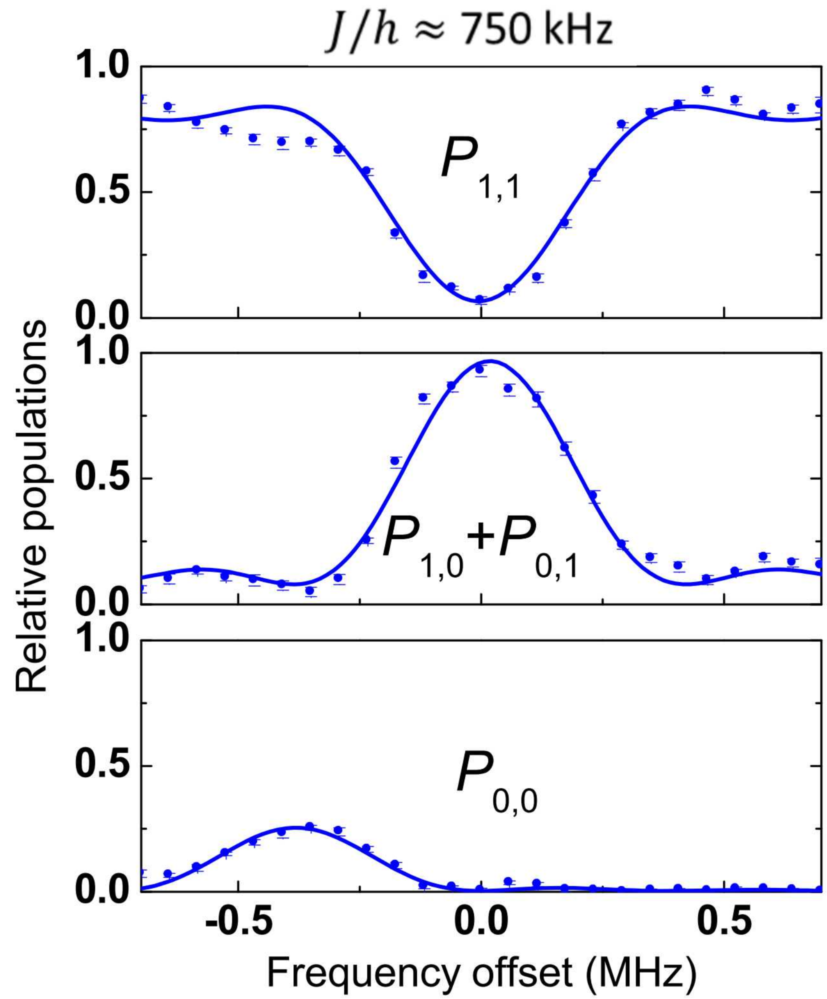


Strong interaction

Can be either positive or negative

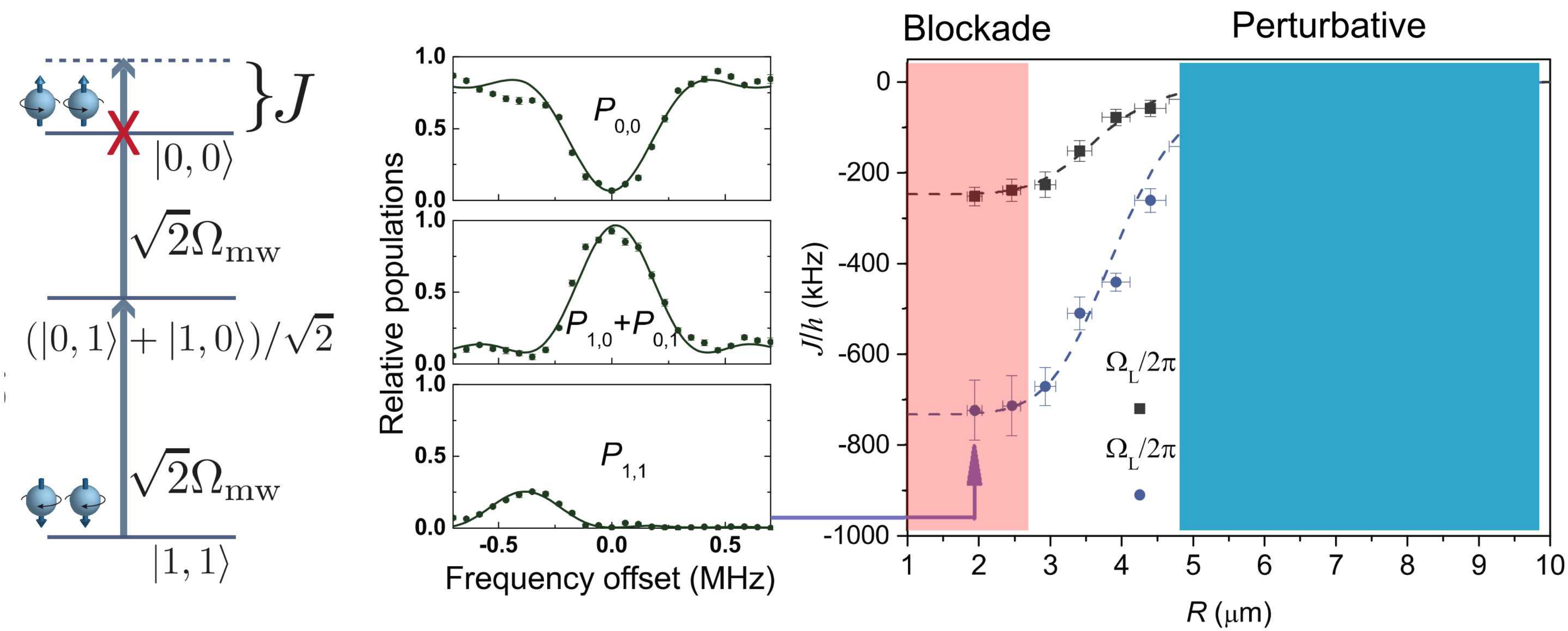
Two-qubit microwave resonances





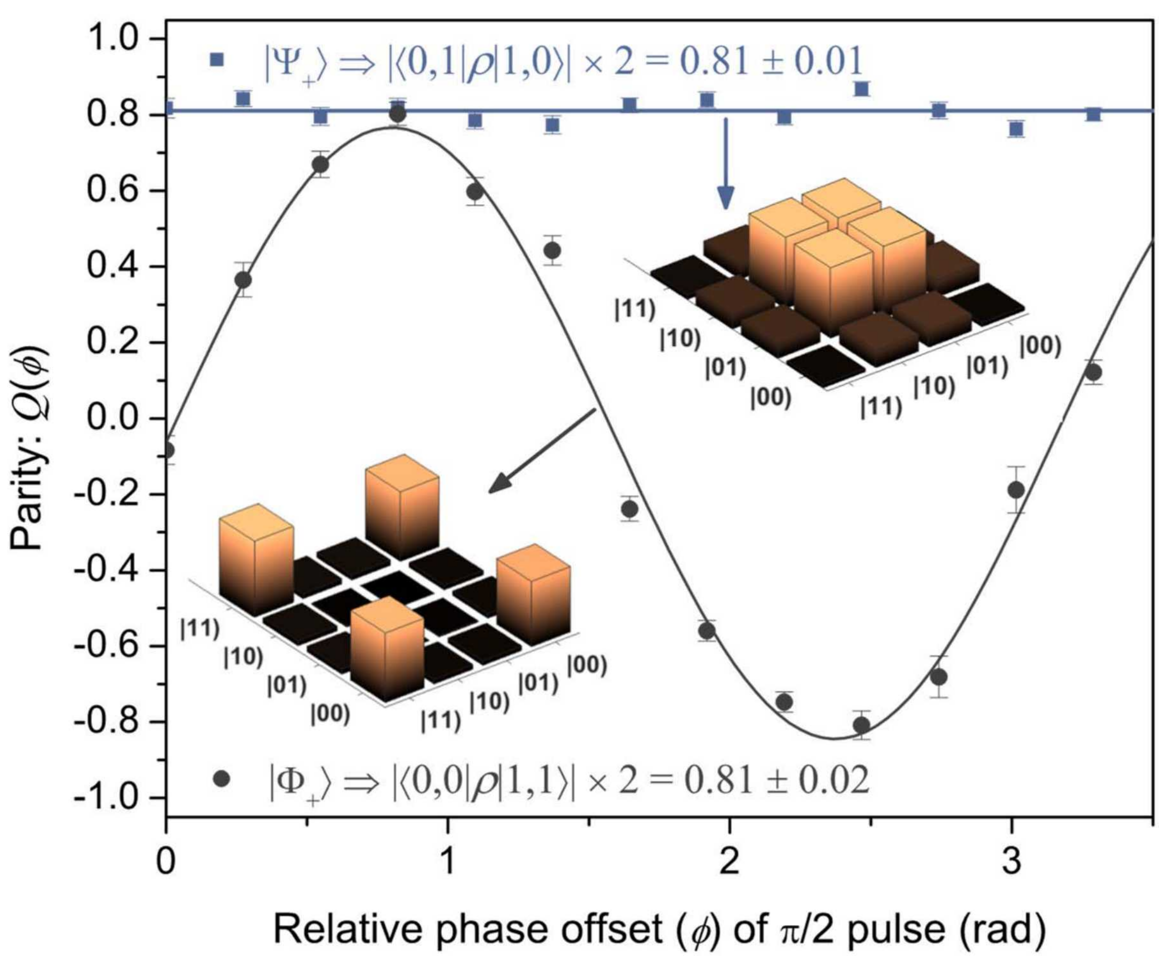
Observing blockade on hyperfine qubit

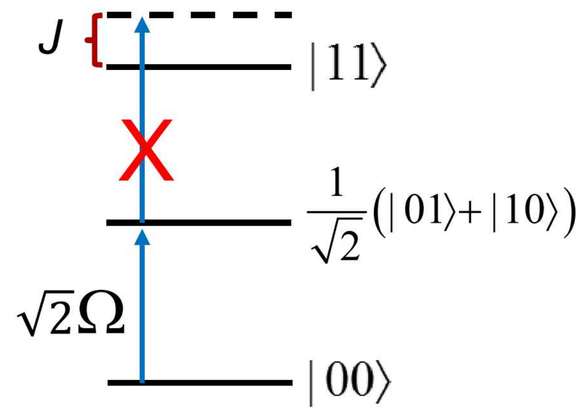
Direct measurement of two-qubit interaction strength *J* as a function of two-atom separation with different dressing conditions.



Spin-flip blockade

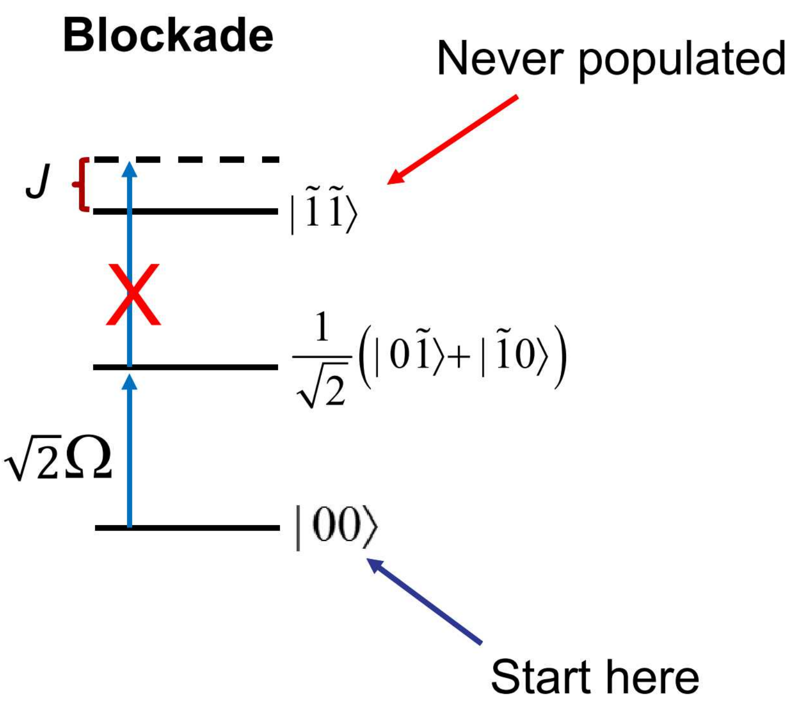
Verify the entanglement via parity measurements





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

Spin-flip blockade vs. CPHASE



Controlled Phase (CPHASE)

- Utilize nonlinear Hamiltonian that can be turned on at will:

$$\hat{H}_{DD} = J\,|\tilde{1}\tilde{1}\rangle\langle\tilde{1}\tilde{1}|$$

- Start in any state you want, e.g.,

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

$$\hat{H}_{DD}$$

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

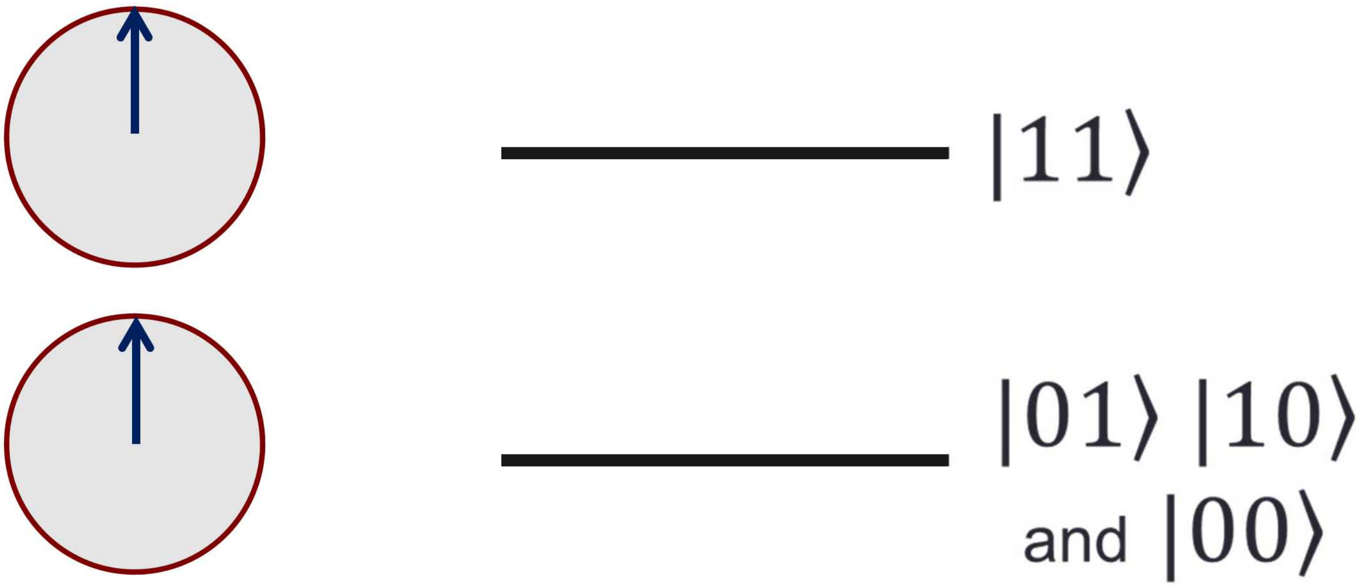
Entangled state!

Generating Entanglement

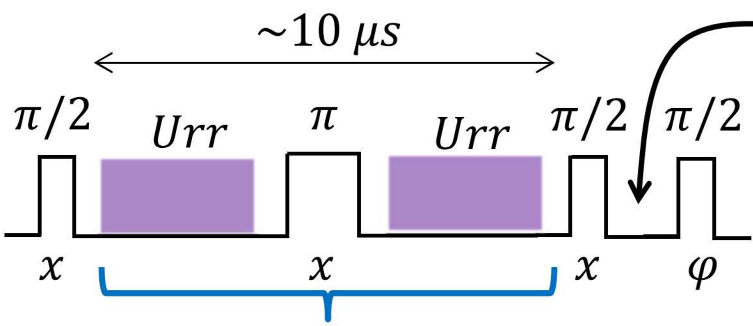
$\hat{H}_{DD} = J\,|11\rangle\langle 11|$

Phase:

Laser ONFF

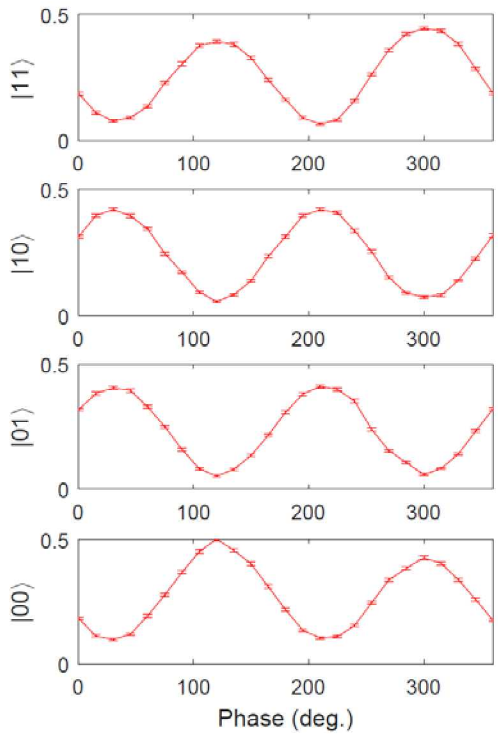


Dressed CPHASE gate

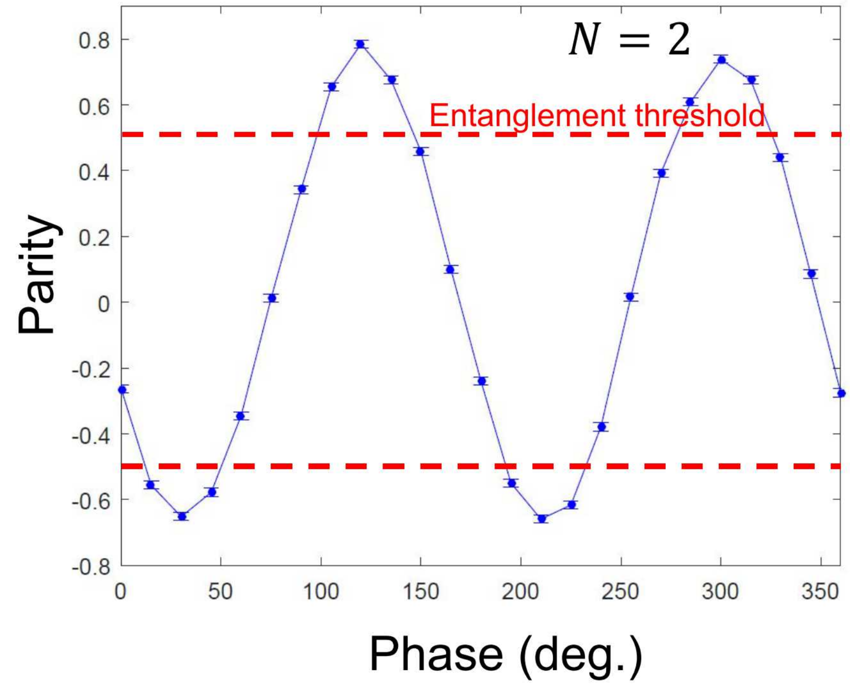


$$|\psi\rangle = \frac{|\uparrow\uparrow\rangle + |\downarrow\downarrow\rangle}{\sqrt{2}}$$

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



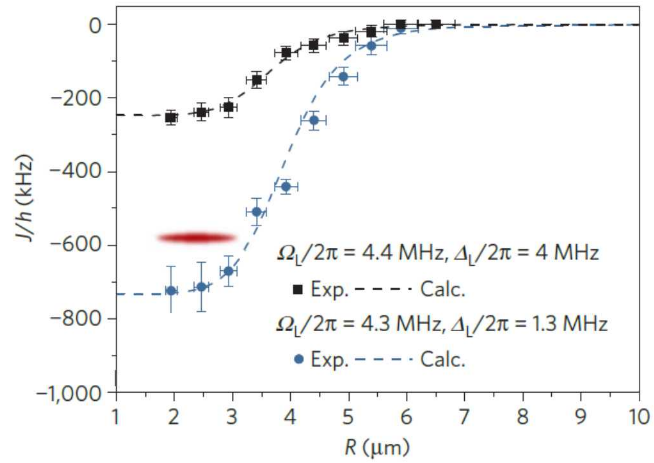
$$\langle \hat{\Pi} \rangle \propto \sin N\varphi$$

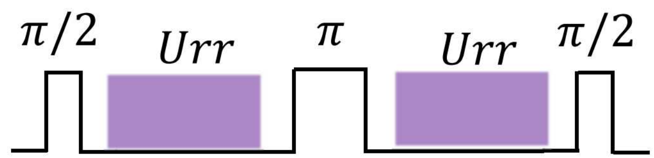


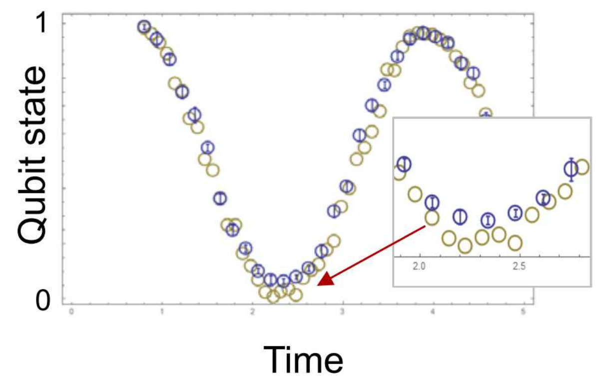
J. J. Bollinger *et al.*, “Optimal frequency measurements with maximally correlated states.” Phys. Rev. A **54**(6) (1996).

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%

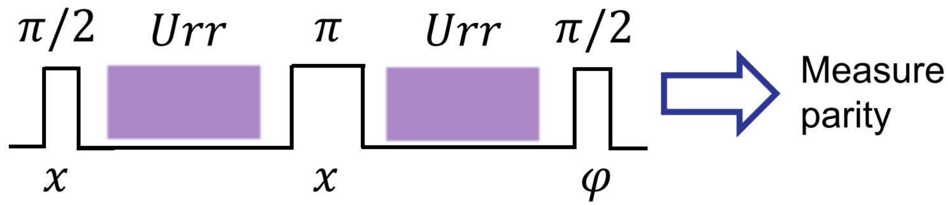




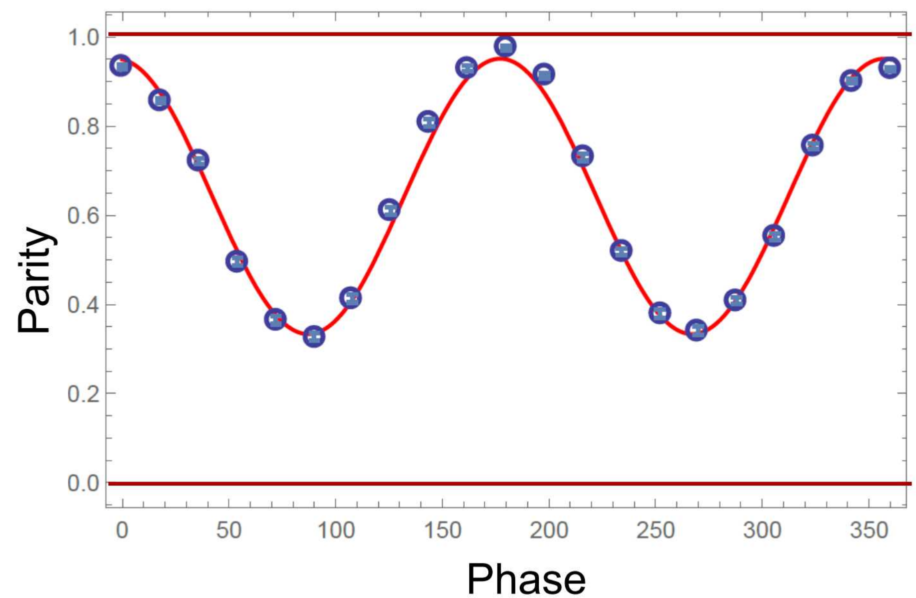


Local oscillator noise

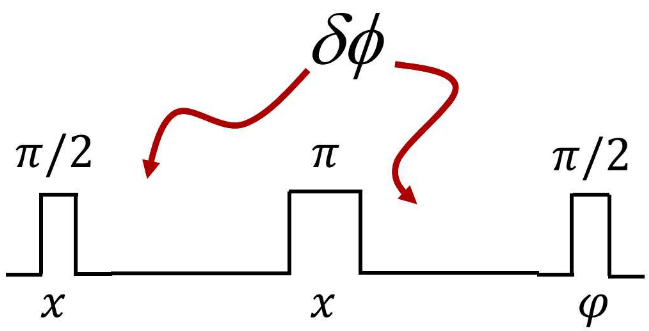
- Sequence to test qubit rotation operations:



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



- Measured results consistent with 0.5 rad RMS phase fluctuations:

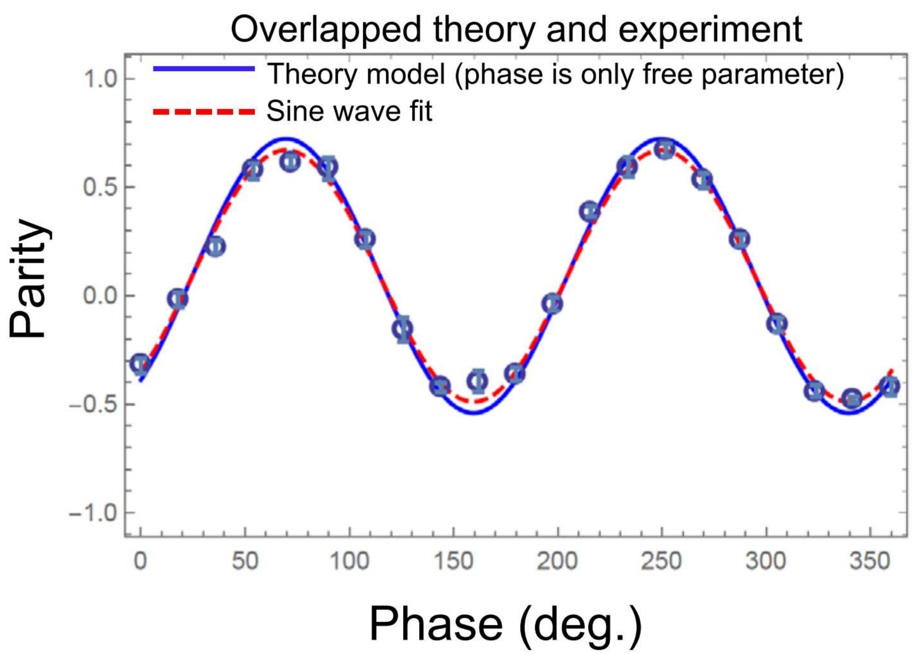


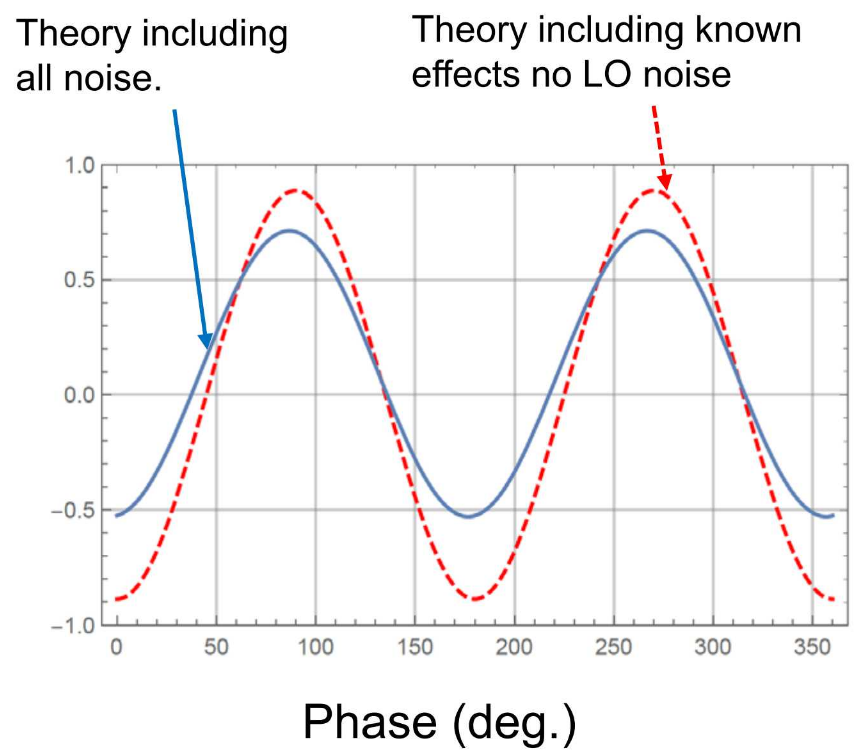
- Potential sources: Raman Laser linewidth and near-resonant amplified spontaneous emission pedestal.

CPHASE limitations

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

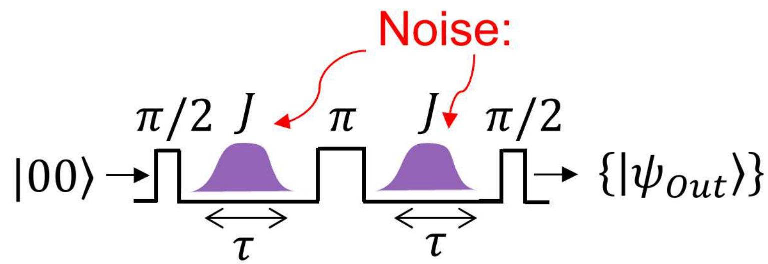
→ Theory model with measured noise parameters matches data.





Error budget for CPHASE gate

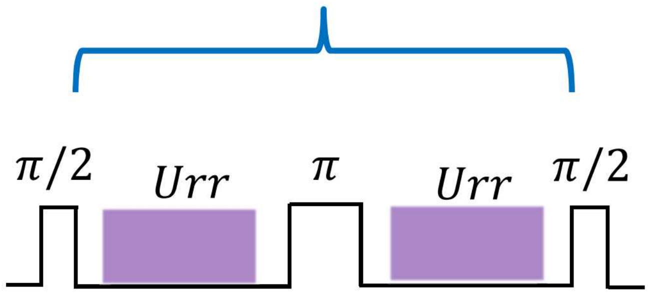
Fidelity = $\langle \psi_{tar} | \rho_{out} | \psi_{tar} \rangle$



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**

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.

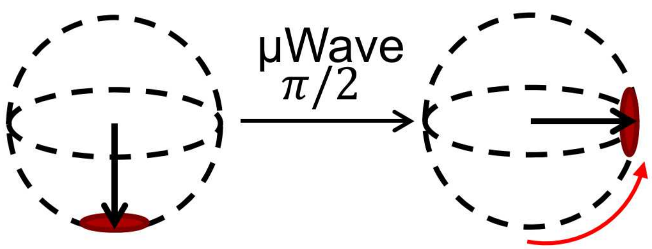
- For *N* atoms all within a blockade radius, an *N*-atom cat state forms at $J \times \tau = \pi/2$

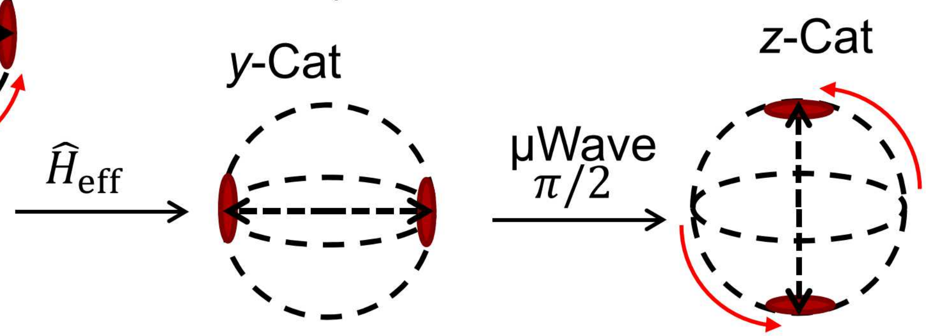
(2-atom case)

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

(2-atom case)

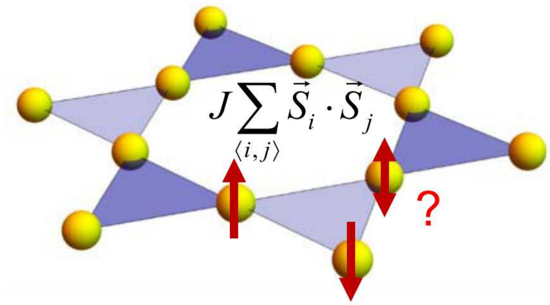
$$\frac{|\uparrow\uparrow\rangle + |\downarrow\downarrow\rangle}{\sqrt{2}}$$



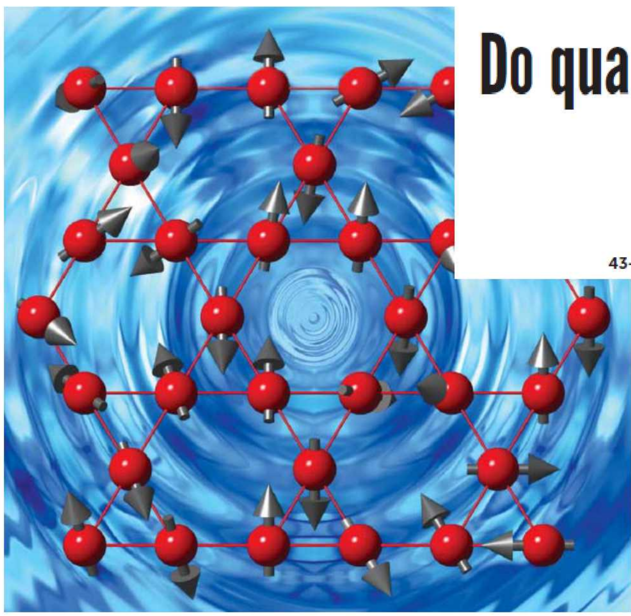


Scaling to larger systems

Rydberg physics:
- Enable creation of large-scale entangled states.
- Create geometries that can simulate interesting, physically-relevant, models of quantum magnetism.



Kagome lattice



Do quantum spin liquids exist?

Takashi Imai and Young S. Lee

The search for the hypothetical state has been a 43-year-long slog, one whose end may now be in sight.

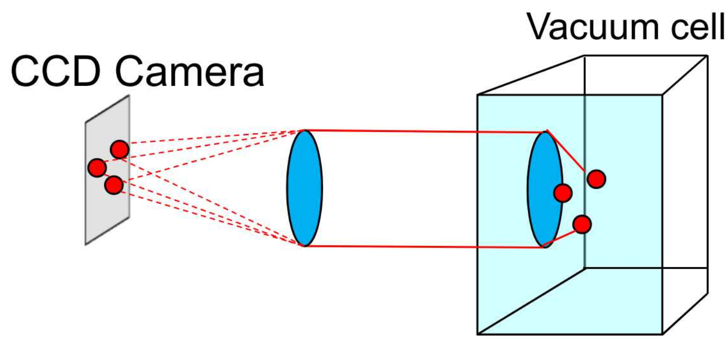
Methods for realizing Hamiltonians for quantum magnetism:

$$\hat{H} = \sum_{\langle ij\rangle} \alpha\hat{S}_x^i\cdot\hat{S}_x^j + \beta\hat{S}_y^i\cdot\hat{S}_y^j + \gamma\hat{S}_z^i\cdot\hat{S}_z^j$$

Glaetzle *et al.*, Phys. Rev. Lett. **114**, 173002 (2015).

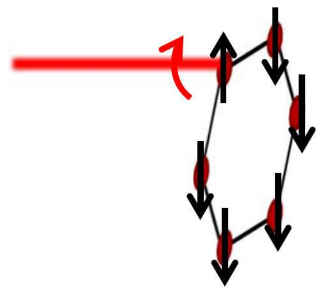
Technical challenges

1. Single-site imaging capabilities with 1 μm-scale resolution.



✓-Established techniques exist

2. Single-site addressing

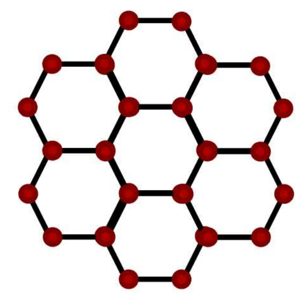


✓-Established techniques exist

3. **Reproducible atomic configurations:**

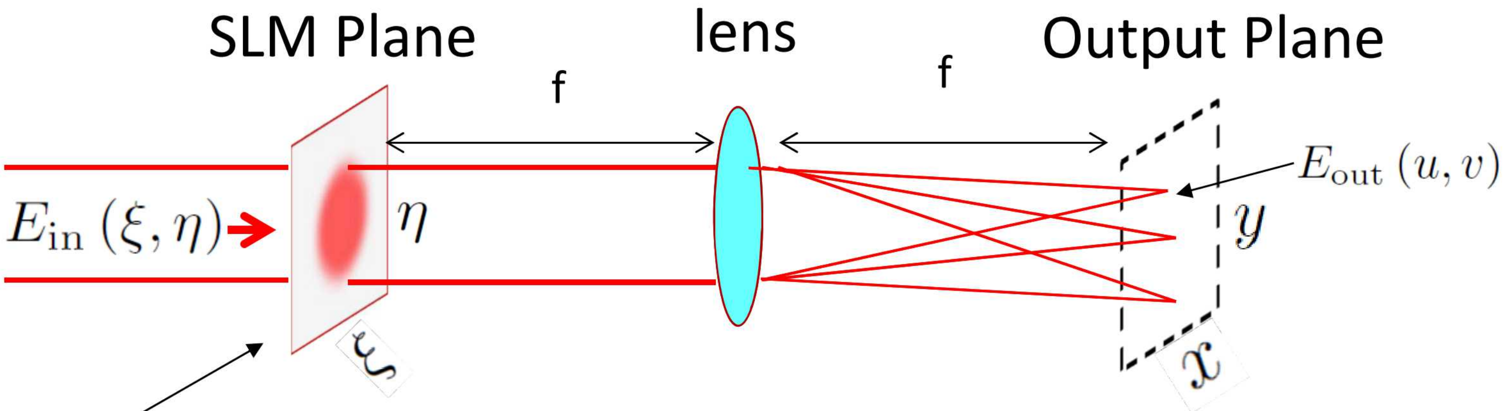
-Example: unity filling-factor lattice.

<u>-How to fill complex patterns consistently?</u>



Background: Physical optics

We utilize the Fourier-Transform properties of a lens in scalar diffraction theory (i.e., treat the electric field as a complex-valued scalar field). Here, the output field is related to the phase-imprinted input field by a scaled Fourier Transform.



$$\mathcal{M}(\xi,\eta) = \exp[i\phi(\xi,\eta)]$$

Phase mask is imprinted on input field

Output field is a scaled Fourier transform of the field in the SLM plane. The SLM plane field is given by the product of the input field and phase mask.

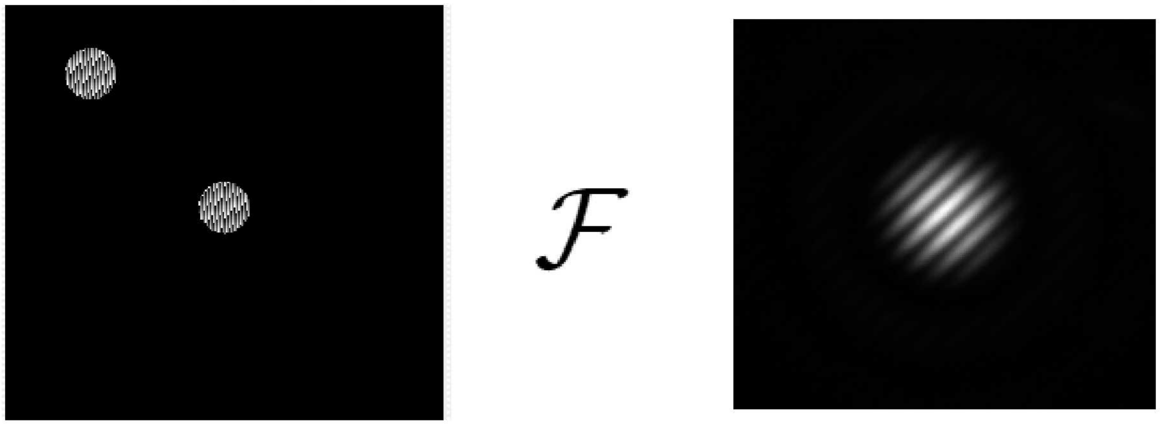
$$E_{\text{out}}(u,v) = \mathcal{F}[E_{\text{in}}(\xi,\eta)\,\mathcal{M}(\xi,\eta)]$$

Where output coordinates are scaled as:

$$v = y/(\lambda f),\; u = x/(\lambda f)$$

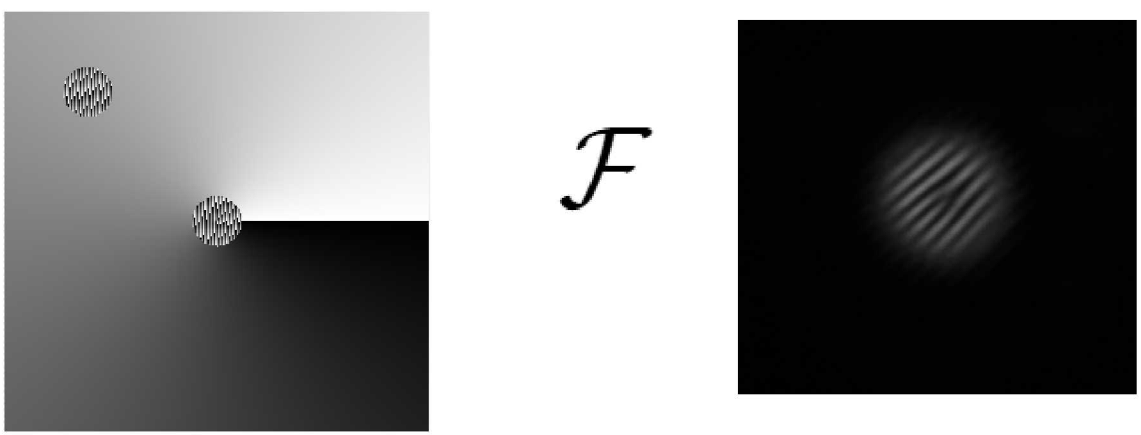
Control of point source interference for measuring local phase

Phase mask



Two sources in the Fourier plane (right) diffract and interfere in the image plane (left).

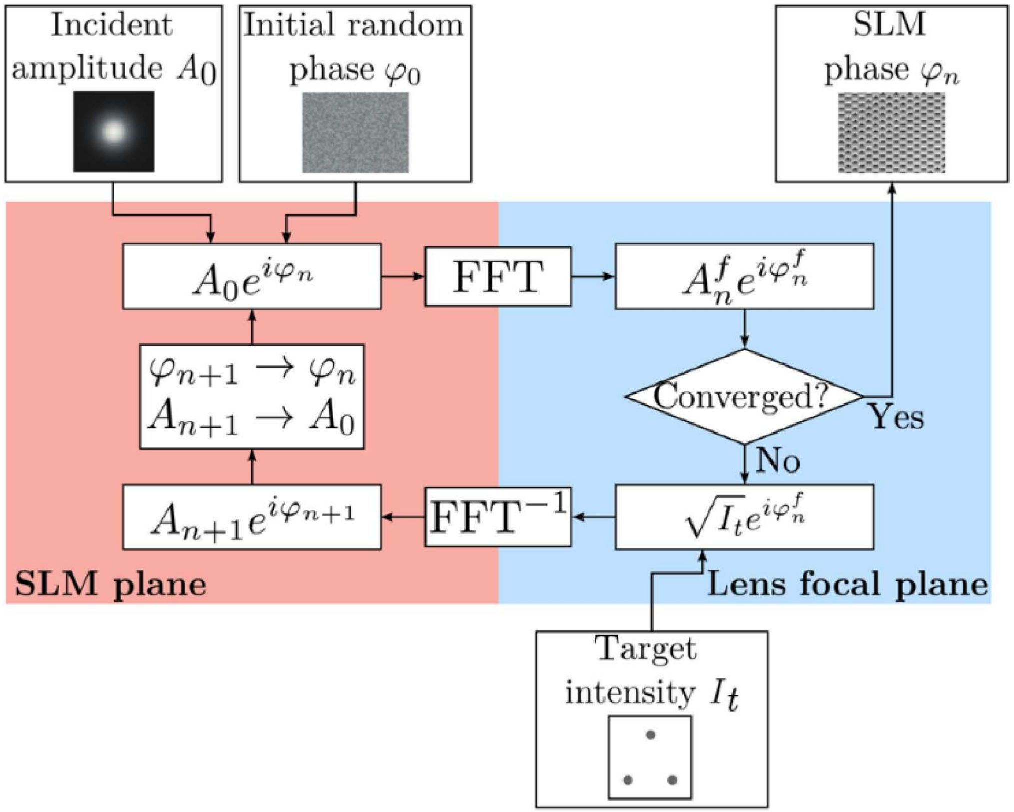
Phase mask



As above, but now the spot in the middle contains a phase singularity.

Background: Computing holograms

Gerchberg-Saxton loop



- An arbitrary complex field is completely defined by its Fourier Transform, which includes both amplitude and phase.
- The Gerchberg-Saxton (GS) algorithm attempts to find a phase-only pattern that Fourier Transforms into a desired intensity pattern.
- The GS algorithm iterates between the Fourier (SLM plane) and the image plane (Lens focal plane).
- Before iterating to the Fourier plane, the field amplitude is replace with the desired amplitude (phase is kept).
- Before iterating back to the image plane, the amplitude is replaced by the input field amplitude.

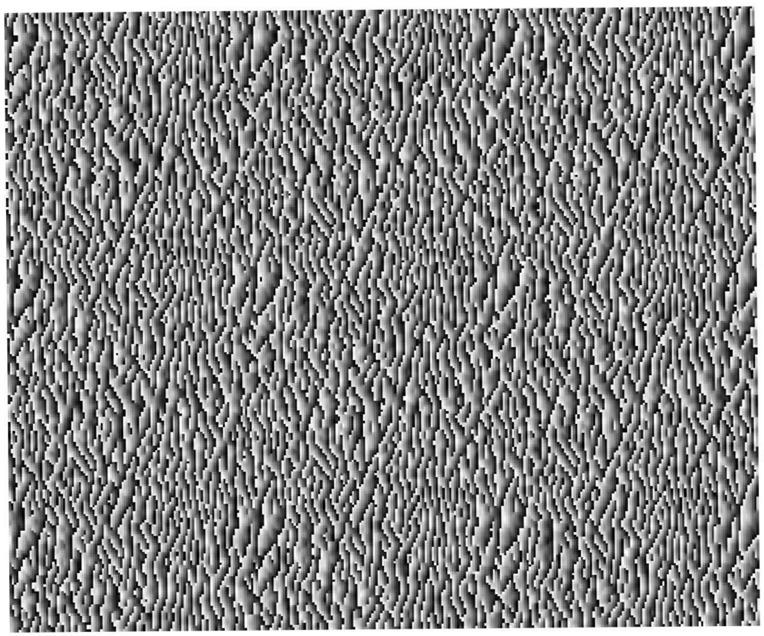
Image from: F. Nogrette, *et al.*, "Single-Atom Trapping in Holographic 2D Arrays of Microtraps with Arbitrary Geometries," Phys. Rev. X **4**, 021034 (2014).

Generation and control of >500 of individual traps

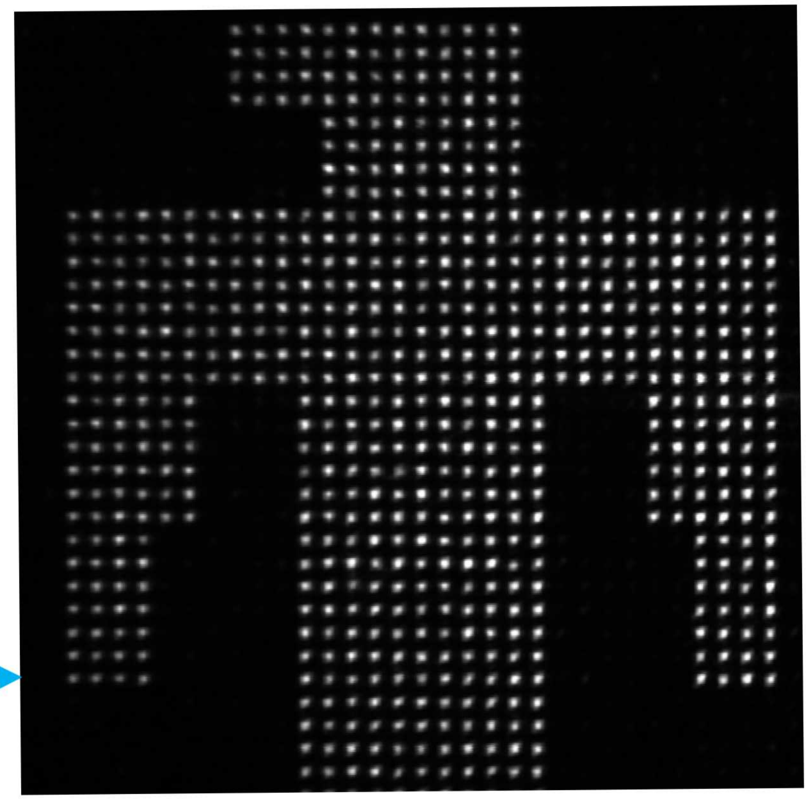
Sandia National Laboratories

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

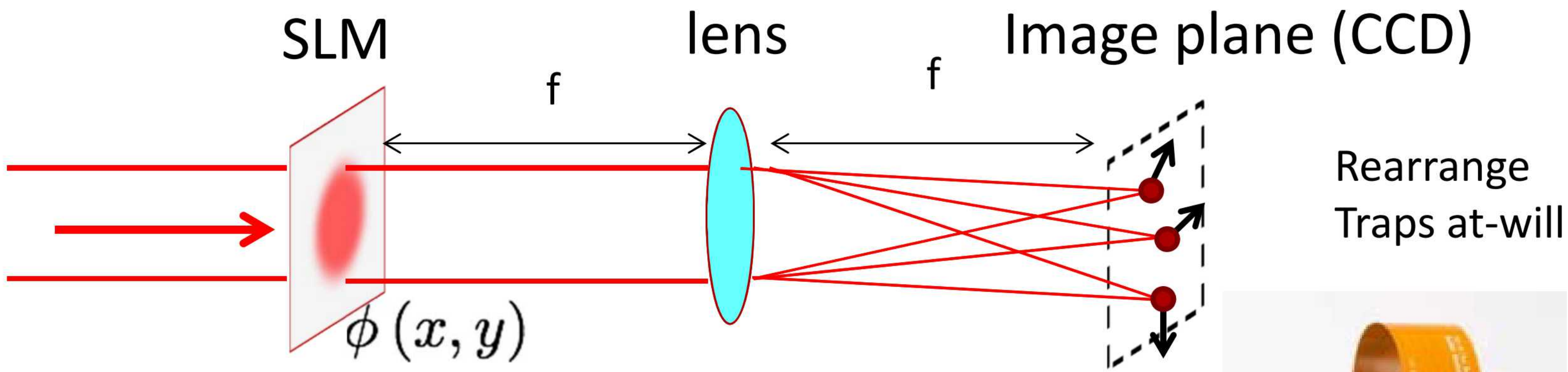
Phase to SLM



Intensity profile (measured)



Generating dynamical traps for deterministic loading and manipulation.



1. Minimize trap distortion as frames advance through tailored algorithms.

2. Compute SLM "movie", comprising ~100 frames with as little dead time as possible using parallel computation.

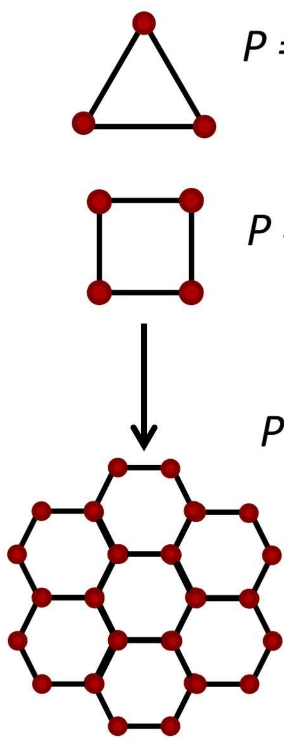
3. Verify that trap motion will not cause trap loss via measurement of trap intensity fluctuations.

Deterministic loading

Without dynamic control

Probability of perfect loading scales exponentially with atom number

1 second



$P = 0.125$

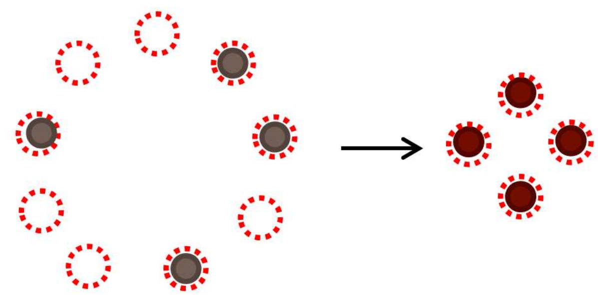
$P = 0.0625$

$P = 6 \times 10^{-8}$

1 month

With dynamic control

e.g., Attempt to load 9 traps, reconfigure to a desired pattern with four atoms.



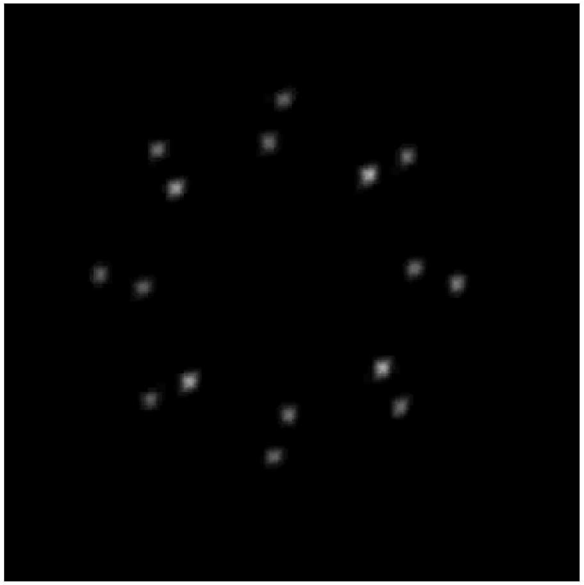
Scale to larger arrays

See:

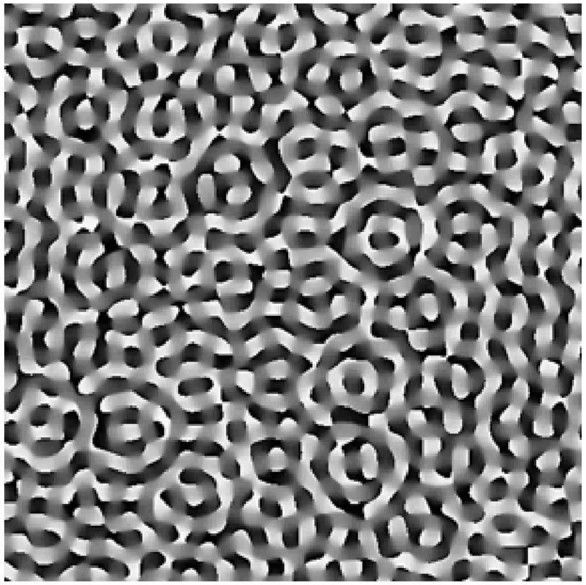
W. Lee et al., Phys. Rev. A **95**, 053424 (2017)

Dynamic control of hologram-generated traps (movie disabled)

30 fps, real time

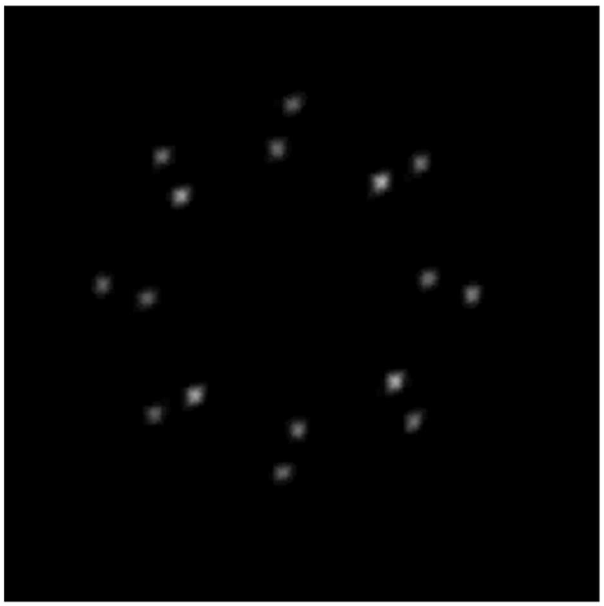


Phase hologram

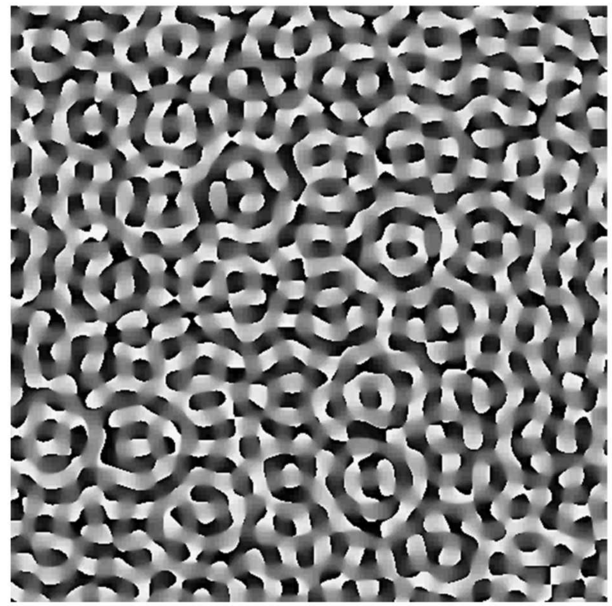


Dynamic control of hologram-generated traps

30 fps, real time



Phase hologram



Dynamic control of hologram-generated traps (movie disabled)

500 fps played at 30 fps

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

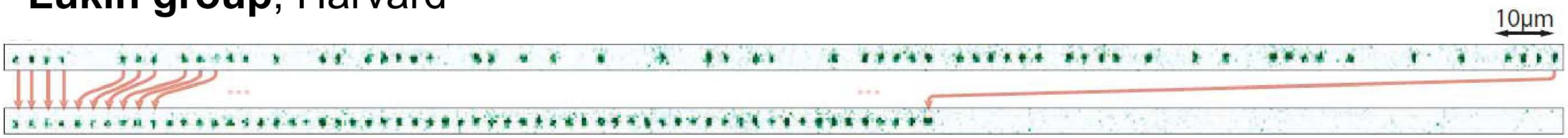
Dynamic control of hologram-generated traps

500 fps played at 30 fps

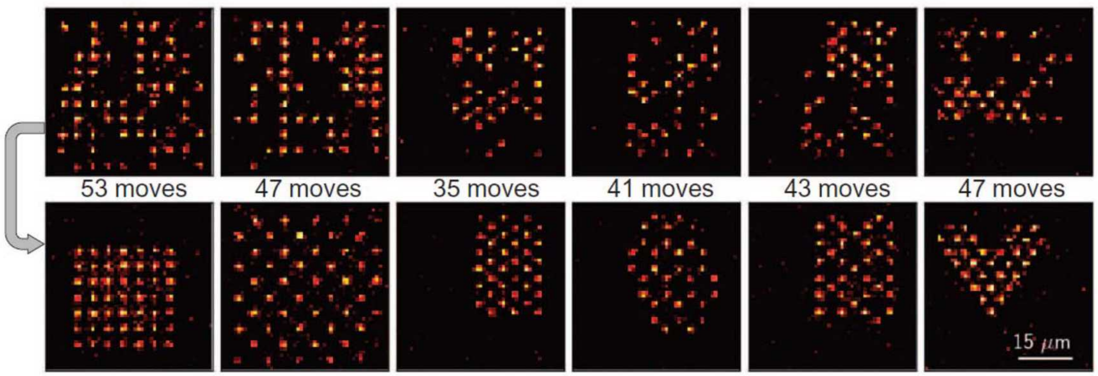
-Optimize techniques for calculating hologram with as little phase discontinuity between frames as possible.

Defect-free neutral atom arrays

Lukin group, Harvard[1]

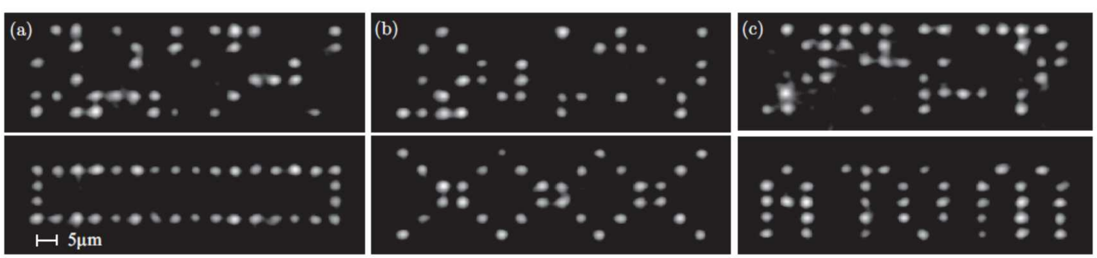


Browaeys group, Institut d'Optique (France)[2]



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

Ahn Group, KAIST (South Korea)[3]

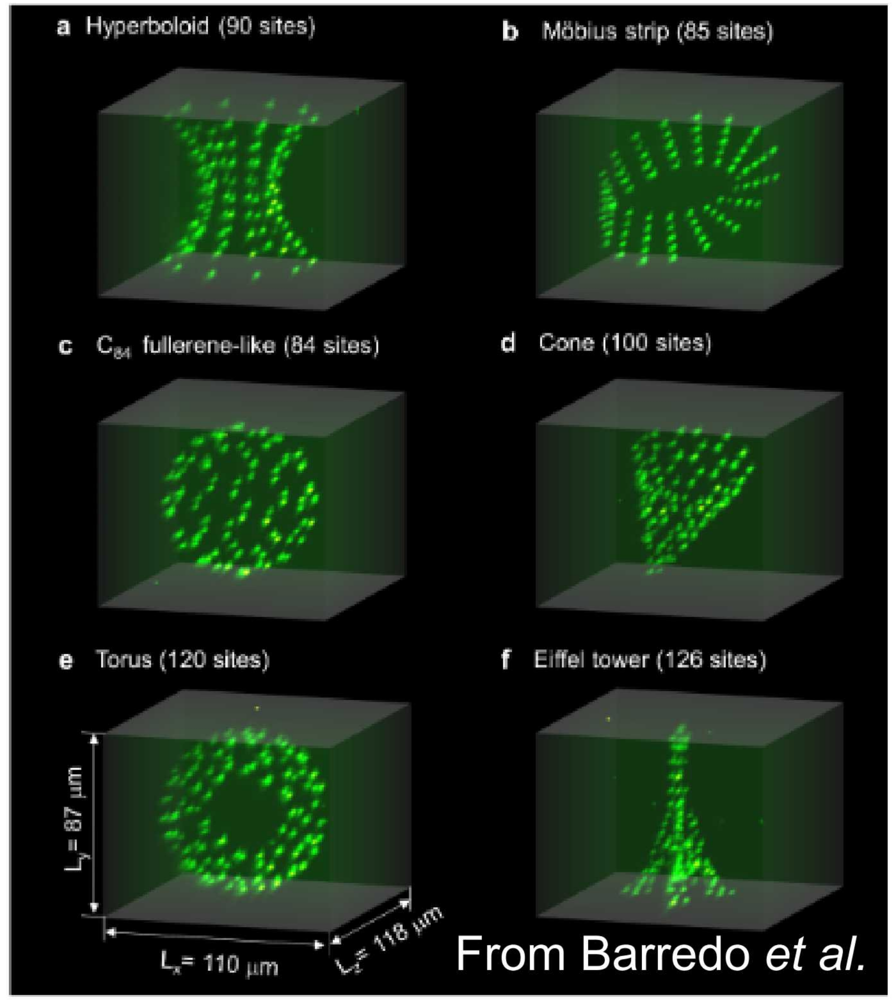


1. M. Endres et al., Science 354, 1024 (2016)
2. D. Barredo et al., Science 354, 1021 (2016)
3. W. Lee et al., Phys. Rev. A **95**, 053424 (2017)

Defect-free neutral atom arrays

Now in 3D

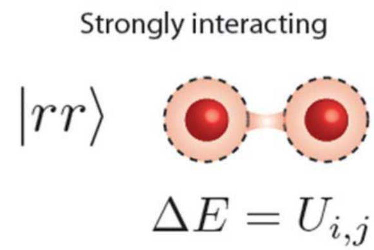
- 3D Gerchberg-Saxton algorithms allows 3D control of trap sites.
- Opens the door to studying complex quantum systems with neutral atoms.

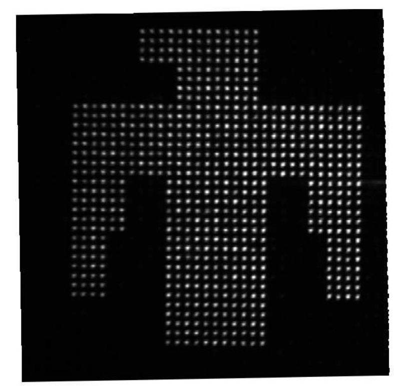


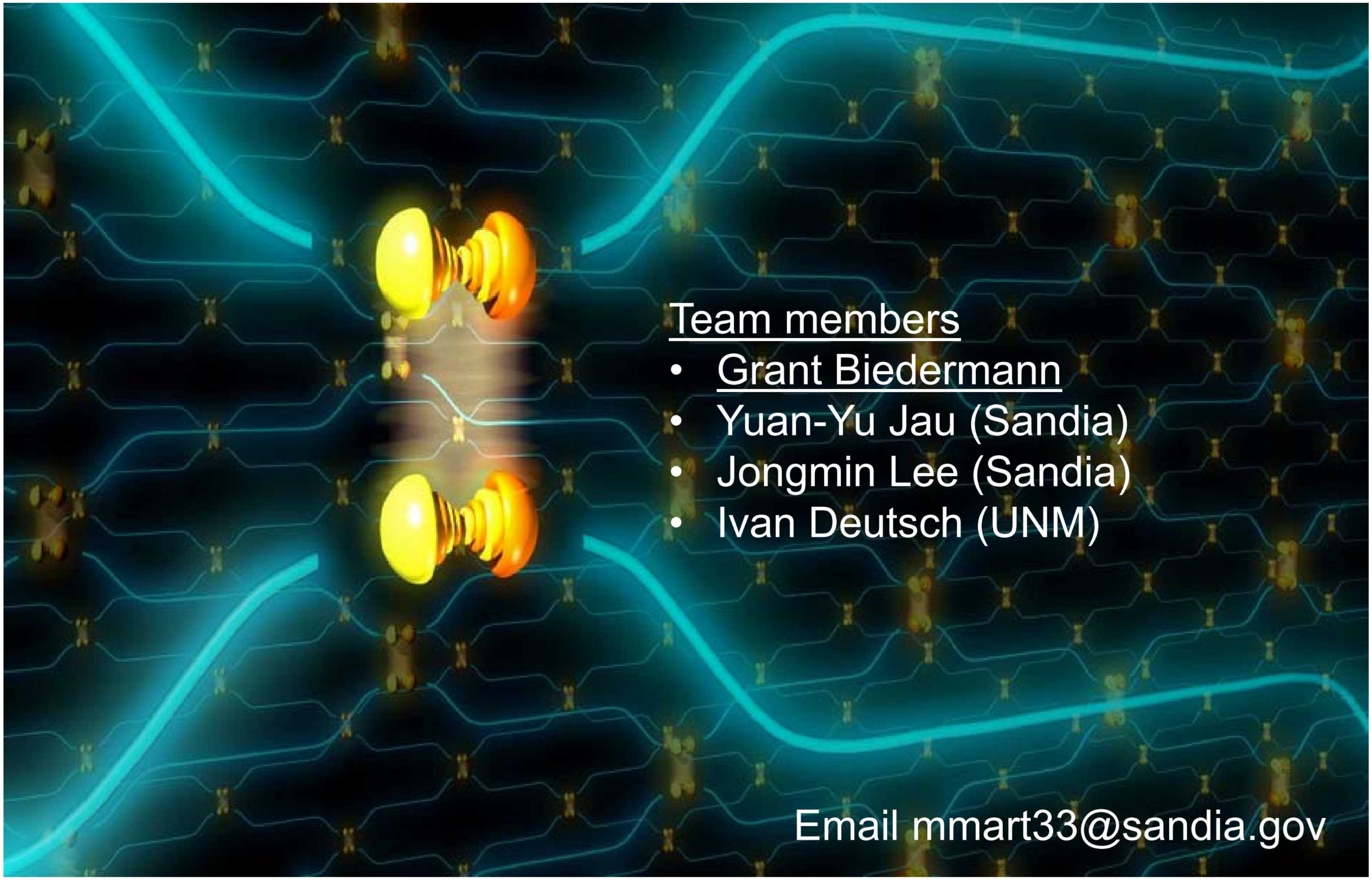
D. Barredo, V. Lienhard, S. de Léséleuc, T. Lahaye, A. Browaeys, "Synthetic three-dimensional atomic structures assembled atom by atom", arXiv:1712.02727 (2017).

Concluding remarks

- Optical systems are enabling big advances in atomic physics!
- Single-photon Rydberg dressing opens up possibilities for large-scale entanglement via both quantum control direct Hamiltonian evolution, and quantum simulation.
- Protocols demonstrated at SNL show that high-quality entanglement between neutral atoms is not far off.






Team members
• Grant Biedermann
• Yuan-Yu Jau (Sandia)
• Jongmin Lee (Sandia)
• Ivan Deutsch (UNM)
Email mmart33@sandia.gov