SAND2015-4606PE

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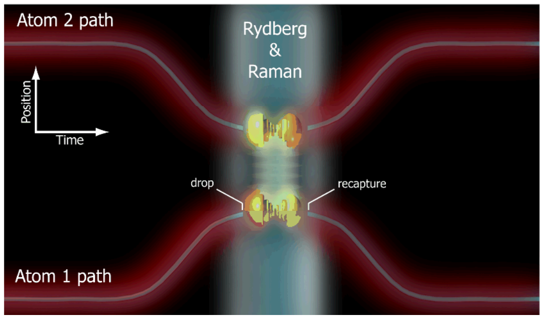
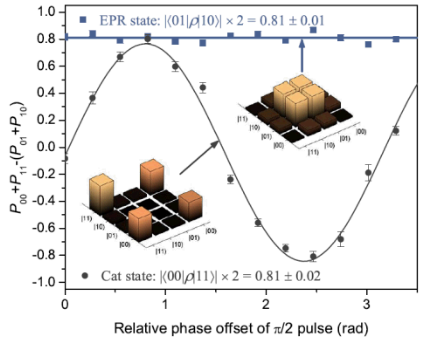
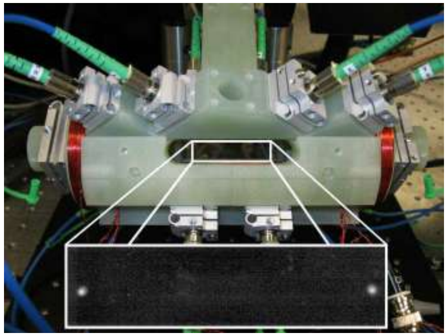






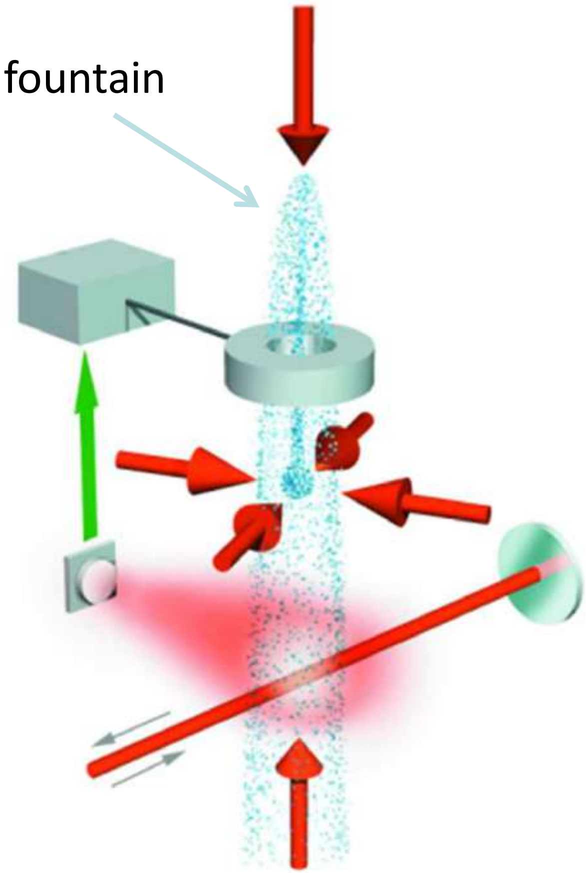
Sensing with neutral atoms

Grant Biedermann

UNM CQuIC

Quantum-Coherence

Qubit fountain



Atomic fountain principle

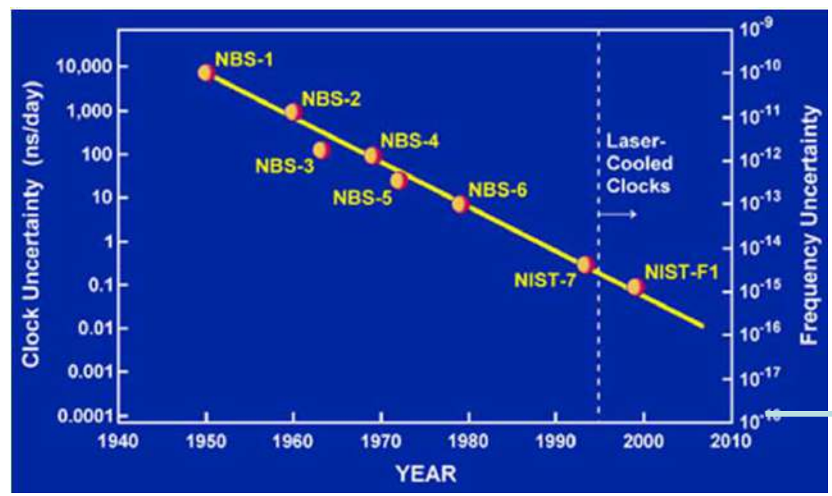
http://smsc.cnes.fr/PHARAO/GP_instrument.htm

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

- Example: atomic clocks

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

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

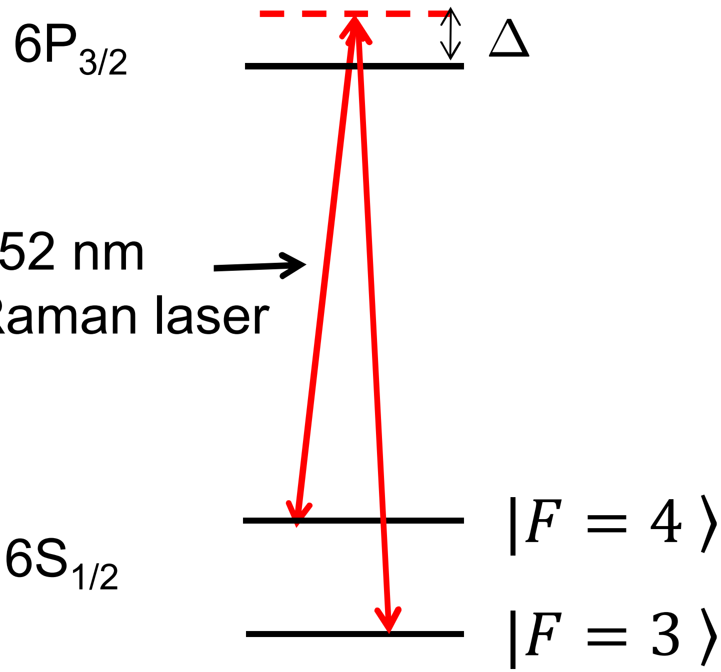


Optical clocks

http://www.nist.gov

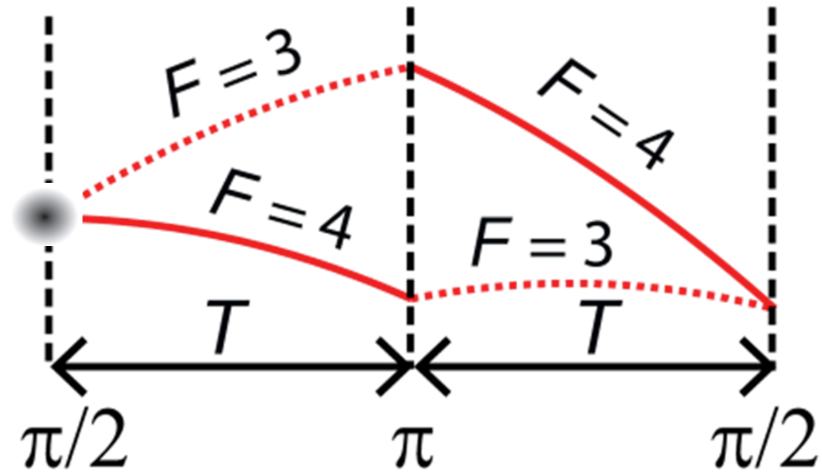
Typical accuracy now better than one part in 10^{15}

Light-pulse atom interferometry



stimulated Raman transition

wavepacket trajectory

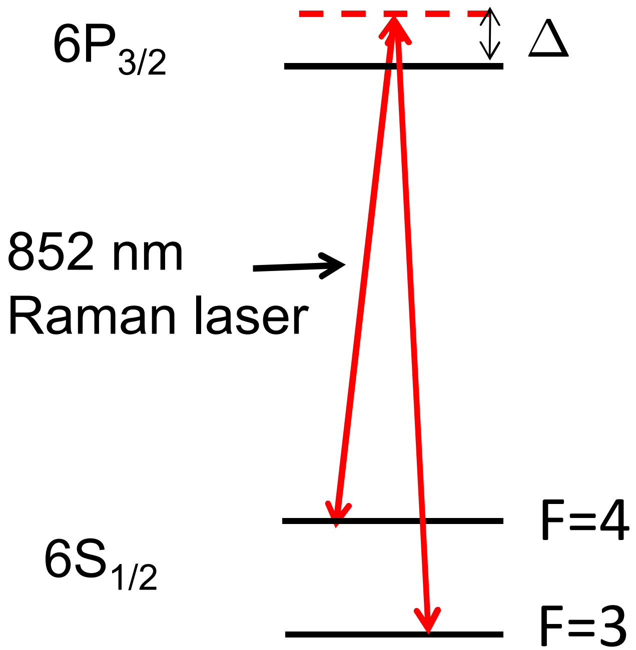


- Exceptional accelerometers and gyroscopes nrad/√Hz, n*g*/√Hz to p*g*/√Hz
- Large commercial and govt. interest in fielding this technology

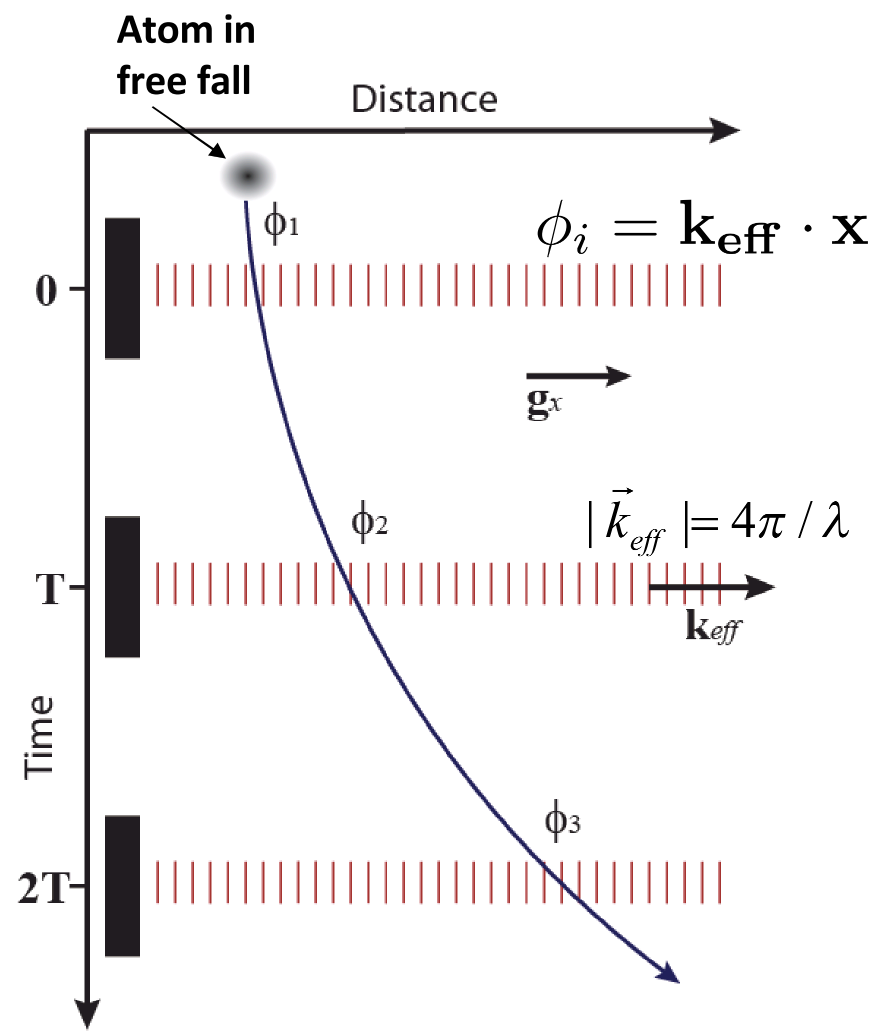
Kasevich, and Chu, Phys. Rev. Lett. 67, 181–184 (1991)

Gustavson, Landragin, and Kasevich, Class. Quantum. Grav 17, 2385–2398 (2000).

Light-pulse atom interferometry



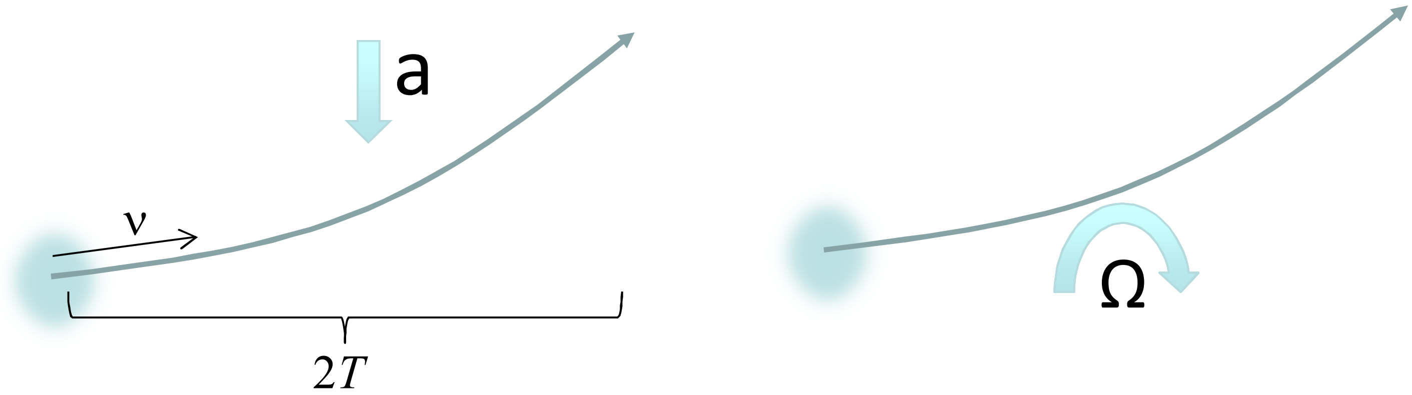
stimulated Raman transition



For an atom starting in F=3: $P_{F=4} = \frac{1}{2}(\cos \Delta\phi)$ & $\Delta\phi = \phi_1 - 2\phi_2 + \phi_3$

Measuring acceleration and rotation with a particle in free-fall

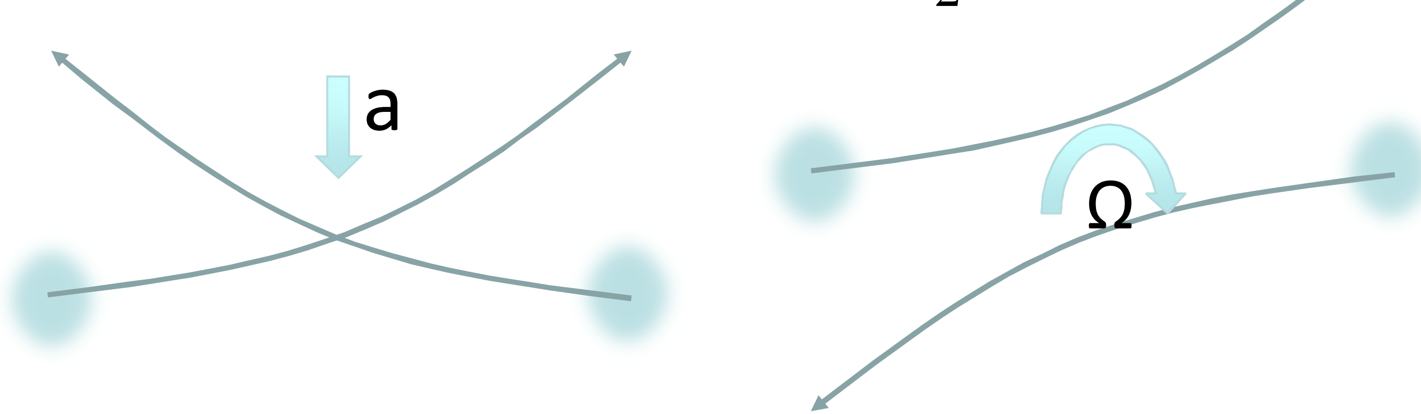
1-particle



Interferometer phase shift: $\Delta\phi = \vec{k}_{eff} \cdot \left(\vec{a}T^2 - 2(\vec{v} \times \vec{\Omega})T^2\right)$

$$P_{F=4} = \frac{1}{2}\left(\cos\Delta\phi\right)$$

2-particles



Sensitivity increases with T^2

Launch and recapture

Steady state atom number:

$$N_s = \frac{\alpha\eta T_c}{\beta T_c + (1 - r_0)}.$$

Base recapture efficiency r_0 = 96 %

Benefits

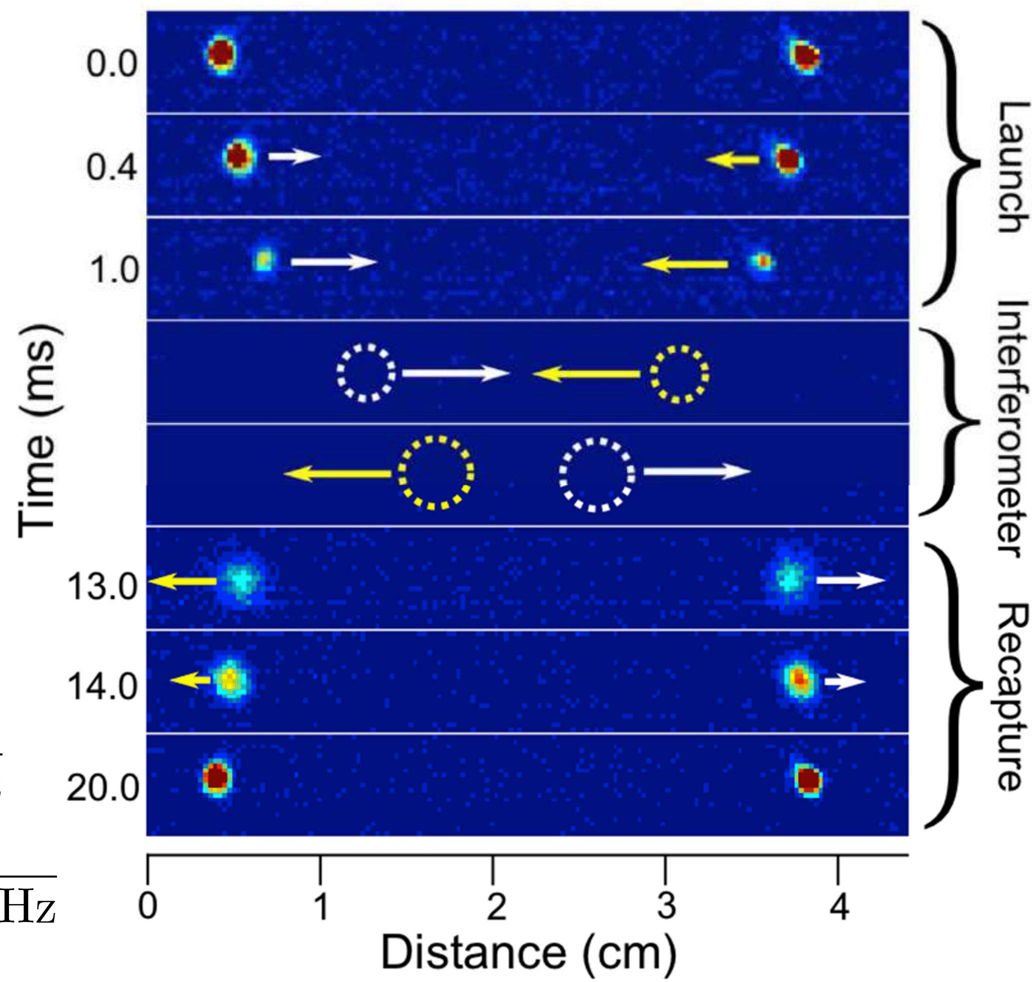
- Increases signal by 10x
- Data rates > 50 Hz
- Minimizes cycle dead time
- Reduced complexity
- Sufficient for:

$33\ \mathrm{ng}/\sqrt{\mathrm{Hz}}$ & $70\ \mathrm{nrad/s}/\sqrt{\mathrm{Hz}}$

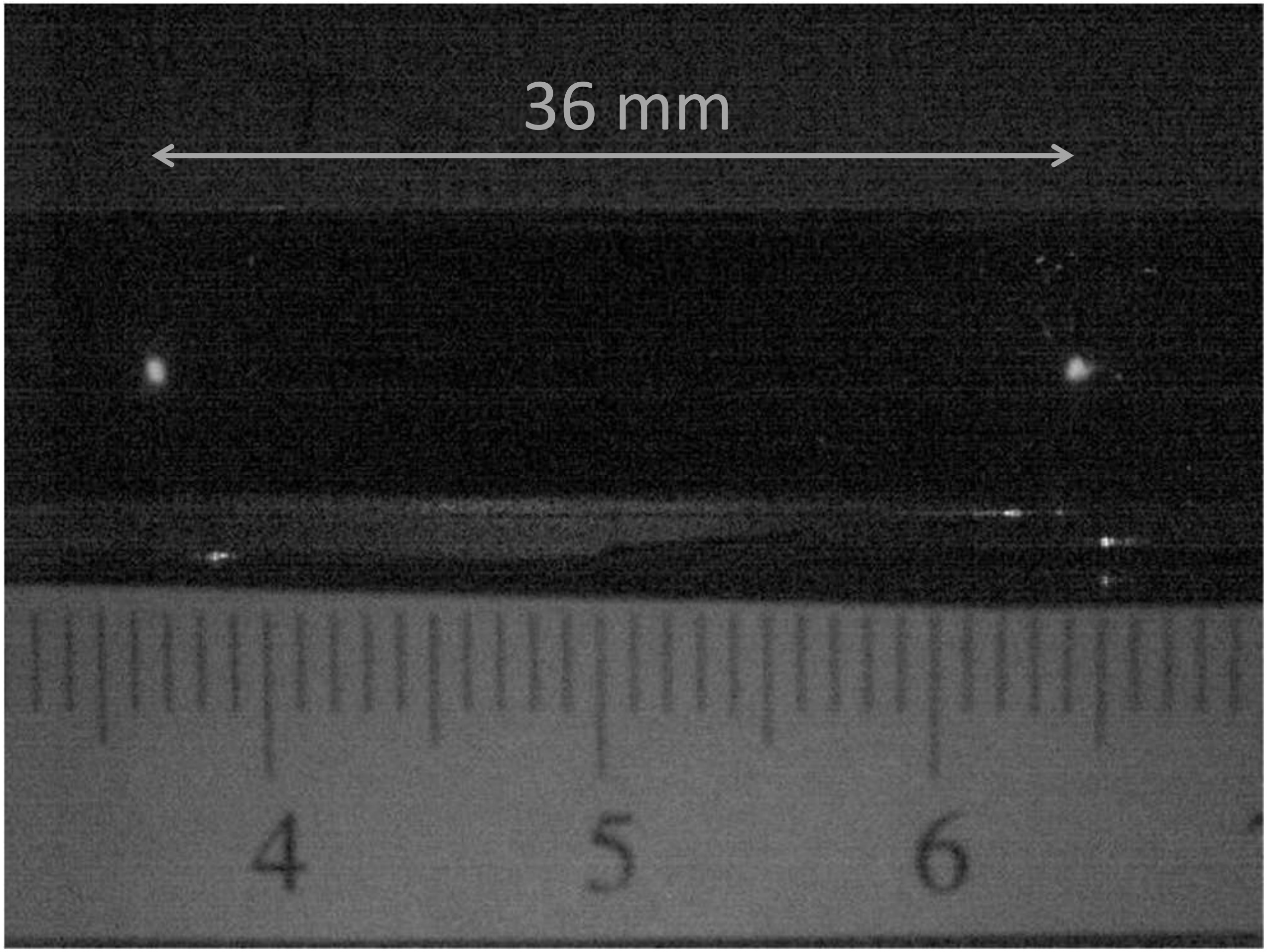
- Demonstrated:

$900\ \mathrm{ng}/\sqrt{\mathrm{Hz}}$ & $1100\ \mathrm{nrad/s}/\sqrt{\mathrm{Hz}}$

CCD images of ensemble exchange

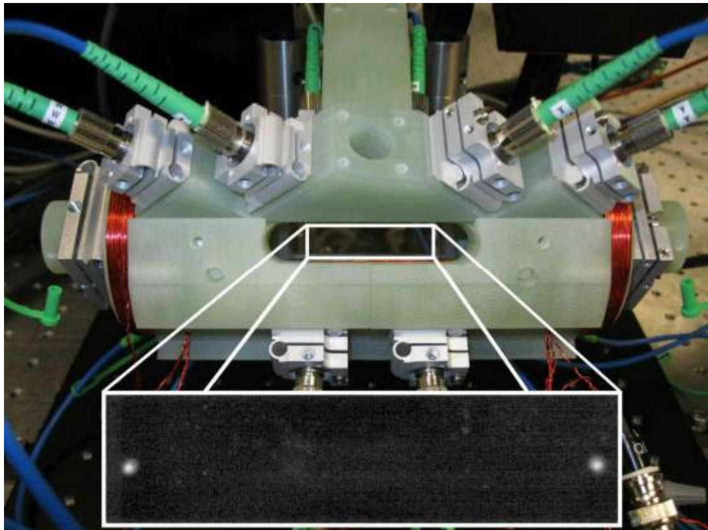


Launch and recapture

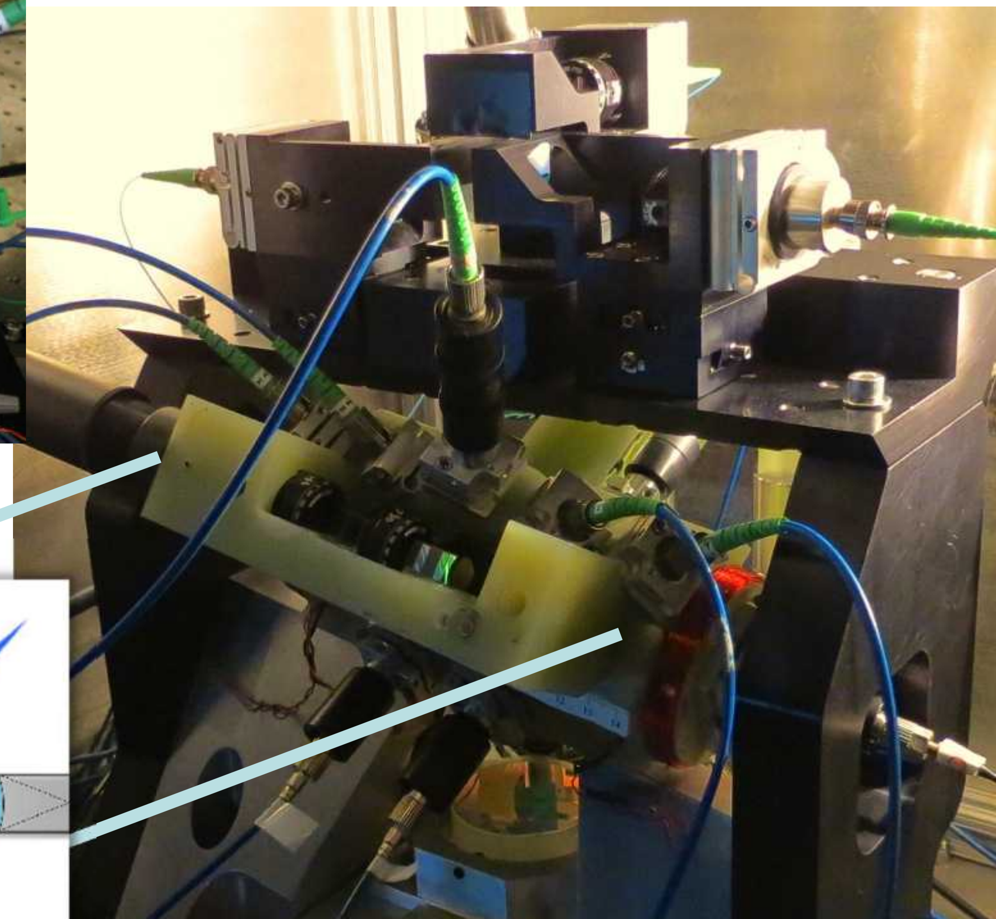


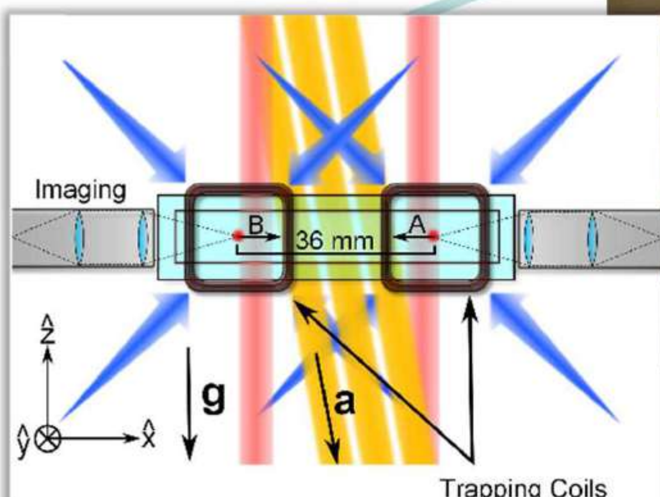
- Repeats at ≈ 60 measurements per second

Experiment platform



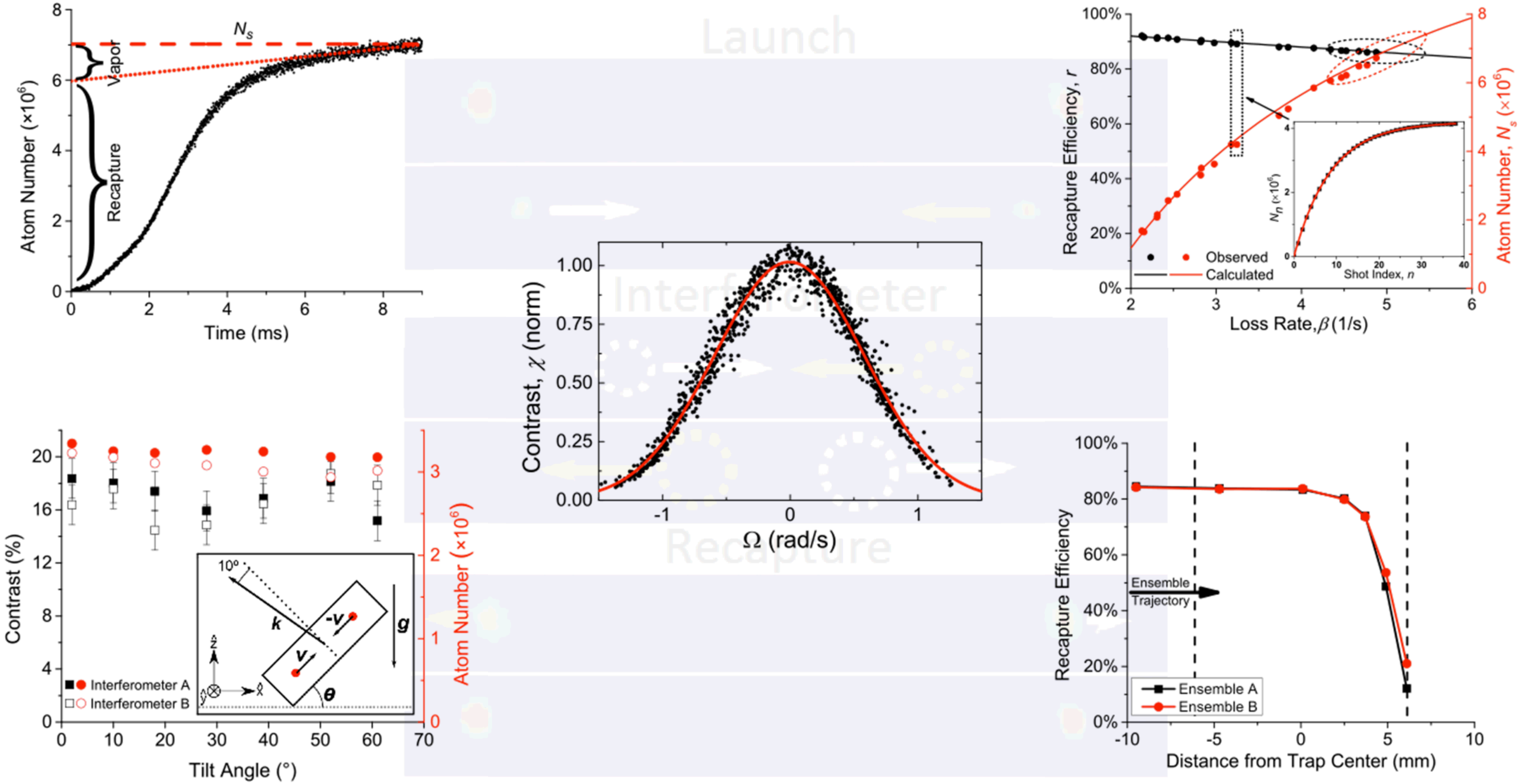
Picture of interferometer sensor





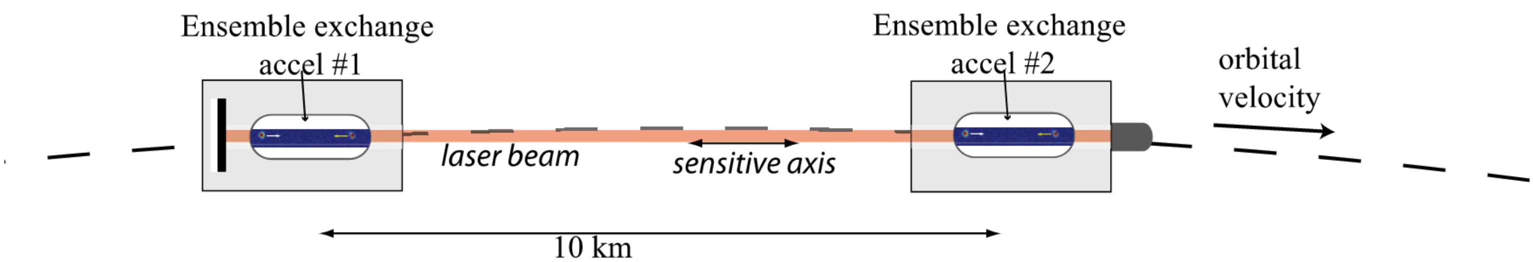
Characterizing ensemble exchange

- Dynamic aspects of Ensemble Exchange characterized
- Robust to rotations, tilts and displacements



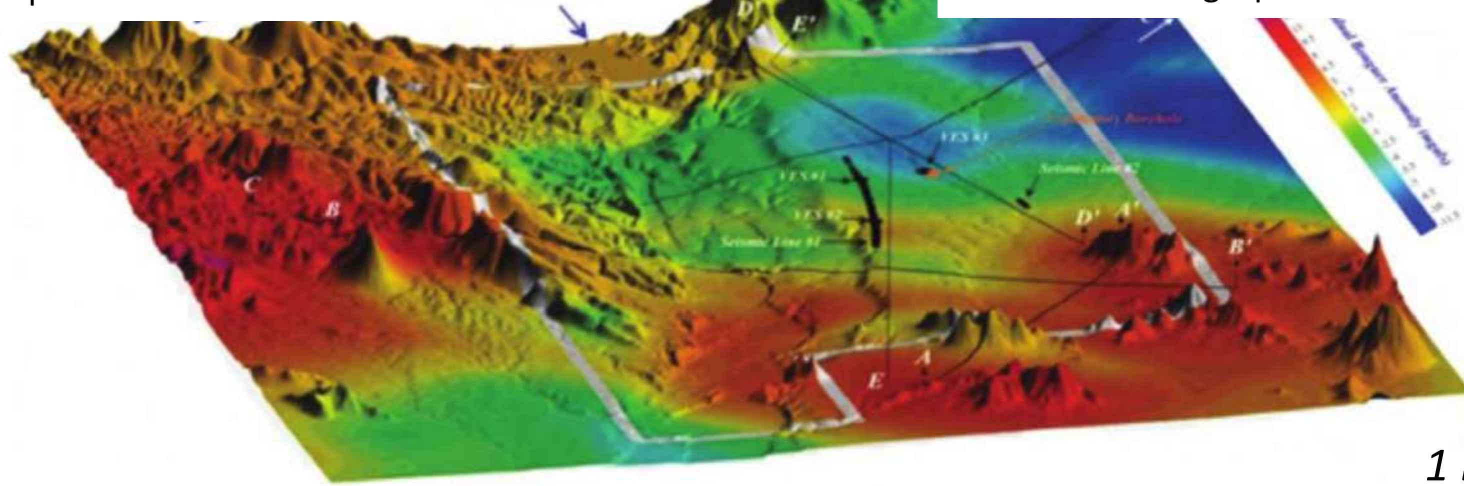
Gradiometer survey—path finder

Simultaneous opposed gradiometers—bias rejection



- 10^4 s stability—multiple orbital passes (SOA < 1 s)
- 10^{-3} E per shot with ground based performance—likely to improve in space 10^3x
- 10^4 x improvement over SOA

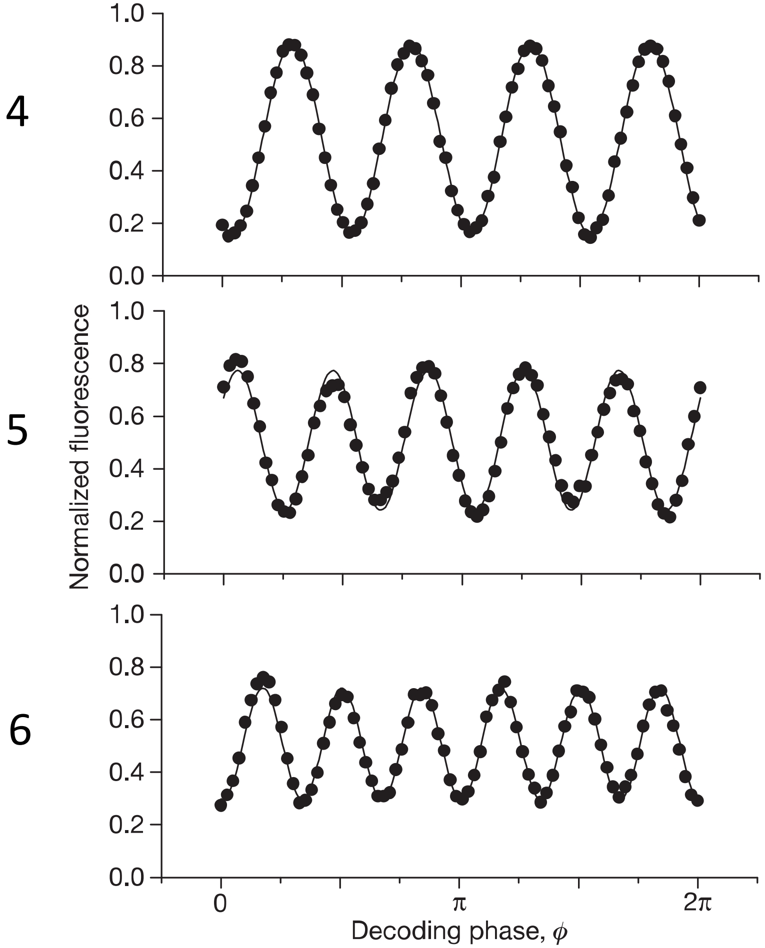
- Improved gravity maps in contested areas for GPS-denied navigation
- Other targets
    - Soil erosion (10^{-3} E)
    - Water table levels (5×10^{-3} E)
    - Strategic petroleum reserves (10^{-6}E)



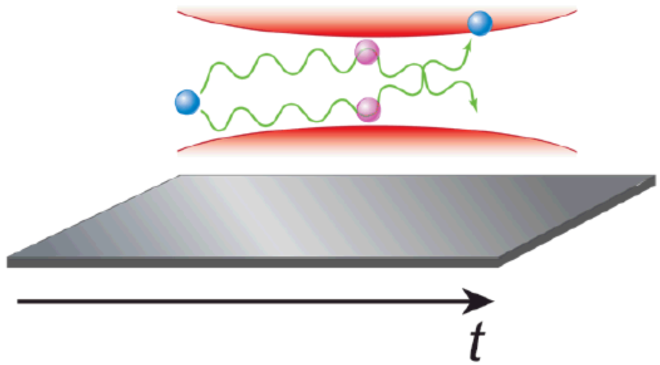
$1\ E = 10^{-9}\ /s^2$

Entangled states for metrology

Cat states with ions [1]



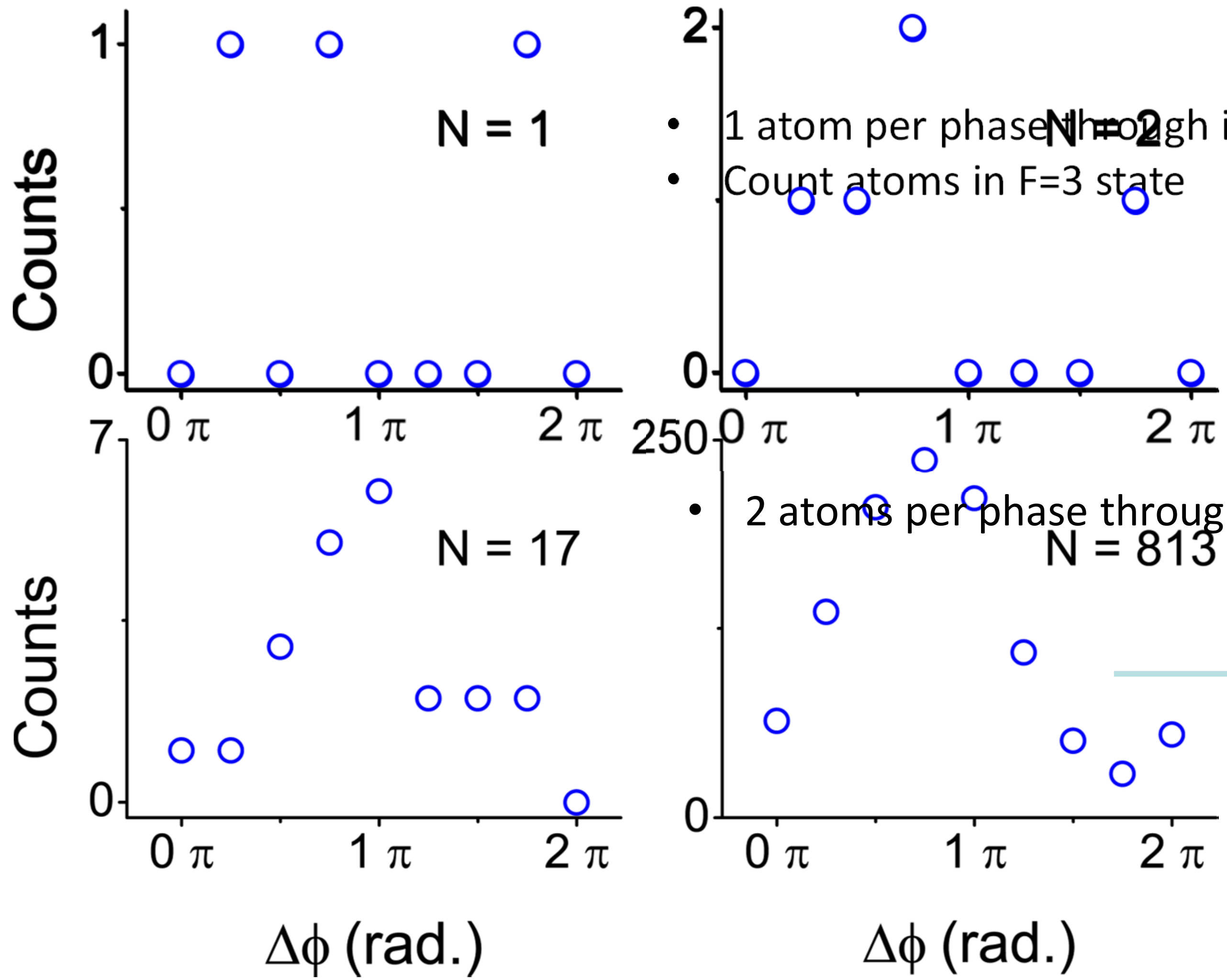
Atom interferometer with single atoms



E. Rasel, Physics **5**, 135 (2012)

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

Building a fringe, one atom at a time

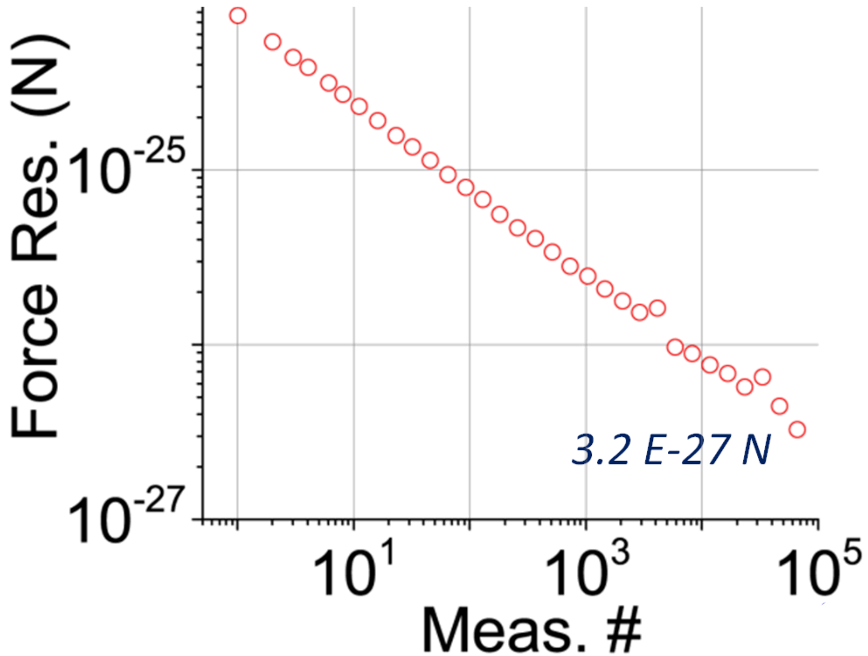


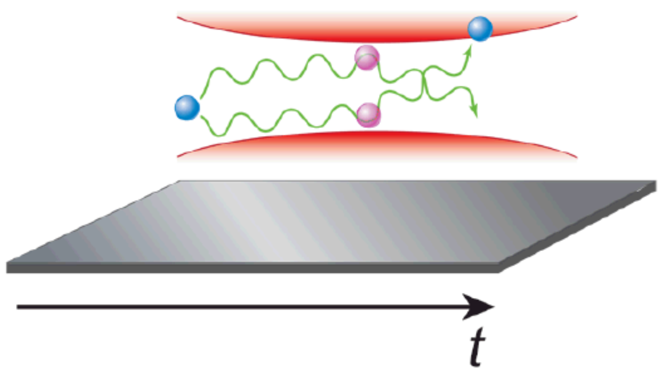
- 1 atom per phase through interferometer.
- Count atoms in F=3 state

- 2 atoms per phase through interferometer.

→ 7,317 atoms

Single atom interferometry

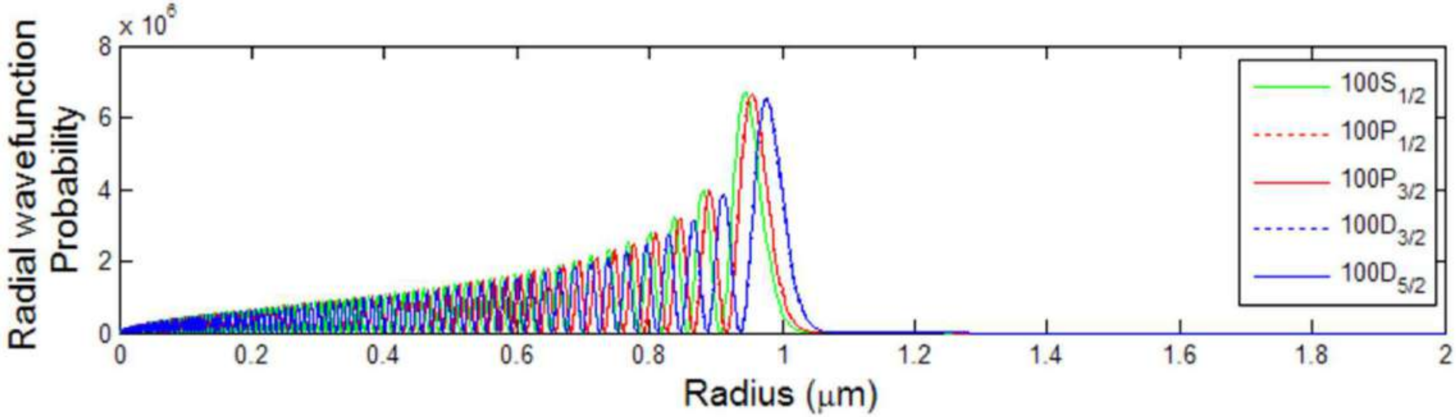




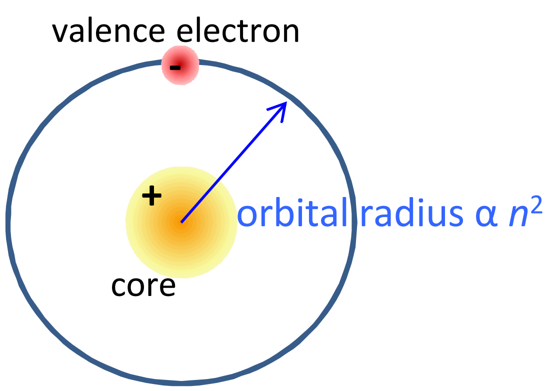
- We showed one can use single atoms
- Single atom control: gateway to harnessing quantum control in sensing
- 10^{-27} N ≈ m*g* for a cesium atom

Rydberg state mediated interaction

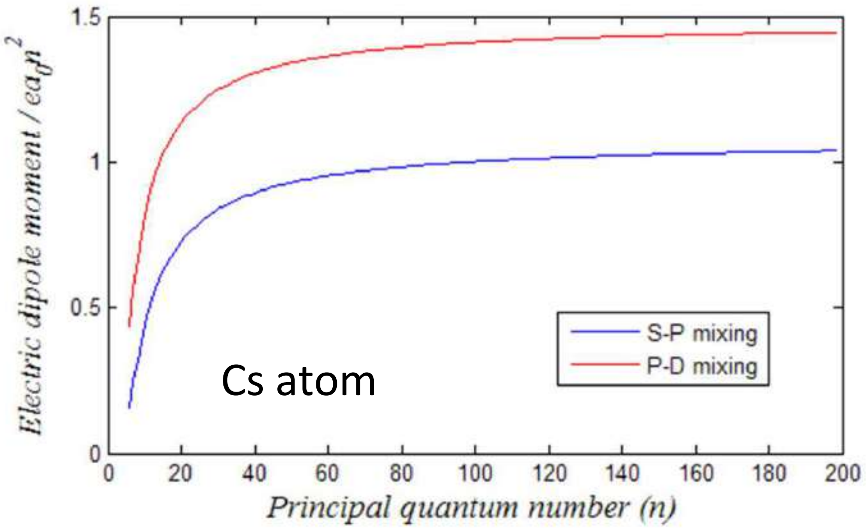
An example of the radial wavefunctions of a Cs atom at n = 100:



A Rydberg atom can have a strong electric dipole moment.

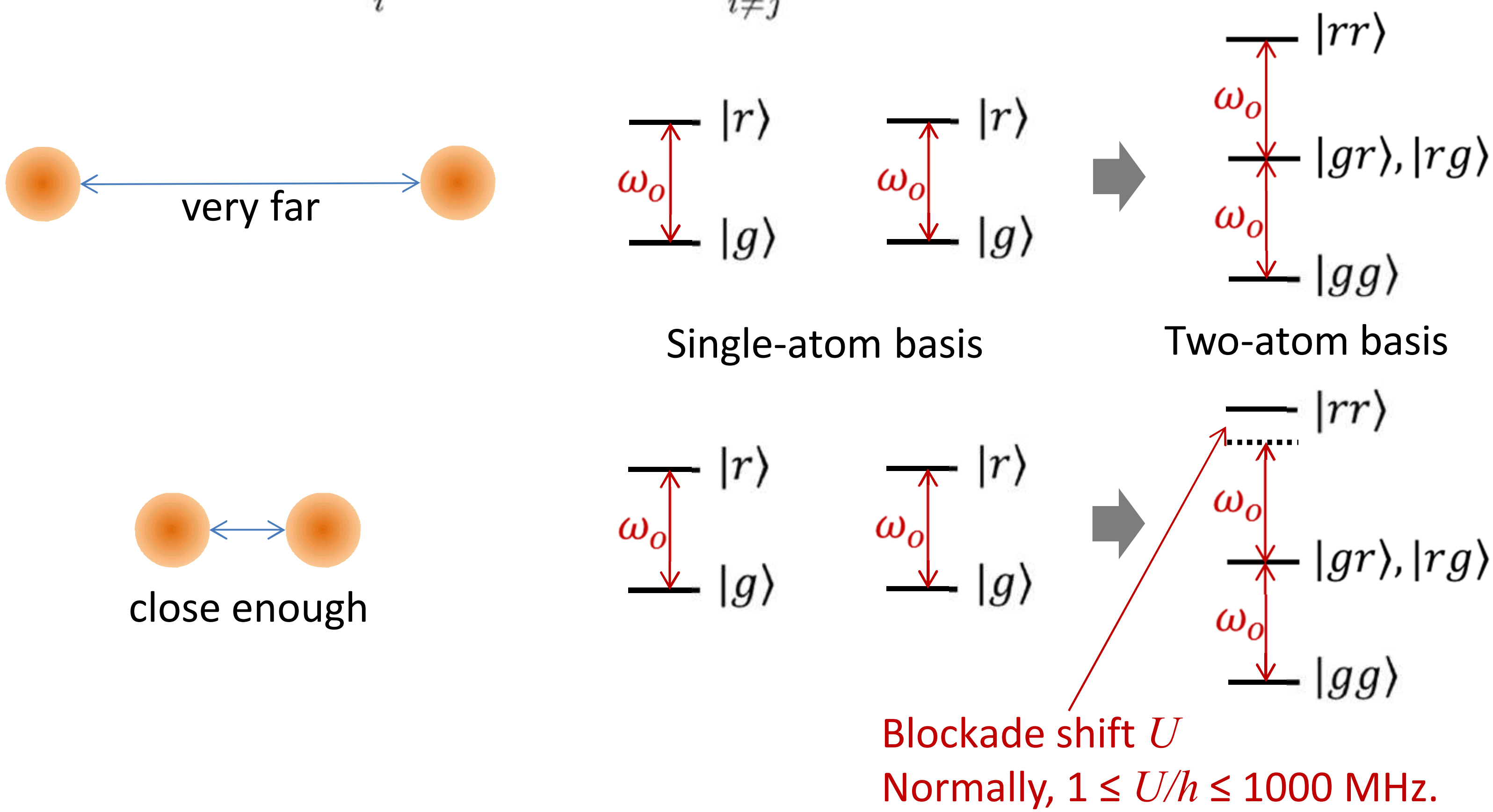


A classical picture of an atom



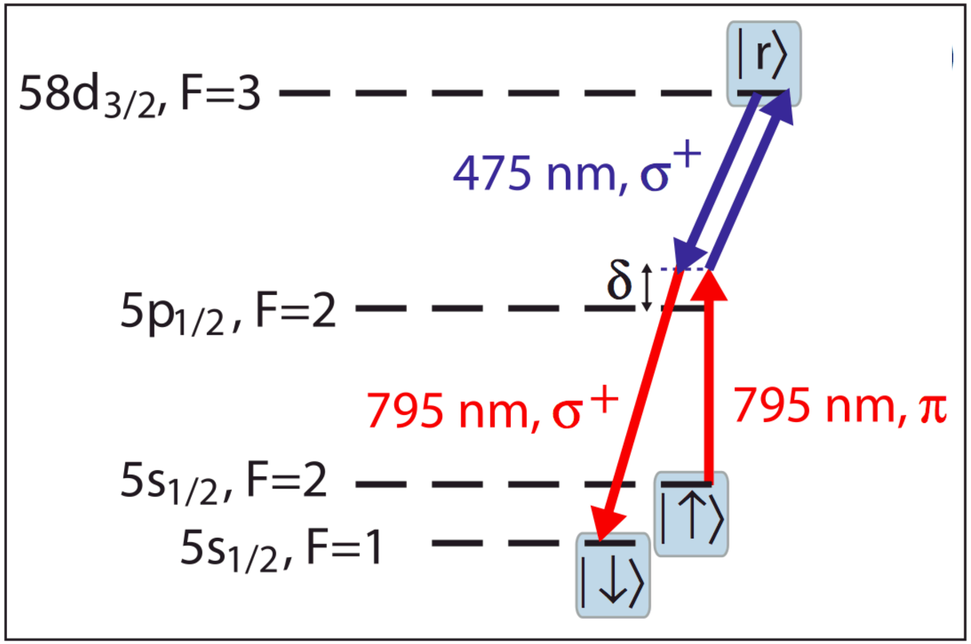
Blockade & electric dipole-dipole interaction

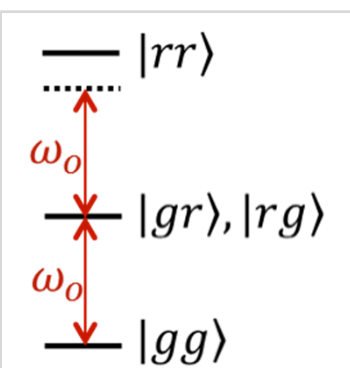
$$H_{\text{atoms}} = \sum_i H_0^{(i)} + \frac{1}{4\pi\varepsilon_0 r^3} \sum_{i\neq j} \left(\mathbf{D}^{(i)} \cdot \mathbf{D}^{(j)} - 3\mathbf{D}^{(i)} \cdot \hat{\mathbf{r}}\hat{\mathbf{r}} \cdot \mathbf{D}^{(j)}\right)$$



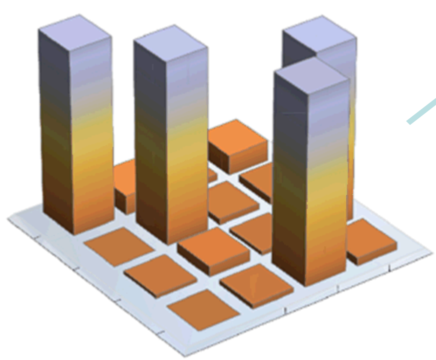
On-demand interactions

Two-atom entanglement using Rydberg blockade

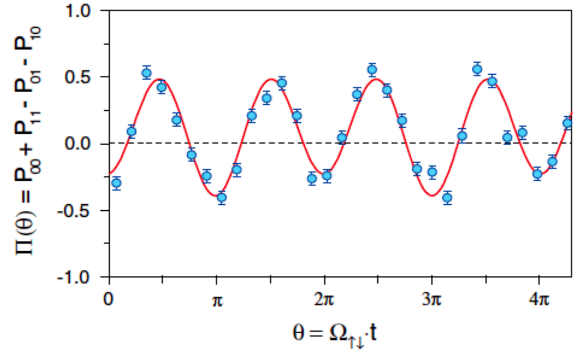




CNOT gate

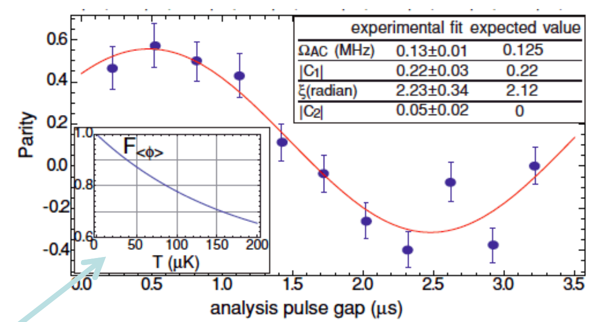


Paris



Wilk et al., PRL 104, 010502 (2010)

Wisconsin



	experimental fit	expected value
Ω_{AC} (MHz)	0.13±0.01	0.125
$\|C_1\|$	0.22±0.03	0.22
ξ(radian)	2.23±0.34	2.12
$\|C_2\|$	0.05±0.02	0

Zhang et al., PRA 82, 030306(R) (2010)

Many body systems

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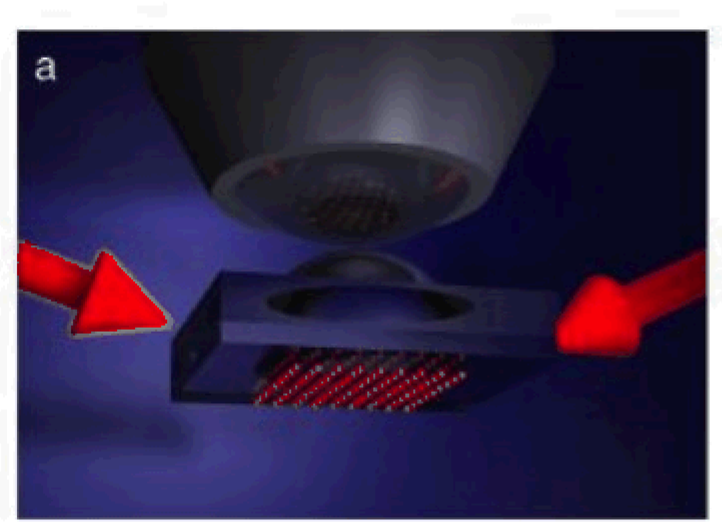
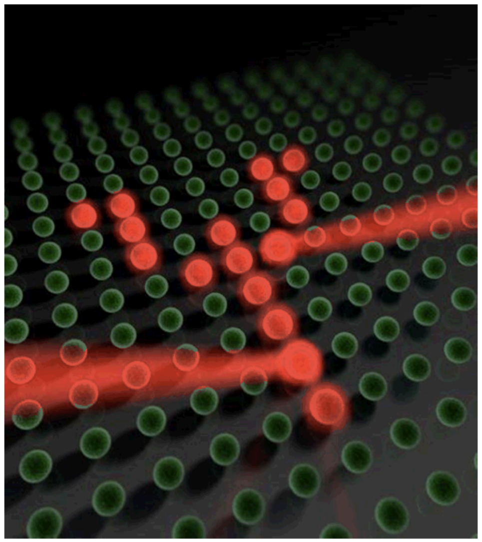
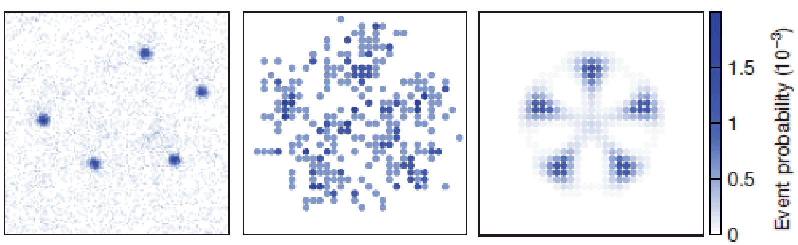


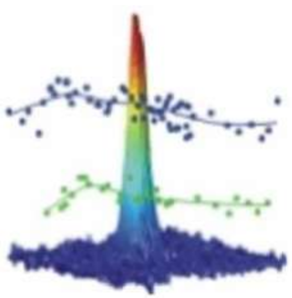
“Quantum Gas Microscope” Nature 462,74 (2009)



“Quantum simulation”, Nature Physics 8, 267 (2012)



“Rydberg interactions in a lattice”, Nature 491, 87 (2012)

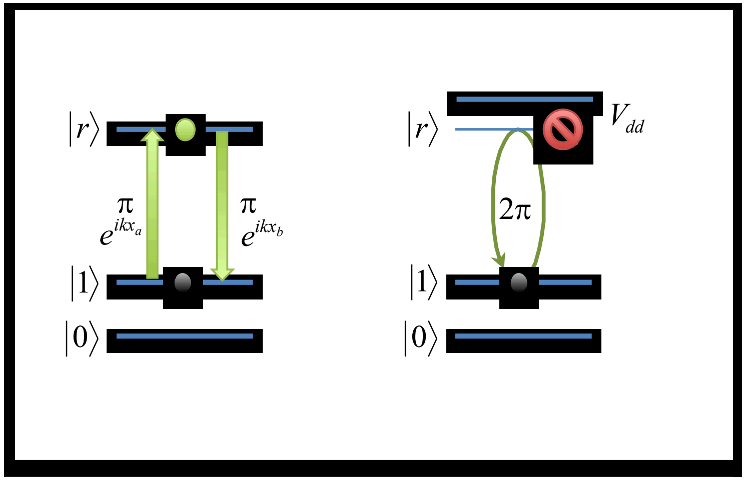


“Rydberg excitations in a BEC”, PRL 100, 033601 (2008)

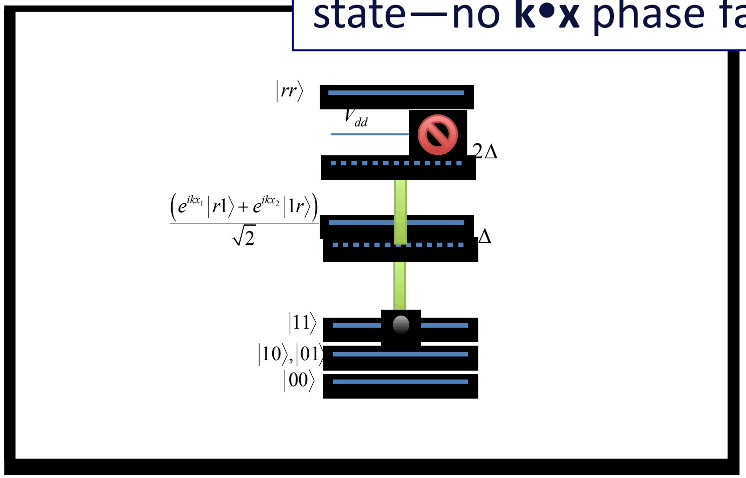
New options for Rydberg-state-mediated interactions

Comparison of methods

Population remains in ground state—no **k•x** phase factors!



Direct excitation



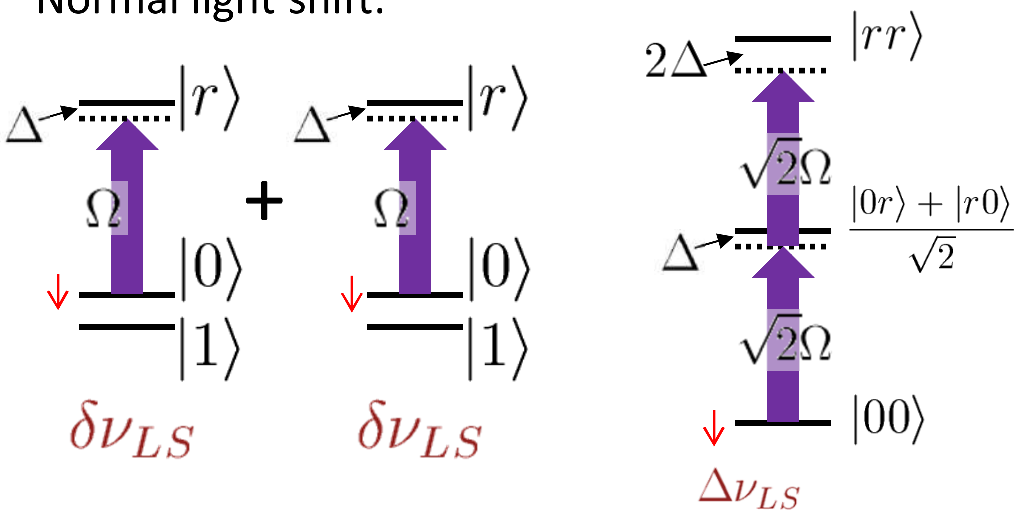
Rydberg dressed

"Elaborate theoretical proposals for the realization of various complex phases and applications in quantum simulation exist. Also a simple model has been already developed that describes the basic idea of Rydberg dressing in a two-atom basis. However, an experimental realization has been elusive so far."

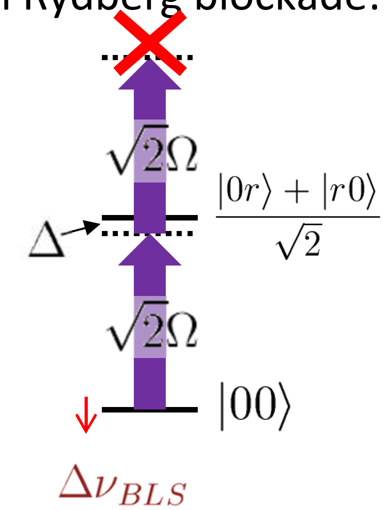
T. Pfau's group, Stuttgart, Germany
J. B. Balewski, *et al.*, *N. J. Phys.* 16, 063012 (2014)

Interaction between two Rydberg-dressed atoms

Normal light shift:



With Rydberg blockade:



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

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

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

Rydberg-dressed interactions

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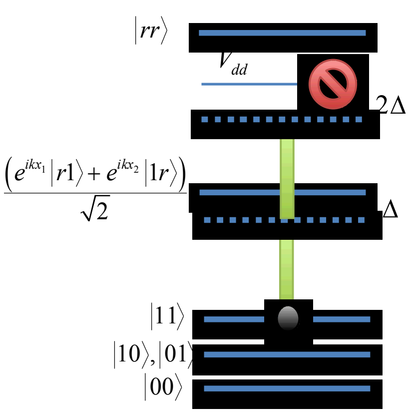
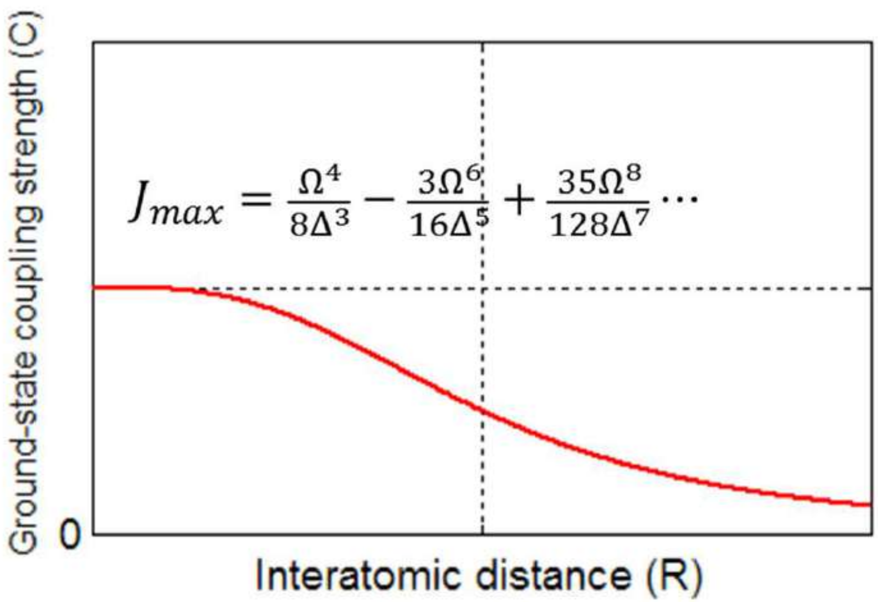
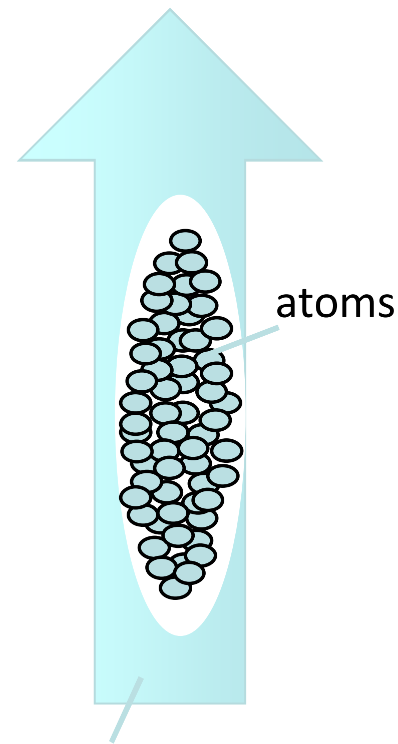
Tunable interaction strength (J), low sensitivity to atom motion, and effectively strong ground-state interactions.

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



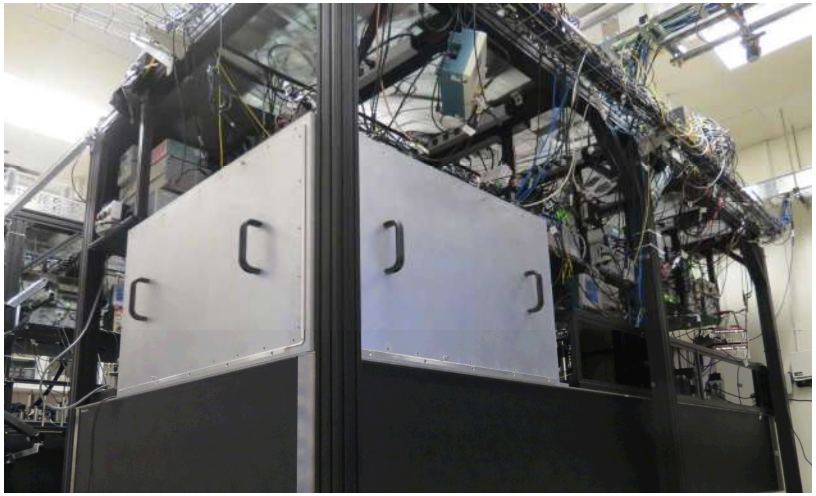


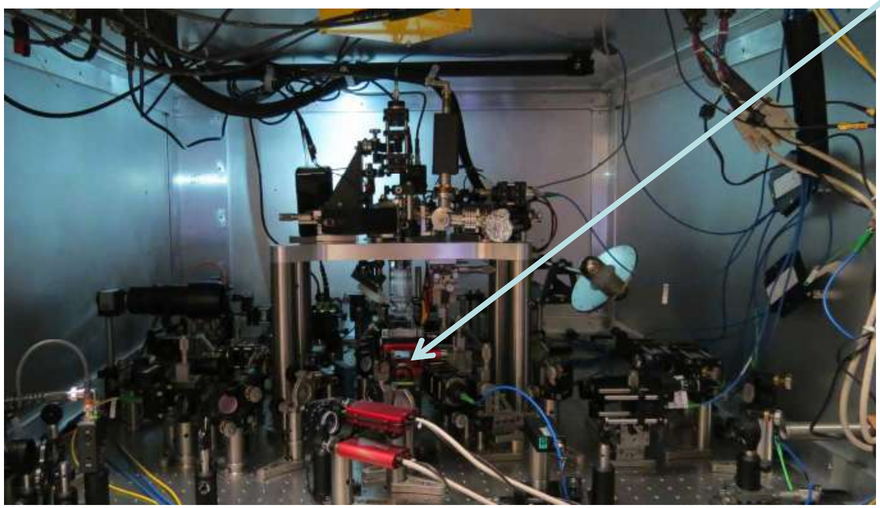


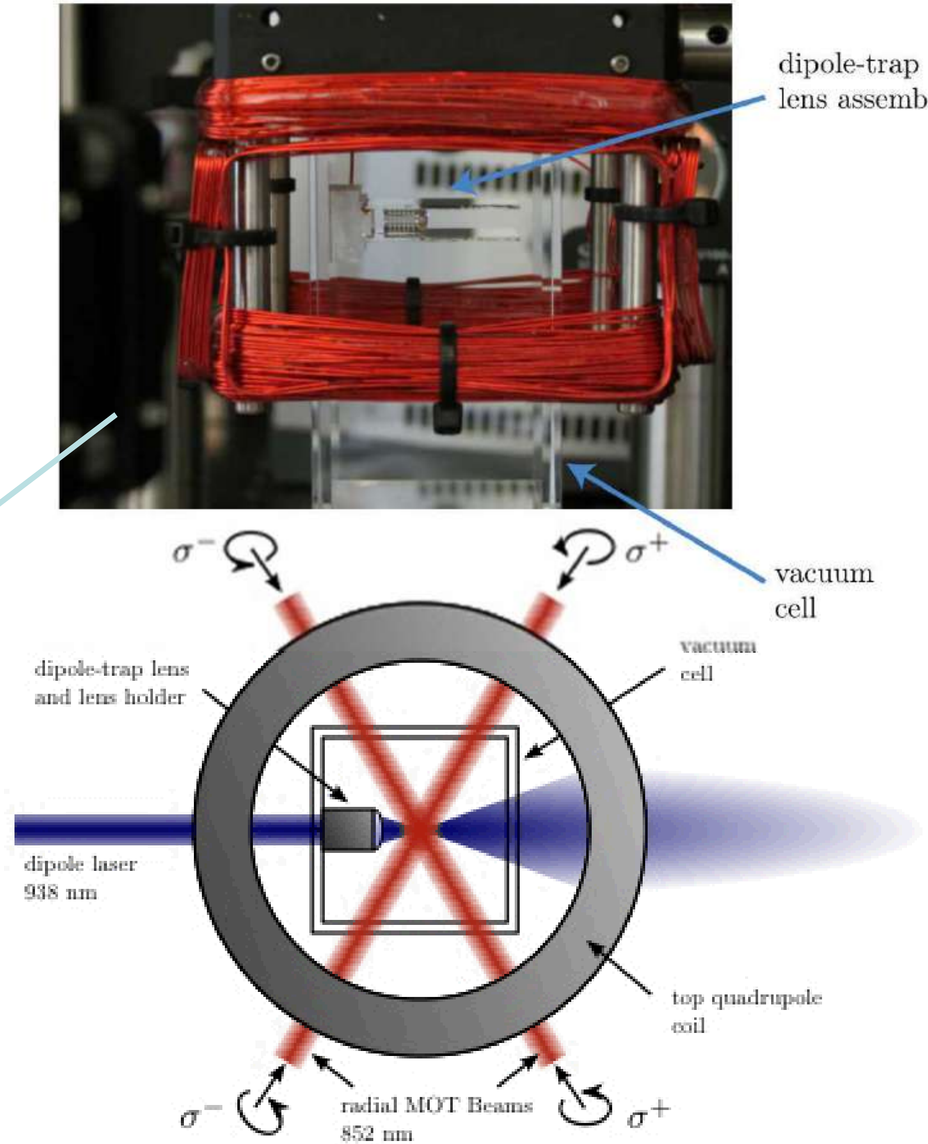
I. Bouchoule, K. Mølmer, Phys. Rev. A 65, 041803 (2002).
J. Johnson, S. Rolston, Phys. Rev. A 82, 033412 (2010).

Favors small detuning

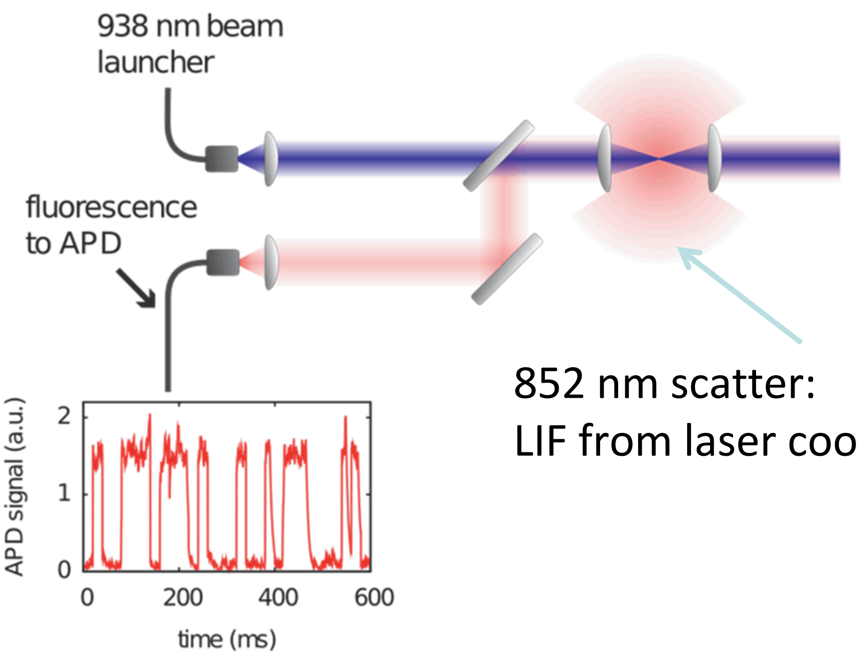
Apparatus



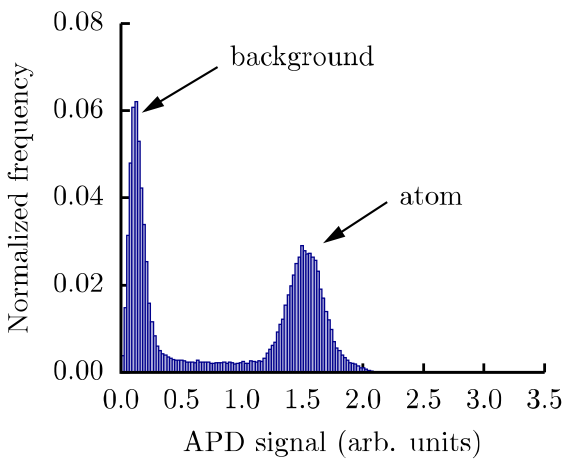



dipole-trap
lens assemb
vacuum
cell
σ−
σ+
dipole-trap lens
and lens holder
vacuum
cell
dipole laser
938 nm
top quadrupole
coil
σ−
radial MOT Beams
852 nm
σ+

Single atom control



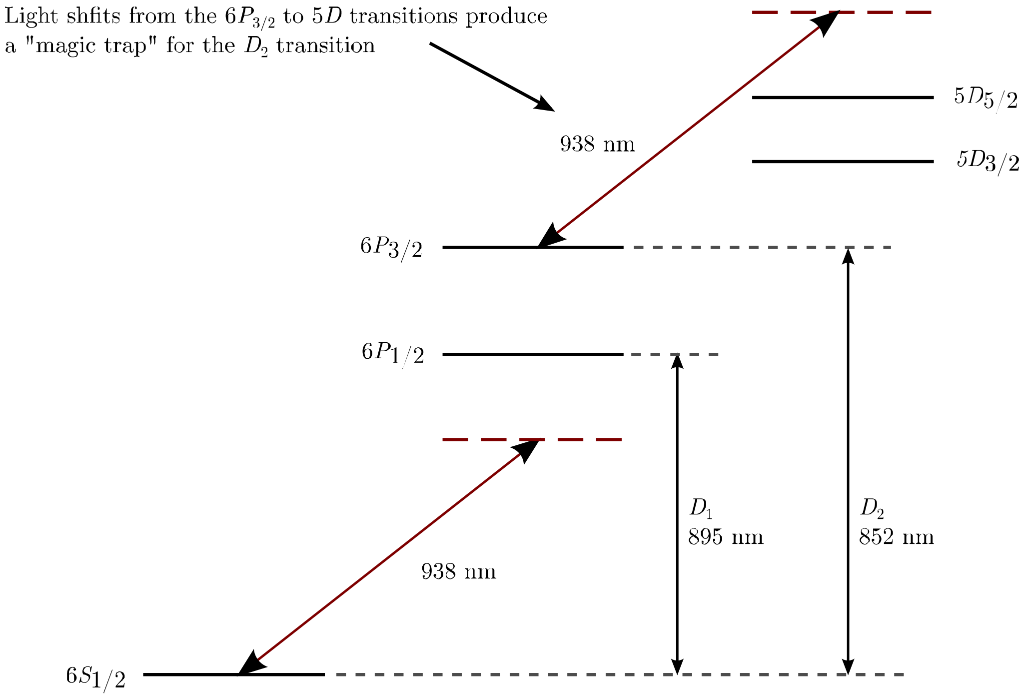
852 nm scatter:
LIF from laser cooling light

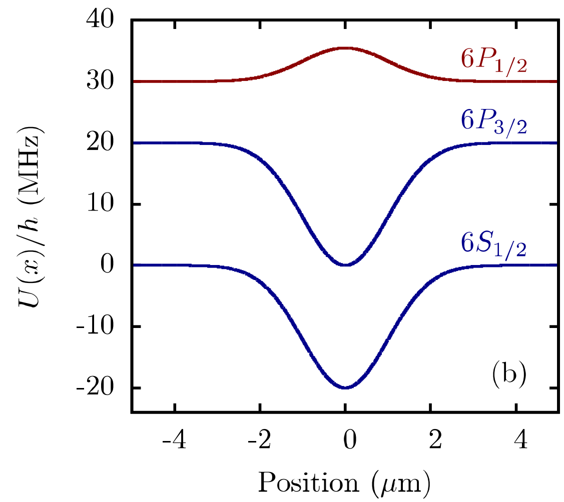


Spot size ≈ 1 μm—collisional blockade

N. Schlosser, G. Reymond, I. Protsenko, and P. Grangier, Nature (London) 411, 1024 (2001).

Single atom control

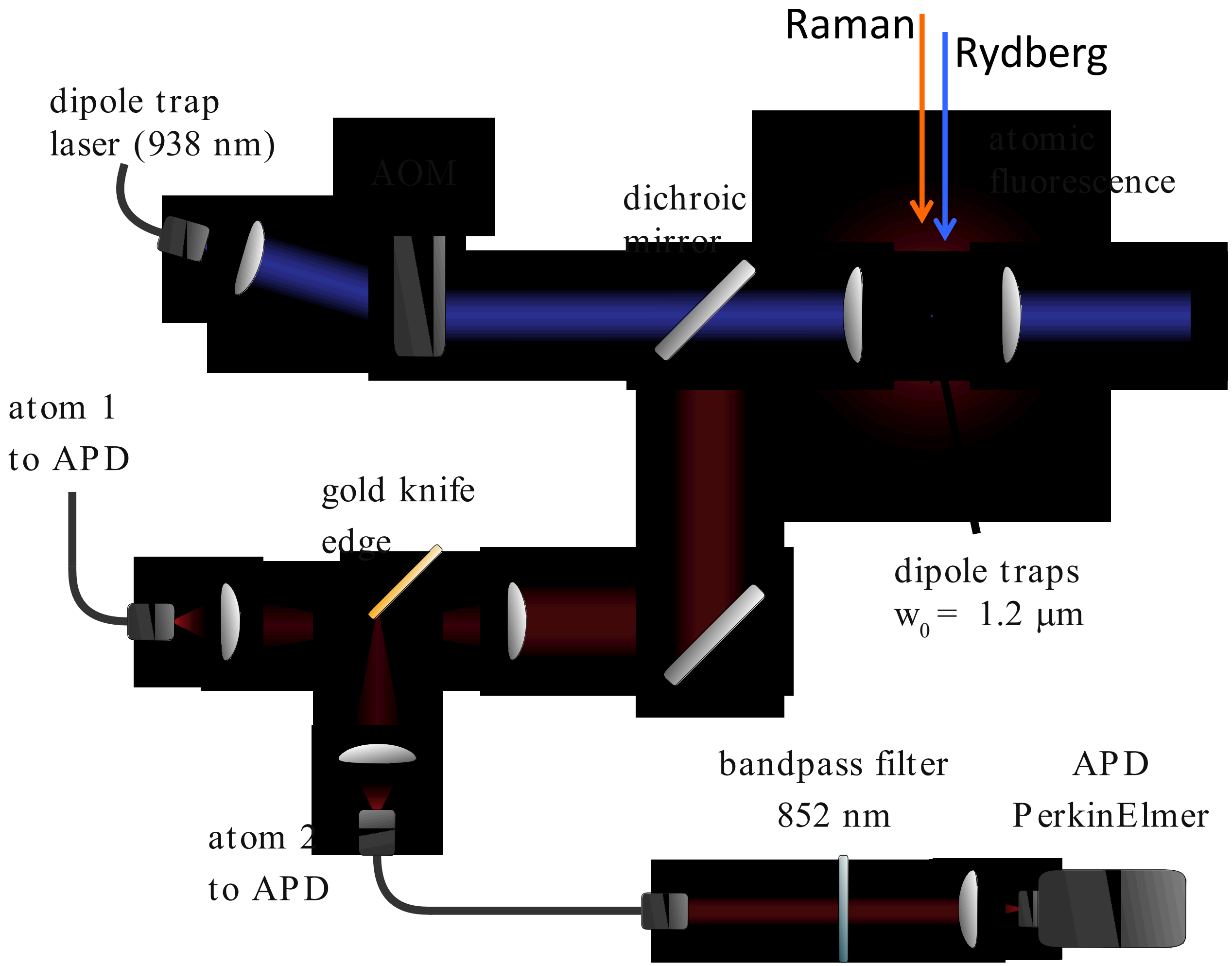




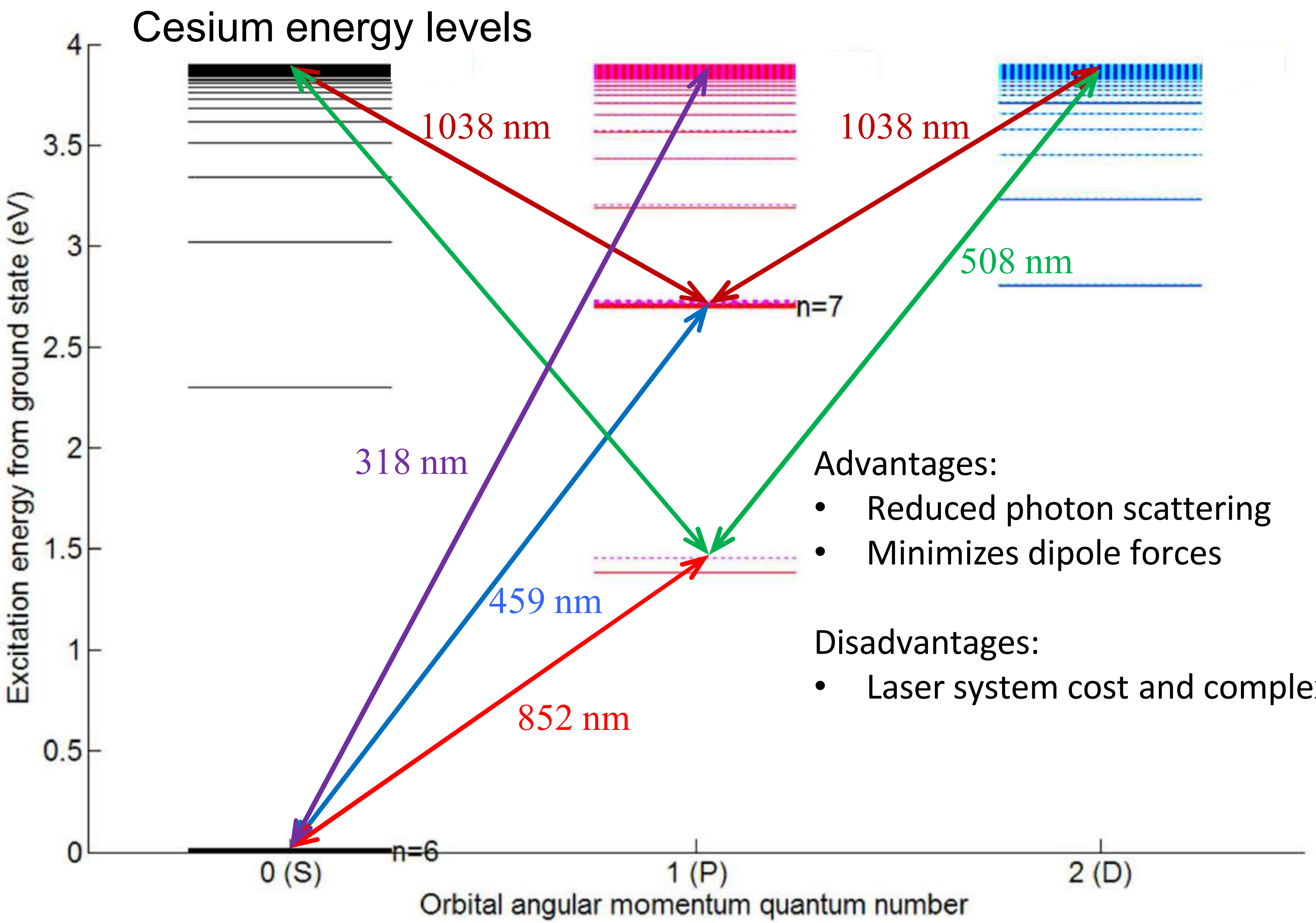
- ≈ 5 mW, 43 nm red
- focused to ≈ 1 μm
- gives ≈ 20 MHz or ≈ 1 mK

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

Experiment schematic



Optimizing for long-term relationships

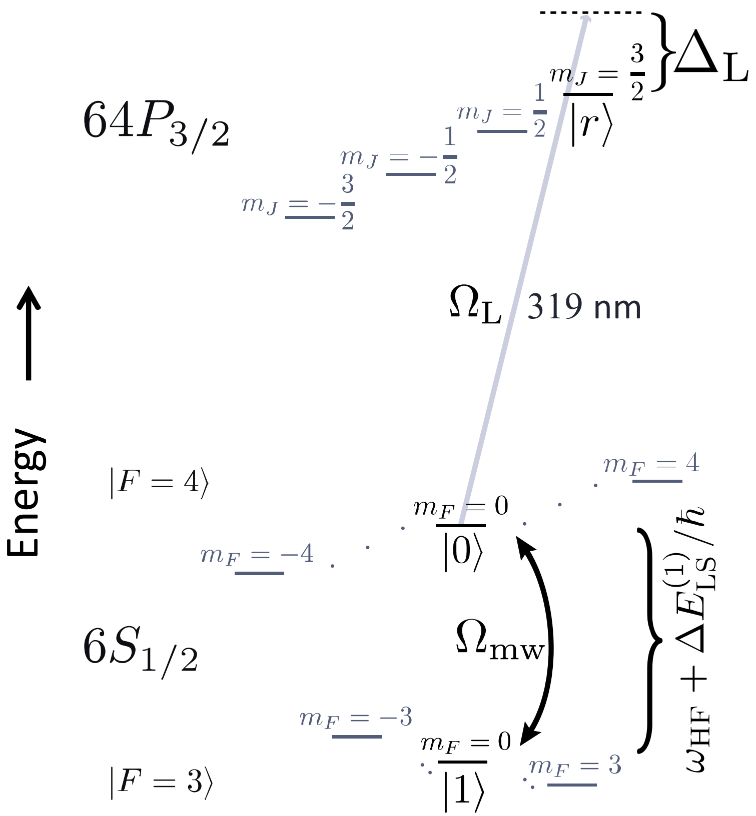


Advantages:
- Reduced photon scattering
- Minimizes dipole forces

Disadvantages:
- Laser system cost and complexity

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

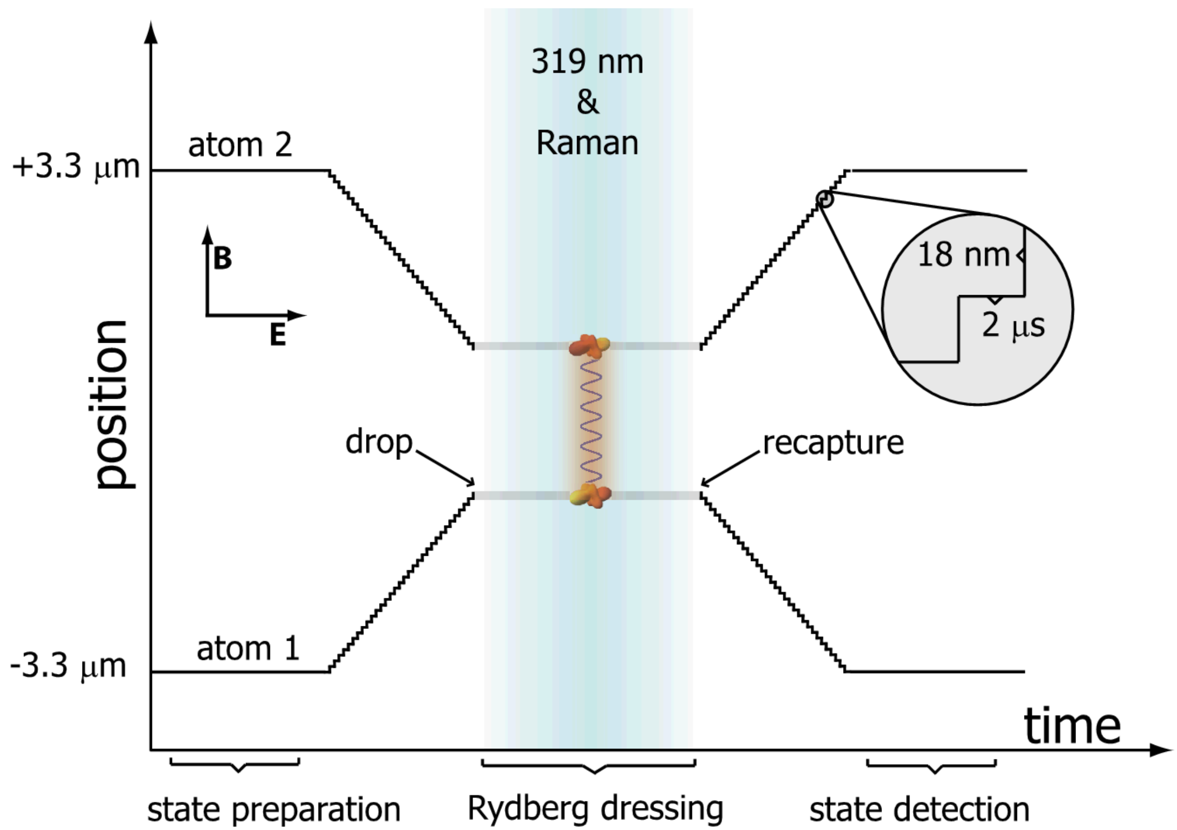
Rydberg-dressed ground state interaction



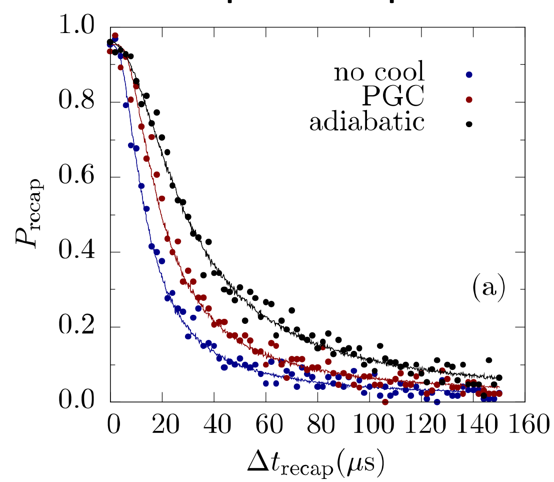
Single atom picture

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

Dynamic atom positioning

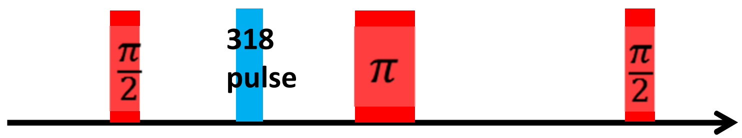


Drop & recapture

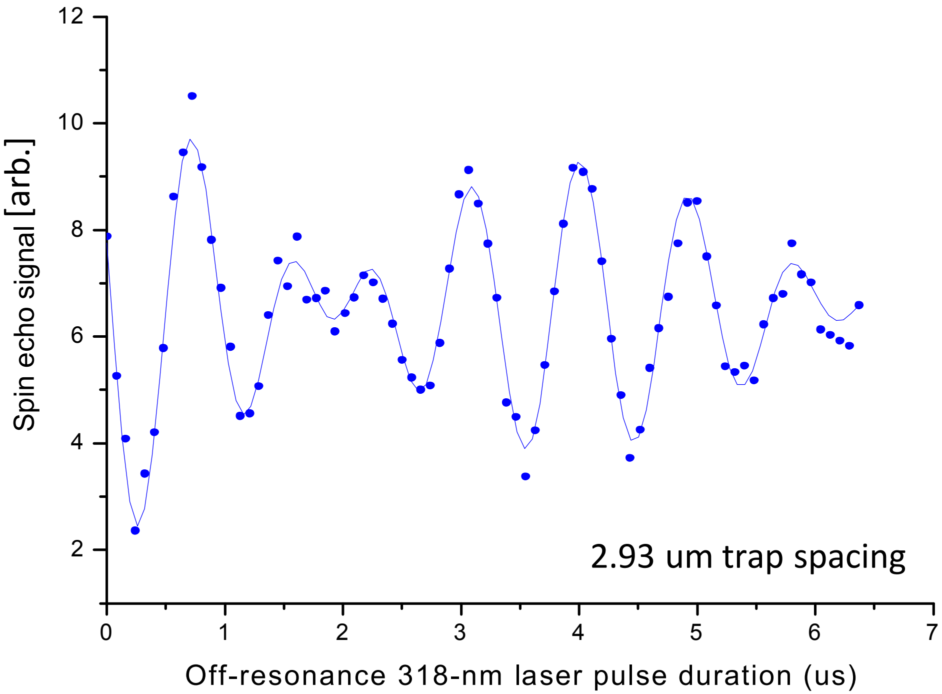


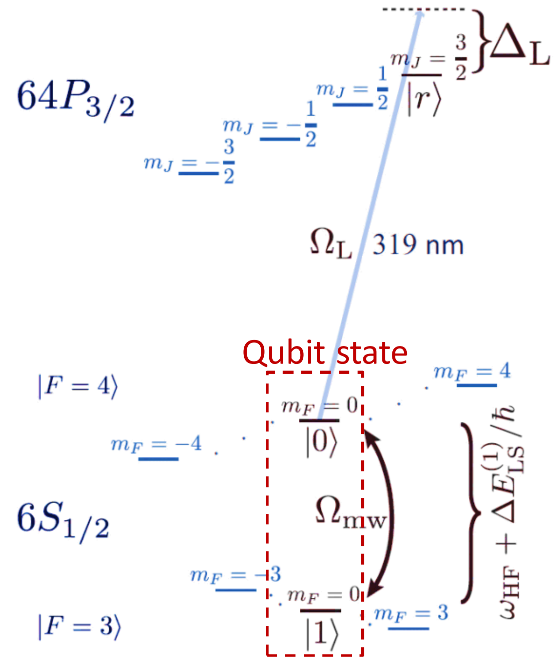
First evidence of Rydberg-dressed interaction

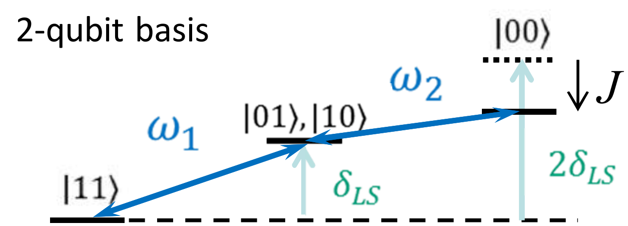
Microwave transition is via Raman laser



318-nm laser dressed spin echo sequence

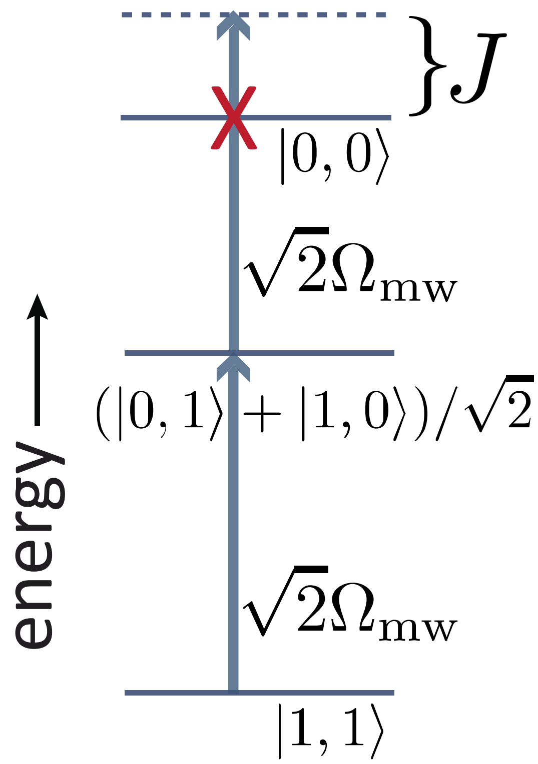


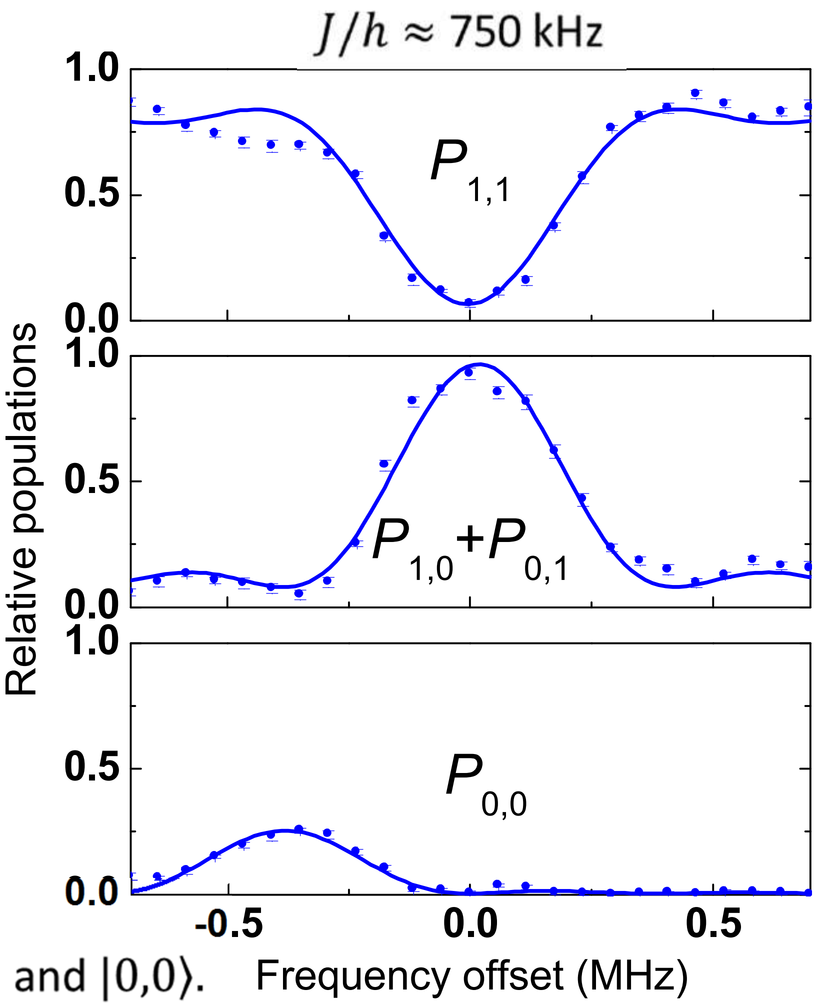




A frequency beat note is generated if $\omega_1 \neq \omega_2$

Two-qubit microwave resonances

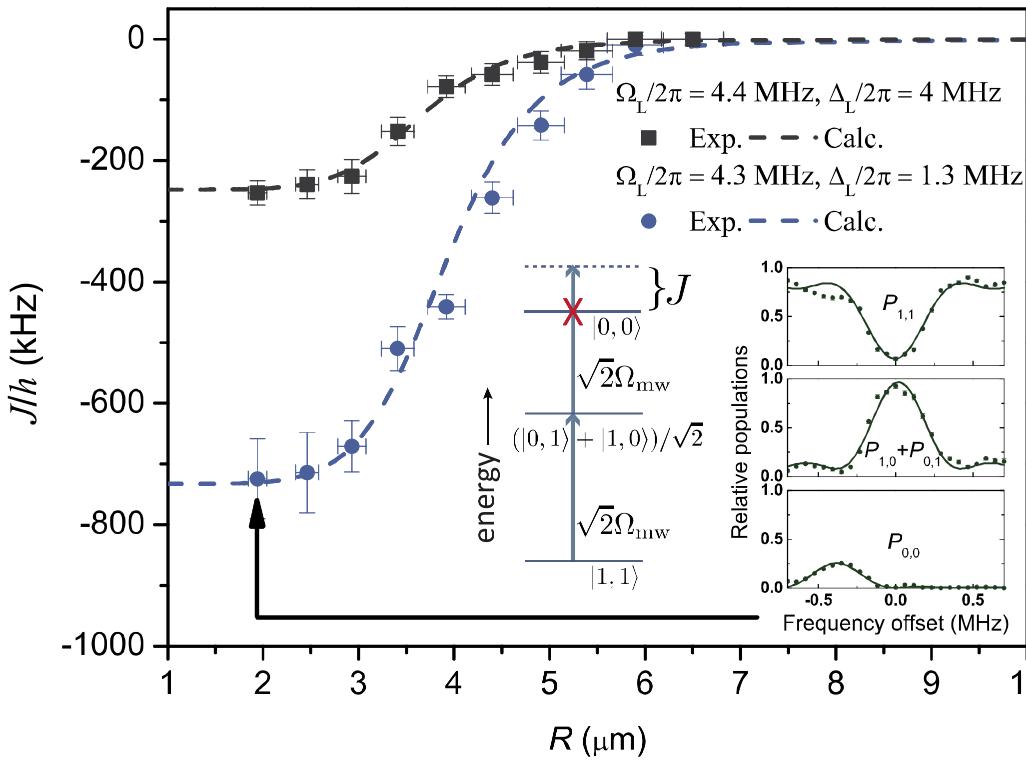


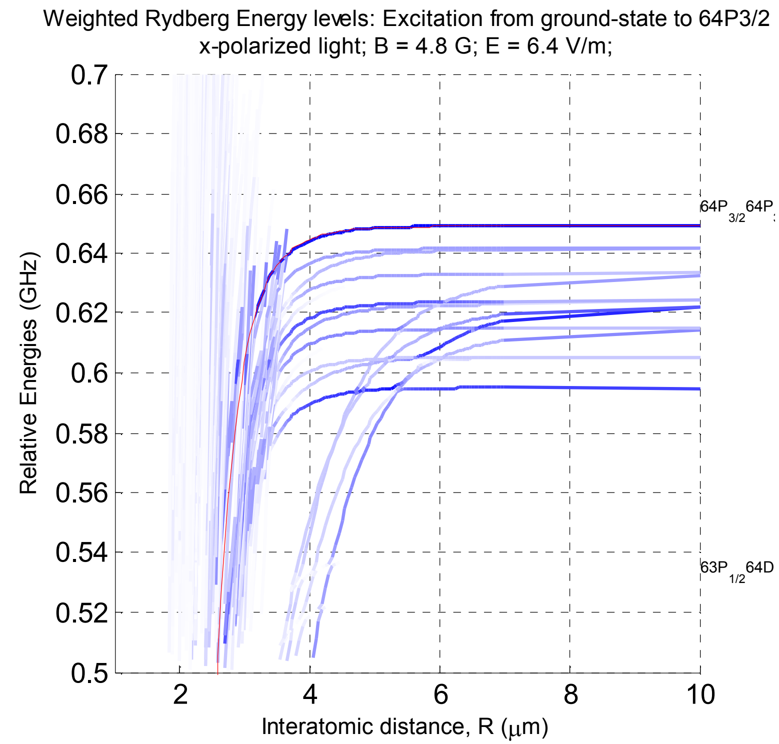


$P_{1,1}$, $P_{1,0}$, $P_{0,1}$, and $P_{0,0}$ denote relative populations of state $|1,1\rangle$, $|1,0\rangle$, $|0,1\rangle$, and $|0,0\rangle$.

J vs. R, no longer elusive

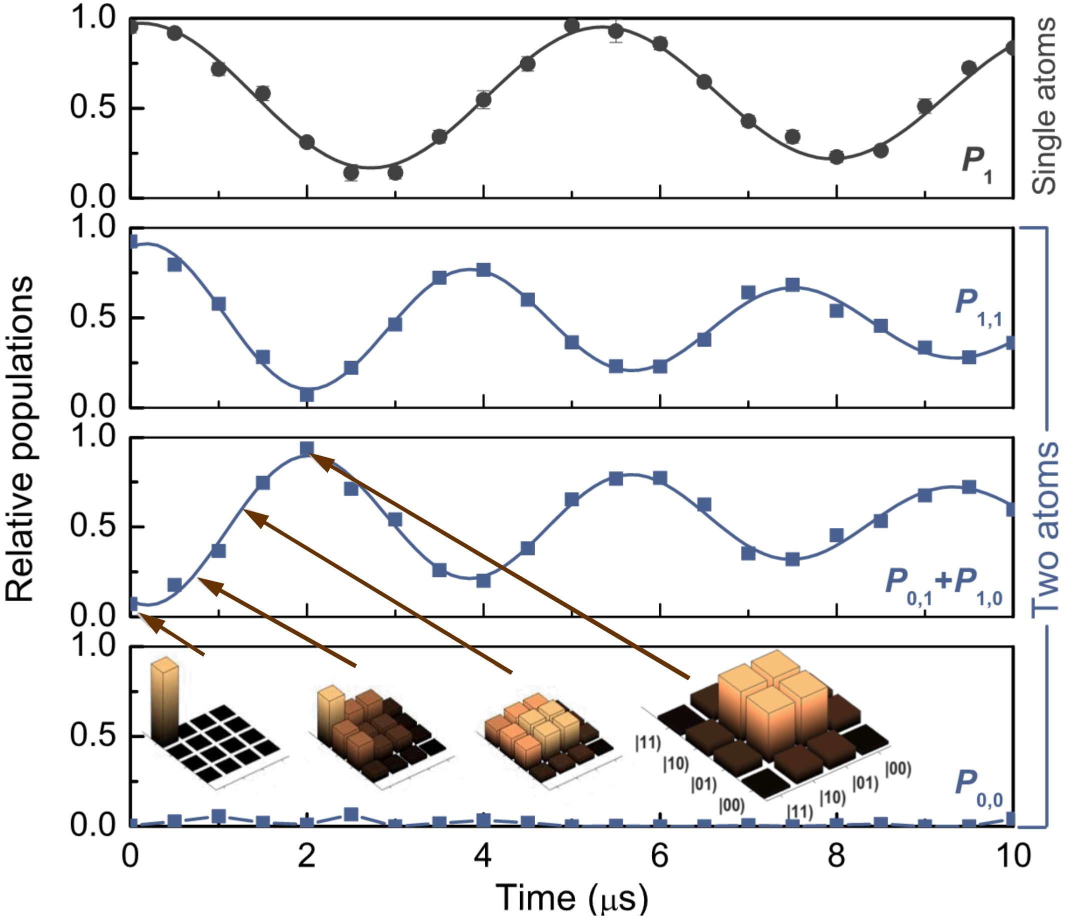
Direct measurement of two-qubit interaction strength J as a function of two-atom separation with two conditions.





Producing Bell-state entanglement

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



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

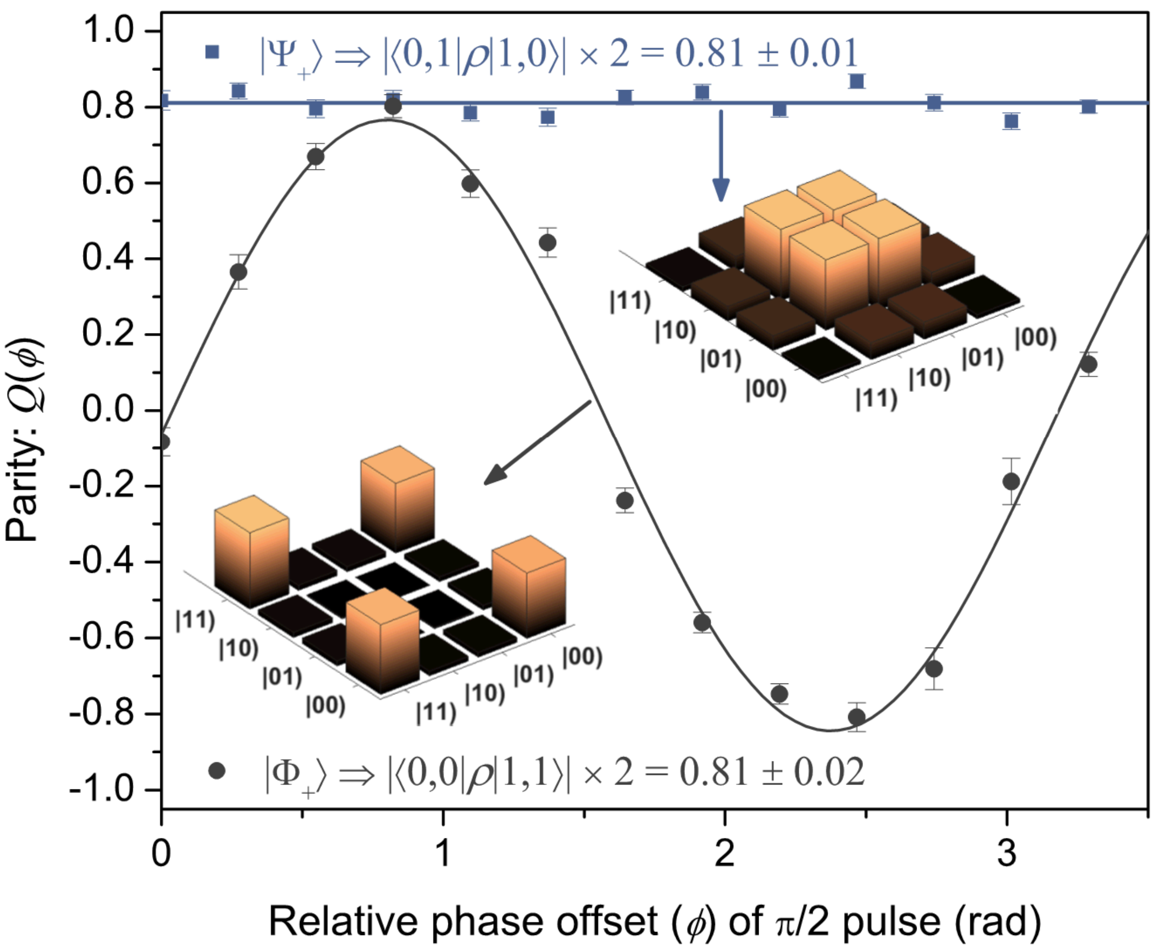
Two-atom Rabi oscillation: $|11\rangle \leftrightarrow (|10\rangle + |01\rangle)/\sqrt{2}$

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

Process occurs entirely and directly in the ground state

Entanglement Fidelity ≥ 81%

Verify the entanglement via parity measurements



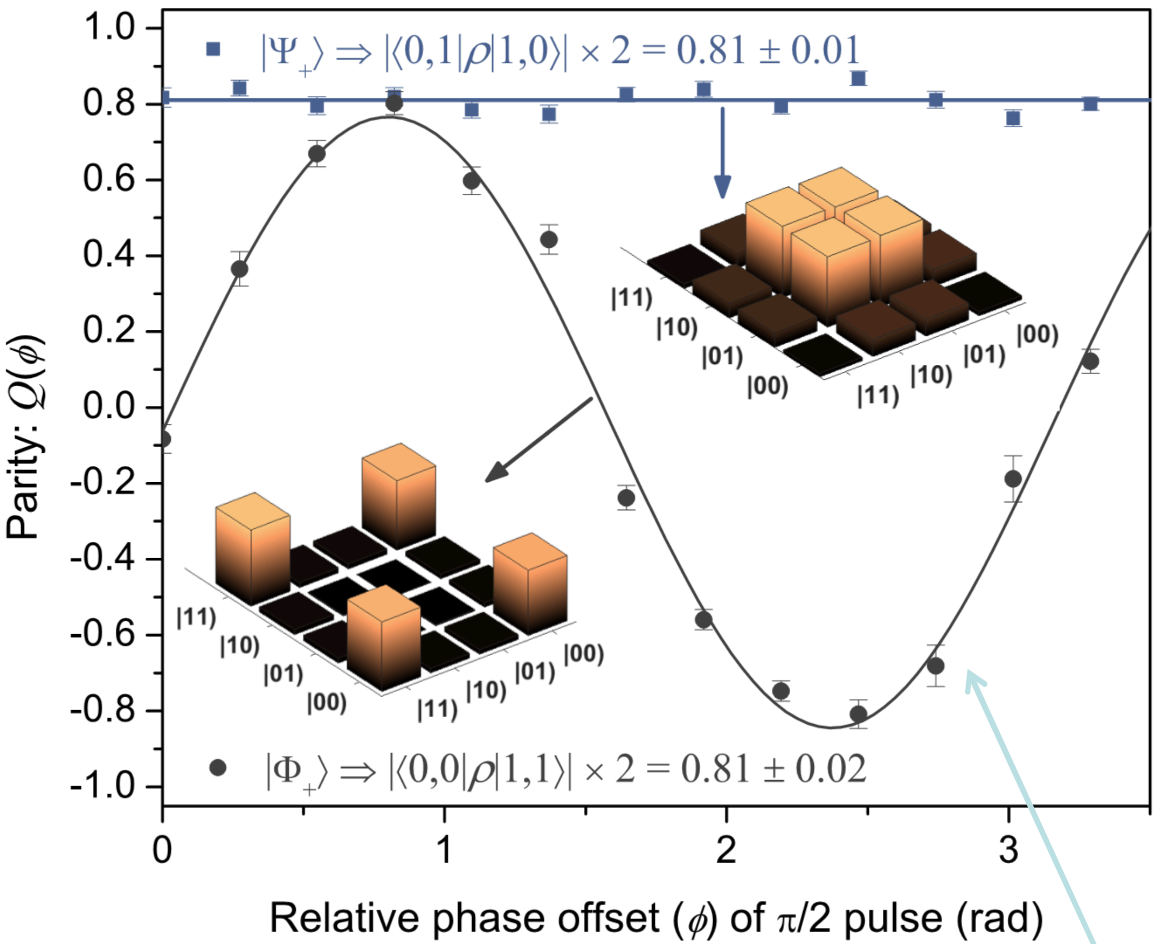
Prepare two Cs atoms in Bell state $|\Psi_+\rangle$ or $|\Phi_+\rangle$

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

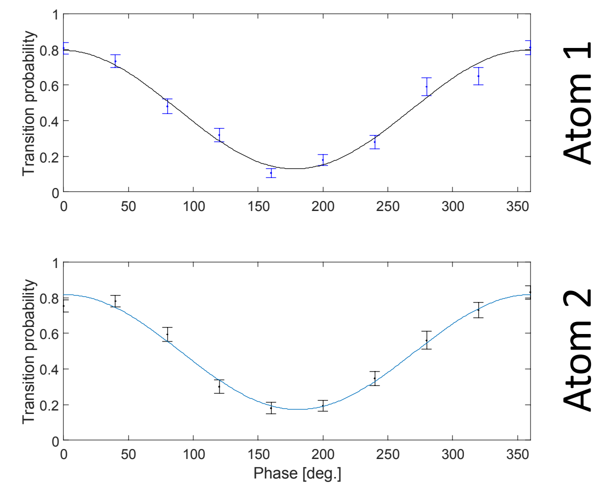
Perform parity measurement $Q = P_{11} + P_{00} - (P_{01} + P_{10})$

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

Application to metrology

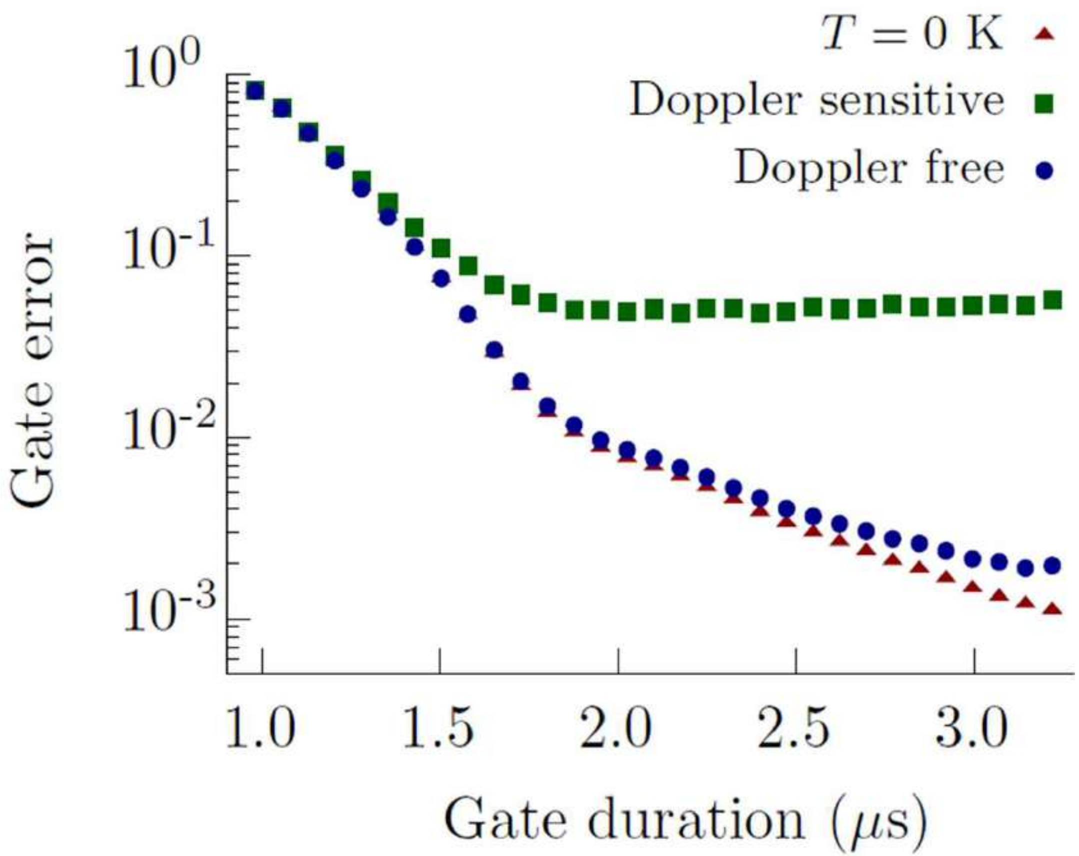


2-atom interferometer



Cat state 2x response to phase

Simulated CPHASE gate fidelities



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

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

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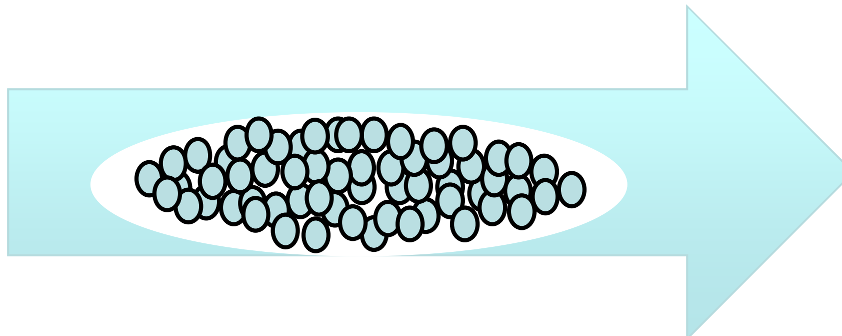
Quantum Control of Ensembles

Symmetrically couple ensemble of atoms localized with Rydberg blockade radius



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

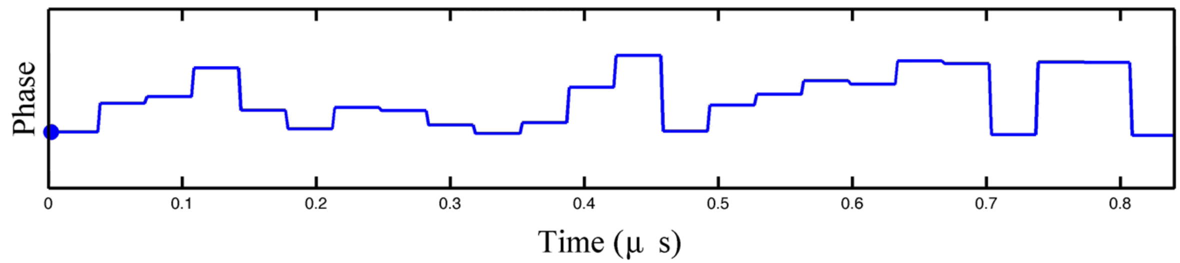
$$H\underbrace{\left[\phi(t)\right]}_{Control}$$

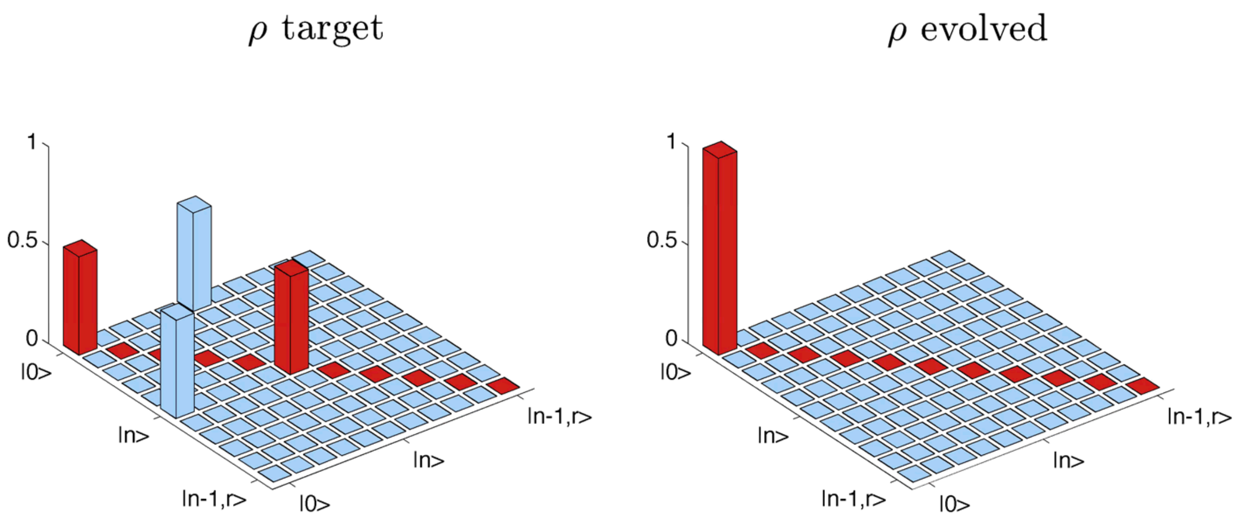
<u>For *n* atoms</u>

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

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

Example: A 5-atom "Cat State"





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

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

Summary and outlook

- Ensemble exchange technique potentially useful for deployed inertial sensors and Gradiometer survey pathfinder facility
- We have demonstrated an effective ground-state interaction J/h ~ 1 MHz via the Rydberg dressing technique
- We have shown neutral atom entanglement with a fidelity ≥ 81(2)%
- With two-atom survival of 74% and 10 s^{-1} data rate, we produce 6 entangled pairs per second
- Multi-atom entanglement can be achieved based a similar approach or with optimal control
- We are investigating atom interferometry with cat states and N > 2

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Yuan-Yu Jau (Sandia)

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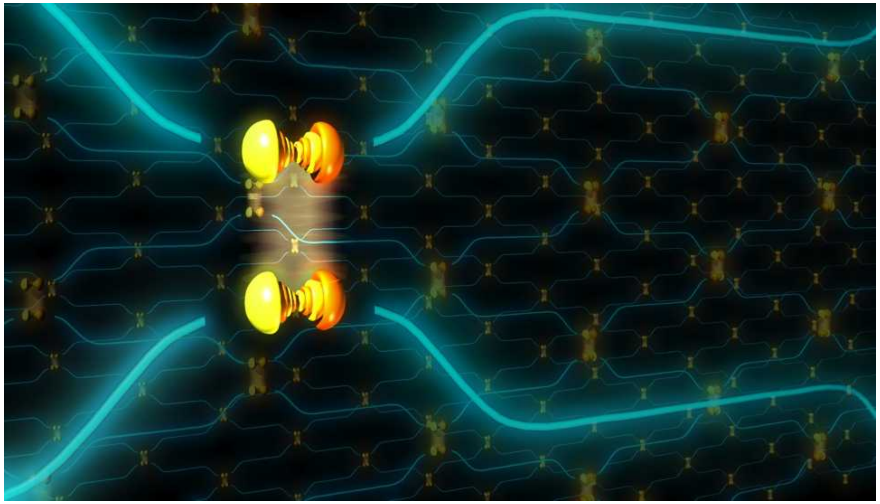
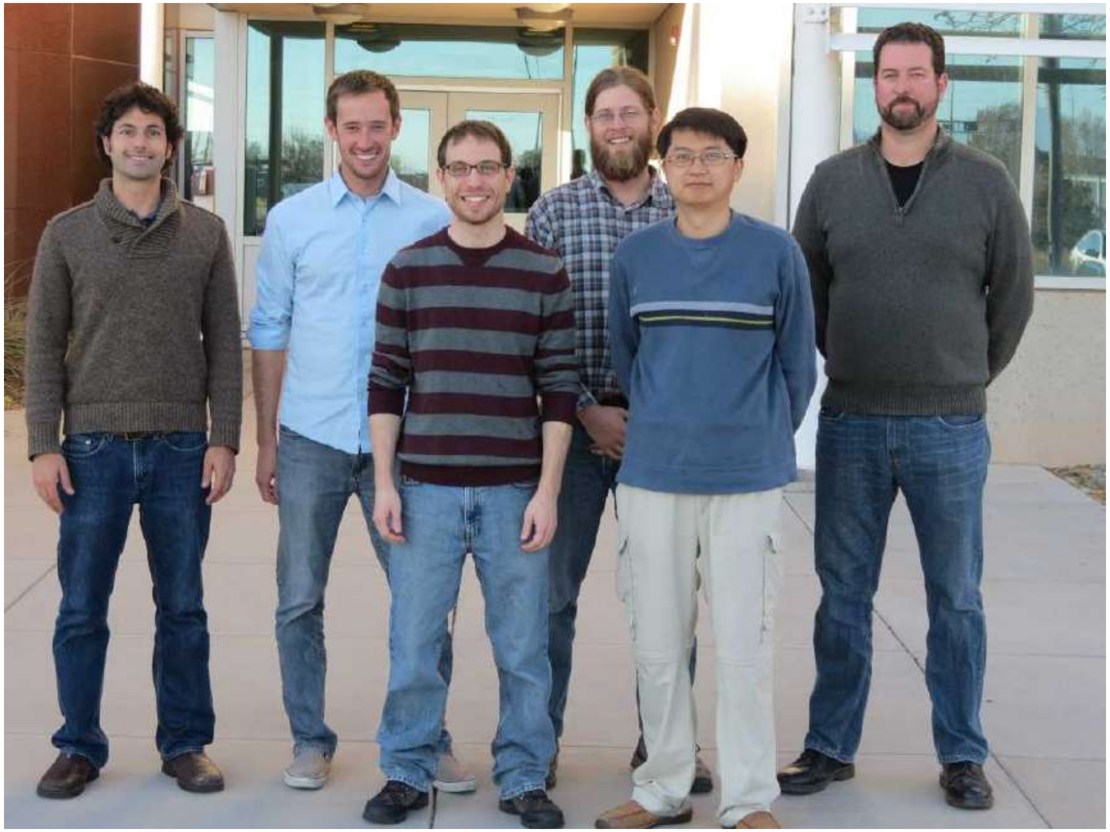


Acknowledgements



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