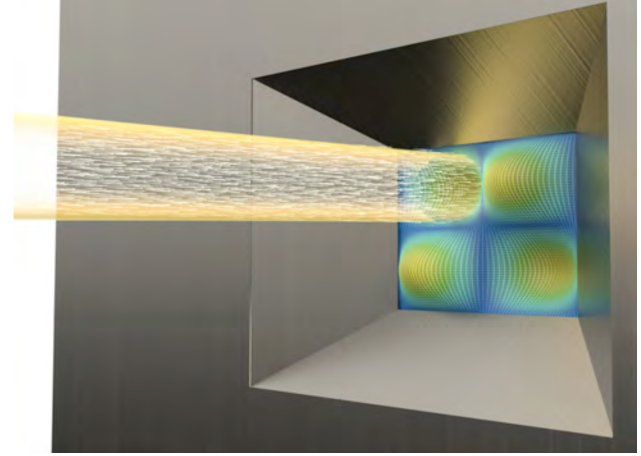
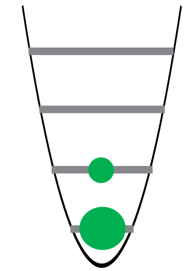



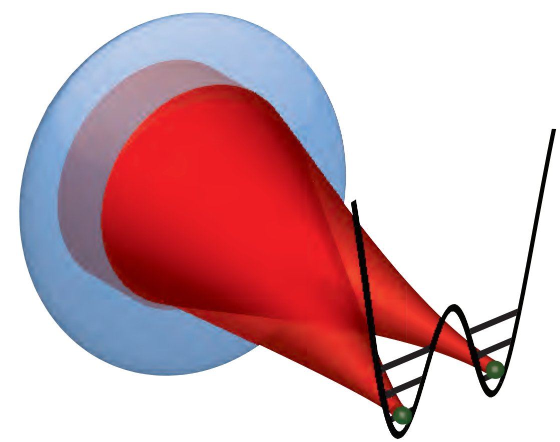
Cindy Regal

Condensed Matter Summer School, 2018

Day 1: Quantum optomechanics

Day 2: Quantum transduction

Day 3: Ultracold atoms from a qubit perspective



JILA NIST CU

Reading from yesterday

M. J. Collett and C. W. Gardiner, “Squeezing of intracavity and traveling wave light fields produced in parametric amplification” Phys. Rev. A 30, 1386 (1984)

Amir H Safavi-Naeini and Oskar Painter, “Proposal for an optomechanical traveling wave phonon–photon translator” New J. Phys 13, 013017 (2011)

M. Tsang, “Cavity quantum electro-optics”, Phys. Rev. A 81, 063837 (2010)

R. W. Andrews, R. W. Peterson, T. P. Purdy, K. Cicak, R. W. Simmonds, C. A. Regal, and K. W. Lehnert, “Bidirectional and efficient conversion between microwave and optical light” Nature Physics 10, 321 (2014)

Day 1: Quantum optomechanics – quantum limits to continuous displacement detection

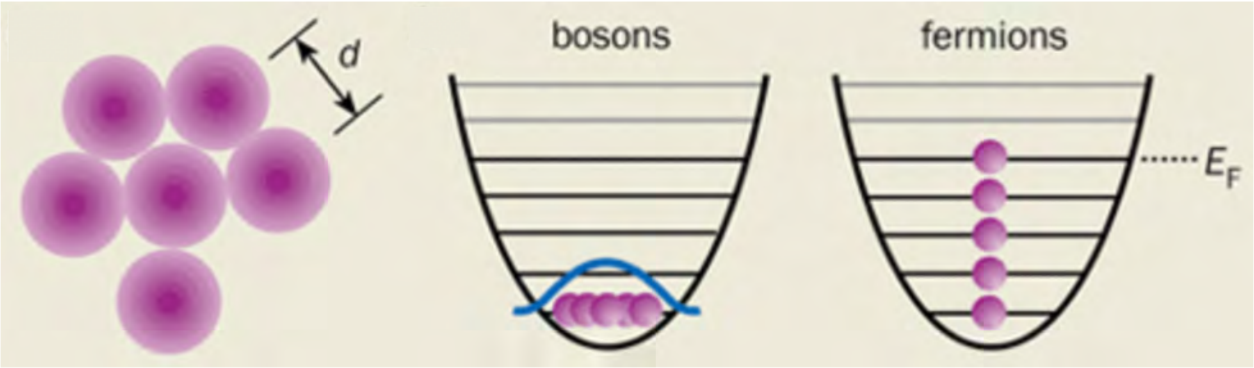
Day 2: Quantum transduction – conversion from microwave (superconducting qubits) to optical photons (transmission domain)

Machinery is that of linear equations / gaussian states
Useful to understanding from perspective of quantum metrology, transducers
Learn what you can't do without a strong nonlinearity

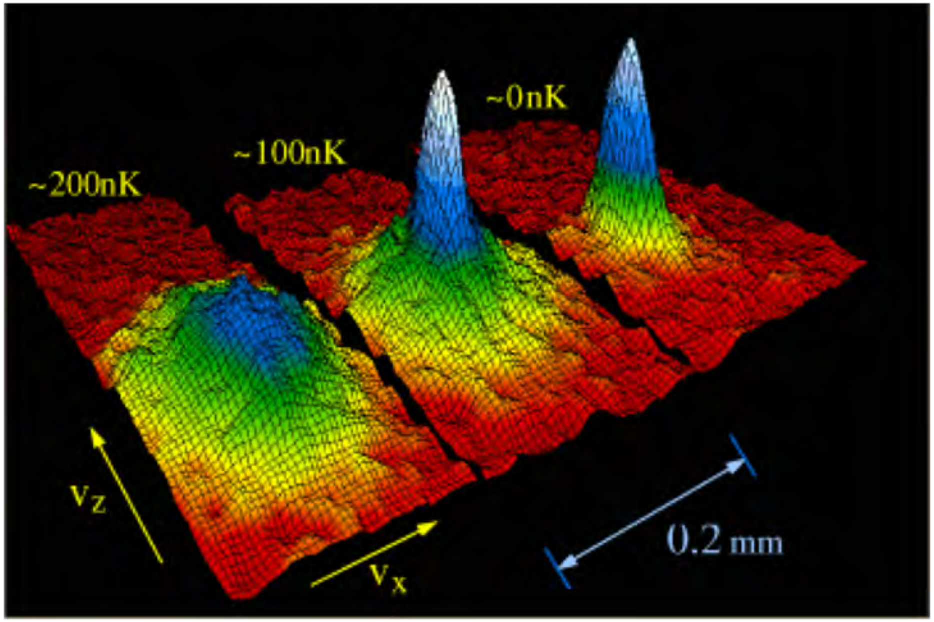
Day 3: Ultracold atoms from a qubit perspective – interfering and entangling bosonic atoms

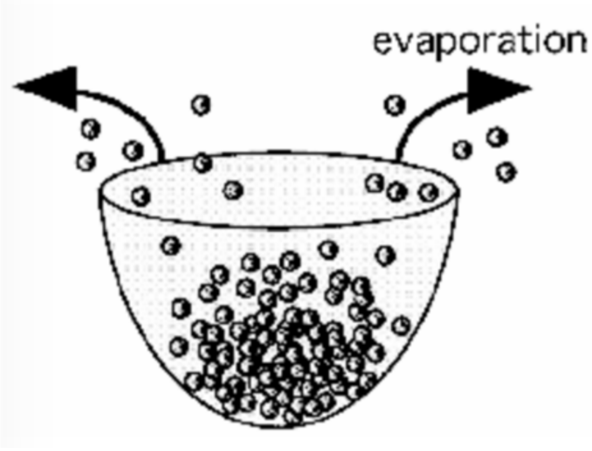
Ultracold atoms
Controlling individual neutral atoms
The Hong-Ou-Mandel effect with atoms
Some examples of creating a Bell State

Ultracold atoms



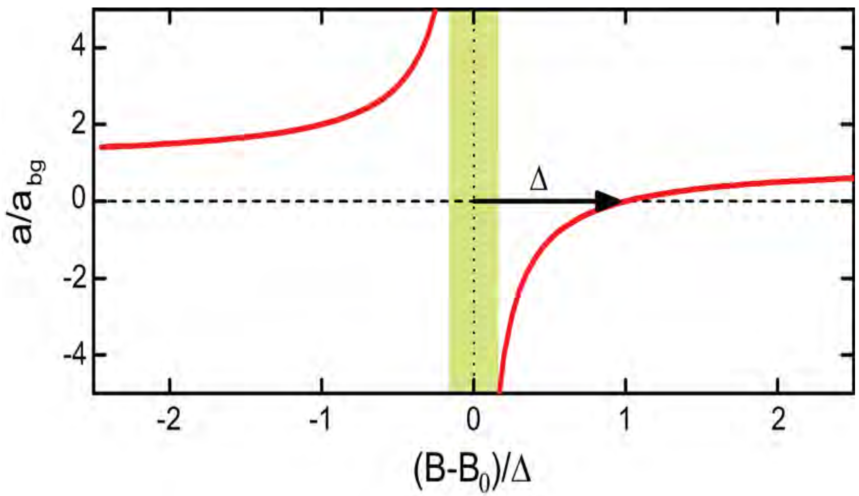
2 D velocity distributions



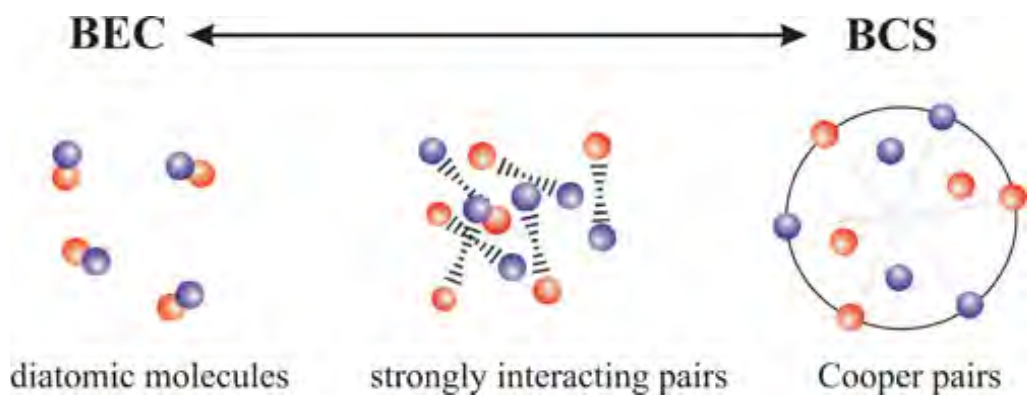


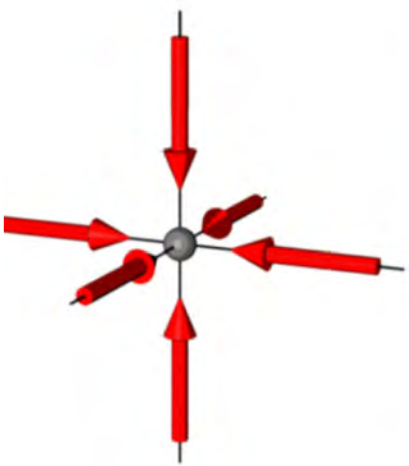
Ultracold atoms

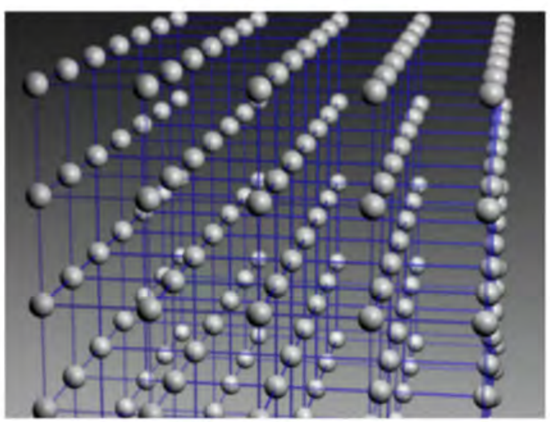
Stronger interactions



Tunable interactions
Feshbach scattering resonance

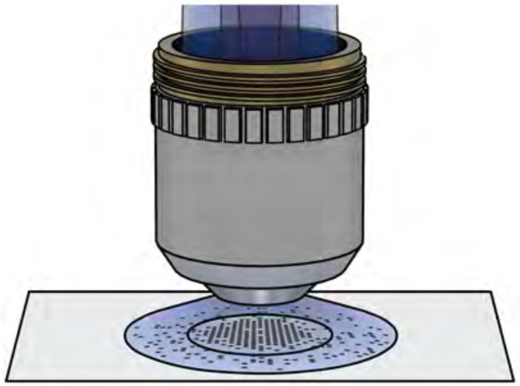


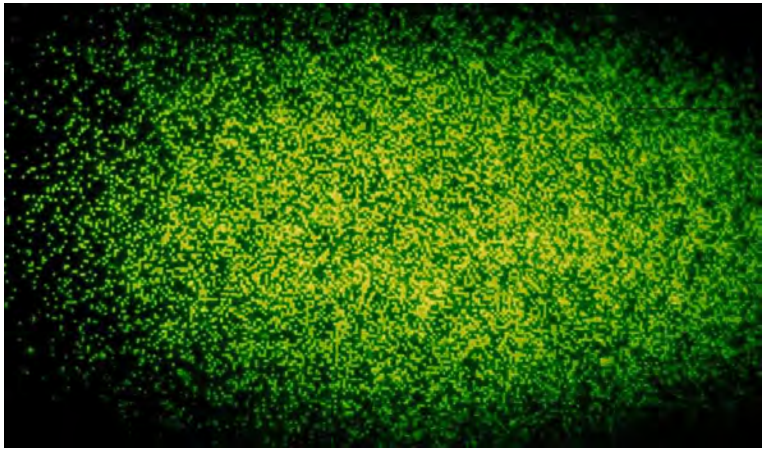


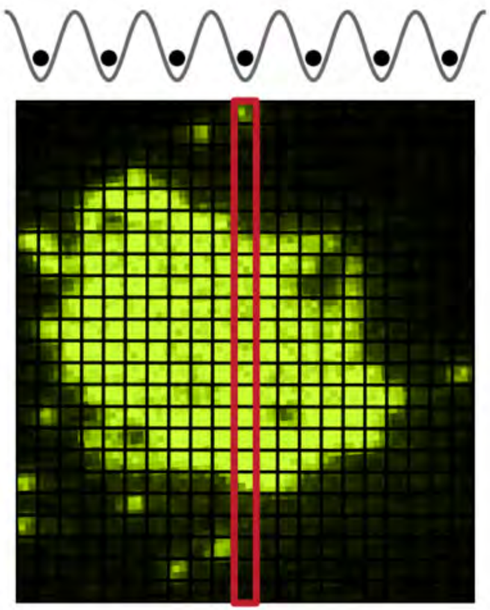


Optical lattices

Quantum gas microscopes







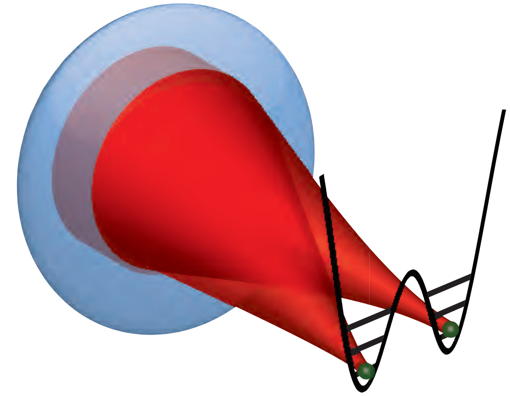
Images: Greiner group, Harvard

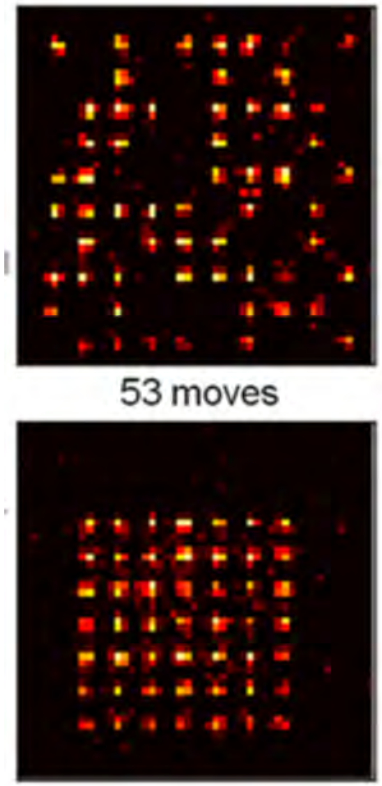
Optical tweezers

Sub-poissonian loading of single atoms in a microscopic dipole trap

Nicolas Schlosser, Georges Reymond, Igor Protsenko & Philippe Grangier

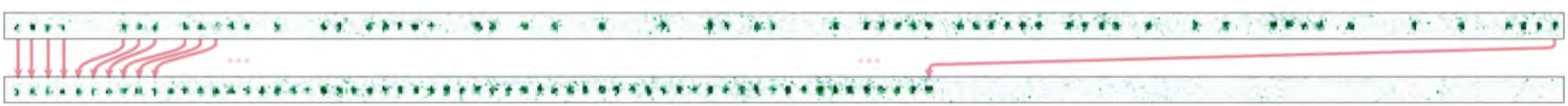
NATURE | VOL 411 | 28 JUNE 2001





Scalability of grabbing onto atoms

D. Barredo *et al.* Science (2016)
M. Endres *et al.*, Science (2016)



Outline

Isolating single alkali atoms, 'single atom' source
Bringing many of them together

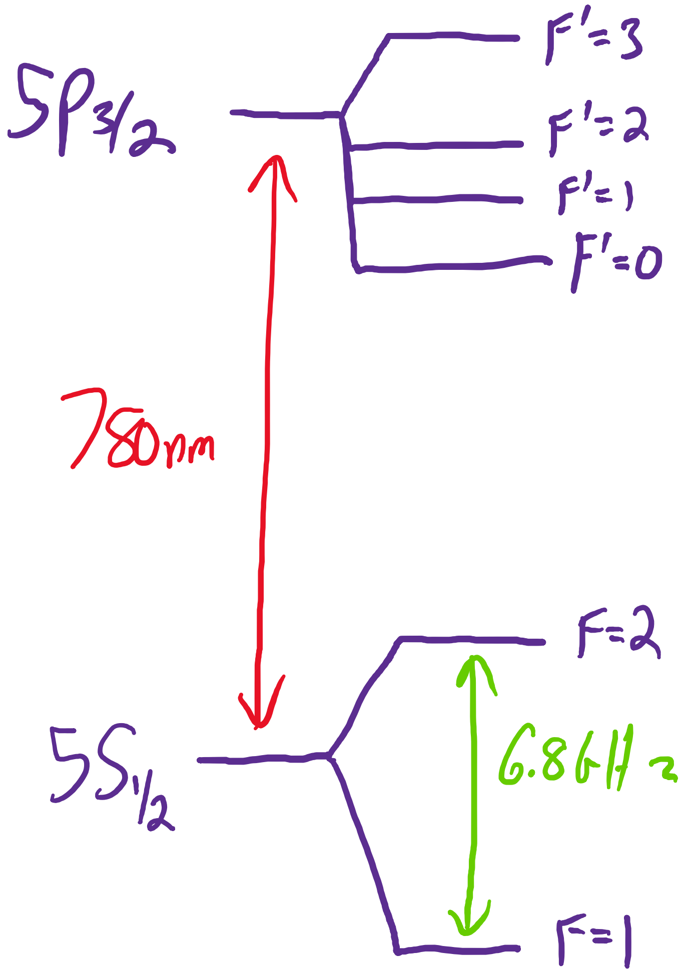
Raman sideband cooling – controlling purity of state

Interfering bosonic atoms – atomic Hong-Ou-Mandel effect

Creating entangled Bell states and characterizing: 3 ways

- Rydberg blockade
- Spin-exchange, contact interaction
- Interference and measurement

Rubidium structure



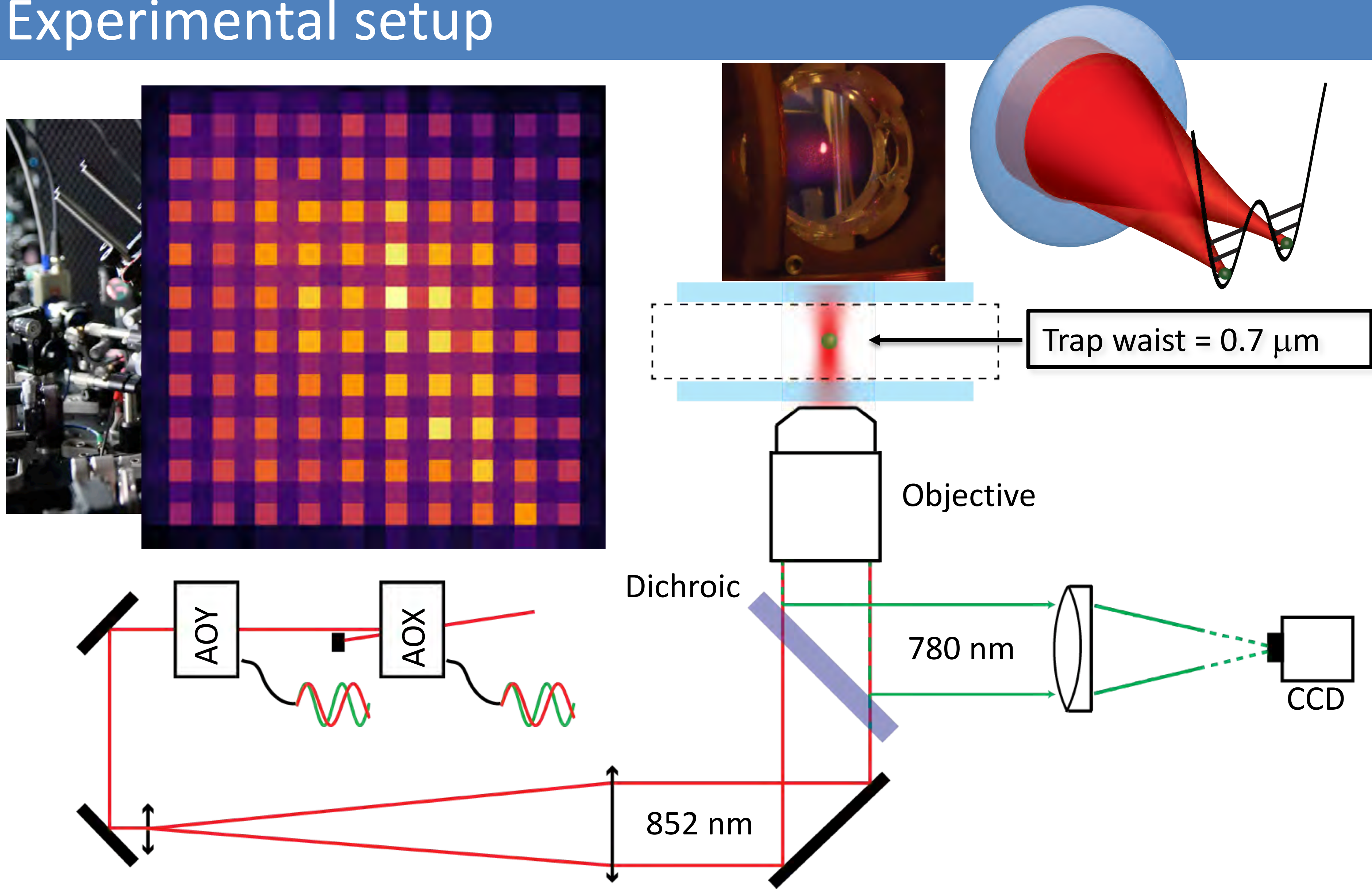
$J=3/2,\ I=3/2$

$|\uparrow\rangle = |F=2, m_F=2\rangle$

$|\downarrow\rangle = |F=1, m_F=1\rangle$

$J=1/2,\ I=3/2$

Experimental setup



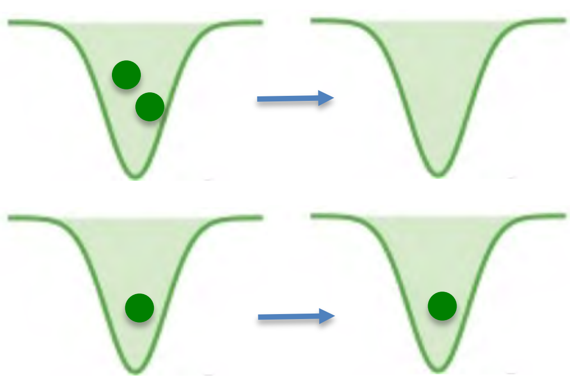
Loading single atoms

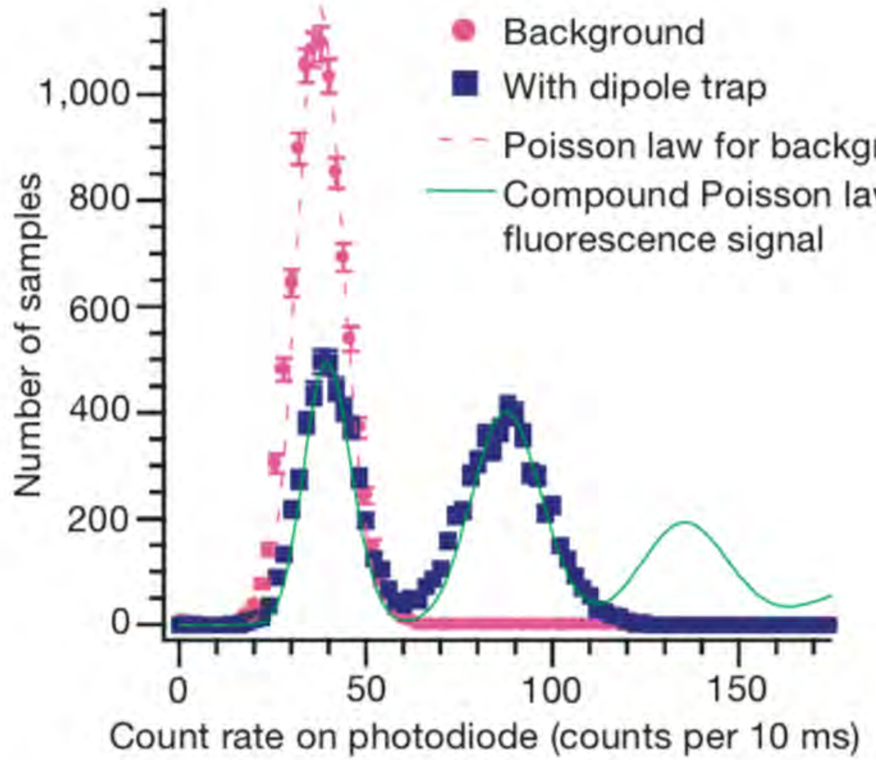
Sub-poissonian loading of single atoms in a microscopic dipole trap

Nicolas Schlosser, Georges Reymond, Igor Protsenko & Philippe Grangier

NATURE | VOL 411 | 28 JUNE 2001

“Parity loading”





Loading single atoms

Sub-poissonian loading of single atoms in a microscopic dipole trap

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NATURE | VOL 411 | 28 JUNE 2001

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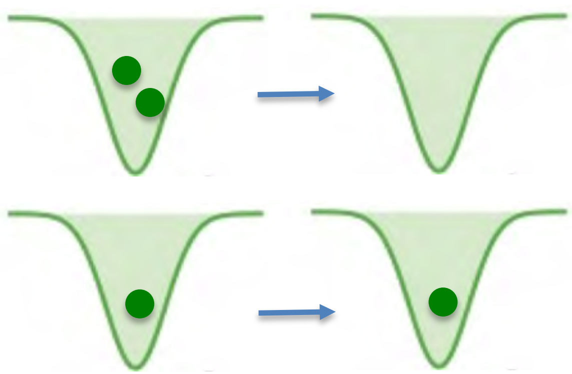
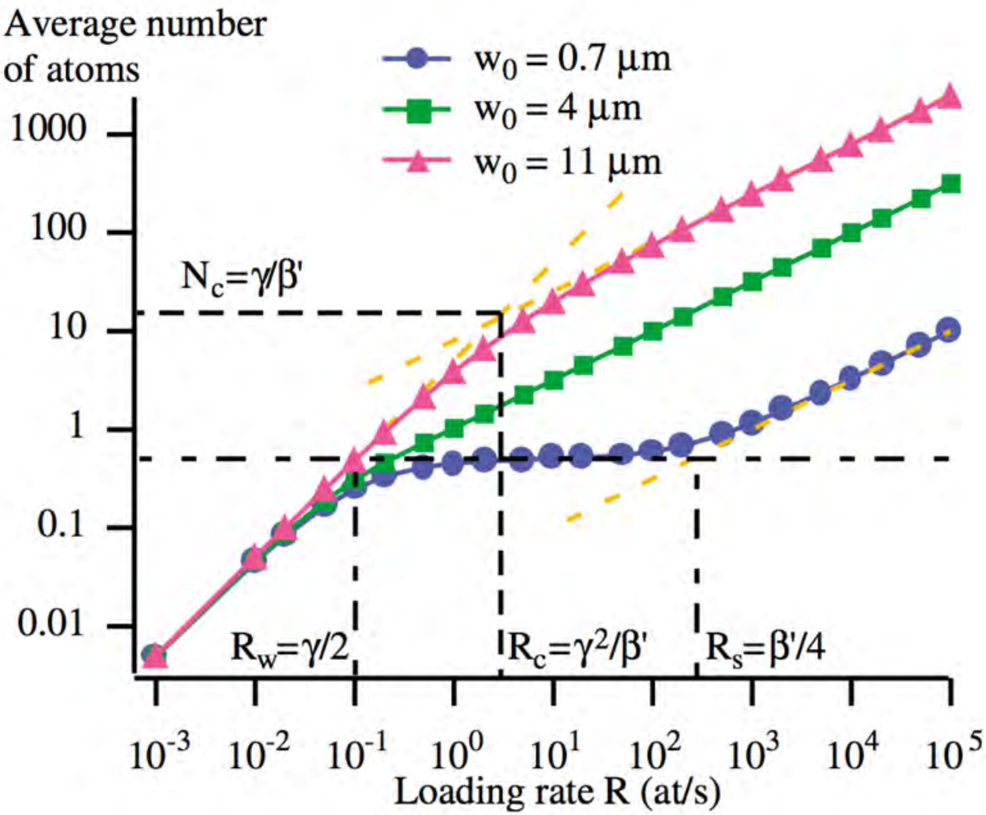
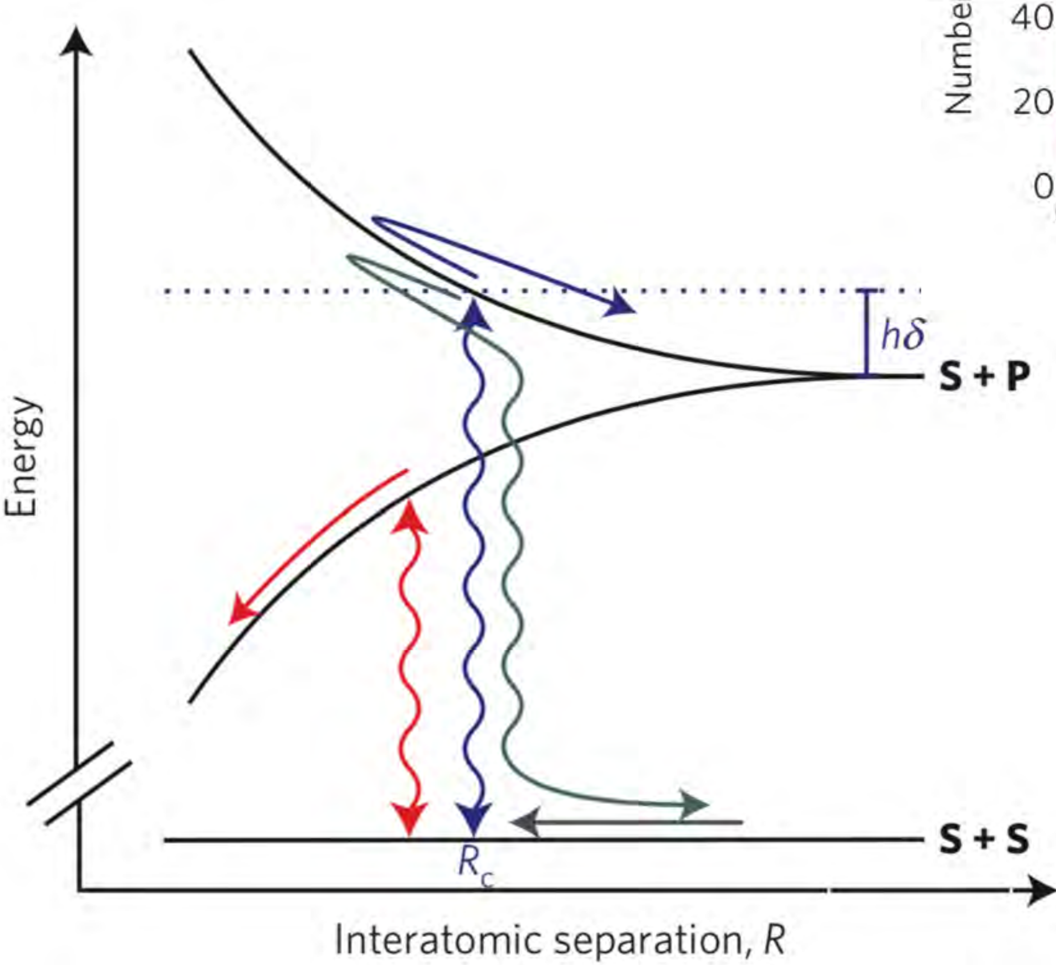
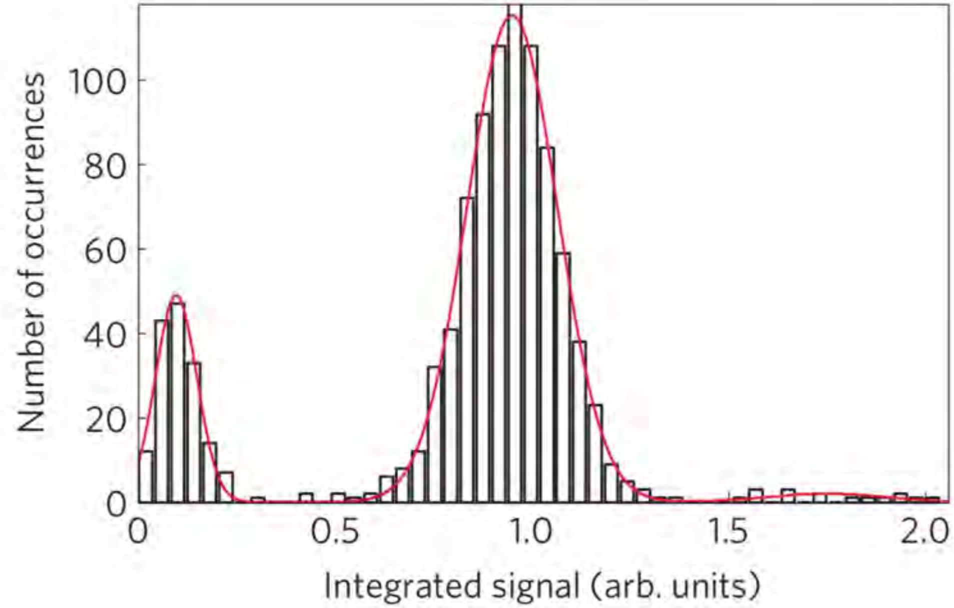


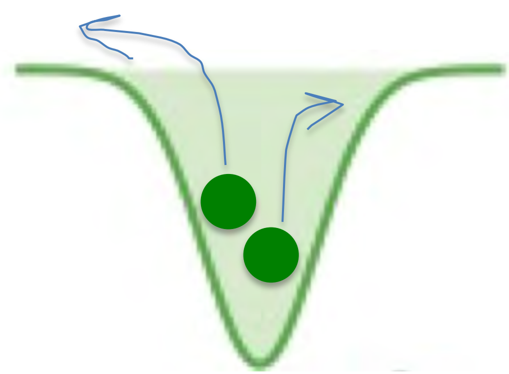


Schlosser *et al.*, PRL (2002)

Better than parity loading

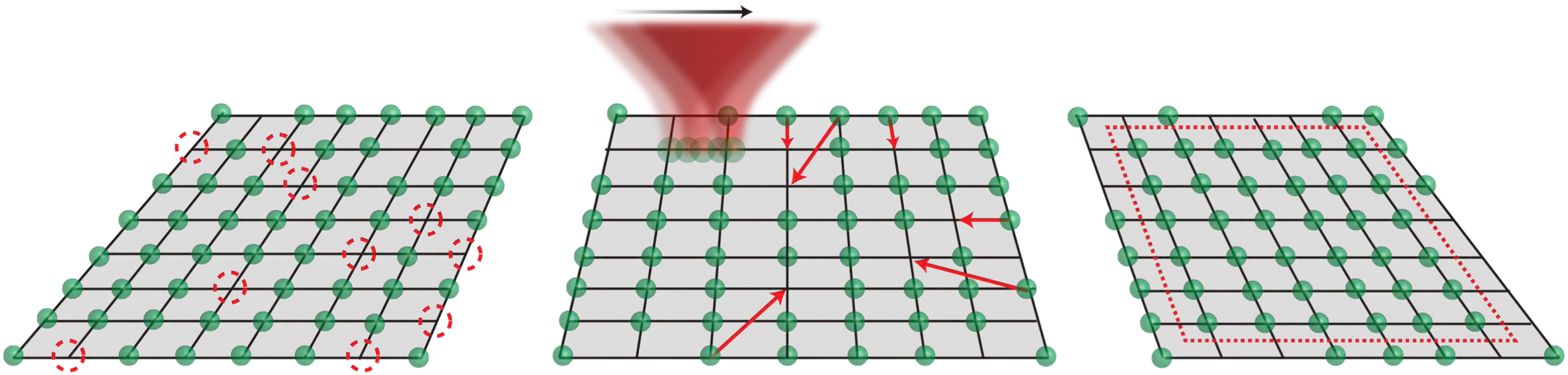






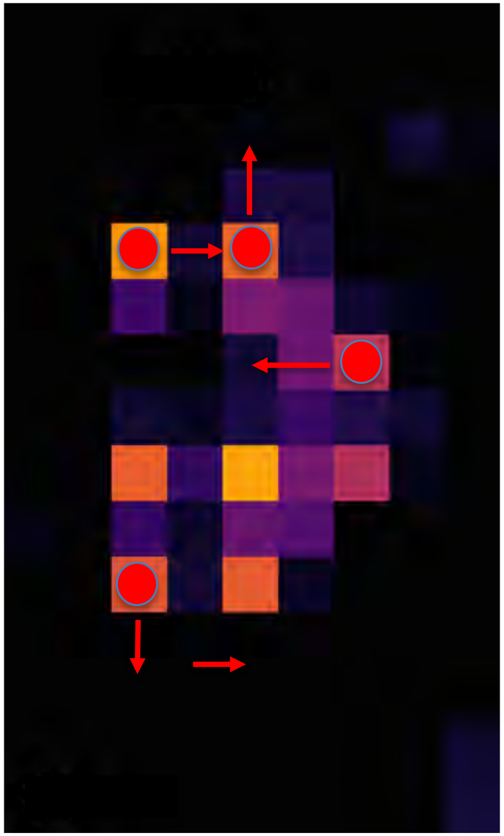
T. Grunzweig *et al.,* Nature Physics (2010)

Larger arrays



Low entropy
bosonic state

Loading atoms and arranging in 2D

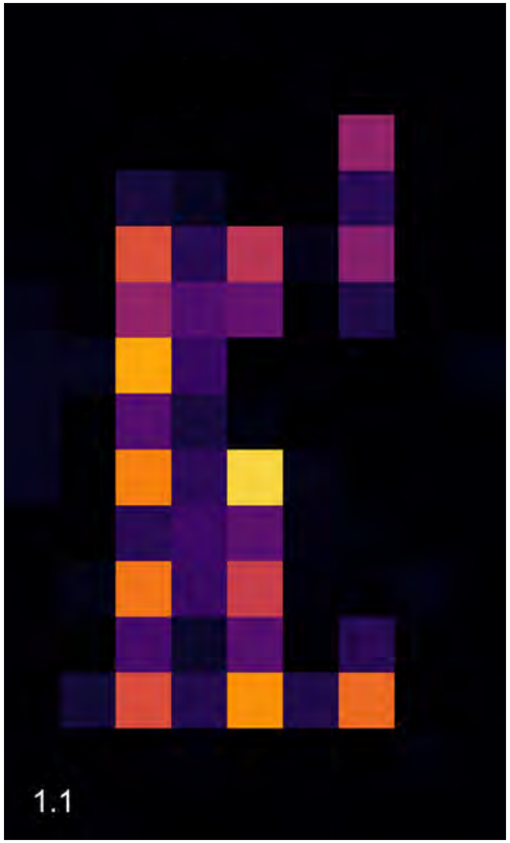


Random filling of 3X6 array

Form line in center

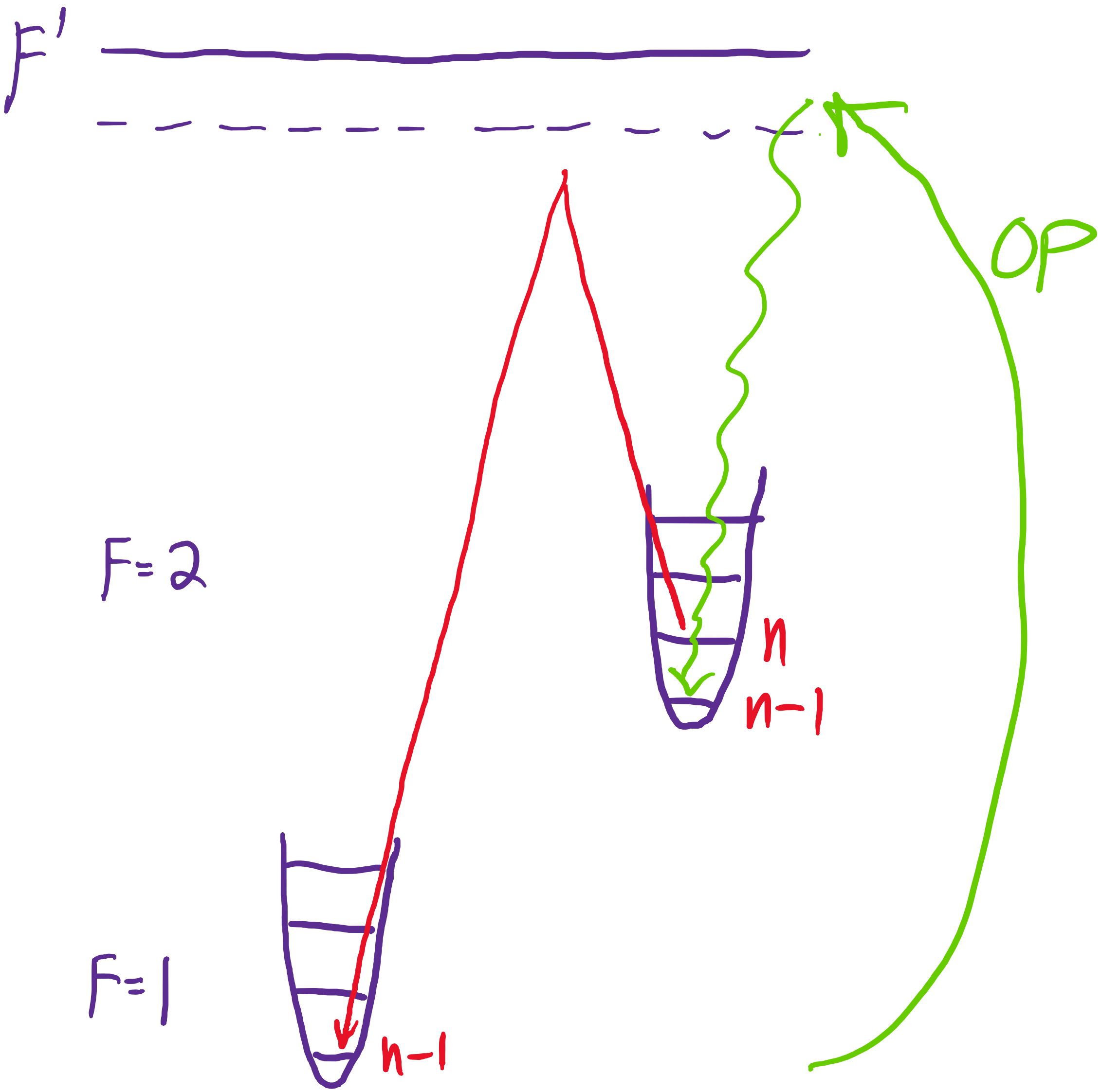
Loading atoms and arranging in 2D

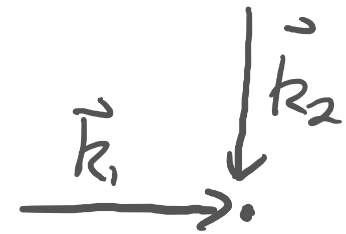
Loading atoms and arranging in 2D



(movies of atoms being rearranged)

Raman sideband cooling





$$\vec{\Delta k} = \vec{k}_1 - \vec{k}_2$$

$$\eta = x_{zp} \Delta k$$

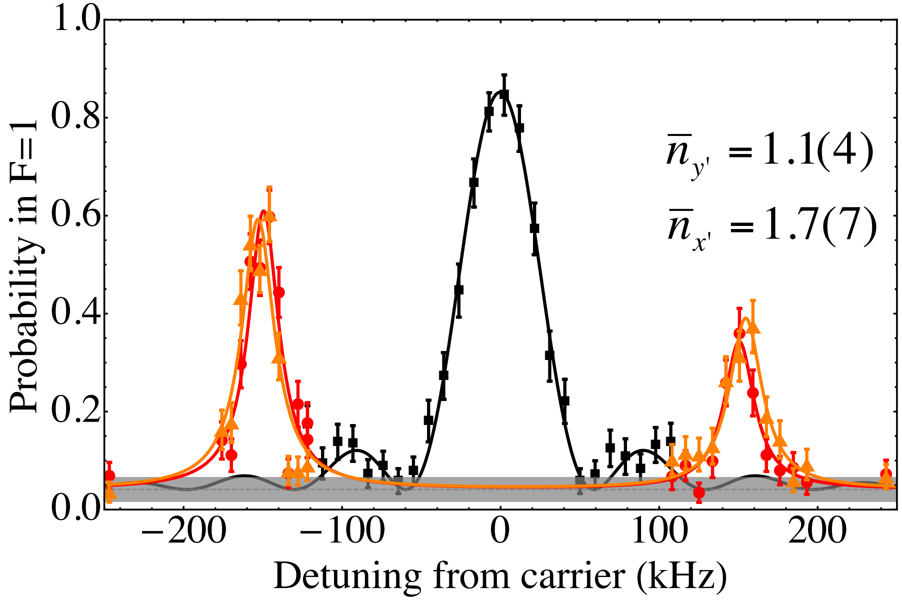
$$x_{zp} = \sqrt{\frac{\hbar}{2m\omega_0}}$$

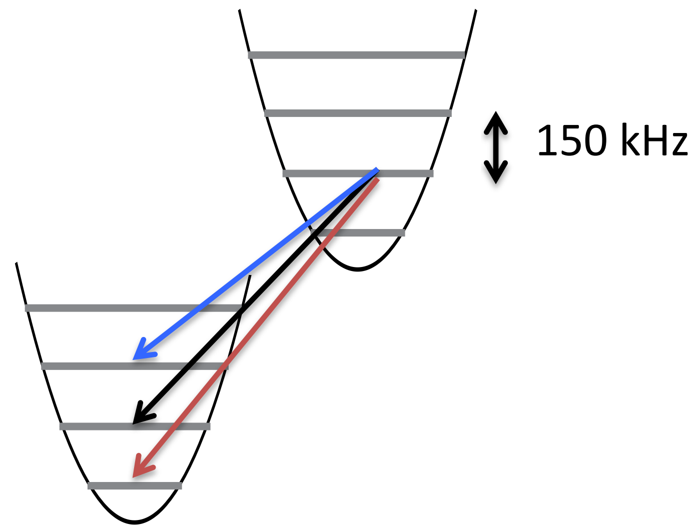
$$x_{zp} \sim 20\,\text{nm}$$

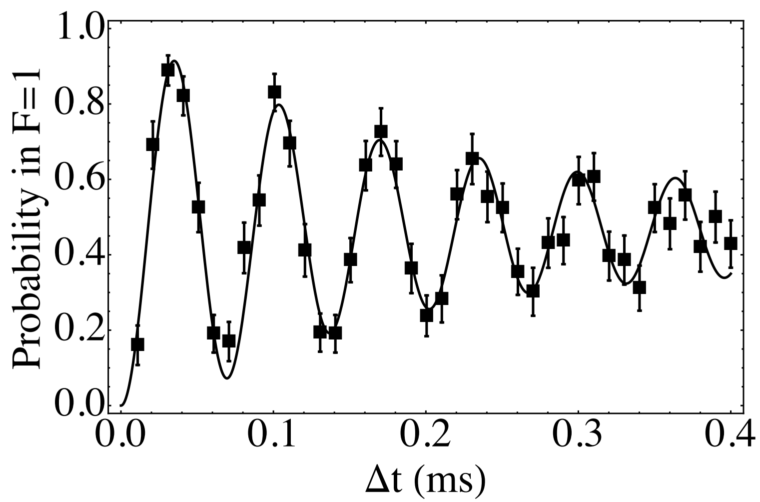
$$\omega_0 \sim 2\pi \times 100\,\text{kHz}$$

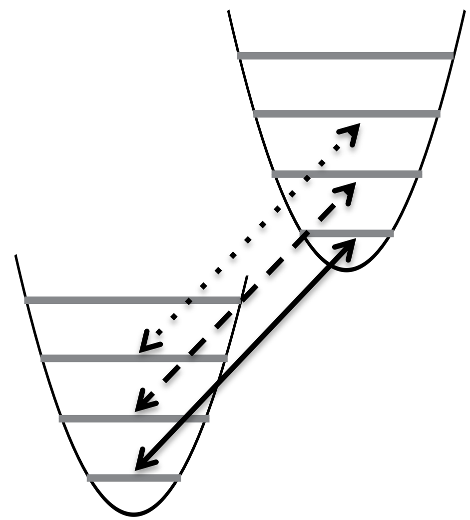
Spectroscopic measure of pre-cooling

Motional spectroscopy





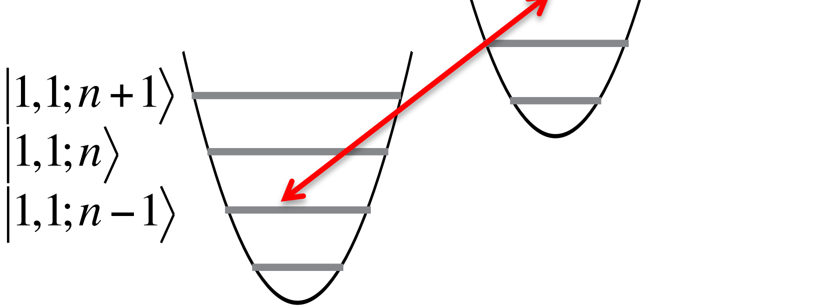




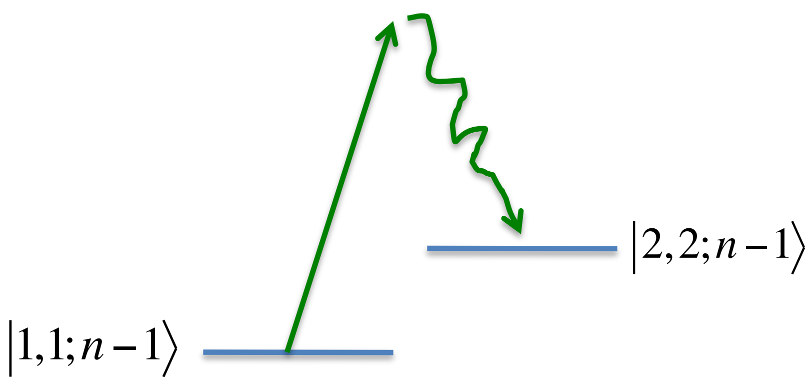
Spectroscopic measure of pre-cooling

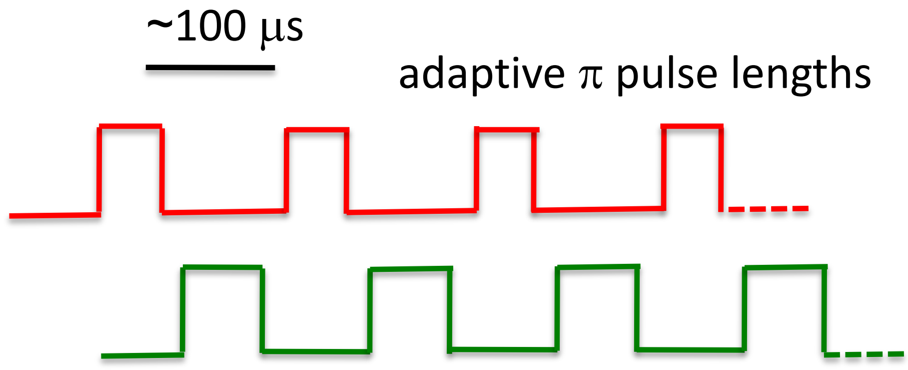
1. Coherently drive

$\Delta n = -1$

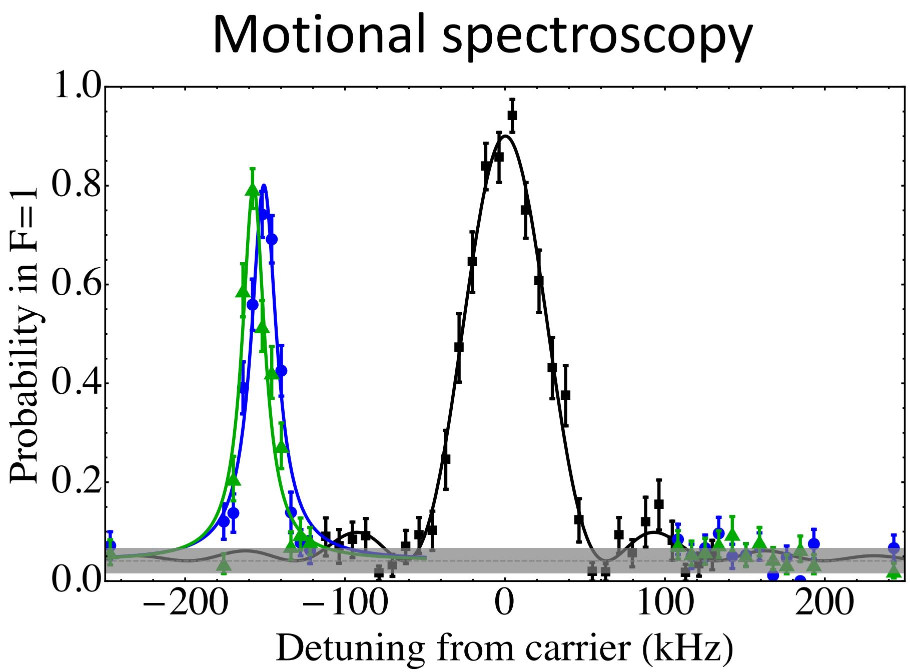


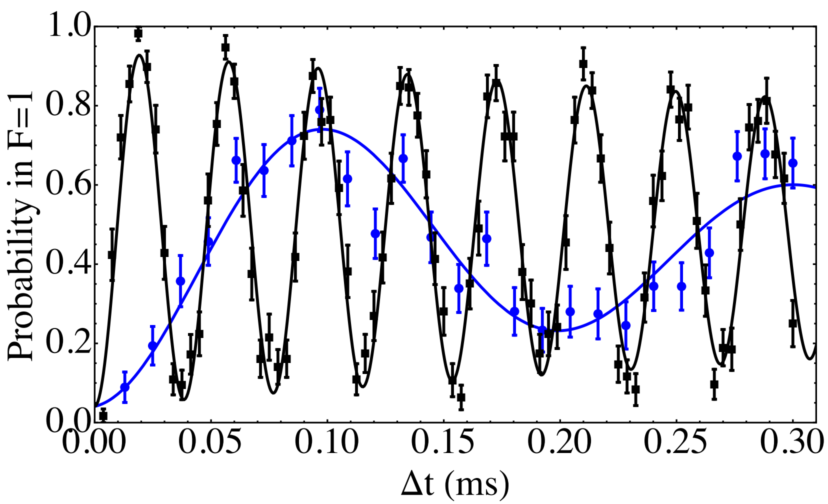
2. Pump back to $|2,2;n-1\rangle$ state

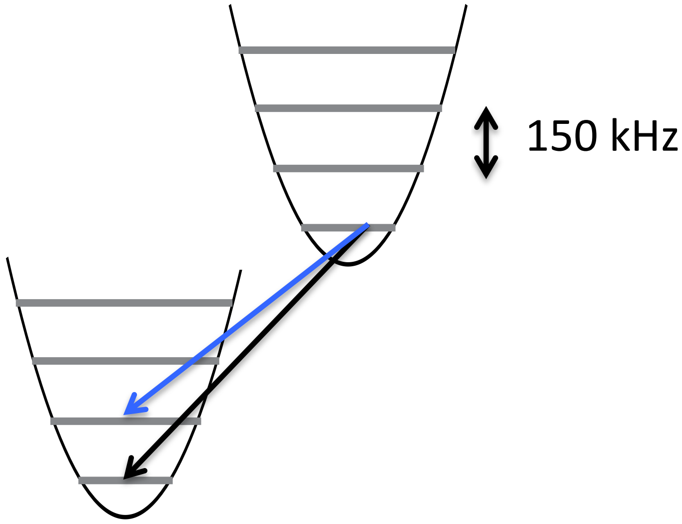


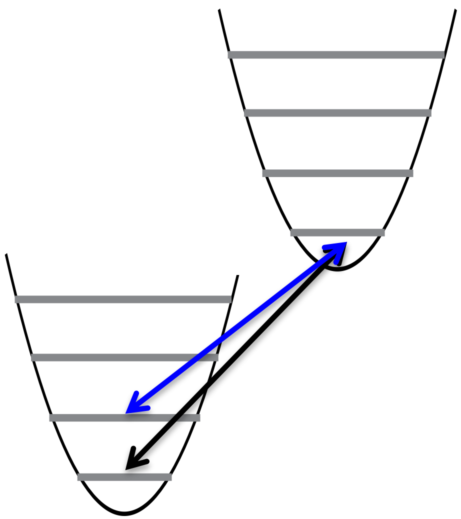


After sideband cooling





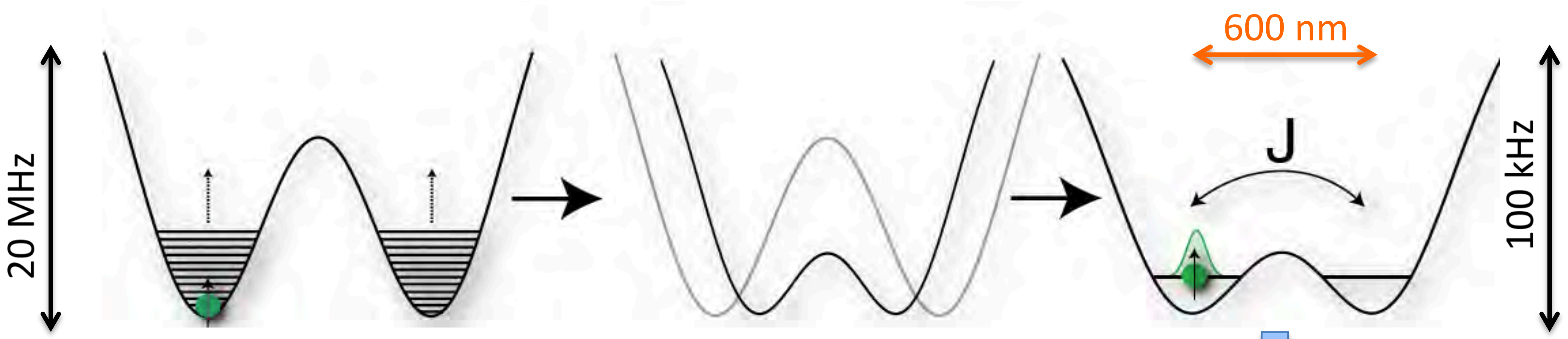




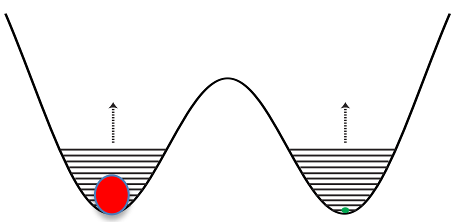
A.M. Kaufman…C. A. Regal, PRX (2012)
Thompson…Lukin, PRL (2013)
A. Reiserer…G. Rempe, PRL (2013)

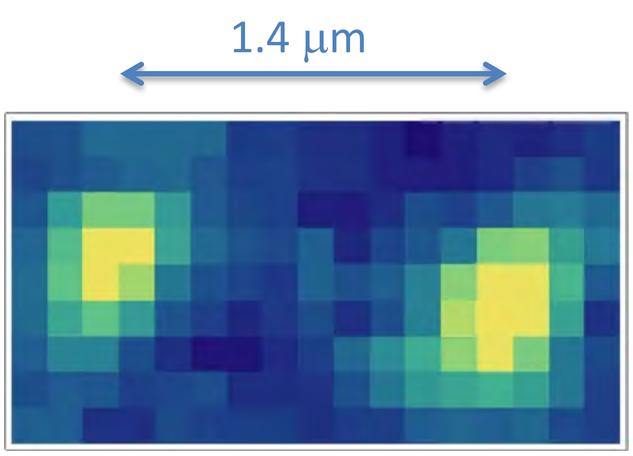
Tunneling between traps

Wells deep, far apart: Sweep and drop: Do physics



Rapidly pin for imaging





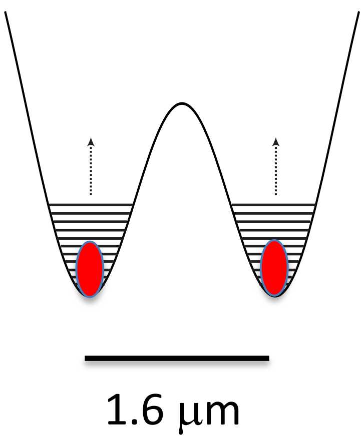
Move atoms on micron scale

Detection: Follow the atoms

set of single-atom images

This measurement used 60% stochastic loading

..but ability to follow initial and final states can also remove entropy



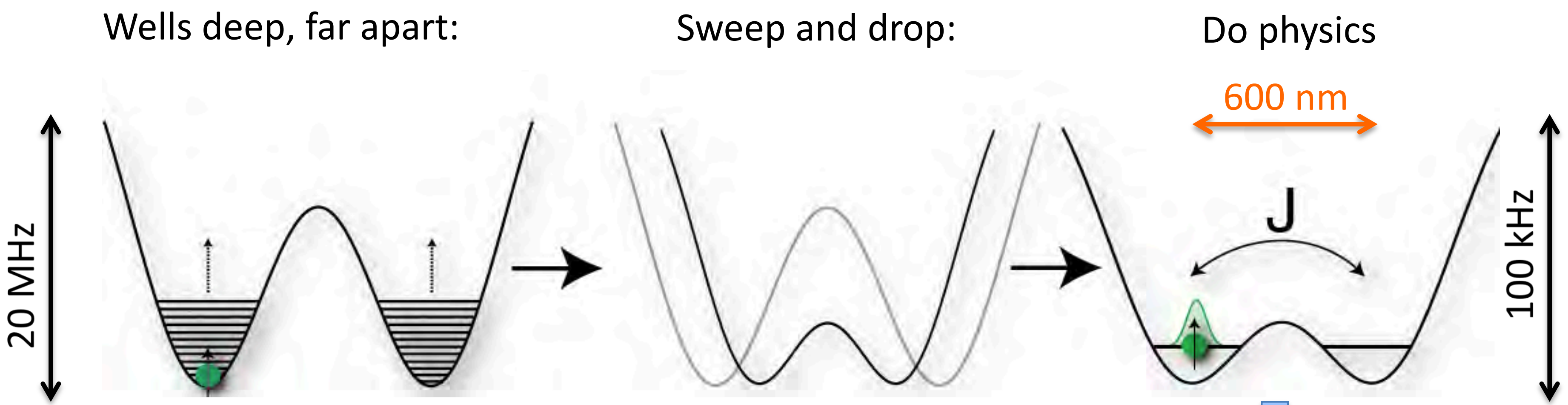
Images: Thermal atoms in deep, separated traps

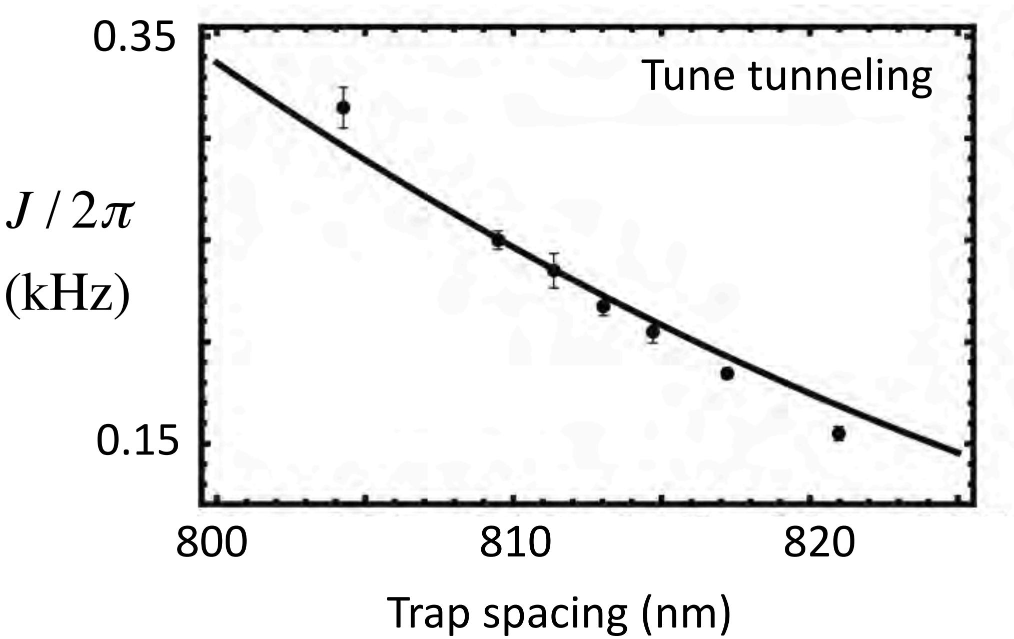
Detection: Follow the atoms

Image 1
(before tunneling)

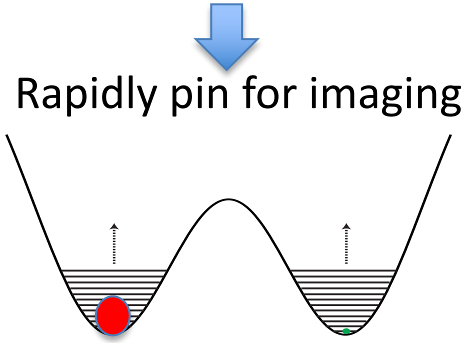
Image 2
(after tunneling)

Tune tunneling rate





Rapidly pin for imaging



Detection: Follow the spin

Also can retrieve spin information (spatially-resolved on EMCCD)

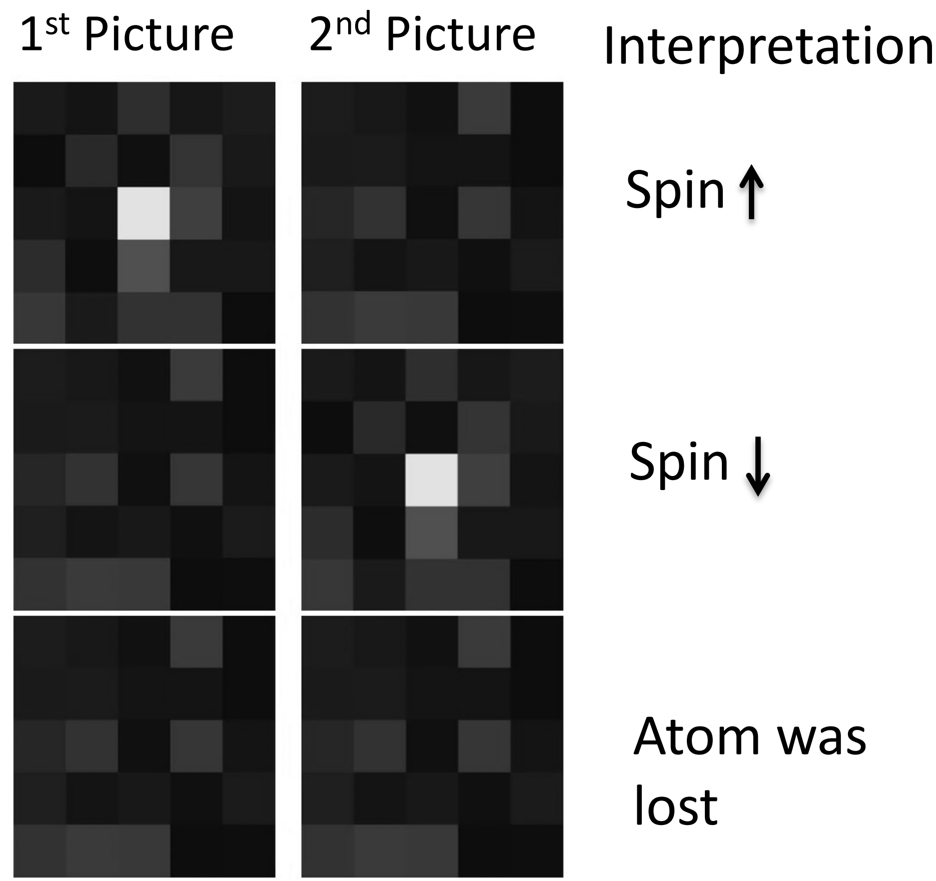
$\uparrow |F = 2, m_F = 2\rangle$

$\downarrow |F = 1, m_F = 1\rangle$

Selectively detect one state (1st picture)

Microwave π pulse

Detect again (2nd picture)



A. Fuhrmanek…A. Browaeys, PRL (2011)
B. M. J. Gibbons…M. S. Chapman, PRL (2011)

Hong-Ou-Mandel interference of photons

Measurement of Subpicosecond Time Intervals between Two Photons by Interference

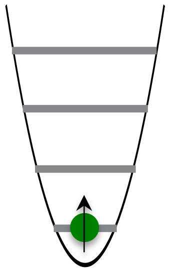
C. K. Hong, Z. Y. Ou, and L. Mandel

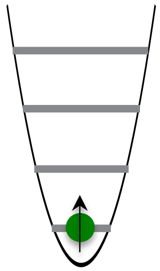
Department of Physics and Astronomy, University of Rochester, Rochester, New York 14627

(Received 10 July 1987)

A fourth-order interference technique has been used to measure the time intervals between two photons, and by implication the length of the photon wave packet, produced in the process of parametric down-conversion. The width of the time-interval distribution, which is largely determined by an interference filter, is found to be about 100 fs, with an accuracy that could, in principle, be less than 1 fs.

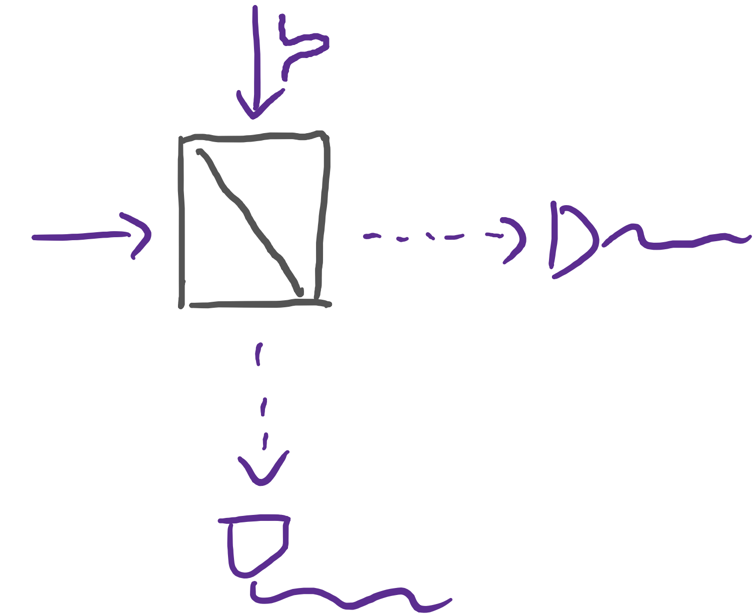
In analogy to original HOM, two-particle quantum interference can diagnose our state purity (even better than our sideband asymmetry)





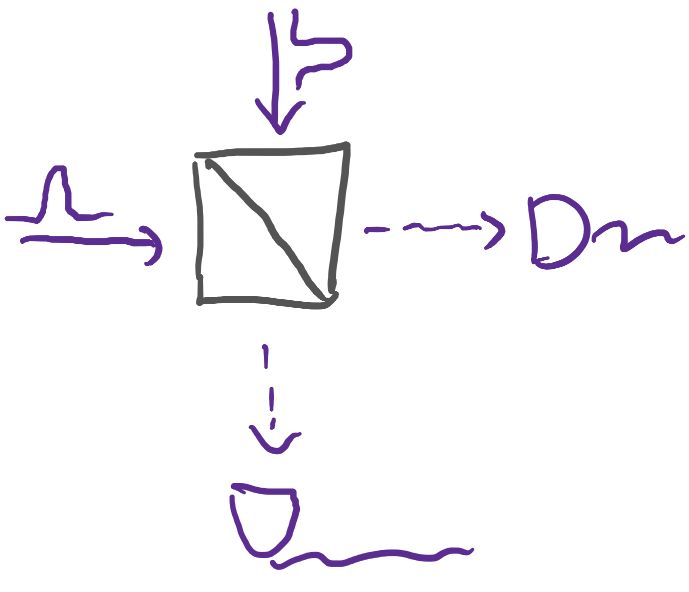
“single atom source”

HOM effect with photons

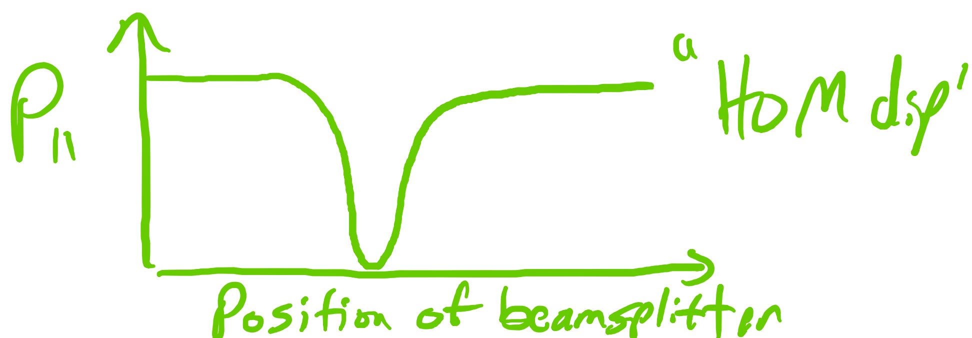


$$|1,0\rangle \to \frac{1}{\sqrt{2}}\left(|1,0\rangle + |0,1\rangle\right)$$

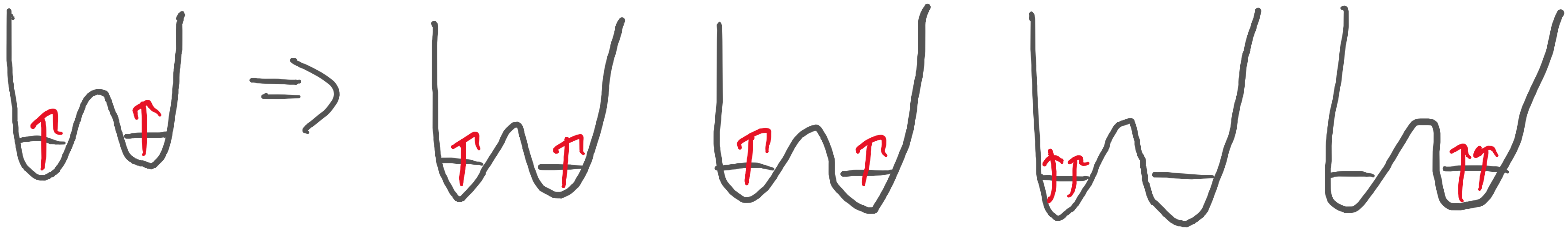
mixes modes



$$|1,1\rangle \to \frac{1}{\sqrt{2}}\left(|2,0\rangle + |0,2\rangle\right)$$



HOM effect with atoms



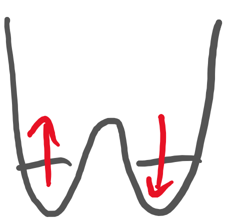
Boson $|\psi_{in}\rangle = \frac{1}{\sqrt{2}}\left(|L\rangle_1 |R\rangle_2 + |R\rangle_1 |L\rangle_2\right)$

$|\psi_{out}\rangle = \frac{1}{\sqrt{2}}\frac{1}{2}\left(\left(|L\rangle + i|R\rangle\right)\left(|R\rangle + i|L\rangle\right) + \left(|R\rangle + i|L\rangle\right)\left(|L\rangle + i|R\rangle\right)\right)$

$= \frac{1}{\sqrt{2}}\left(|R\rangle|R\rangle + |L\rangle|L\rangle\right)$ $\boxed{P_{11} = 0}$ $\frac{1}{\sqrt{2}}\left(|2,0\rangle + |0,2\rangle\right)$

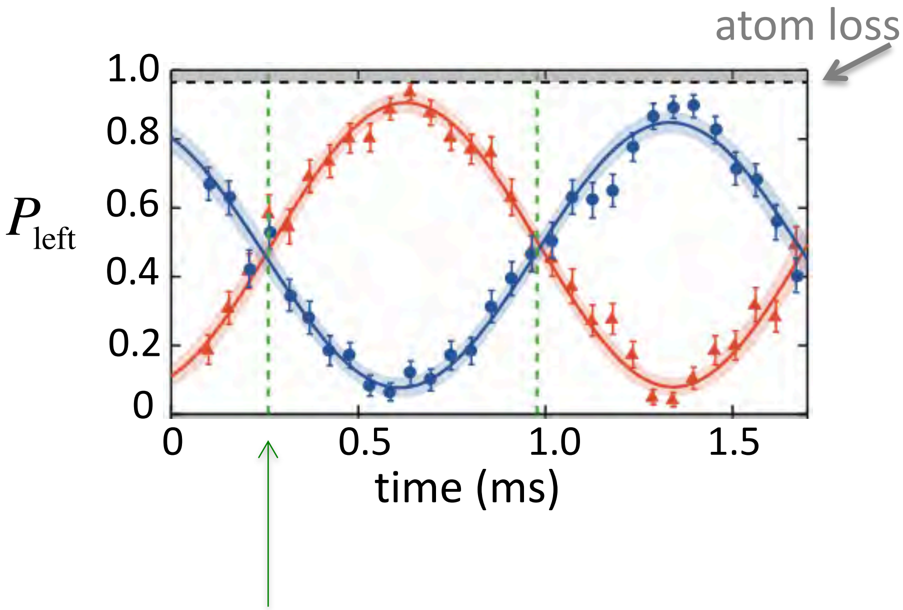
Fermions $|\psi_{in}\rangle = \frac{1}{\sqrt{2}}\left(|L\rangle_1 |R\rangle_2 + |R\rangle_1 |L\rangle_2\right)$

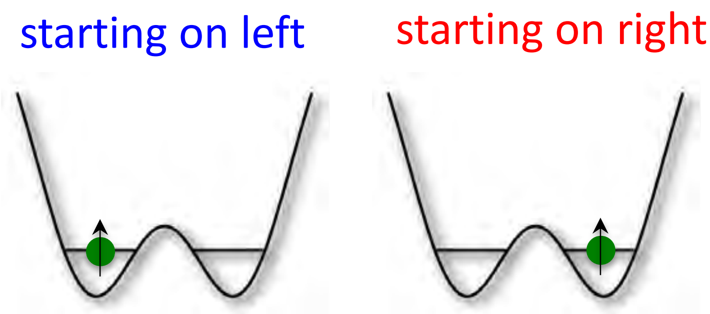
$|\psi_{out}\rangle = \frac{1}{\sqrt{2}}\left(|L\rangle|R\rangle - |R\rangle|L\rangle\right)$ $\boxed{P_{11} = 1}$ $|1,1\rangle$



Distinguished in another d.o.f. $\boxed{P_{11} = 0.5}$

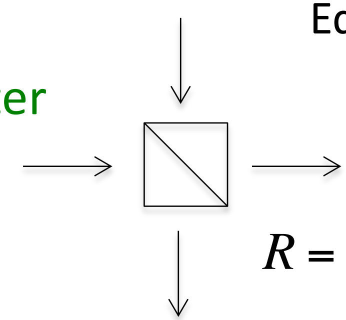
Tunneling as a beamsplitter





balanced beamsplitter

Equal superposition of two wells

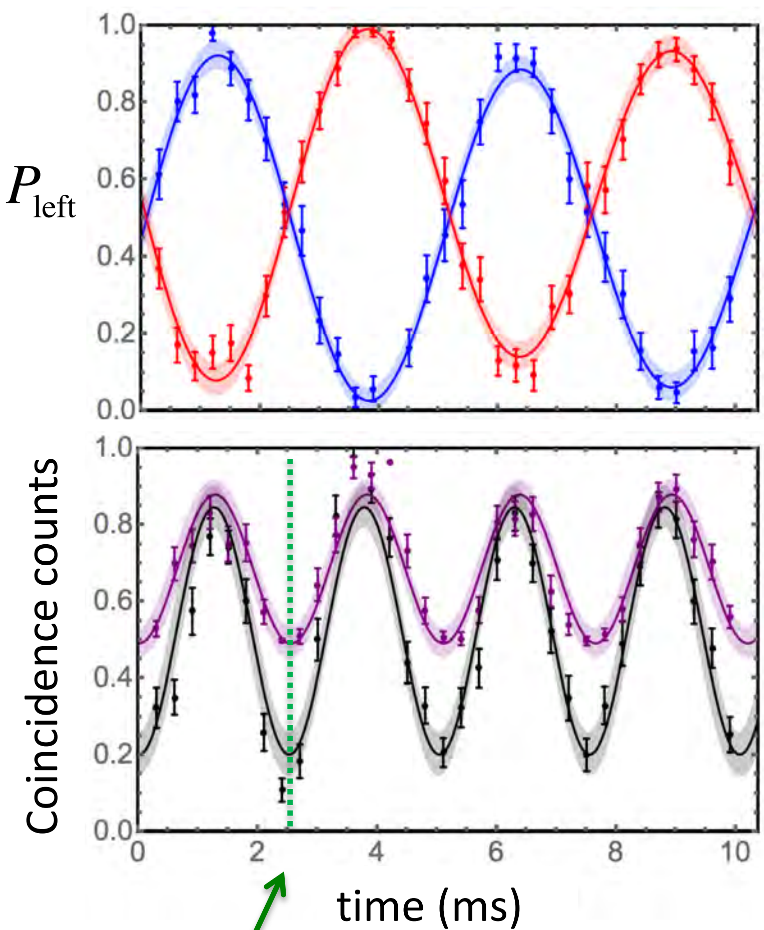


$R = T = 0.5$

Note:

- identical input and output ports
- *R* , *T* vary with tunneling time

Coincidence below distinguishable expectation

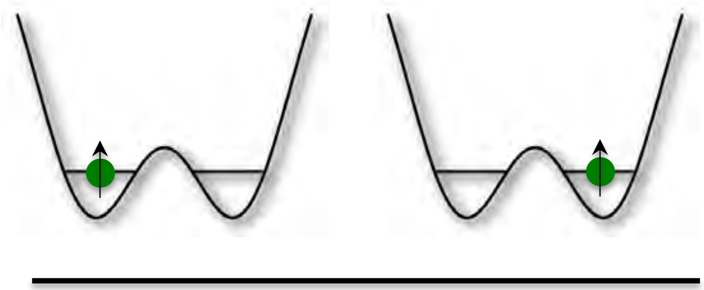


balanced beamsplitter

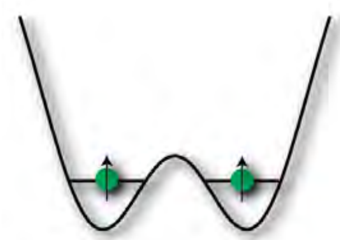
distinguishable expectation from single-atom data

starting on left

starting on right



starting with two atoms

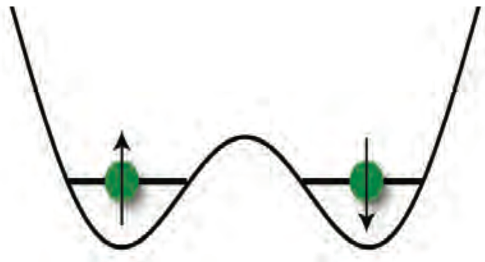


A. M. Kaufman *et al.*, Science (2014)

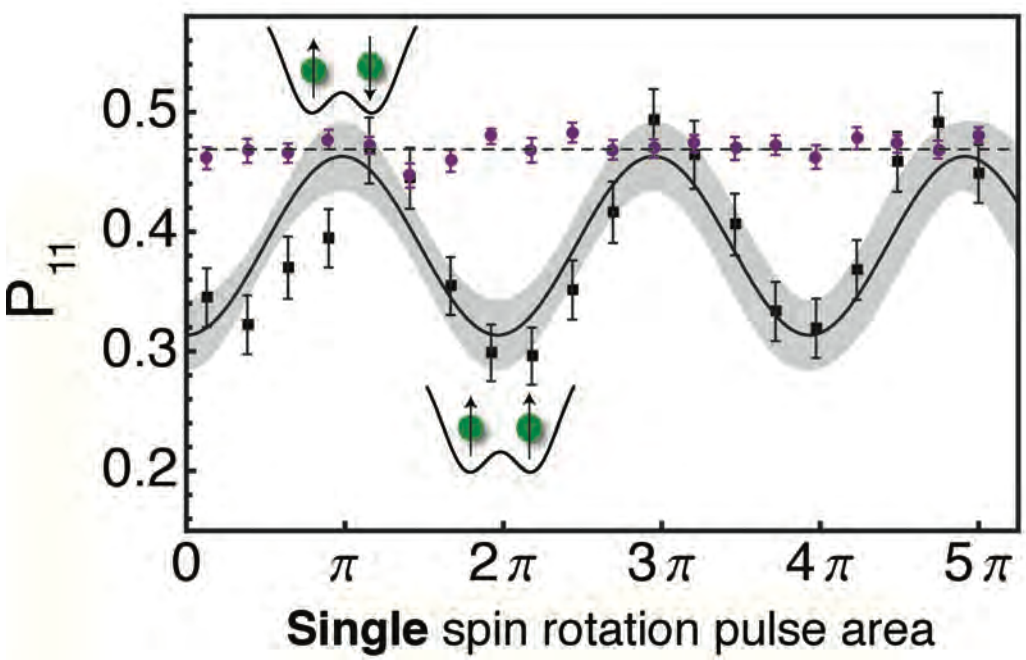
R. Lopes *et al.*, Nature (2015)

Tuning distinguishability

Rotate one spin (analogous to polarization with photons)



At balanced beamsplitter point

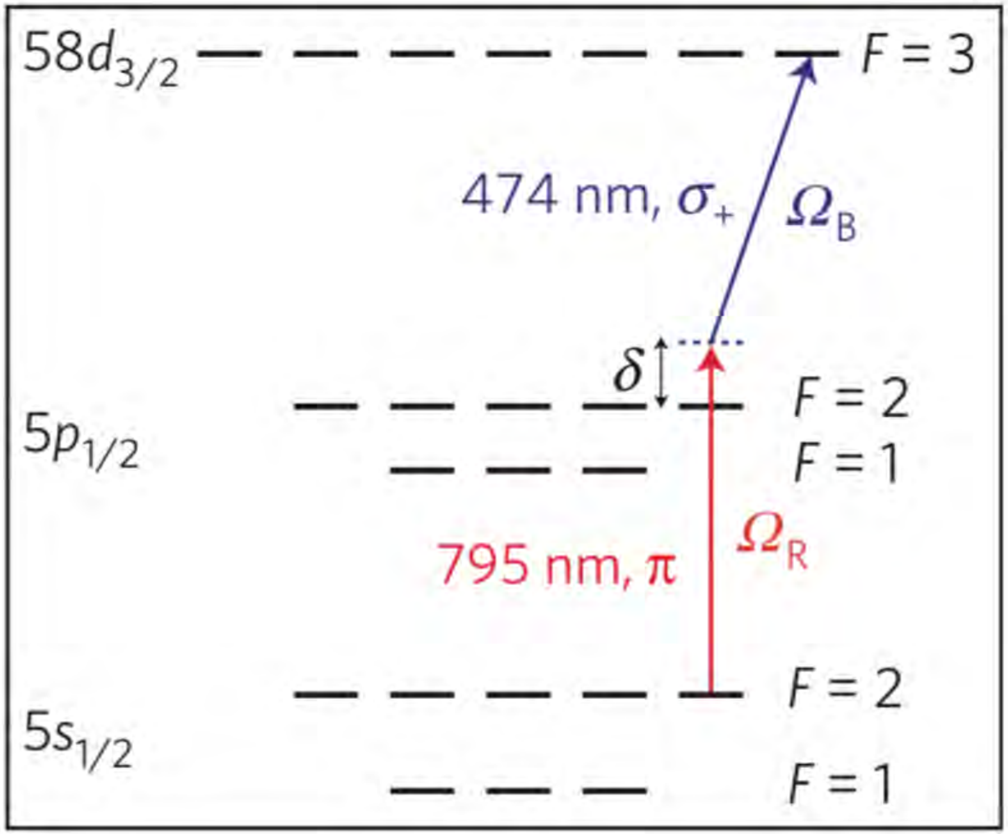


Rabi oscillations on right spin only

Generating spin entanglement

Three ways…

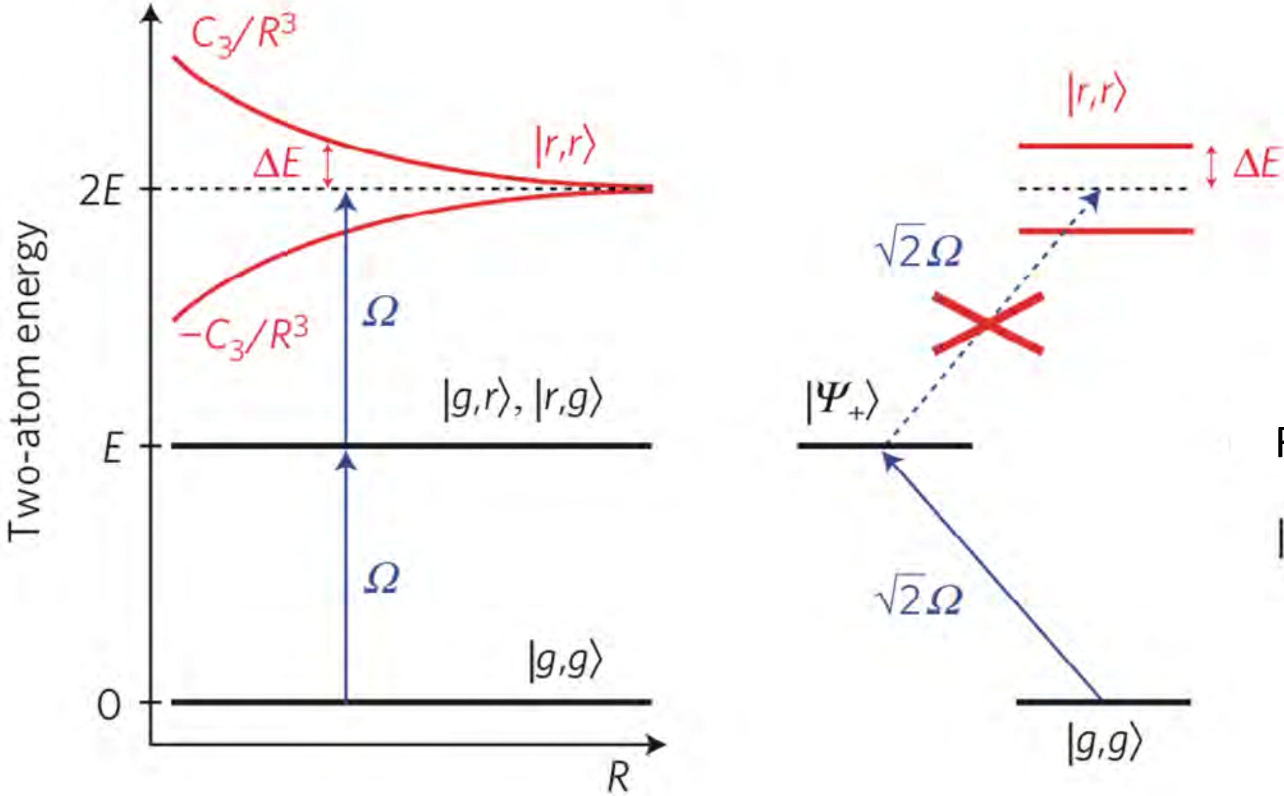
Rydberg blockade



Images from: A. Gaetan et al., Nature Physics (2009)

Two-atom entanglement:
Wilk *et al*., PRL (2010)
Isenhower *et al*., PRL (2010)
Many-body physics in arrays, *e.g.:*
H. Labuhn *et al.,* Nature (2016)
H. Bernien *et al.,* Nature (2017)

Rydberg blockade



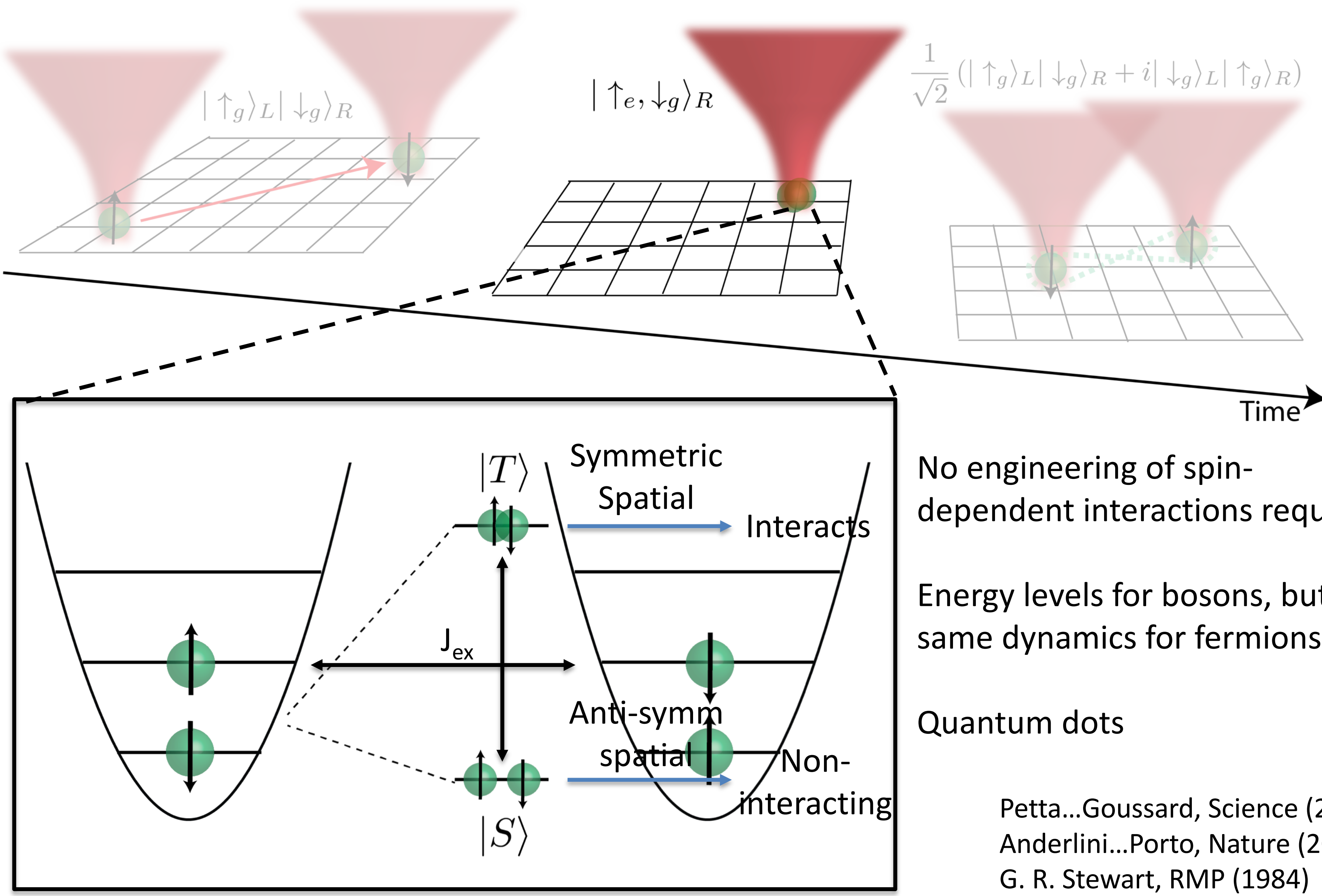
Re-map to gnd-state spin

$$|\Psi\rangle = \frac{1}{\sqrt{2}}(|\downarrow,\uparrow\rangle + e^{i\phi}|\uparrow,\downarrow\rangle)$$

Two-atom entanglement:
Wilk *et al*., PRL (2010)
Isenhower *et al*., PRL (2010)
Many-body physics in arrays, e.g.:
H. Labuhn *et al.,* Nature (2016)
H. Bernien *et al.,* Nature (2017)

Images from: A. Gaetan et al., Nature Physics (2009)

Spin-exchange



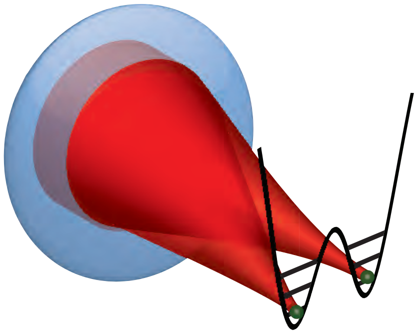
No engineering of spin-dependent interactions required

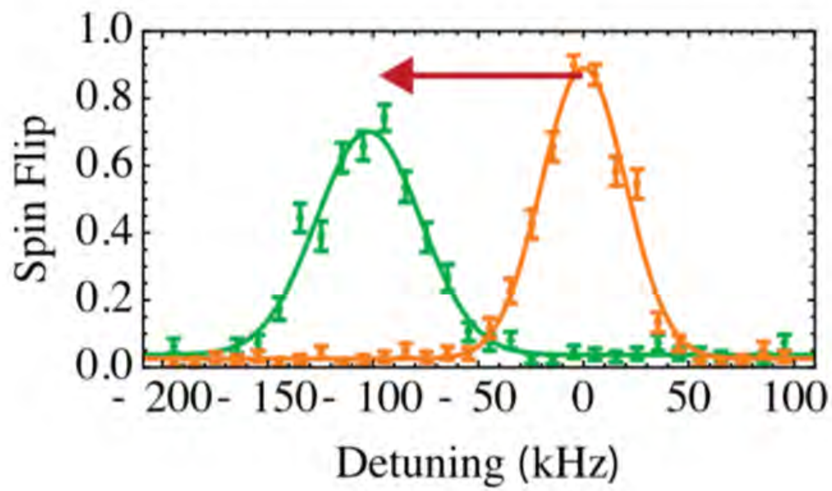
Energy levels for bosons, but see same dynamics for fermions

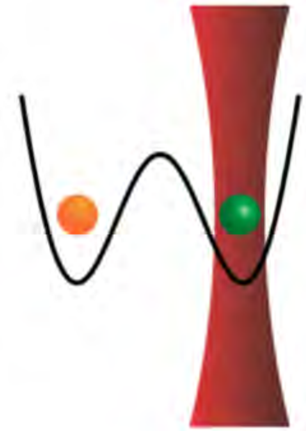
Quantum dots

Petta…Goussard, Science (2005)
Anderlini…Porto, Nature (2007)
G. R. Stewart, RMP (1984)

Protocol for initialization and measurement

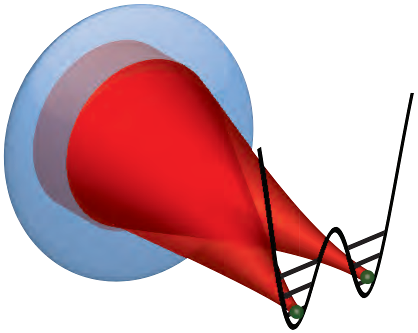


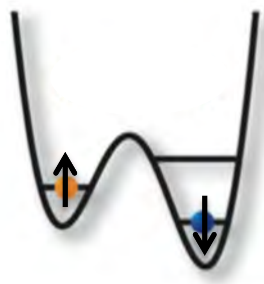




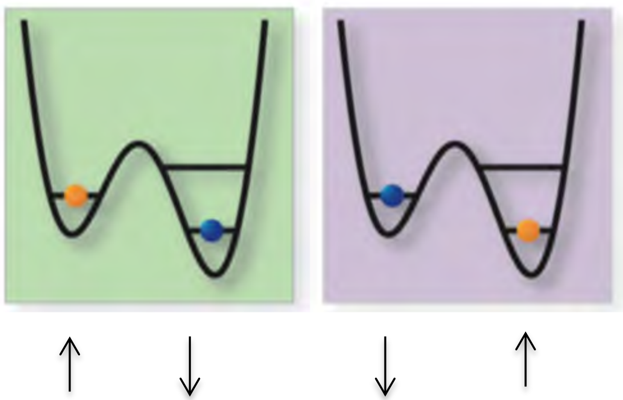
Initialize spins by intensity shifts in deep tweezers

Protocol for initialization and measurement



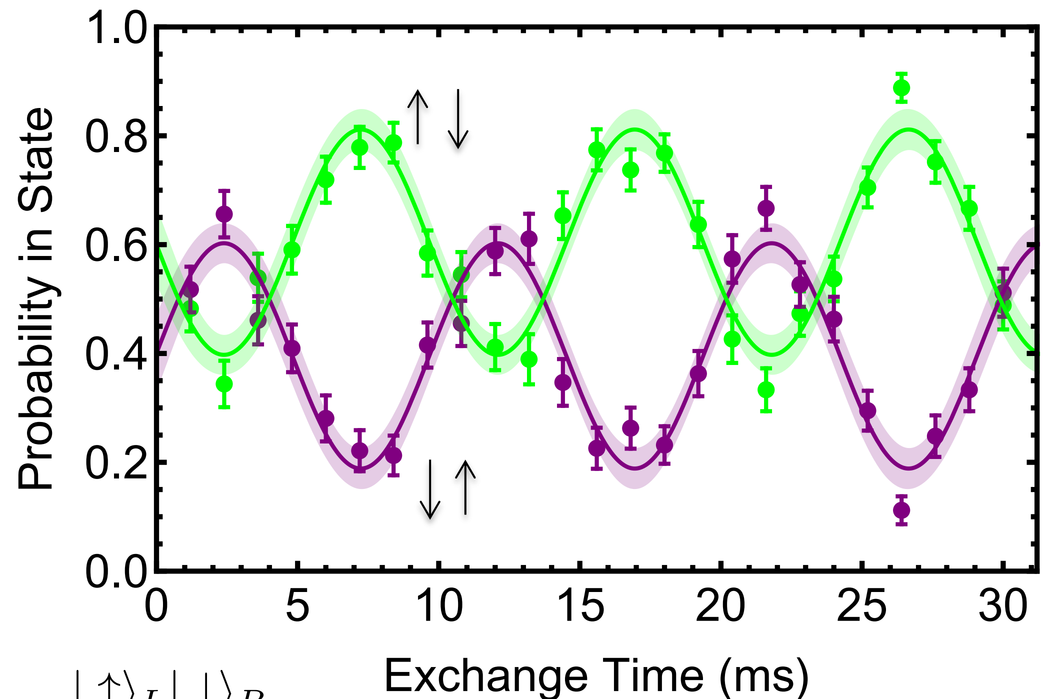


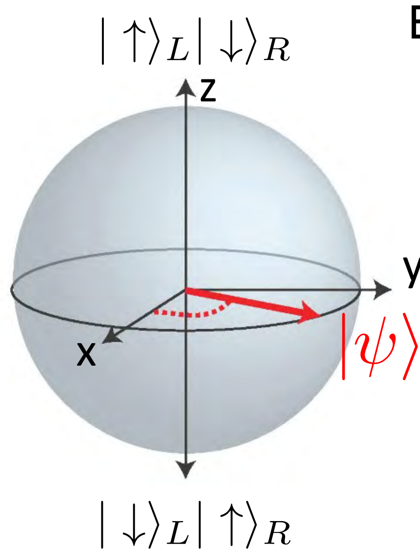
Spin-exchange



Stop at right time to get....

$$\frac{1}{\sqrt{2}}(|\downarrow\rangle_L\,|\uparrow\rangle_R \pm i\,|\uparrow\rangle_L\,|\downarrow\rangle_R)$$



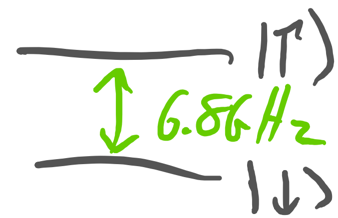


Parity measurement

Generally $\frac{1}{\sqrt{2}}\left(|\uparrow\rangle_L|\downarrow\rangle_R + e^{i\phi}|\downarrow\rangle_L|\uparrow\rangle_R\right)$

$|S_0\rangle = \frac{1}{\sqrt{2}}\left(|\uparrow\rangle_L|\downarrow\rangle_R - |\downarrow\rangle_L|\uparrow\rangle_R\right)$ aka $|\Psi_-\rangle$ Bellstate

$|T_0\rangle = \frac{1}{\sqrt{2}}\left(|\uparrow\rangle_L|\downarrow\rangle_R + |\downarrow\rangle_L|\uparrow\rangle_R\right)$ aka $|\Psi_+\rangle$ Bellstate



Global μwave $\rightarrow \frac{1}{\sqrt{2}}\left(|\uparrow\rangle + i|\downarrow\rangle\right)$

$|S_0\rangle \rightarrow |S_0\rangle$

$|T_0\rangle \rightarrow \frac{1}{\sqrt{2}}\left(|\uparrow\rangle_L|\uparrow\rangle_L + |\downarrow\rangle_R|\downarrow\rangle_R\right) = |\Phi_+\rangle$ Bellstate

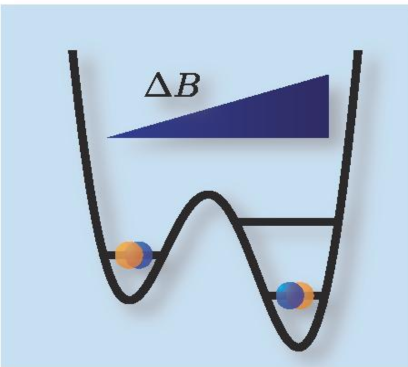
Parity measurement

Map to parity (spins same − spins different)

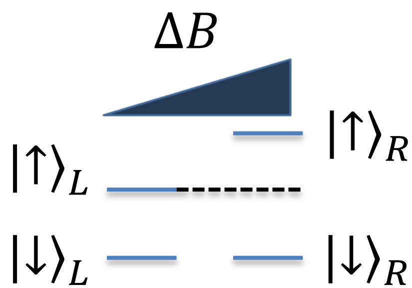
Π	+1	−1	−1	+1
Spin L	↑	↑	↓	↓
Spin R	↑	↓	↑	↓

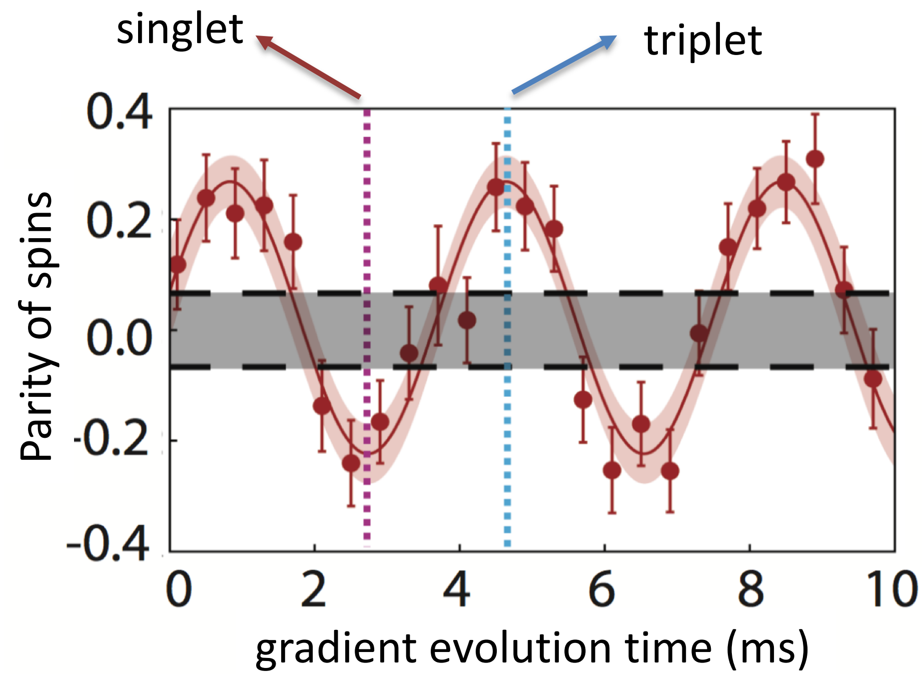
Entanglement

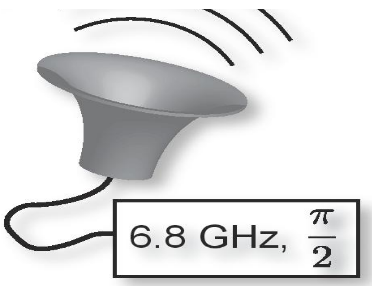
$$\frac{1}{\sqrt{2}}(|\downarrow\rangle_L|\uparrow\rangle_R \pm i|\uparrow\rangle_L|\downarrow\rangle_R)$$



Magnetic field breaks degeneracy - rotates through singlet and triplet







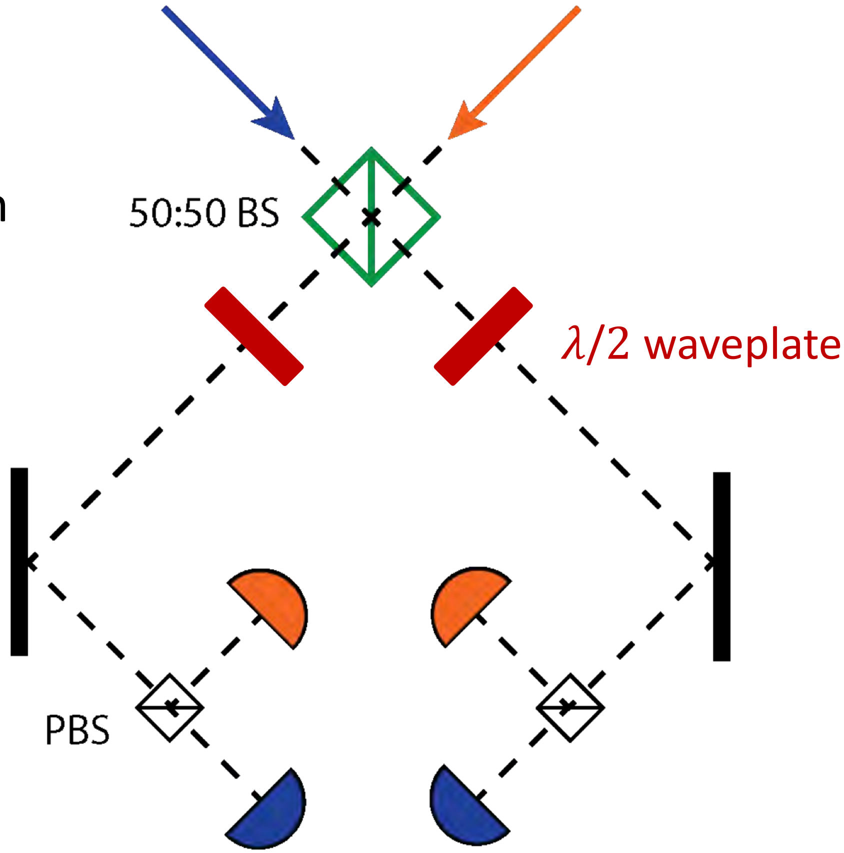
Read out parity with global microwave pulse

Spatially resolved entanglement of ultracold atoms:
M. Endres *et al*., PRL (2015); A. M. Kaufman *et al*., Nature (2015)

Entanglement in macroscopic observables: for example…
B. Lucke *et al,* Science 334, 773 (2011)
H. Strobel *et al*., Science 345, 424 (2014)

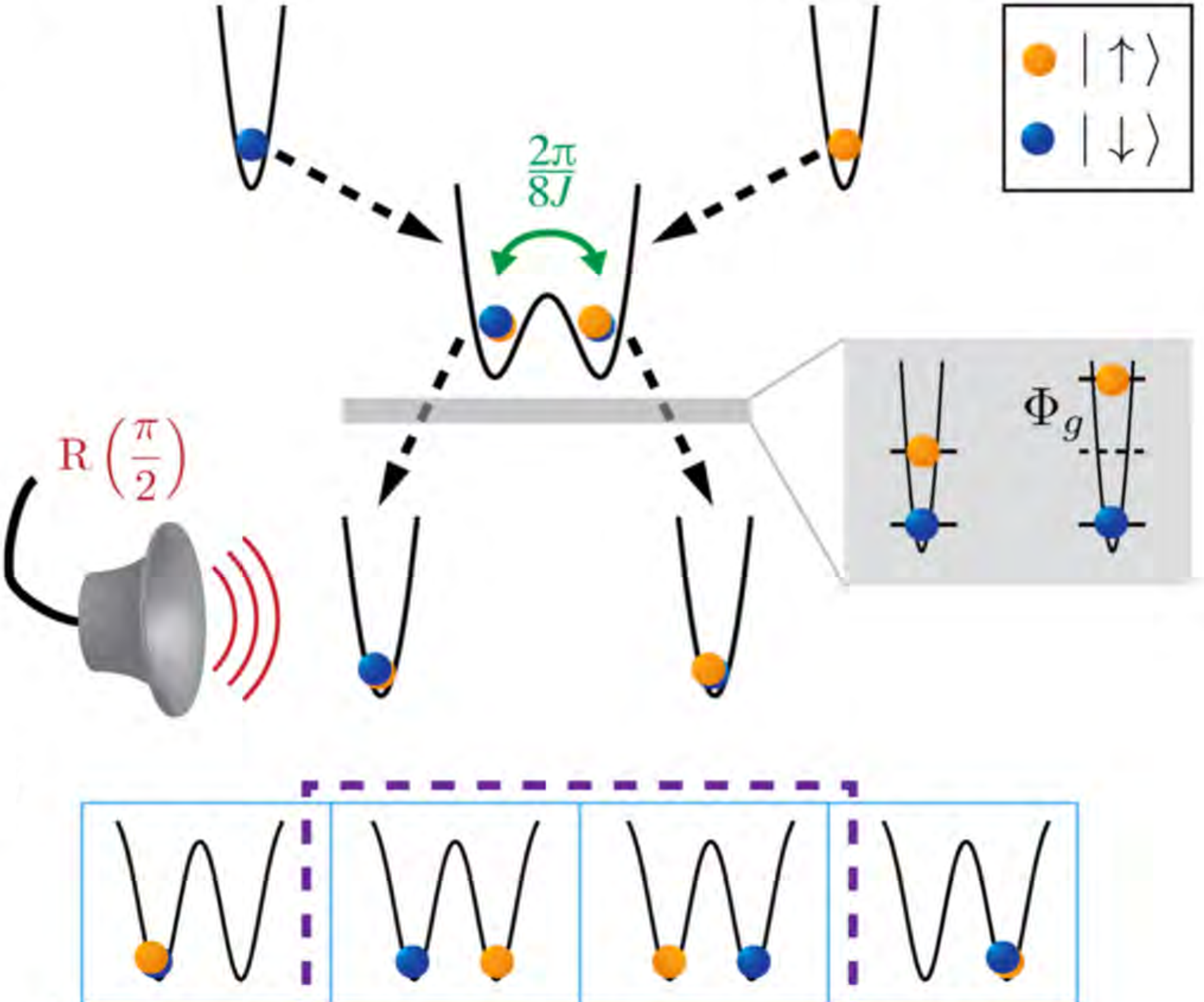
Polarization entangled state

- Two identical bosons
- Two input spatial modes
- Plus one distinguishable degree of freedom (polarization or spin)
- *No interaction but do have measurement*



Shih and Alley, Phys. Rev. Lett. (1988).

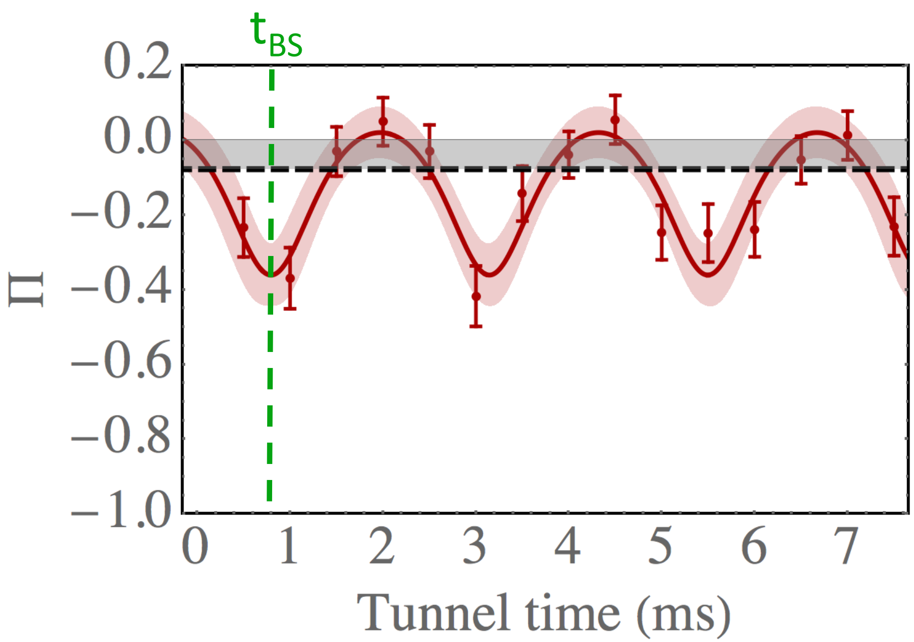
Atomic post-selection



$$\frac{1}{2}\left(i|2,0\rangle\,|T_0\rangle + |1,1\rangle\,(|\downarrow,\uparrow\rangle - |\uparrow,\downarrow\rangle) + i|0,2\rangle\,|T_0\rangle \right)$$

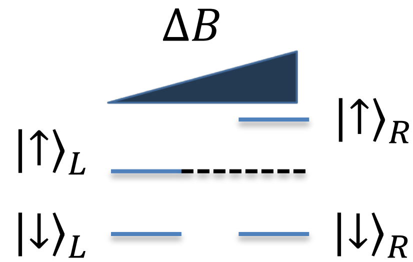
Parity readout

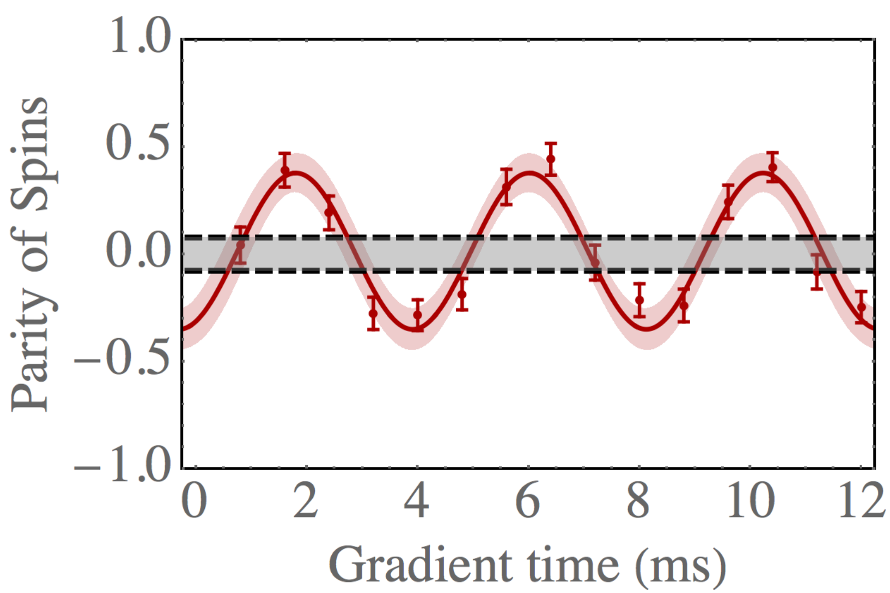
- Perform global microwave $\frac{\pi}{2}$ rotation
- Measure parity of spins

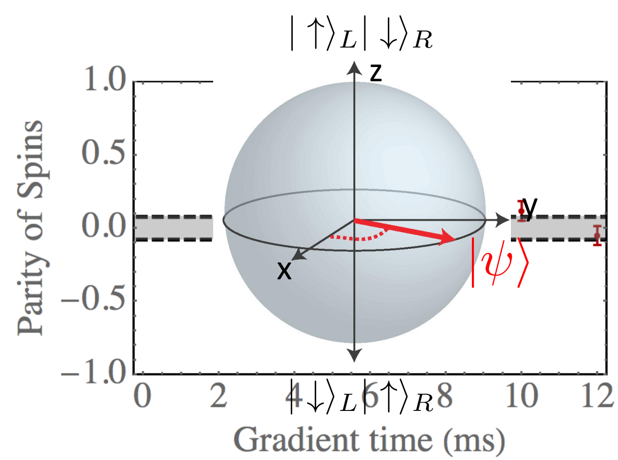


Measurement-based entanglement

- Add a spin-dependent energy shift between the left and right wells
  - Rotate singlet to triplet
- No parity oscillations before tunneling
- Fidelity limited by state preparation
- Certain insensitivities compared to onsite-exchange







B. L. Lester *et al*, PRL (2017)

More reading

A.M. Kaufman, M.C. Tichy, F. Mintert, A.M. Rey, C.A. Regal, “The Hong-Ou-Mandel effect with atoms” Advances In Atomic, Molecular, and Optical Physics 67, 377 (2018).

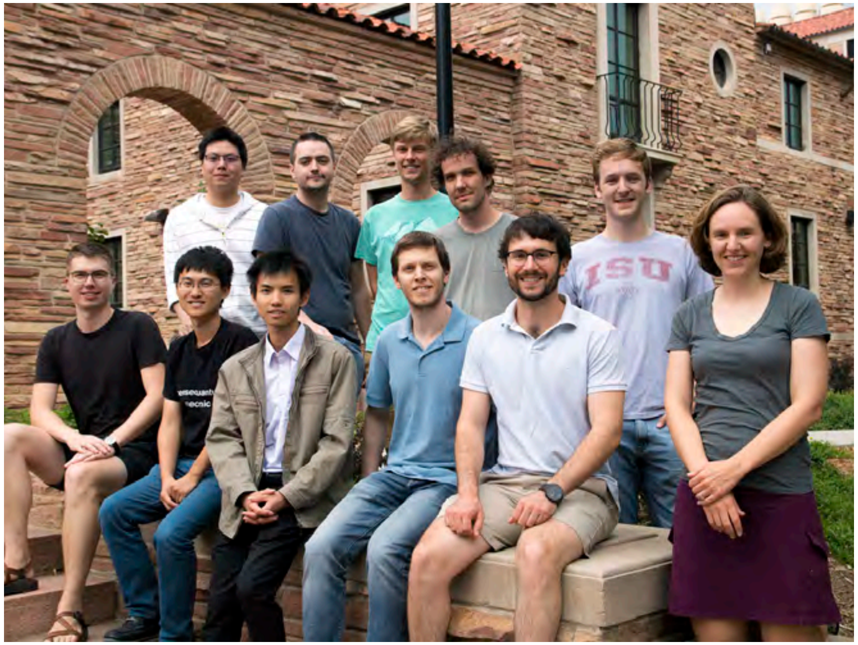
Y. Wang, A. Kumar, T. Y. Wu, David S. Weiss, “Single-qubit gates based on targeted phase shifts in a 3D neutral atom array”, Science 352, 1562 (2016).

M Saffman, “Quantum computing with atomic qubits and Rydberg interactions: progress and challenges” J. Phys. B: At. Mol. Opt. Phys. 49, 202001 (2016).

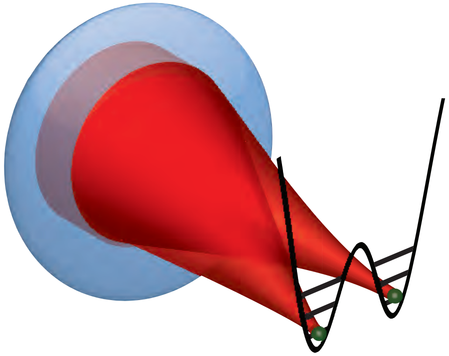
R. Islam, R. Ma., P. M. Preiss, E. M. Tai, A. Lukin, M. Rispoli, M. Greiner “Measuring entanglement entropy in a quantum many-body system”, Nature 528, 758 (2015).

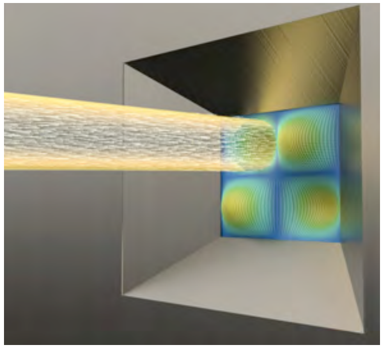
The team

Regal group



Tweezers team: Mark Brown, Yiheng Lin, Tobias Thiele, Brian Lester, Adam Kaufman, Chris Kiehl





Theory collaborators:
A. M. Rey
E. Knill
M. L. Wall
L. Isaev
R. Lewis-Swan