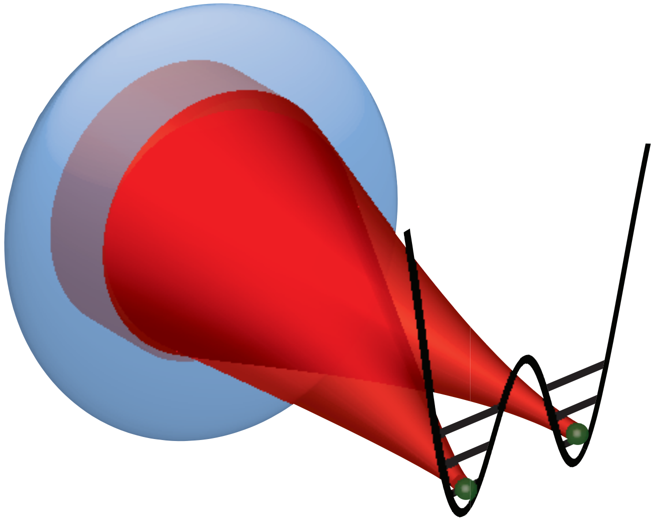
Entanglement and spin-motional physics with bosons in optical tweezers



Cindy Regal

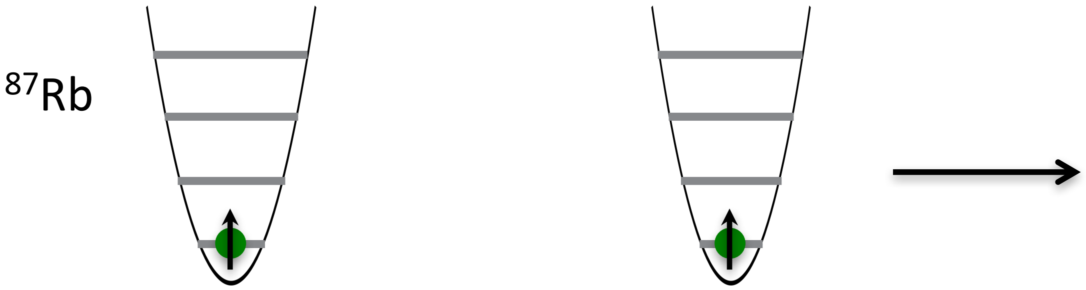
Brian Lester
Yiheng Lin
Adam Kaufman
Mark Brown

KITP few-body physics program 2016

Michael Wall, Michael Foss-Feig, Leonid Isaev, Ana Maria Rey

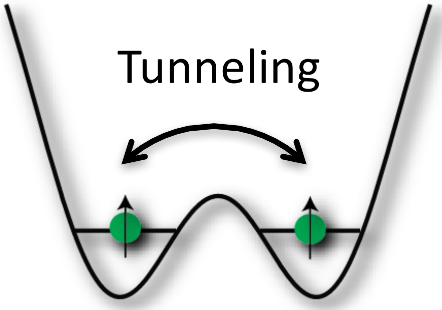
Quantum statistics with independent atoms

Independent atoms in separated traps



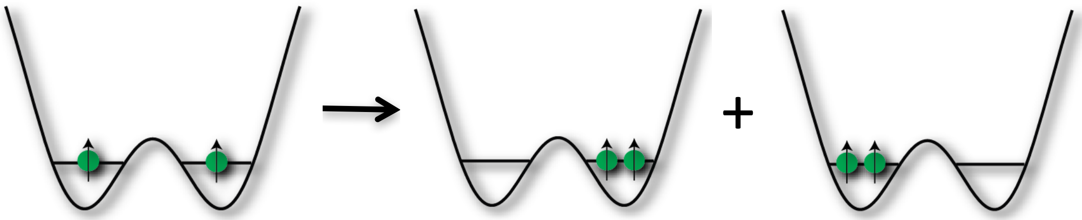
Ground state preparation via
Raman-sideband cooling

Observe interference



Small interactions (U < J)

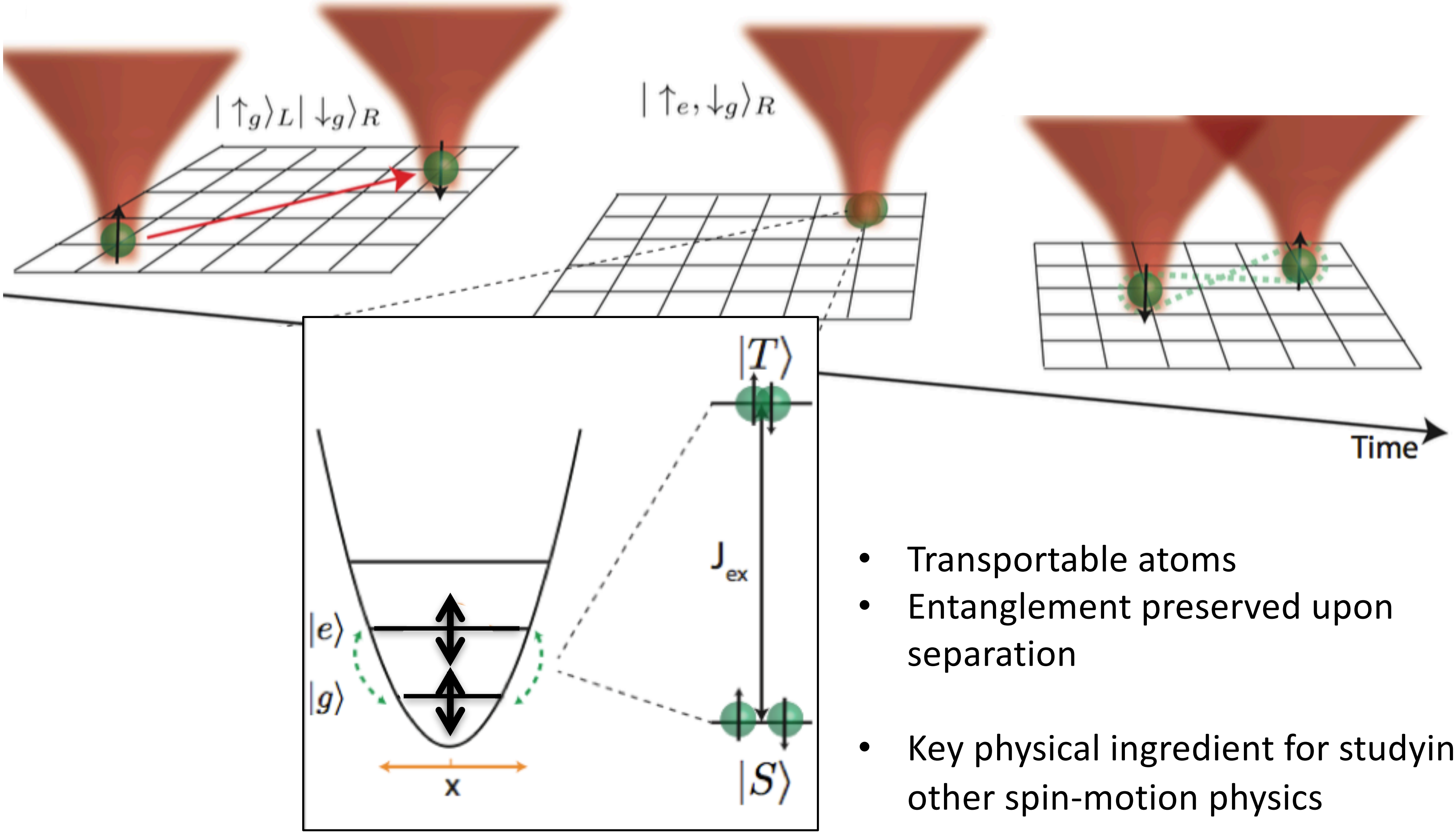
Hong-Ou-Mandel (HOM) effect:
start with Fock states



Consequence of initial bosons in pure state – indistinguishable

- Single-atom optics

Spin entanglement using spin exchange



- Transportable atoms
- Entanglement preserved upon separation

- Key physical ingredient for studying other spin-motion physics

Anderlini *et al.*, Nature (2007)
Hayes *et al.*, PRL (2007)

Outline

- Introduction to techniques

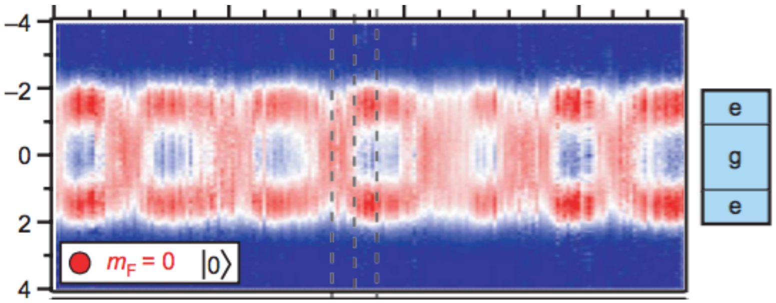
- Examples:
  - HOM: Mixing spatial modes
  - Measuring spin entanglement
  - Interfering atoms: Post selection of singlet state

- To consider in context of few-body group
  - New probes and initialization
  - Collisional physics for state preparation
  - While this talk dwells on 2 atoms, 10 - 100 is natural goal
  - Rb – proof of concepts – larger gains yet to come with *alkaline earth atoms, molecules, fermions…*
  - More exotic traps with atom spacings 100 nm scale?
  - Adiabatically connect to ground state of less confining trap for delocalized states?
  - Here scattering length small (sometimes effectively zero); could combine with Feshbach resonance
  - Precise measurements that avoid inhomogeneous broadening?

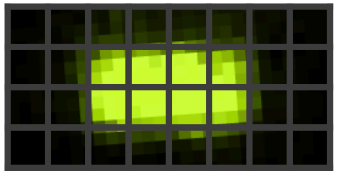
Experimental context

Like experiments in superlattices and quantum gas microscopes

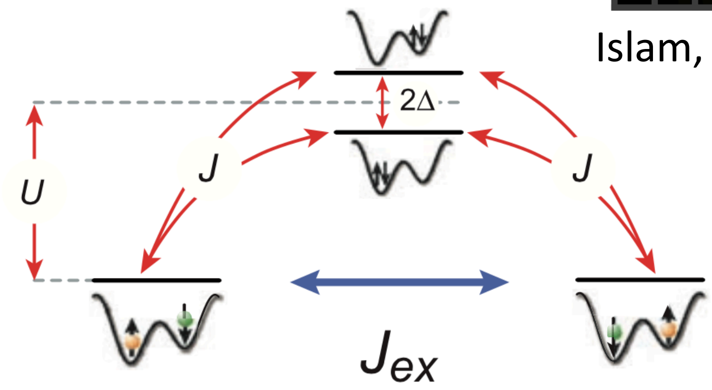
Add different flavors of flexibility / natural experiments, building state gives access to *information* about initialized microscopics



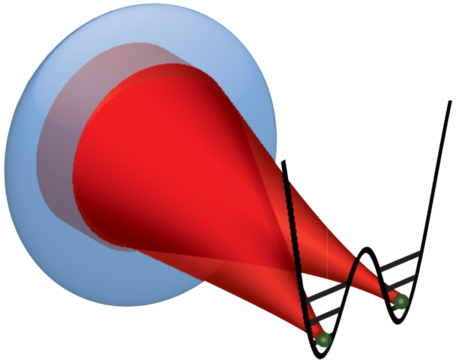
Exchange in array of double wells
Anderlini *et al.*, Nature (2007)



Islam, *et. al.*,Nature (2015)



Superexchange
Trotzky *et al.,* Science (2008)

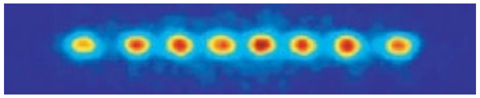


Evaporatively cooled fermions:
Selim Jochim group

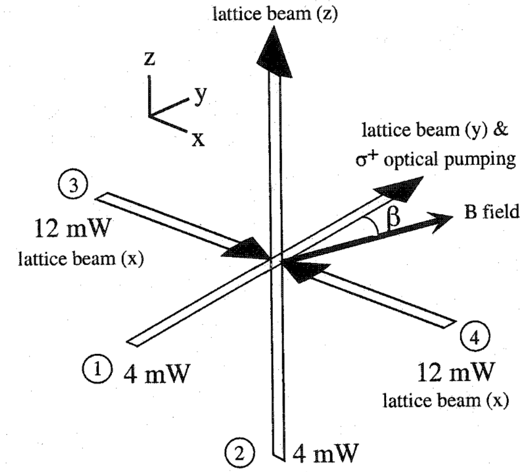
Raman sideband cooling atoms

Considerable history:

- Ions

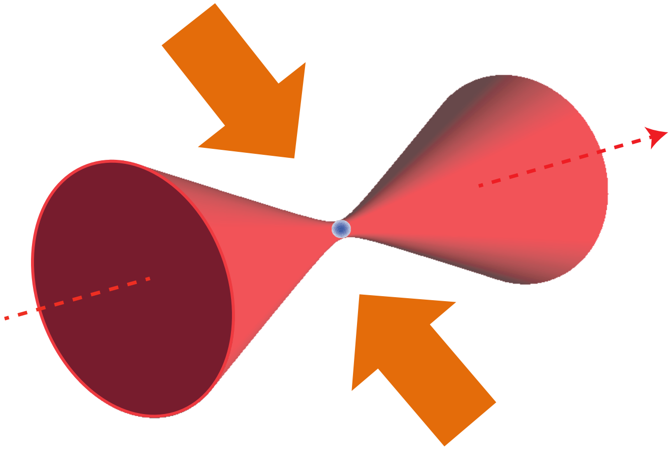


- Neutral atoms in lattices:
  - Large lattice experiments
  - Addressable atoms: Cavity lattice experiments, other recent work in lattices

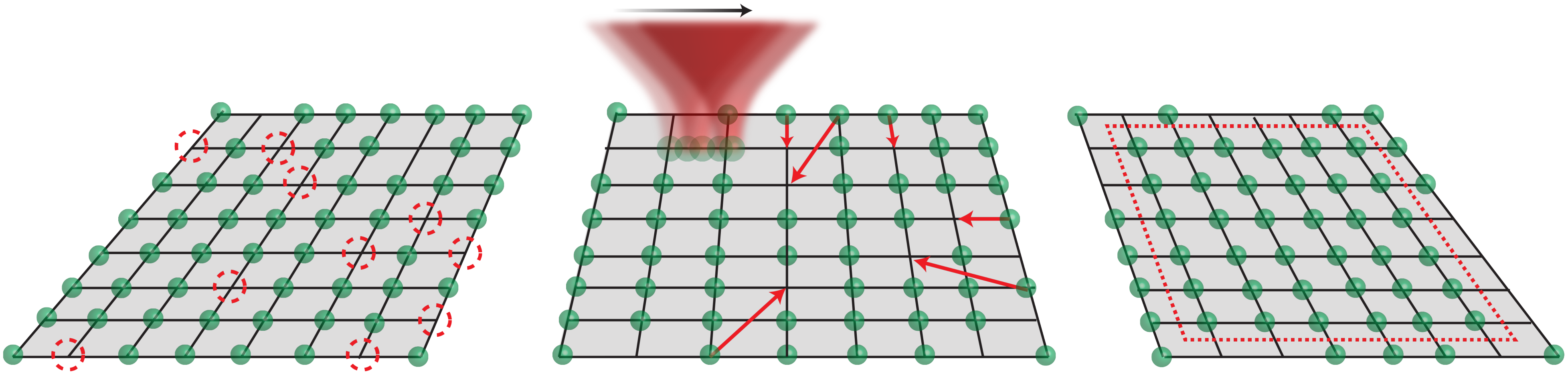


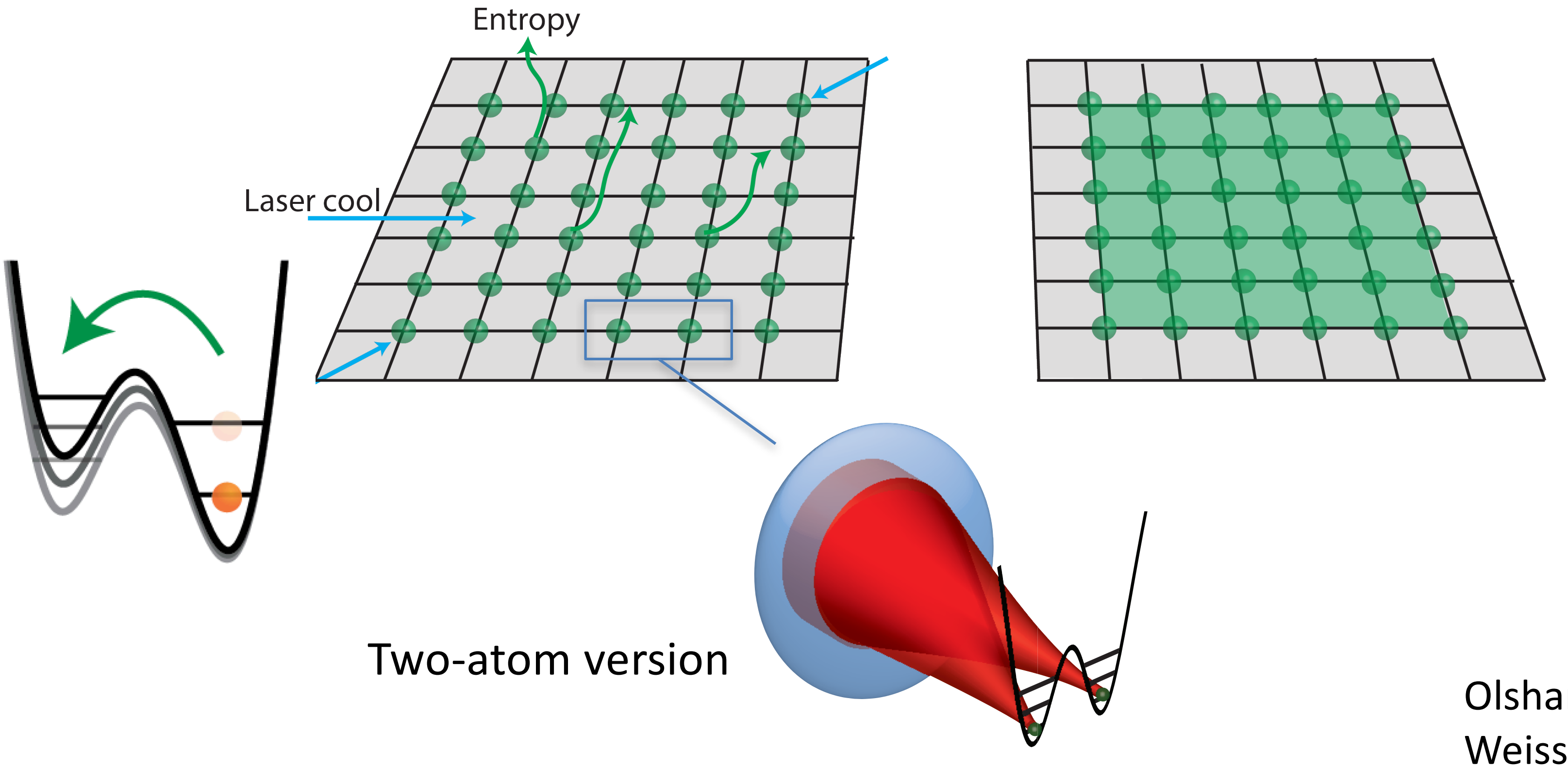
S. Chu group

- This talk:
  - Neutral atoms in movable, low-dimensional set of optical tweezer
  - Cooled like in *ion* experiments
  - But availability of particle overlap gives protocols more like *photons or quantum dots*
  - Of course ultimate goal is many atoms, or a few (for certain questions)



Quantum gas assembly

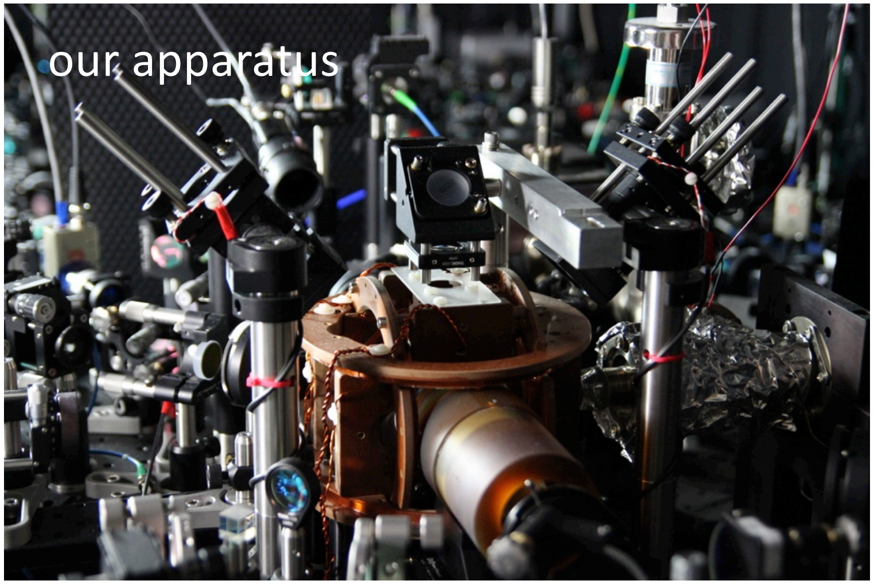




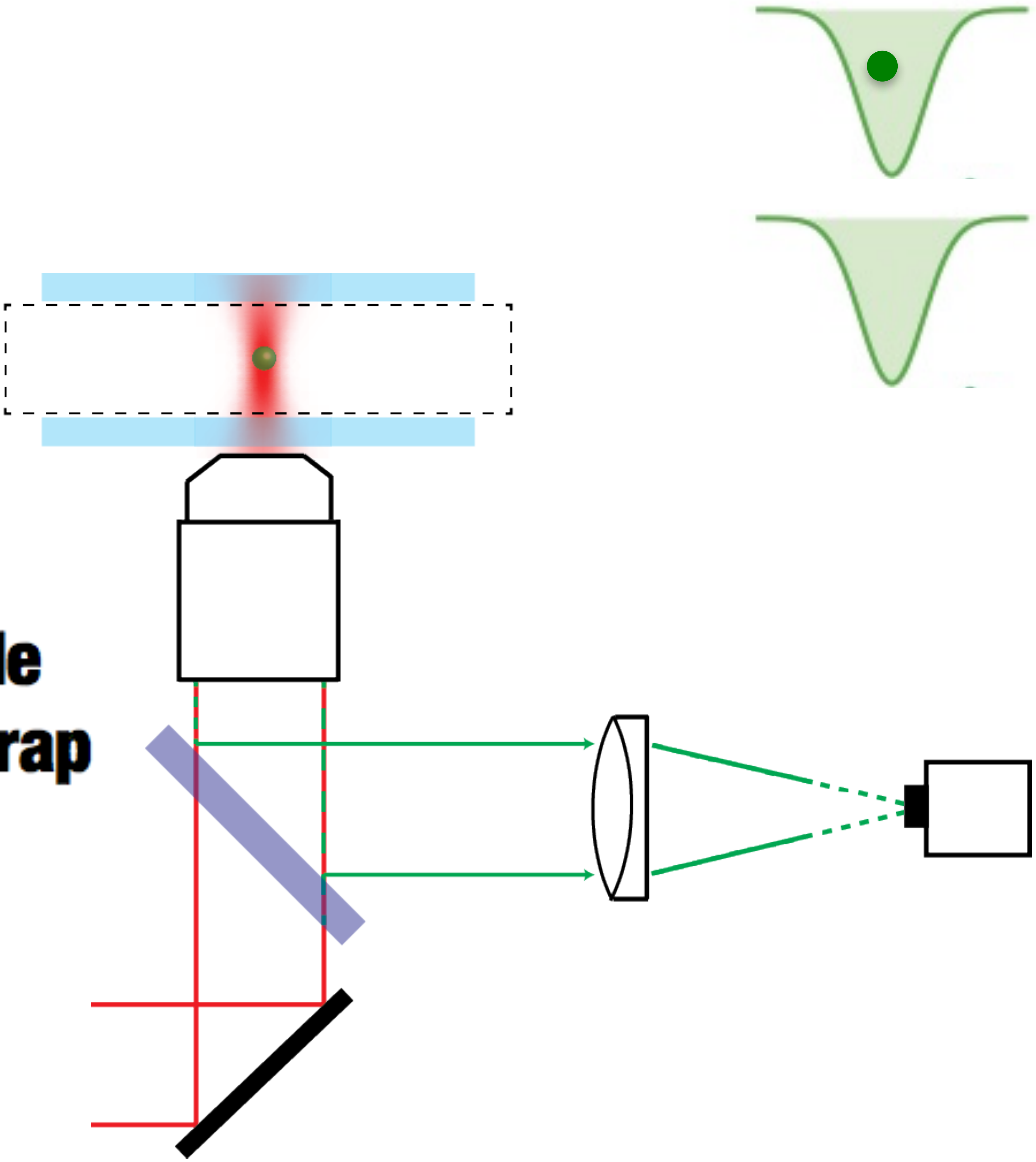
Two-atom version

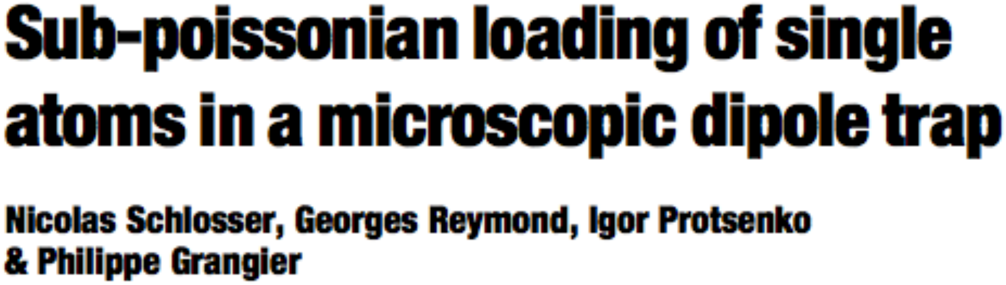
Olshanii *et al.*, PRL (2002)
Weiss *et. al.*, PRA (2004)

Single neutral atoms in optical tweezers



“Parity loading”

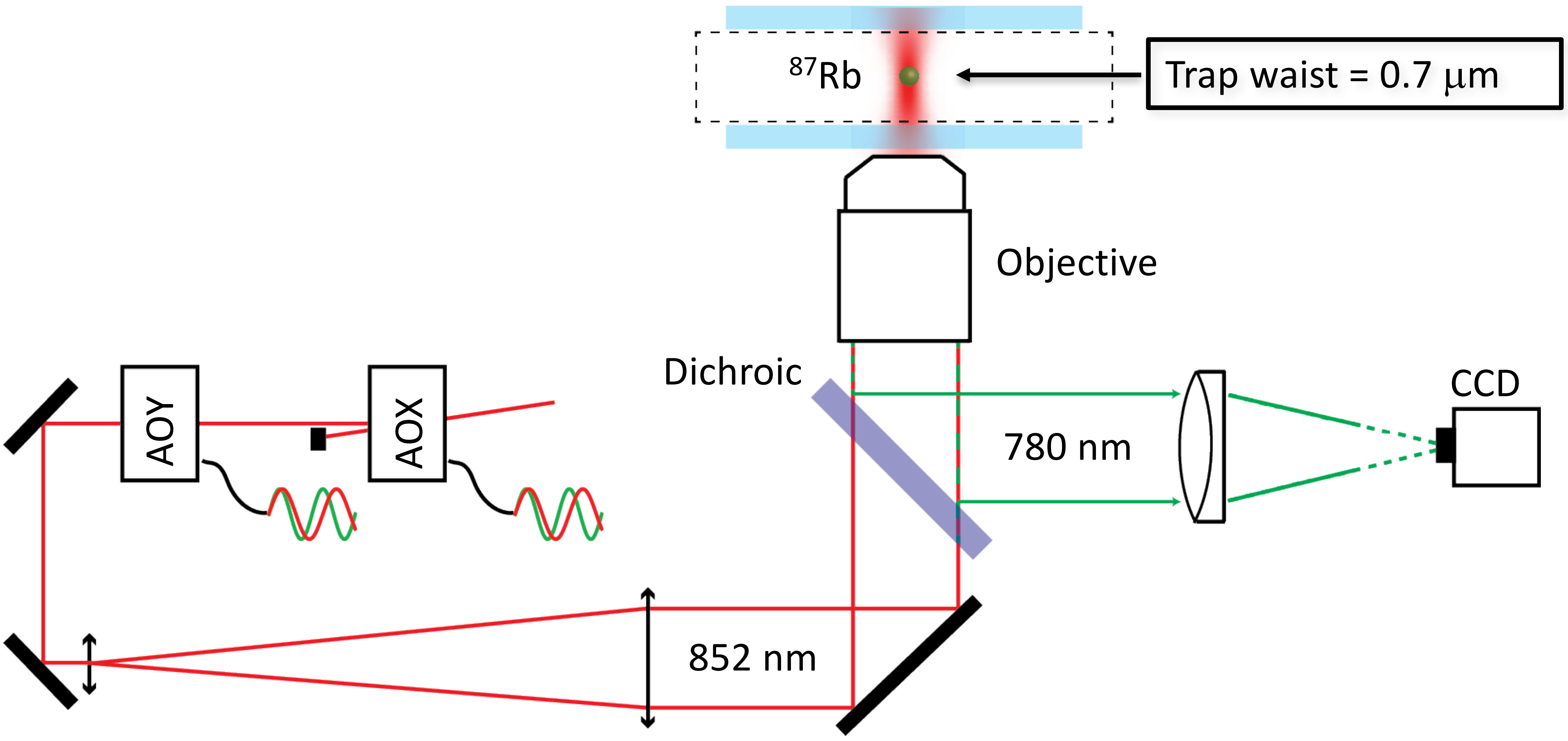




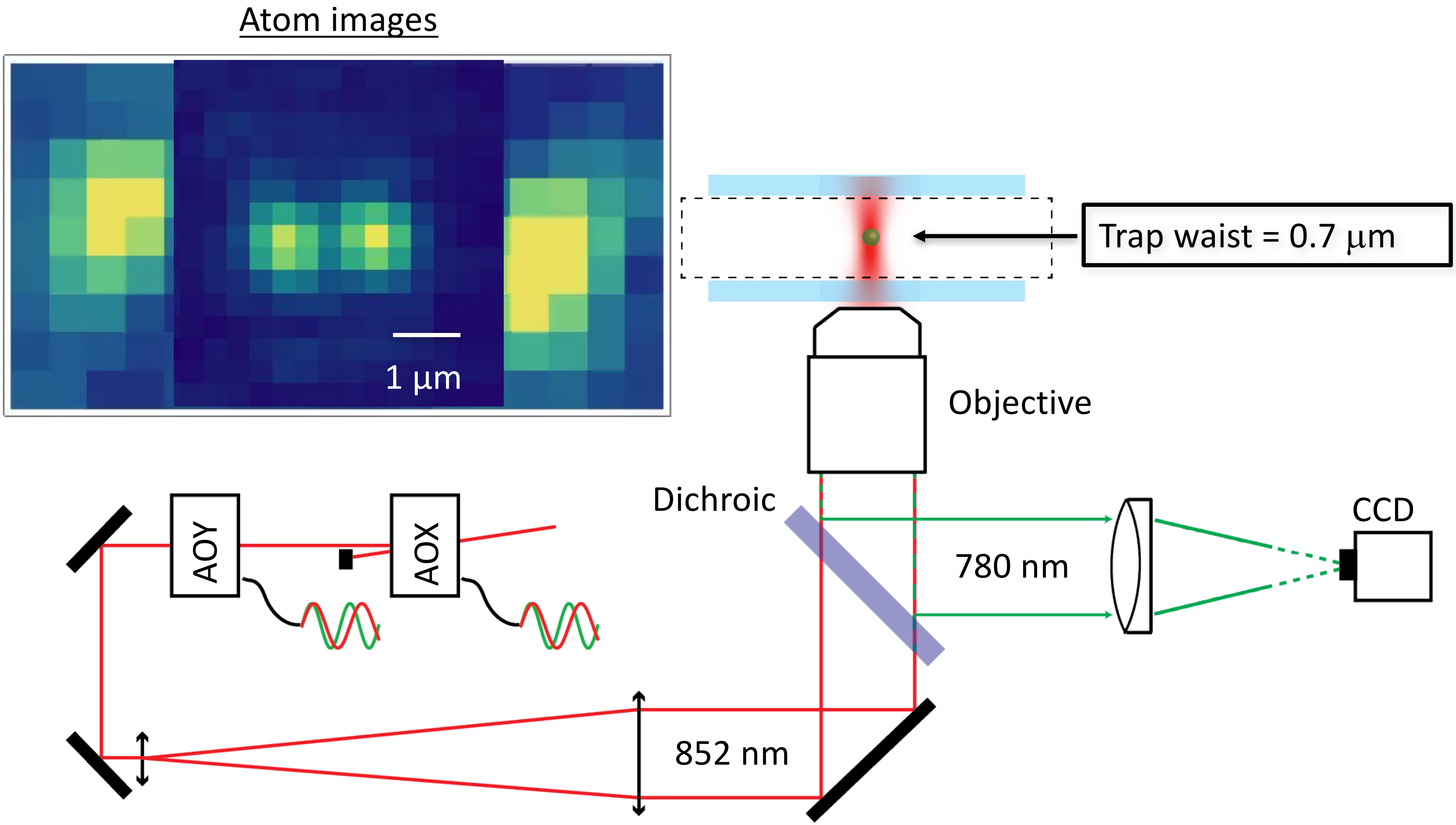
Sub-poissonian loading of single atoms in a microscopic dipole trap

Nicolas Schlosser, Georges Reymond, Igor Protsenko & Philippe Grangier

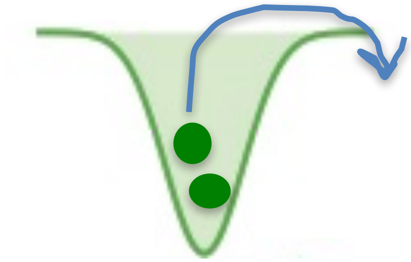
Single neutral atoms in optical tweezers

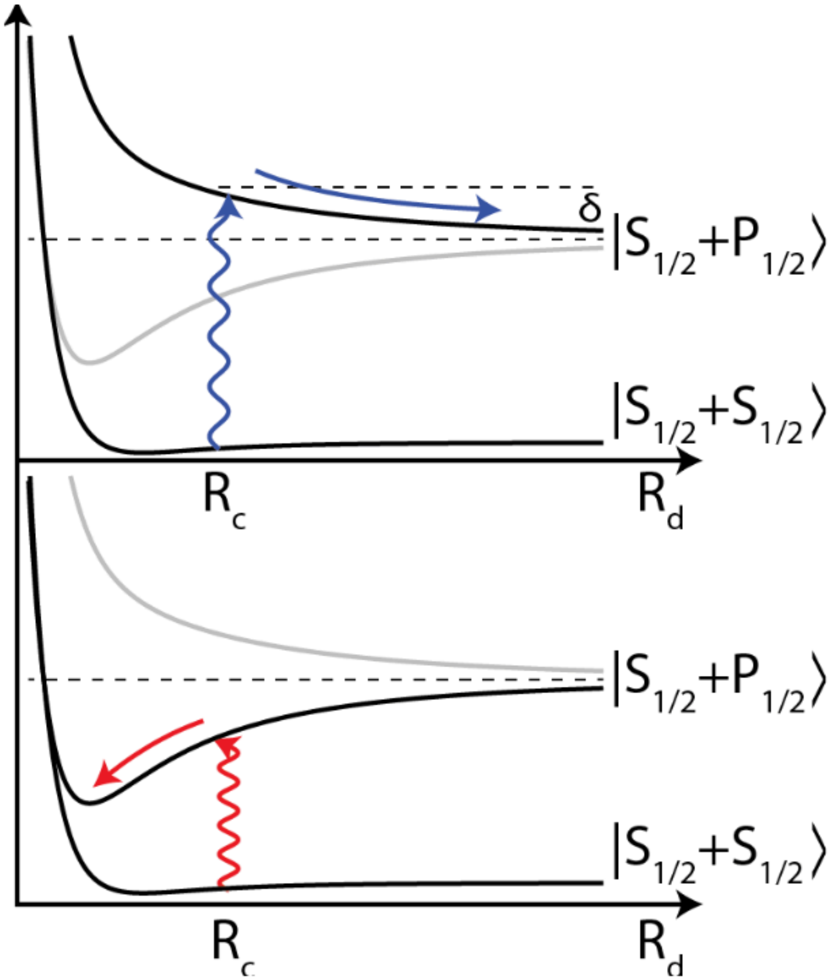


Single neutral atoms in optical tweezers



Tailor light-assisted collisions

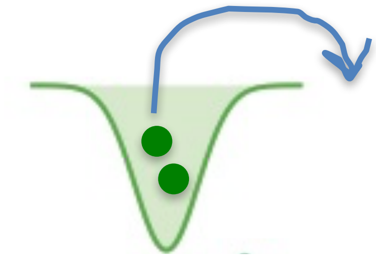




Mikkel Andersen Group
New Zealand ^{85}Rb

Grunzweig *et al.*, Nature Phys. (2010)

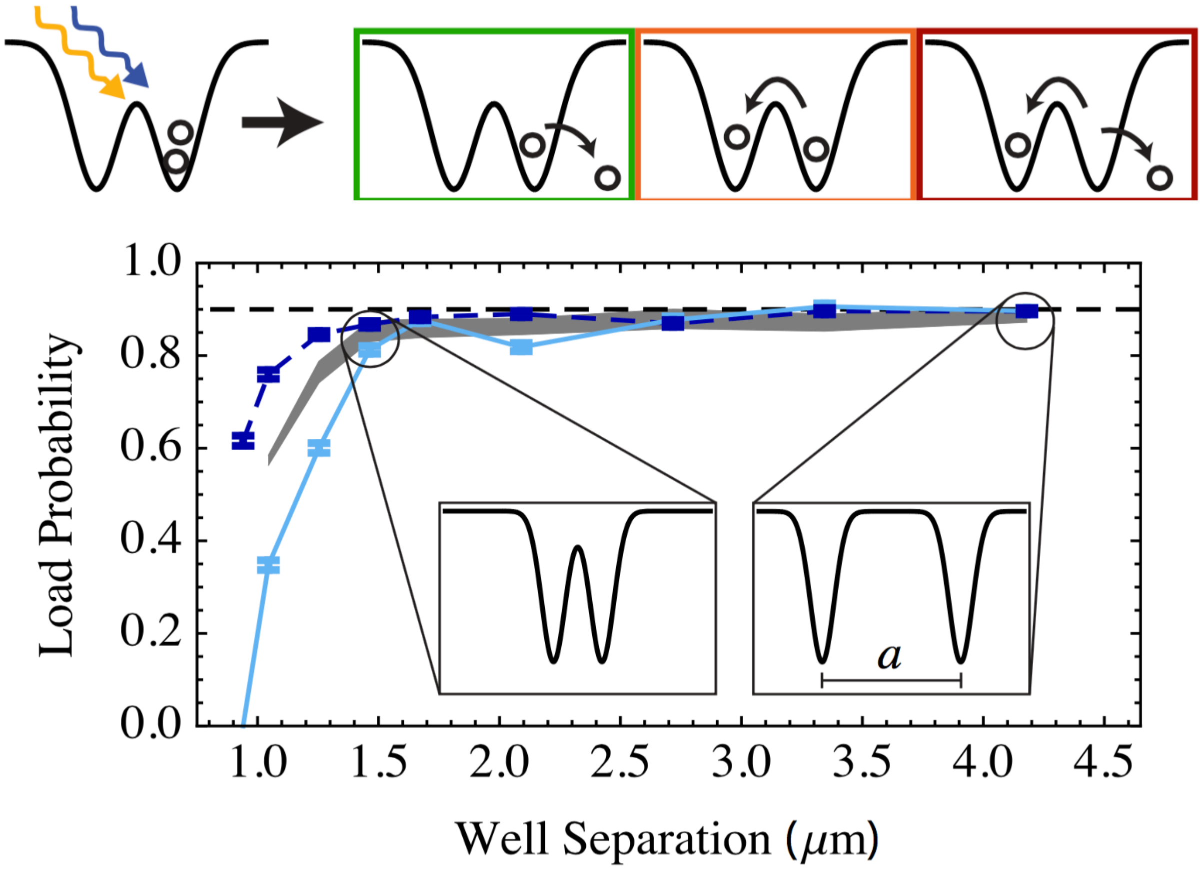
Near-deterministic loading of single atoms



- Smaller volume traps

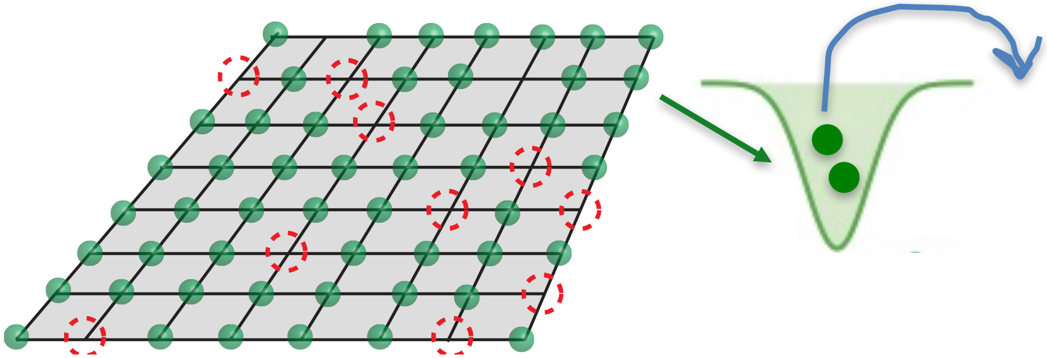
(light applied during MOT loading)

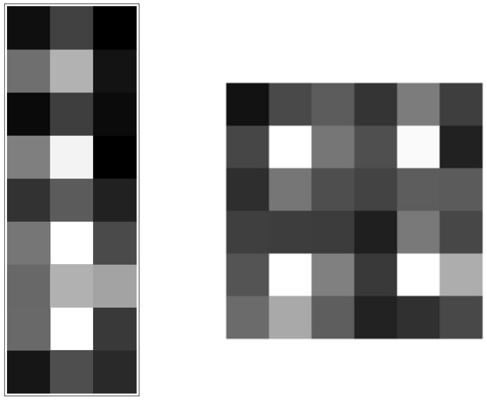
- Understand spacing scaling



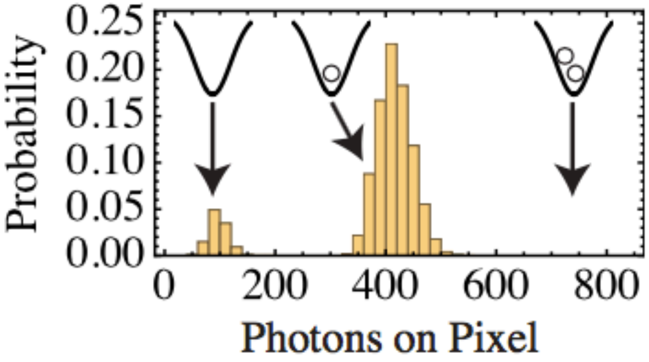
Grunzweig *et al.*, Nature Phys. (2010)
B. J. Lester *et al,* PRL (2015)

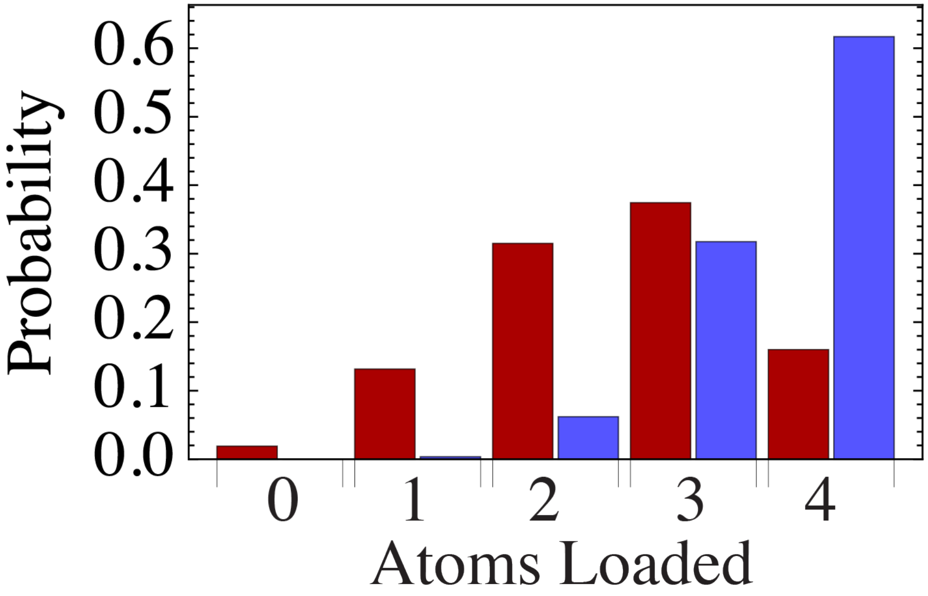
Loading arrays of atoms





90%



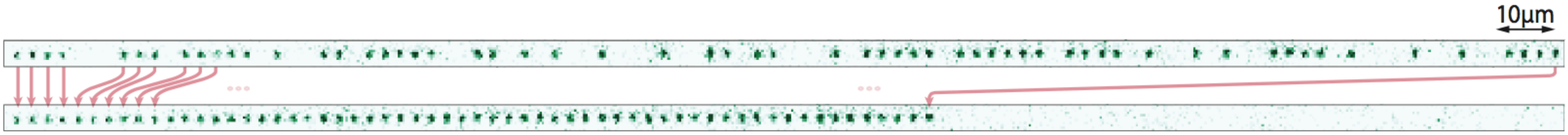


Many more traps

Grunzweig *et al.*, Nature Phys. (2010)
B. J. Lester *et al.*, PRL (2015)

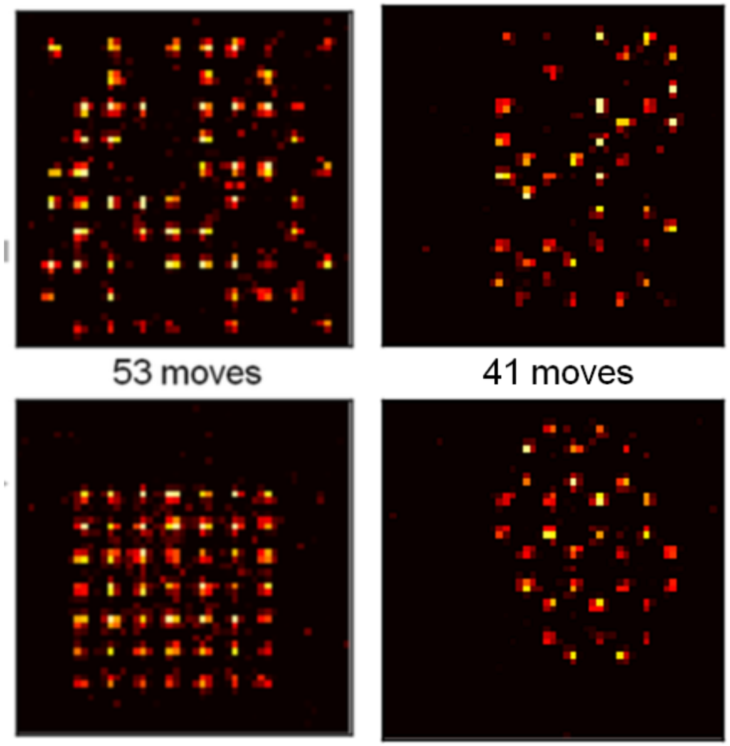
Moving larger arrays

Rearrange many atoms: Paris and Harvard

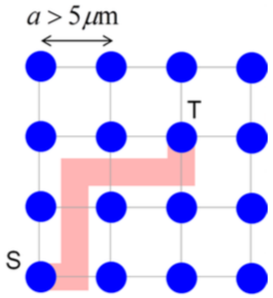


Endres, *et al.*, arXiv:1607.03044 (2016)

Barredo, *et al.*, arXiv:1607.03042 (2016)


53 moves

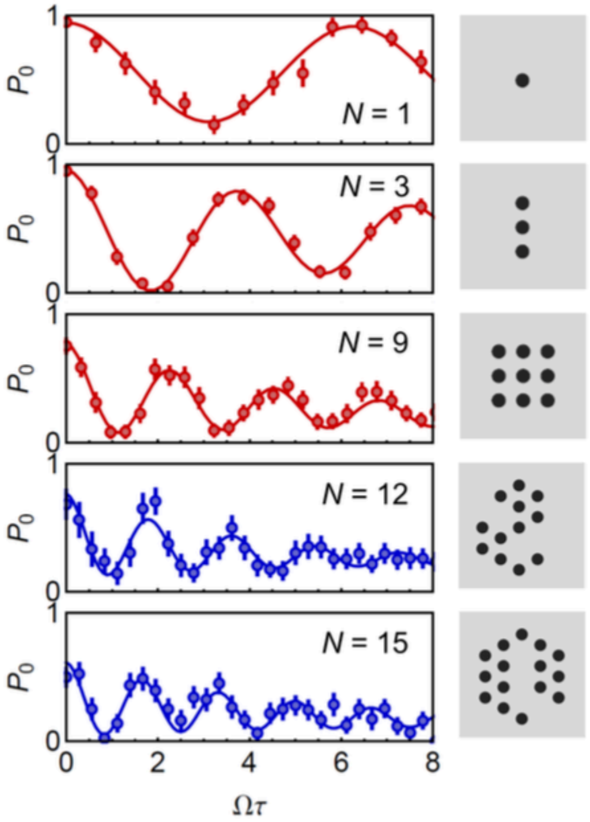
41 moves



First atom sorting machine: Meschede group, 2006

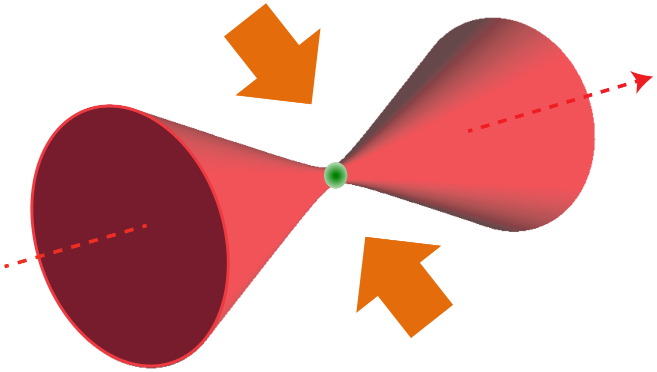
Rydberg physics in arrays

LaBuhn *et al.,* arXiv:1509.04543

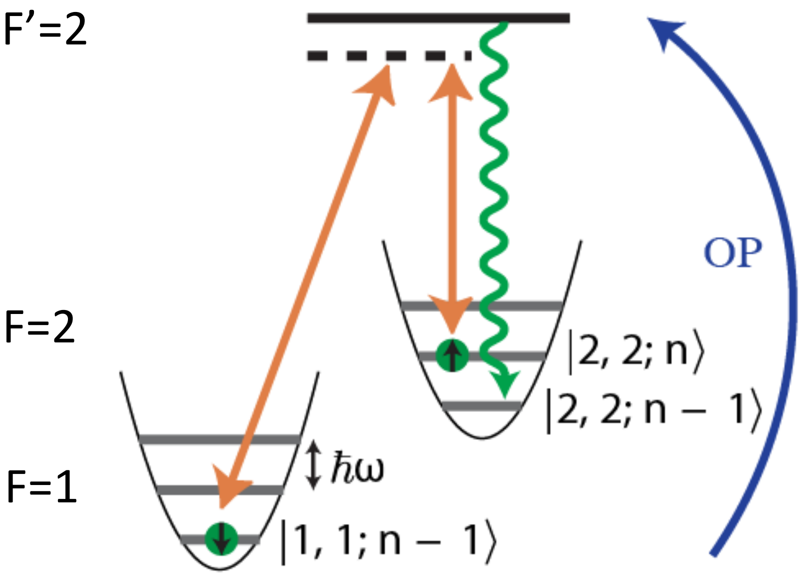


See also Wilk *et al.* PRL (2010); Zhang *et al.*, PRL (2010)

Raman sideband cooling single neutral atoms



External cooling beams



Alternate coherent and dissipative steps

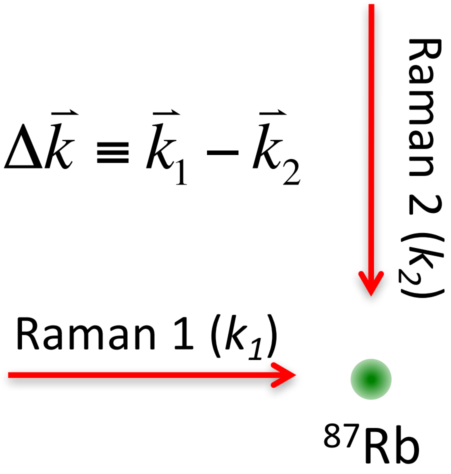
Requirements and challenges:

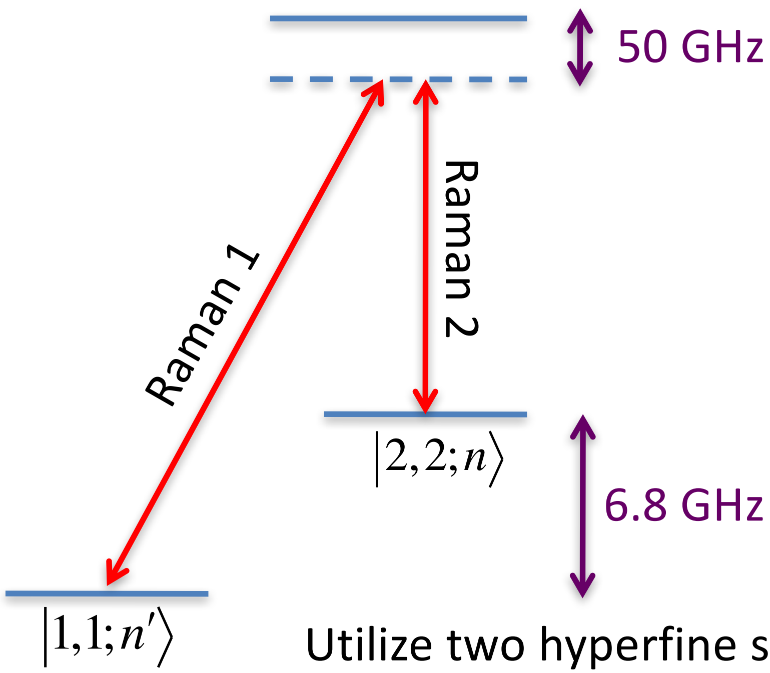
- Large trap frequency ω
    - small Lamb-Dicke parameter
    - larger Rabi rate possible
- Good precooling via PGC
- Consider effects of non-paraxial focus

Monroe *et al.*, PRL (1995)
H. Perrin *et al.*, Europhys. Lett. (1998)
S. Hamman *et al.*, PRL (1998)
V. Vuletic *et al.*, PRL (1998)

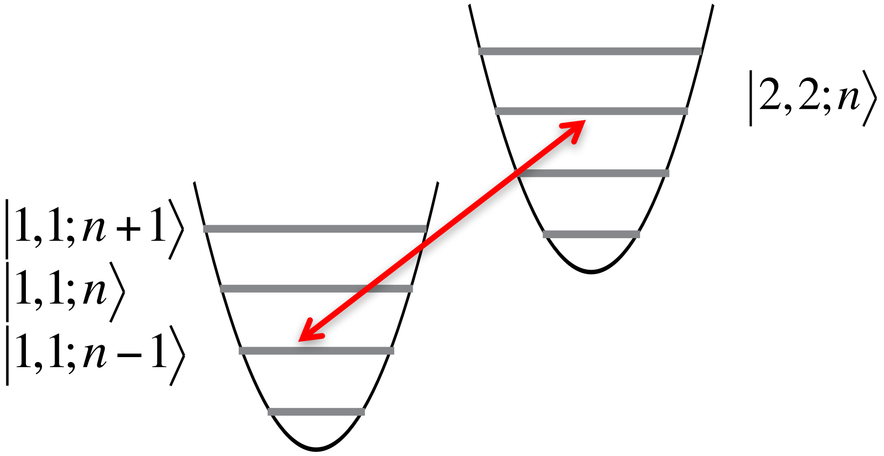
Raman sideband transitions

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



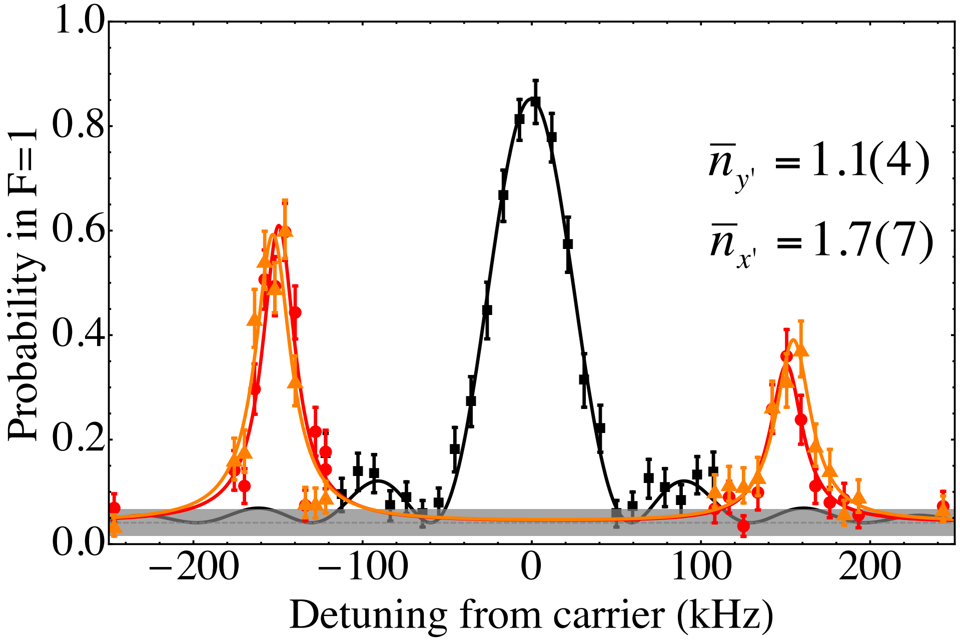


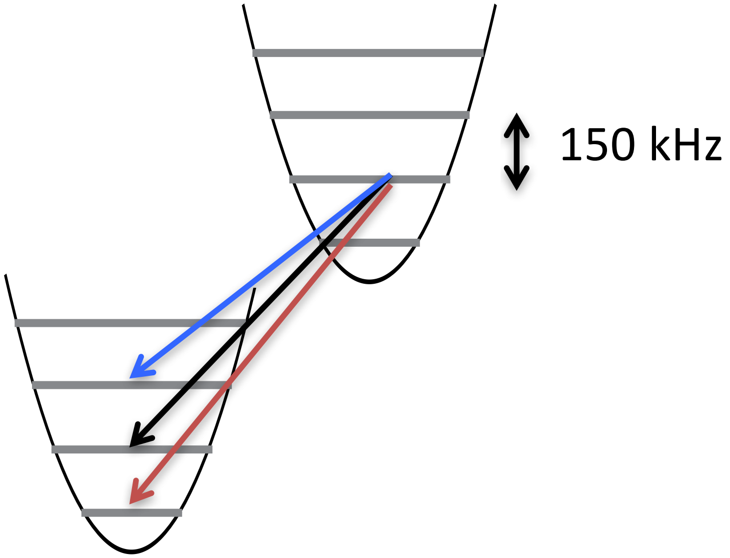
Utilize two hyperfine states of ^{87}Rb

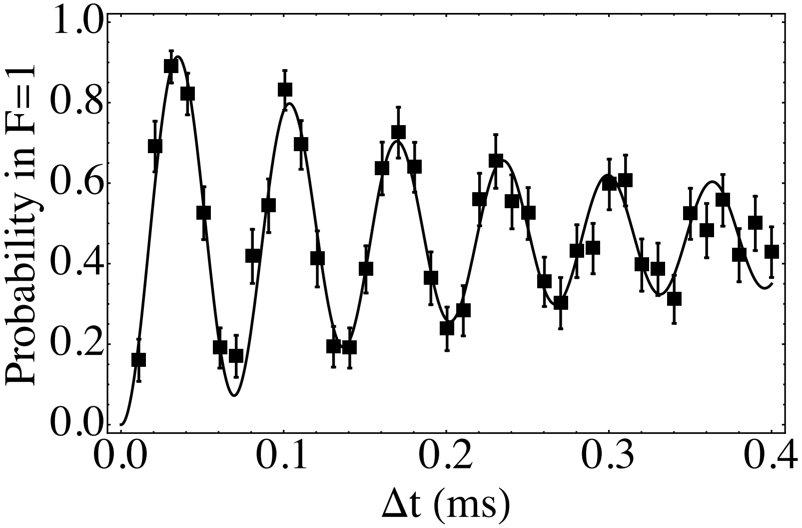


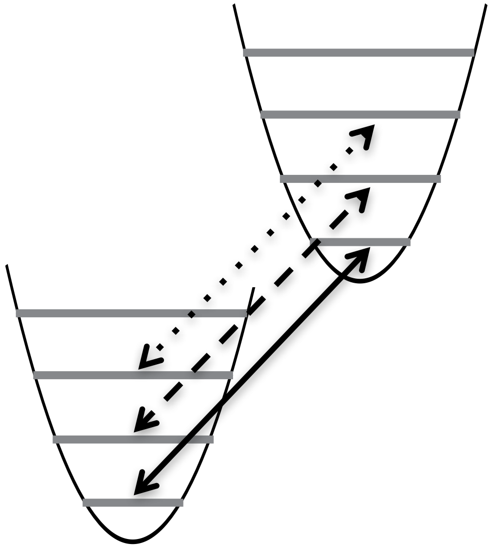
Spectroscopic measurement of precooling

Motional spectroscopy

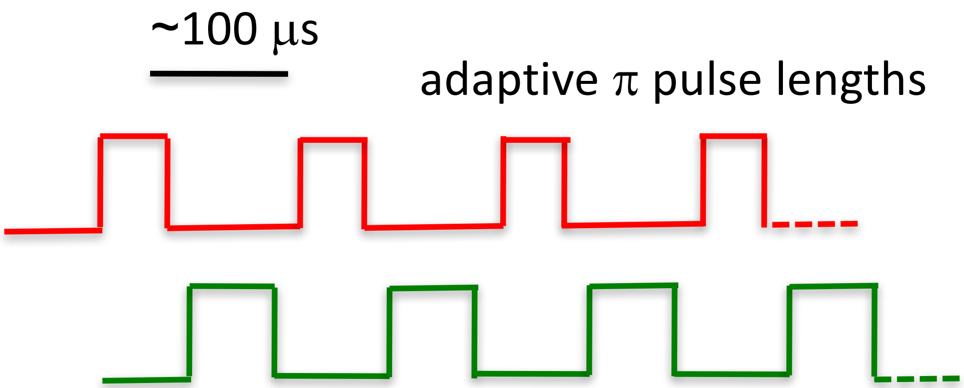






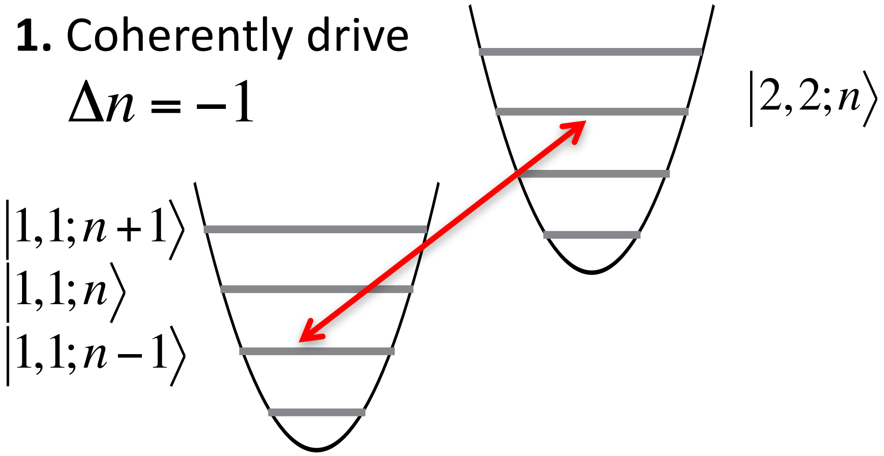


Cooling sequence



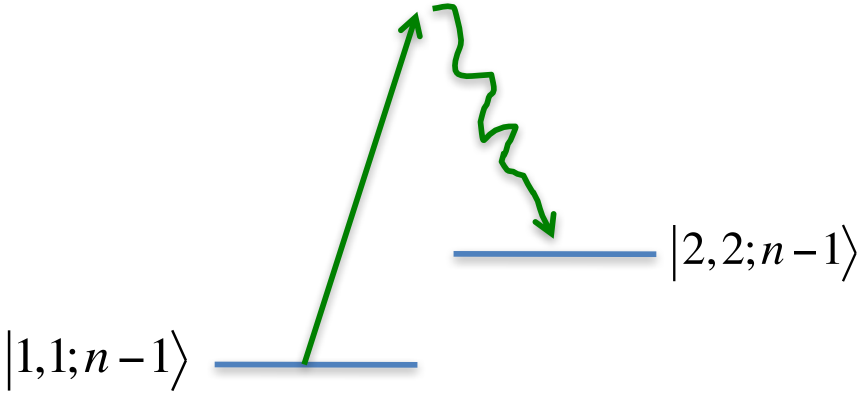
1. Coherently drive

$\Delta n = -1$



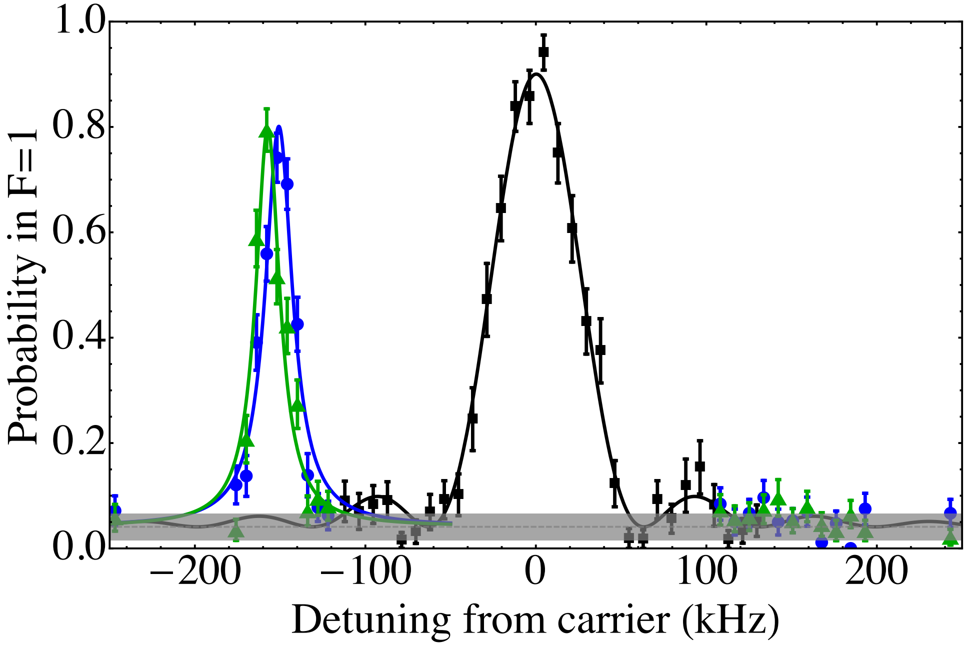
2. Pump back to $|2,2;n-1\rangle$ state: cool efficiently in Lamb-Dicke regime

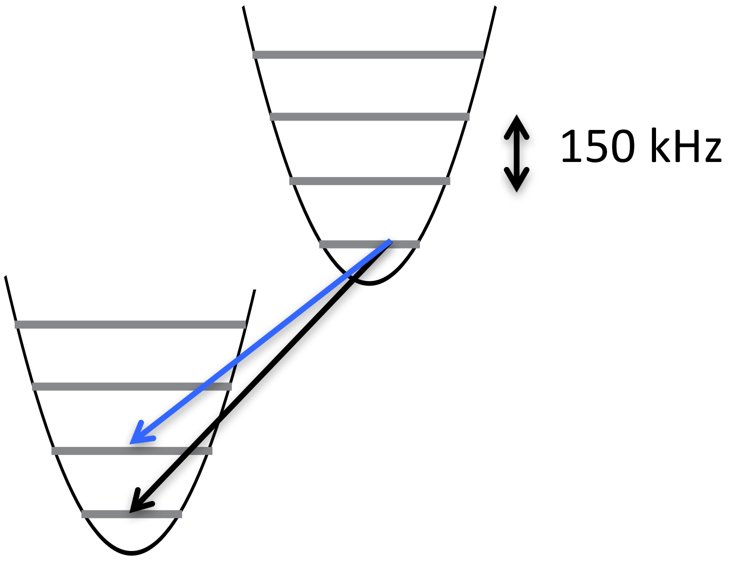
$$P_{\text{return}} \sim 1-(2\bar{n}+1)\eta_{OP}^{2}$$

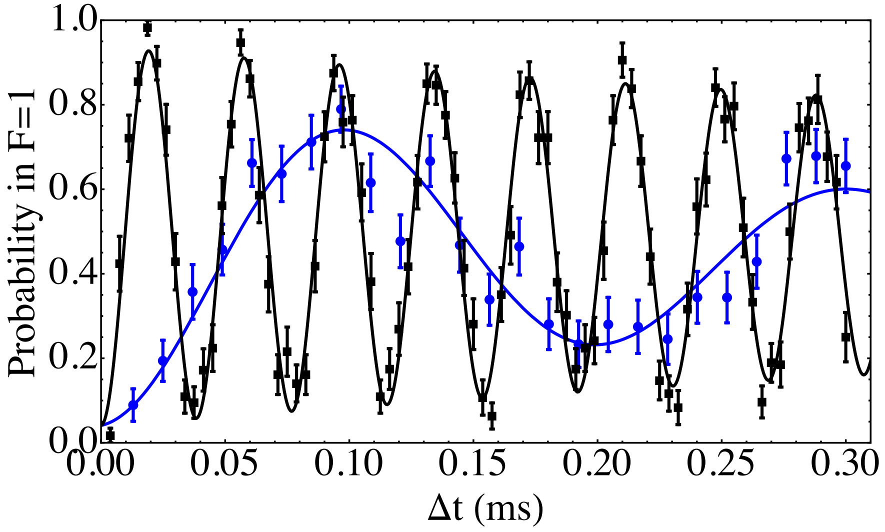


Radial ground state cooling

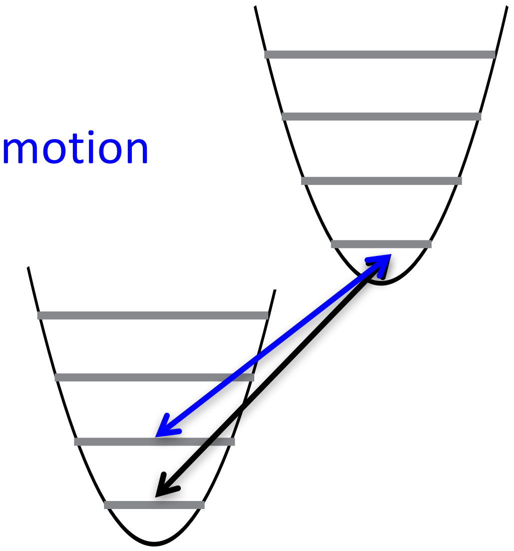
Motional spectroscopy





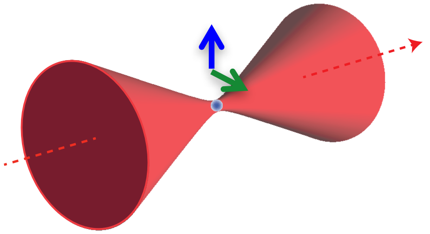


Coherent
control of motion



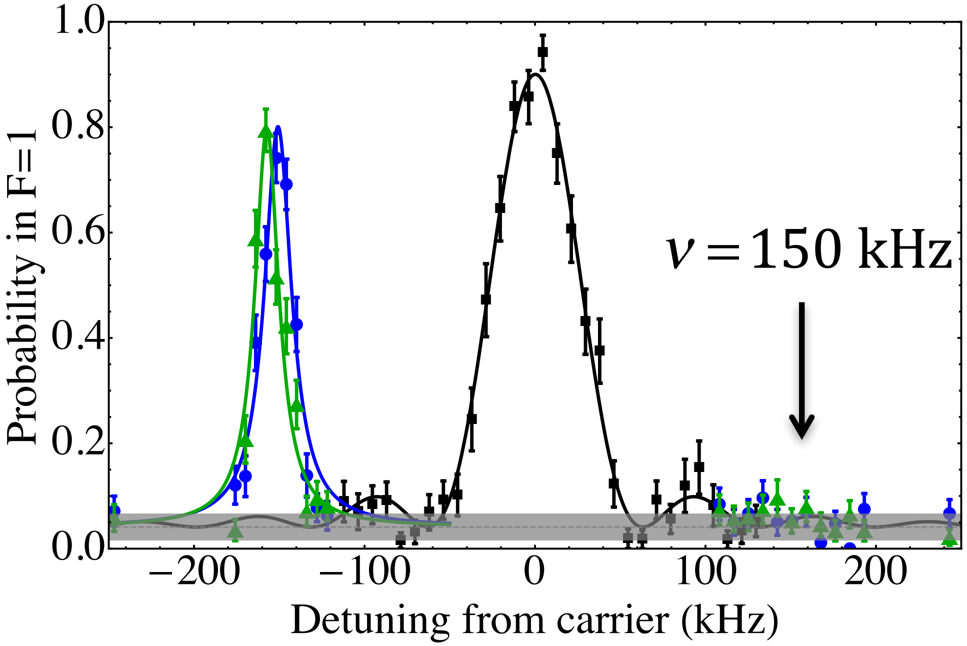
3D ground state cooling in an optical tweezer

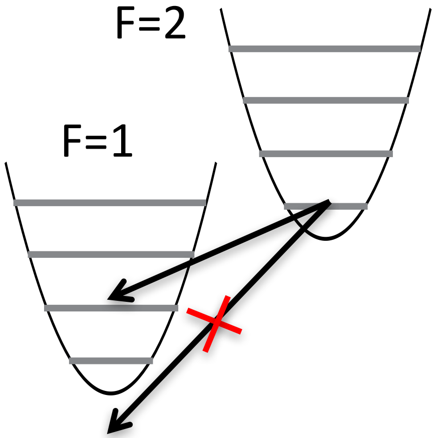
Radial



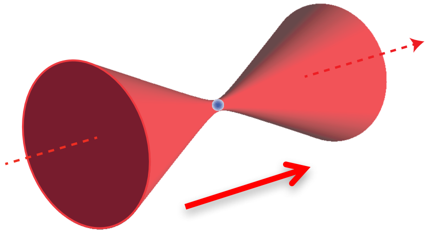
via sub-doppler cooling start at

$\bar{n} \sim 1$





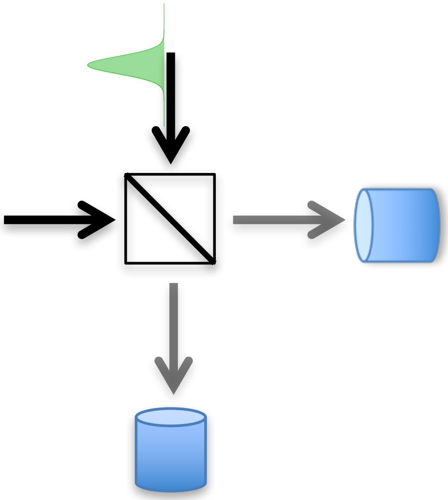
Axial



3D ground state fraction 90(7)%

Kaufman *et al.*, PRX (2012); Thompson *et al.*, PRL (2013);
cold fermions in tweezers: Serwane *et al.*, Science (2011)

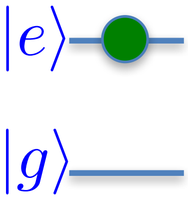
Hong-Ou-Mandel with photons

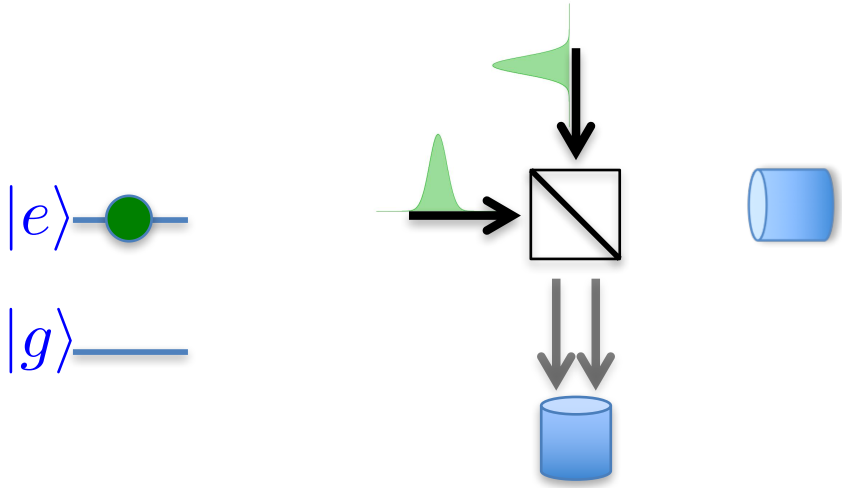


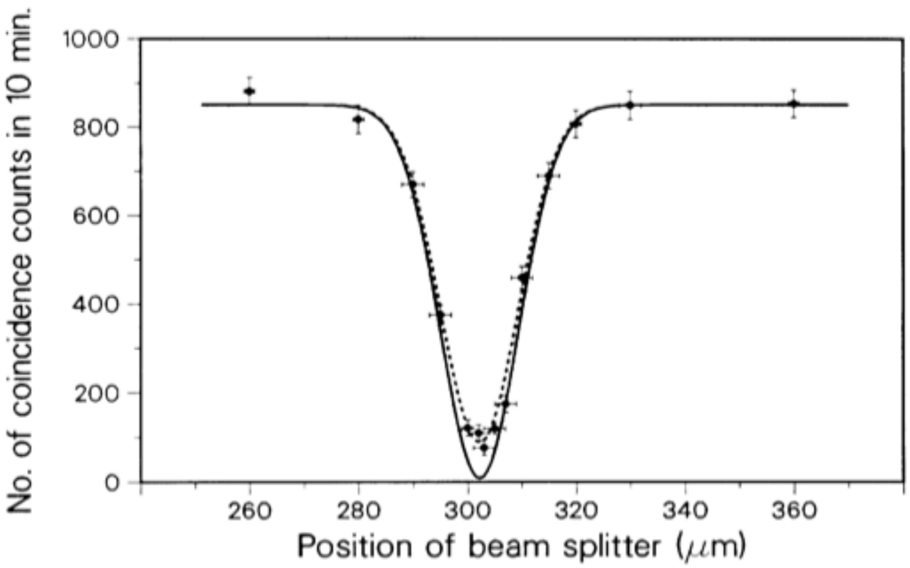
$$|1,0\rangle \rightarrow \frac{1}{\sqrt{2}}(|1,0\rangle + |0,1\rangle)$$

Hong-Ou-Mandel interference of photons

Spontaneous
emission



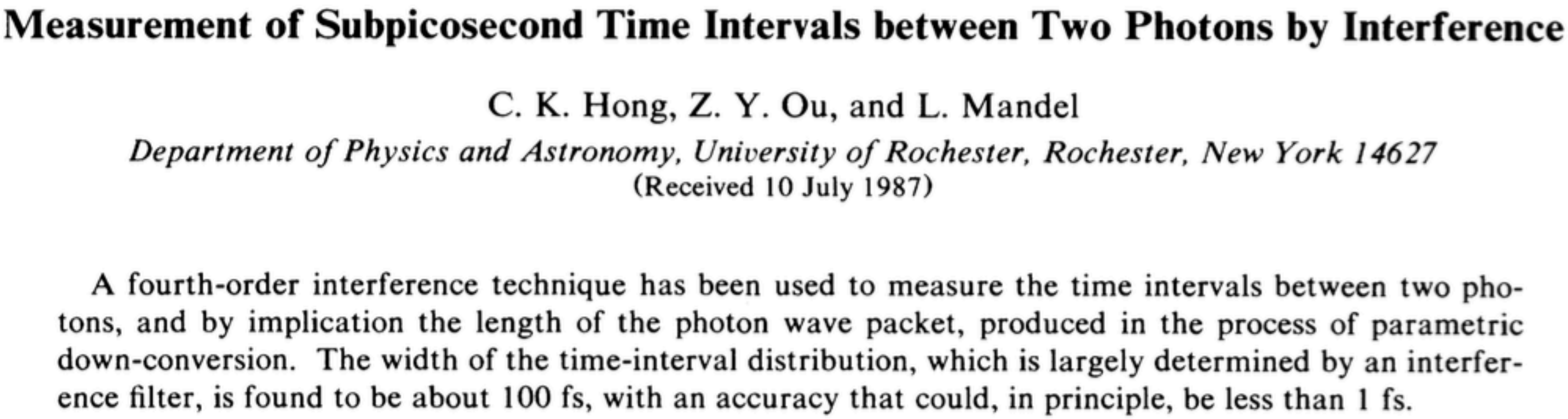




$$|1,1\rangle \rightarrow \frac{1}{\sqrt{2}}\left(|2,0\rangle + |0,2\rangle\right)$$

C. K. Hong, Z. Y. Ou, and L. Mandel, Phys. Rev. Lett. (1987).
For example: Beugnon…Grangier, Nature (2006)
M. Tichy *et al.*, J. Phys. B (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

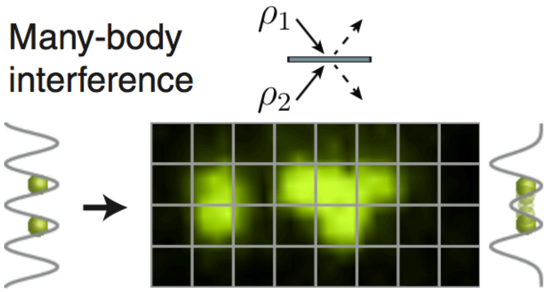
Department of Physics and Astronomy, University of Rochester, Rochester, New York 14627

(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

And in QGM experiments now diagnosing many-body states…



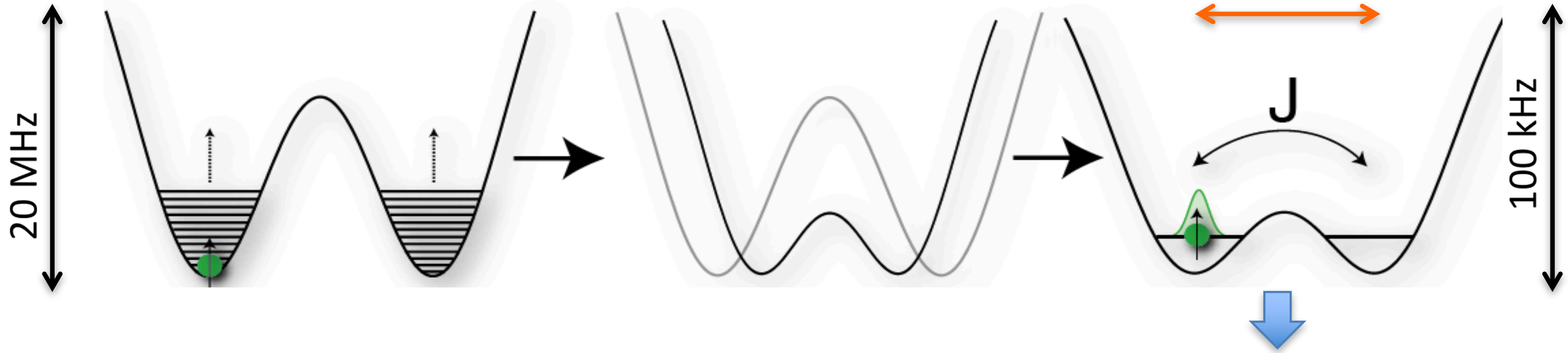
Greiner group

Our beamsplitter: Tunneling

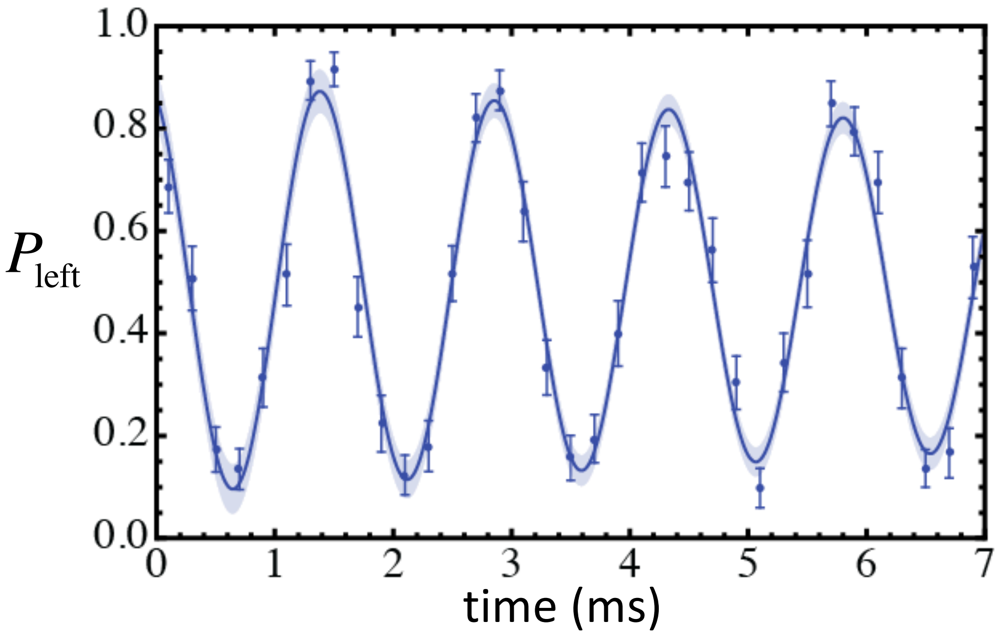
Wells deep, far apart:

Sweep and drop:

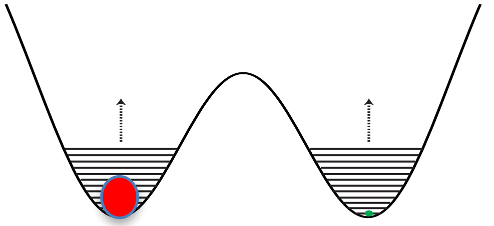
Do physics



Single-atom ground-state tunneling



Rapidly pin for imaging



Bias tuned to 0

$$J / 2\pi = 340\ \text{Hz}$$

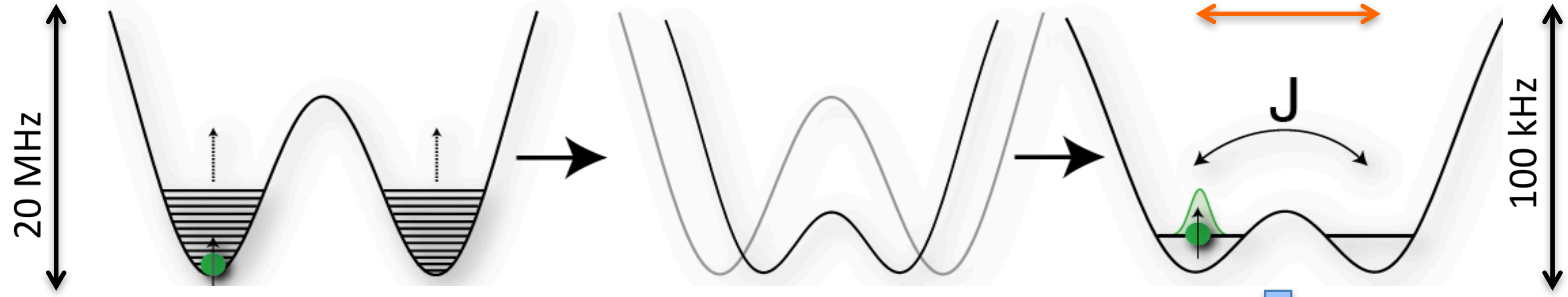
$$U = 0.2J$$

Initiate tunneling experiments

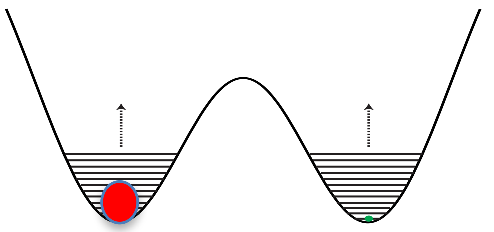
Wells deep, far apart:

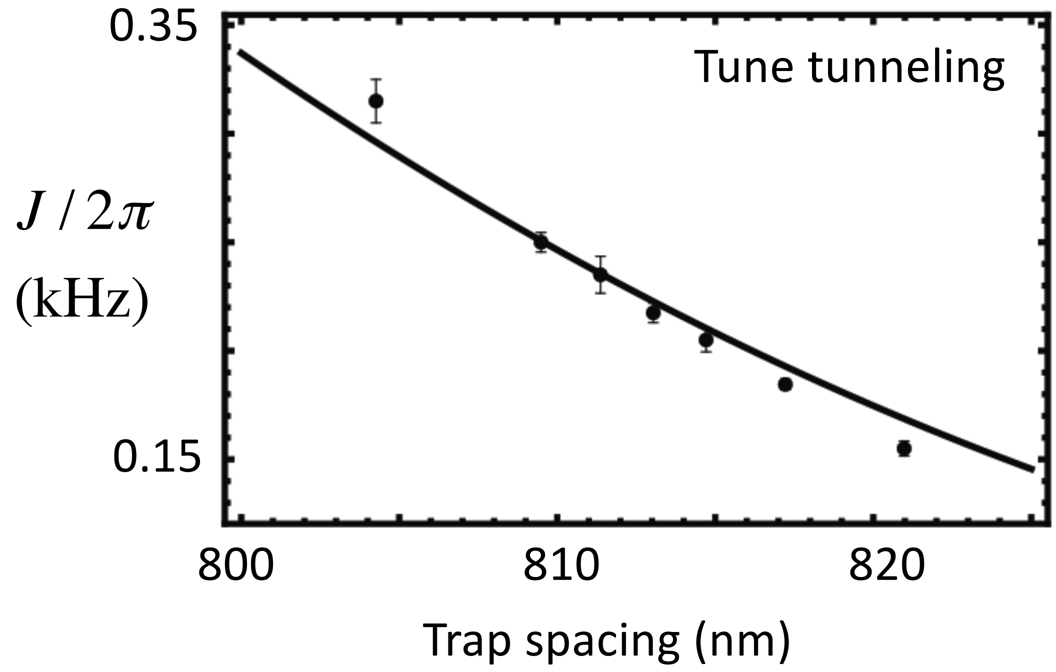
Sweep and drop:

Do physics

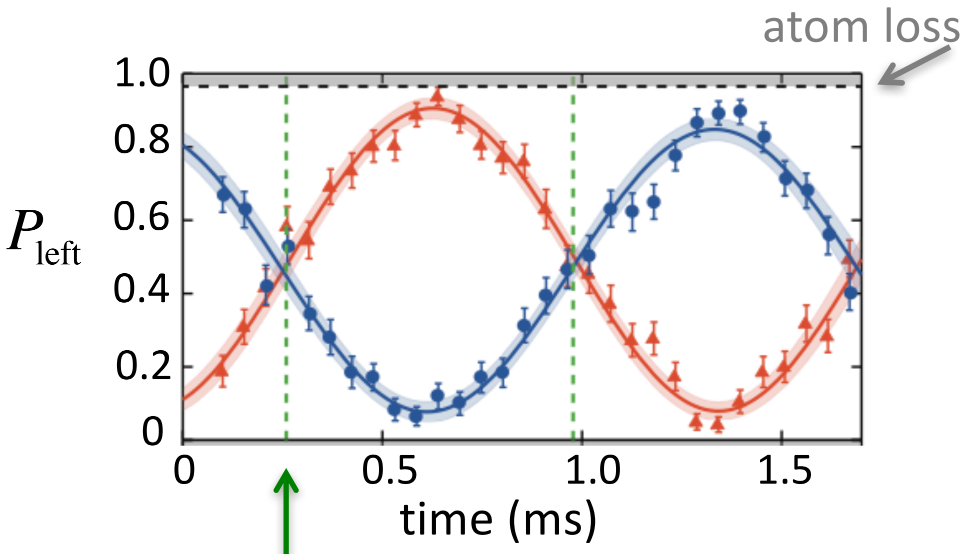


Rapidly pin for imaging



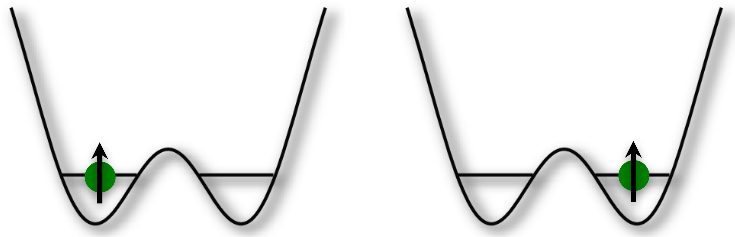


Tunneling as a beamsplitter



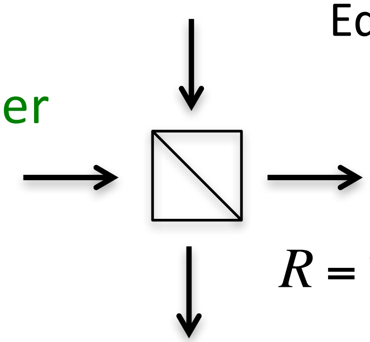
starting on left

starting on right



balanced beamsplitter

Equal superposition of two wells



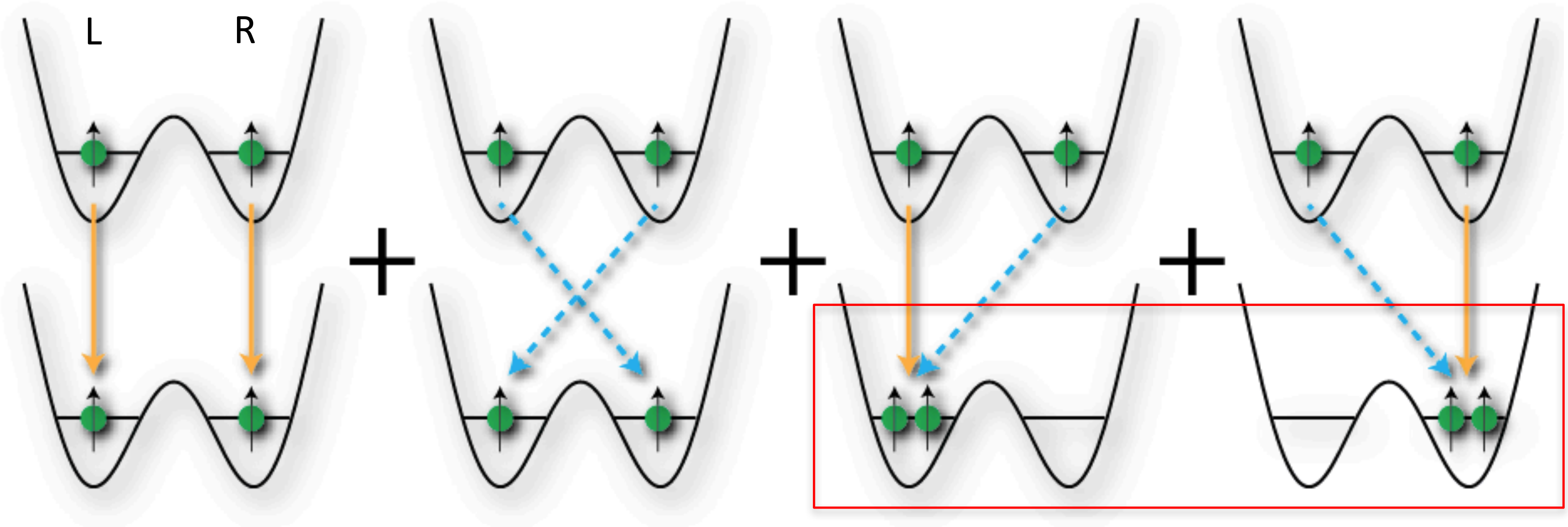
$R = T = 0.5$

Note:

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

Quantum statistics in atom equivalent

initial: $\hat{a}_L^\dagger \hat{a}_R^\dagger |0,0\rangle = |1,1\rangle$



Bunching / Bose enhancement

final: $\frac{1}{2}(\cancel{\hat{b}_L^\dagger \hat{b}_R^\dagger - \hat{b}_R^\dagger \hat{b}_L^\dagger} + i(\hat{b}_L^\dagger)^2 + i(\hat{b}_R^\dagger)^2)|0,0\rangle$

Bosons

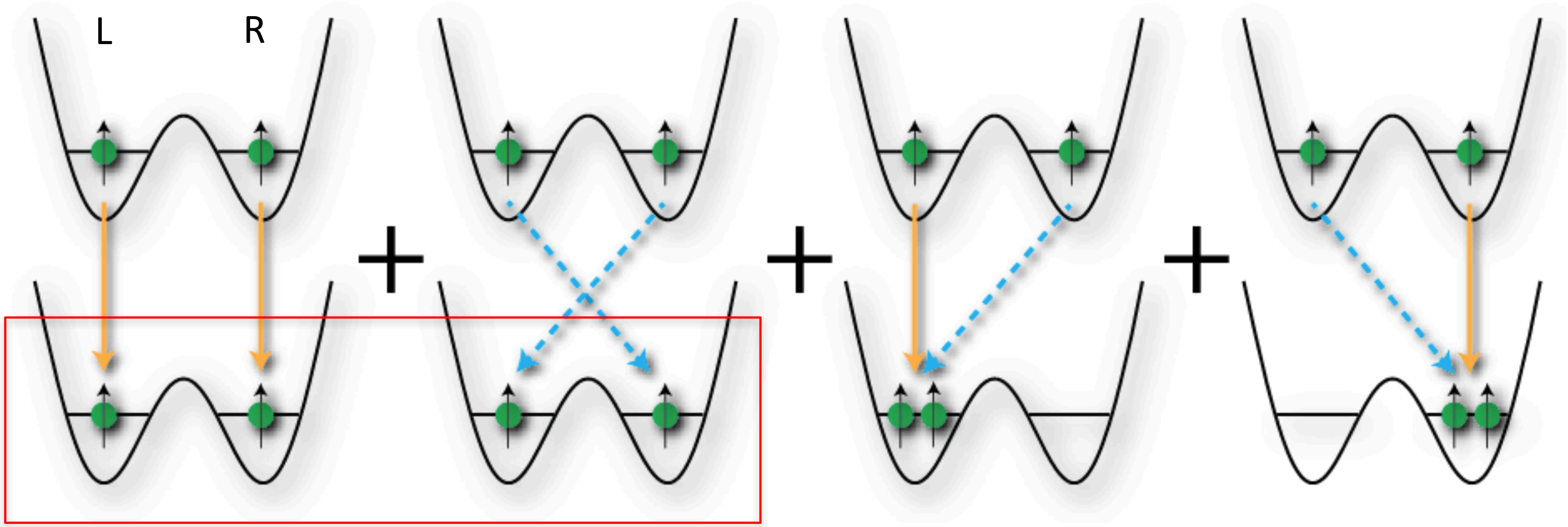
$$\downarrow \qquad\qquad \downarrow$$

$$\sqrt{2}\,|2,0\rangle + \sqrt{2}\,|0,2\rangle$$

$$P_{11} = 0$$

Quantum statistics in atom equivalent

initial: $\hat{a}_L^\dagger \hat{a}_R^\dagger |0,0\rangle = |1,1\rangle$



Antibunching / Pauli blocking

final: $\frac{1}{2}(\hat{b}_L^\dagger \hat{b}_R^\dagger - \hat{b}_R^\dagger \hat{b}_L^\dagger + \cancel{i(\hat{b}_L^\dagger)^2} + \cancel{i(\hat{b}_R^\dagger)^2})|0,0\rangle$

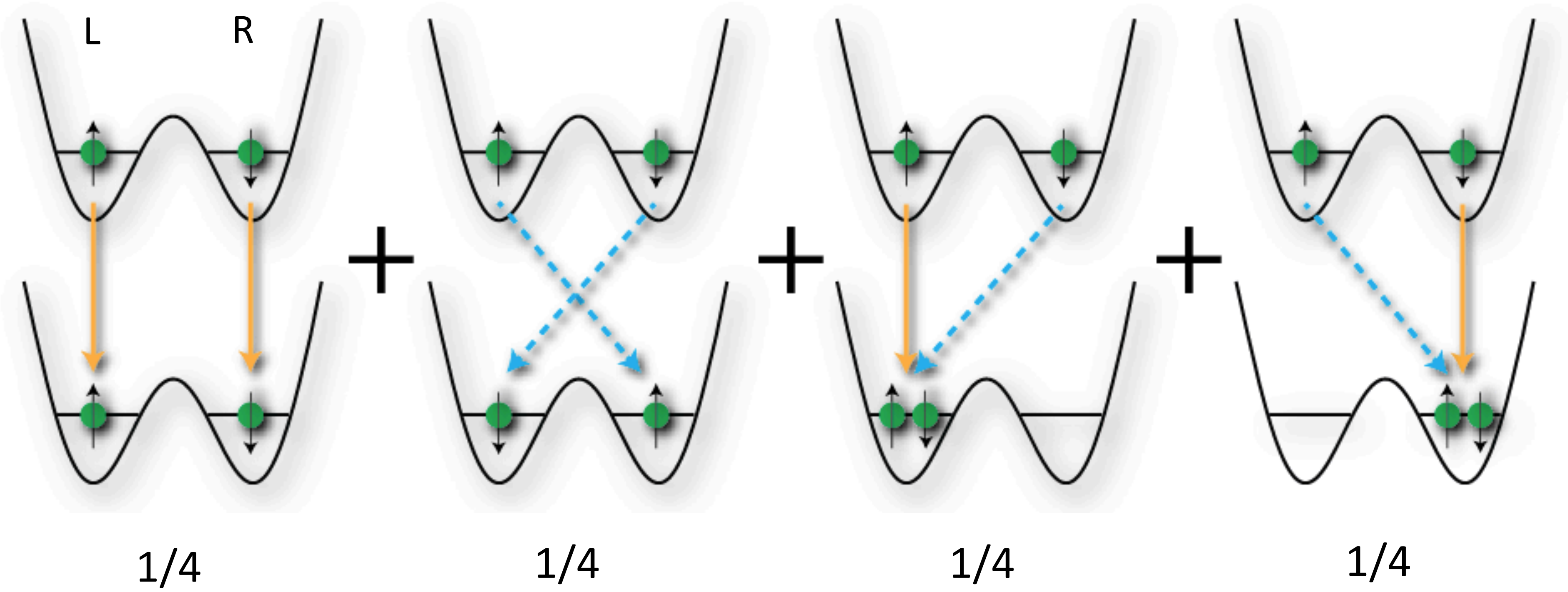
$\downarrow$

$+\hat{b}_L^\dagger \hat{b}_R^\dagger$

Fermions

$P_{11} = 1$

Quantum statistics in atom equivalent



flip two independent coins

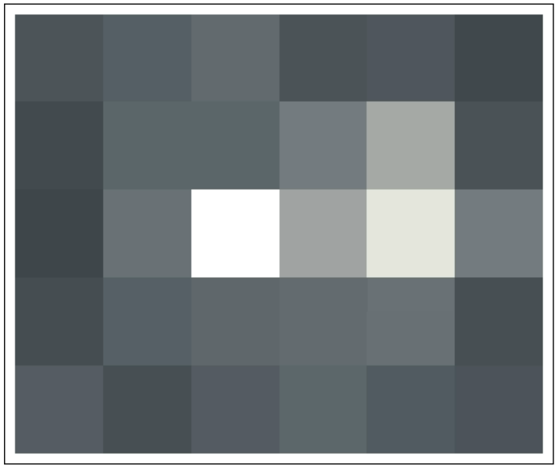
Distinguishable particles

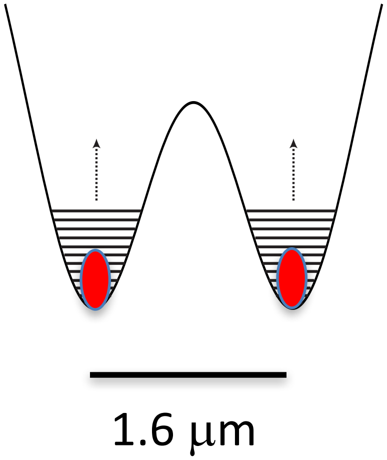
(in some other degree of freedom)

$$P_{11} = 0.5$$

The experiment: Follow the atoms

set of single-atom images





This measurement used 60% stochastic loading

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

Images: Thermal atoms in deep, separated traps

The experiment: Follow the atoms

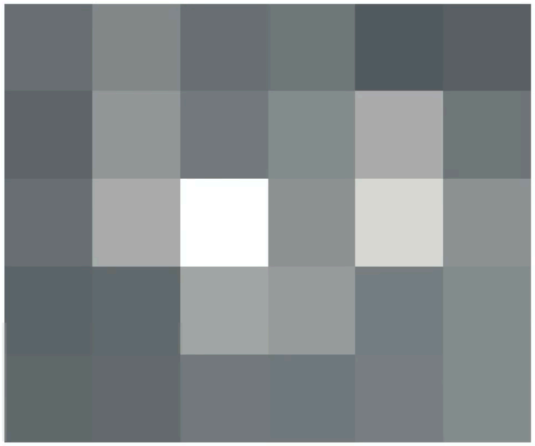


Image 1

(before tunneling)

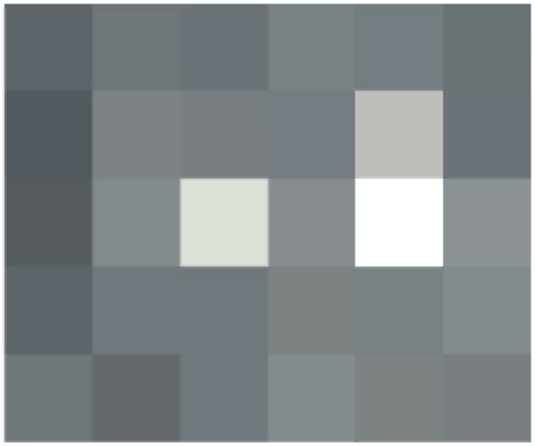


Image 2

(after tunneling)

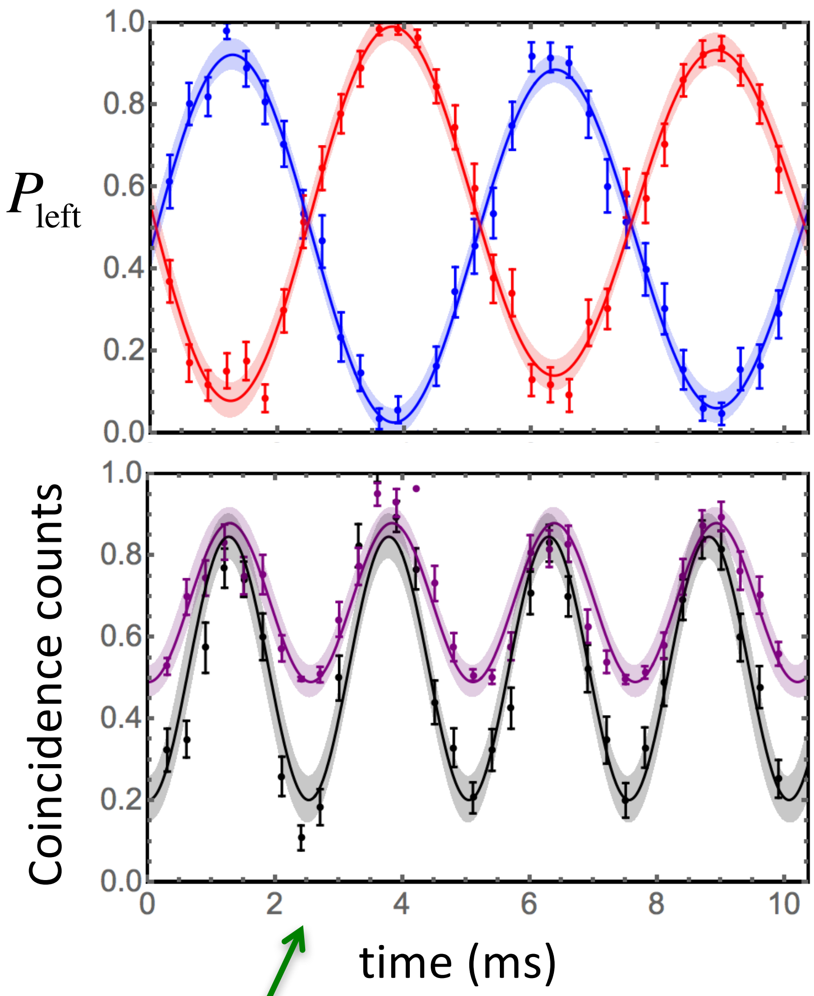
(still see only 0 or 1 light-assisted collisions)

Coincidence count:

Expectation:

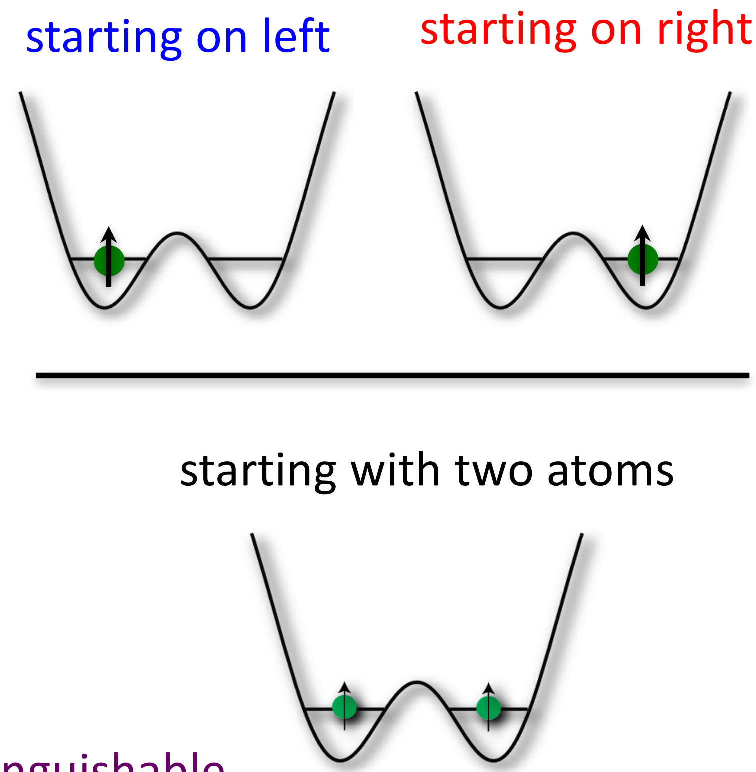
- 0 for bosons
- 50% of time for distinguishable particles (flipping coin)

Coincidence counts below distinguishable expectation



balanced
beamsplitter

distinguishable
expectation from
single-atom data


starting on left

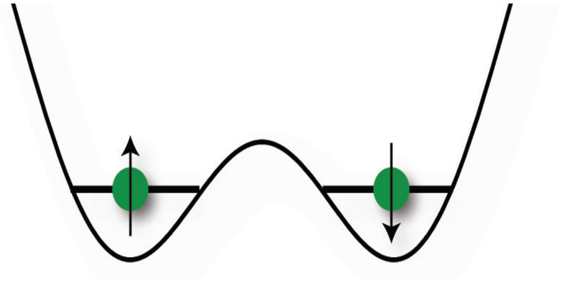
starting on right

starting with two atoms

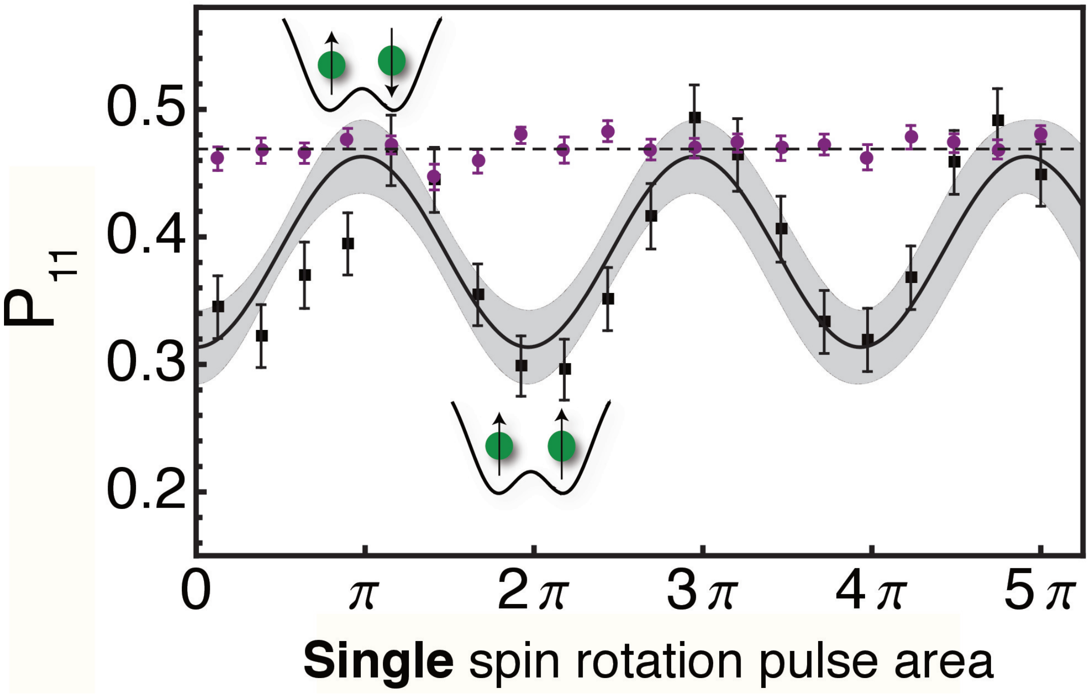
A. M. Kaufman *et al.,* Science (2014)
R. Lopes *et al.*, Nature (2015)

Tuning distinguishability

Rotate one spin (analogous to polarization with photons)

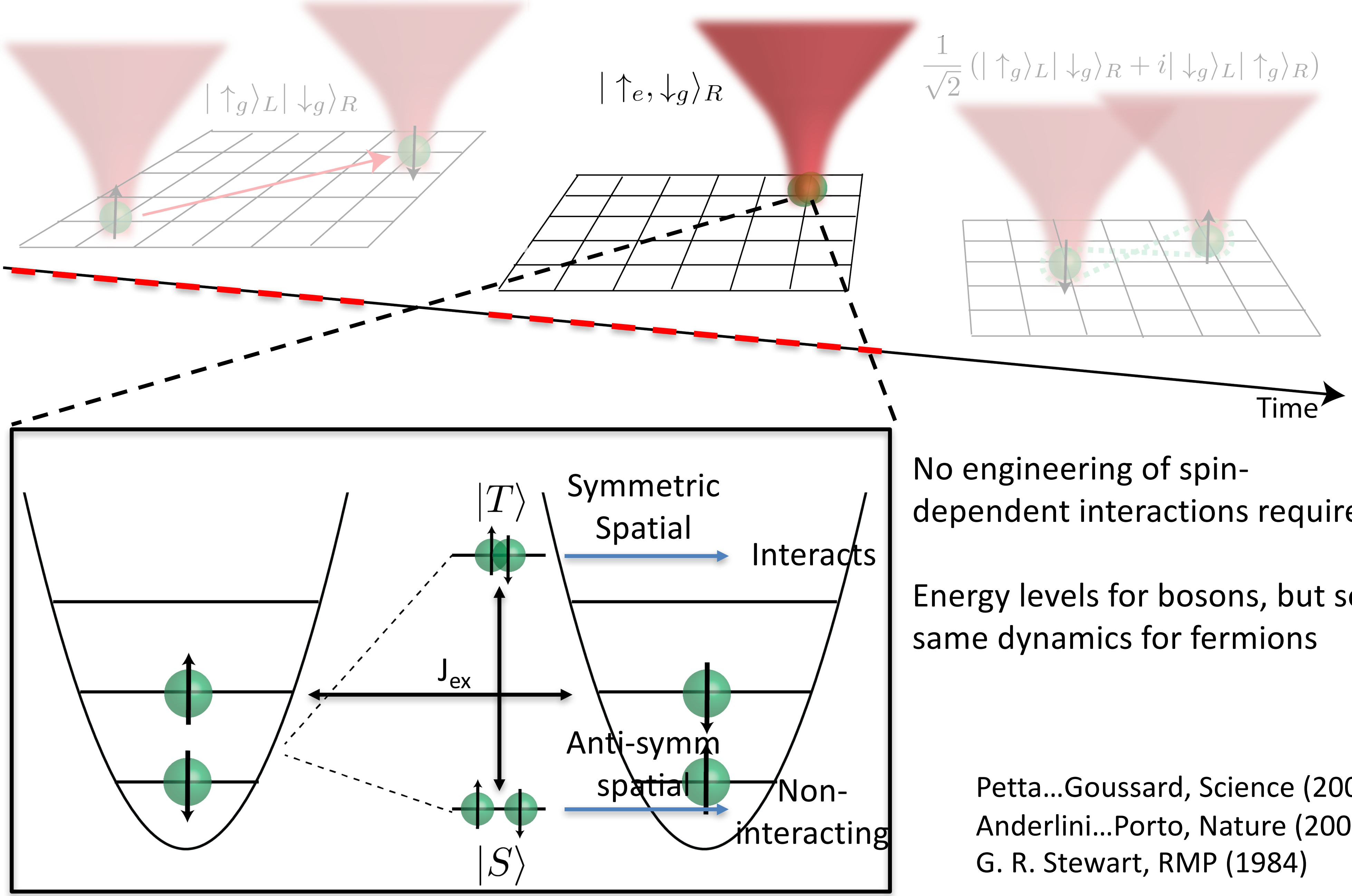


At balanced beamsplitter point



Rabi oscillations on right spin only

Spin entanglement using spin exchange



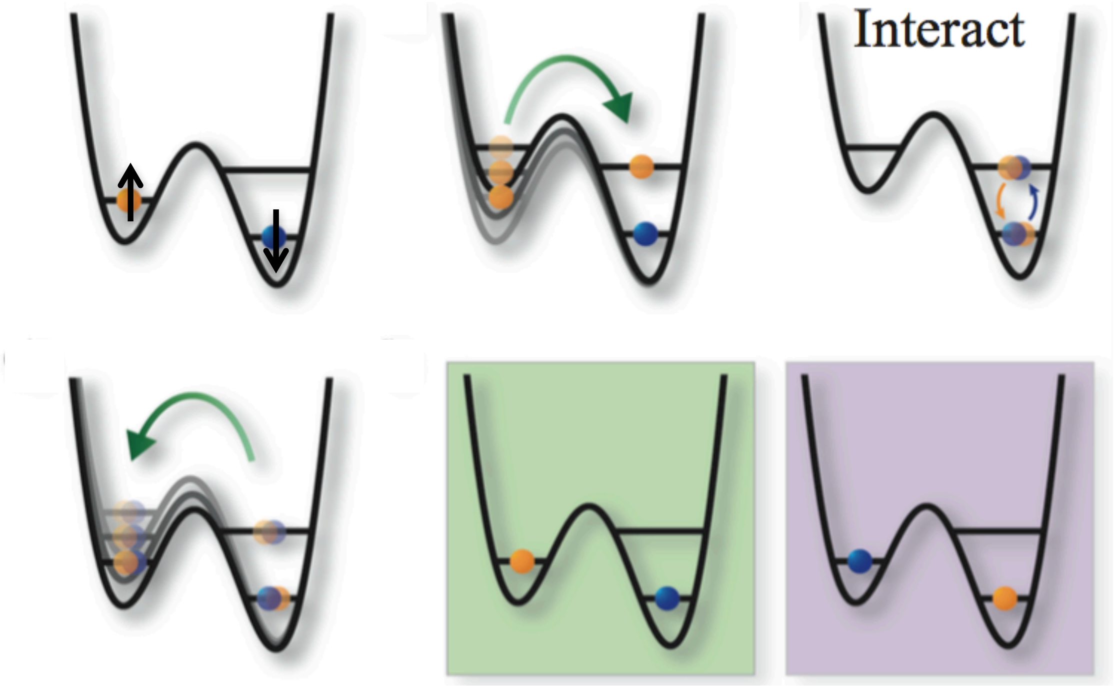
No engineering of spin-dependent interactions required

Energy levels for bosons, but see same dynamics for fermions

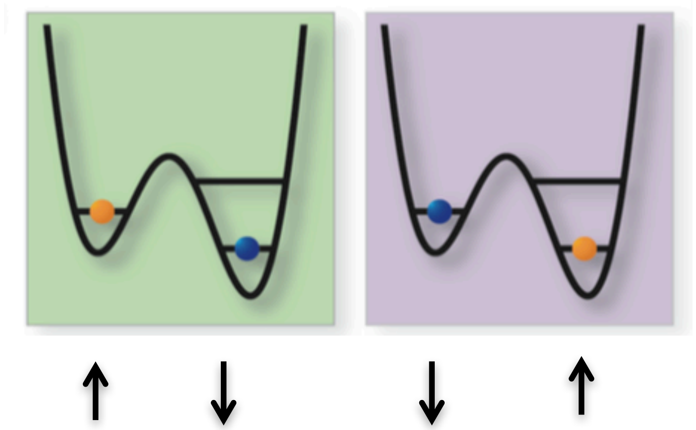
Petta…Goussard, Science (2005)
Anderlini…Porto, Nature (2007)
G. R. Stewart, RMP (1984)

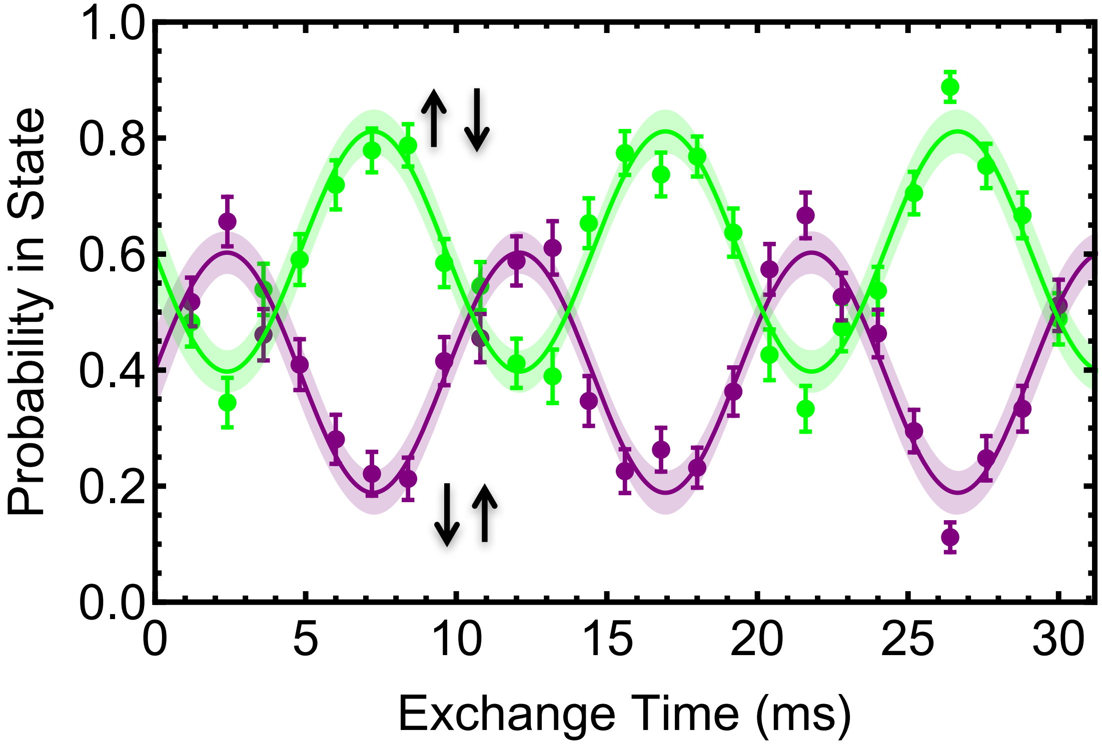
Protocol for initializing spin exchange and measuring

Create initial state with single tweezer addressing



Spin exchange

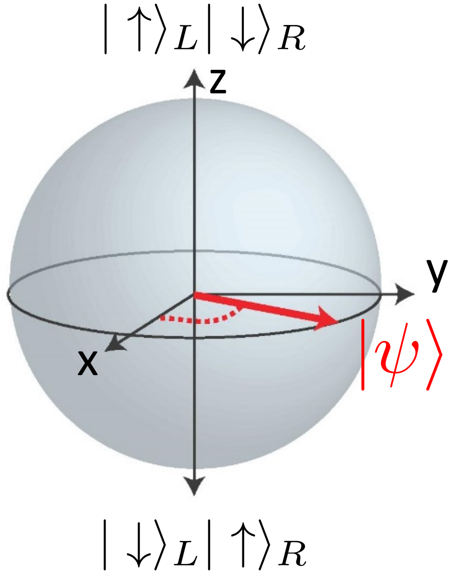




Stop at right time to get….

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

Want to verify phase is preserved upon separating particles



Observables: Mixing with global microwave rotation

Example:

Singlet maps back to itself

$$\frac{1}{\sqrt{2}}(|\uparrow\rangle_L|\downarrow\rangle_R - |\downarrow\rangle_L|\uparrow\rangle_R) \rightarrow \frac{1}{\sqrt{2}}(|\uparrow\rangle_L|\downarrow\rangle_R - |\downarrow\rangle_L|\uparrow\rangle_R)$$

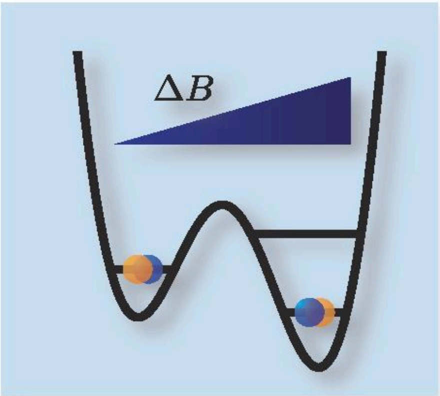
Triplet does not

$$\frac{1}{\sqrt{2}}(|\uparrow\rangle_L|\downarrow\rangle_R + |\downarrow\rangle_L|\uparrow\rangle_R) \rightarrow \frac{1}{\sqrt{2}}(|\uparrow\rangle_L|\uparrow\rangle_R + |\downarrow\rangle_L|\downarrow\rangle_R)$$

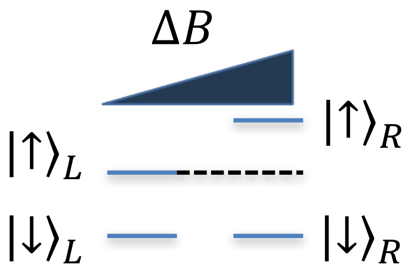
Map to parity (spins same minus spins different)

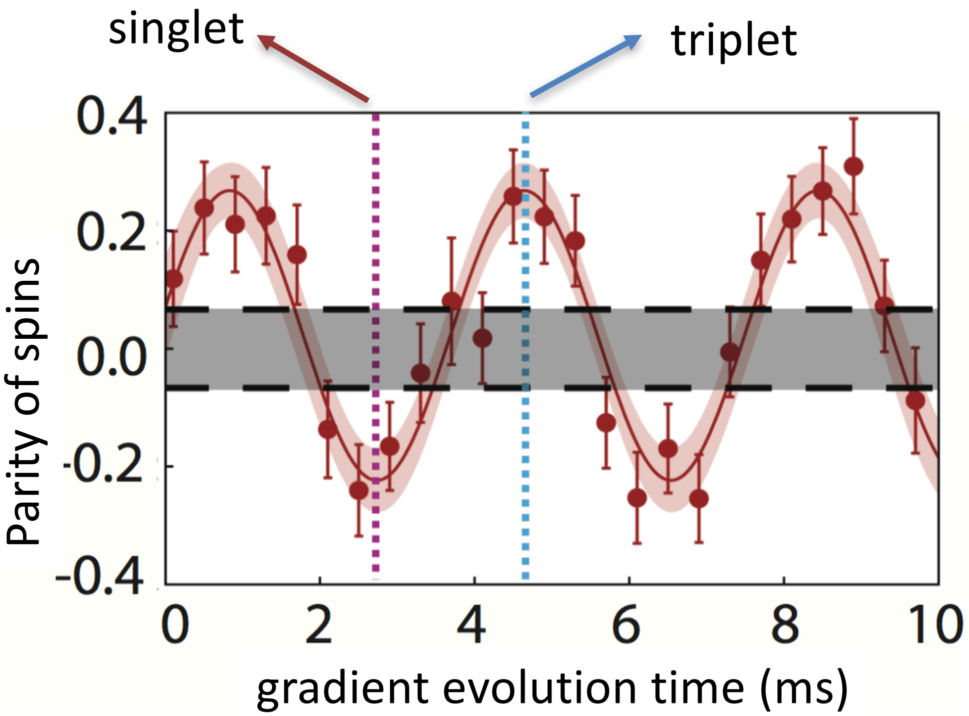
Verifying entanglement

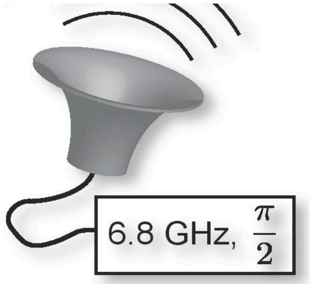
$$\frac{1}{\sqrt{2}}(|\downarrow\rangle_L|\uparrow\rangle_R \pm i|\uparrow\rangle_L|\downarrow\rangle_R)$$



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)
Rydberg atoms: Wilk *et al.* PRL (2010); Zhang *et al*., PRL (2010)

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

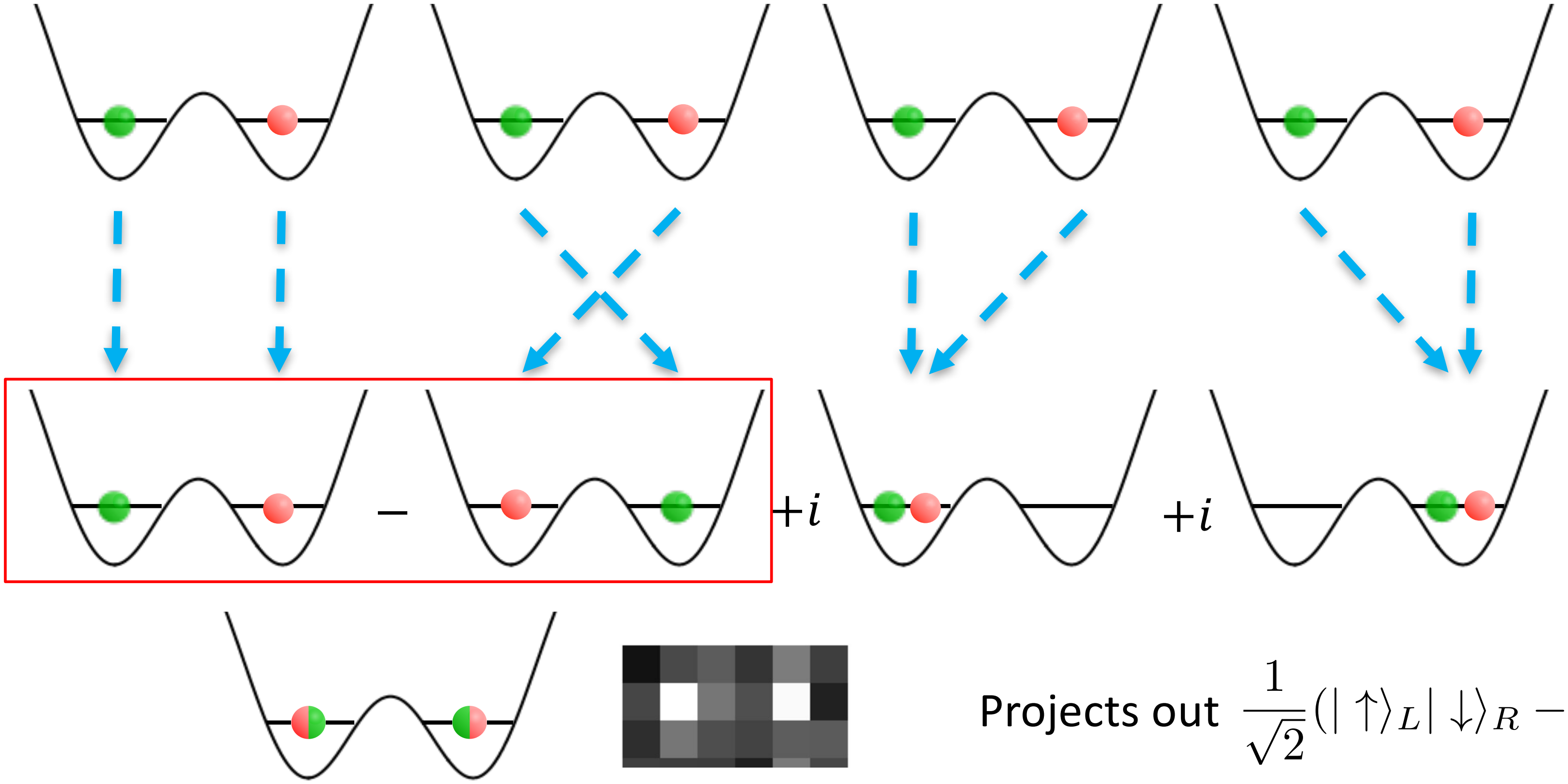
Creating spin entangled state without interaction

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

Illustrative thought experiment
Can we achieve this through mode beamsplitter?
No atom interactions….but do have measurement
(heart of many photon proposals)

● spin $|\uparrow\rangle$

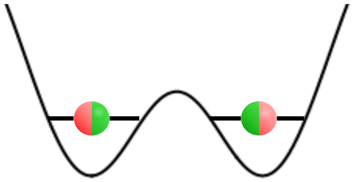
● spin $|\downarrow\rangle$

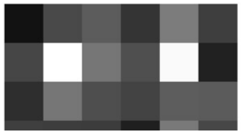


Projects out $\frac{1}{\sqrt{2}}(|\uparrow\rangle_L|\downarrow\rangle_R - |\downarrow\rangle_L|\uparrow\rangle_R)$

Creating spin entangled state without interaction

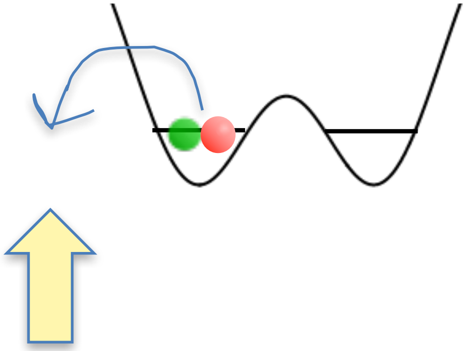
$$\frac{1}{\sqrt{2}}(|\uparrow\rangle_L|\downarrow\rangle_R - |\downarrow\rangle_L|\uparrow\rangle_R)$$

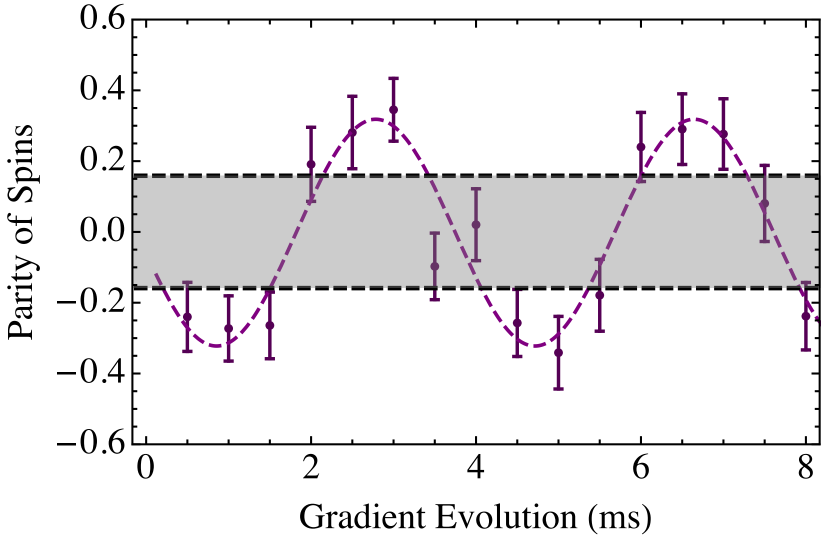


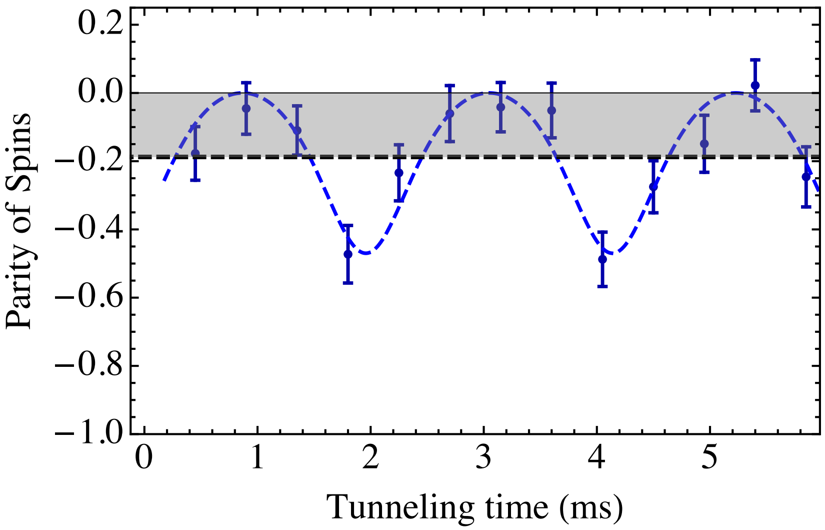


Postselect on

Heralding could make useful….

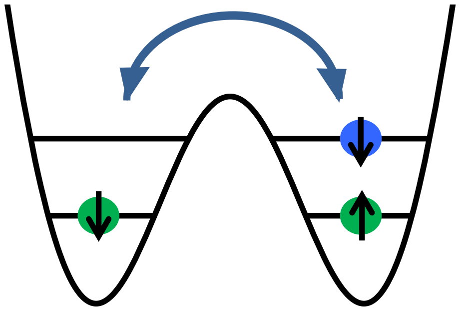






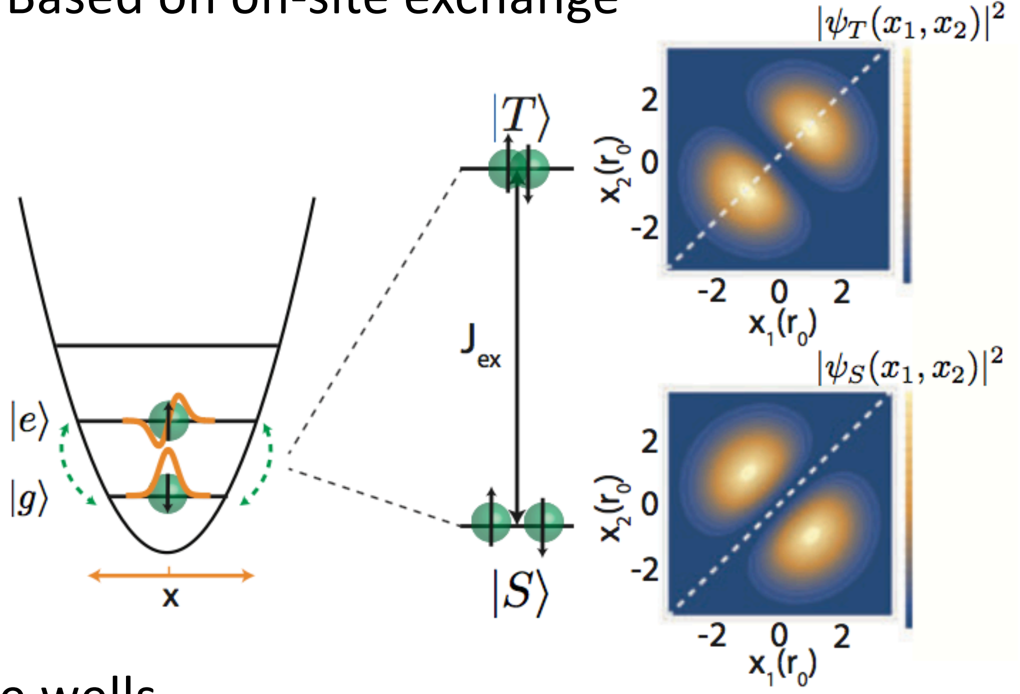
Preliminary data; more statistical significance required

A 3-atom configuration

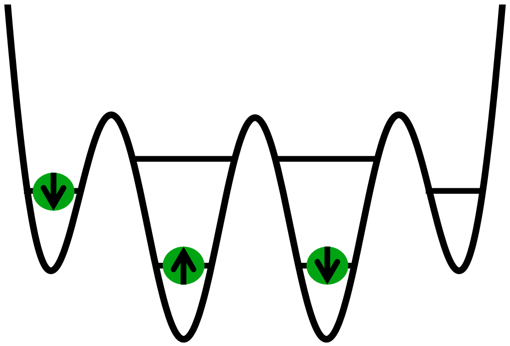


Kondo physics

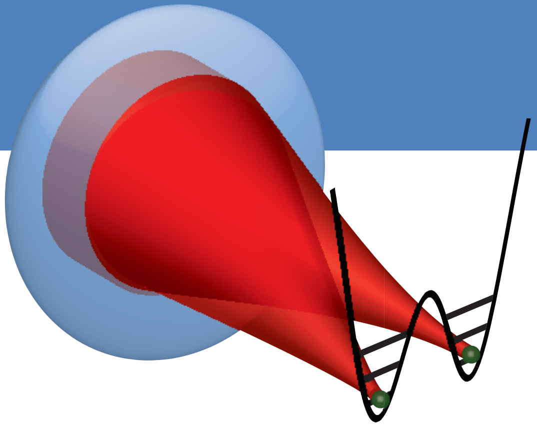
Based on on-site exchange



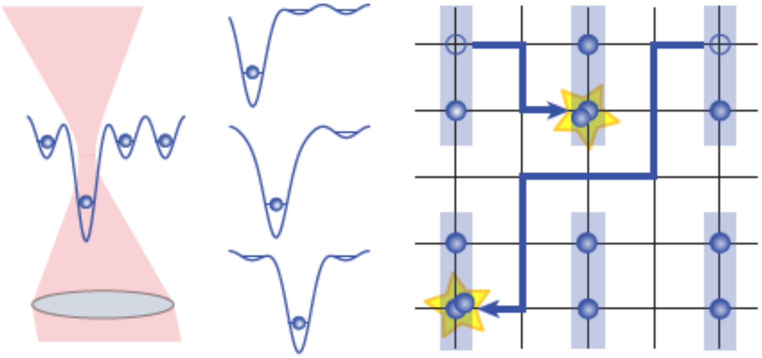
Read out multiple bands with multiple wells



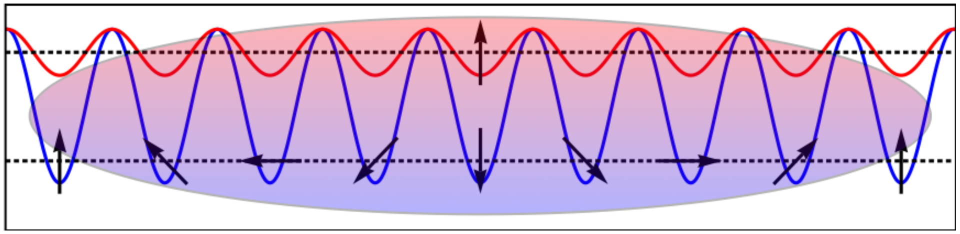
Conclusions



- Single neutral atoms
  - “single-atom optics” (noninteracting atoms)
  - Extensions to cascaded beamsplitters with boson inputs
  - Use local spin-exchange and movable atoms (interacting atoms)
  - Basic spin-motional coupling has interesting implications even at few-atom level



Weitenberg et al., PRA (2011)



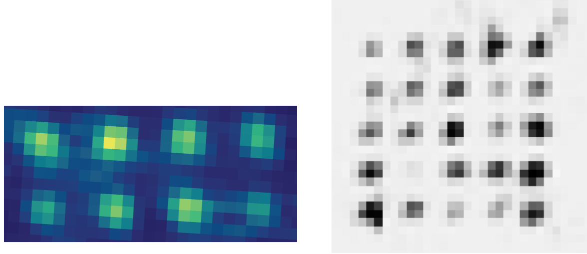
Rey group

Revisit outline

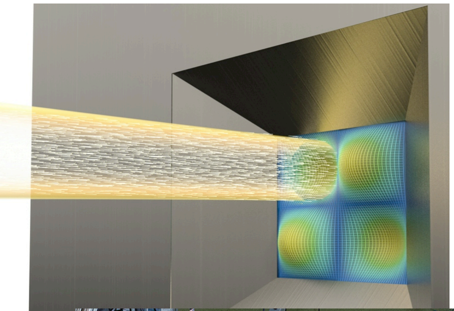
- To consider in context of few-body group
    - New probes and initialization
    - Collisional physics for state preparation
    - While this talk dwells on 2 atoms, 10 - 100 is natural goal
    - Rb – proof of concepts – real gains yet to come with *alkaline earth atoms, molecules, fermions*…
    - More exotic traps with atom spacings 100 nm scale?
    - Adiabatically connect to ground state of less confining trap for delocalized states?
    - Here scattering length small (sometimes effectively zero); could combine with Feshbach resonance
    - Precise measurements that avoid inhomogeneous broadening?

Our group

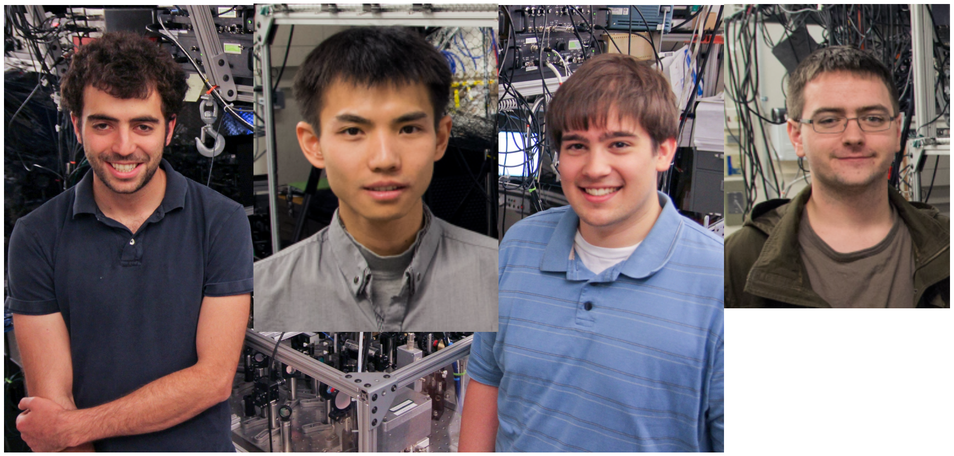
Experiments harnessing control of motion at quantum limits….



…from single neutral atoms

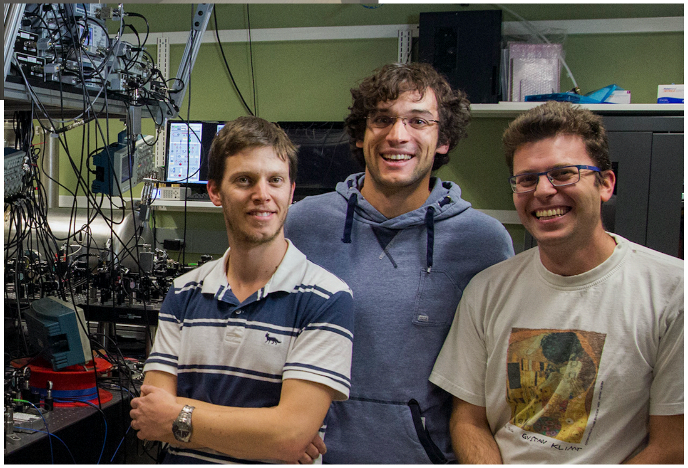


…to mm-scale membrane



Adam Kaufman Brian Lester Mark Brown

Yiheng Lin Niclas Luick



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JILA amo NSF