Sub-lattice Control in a State-dependent Double-well Lattice

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Research Directions

- Quantum information processing
  w/ neutral atoms

- Correlated many-body physics
  w/ neutral atoms

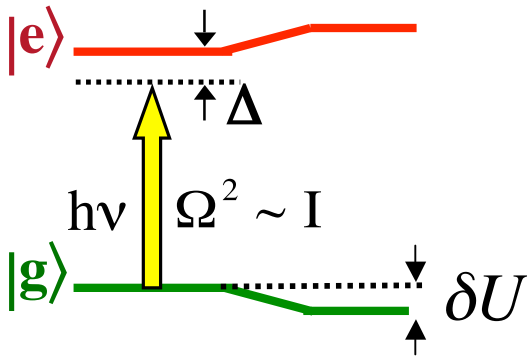
- Engineering new optical trapping and
  control techniques

This Talk

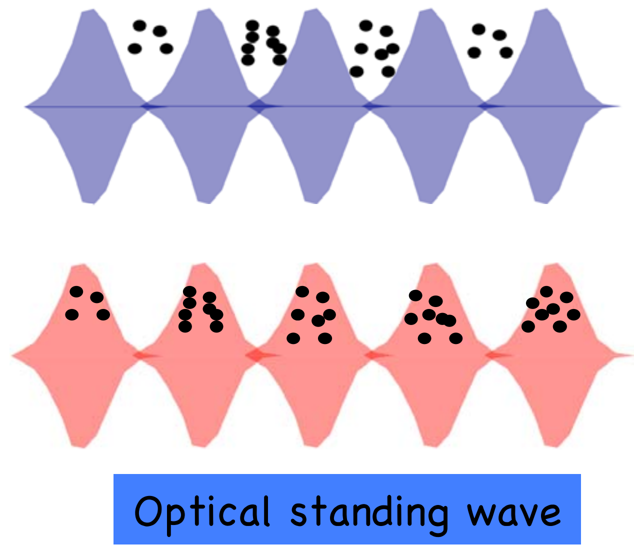
- Realizing a dynamic double-well lattice
    - Demonstration of tools
    - Using state-dependence
    - Combining tools: toward a swap gate
- Future

    potential applications to lattice simulation

Basic Tool: Light Shifts



Intensity
and **state**
dependent
light shift

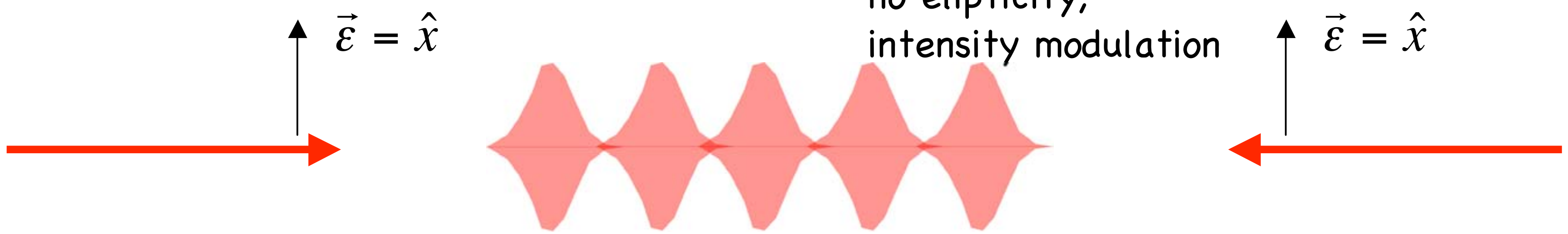


Red detuning → attractive
Blue detuning → repulsive

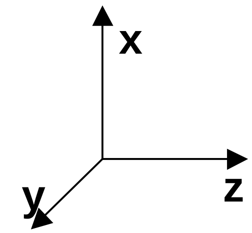
Flexibility to tune scalar vs. vector component

Basic Tool: Light Shifts

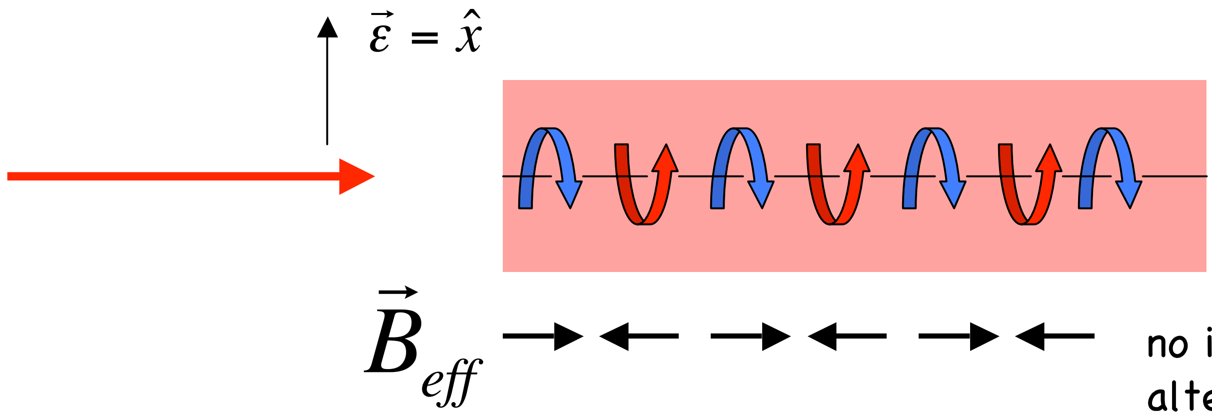
Example: lin ∥ lin



no elipticity,
intensity modulation



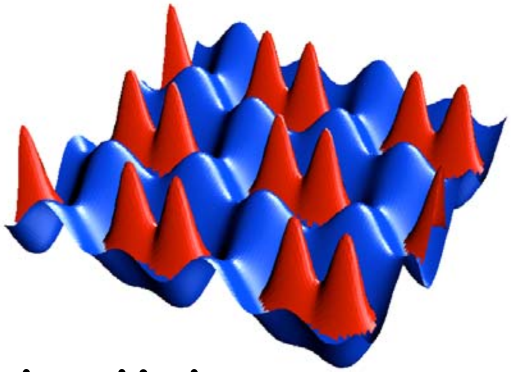
Example: lin ⊥ lin



no intensity modulation,
alternating circular polarization

Position dependent
effective magnetic field

Double-Well Lattice



Motivation for the double-well lattice:

Isolate *pairs* of atoms in controllable potential, to test

- addressing ideas
- controlled interactions, at 2-atom level

etc.

Provide new possibilities for cold atom lattice physics

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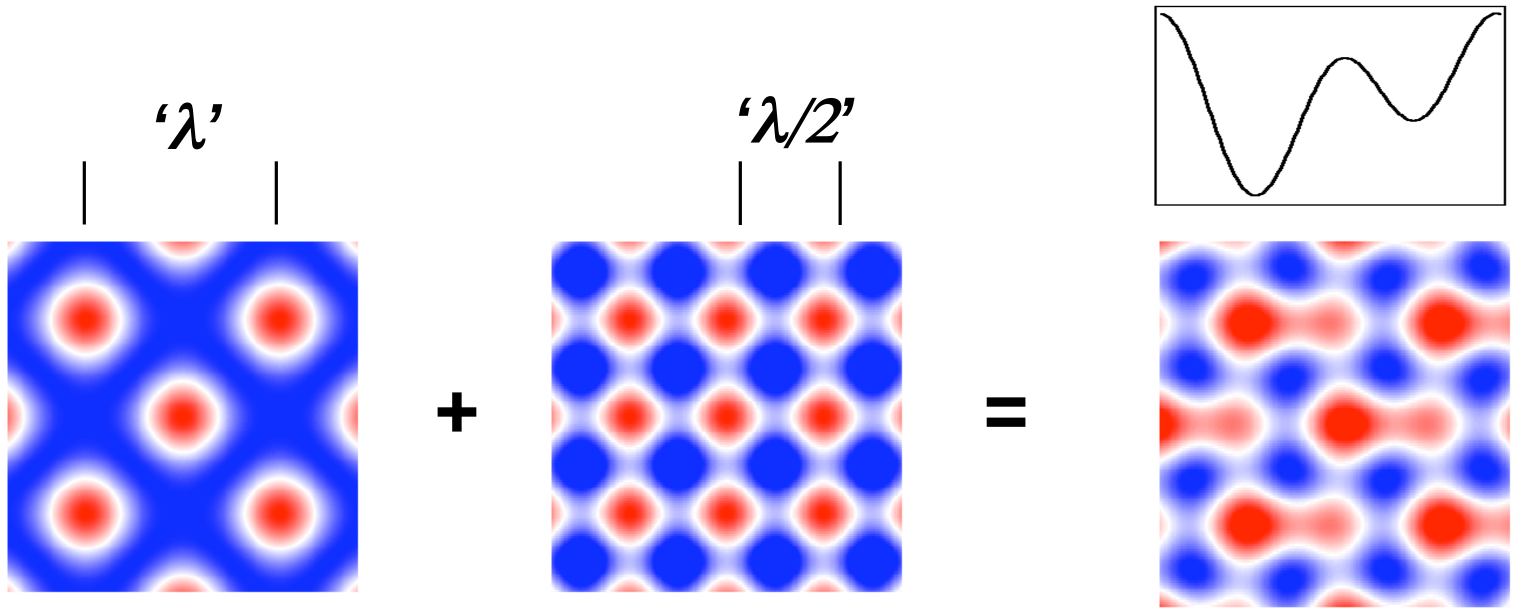
Phase Stable 2D Double Well

Basic idea:

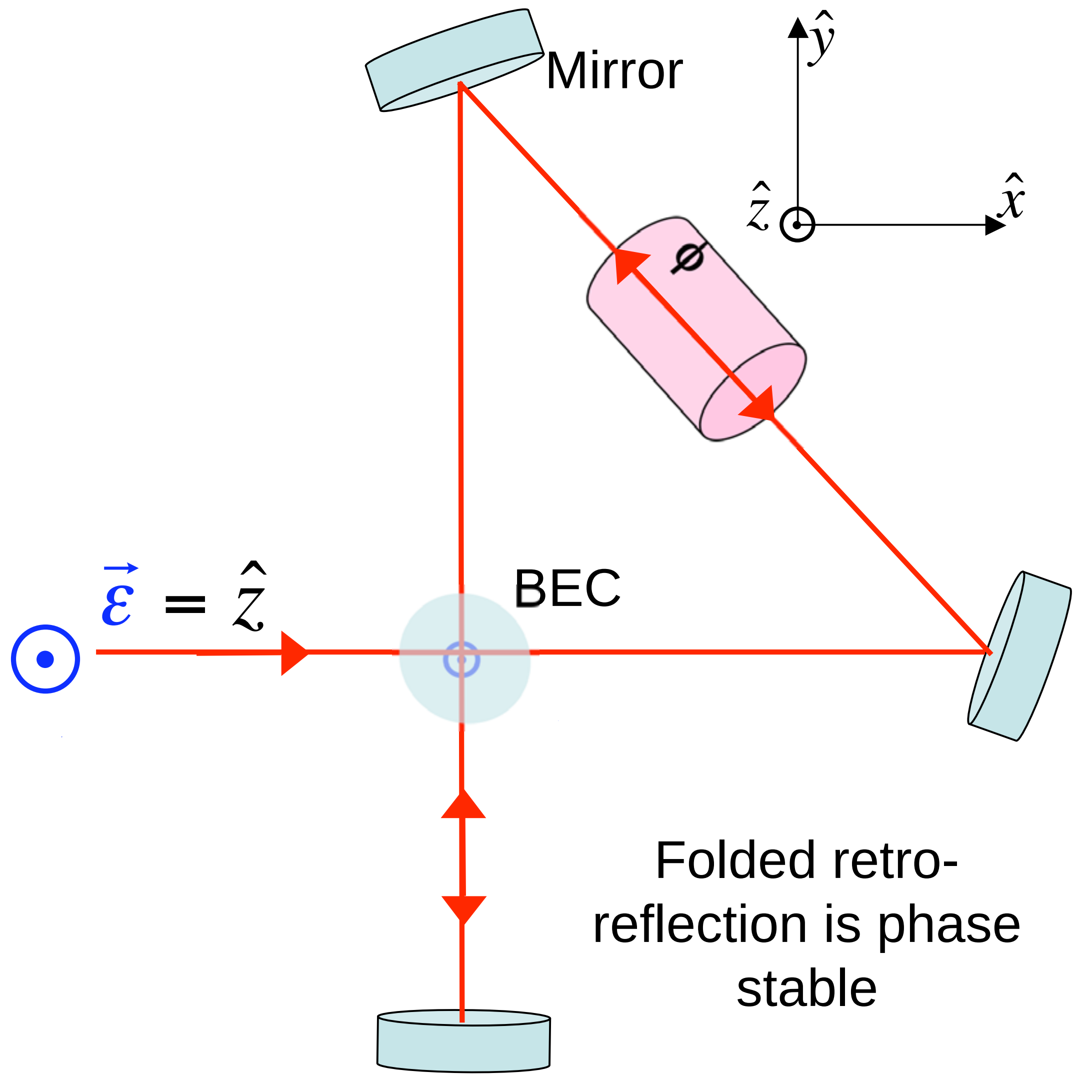
Combine two different period lattices with adjustable

- intensities
- positions

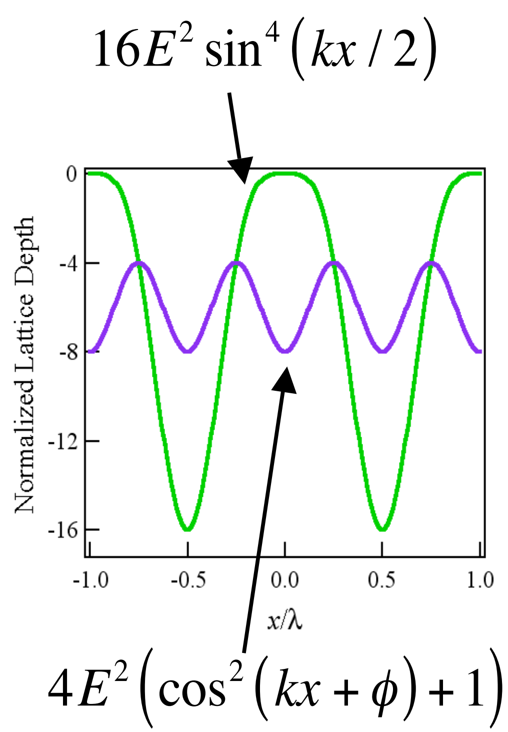
Mott insulator $\rightarrow$ single atom/site



Polarization Controlled 2-period Lattice



Folded retro-reflection is phase stable

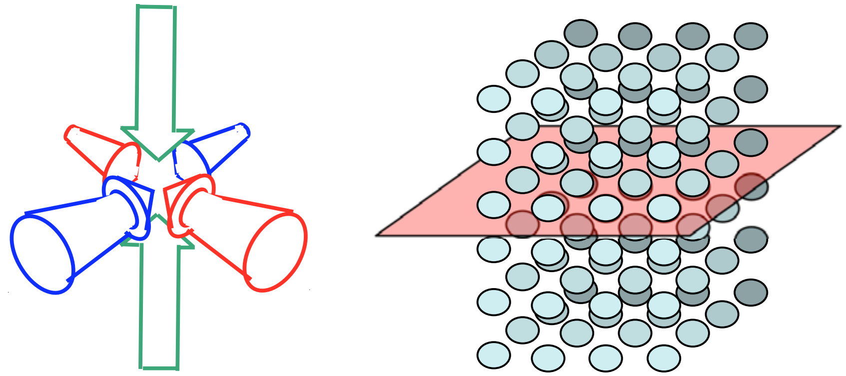


Sebby-Strabley et al., PRA **73** 033605 (2006)

Polarization Controlled 2-period Lattice

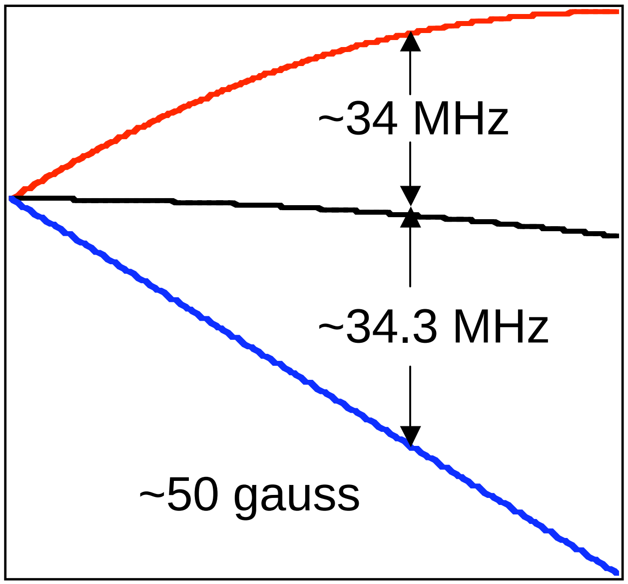
Add an independent, deep vertical lattice

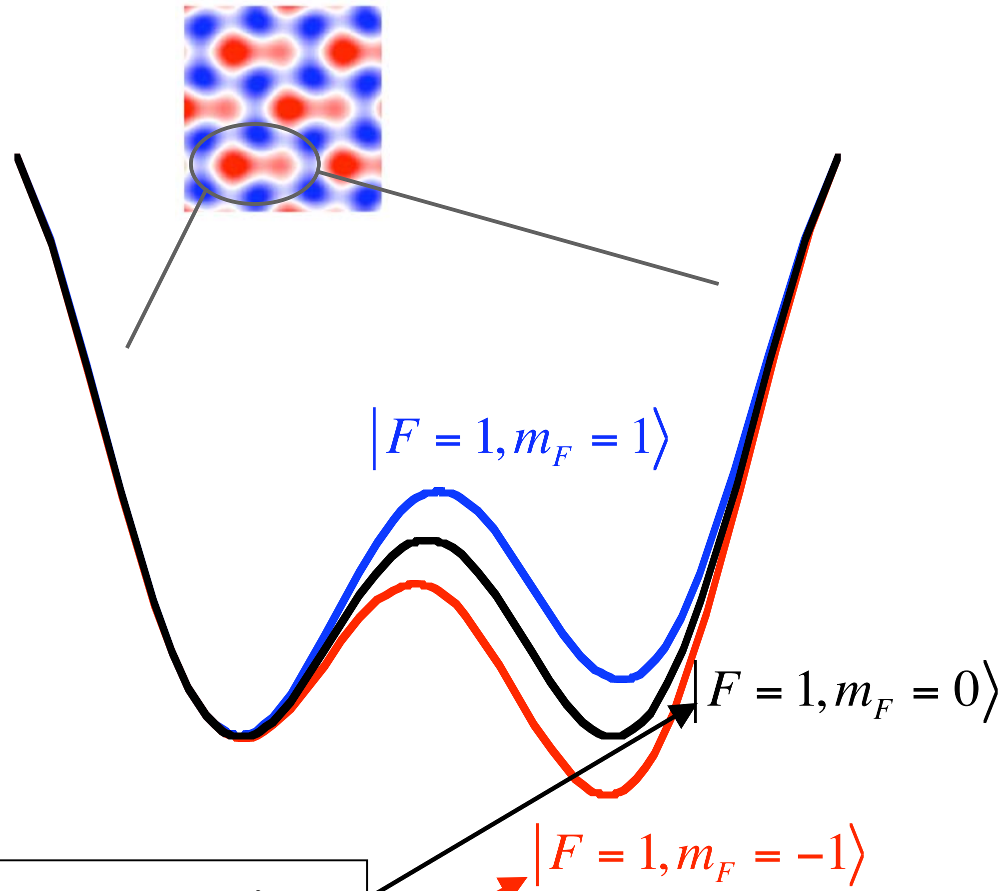
Provides an independent array of 2D systems



State Dependent Potential

We use the quadratic Zeeman shift to isolate a pseudo spin-1/2





For the demonstrations shown here, we use these 2 states in ^{87}Rb

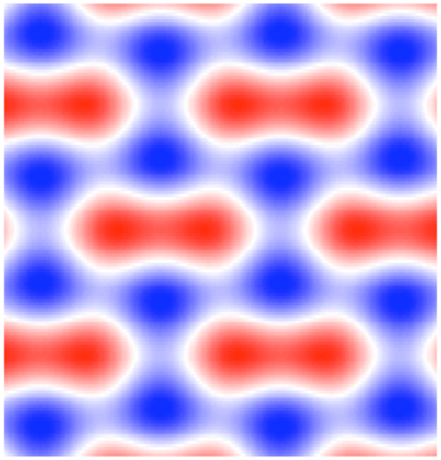
Lattice Features

X-Y directions coupled

- Checkerboard topology
- Not sinusoidal (in all directions)

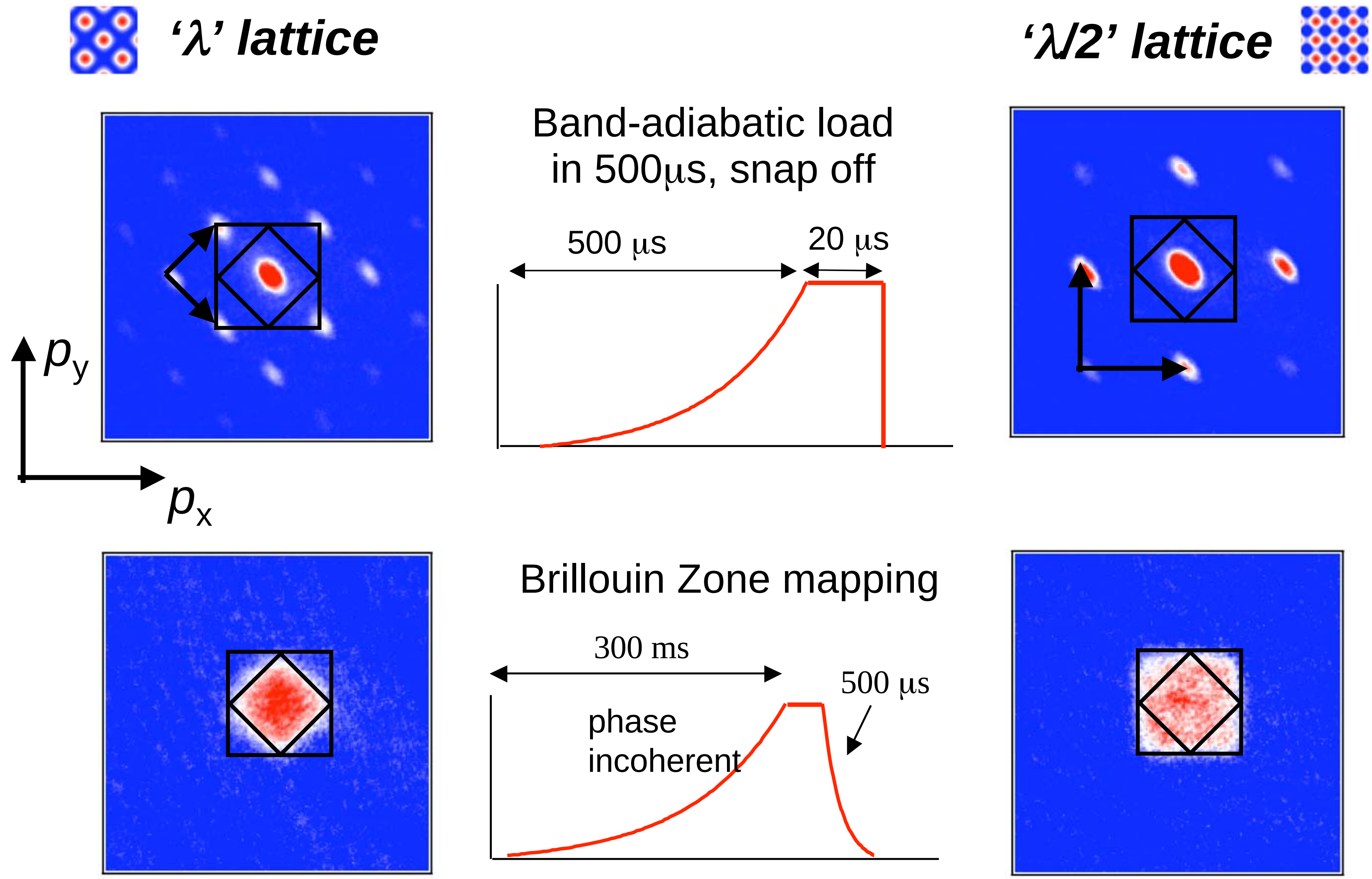
$$\cos^2(x+y)\cos^2(x-y) \longrightarrow \cos^4(x)$$

e.g., leads to very different tunneling



- spin-dependence in sub-lattice

Reciprocal Lattices and Brillouin Zones



This Talk

- Realizing a dynamic double-well lattice

  2D Mott physics

  - De … ols
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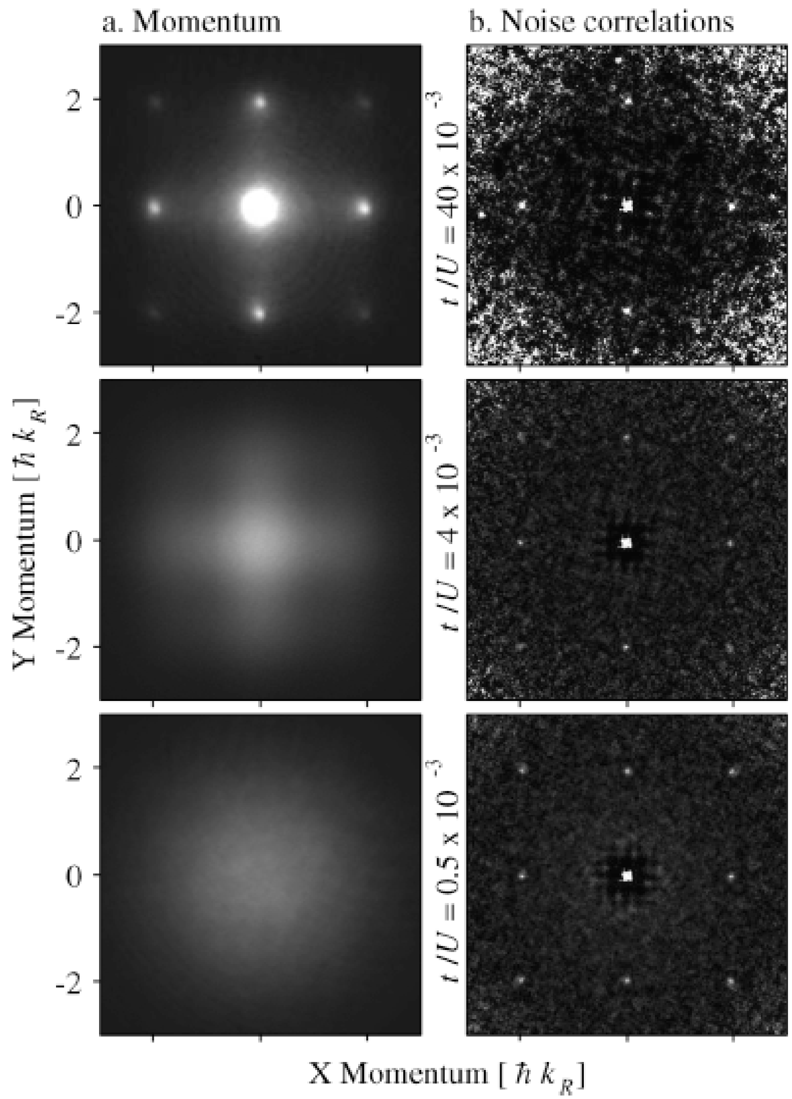
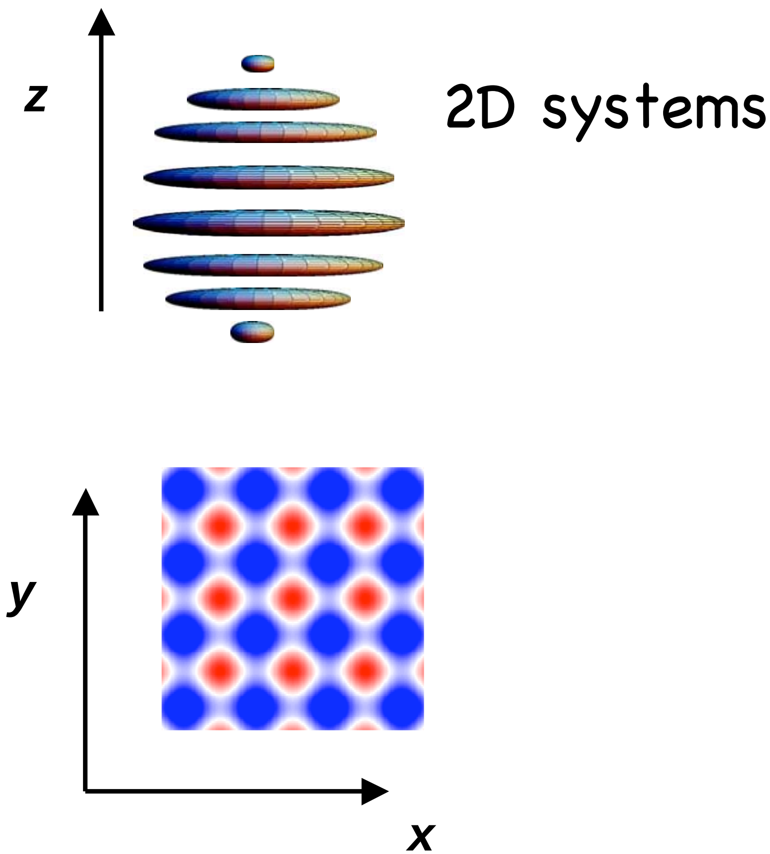
2D Mott-insulator

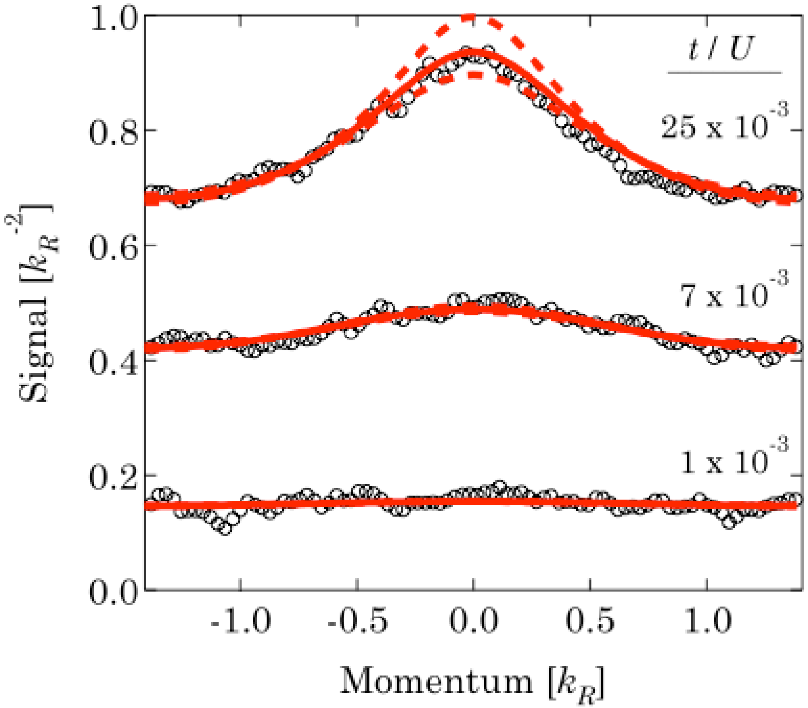


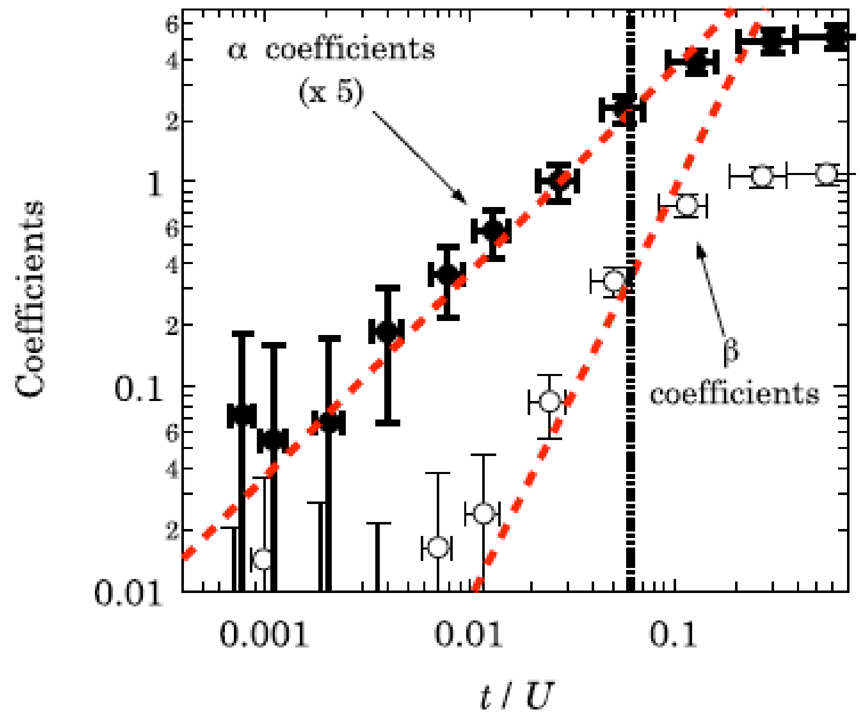


Spielman, Phillips, TP
PRL **98**, 080404 (2007)

2D Mott-insulator

Momentum distribution

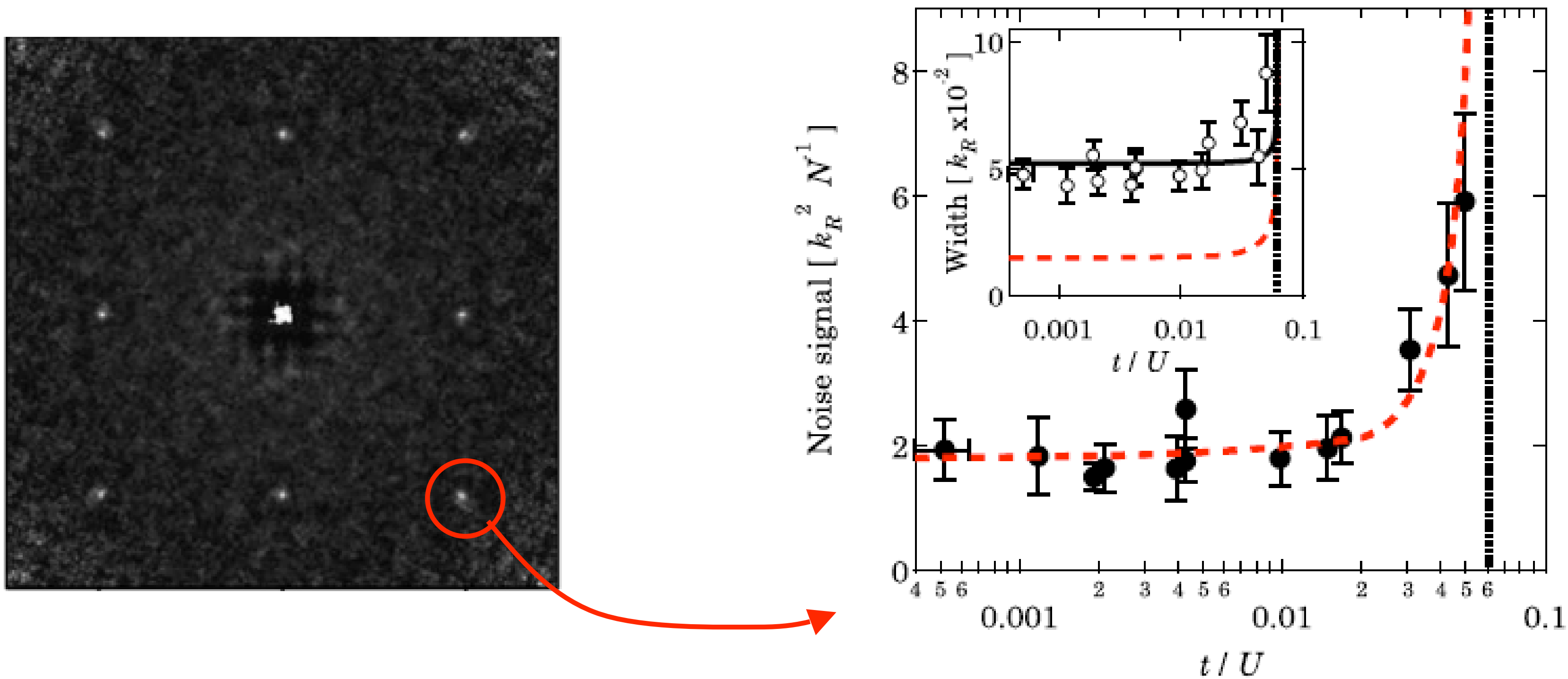




Quite good comparison to a homogeneous theory
(no free parameters)

Sengupta and Dupuis, PRA 71, 033629

Information in the Noise?



Signal and width

Some information available…

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Dynamic Lattice Manipulation

Use double well split/combine control to, e.g.

- characterize particular number distribution
- construct particular number distributions
- adiabatically populate vibrational levels
- distinguish left/right populations

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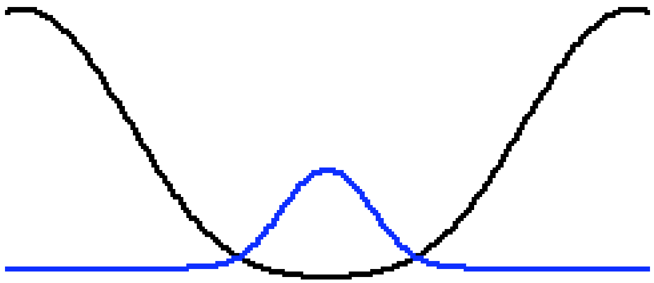
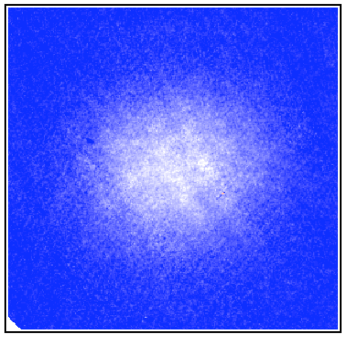
Double Slit Diffraction

Slowly load mostly-λ lattice, snap off

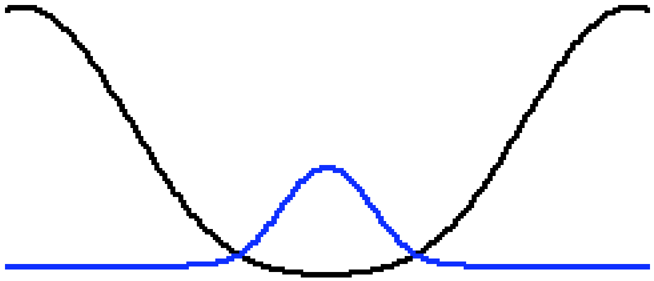


load in ~**300 ms**
phase scrambled

Single slit diffraction

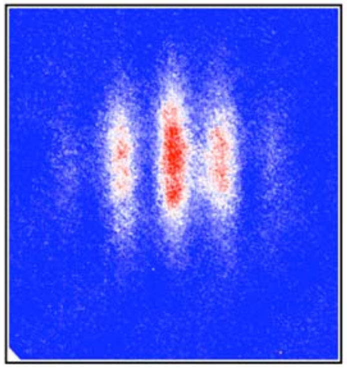


Coherently split single well

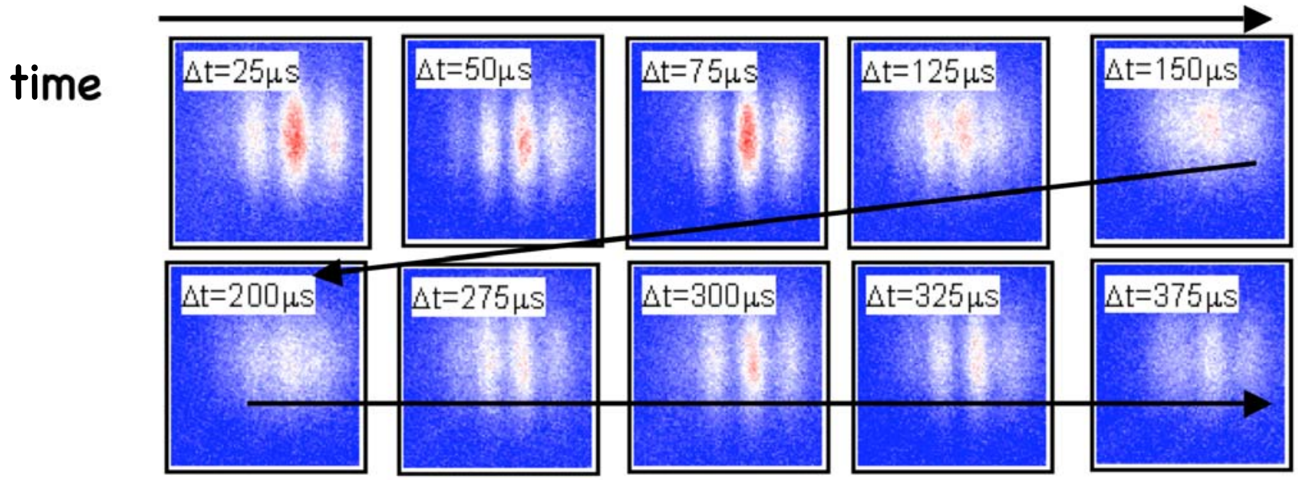


split in ~**200 μs**
coherent split

Double slit diffraction

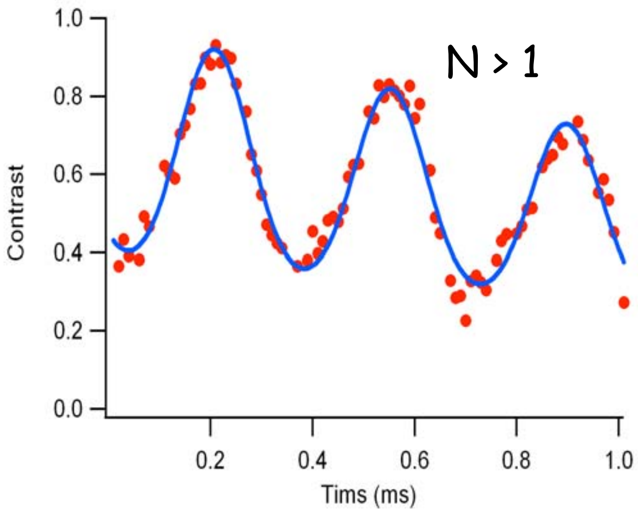


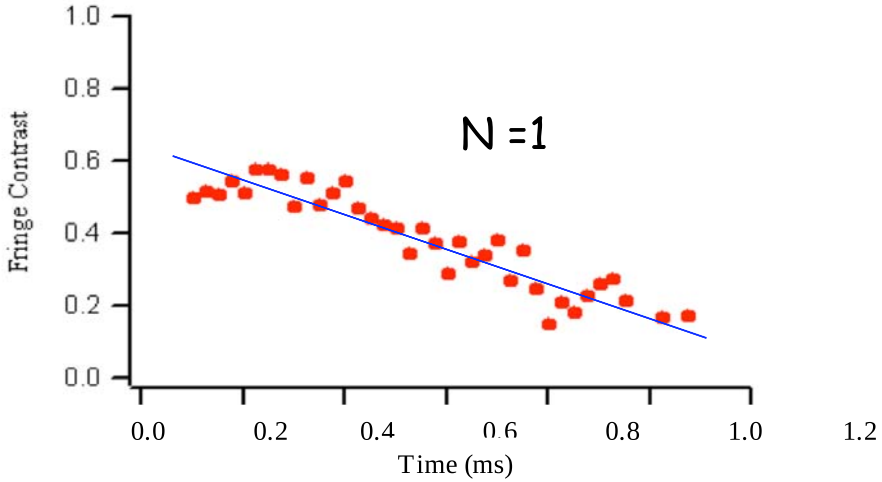
Time dependence of diffraction



In 3D lattice, see:
Greiner et al.
Nature, **419** (2002)

Time dependence confirms single-atom loading

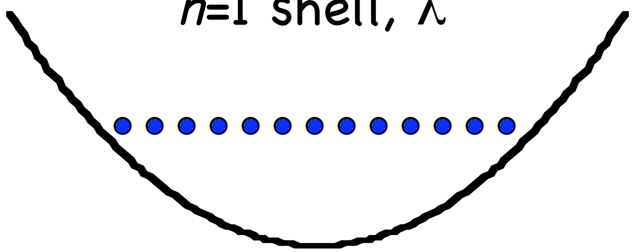




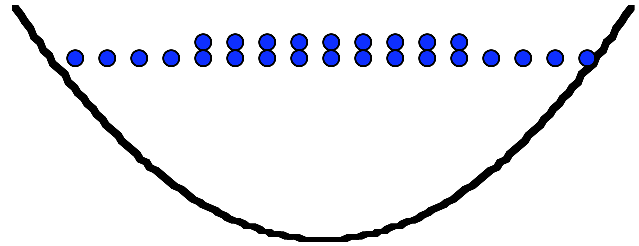
Constructing n=2 Shell

Normally available n=2 and n=1 shells

n=1 shell, λ

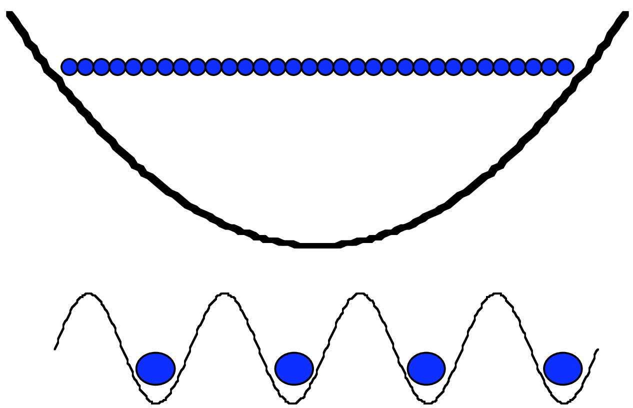


n=2 core, n=2 shell, λ

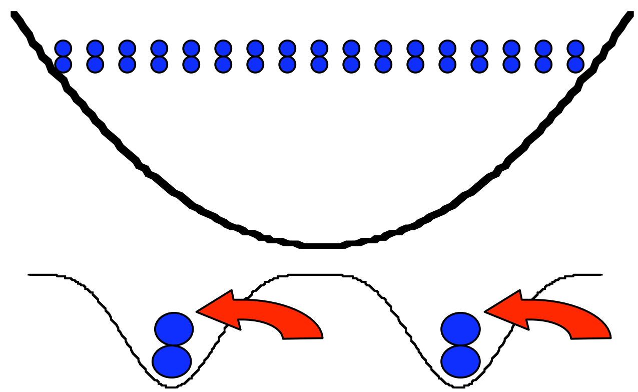


Adiabatically purify n=2 shell

n=1 shell, $\lambda/2$

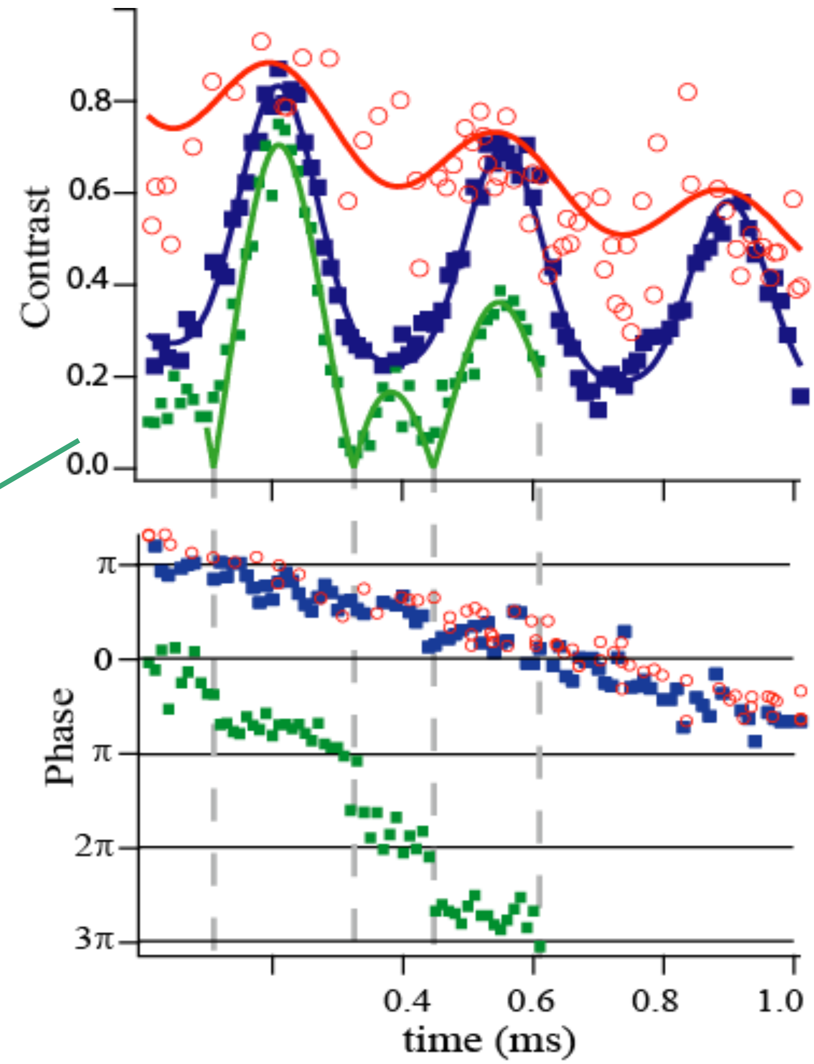


n=2 shell, λ



Number Distribution Dependence

Red- load n≈1 into λ
Blue- load n>1 into λ
Green-
construct pairs in λ



For n=2, collapse and revival shows revivals at half the original period.

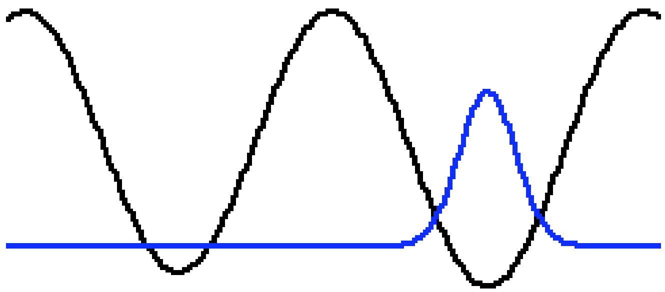
May provide hole populations (dominant infidelity)

Indications:
Fermionized but not necessarily Mott

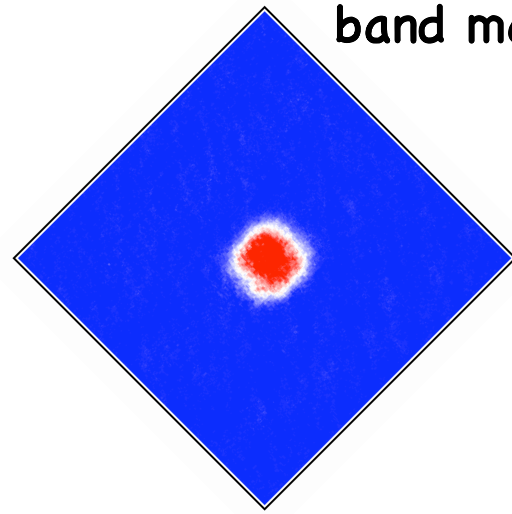
Sebbey-Strabley et al. , PRL in press (quant-ph/0701110)

Probe: Selective Removal of Sites

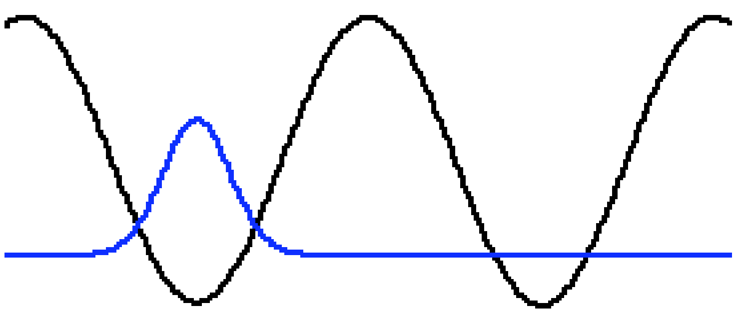
Load right well → expel left



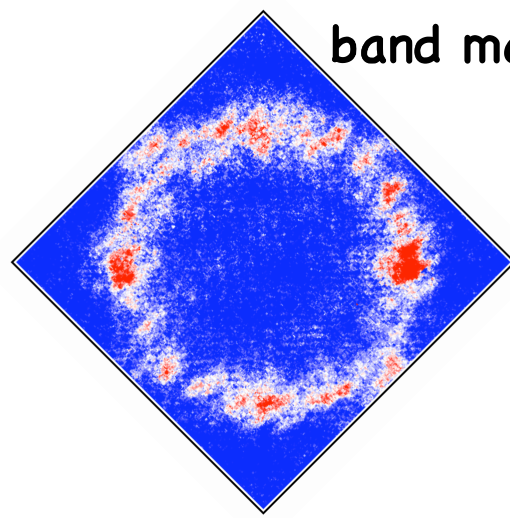
band map



Load left well→ expel left

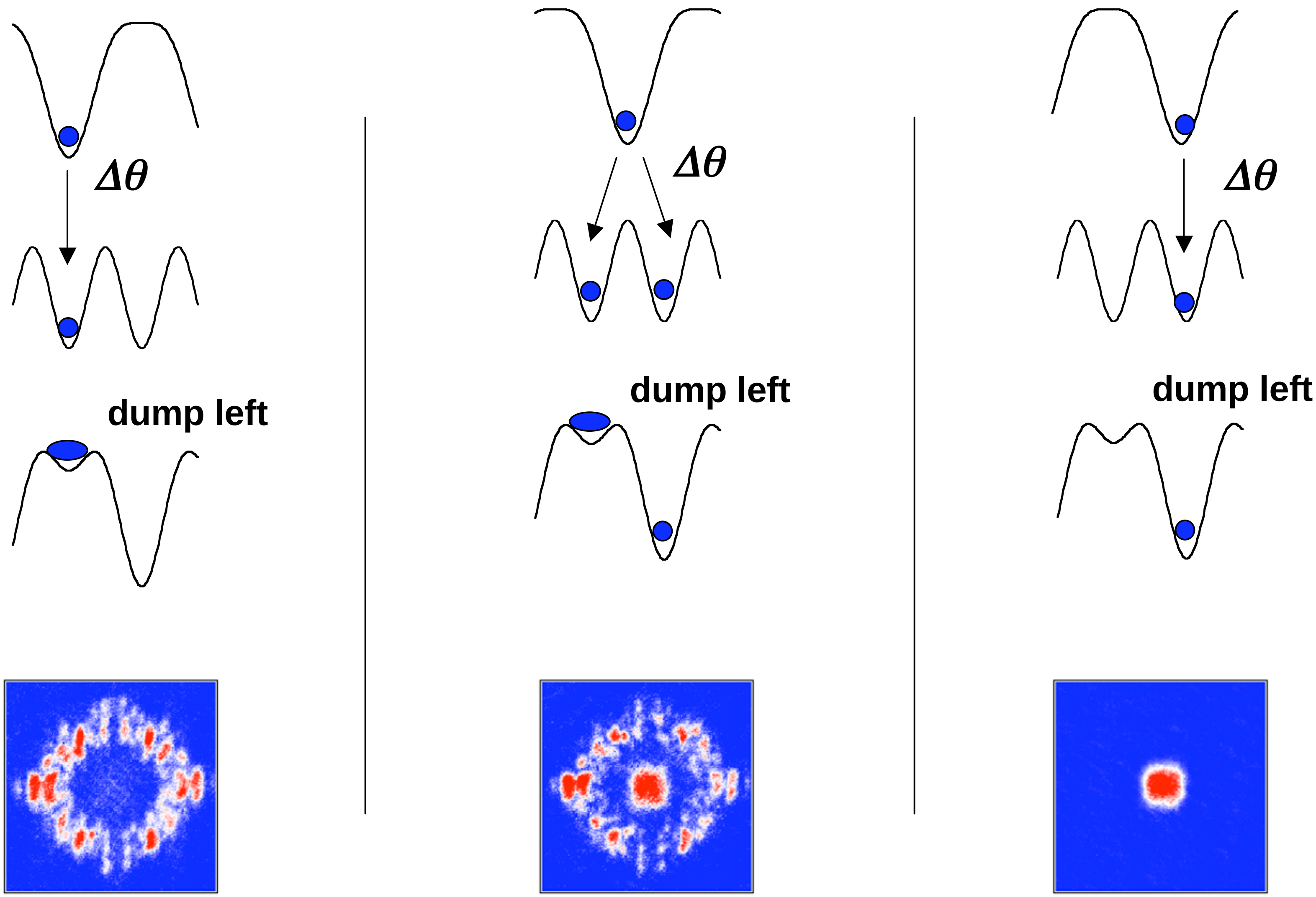


band map

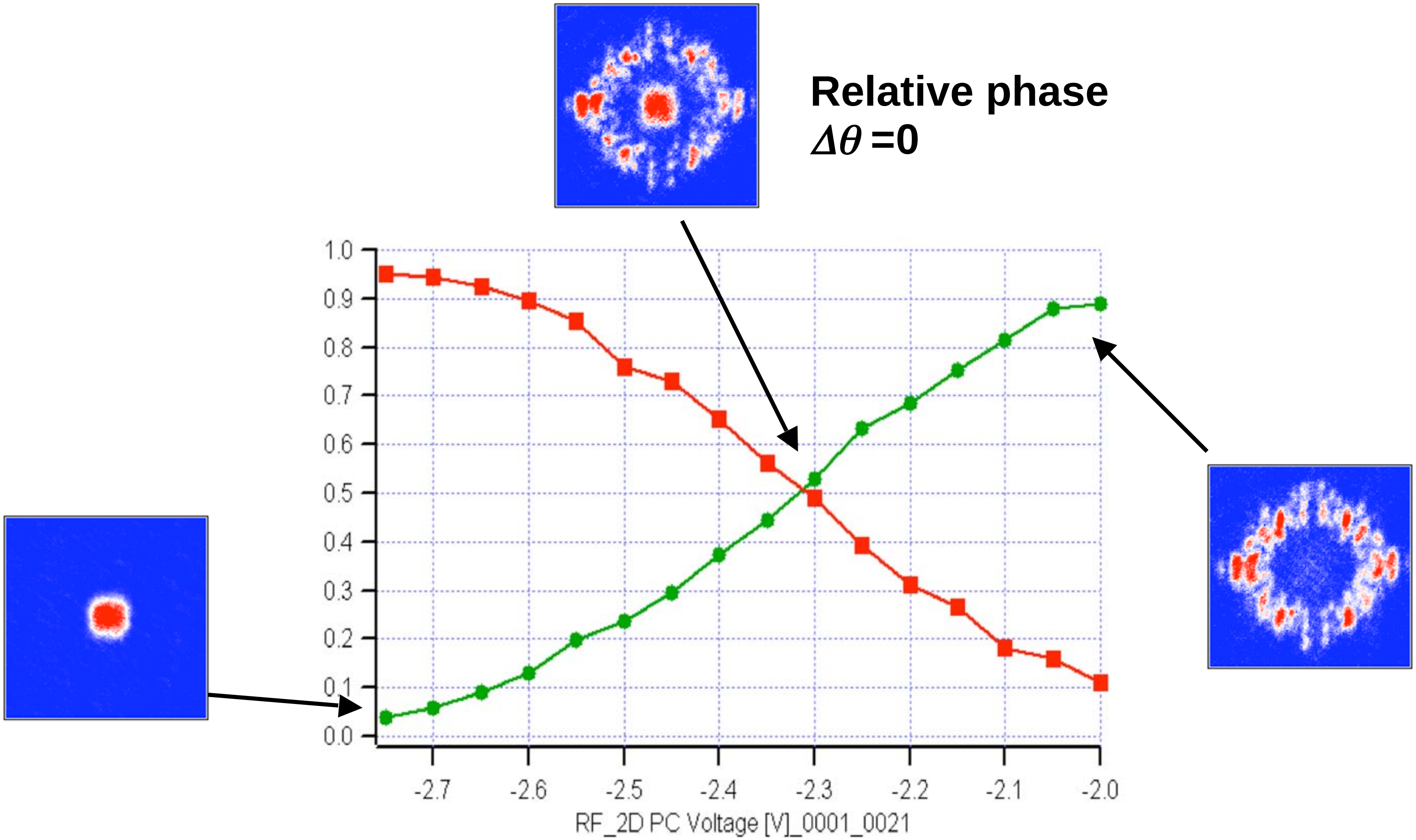


Starting 'λ/2' 30 E_R

“Expelling” as a left/right probe

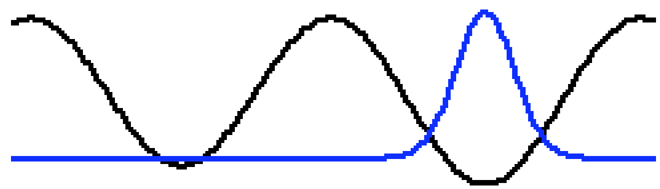


"Expelling" as a left/right probe

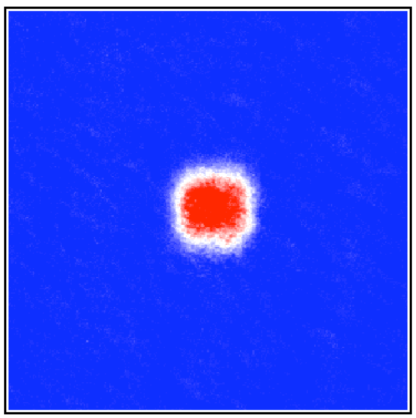


Scan the relative phase between lattices

Adiabatic transfer "excitation"

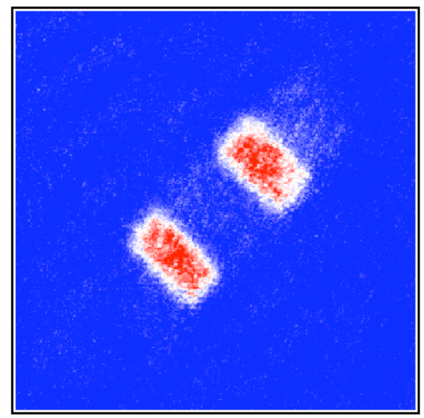


mapped at t_0
from 'λ' lattice



~ ms transfer time

mapped at t_f
from 'λ/2' lattice



atoms can be put on the same site, (but different vibrational level), allowed to interact, and then separated adiabatically

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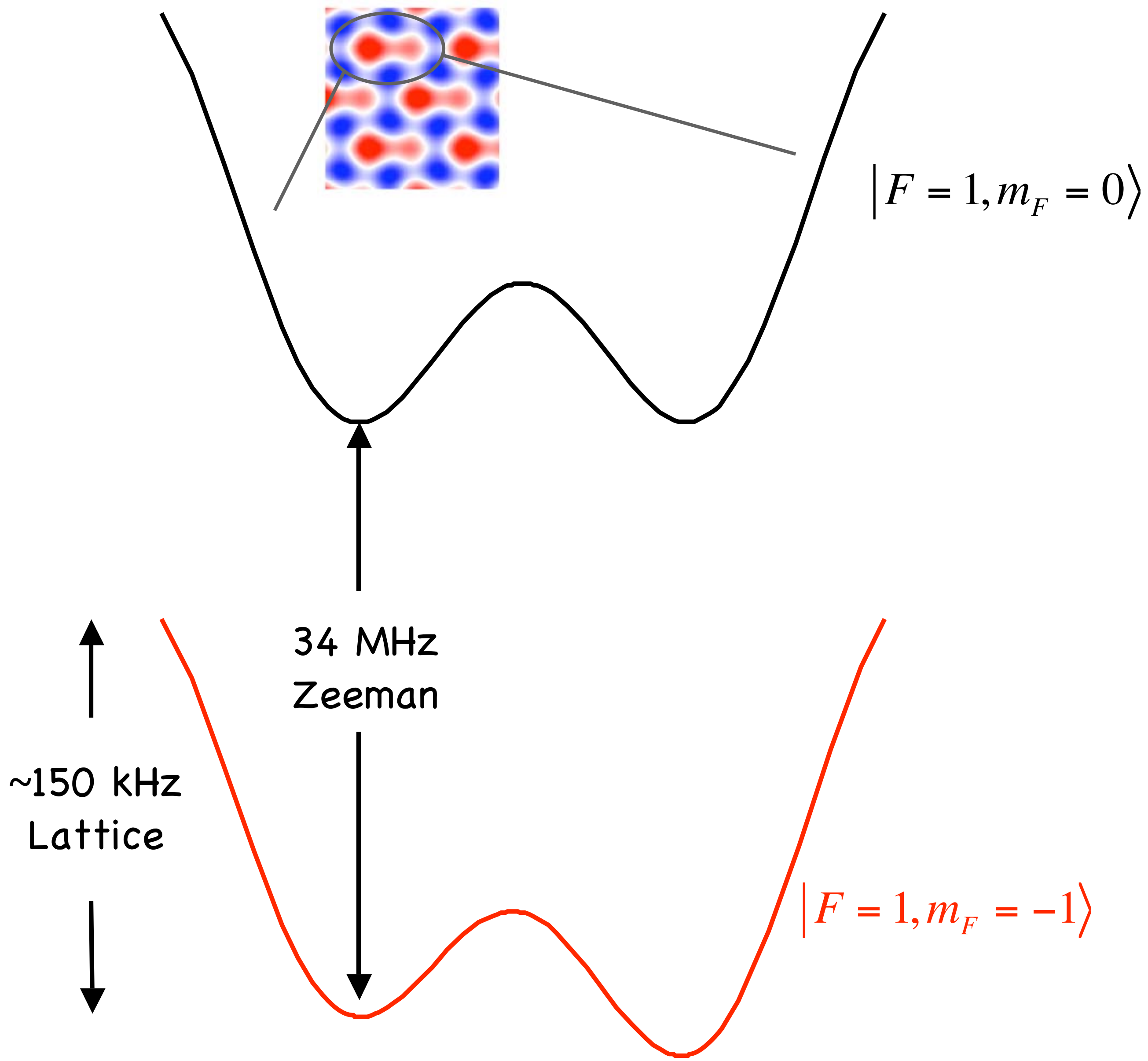
State Dependent Potential



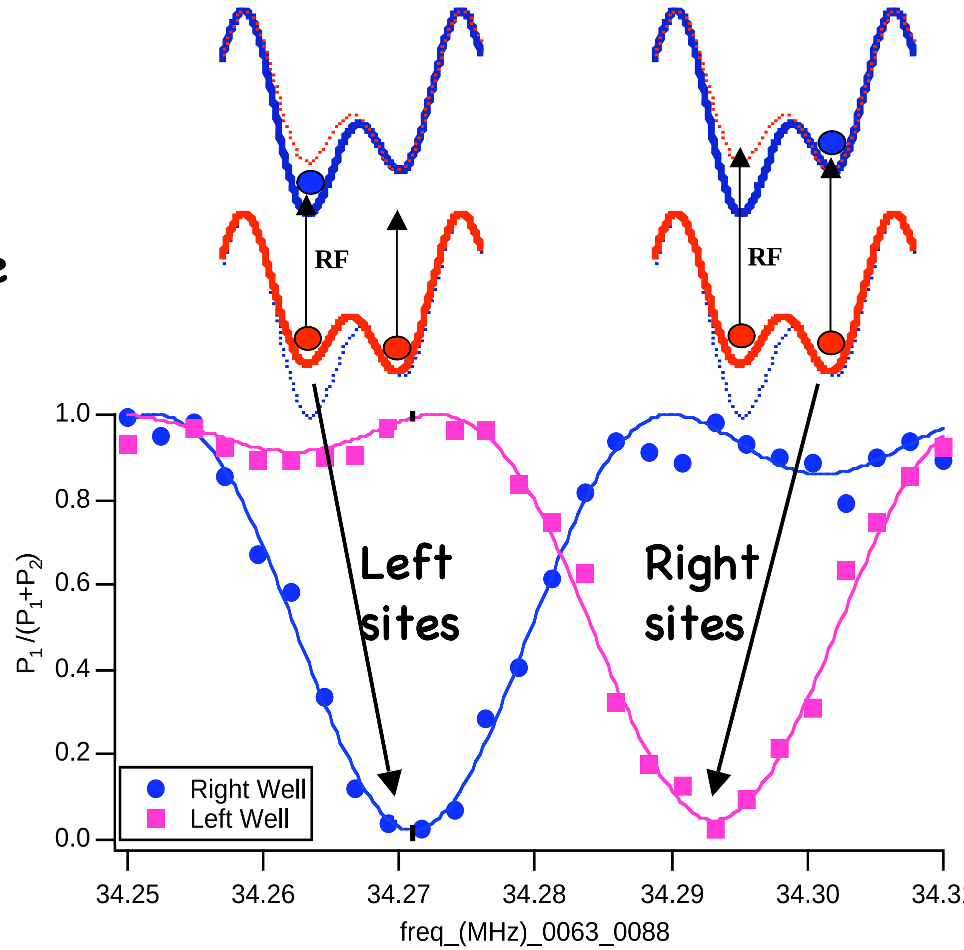
Sub-Lattice Addressing

Start with atoms in m=-1

Apply RF to spin flip to m=0

"Evaporate" m=0 atoms

Measure m=-1 occupation in the left or right well.



sub-lattice addressing by light shift gradient

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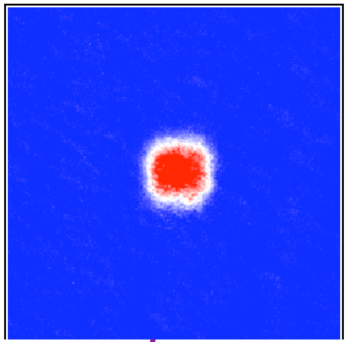
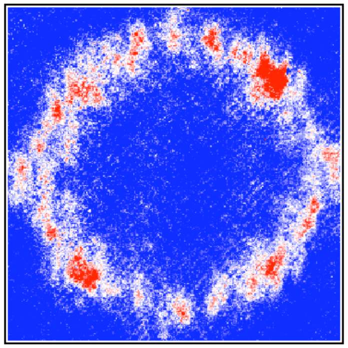
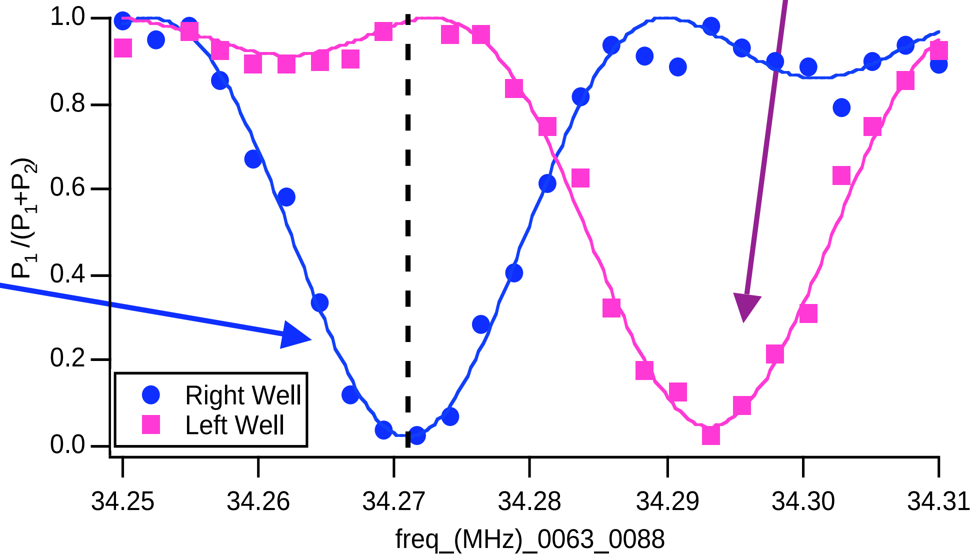
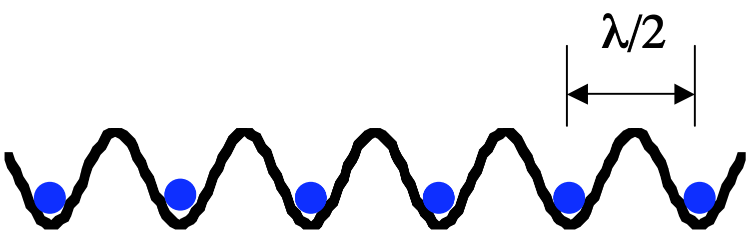






Lee et al., quant-ph/0702039

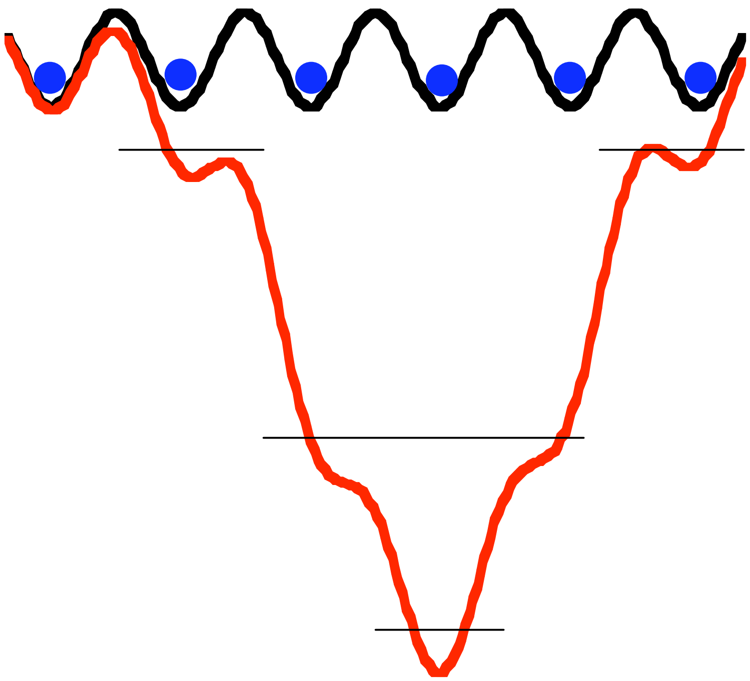
Example: Addressable One-qubit gates



Atoms at sub-λ spacing

-focused beam sees several sites

Example: Addressable One-qubit gates

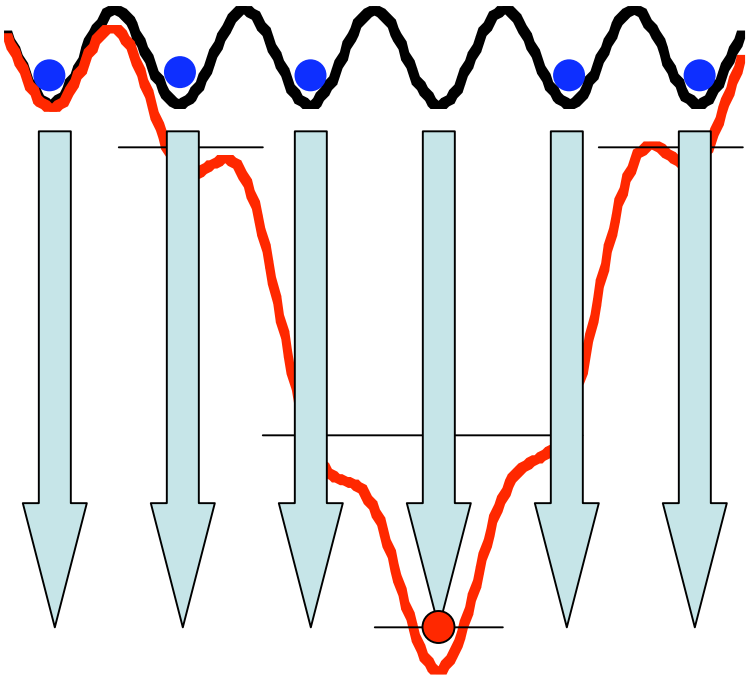


Atoms at sub-λ spacing

-focused beam sees several sites

- state dependent shifts effective field gradients

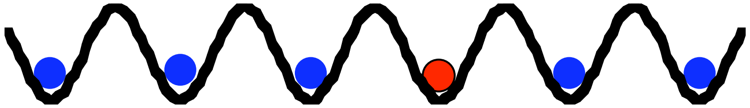
Example: Addressable One-qubit gates



RF, μwave
or Raman

Atoms at sub-λ spacing
- -focused beam sees several sites
- - state dependent shifts effective field gradients

Example: Addressable One-qubit gates



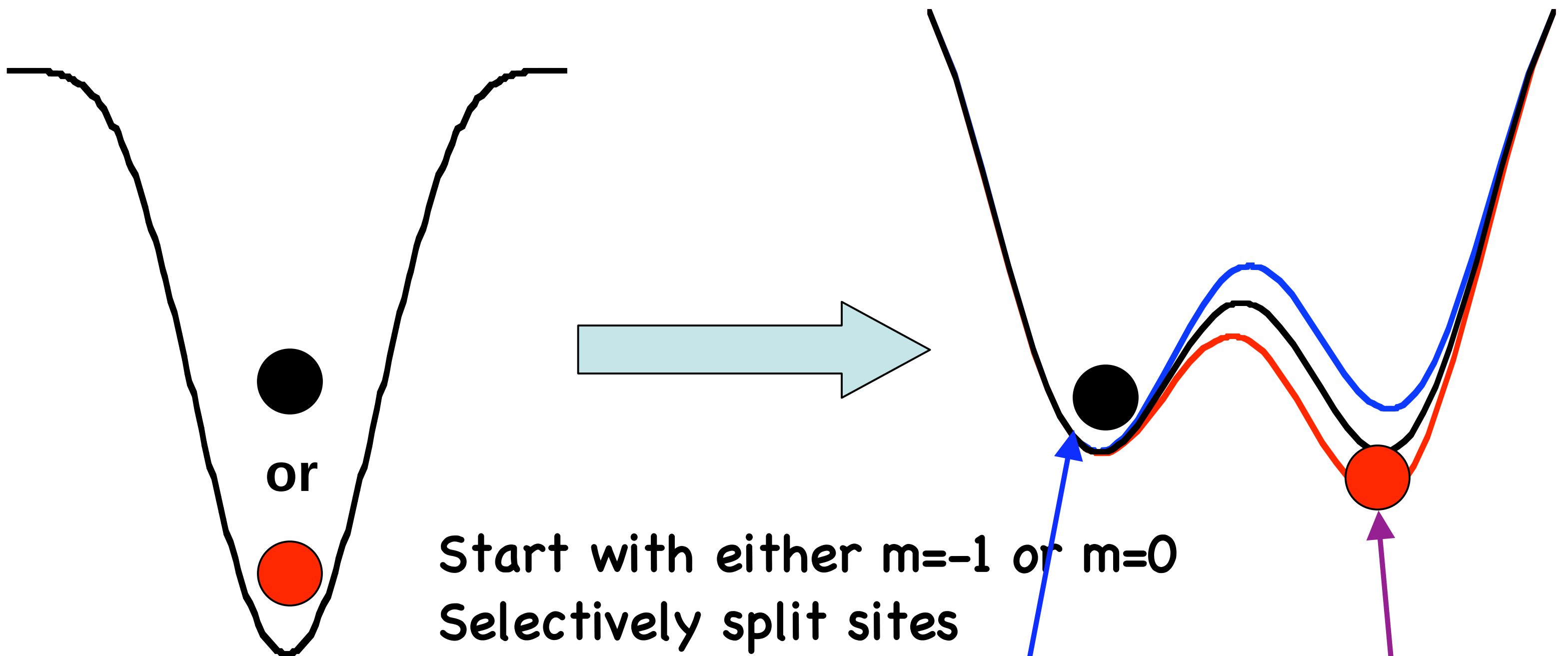
Atoms at sub-λ spacing

-focused beam sees several sites

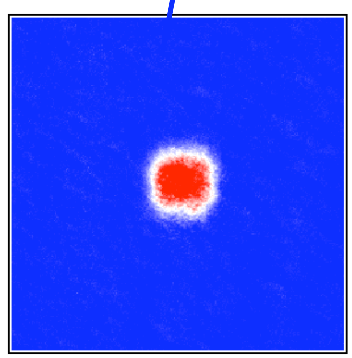
- state dependent shifts effective field gradients

- frequency addressing

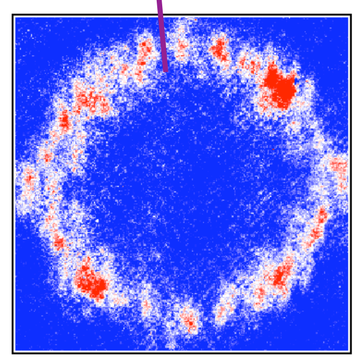
State selective motion/splitting



Start with either m=-1 or m=0
Selectively split sites



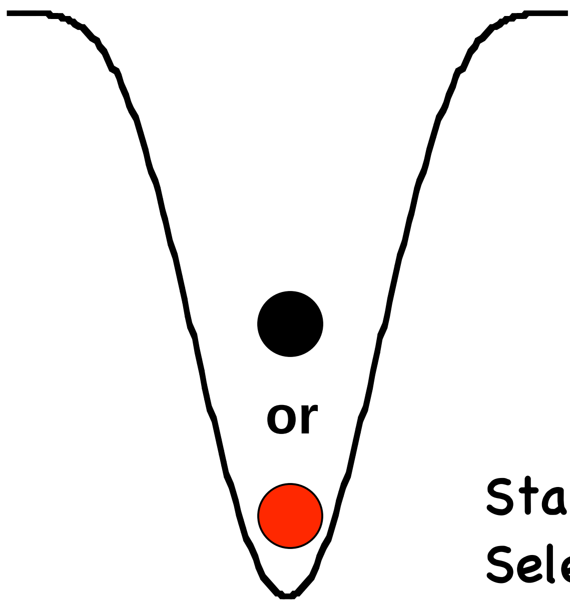
m=0 on left

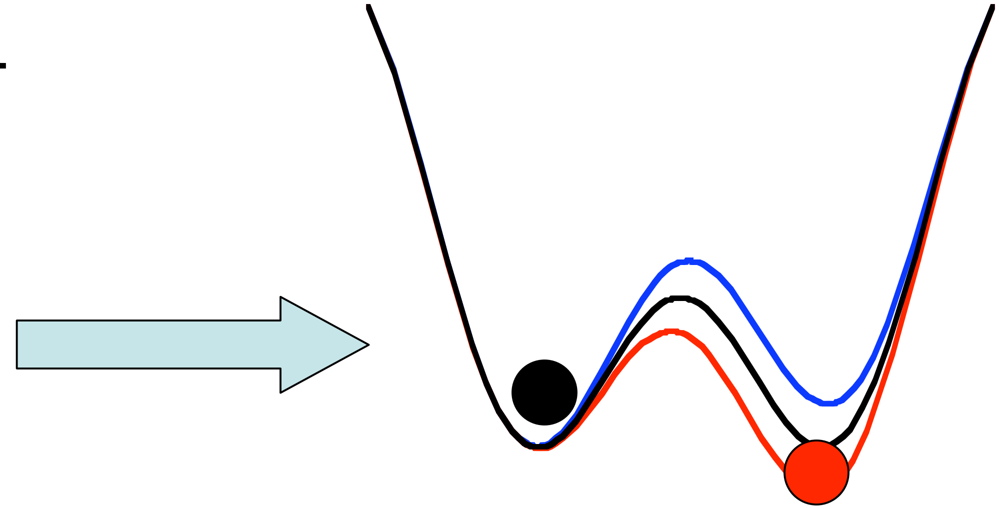


m=-1 on right

Similar to
Mandel et al., PRL 91 (2003)
but confined to a double-well

State selective motion/splitting





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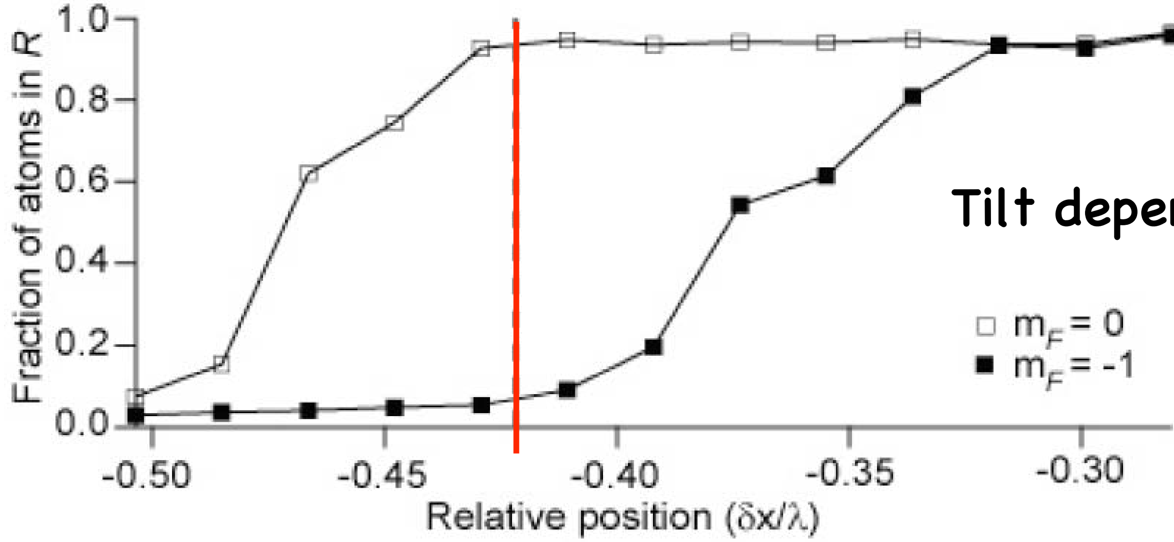
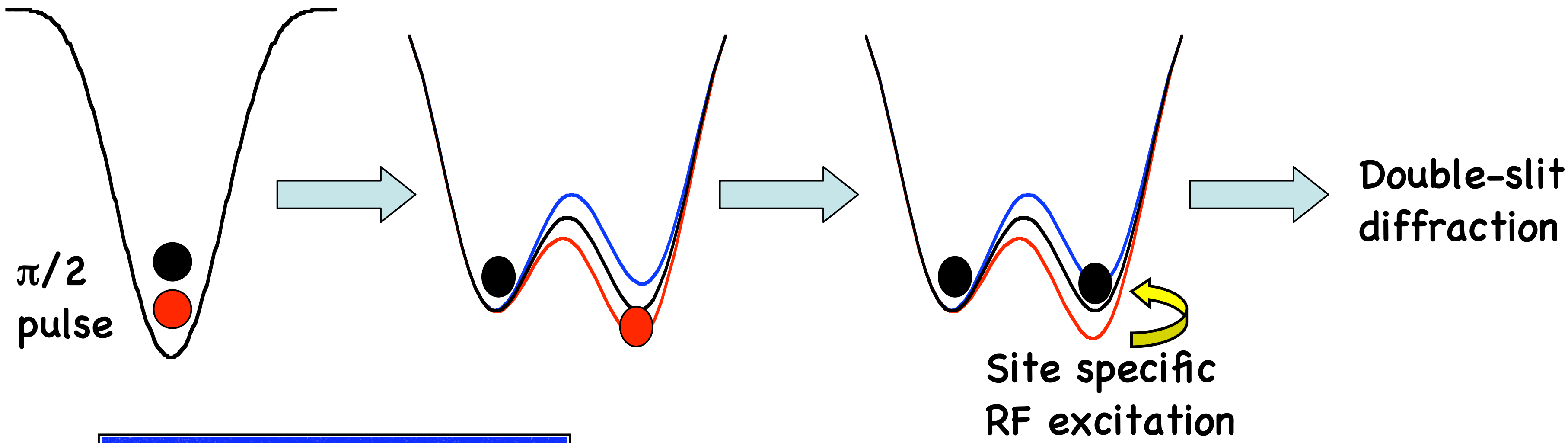
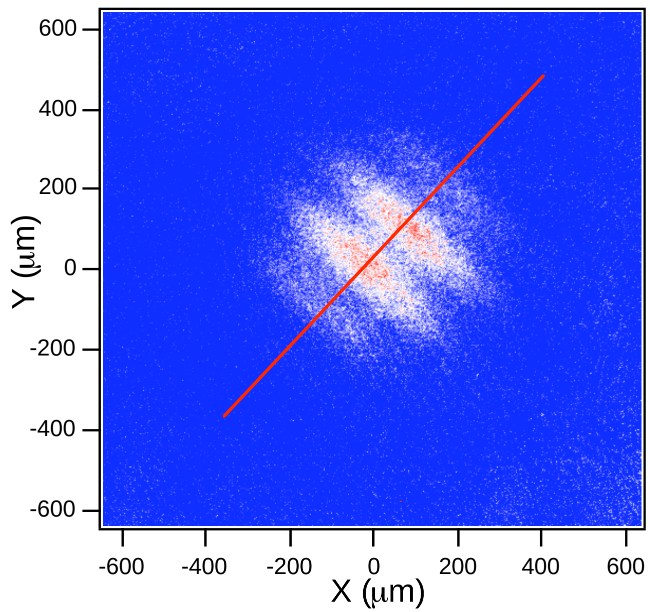
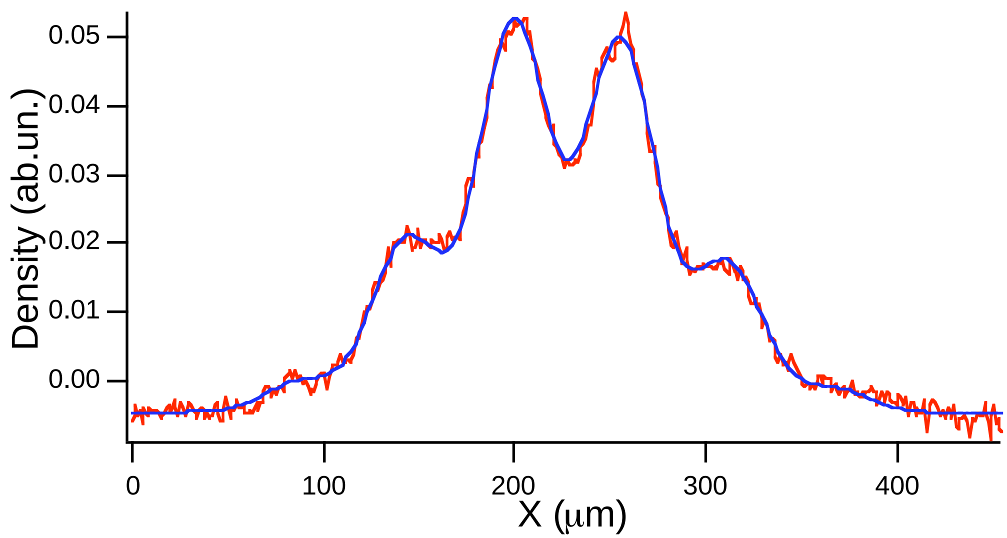


Tilt dependence

Coherent State-Dependent "Splitting"







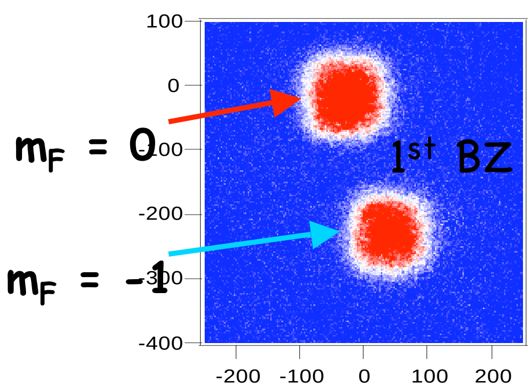
(Actually, folded into a spin-echo sequence)

Lee et al., quant-ph/0702039

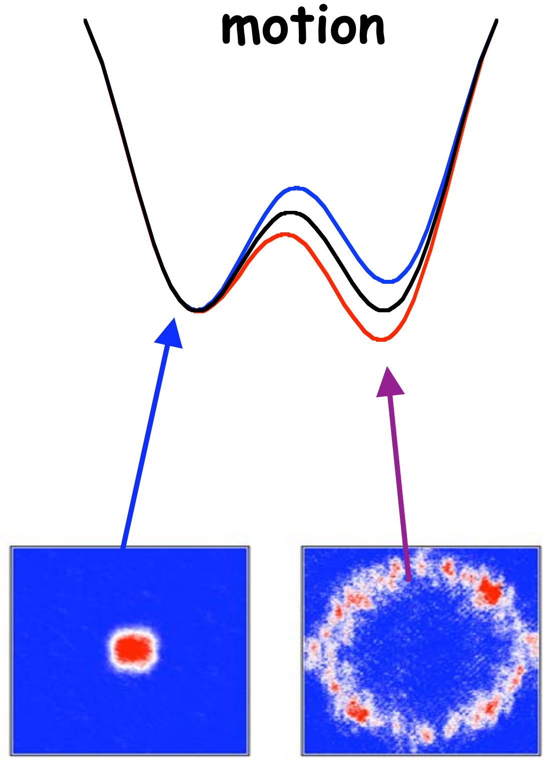
State dependent detection

- via Stern-Gerlach
- via state-dependent motion

Stern-Gerlach



State dependent motion



m=0 on left *m*=-1 on right

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- Future

  potential applications to lattice simulation

Putting it all together: a $\sqrt{\text{swap}}$ gate

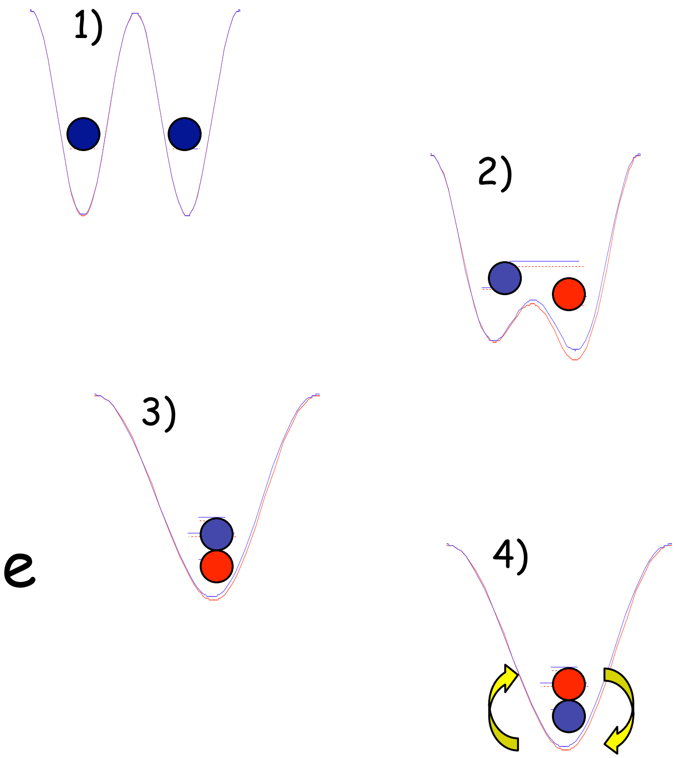
Step 1: load single atoms into sites

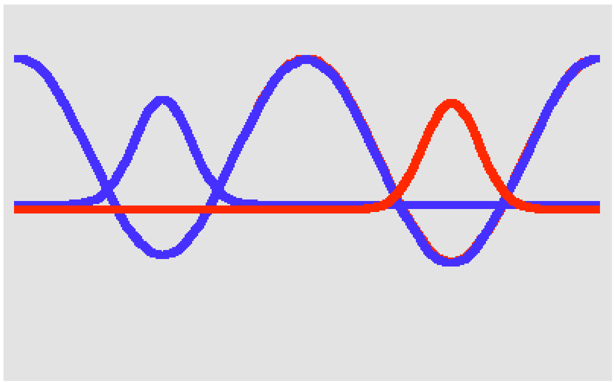
Step 2: spin flip atoms on right

Step 3: combine wells into same site

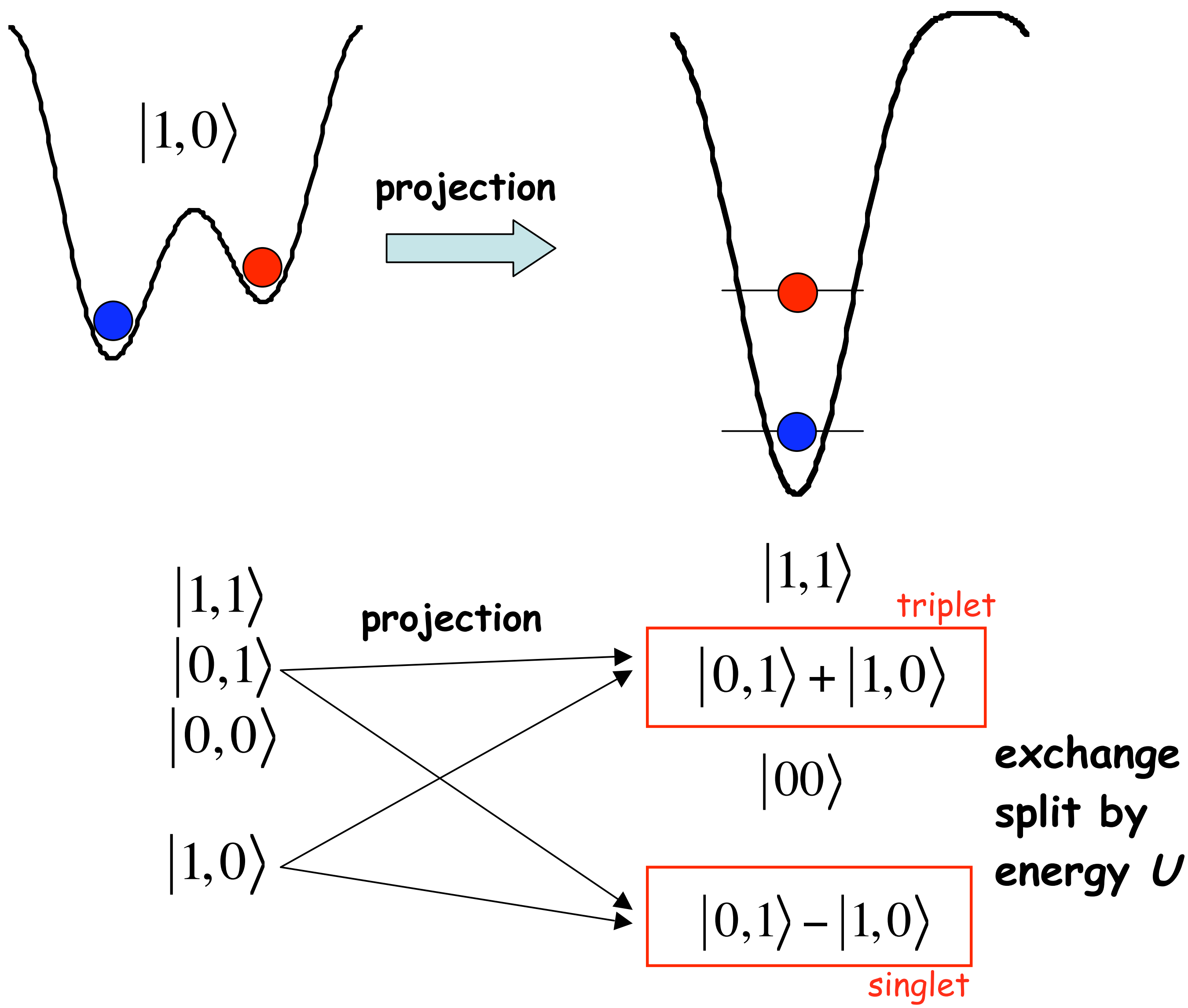
Step 4: wait for time T

Step 5: measure state occupation
(vibrational + internal)

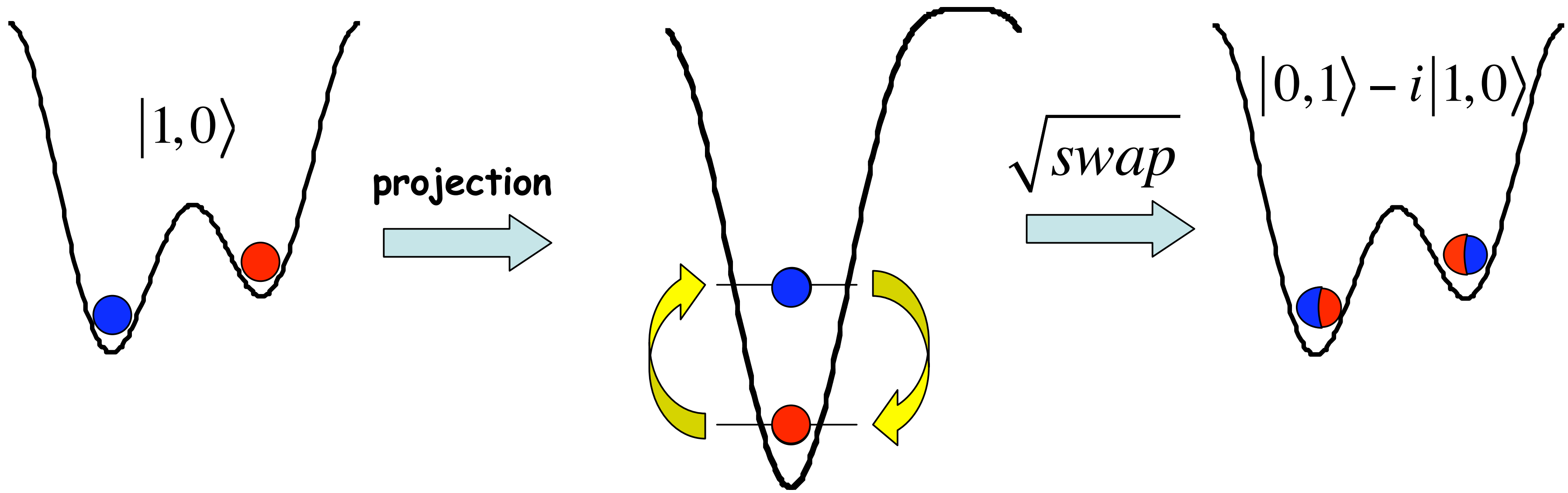




Exchange Gate: $\sqrt{swap}$



Exchange Gate: $\sqrt{swap}$



$|1,1\rangle$

$|0,1\rangle$

$|0,0\rangle$

$|1,0\rangle$

projection

$|1,1\rangle$

triplet

$\boxed{|0,1\rangle + |1,0\rangle}$

$|00\rangle$

$\boxed{|0,1\rangle - |1,0\rangle}$

singlet

exchange split by energy *U*

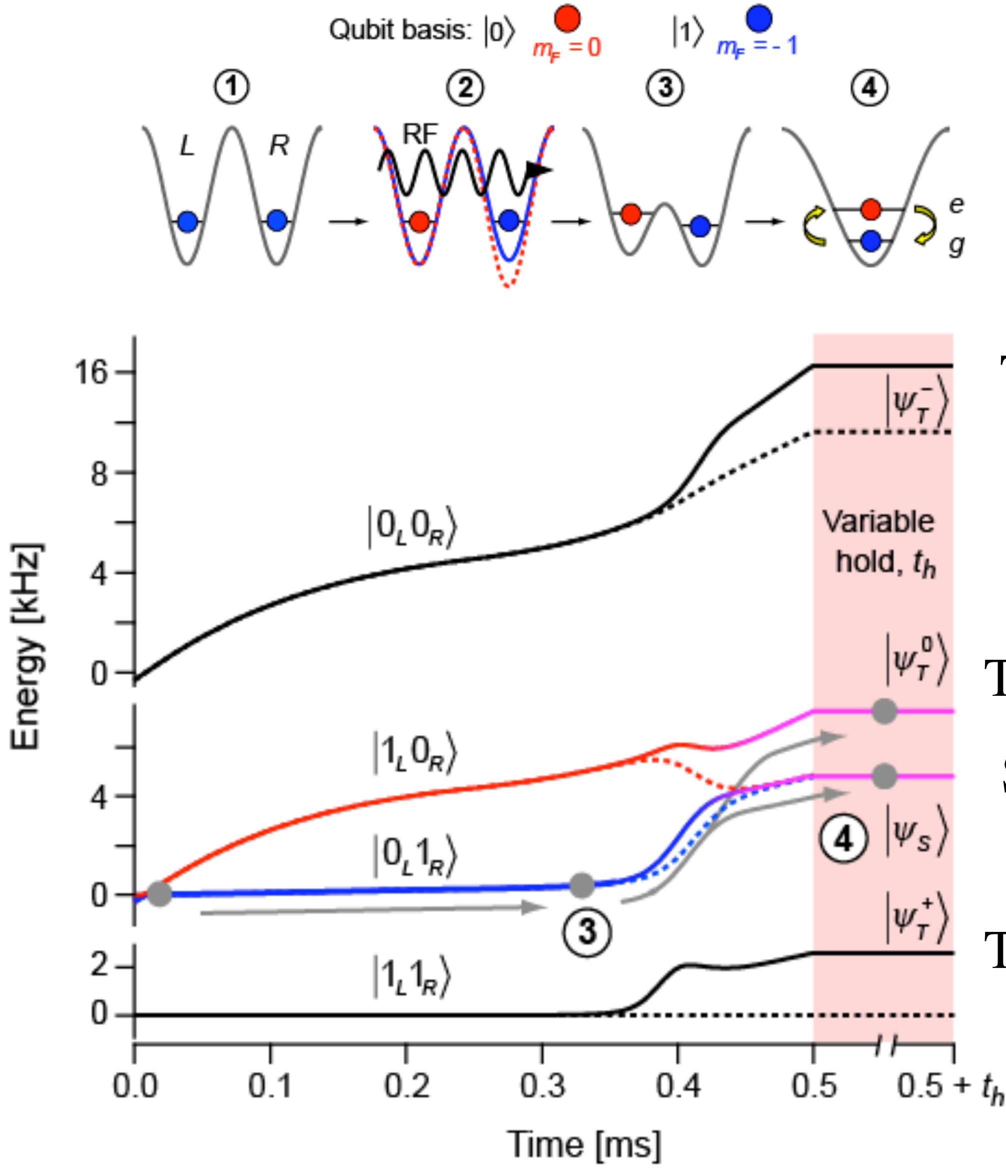
$|1,1\rangle$

$|0,1\rangle + i|1,0\rangle$

$|0,0\rangle$

$|0,1\rangle - i|1,0\rangle$

Controlled Exchange Interactions



$$T_1 = |\uparrow\uparrow\rangle$$

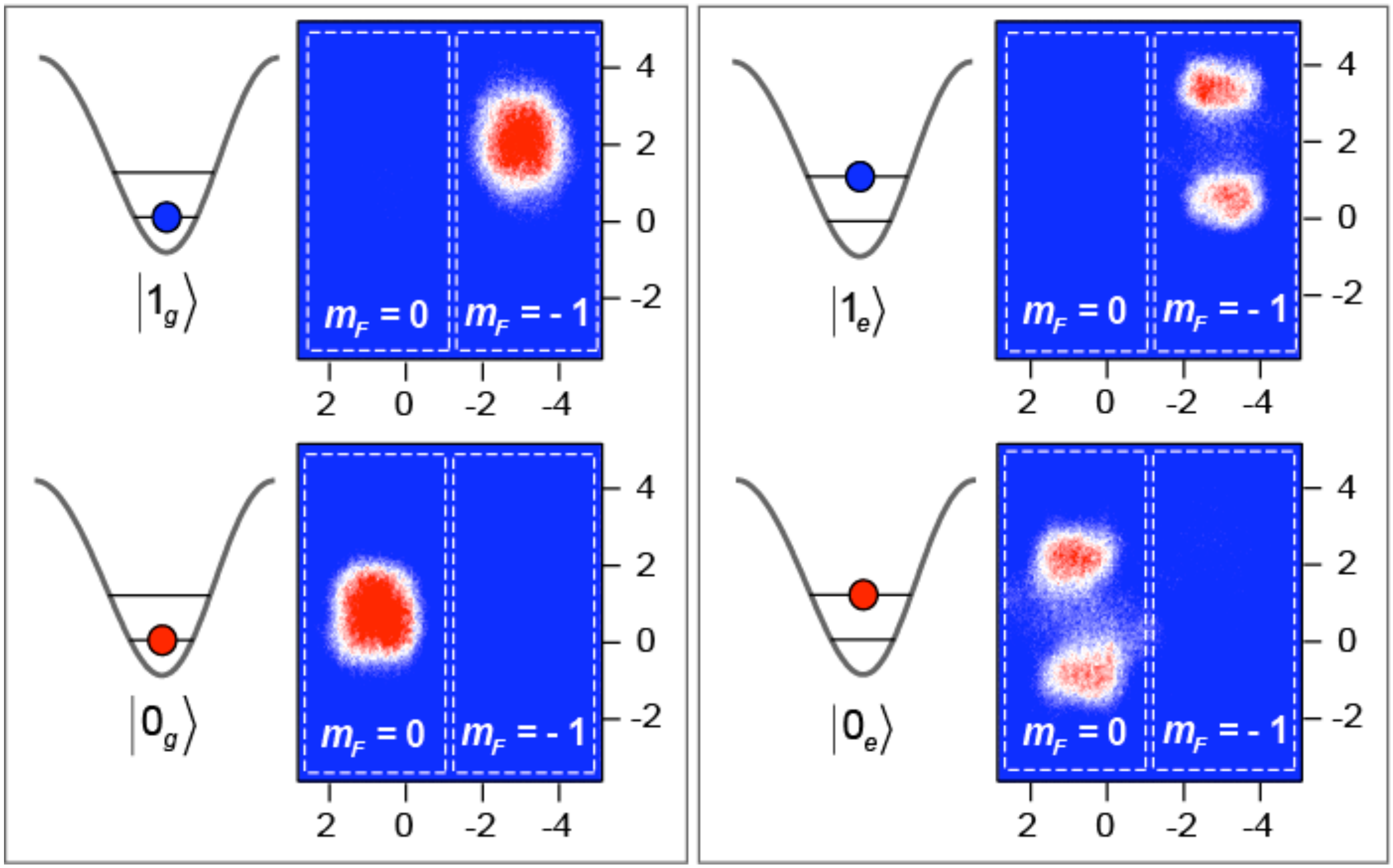
$$T_0 = |\uparrow\downarrow\rangle + |\downarrow\uparrow\rangle$$

$$S = |\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle$$

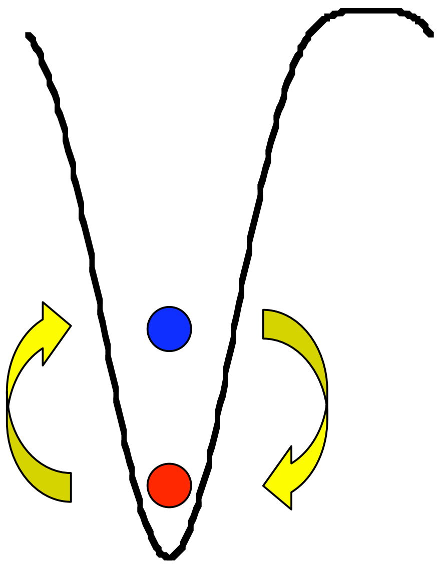
$$T_{-1} = |\downarrow\downarrow\rangle$$

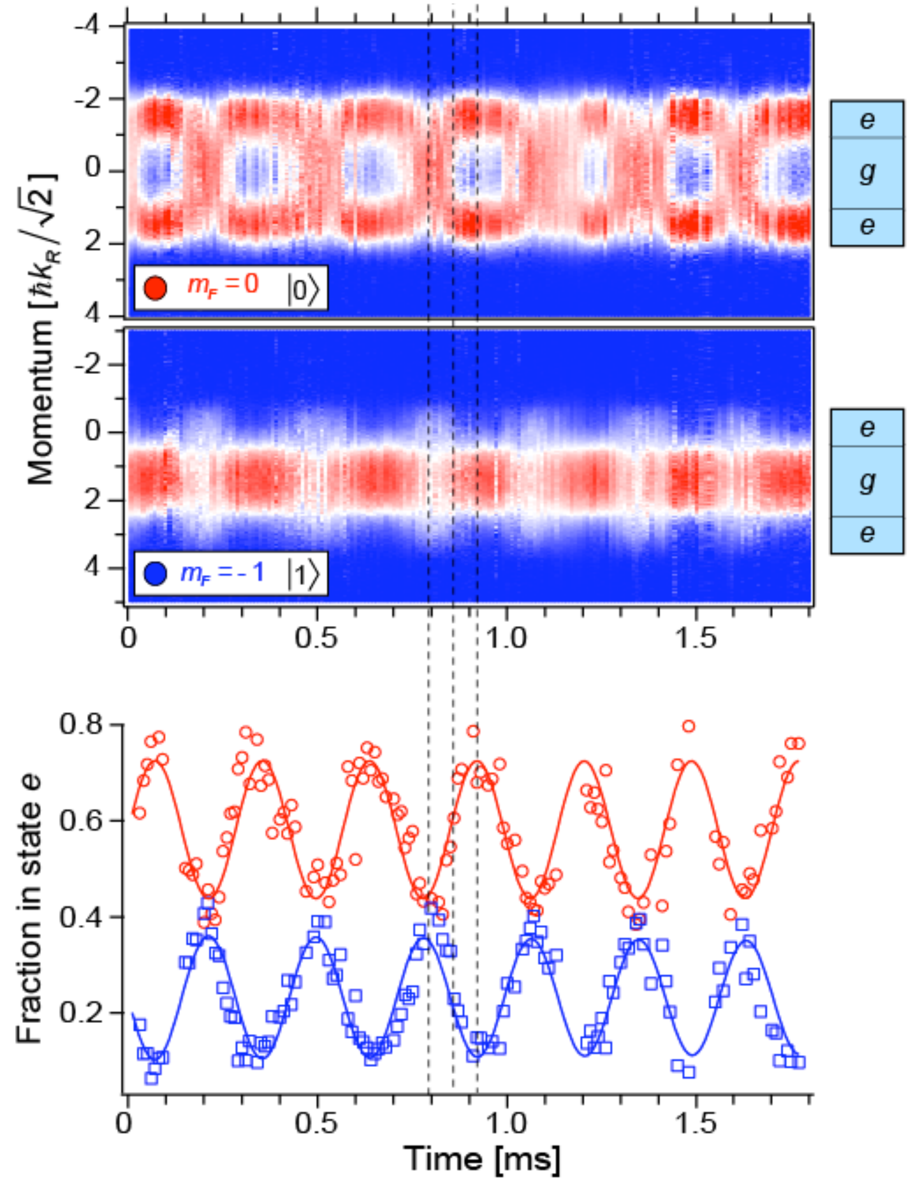
Basis Measurements

All axes are momentum [$\hbar k_R/\sqrt{2}$]



Swap Oscillations



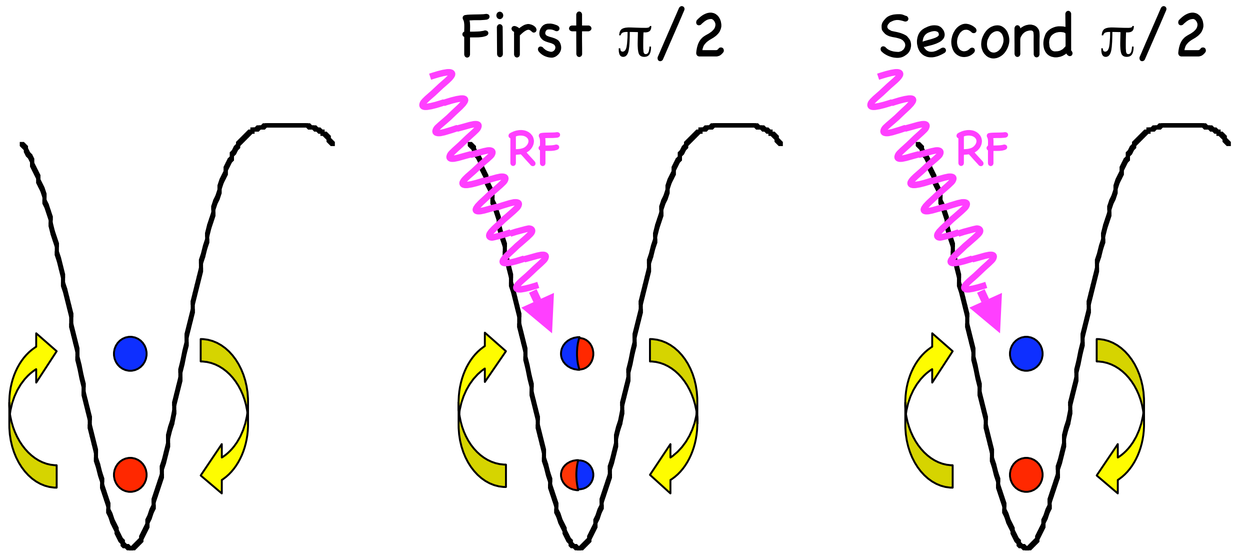


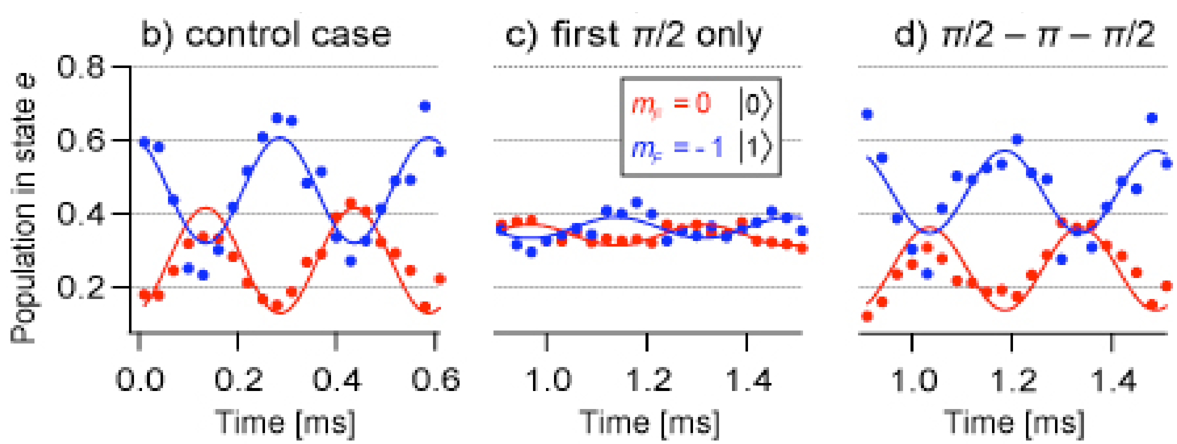
Onsite exchange -> fast 140μs swap time

~700μs total manipulation time

Population coherence
preserved for >10 ms.
(despite 150 s T2*!)

Coherent Evolution





Current (Improvable) Limitaitons

- Initial Mott state preparatio
  (30% holes -> 50% bad pairs)

- Imperfect vibrational motion ~85%

- Imperfect projection onto T_0, S ~95%

- Sub-lattice spin control >95%

- Field stability
  move to clock states
  (state-dependent control through intermediate states)

This Talk

- Realizing a dynamic double-well lattice
  - Demonstration of tools
  - Using state-dependence
  - Combining tools: toward a swap gate

- **Future**

  potential applications to lattice simulation

Tools for lattice systems

State preparation, e.g.

- ‘filter’ cooling
- constructing anti-ferromagnetic state.

Diagnostics, e.g.

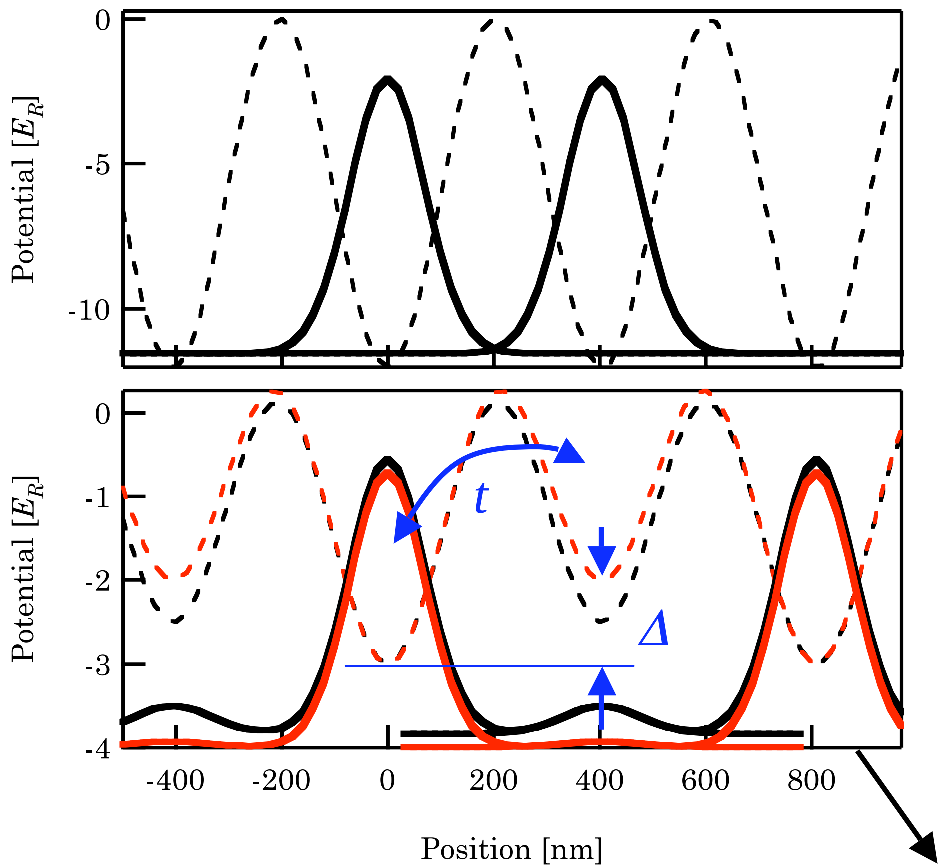
- number distributions (including holes)
- neighboring spin correlations

Realizing lattice Hamiltonians, e.g.

- band structure engineering
- ‘stroboscopic’ techniques
- coupled 1D-lattice “ladder” systems
- RVB physics

⋮

Wannier function control



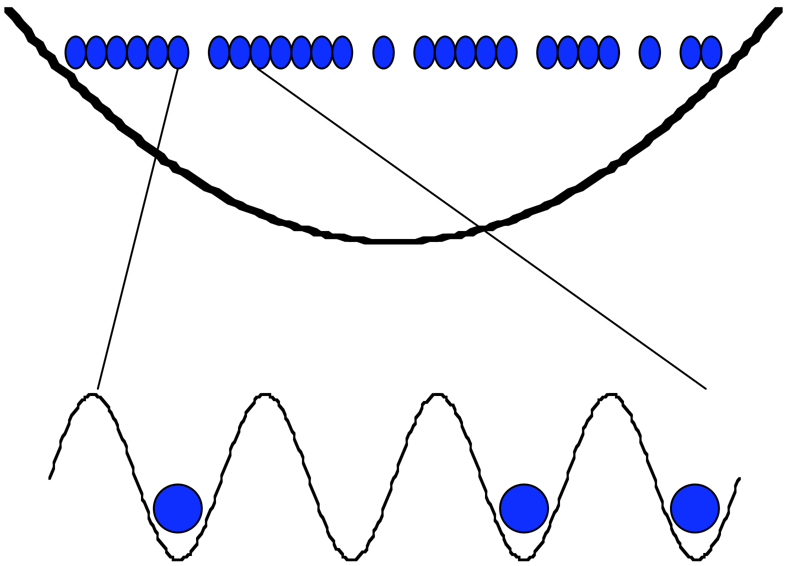
Two band Hubbard model
state-dependent control of:
t/U, Δ/U, position of λ-lattice

Ian Spielman

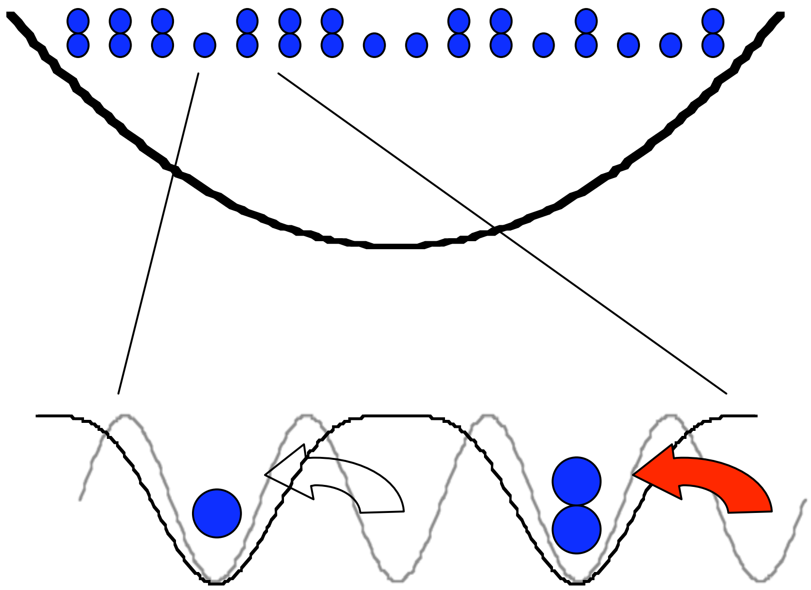
Characterizing Holes

In a fixed period lattice,
difficult to measure "holes"

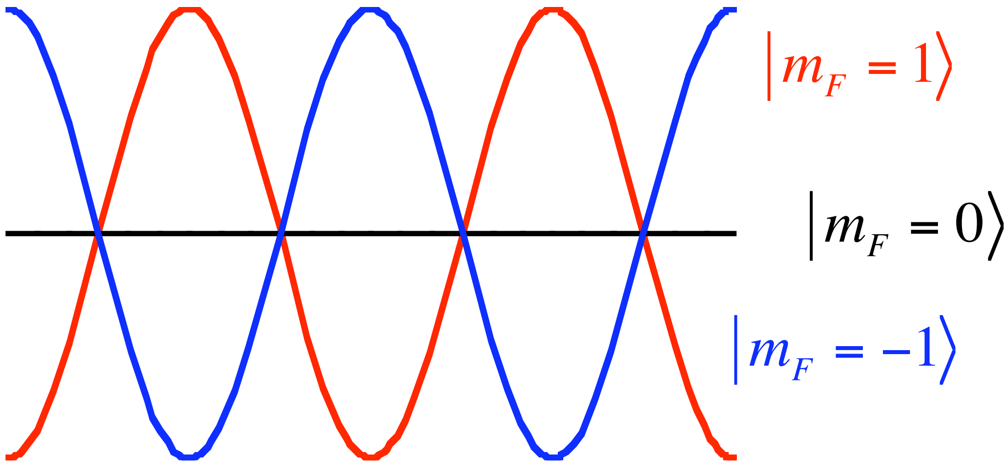
Isolated holes in $\lambda/2$



Combine holes
with neighbors



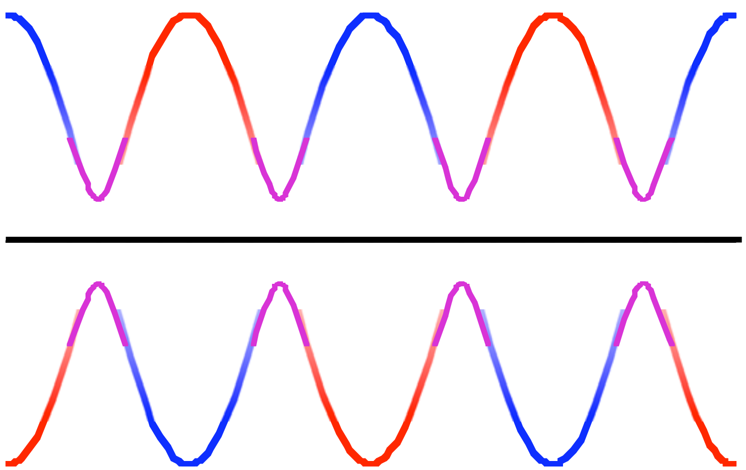
Coupling spin and motion



Purely vector part of

lin $\perp$ lin

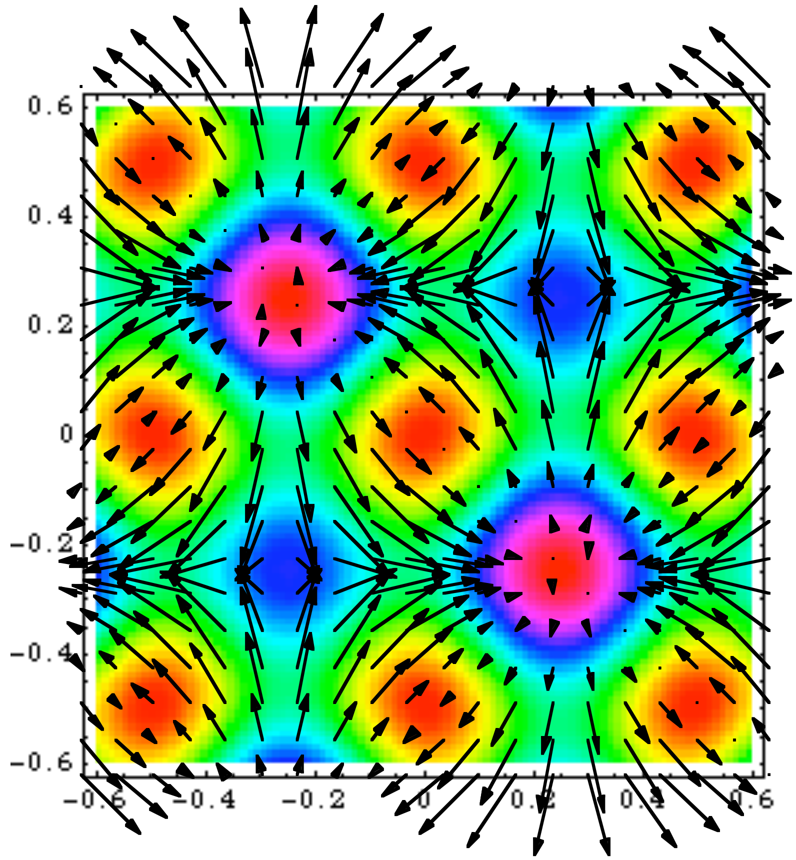
with no coupling
(large Zeeman splitting)



Can be coupled with perpendicular DC or RF fields

couples spin to Bloch state motion

Coupling spin and motion



local effective field

alternating plaquettes

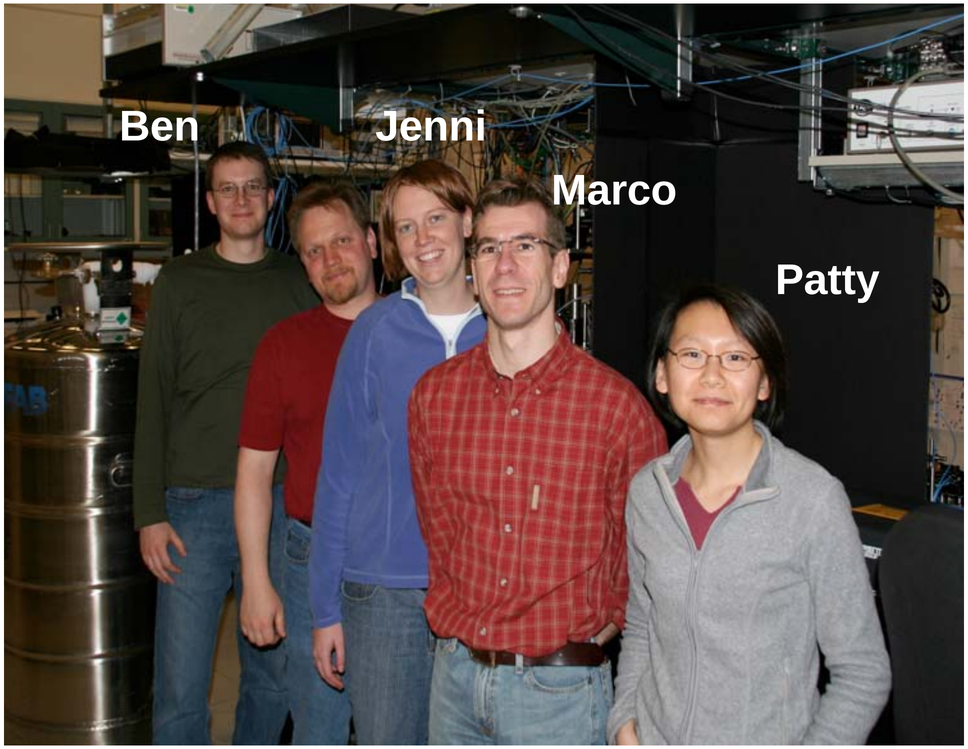
People

Postdocs

Jenni Sebby-Strabley
Marco Anderlini
Ben Brown
Patty Lee

Nathan Lundblad

Student
John Huckans



Lasercooling Group

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The End