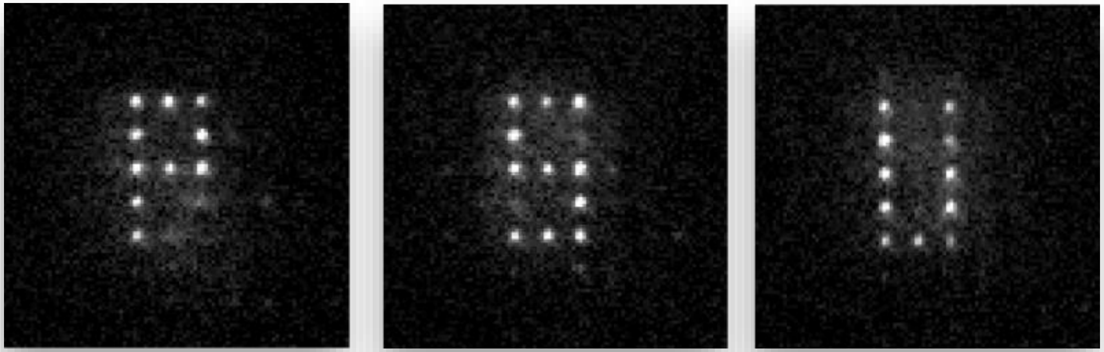
Neutral Atom Quantum Computing

Current group
Laura Zundel
Cheng Tang
Aishwarya Kumar
Josh Wilson
Teng Zhang
Tsung-Yao Wu
Neel Malvania
Felipe Giraldo
Fan Zhou
David Weiss

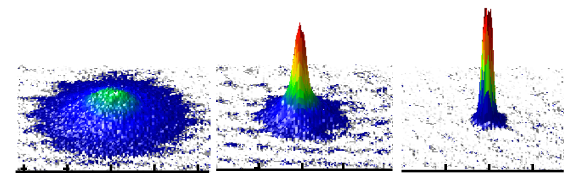
Penn State



Supported by the NSF
(and DARPA)

Outline

Thanks to B. DeMarco, T. Porto, D. Meschede, I. Bloch and M. Saffman for sharing slides

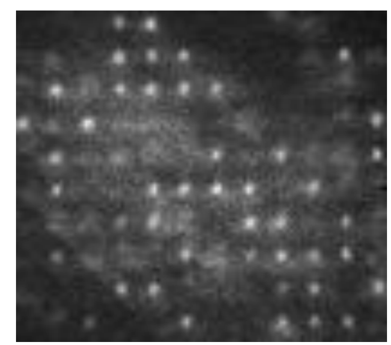


I: Basic Atomic Physics Technology

- *A. Atomic qubit states*
- *B. Light-atom interactions*
- *C. Atom cooling and trapping*
- *D. Ultracold collisions*
- *E. Optical lattices*

II. Neutral Atom Quantum Computing

state preparation, state measurement, single qubit gates, two qubit gates



10^6 atomic qubits in < 5 mm^2 or <0.5 mm^3
All atoms of a species are identical
Can be very isolated from the environment
Very good preparation and measurement

Warning: There are many QC-relevant neutral atom experimental methods and experiments that I will not discuss.

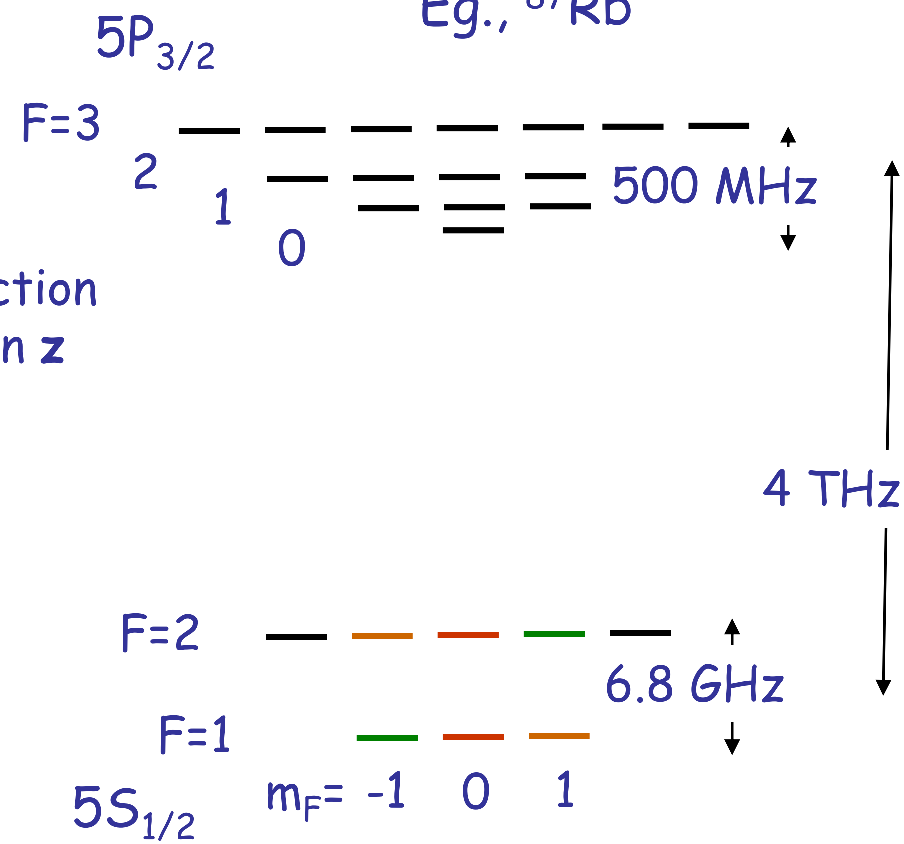
I.A

Atoms have a lot of internal states

$$\left| n\, {}^{2S+1}L_J, I, F, m_F \right\rangle$$

- principal quantum number → n
- electron spin → $2S+1$
- orbital angular momentum → L
- **J=L+S** → J
- nuclear spin → I
- total spin, **F=J+I** → F
- Projection of **F** on **z** → m_F

Eg., ^{87}Rb



Important Selection rules

Electric dipole: $\Delta L=\pm1$

Magnetic dipole: $\Delta L=0$

$\Delta J=0, \pm1$

$\Delta F=0, \pm1$

$\Delta m_F=0, \pm1$

Good qubit states → (first order) magnetic field insensitive states

→ (first order) magnetic field insensitive superpositions

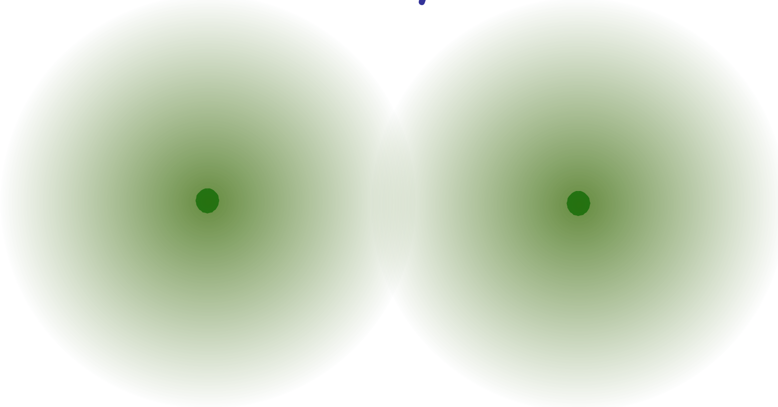
Also qudits possible

Rydberg atoms

Recall for hydrogen $E_n = -\frac{m}{2\hbar^2}\left(\frac{Ze^2}{4\pi\varepsilon_o}\right)^2 \frac{1}{n^2}$, $r \propto n^2$ and $\Gamma_o \propto n^3$

For single electron excitations close enough to dissociation, all atoms have these dependences on n.

Atoms in Rydberg states can have large electric dipole interactions with similarly excited atoms, $\propto n^4/r^3$



This long range interaction can also be used for entanglement

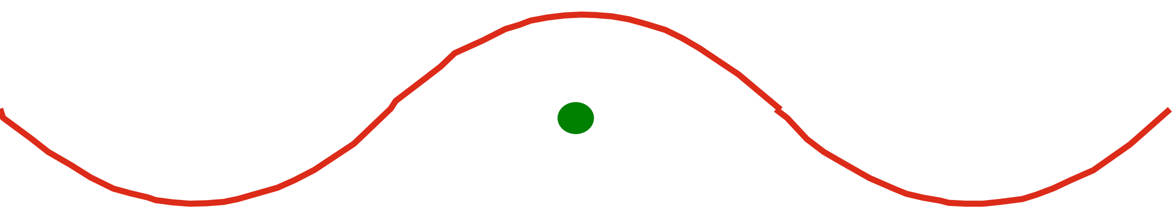
I.B

Light-Atom Interactions

Electric dipole transitions:

$$H_{ED} = -e\sum_{i=1}^{Z} \boldsymbol{r}_i \bullet E_o \boldsymbol{\varepsilon} \cos(\omega t)$$

$$= -\boldsymbol{p}_d \bullet E_o \boldsymbol{\varepsilon} \cos(\omega t)$$

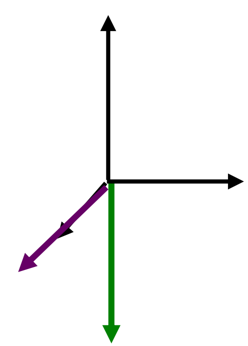


Magnetic dipole transitions: $H_{MD} = -\frac{\mu_B}{\hbar}(\boldsymbol{L} + 2\boldsymbol{S}) \bullet \boldsymbol{B} \cos(\omega t)$

The Rabi frequency: $\Omega \equiv \frac{\langle e | H_{\text{int}} | g \rangle}{\hbar}$

Two-level system calculations

➔ The Bloch equations $\boldsymbol{\rho} \equiv u\,\hat{1} + v\,\hat{2} + w\,\hat{3}$



The solution

$$\frac{d\boldsymbol{\rho}}{dt} = \boldsymbol{\Omega} \times \boldsymbol{\rho}$$

$$\boldsymbol{\Omega} \equiv \Omega\,\hat{1} - \delta\,\hat{3}$$

u = the in phase part of the atomic coherence

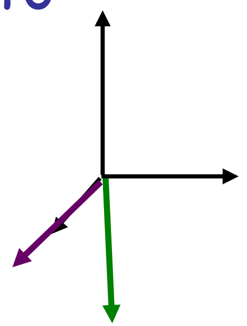
v = the out of phase part of the atomic coherence

w = the population inversion, $\rho_{ee}-\rho_{gg} = P_e - P_g$

$\delta \equiv \omega - \omega_o$, the detuning

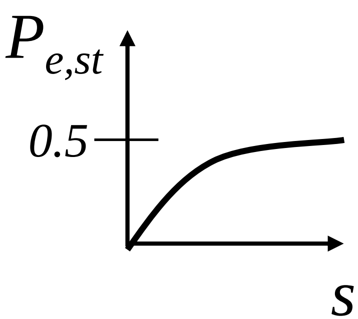
Optical Bloch Equations with Dissipation

Coupling to the vacuum (spontaneous emission) leads to steady state solutions. Γ= the spontaneous emission rate



$$s \equiv \frac{\left(\frac{\Omega}{2}\right)^2}{\delta^2 + \left(\frac{\Gamma}{2}\right)^2} \equiv \frac{I}{I_s} \frac{1}{1+\left(\frac{2\delta}{\Gamma}\right)^2}$$

saturation parameter



$$u_{st} = \frac{2\delta}{\Omega}\left(\frac{s}{1+s}\right); \quad v_{st} = \frac{\Gamma}{\Omega}\left(\frac{s}{1+s}\right); \quad P_{e,st} = \frac{1}{2}\left(\frac{s}{1+s}\right)$$

For $\delta=0$, the response is 90° out of phase with the driving field.

For $\delta>>\Gamma$, the response is in phase and $\Gamma_{scat}=\Gamma P_{e,st}<<\Gamma$.

For $\delta<<\Gamma$, the response is 180° out of phase and $\Gamma_{scat}<<\Gamma$.

Mechanical Force of Light

atom's com momentum

Ehrenfest's Thm: $$\langle \boldsymbol{F} \rangle = \frac{d\langle \boldsymbol{p} \rangle}{dt} = -\left\langle \frac{\partial H_{\text{int}}}{\partial r} \right\rangle = \langle \boldsymbol{p_d} \bullet \nabla \boldsymbol{E} \rangle$$

$$\boldsymbol{E} = E_o \boldsymbol{\varepsilon} \cos(\omega t + \phi(r))$$

$$\boldsymbol{p_d} \equiv \langle e\boldsymbol{r} \rangle = e\boldsymbol{r_{ge}} \left[u \cos(\omega t) - v \sin(\omega t) \right]$$

averaging over an optical cycle, and taking steady state values

$$\boldsymbol{F} = \frac{er_{ge}}{2} \left[u_{st} \nabla \mathrm{E}_o + v_{st} \nabla \phi \right]$$

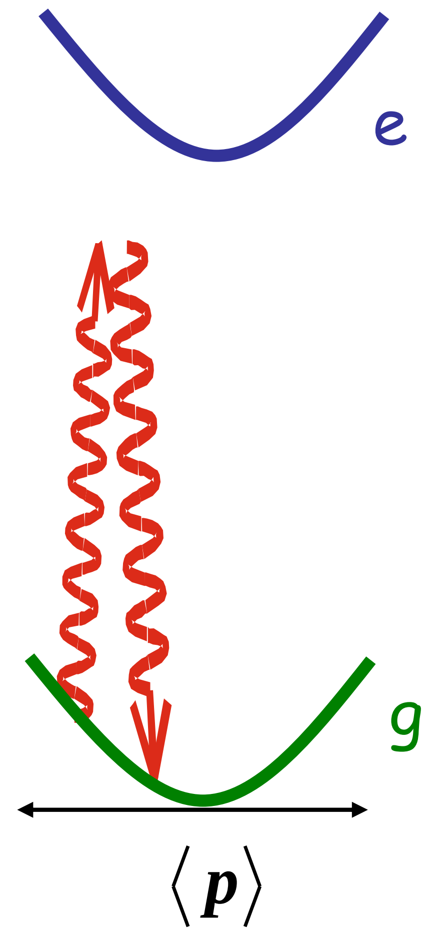
the dipole force

the scattering force

The Scattering Force

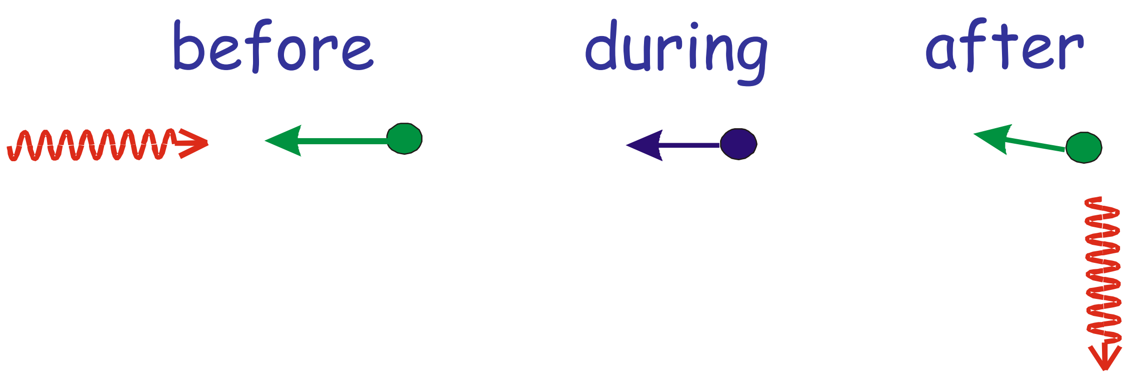
$$\boldsymbol{F}_{scat} = \frac{e r_{ge}}{2} v_{st} \nabla \phi$$

For a traveling wave, $\boldsymbol{E} = E_o \boldsymbol{\varepsilon} \cos(\omega t - \boldsymbol{k} \bullet \boldsymbol{r})$



$$\boxed{\boldsymbol{F}_{scat} = P_{e,st} \Gamma \hbar \boldsymbol{k}}$$

It's the only net force right on resonance.



For s<<1 it's a single two-photon process.

The Optical Dipole Force

$$\boldsymbol{F}_{dip} = \frac{e r_{ge}}{2} u_{st} \nabla \mathrm{E}_o$$

For $\delta >> \Gamma$, $u_{st} \approx \frac{\Omega}{2\delta}$ and $\boldsymbol{F}_{dip} = \frac{\Omega}{2\delta}\nabla\Omega.$

$$\boldsymbol{F}_{dip} = -\nabla U_{AC}$$

in-phase part

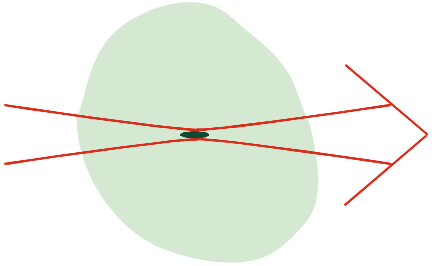
where the AC Stark shift

$$U_{AC} = \langle -\vec{\boldsymbol{p}}_d \bullet \boldsymbol{E} \rangle = \frac{\hbar\Omega^2}{4\delta} \propto I$$

$\delta > 0$ ➔ atoms attracted to light

$\delta < 0$ ➔ atoms repelled from light

The dipole force is conservative.
Far from resonance that's all there is.



If you know I(**r**) you know the shape of the trap

Detecting Atoms

Fluorescence

on or near resonance

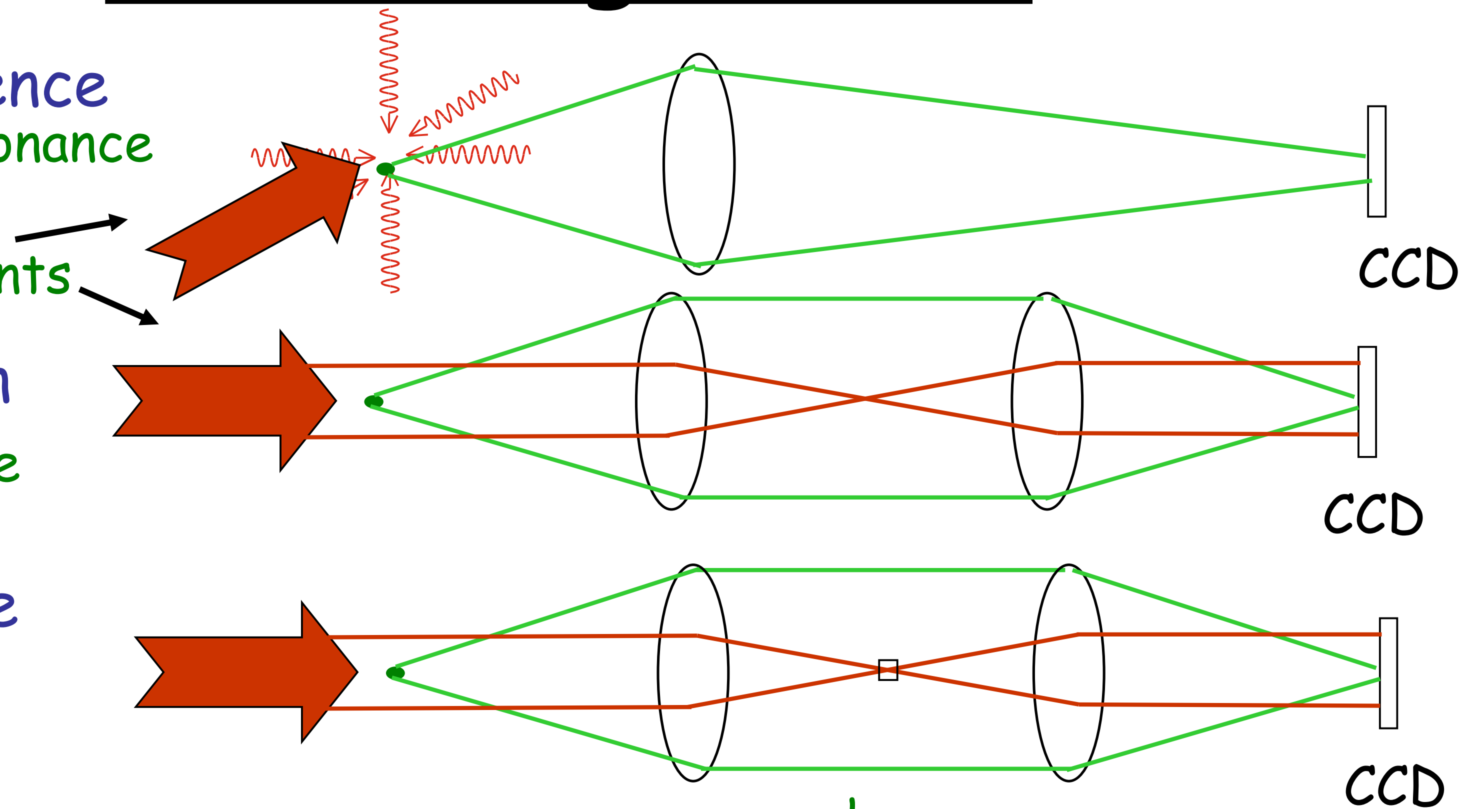
high and low intensity variants

Absorption

on resonance

Dispersive

far from resonance



A single atom can also shift a high-Q cavity off-resonance.

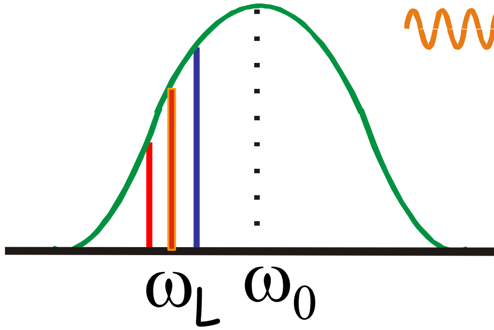
All these methods can be hyperfine state sensitive.

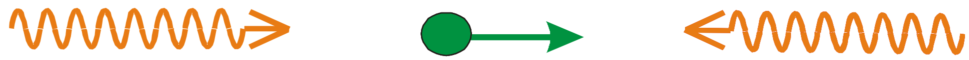
One can also ionize atoms and count them. The detection efficiency is then <~90%, not good for Q.C.

I.C

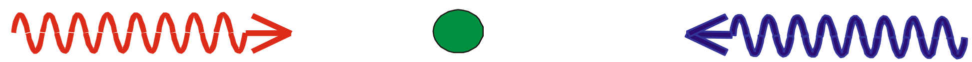
Laser Cooling

Doppler Cooling





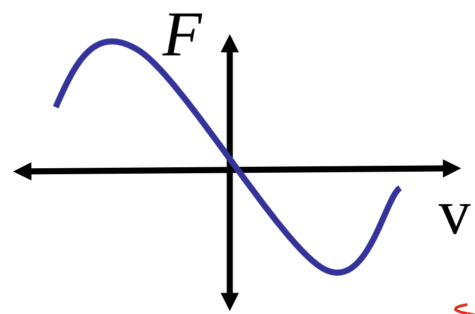
Lab frame



Atom's frame

$$F_{cool} = F_{scat+} + F_{scat-}$$

$$F_{cool} = 4\hbar k^2 \frac{I}{I_s} \frac{\frac{2\delta}{\Gamma}}{\left[1+\left(\frac{2\delta}{\Gamma}\right)^2\right]^2} \mathrm{v} = -\alpha \mathrm{v}$$



Momentum diffusion

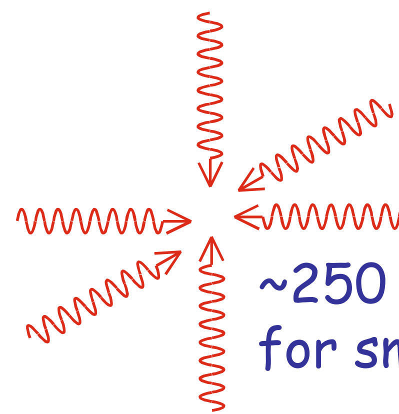
$$D_p = \frac{d(p^2)}{2dt} = \frac{2(\hbar k)^2}{2}\Gamma_{sc}$$

Temperature $T = \dfrac{D_p}{\alpha}$

$$= \frac{\hbar\Gamma}{4} \frac{\left(1+\left(\frac{2\delta}{\Gamma}\right)^2\right)}{\frac{2\delta}{\Gamma}}$$

Optical Molasses

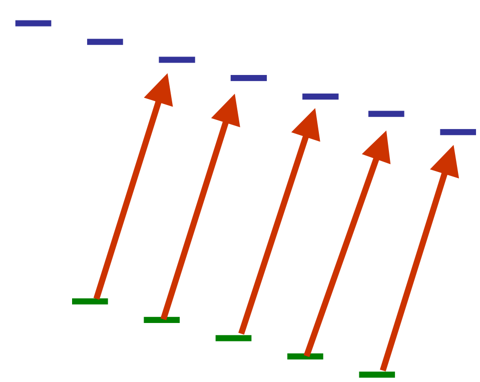
$$T_{min} = \frac{\hbar\Gamma}{2}$$



~250 μK, less for small Γ

Polarization Gradient Cooling

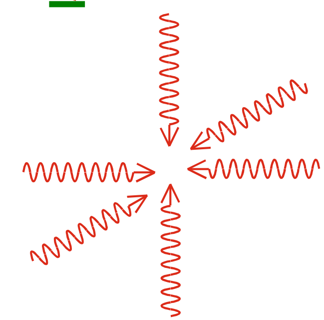
Uses both F_{dip} and F_{scat}.



Requirements

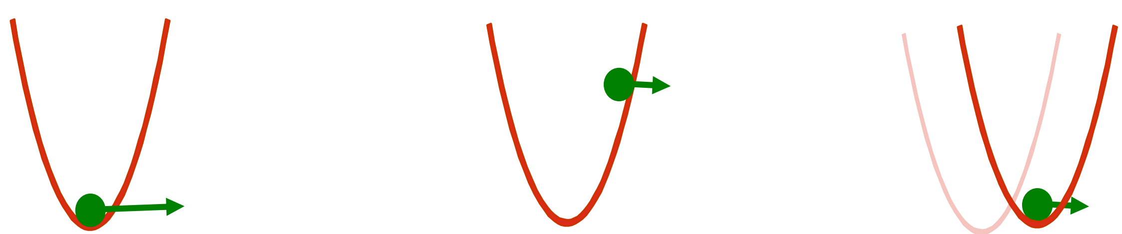
1. Atoms optically pump to the most ac Stark shifted state
2. There are polarization gradients.

Eg., the polarization must change in a 3D standing wave



There are 2 types of PGs, helicity and orientation.

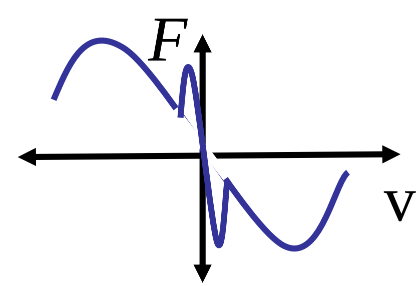
↑ dominant in 3D



Atoms move away from their optically pumped state

They lose kinetic energy climbing potential hills

They optically pump to a new lowest state.

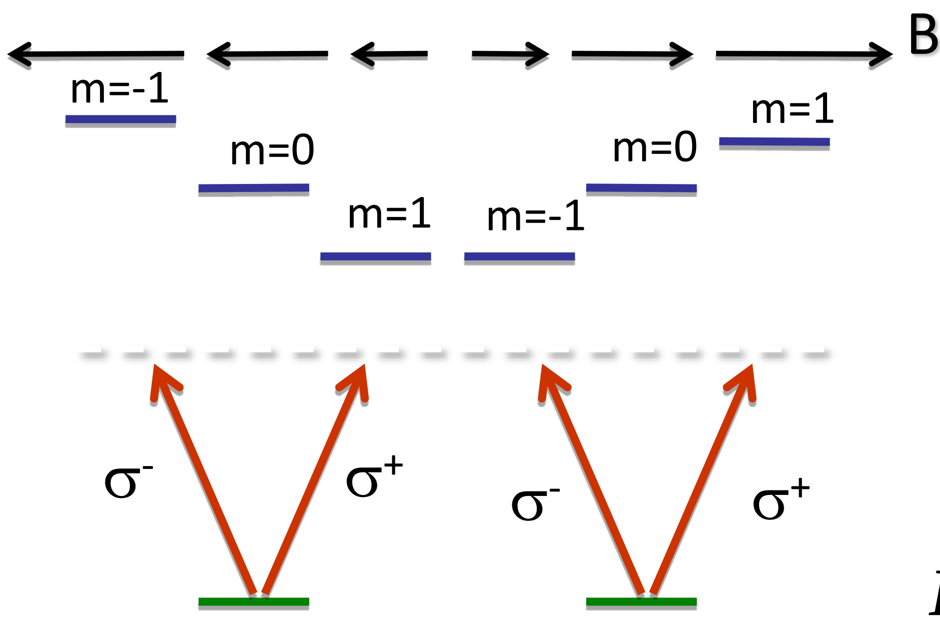


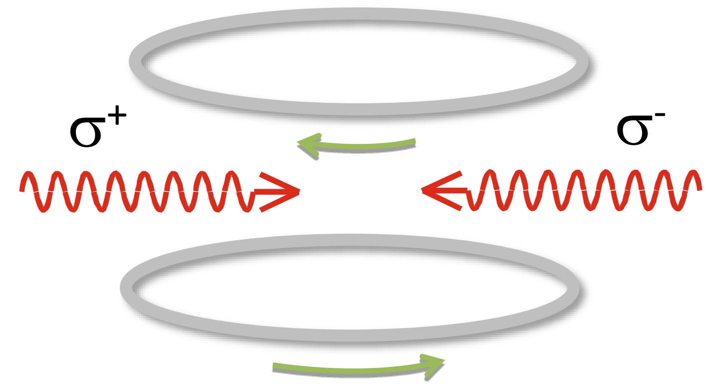
$T \sim 5(\hbar k)^2/2m$

a few μK

The Magneto-Optic Trap

3D optical molasses for cooling
plus 3D magnetic field gradients for trapping





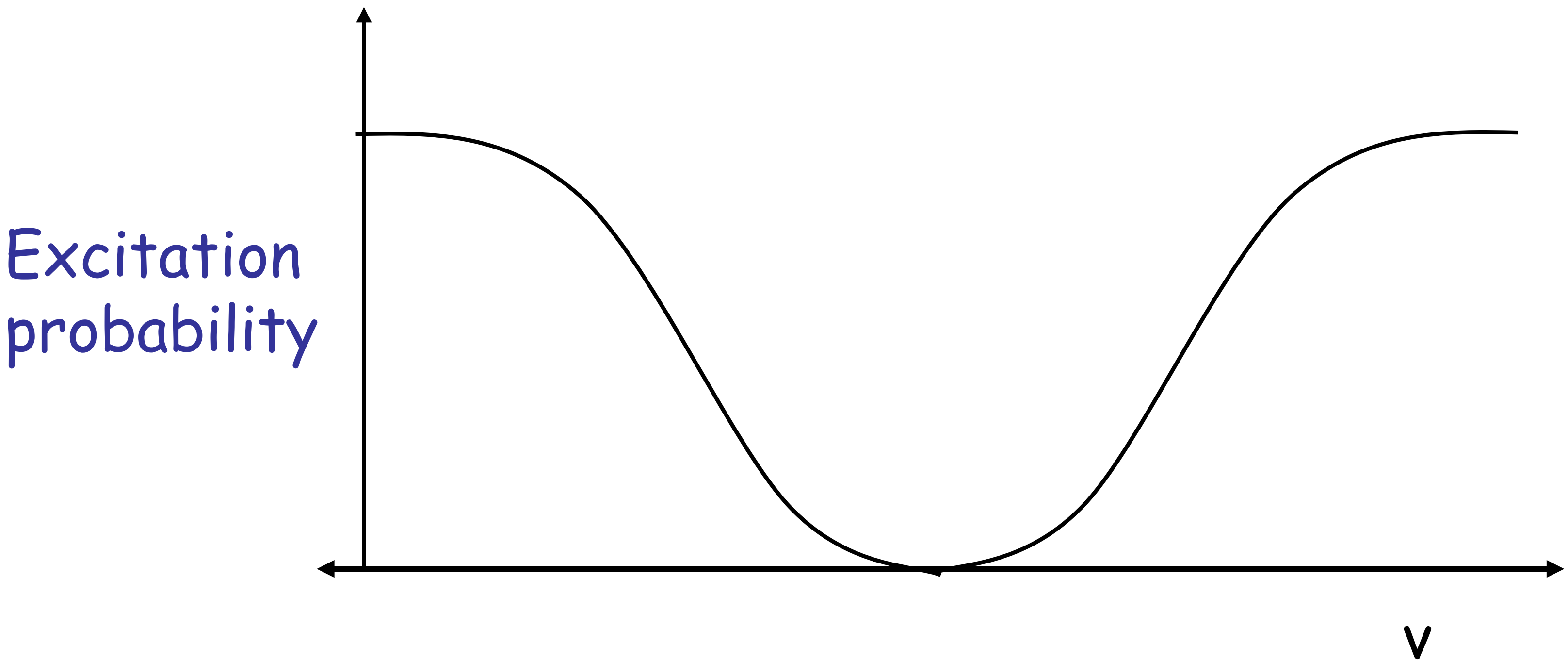
spherical quadrupole coils

$$\boldsymbol{F} = -\alpha \boldsymbol{v} - \kappa \boldsymbol{r} \qquad \kappa = \mu_B B' \alpha / \hbar k$$

Load the MOT from a slowed beam, or using the low velocity thermal tails of vapor cell.
It is a dissipative trap that dramatically increases the phase space density. Can collect up to ~10^{10} atoms.

Dark State Laser Cooling

The "recoil limit" is not a limit.

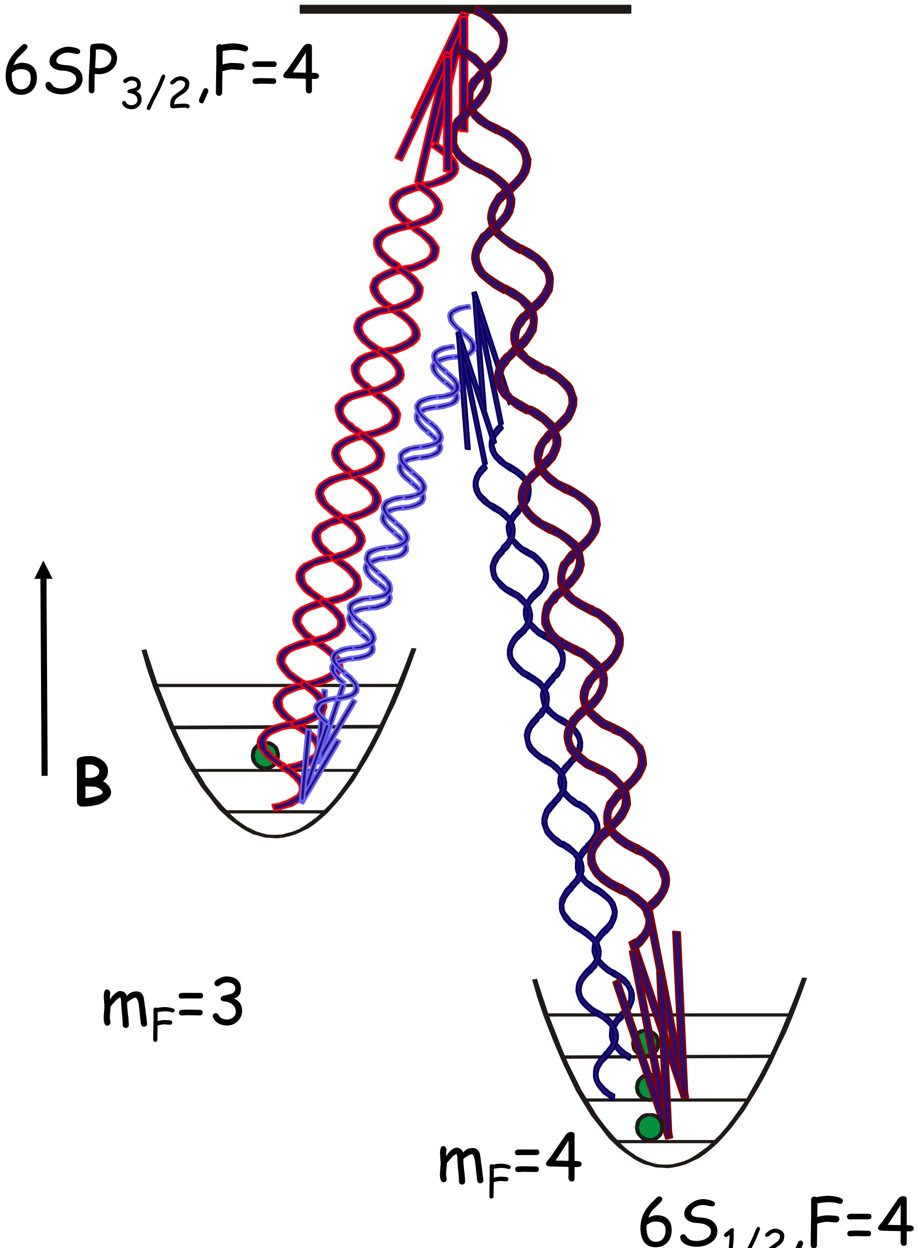


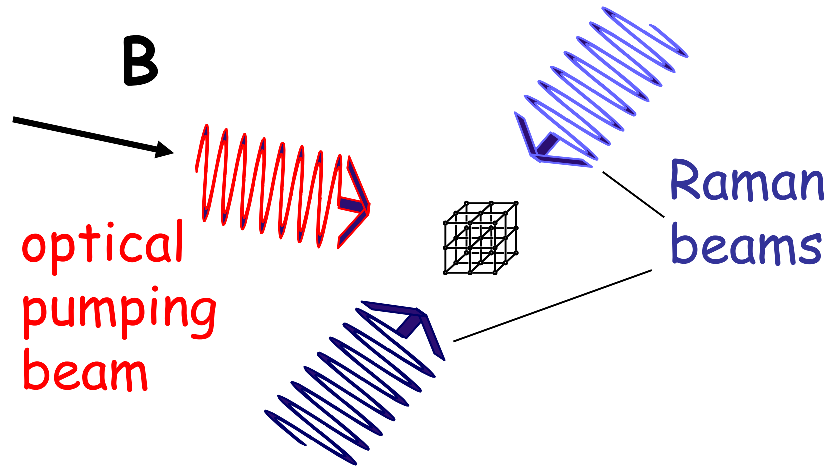
The limits to laser cooling are practical, not fundamental (eg., photon rescattering, imperfectly dark states)

Examples: VSCPT, Raman cooling, sideband cooling, Raman sideband cooling, projection cooling.

Laser cooling can initialize atomic qubits

3D Raman Sideband Cooling

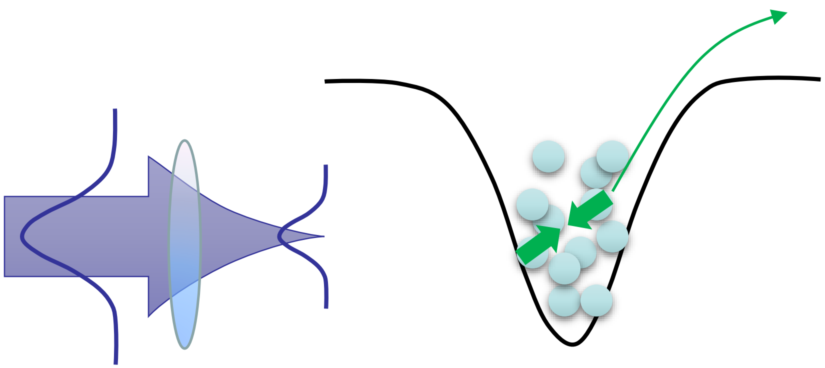




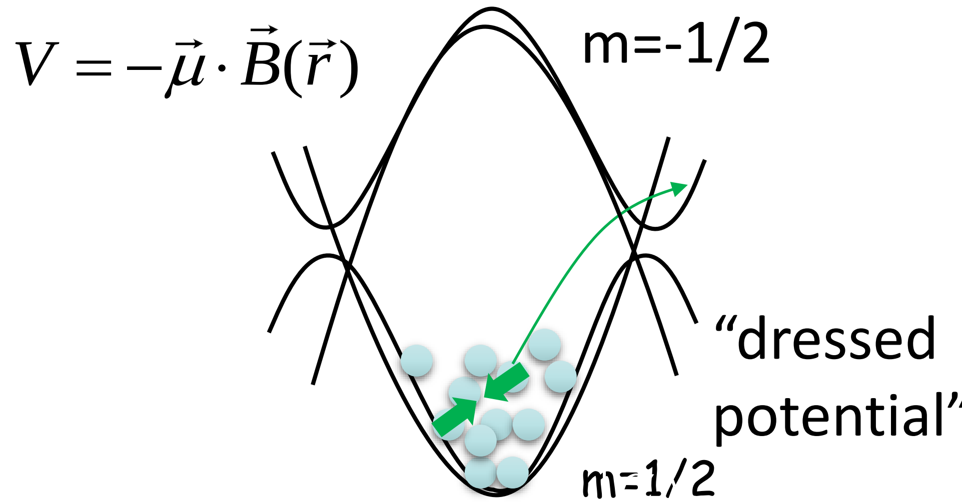
1. A Raman pulse transfers atoms from v → v-1.
2. Optical pumping returns the atoms to 4,4 state; v tends to stay the same.
3. $\omega_x \neq \omega_y \neq \omega_z$, so dark states become light
4. repeat

Kerman et al. PRL **84** 439 (2000)
Han,Wolf,Oliver,DePue,DSW. PRL **85** 724 (2000)

Evaporative Cooling



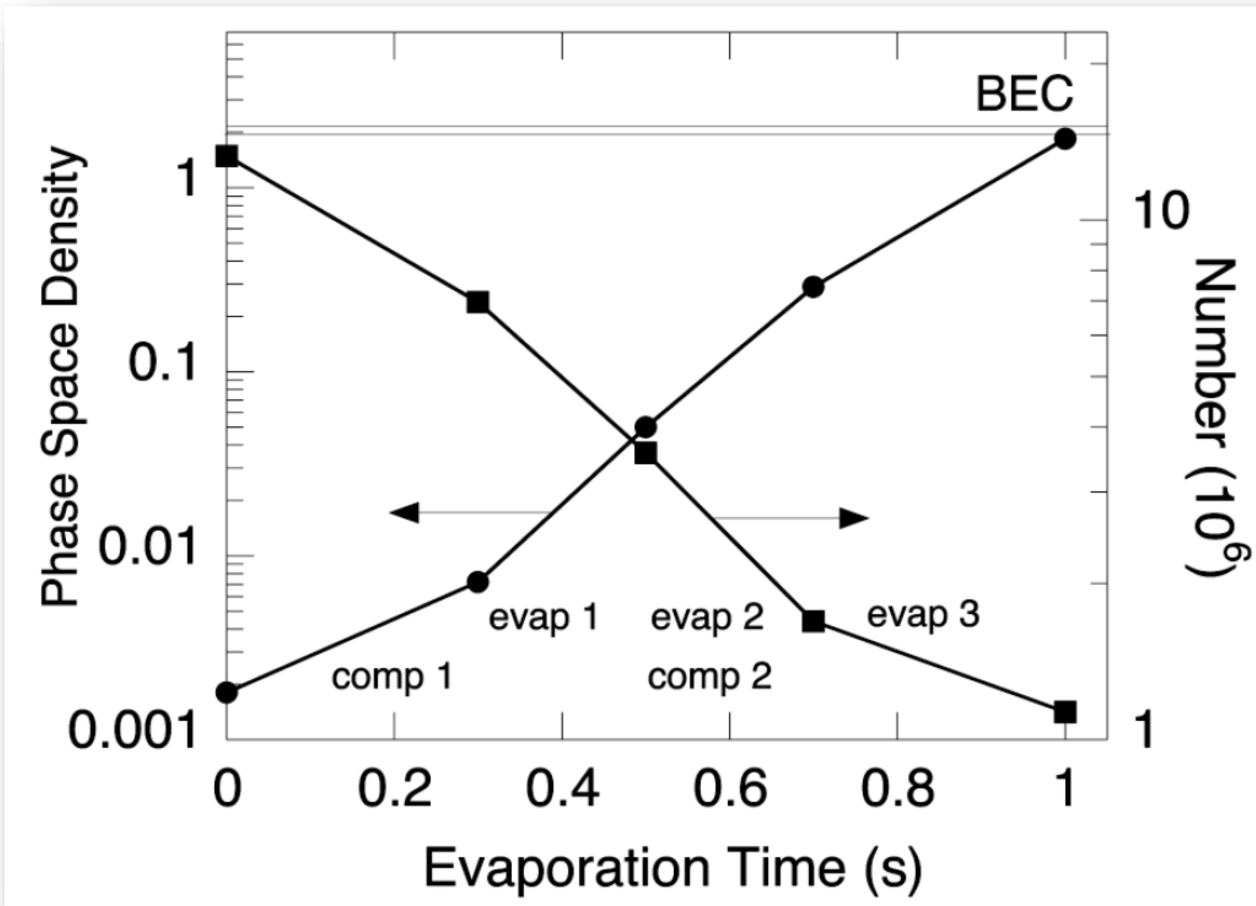
Far off-resonance dipole trap



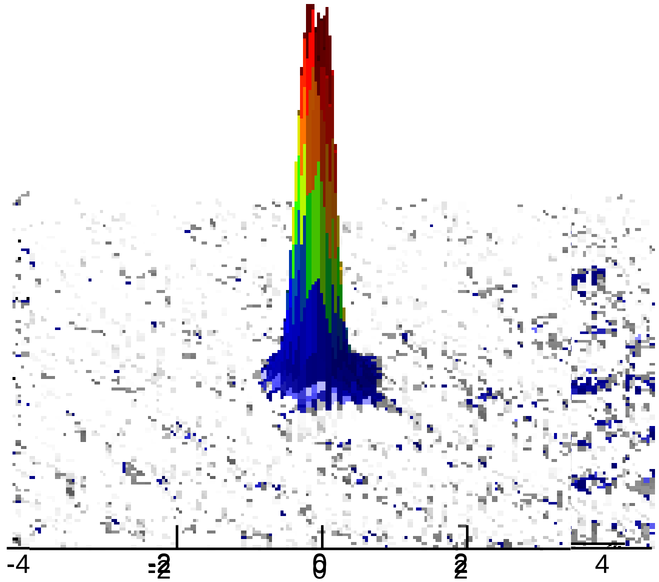
Magnetic trap (Ioffe-Prichard, TOP,…)

- Collisions eject highest energy atoms from trap
- Collisions rethermalize gas
- Trap depth lowered for forced evaporative cooling

Evaporative Cooling Data



BEC



1 s 1.5 s 2.0 s

Evaporation times (ranges from 1 to 60 s)

3.5×10^{5} BEC atoms every 3 s

By various methods, 10^{3} to 10^{8} quantum degenerate atoms.

Bosons:

^{87,85}Rb, ^{23}Na, ^{7}Li, ^{133}Cs, H, ^{39}K, ^{41}K, ^{4}He*, ^{17x}Yb, ^{52}Cr, ^{164}Dy, ^{84,86}Sr

Fermions: ^{40}K, ^{6}Li, ^{173}Yb, ^{87}Sr Many others have been laser cooled.

Quantum Degenerate Gases

The distribution of particles in eigenstates depends on F.

$$f(\varepsilon) = \frac{1}{e^{(\varepsilon-\mu)/k_BT} \pm 1} \qquad P(\varepsilon) = f(\varepsilon)\,g(\varepsilon)$$

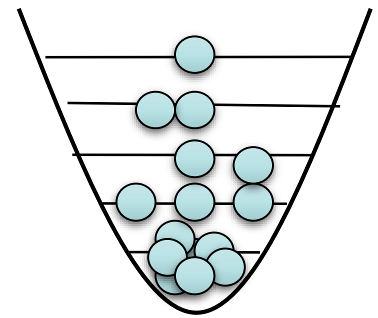
$$N = \int_0^\infty g(\varepsilon)\,f(\varepsilon,\mu,T)\,d\varepsilon$$

$$U = \int_0^\infty \varepsilon\,g(\varepsilon)\,f(\varepsilon,\mu,T)\,d\varepsilon$$

The particle number and the total energy are conserved, and N and U then determine the chemical potential, μ, and T

Bose Einstein Condensation

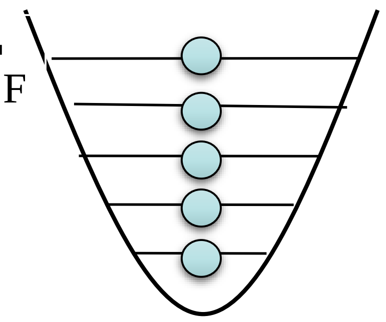
For bosons below $T_c \Rightarrow$ macroscopic occupation of single quantum state



Degenerate Fermi gases

For fermions below $T_F \Rightarrow$ atoms start to fill up states below the Fermi energy

$E_F = k_B T_F$

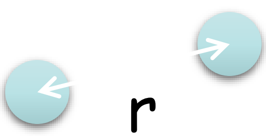


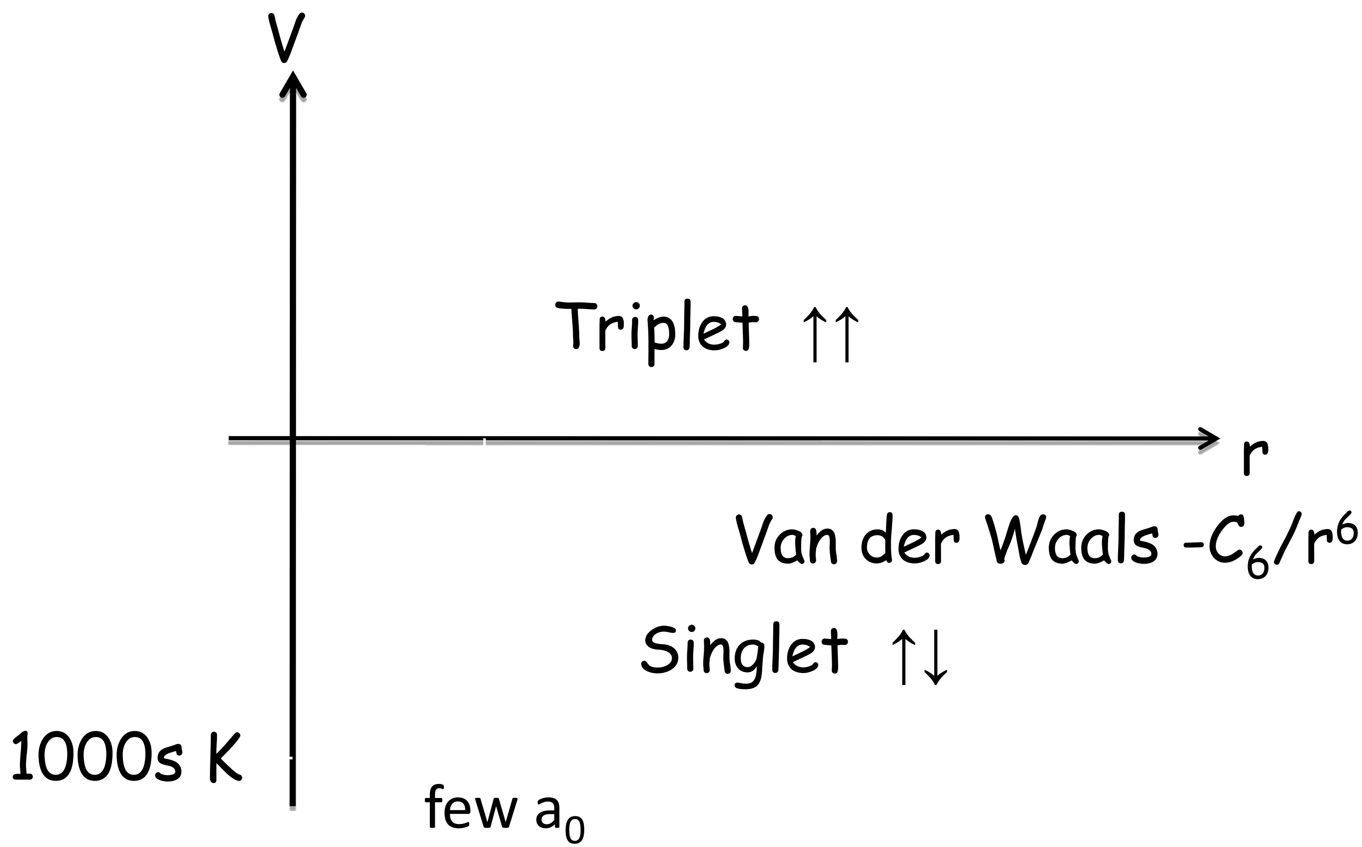
I.D

Ultra-cold Collisions

They are not like hot collisions.

Intermolecular potential





Cold collisions depend on the long range behavior.

The Mean Field

S-wave interactions can be accounted for with the Huang pseudo-potential

$$V(r) = \frac{4\pi\hbar^2}{m} a\delta^3(\vec{r})$$

- Long range behavior correct $R \propto 1 - a/r$
- Enforces boundary condition $\Psi(r = a) = 0$

This leads to the Gross-Pitaevskii equation (non-linear S.E.)

$$\left[-\frac{\hbar^2}{2m}\nabla^2 + V(\vec{r}) + \frac{4\pi\hbar^2}{m} a|\Psi|^2\right]\Psi = E\Psi = \mu\Psi \qquad \psi = \frac{1}{\sqrt{N}}\phi_0$$

The effects of collisions are taken into account by the mean field term. There is nothing irreversible about it!

As long as ψ is well known,

collisions can be used for entanglement.

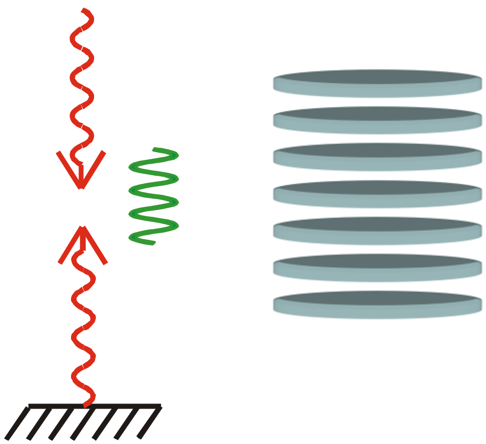
Optical Lattices

Calculable, versatile atom traps

$U_{AC} \propto$ Intensity

Far from resonance,
no light scattering

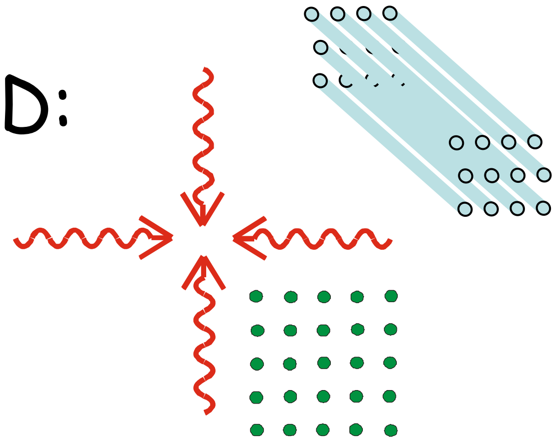
1D:



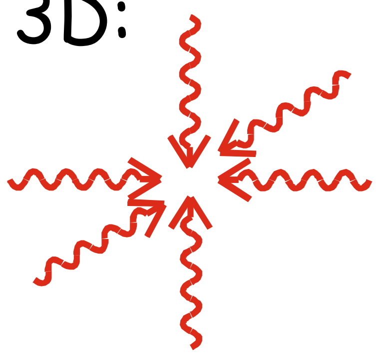
electron
electric dipole
moment search

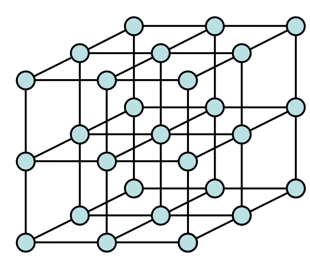
1D Bose gases

2D:



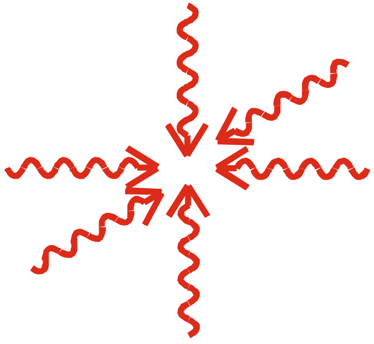
3D:





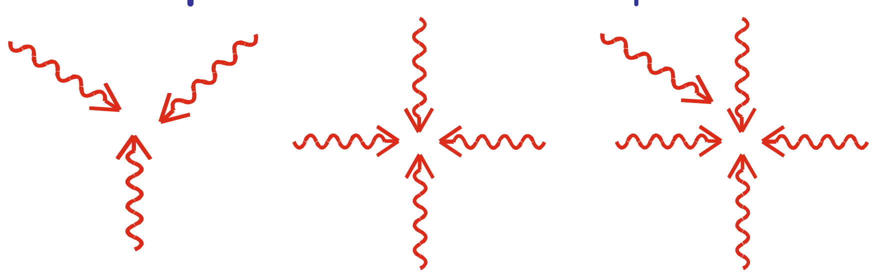
quantum computing

Optical Lattice options



If all beam pairs have different frequencies, they do not mutually interfere. Otherwise they do.

They can be m_F state-independent if all the light looks linearly polarized, or else the lattice depends on the m_F state.



They symmetry can be triangular, square or quasi-crystalline.

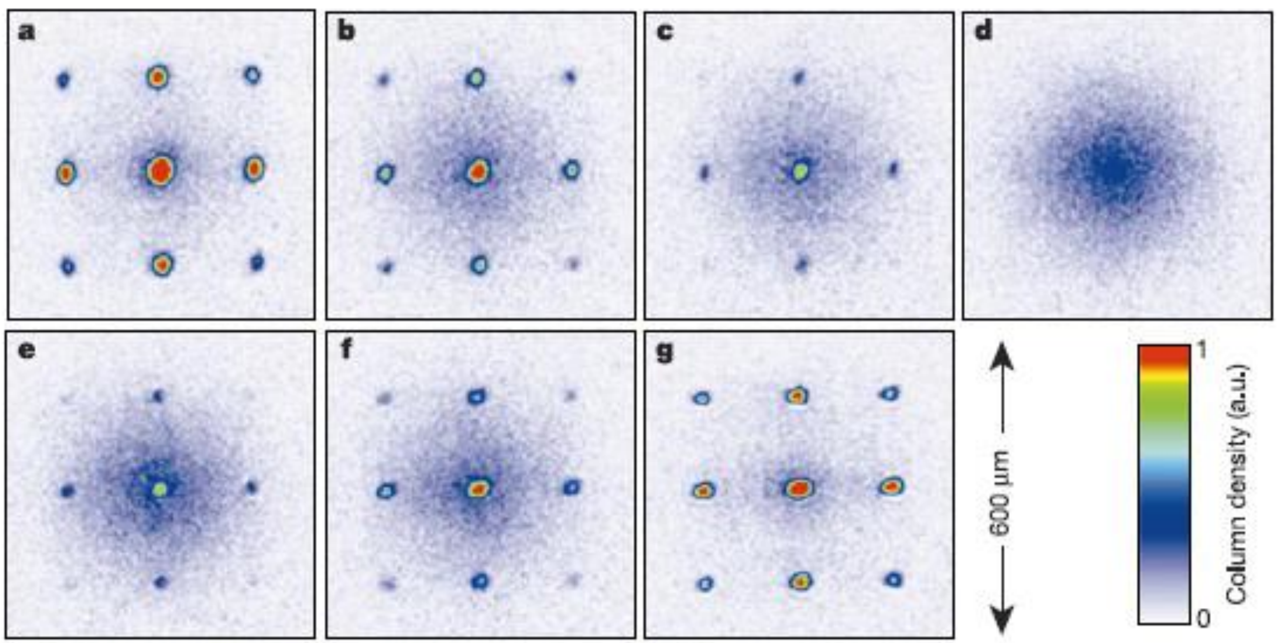
The lattice spacing can be adjusted by changing beam angles.

Double-well lattices can be produced.

Collapse and Revival

Prepare atoms in a superposition of number states at each lattice site

$$|\alpha\rangle(t) = e^{-|\alpha|^2/2}\sum_n \frac{\alpha^n}{\sqrt{n!}} e^{-\frac{i}{2}Un(n-1)t/\hbar}|n\rangle$$



Bloch

These collisions are coherent

Bose-Hubbard Hamiltonian

Expanding the field operator in the Wannier basis of localized wave functions on each lattice site, yields :

$$\hat{\psi}(\boldsymbol{x}) = \sum_i \hat{a}_i w(\boldsymbol{x} - \boldsymbol{x}_i)$$

Bose-Hubbard Hamiltonian

$$H = -J \sum_{\langle i,j \rangle} \hat{a}_i^\dagger \hat{a}_j + \sum_i \varepsilon_i \hat{n}_i + \frac{1}{2} U \sum_i \hat{n}_i (\hat{n}_i - 1)$$

Tunneling matrix element

$$J = -\int d^3x\, w(\boldsymbol{x} - \boldsymbol{x}_i) \left(-\frac{\hbar^2}{2m} \nabla^2 + V_{lat}(\boldsymbol{x}) \right) w(\boldsymbol{x} - \boldsymbol{x}_j)$$

On-site interaction matrix element

$$U = \frac{4\pi \hbar^2 a}{m} \int d^3x \left| w(\boldsymbol{x}) \right|^4$$

M.P.A. Fisher et al., PRB 40, 546 (1989); D. Jaksch et al., PRL 81, 3108 (1998)

Superfluid Limit

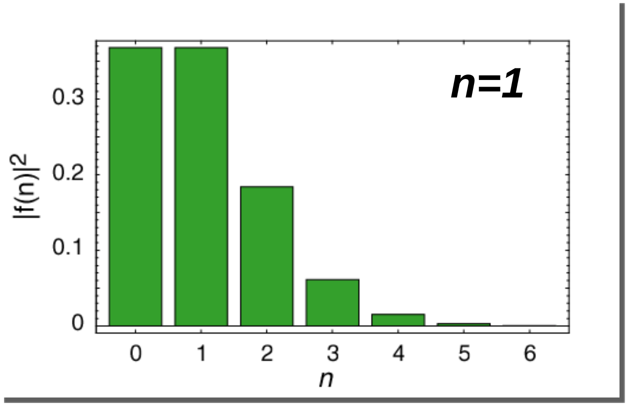
$$H = -J \sum_{i,j} \hat{a}_i^\dagger \hat{a}_j + \frac{1}{2} U \sum_i \hat{n}_i (\hat{n}_i - 1)$$

Atoms are delocalized over the entire lattice !
Macroscopic wave function describes this state very well.

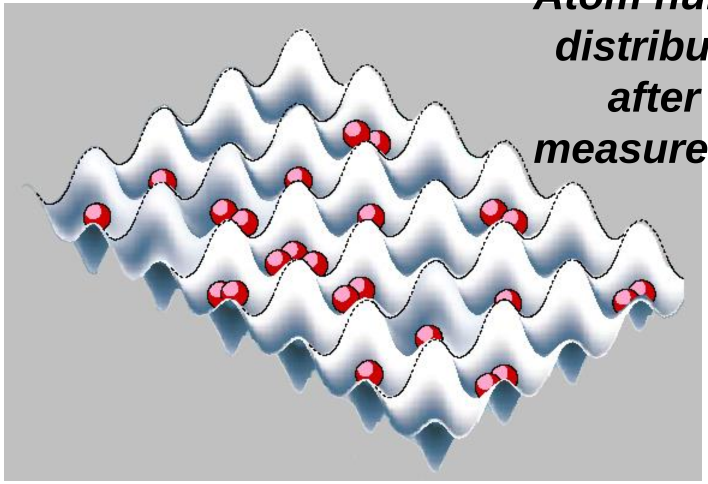
$$\left| \Psi_{SF} \right\rangle \propto \left(\sum_{i=1}^{M} \hat{a}_i^\dagger \right)^N \left| 0 \right\rangle$$

$$\left\langle \hat{a}_i \right\rangle_i \neq 0$$

Poissonian atom number distribution per lattice site



Atom number distribution after a measurement



Mott-Insulator Limit

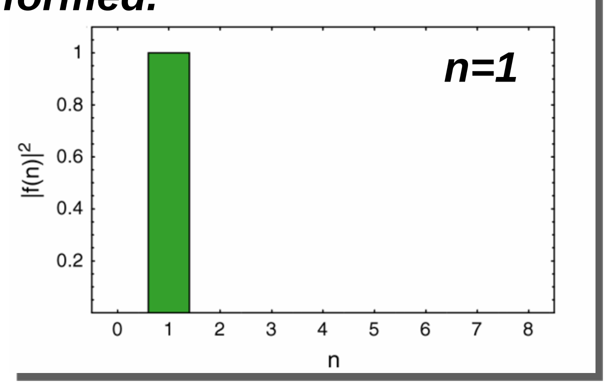
$$H = -J\sum_{i,j} \hat{a}_i^\dagger \hat{a}_j + \frac{1}{2}U\sum_i \hat{n}_i(\hat{n}_i - 1)$$

Atoms are completely localized to lattice sites !

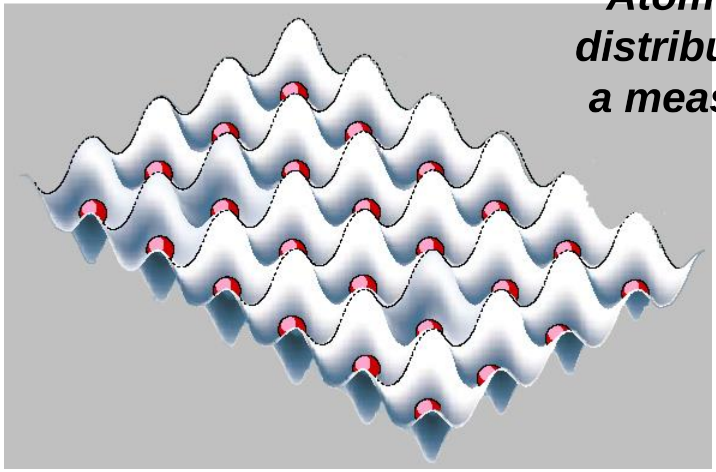
$$\left|\Psi_{Mott}\right\rangle \propto \prod_{i=1}^{M} \left(\hat{a}_i^\dagger\right)^n \left|0\right\rangle$$

$$\left\langle \hat{a}_i \right\rangle_i = 0$$

Fock states with a vanishing atom number fluctuation are formed.

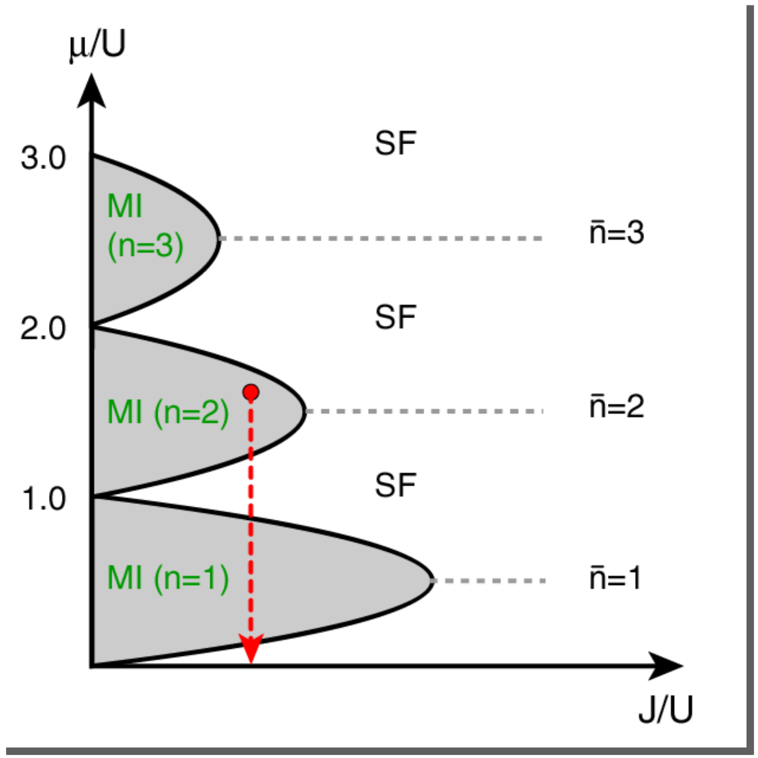


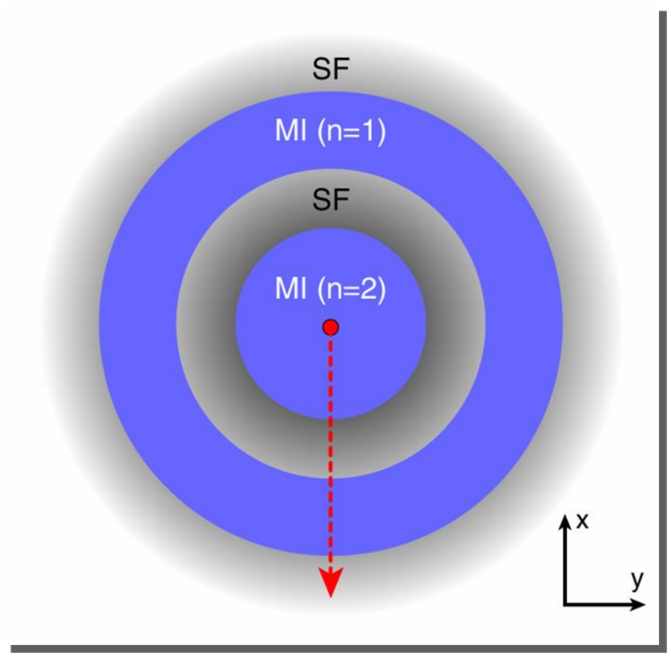
Atom number distribution after a measurement



Superfluid - Mott-Insulator Phase Diagram

Jaksch et al. PRL 81, 3108 (1998)



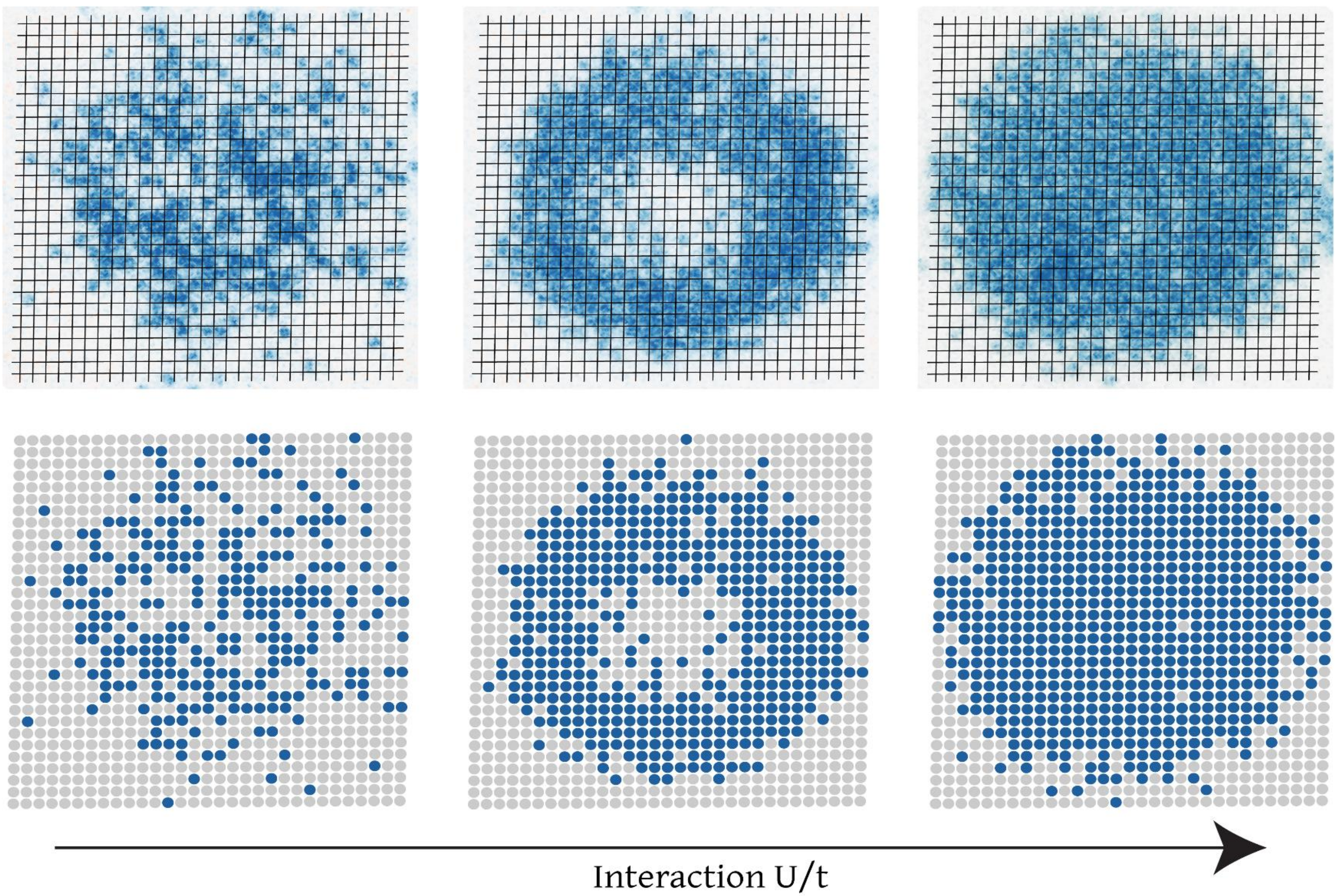


For an inhomogeneous system an effective local chemical potential can be introduced

One can imagine initializing an optical lattice quantum computer in this way. (although it's hard to correct imperfections)

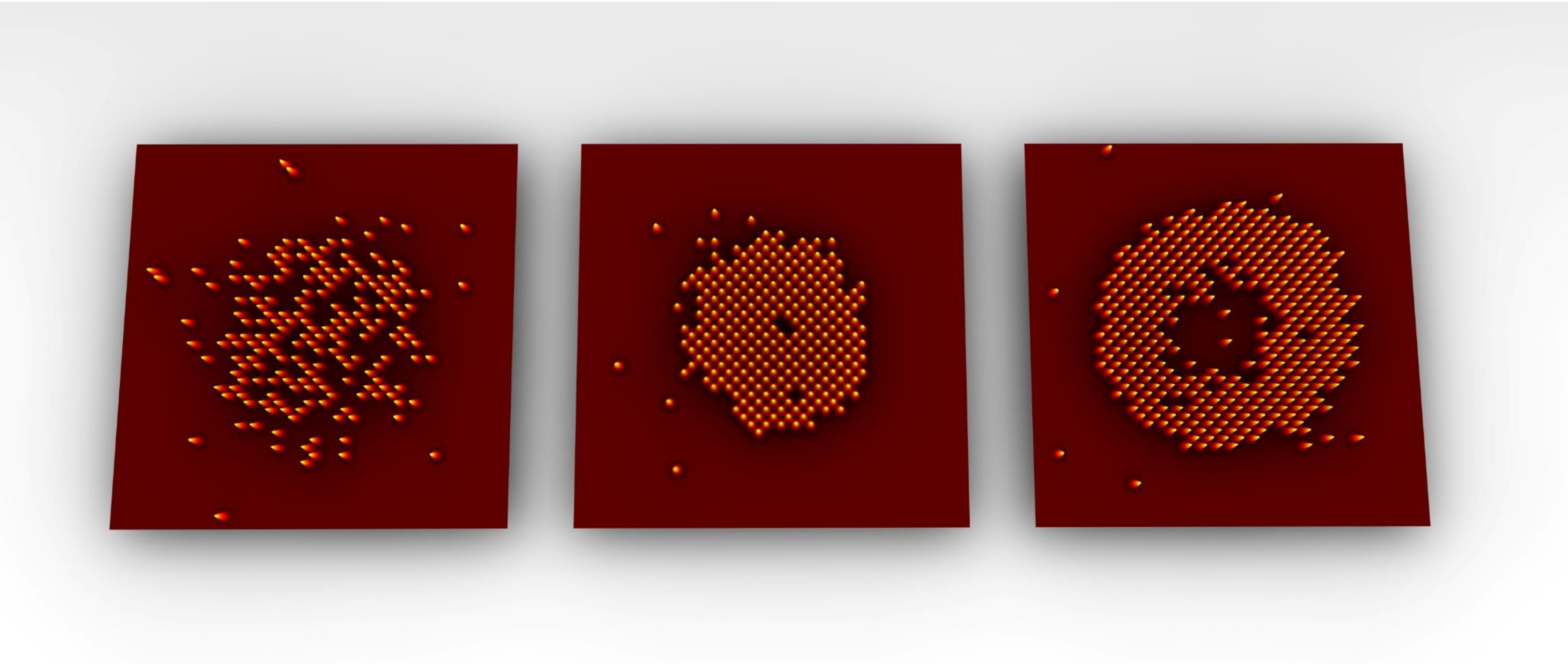
A Fermi gas microscope

image from the Greiner group



A Bose gas microscope

image from the Bloch group

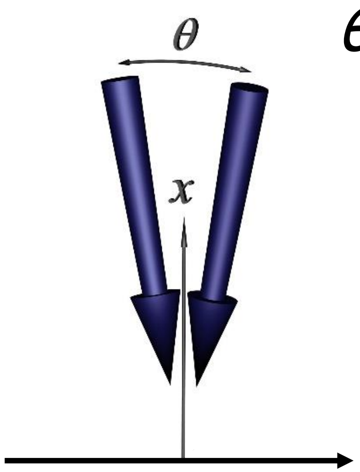


The tunneling that drives the SF-MI transition makes it hard to isolate qubits

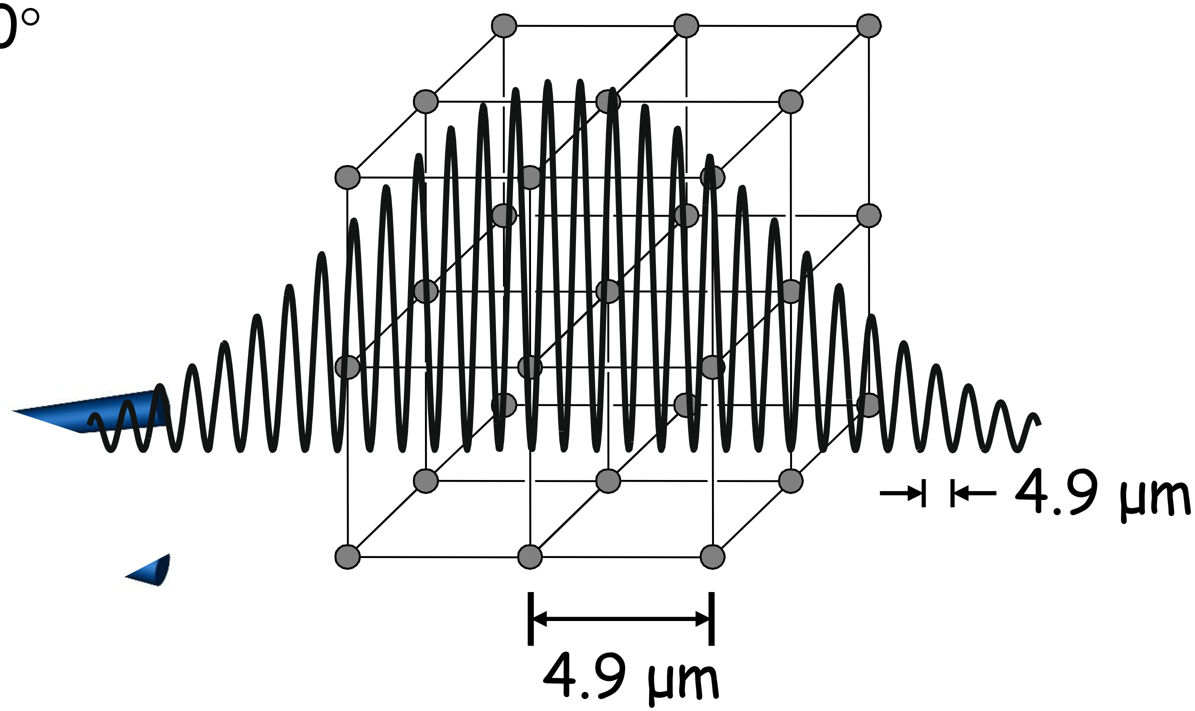
II.

3D Optical Lattice with Large Spacing (Penn State)

Our basic approach: start with many nearby qubits ➔ demonstrate gates ➔ execute them in parallel.



$\theta = 10°$



Blue-detuned: atoms trapped at intensity minima

balanced lattice beam paths

adjustable lattice spacing

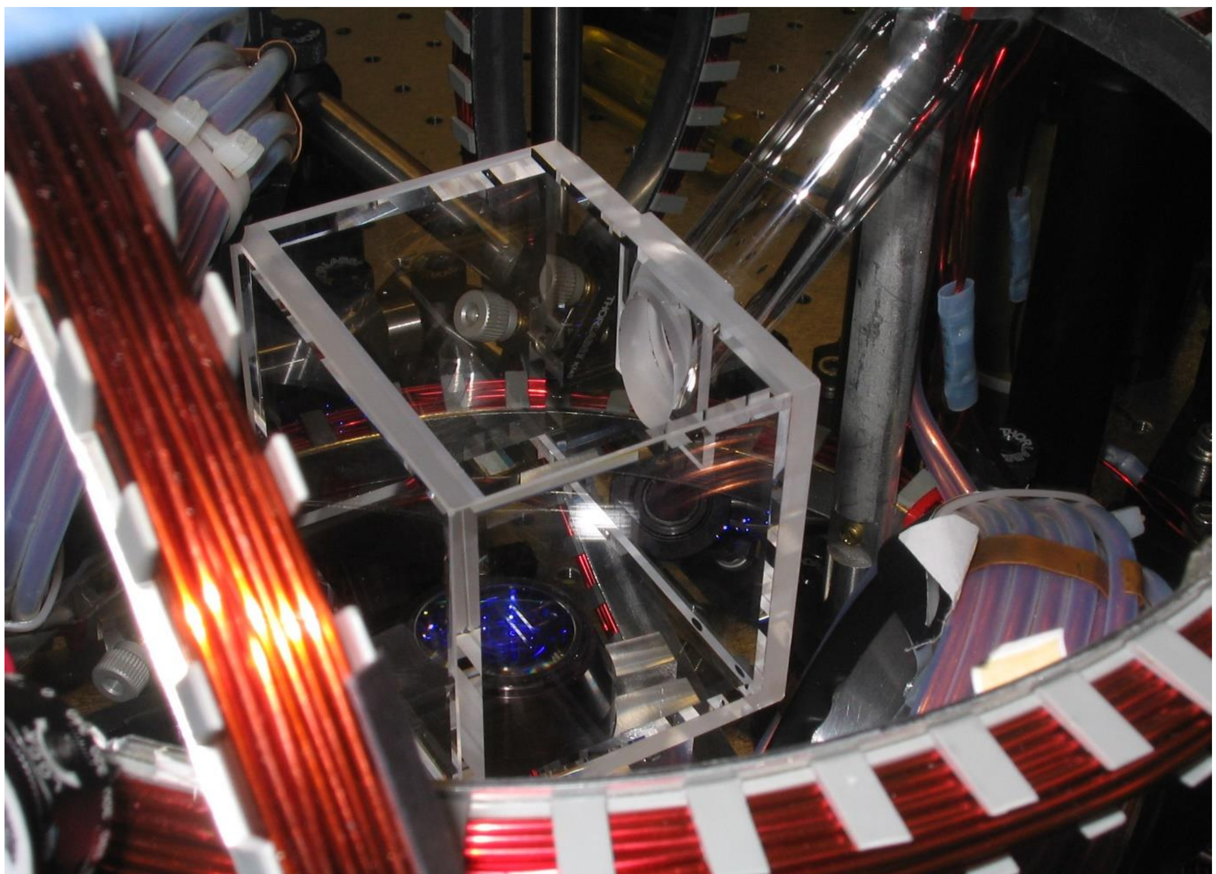
effectively linear polarization everywhere

Loading the Lattice

Fused silica vacuum cell with good optical access from 6 sides

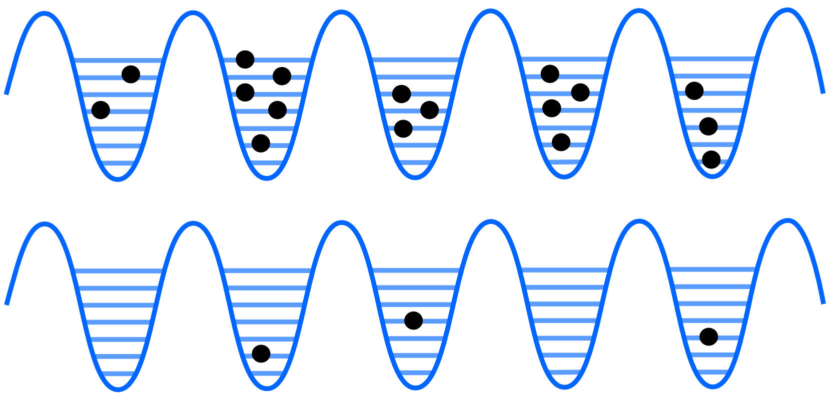
Load a small magneto-optic trap (MOT) with cesium atoms

Turn on the 3D lattice around atoms in MOT



Cooling Single Atoms in a 3D Optical Lattice

Load an average of 6 atoms per site in the lattice

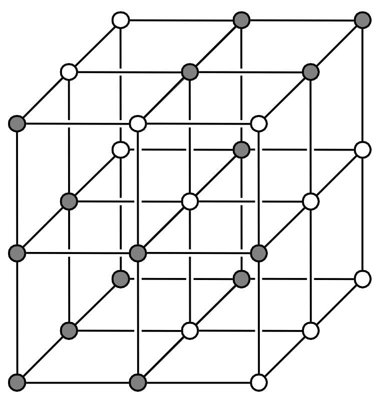


Before polarization gradient cooling

After polarization gradient cooling

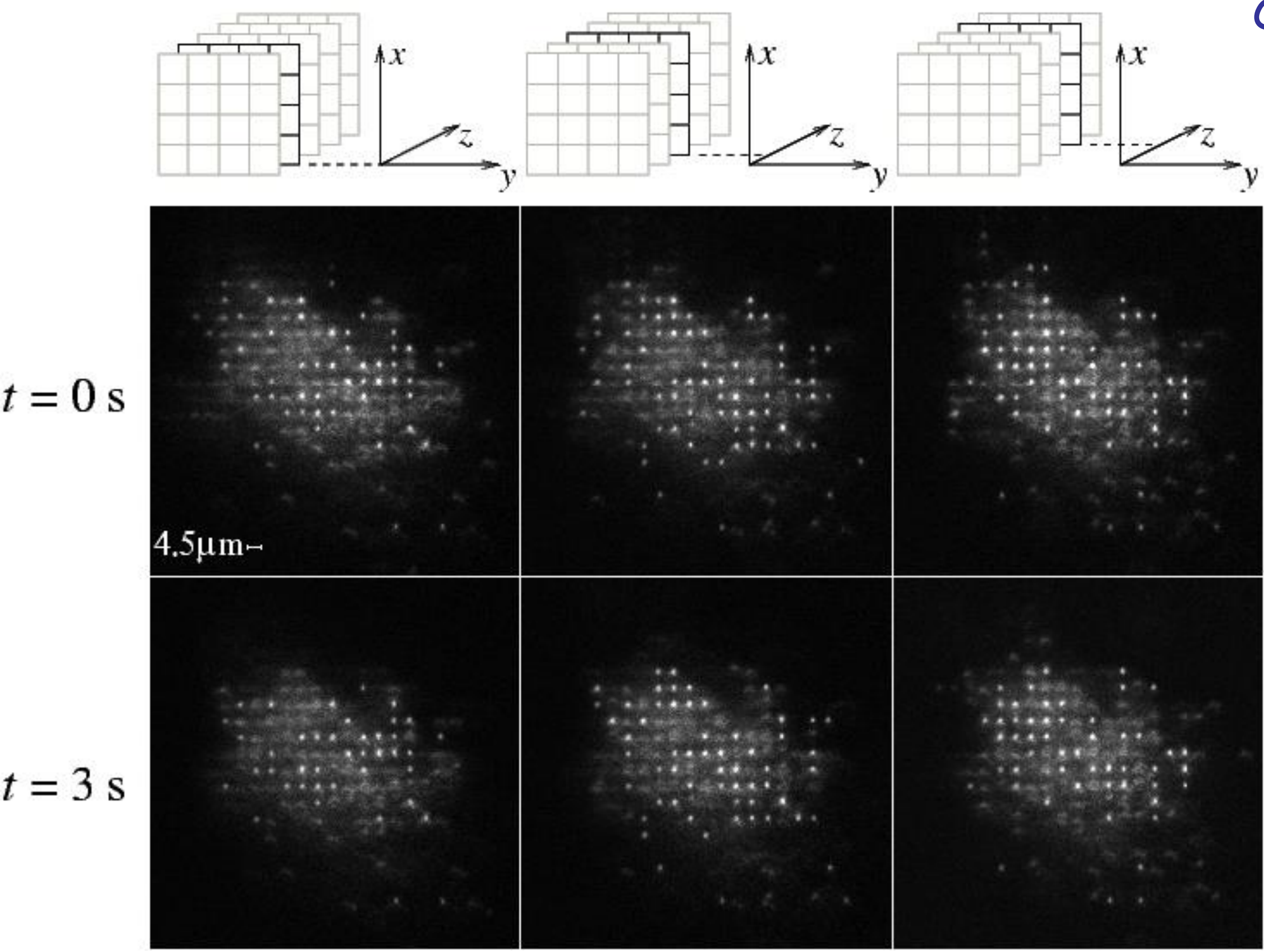
Losses occur in pairs due to light-assisted collisions

A random half of the lattice sites are occupied by a single atom



DePue, McCormick, Winoto, Oliver, DSW, PRL **82** 2262 (1999)

Imaging multiple planes



~250 atoms in central region

Image the cooling light

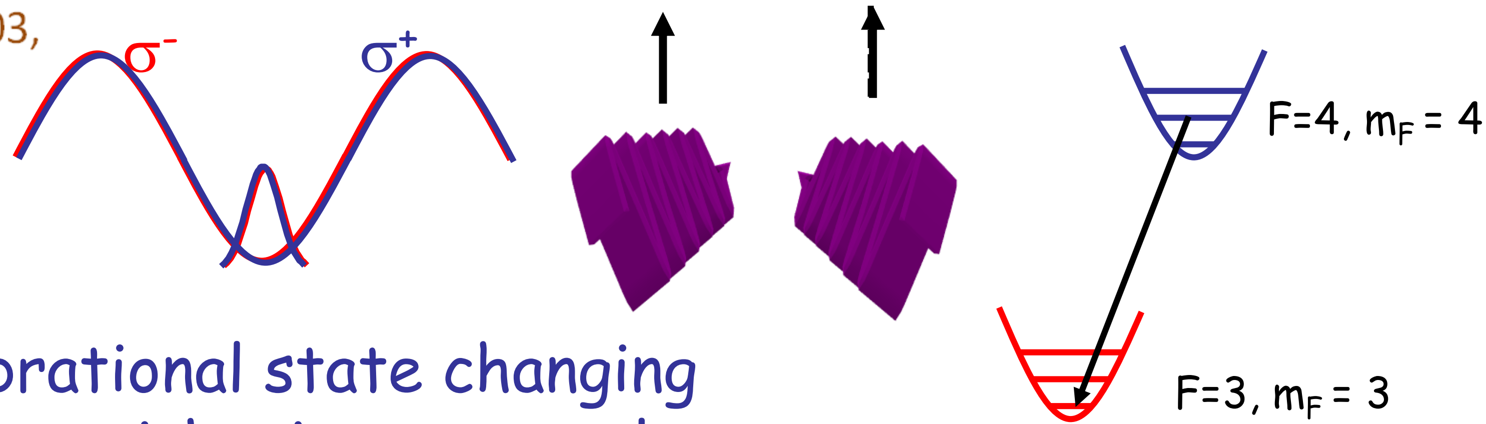
$k_B T \ll U_{lat}$

Linear gray scale: no image processing

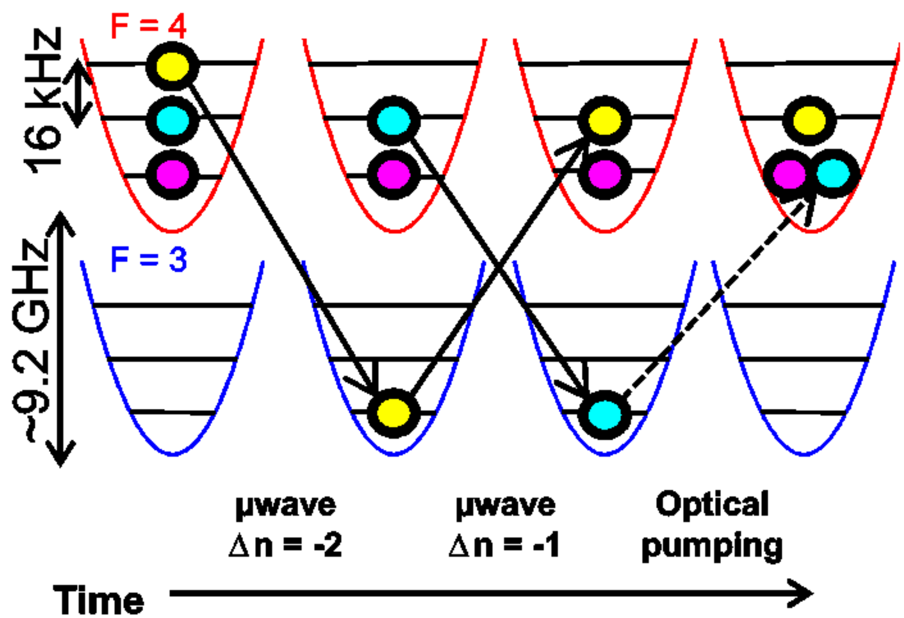
Nelson, Li & DSW, *Nature Physics* **3**, 556 (2007).

Projection sideband cooling

Főrster et al., PRL 103, 233001 (2009)



Drive vibrational state changing transitions with microwave pulses

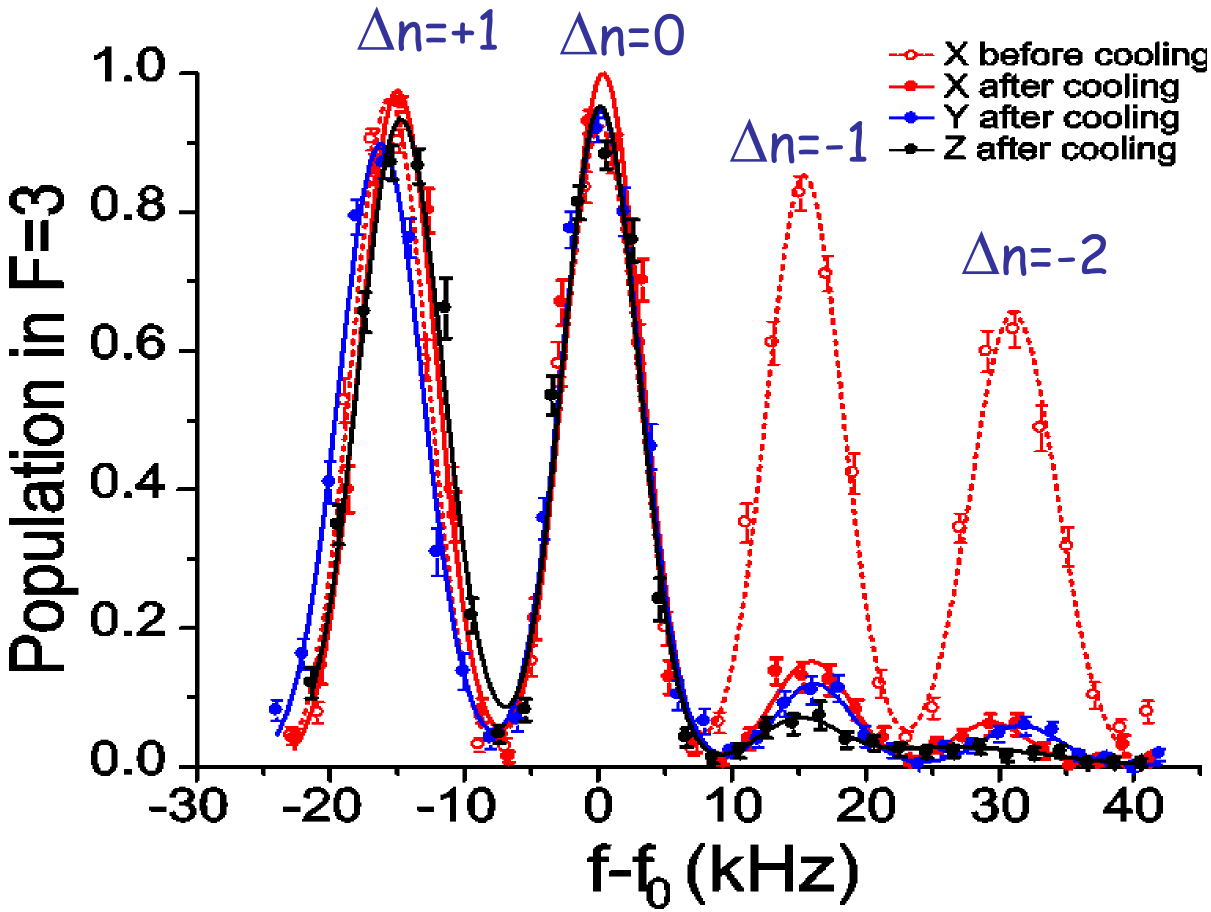


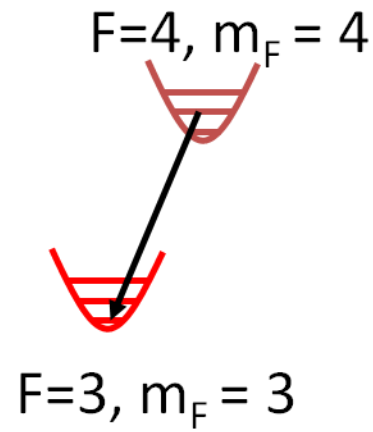
Use adiabatic fast passage for robustness.
Cycle through each direction.
Fewest possible optical pumping steps.

Especially useful for weak Lamb-Dicke limit

3D projection cooling results

After 25 cycles

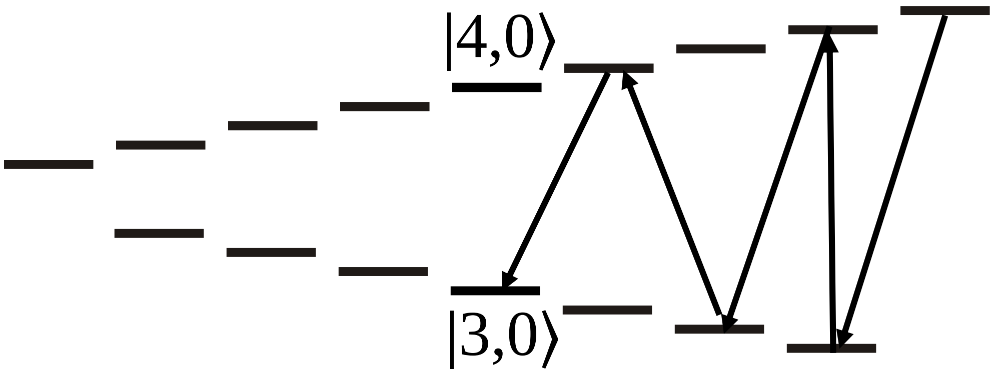




76% of the atoms are in the 3D vibrational ground state (~200 nK) (Recently, 87%.)

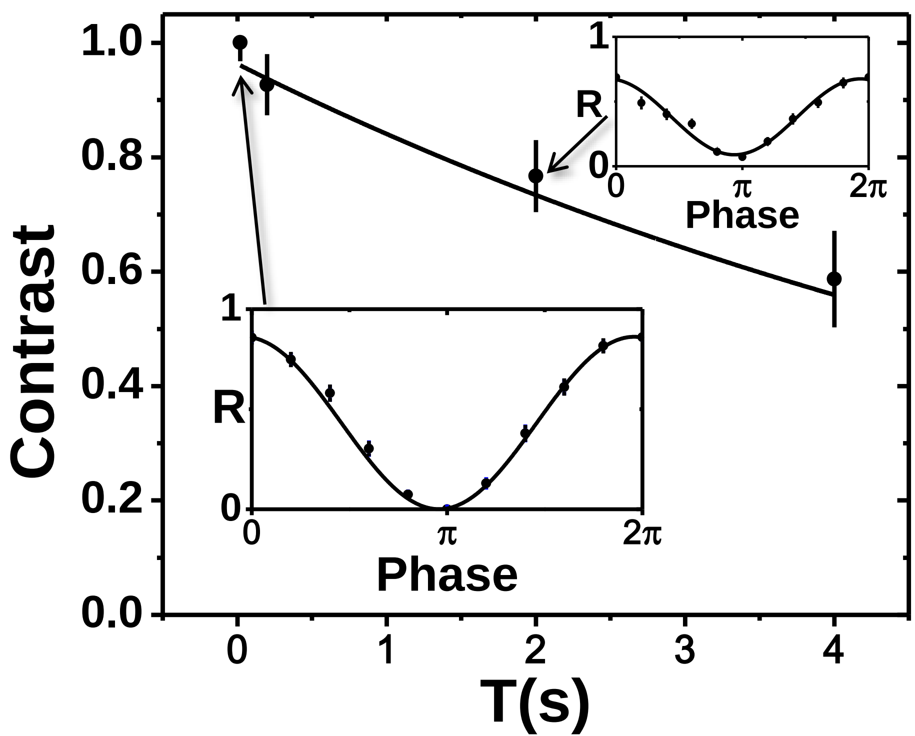
X. Li, T. Corcovilos, Y. Wang, and DSW, *PRL* **108**, 103001 (2012)

Long coherence times



Adiabatic rapid passage pulse transfer to clock states

Spin echo spectroscopy between clock states (π/2-π-π/2)

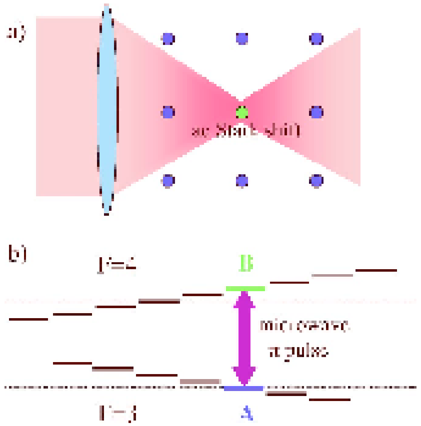


T_1 times exceed 7 s (**now ~20 s!**)

Vacuum lifetimes exceed 80 s

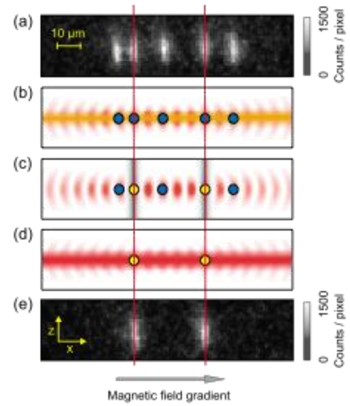
Single site addressing

Theory Proposal



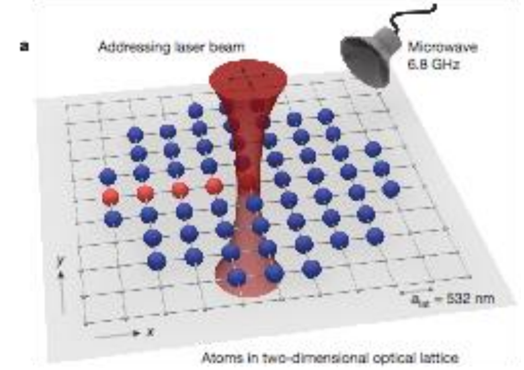
Penn State, 2004
JQI, 2007

State-flipping in 1D



Bonn, 2004

State-flipping in 2D

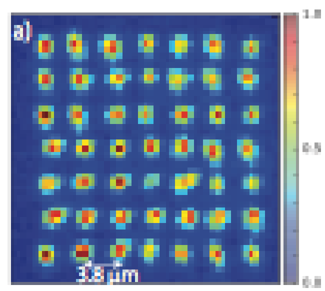


Munich, 2011

Coherent addressing of a single <2% filled plane

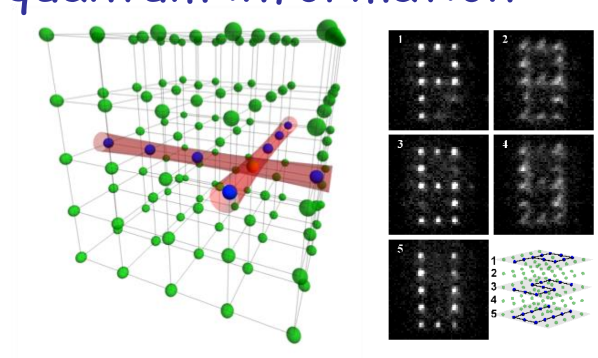
Arizona, 2013

Universal targeted gate without neighboring quantum information



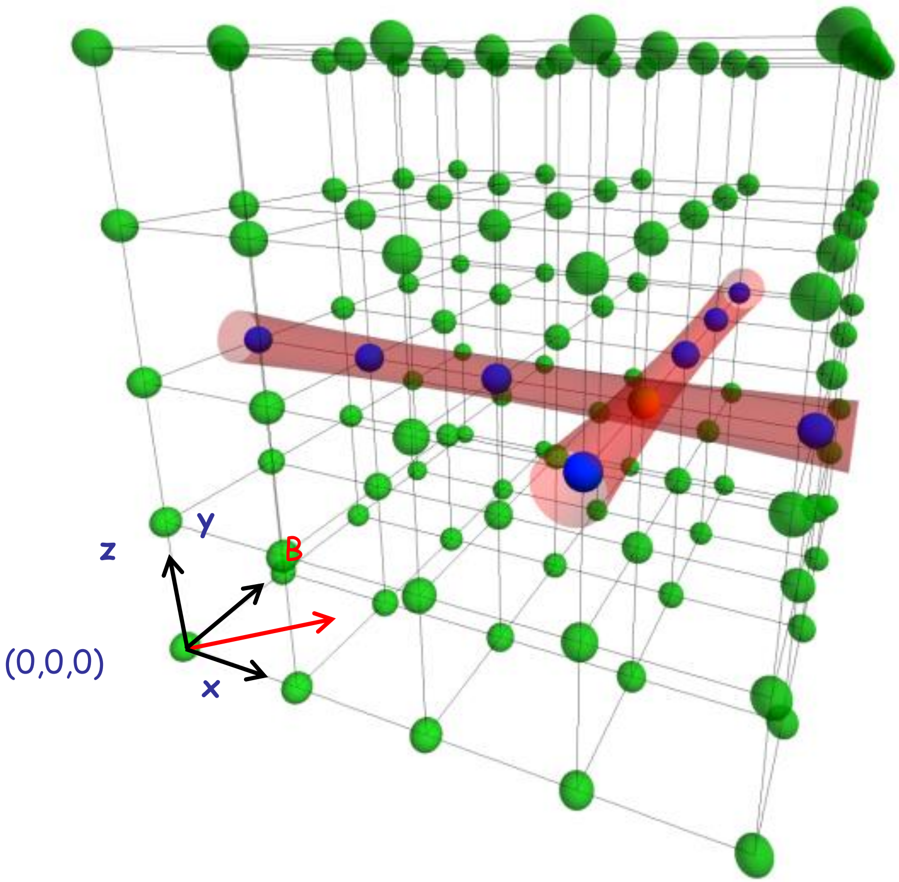
Wisconsin, 2015

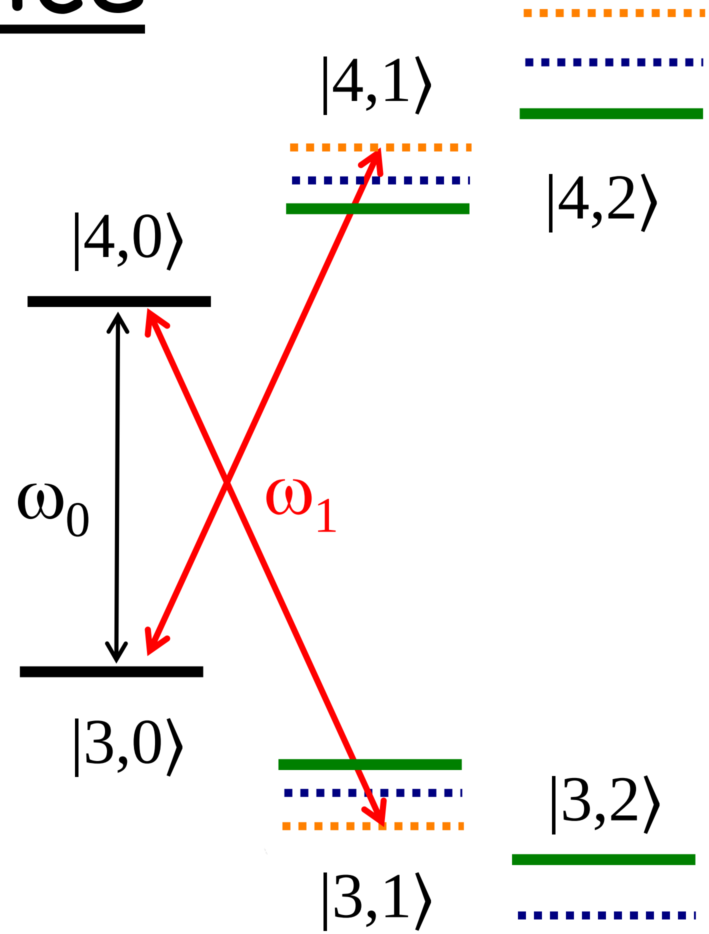
Coherent addressing without affecting nearby quantum information



Penn State, 2015, 2016

Single site addressing in a 3D lattice

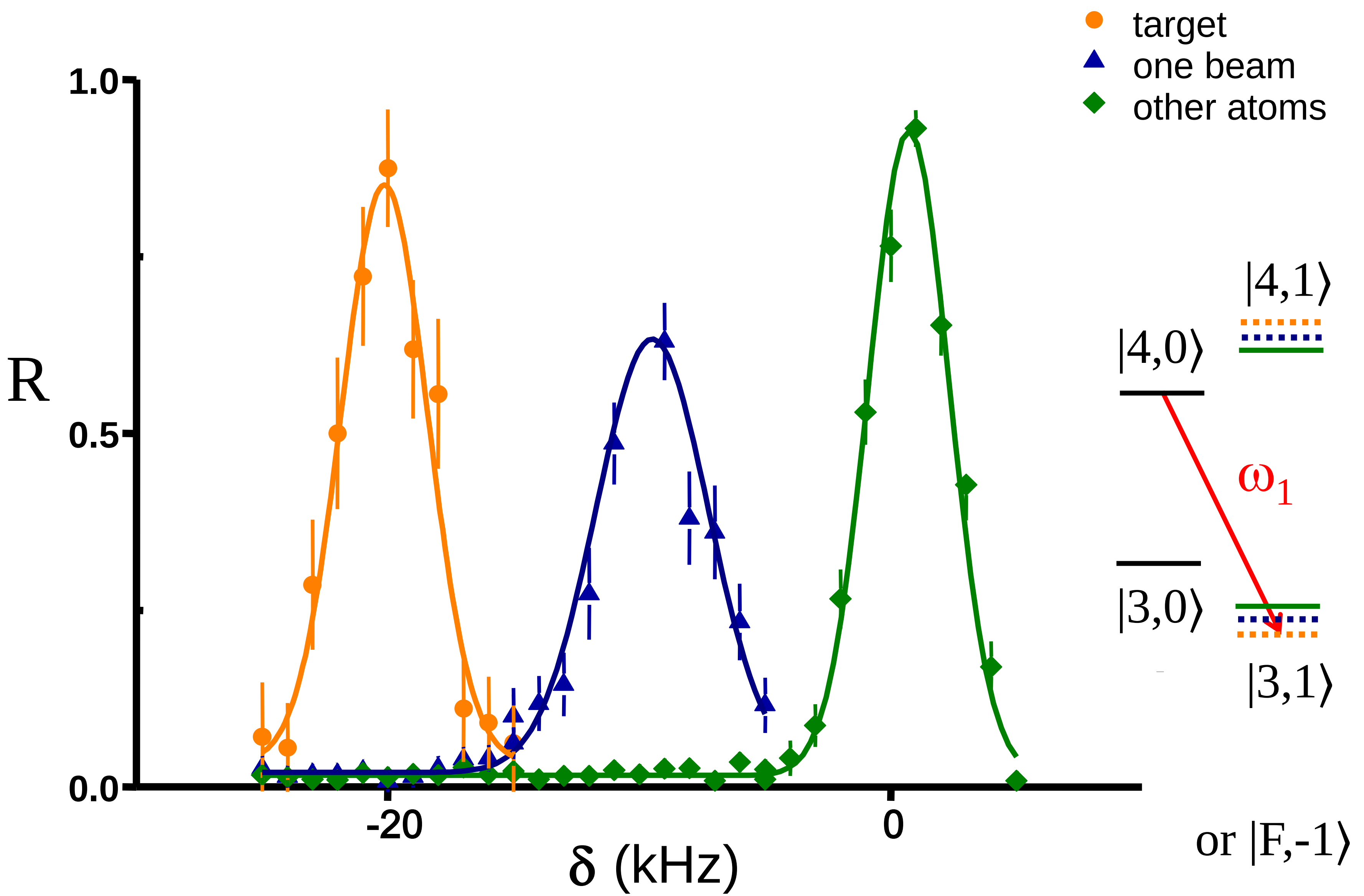




DSW, Vala, Thapliyal, Myrgren, Vazirani, Whaley, PRA **70**, 040302 (2004); Weitenberg et al., Nature **471**, 319 (2011); Xia, et al. PRL **114**, 100503 (2015); Y. Wang, X. Zhang, T. Corcovilos, A. Kumar & DSW. PRL. 115, 043003 (2015)

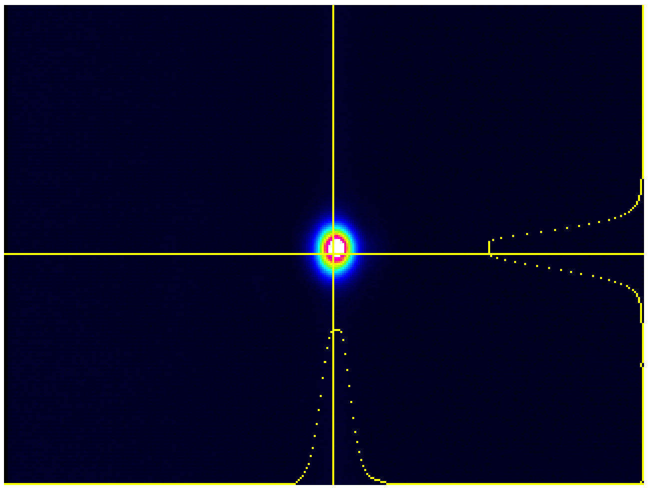
Access atoms in a 125 site volume

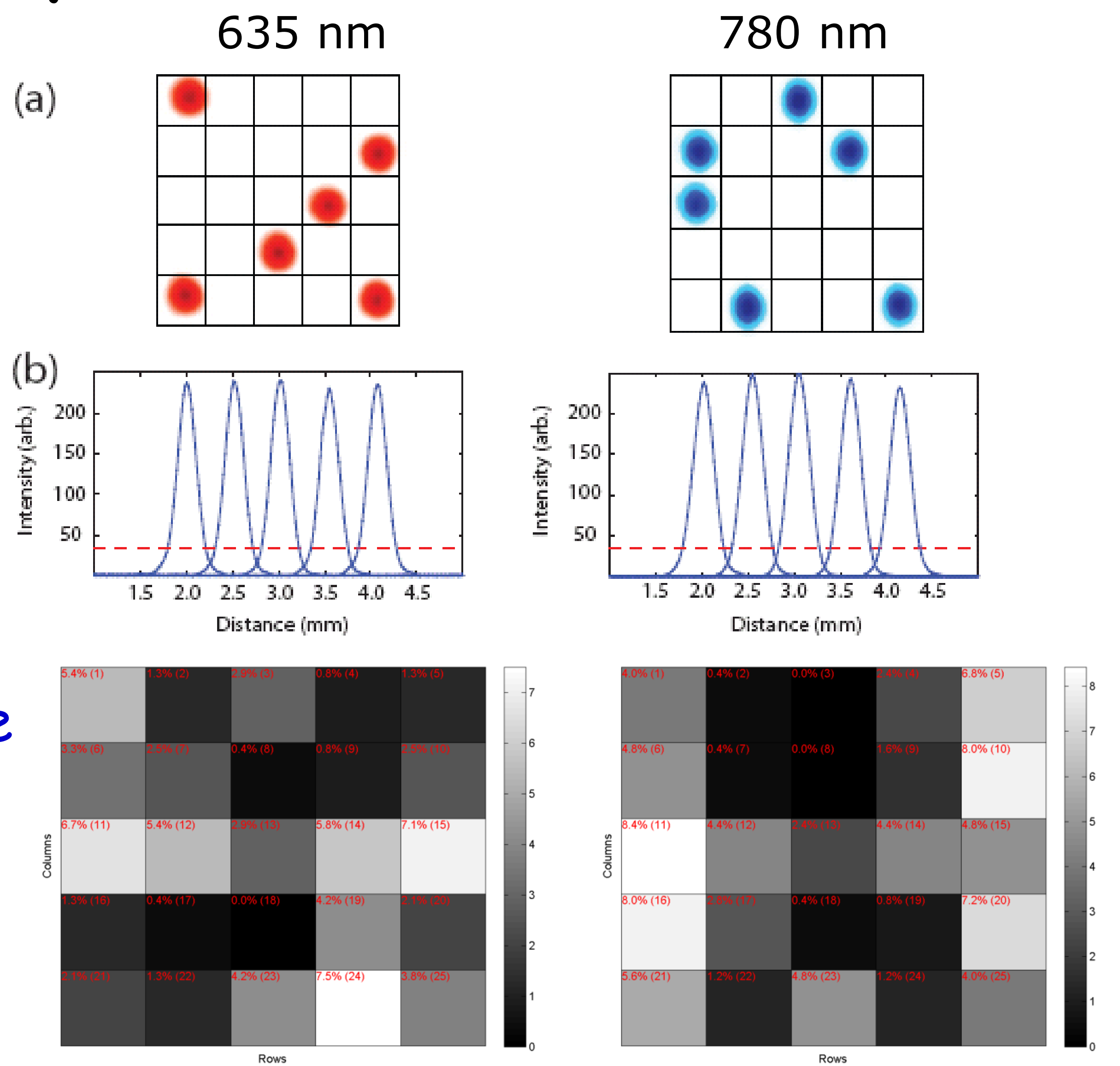
Addressing spectroscopy



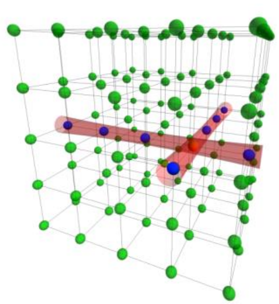
MEMS beam steering capability

Jungsang Kim group



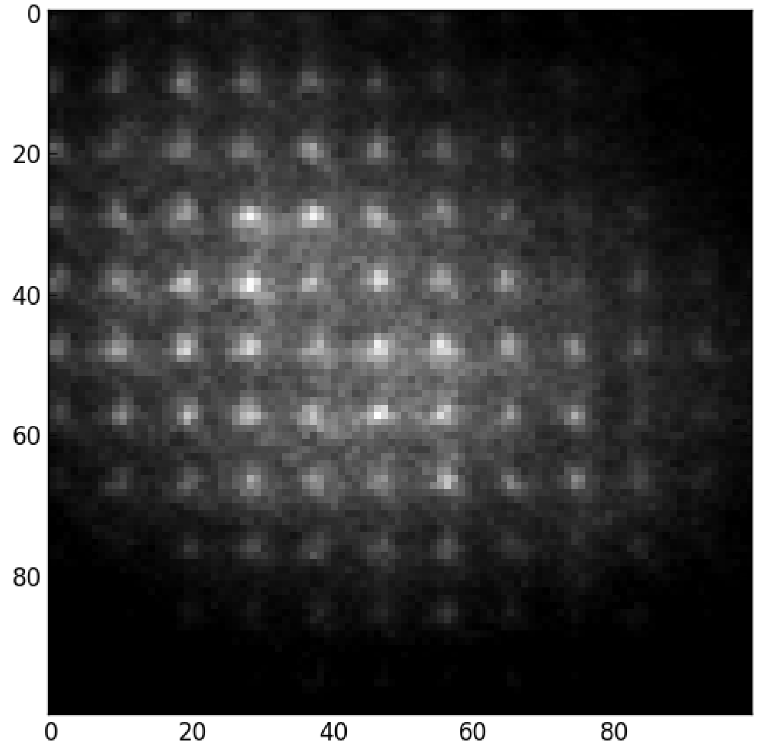


- Full addressability to 25 sites in a plane
- <5 μs redirection time



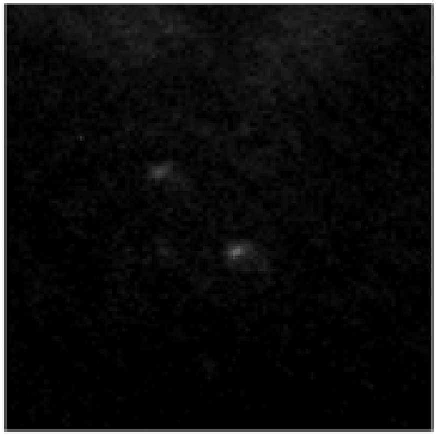
All atoms in a plane, average pictures

from ~20 implementations



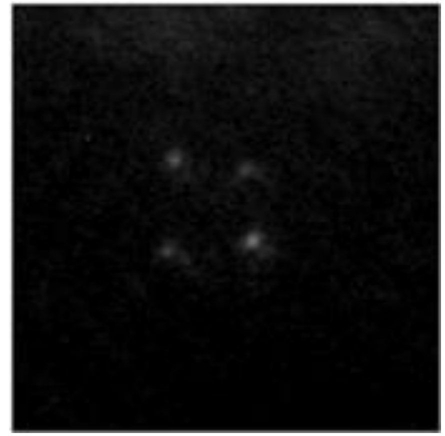
State changing atoms at single sites

1



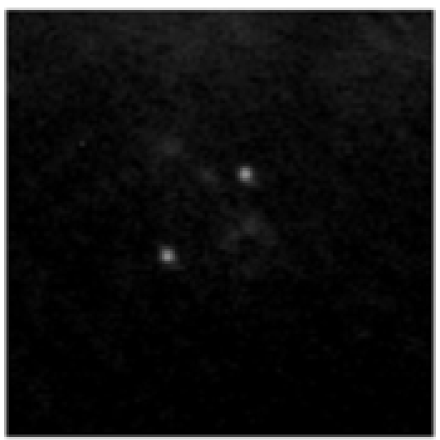
2

3

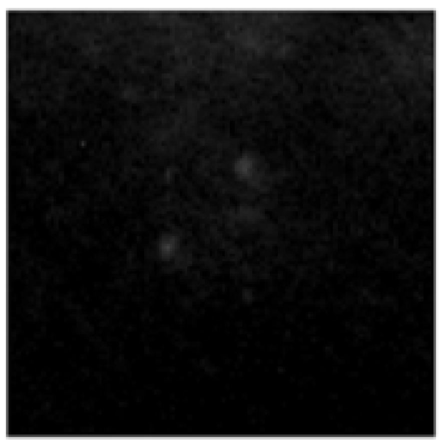


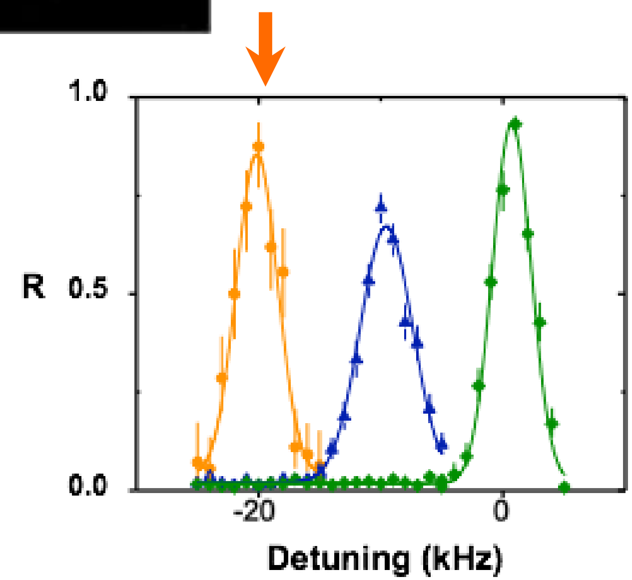
2 atoms in each of two planes

4



5



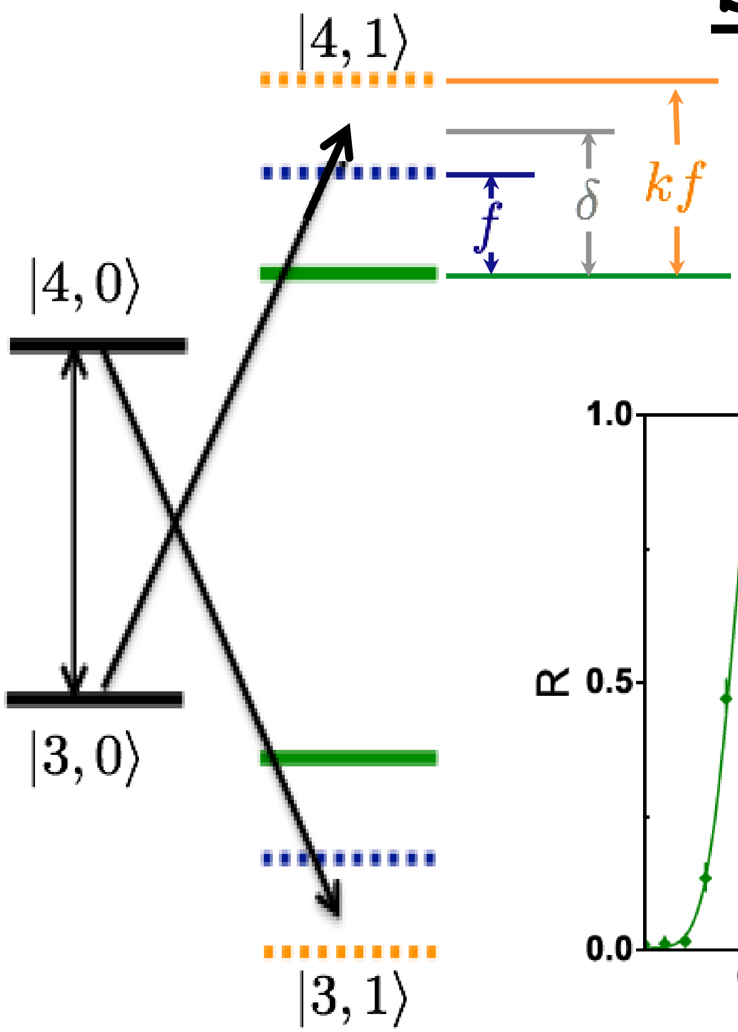


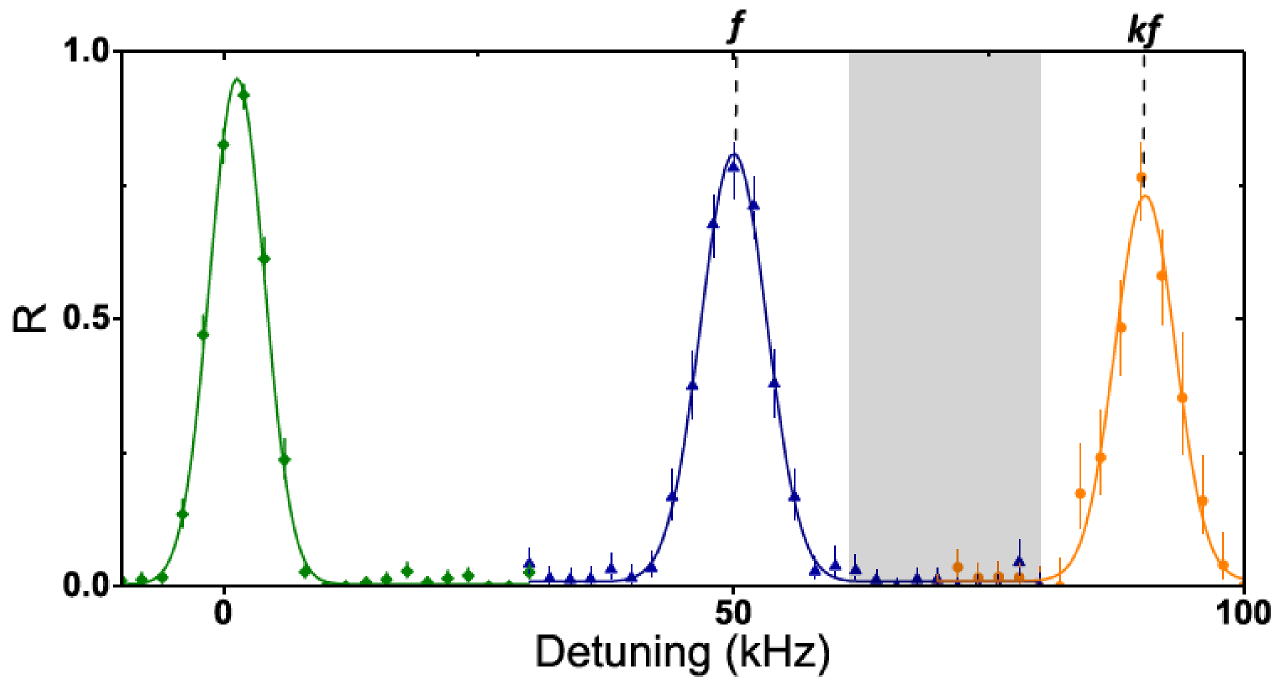
Arbitrary single qubit gates demonstrated:

Y. Wang, X. Zhang, T. Corcovilos, A. Kumar & DSW. PRL. 115, 043003 (2015)

Single qubit gates based on targeted phase shifts (much better)

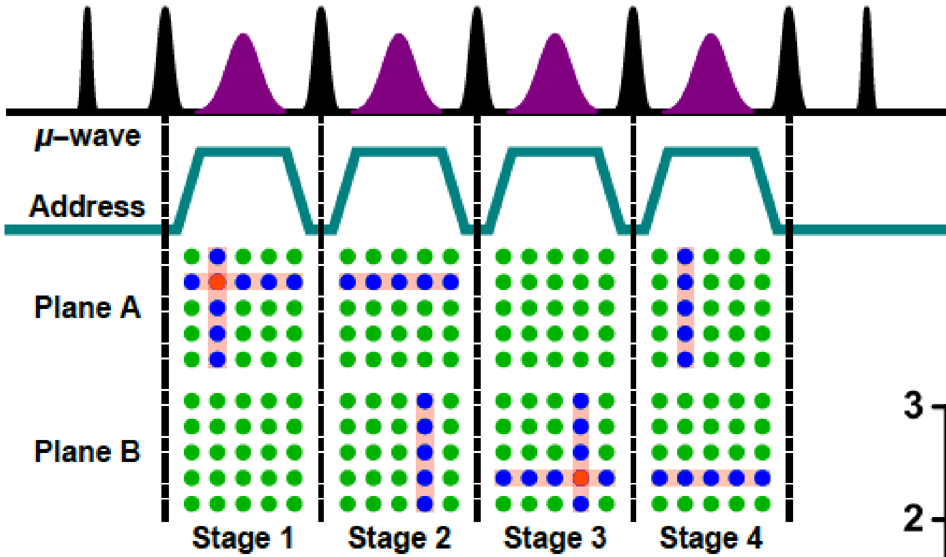
Without leaving the storage basis, use microwave ac Zeeman shifts to alter the phase of the target site

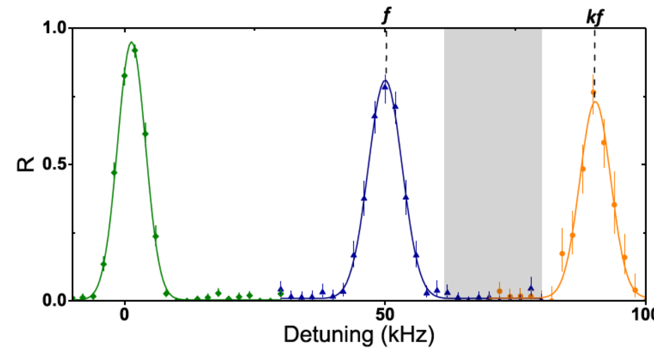




Y. Wang, A. Kumar, T-Y Wu, & DSW. arXiv:1601.03639 (2016), submitted

The phase gate structure

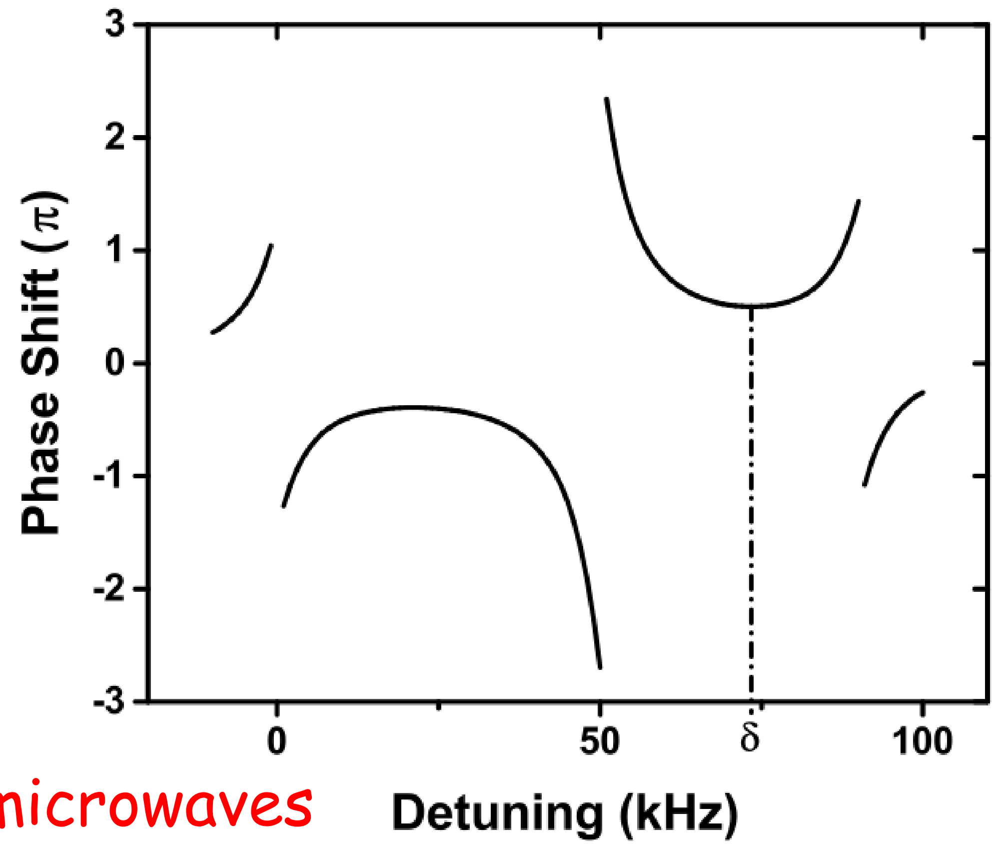




Phase of target site

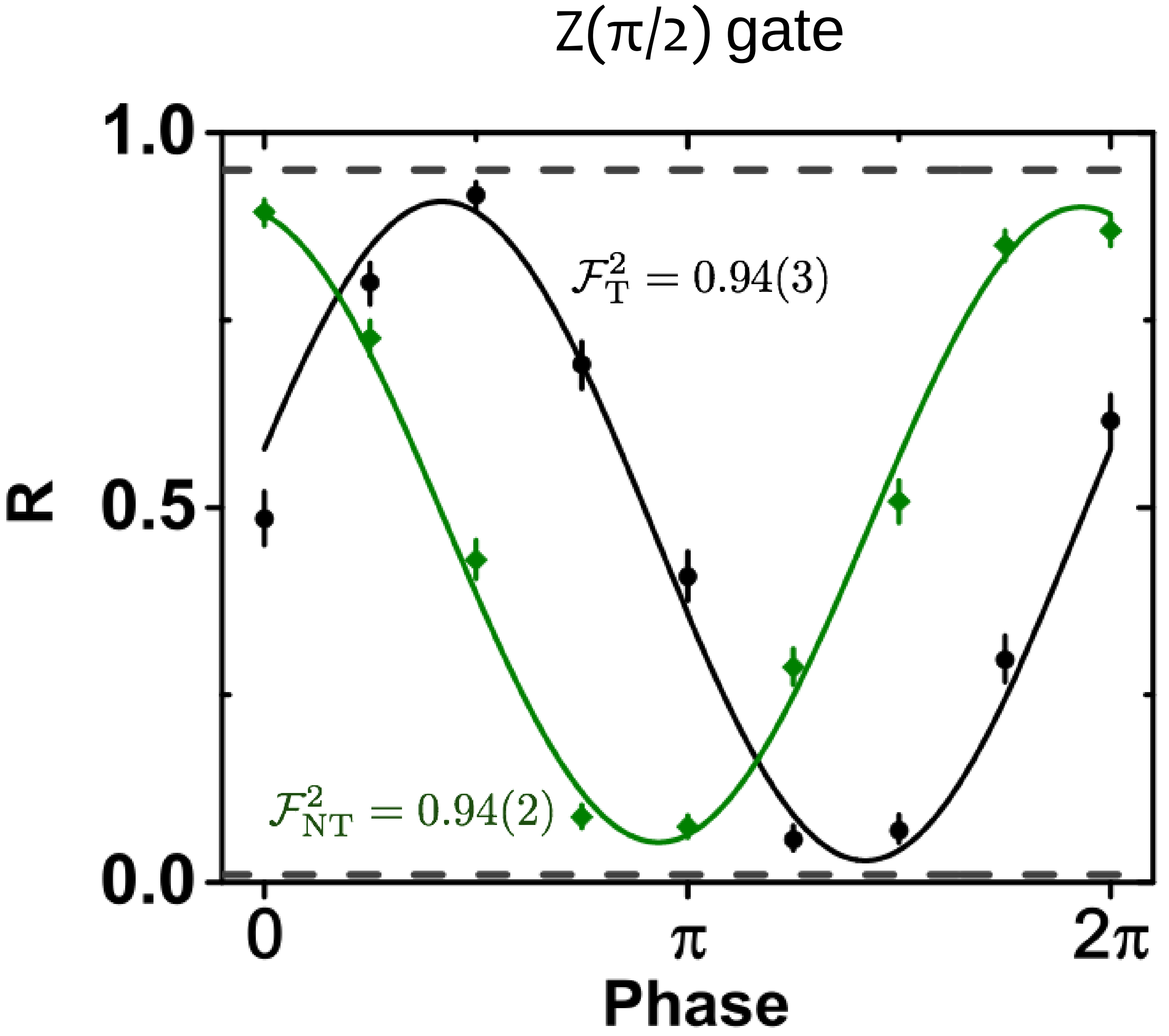
$$\frac{\Omega^2 t}{2(\delta - kf)} - \frac{\Omega^2 t}{2(\delta - f)} + \frac{\Omega^2 t}{2\delta} - \frac{\Omega^2 t}{2(\delta - f)}$$

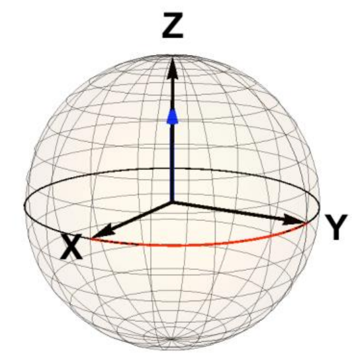
For target sites, the phase shift is only second order sensitive to the ac Stark shift of the addressing light, and hence only fourth order sensitive to alignment fluctuations.



Fidelity depends mostly on microwaves

Gates at 48 randomly chosen sites





error per gate (EPG):
$\mathcal{E} = 13(7) \times 10^{-4}$

an average of **20** qubits experience the phase gate during each implementation

Generating a universal set of gates

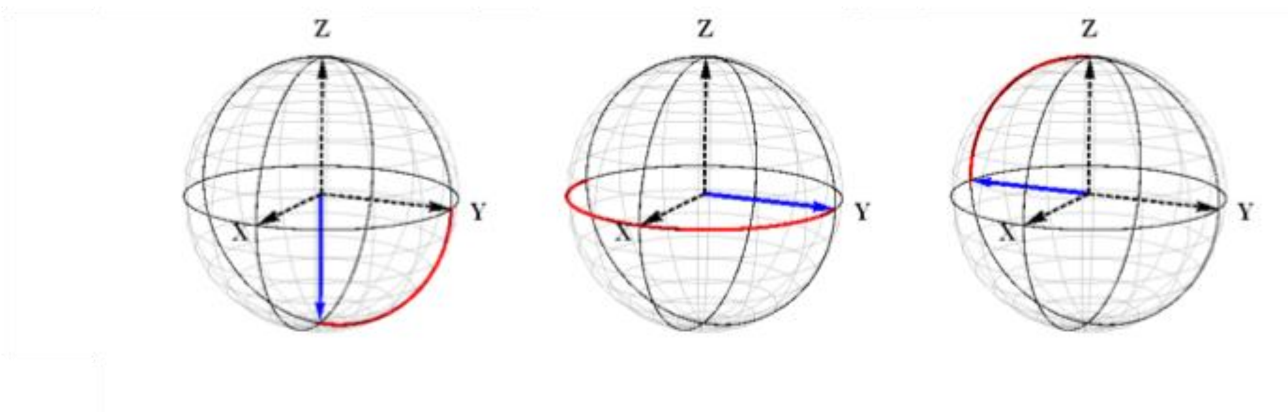
Rotations about the X and Y axes can be implemented by sandwiching a targeted phase gate between global microwaves $\pi/2$ pulses

Global rotations

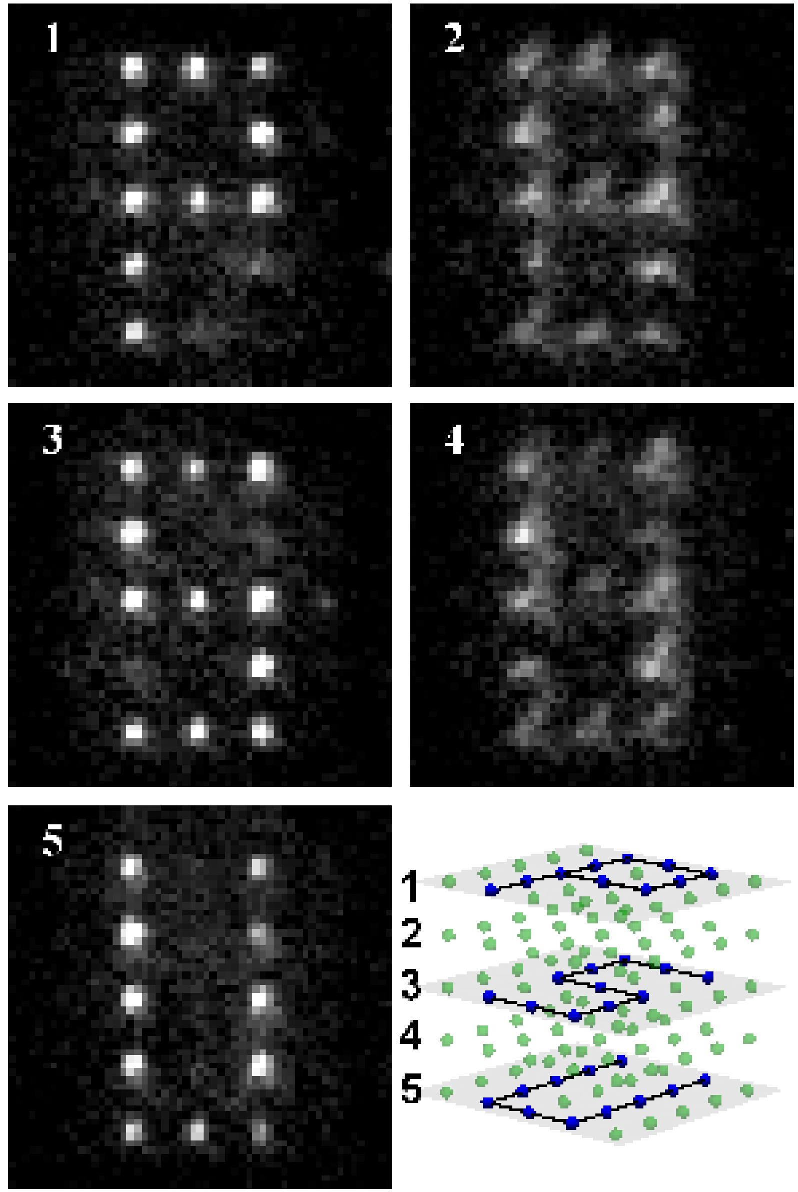
$$R_x\left(\frac{\pi}{2}\right) R_z(\theta)\, R_x\left(-\frac{\pi}{2}\right) = R_y(\theta)$$

Targeted Phase Gate

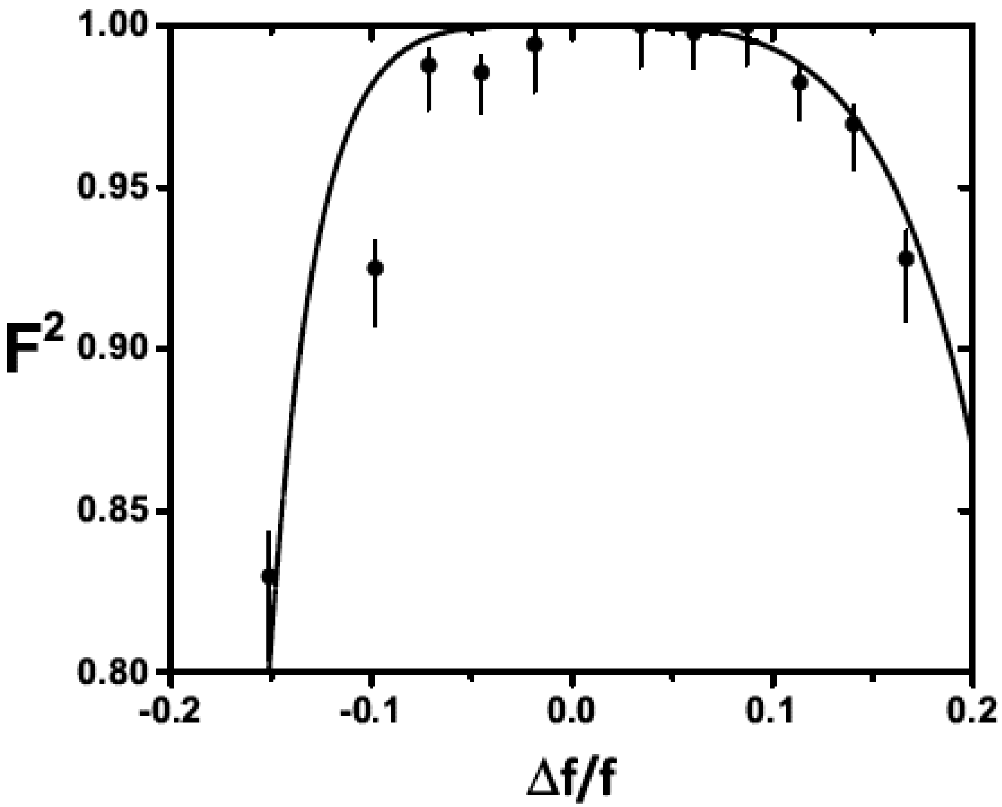
A simple example, $R_y(\pi)$

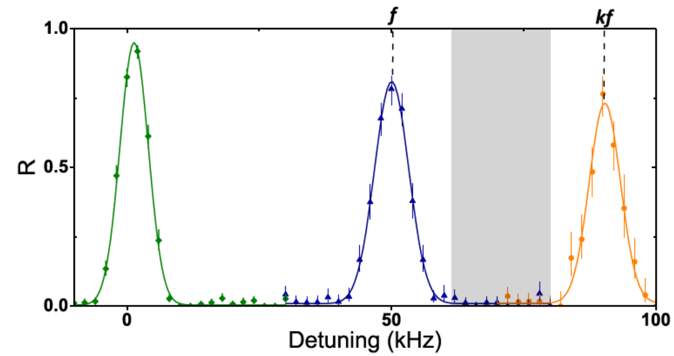


Quantum gates in any pattern



Addressing Robustness

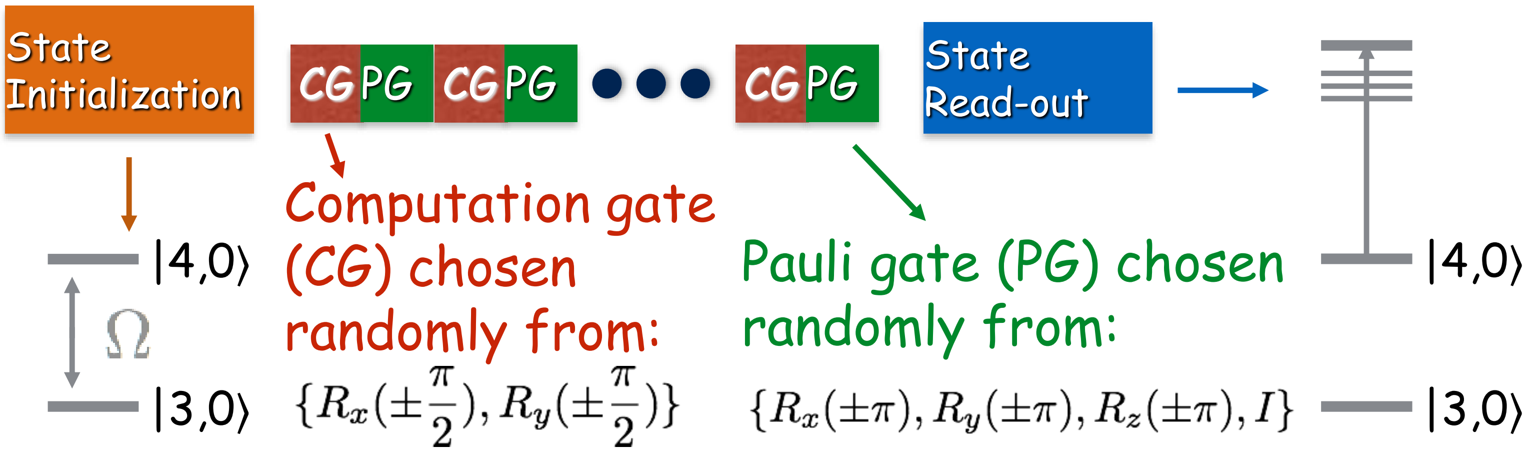


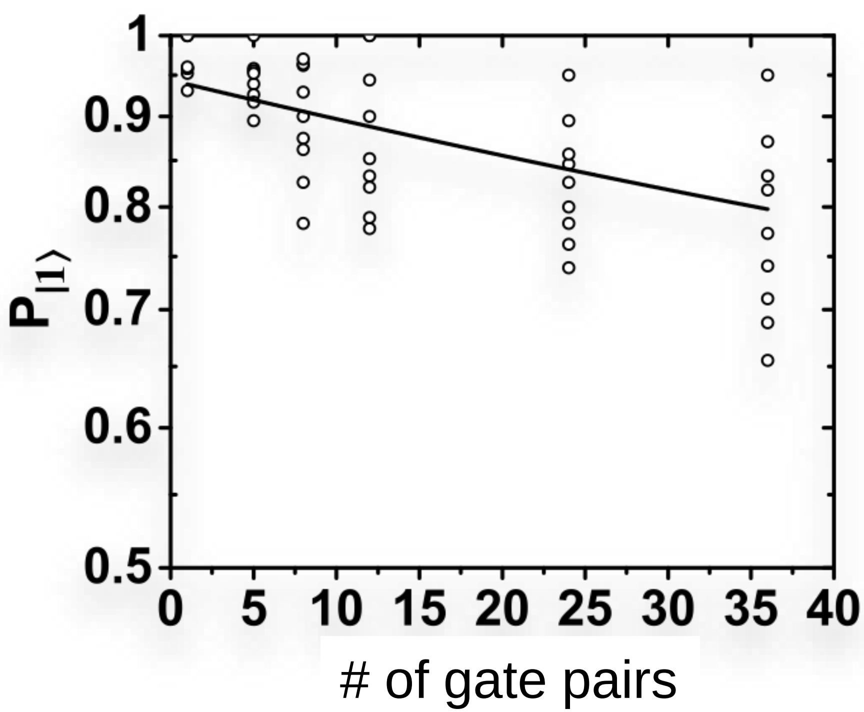


$$\frac{\Omega^2 t}{2(\delta - kf)} - \frac{\Omega^2 t}{2(\delta - f)} + \frac{\Omega^2 t}{2\delta} - \frac{\Omega^2 t}{2(\delta - f)}$$

Randomized Benchmarking

E. Knill *et al.* Phys. Rev. A, 77(1). 2008





$$\overline{\mathcal{F}^2} = \frac{1}{2} + \frac{1}{2}(1 - d_{\text{if}})(1 - 2\mathcal{E}_{2t})^l$$

$$\mathcal{E}_{2t} = (55 \pm 16) \times 10^{-4}$$

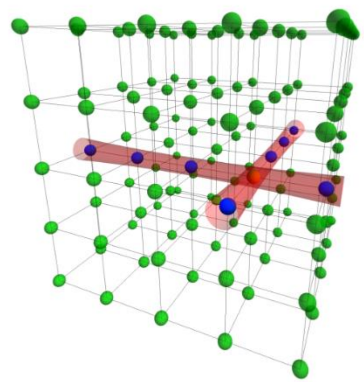
Error per gate: $(33\pm16) \times 10^{-4}$

Cross talk error: $(17\pm2) \times 10^{-4}$

There is a clear path to fault-tolerance

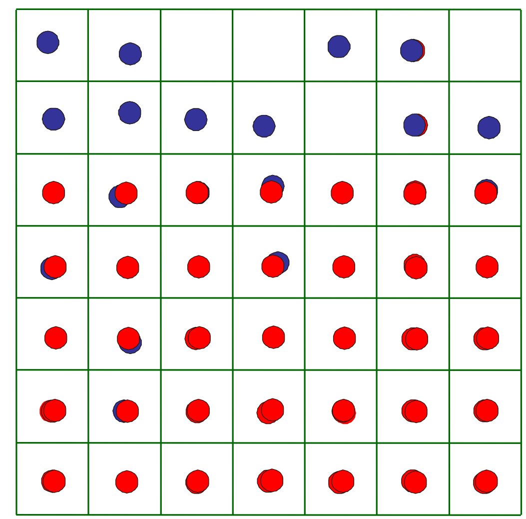
Lattice compacting

Focused beam & microwaves gives site-selective state change

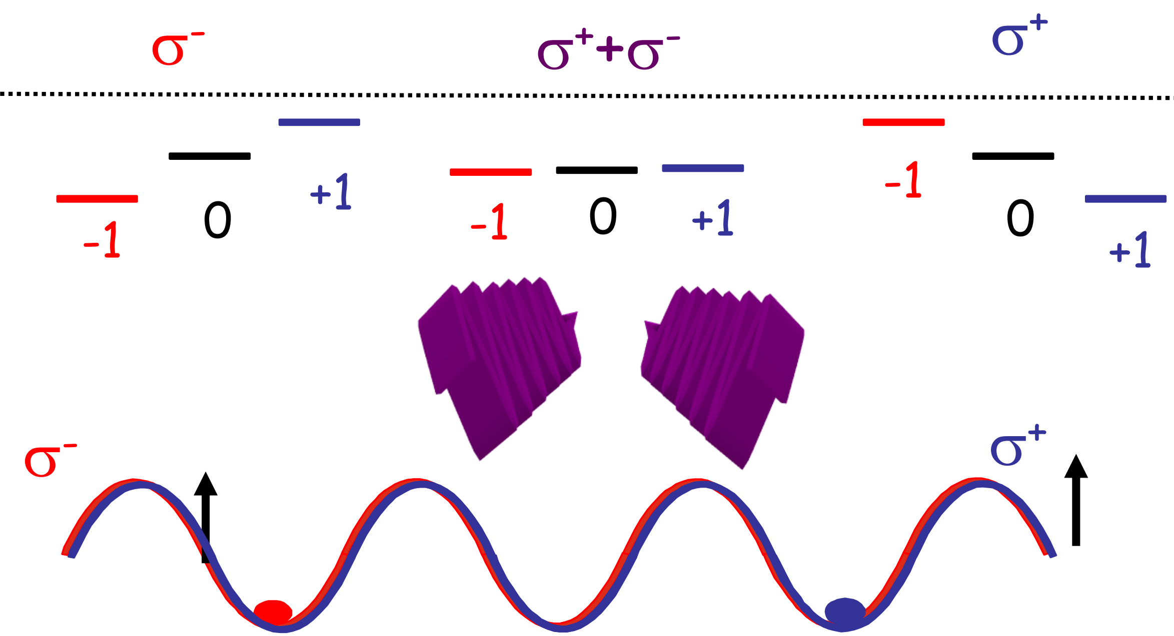


DSW, Vala, Thapliyal, Myrgren, Vazirani, Whaley, PRA **70**, 040302 (2004)

Robens, Zopes, Alt, Brakhane, Meschede, and Alberti, PRL **118**, 065302 (2017).



Rotating polarizations gives state-selective translations



Brennen, Caves, Jessen & Deutsch PRL **82**, 1060 (1999).

In 3D, compact N atoms in $<4N^{1/3}$ steps.

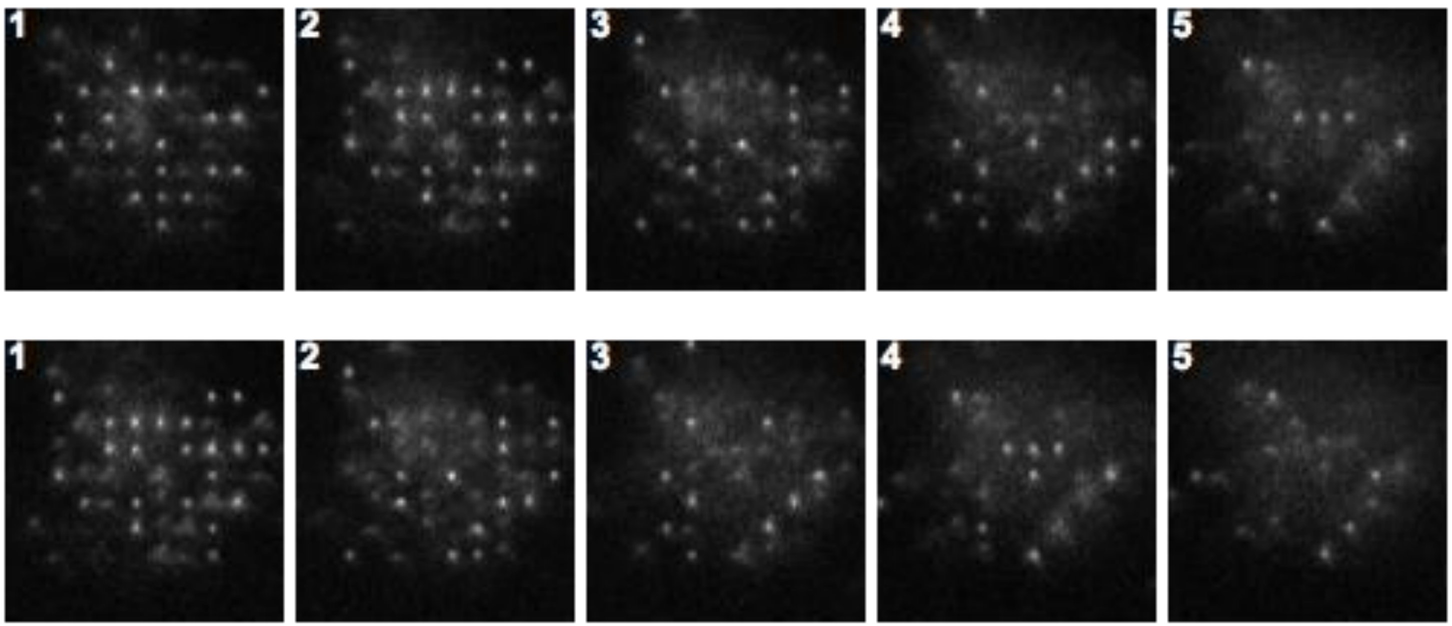
~50 ms for 125 sites

Can check for and fix errors

Global motion step

No more averaged pictures

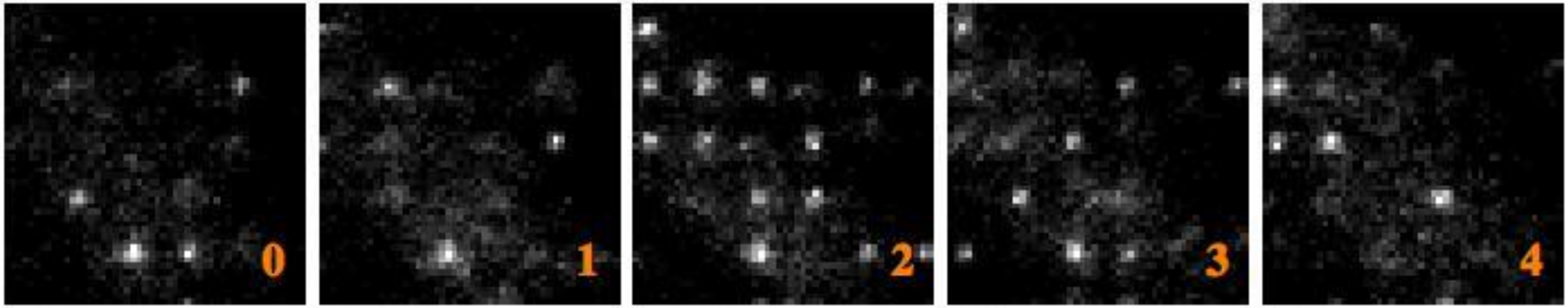
Before



After

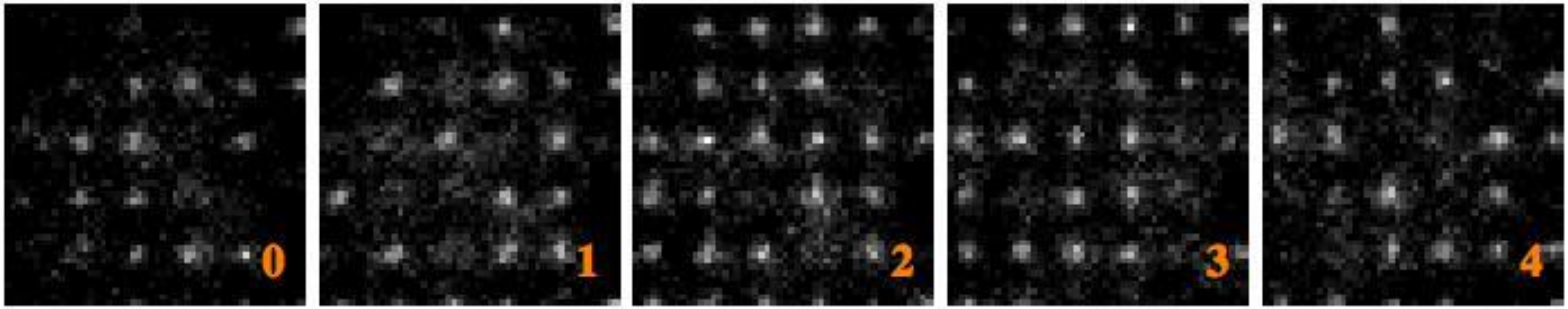
Shift the center plane atoms all the way to the left

Before



Fill the center plane

Before



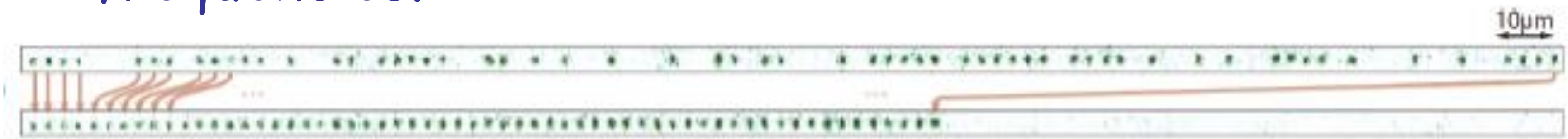
Other atom sorting in 1D and 2D

Endres, et al., *Science* **354**, 1024(2016); Barredo, Léséleuc, Lienhard, Lahaye, Browaeys, *Science* **354**, 1021 (2016).

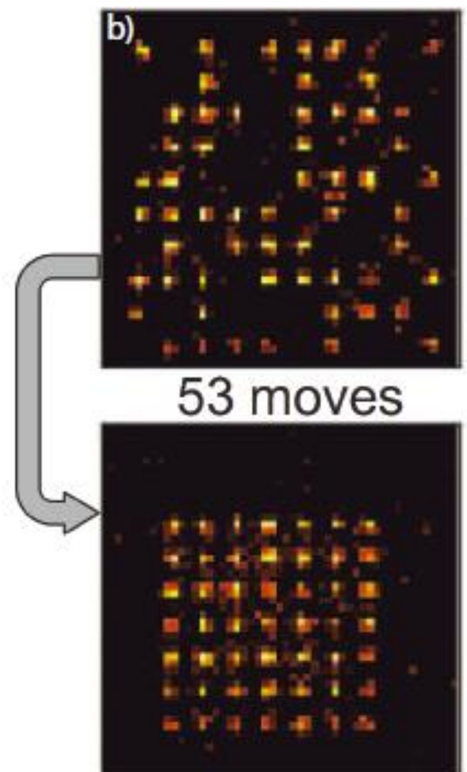
We are working on operational fidelity, then complete 3D sorting

Atom Sorting

Harvard/MIT: 1D: array of tweezers from an AOM, eliminate empty traps and shift traps by shifting RF frequencies.



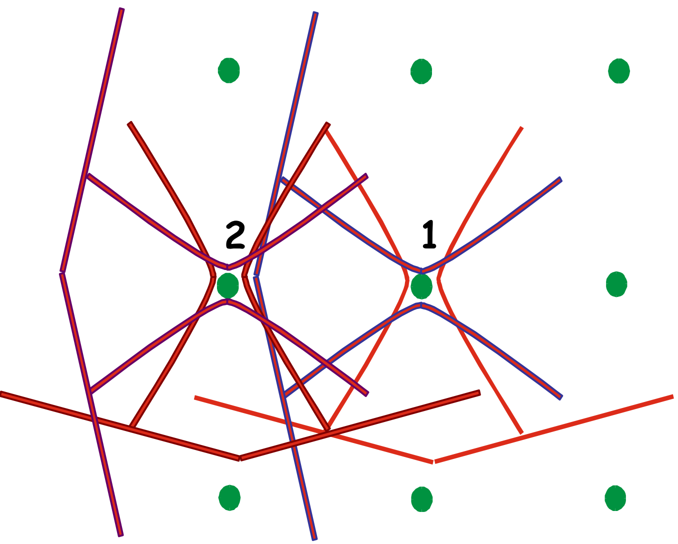
Palisseau: 2D: use a moving optical tweezer to fill a stationary atom arrray



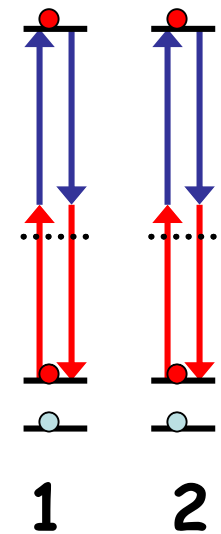
Rydberg entanglement

Jaksch et al. PRL **85** 2208 (2000)

Use crossed beams and a two-photon transition to a high Rydberg state.



Atom 2 will not be resonant **if** Atom 1 is excited.



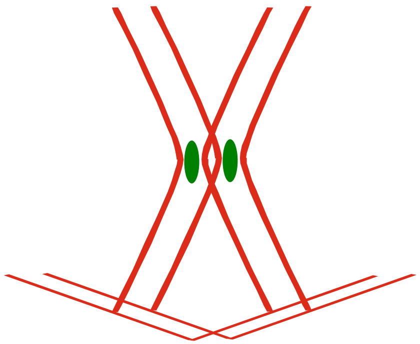
In 3D each atom has 26 pretty near neighbors

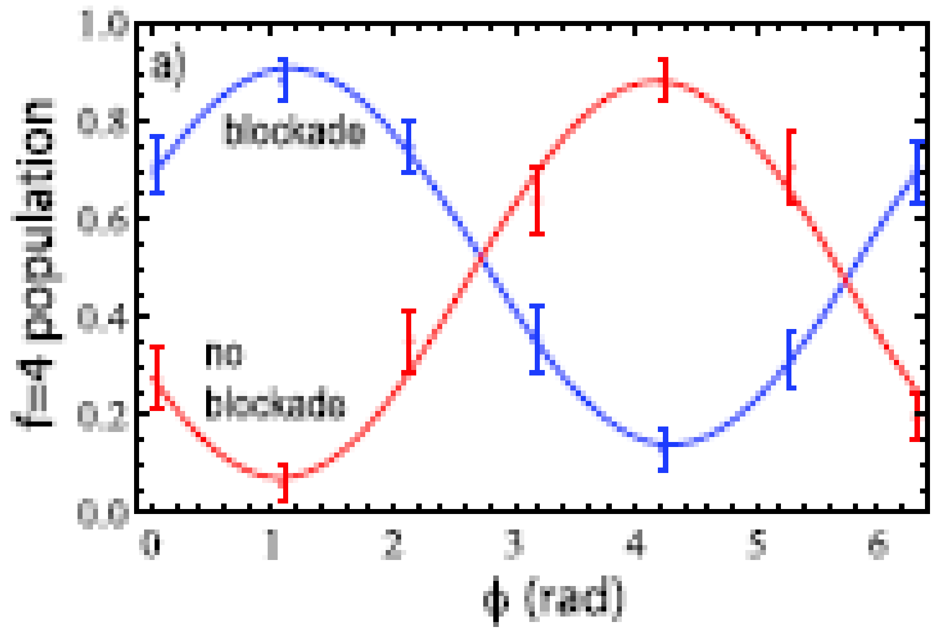
Input	Output
0,0	0,0
0,1	0,-1
1,0	-1,0
1,1	$-1,1e^{-\delta}$

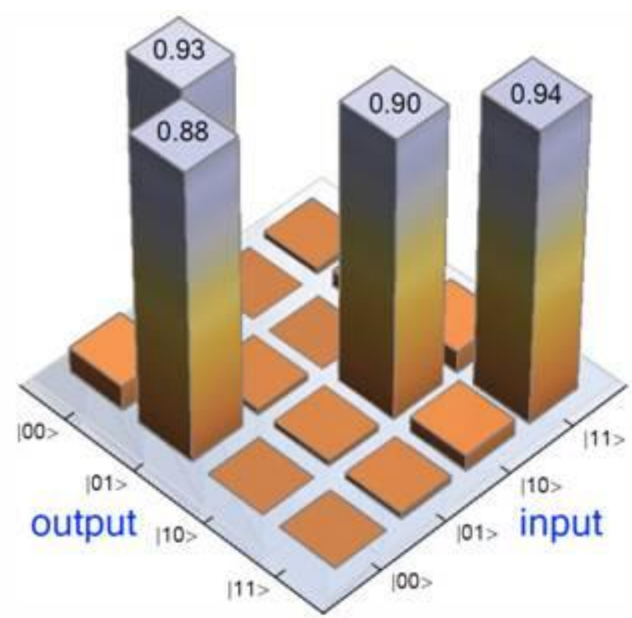
time: as small as 100 ns

Additional 1-qubit gates makes it a C-Not

Experimental Rydberg Gates

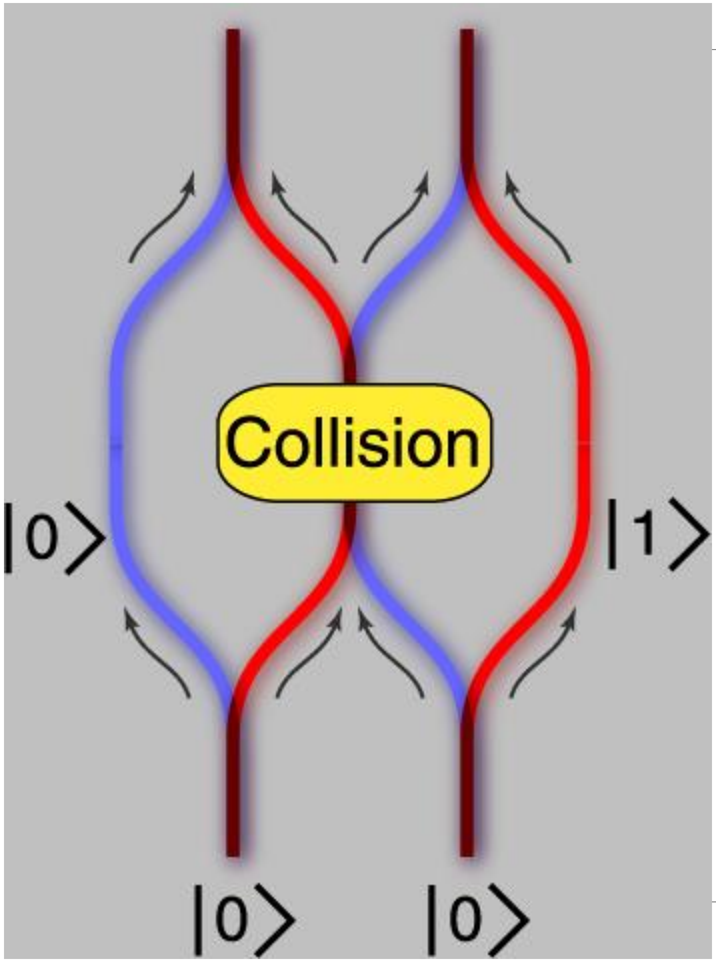


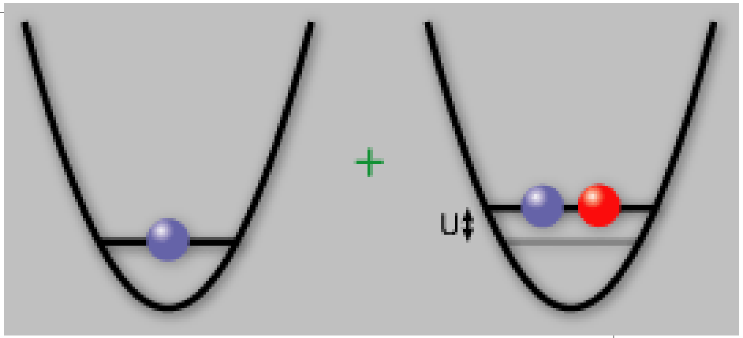




Maller, Lichtman Xia, Sun, Piotrowicz, Carr, Isenhower, Saffman, *Phys. Rev. A* **92** 022336 (2015; Wilk, Gaëtan, Evellin, Wolters, Miroshnychenko, Grangier, Browaeys, *Phys. Rev. Lett.* **104** 010502 (2010); Jau, Hankin, Keating, Deutsch, Biedermann, *Nat. Phys.* **12** 71 (2016);

Controlled Collisions





$$U = \frac{4\pi\hbar^2 a}{m} \int |w_0(x)|^2 \cdot |w_1(x)|^2 \, d^3x$$

$$E = U \cdot n_0 \cdot n_1$$

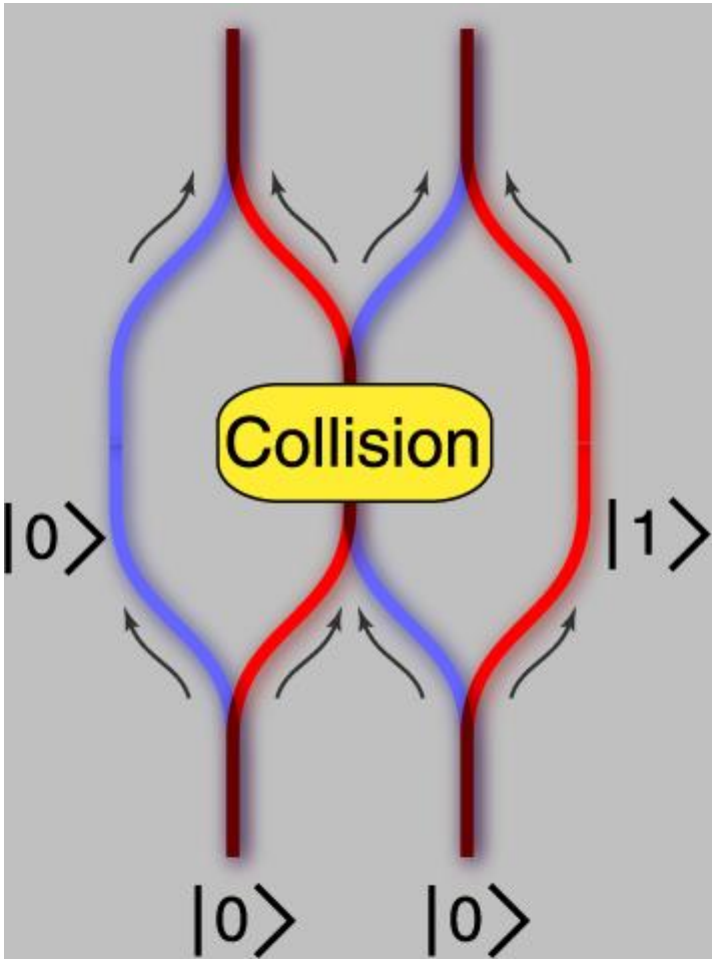
In time t_{Hold} a phase factor of

$$e^{i\varphi} = e^{iEt_{Hold}/\hbar}$$

is acquired.

D. Jaksch et al., PRL 82,1975 (1999)

Collisional Quantum Gate



Input state	Final state
$\|0\rangle\|0\rangle$	$\|0\rangle\|0\rangle$
$\|0\rangle\|1\rangle$	$\|0\rangle\|1\rangle$
$\|1\rangle\|0\rangle$	$\|1\rangle\|0\rangle \cdot e^{i\phi}$
$\|1\rangle\|1\rangle$	$\|1\rangle\|1\rangle$

This sort of gate is very demanding on atom temperature

D. Jaksch et al., PRL 82,1975 (1999)

Work at JILA (Regal) with two optical tweezers.

Conclusion

There are a lot of ways to manipulate the internal and external states of atoms.

10^6 atomic qubits in < 5 mm^2 or <0.5 mm^3

There has been significant progress in fidelity improvement and scaling up to many usable qubits in the same system.

atom arrays: tweezers, lattices
single qubit gates: stimulated Raman, phase
two qubit gates: Rydberg, collisional

The next steps will be higher fidelity two-qubit gates and introduction of error correction.