Adiabatic preparation and non-equilibrium dynamics of AF order in a optical lattice

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Joint Quantum Institute

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Today's Talk

"Magic" Wavelength Light shift cancellation

Non-equilibrium dynamics:

Constructing AF order in a Ferromagnetic system

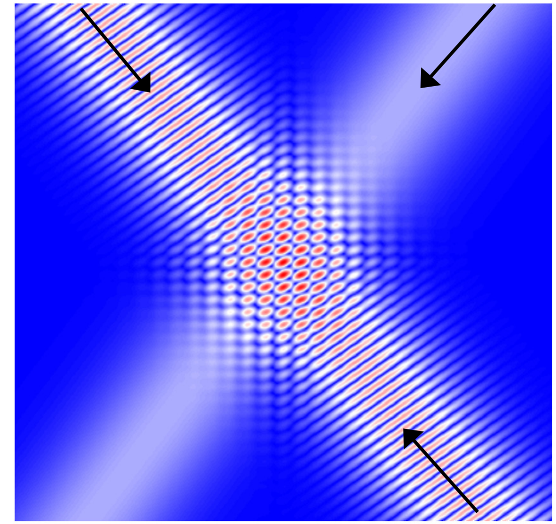
(ongoing)

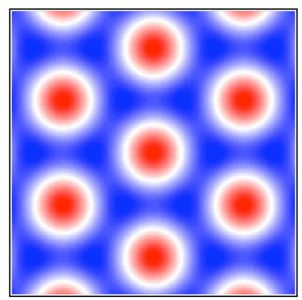
Our Bread and Butter: Light Shifts

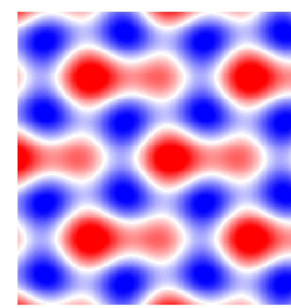
Any Light intensity pattern
→ nearly arbitrary potentials

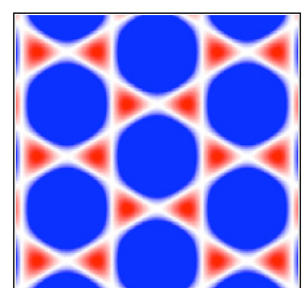
Simplest cases:

optical lattices

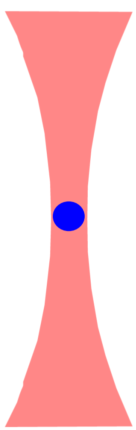




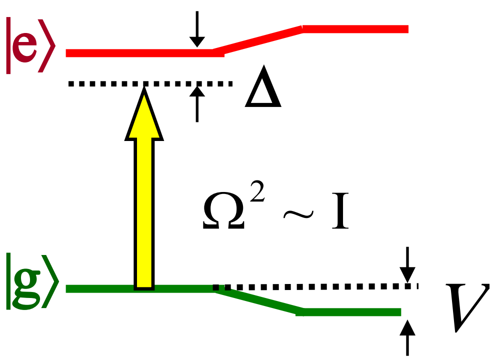




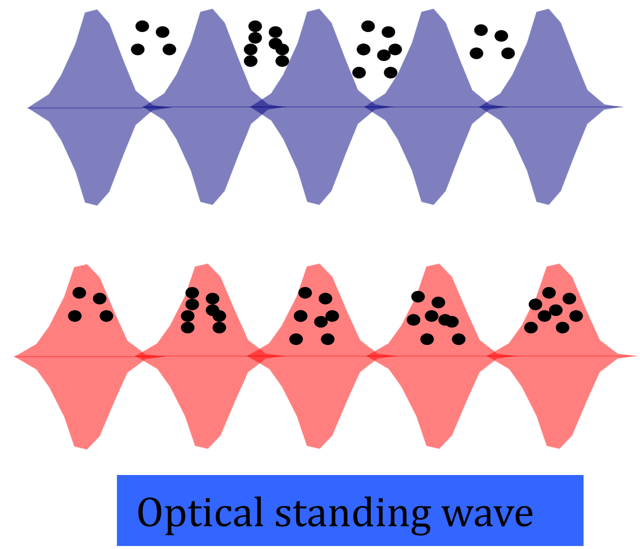
single optical
tweezers



Light Shift Potentials



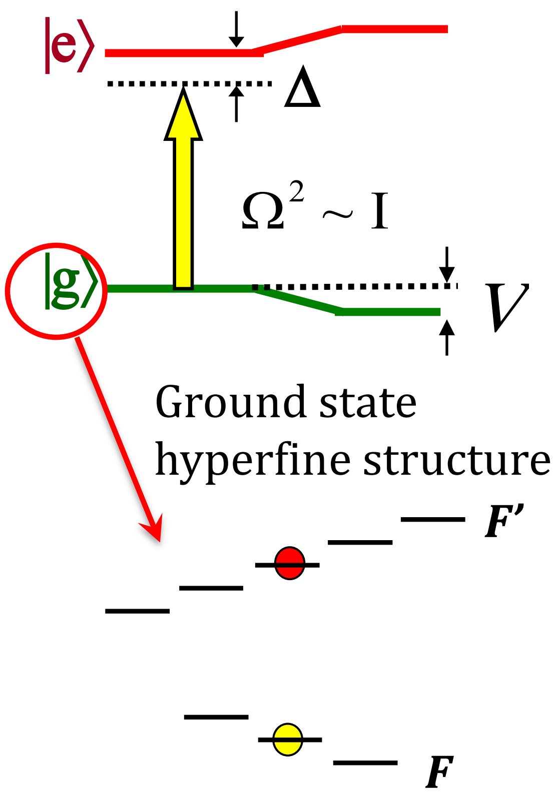
Intensity *and*
state
dependent
light shift



Red detuning → attractive

Blue detuning → repulsive

Light Shift Potentials

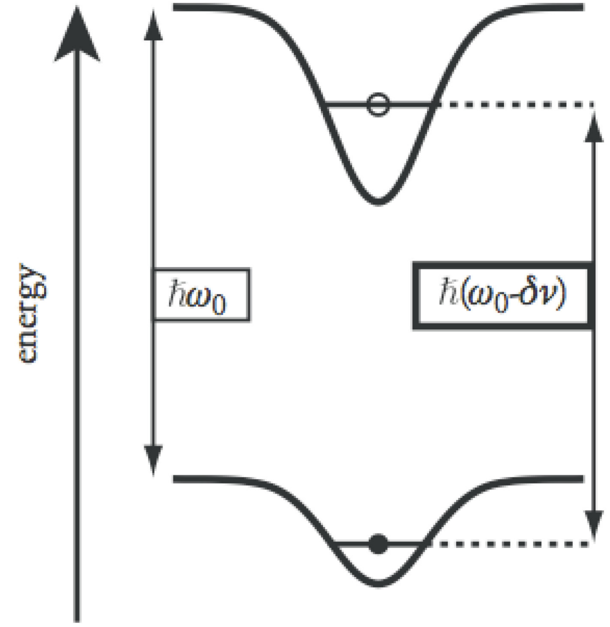


$$V \propto \frac{I}{\Delta}$$

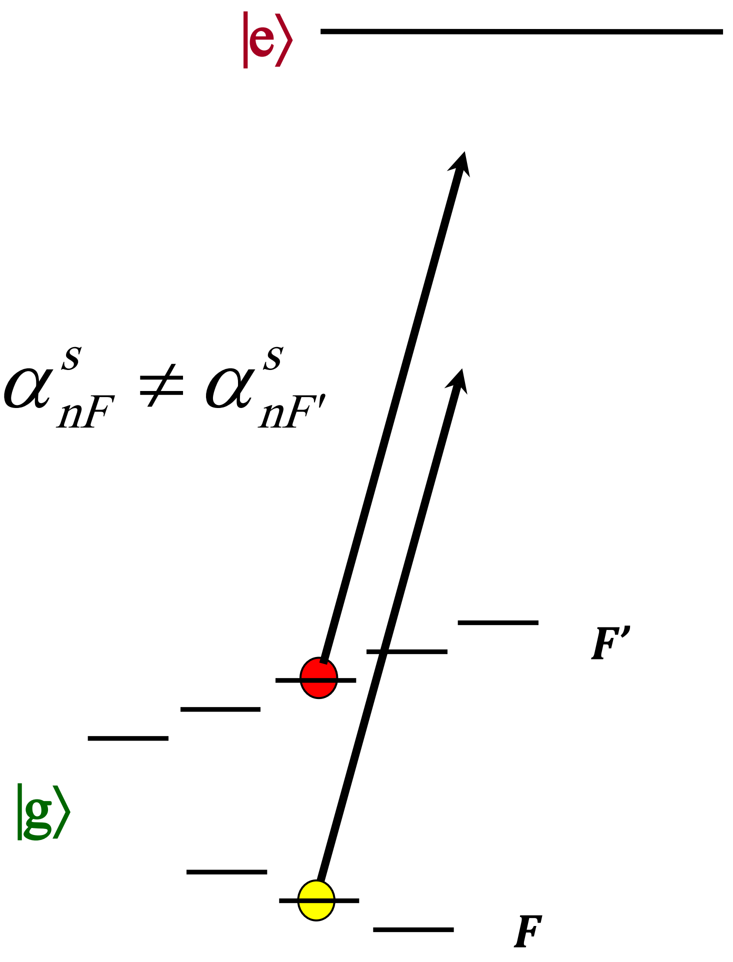
$$\Gamma_{scatt} \propto \frac{I}{\Delta^2}$$

Differential Light Shifts for Alkali's

$$H_{nF} = \left(\frac{1}{2}E_0\right)^2 \left[\alpha^s_{nF}\right]$$



$$\alpha^s_{nF} \neq \alpha^s_{nF'}$$

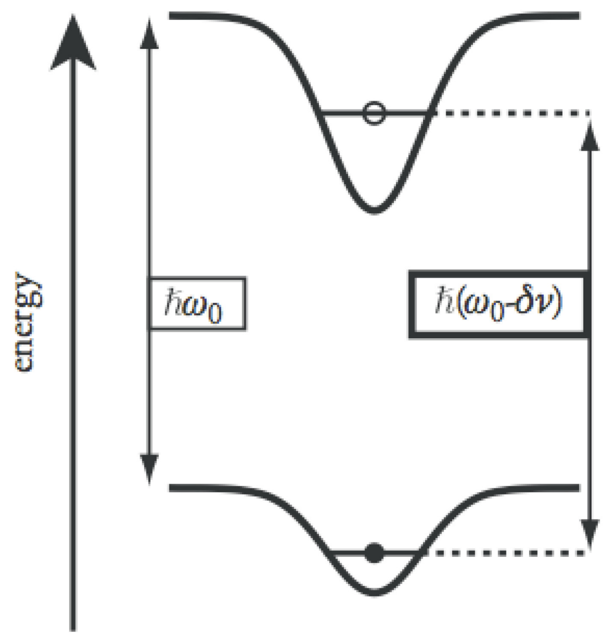


Differential Light Shifts for Alkali's

"… there is no magic wavelength…" for hyperfine states of alkali's

Rosenbusch, *et al.* PRA **79**, 013404 (2009).

$$H_{nF} = \left(\frac{1}{2}E_0\right)^2 \left[\alpha^s_{nF}\right]$$



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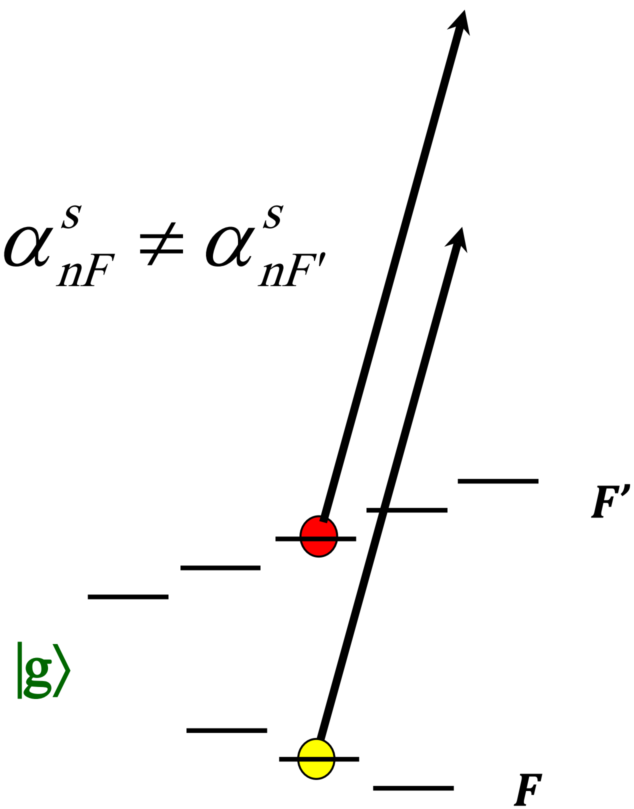
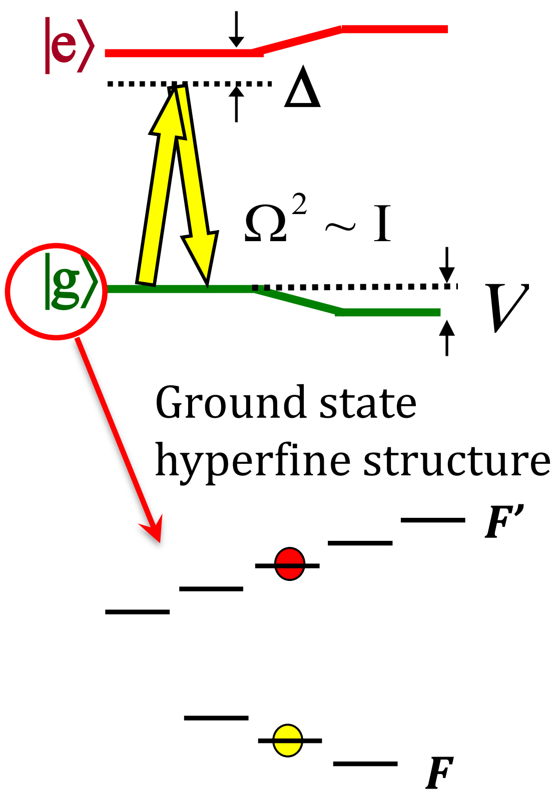


Light Shift Potentials



Electric dipole coupling
has vector structure:

$$\vec{d} \cdot \vec{E}$$

Light shift is second order

$$\propto \frac{(\vec{E} \cdot \vec{d})(\vec{d} \cdot \vec{E})}{\Delta}$$

Second rank tensor

Light Shift Potentials

Scalar $\propto |E|^2 = I$

Tensor $\propto F_z^2 E_z^2$

$$\mathbf{E}^* \cdot \hat{\mathbf{d}}\hat{\mathbf{d}} \cdot \mathbf{E} = \frac{|\mathbf{E}|^2 |\hat{\mathbf{d}}|^2}{3} - \frac{1}{2}(\mathbf{E}^* \times \mathbf{E}) \cdot (\hat{\mathbf{d}} \times \hat{\mathbf{d}}) + \mathrm{Tr}\left(\sum_k (\mathbf{E}^*\mathbf{E})^S_{ik} (\hat{\mathbf{d}}\hat{\mathbf{d}})^S_{kj}\right)$$

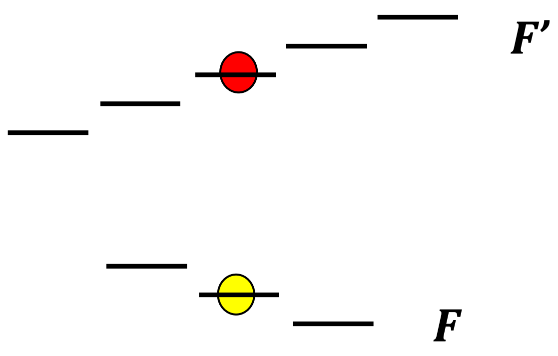
Vector (B-field) $\propto (\vec{E}^* \times \vec{E}) \cdot \vec{F} = -\vec{\mu}_B \cdot \vec{B}_{eff}$

"Magic" Wavelengths for Alkali's

Vector + Scalar Light shift can cancel

$$H_{nF} = \left(\frac{1}{2}E_0\right)^2 \left[\boxed{\alpha^s_{nF} + \alpha^v_{nF}(i\vec{\varepsilon}^* \times \vec{\varepsilon}) \cdot \hat{F}} + \alpha^t_{nF}\left(\frac{3\left|\vec{\varepsilon} \cdot \hat{F}\right|^2 - \hat{F}^2\left|\vec{\varepsilon}\right|^2}{F(2F-1)} \right) \right]$$

$$\alpha^s_{nF} + \alpha^v_{nF} m_F = \alpha^s_{nF'} + \alpha^v_{nF'} m_{F'}$$



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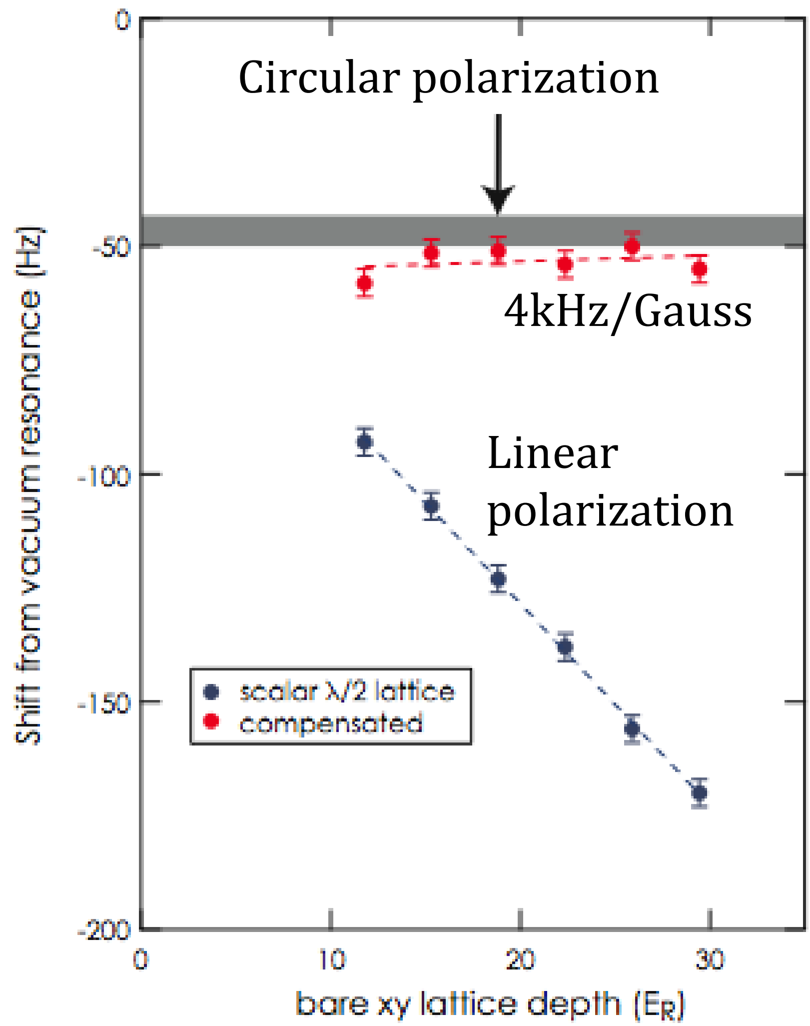
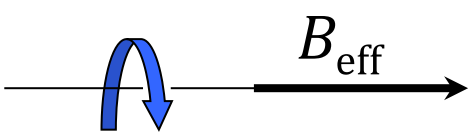


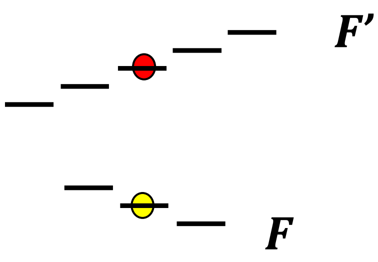
Implies:

-Circular polarization

-Finite B-field sensitivity

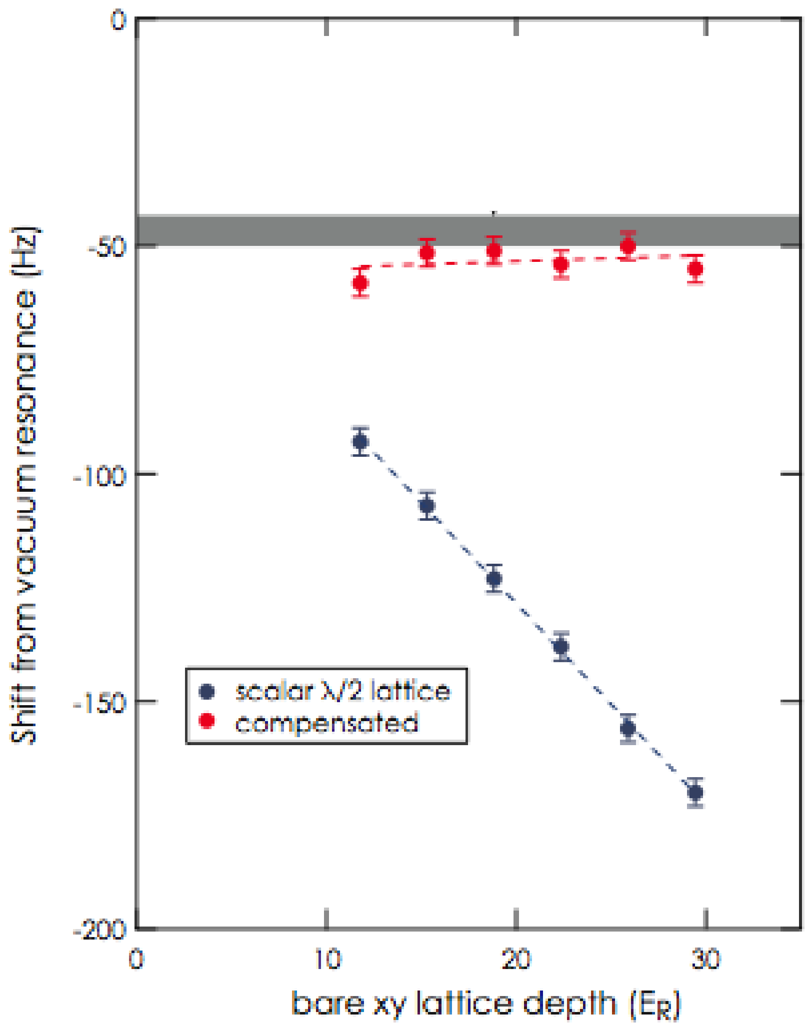


Use m_F=0 at finite field



“Magic” Wavelengths for Alkali’s

Vector + Scalar Light shift can cancel



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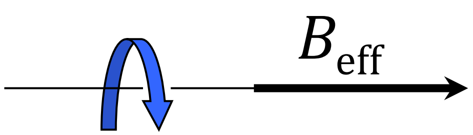


See:

Flambaum, PRA **79**, 013404 (2009)

Schleier-Smith, PRL **104**, 073604 (2010)

Kuzmich, (2010)

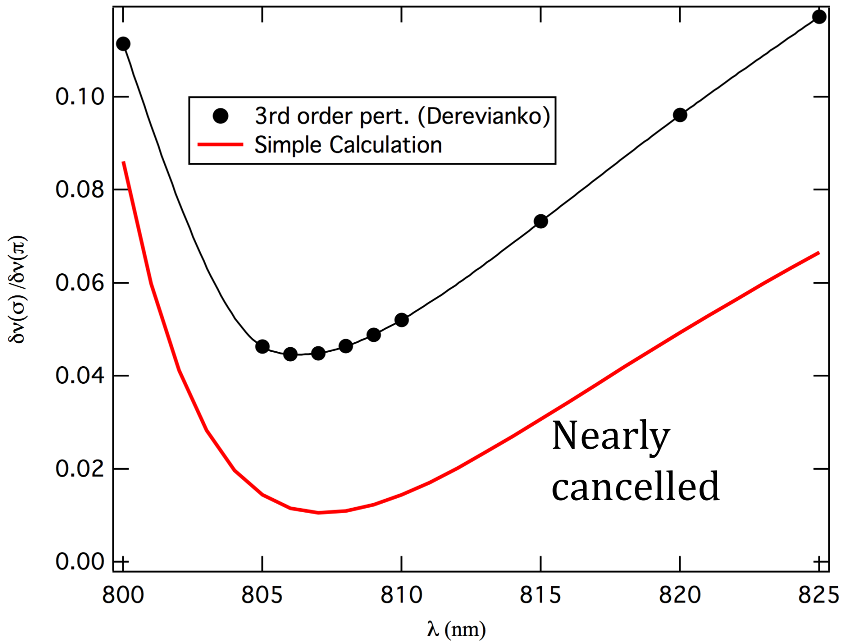
B-field *and* Light Insensitivity?

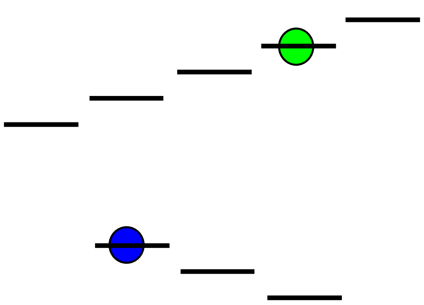
Vector shifts ≠ B-fields

$$H_{nF} = \left(\frac{1}{2}E_0\right)^2 \left[\alpha^s_{nF} + \alpha^v_{nF}(i\vec{\varepsilon}^* \times \vec{\varepsilon}) \cdot \hat{F}\right]$$

Interacts only with electrons
Differs from Zeeman by:

$$\mu_N \hat{I} \cdot B_{\text{eff}}$$





Derevianko, PRL **105**, 033002 (2010).

B-field *and* Light Insensitivity?

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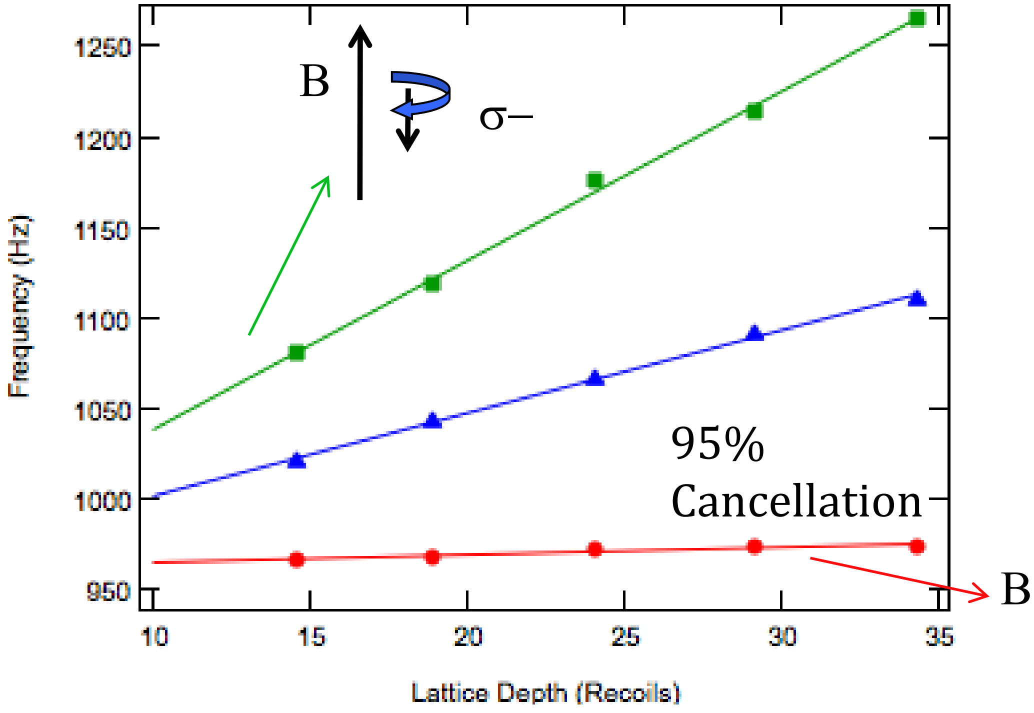
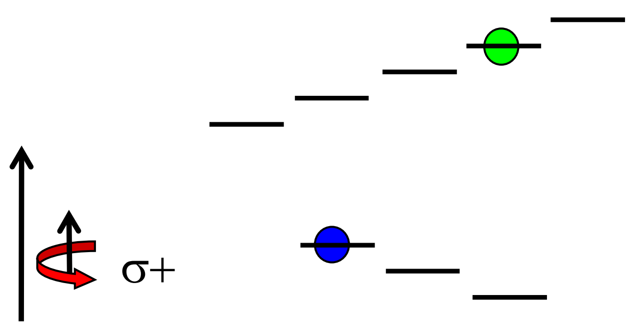


m_F = +/- 1

B=3.2 Gauss



B-field *and* Light Insensitivity?

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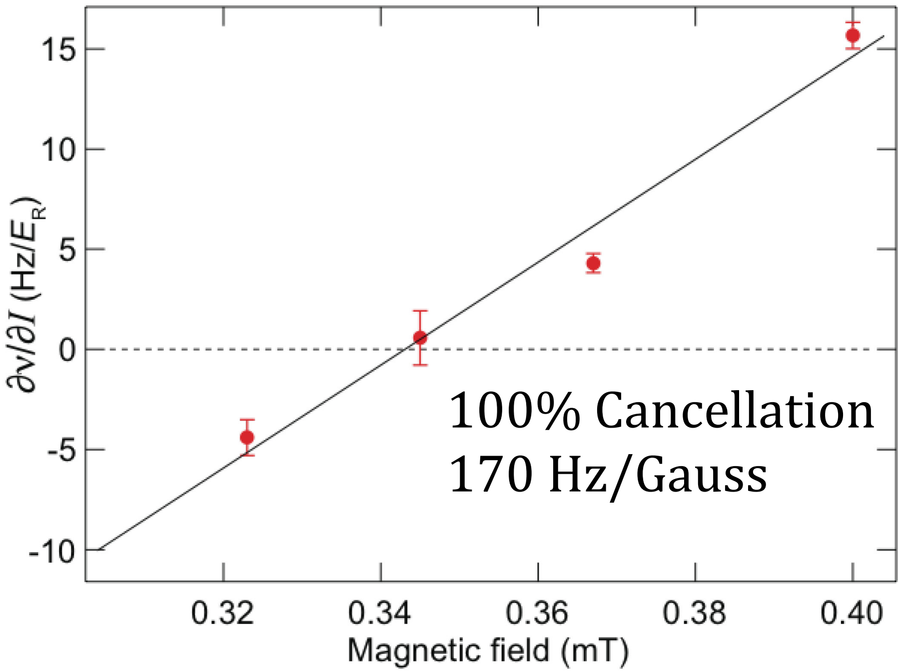
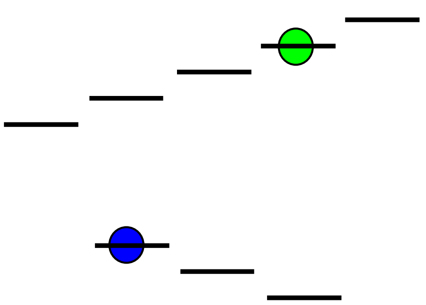
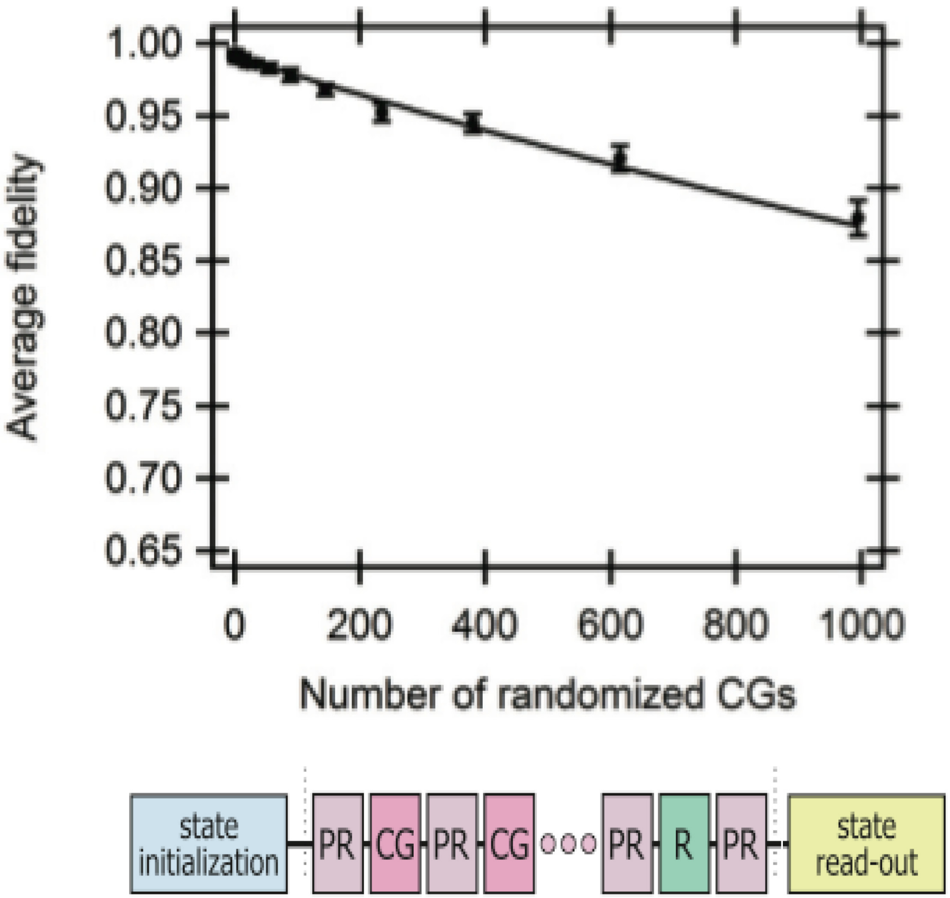




Very Good Spin Control



Randomized Benchmarking of Single spin rotation

Average 1-gate error rate: 1.4×10^{-4}

Today's Talk

"Magic" Wavelength Light shift cancellation

Non-equilibrium dynamics:

Constructing AF order in a Ferromagnetic system

(ongoing)

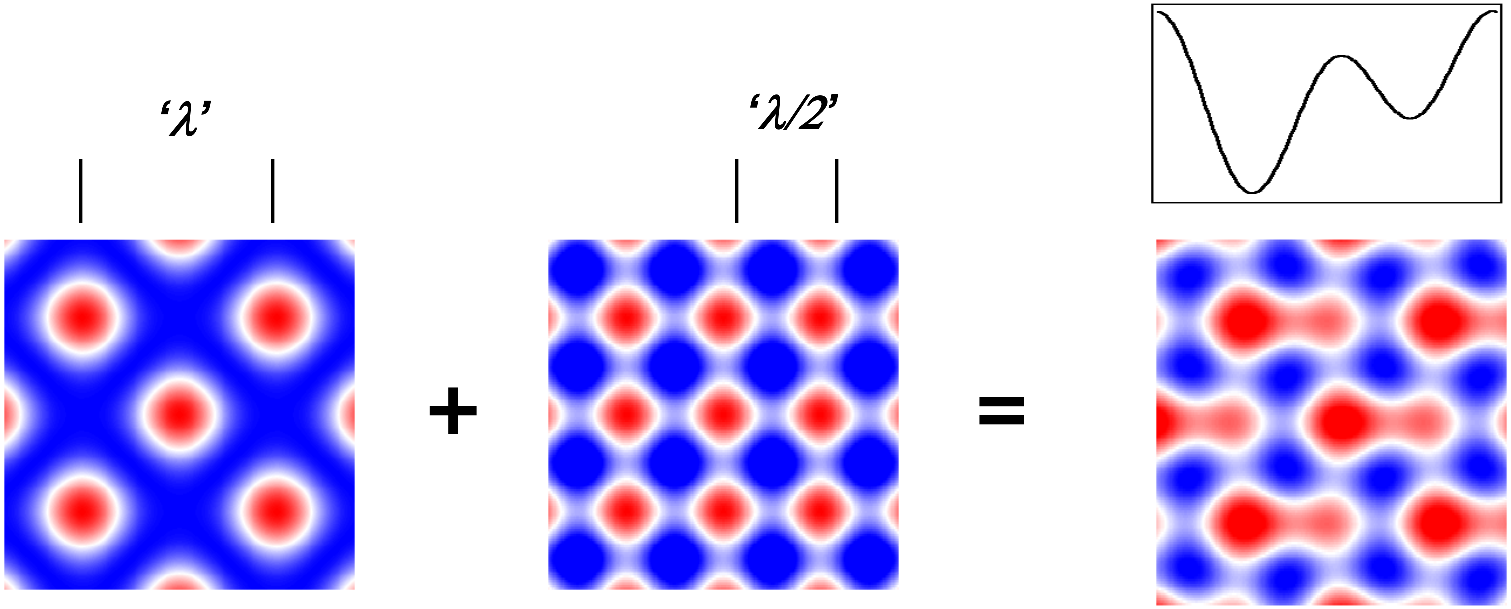
Non-Equilibrium Systems

- exploit the coherent nature of cold atoms
    - dynamics
    - pseudo-equilibrium

- since coherent processed dominate, we *must* understand coherent dynamics

- gain understanding in traditional CM context where experiments are not available

Our System: 2D Double Well



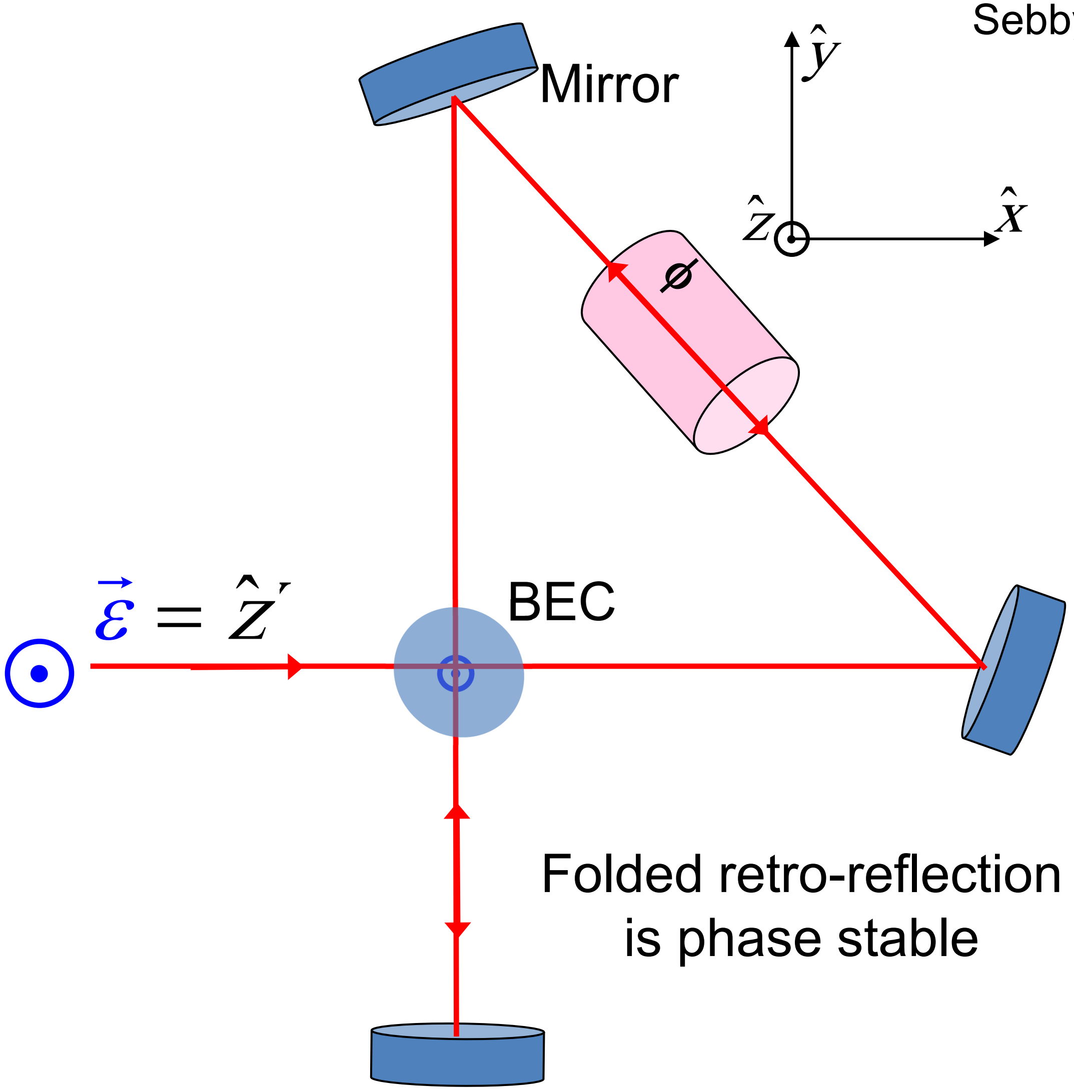
Basic idea:

Combine two different period lattices with adjustable
- intensities
- positions

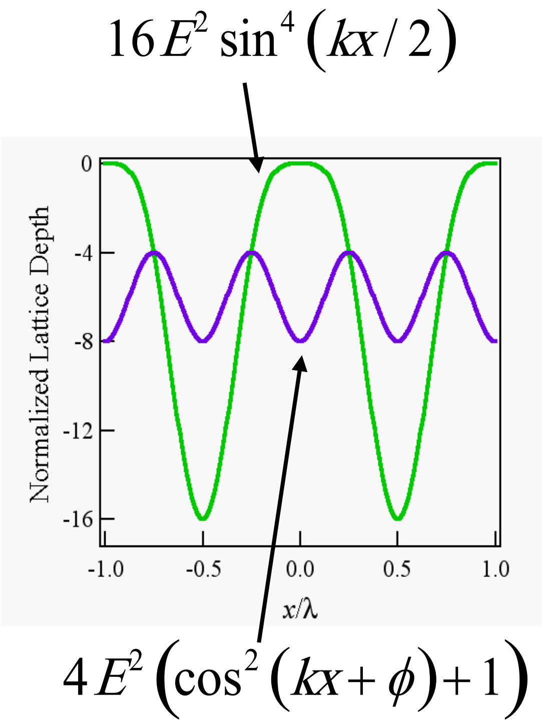
Mott insulator → single atom/site

Polarization Controlled 2-period Lattice

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



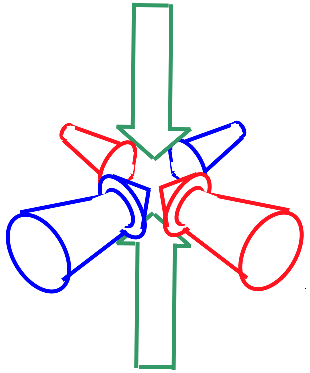
Folded retro-reflection is phase stable

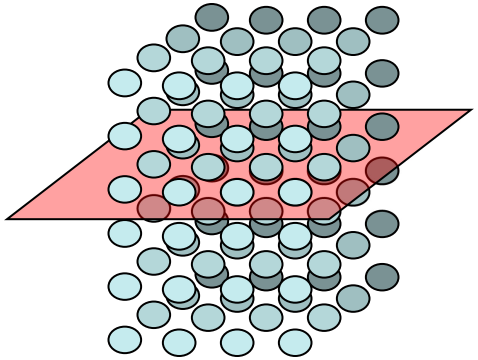


Polarization Controlled 2-period Lattice

Add an independent, deep vertical lattice

Provides an independent array of 2D systems



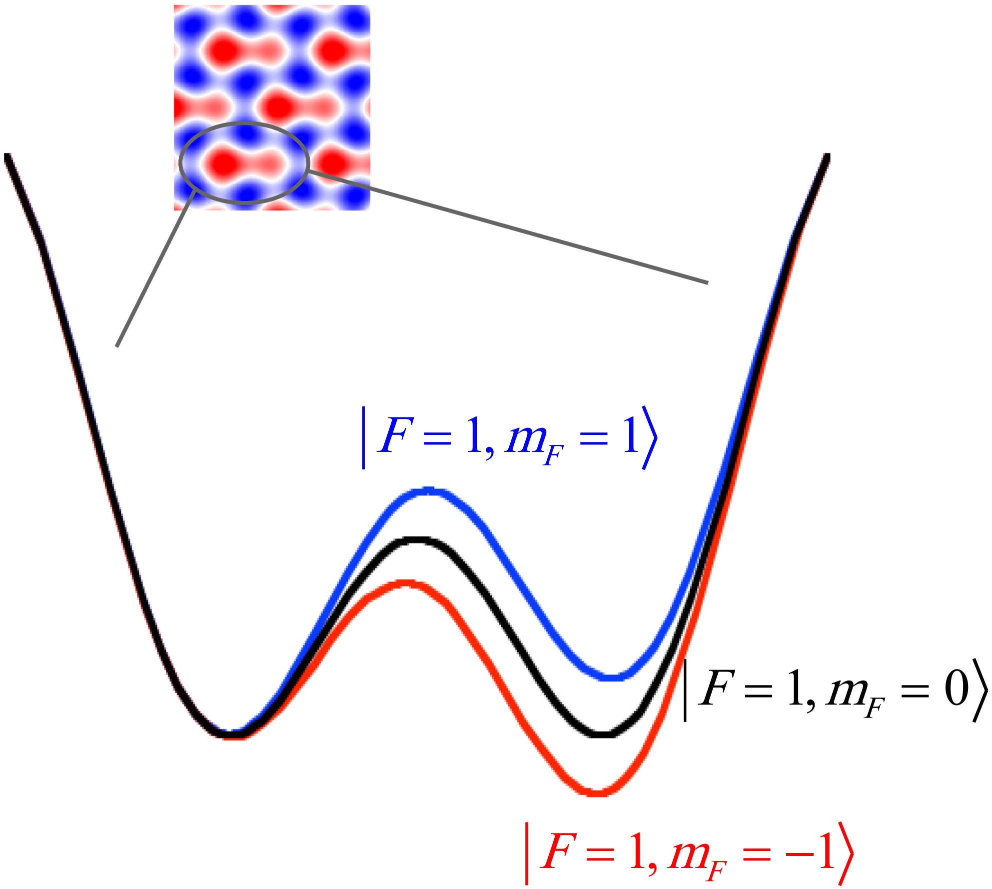


State Dependent Potential

Vector light shift + bias B-field:
controllable

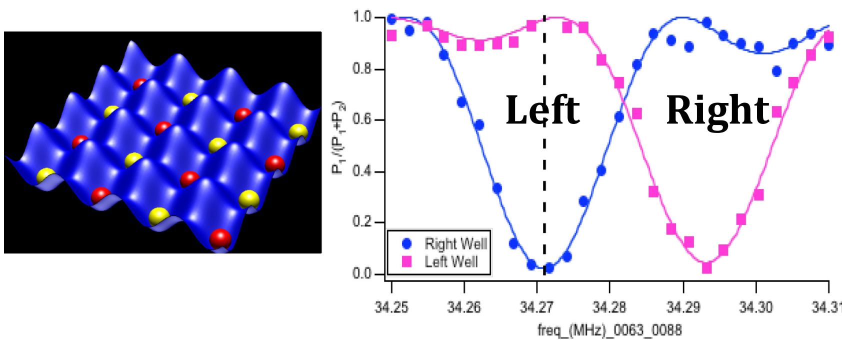
state-dependent barriers

state-dependent tilt

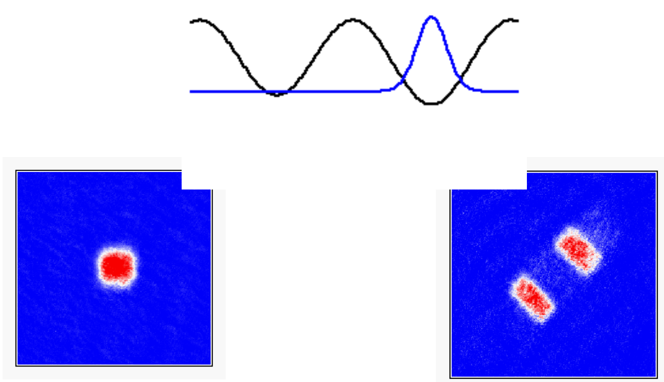


Effective Zeeman Fields

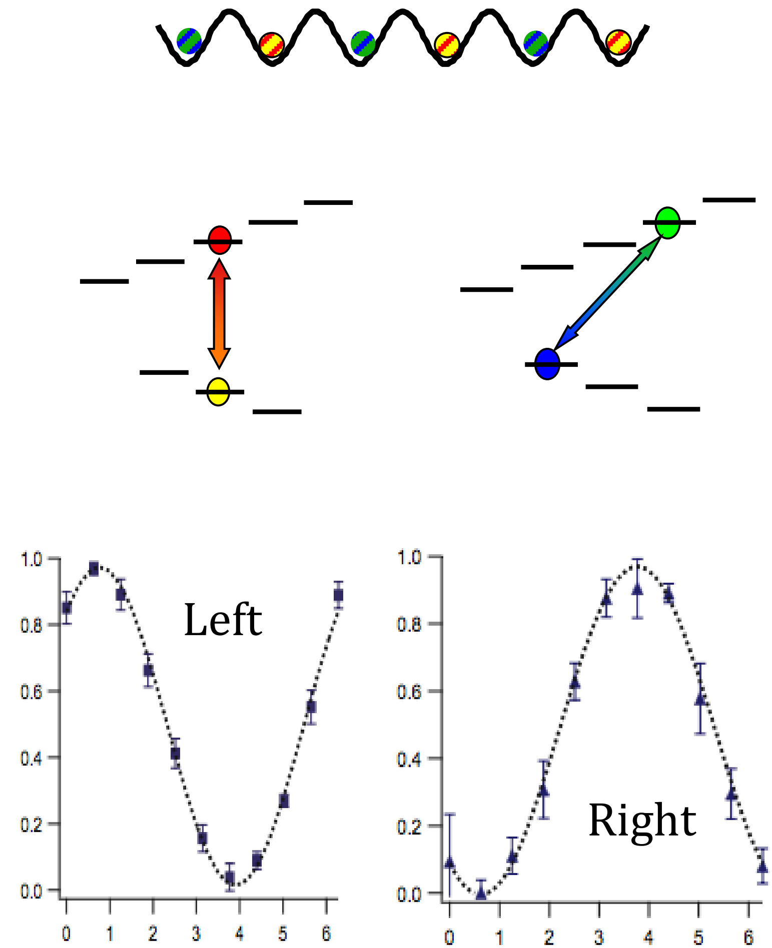
Sub-lattice addressing:
Optical MRI



Atom motion between wells
(including spin-dependent)

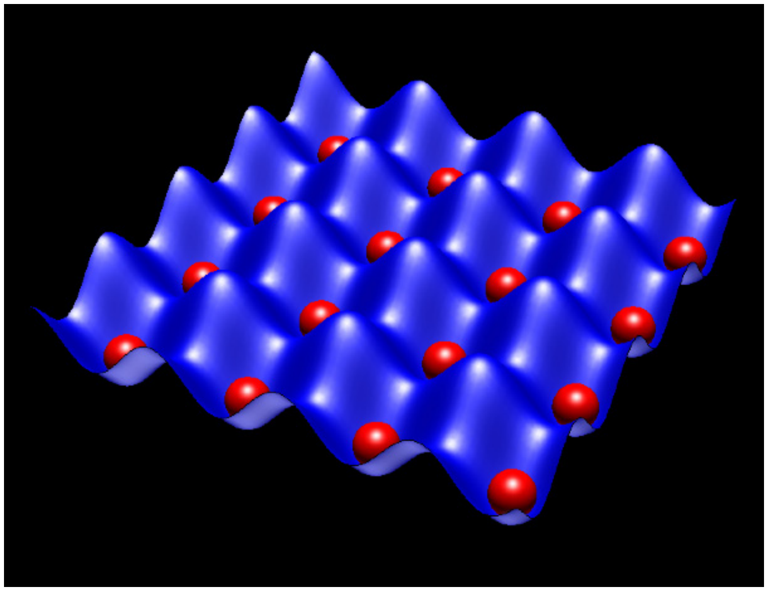


Sub-lattice Clock addressing



Cold Atom Magnetic Systems

Mott state with super-exchange



$$H = -\sum_{\langle ij \rangle \sigma} t_\sigma \left(\hat{a}_{i\sigma}^{+} \hat{a}_{j\sigma} + \text{h.c.} \right)$$

$$+ \frac{1}{2} \sum_{i\sigma} U_\sigma n_{i\sigma} \left(n_{i\sigma} + 1 \right) + \sum_{i} U_{\sigma\sigma'} n_{i\sigma} n_{i\sigma'}$$

Project onto Mott State

$$H = -J \sum_{\langle ij \rangle \sigma} \hat{\sigma}_i \hat{\sigma}_j$$

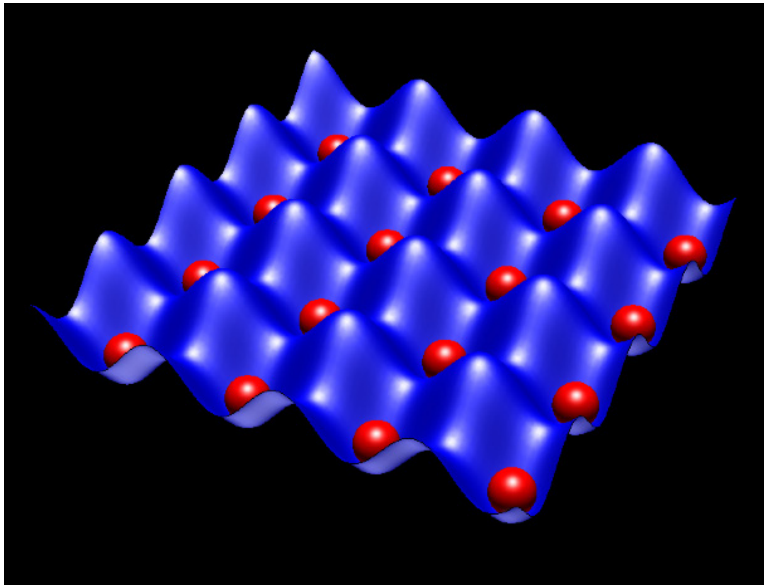
Duan, Demler, Lukin,
PRL 91 090402 (2003)

$$J = \frac{t^2}{U} \quad U_\sigma = U_{\sigma'} = U_{\sigma\sigma'}$$

$$t_\sigma = t_{\sigma'}$$

Cold Atom Magnetic Systems

Mott state with super-exchange



$$H = -\sum_{\langle ij \rangle \sigma} t_\sigma \left(\hat{a}^+_{i\sigma} \hat{a}_{j\sigma} + \text{h.c.} \right) + \frac{1}{2} \sum_{i\sigma} U_\sigma n_{i\sigma} \left(n_{i\sigma} + 1 \right) + \sum_i U_{\sigma\sigma'} n_{i\sigma} n_{i\sigma'}$$

Challenges:

$\frac{t^2}{U}$ very small

$t \leq E_R$, limited by E_R

Entropy challenging

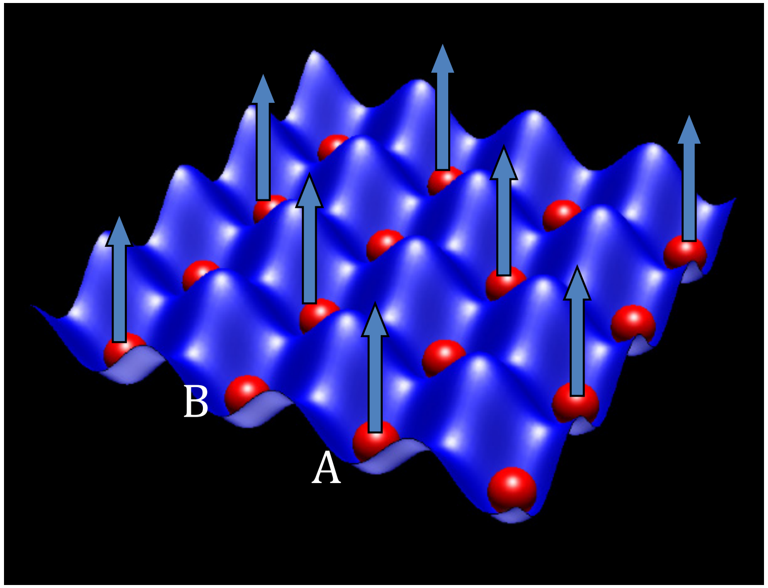
Duan, Demler, Lukin,
PRL 91 090402 (2003)

$$J = \frac{t^2}{U} \quad U_\sigma = U_{\sigma'} = U_{\sigma\sigma'}$$

$$t_\sigma = t_{\sigma'}$$

Cold Atom Magnetic Systems

Staggered B-field



Light induced Zeeman-fields:

$$H = -\sum_{\langle ij \rangle \sigma} t_\sigma \left(\hat{a}^+_{i\sigma} \hat{a}_{j\sigma} + \text{h.c.} \right)$$

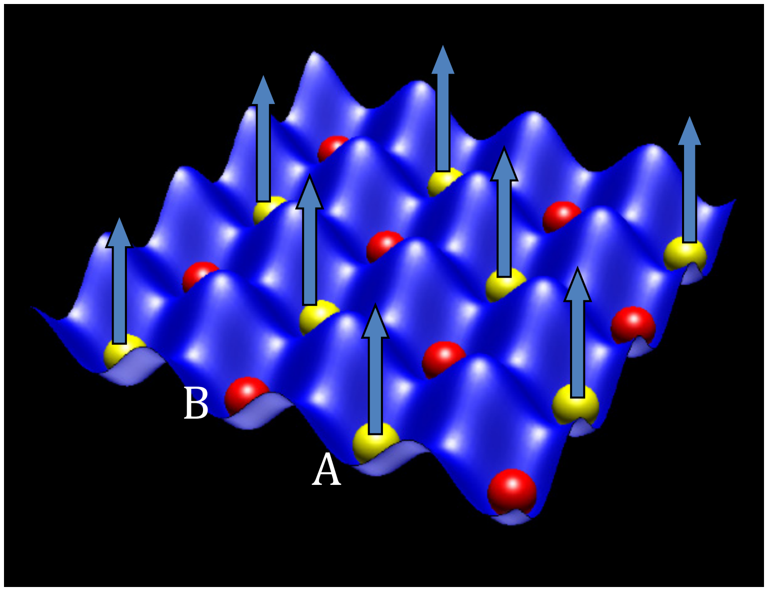
$$+ \frac{1}{2} \sum_{i\sigma} U_\sigma n_{i\sigma} \left(n_{i\sigma} + 1 \right) + \sum_i U_{\sigma\sigma'} n_{i\sigma} n_{i\sigma'}$$

$$+ h(t) \sum_{i \in A} \left(n_{i\sigma} - n_{i\sigma'} \right)$$

$$H = -J \sum_{\langle ij \rangle \sigma} \hat{\sigma}_i \cdot \hat{\sigma}_j + h(t) \sum_{i \in A} \hat{\sigma}^z_i$$

Cold Atom Magnetic Systems

microwave control



Light induced Zeeman-fields:

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$$+ \frac{1}{2} \sum_{i\sigma} U_\sigma n_{i\sigma} \left(n_{i\sigma} + 1 \right) + \sum_{i} U_{\sigma\sigma'} n_{i\sigma} n_{i\sigma'}$$

$$+ h(t) \sum_{i \in A} \left(n_{i\sigma} - n_{i\sigma'} \right)$$

$$H = -J \sum_{\langle ij \rangle \sigma} \hat{\sigma}_i \cdot \hat{\sigma}_j + h(t) \sum_{i \in A} \hat{\sigma}^{Z}_{i}$$

Many-Body State Preparation

Original Basic idea: can we use *h(t)* to

Fermions ⟶ - prepare many-body AF ground state?

Bosons ⟶ - prepare excited many-body state?

Many-Body State Preparation

Original Basic idea: can we use *h(t)* to

- prepare many-body AF ground state?

- prepare excited many-body state?

For $J << h << U$,

h can gap the system without destroying Mott state (to lowest order)

Many-Body State Preparation

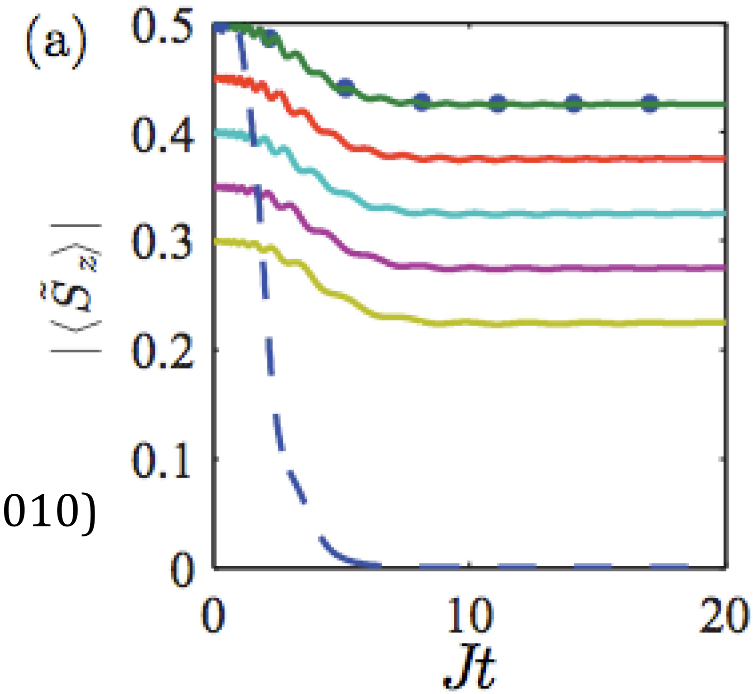
Original Basic idea: can we use *h(t)* to

- prepare many-body AF ground state?

- prepare excited many-body state?

Eases adiabatic state preparation

Sorensen et al. PRA 81 061603 (2010)



Many-Body State Preparation

Original Basic idea: can we use *h(t)* to

- prepare many-body AF ground state?

- prepare excited many-body AF state?

Highest excited state of $H = -J\sum_{\langle ij\rangle\sigma}\hat{\sigma}_i \cdot \hat{\sigma}_j$ is anti-ferromagnetic

Highest energy state is often more interesting than the lowest

J. J. Garcıa-Ripoll, *et al*. PRL 93, 250405 (2004)
Sorensen et al. PRA 81 061603 (2010)

Many-Body State Preparation

Original Basic idea: can we use *h(t)* to

- prepare many-body AF ground state?

- prepare excited many-body AF state?

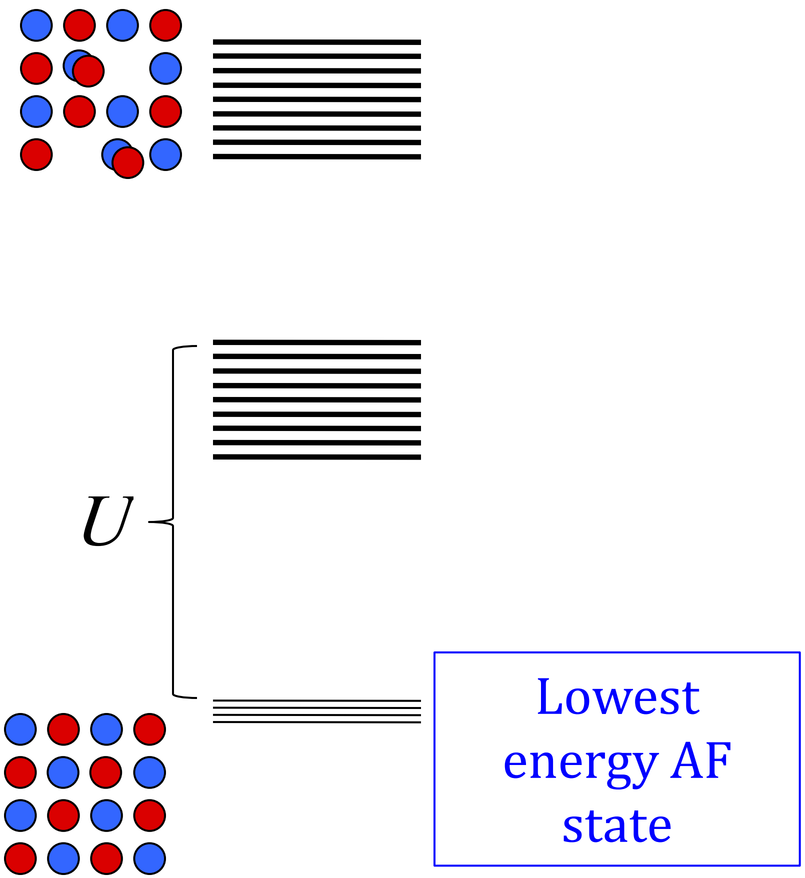
Highest excited state of $H = -J \sum_{\langle ij \rangle \sigma} \hat{\sigma}_i \cdot \hat{\sigma}_j$ is anti-ferromagnetic

High order relaxation is important!

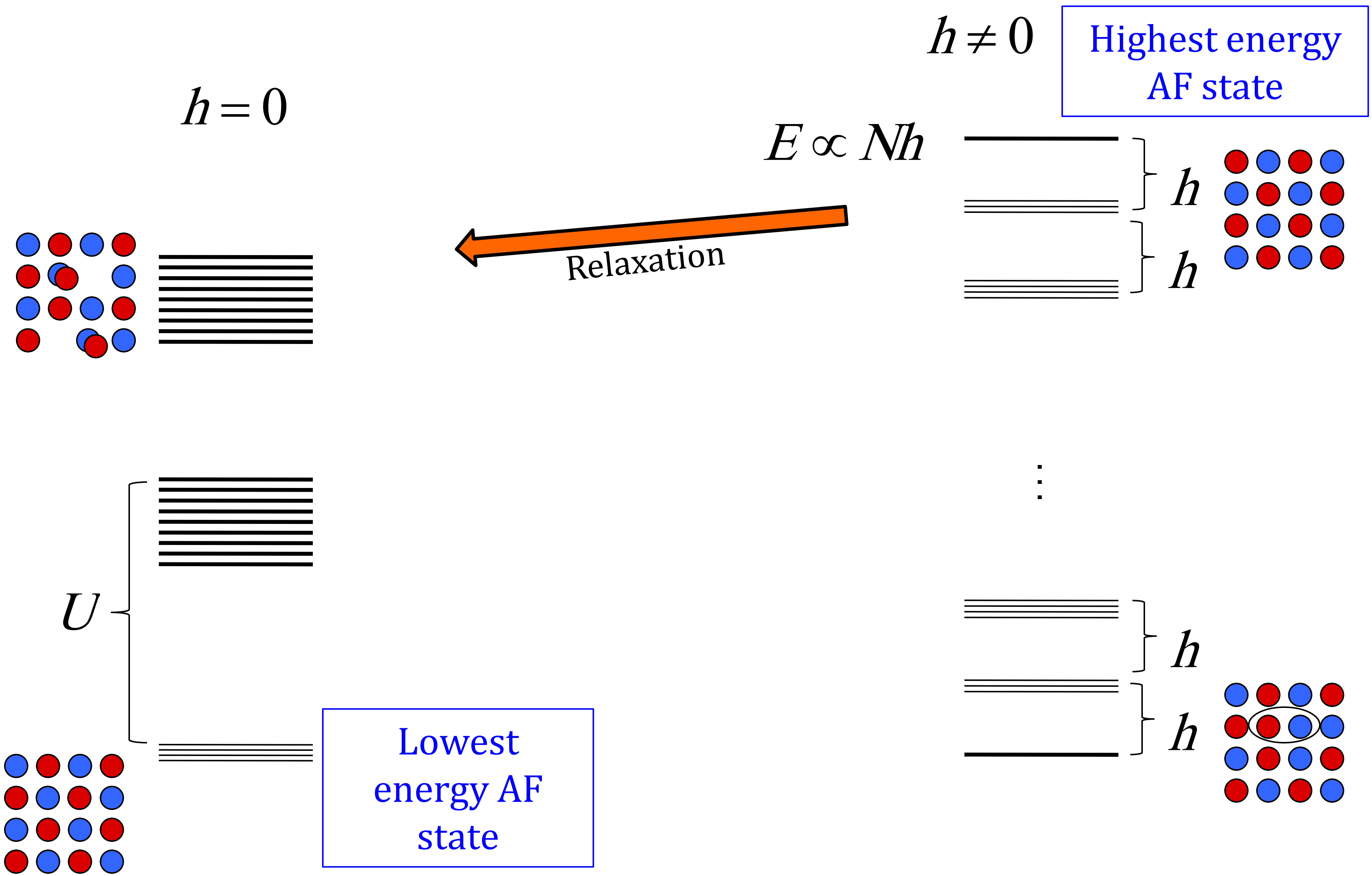
J. J. Garcıa-Ripoll, *et al*. PRL 93, 250405 (2004)
Sorensen et al. PRA 81 061603 (2010)

Many-Body Relaxation

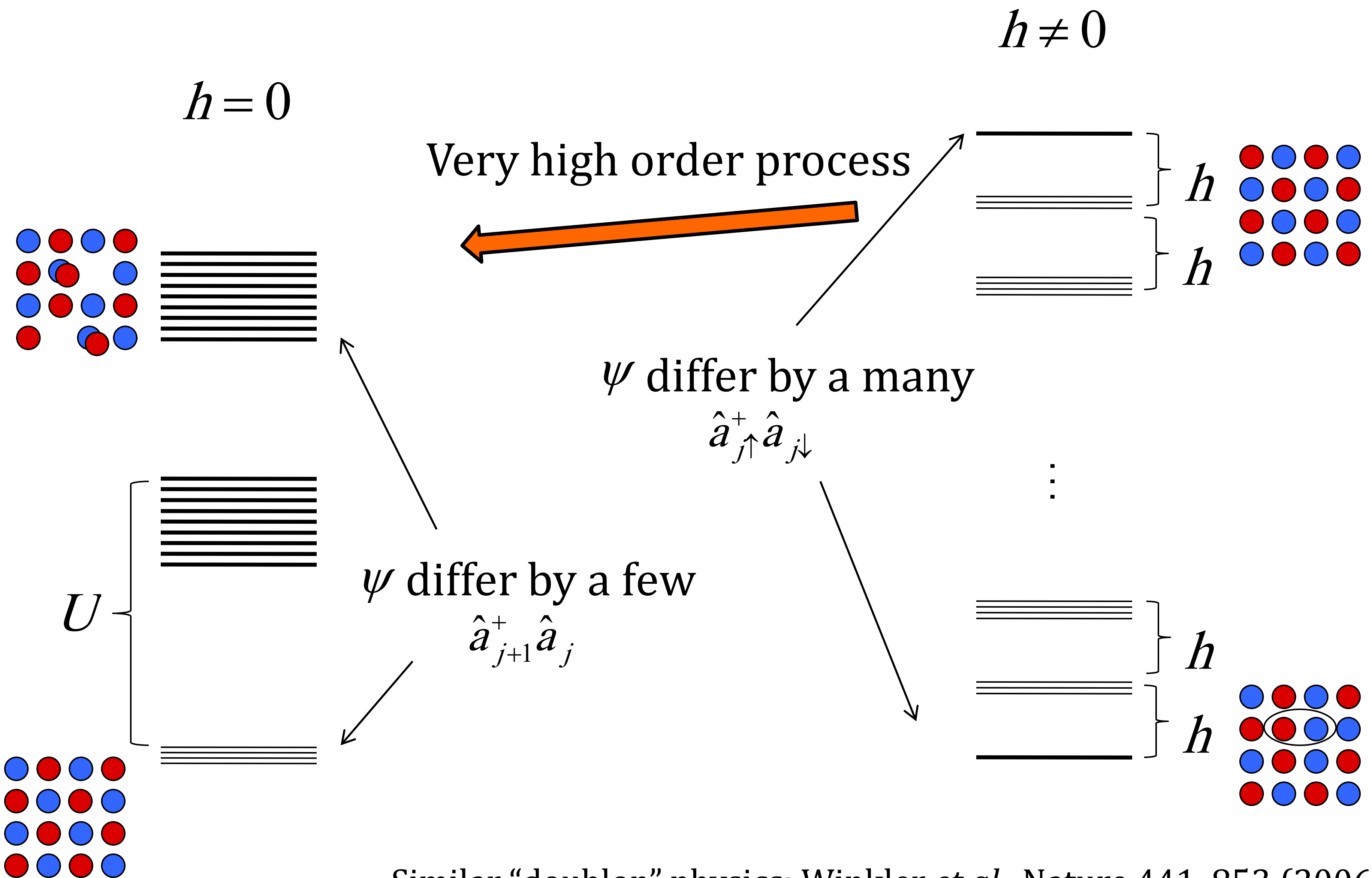
$$h = 0$$



Many-Body Relaxation



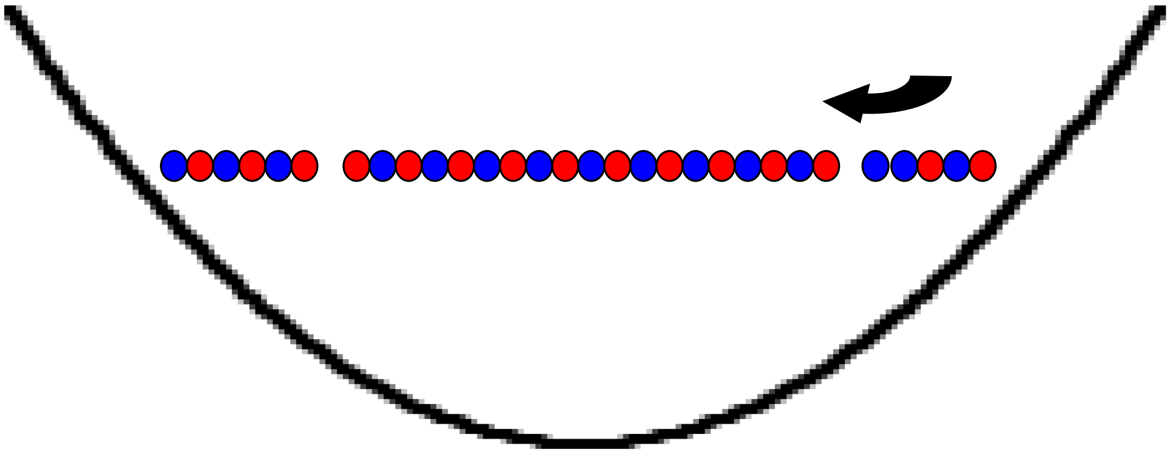
Many-Body Relaxation



Similar “doublon” physics: Winkler *et al.*, Nature 441, 853 (2006).

Edge and Hole Effects?

How do holes (thermal or from the edges) affect dynamics?



Inhomogeneous, trapped system

Progress:

Initial state preparation

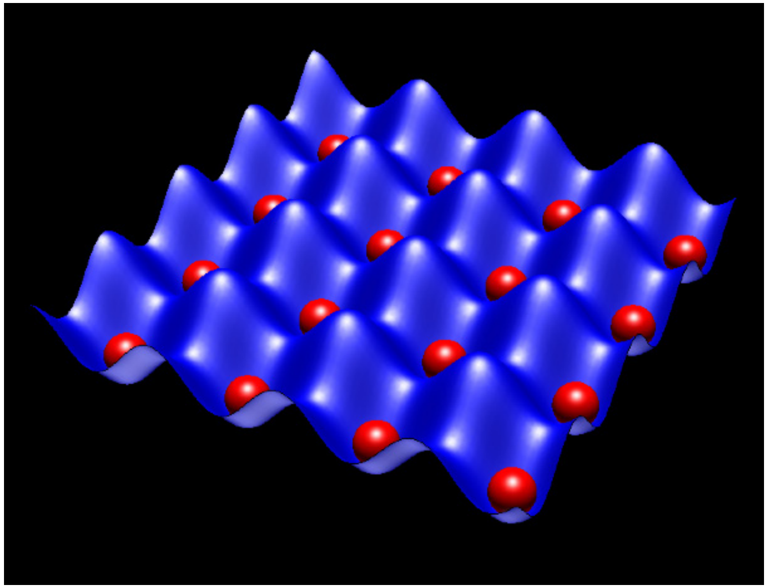
Spin control/readout

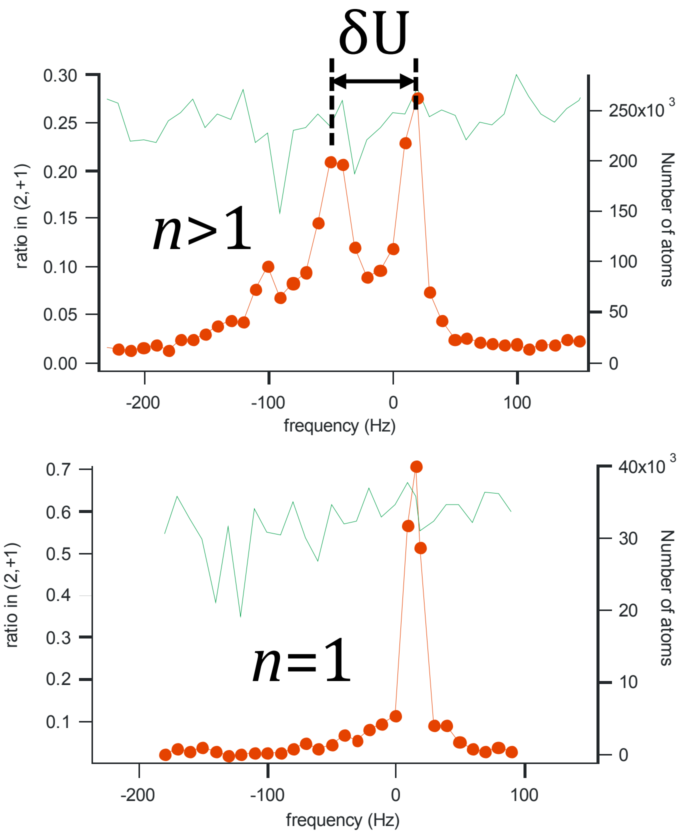
Adiabatic preparation

Relaxation

Preparing Single Atom per Site

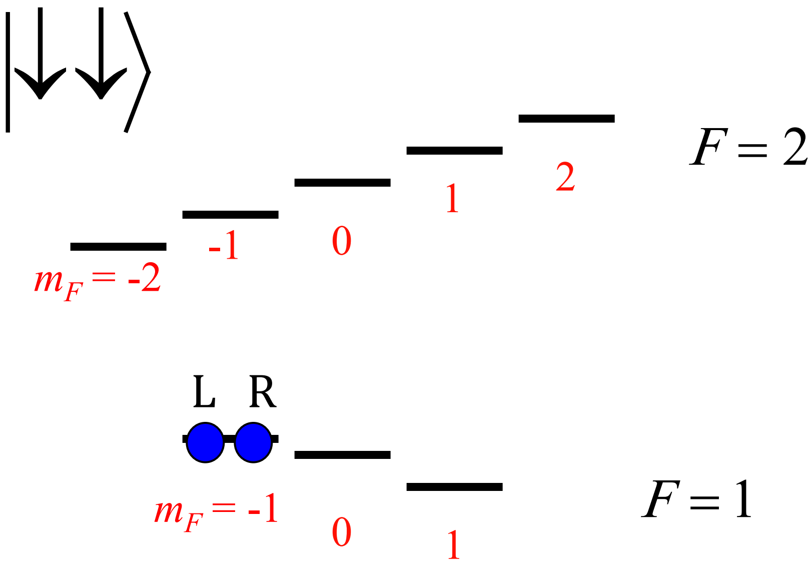
Starting point: Mott-insulator:

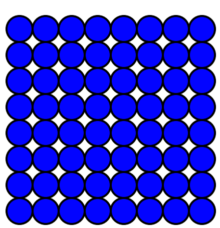


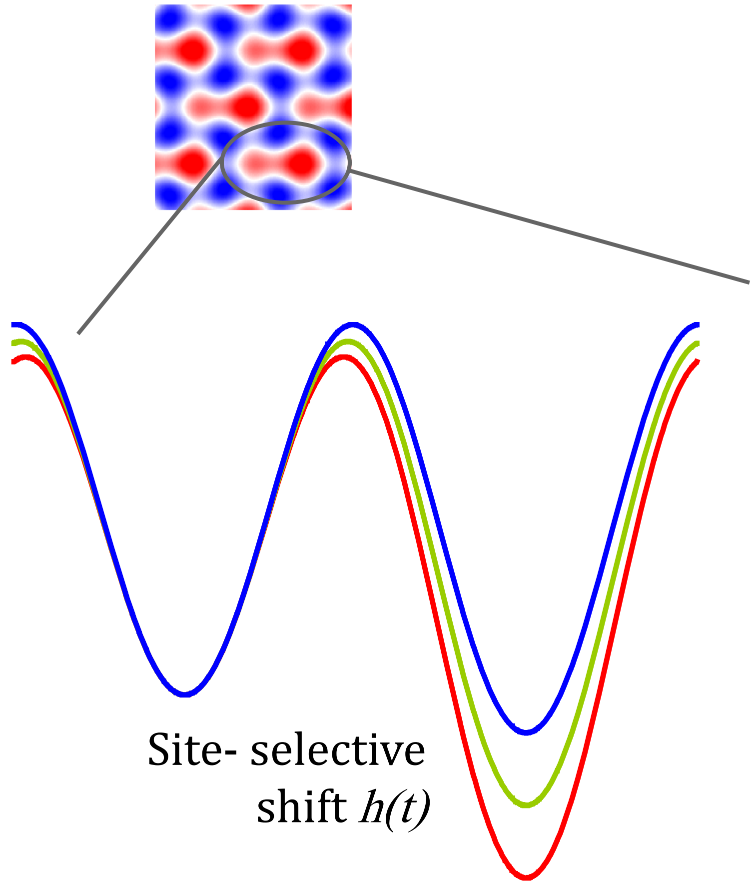


Sub-Lattice State Preparation/Readout

Prepare any spin state independently in L or R

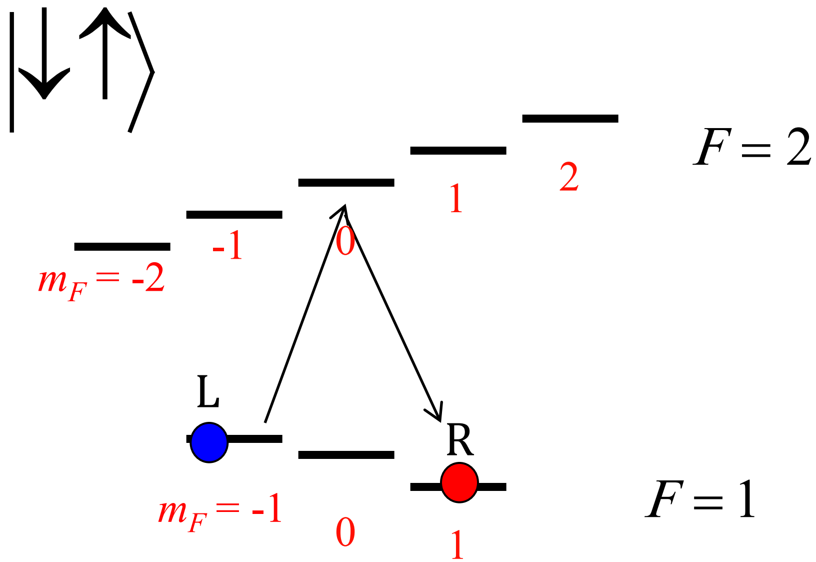


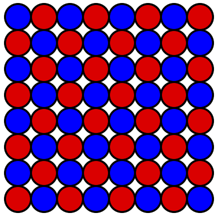


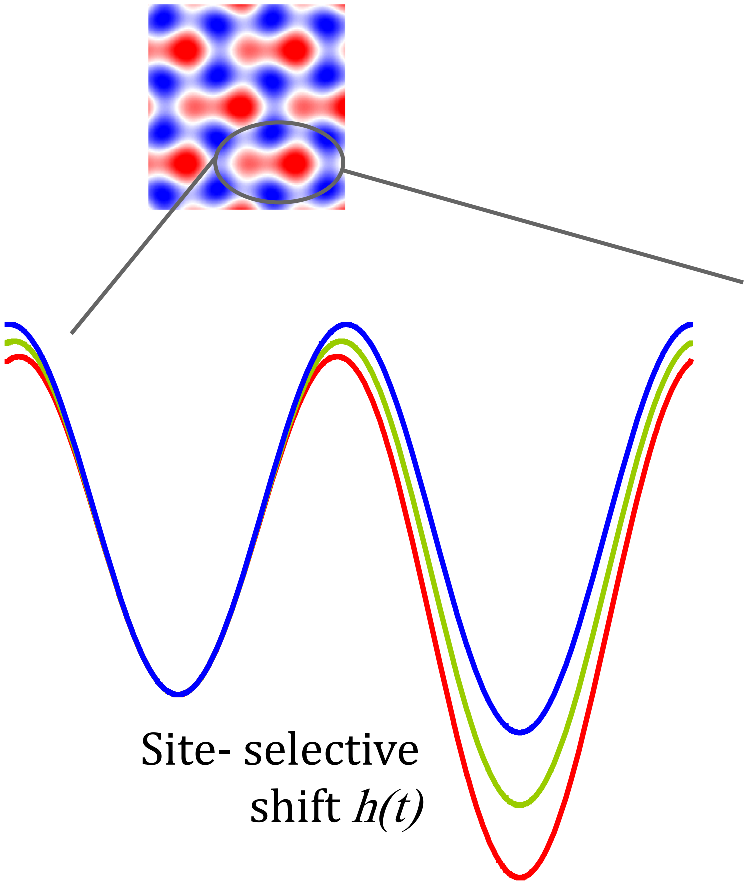


Sub-Lattice State Preparation/Readout

Prepare any spin state independently in L or R

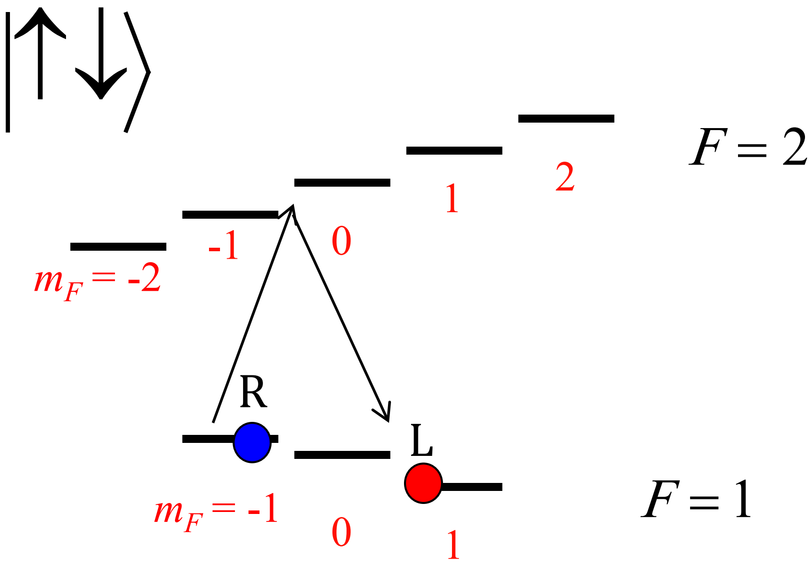


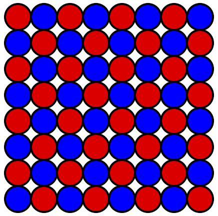


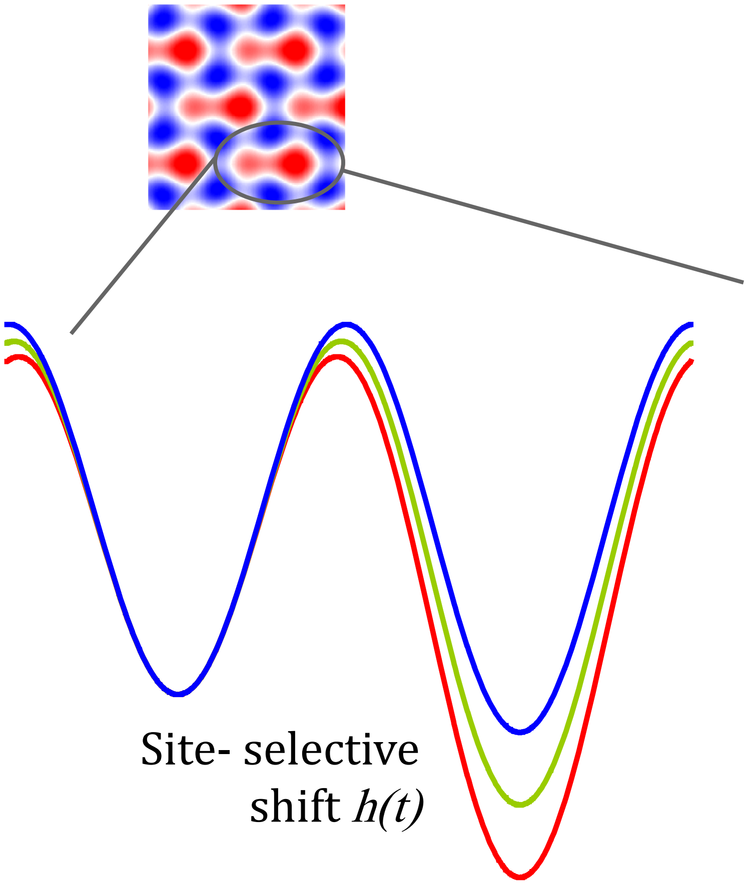


Sub-Lattice State Preparation/Readout

Prepare any spin state independently in L or R

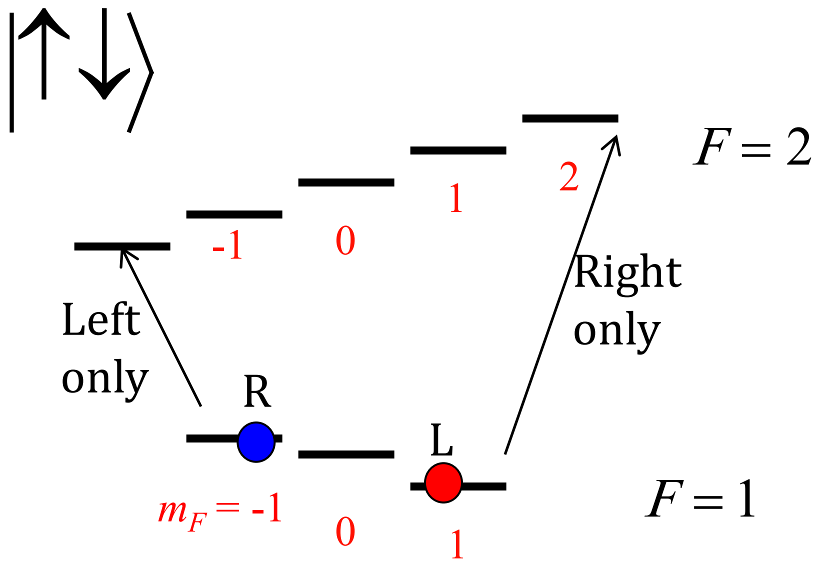


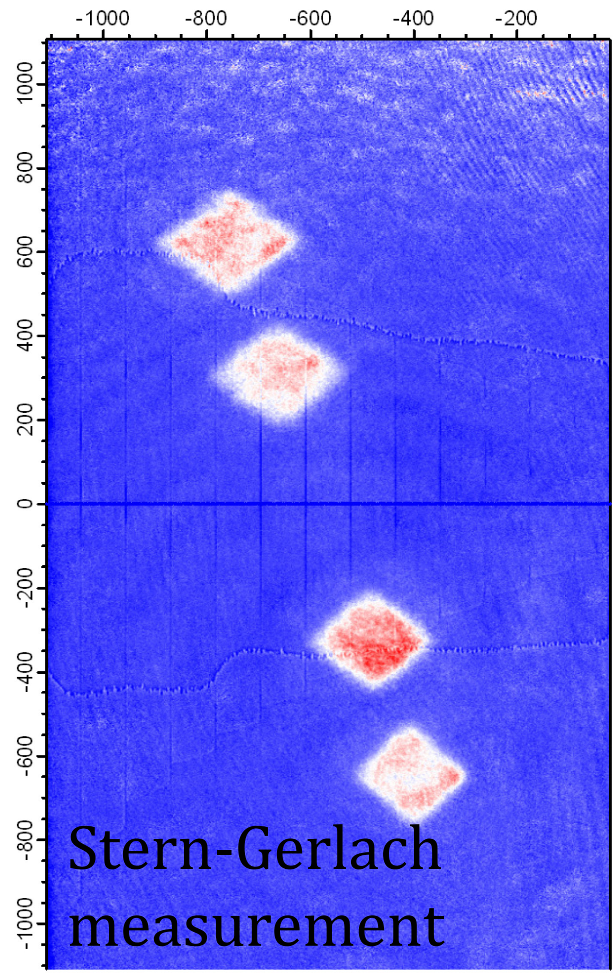




Sub-Lattice State Preparation/Readout

Read out any spin state independently in L or R

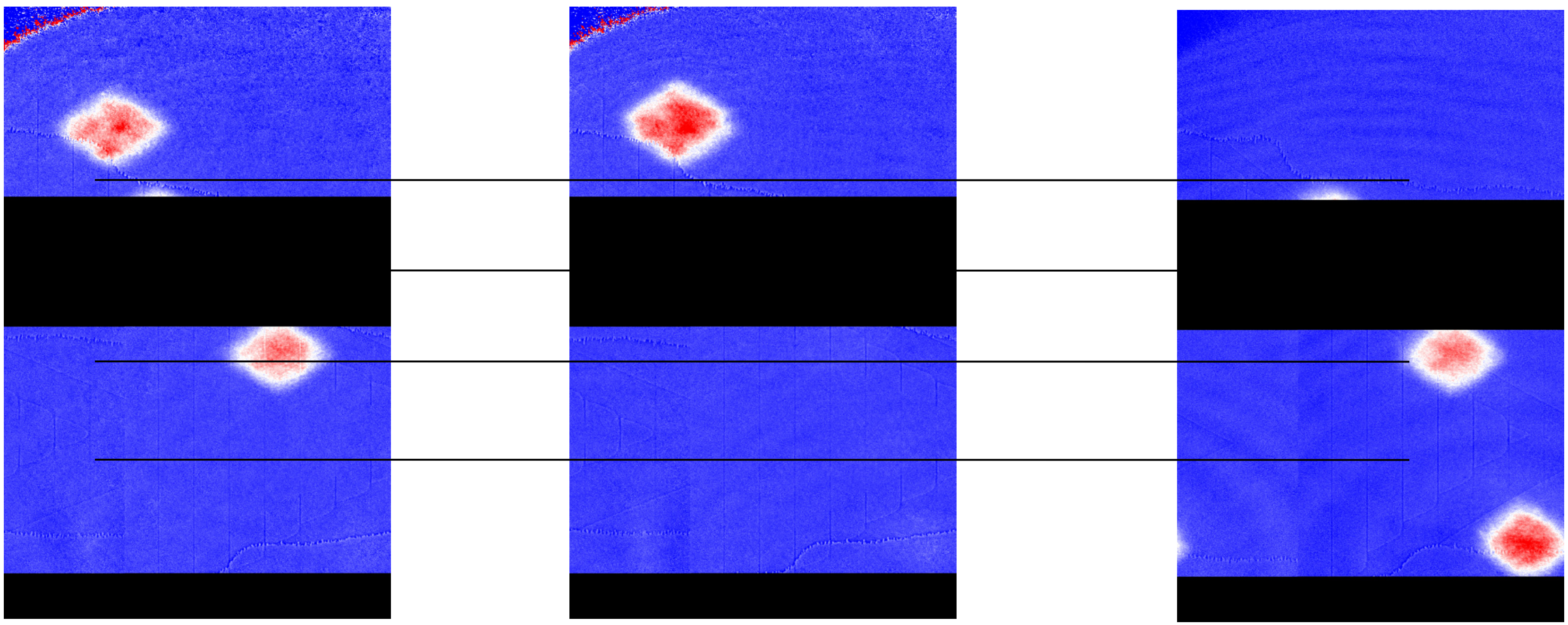




Sub-Lattice State Preparation/Readout

Read out any spin state independently in L or R

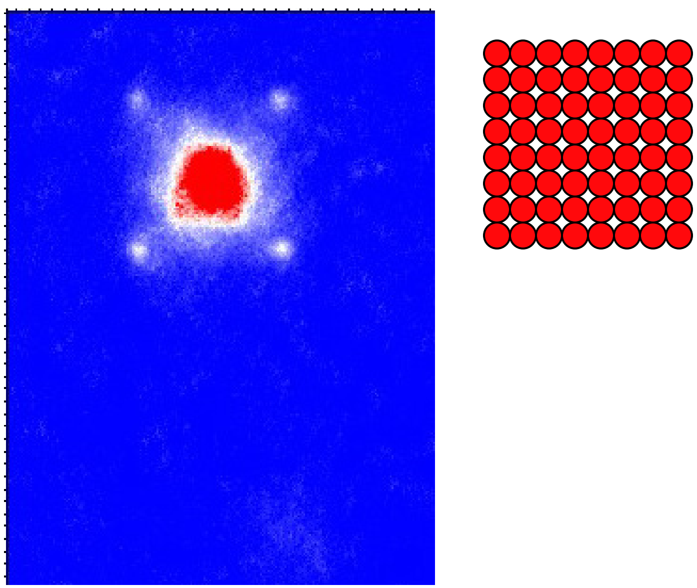
$|\downarrow\downarrow\rangle$ $|\downarrow\uparrow\rangle$ $|\uparrow\downarrow\rangle$



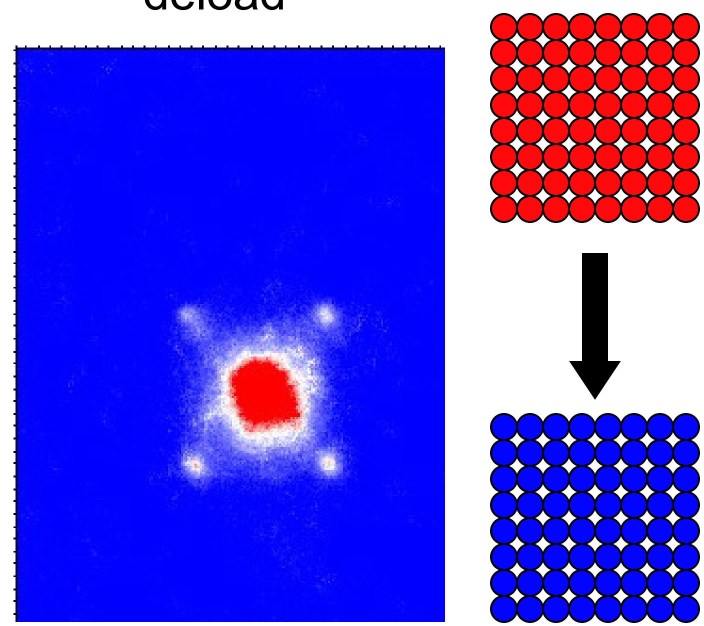
Spin-flip doesn't cause heating

Mott state robust against spin flips

Load into Mott state
and deload

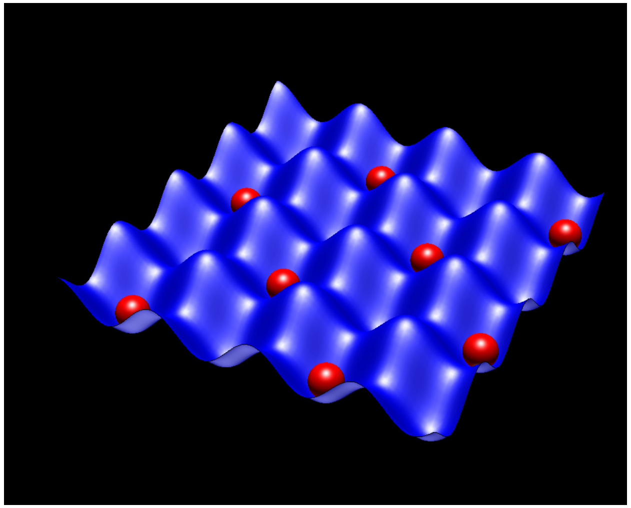


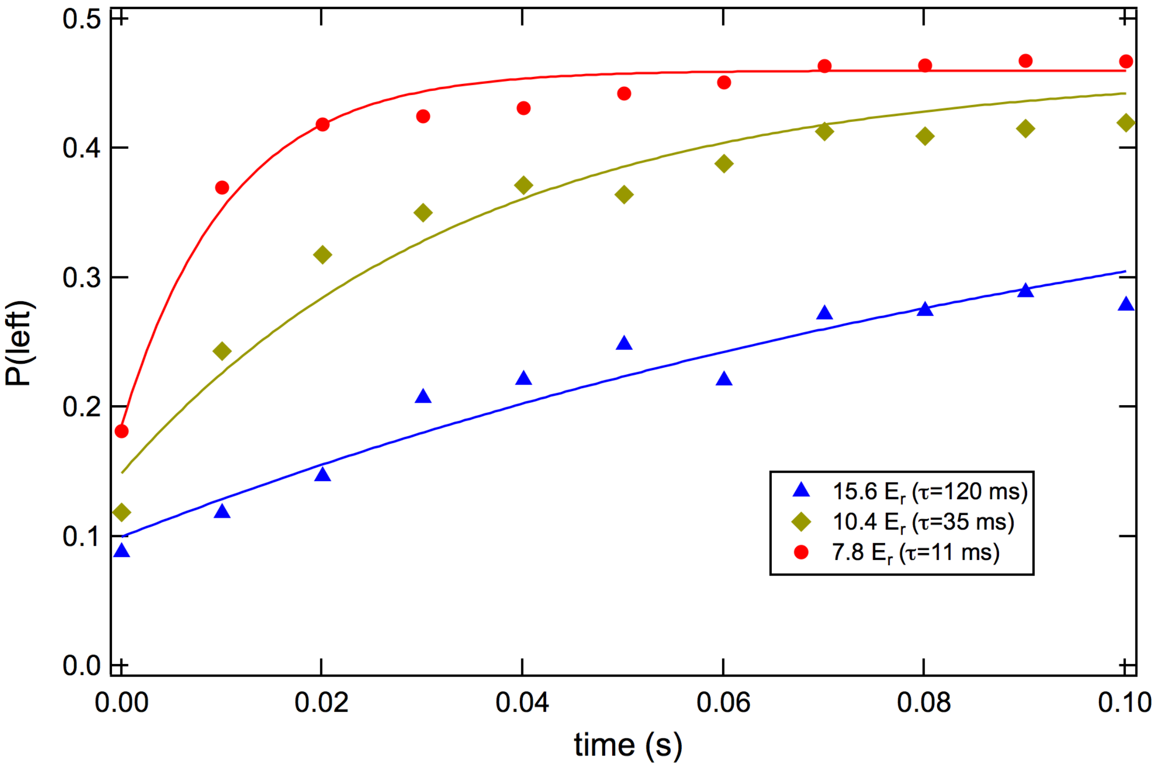
Load into Mott state
flip ALL the spins and
deload



Single Particle Tunneling

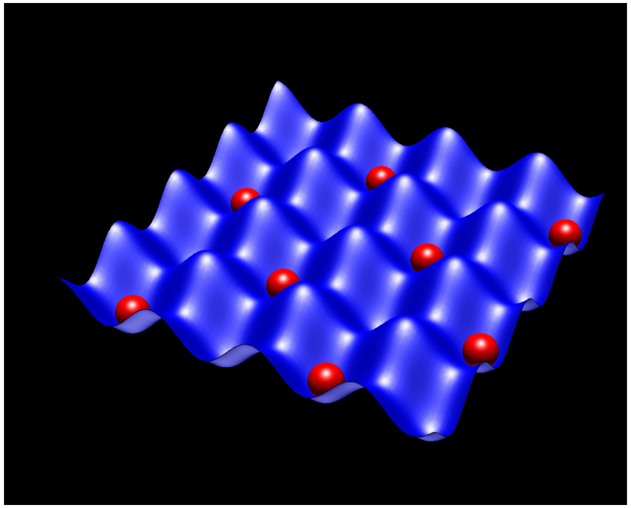
Prepare alternate sites empty, watch population

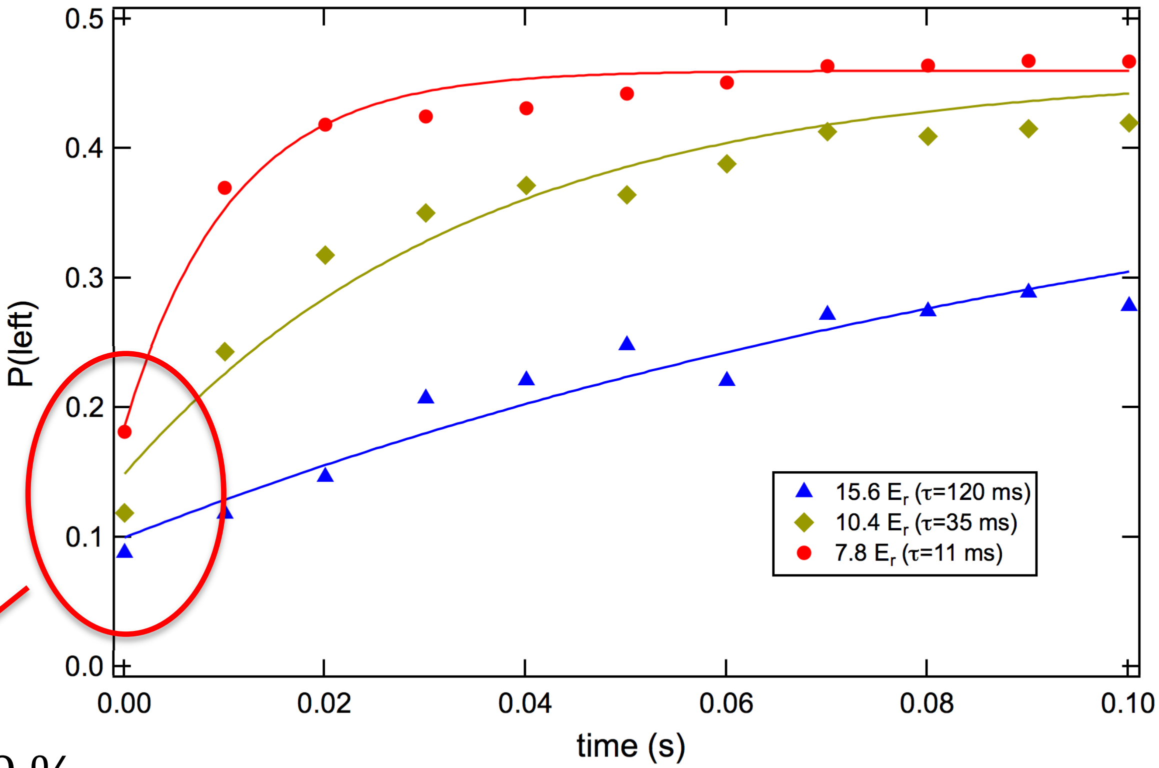




Single Particle Tunneling

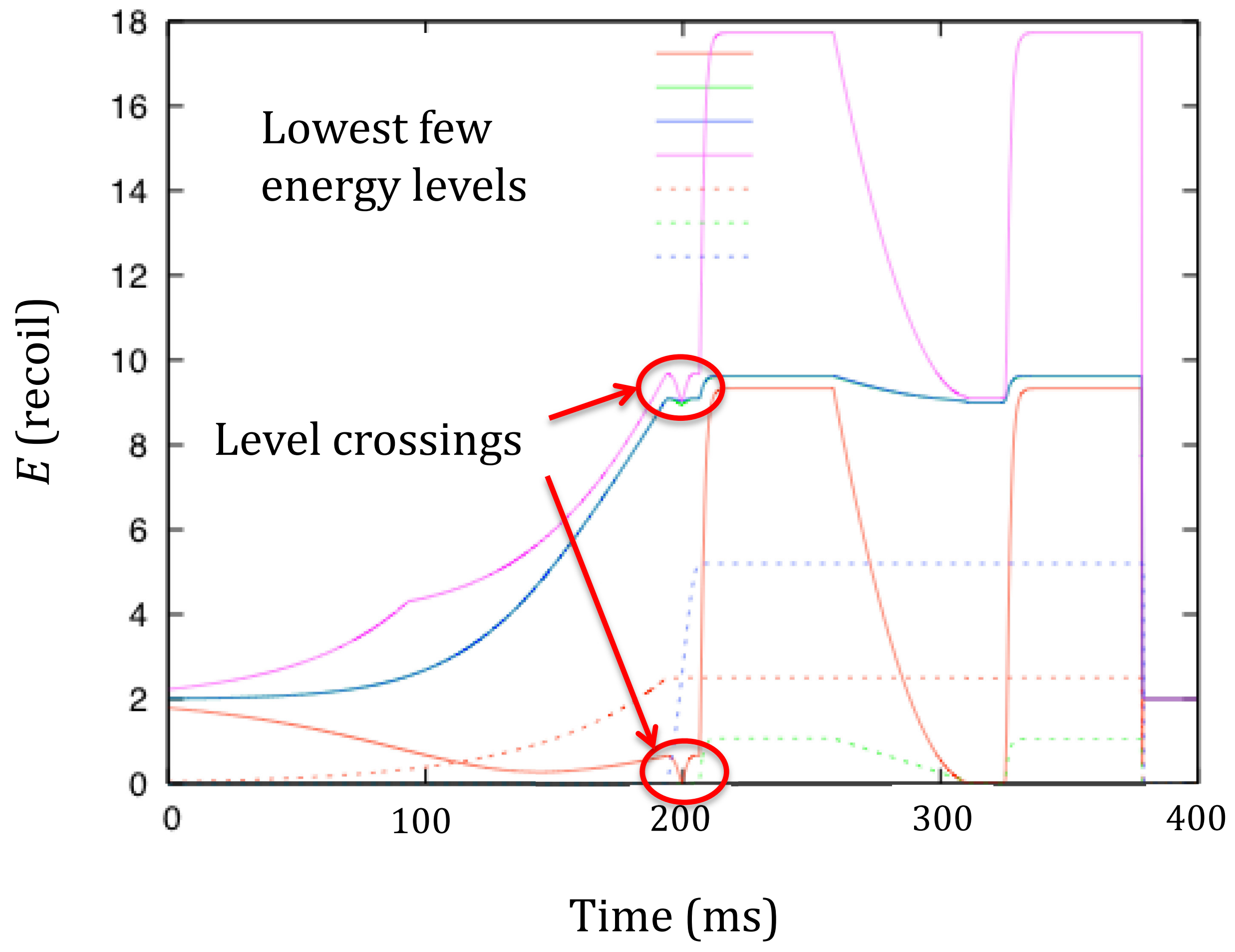
Prepare alternate sites empty, watch population





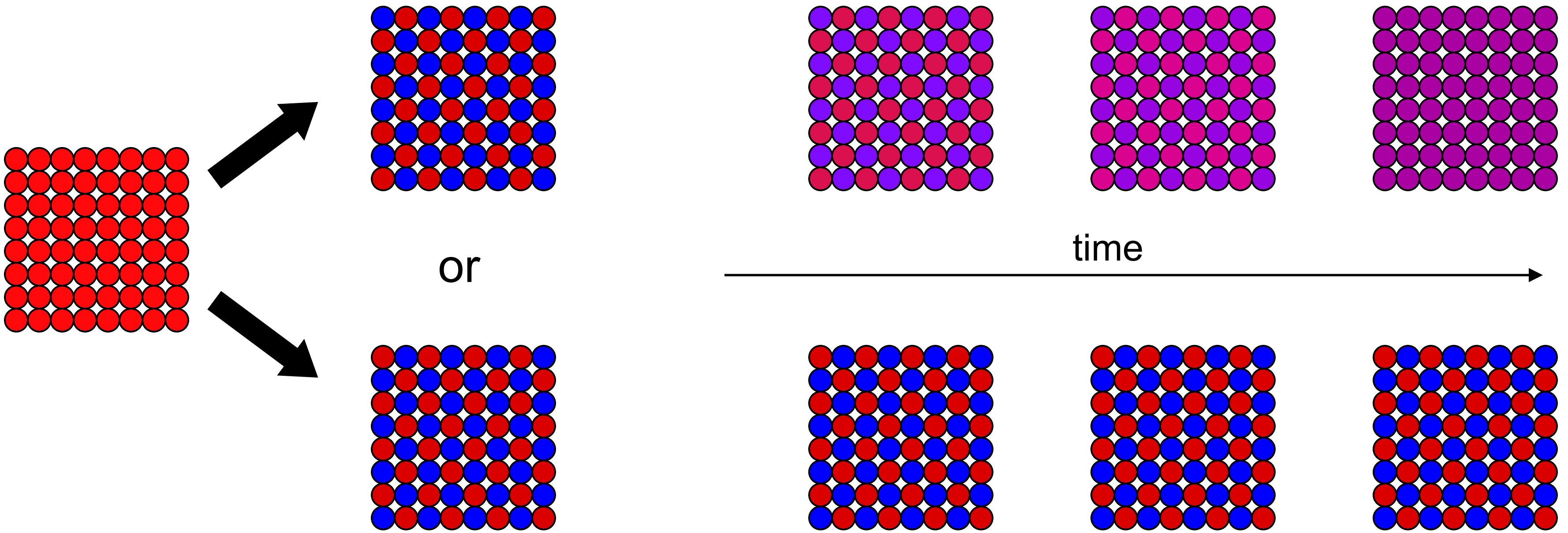
Spin-state preparation ~99 %,
but initial state is not perfect…

Adiabatic Manipulation



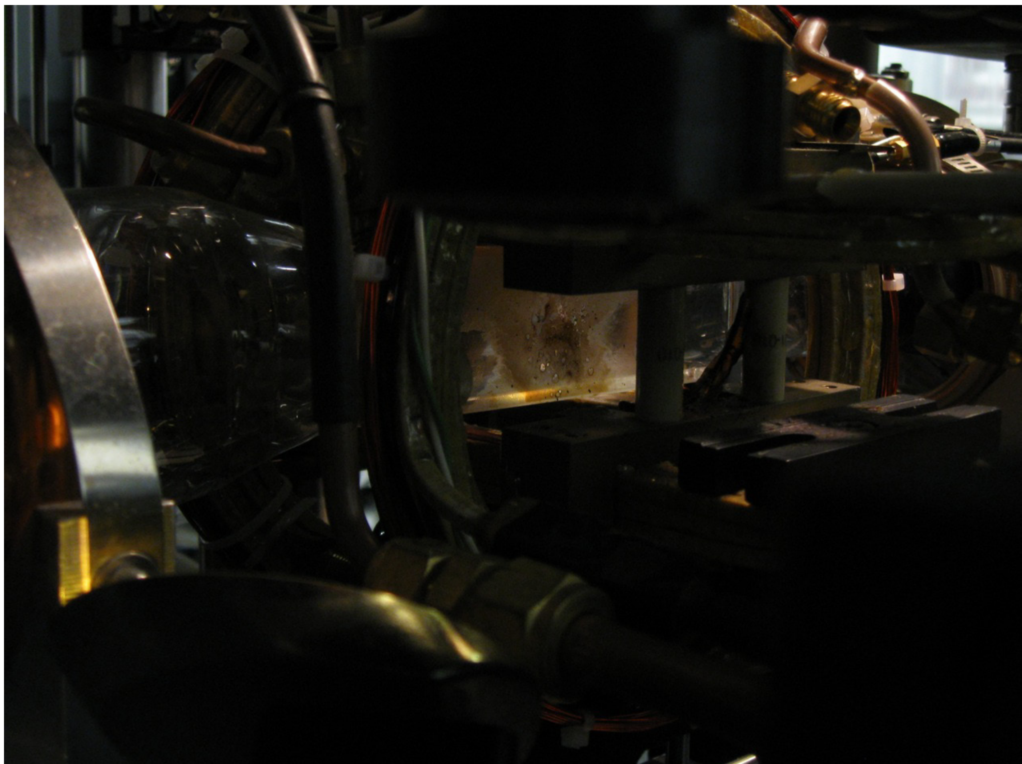
Next Measurement

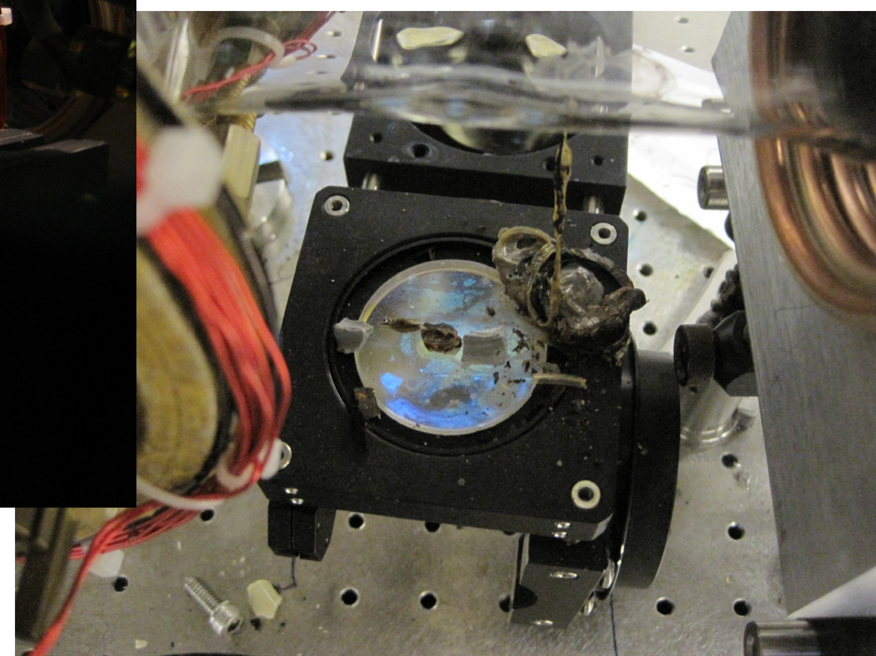
- prepare state
- adiabatically remove staggered field
- measure staggered magnetization vs. time



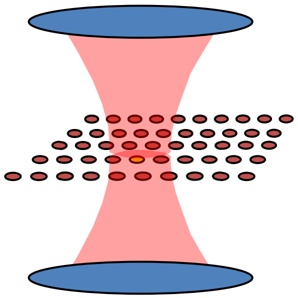
Accelerated Planned Upgrade

Nature decided we needed to move faster!

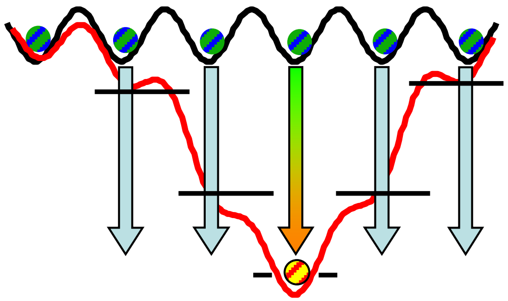


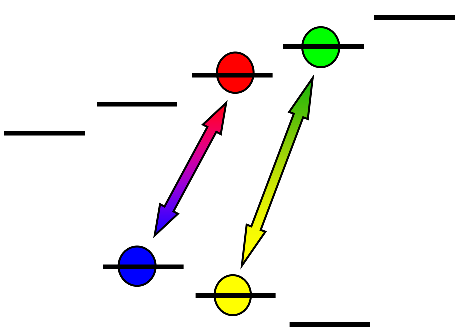


Motivation for Upgrade



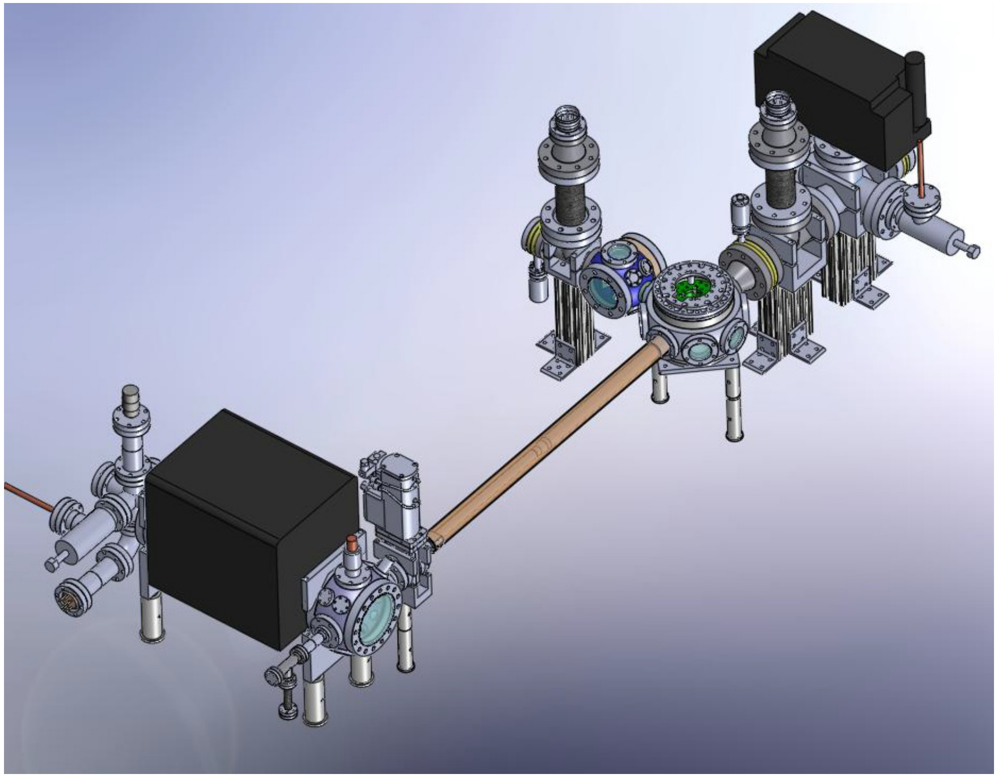
Individual addressing for
- measurement
- entanglement generation



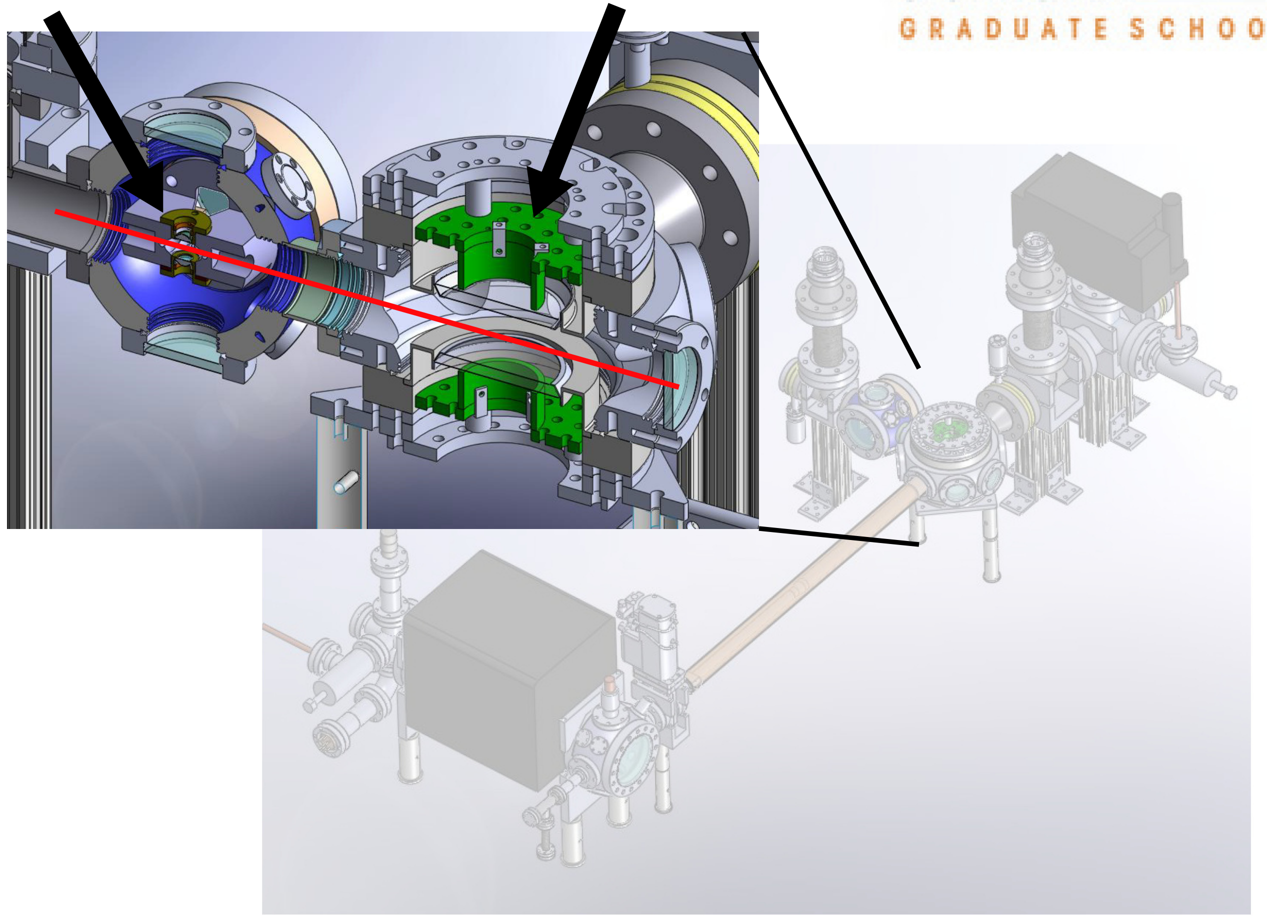


Greiner, Harvard
Kuhr, Bloch, Munich

Addressing Optical Lattices

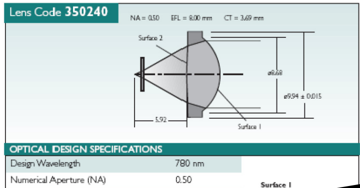


Addressing Optical Lattices

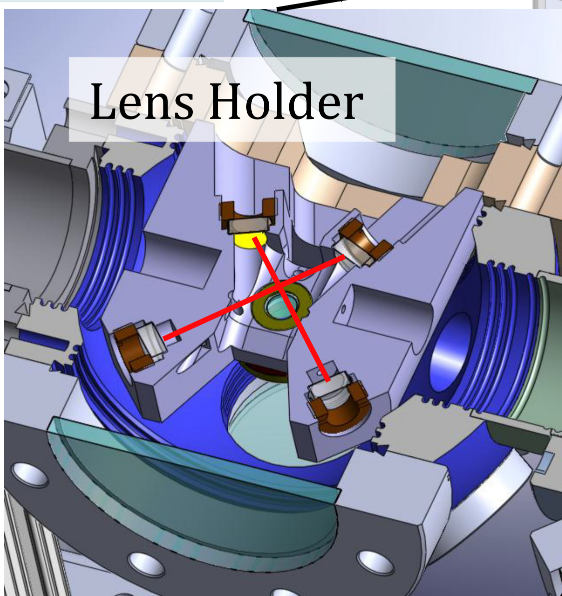


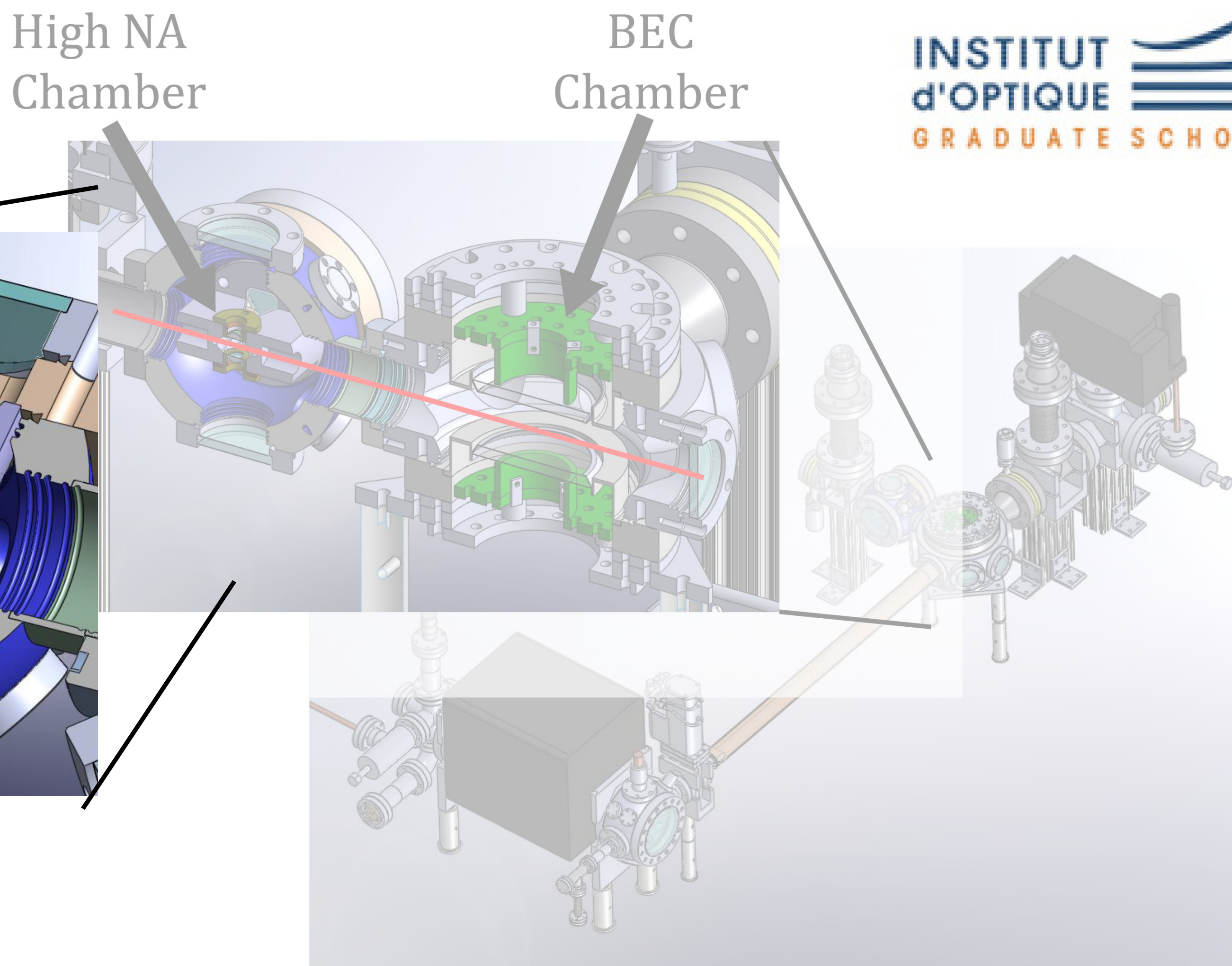
Addressing Optical Lattices

Comercial aspheres



OPTICAL DESIGN SPECIFICATIONS	
Design Wavelength	780 nm
Numerical Aperture (NA)	0.50





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