Quantum Computing with neutral atoms and artificial ions

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FULBRIGHT

Information Society Technologies

NIST National Institute of Standards and Technology
Technology Administration, U.S. Department of Commerce

NIST CENTENNIAL 1901-2001

Outline

- [Quantum Computing based on] neutral atoms in optical lattices
  - spin-dependent lattices
  - high fidelity loading of large lattice arrays beyond Mott insulator

Rabl et al.

- Entangling atoms
  - two-atoms Feshbach & photoassociation gates
  - atoms in pipeline structures

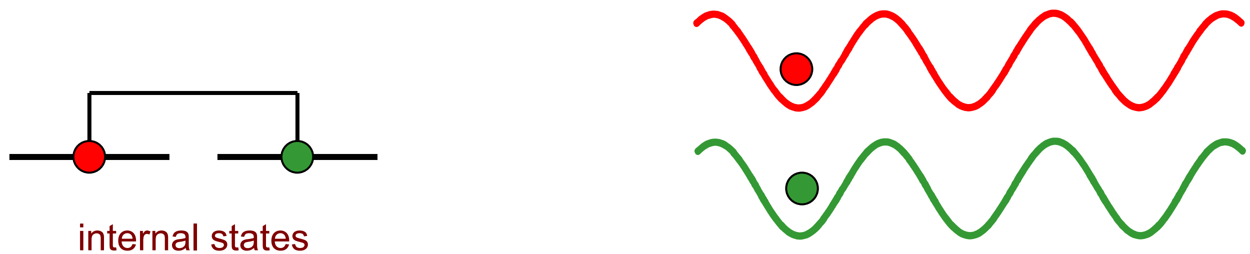
Dorner et al.

experiments by
I. Bloch et al., LMU
& NIST Gaithersburg

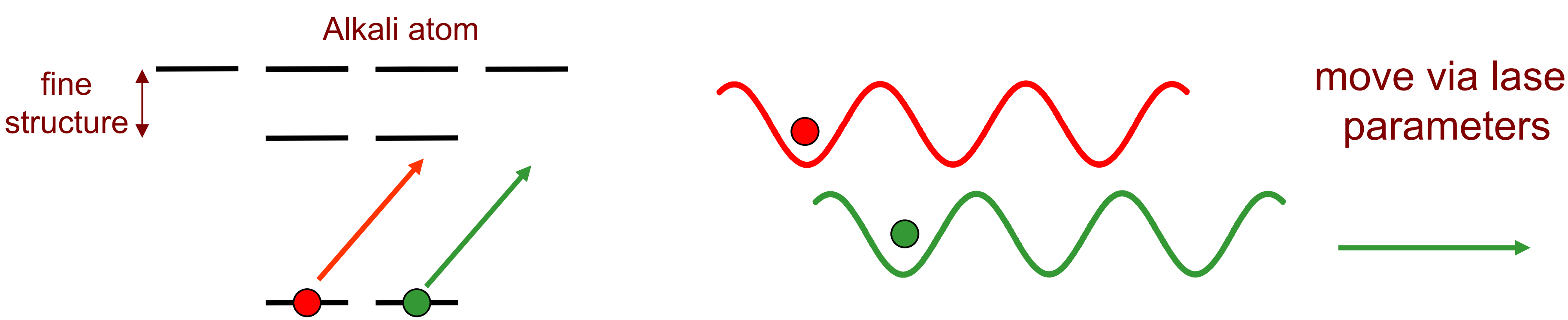
- All-optical quantum computing with quantum dots
  - Suppressing decoherence via quantum-optical techniques

Background: atoms in spin-dependent optical lattices

- optical lattice: spatially varying AC Stark shifts by interfering laser beams
- trapping potential depends on the internal state



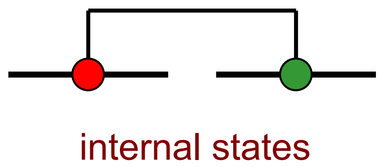
- we can move one potential relative to the other, and thus transport the component in one internal state

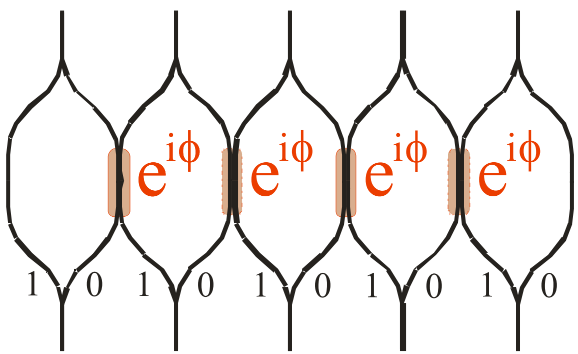


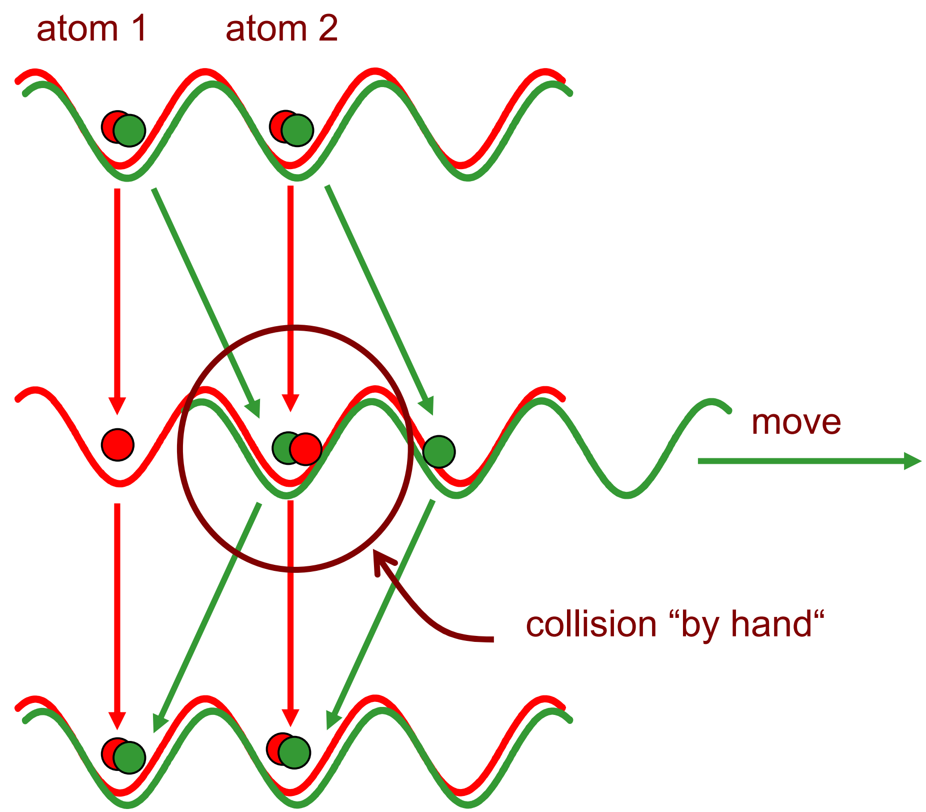
theory: Jaksch et al.

exp.: I. Bloch et al.

- interactions by moving the lattice + colliding the atoms “by hand”







- Ising type interaction: building block of the Universal Quantum Simulator

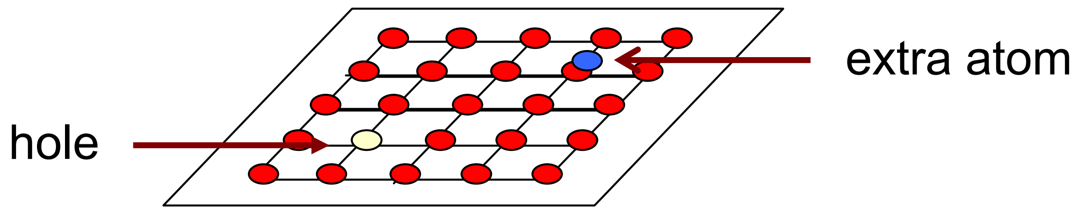
$$H \quad \frac{J}{2} \quad {}_{a,b} \quad {}_{z}^{a} \quad {}_{z}^{b}$$

nearest neighbor, next to nearest neighbor ....

Theory: Zoller – Cirac et al. (Ibk & MPQ)

Correcting defects in optical lattices

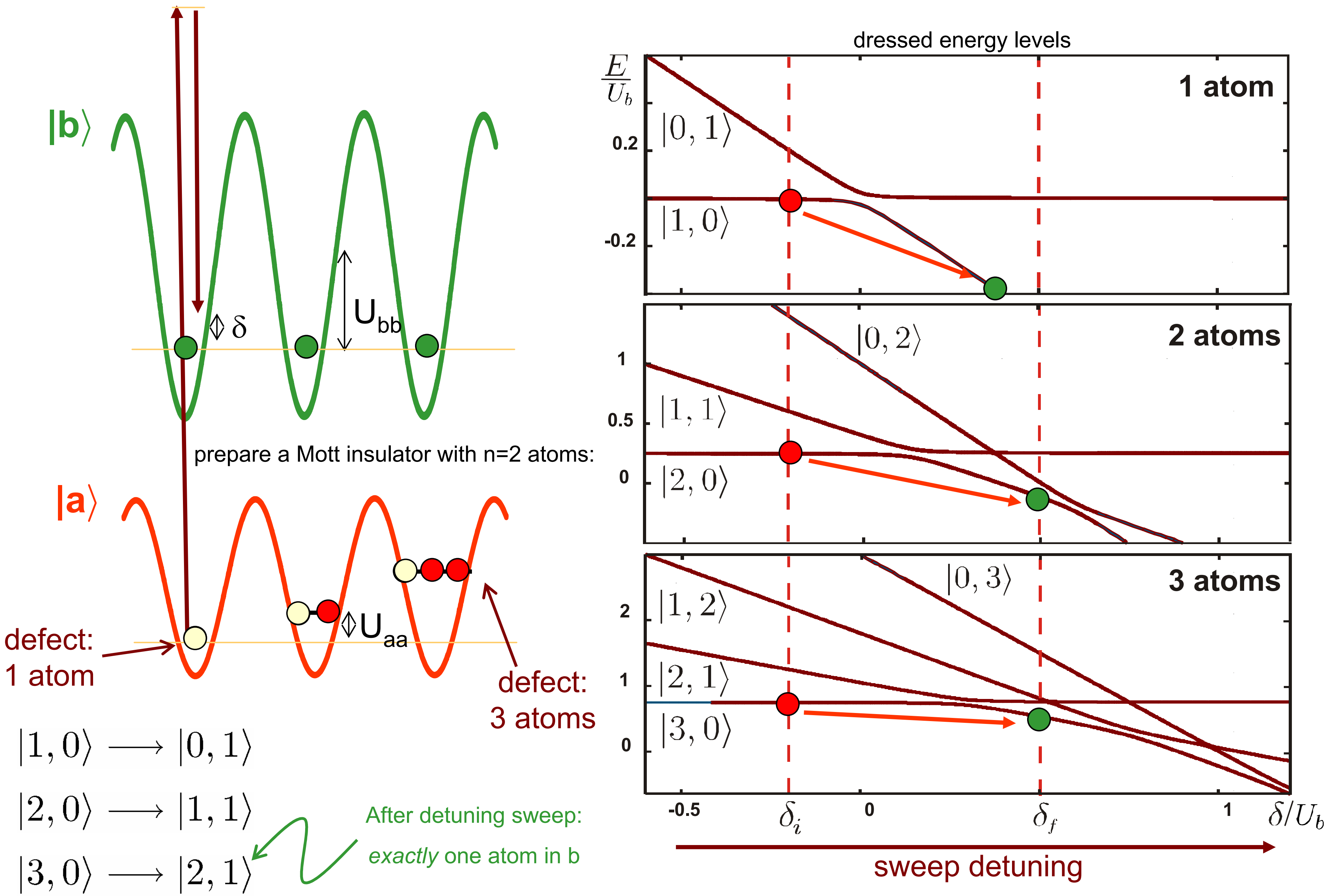
- Preparation of qubits via a superfluid – Mott insulator phase transition
- Mott insulator have still some defects ...
  present LMU exp.: approx. 1 out of 10 (not optimized)



- Questions:
  - ✓ Even "more regular" loading?
  - ✓ Can we heal defects?
  - ✓ Self-healing?

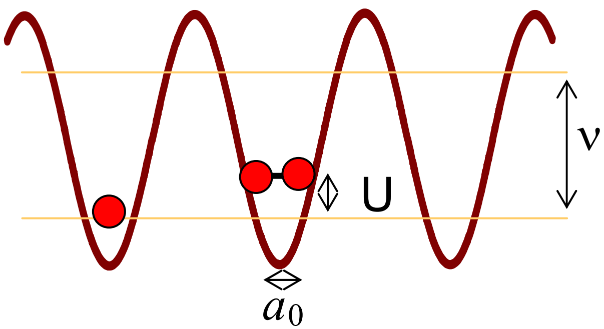
  Rem: it seems difficult to do this in normal solids

Defect free optical crystals (for quantum computing)



Collision gates & speed

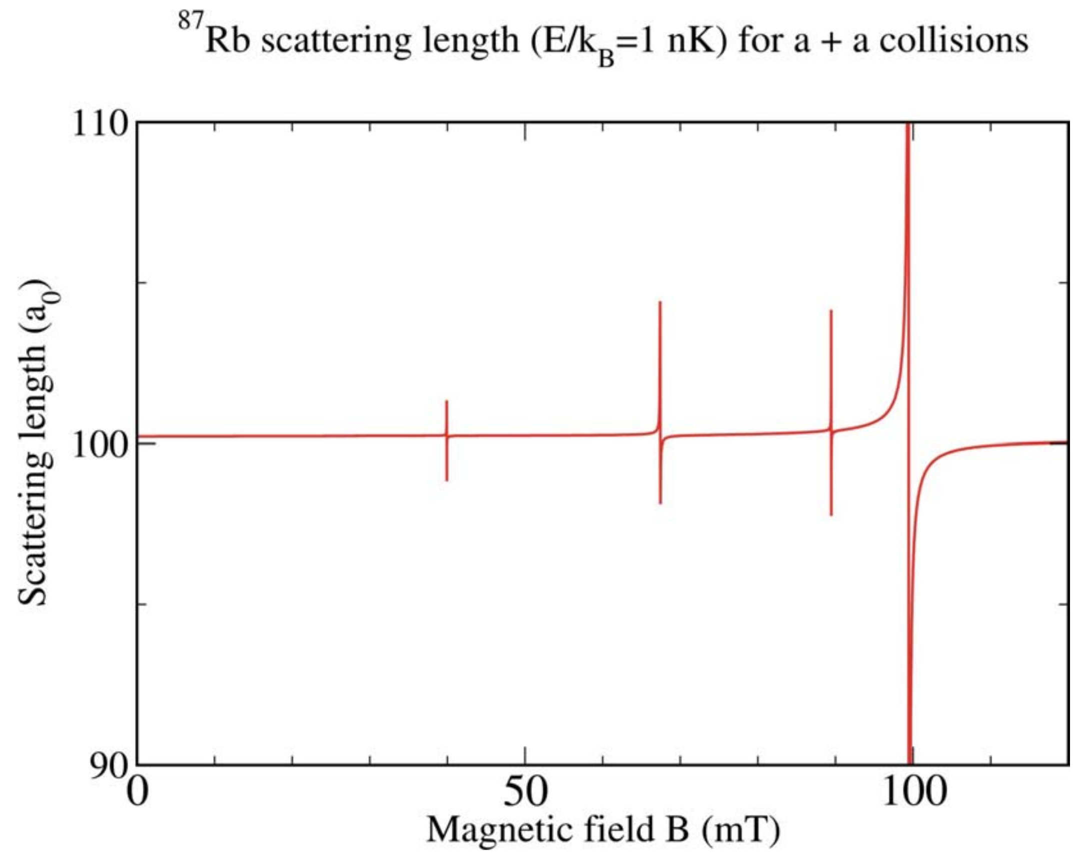
- validity of the Hubbard model

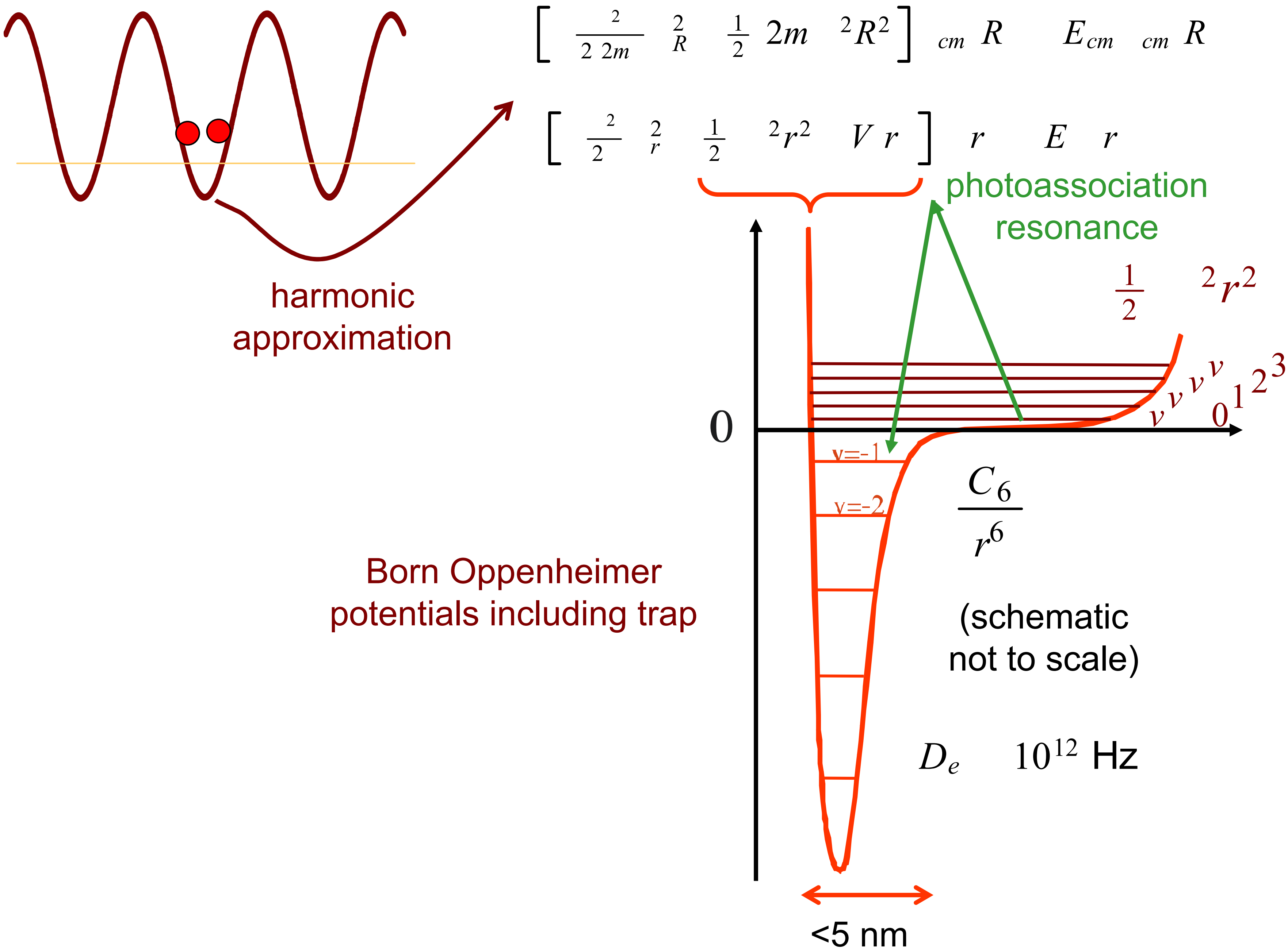


$$U \quad \frac{4\ a_s\ {}^2}{m} \quad d^3x|w\ x\ |^4$$

scattering length a_s a_0

- we can tune to a resonance to have a (free space) scattering length




[2 / 2 2m 2 R 1/2 2m 2 R2] cm R Ecm cm R
[2 / 2 2 r 1/2 2 r2 V r] r E r
photoassociation resonance
harmonic approximation
1/2 2 r2
v0 v1 v2 v3
0
v=-1
v=-2
C6 / r6
Born Oppenheimer potentials including trap
(schematic not to scale)
De 10^12 Hz
<5 nm

Coupling into molecular states via a “Feshbach ramp”

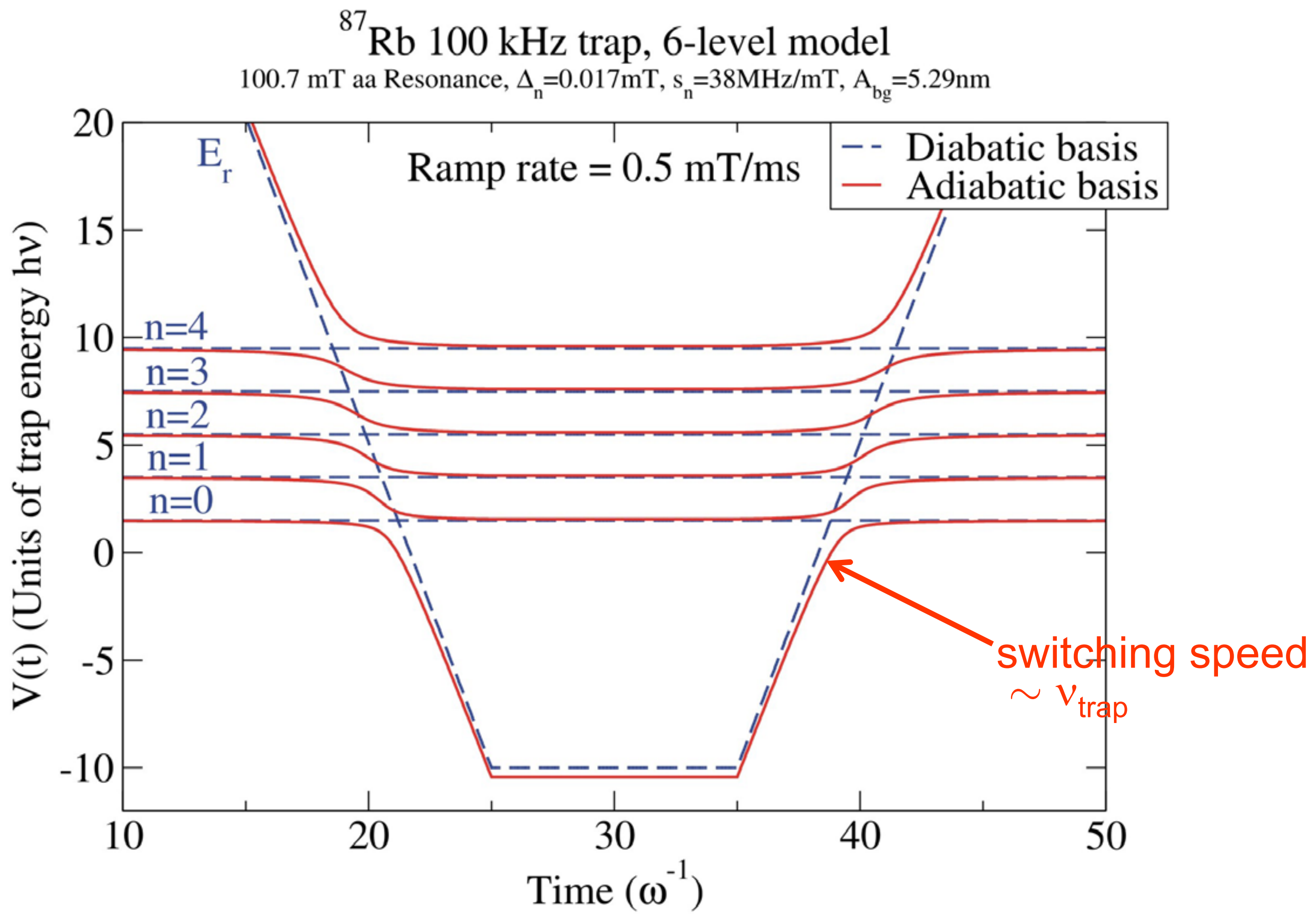


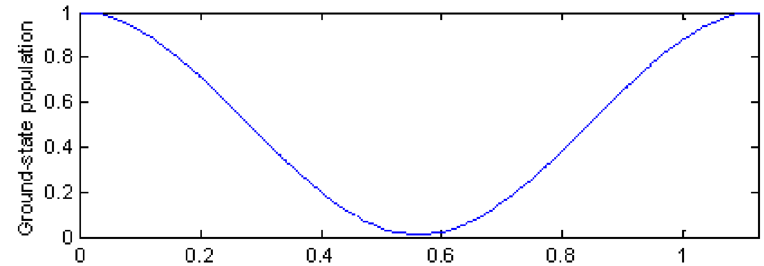
FIG. 7. Diabatic and adiabatic energy levels of a double Feshbach ramp. The bare resonance energy is held at a constant value between times $t\omega_h$ of 25 and 35, then ramped back across threshold with a ramp functions that is the inverse of the rst one.

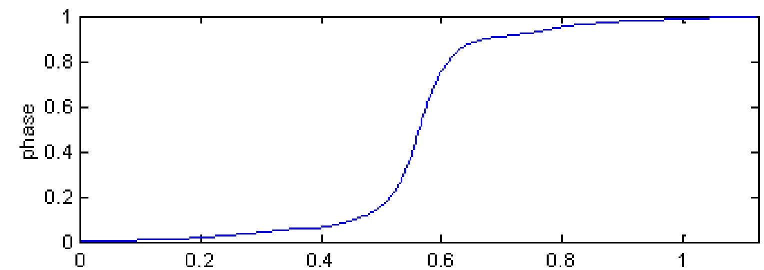
Feshbach switching in a spherical trap

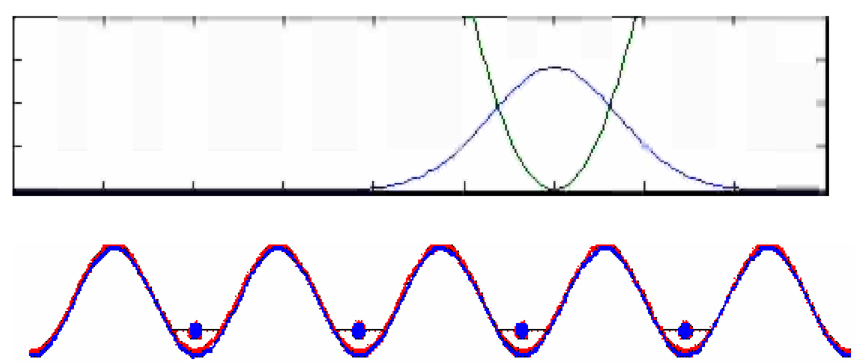
- Start with the Feshbach resonance state 10 trap units above threshold
- Switch it suddenly close to threshold
- Wait ~ 1 trap time (~ μs assuming MHz trap)
- Switch back
- A phase π is accumulated
- Fidelity: 0.9996

- No state dependence required, however difficult atom separation with state-independent potential

- State dependence: lattice displacement
- Non-adiabatic transport in optical lattice: simulation with realistic potential shape
- Fidelity 0.99999 in 1.5 trap times through optimal control theory



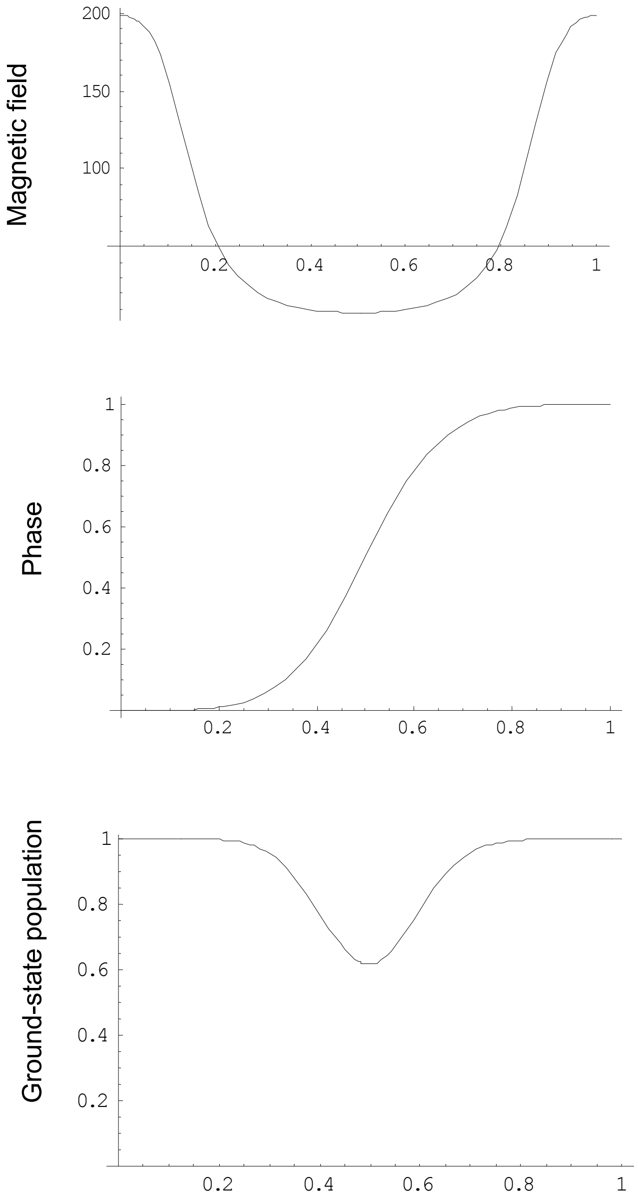




Feshbach ramp in an elongated trap

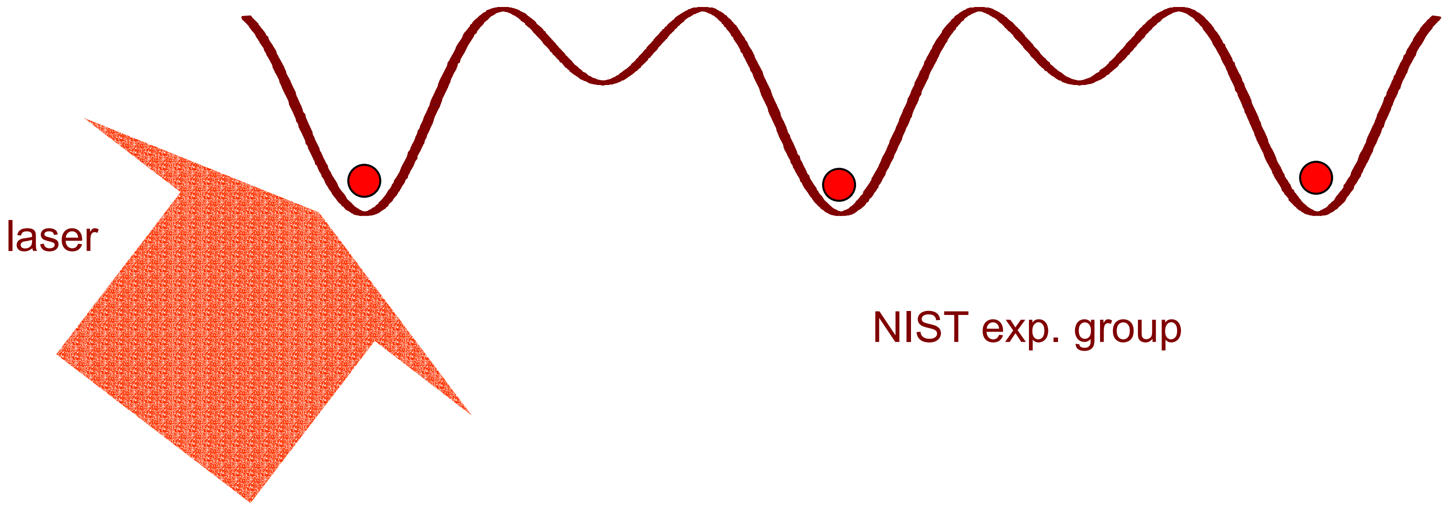
- Assumptions:
  - Cigar-shaped trap
  - Transverse motion “frozen”
- Lower longitudinal density of states
  - Bigger coupling to each level
  - Smaller non-adiabatic crossing
- Smoothly varying magnetic field
- Phase gate in 1 trap time with fidelity 0.9996
- Disadvantage: quasi-1D requirement limits trap frequency & speed

- Idea: use this in a “free-fall” scheme where no state-dependent potential would be needed

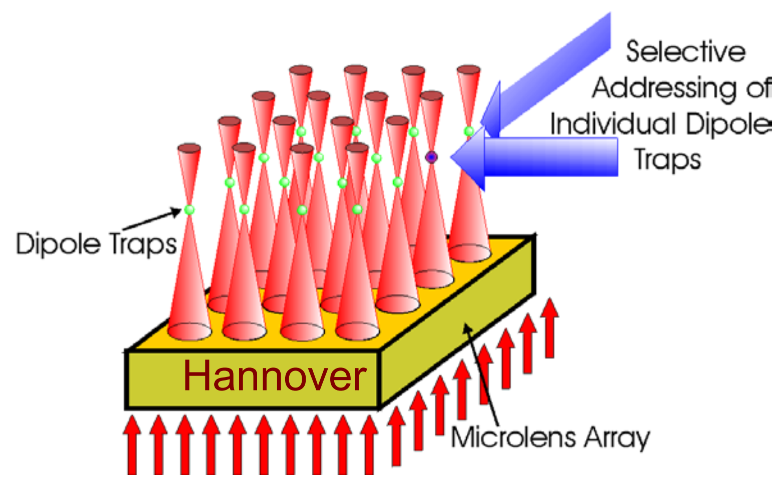


Alternative trap designs

- pattern loading, e.g for addressing single atoms

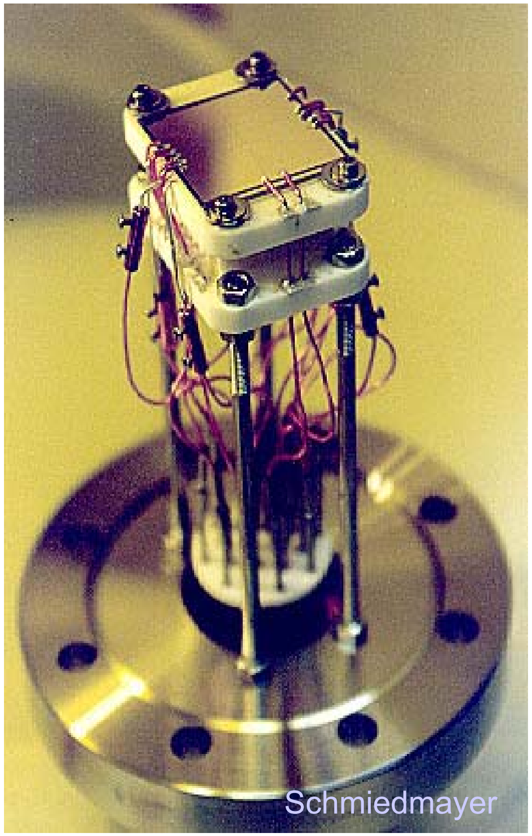


- Microlens arrays



Atom chips

- magnetic traps



Heidelberg, Munich, Harvard, Orsay

issues:

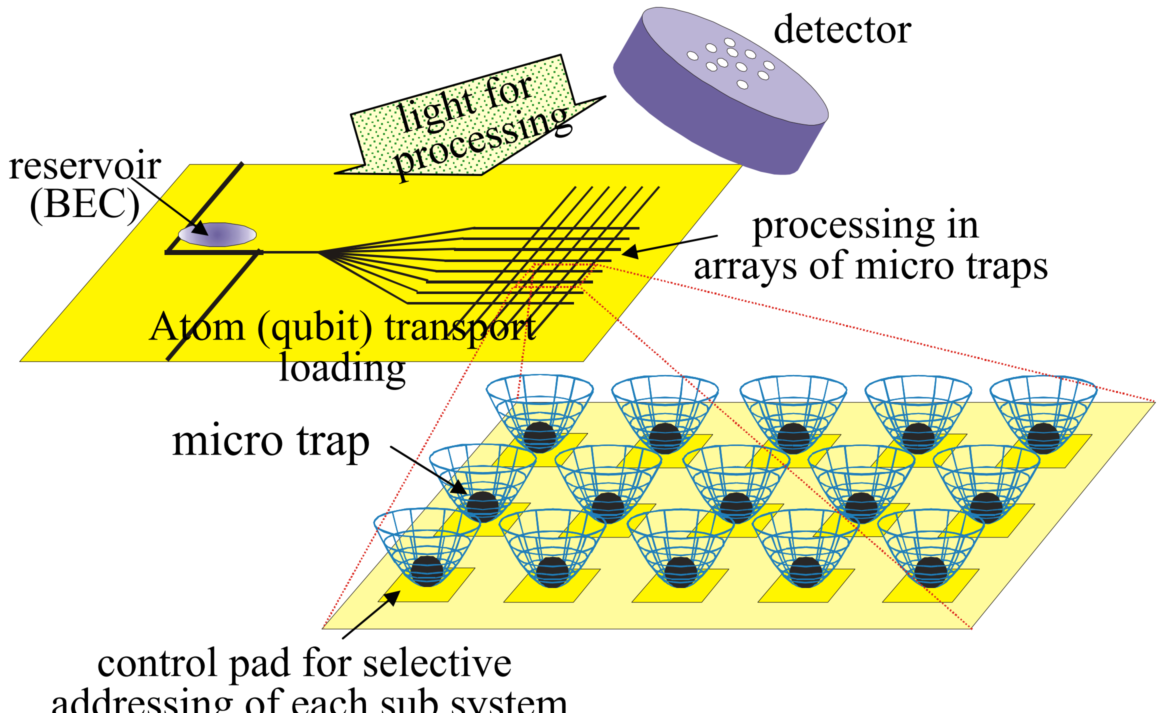
✓ conservative potential surface effects

✓ single atom loading

✓ laser cooling

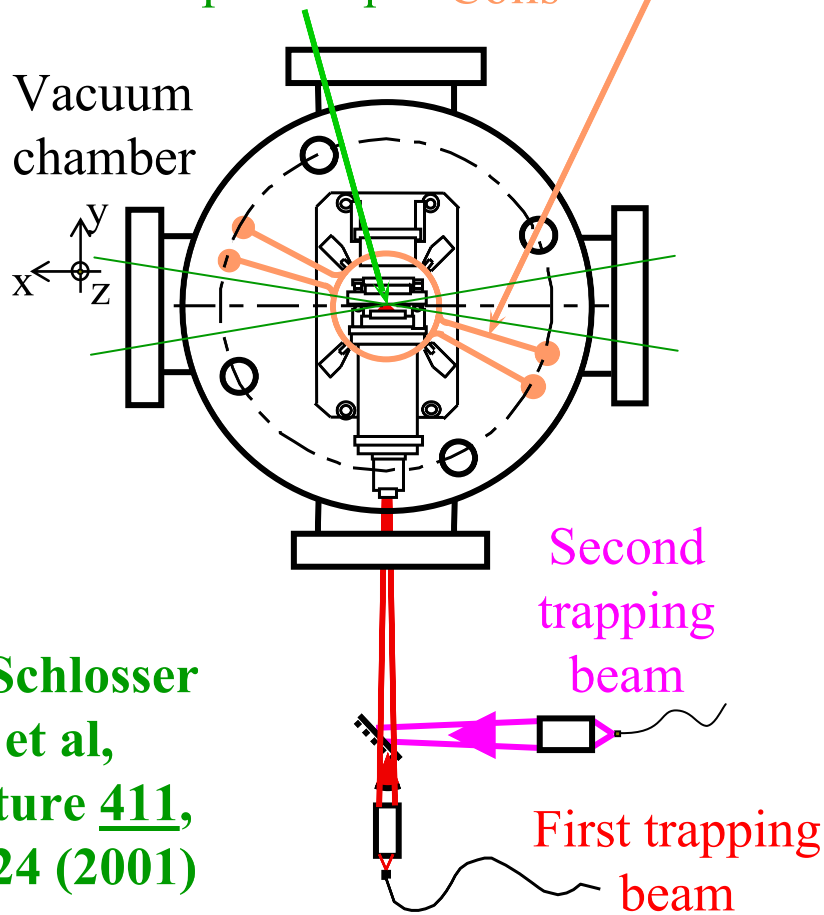
linear ion trap

✓ loading from a BEC Mott insulator loading?



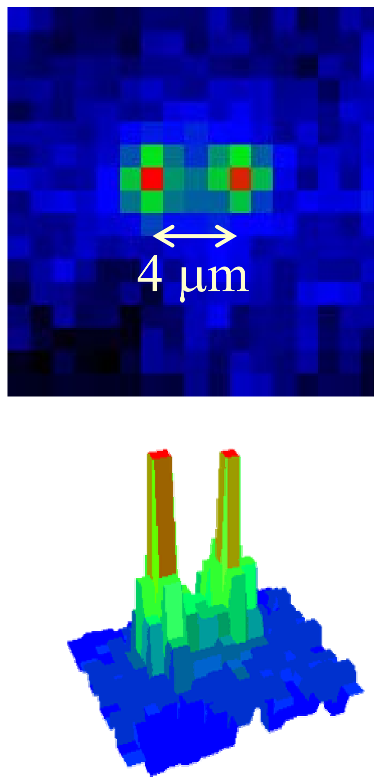
Optical-tweezers double trap for two single atoms

- A single atom is trapped in each site



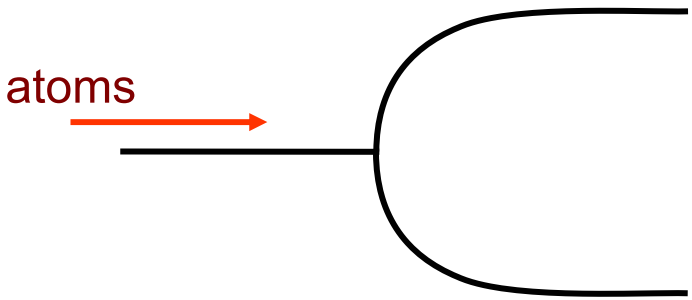
N. Schlosser et al, Nature 411, 1024 (2001)

Resolution of the imaging system: one micron per pixel

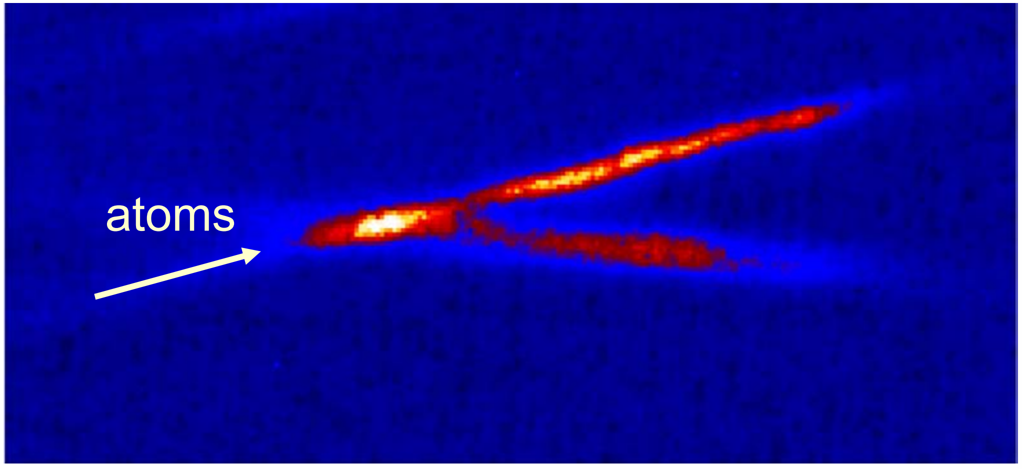


Atoms in 1D pipelines

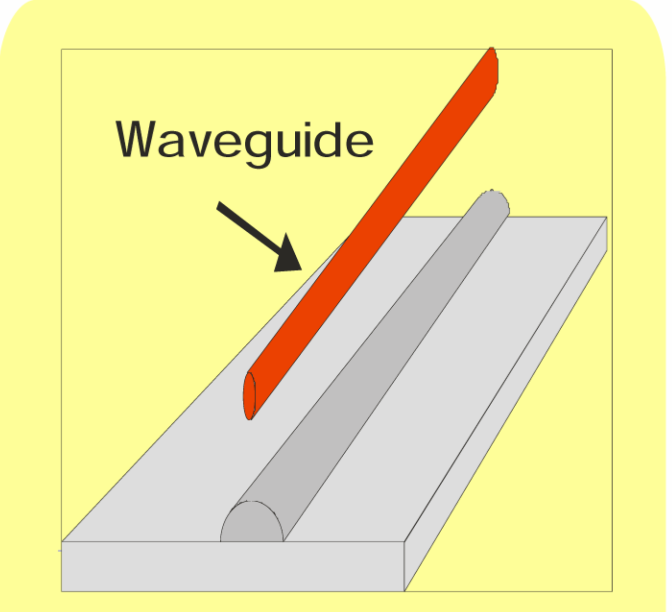
- beamsplitter



- motivation: 1D experiments with optical (and magnetic) traps

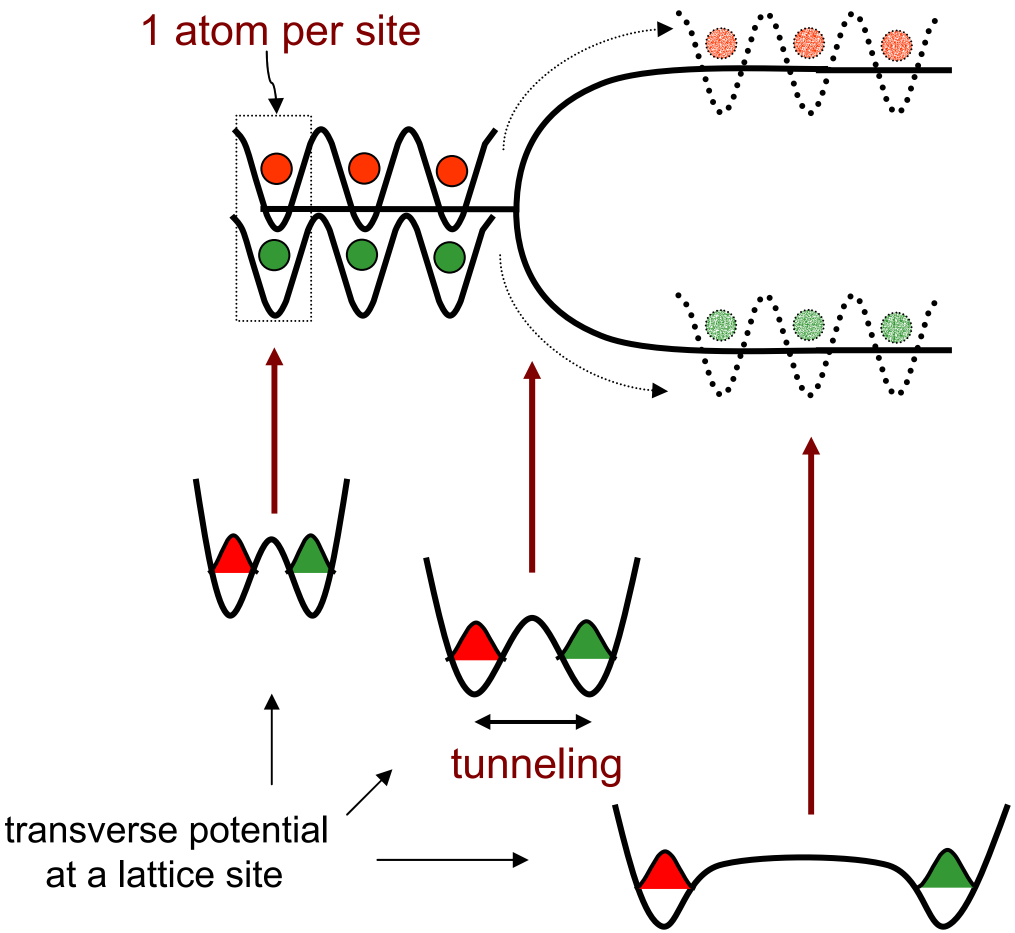


beam splitter (Hannover)



Atoms in 1D lattices

Beam splitter

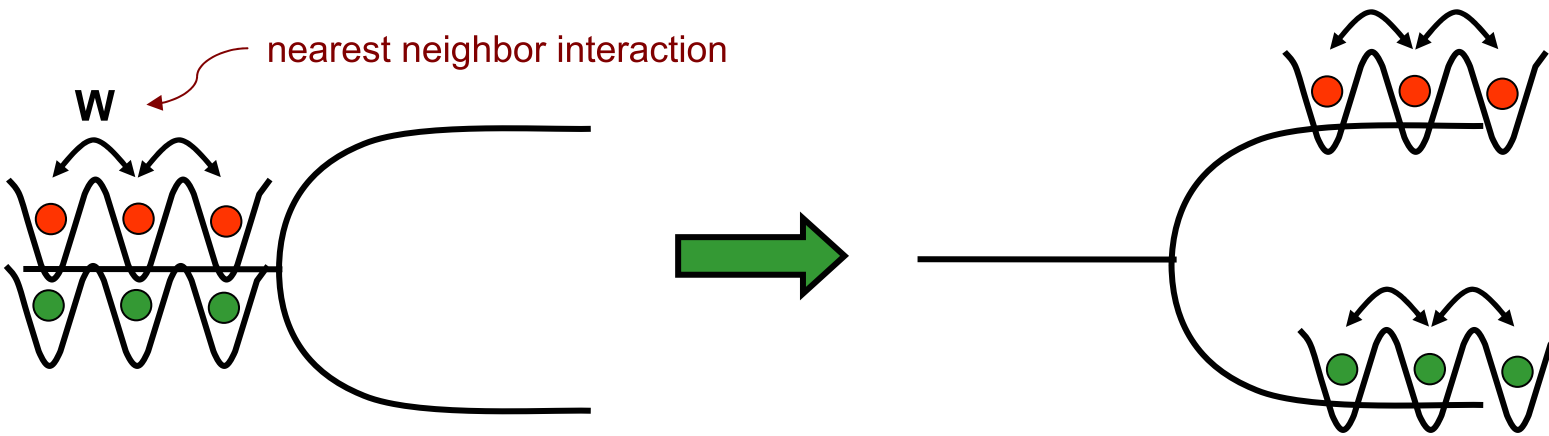


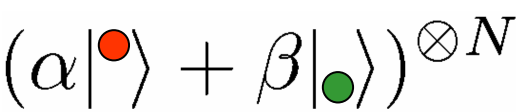
atoms in a longitudinal lattice are moved across a beam splitter

splitter increases “spatial separation” of the wells in an adiabatic way

Atoms in 1D lattices

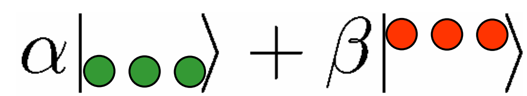
Beam splitter: attractive or repulsive interaction between adjacent atoms





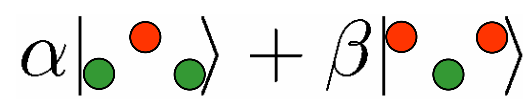
product state

attractive



max entangled state

repulsive



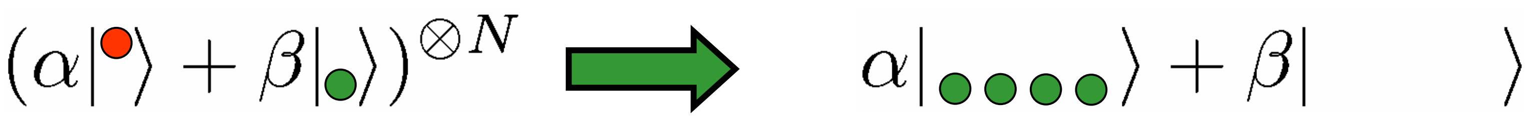
max entangled state

Nearest neighbor interaction: cold collisions, dipole-dipole (Rydberg atoms)
Jaksch et al. PRL 82, 1975 (1999), Jaksch et al. PRL 85, 2208 (2000)

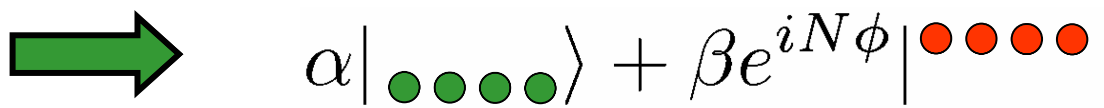
Atoms in 1D lattices

Motivations:

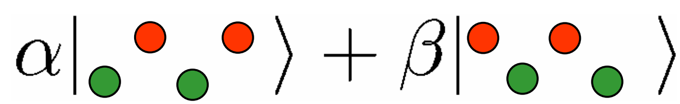
➔ **Interferometry (attractive interaction)**



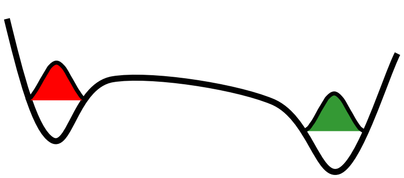
very sensitive to (global) unbalance



➔ **Store qubit in a protected quantum memory (repulsive interaction)**



unbalance:



insensitive to (global) unbalance

Quantum Information Processing

Identifying the ground states as qubits:

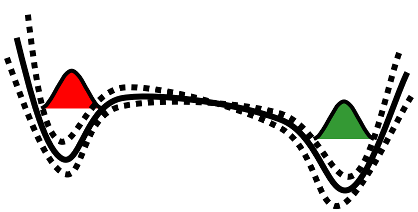
$$|0\rangle = |\downarrow\uparrow \ldots \downarrow\uparrow\rangle$$

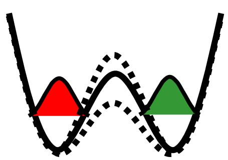
$$|1\rangle = |\uparrow\downarrow \ldots \uparrow\downarrow\rangle$$

→ J_x = 0: Two degenerate ground states form a protected quantum memory

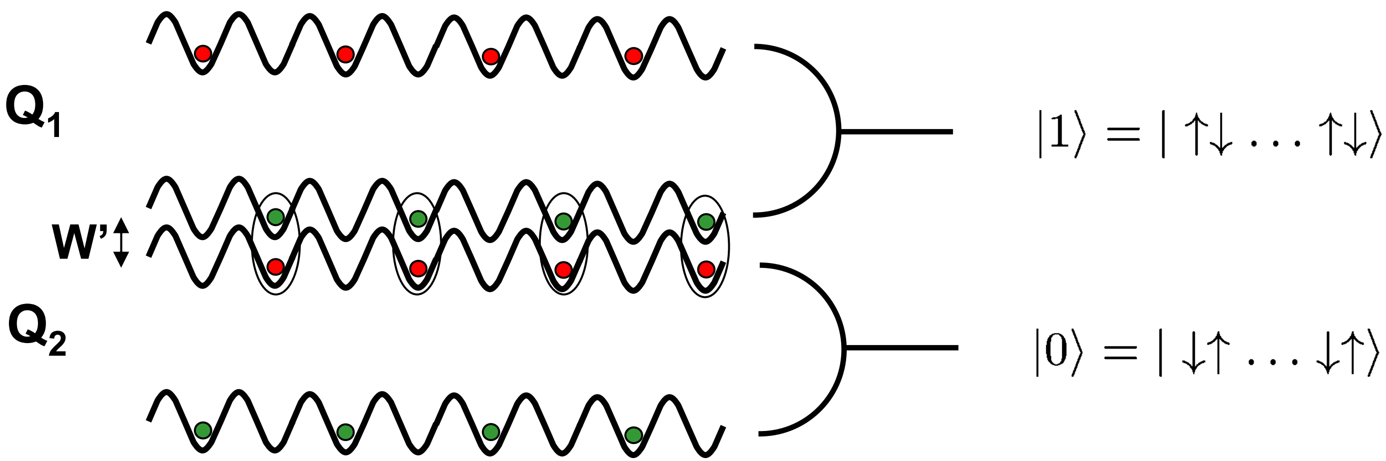
- Separated by a gap 2W from the higher excited states
- Insensitive to global fluctuations of the form $\sim \sum_{l=1}^{N} \sigma_l^{x,y,z}$

(fluctuations in unbalance, fluctuations in tunneling barrier)





Two qubit gates



➔ **Interaction W' leads to state selective time evolution**

Truth table:

$$|0\rangle|0\rangle \longrightarrow |0\rangle|0\rangle$$

$$|1\rangle|1\rangle \longrightarrow |1\rangle|1\rangle$$

$$|0\rangle|1\rangle \longrightarrow \mathrm{e}^{-i\phi}|0\rangle|1\rangle$$

$$|1\rangle|0\rangle \longrightarrow \mathrm{e}^{-i\phi}|1\rangle|0\rangle$$

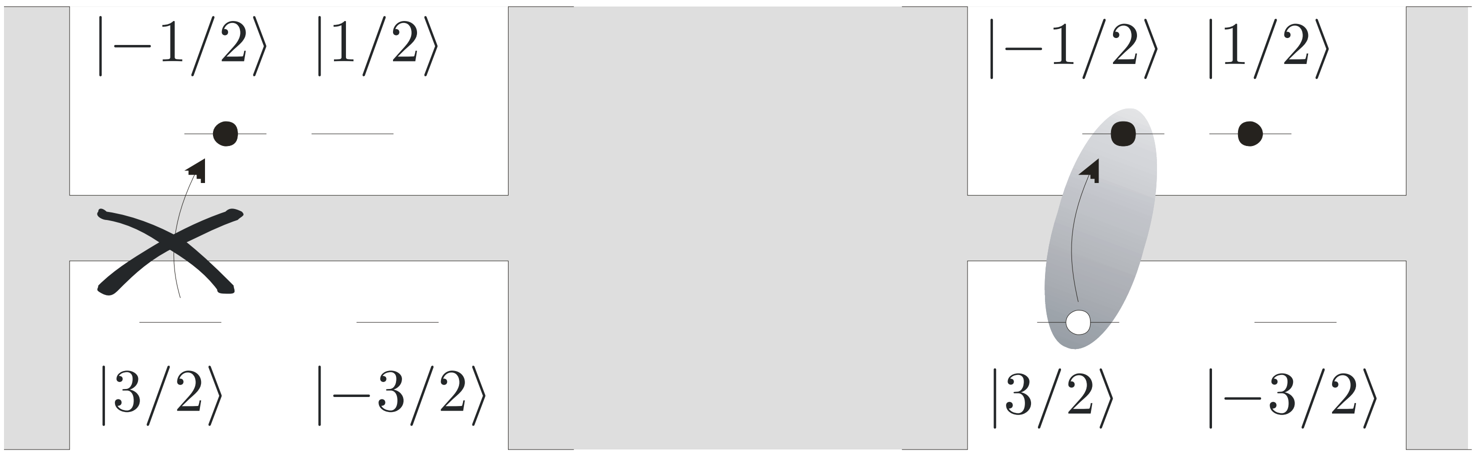
Collectively enhanced phase:

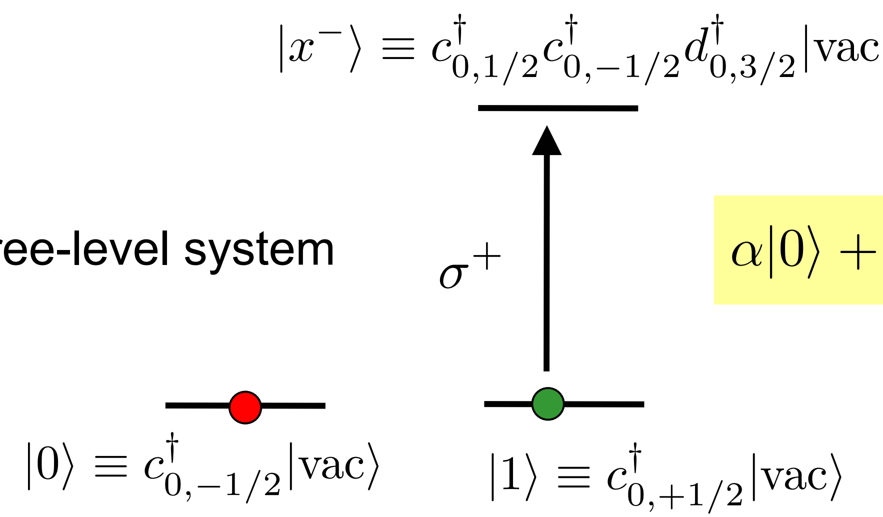
$$\phi = NW'\tau/2$$

All-optical spin quantum gates in quantum dots

- QIP: solid state implementation
  + scalable, fast
  + in line with present nanostructure developments
  - decoherence
- ... coming from quantum optics
  - quantum dots are like artificial atoms: „engineering“ atomic structure
  - spin-based optical quantum gates in semiconductor quantum dots
- ideas from quantum optics may help in suppressing decoherence

Coupling spin to charge via Pauli blocking

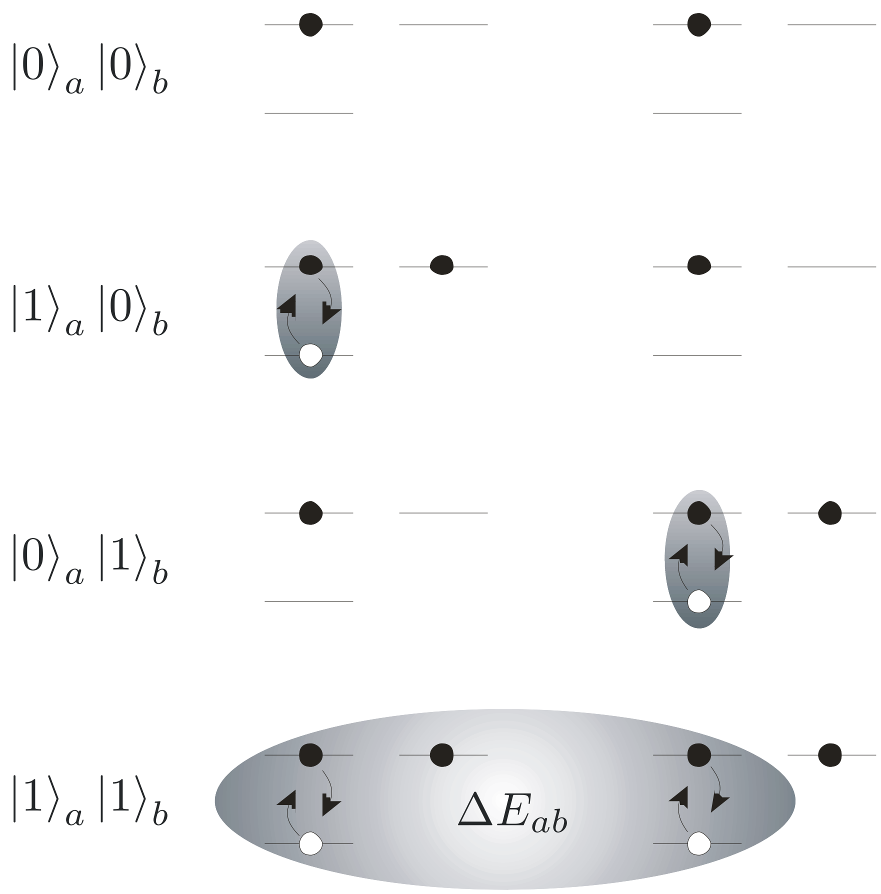




Idealized model: three-level system

$$\alpha|0\rangle + \beta|1\rangle \longrightarrow \alpha|0\rangle + \beta|x^-\rangle$$

Selective phase via bi-excitonic interaction

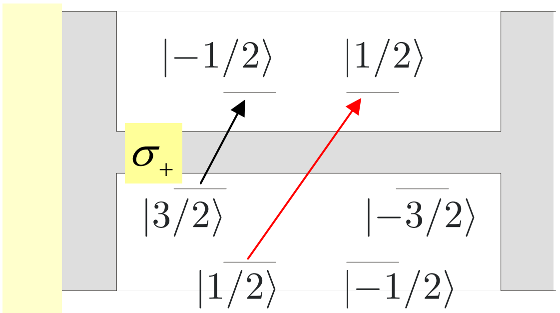


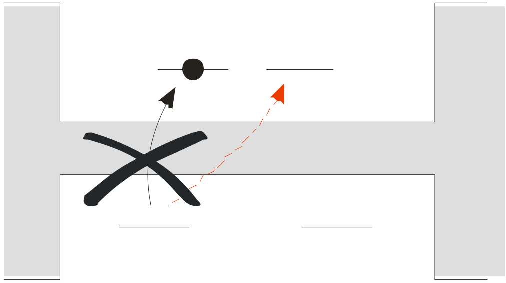
- Laser addressing
- Exciton couples only to state |1>
- External electric field displaces electrons and holes
- Dipole-dipole interaction induces logical phase

$$|0\rangle|0\rangle \rightarrow |0\rangle|0\rangle$$
$$|0\rangle|1\rangle \rightarrow |0\rangle|1\rangle$$
$$|1\rangle|0\rangle \rightarrow |1\rangle|0\rangle$$
$$|1\rangle|1\rangle \rightarrow e^{i\Delta E_{ab}t}|1\rangle|1\rangle$$

Hole mixing problem

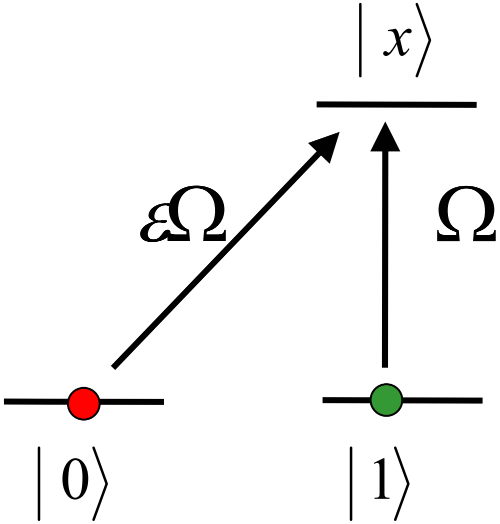
- Light holes couple to electron +1/2 states via σ+ light
- Actual hole eigenstates comprise a certain admixture from light holes





- Pauli blocking does not work perfectly
- A π + π pulse for the transition |1> - |x> will leave behind some excitonic population

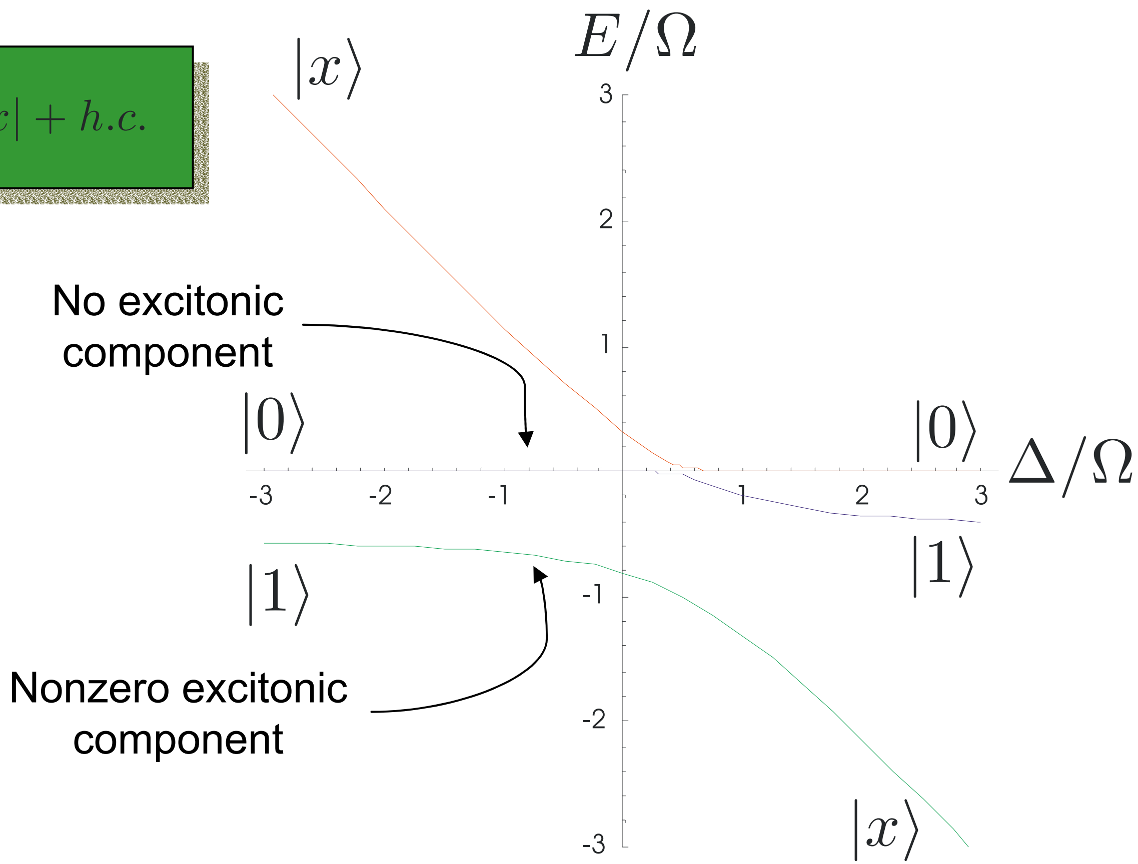
- A different gate operation procedure is needed
- Model including hole mixing via effective weak coupling to state |0>
- Typical value for ε: ~10%



Hole-mixing tolerant laser excitation

$$H_1 \quad = \quad H_0 + \delta \left|1\right\rangle \left\langle 1\right| + \frac{\varepsilon\Omega}{2} \left|0\right\rangle \left\langle x\right| + h.c.$$

- Start far from resonance
- Adiabatically change the detuning towards resonance
- Reach |x> from |1> but not from |0>
- Adiabatically de-excite by returning to the initial situation



$$\alpha \left|0\right\rangle + \beta \left|1\right\rangle \quad \rightarrow \quad \alpha \left|0\right\rangle + \beta \left(\cos\frac{\theta}{2} \left|1\right\rangle - \sin\frac{\theta}{2} \left|x\right\rangle \right)$$

Adiabatically suppressing decoherence in gate operation

pulse shapes

$$\Omega(t) = \Omega_0 e^{-(t/\tau_\Omega)^2}$$

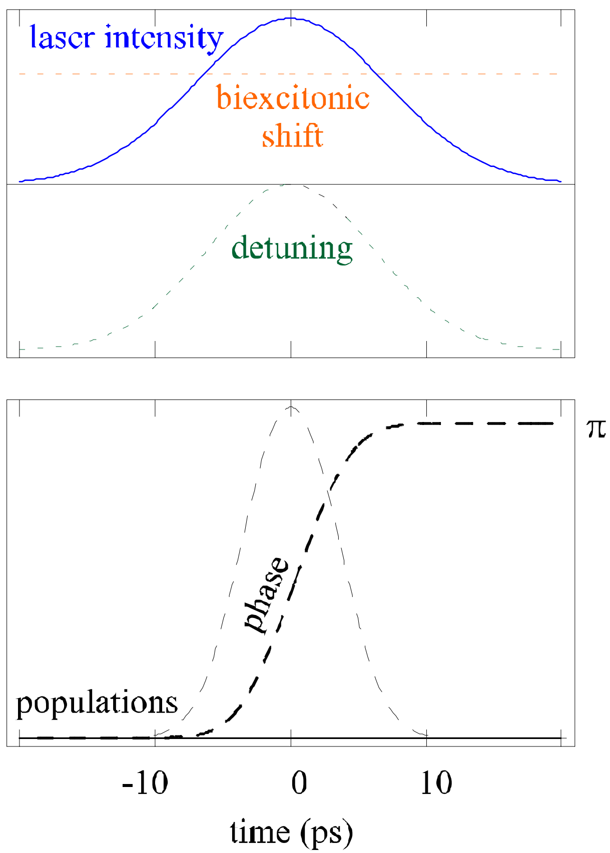
$$\Delta(t) = \Delta_\infty \left[1 - e^{-(t/\tau_\Delta)^2}\right]$$

$\Omega_0 = 3$ meV
$\tau_\Omega = 10$ ps
$\Delta E_{ab} = 2$ meV

$\delta = 0.5$ meV

$\Delta_\infty = 3$ meV
$\tau_\Delta = 8.72$ ps

residual population in the unwanted excitonic states is smaller than 10^{-6} after gate operation



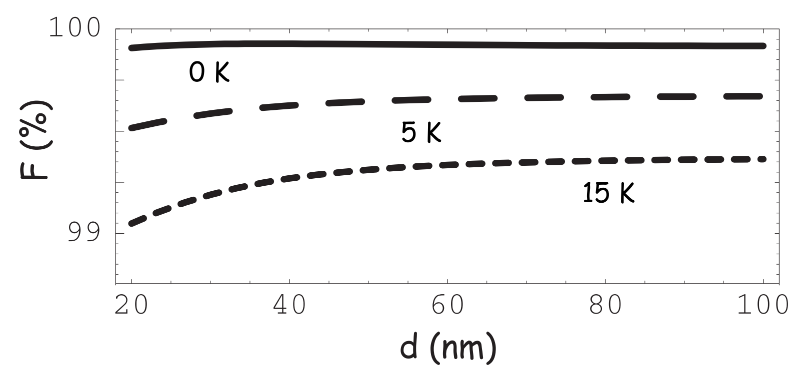
coupling to phonons induces dephasing: spin-phonon model

$$\sum \lambda_{j\mathbf{q}}(b_{j\mathbf{q}} + b^\dagger_{j\mathbf{q}})\,|x\rangle\langle x| + \omega_j(\mathbf{q}) b^\dagger_{j\mathbf{q}} b_{j\mathbf{q}}$$

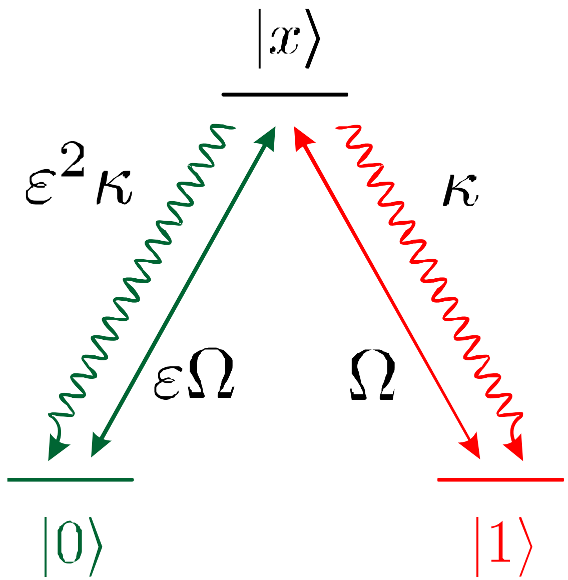
phonon Hamiltonian in dressed-state basis

$$H_{\rm ph} = \left[E_+ + \sum_{\mathbf{q}} \omega(\mathbf{q}) b^\dagger_{\mathbf{q}} b_{\mathbf{q}} + \cos^2\frac{\theta}{2}\lambda_{\mathbf{q}}\left(b^\dagger_{\mathbf{q}} + b_{\mathbf{q}}\right)\right]|+\rangle\langle+|$$
$$+ \left[E_- + \sum_{\mathbf{q}} \omega(\mathbf{q}) b^\dagger_{\mathbf{q}} b_{\mathbf{q}} - \sin^2\frac{\theta}{2}\lambda_{\mathbf{q}}\left(b^\dagger_{\mathbf{q}} + b_{\mathbf{q}}\right)\right]|-\rangle\langle-|$$
$$- \frac{\sin\theta}{2}\sum \lambda_{\mathbf{q}}\left(b^\dagger_{\mathbf{q}} + b_{\mathbf{q}}\right)\left(|+\rangle\langle-| + |-\rangle\langle+|\right)$$

- The same procedure avoids the effect of both hole mixing and phonon decoherence

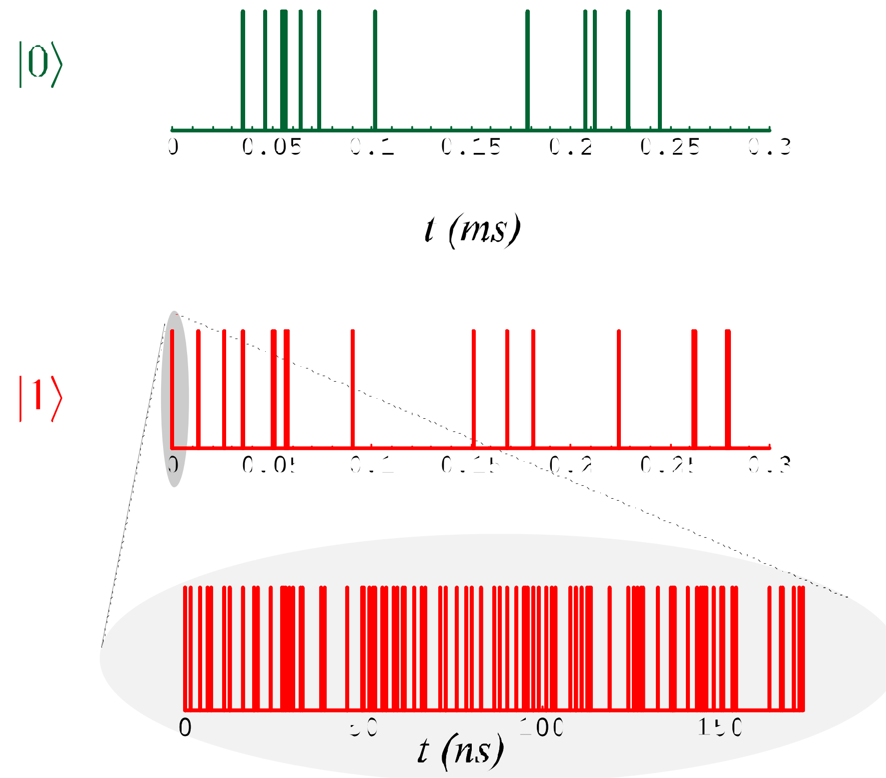


Qubit read-out



level scheme with decay

photon count simulation



error probability (~0.2% with
80% counting efficiency and 10% mixing)

$$P_\varepsilon = \frac{\varepsilon^2(1-\eta)}{\varepsilon^2+\eta}\left[1-\left(\frac{1-\eta}{1+\varepsilon^2}\right)^{1+\varepsilon^{-2}}\right]$$

Summary

- [Quantum Computing based on] neutral atoms in optical lattices
  - spin-dependent lattices
  - high fidelity loading of large lattice arrays beyond Mott insulator

- Entangling atoms
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  - atoms in pipeline structures

- All-optical quantum computing with quantum dots
  - Suppressing decoherence via quantum-optical techniques