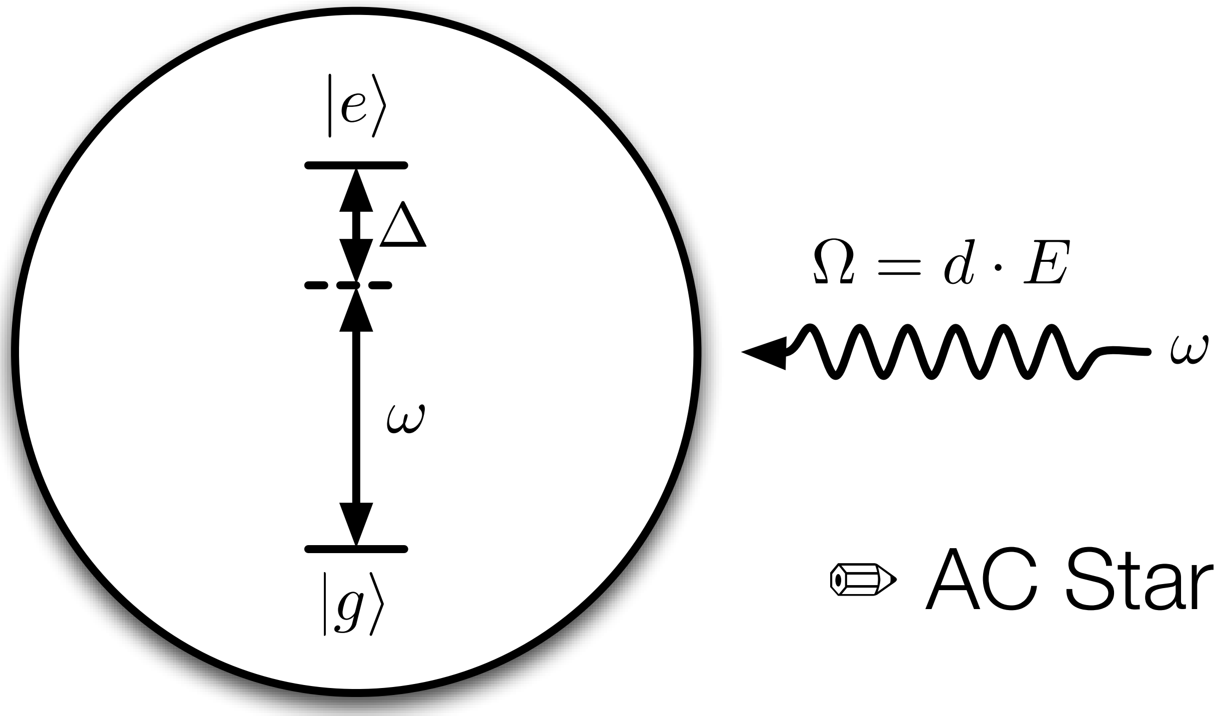
Addressing Individual Atoms in Optical Lattices with Standing-Wave Driving Fields

Jaeyoon Cho (KRISS)
quant-ph/0703185, Phys. Rev. Lett. (in press)

Acknowledgments: Dr. Hee Su Park
Pre-Dr. Sun Kyung Lee
Dr. Sang-Kyung Choi

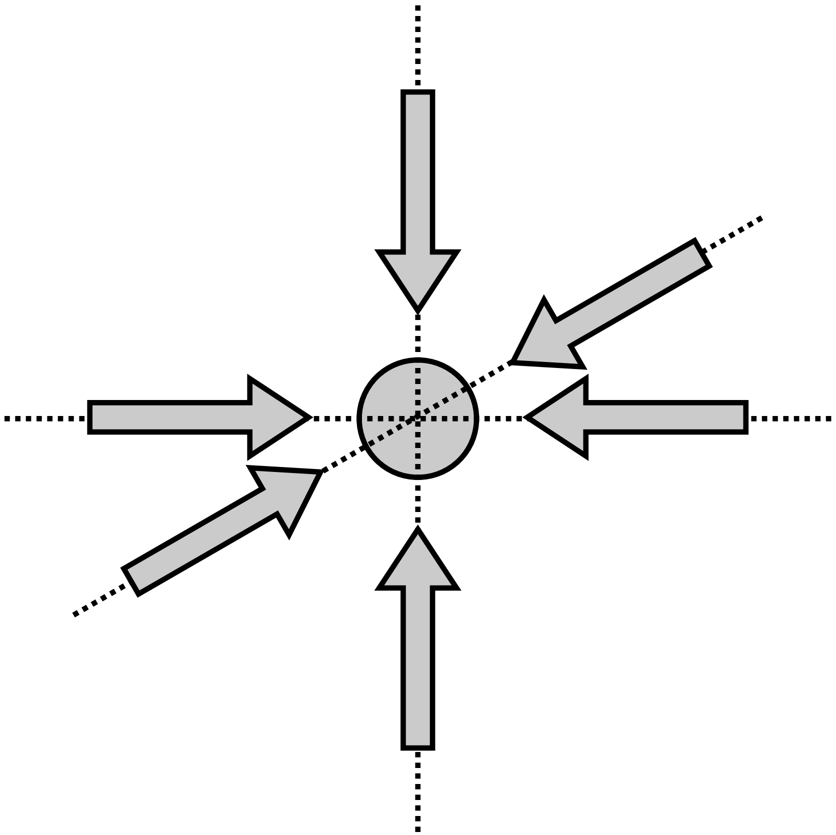
Light-induced potential

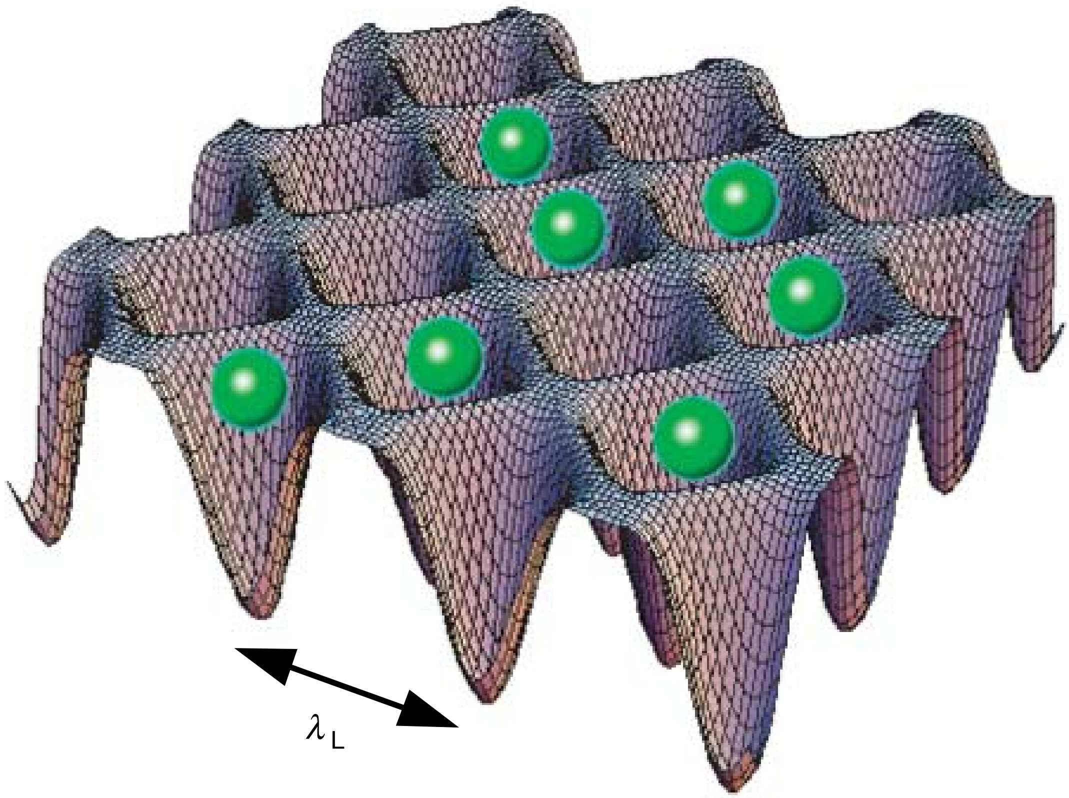


✏ AC Stark shift ($\Delta \gg \Omega$)

$$V = -\frac{(d \cdot E)^2}{\Delta}$$

Optical lattice





Takamoto *et al.*, Nature **435**, 321 (2005)

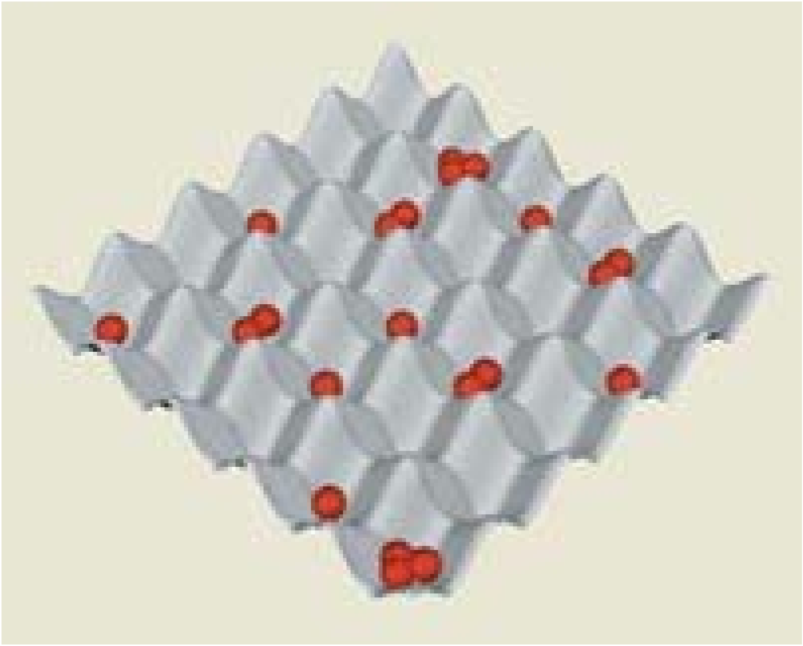
Bose-Hubbard model

$$H = \boxed{-J \sum_{\langle i,j \rangle} b_i^\dagger b_j} + \boxed{\frac{1}{2} U \sum_i \hat{n}_i(\hat{n}_i - 1)} + \sum_i \epsilon_i \hat{n}_i$$

tunneling   on site repulsion

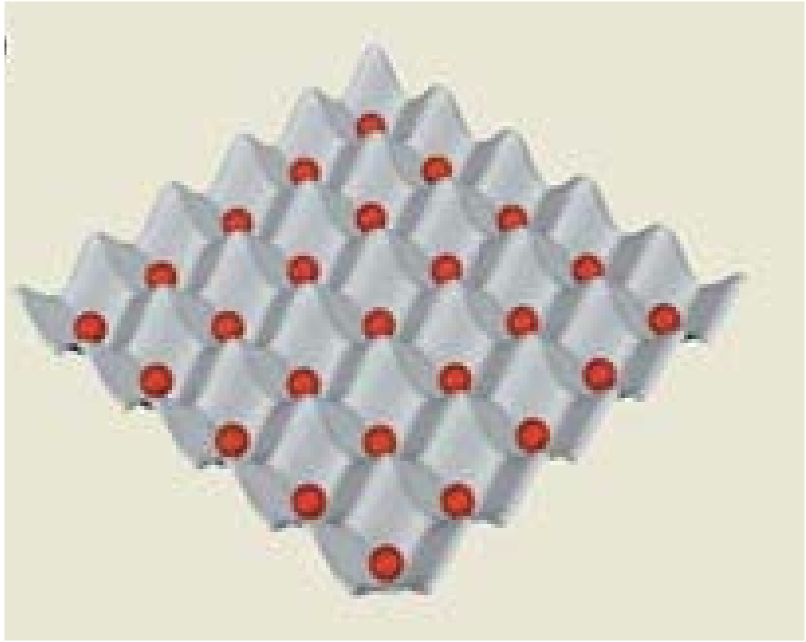
Jaksch *et al.*, Phys. Rev. Lett. **81**, 3108 (1998)

Superfluid-Mott insulator phase transition



$J \gg U$

superfluid

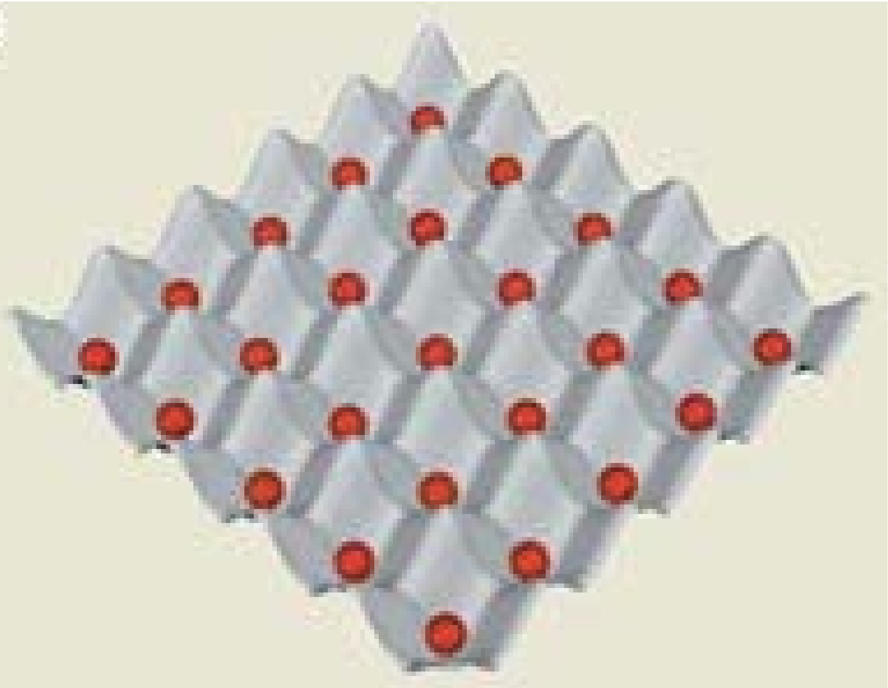


$J \ll U$

Mott insulator

Greiner *et al.*, Nature **415**, 39 (2002)
Bloch, http://physicsweb.org/articles/world/17/4/7

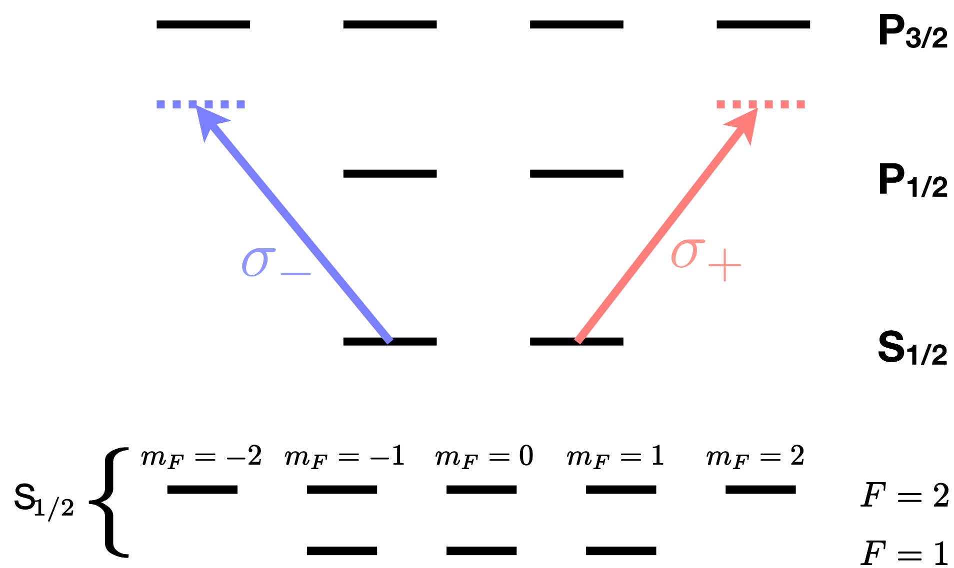
Quantum register array



✏ unitary operation?

✏ measurement?

State-dependent lattice potential



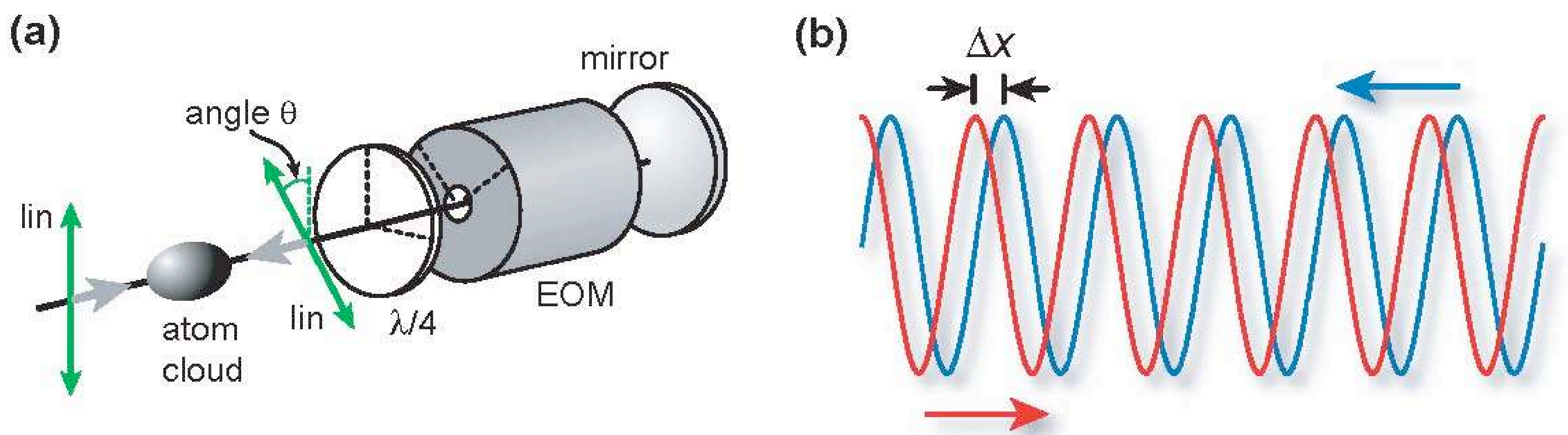
$$V_{|F=2,m_F=2\rangle}(x) = V_+(x)$$

$$V_{|F=1,m_F=1\rangle}(x) = \frac{3}{4}V_+(x) + \frac{1}{4}V_-(x)$$

$$V_{|F=1,m_F=-1\rangle}(x) = \frac{1}{4}V_+(x) + \frac{3}{4}V_-(x)$$

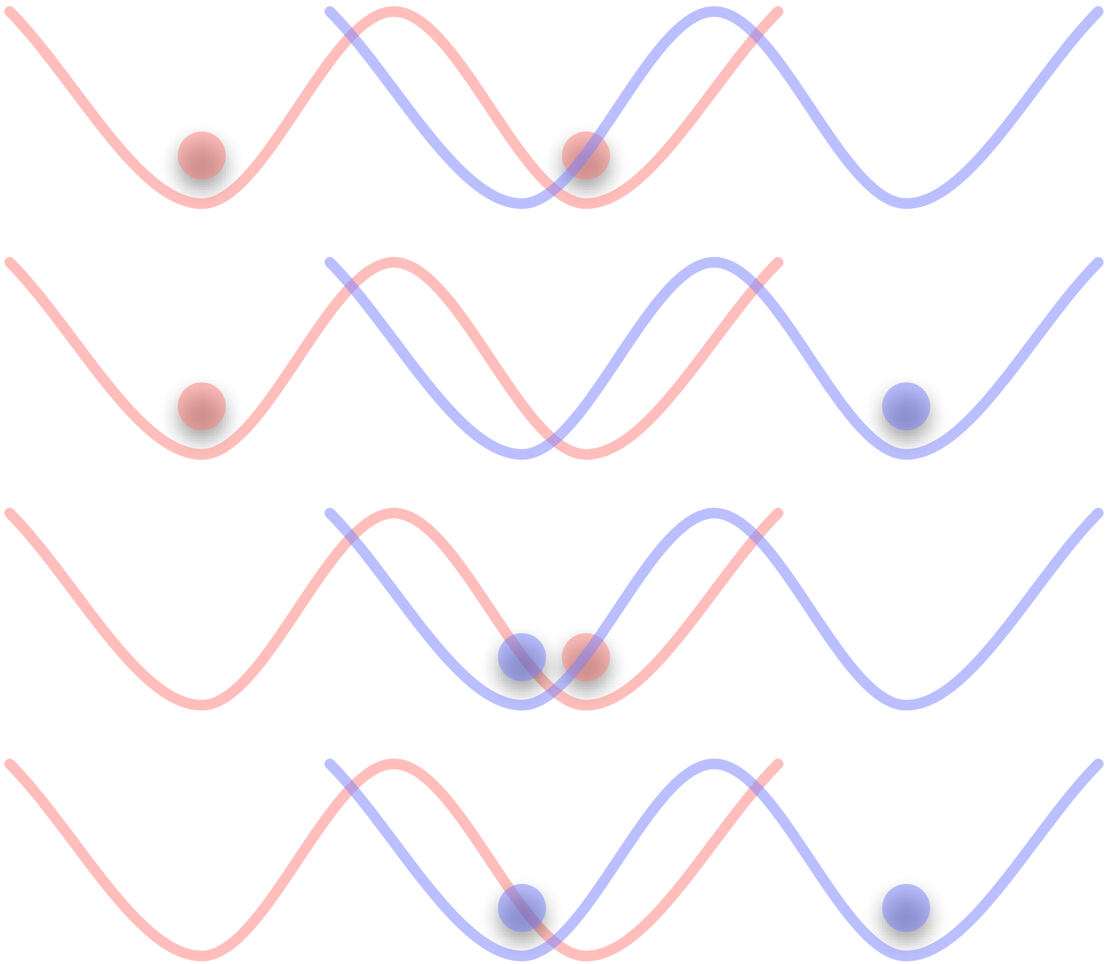
Jaksch *et al.*, Ann. Phys. **315**, 52 (2005)

State-dependent lattice potential



Mandel *et al.*, Nature **425**, 937 (2003)
Treutlein *et al.*, quant-ph/0605163

Controlled-phase operation



$$|a\rangle|a\rangle$$

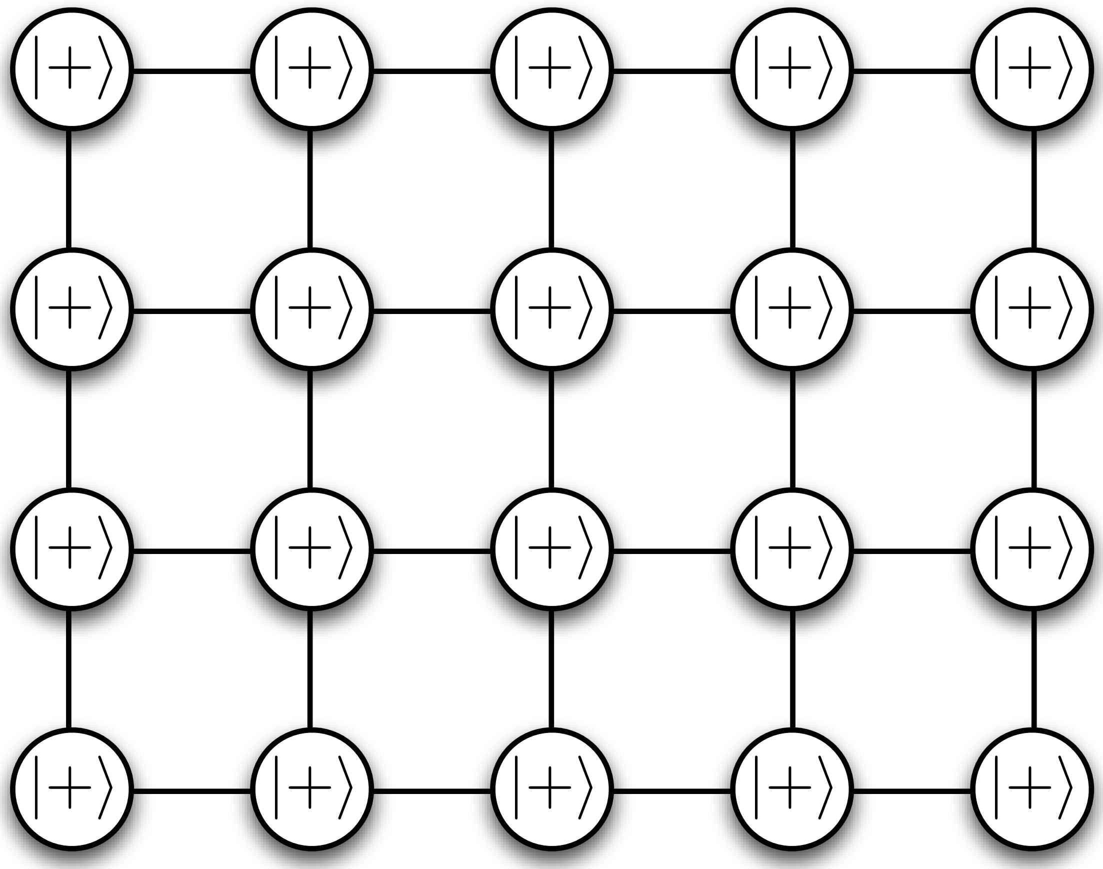
$$|a\rangle|b\rangle$$

$$e^{i\theta}|b\rangle|a\rangle$$

$$|b\rangle|b\rangle$$

Jaksch *et al.*, Phys. Rev. Lett. **82**, 1975 (1999)
Mandel *et al.*, Nature **425**, 937 (2003)

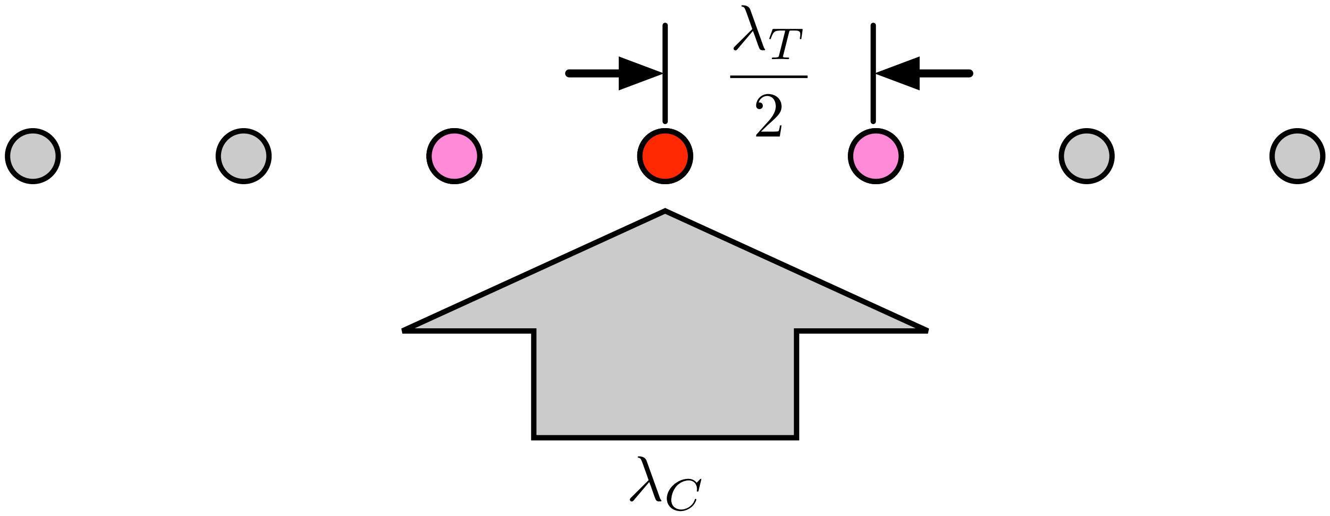
Cluster state



✏ single-qubit operation?

Mandel *et al.*, Nature **425**, 937 (2003)

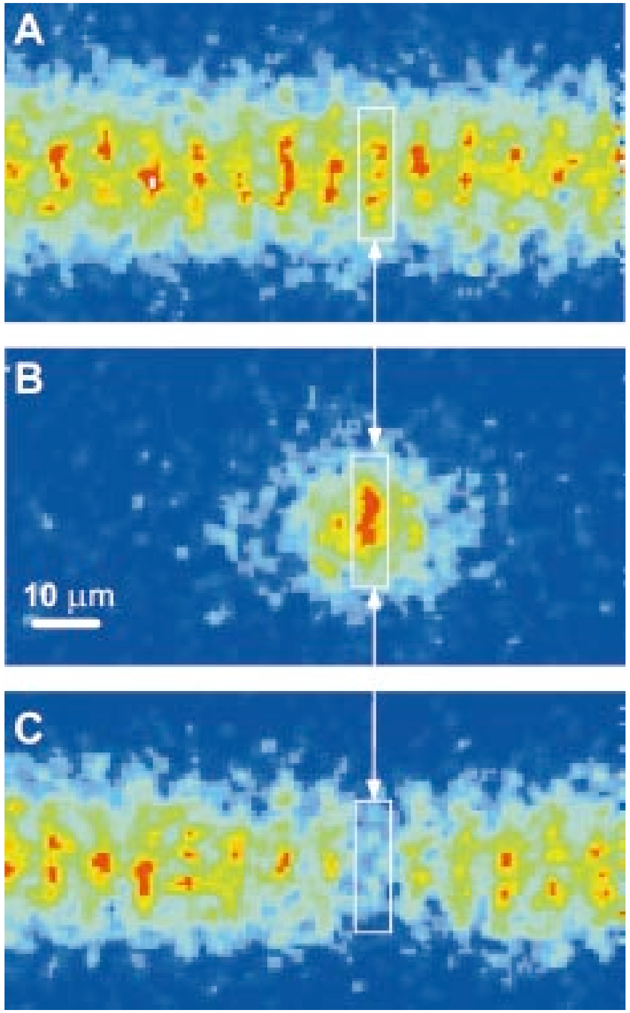
Individual-atom addressing



$$\lambda_C \gtrsim \lambda_T$$

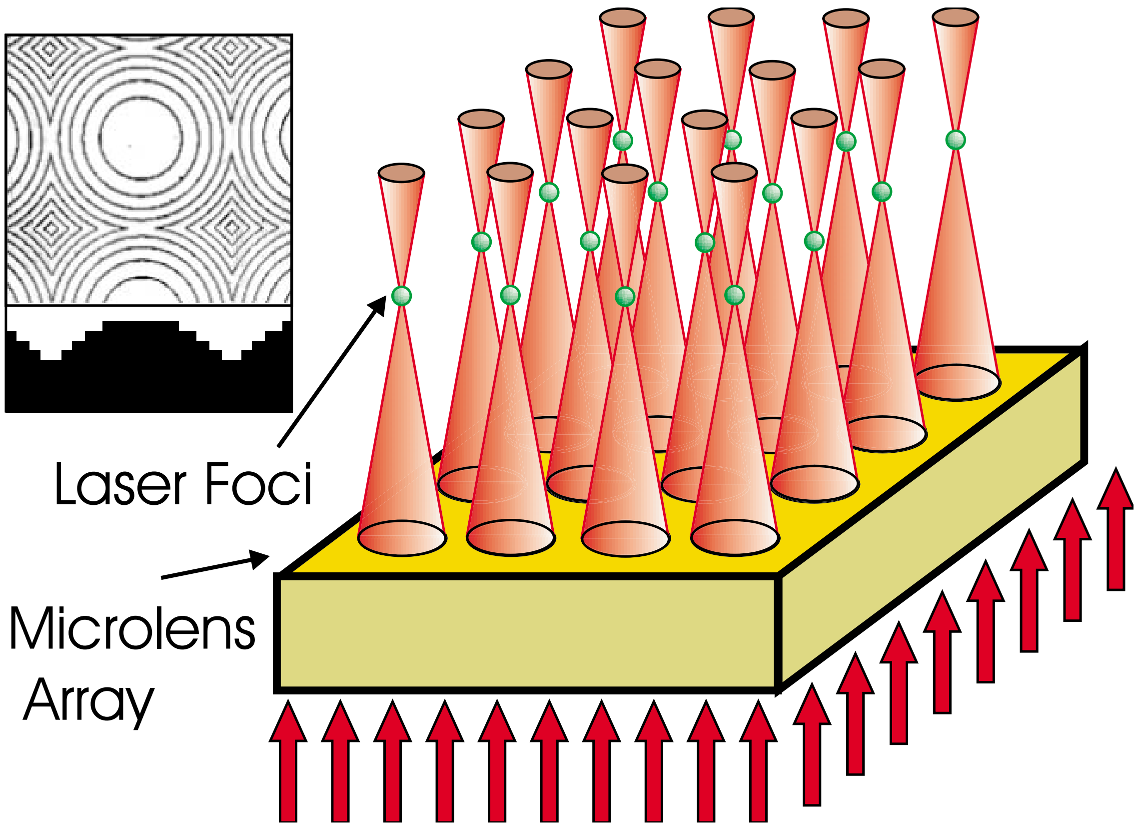
diffraction limit!

CO_2 laser optical lattice



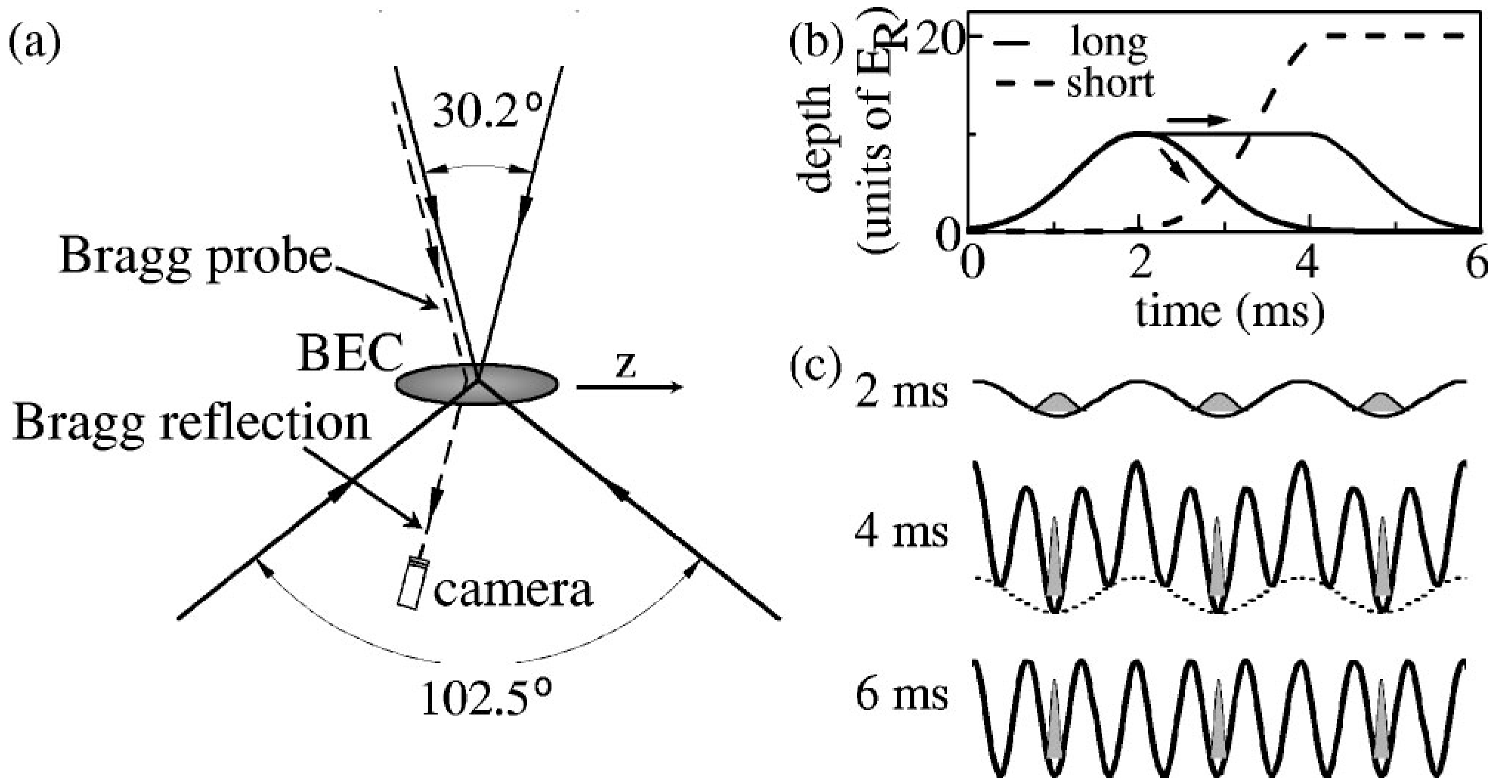
Scheunemann *et al.*, Phys. Rev. A **62**, 051801(R) (2000)

Micro-trap array



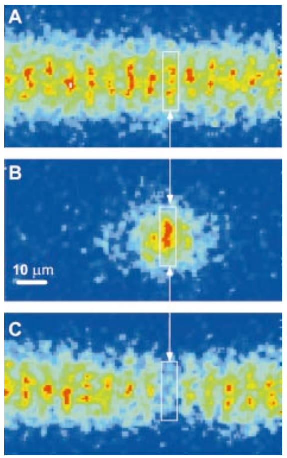
Dumke *et al.*, Phys. Rev. Lett. **89**, 097903 (2002)

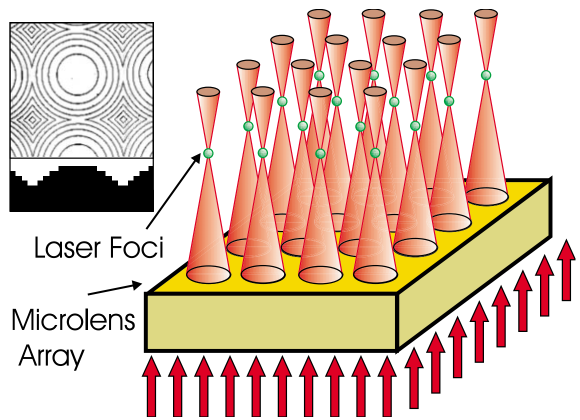
Patterned loading of an optical lattice

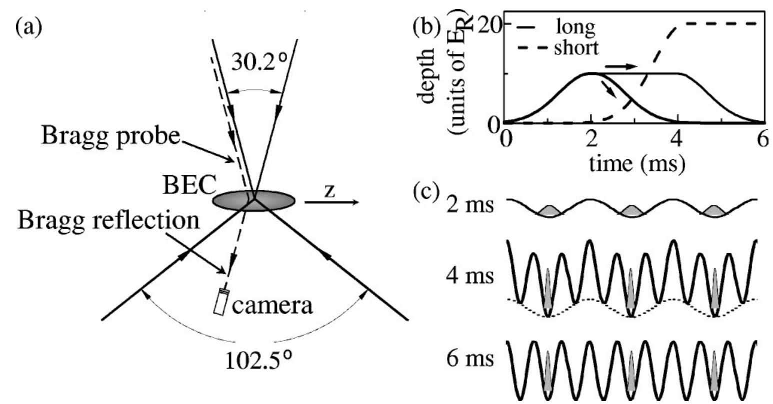


Peil *et al.*, Phys. Rev. A **67**, 051603(R) (2003)

Individual-atom addressing?



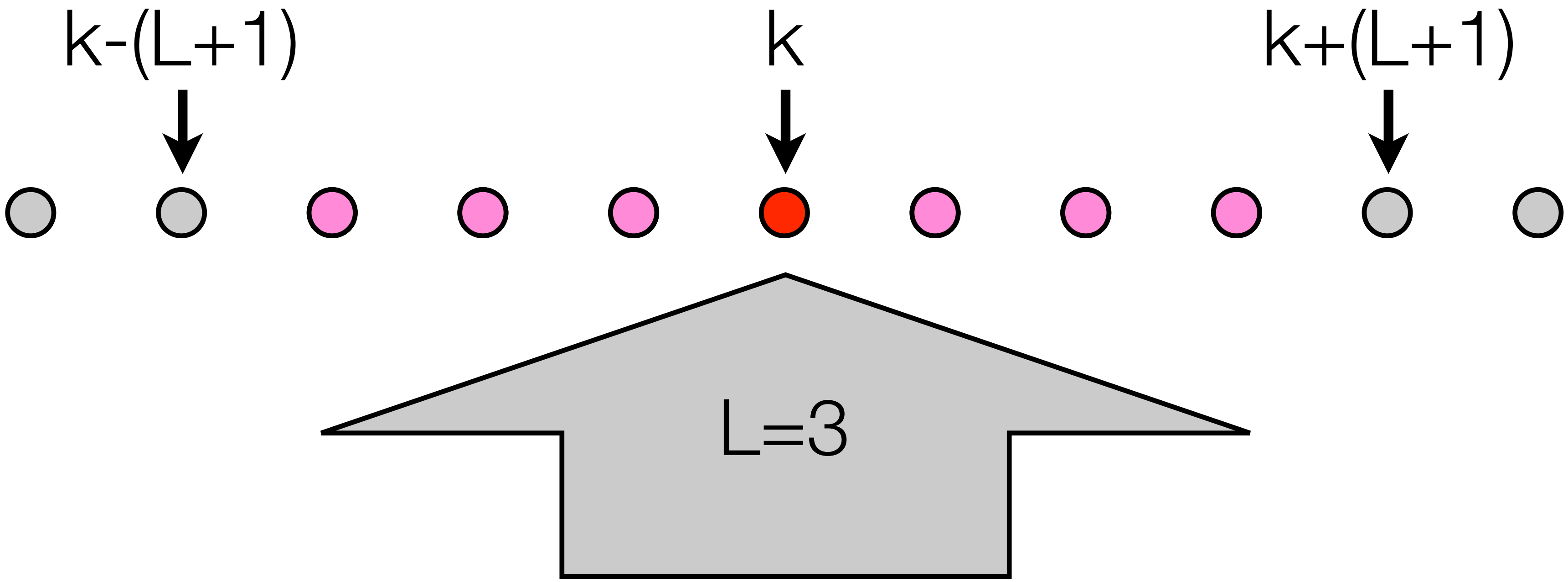




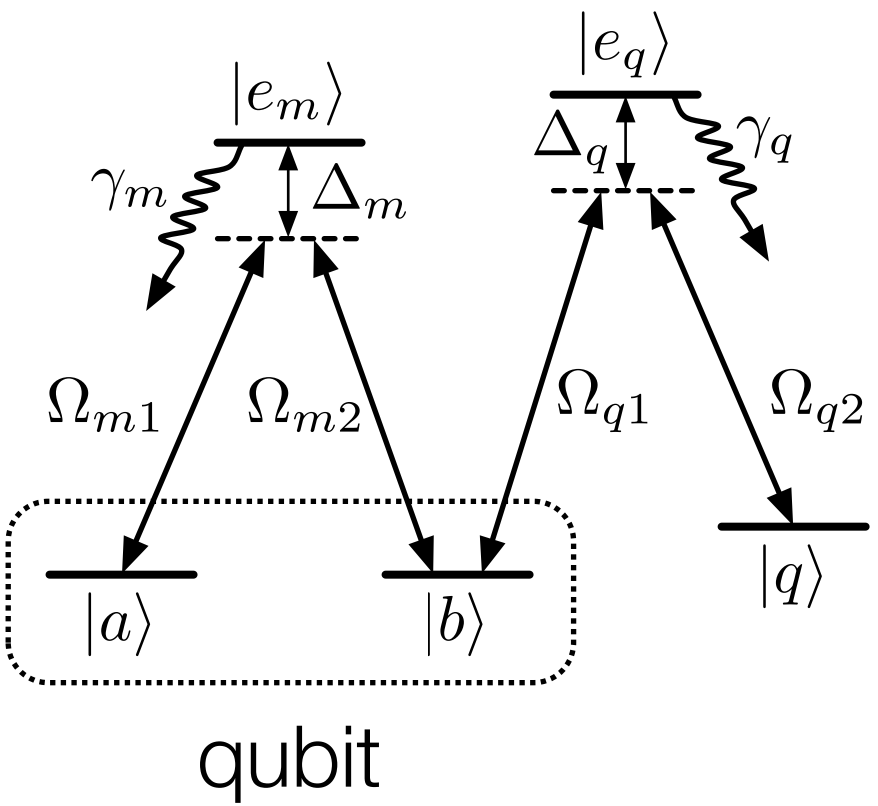
- ✏ One atom per site? Two-qubit operation?
- ✏ Other methods: external field, pointer atom, ...
  - → Complexity? Precision?

Scheme

Assumption

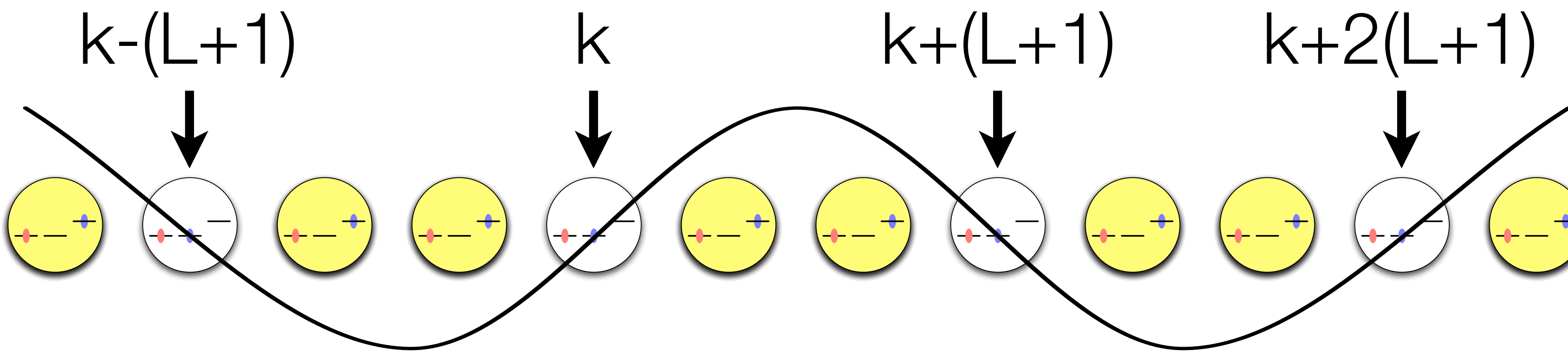


Atomic levels and transitions

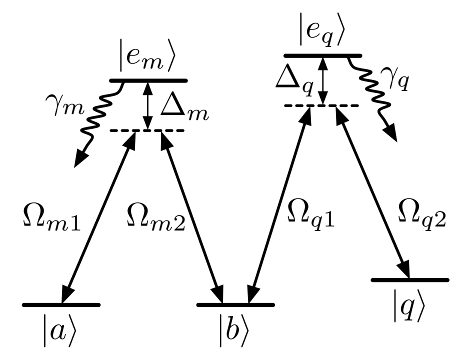


Position-dependent atomic population transfer

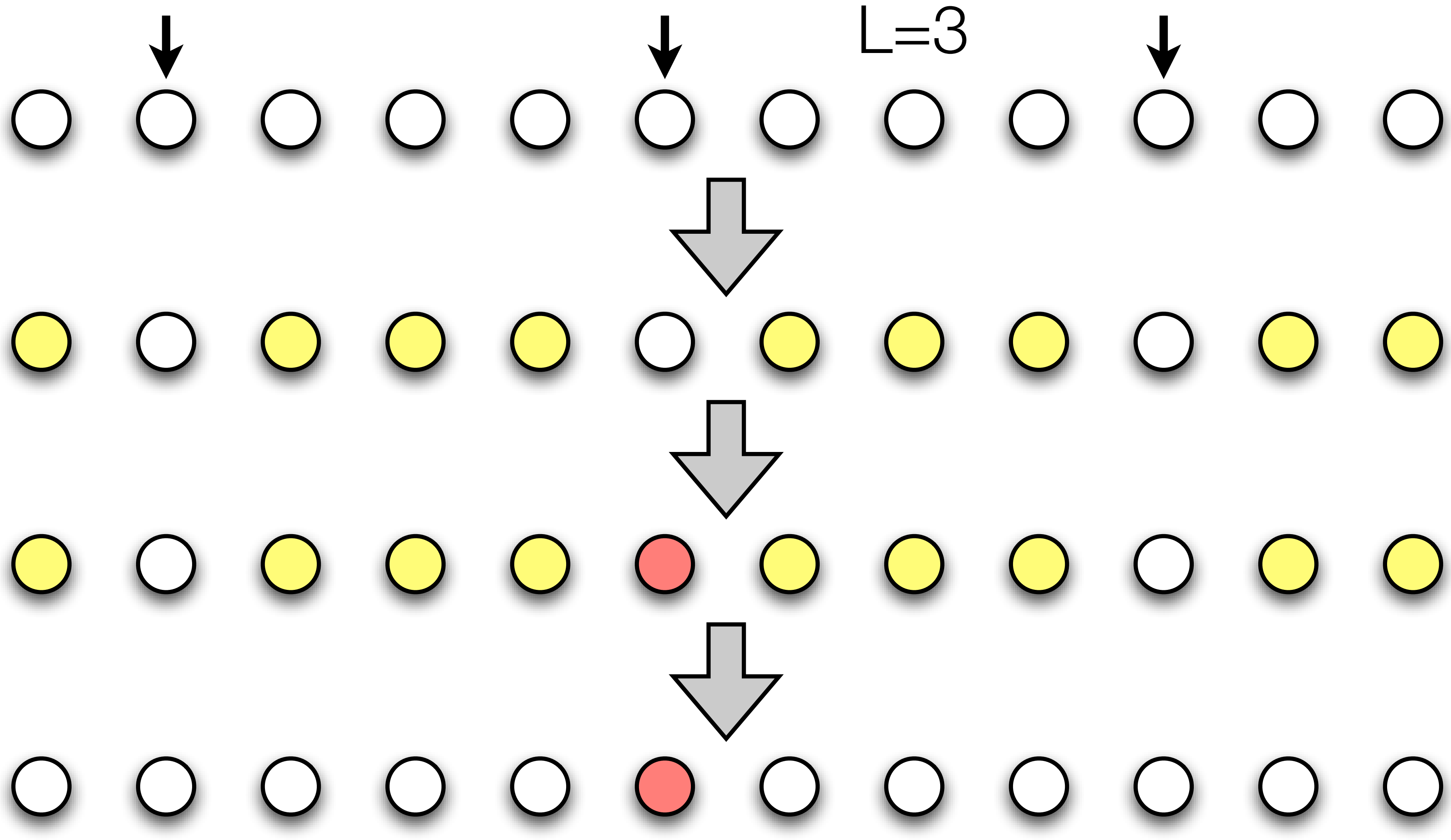
“superlattice”



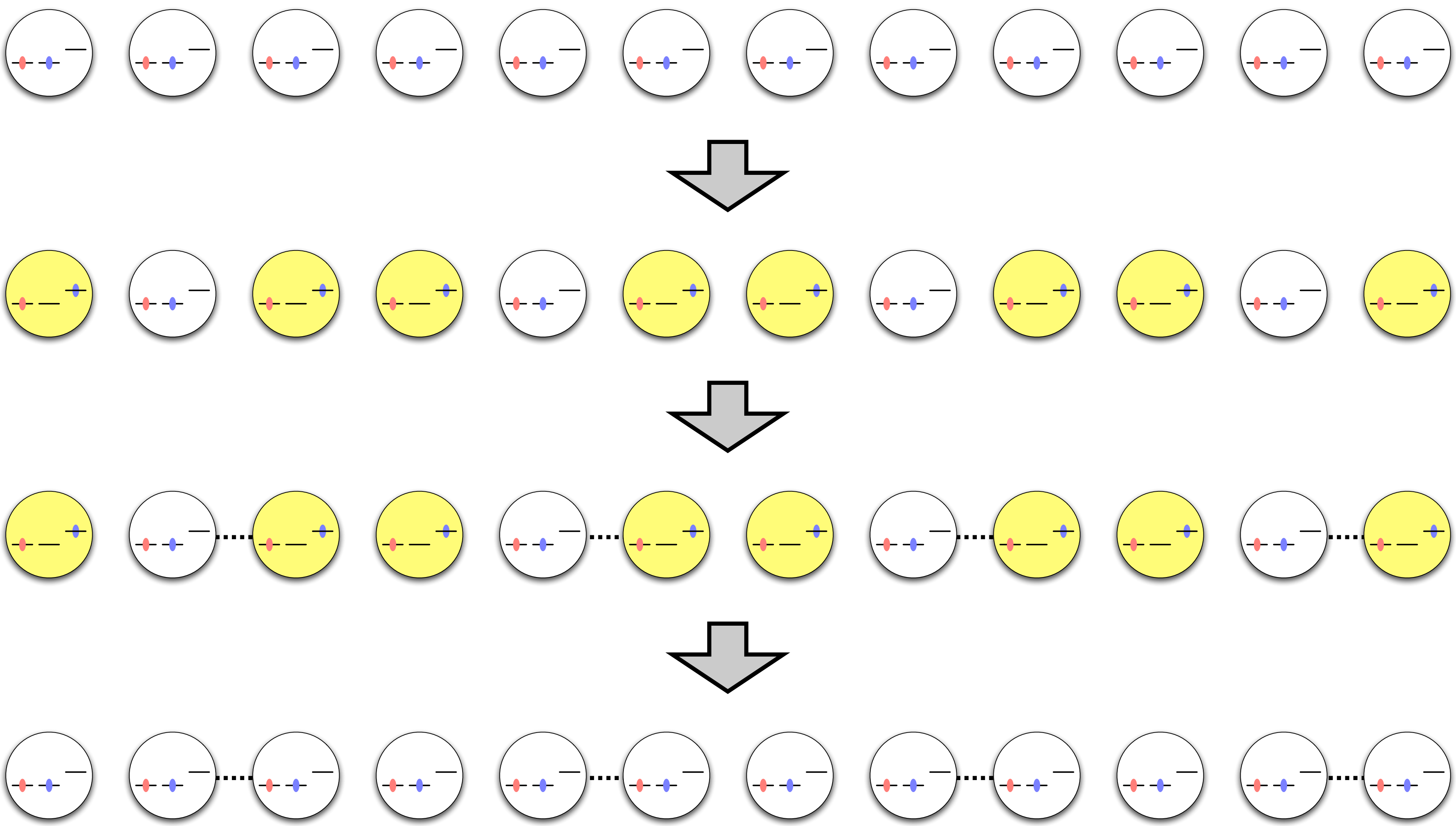
“quenching operation”.



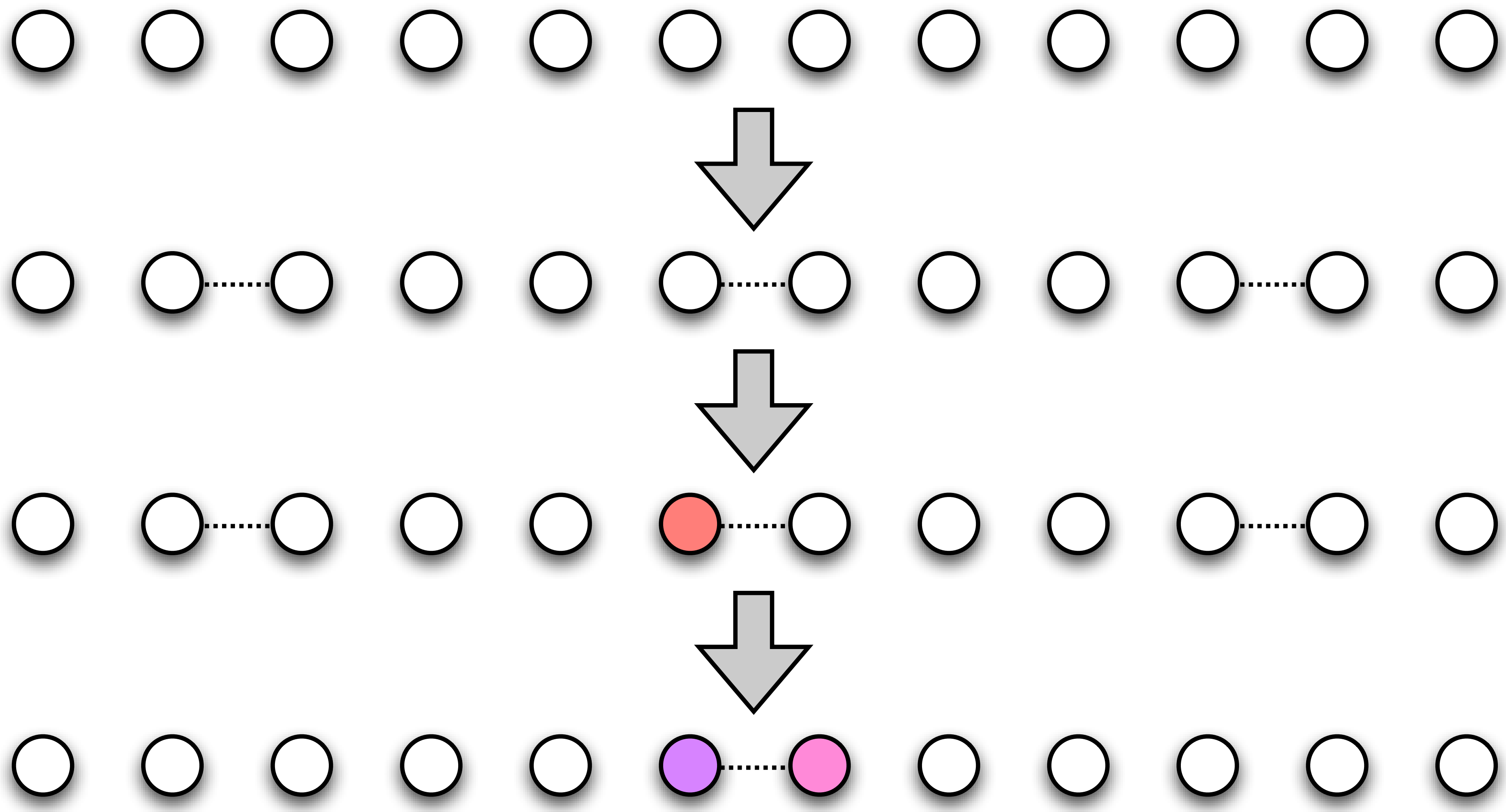
Single-atom addressing



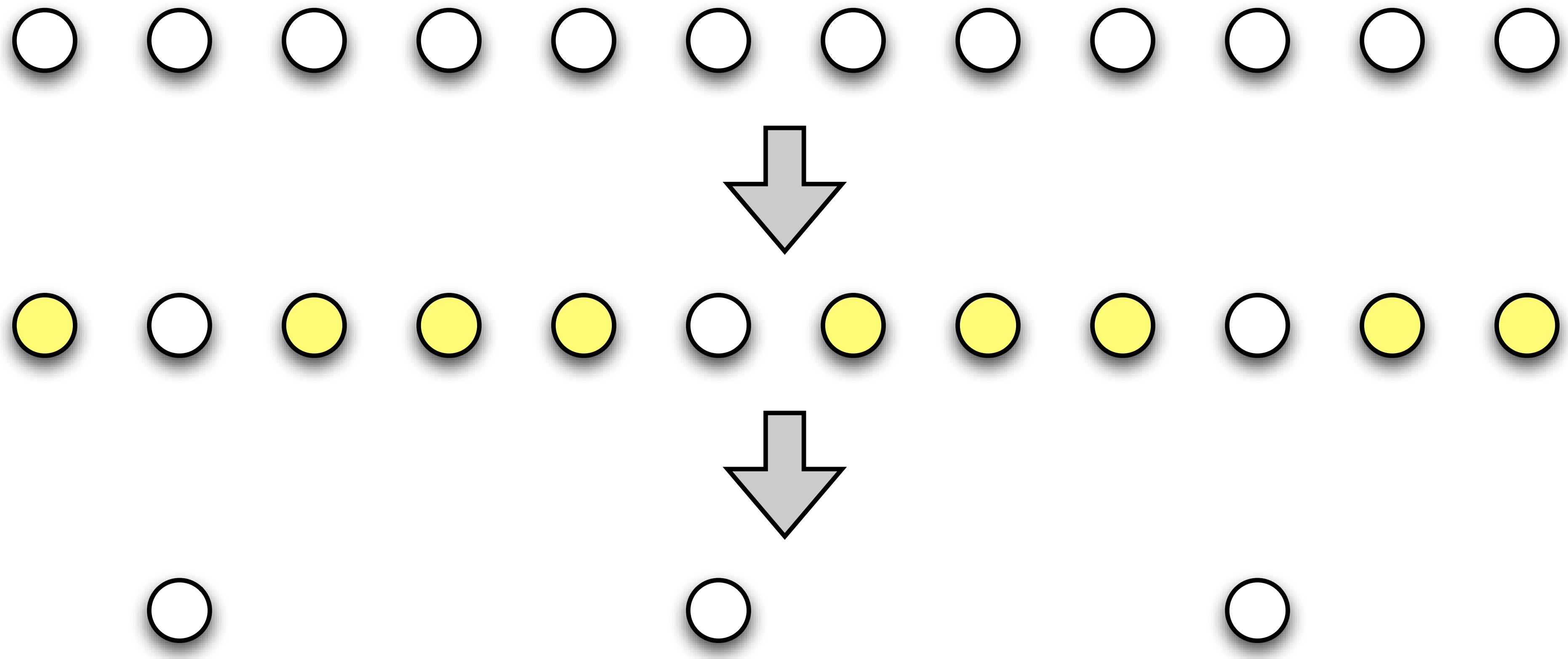
Collective two-qubit operation



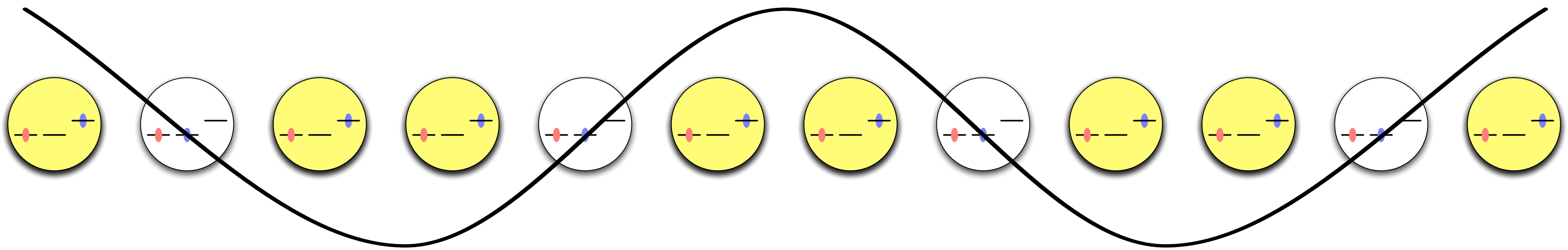
Selective two-qubit operation

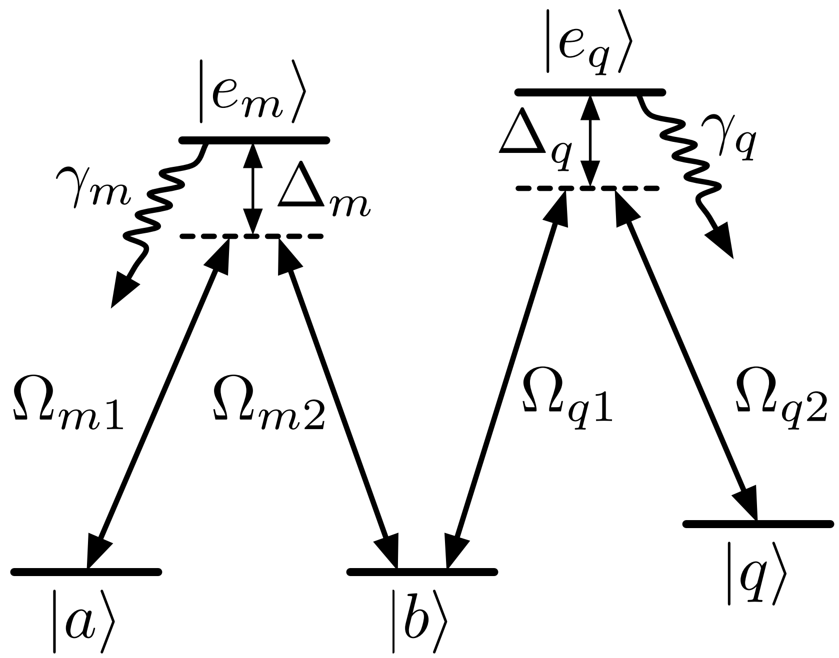


Patterned loading

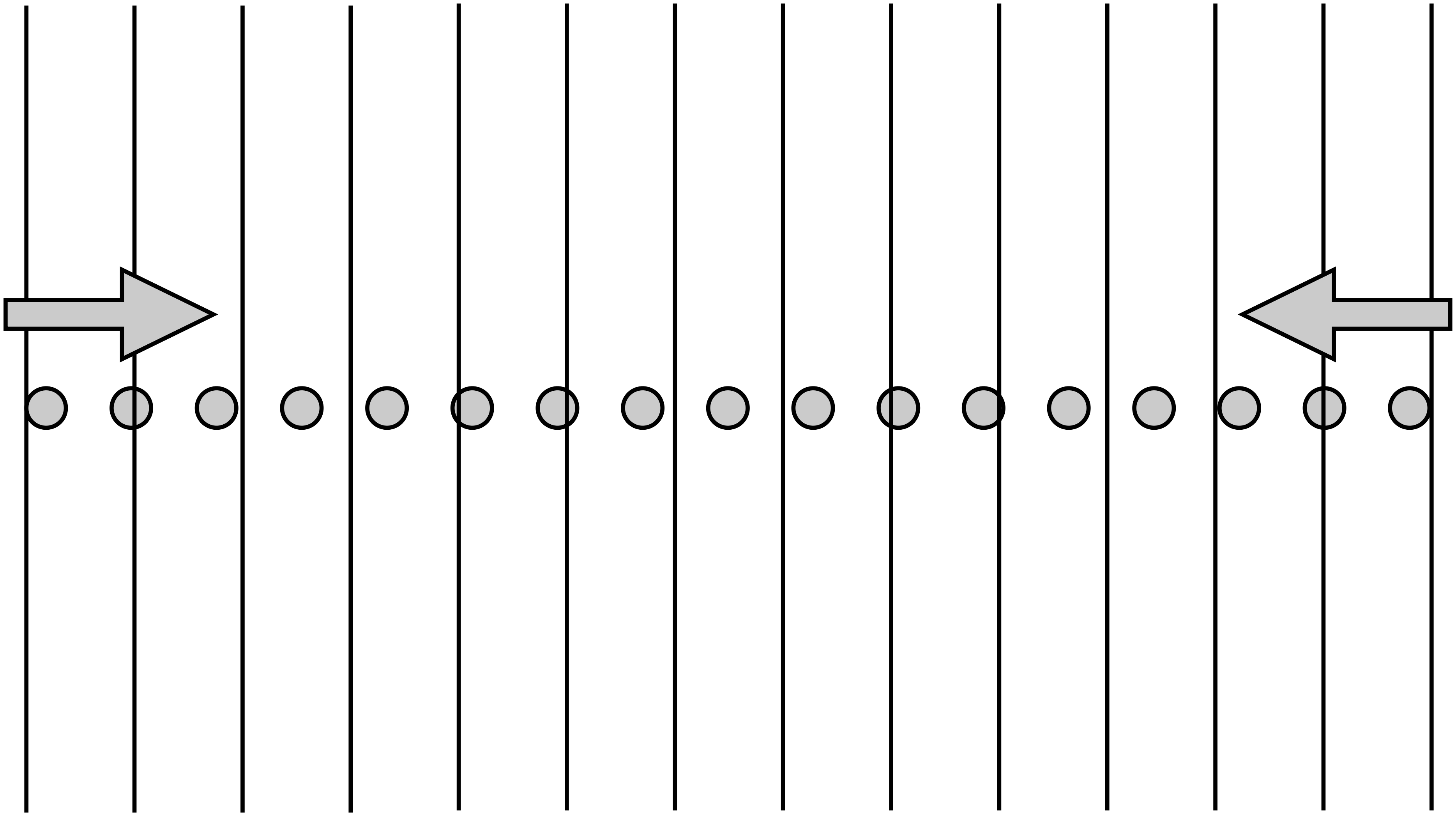


Quenching operation?

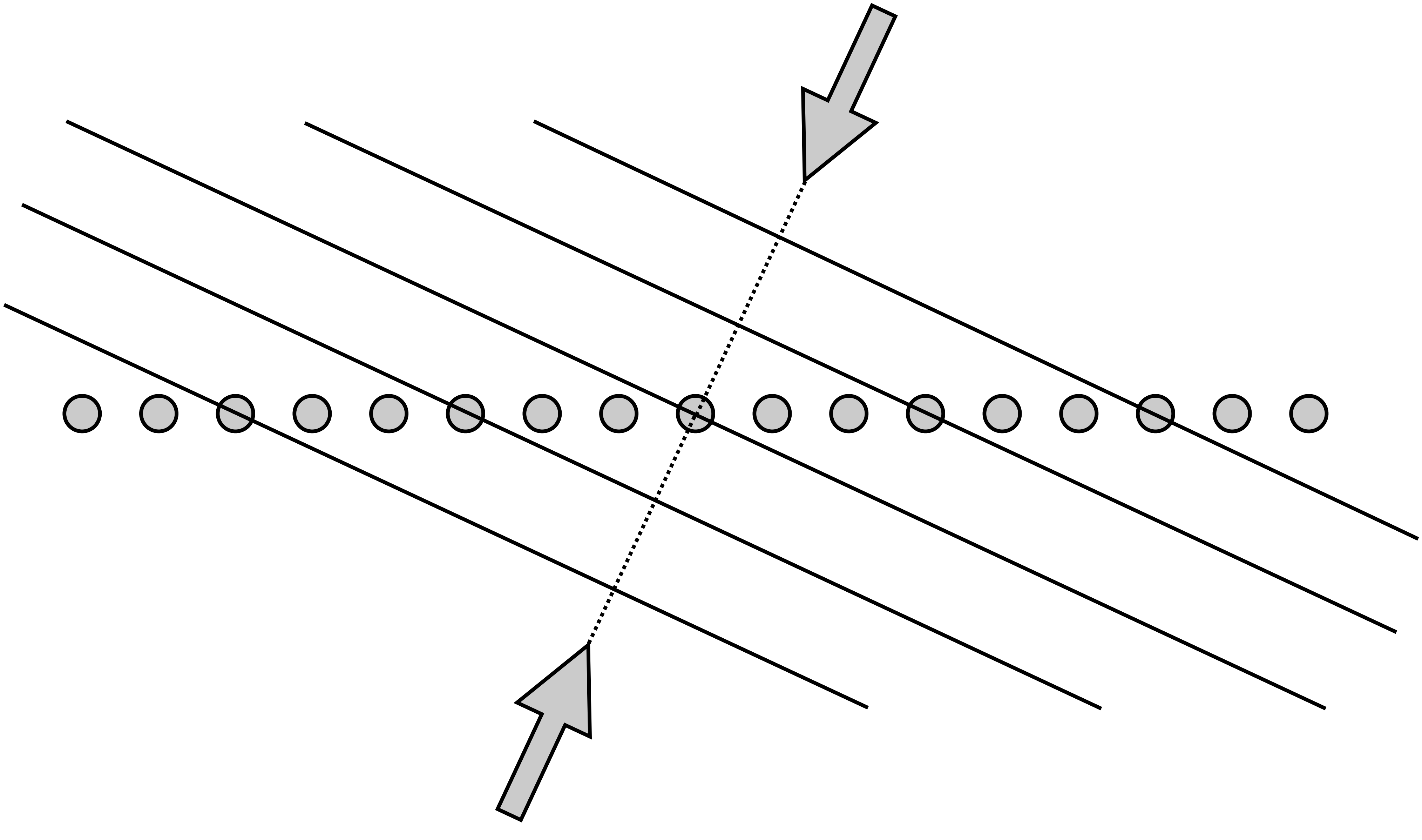




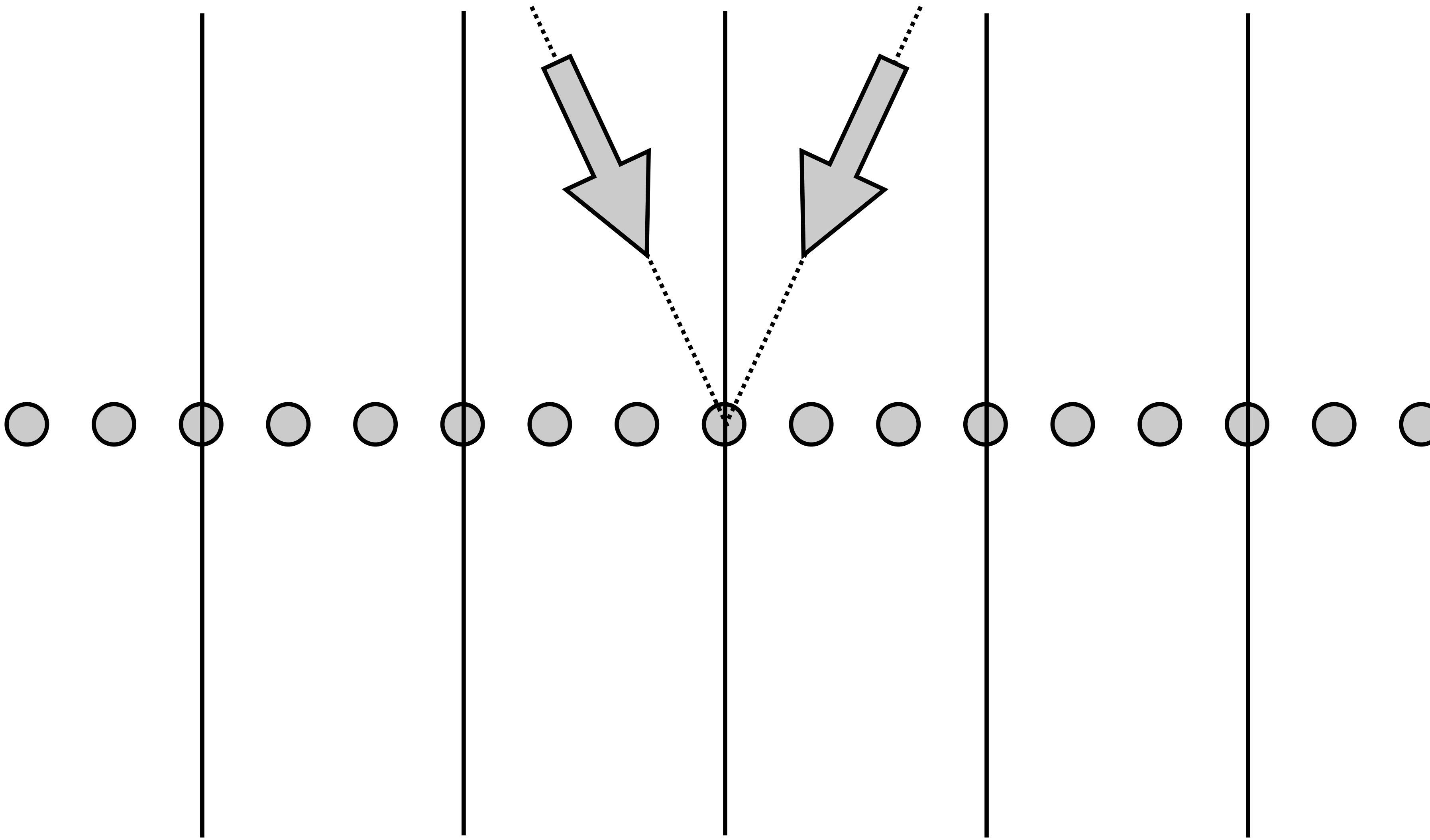
Arbitrary standing-wave field



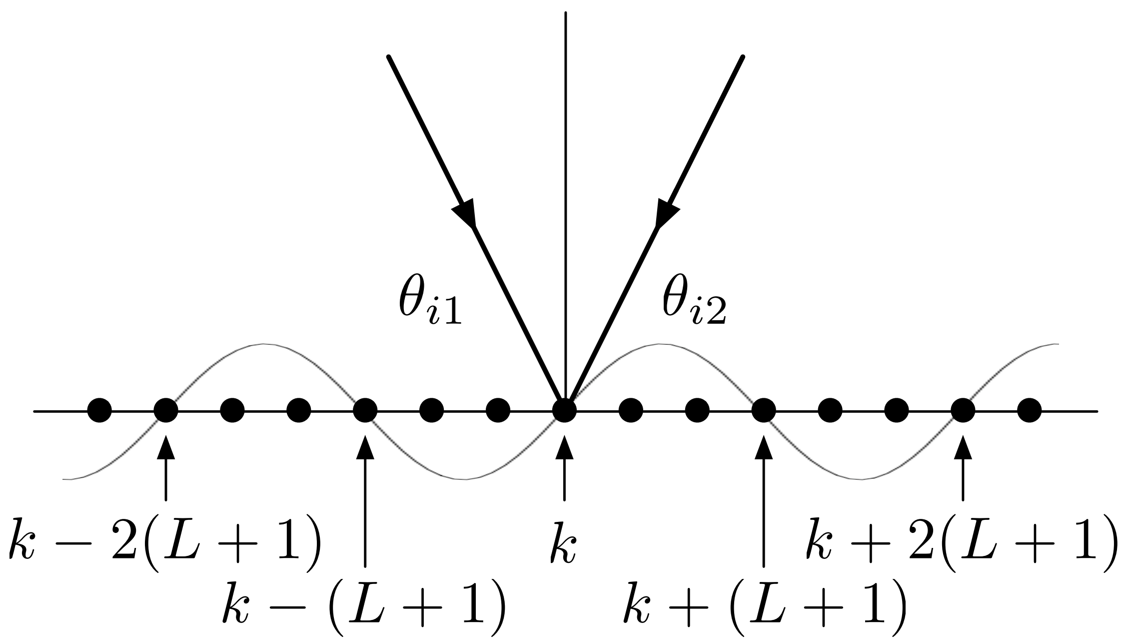
Arbitrary standing-wave field

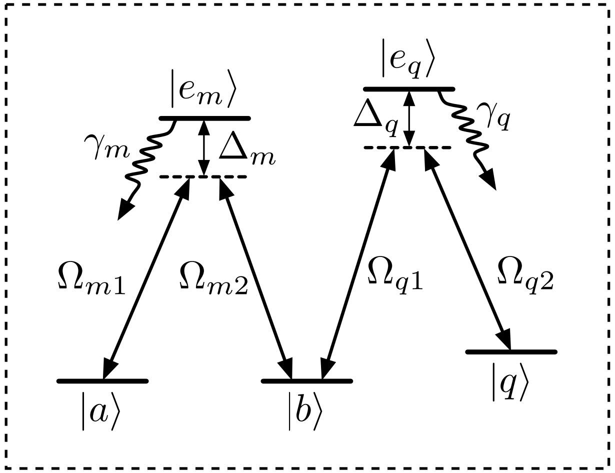


Arbitrary standing-wave field



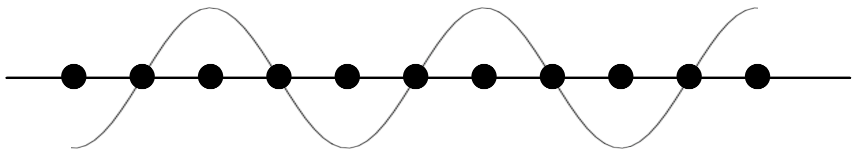
Standing-wave driving field

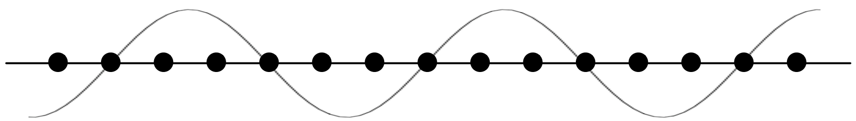


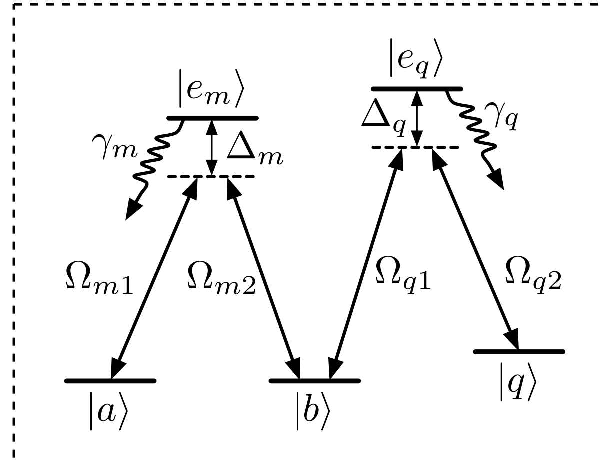


$$\Omega_{qi}^{(s)}(t) = e^{-\eta^2/2}\Omega_0 \sin\left(\pi \frac{s-k}{L+1}\right)\Omega_i(t)$$

Standing-wave driving field

L=1 

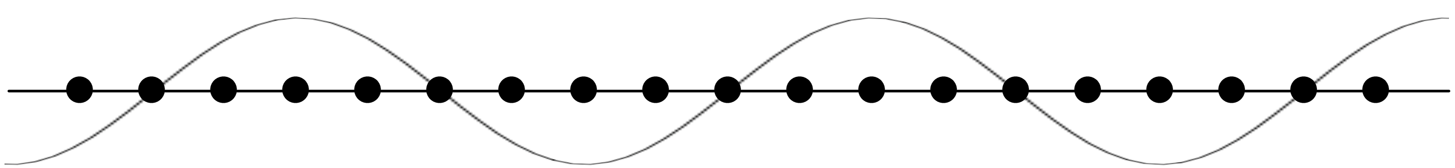
L=2 



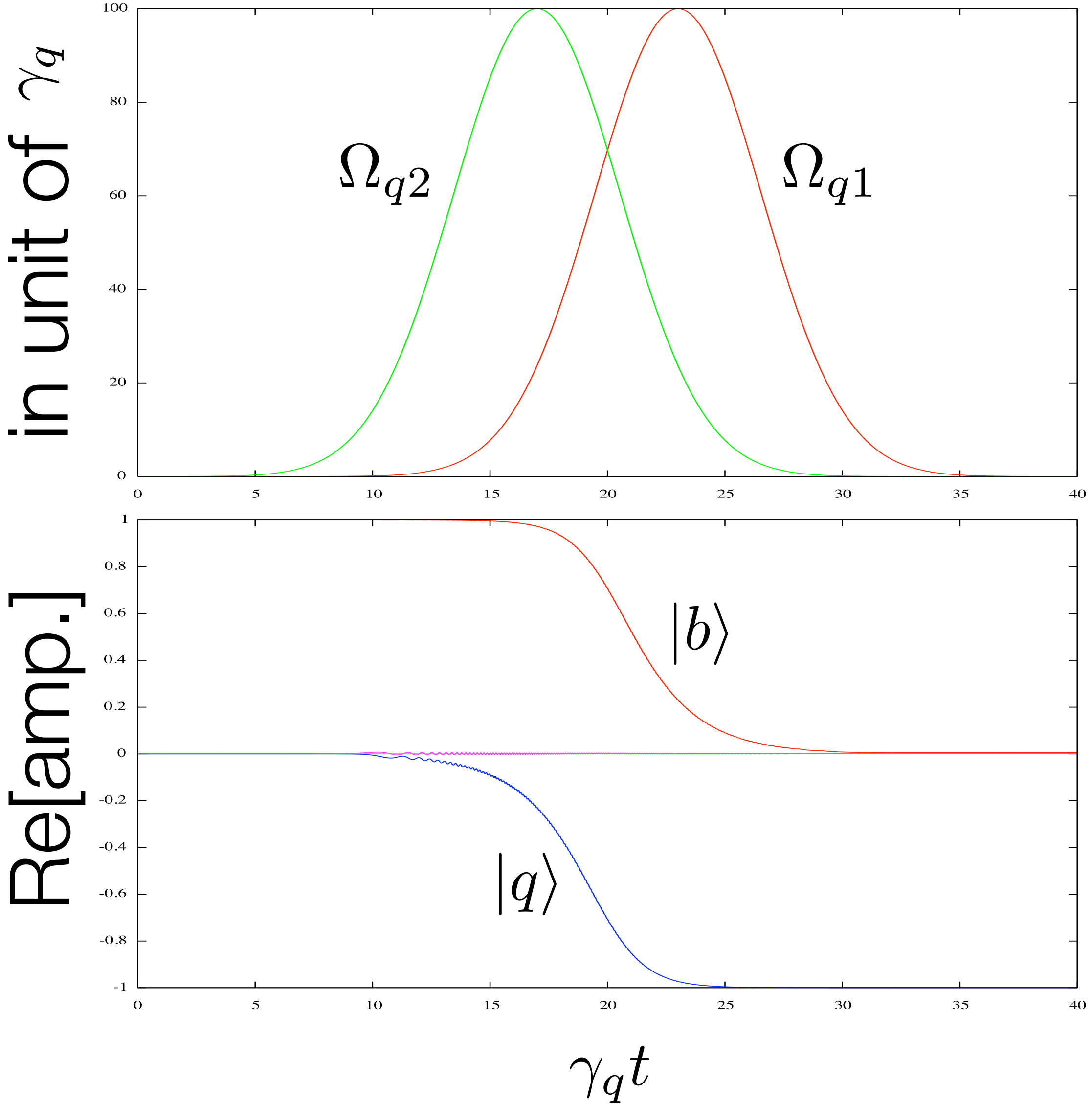
✏ Raman transition ($\Delta_q \gg \left|\Omega_{qi}^{(s)}\right|$)

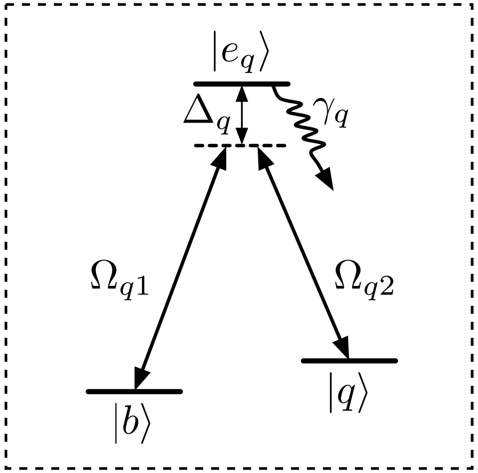
$$\Omega^{(s)} = \frac{\Omega_{q1}^{(s)}\Omega_{q2}^{(s)}}{\Delta_q}$$

✏ When L=3,4,5,...?



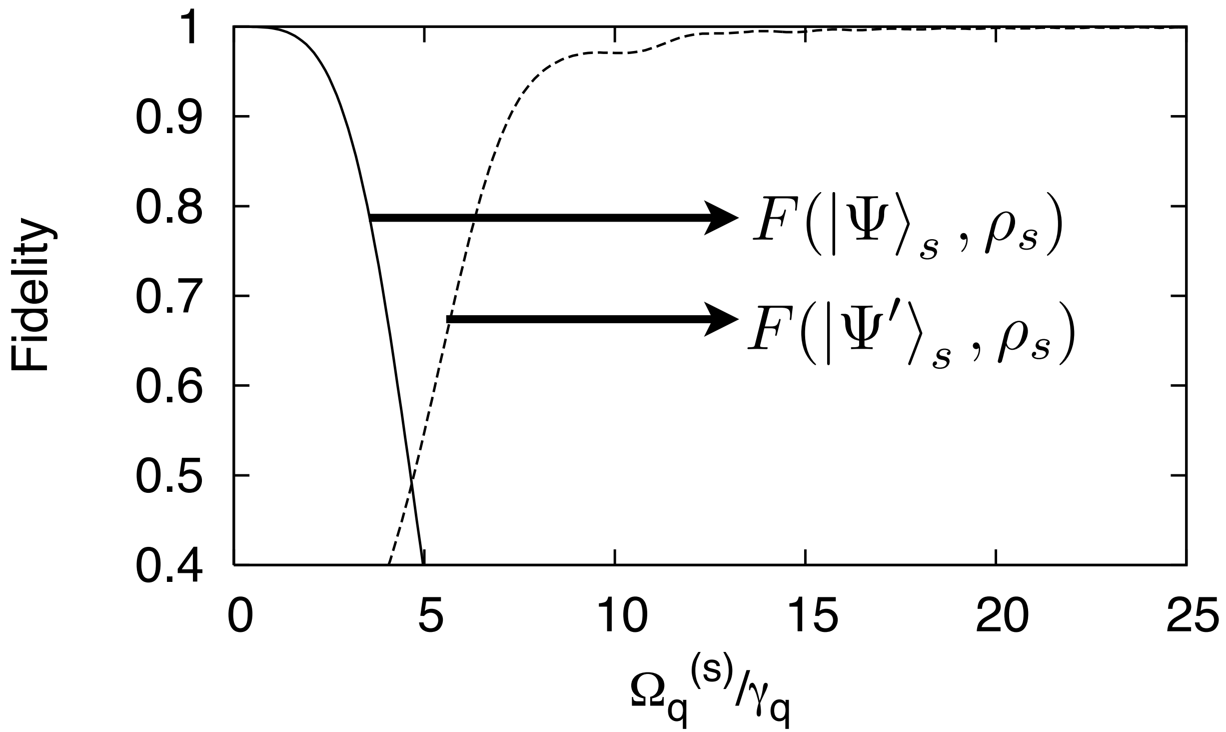
Stimulated Raman Adiabatic Passage (STIRAP)

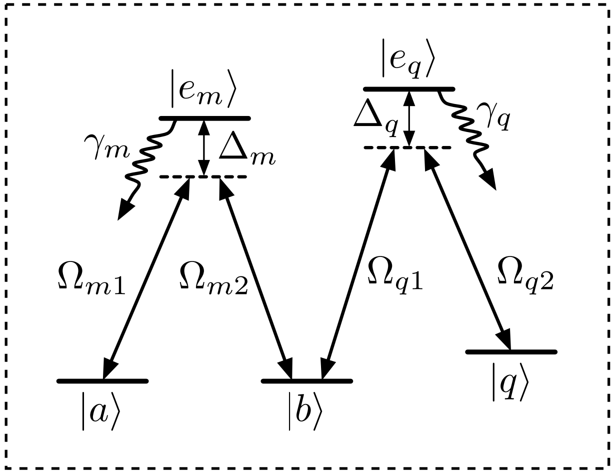




$$\Delta_q = 100\gamma_q$$

Stimulated Raman Adiabatic Passage (STIRAP)

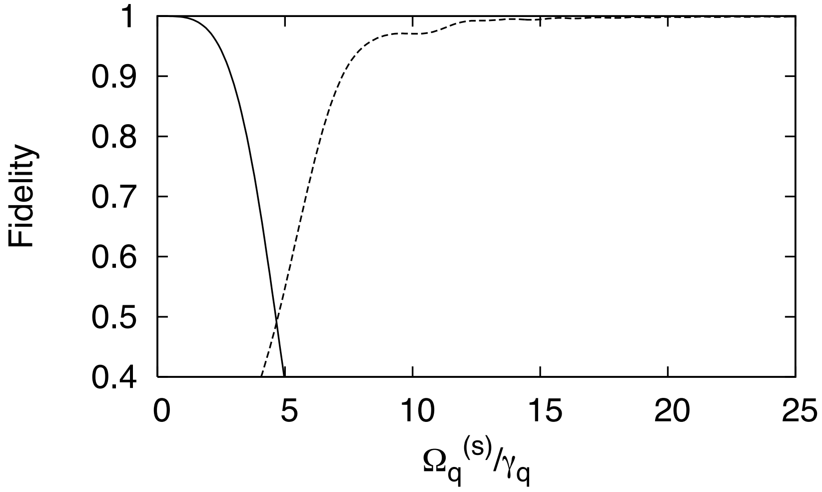


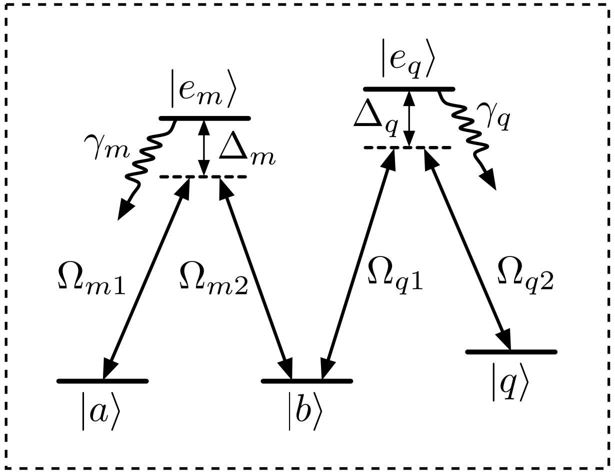


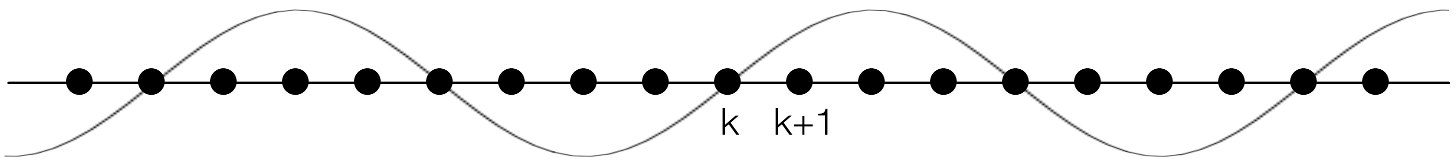
$$|\Psi\rangle_s = \frac{1}{\sqrt{2}}(|a\rangle_s + |b\rangle_s) \rightarrow |\Psi'\rangle_s = \frac{1}{\sqrt{2}}(|a\rangle_s + |q\rangle_s)$$

$$\searrow \rho_s$$

Quenching operation for an arbitrary L

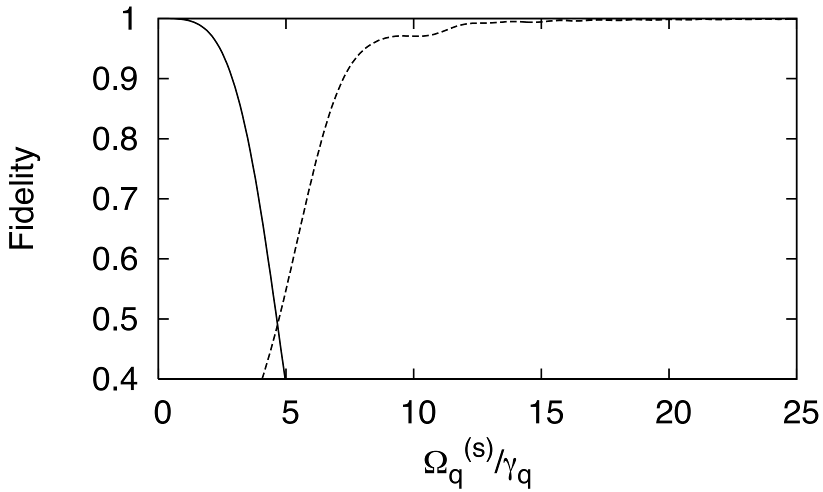


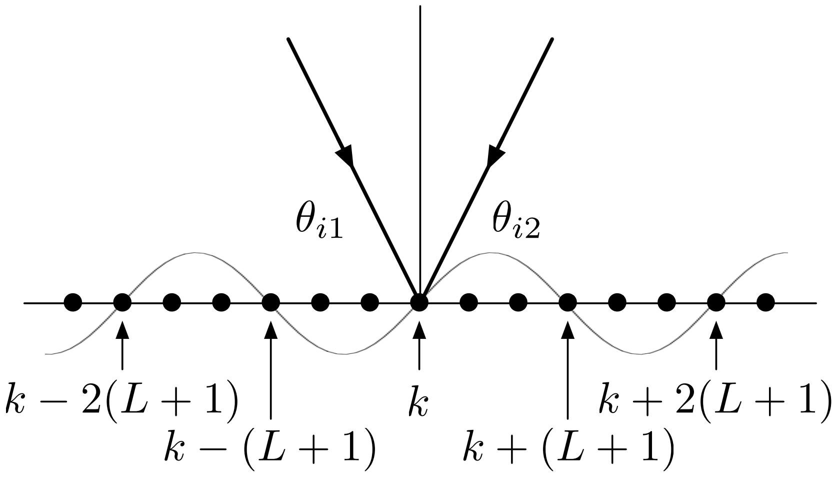




We take $\Omega_q^{(k+1)} >$ (threshold).

Required precision





$$(L+1)(N\Delta\theta + \Delta\phi/\pi) \lesssim \text{const.}$$

(N: # of atoms)

Conclusion

- Simple scheme for addressing individual atoms in one- or two-dimensional optical lattices.
- It allows single-atom operations, two-atom operations, patterned loading, and so on.
- It is robust against considerable imperfections and actually within current technology.