INTERACTING IONS IN THE LAB

Experimental Qubits: E2 transition

Interaction Hamiltonian

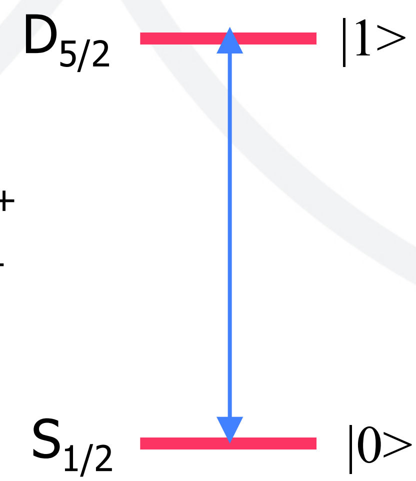
$$\tilde{H}_L = \frac{1}{2}\hbar\Omega_R\left(\sigma_+ e^{i\phi} + \sigma_- e^{-i\phi}\right)$$

need to keep phase ϕ stable,

optical radiation: $\omega \approx 5\times 10^{14}$ Hz

Electric quadrupole

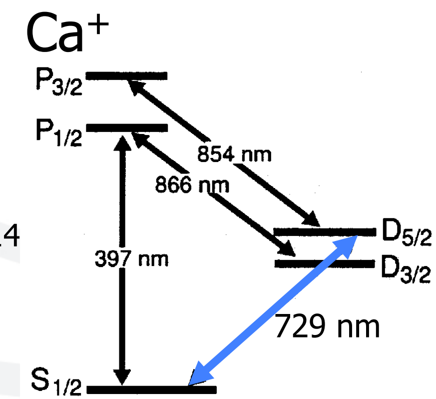
Ba^+, Ca^+
Sr^+, Yb^+



Qubits: E2 transition

Example

$$\Delta\omega / \omega \approx 10^{-14}$$



Ch. Roos et al. PRL **83**, 4713 (1999)

Electric quadrupole

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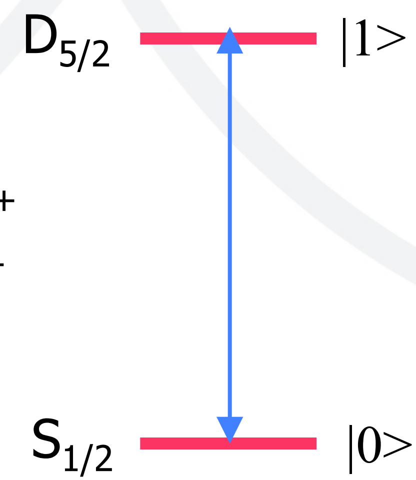
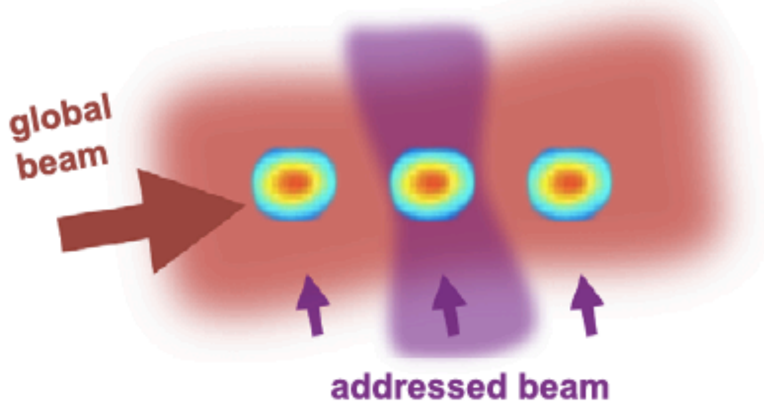
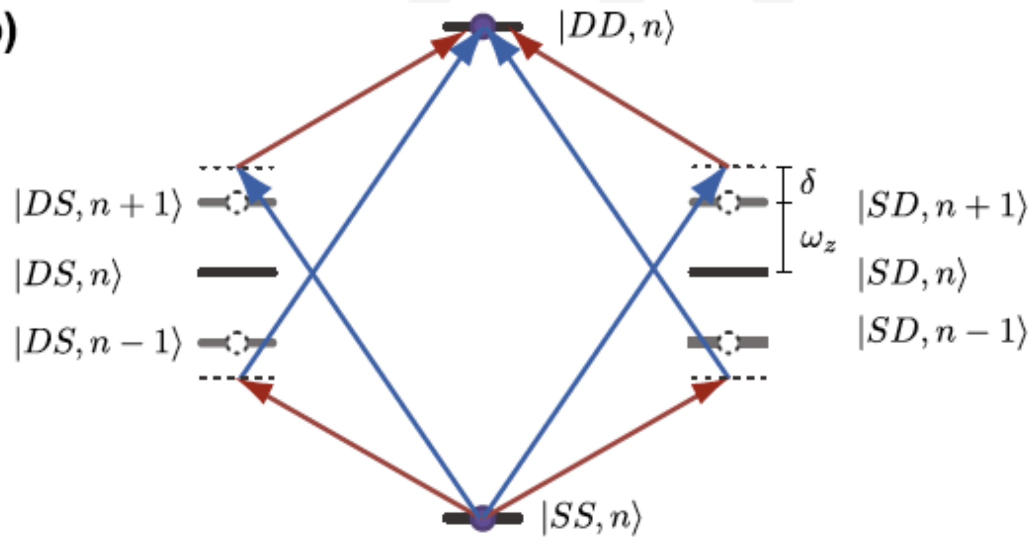


Elementary quantum logic using E2 transition

Example





$$S_\phi = \sum_{i=0}^{N}(\sigma_x^{(i)}\cos\phi + \sigma_y^{(i)}\sin\phi)$$

$$R_\phi(\theta) = \mathrm{e}^{-i\theta S_\phi/2}$$

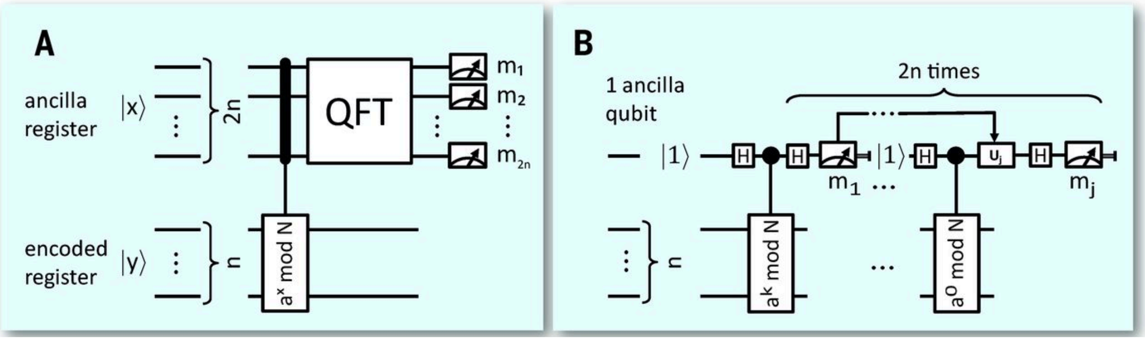
$$S_z^{(j)}(\theta) = \mathrm{e}^{-i\theta\sigma_z^{(j)}/2}$$

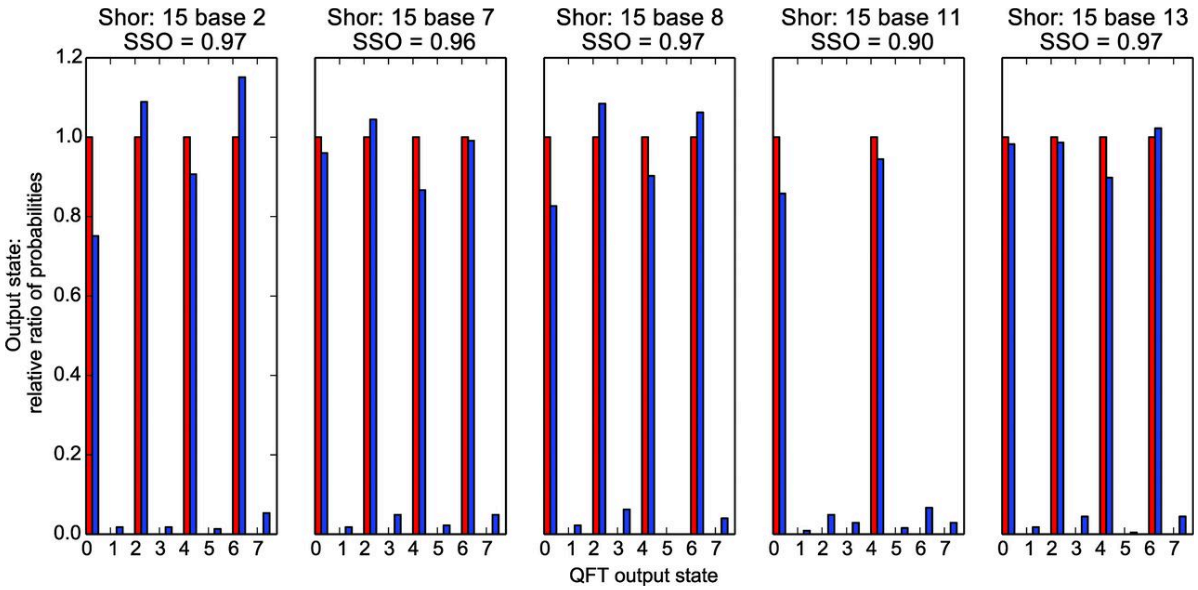
$$\mathrm{MS}_\phi(\theta) = \mathrm{e}^{-i\theta S_\phi^2/4}$$

K. Mølmer and A. Sørensen, PRL **82**, 1835 (1999).

Schindler et al., NJP **15,** 123012 (2013)

Factoring using Shor's Algorithm





Th. Monz et al., Science **351**, 1068 (2016)

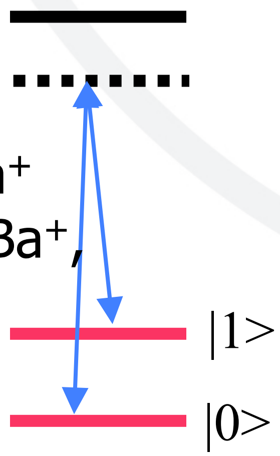
Qubits: Hyperfine or Zeeman transition

Raman transition:

$$\vec{k}_1 - \vec{k}_2 \neq \vec{0}$$

$$\Omega_R \propto \frac{\Omega_1 \Omega_2}{\Delta}$$

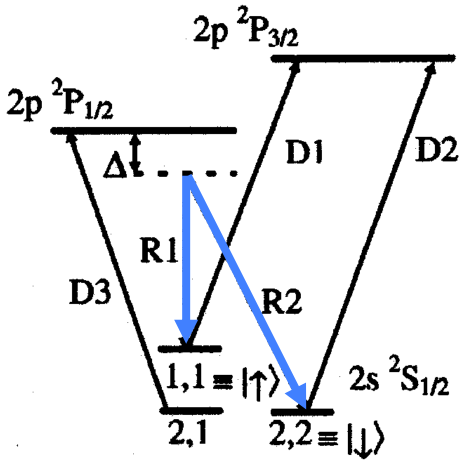
$^{9}Be^{+}$, $^{25}Mg^{+}$, $^{43}Ca^{+}$ $^{87}Sr^{+}$, $^{111}Cd^{+}$, $^{137}Ba^{+}$, $^{171}Yb^{+}$



Qubits: Hyperfine or Zeeman transition

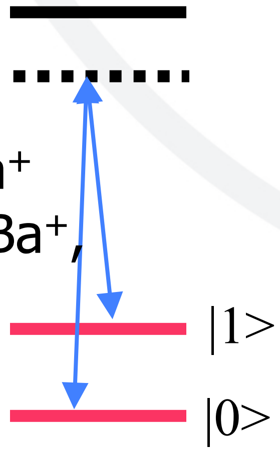
Example

Be$^+$



C. Monroe et al., PRL **75** (1995)

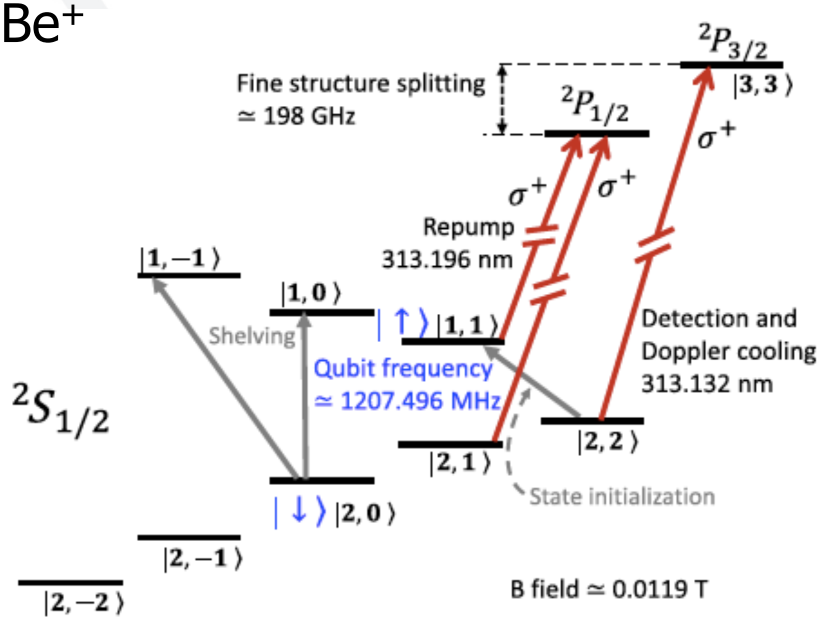
$^9Be^+$, $^{25}Mg^+$, $^{43}Ca^+$
$^{87}Sr^+$, $^{111}Cd^+$, $^{137}Ba^+$,
$^{171}Yb^+$

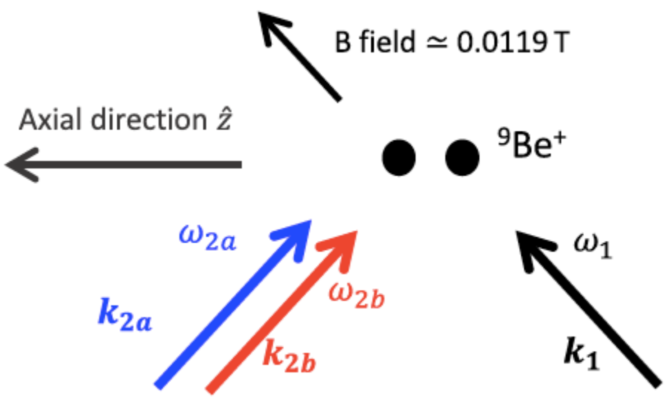


Qubits: Hyperfine or Zeeman transition

Example: High fidelity gates

Be^+



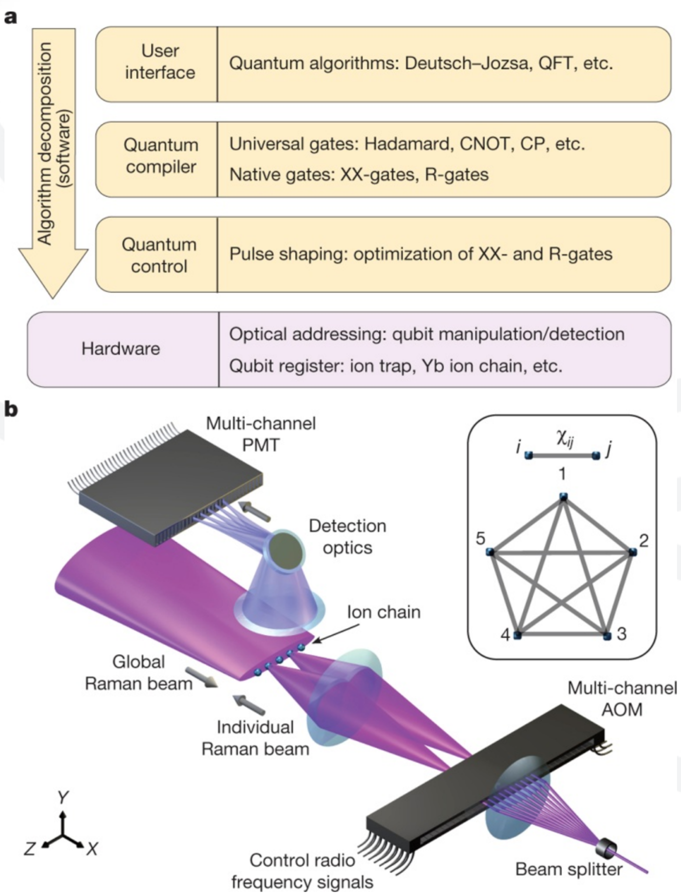


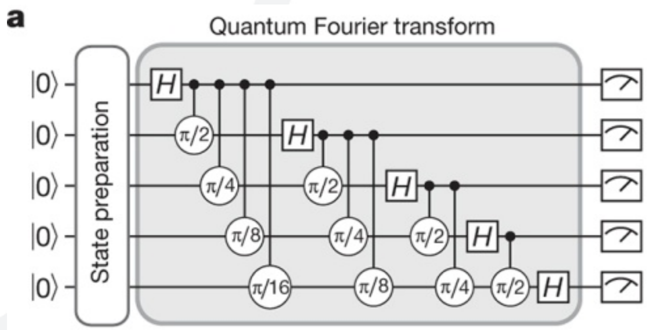
Doppler cooling, repumping, detection

Gate: Raman transitions

J.P. Gaebler et al., PRL **117** (2016)

Trapped Ion Quantum Computer
Example

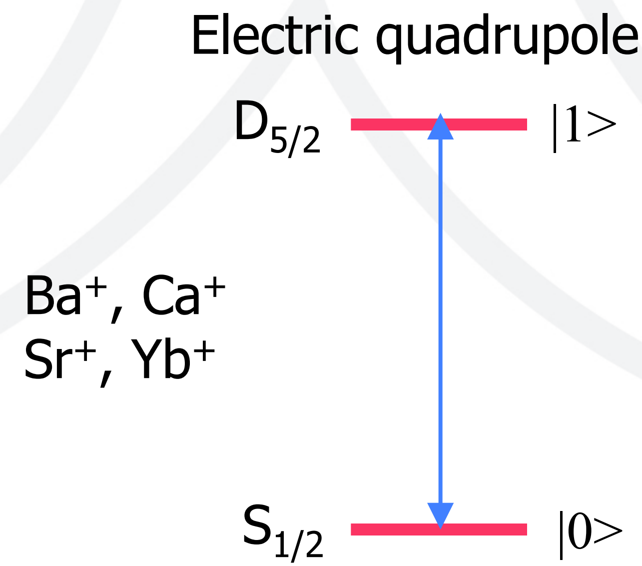




S. Debnath et al. Nature **536**, 63 (2016).

Qubits: E2 transition

Example



Precise coherent operations demand:

- high phase stability,
- high absolute stability of centre frequency
- high amplitude stability

(need good beam quality, pointing stability, diffraction)

Qubits: Hyperfine or Zeeman transition

Example

$^{9}Be^{+}$, $^{25}Mg^{+}$, $^{43}Ca^{+}$
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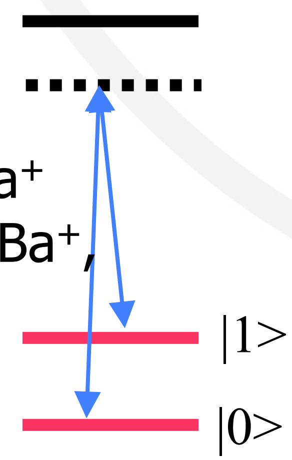


Precise coherent operations demand:

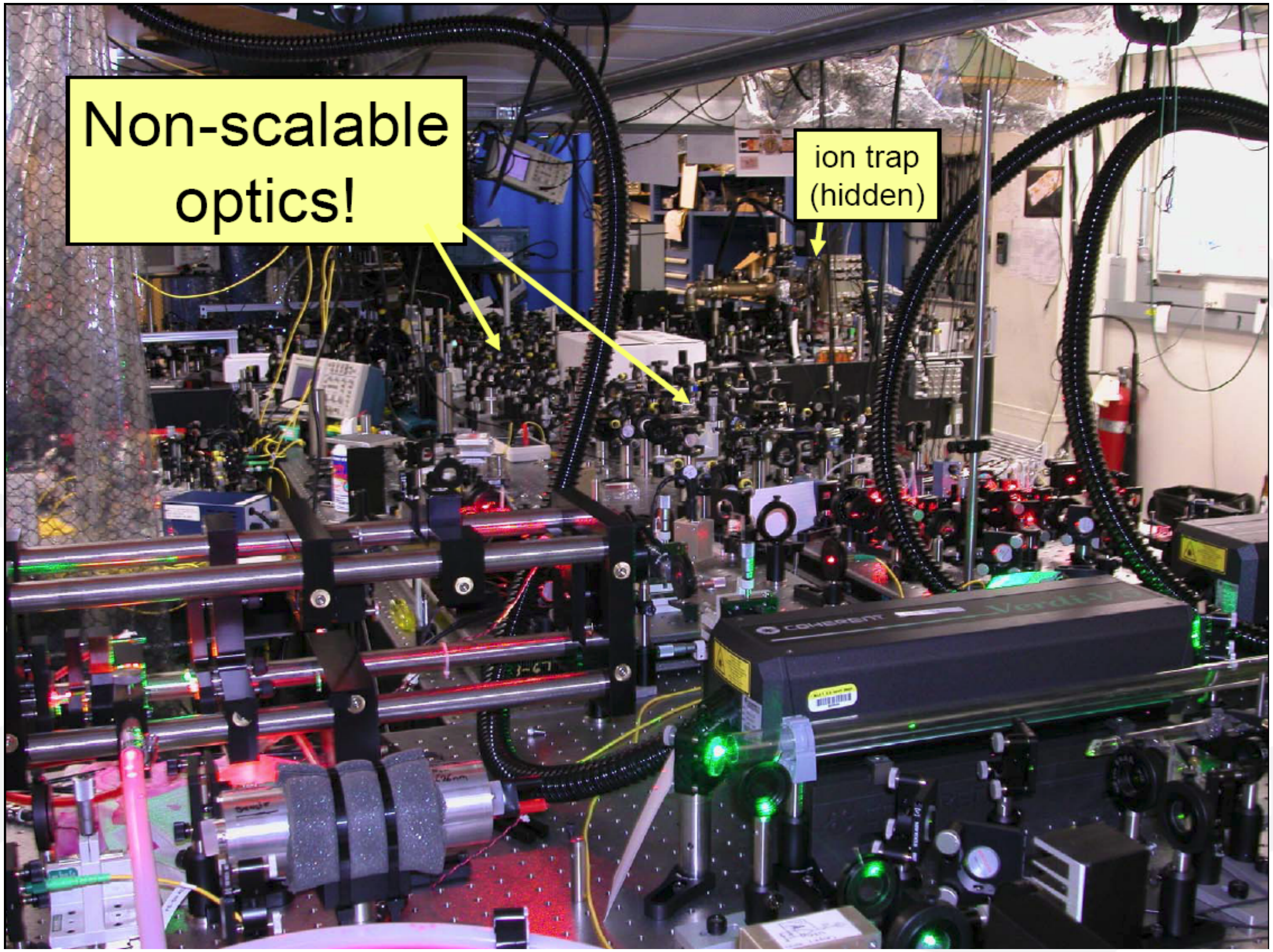
- high phase stability,
- high absolute stability of centre frequency
- high amplitude stability

(need good beam quality, pointing stability, diffraction)

- Avoid spontaneous scattering

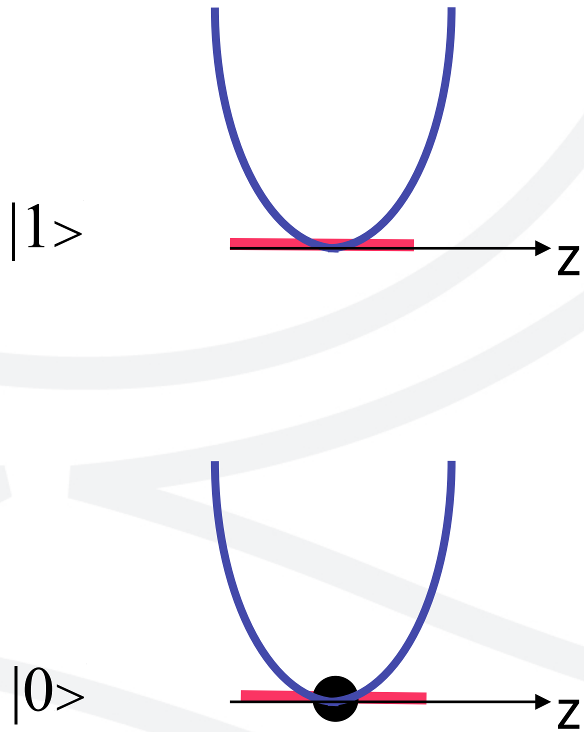
Quantum Information with Trapped Ions

Slide prepared by Dave Wineland



Magnetic **G**radient **I**nduced **C**oupling

MAGIC: Spin-Motion Coupling despite $\eta \approx 0$



PRL **87** (2001).
In "*Laser Physics at the Limit*", Springer, 2002. quant-ph/0111158.
Adv. At. Mol. Opt. Phys. **49** (2003). quant-ph/0305129

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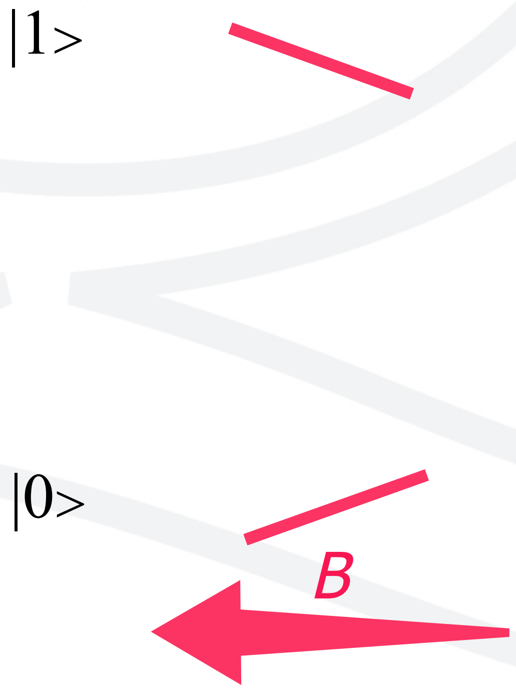

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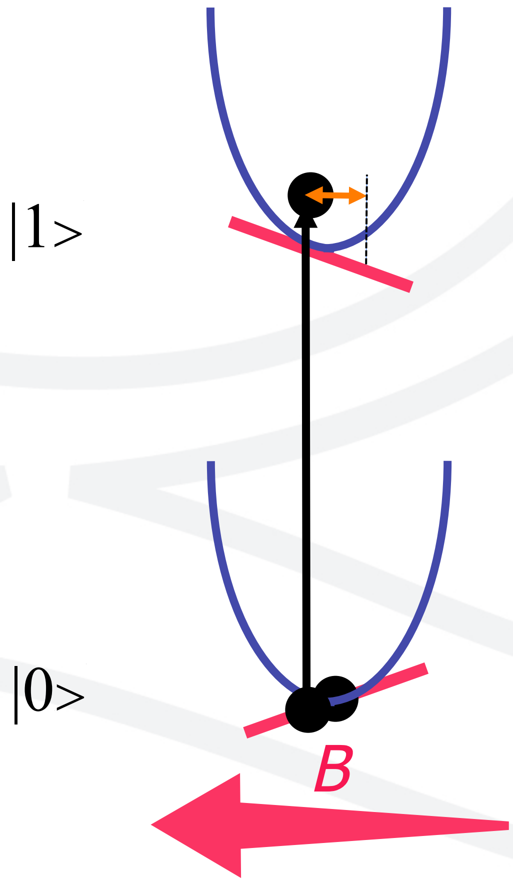

$$\eta_{eff} = d_z \,/\, \Delta z$$

PRL **87** (2001).
In "*Laser Physics at the Limit*", Springer, 2002. quant-ph/0111158.
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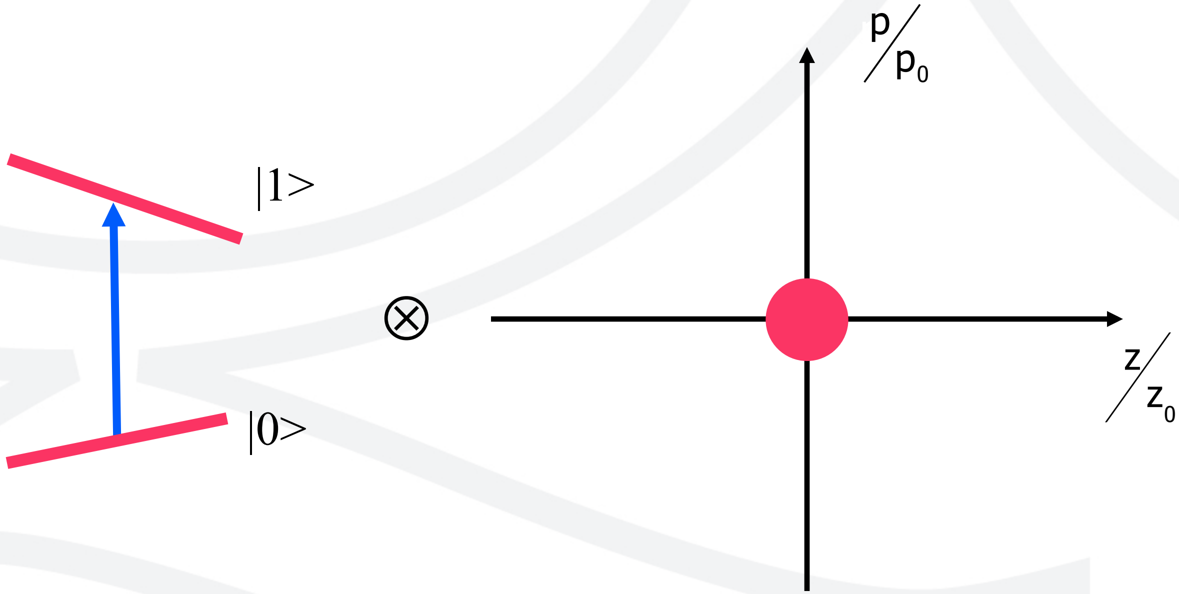
Coupling internal and motional states

Semi-classical illustration

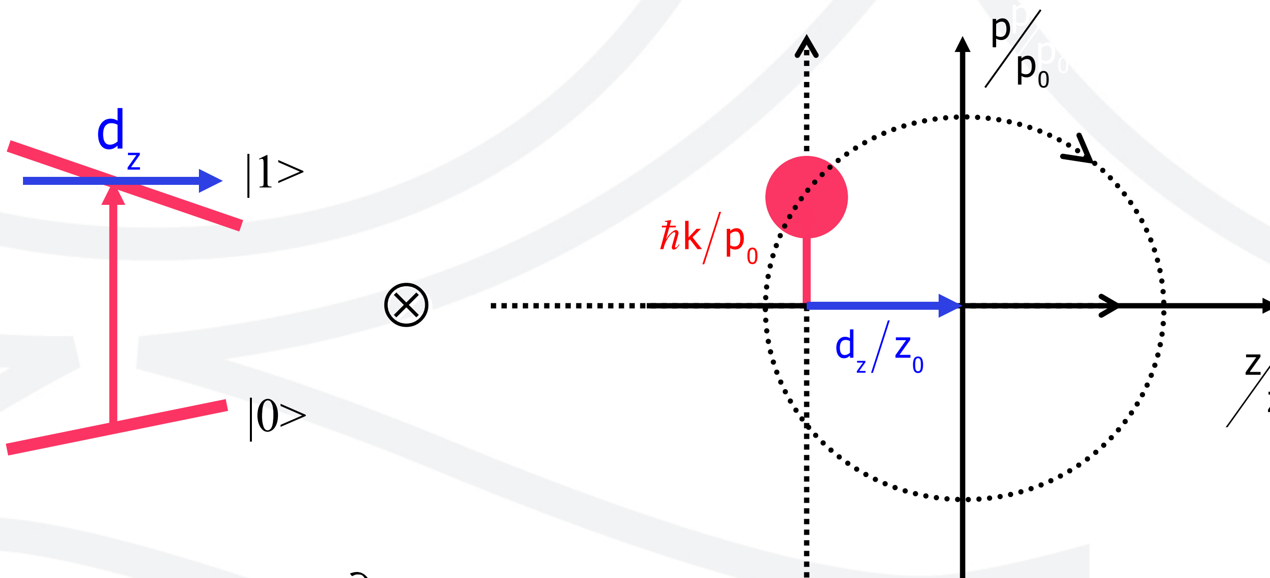
Spin-dependent force (magnetic gradient)



Coupling internal and motional states

Semi-classical illustration. QM calculation

Spin-dependent force (magnetic gradient)



Equilibrium shifted by $d_z = -\hbar \frac{\partial_z \omega}{m\nu^2}$

PRL **87** (2001). Adv. At. Mol. Opt.Phys. **49**, 295 (2003).

Coupling internal and motional states

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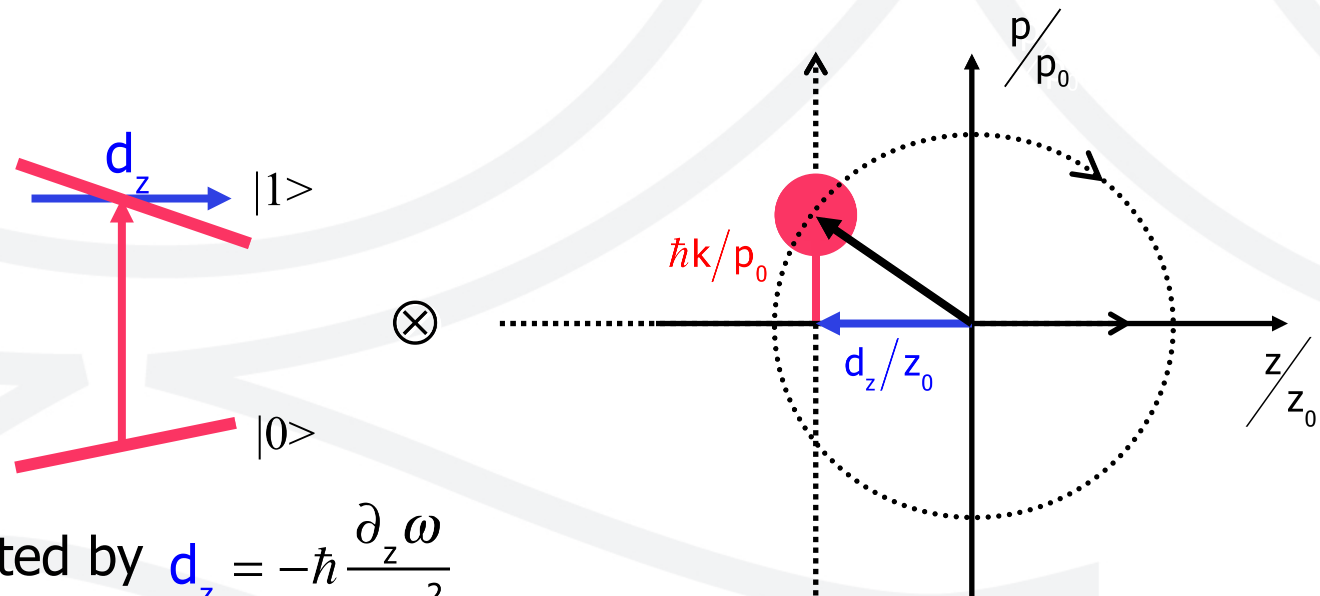


Equilibrium shifted by $d_z = -\hbar \frac{\partial_z \omega}{m\nu^2}$

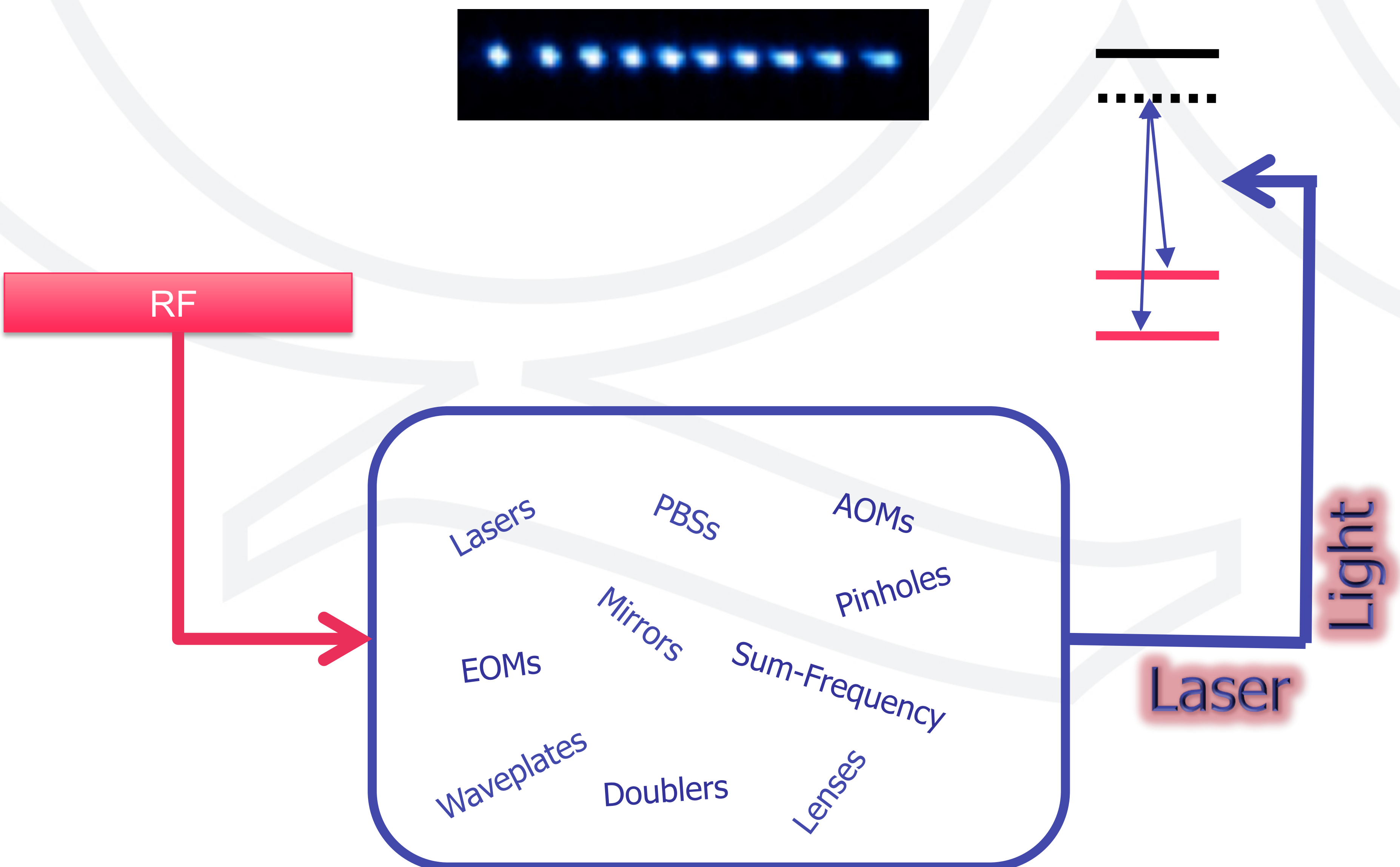
Effective Lamb-Dicke parameter:

$$\eta' \equiv \eta - i\kappa \qquad \text{where } \kappa \equiv \frac{d_z}{z_0} = z_0 \frac{\partial_z \omega}{\nu}$$

$$H_I \propto \sigma_+ \exp\left[i\left(\eta' a + \eta'^* a^+\right)\right] + \text{h.c.}$$

PRL **87** (2001). Adv. At. Mol. Opt. Phys. **49**, 295 (2003).

Coupling and Addressing Trapped Ions



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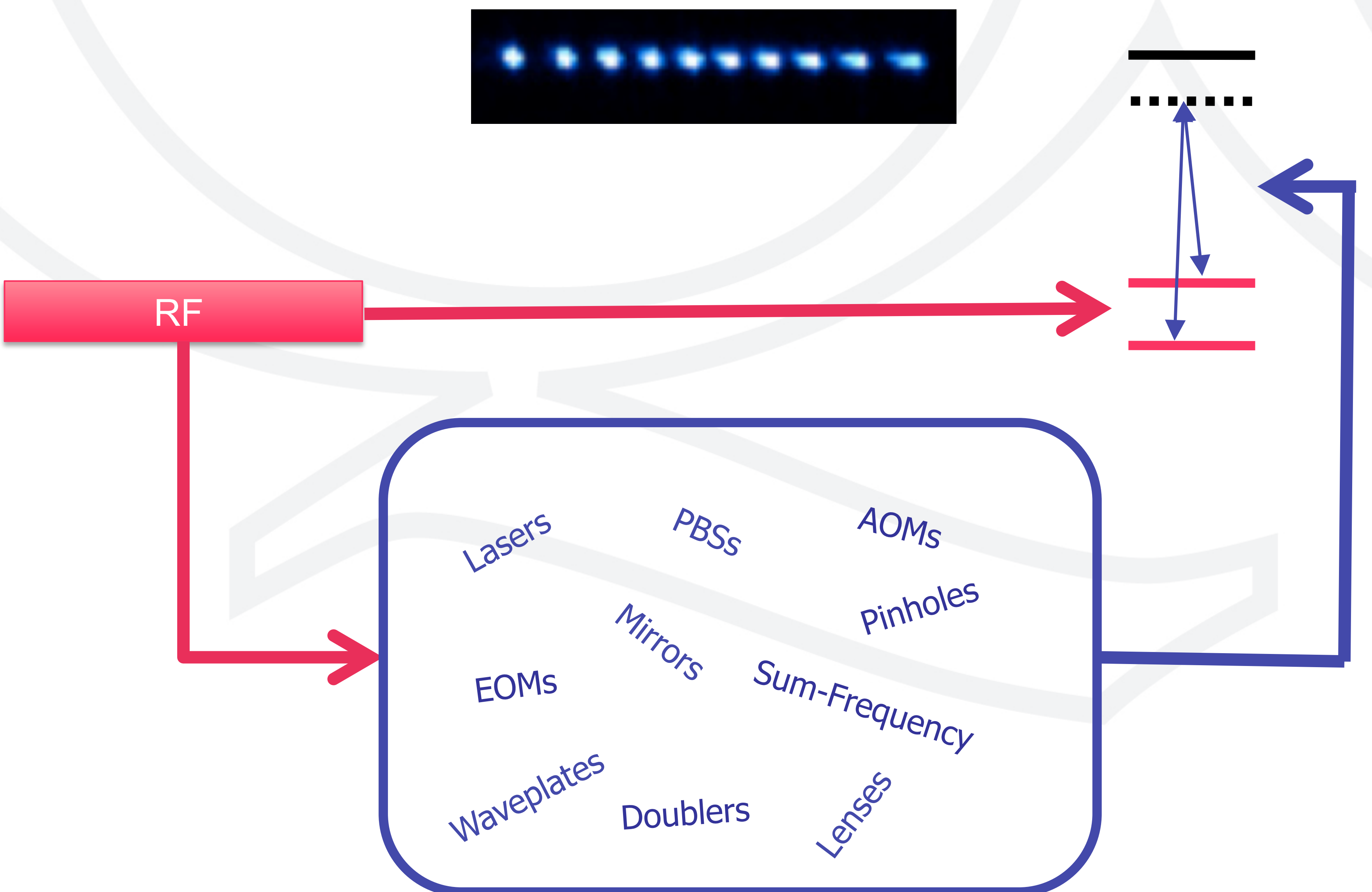
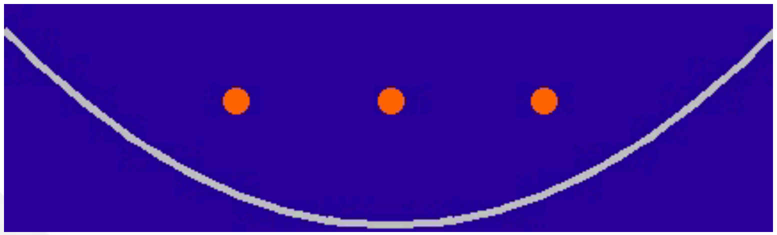
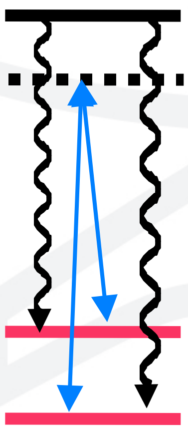


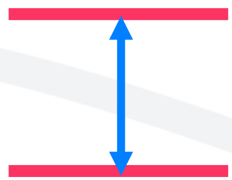
Coupling and Addressing Trapped Ions

Trapped Ions for QIS

Coupling and Addressing Qubits using **RF-waves**







Technical challenges

- Stability of frequency ✔
- Stability of phase ✔
- Stability of intensity ✔
- Ambient fields ?
- Shuttling ✔

Fundamental problems

- Spontaneous scattering ✔
- Addressing errors ✔
- Thermal excitation ✔ ?