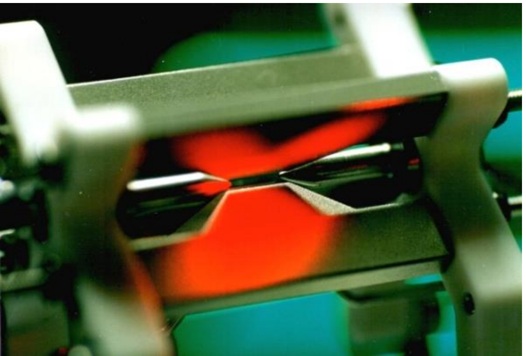
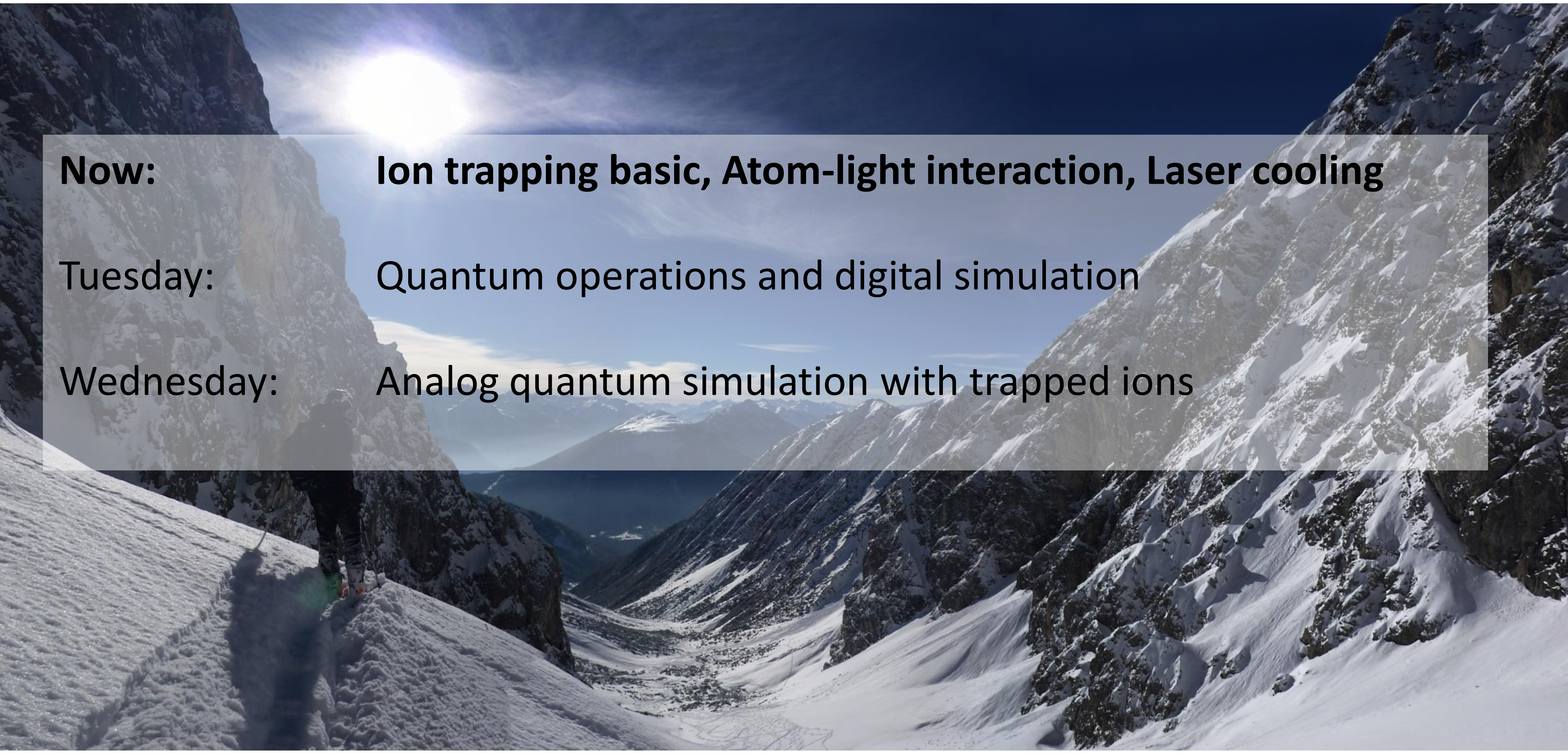
Quantum science with trapped ions



Philipp Schindler

Outline

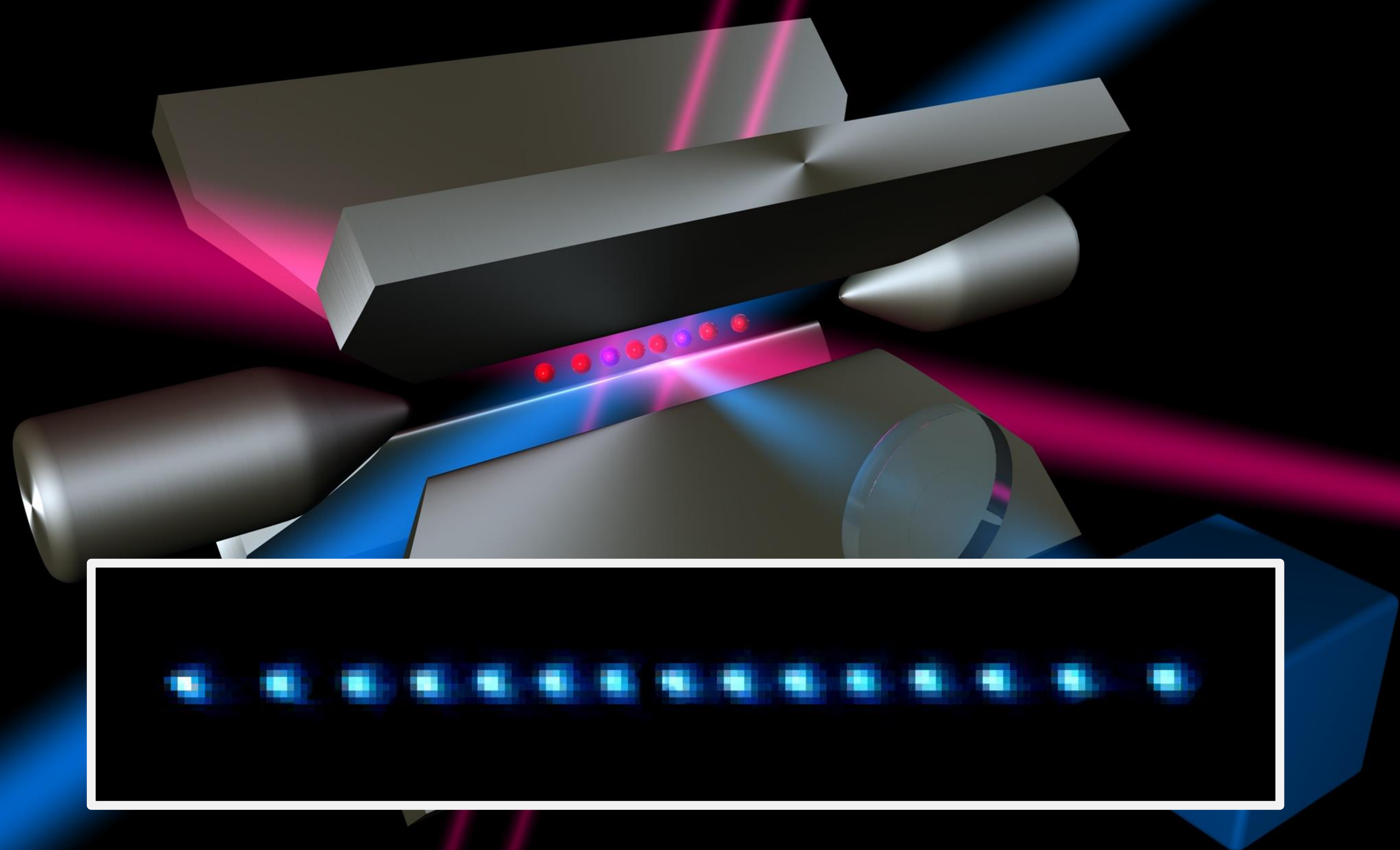


Now: **Ion trapping basic, Atom-light interaction, Laser cooling**

Tuesday: Quantum operations and digital simulation

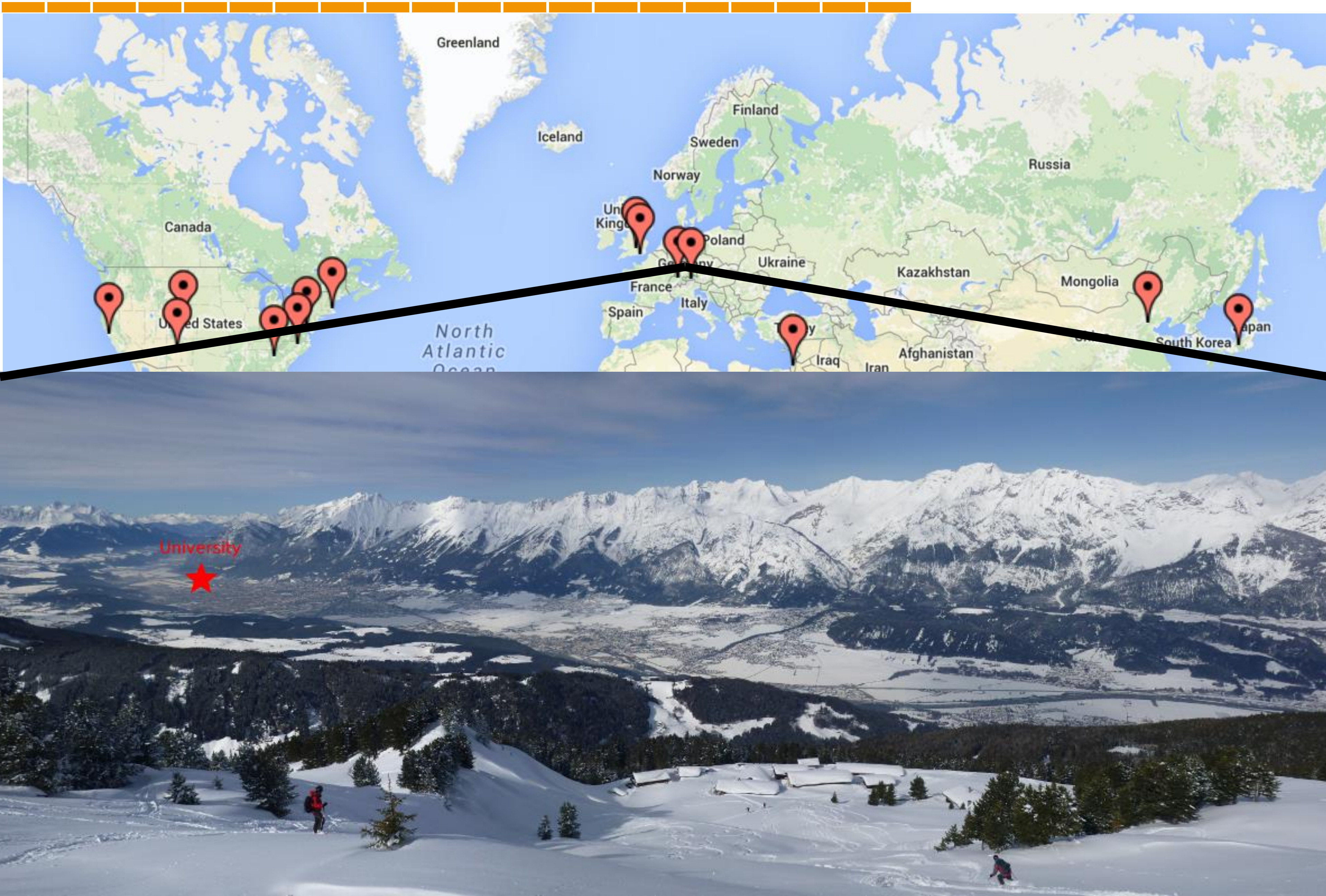
Wednesday: Analog quantum simulation with trapped ions

The Quantum Information Processor with Trapped Ca^+ Ions



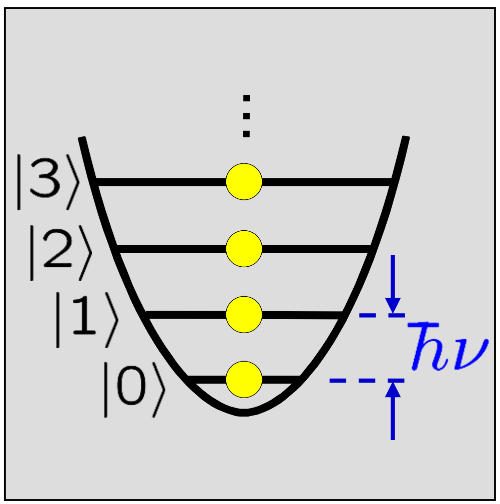
P. Schindler et al., New. J. Phys. 15, 123012 (2013)

Ion trap QC around the globe



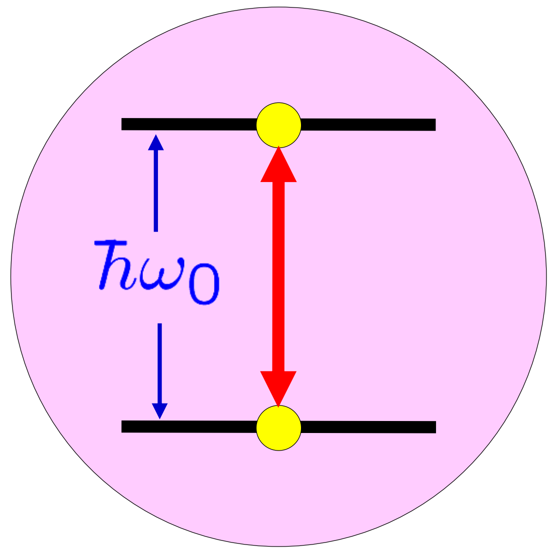
The ideal world

Harmonic oscillator



$\otimes$

Quantum bit



$$|D_{5/2}\rangle \equiv |\uparrow\rangle \equiv |\mathbf{0}\rangle$$

$$|S_{1/2}\rangle \equiv |\downarrow\rangle \equiv |\mathbf{1}\rangle$$

motional states

$$|0\rangle, |1\rangle, |2\rangle, |3\rangle, \ldots$$

internal states

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

Ion traps – How do they work

- Blackboard: How to trap a charged particle.

„Quantum dynamics of single trapped ions“

D. Leibfried, R. Blatt, C. Monroe, D. Wineland

Rev. Mod. Phys. **75**, 281-324 (2003)

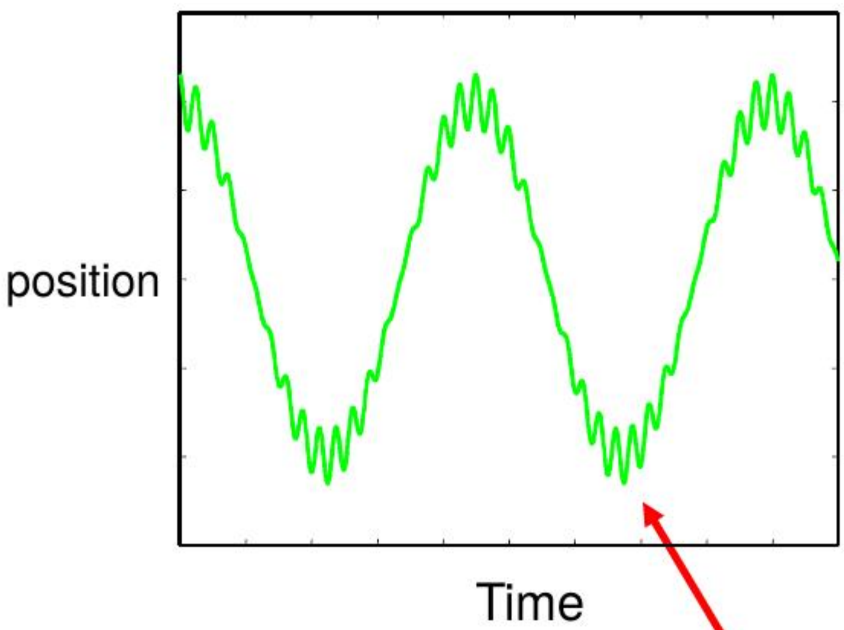
„Experimental Issues in Coherent Quantum-State Manipulation of Trapped Atomic Ions“

D. Wineland et al.

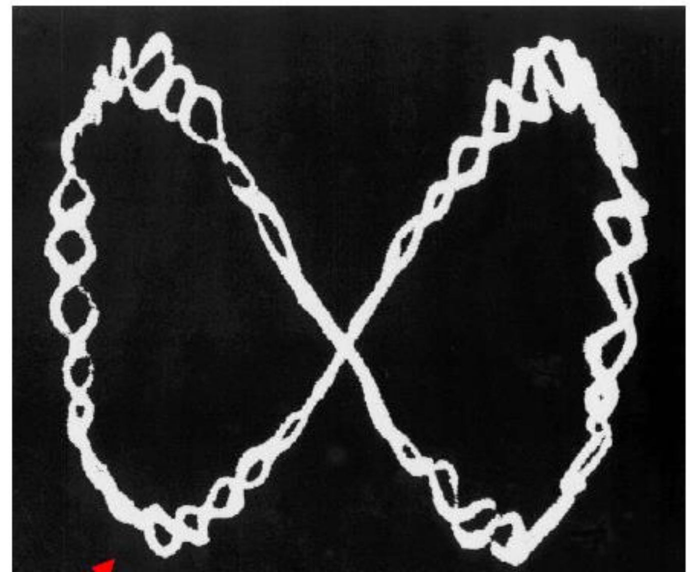
J. Res. Natl. Inst. Stand. Technol. **103**, 259-328 (1998)

Micromotion

1d-solution of Mathieu equation



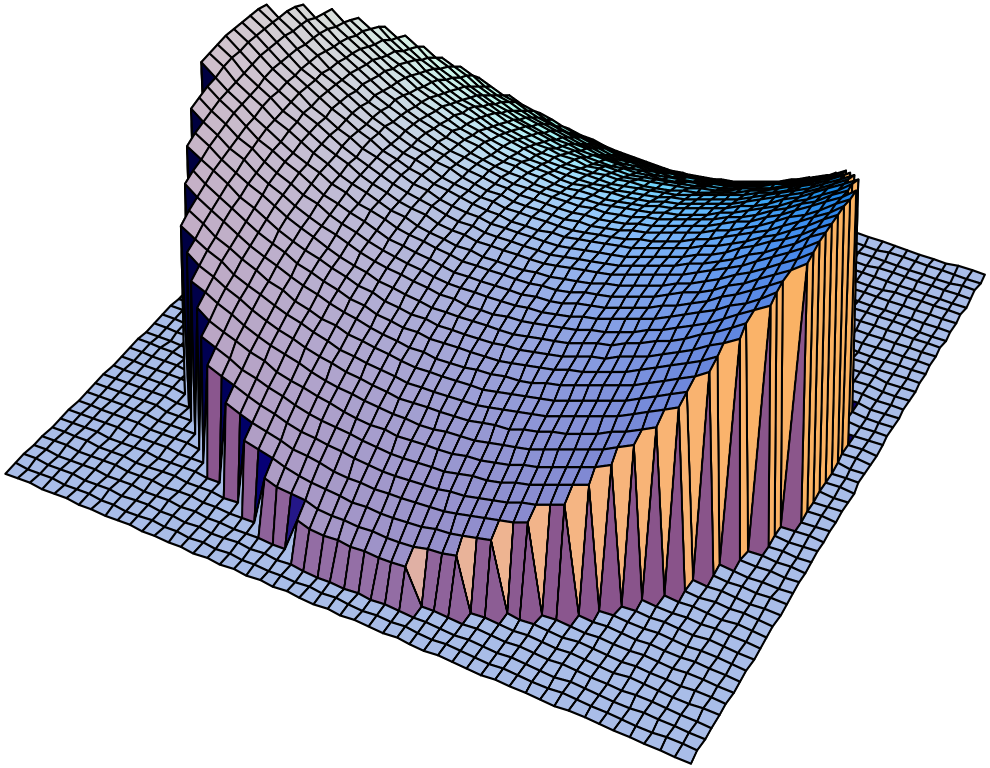
Aluminium particle in trap

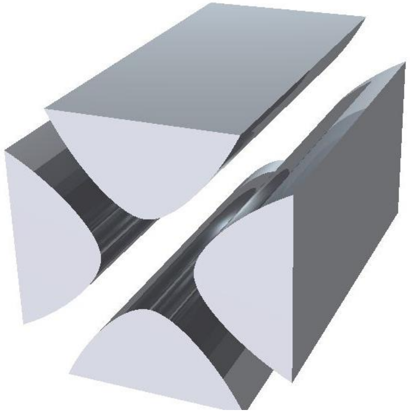


Wuerker, Shelton, Langmuir,
J. Appl. Phys. **30**, 342 (1959)

micromotion

2D linear Paul trap





Exact: Mathieu equation

$$\frac{d^2x}{d\tau^2} + (a - 2q\cos(2\tau))x = 0$$

$$\frac{d^2y}{d\tau^2} - (a - 2q\cos(2\tau))y = 0$$

$$q = \frac{2eU_{rf}}{mr_0^2\Omega^2} \qquad a = \frac{4eU}{mr_0^2\Omega^2}$$

$$\tau = \frac{\Omega t}{2}$$

q - and a - parameter

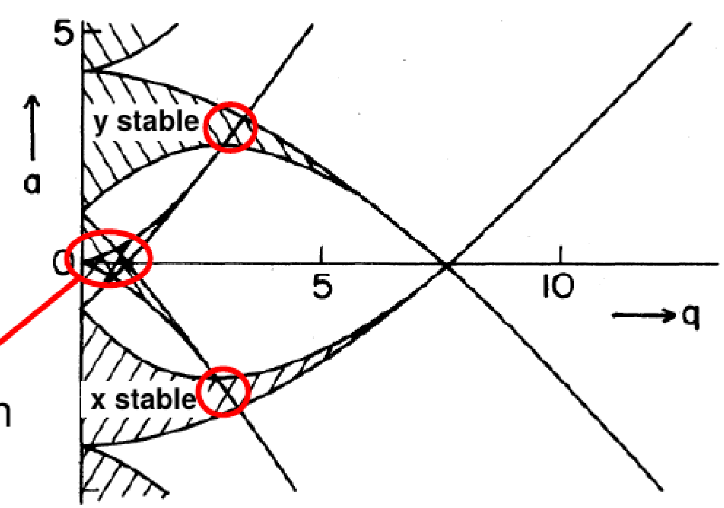
Stable trajectories for certain parameters:

$$x(\tau) = Ae^{i\beta_x\tau}\sum_{n=-\infty}^{\infty} C_{2n}e^{i2n\tau} + Be^{-i\beta_x\tau}\sum_{n=-\infty}^{\infty} C_{2n}e^{-i2n\tau}$$

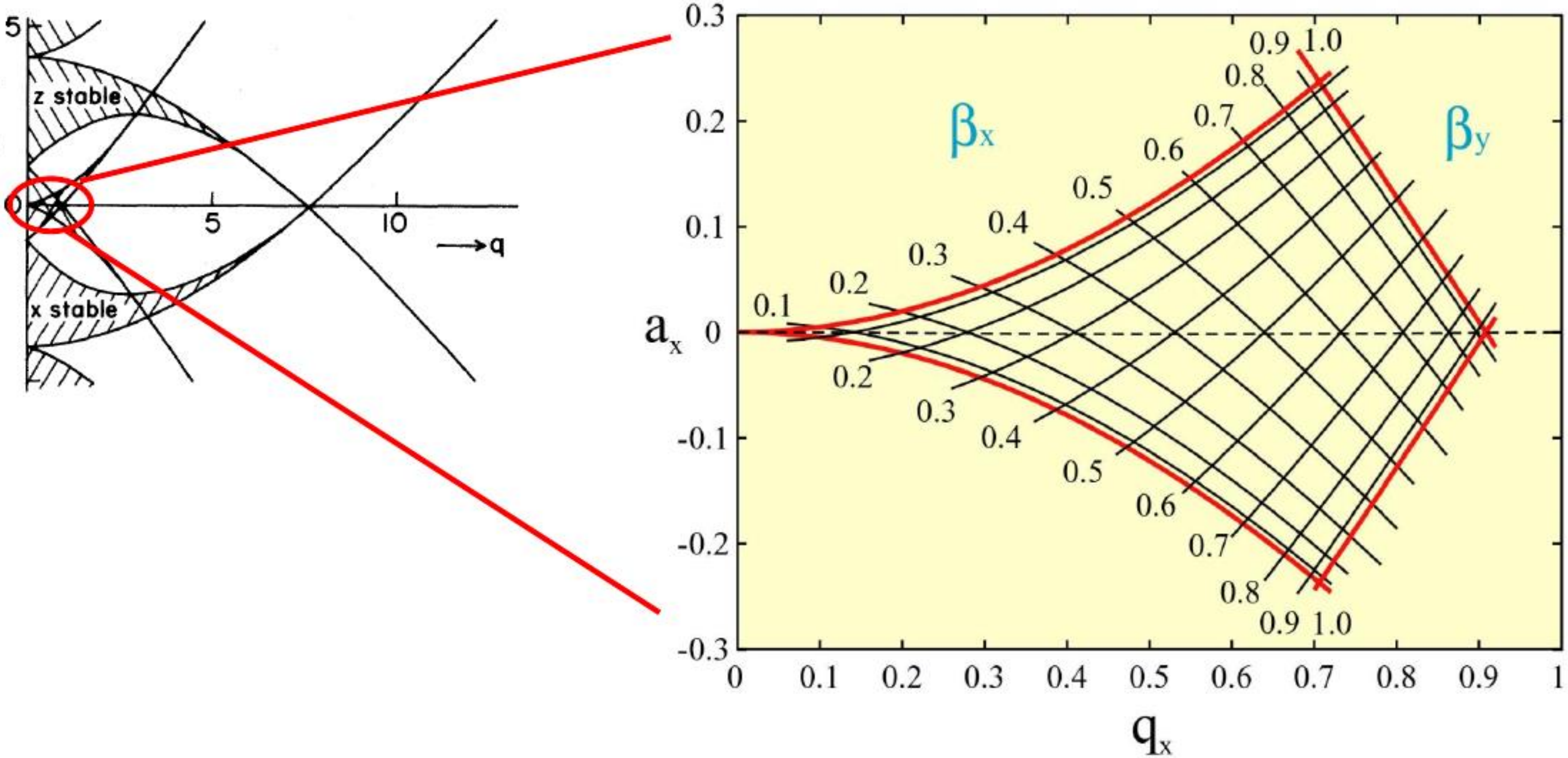
$$\beta = \beta(a,q)$$
$$C_{2n} = C_{2n}(a,q)$$

Stability diagram

first stability region



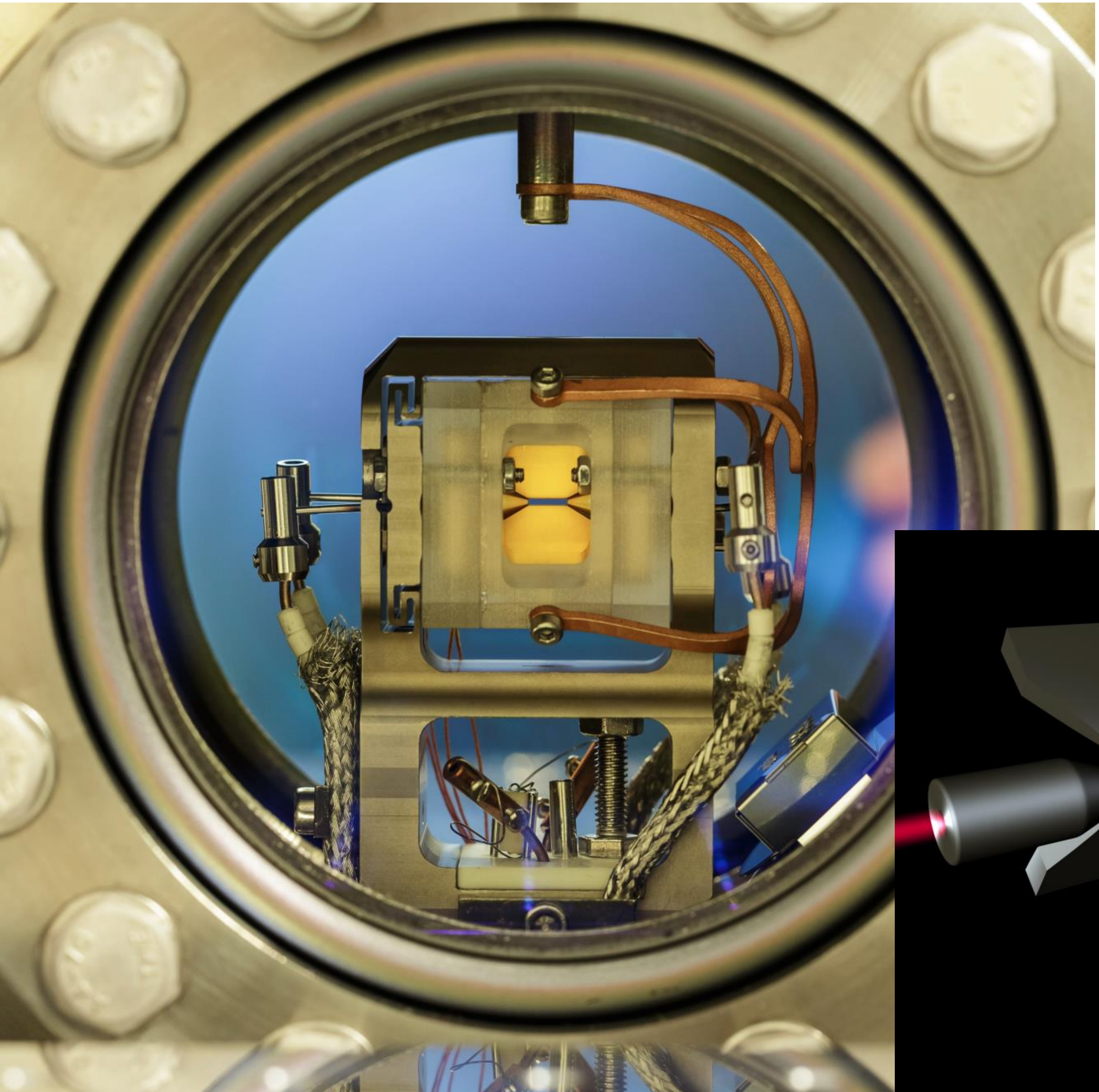
Stability region

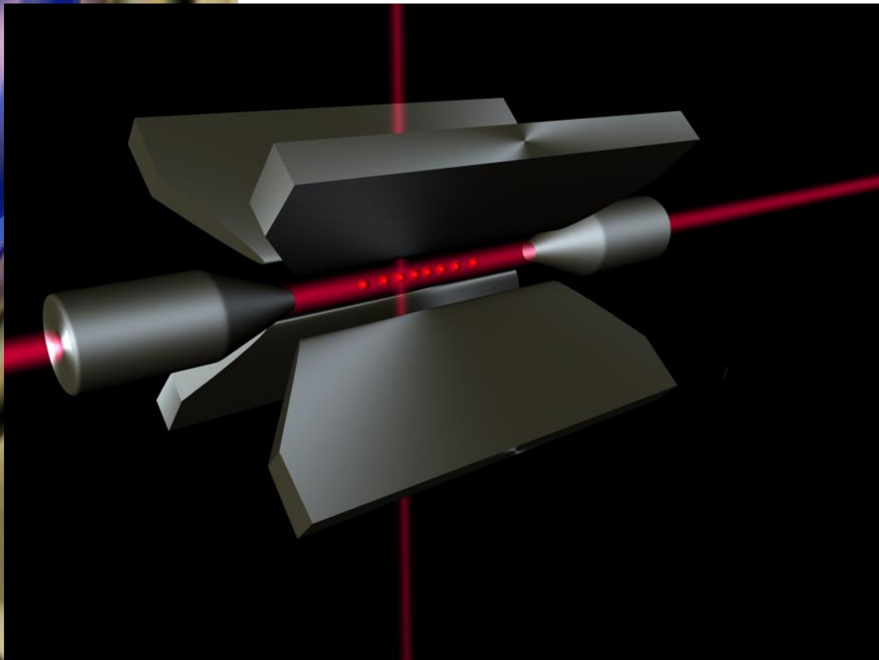


If $q_x^2, |a_x| \ll 1$: Pseudopotential approximation:

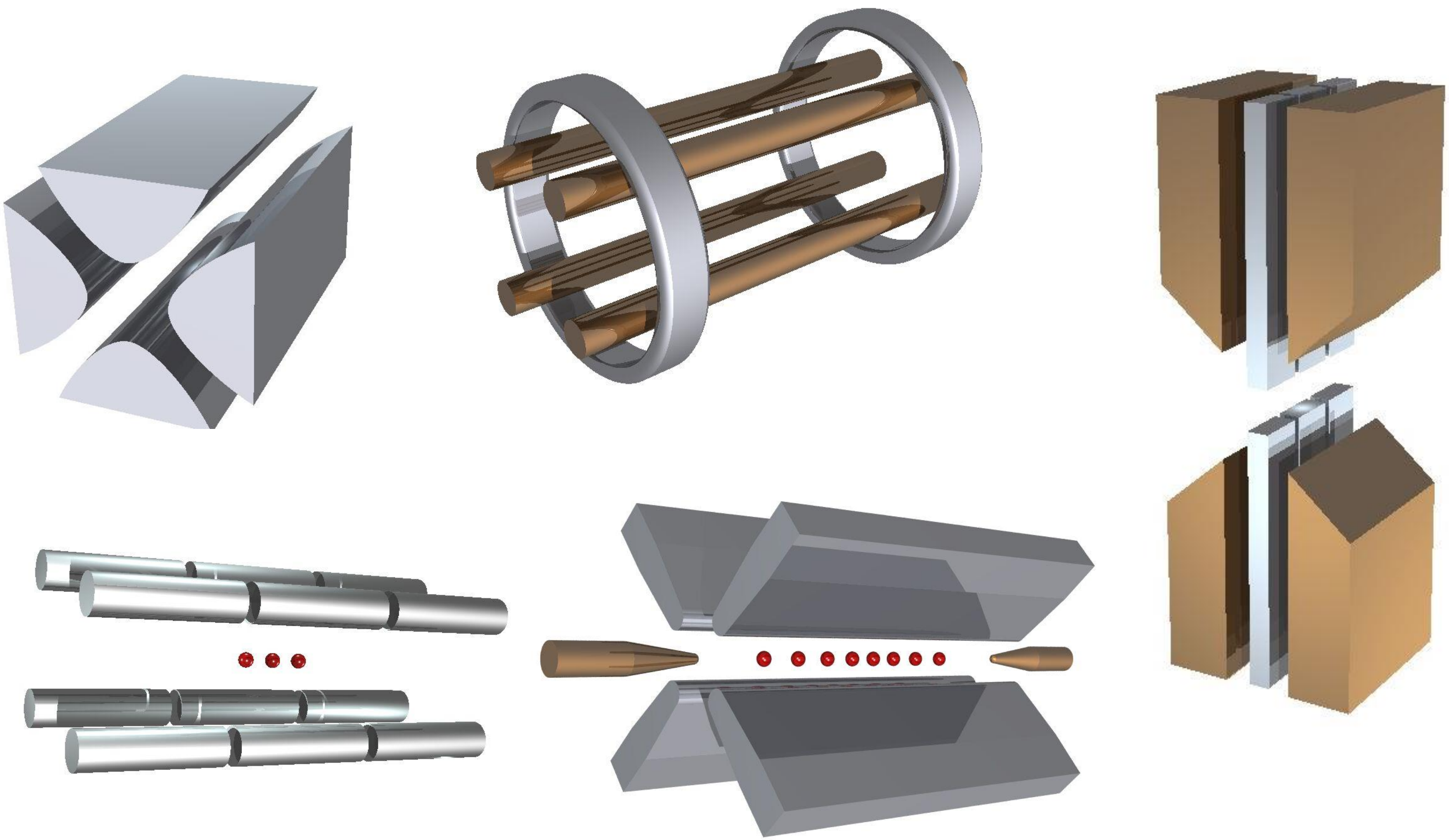
Time-averaged electrical forces create a harmonic potential.

How does it look like?



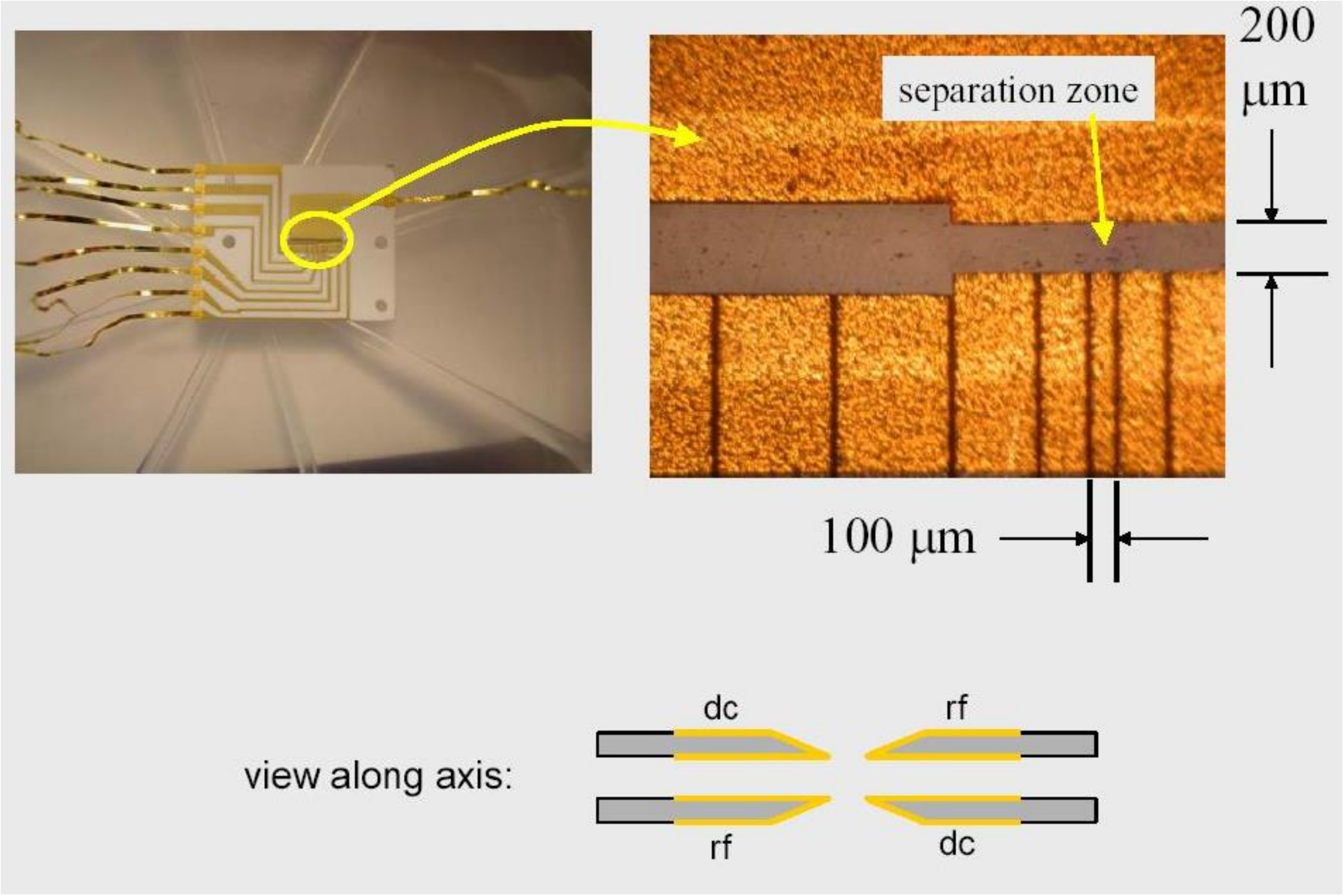


Different linear ion traps



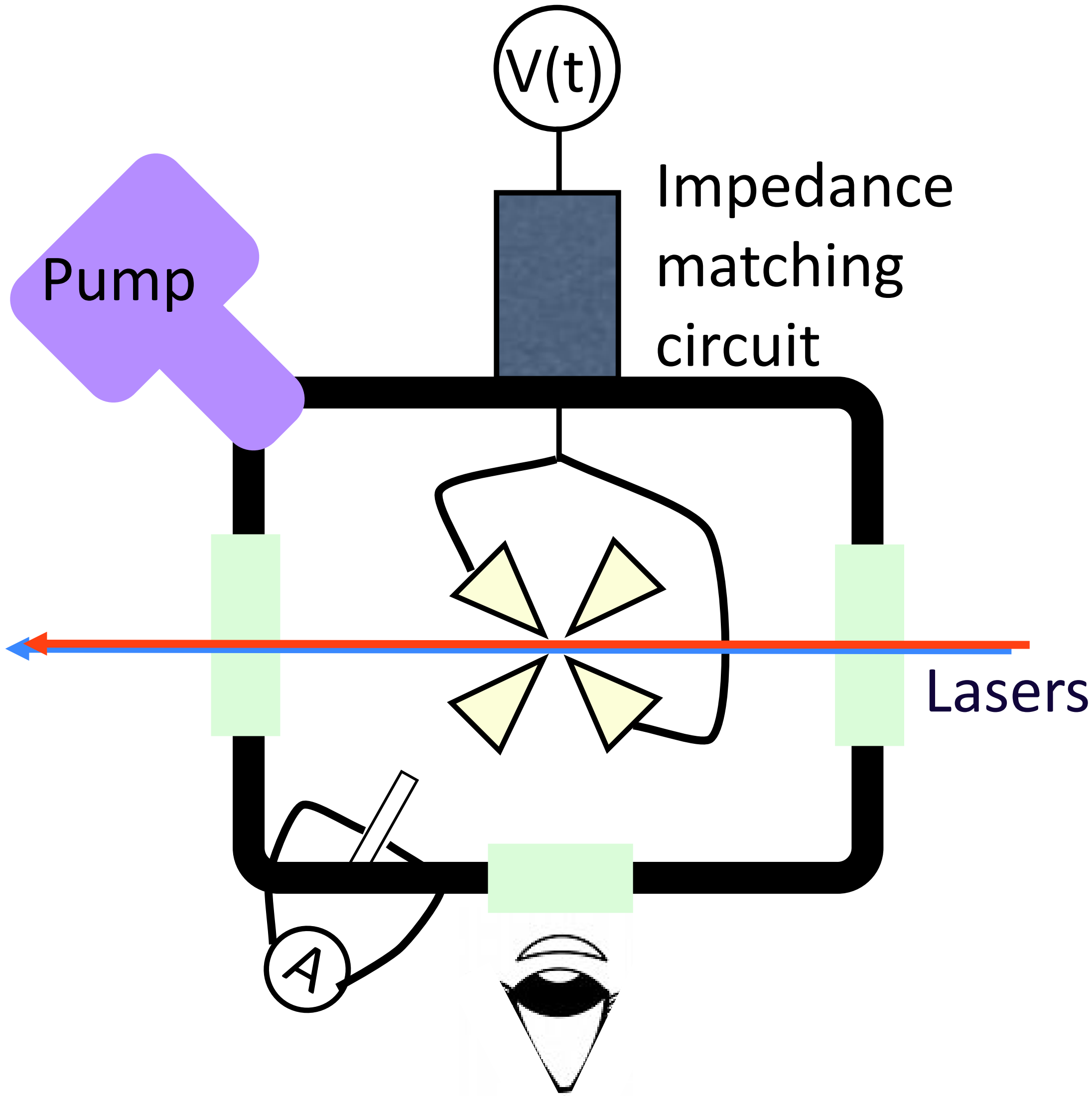
Trap designs differ almost solely in effective distance

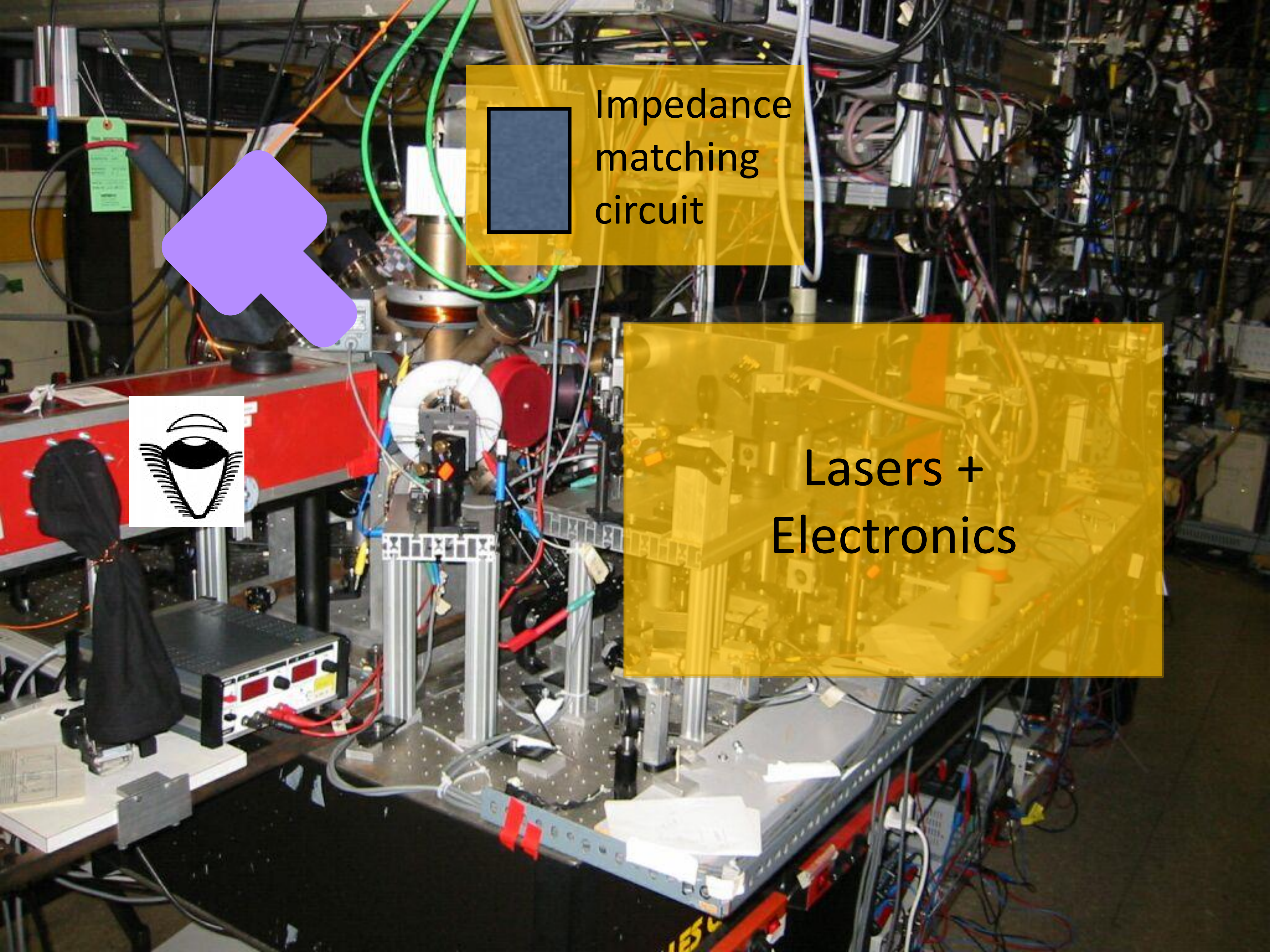
Microtraps



Wineland, NIST

What equipment do I need?




Impedance matching circuit
Lasers + Electronics

Summary

- Charge particles cannot be trapped in 3D by static fields
- Radio-frequency Paul traps are 3D harmonic oscillators
- Motion of particle: Mathieu equation have stability region

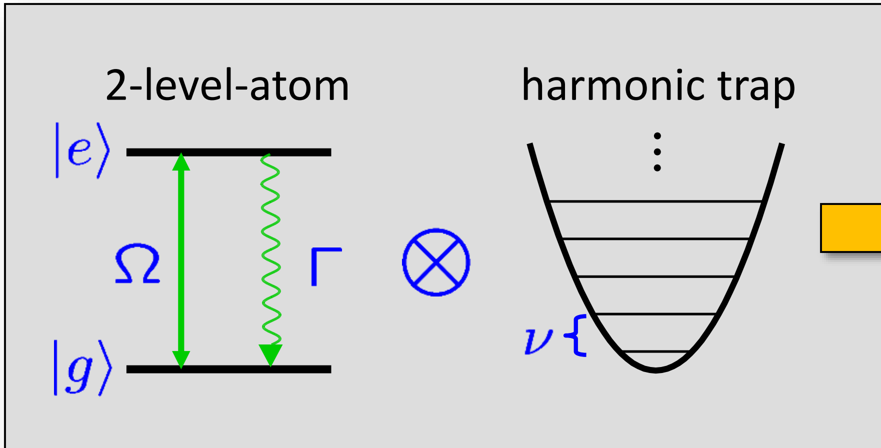
Laser ion interaction

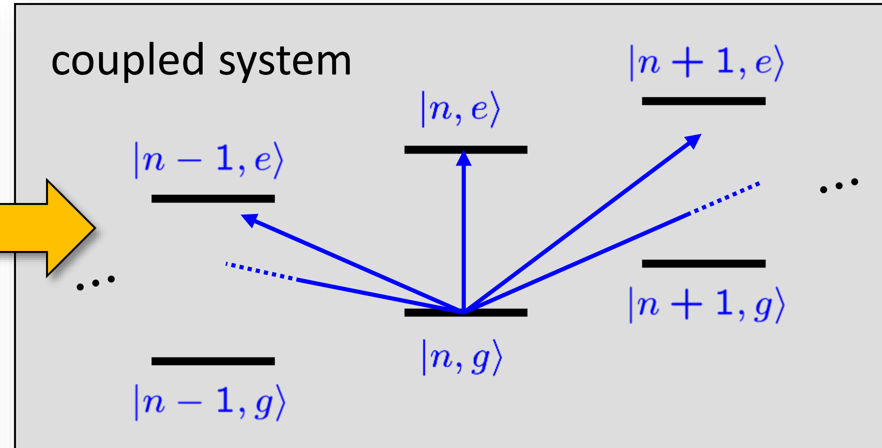
- Blackboard: How can we manipulate a single trapped ion with laser light?

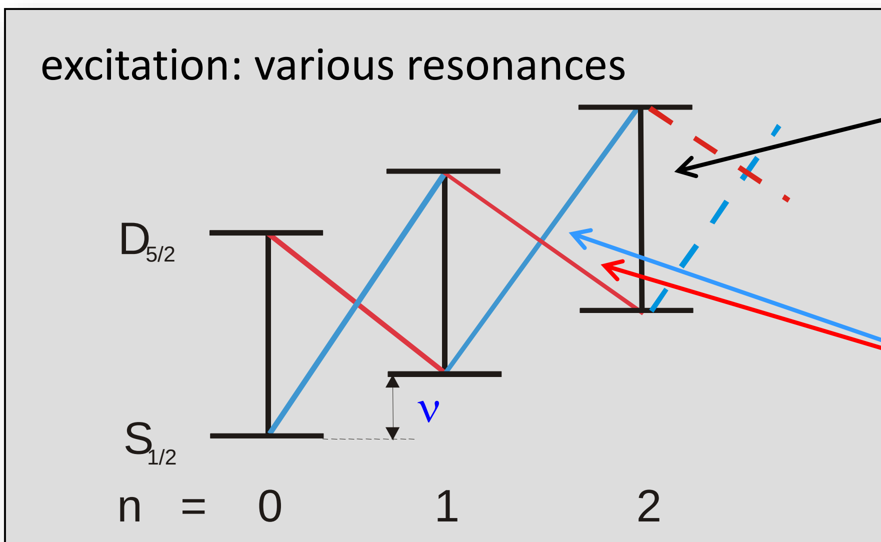
PhD thesis, Christian Roos
www.quantumoptics.at

The trapped ion toolbox, Roee Ozeri
Contemporary Physics, 52:6, 531-550 (2011)

Qubit manipulation







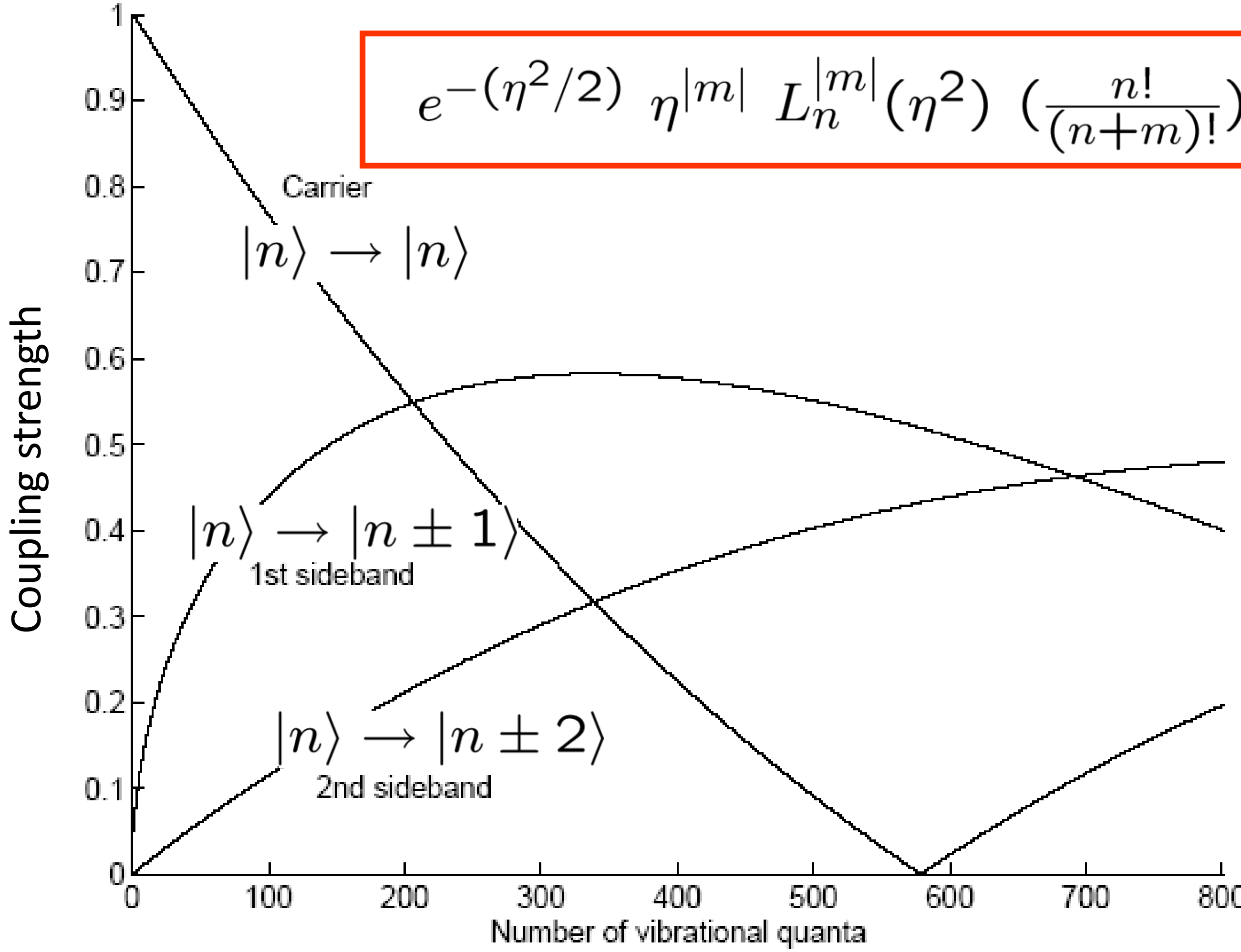
Carier:
manipulate qubit
→ internal superpositions

Sidebands:
manipulate motion and qubit
→ create entanglement

Beyond the Lamb Dicke regime

$$\hbar\frac{\Omega_{Rabi}}{2}\langle n|e^{i\eta(a+a^\dagger}|m\rangle =$$

$$\boxed{e^{-(\eta^2/2)}\ \eta^{|m|}\ L_n^{|m|}(\eta^2)\ (\frac{n!}{(n+m)!})^{sign(m)/2}}$$



D. Leibfried et al, Rev. Mod. Phys. **75**, 281-324 (2003)