Quantum information processing with trapped ions

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The remaining QIP challenge

DiVincenzo requirements:

I. A scalable physical system with well characterized qubits

II. The ability to initialize the state of the qubits to a simple fiducial state

III. Long relevant decoherence times, much longer than the gate time

IV. A universal set of quantum gates (single qubit rot., two qubit gate)

V. A qubit-specific read out capability

Overview

- Introduction to ion traps
- Atomic physics for ion-qubits
- Manipulation of ion-qubits with laser fields
- Scalable QIP with trapped ions
- Example experiments

Please ask questions! (dil@boulder.nist.gov)

More exhaustive, formal and rigorous treatments:
[1] D. J. Wineland, C. Monroe, W. M. Itano, D. Leibfried, B. E. King, and D. M. Meekhof, J. Res. Nat. Inst. Stand. Tech. 103, 259 (1998); M. Sasura and V. Buzek, J. Mod. Opt. 49, 1593 (2002); D. Leibfried, R. Blatt, C. Monroe, and D. Wineland, Rev. Mod. Phys. 75, 281 (2003); H. Häffner, C. F. Roos, and R. Blatt, Physics Reports 469, 155 (2008); D. Kielpinski, Front. Phys. China 3, 365 (2008)

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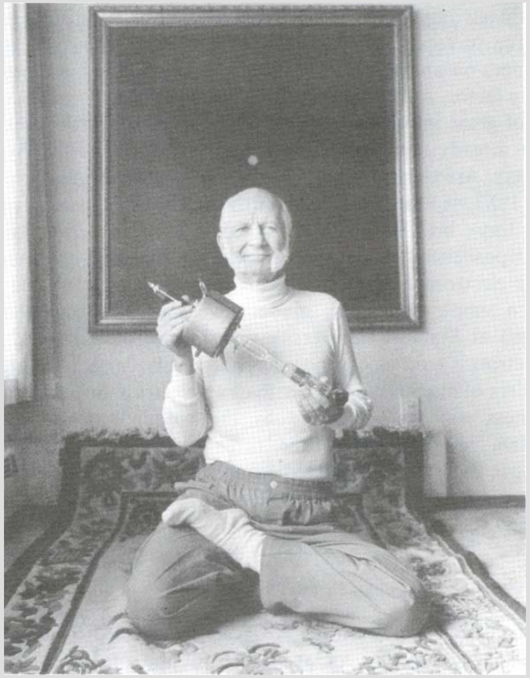
- Example experiments

Traps for single charged particles

Paul trap 1956
AC/DC electric fields

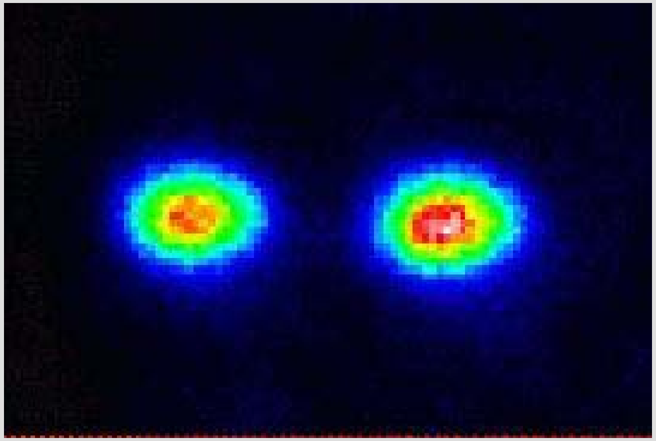
Wolfgang Paul

Penning trap 1959
(Dehmelt, Gräff)
DC electric/magnetic fields



Hans Dehmelt

1980/1981 single trapped and laser cooled atomic ions at Univ. of Heidelberg and NIST



CCD image of two trapped and laser cooled $^9Be^+$ ions in a Paul-trap at NIST

Pseudopotential approximation

equations of motion of ion described by Mathieu equations; can be rigorously solved
"pseudopotential approximation" often sufficent:

$$m\ddot{x} = q\mathbf{E}\cos(\Omega_{\mathrm{rf}}t)$$

assume field is slowly varying over space, then to first order ion will "quiver" at the drive frequency

$$x = -\frac{q\mathbf{E}}{m\Omega_{\mathrm{rf}}^2}\cos(\Omega_{\mathrm{rf}}t)$$

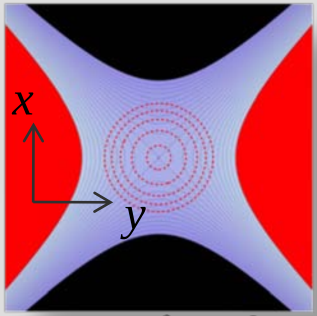
associate kinetic energy with this "micro-motion" and average over one cycle of the driving field

$$U_{\mathrm{kin}} = q \times \Phi_{\mathrm{pp}} = q \times \frac{q\mathbf{E}^2}{4m\Omega_{\mathrm{rf}}^2}$$

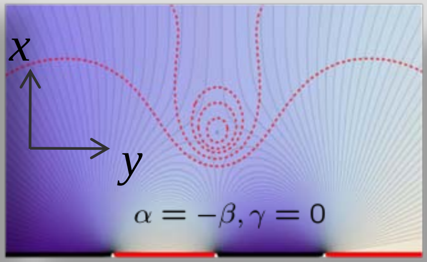
typically ion is trapped at field-zero with approx. quadratic spatial field dependence

$$\Phi_{\mathrm{el}} = V_0\cos(\Omega_{\mathrm{rf}}t)\frac{1}{2}(\alpha x^2+\beta y^2+\gamma z^2),\quad \alpha+\beta+\gamma = 0$$ (Laplace)

$$\Phi_{\mathrm{pp}} = \frac{qV_0^2}{4m\Omega_{\mathrm{rf}}^2}(\alpha^2x^2+\beta^2y^2+\gamma^2z^2)$$



$\alpha = -\beta, \gamma = 0$

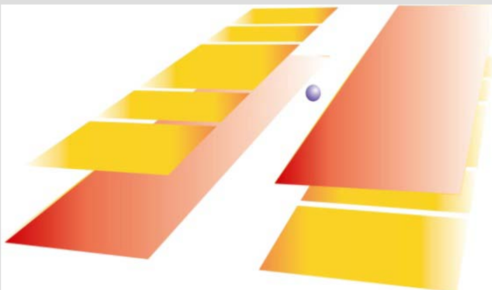


surface electrode trap

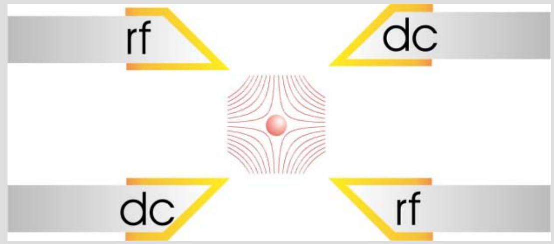
electric equi-potential lines (black thin)
harmonic equi-pseudo-potential lines (red dashed)

The linear Paul trap

radial confinement:



radial cross section

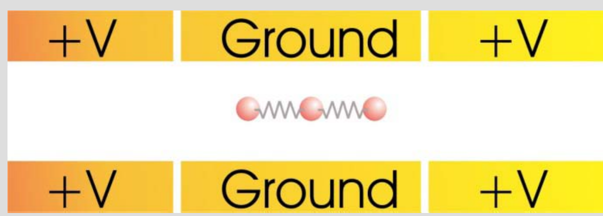


ac quadrupole potential

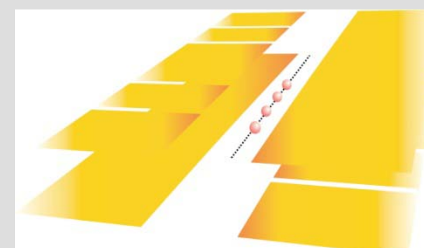
harmonic time averaged pseudo-potential

axial confinement:

axial cross section



Coulomb interaction couples ions ⇒ normal modes of vibration

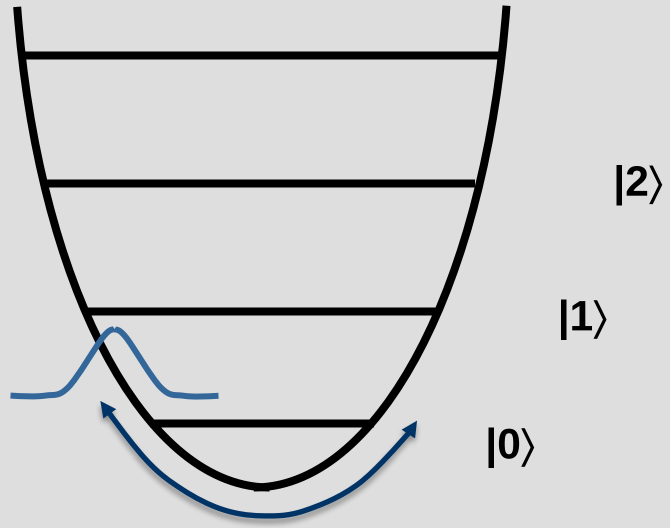


radial conf. >> axial conf. ⇒ ions align along trap axis

Harmonic oscillators

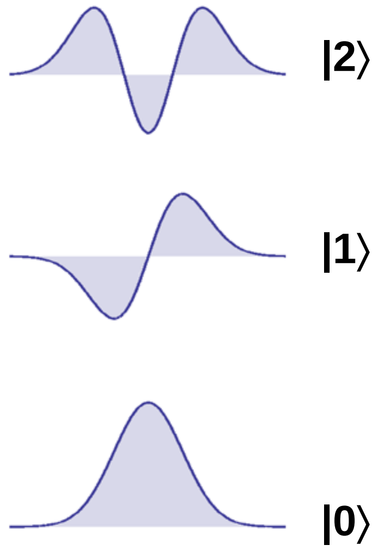
Examples:

pendulum
vibrating string
ball on spring
cantilevers
resonant circuits
light field
quantum fields
...
trapped ions



parabolic potential
sinusoidal oscillations

q.m. wavefunctions

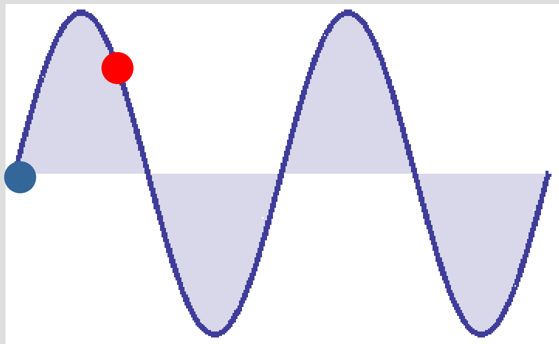


energy eigenfunctions are stationary in time... so where's the pendulum ?

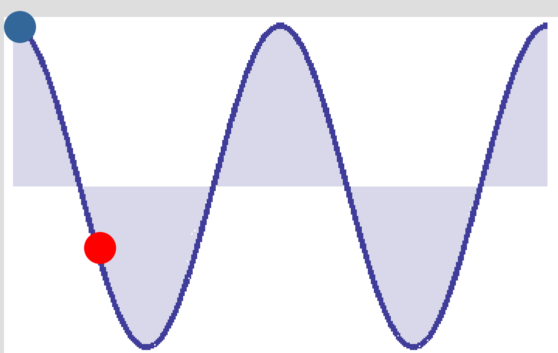
use superposition of energy eigenfunctions, called "coherent states" (Schrödinger 1926, Glauber 1963) to shape "oscillating ground states"

Phase space

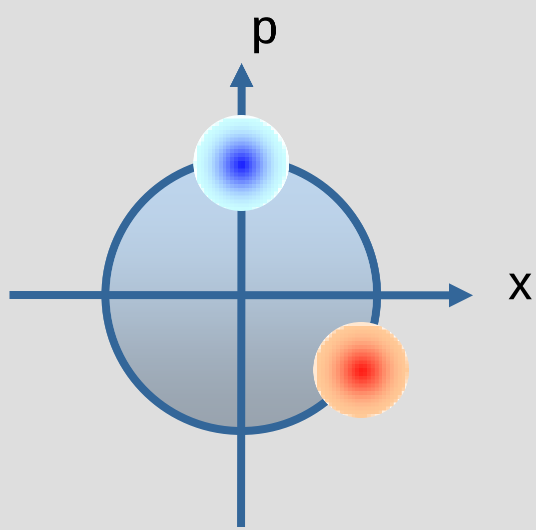
classical sinusoidal oscillation



position x



momentum p (mass x velocity)



quantum mechanics:
Heisenberg uncertainty

$$\Delta x \Delta p \geq \hbar/2$$

Gaussian wave-packet of coherent state fulfills the equality.

frame rotating at oscillation frequency

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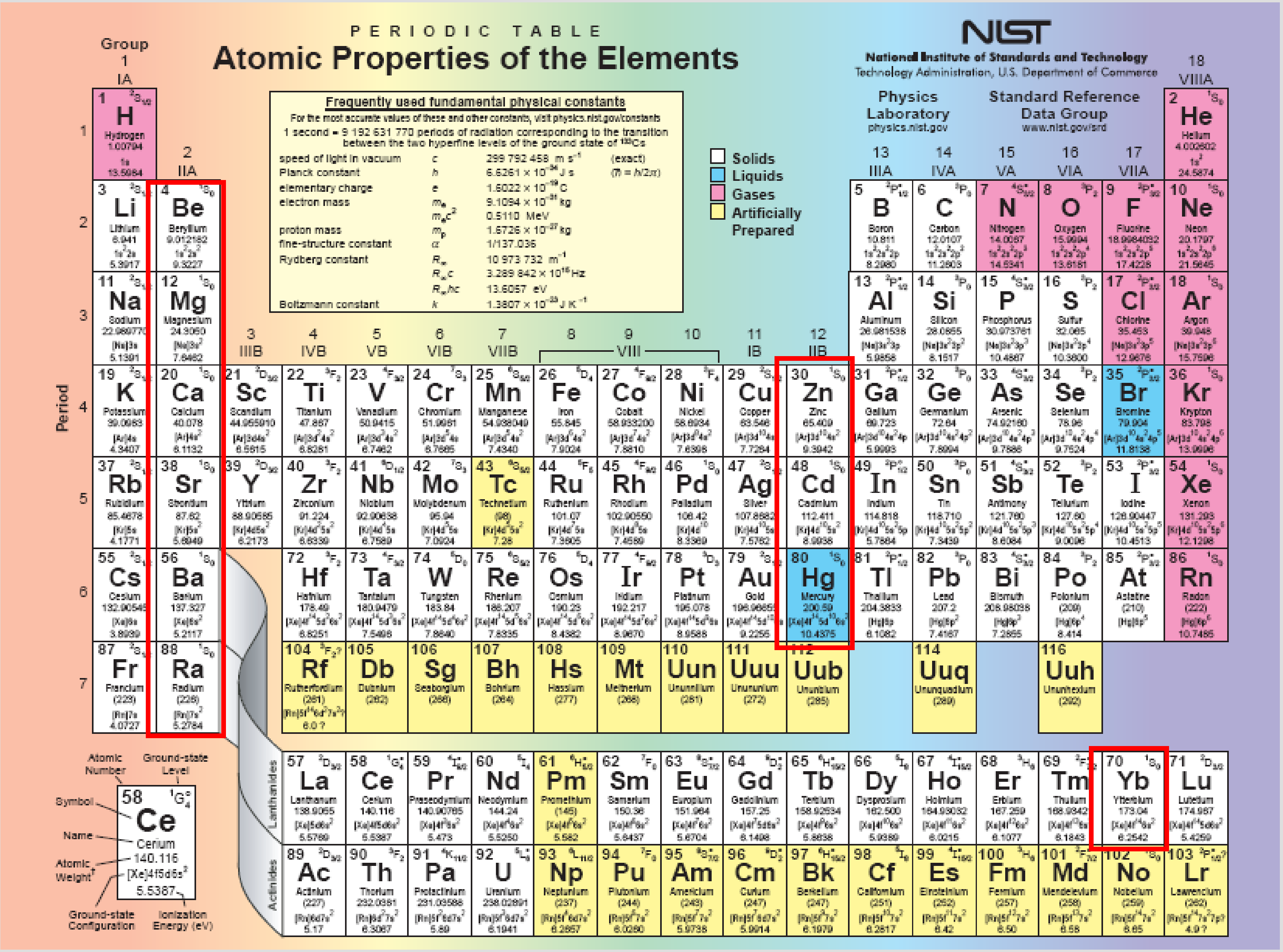
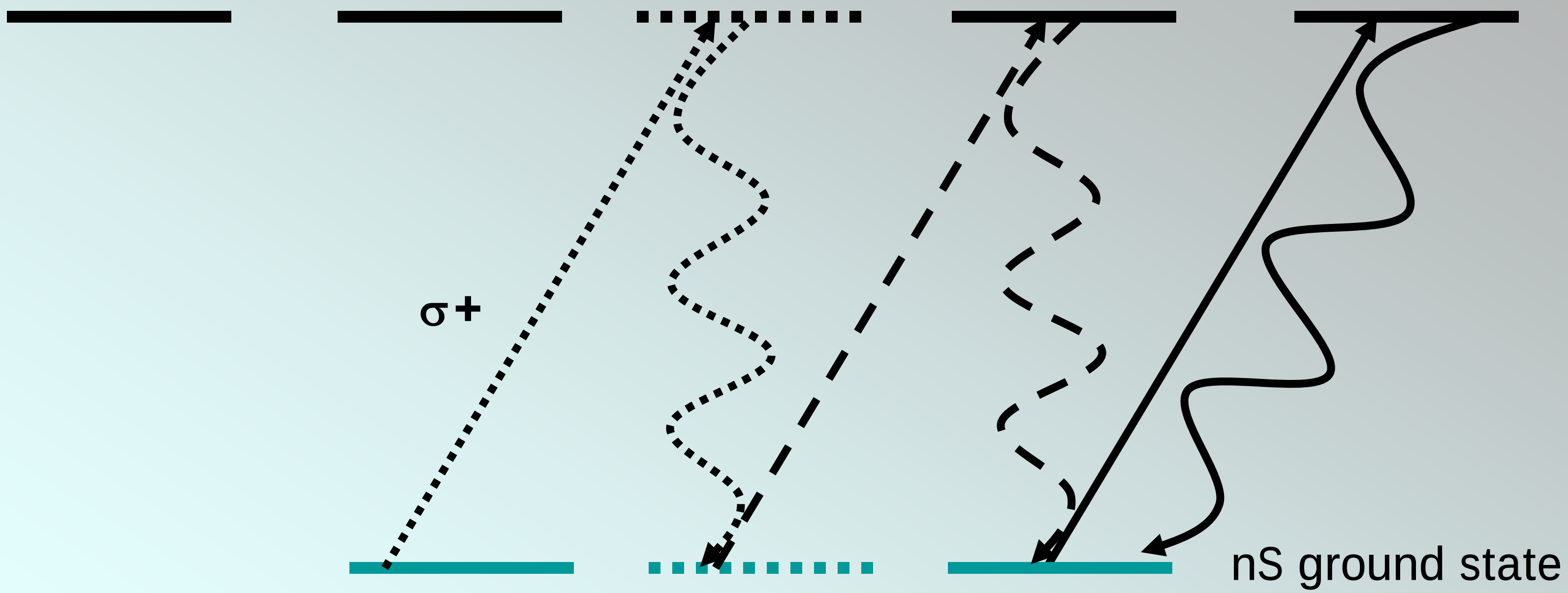
One electron systems



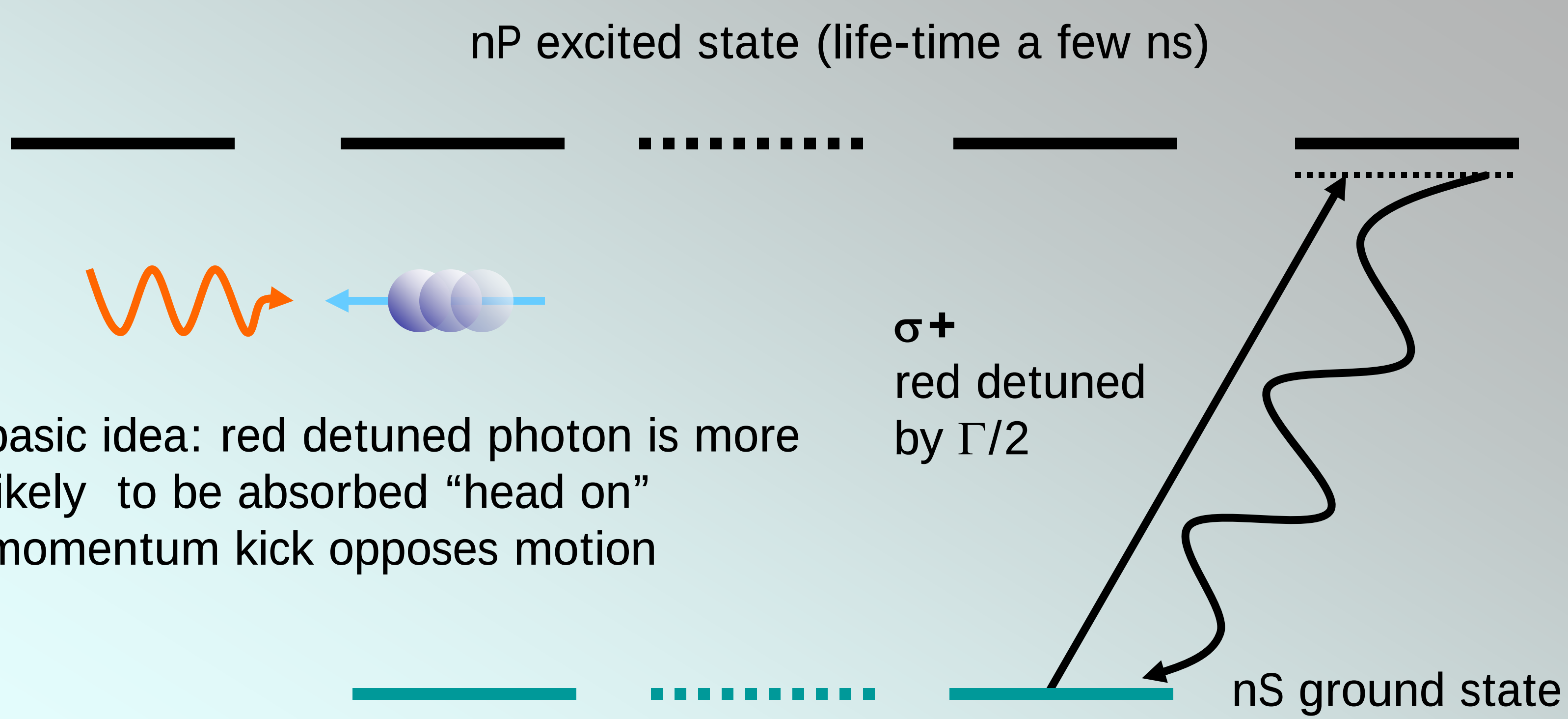
Resonant S → P transition

nP (2P for Be^+) excited state (life-time a few ns)



optically pump for state preparation

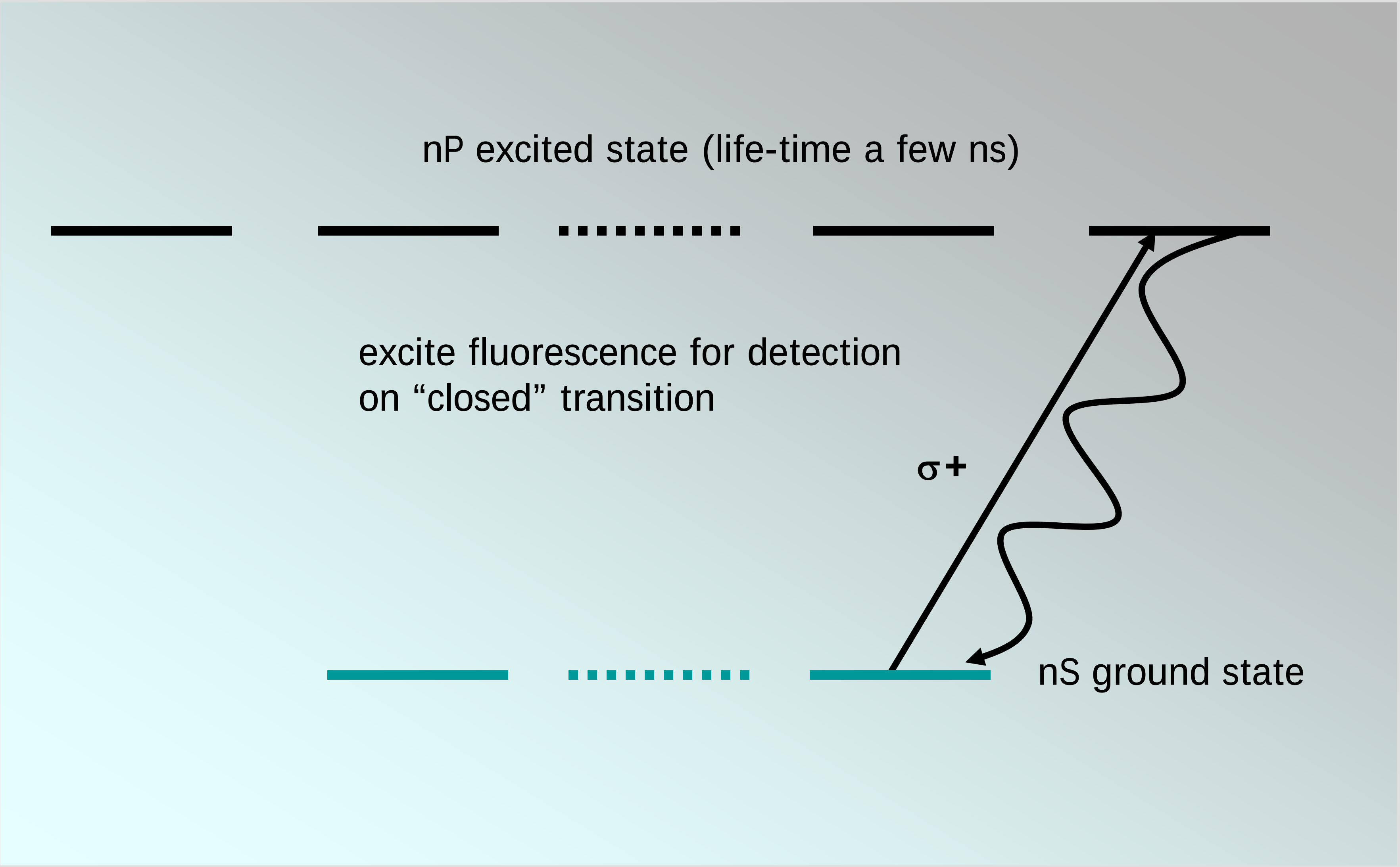
Resonant S → P transition



basic idea: red detuned photon is more likely to be absorbed "head on"
momentum kick opposes motion

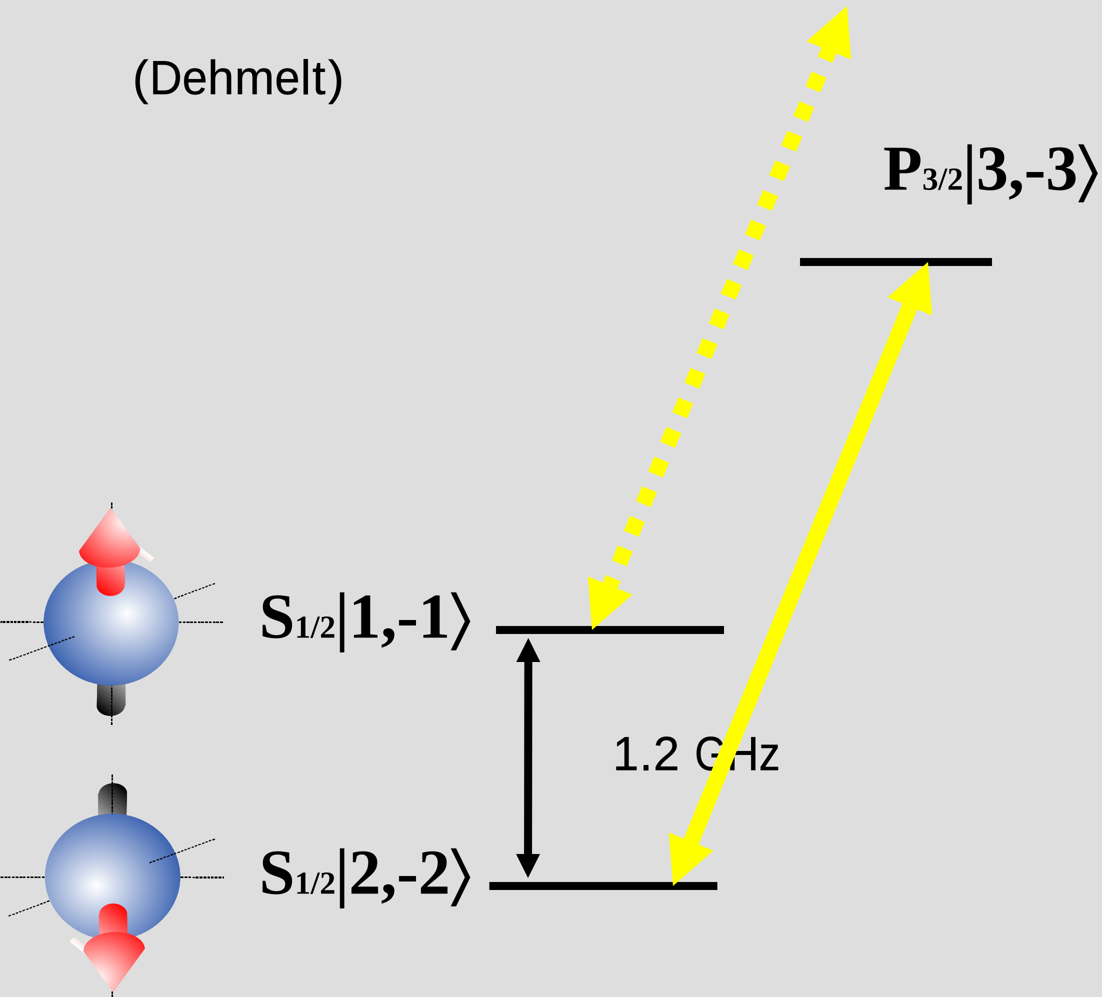
Doppler cooling

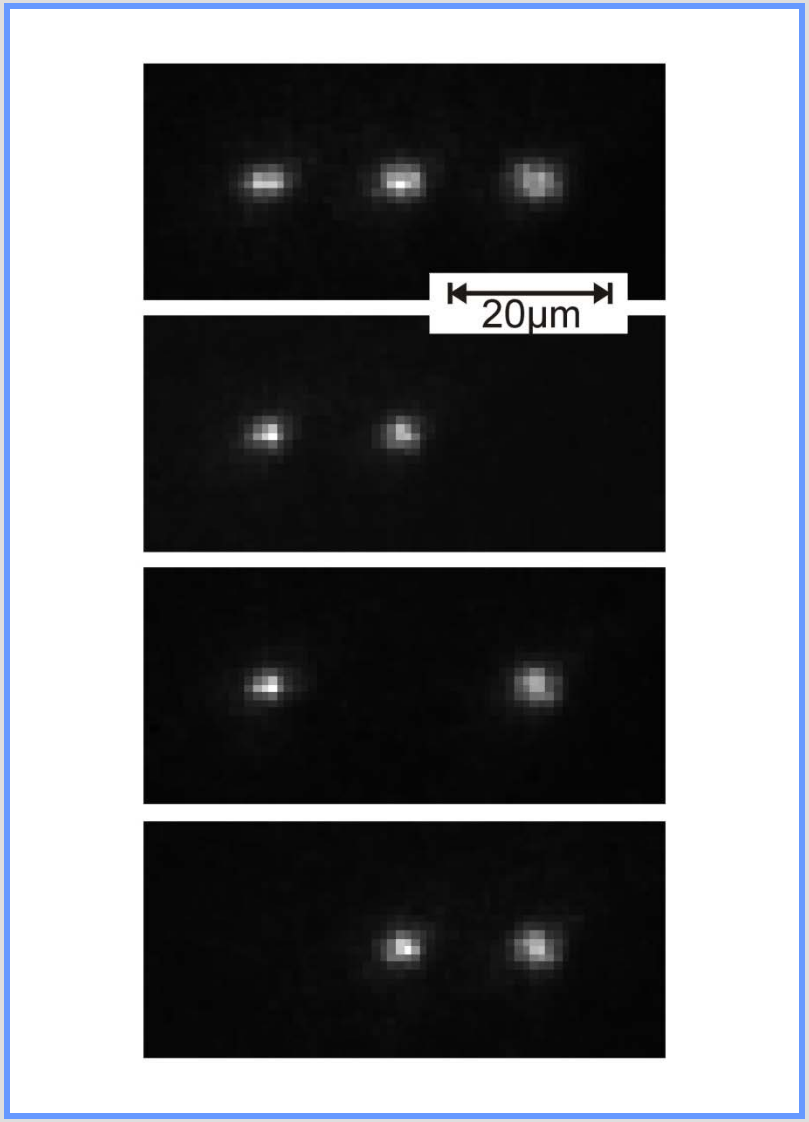
Resonant S → P transition



Electron shelving detection

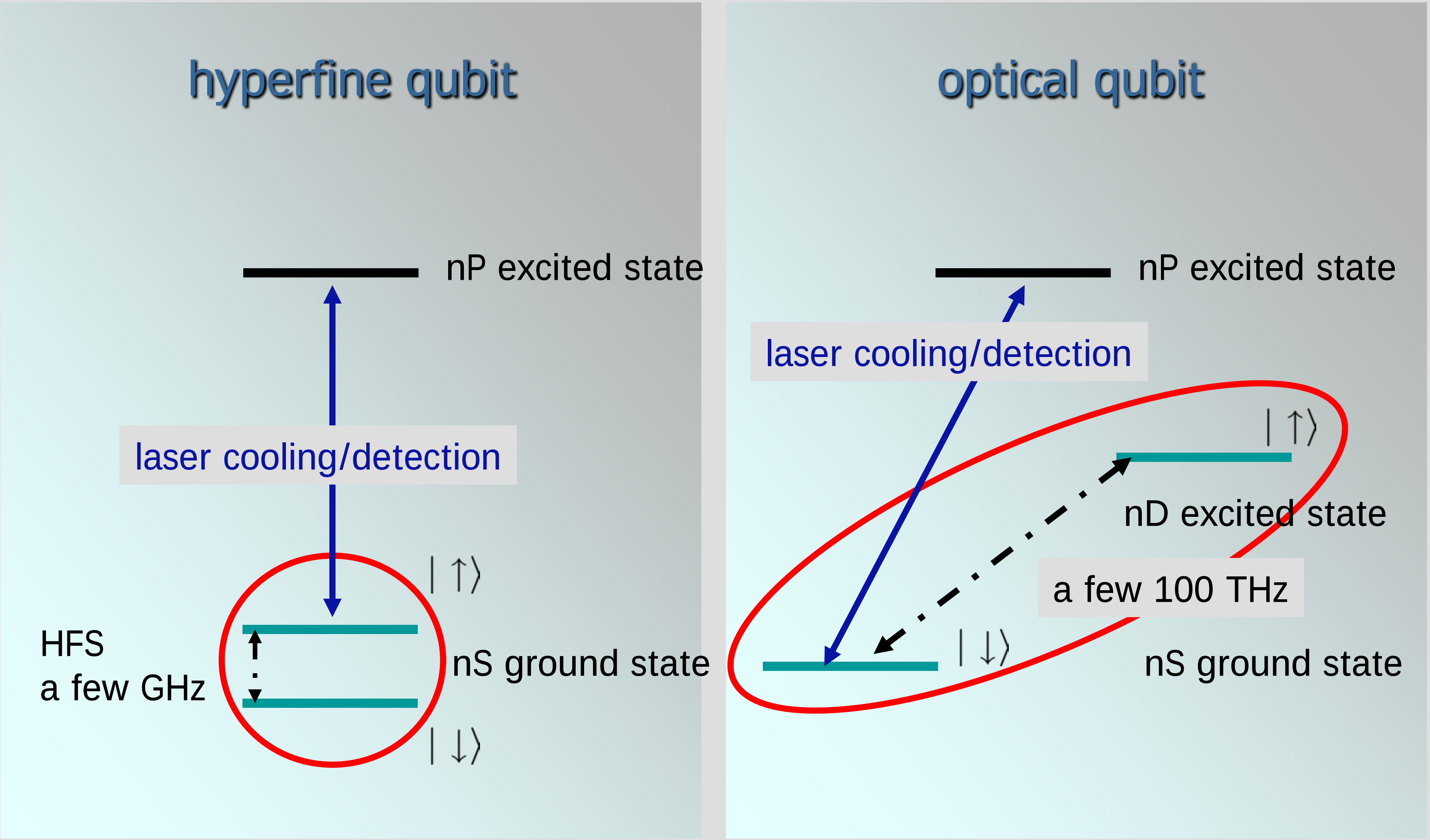
(Dehmelt)





3 Ca^+ ions, Univ. of Innsbruck
[PRA **60**, 145 1999]

Ion qubits (|↓⟩, |↑⟩)



hyperfine qubit
nP excited state
laser cooling/detection
|↑⟩
HFS
a few GHz
nS ground state
|↓⟩
optical qubit
nP excited state
laser cooling/detection
|↑⟩
nD excited state
a few 100 THz
|↓⟩
nS ground state

Possible qubits

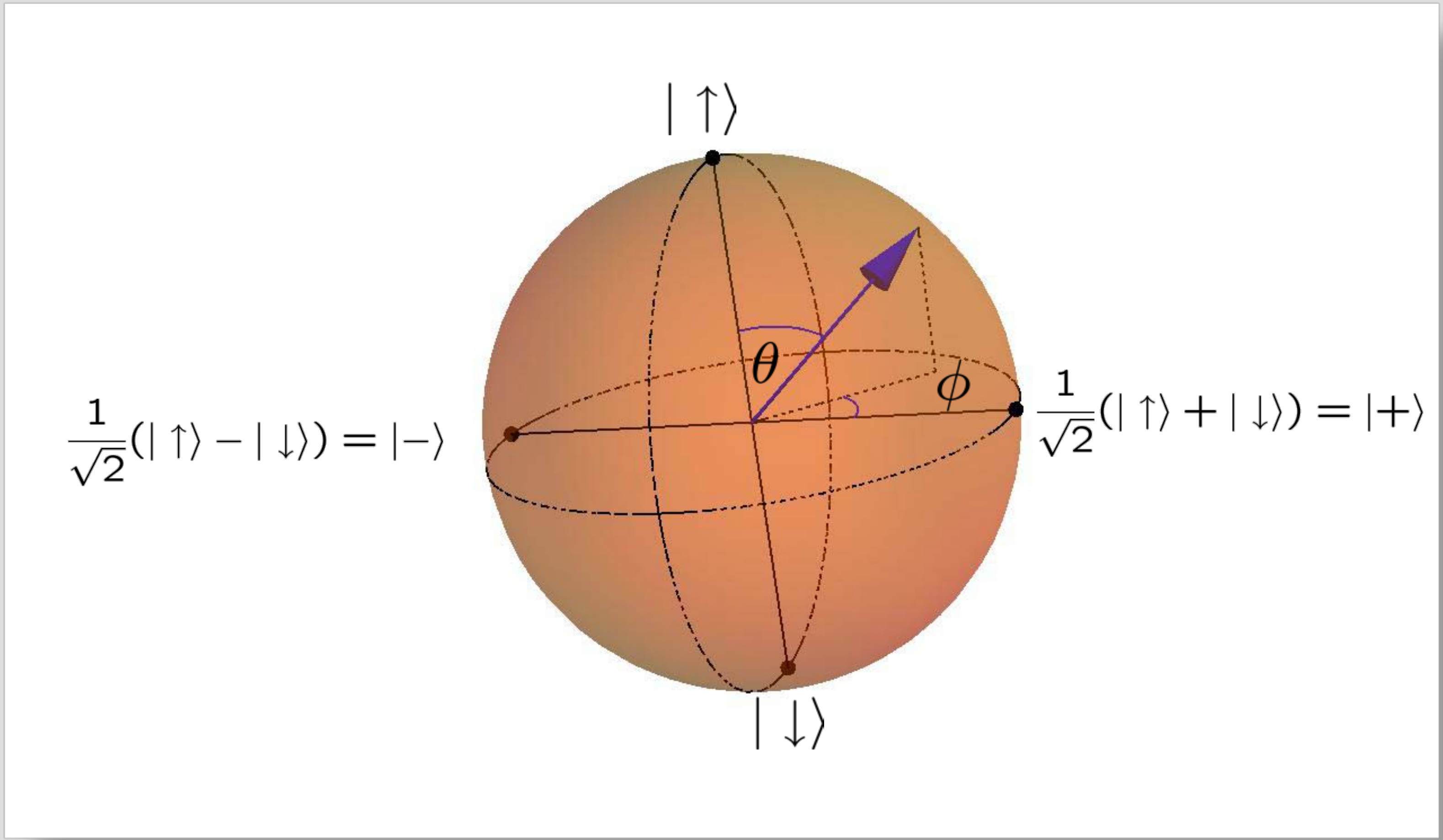
(list is not exhaustive)

	hyperfine qubit	hyperfine+ optical qubit	optical qubit
degrees of freedom	nuclear spin electron spin	nuclear spin electron spin electron energy	electron energy
species	$^{9}Be^{+}$, $^{25}Mg^{+}$, $^{111}Cd^{+}$, $^{67}Zn^{+}$ $^{137}Ba^{+}$,$^{171}Yb^{+}$	$^{43}Ca^{+}$, $^{87}Sr^{+}$, $^{199}Hg^{+}$	$^{40}Ca^{+}$, $^{88}Sr^{+}$

Bloch sphere picture

$$|\Psi\rangle = \alpha|\uparrow\rangle + \beta|\downarrow\rangle; \quad |\alpha|^2 + |\beta|^2 = 1$$

$$|\Psi\rangle = e^{i\gamma}(\cos\theta/2|\uparrow\rangle + e^{i\phi}\sin\theta/2|\downarrow\rangle)$$



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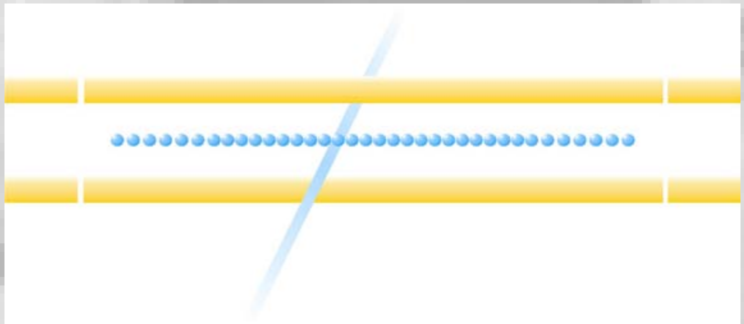
The initial idea

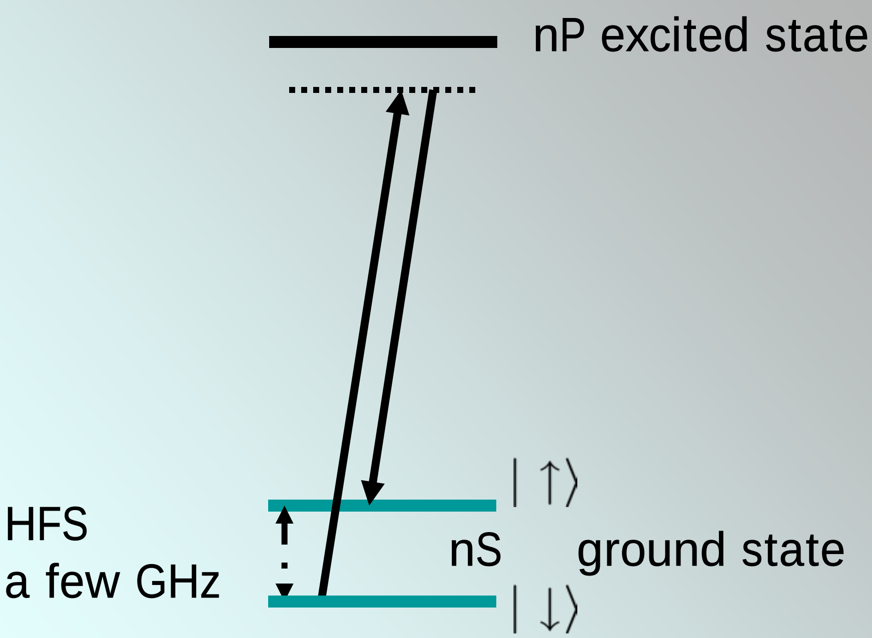


- Ions are used for atomic clocks ⇒ well characterized qubits
- Ions can be optically pumped and cooled to the trap ground state
- ⇒ well defined initial system state (see David Lucas' talk)
- Ions can be read out with high fidelity
- Atomic clocks can have coherence times of many seconds
- Shared eigenmodes of oscillation can provide qubit-qubit coupling

J. I. Cirac and P. Zoller, Phys. Rev. Lett. 74, 4091 (1995).

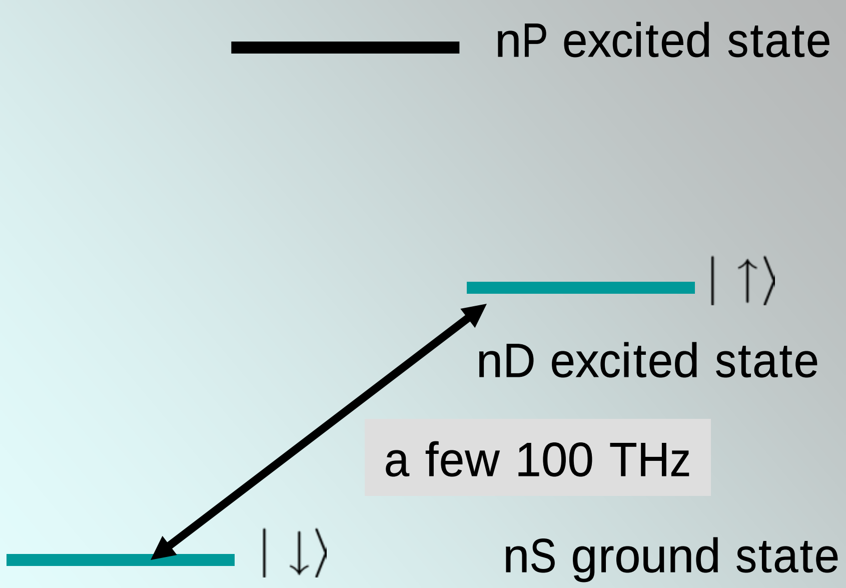
Coherent excitations

hyperfine qubit



stimulated Raman interaction
ground states
difference frequency stable

optical qubit



direct laser interaction
excited state (τ order 1 s)
absolute frequency stable

Excitation spectrum for ion in trap (internal+motion) similar in both cases

Interaction Hamiltonian

basic coupling, Ω_0 contains details (Raman or optical etc.)

$$H_I = \hbar\Omega_0 e^{-i([\delta_0-\omega_0]t+\phi)} e^{i\Delta\mathbf{k}\cdot\mathbf{r}} |\uparrow\rangle\langle\downarrow| + \text{h.c.}$$

light detuning and phase

ion motion in trap

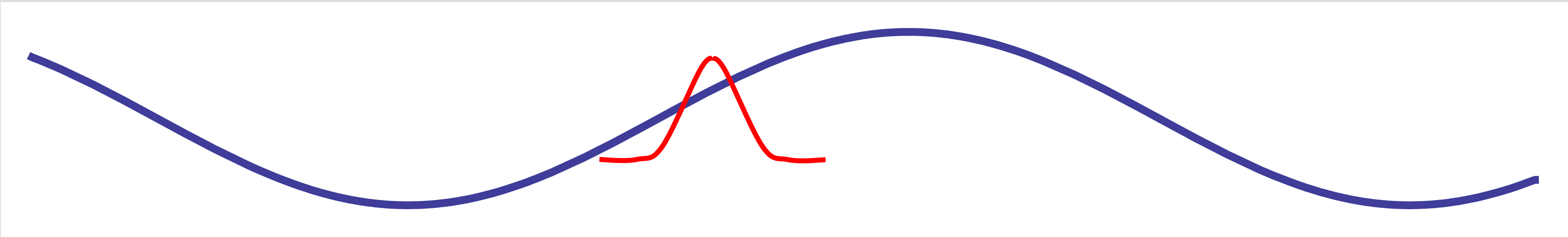
$$e^{i\Delta\mathbf{k}\cdot\mathbf{r}} = e^{i\eta(a_i^\dagger + a_i)} \simeq 1 + i\eta(a_i^\dagger + a_i)$$

Lamb-Dicke approximation

$$\eta = \sqrt{\frac{E_{\text{rec}}}{E_{\text{h.o.}}}} = \sqrt{\frac{\hbar^2 k^2}{2m\hbar\omega}} = 2\pi\frac{a_0}{\lambda} \ll 1$$

a_0 typically order 10 nm for a few MHz trap frequency, λ typically 200-400nm

Interaction Hamiltonian



over the extension of the wavefunction the electric field is to first order constant with a gradient term smaller by order η that can force the motion

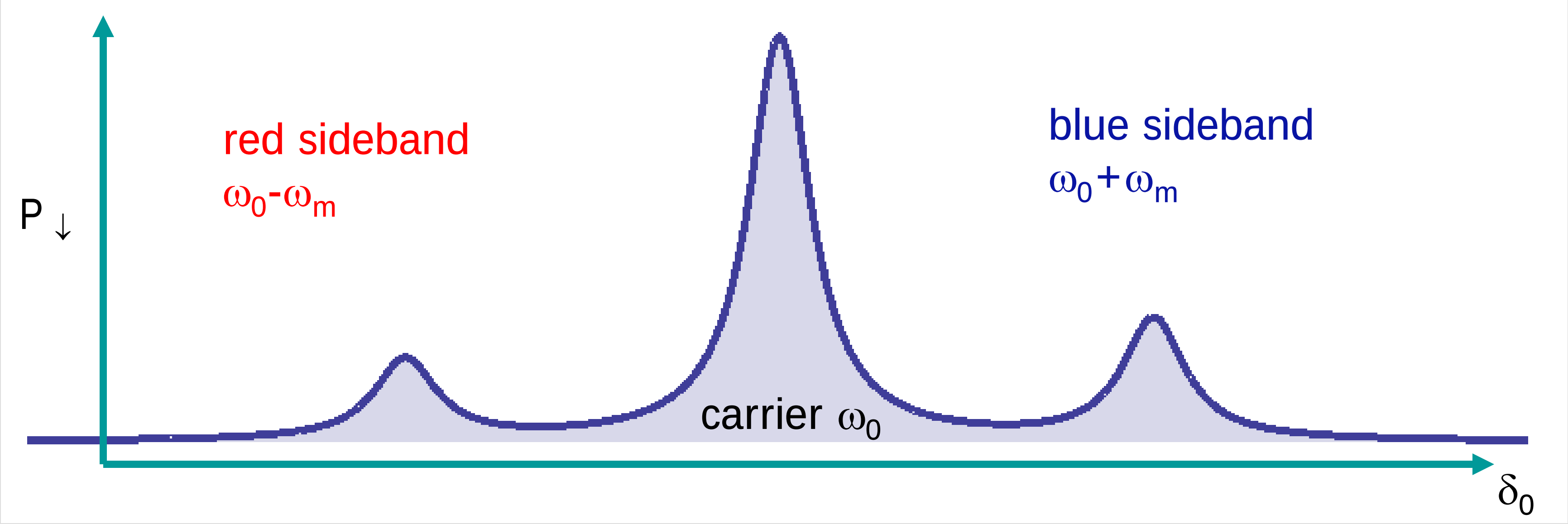
interaction picture operator $a_i = a e^{-i\omega_m t}$

$$H_I \simeq \hbar\Omega_0 e^{-i([\delta_0-\omega_0]t+\phi)} |\uparrow\rangle\langle\downarrow| + \text{h.c.}$$ (carrier)

$$+i\hbar\eta\Omega_0 e^{-i([\delta_0-(\omega_0+\omega_m)]t+\phi)} a^\dagger |\uparrow\rangle\langle\downarrow| + \text{h.c.}$$ (blue sideband)

$$+i\hbar\eta\Omega_0 e^{-i([\delta_0-(\omega_0-\omega_m)]t+\phi)} a |\uparrow\rangle\langle\downarrow| + \text{h.c.}$$ (red sideband)

Sideband spectrum

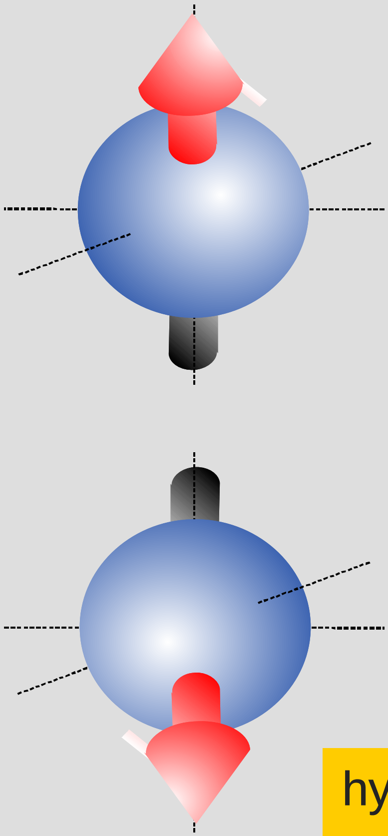


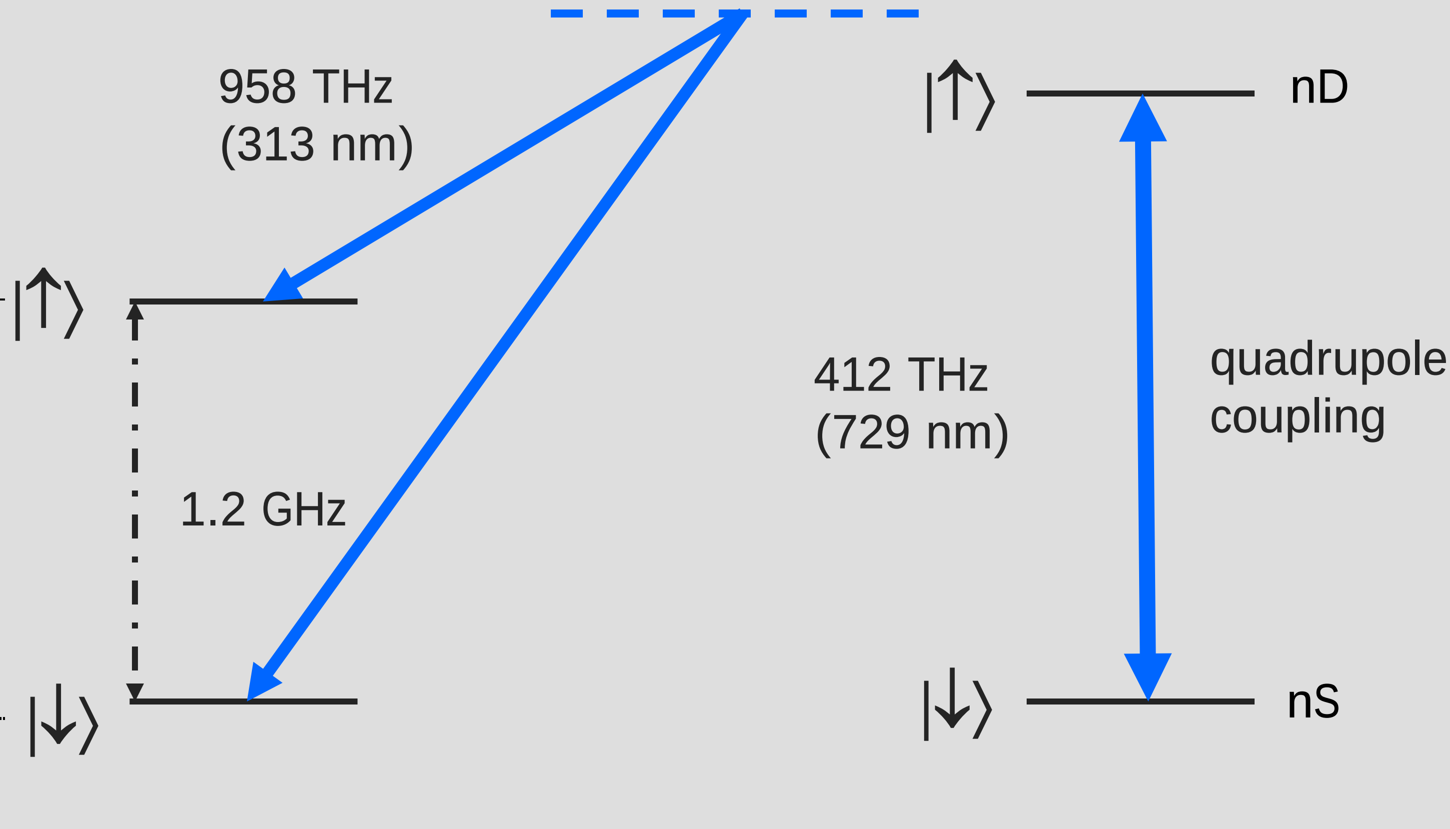
sideband thermometry: $$\frac{I_{\text{red}}}{I_{\text{blue}}} = \frac{\bar{n}}{\bar{n}+1}$$

red sideband vanishes for $\bar{n} \longrightarrow 0$ (motional ground state)

for N ions get 3 N sideband manifolds

Single qubit rotations





hyperfine ground states

$^{9}Be^{+}$ decoherence time > 10 s
C. Langer *et al.*,
Phys. Rev. Lett. **95**, 060502 (2005)

S/metastable D state

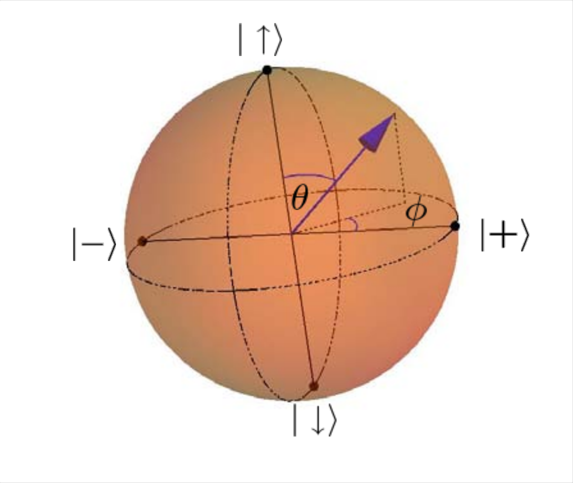
$^{40}Ca^{+}$ decoherence time $\approx$ 1 s
Univ. Innsbruck

Universal two-qubit gates

theoretical proposals:

J. I. Cirac and P. Zoller, Phys. Rev. Lett. **74**, 4091 (1995).
A. Sørensen and K. Mølmer, Phys. Rev. Lett. **82**, 1971 (1999).
E. Solano, R. L. de Matos Filho, and N. Zagury, Phys. Rev. A **59**, 2539 (1999).
G. J. Milburn, S. Schneider, and D. F. V. James, Fortschr. Physik **48**, 801 (2000).
A. Sørensen and K. Mølmer, Phys. Rev. A **62**, 02231 (2000).
X.Wang, A. Sørensen, and K. Mølmer, Phys. Rev. Lett. **86**, 3907 (2001).

Cirac-Zoller gate contains all basic ingredients
Molmer-Sorensen+phase gates insensitive to motional state



M&S and phase gates equivalent in complementary basis:

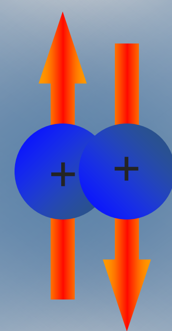
$\{|\uparrow\rangle, |\downarrow\rangle\}$ phase gate ⟷ M&S $\{|+\rangle, |-\rangle\}$

first universal gate implementation (M&S) Sackett et al., Nature **404**, 256(2000)
first C&Z gate, Schmidt-Kaler et al., Nature **422**, 408 (2003)
first phase gate, Leibfried et al. Nature, **422**, 412 (2003)
since then more M&S/phase gate work at Michigan/Maryland and Innsbruck
detailed theoretical description of all 3 gates: P J Lee et al. , J. Opt. B **7,** S371 (2005).

Laser excitation of the harmonic oscillator:

ω_{light}

$\omega_{\text{light}} + \omega_{trap}$



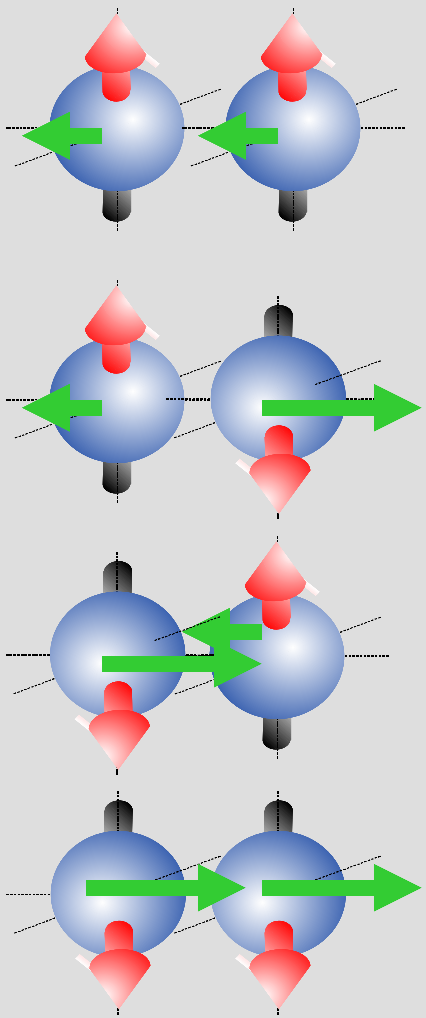
Laser excerts light force on atom

Detuned beams beat in amplitude at trap frequency

Resonant light force excites motion

Spin-up and spin-down feel different force (even in superposition)

Stretch mode excitation

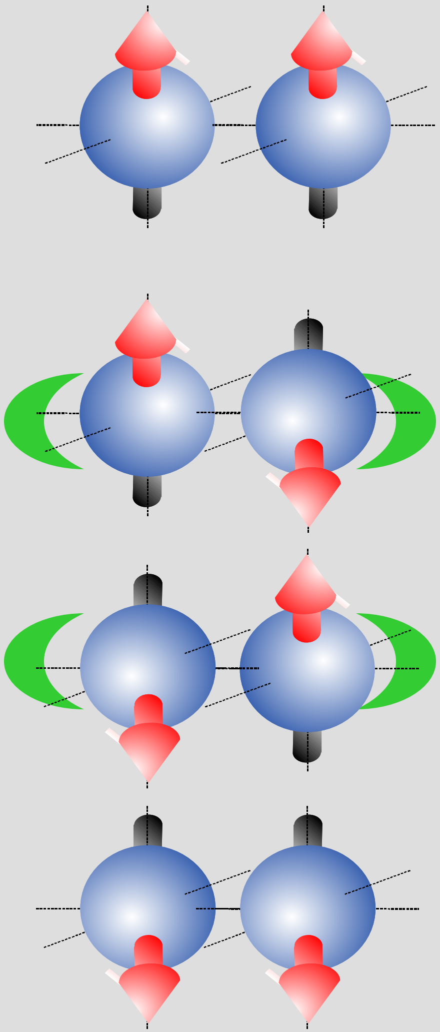


no differerential force

differerential force

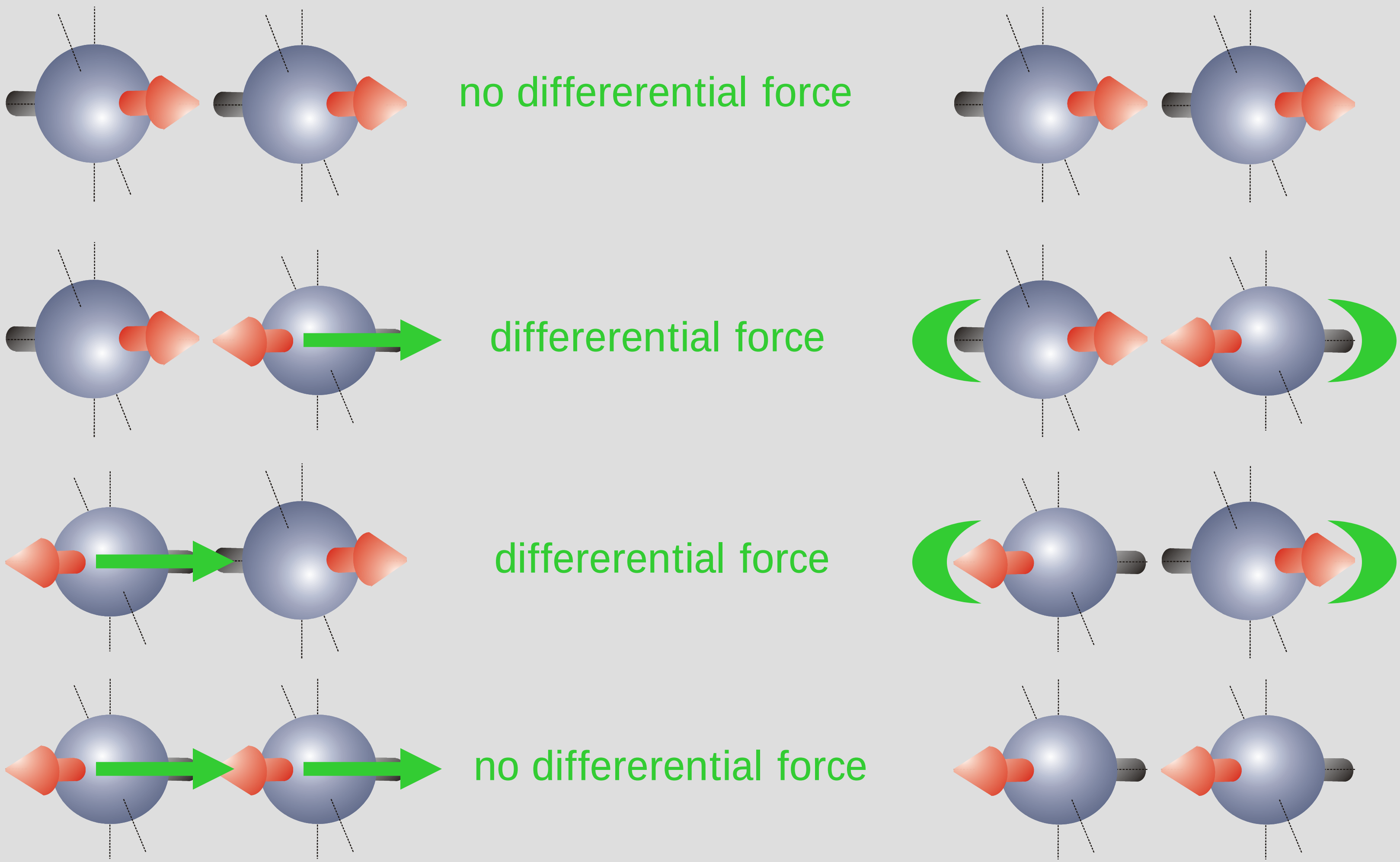
differerential force

no differerential force



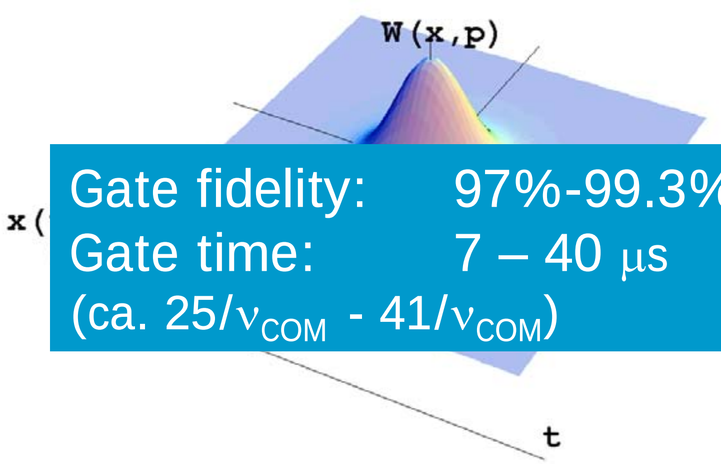
M&S stretch mode excitation

$\{|\uparrow\rangle, |\downarrow\rangle\}$ ⟷ phase gate / M&S ⟷ $\{|+\rangle, |-\rangle\}$



Phase space picture

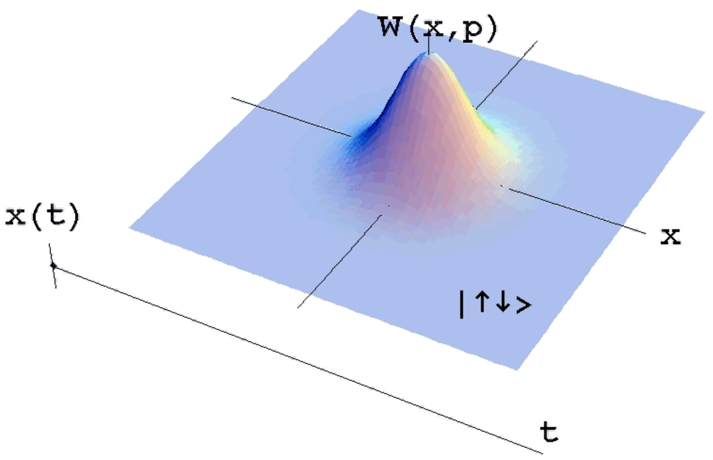
(needs animation)

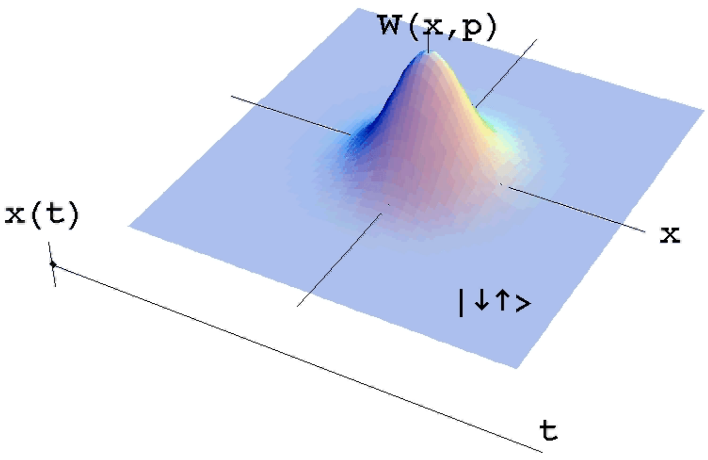


Gate fidelity: 97%-99.3%

Gate time: 7 – 40 μs

(ca. $25/\nu_{COM}$ - $41/\nu_{COM}$)





$$|\downarrow\downarrow\rangle \rightarrow |\downarrow\downarrow\rangle$$

Same technique can be applied to more ions (including spectators), N-particle entangled states, teleportation, 3-qubit error correction, entanglement purification...

$$|\uparrow\uparrow\rangle \rightarrow |\uparrow\uparrow\rangle$$

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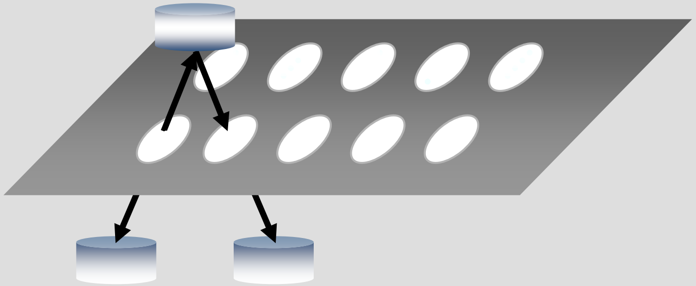
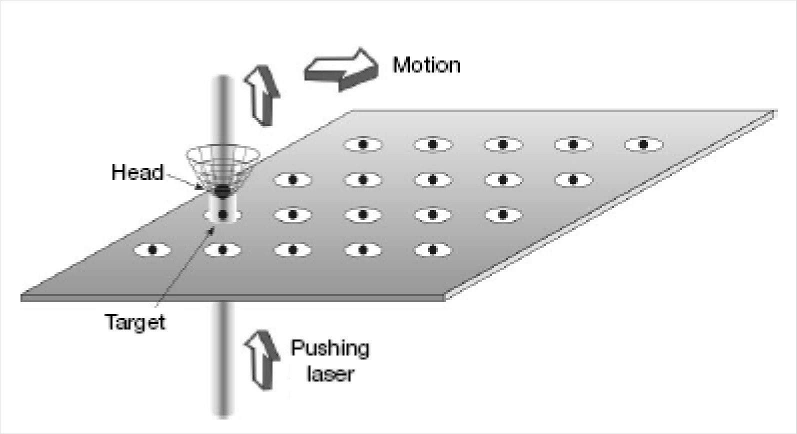
Scaling example approaches

array of elliptical traps
optical cavities as interconnects

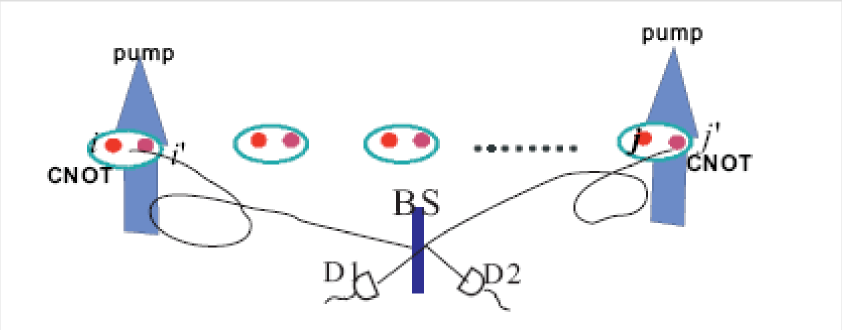


DeVoe, Phys. Rev. A **58**, 910 (1998)

array of single ion traps
“head ion” for interconnects



Cirac & Zoller, Nature **404**, 579 (2000)

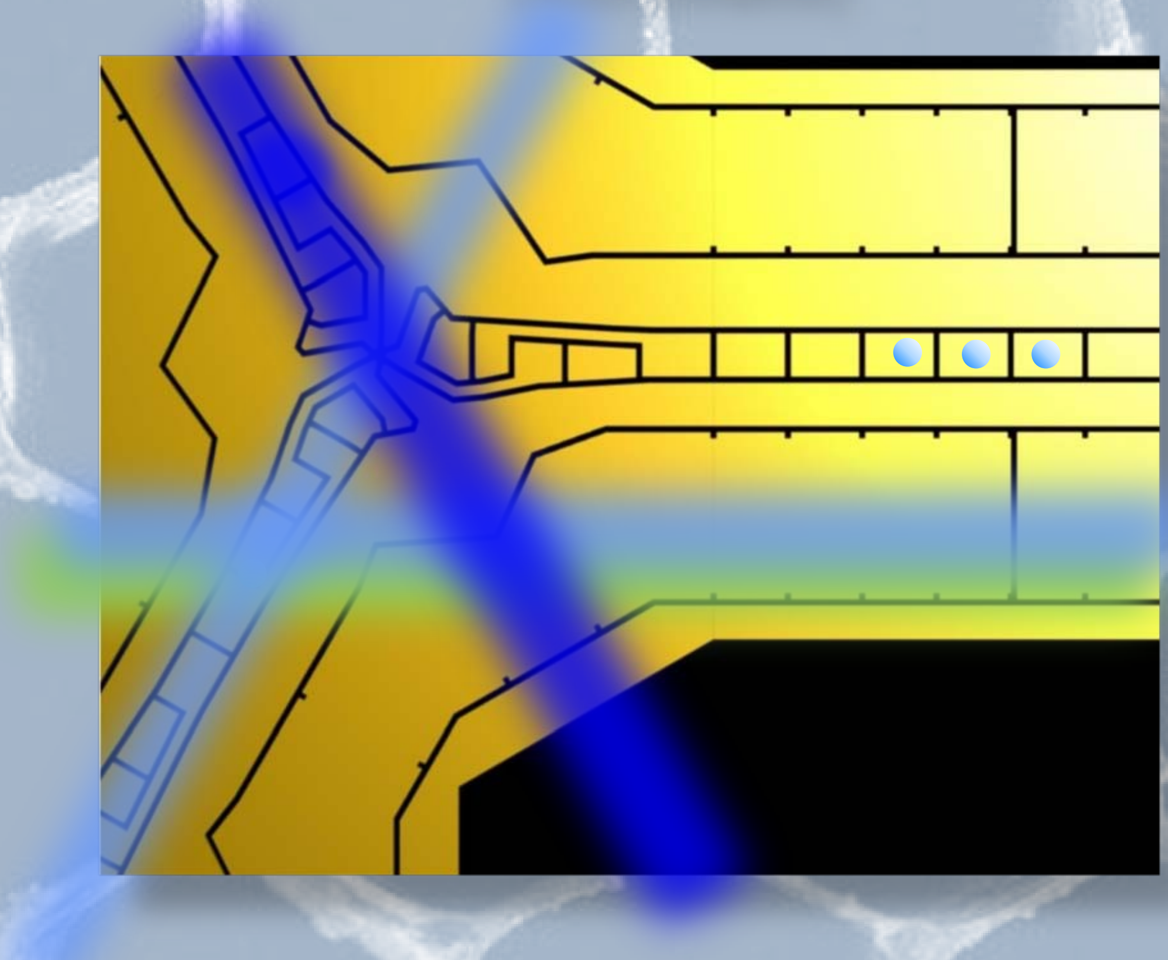


array of two-ion traps
interconnects by probabilistic entanglement

L. M. Duan *et al.*, Quant. Inform. Comp. **4**, 165 (2004)

Multiplexed trap approach

(needs animation)



transport target ions to operation zone

sympathetically cool target ions

perform two-qubit gate, move...

perform single-qubit rotations, move...

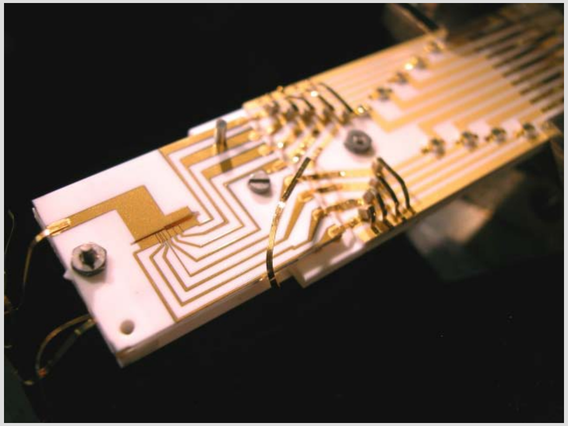
read out ion(s), move...

change conformation for next steps...

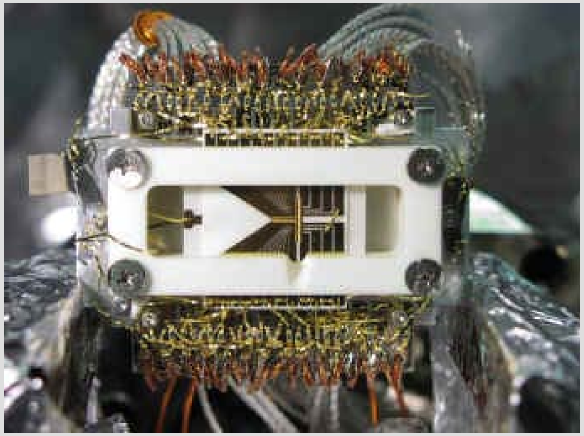
D. J. Wineland, *et al.*,
J. Res. Nat. Inst. Stand. Technol. **103**, 259 (1998);
D. Kielpinski, C. Monroe, and D. J. Wineland,
Nature **417**, 709 (2002).

Other proposals:
DeVoe, Phys. Rev. A **58**, 910 (1998) .
Cirac & Zoller, Nature **404**, 579 (2000) .

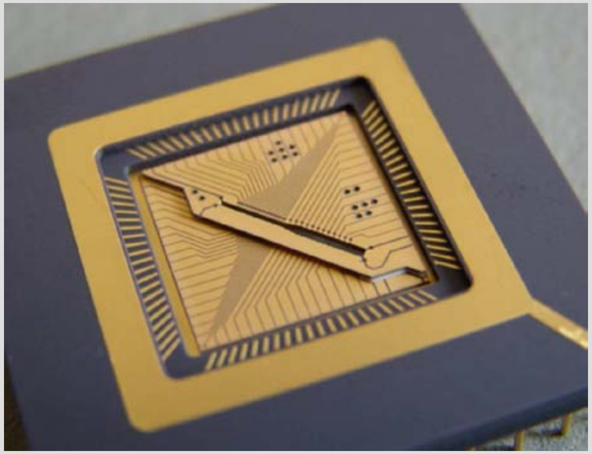
Multi-layer multi zone traps



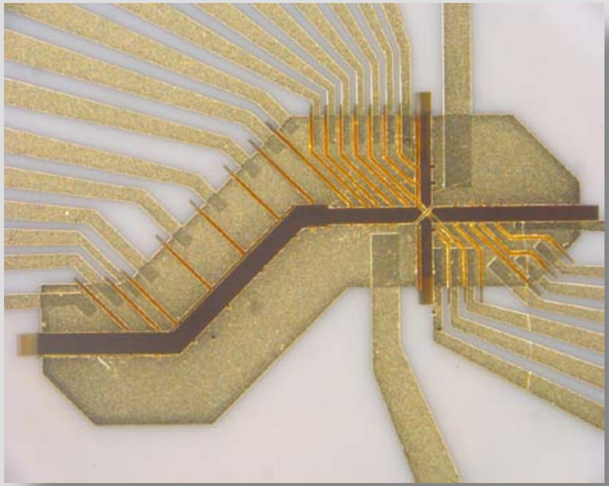
6 zone 2 layer linear trap (NIST, 2003)



9-zone 3-layer T-trap (Michigan, 2006)
first junction transport experiments

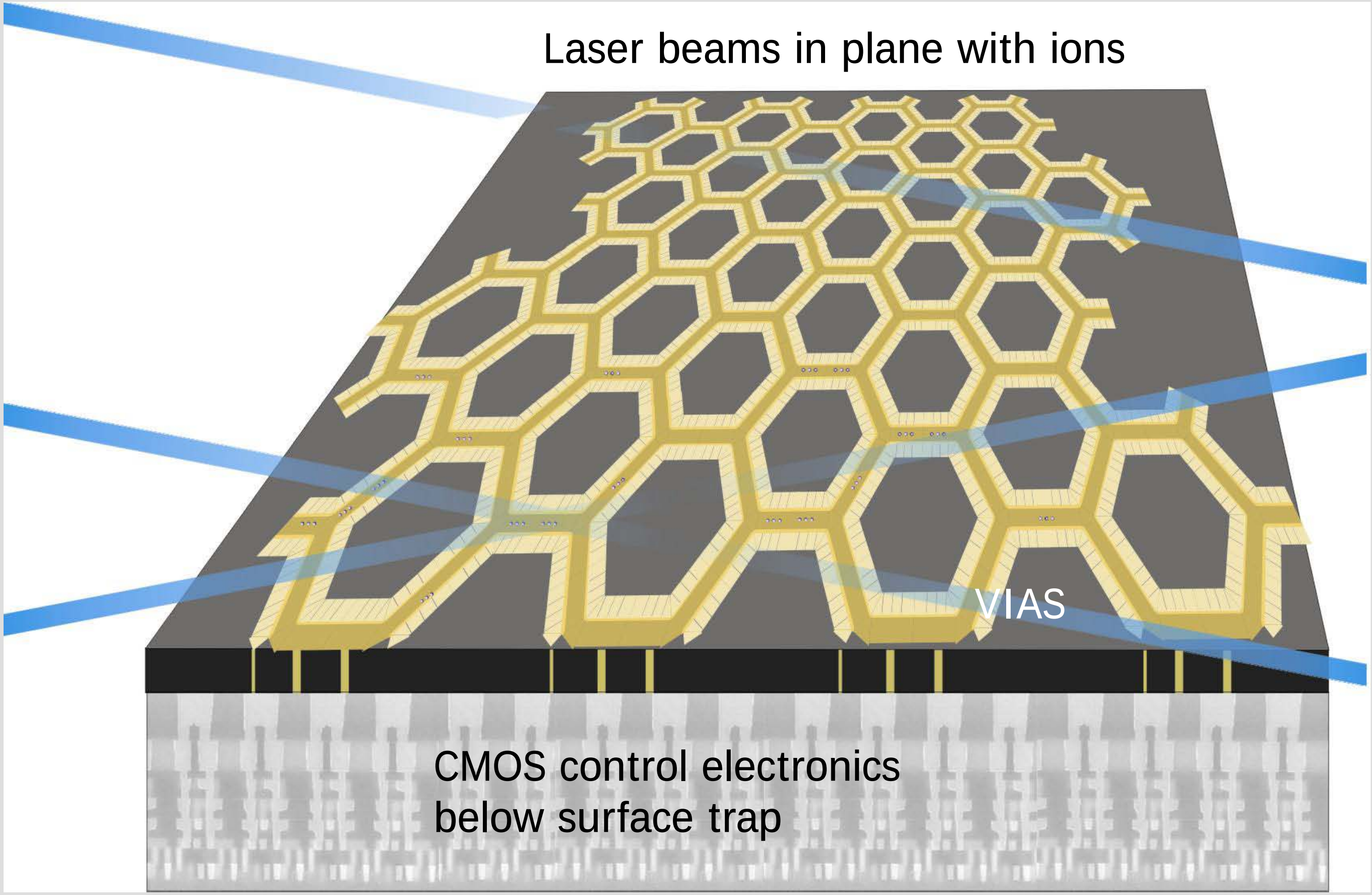


29 zone 2 layer linear trap (Ulm, 2006)



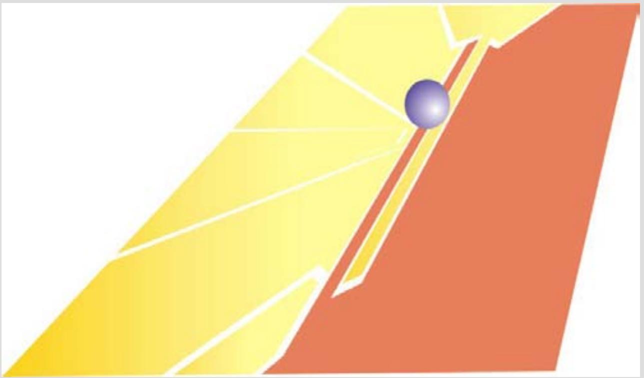
18 zone 2-layer junction trap (NIST, 2007)
for experiments see Dave Wineland's talks

More integrated ion chips ?

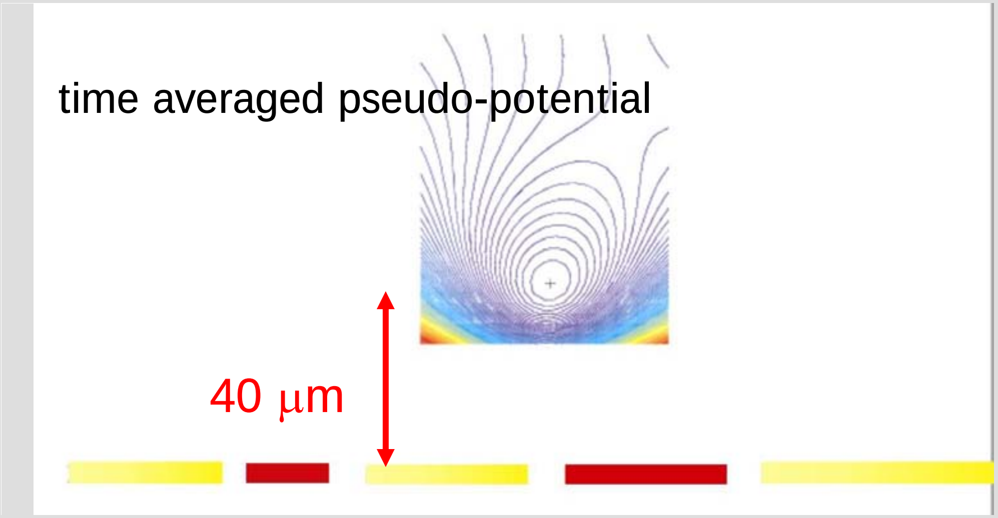


Surface electrode trap basics

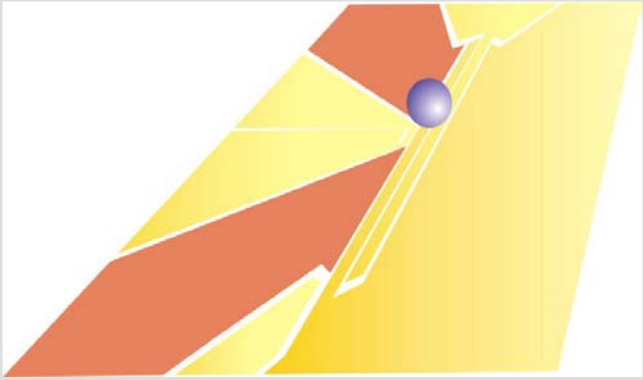
radial confinement:



radial cross section



axial confinement:

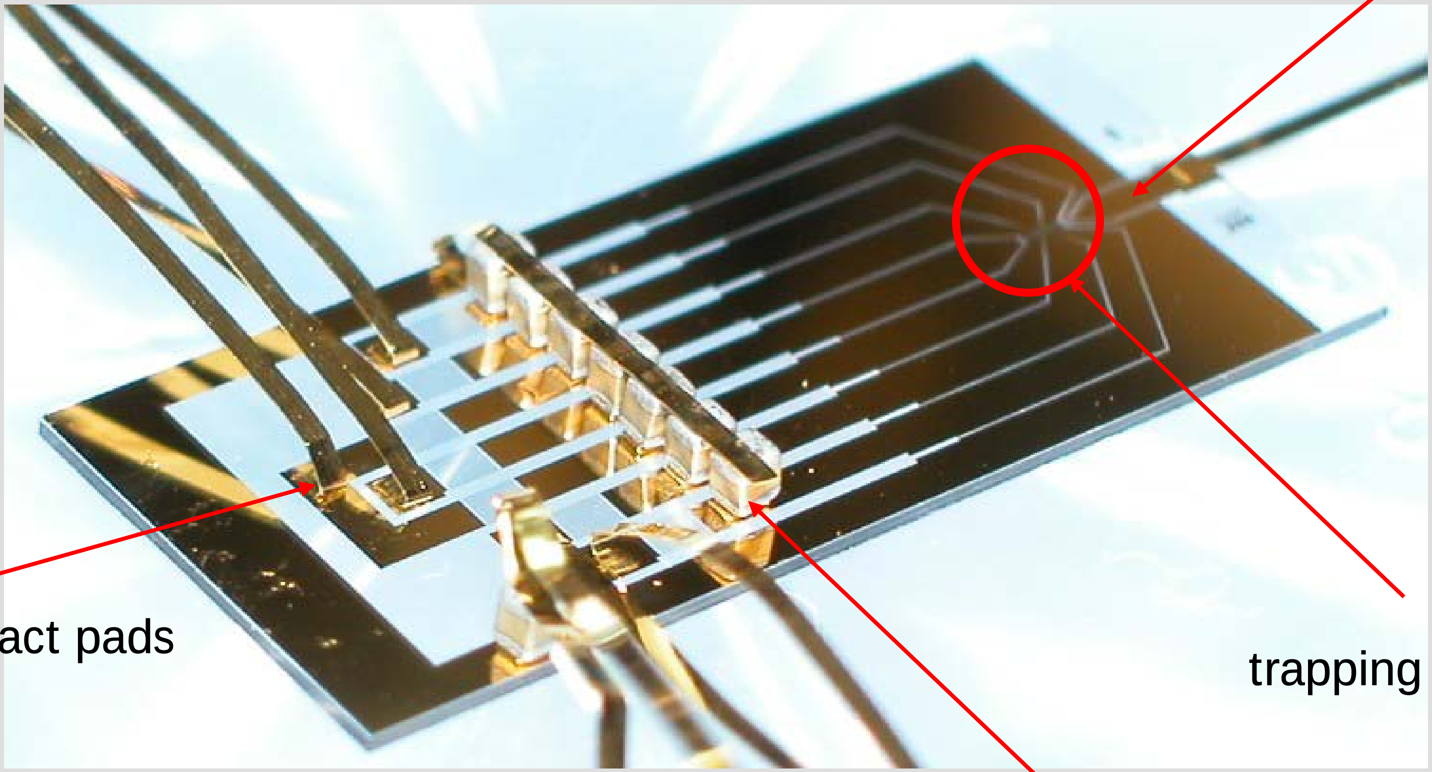


axial cross section

J. Chiaverini *et al.*, Quant. Inform. Comp. 5, 419439 (2005)

NIST Planar Trap Chip

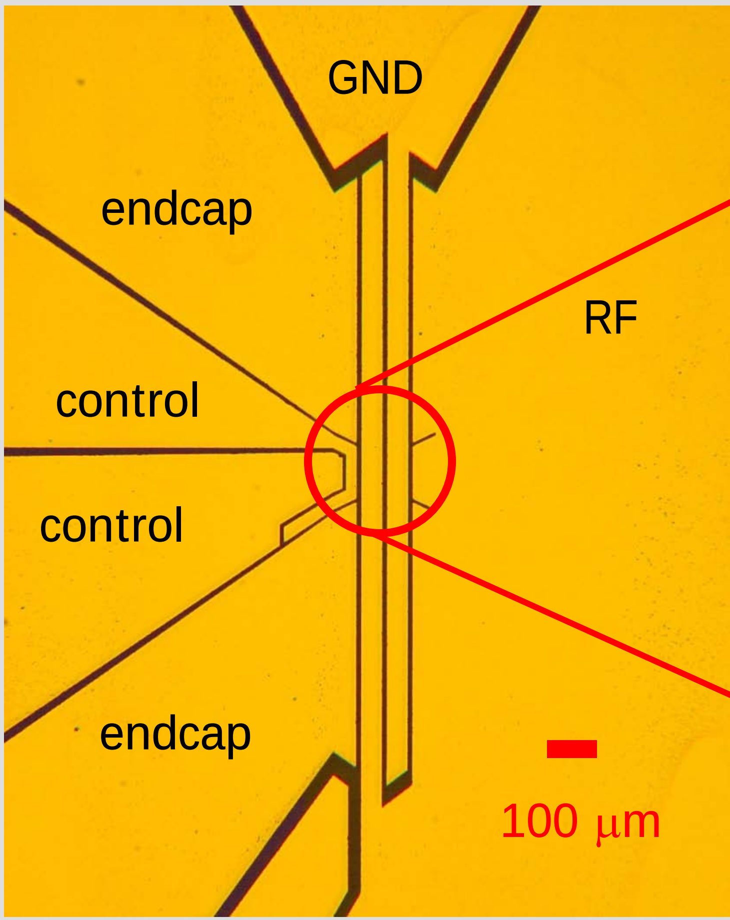
Gold on fused silica



trap designed and manufactured by John Chiaverini, Signe Seidelin (NIST)

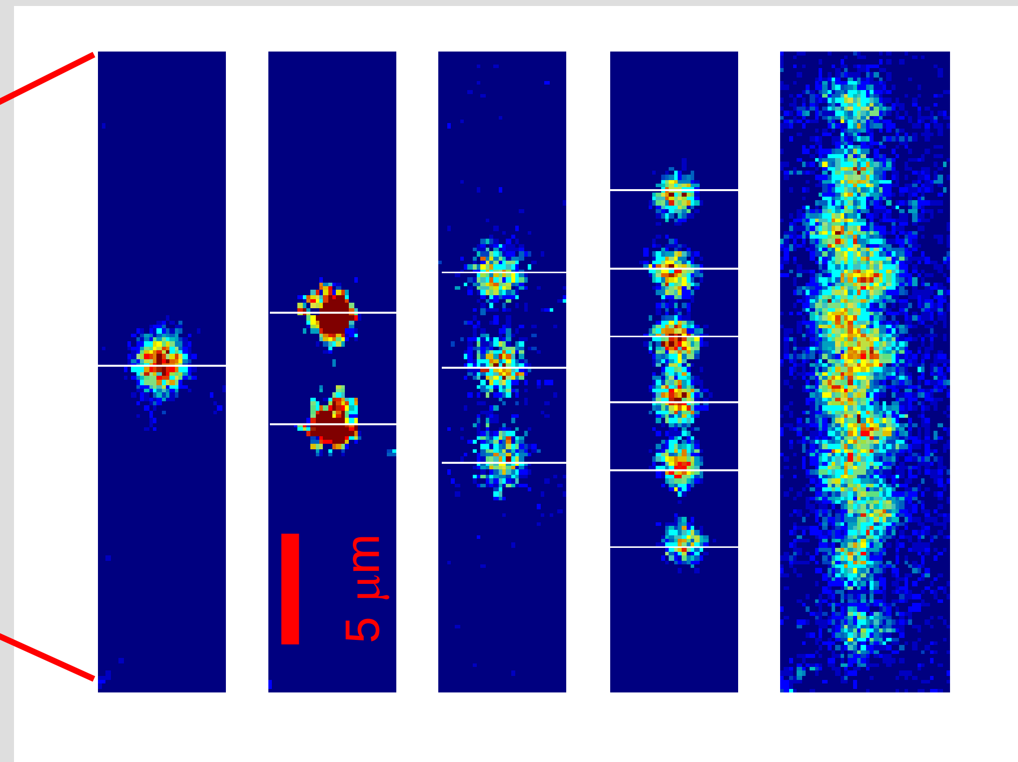
Planar Trap Chip

Magnified trap electrodes



John Chiaverini, Signe Seidelin

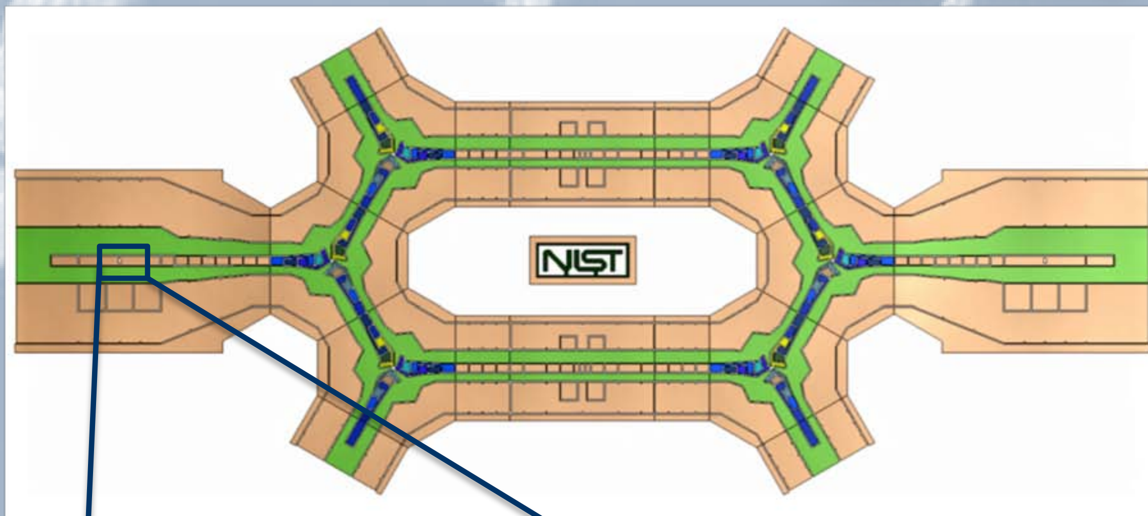
CCD pictures of strings of Mg^+ ions (trapped 40 μm above surface)



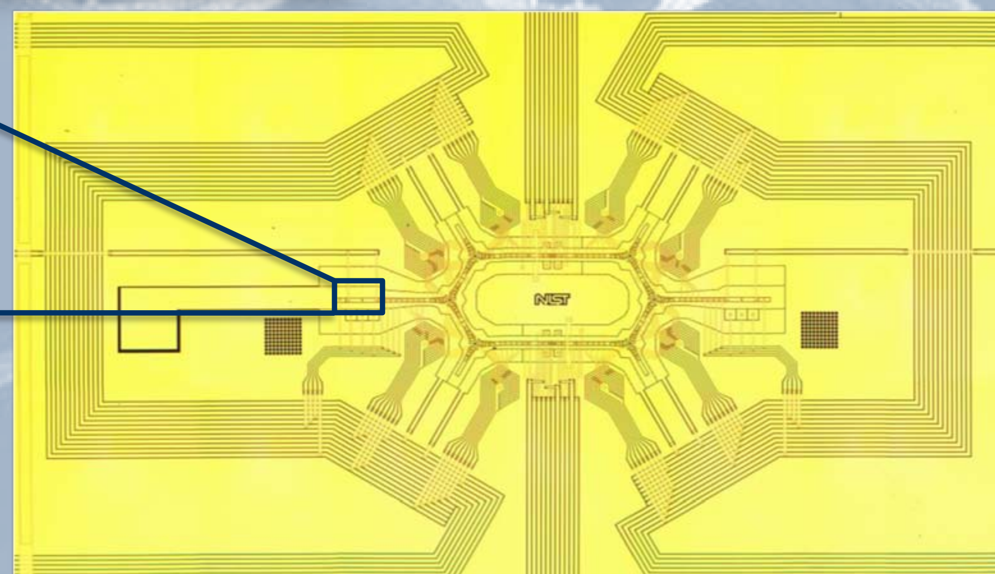
S. Seidelin *et al.*, PRL **96**, 253003 (2006).

NIST trap chip module

(Jason Amini)



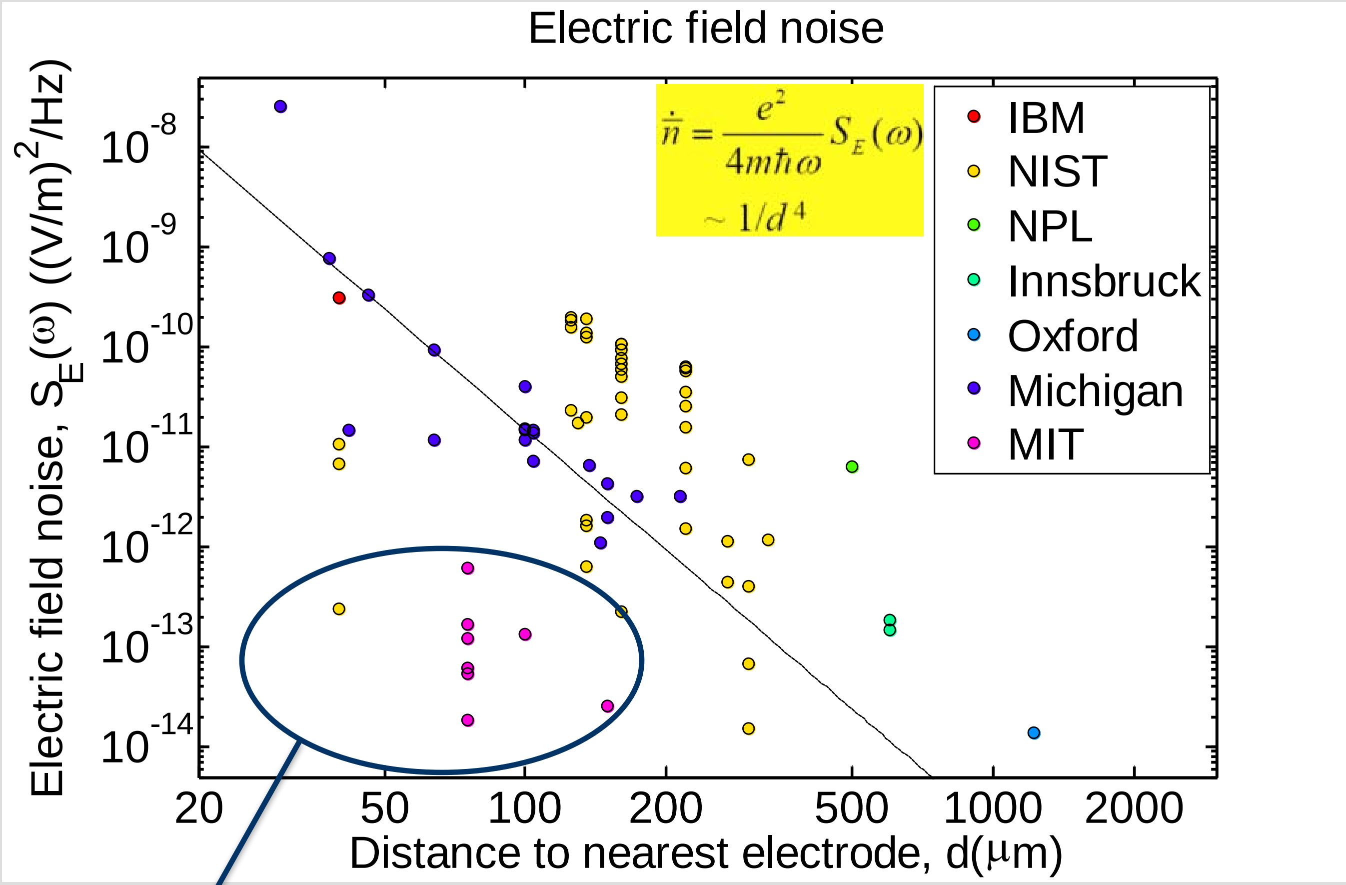
- 2 load zones
- 6 improved junctions
- 150 control electrodes



- backside loading
- motion through junctions
- utilize for multi-qubit work

Motional heating

Heating rate orders of magnitude over Johnson noise, physical origin unknown

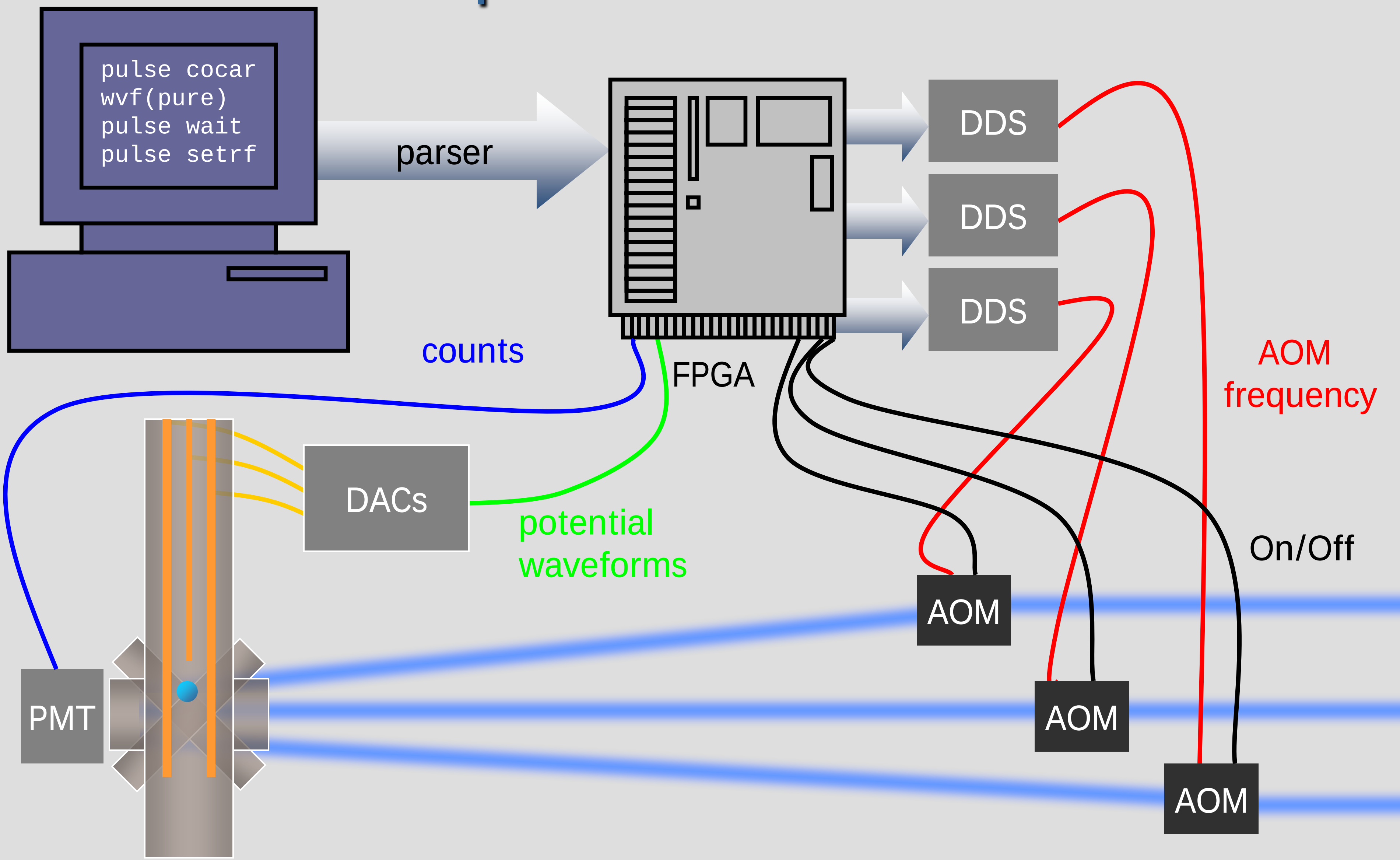


electrode temperature < 12 K

Overview

- Introduction to ion traps
- Atomic physics for ion-qubits
- Manipulation of ion-qubits with laser fields
- Scalable QIP with trapped ions
- Example experiments

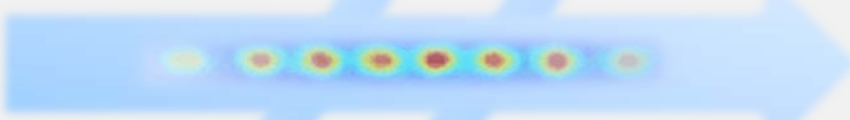
Experiment control



Homework assignment
(example experiments)

- Innsbruck approach: linear ion strings in single well, M&S gates + local shifts

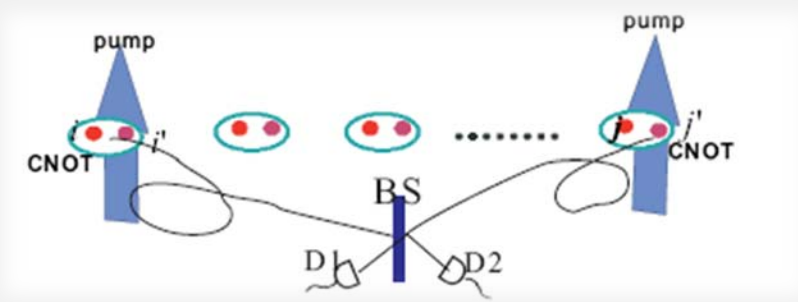
local AC-Stark-shift beams

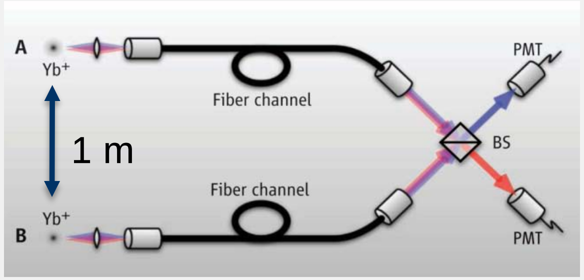


global gate beams,
global spin flips

G. Kirchmair *et al.*, New Journal of Physics **11,** 023002 (2009)
V. Nebendahl *et al.*, PRA **79,** 012312 (2009)

- Michigan/Maryland approach: small local registers linked by photons





D. L. Moehring et al., Nature **449**, 68 (2007)
S. Olmschenk *et al.,* Science **323**, 486 (2009)

- NIST approach: (see earlier in the talk and D. Wineland's talk on Wed.)

Jonathan Home *et al.*, Science **325**, 1227 (2009)
David Hanneke *et al.*, Nature Physics **6**, 13 (2010)

Conclusions

- Coherent manipulation of up to 14 qubits demonstrated in ion traps (see Rainer Blatt’s talk)
- Successful implementation of basic QIP building blocks (teleportation, error correction, entanglement purification, entanglement swapping, multipartite entanglement, ...)
- Development of scalable micro-fabricated ion traps under way with very encouraging first results
- For more of the “latest and greatest”, see other talks in this meeting