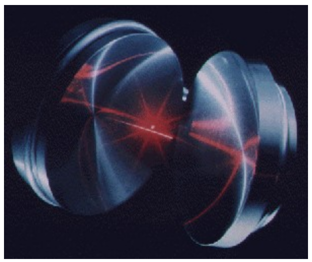
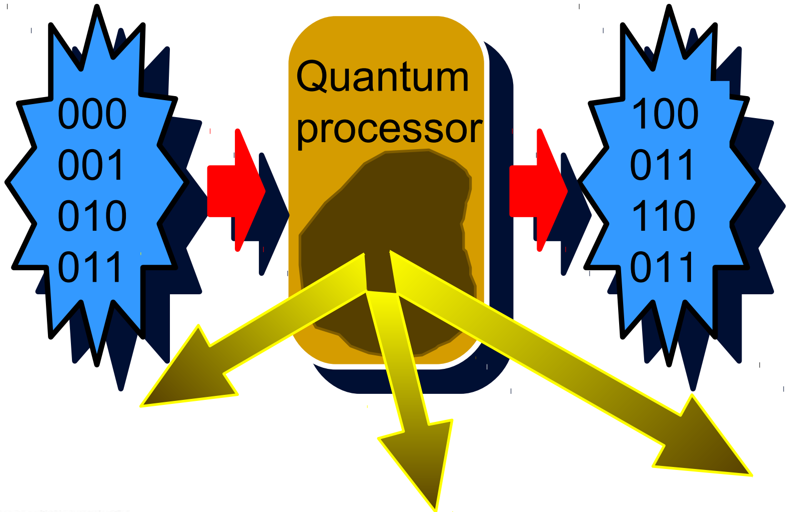
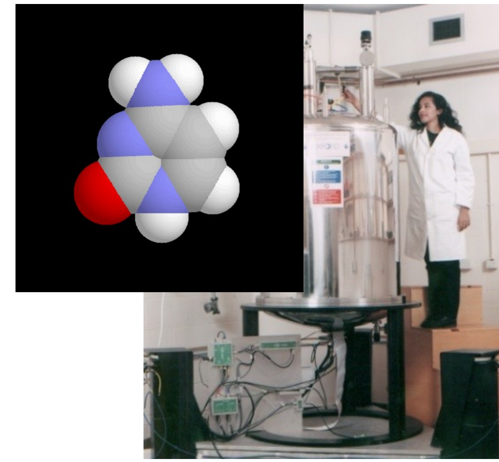
Which technology ?

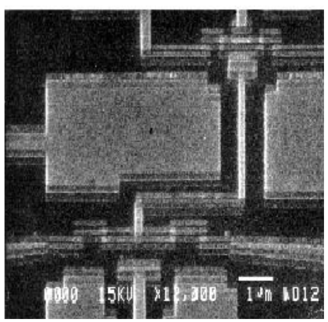


Cavity QED

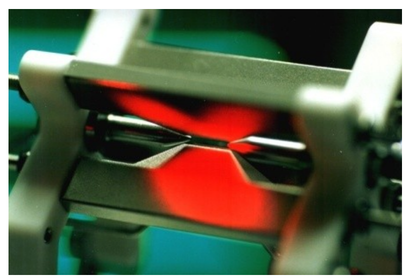


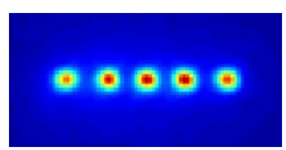


NMR

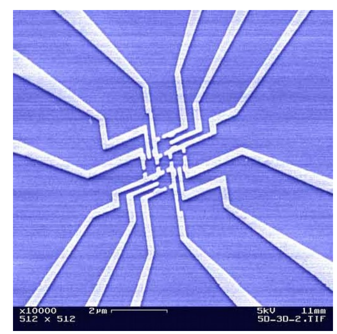


Superconducting qubits



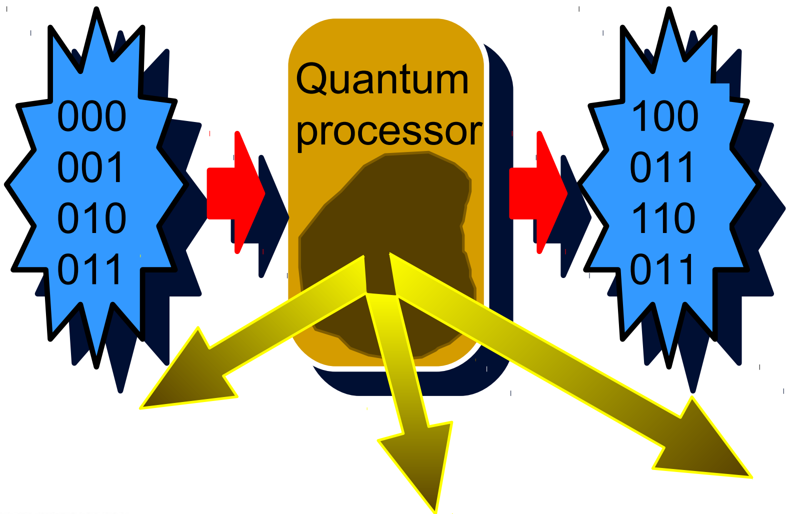


Trapped atoms/ions



Quantum dots

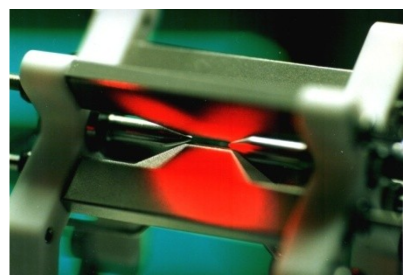
Which technology ?

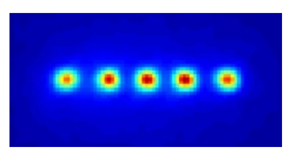


Cavity QED

NMR

Superconducting qubits

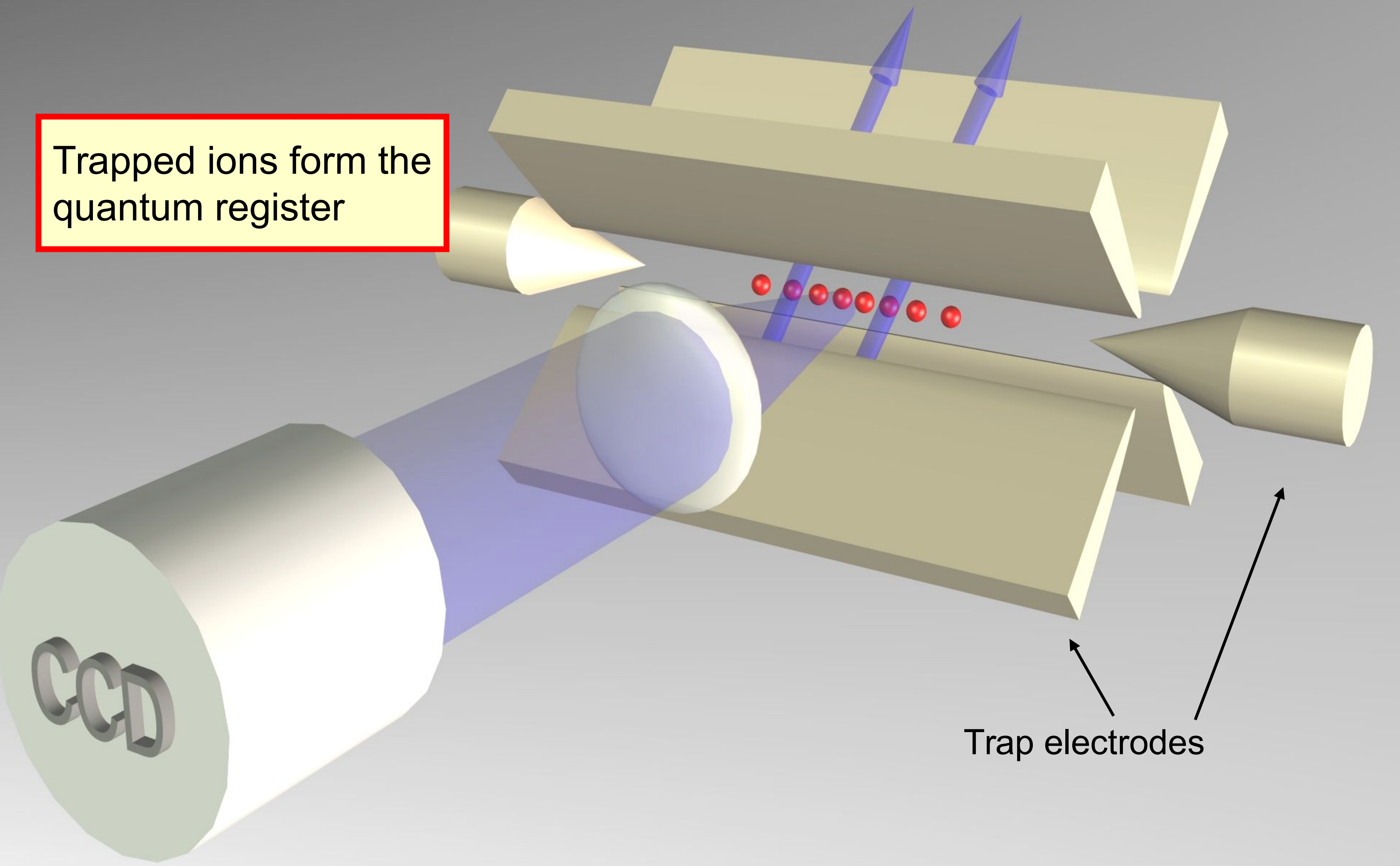


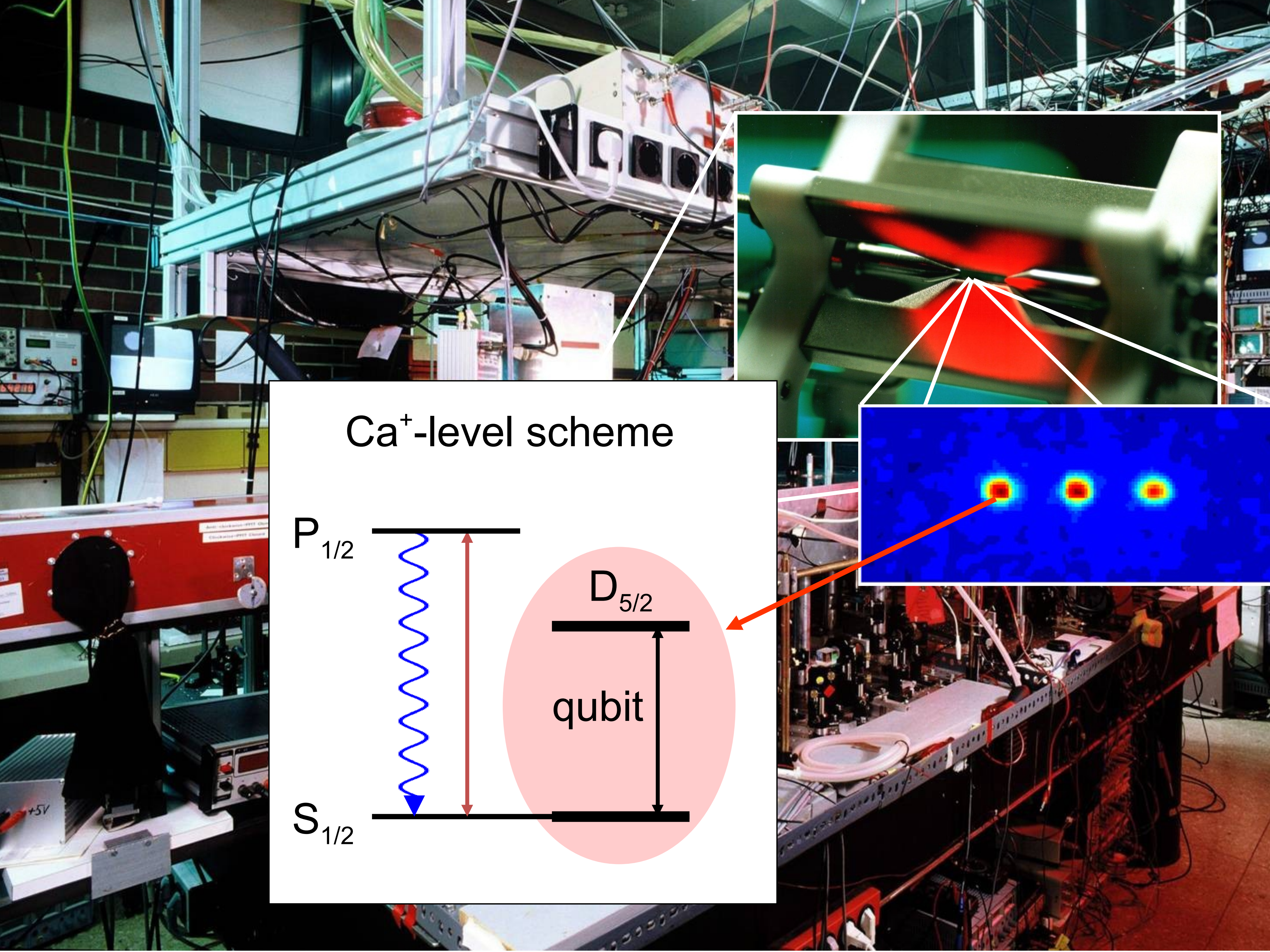


Trapped atoms/ions

Quantum dots

Ion trap quantum computing





Ca+-level scheme
P1/2
D5/2
qubit
S1/2

Di Vincenzo criteria

I. Scalable physical system, well characterized qubits

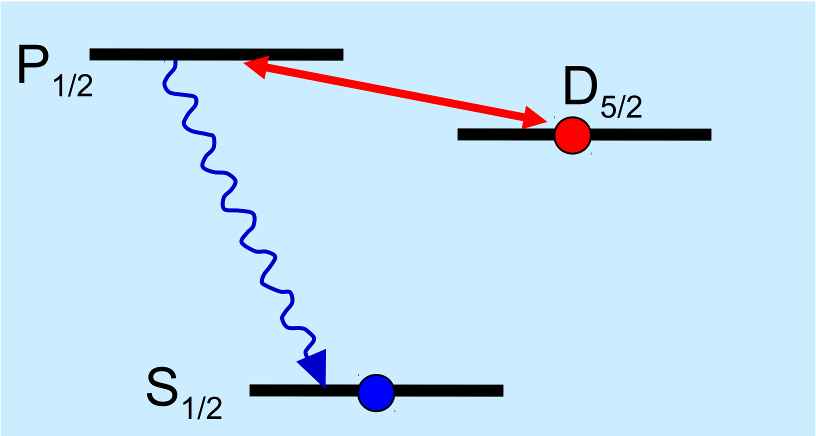
II. Ability to initialize the state of the qubits

III. Long relevant coherence times, much longer than gate operation time

IV. “Universal” set of quantum gates

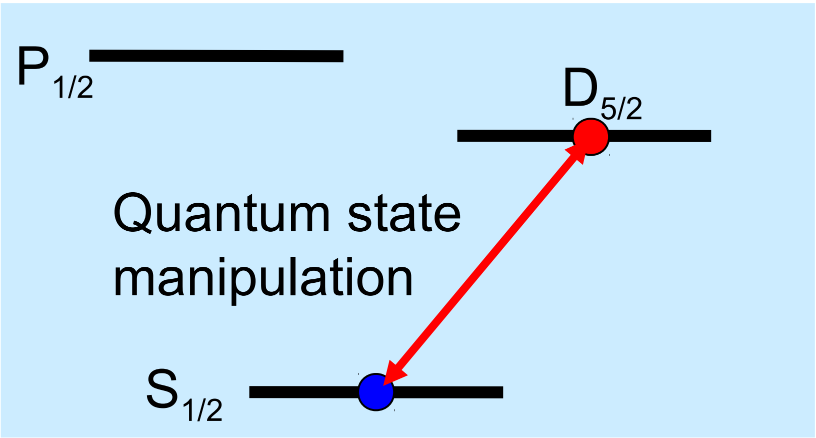
V. Qubit-specific measurement capability

Experimental procedure



1. Initialization in a pure quantum state

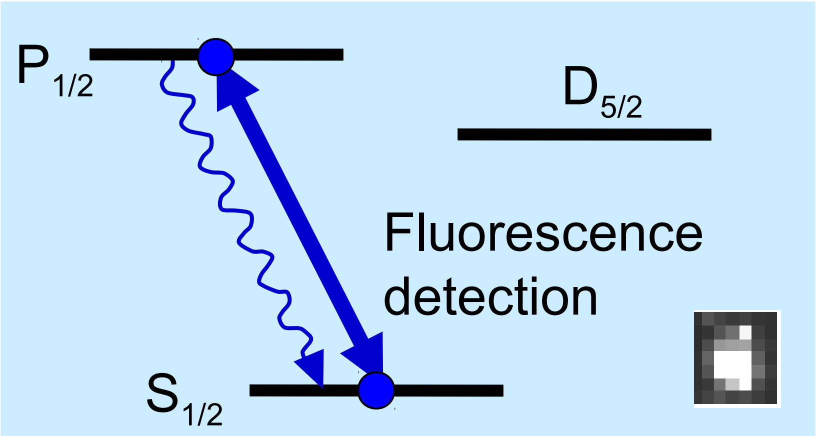
Experimental procedure



1. Initialization in a pure quantum state

2. Quantum state manipulation on $S_{1/2} – D_{5/2}$ transition

Experimental procedure

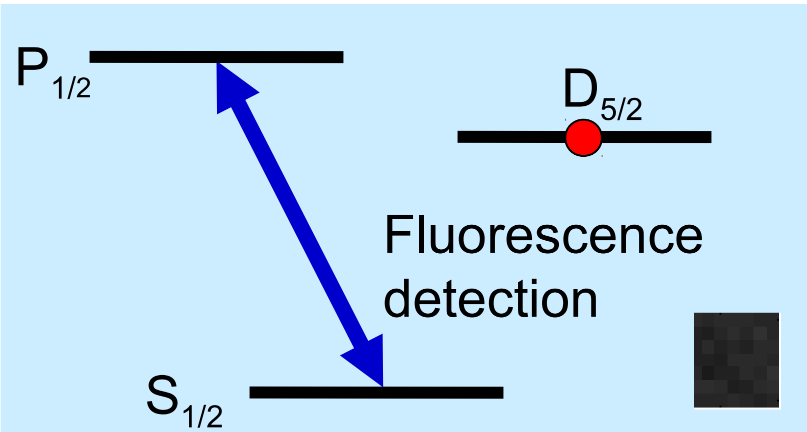


1. Initialization in a pure quantum state

2. Quantum state manipulation on $S_{1/2} – D_{5/2}$ transition

3. Quantum state measurement by fluorescence detection

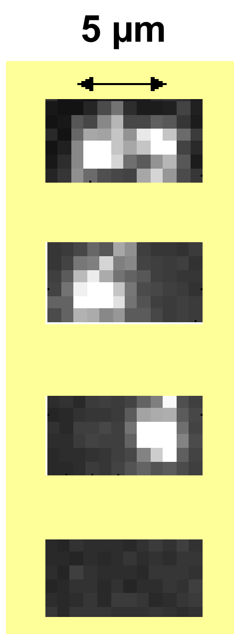
Experimental procedure



1. Initialization in a pure quantum state
2. Quantum state manipulation on $S_{1/2} – D_{5/2}$ transition
3. Quantum state measurement by fluorescence detection

<u>Two ions:</u>

Spatially resolved detection with CCD camera



$|SS\rangle$

$|SD\rangle$

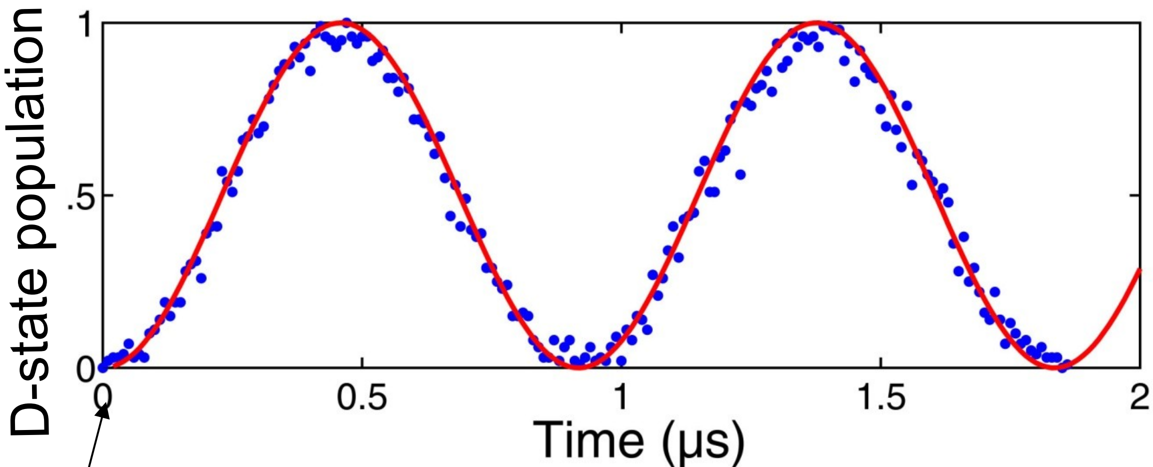
$|DS\rangle$

$|DD\rangle$

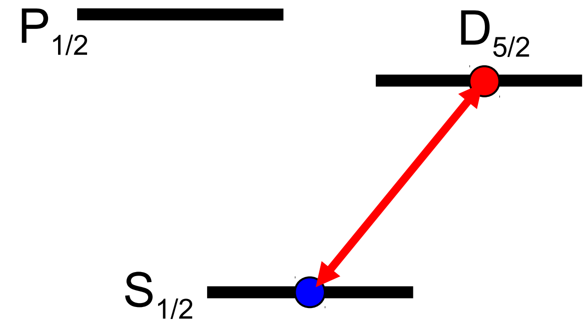
50 experiments / s

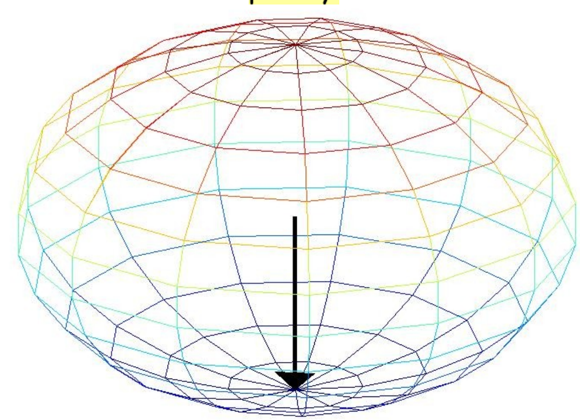
Repeat experiments 100-200 times

Rabi oscillations

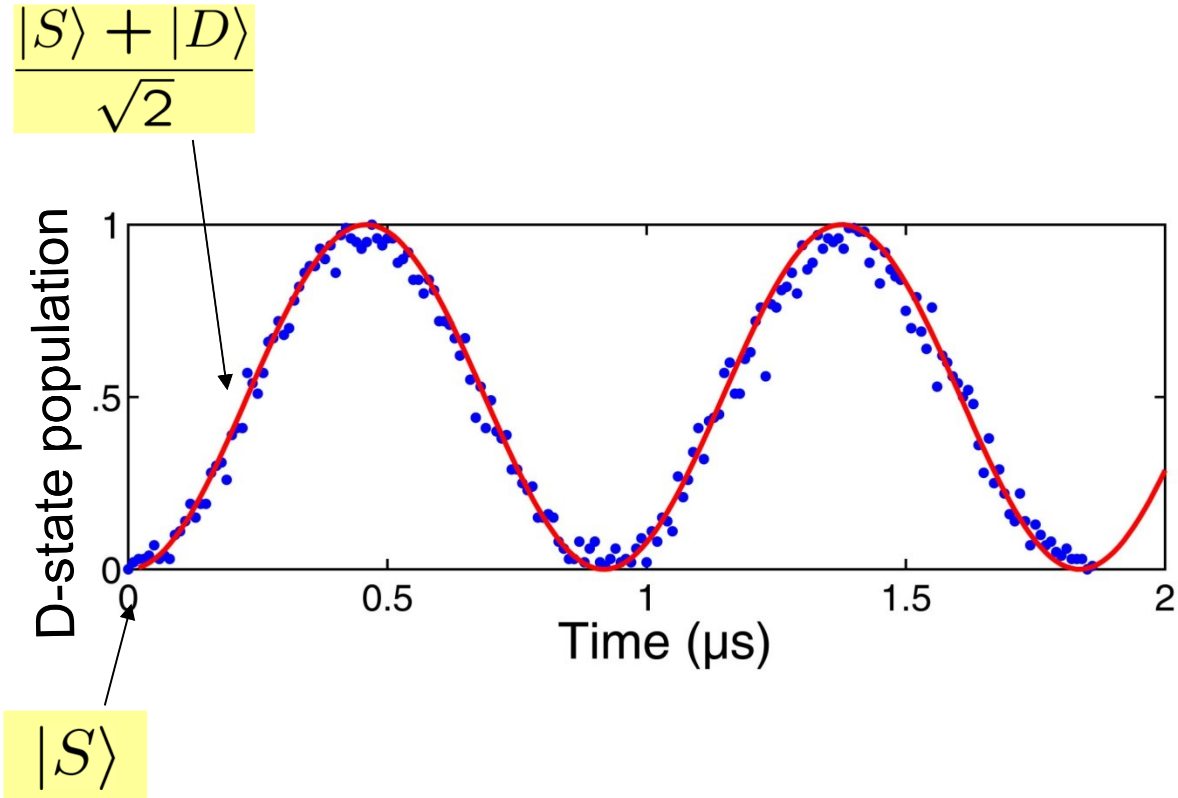


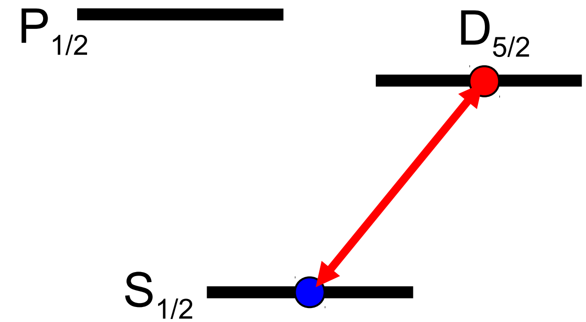
$|S\rangle$

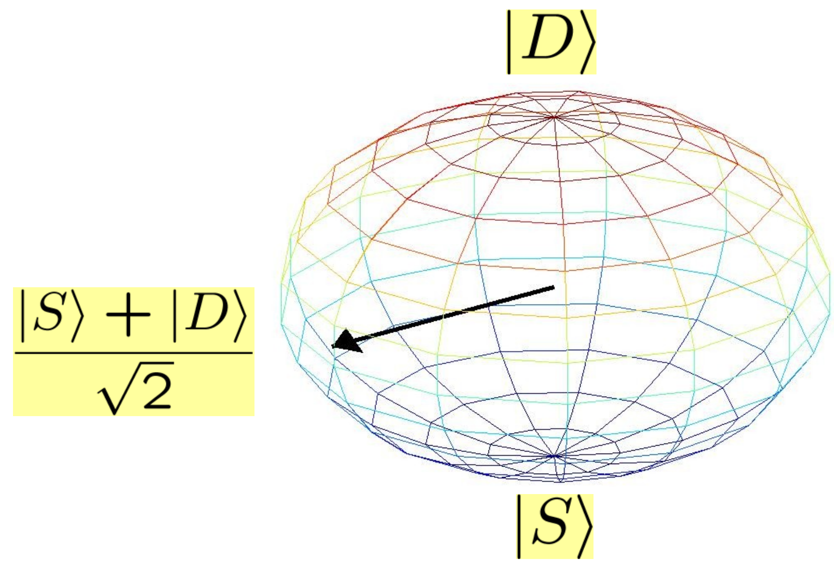




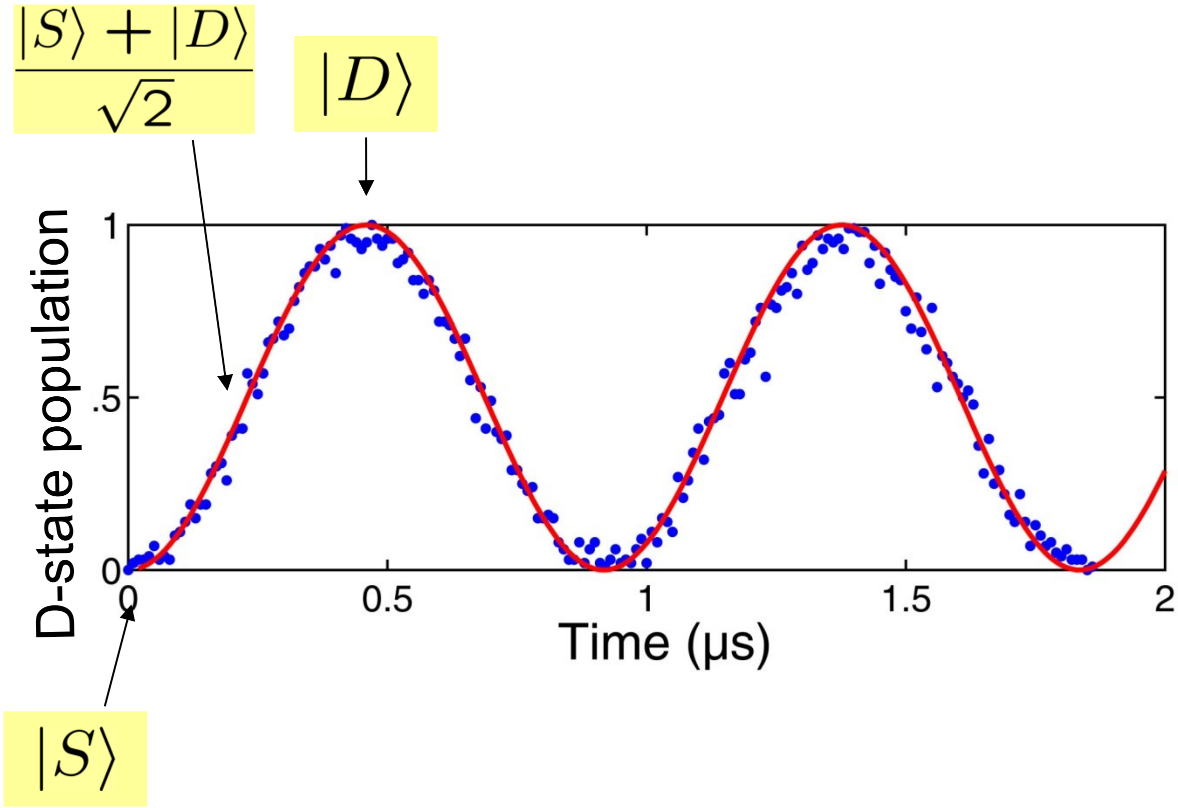
Rabi oscillations

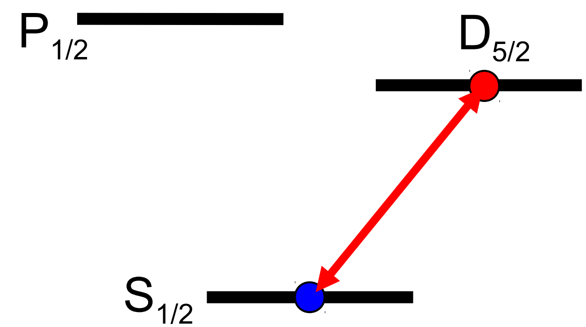


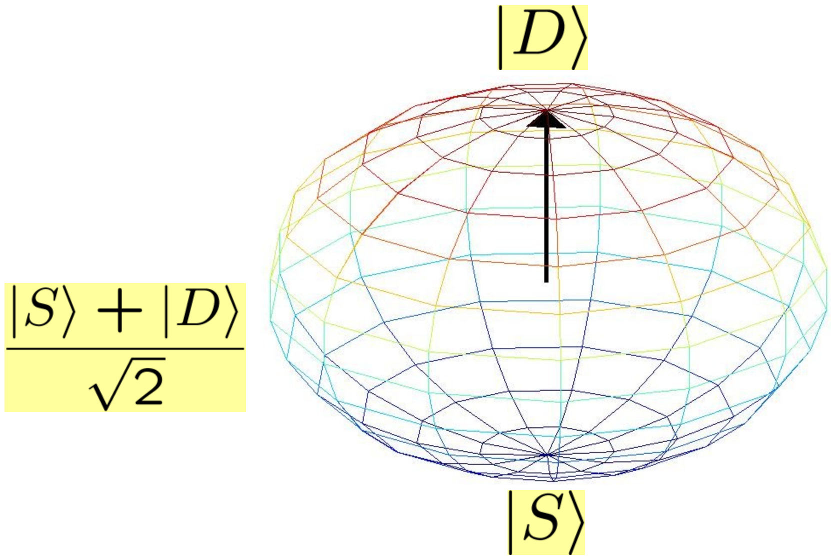




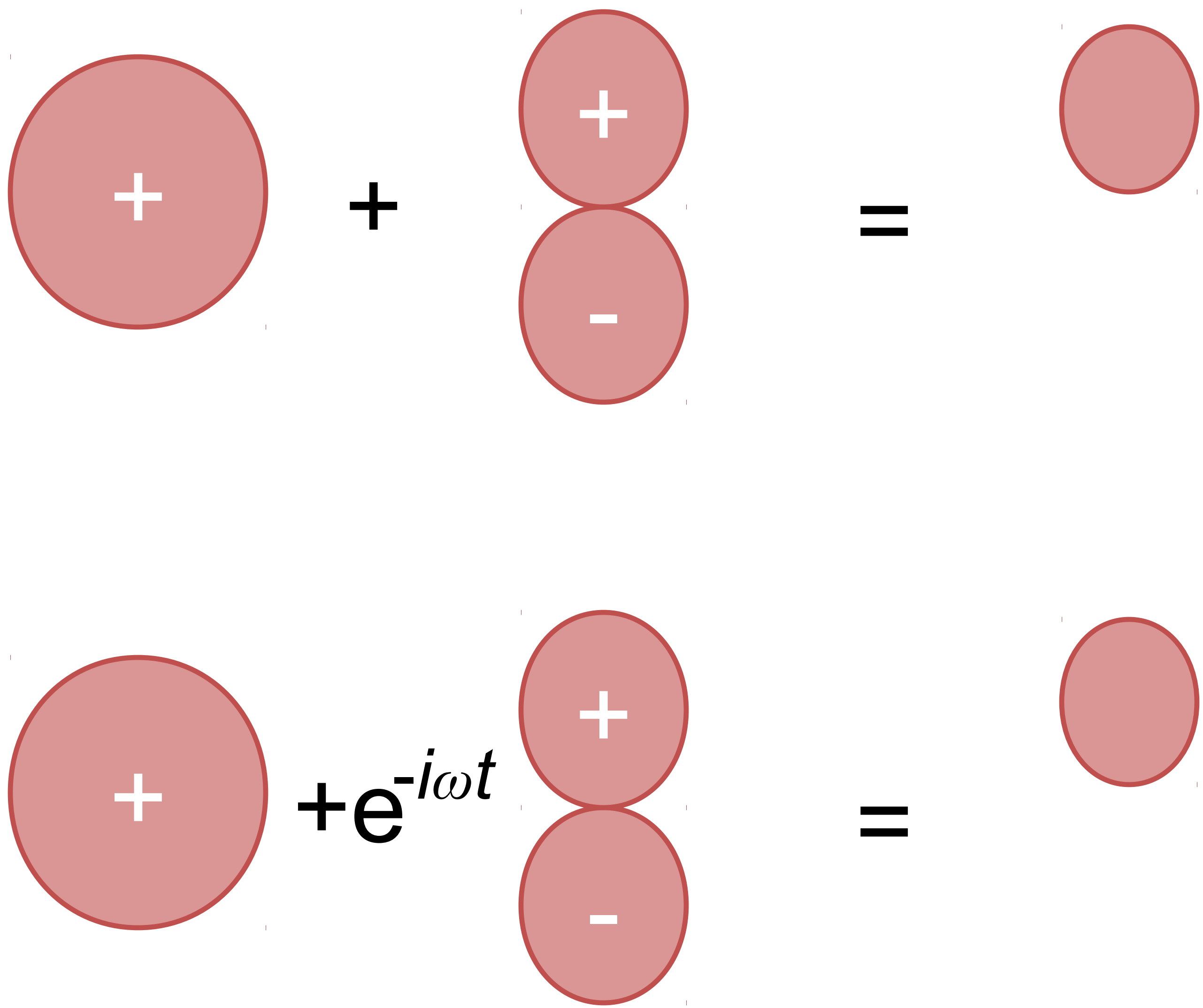
Rabi oscillations



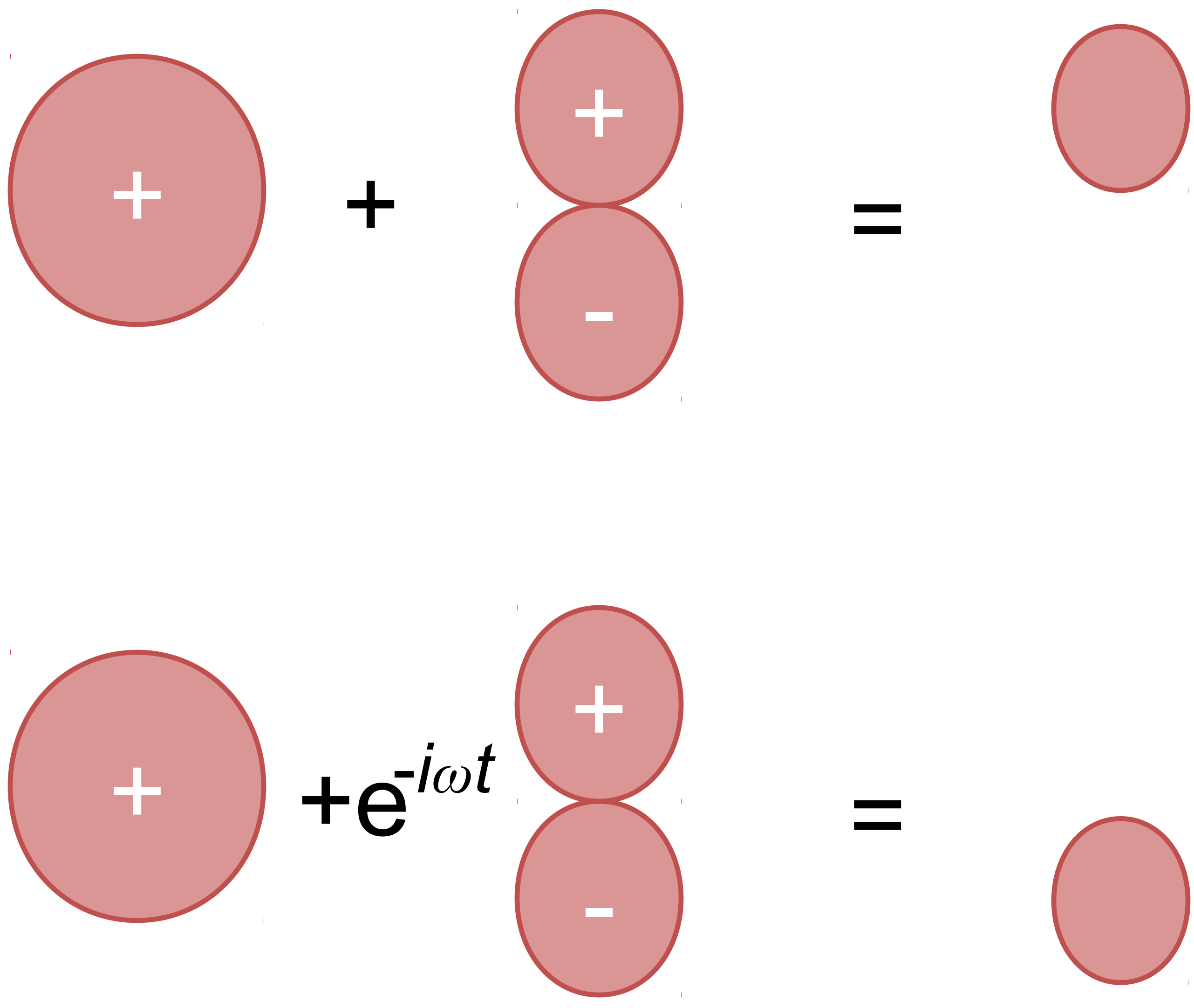




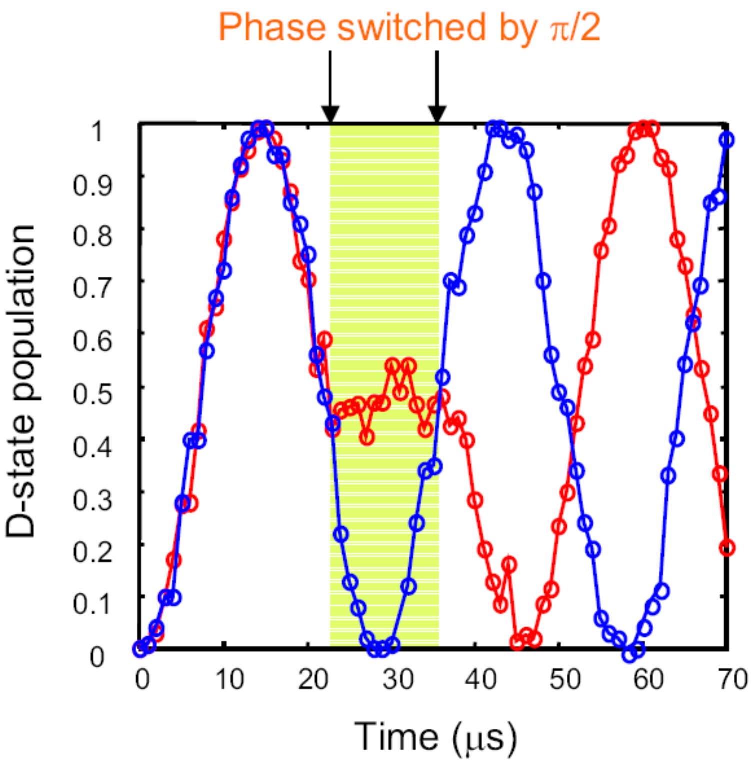
The phase ...



The phase ...

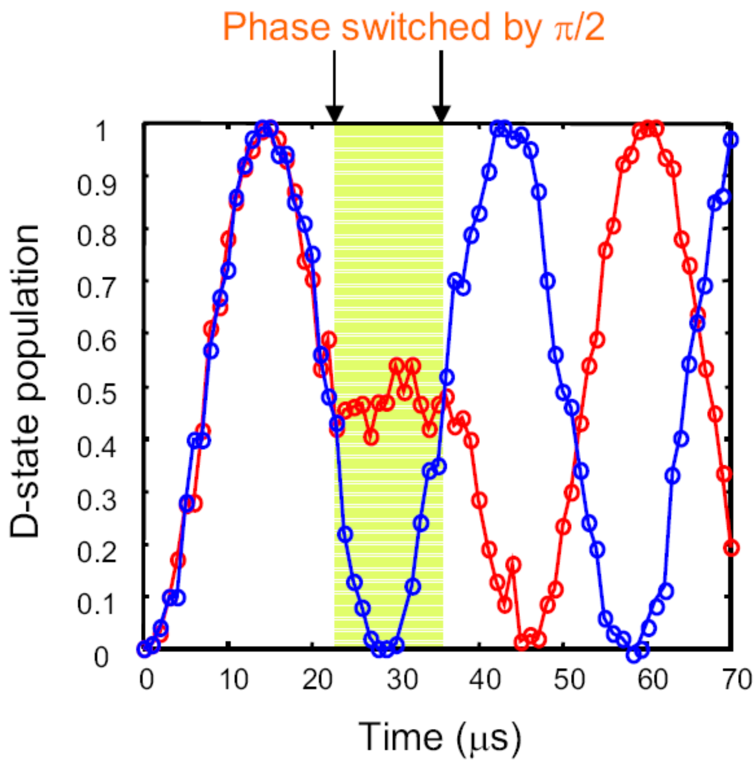


The phase ...

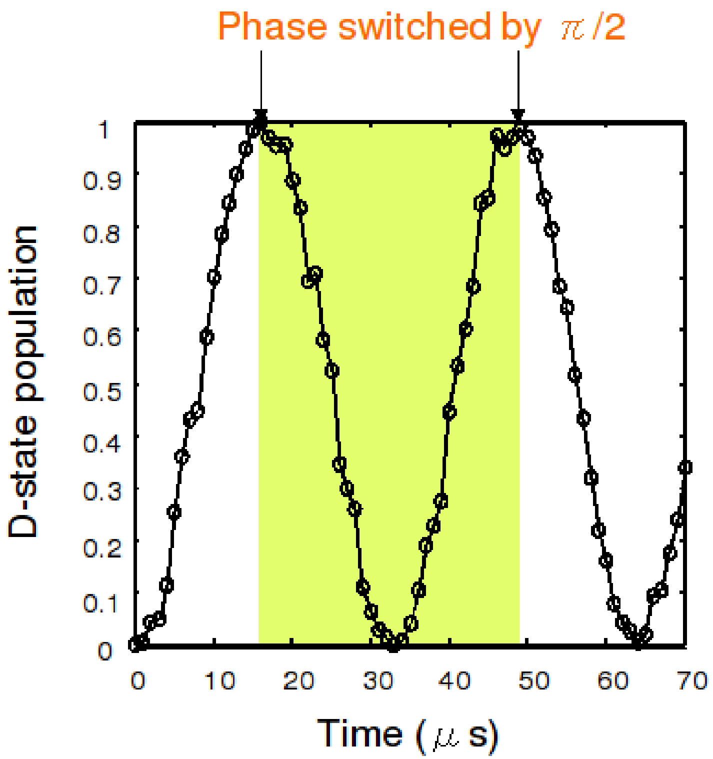


Phase switched by π/2
D-state population
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
10
20
30
40
50
60
70
Time (μs)

The phase ...

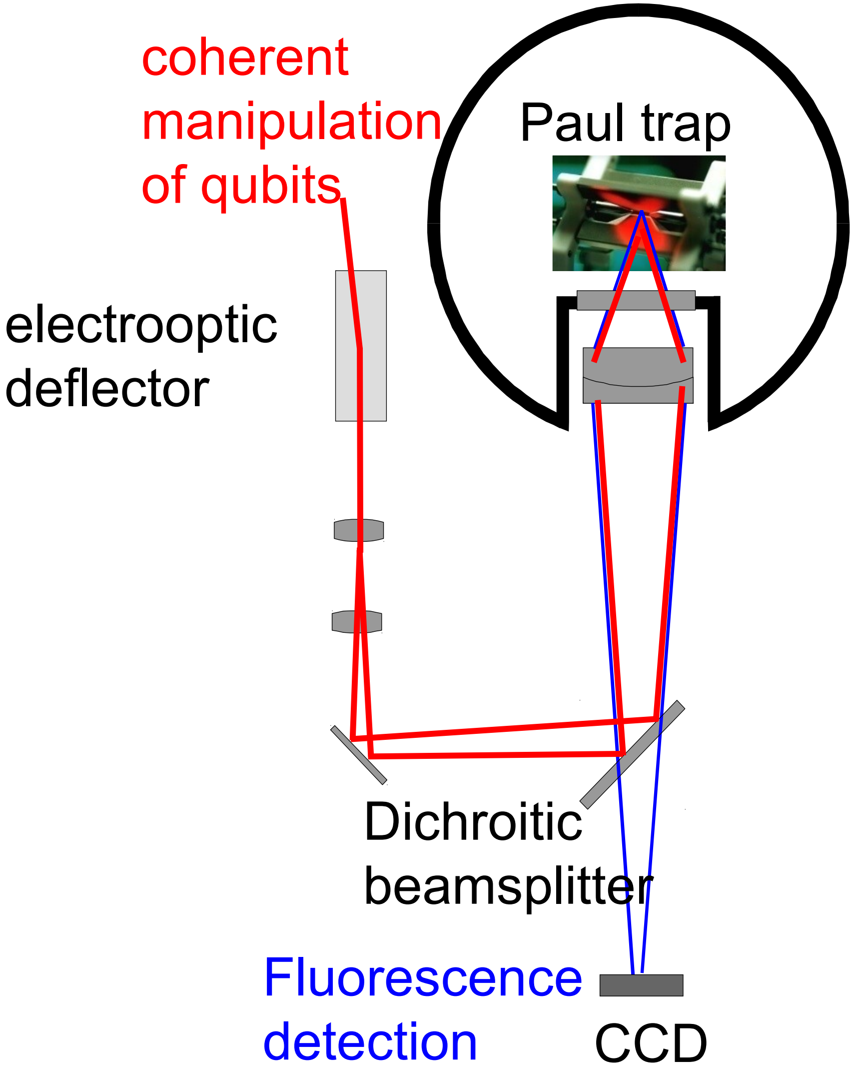


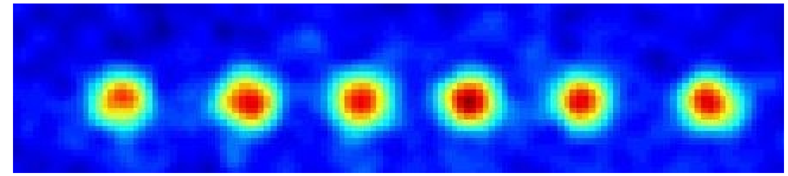
Phase switched by π/2
D-state population
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
10
20
30
40
50
60
70
Time (μs)

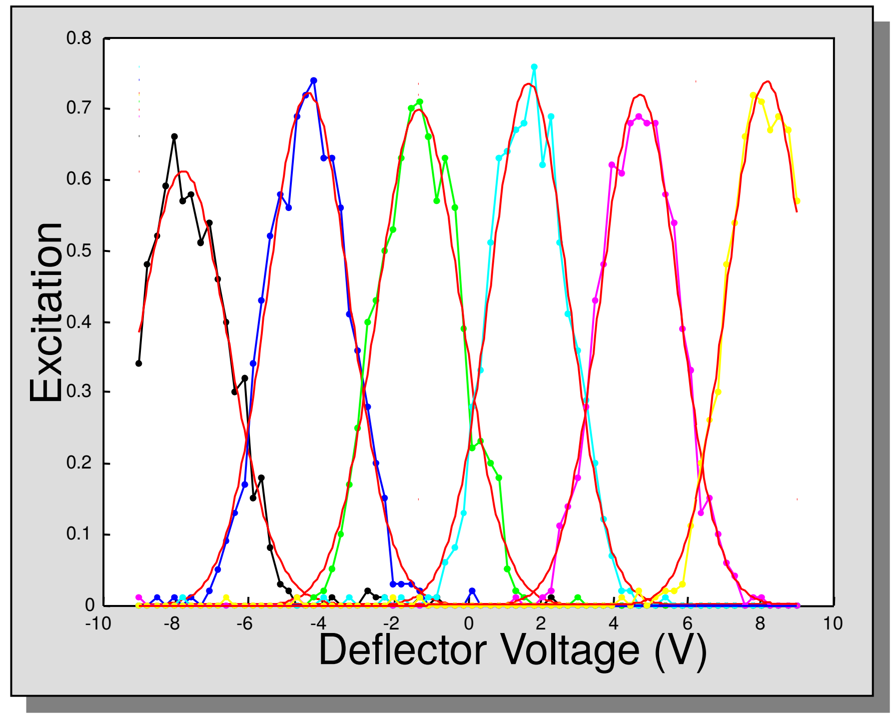


Phase switched by π/2
D-state population
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
10
20
30
40
50
60
70
Time (μ s)

Addressing single qubits





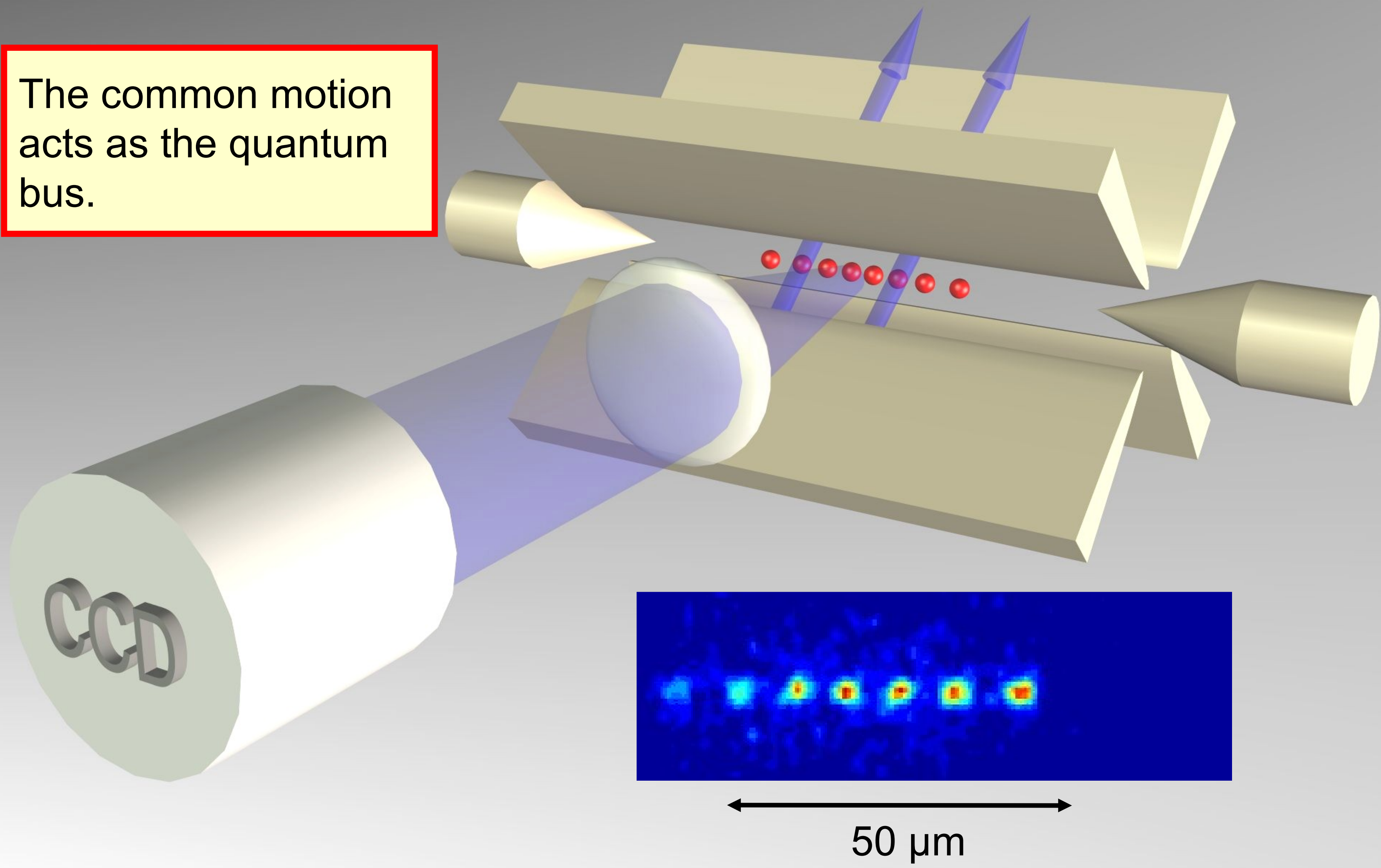


- inter ion distance: ~ 4 μm
- addressing waist: ~ 2 μm

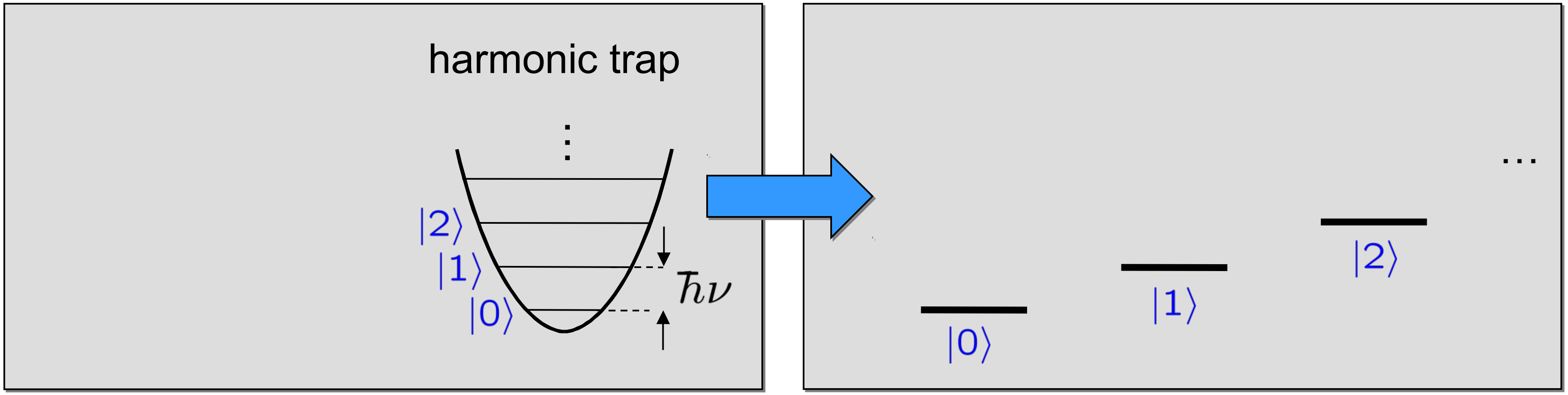
< 0.1% intensity on neighbouring ions

Having the qubits interact

The common motion acts as the quantum bus.

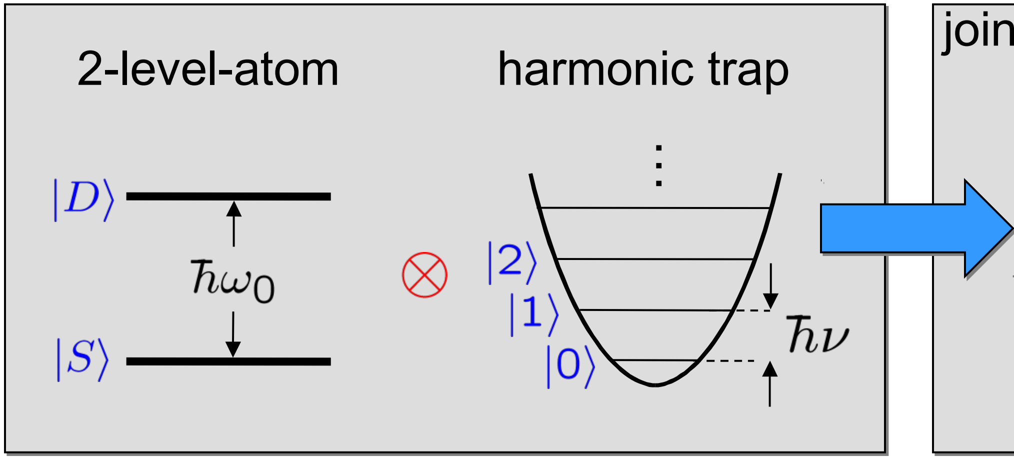


Ion motion

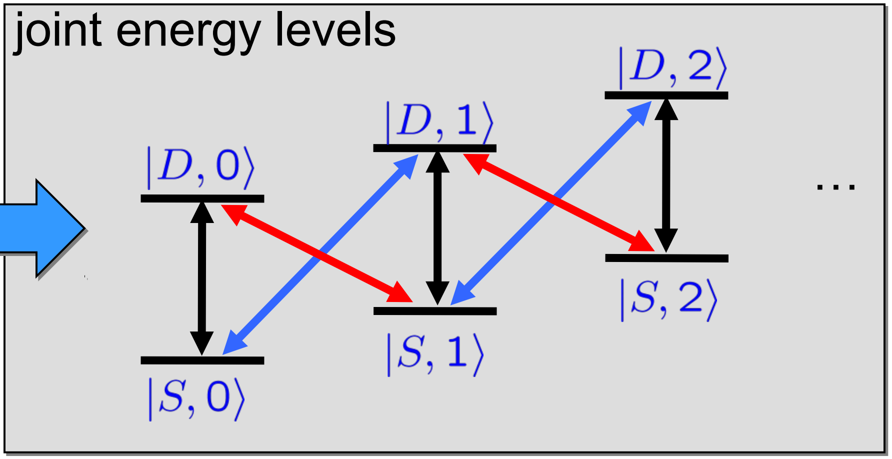


harmonic trap
$|2\rangle$
$|1\rangle$
$|0\rangle$
$\hbar\nu$
$|0\rangle$
$|1\rangle$
$|2\rangle$
...

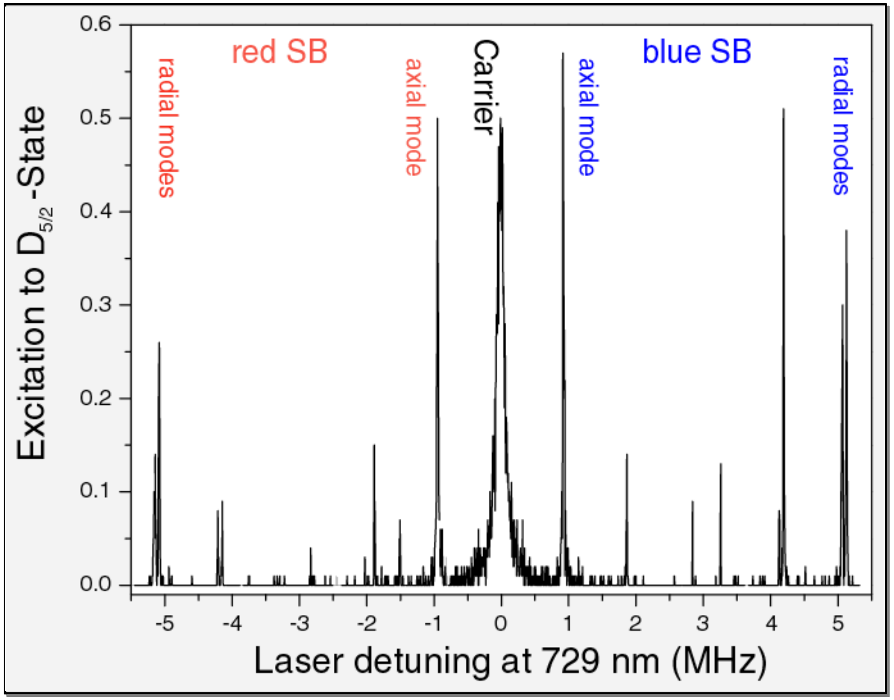
Ion motion



2-level-atom
harmonic trap
$|D\rangle$
$|S\rangle$
$\hbar\omega_0$
$\otimes$
$|2\rangle$
$|1\rangle$
$|0\rangle$
$\hbar\nu$

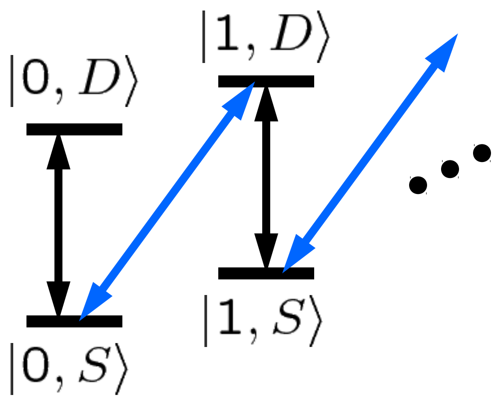


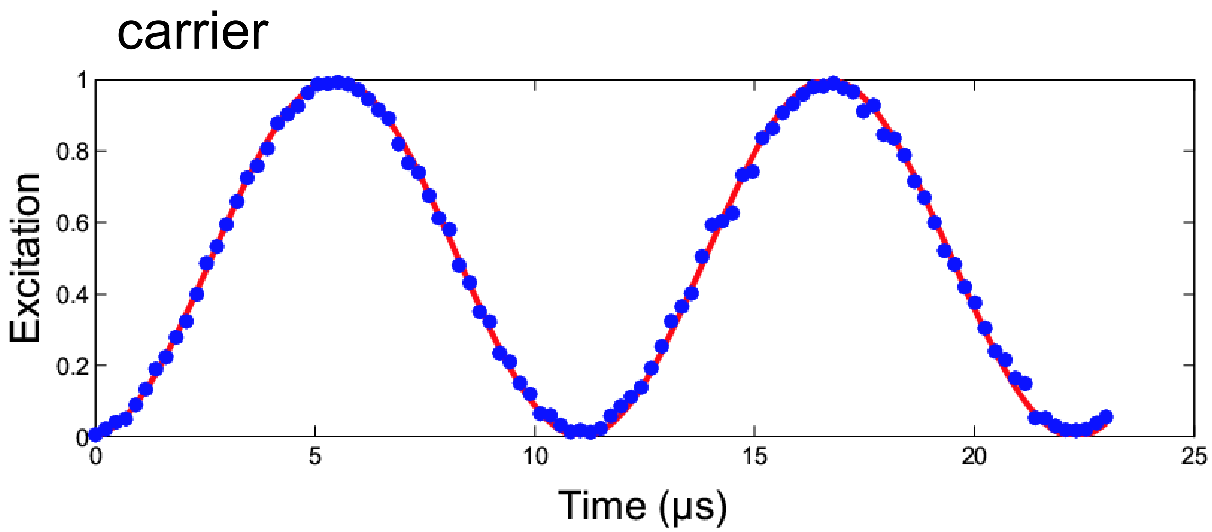
joint energy levels
$|D,0\rangle$
$|D,1\rangle$
$|D,2\rangle$
$|S,0\rangle$
$|S,1\rangle$
$|S,2\rangle$
...



red SB
blue SB
radial modes
axial mode
Carrier
axial mode
radial modes
Excitation to $D_{5/2}$ -State
Laser detuning at 729 nm (MHz)
0.0
0.1
0.2
0.3
0.4
0.5
0.6
-5
-4
-3
-2
-1
0
1
2
3
4
5

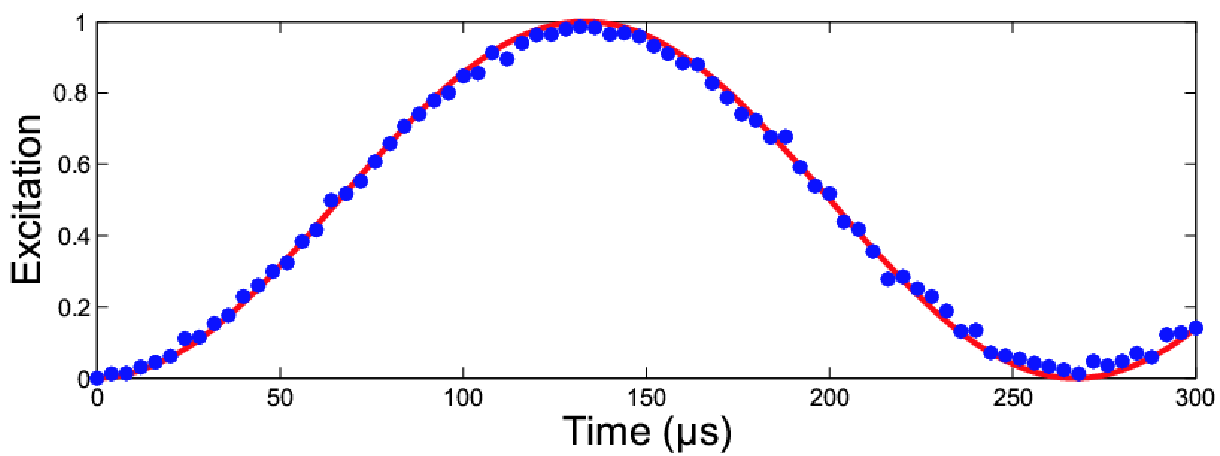
Ion motion





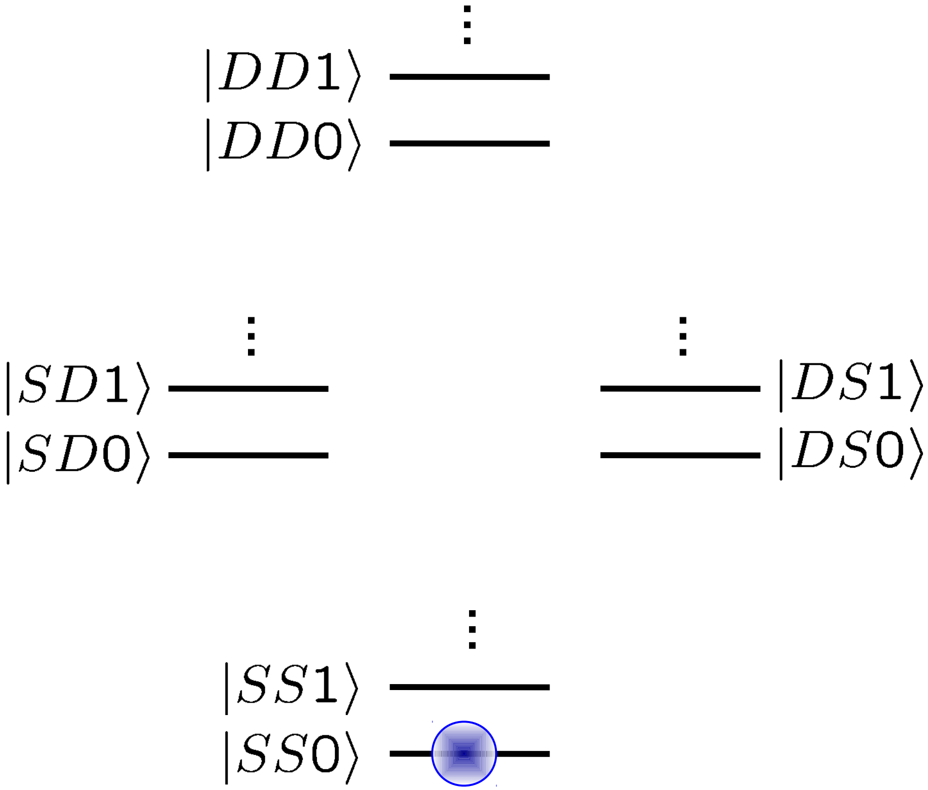
carrier and sideband
Rabi oscillations
with Rabi frequencies

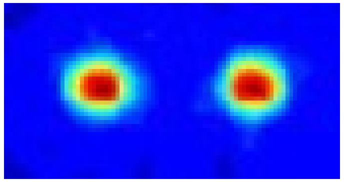
$$\Omega, \quad \eta\Omega$$



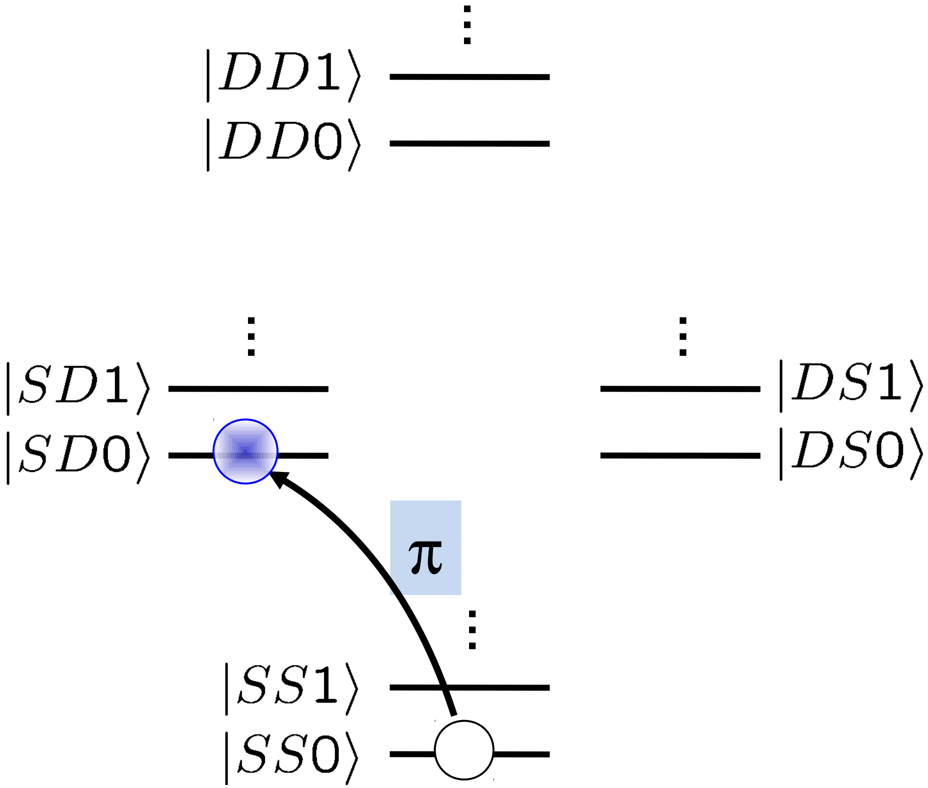
$\eta = kx_0$ Lamb-Dicke parameter

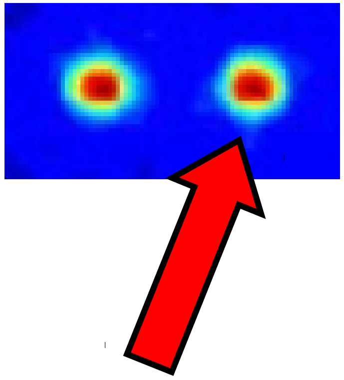
Generation of Bell states



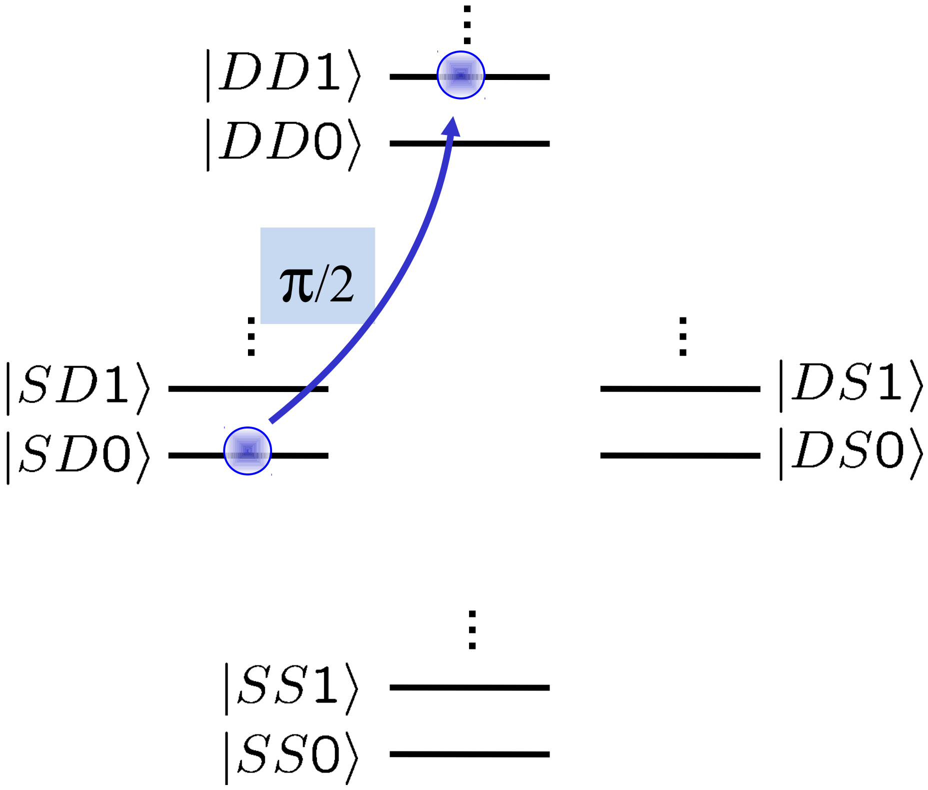


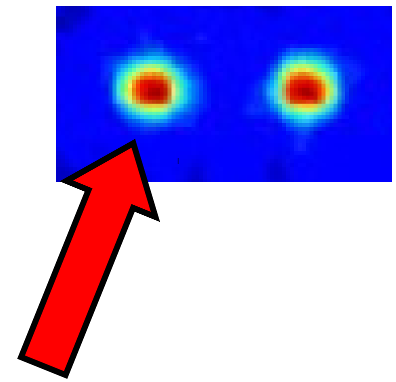
Generation of Bell states



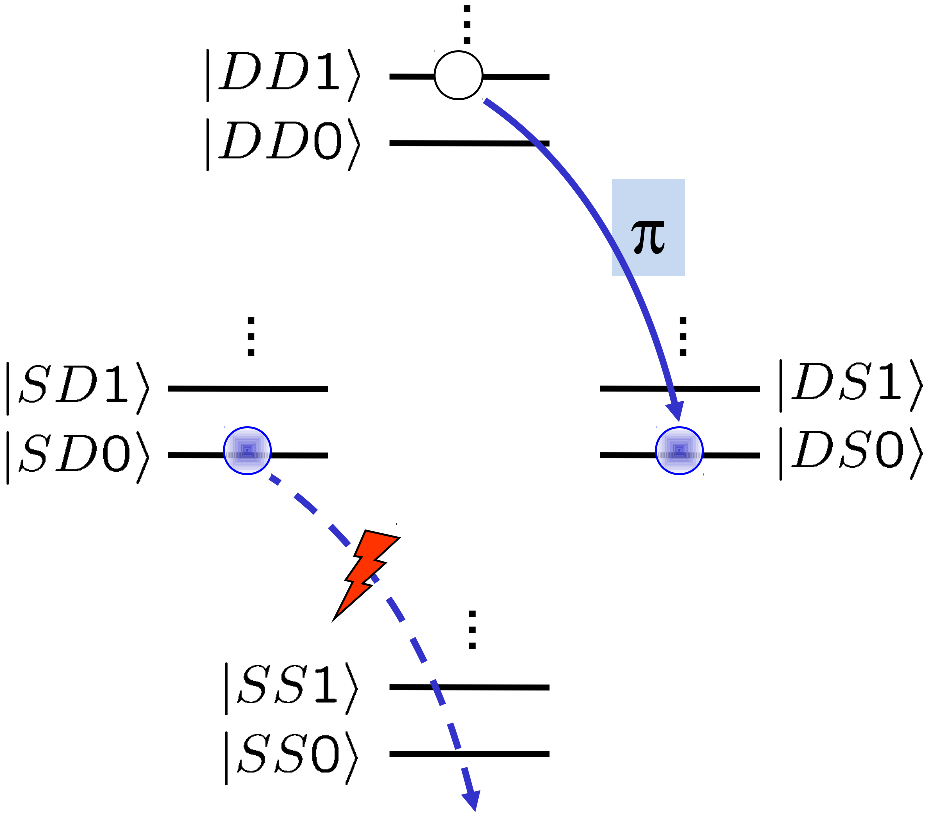


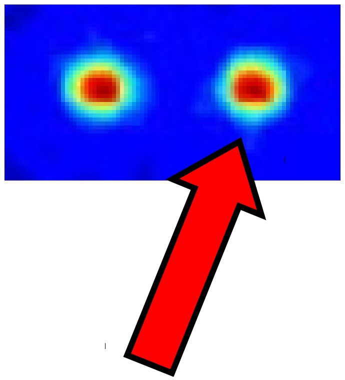
Generation of Bell states



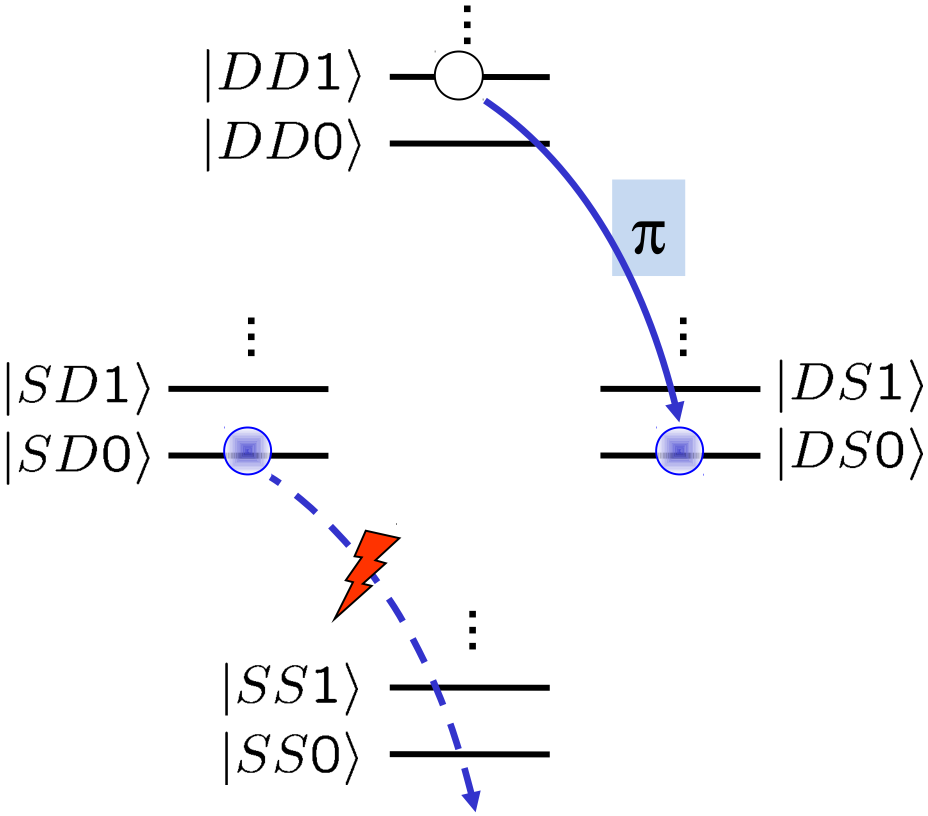


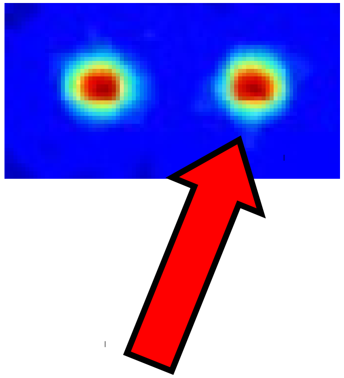
Generation of Bell states





Generation of Bell states





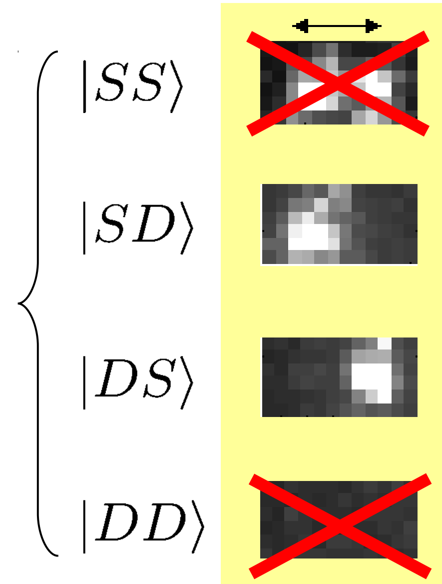
<u>Bell states with atoms</u>

- $^{9}Be^{+}$: NIST (fidelity: 97 %)
- $^{40}Ca^{+}$: Oxford (99.6 %)
- $^{111}Cd^{+}$: Ann Arbor (79%)
- ^{171}Yb: Maryland (96%)
- $^{25}Mg^{+}$: Munich (97%)
- $^{40}Ca^{+}$: Innsbruck (99.3%)

Analysis of Bell states

$$|SD\rangle + |DS\rangle$$

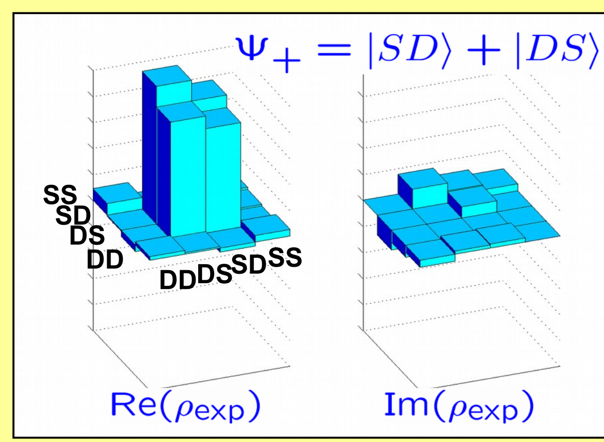
Fluorescence detection with CCD camera:



Coherent superposition or incoherent mixture ?

What is the relative phase of the superposition ?

➡ Measurement of the density matrix:



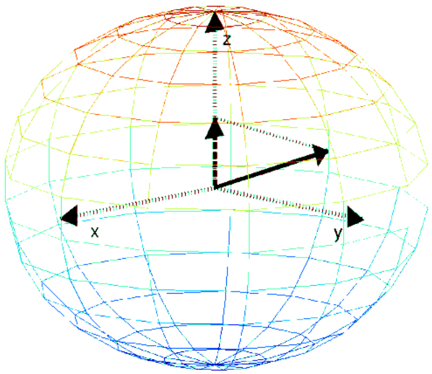
Measuring a density matrix

A measurement yields the *z*-component of the Bloch vector

=> Diagonal of the density matrix

$$\rho = \begin{pmatrix} P_S & C - iD \\ C + iD & P_D \end{pmatrix}$$

$|D\rangle$



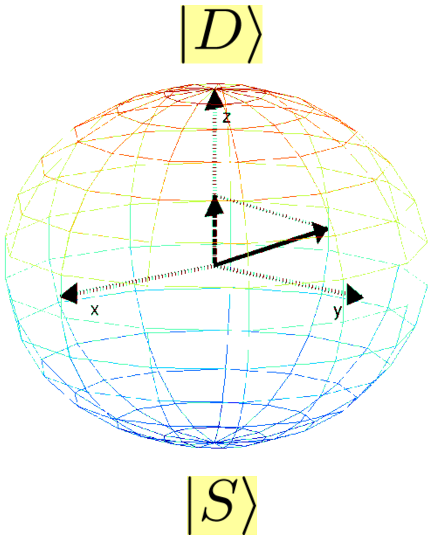
$|S\rangle$

Measuring a density matrix

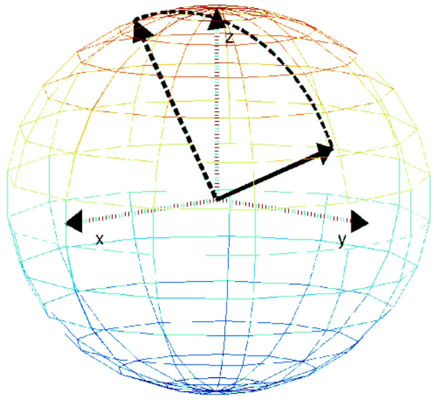
A measurement yields the *z*-component of the Bloch vector

=> Diagonal of the density matrix

$$\rho = \begin{pmatrix} P_S & C - iD \\ C + iD & P_D \end{pmatrix}$$



Rotation around the *x*- or the *y*-axis prior to the measurement yields the phase information of the qubit.



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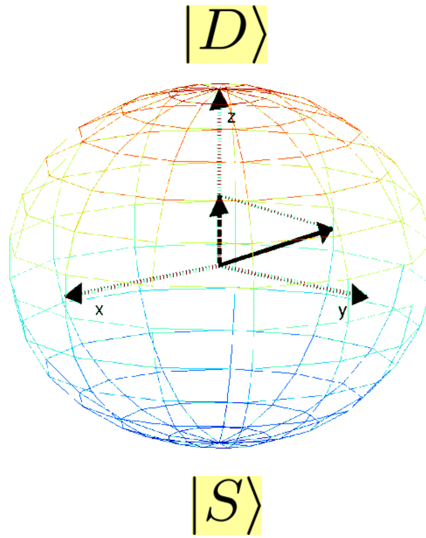
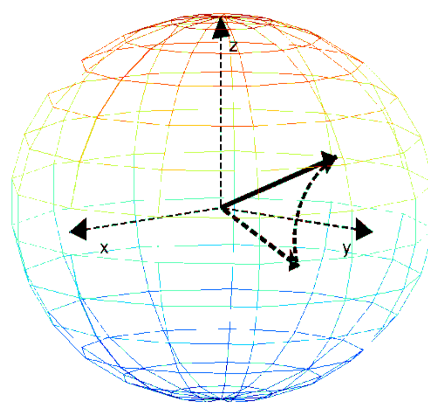
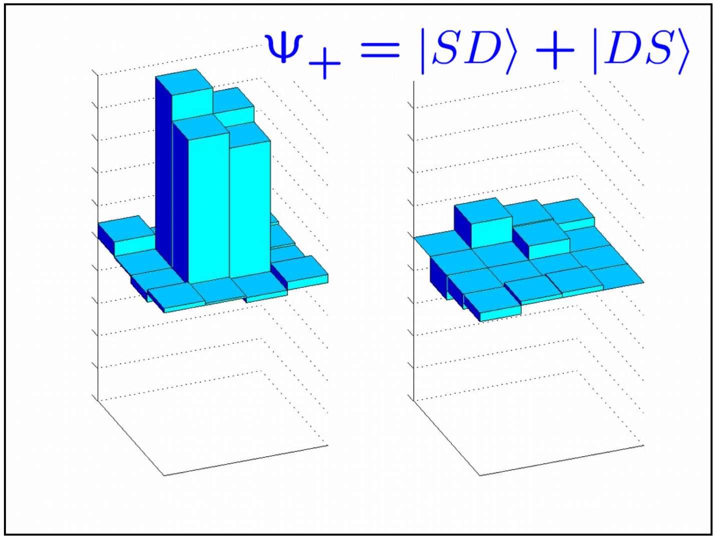


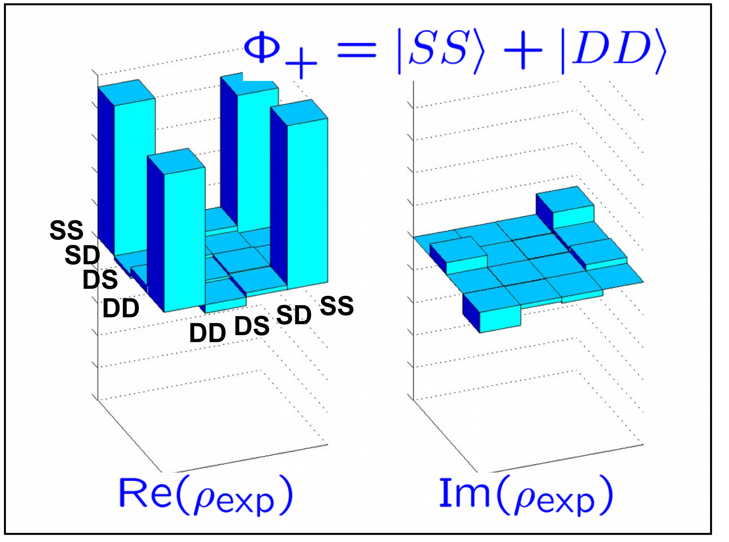
Rotation around the *x*- or the *y*-axis prior to the measurement yields the phase information of the qubit.

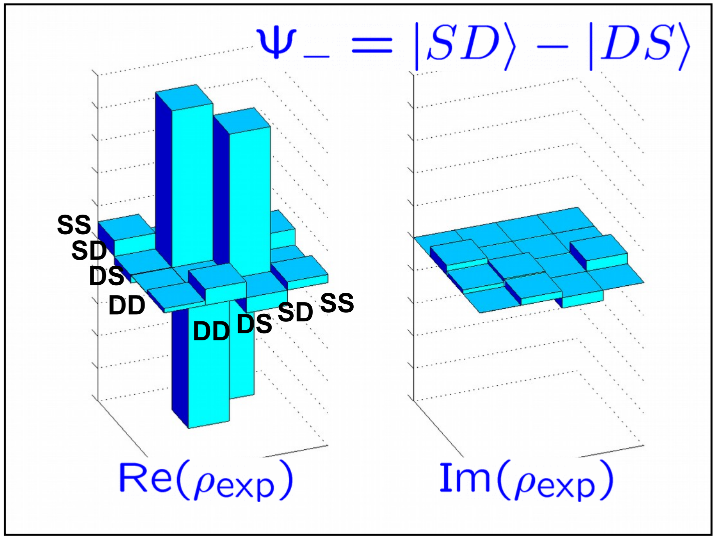
=> coherences of the density m

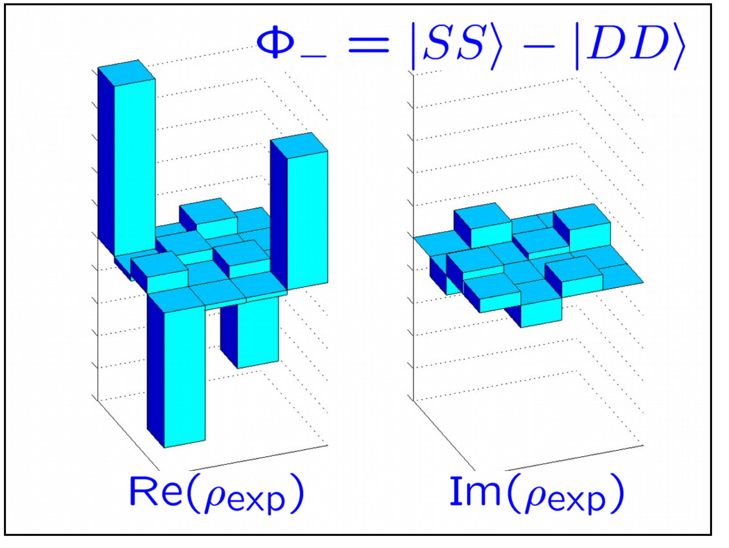


Bell states


$\Psi_+ = |SD\rangle + |DS\rangle$

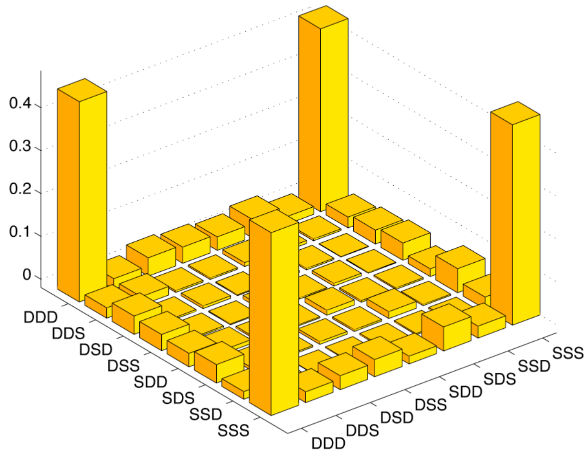

$\Phi_+ = |SS\rangle + |DD\rangle$
SS
SD
DS
DD
DD DS SD SS
$\mathrm{Re}(\rho_{exp})$
$\mathrm{Im}(\rho_{exp})$


$\Psi_- = |SD\rangle - |DS\rangle$
SS
SD
DS
DD
DD DS SD SS
$\mathrm{Re}(\rho_{exp})$
$\mathrm{Im}(\rho_{exp})$

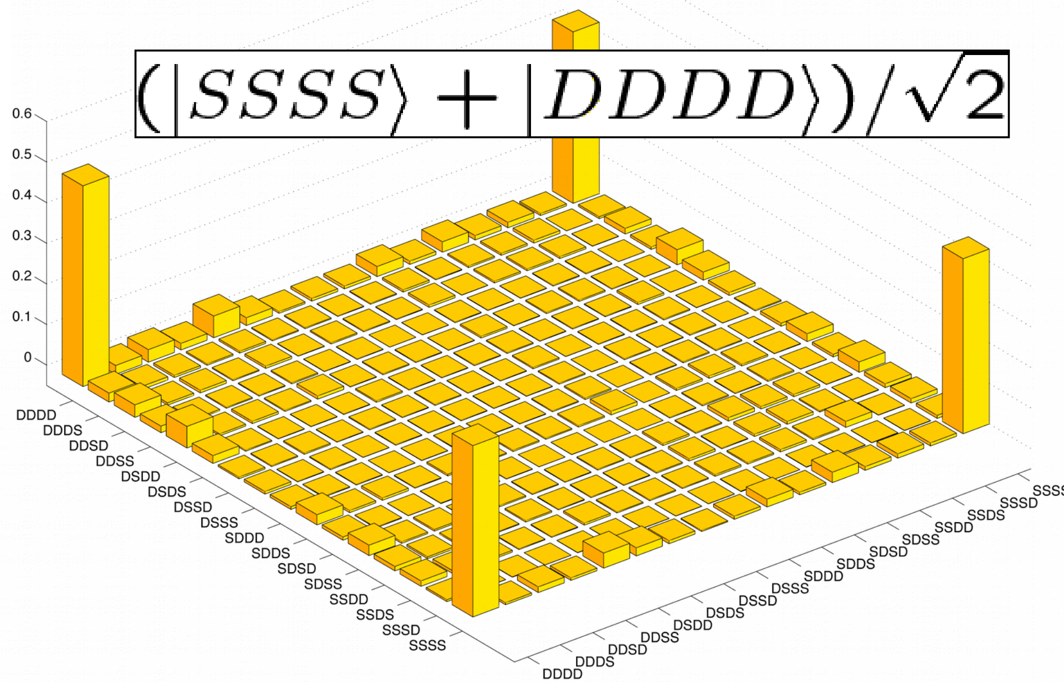

$\Phi_- = |SS\rangle - |DD\rangle$
$\mathrm{Re}(\rho_{exp})$
$\mathrm{Im}(\rho_{exp})$

Generalized Bell states

$$(|SSS\rangle + |DDD\rangle)/\sqrt{2}$$

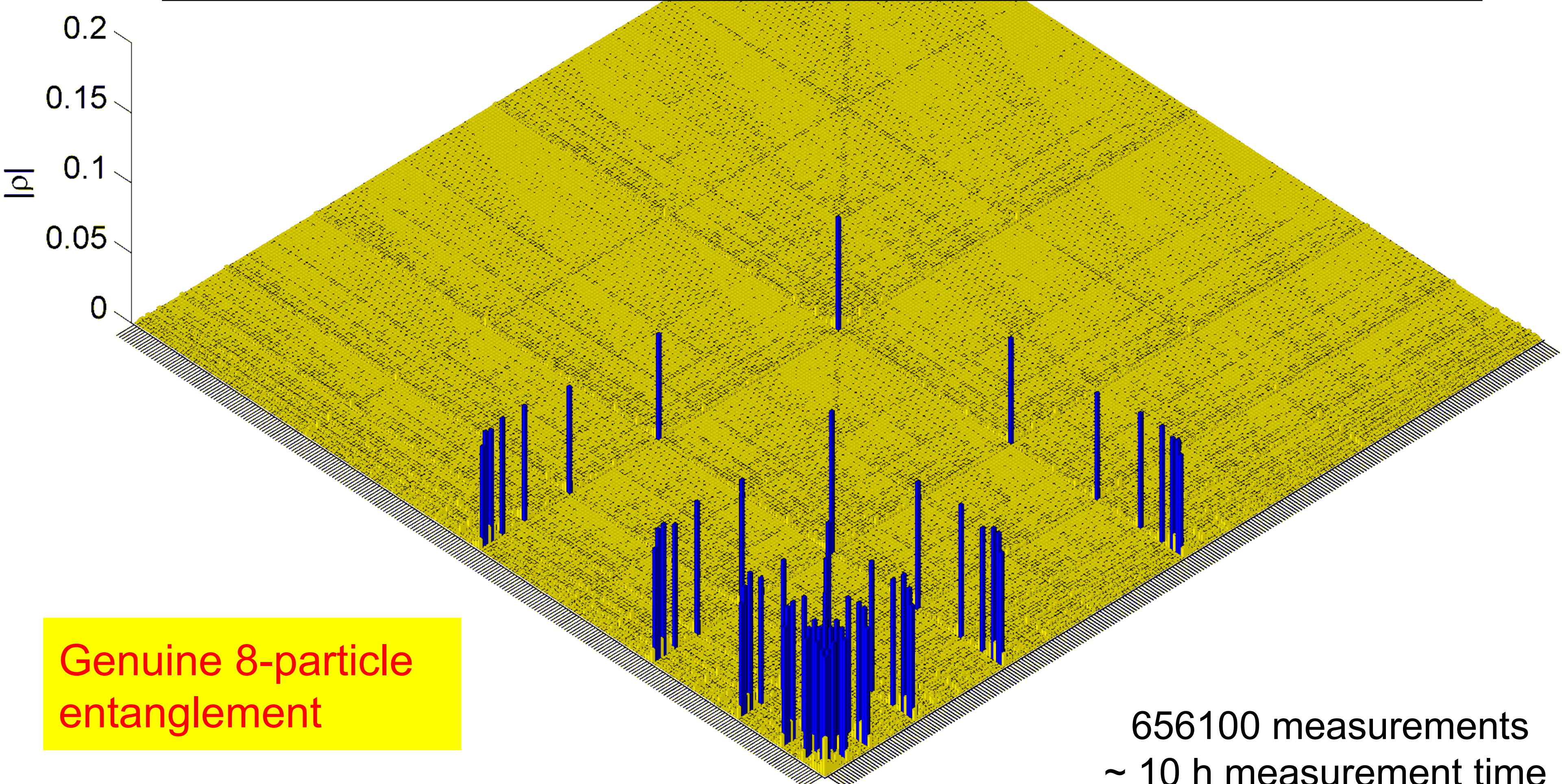


$$(|SSSS\rangle + |DDDD\rangle)/\sqrt{2}$$



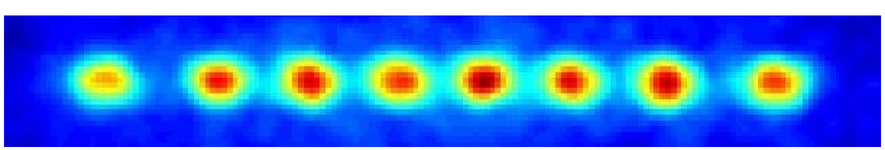
Generalized Bell states

$$\frac{1}{\sqrt{8}}(|DDDDDDDS\rangle + |DDDDDDSD\rangle + \ldots + |SDDDDDDD\rangle)$$



Genuine 8-particle entanglement

656100 measurements
~ 10 h measurement time



Häffner et al., Nature **438**, 643 (2005)

Universal set of quantum gates …

Having the qubits interact

VOLUME 74, NUMBER 20 PHYSICAL REVIEW LETTERS 15 MAY 1995

Quantum Computations with Cold Trapped Ions

J. I. Cirac and P. Zoller*
Institut für Theoretische Physik, Universiät Innsbruck, Technikerstrasse 25, A-6020 Innsbruck, Austria
(Received 30 November 1994)

A quantum computer can be implemented with cold ions confined in a linear trap and interacting with laser beams. Quantum gates involving any pair, triplet, or subset of ions can be realized by coupling the ions through the collective quantized motion. In this system decoherence is negligible, and the measurement (readout of the quantum register) can be carried out with a high efficiency.

PACS numbers: 89.80.+h, 03.65.Bz, 12.20.Fv, 32.80.Pj

...allows the realization of a
universal quantum computer !

$$|D\rangle|D\rangle \rightarrow |D\rangle|D\rangle$$

$$|D\rangle|S\rangle \rightarrow |D\rangle|S\rangle$$

$$|S\rangle|D\rangle \rightarrow |D\rangle|S\rangle$$

$$|S\rangle|S\rangle \rightarrow |S\rangle|D\rangle$$

control target

Having the qubits interact

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$$|D\rangle|D\rangle \rightarrow |D\rangle|D\rangle$$

$$|D\rangle|S\rangle \rightarrow |D\rangle|S\rangle$$

$$|S\rangle|D\rangle \rightarrow |D\rangle|S\rangle$$

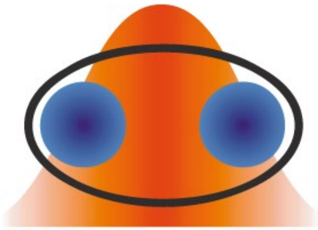
$$|S\rangle|S\rangle \rightarrow |S\rangle|D\rangle$$

control target

Most popular gates:

- Cirac-Zoller gate (Schmidt-Kaler et al., Nature **422,** 408 (2003)).
- Geometric phase gate (Leibfried et al., Nature **422,** 412 (2003)).
- Mølmer-Sørensen gate (Sackett et al., Nature **404**, 256 (2000)).

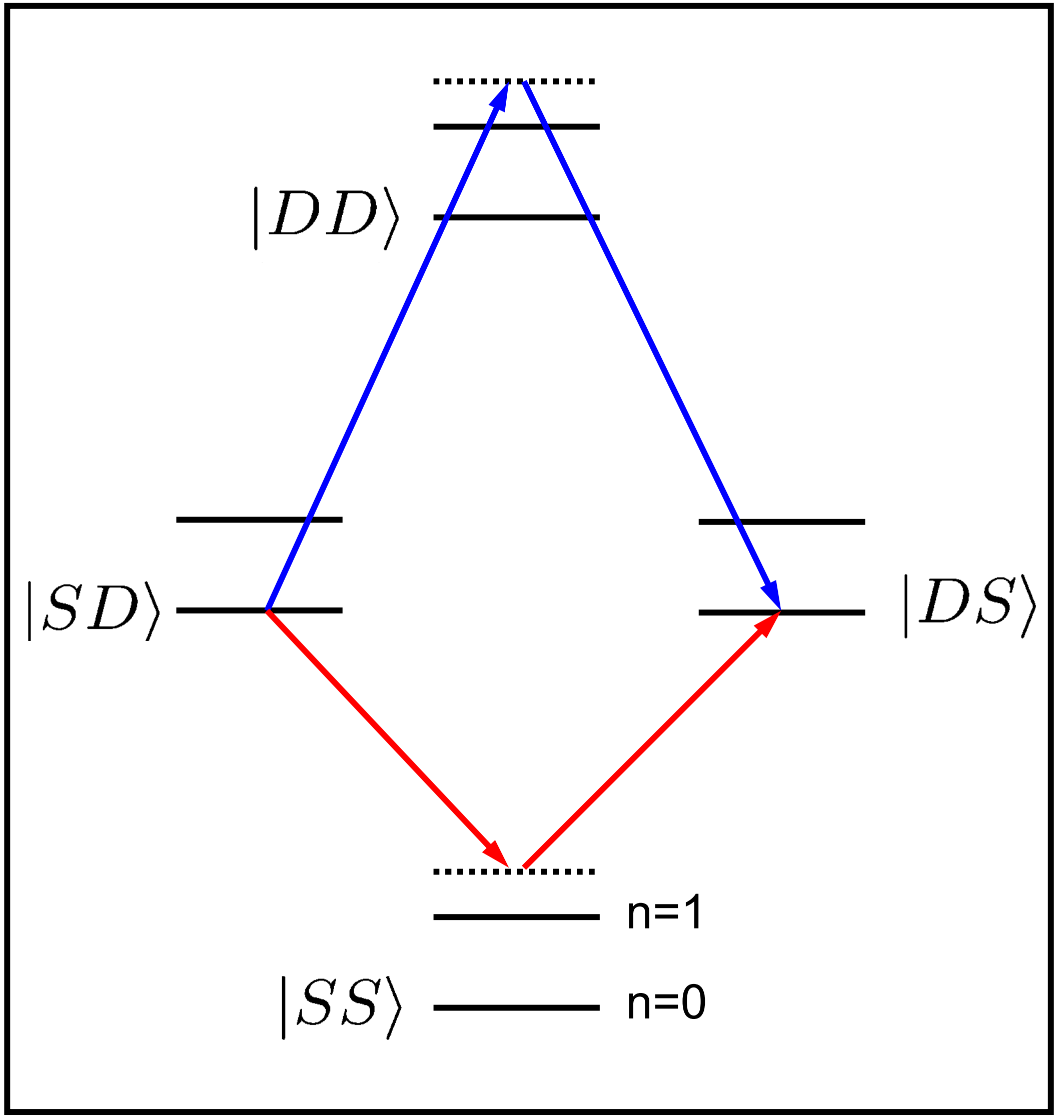
Mølmer-Sørensen gate creates entangled states



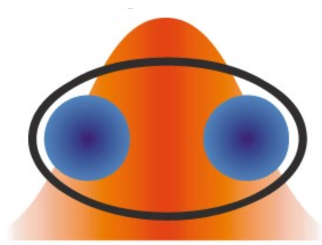
Raman transitions between

$$|SD\rangle \quad \Leftrightarrow \quad |DS\rangle$$

Interaction of two ions via common motion.



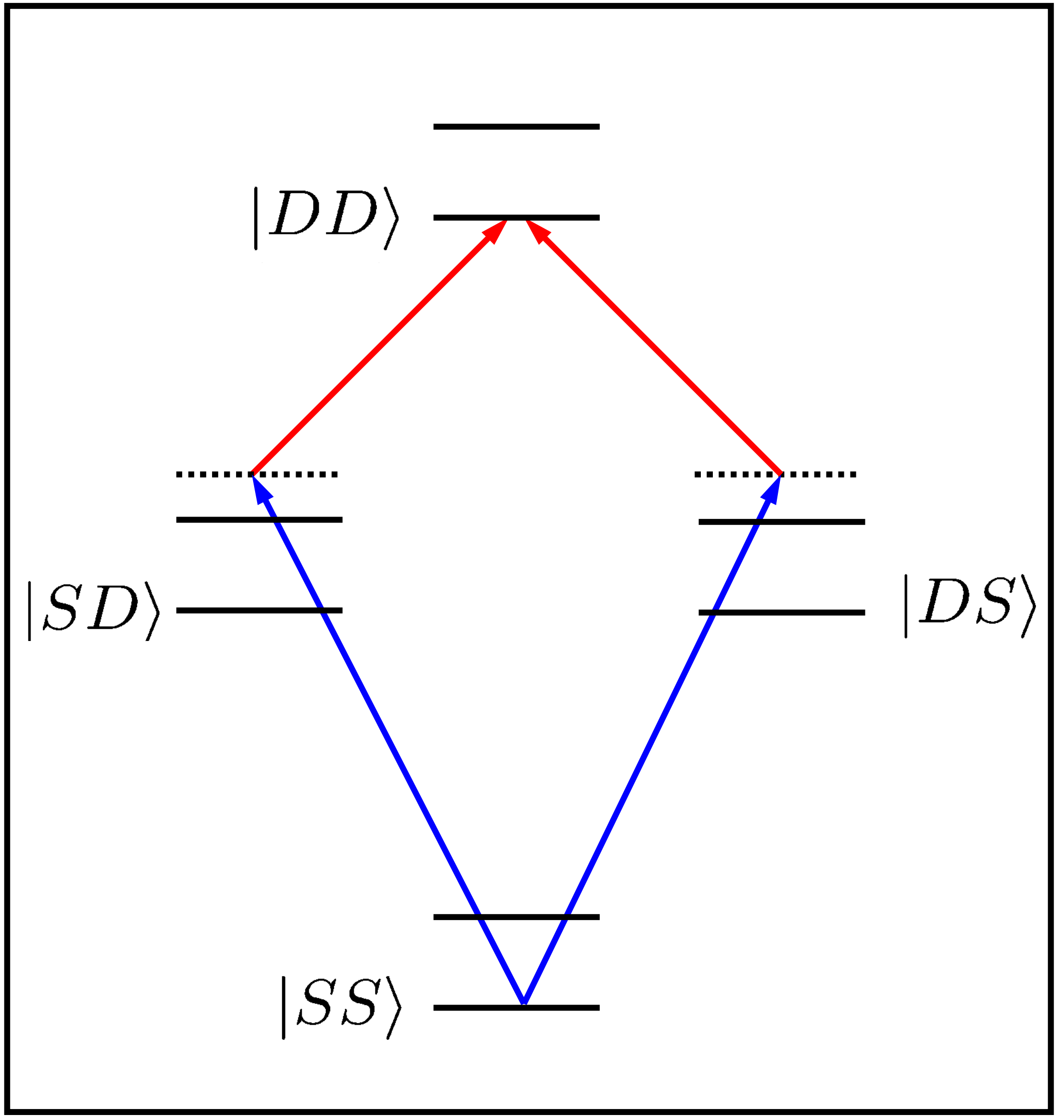
Mølmer-Sørensen gate creates entangled states



Raman transitions between

$$|SS\rangle \quad \Leftrightarrow \quad |DD\rangle$$

Interaction of two ions via common motion.



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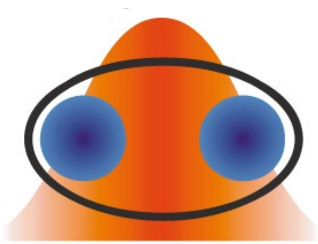

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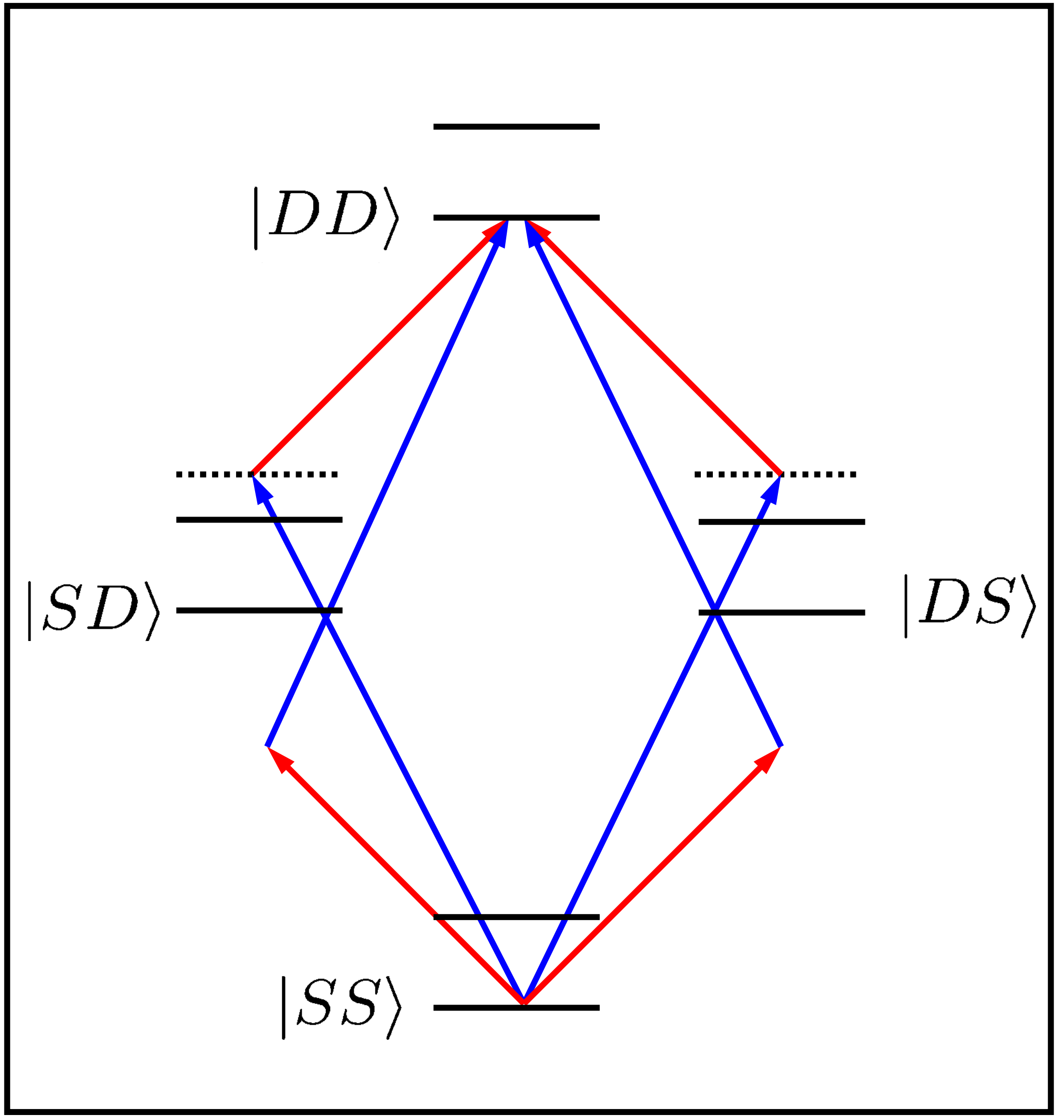
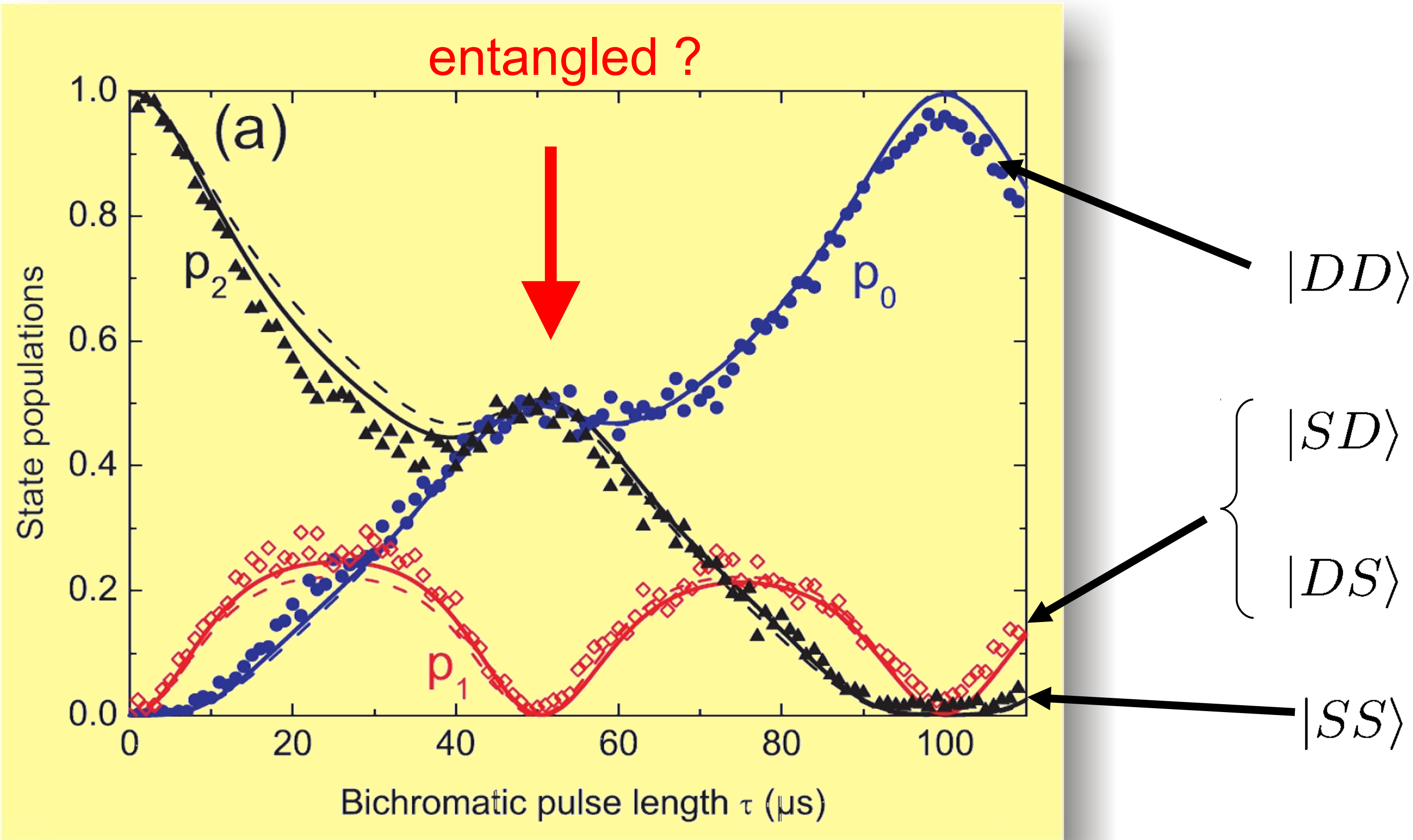


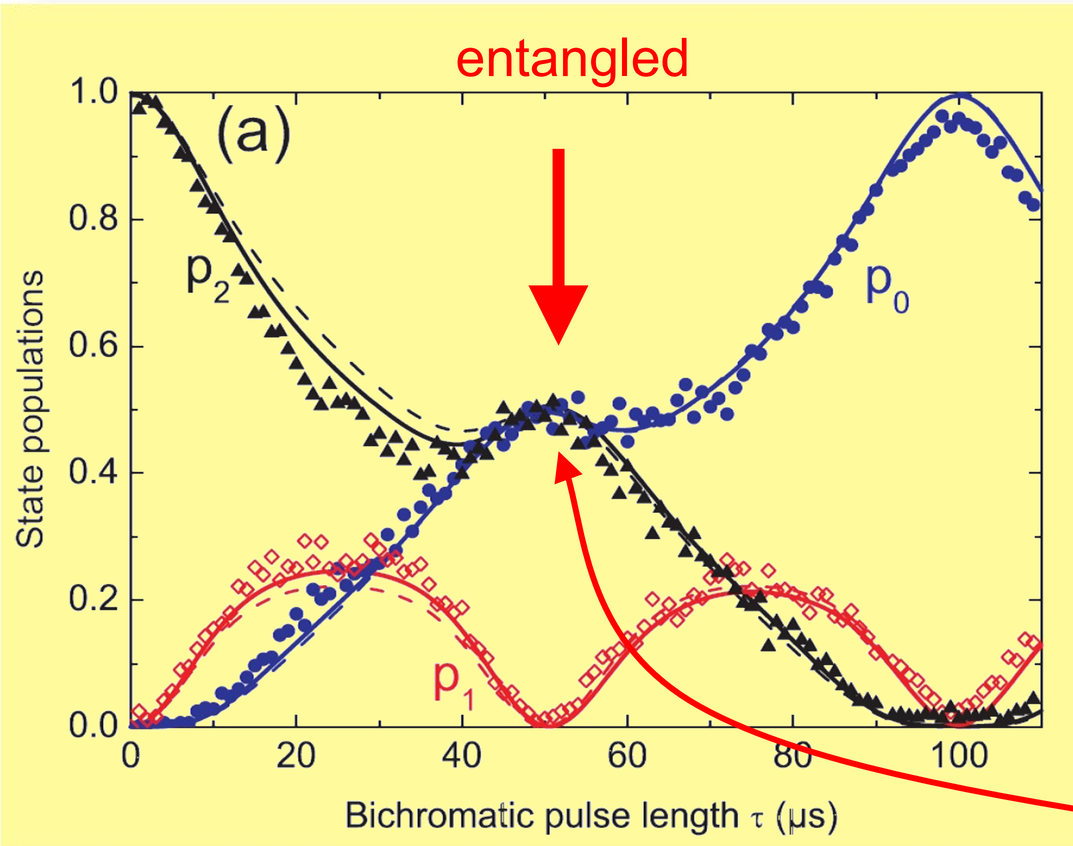
Entangling ions



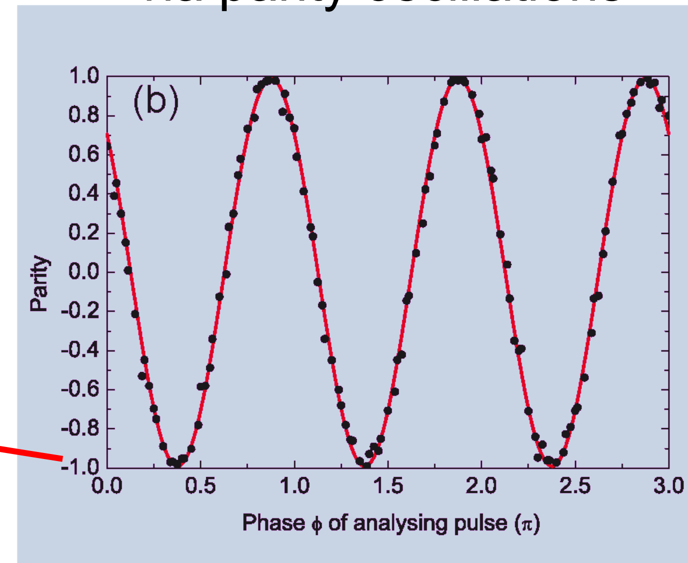
J. Benhelm et al., Nature Physics **4**, 463 (2008)

Theory: C. Roos, NJP **10,** 013002 (2008)

Entangling ions



measure entanglement
via parity oscillations



gate duration 51 μs

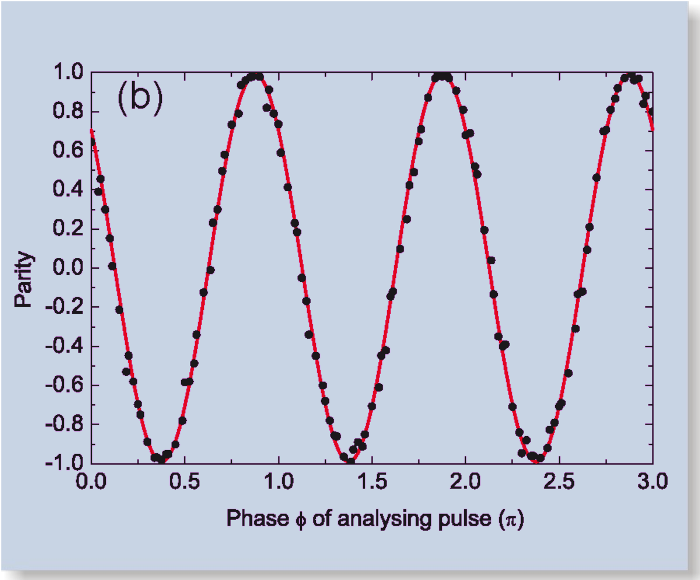
average fidelity: 99.3 (2) %

$$|00\rangle + |11\rangle \xrightarrow{R_2^C(\pi/2,\varphi),R_1^C(\pi/2,\varphi)}$$

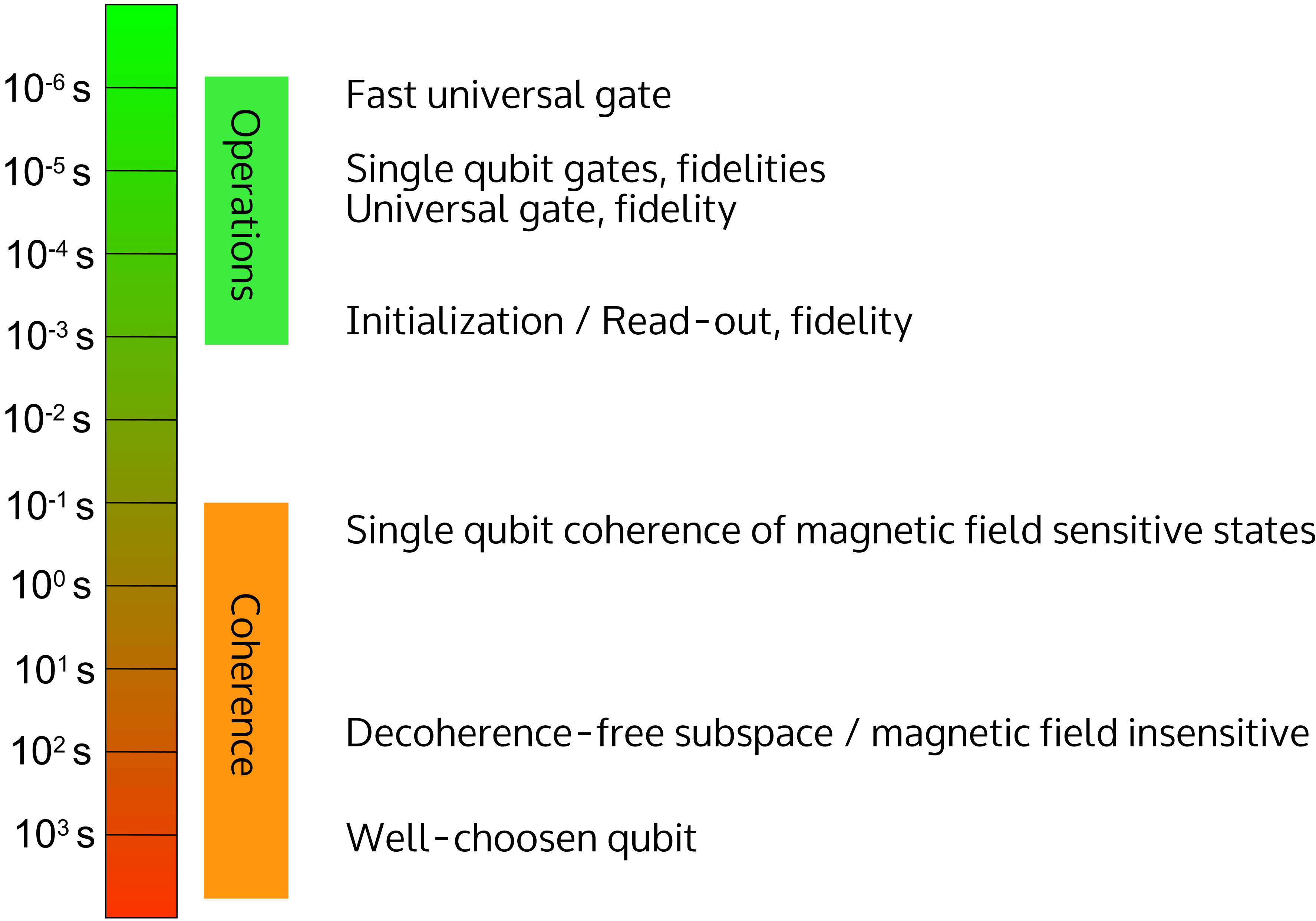
$$\left(|0\rangle + ie^{i\varphi}|1\rangle\right)\left(|0\rangle + ie^{i\varphi}|1\rangle\right) + \left(|1\rangle + ie^{-i\varphi}|0\rangle\right)\left(|1\rangle + ie^{-i\varphi}|0\rangle\right)$$

$$= (1 - e^{-2i\varphi})|00\rangle + ie^{i\varphi}(1 + e^{-2i\varphi})|01\rangle$$

$$+ ie^{i\varphi}(1 + e^{-2i\varphi})|10\rangle + (1 - e^{-2i\varphi})|11\rangle\,,$$



Achieved times scales for ion trap QIP



The DiVincenczo criteria for quantum computing

I. Scalable physical system, well characterized qubits √

II. Ability to initialize the state of the qubits √

III. Long relevant coherence times, much longer than gate operation time √

IV. "Universal" set of quantum gates √

V. Qubit-specific measurement capability √

The DiVincenczo criteria for quantum computing

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II. Ability to initialize the state of the qubits with sufficient fidelity

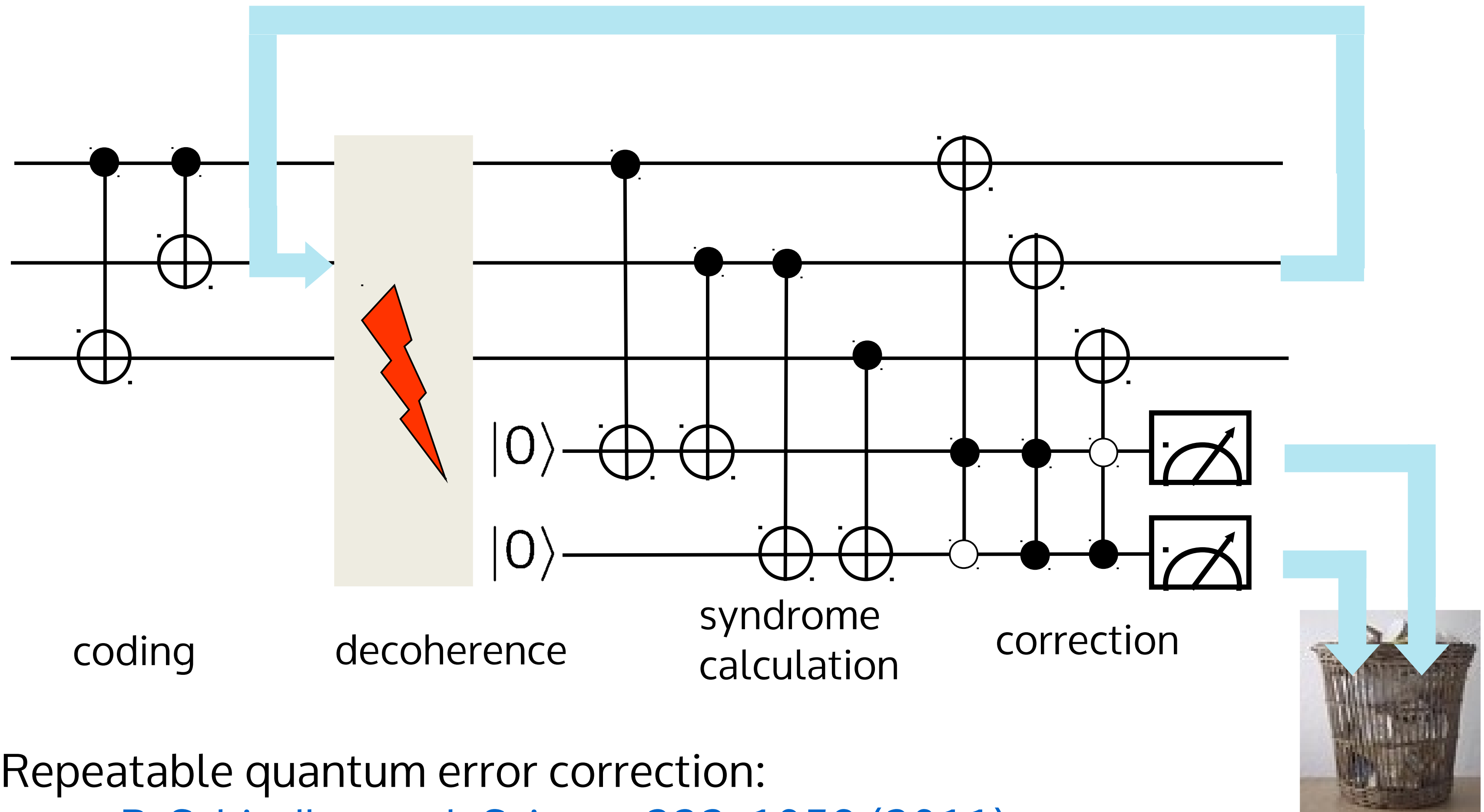
III. Long relevant coherence times, much longer than gate operation time

IV. "Universal" set of quantum gates with sufficient fidelity

V. Qubit-specific measurement capability with sufficient fidelity

→ need to beat the fault-tolerant "threshold"

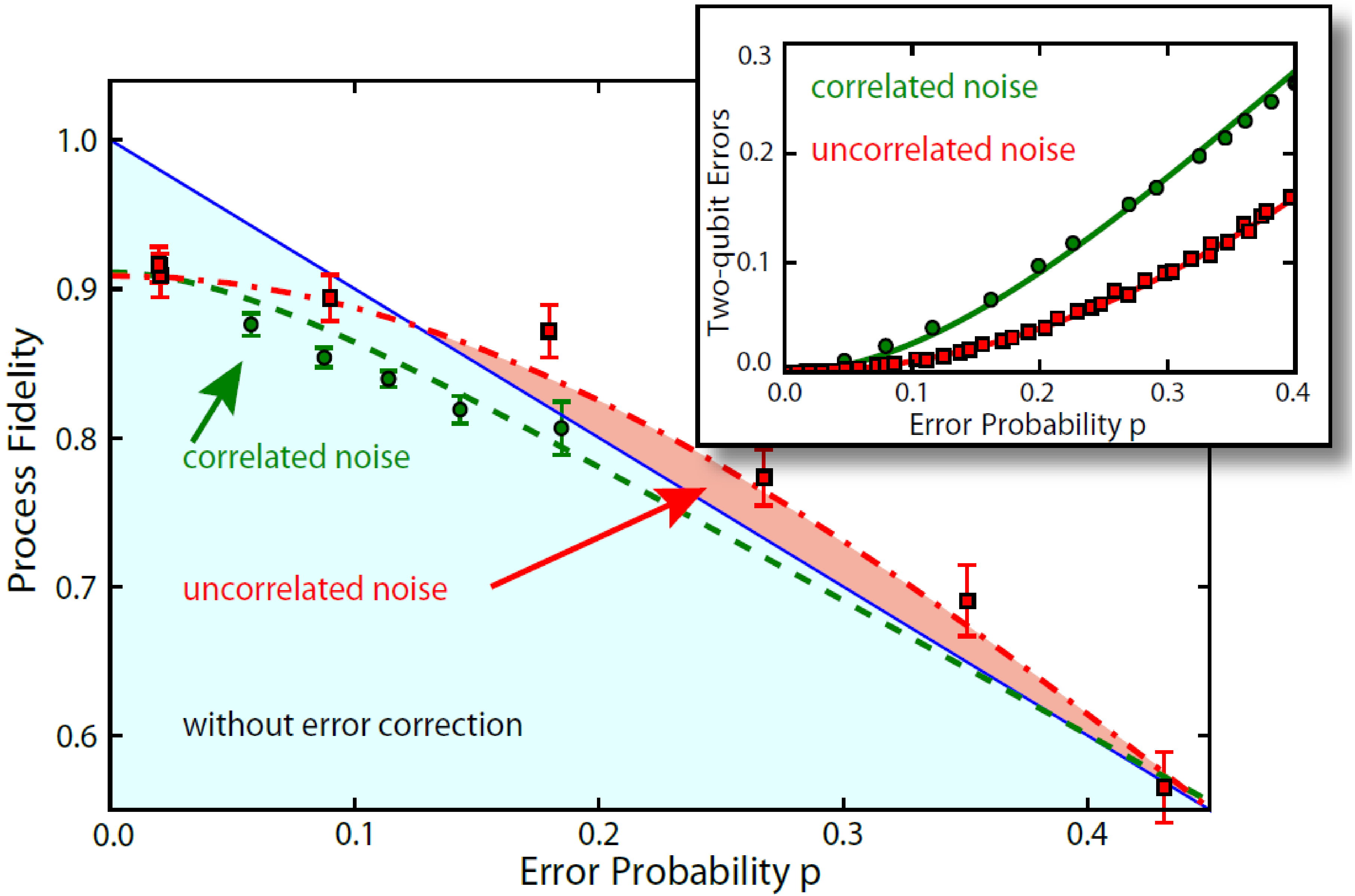
Quantum error correction



Repeatable quantum error correction:

P. Schindler et al, Science 332, 1059 (2011)

Consequences for QEC

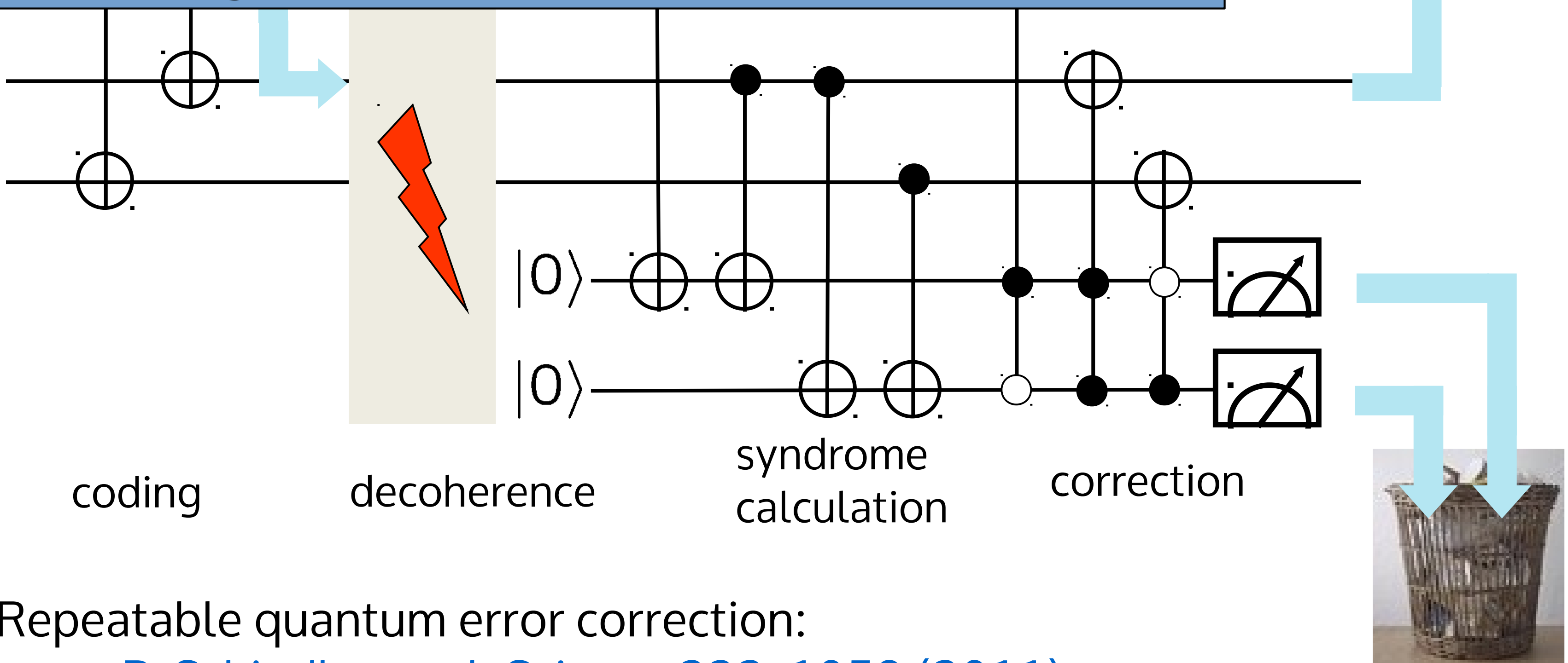


P. Schindler et al, Science (2011)

Threshold for quantum computing: 99.99% fidelity / operation

Status of ion-trap QIP:

- Initialization / Read-out: 99.5% – 99.99%
- Single qubit gates: 99% - 99.999%
- Universal gate: 99.9%



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Scaling of this approach?

Problems :

- Coupling strength between internal and motional states of a N-ion string decreases as

$$\eta \propto \frac{1}{\sqrt{N}}$$

(momentum transfer from photon to ion string becomes more difficult)

-> Gate operation speed slows down

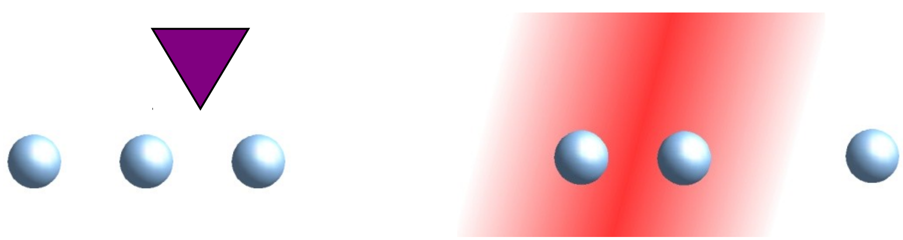
- More vibrational modes increase risk of spurious excitation of unwanted modes

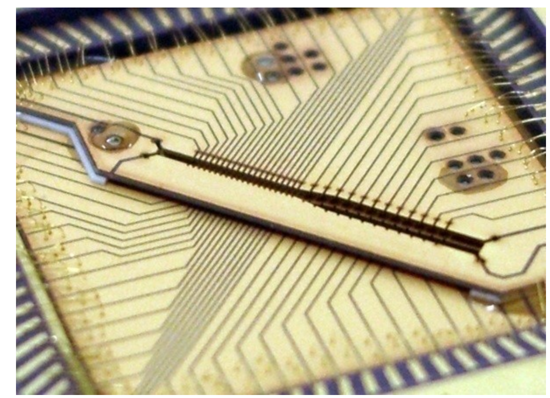
- Distance between neighbouring ions decreases -> addressing more difficult

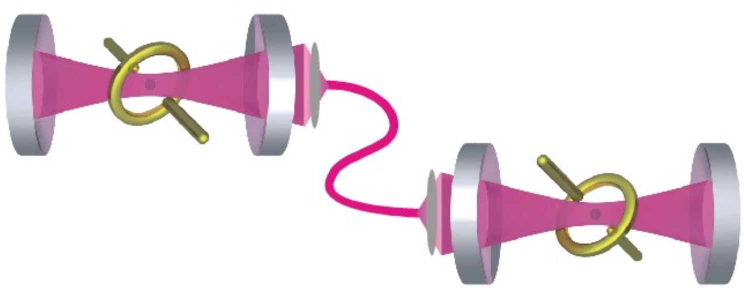
-> Use flexible trap potentials to split long ion string into smaller segments and perform operations on these smaller strings

Scaling of ion trap quantum computers

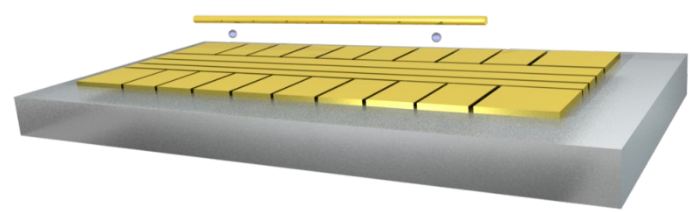
Kielpinski, Monroe, Wineland







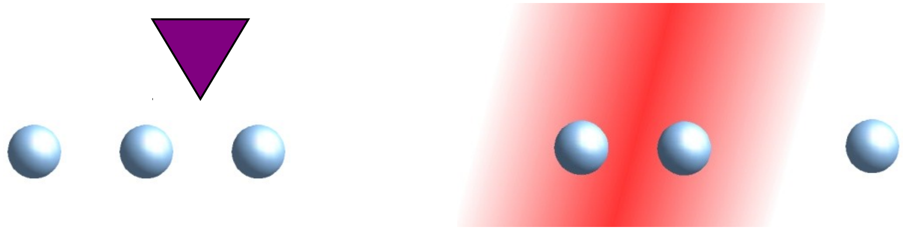
Cirac, Zoller, Kimble, Mabuchi

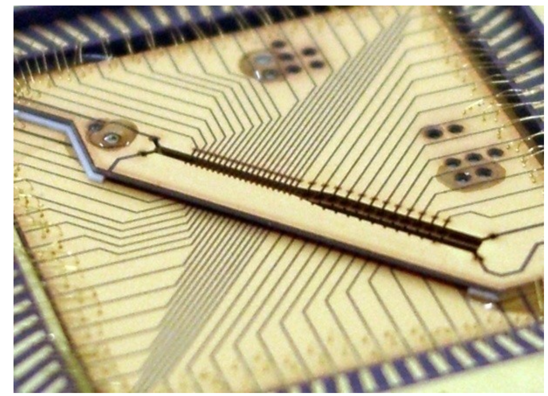


Zoller, Tian, Blatt

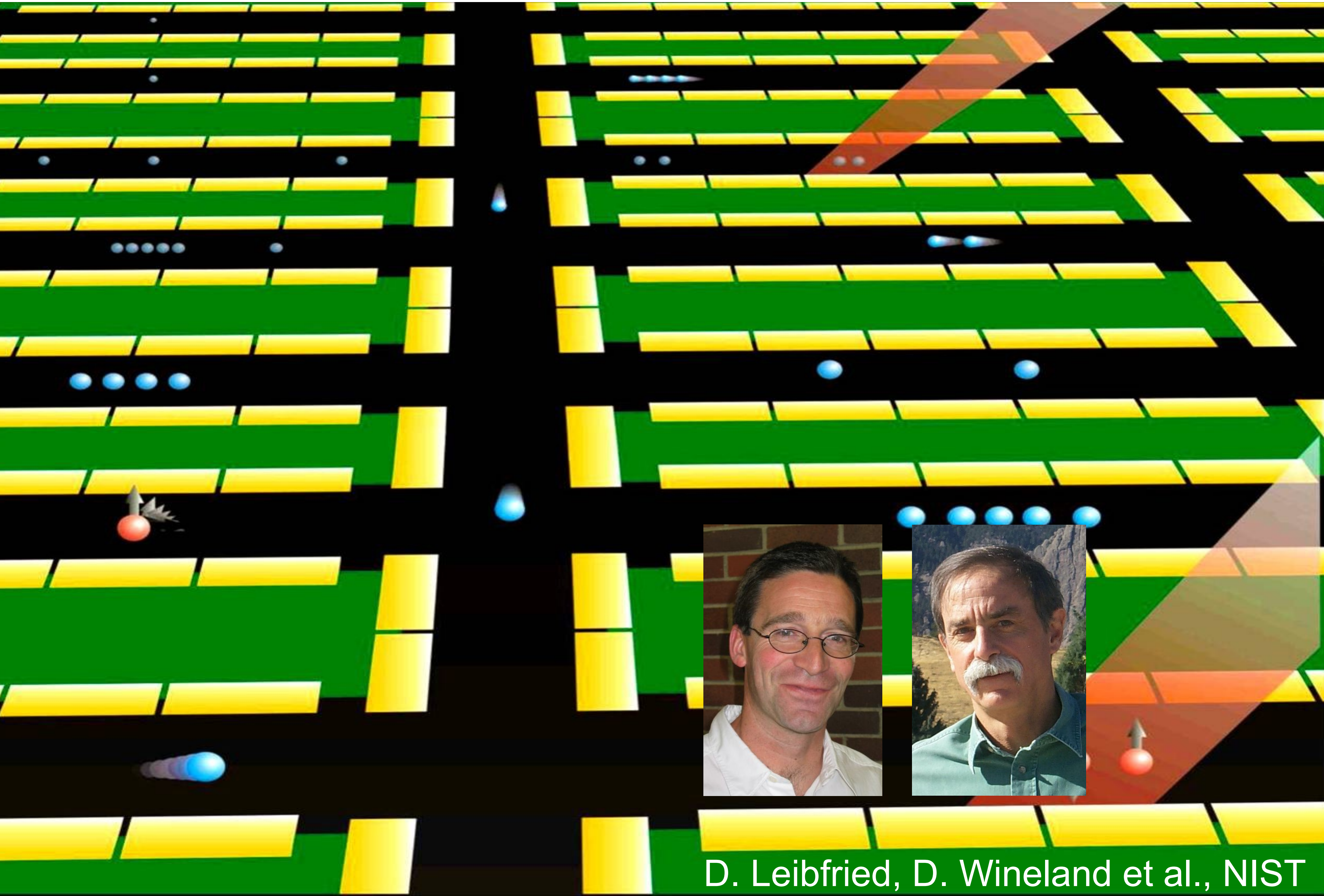
Scaling of ion trap quantum computers

Kielpinski, Monroe, Wineland



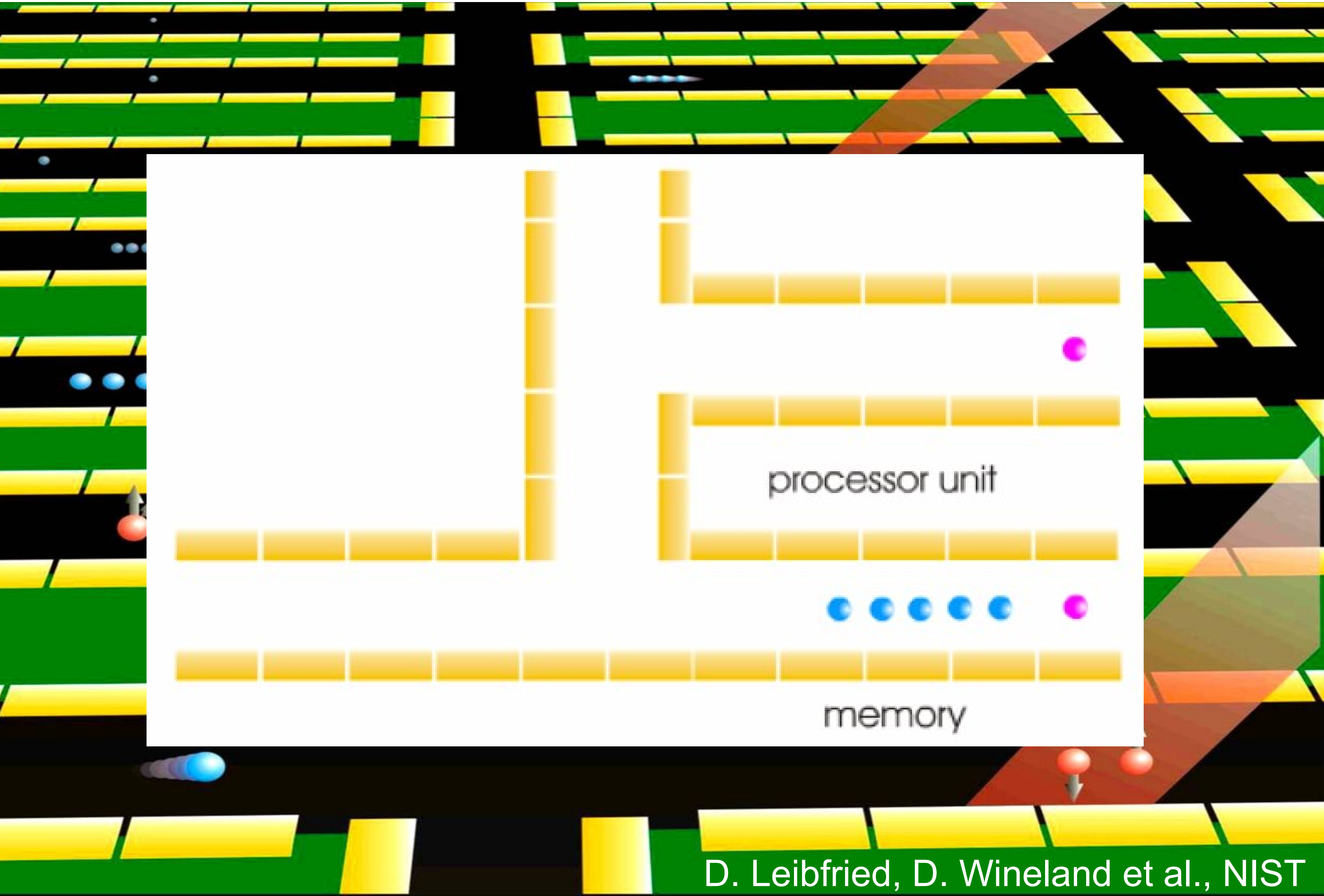


Scaling of ion trap quantum computers



D. Leibfried, D. Wineland et al., NIST

Scaling of ion trap quantum computers

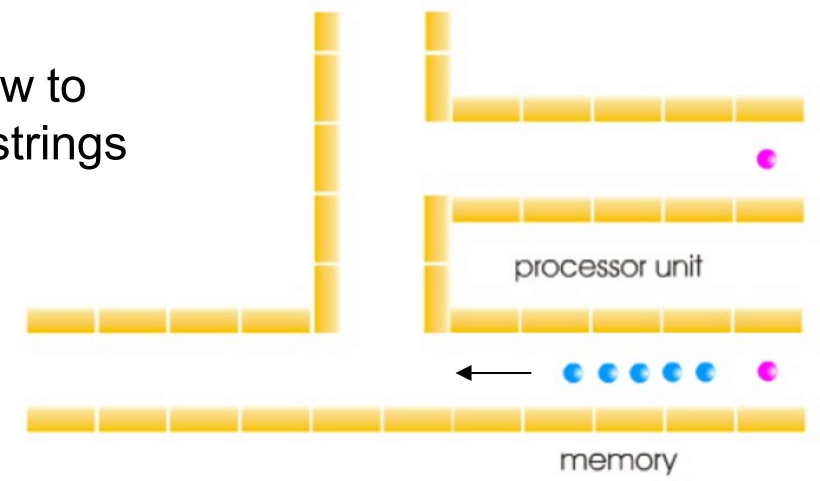


D. Leibfried, D. Wineland et al., NIST

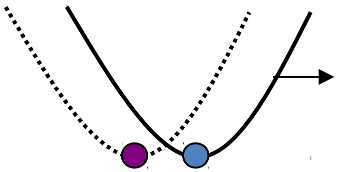
Segmented ion traps as scalable trap architecture

(ideas pioneered by D. Wineland, NIST)

Segmented trap electrode allow to transport ions and to split ion strings



State of the art:



<u>Transport of ions</u>

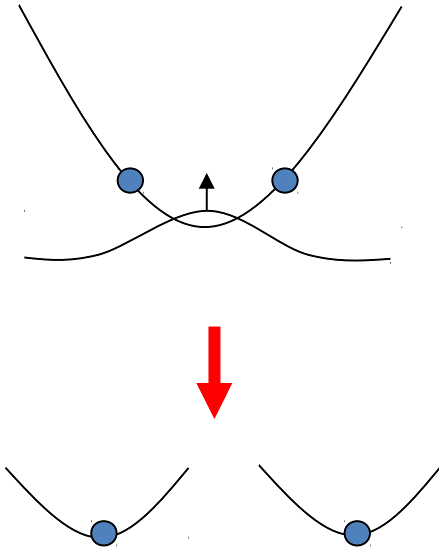
1 mm within 50 μs

no motional heating

<u>Splitting of two-ion crystal</u>

$t_{separation} \approx 200$ μs

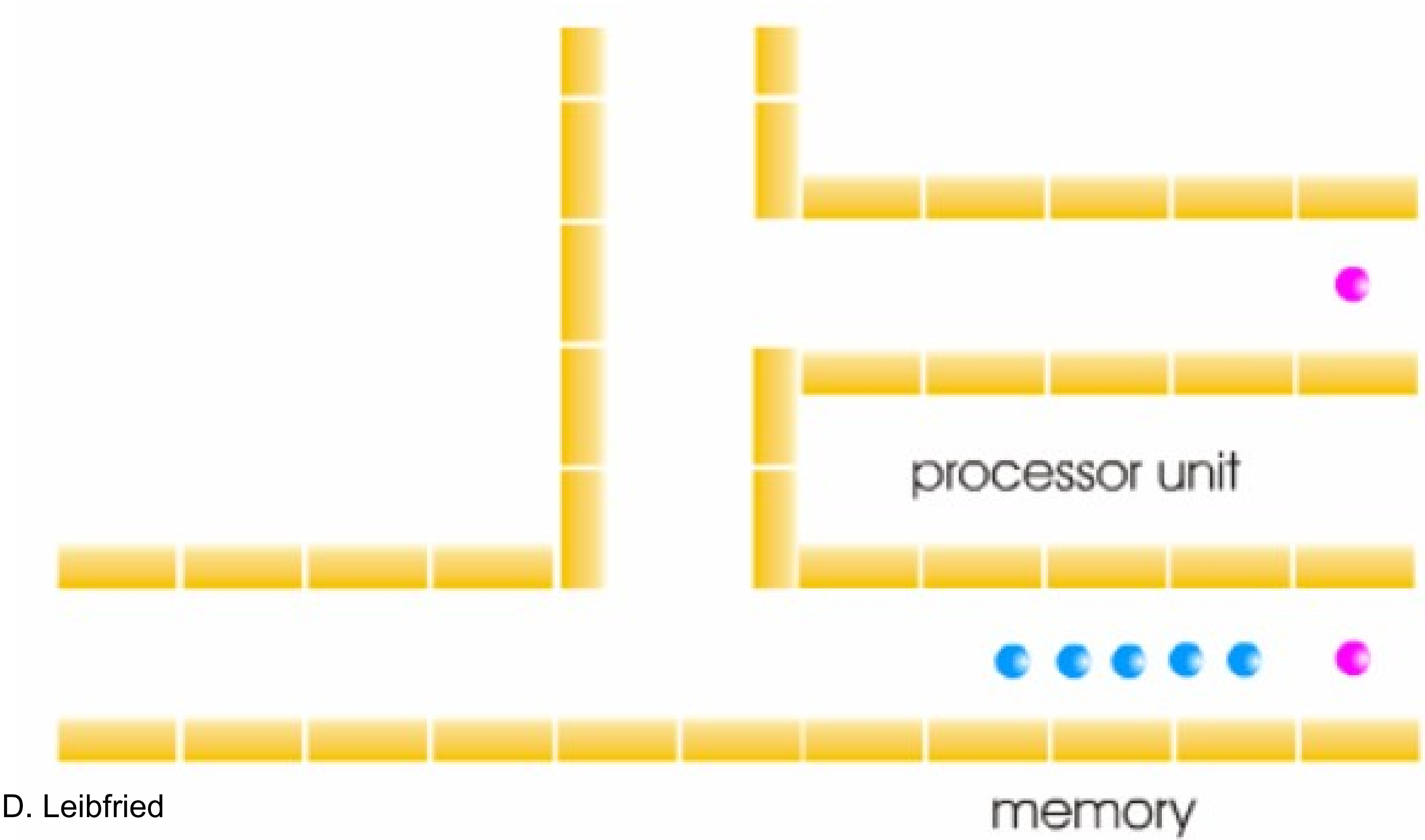
small heating n ≈1



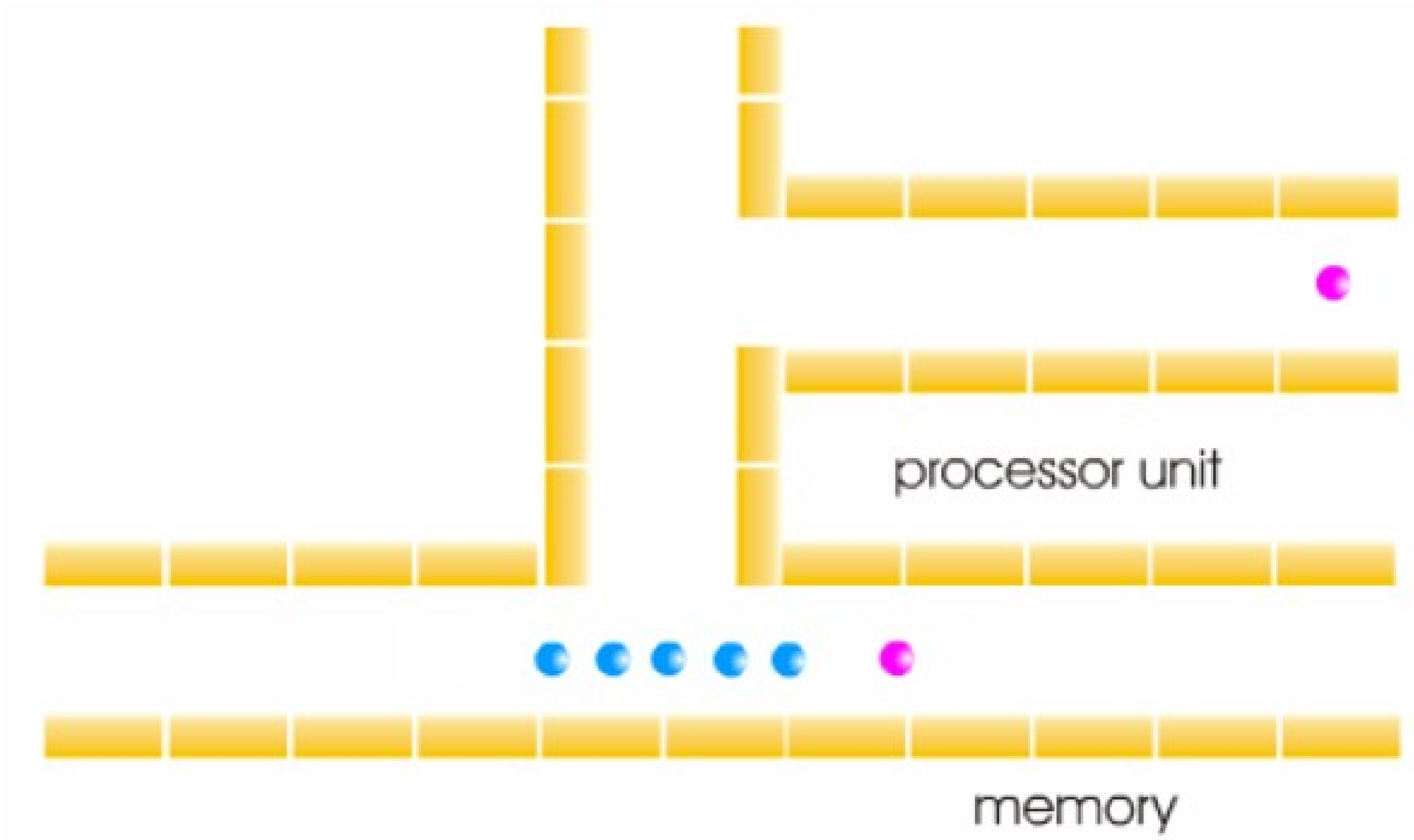
„Architecture for a large-scale ion-trap quantum computer", D. Kielpinski et al, Nature **417**, 709 (2002)

„Transport of quantum states", M. Rowe et al, quant-ph/0205084

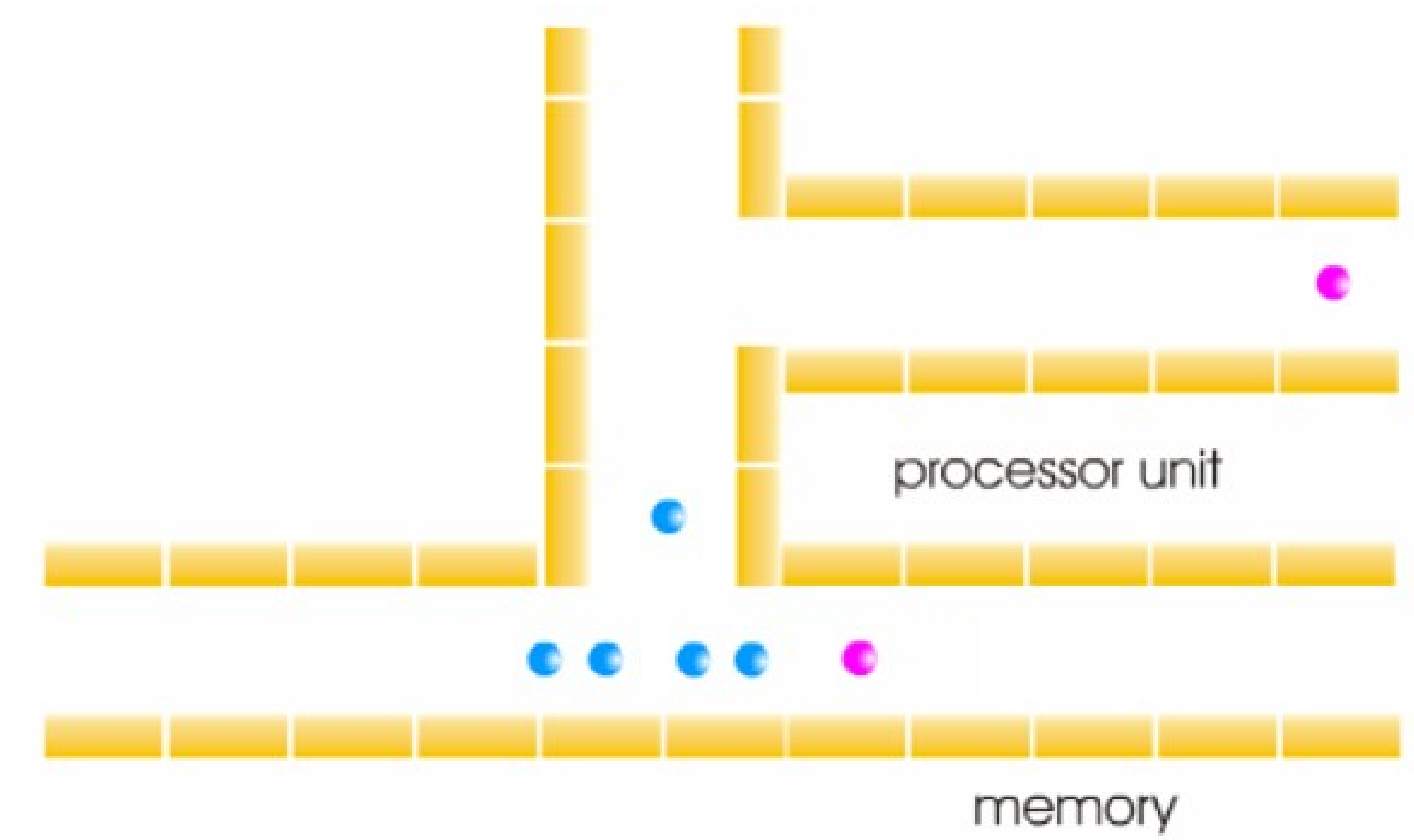
Scaling of ion trap quantum computers



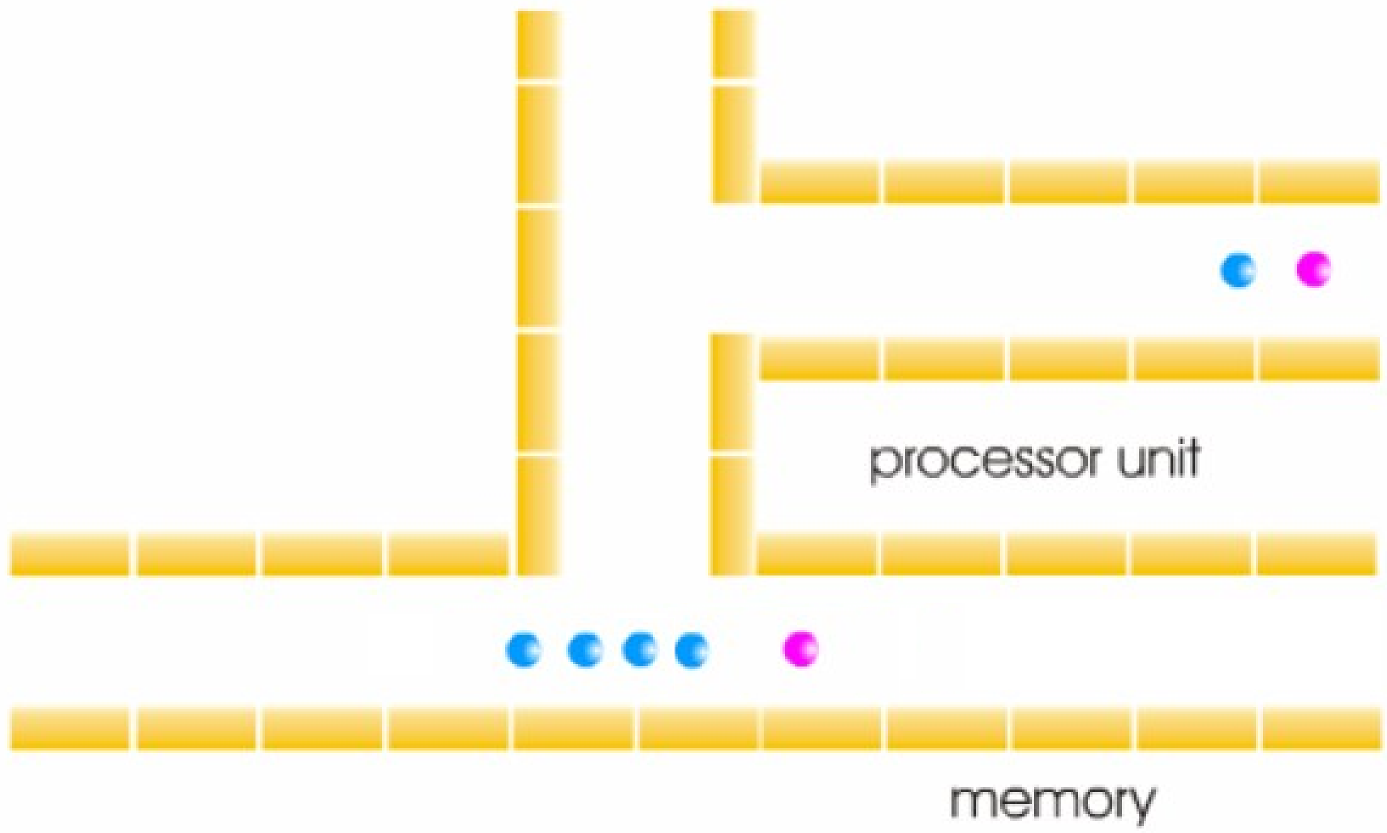
Scaling of ion trap quantum computers



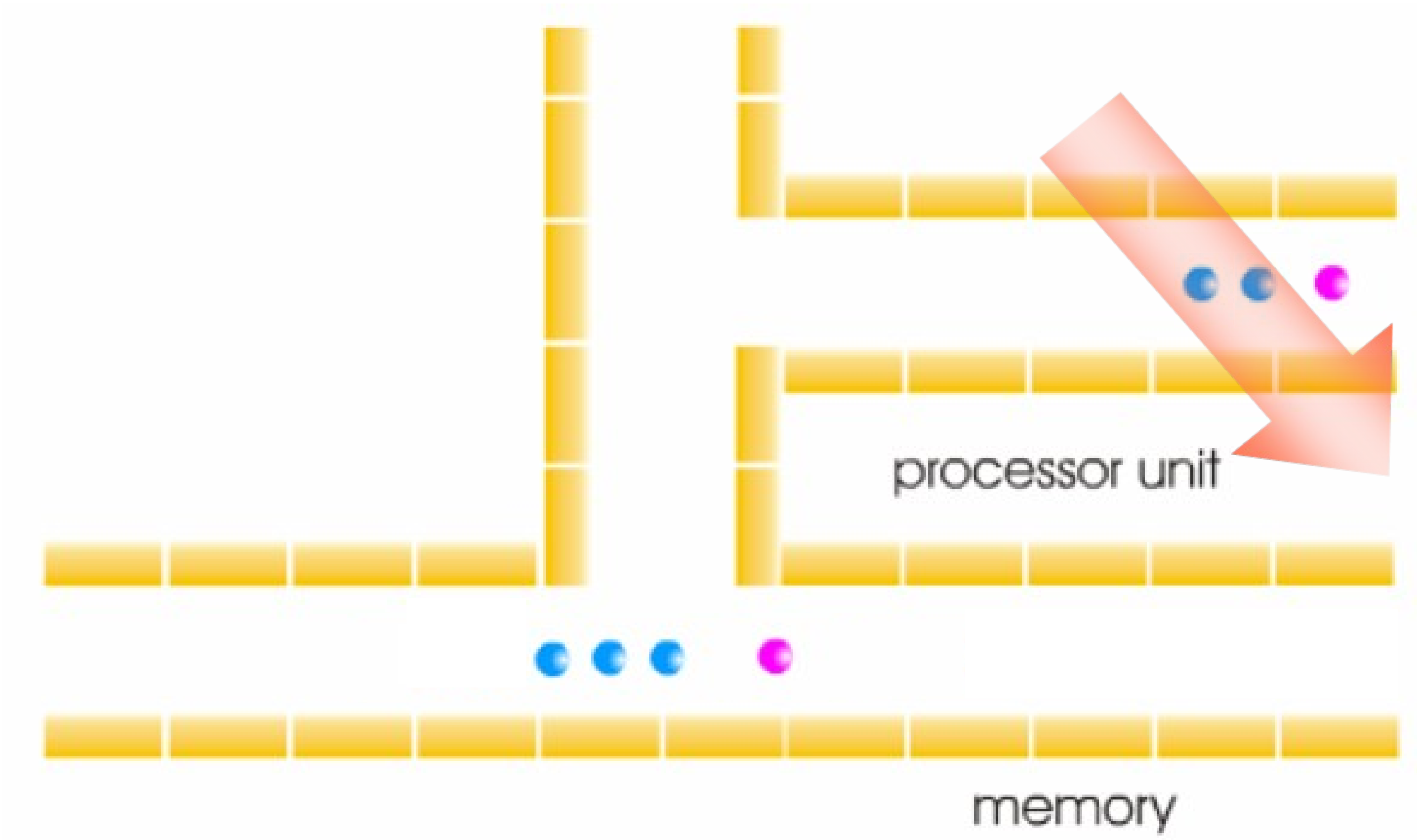
Scaling of ion trap quantum computers



Scaling of ion trap quantum computers



Scaling of ion trap quantum computers



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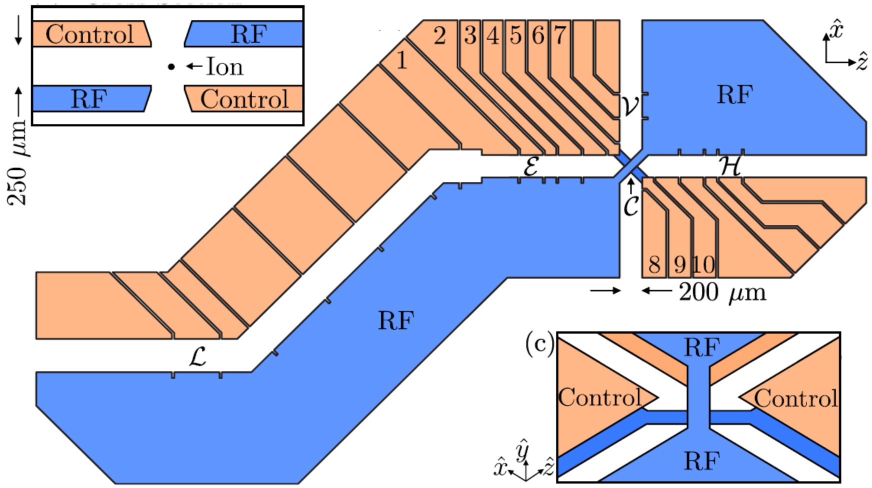
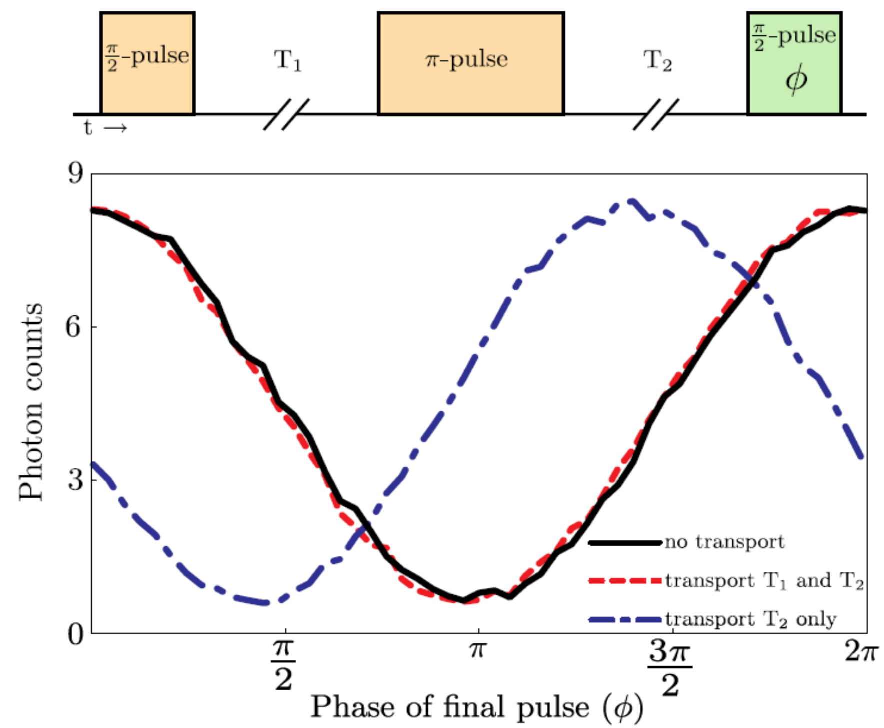
Coherent transport through a junction

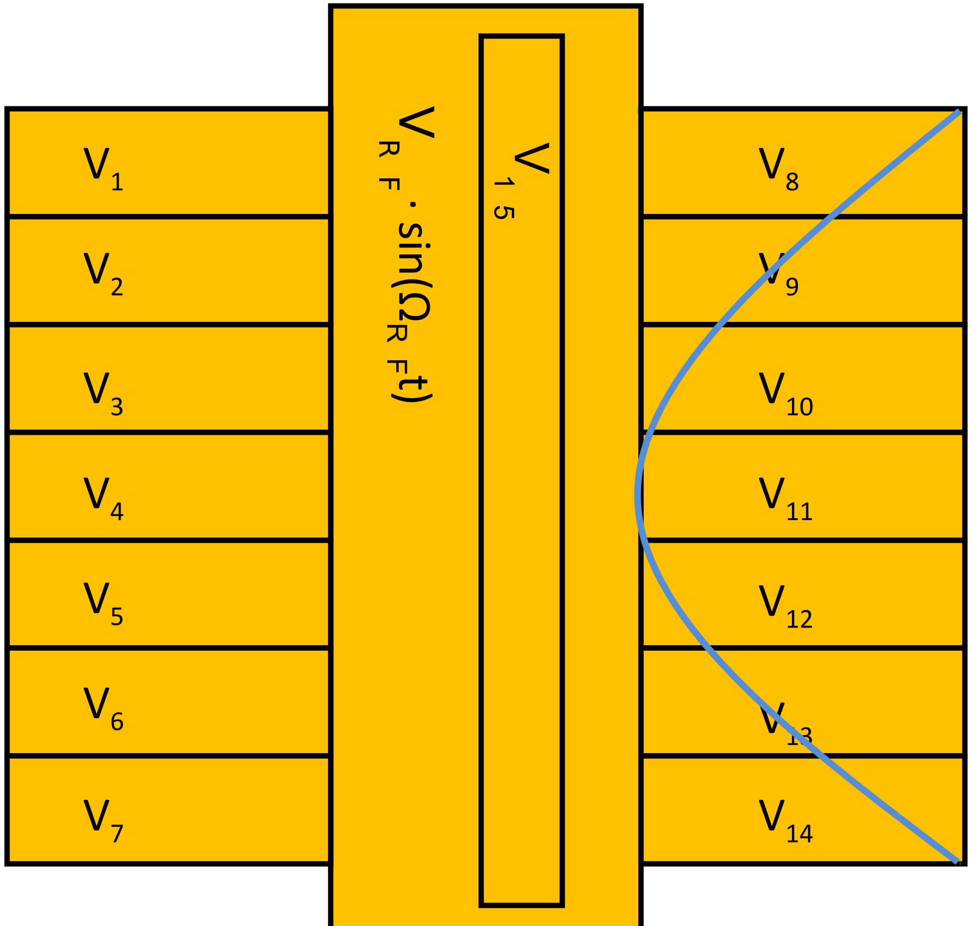


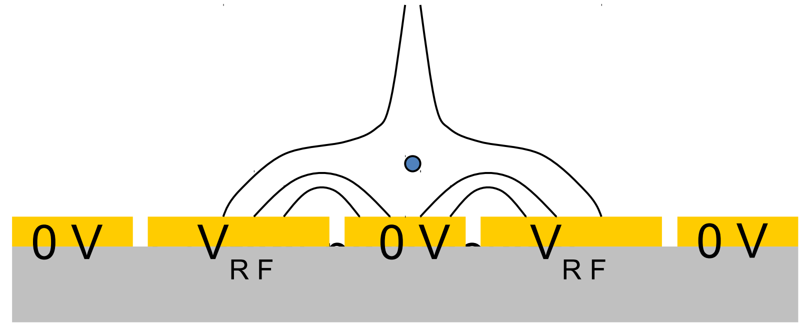
Transport		Energy Gain (recooling method) quanta/trip
$\mathcal{E}$-$\mathcal{C}$-$\mathcal{E}$	1 ion	3.2 ± 1.8
$\mathcal{E}$-$\mathcal{C}$-$\mathcal{H}$-$\mathcal{C}$-$\mathcal{E}$	1 ion	7.9 ± 1.5
$\mathcal{E}$-$\mathcal{C}$-$\mathcal{V}$-$\mathcal{C}$-$\mathcal{E}$	1 ion	14.5 ± 2.0
$\mathcal{E}$-$\mathcal{C}$-$\mathcal{E}$	2 ions	5.4 ± 1.2
$\mathcal{E}$-$\mathcal{C}$-$\mathcal{H}$-$\mathcal{C}$-$\mathcal{E}$	2 ions	16.6 ± 1.8
$\mathcal{E}$-$\mathcal{C}$-$\mathcal{V}$-$\mathcal{C}$-$\mathcal{E}$	2 ions	53.0 ± 1.2



NIST:
Blakestad, *et al.,"High fidelity transport of trapped-ion qubits through an X-junction trap array",* arXiv:0901.0533v1

Surface traps





Ion height $\approx 220\ \mu$m

$\Omega_{RF} \approx 2\pi \cdot 15$ MHz

$V_{RF} \approx 100$ V

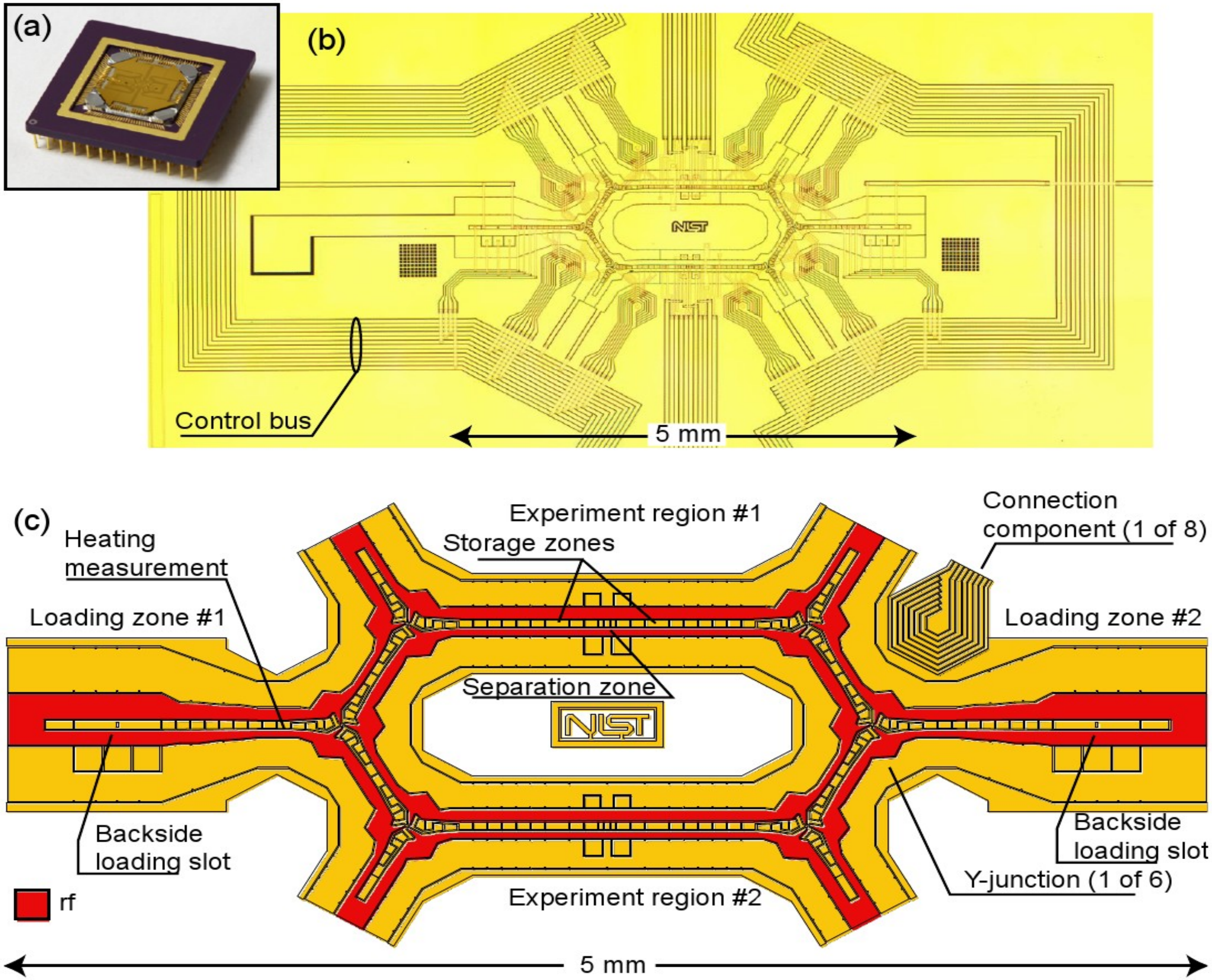
$V_{DC} < 10$ V

$\omega_H \approx 2\pi \cdot 1.3$ MHz

$\omega_V \approx 2\pi \cdot 1.5$ MHz

$\omega_A \approx 2\pi \cdot 300$ kHz

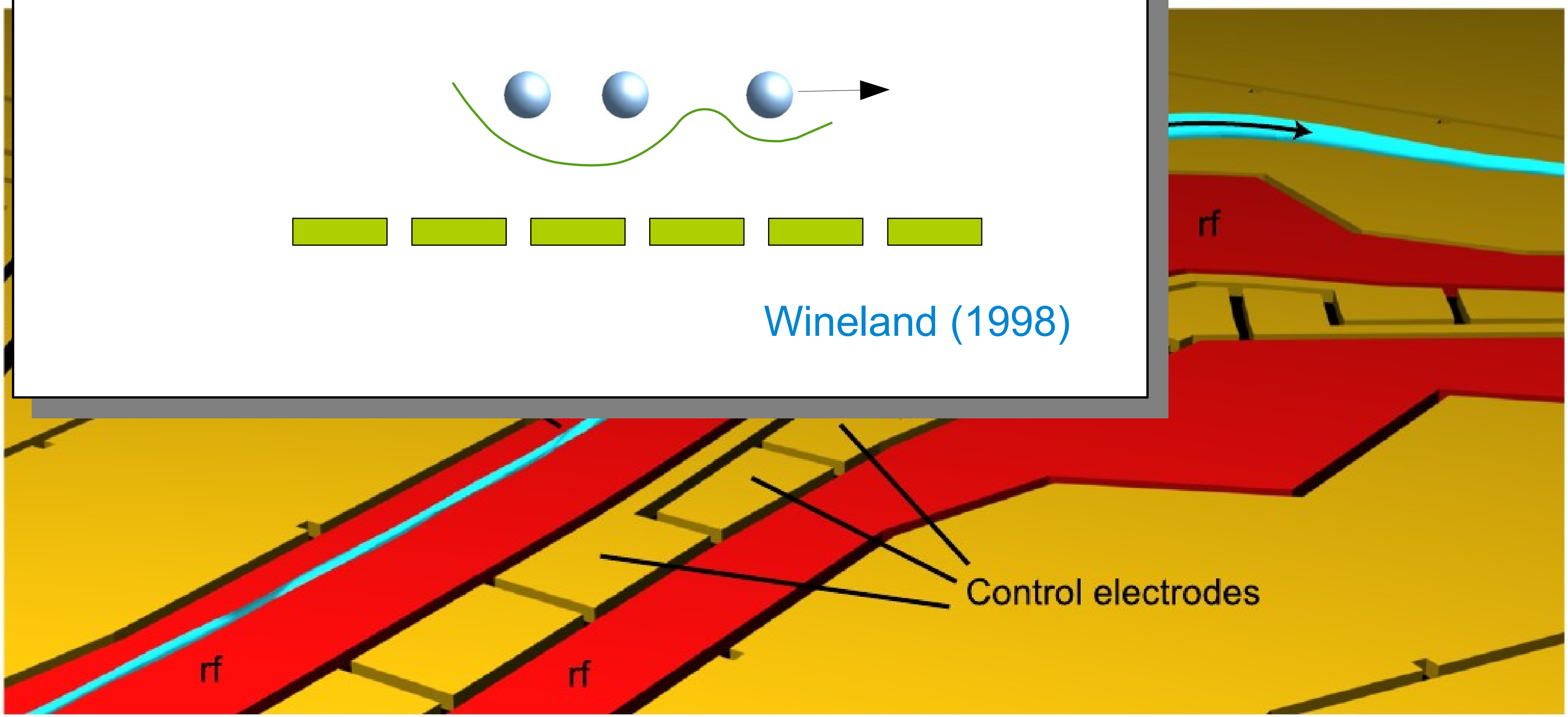
Surface traps



NIST: Amini, *et al.,"Scalable ion traps for quantum information processing" . arXiv:0909.2464v1*

Surface traps

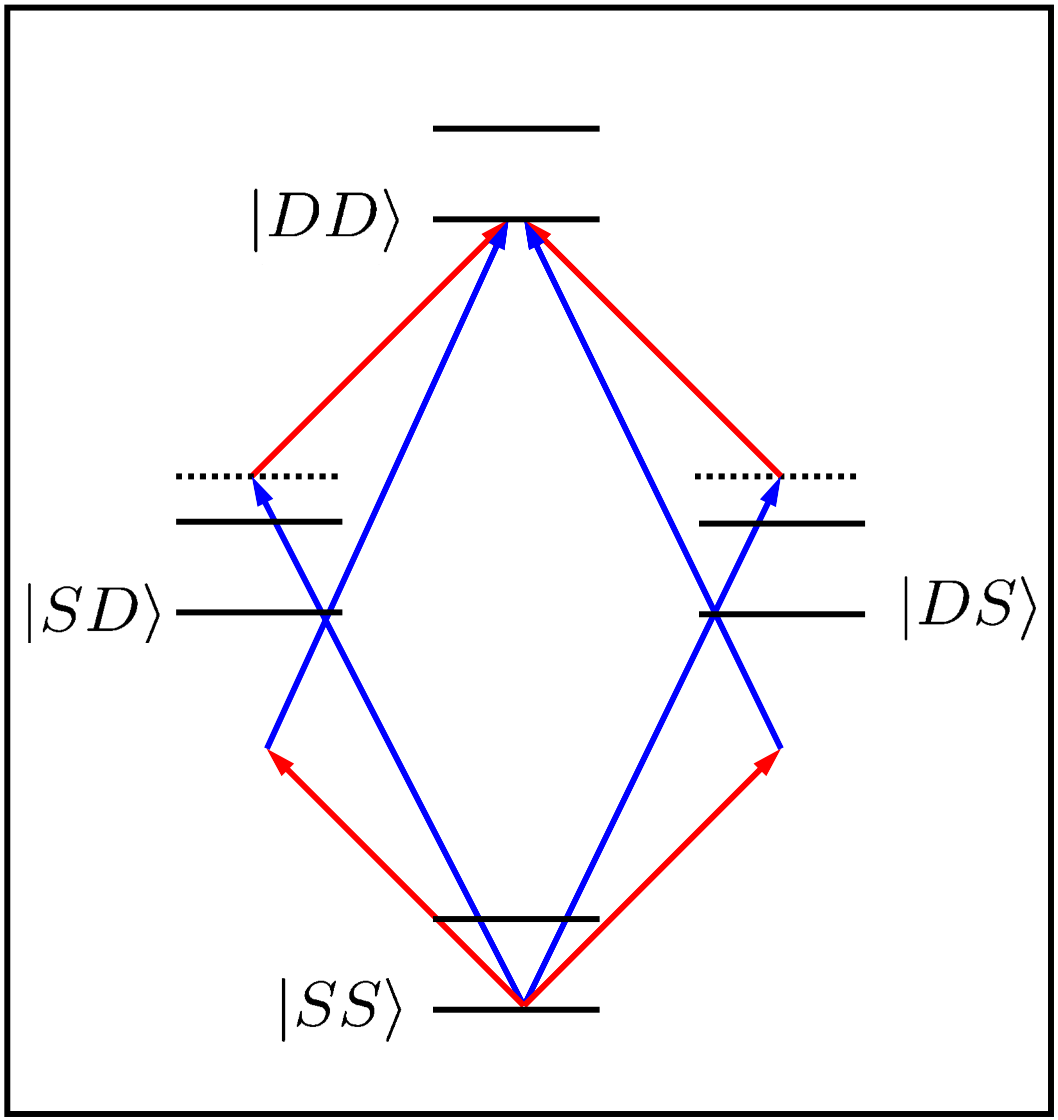
Need to split and merge ion strings fast for multi-qubit gates.



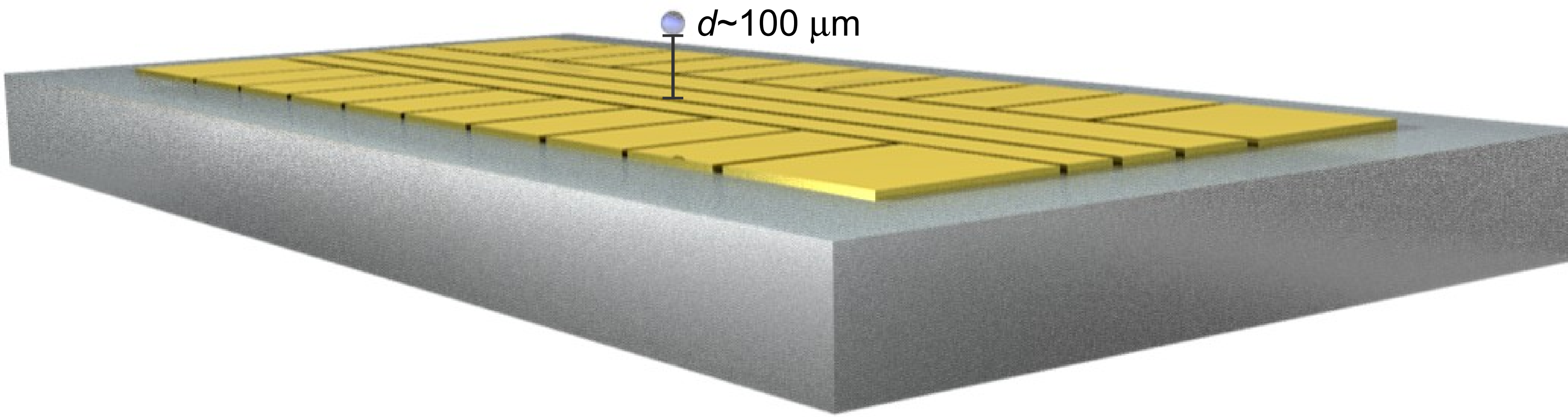
Wineland (1998)

NIST: Amini, *et al.,"Scalable ion traps for quantum information processing" . arXiv:0909.2464v1*

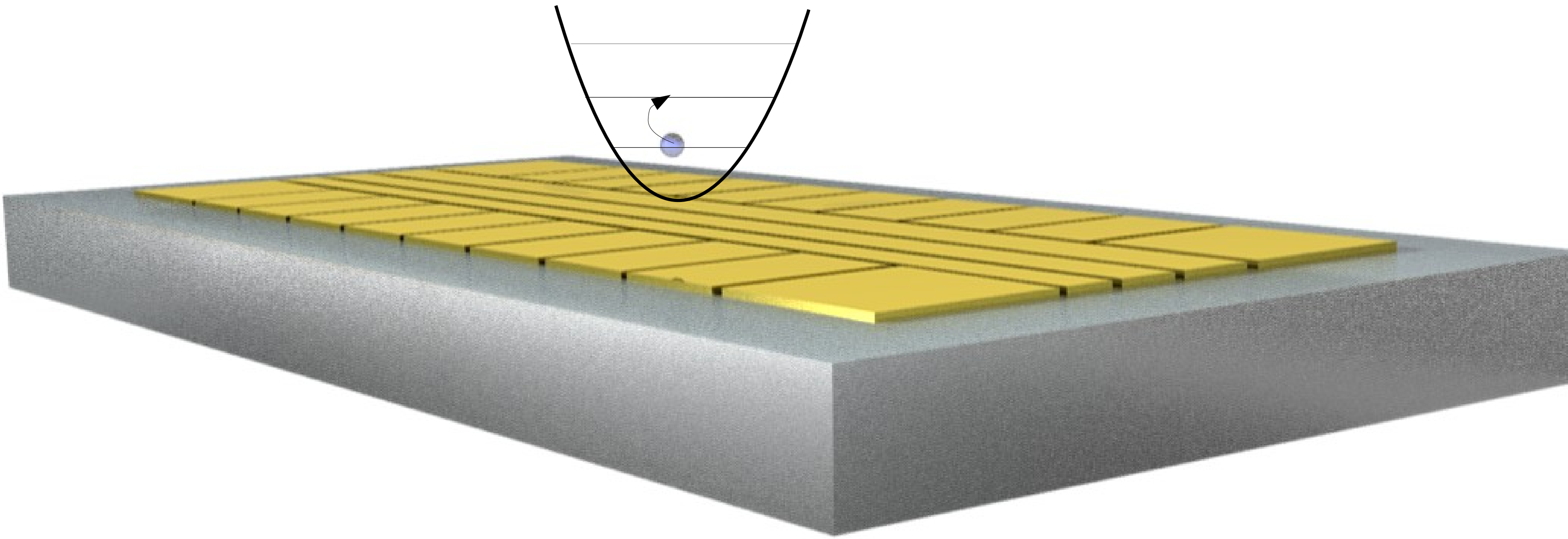
Entangling ions



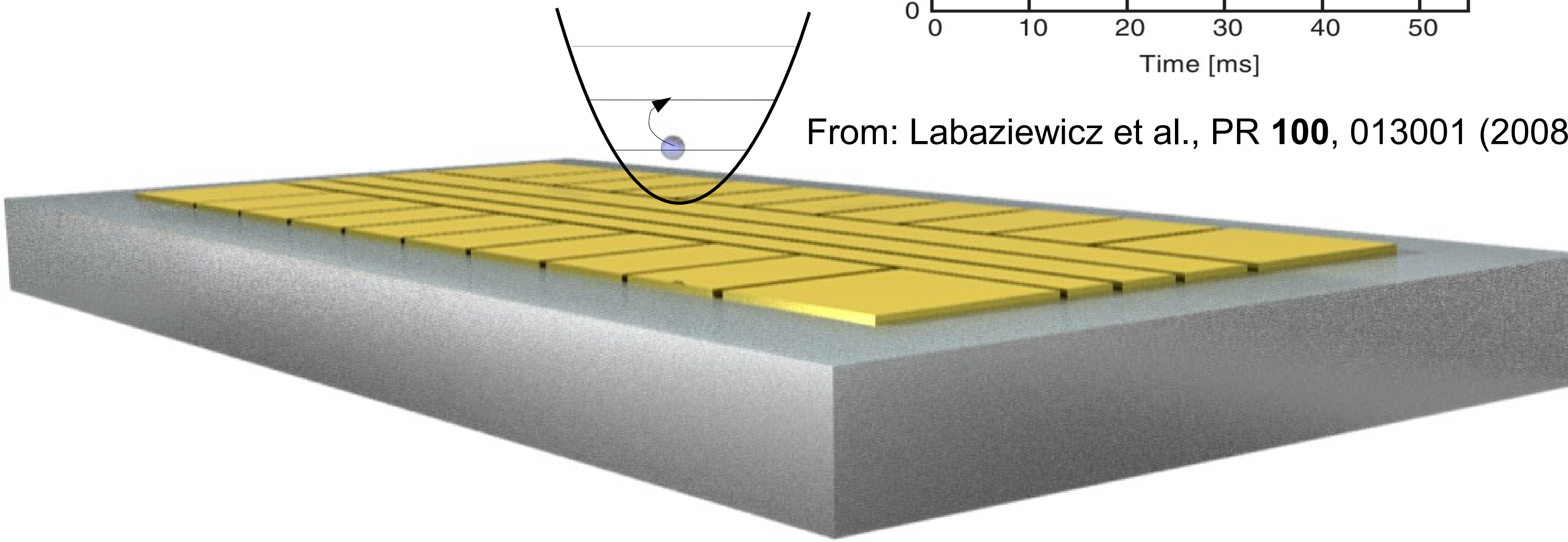
Motional decoherence

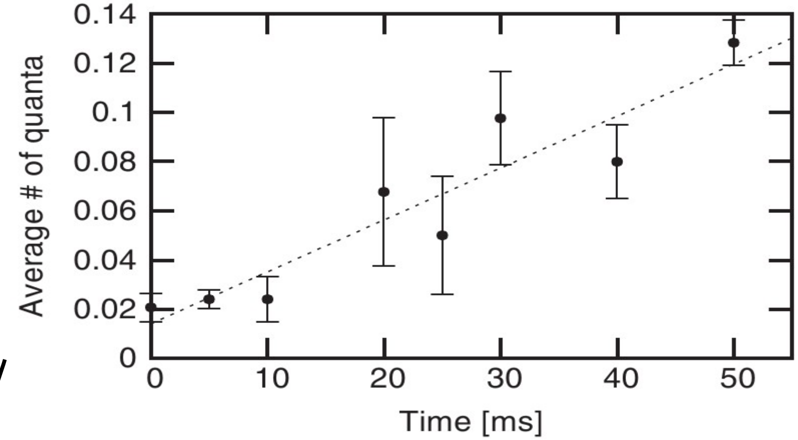


Motional decoherence



Motional decoherence

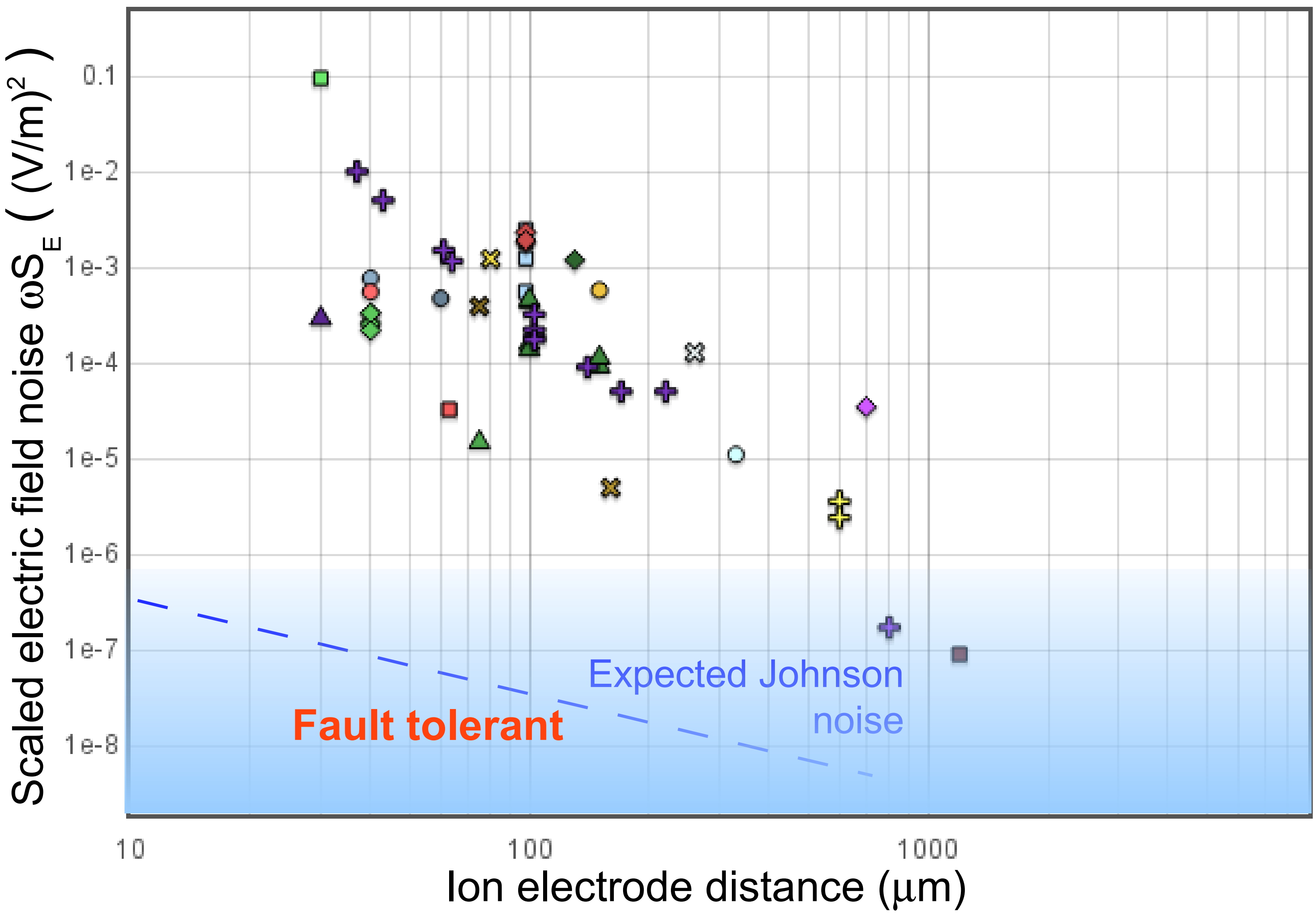




From: Labaziewicz et al., PR **100**, 013001 (2008

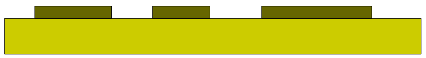
Excessive heating in ion traps

From: http://www.quantum.gatech.edu/heating_rate_plot.shtml

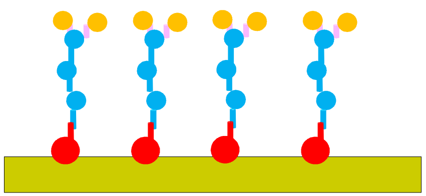


What is causing “the” anomalous heating ?

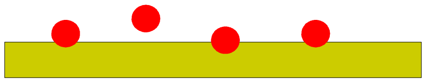
- fluctuating patch potentials, ad-atom diffusion (Wineland 1998)



- independently fluctuating dipoles (Daniilidis 2010)

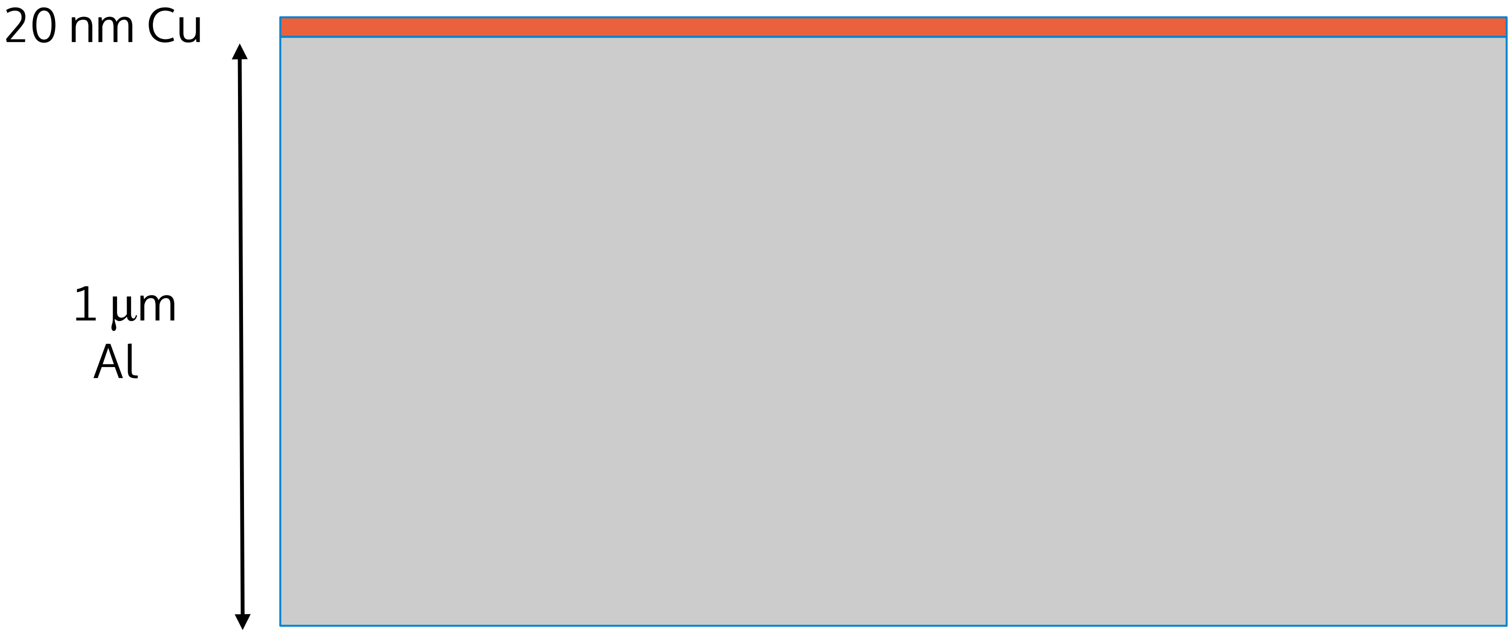


- fluctuating strength of dipoles (Safavi-Naini 2011)

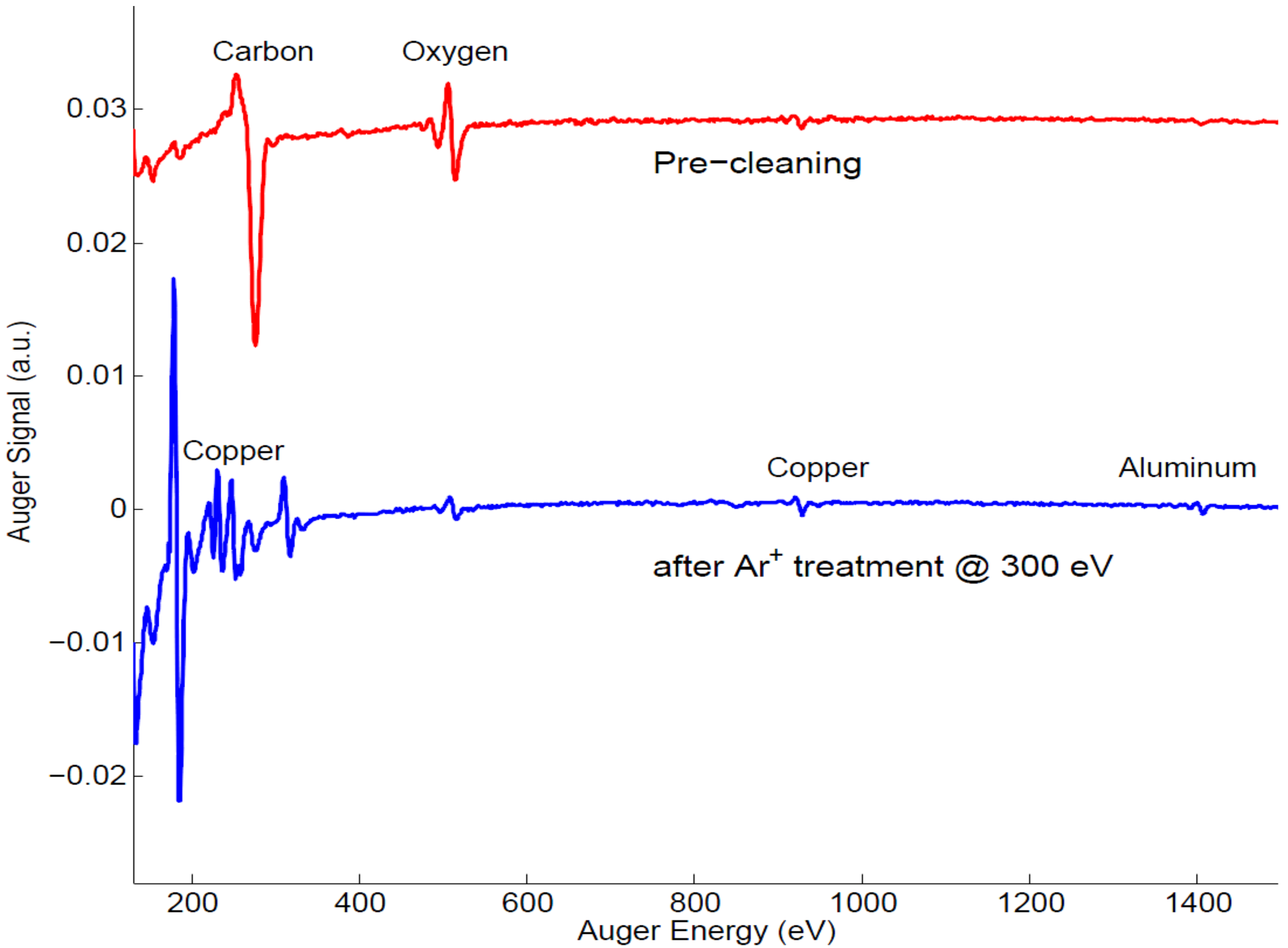


- all of the above and probably something else

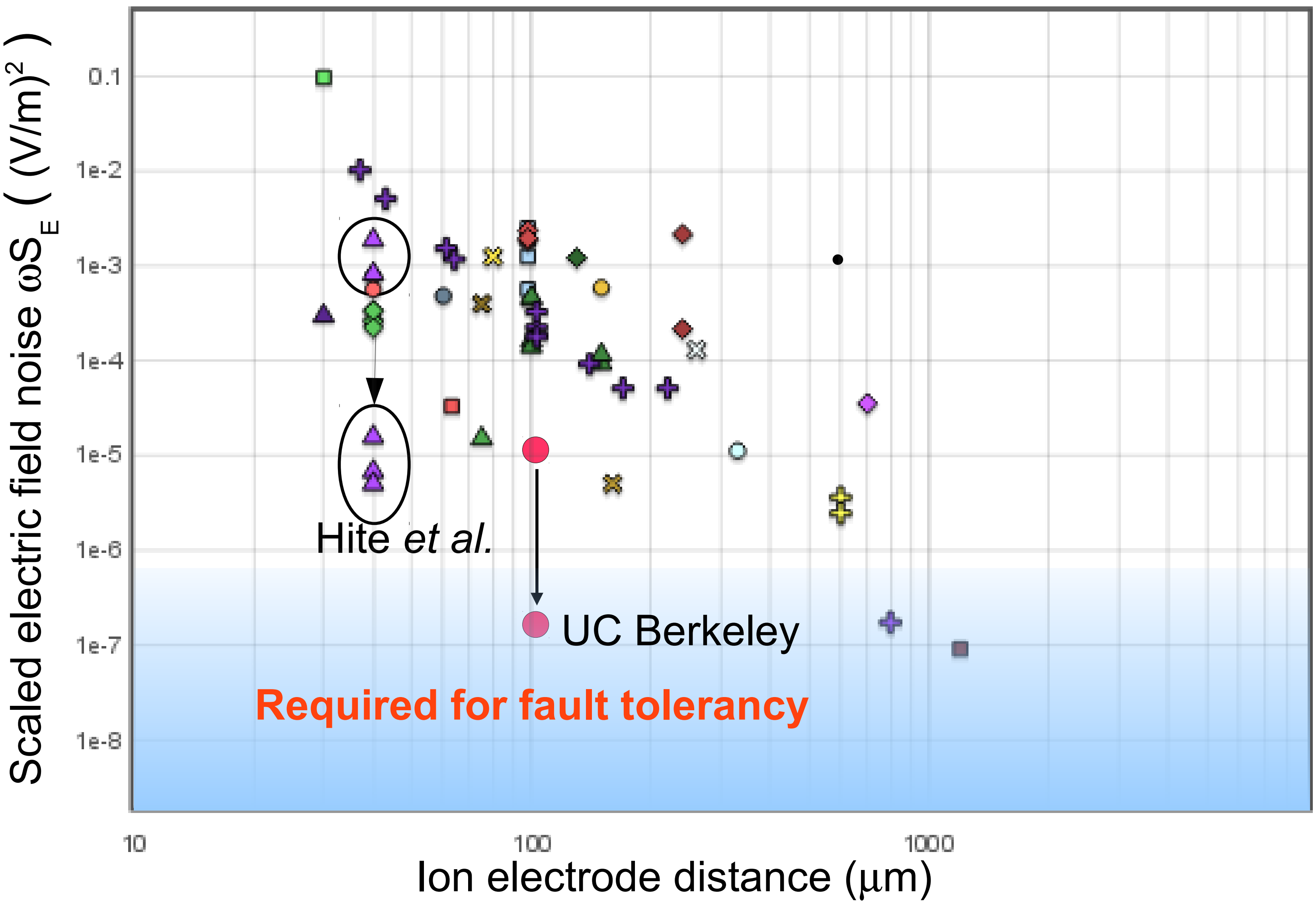
Copper on Aluminum trap



Monitoring the cleaning



Excessive heating in ion traps



More material:

Review on "Quantum computing with trapped ions", H. Häffner, C. F. Roos, R. Blatt, Physics Reports **469**, 155 (2008), http://xxx.lanl.gov/abs/0809.4368

Most recent progress:

NIST, Boulder
http://www.nist.gov/pml/div688/grp10/quantum-logic-and-coherent-control.cfm

Innsbruck
http://www.quantumoptics.at/

University of Maryland:
http://www.iontrap.umd.edu/publications/recent_pubs.html