Quantum applications of ion trapping

Hartmut Häffner, UC Berkeley

1. Introduction to ion trapping
2. Quantum computing
3. Sources of decoherence
4. Quantum emulation/simulation
5. Applications of QIP to precision measurements

Plan

Lecture #1: Introduction
- Paul traps
- Laser ion-interaction

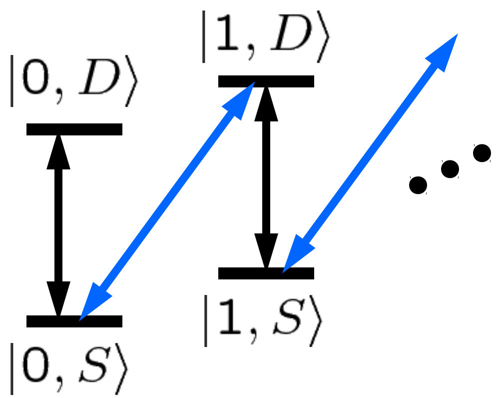
Lecture #2: Quantum computing
- Quantum gates
- Quantum state tomography

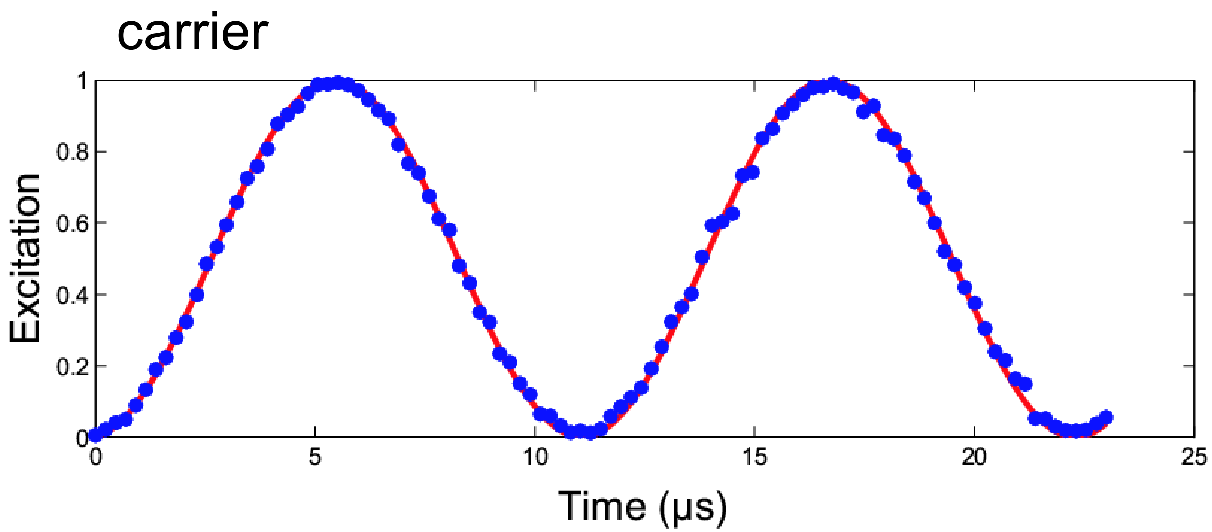
Lecture #3: Decoherence
- Qubit decoherence
- Scaling

Lecture #4: Challenges and quantum simulation
- Scaling and anomalous heating
- Quantum simulation

Lecture #5: Applications
- Atomic clocks, quadrupole shifts
- Michelson-Morley experiment

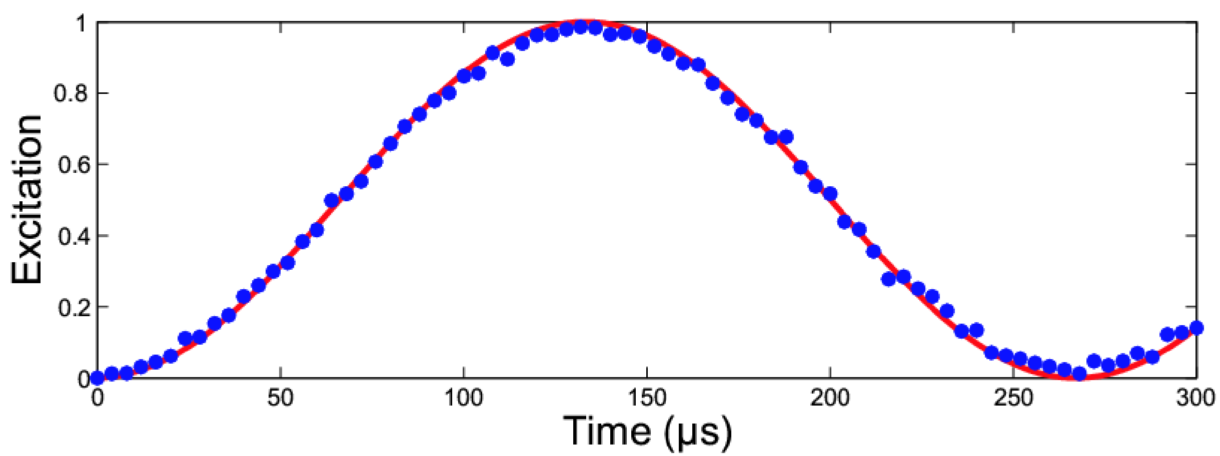
Ion motion





carrier and sideband
Rabi oscillations
with Rabi frequencies

$\Omega, \quad \eta\Omega$

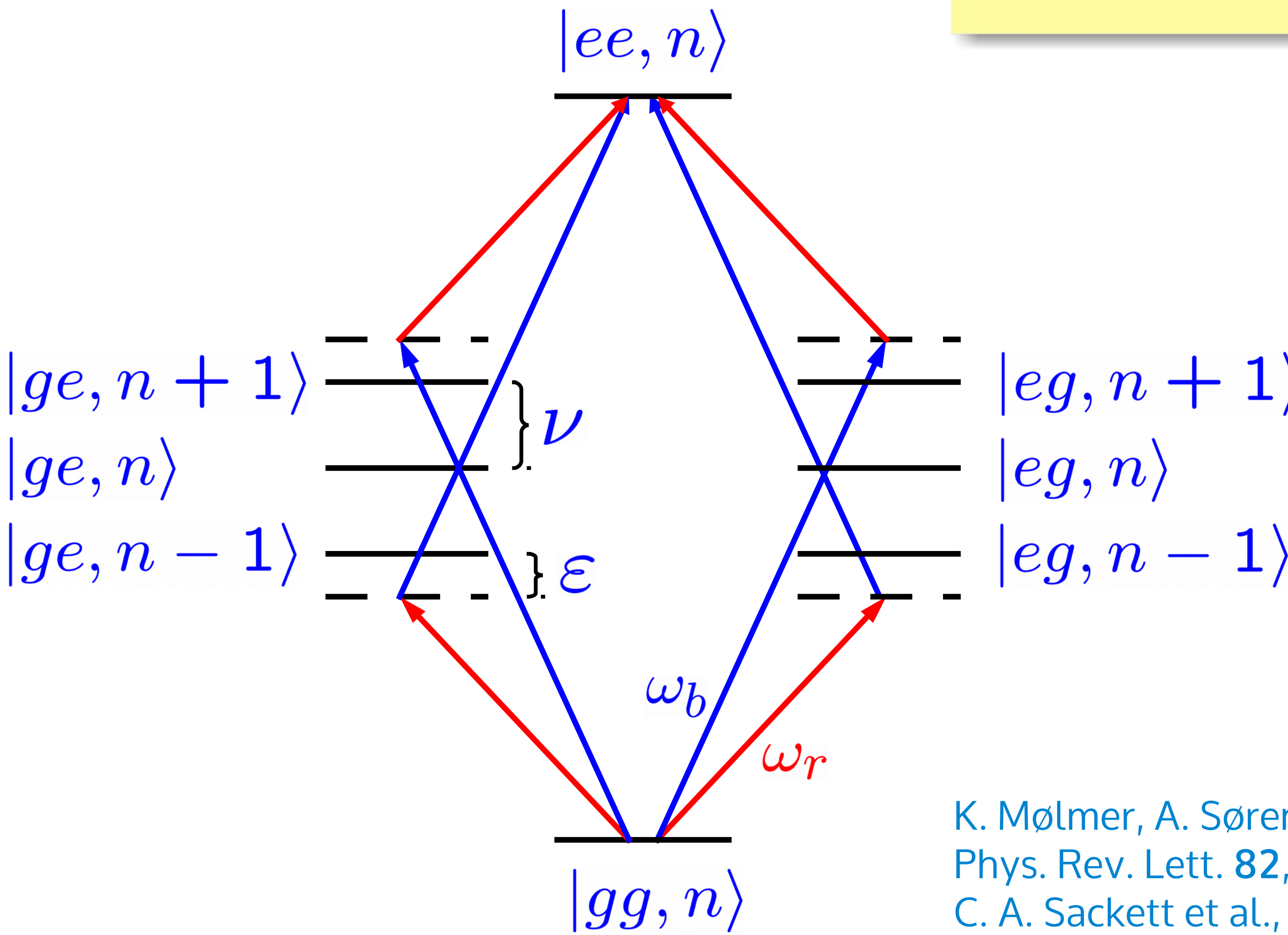


$\eta = kx_0$ Lamb-Dicke parameter

Mølmer - Sørensen gate

$$|gg\rangle \rightarrow |ee\rangle, \quad |ge\rangle \rightarrow |eg\rangle$$

$$\omega_b = \omega_0 + (\nu - \varepsilon)$$
$$\omega_r = \omega_0 - (\nu - \varepsilon)$$



K. Mølmer, A. Sørensen,
Phys. Rev. Lett. **82**, 1971 (1999)
C. A. Sackett et al.,
Nature **404**, 256 (2000)

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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

I. Scalable physical system, well characterized qubits ✓

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

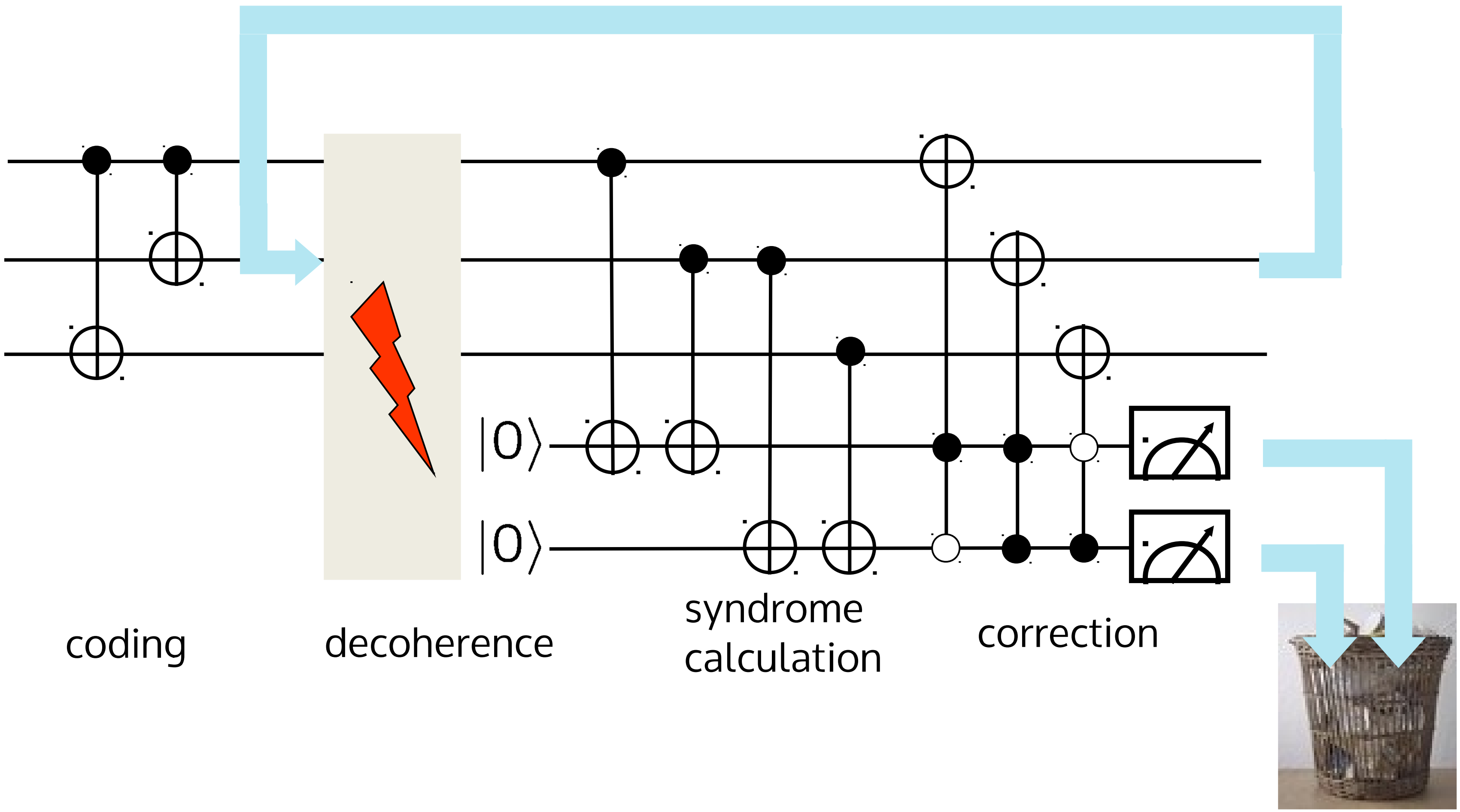
III. Long relevant coherence times, much longer than gate operation time

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

V. Qubit-specific measurement capability with sufficient fidelity

➡ need to beat the fault-tolerant "threshold" of 99% to 99.99% for (all) operations.

Quantum error correction



Anything that can go wrong, will go wrong.

See: http://en.wikipedia.org/wiki/Murphy's_law

- Qubits decohere
    - spontaneous emission
    - magnetic field fluctuations
    - laser frequency fluctuations
- Initialization and read-out errors
- Control errors
    - frequency/phase errors of the control field
    - calibration errors
    - laser intensity noise
    - unwanted side effects (off-resonant excitations)

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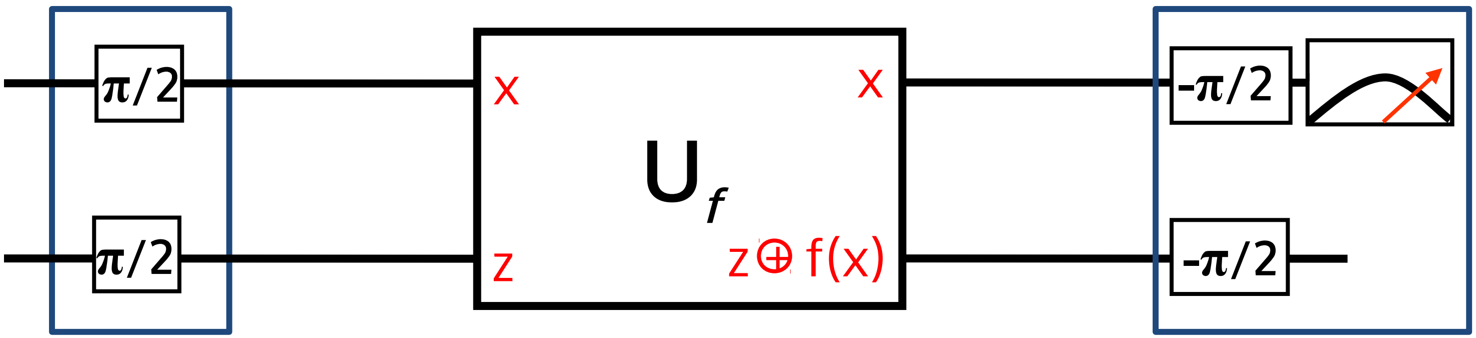
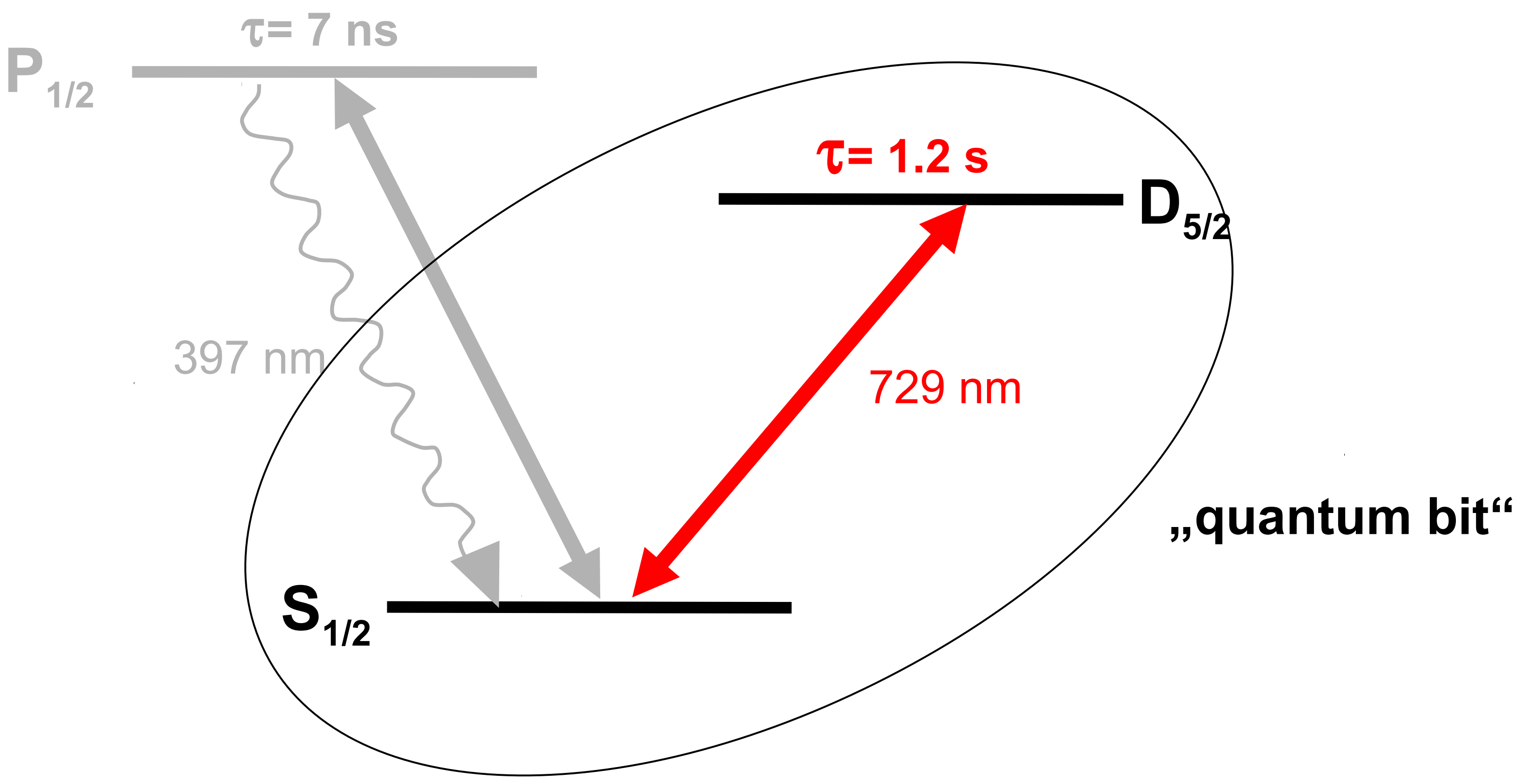
A typical quantum algorithm



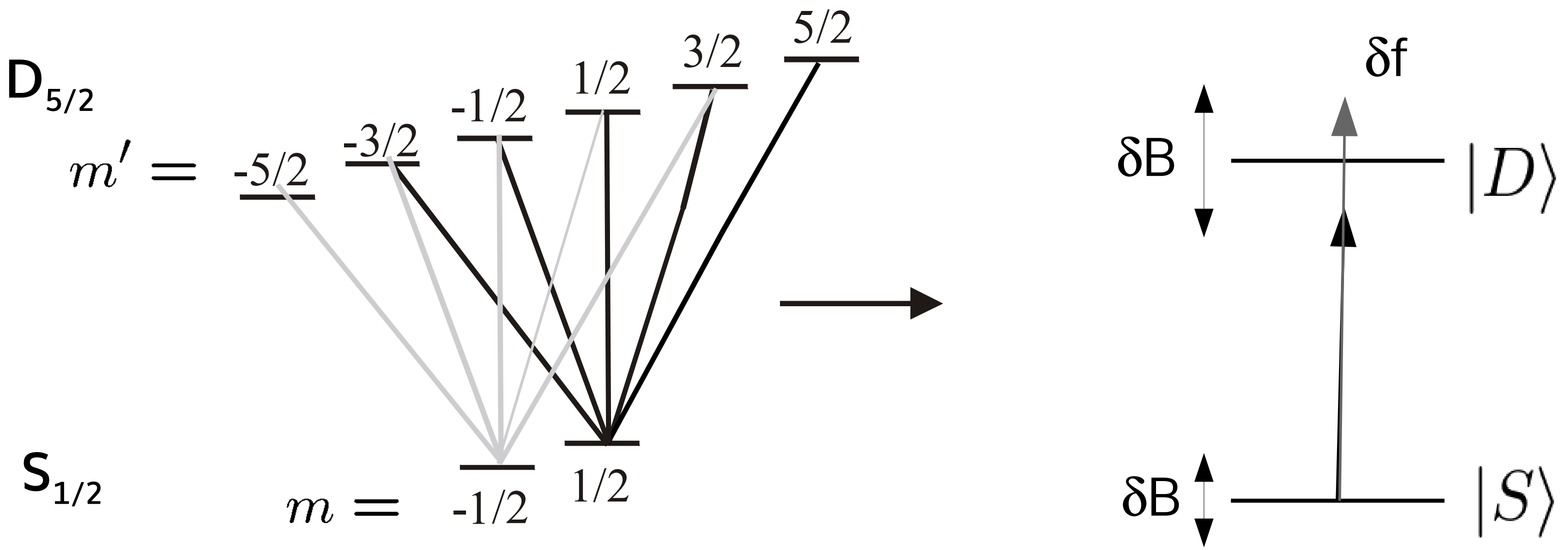
Quantum algorithms can be viewed as generalized Ramsey experiments.

The qubit



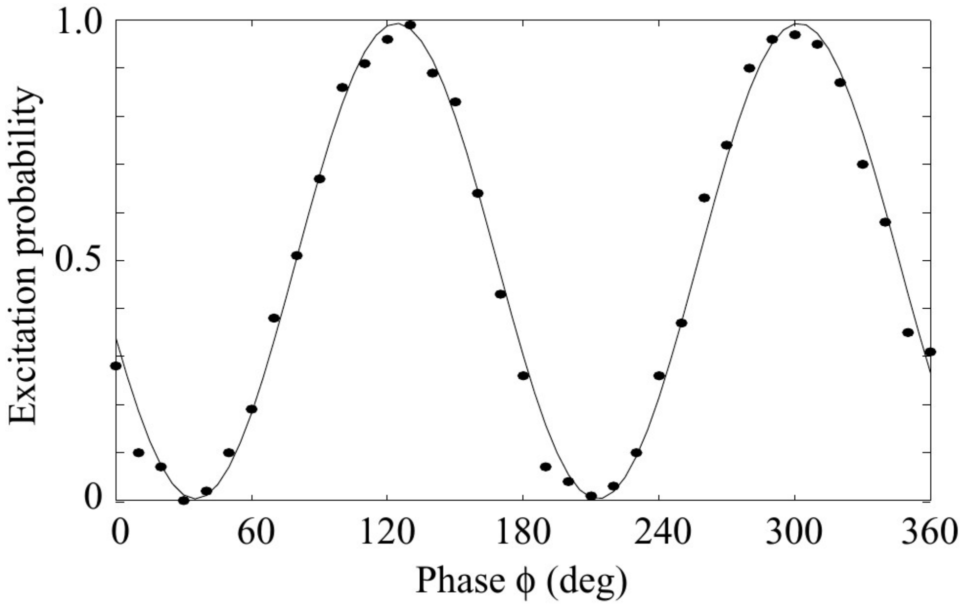
What else can go wrong ?

Zeeman structure in non-zero magnetic field:



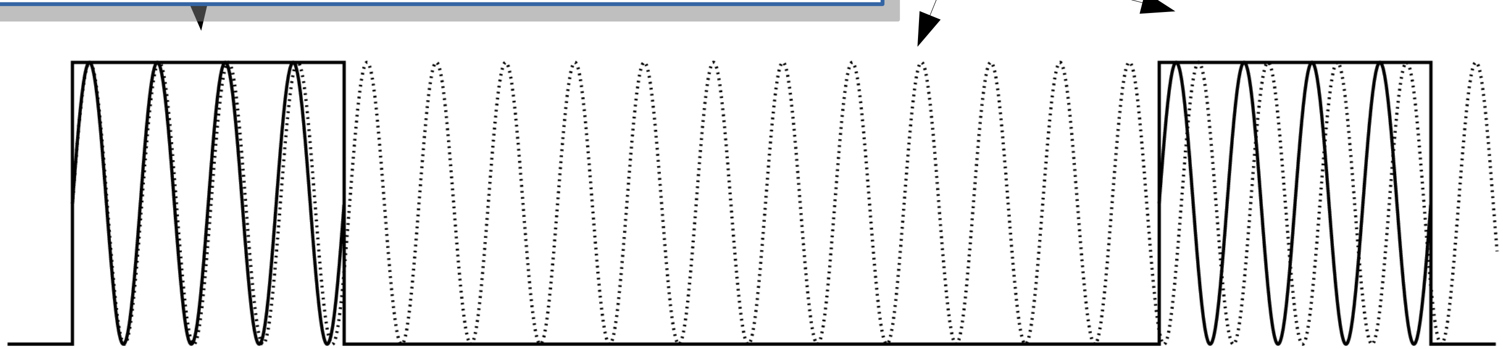
Selection rule for electric quadrupole transition: $m - m' = 0, \pm 1, \pm 2$

Read-out of the phase evolution



From: PhD thesis, Riebe 2005, Innsbruck

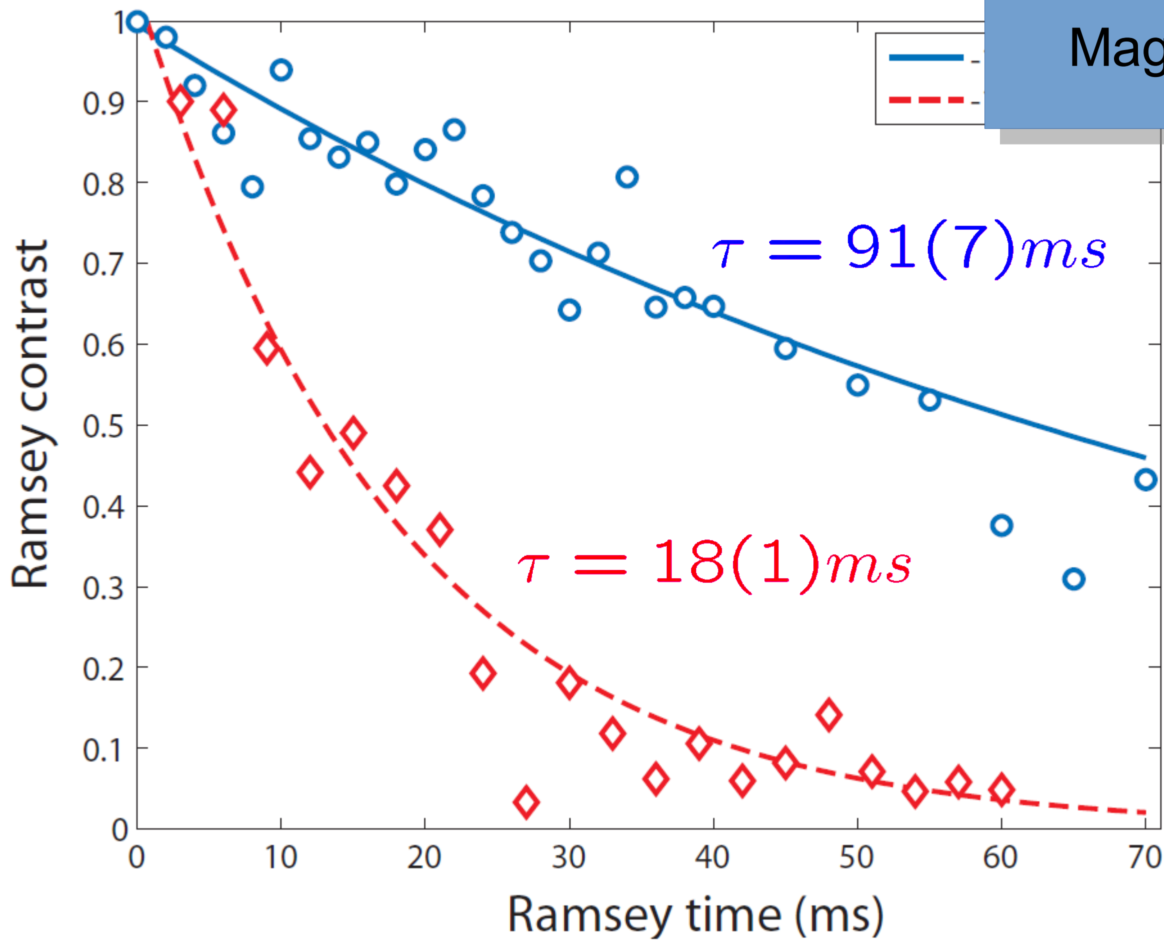
Quadrupole moment

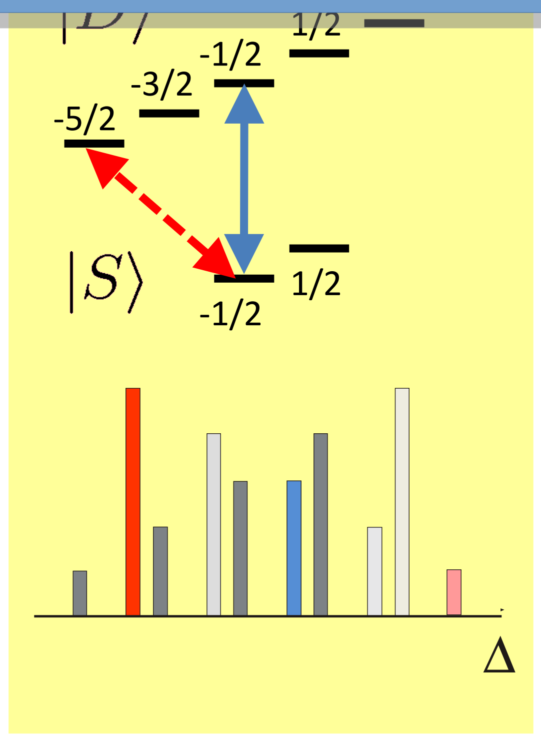


Phase coherence

Laser frequency noise: <10 Hz

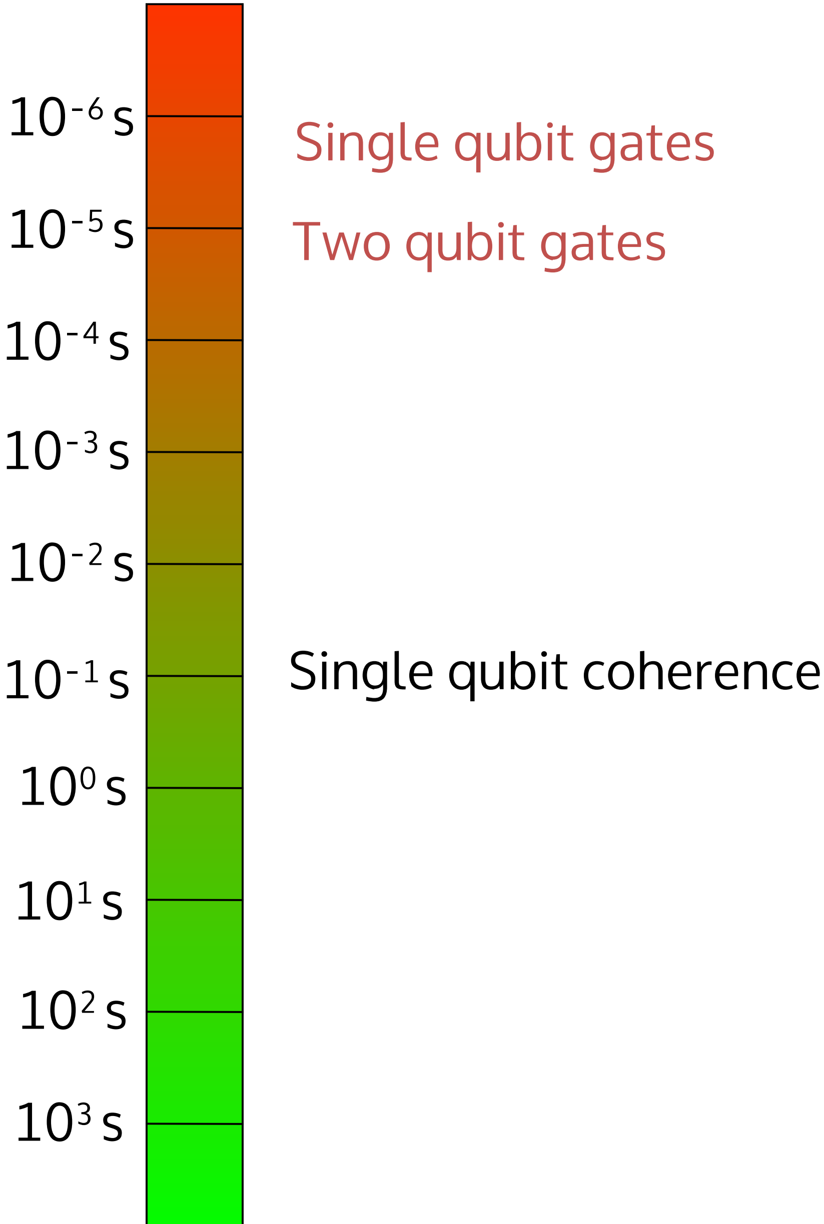
Magnetic field noise: ~10 µG





M. Chwalla, T. Monz, P. Schindler, Innsbruck 2010

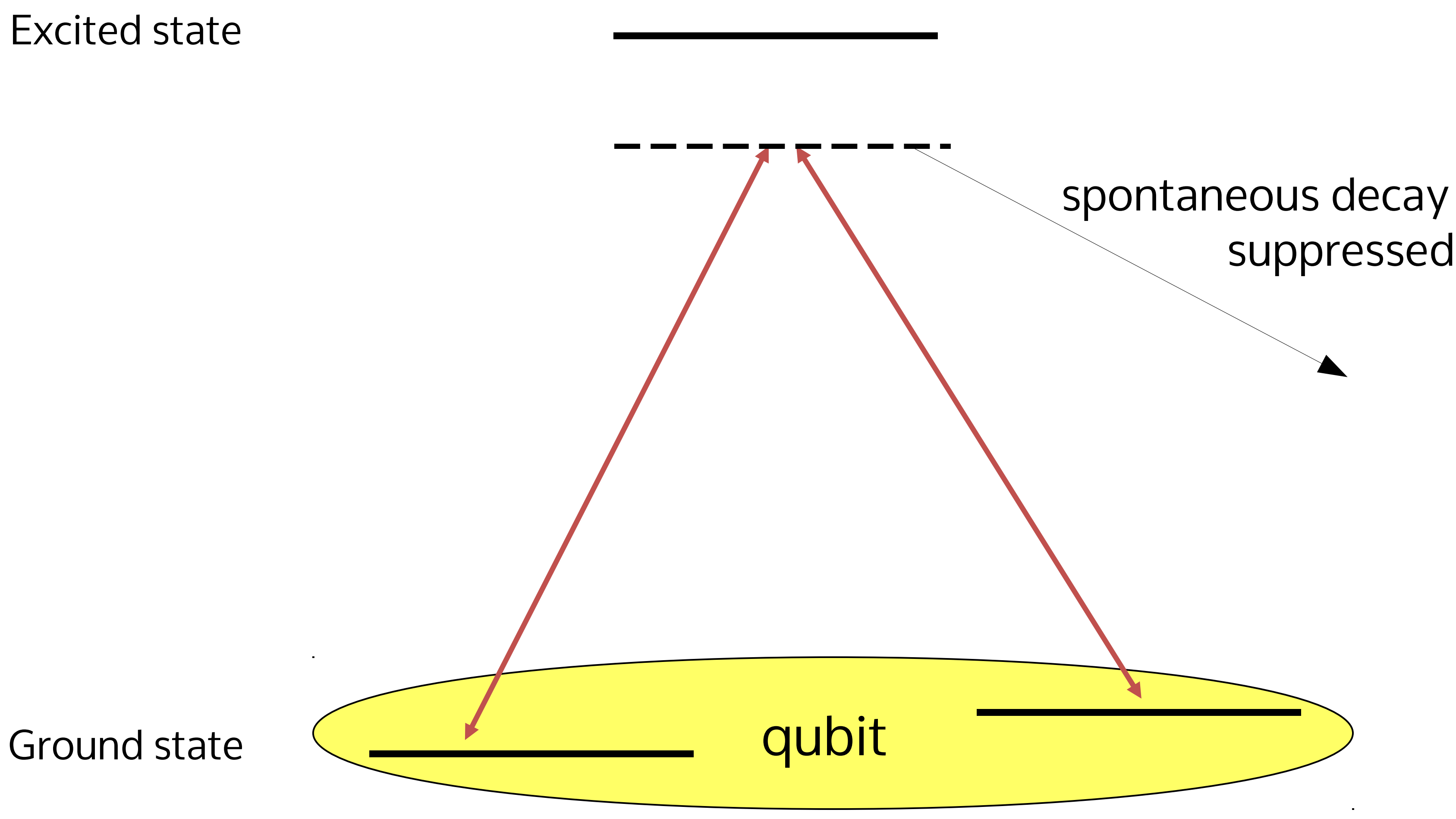
Time scales



10^{-6} s
Single qubit gates
10^{-5} s
Two qubit gates
10^{-4} s
10^{-3} s
10^{-2} s
10^{-1} s
Single qubit coherence
10^{0} s
10^{1} s
10^{2} s
10^{3} s

Long lived qubits

Raman transitions:



Long lived qubits

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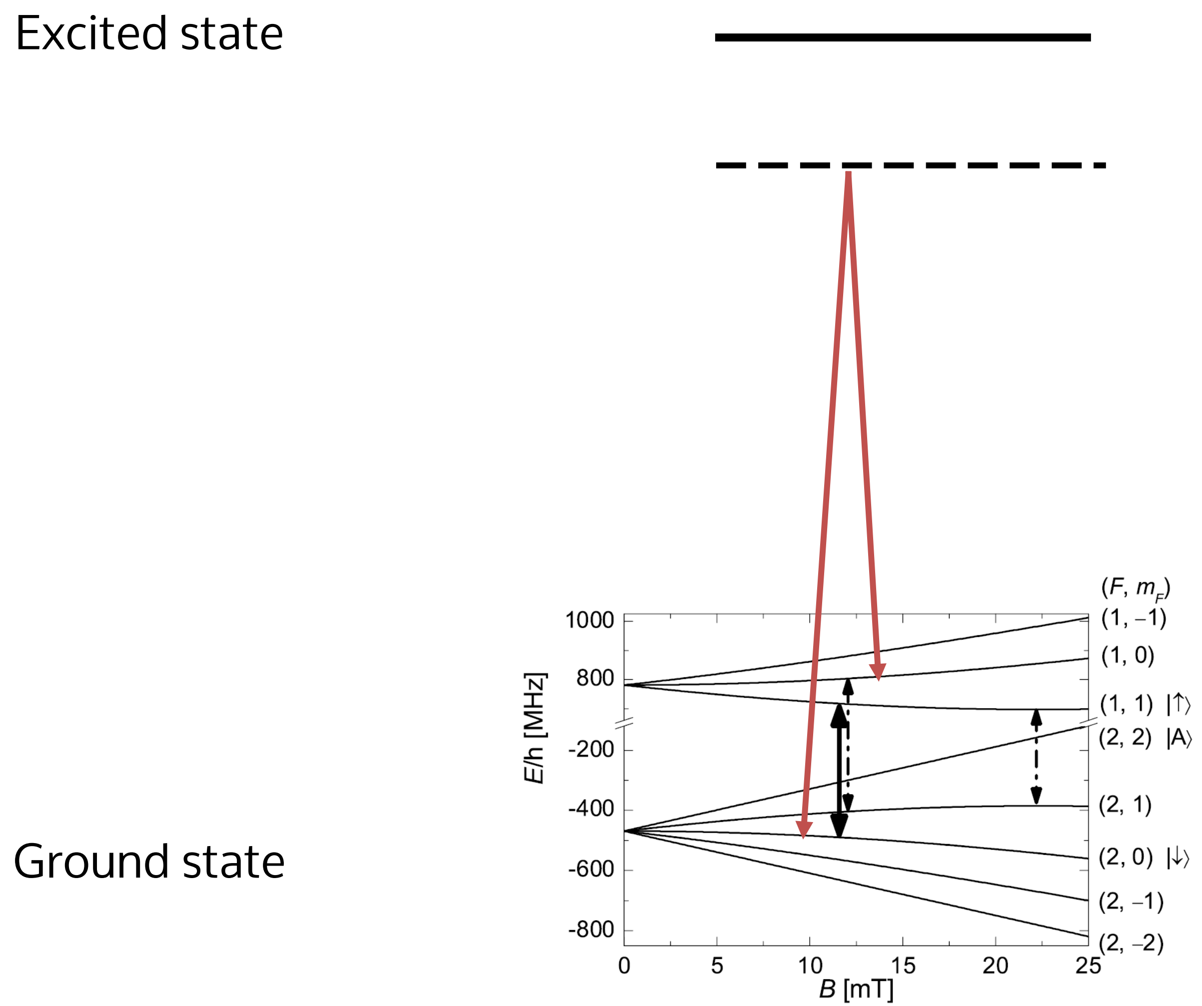
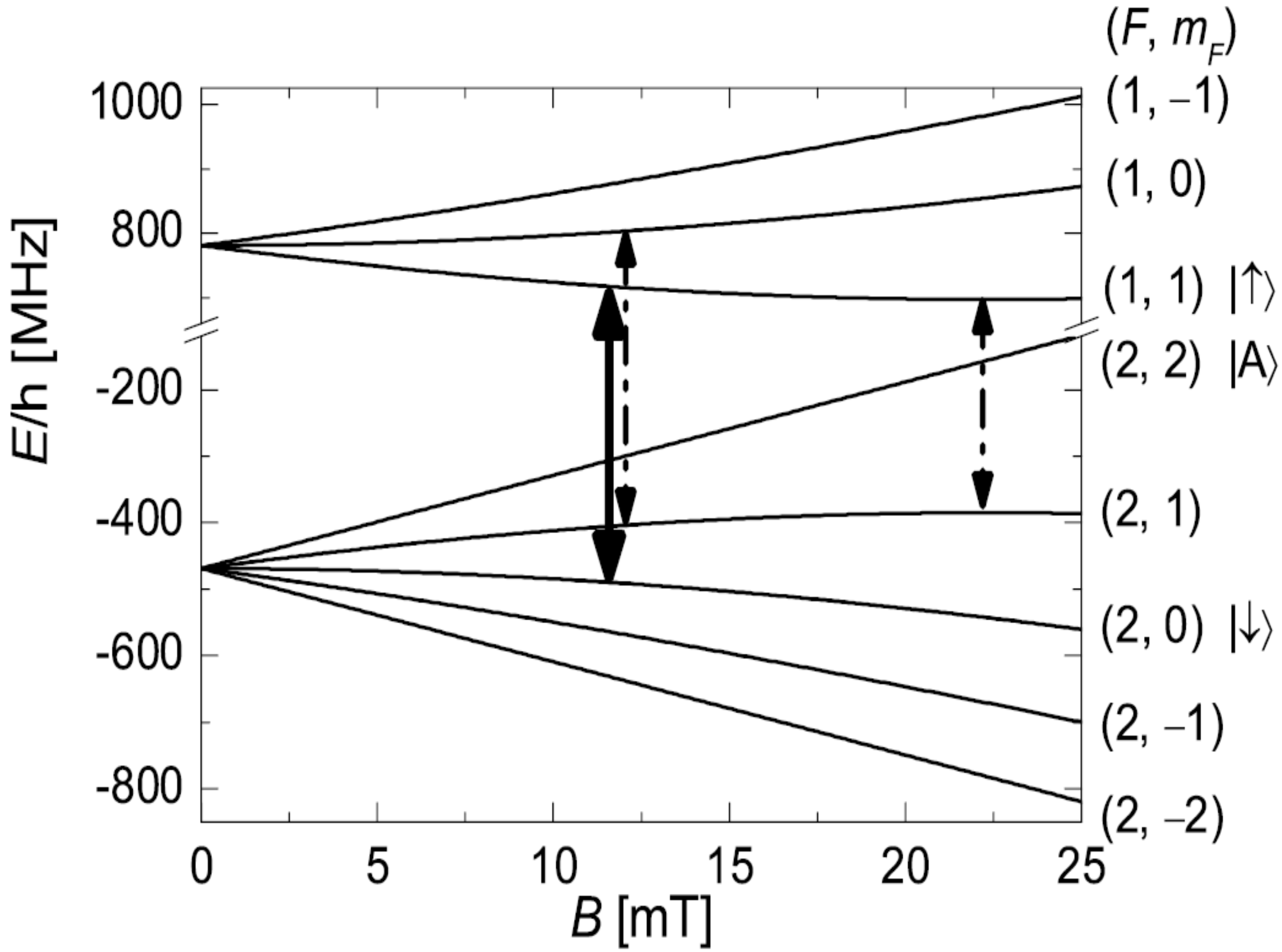
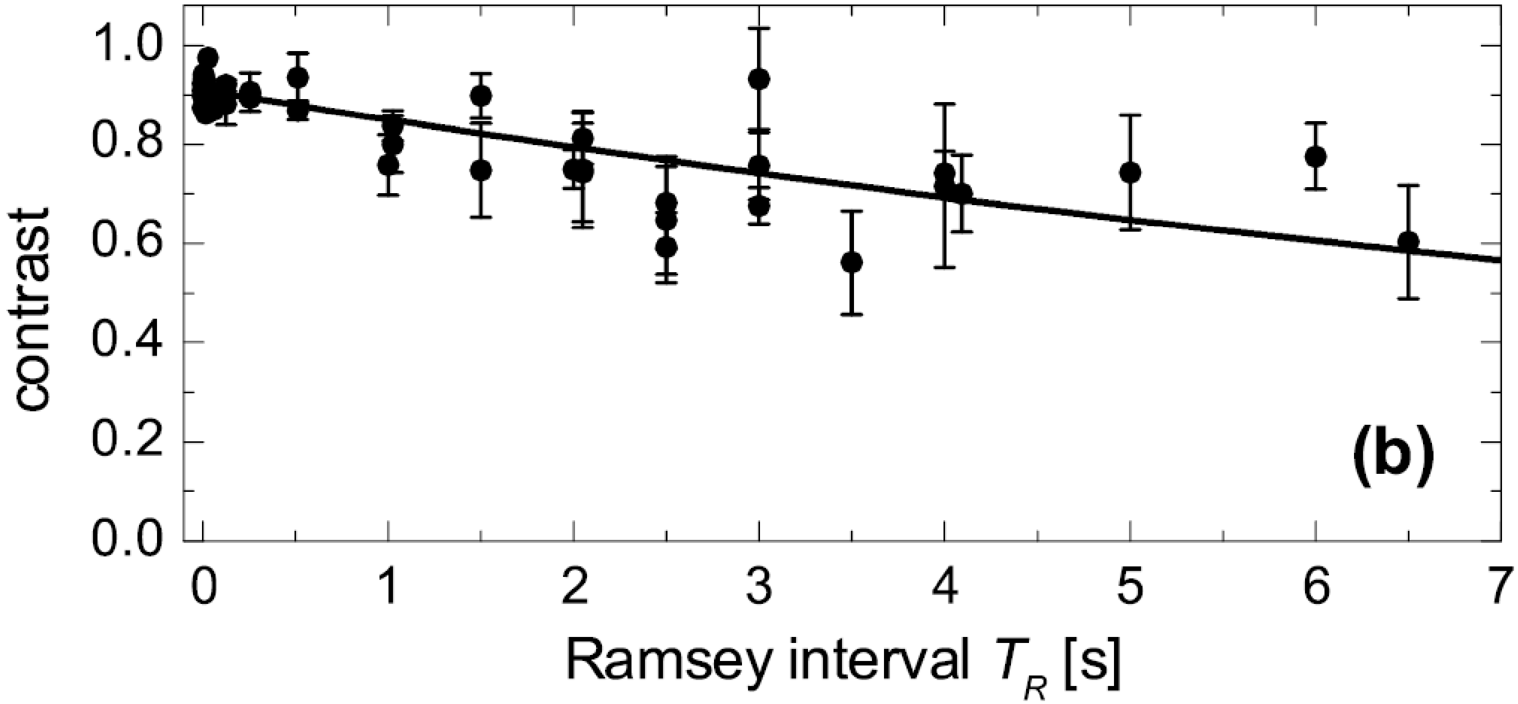


Long lived qubits

Be$^+$ ion

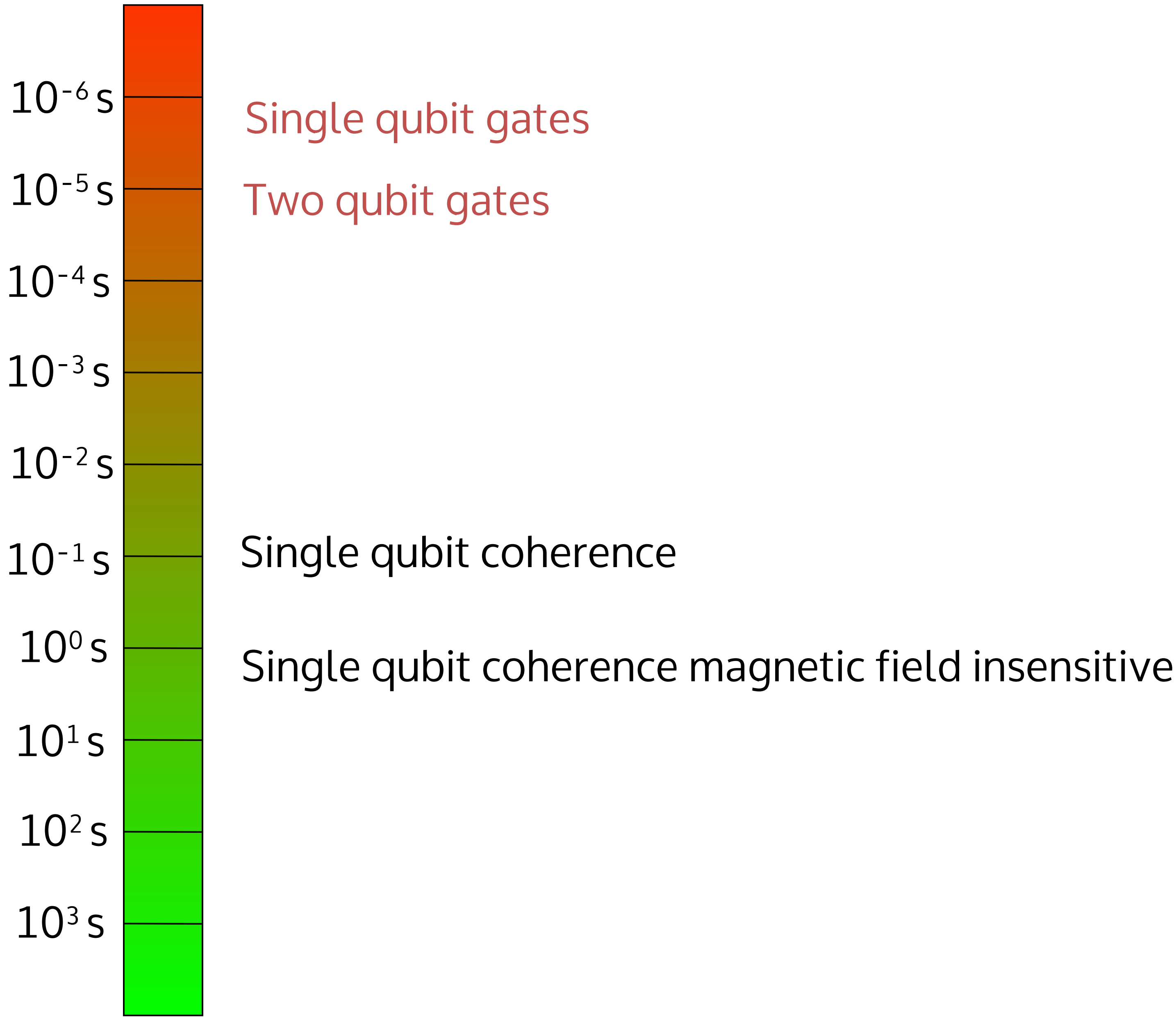


Long lived qubits



From: C. Langer *et al.*, PRL **95**, 060502 (2005), NIST

Time scales



10^{-6} s
Single qubit gates
10^{-5} s
Two qubit gates
10^{-4} s
10^{-3} s
10^{-2} s
10^{-1} s
Single qubit coherence
10^{0} s
Single qubit coherence magnetic field insensitive
10^{1} s
10^{2} s
10^{3} s

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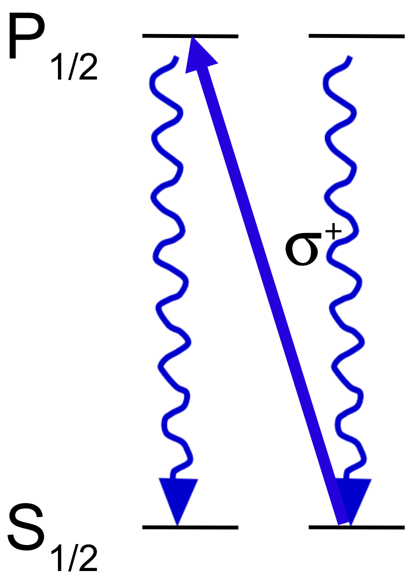
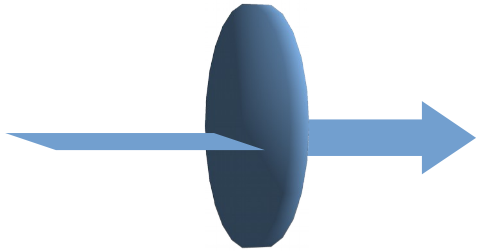
See: http://en.wikipedia.org/wiki/Murphy's_law

Qubit initialization

Algorithm consists of:

- Initialization
- Computation
  - single-qubit gates
  - two-qubit gates
- Read-out



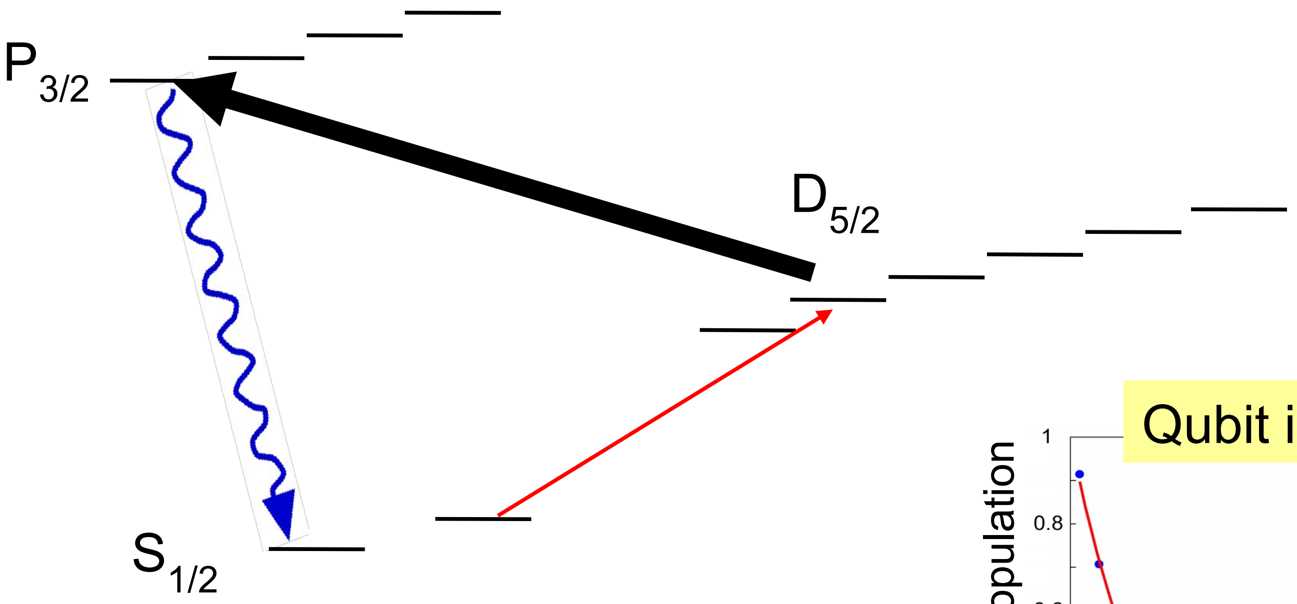


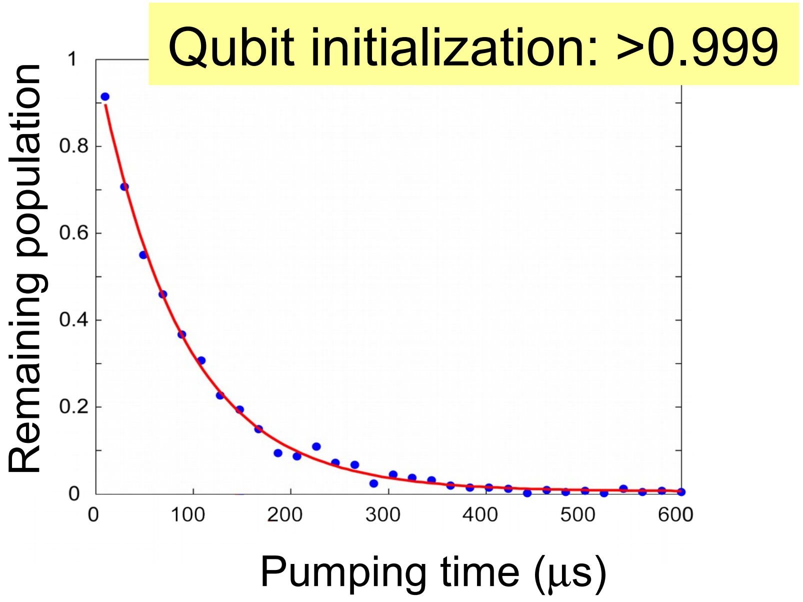
View port

Pumping limited by
- polarization
- beam-field alignment

Qubit initialization

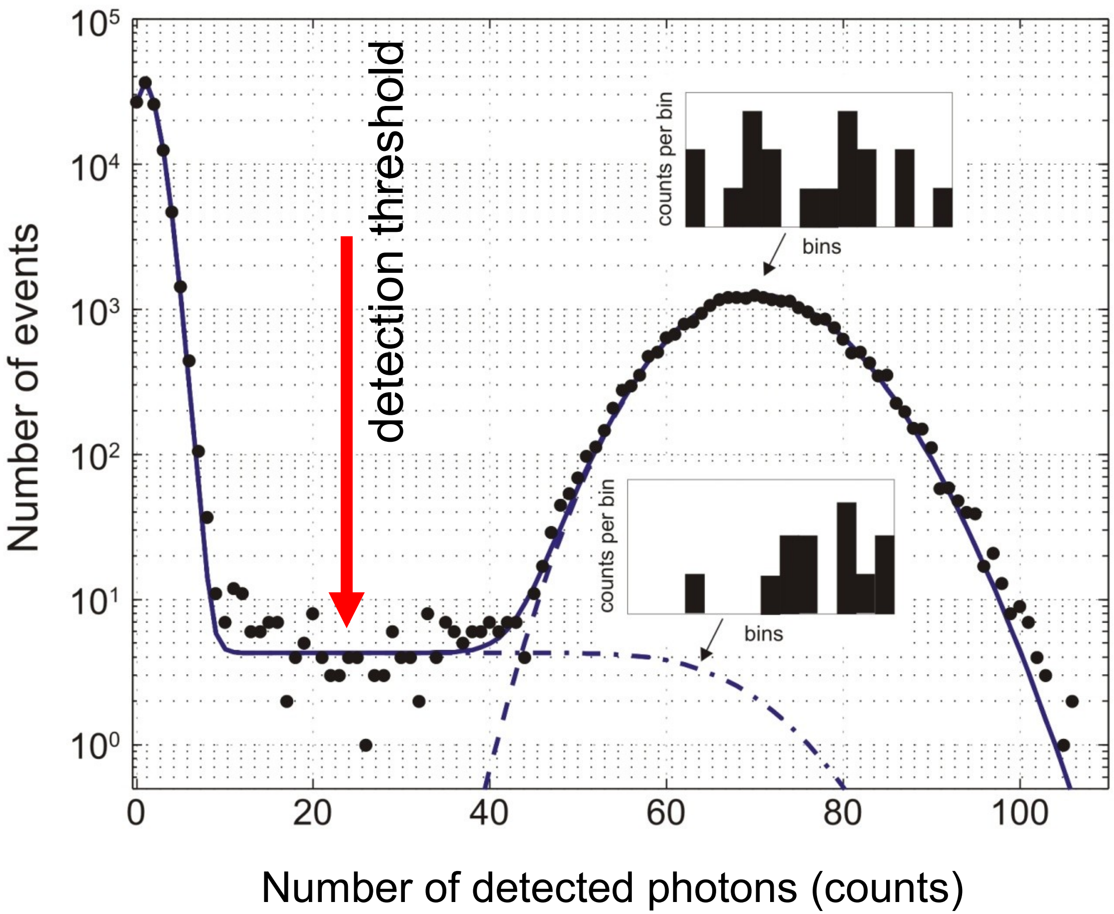
Better fidelities can be reached with frequency selectivity.





Qubit read out

One ion detection histogram
(200 μs collection time, 99% fidelity)

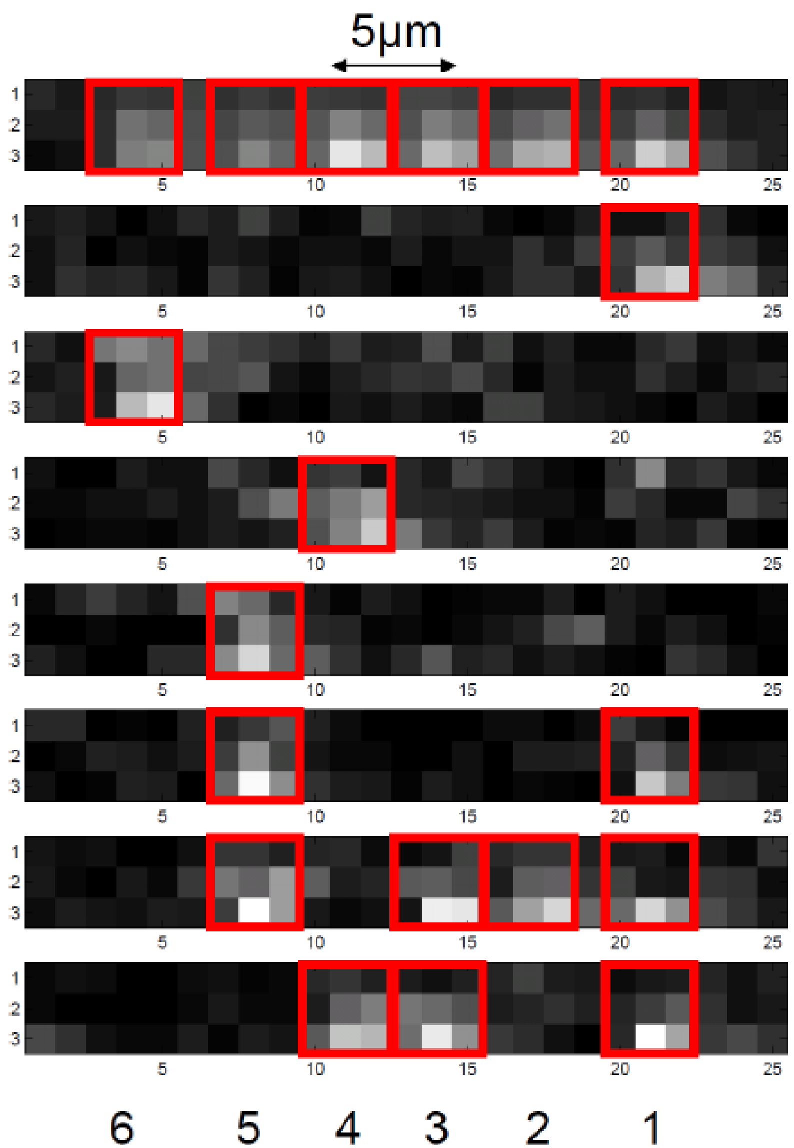


for Bayesian analysis
collect in time bins of 10 μs

- detection by maximum likelihood method reduces error due to spontanous decay

high-fidelity readout: A. H. Myerson *et al.* (Oxford), *Phys. Rev. Lett.* **100**, 200502 (2008)

Qubit read-out



Infidelities:

- Camera: 1% @ 5 ms
- PMT: <1% @ 200 μs

Further improvements possible:

- Adaptive read-out
  (Myerson, PRL 100, 200402 (2008))

- CNOT
  (Schätz, *et al.*, PRL **94**, 010501 (2005))

- Repeated mapping
  (Hume *et al.*, PRL **99**, 120502 (2007))

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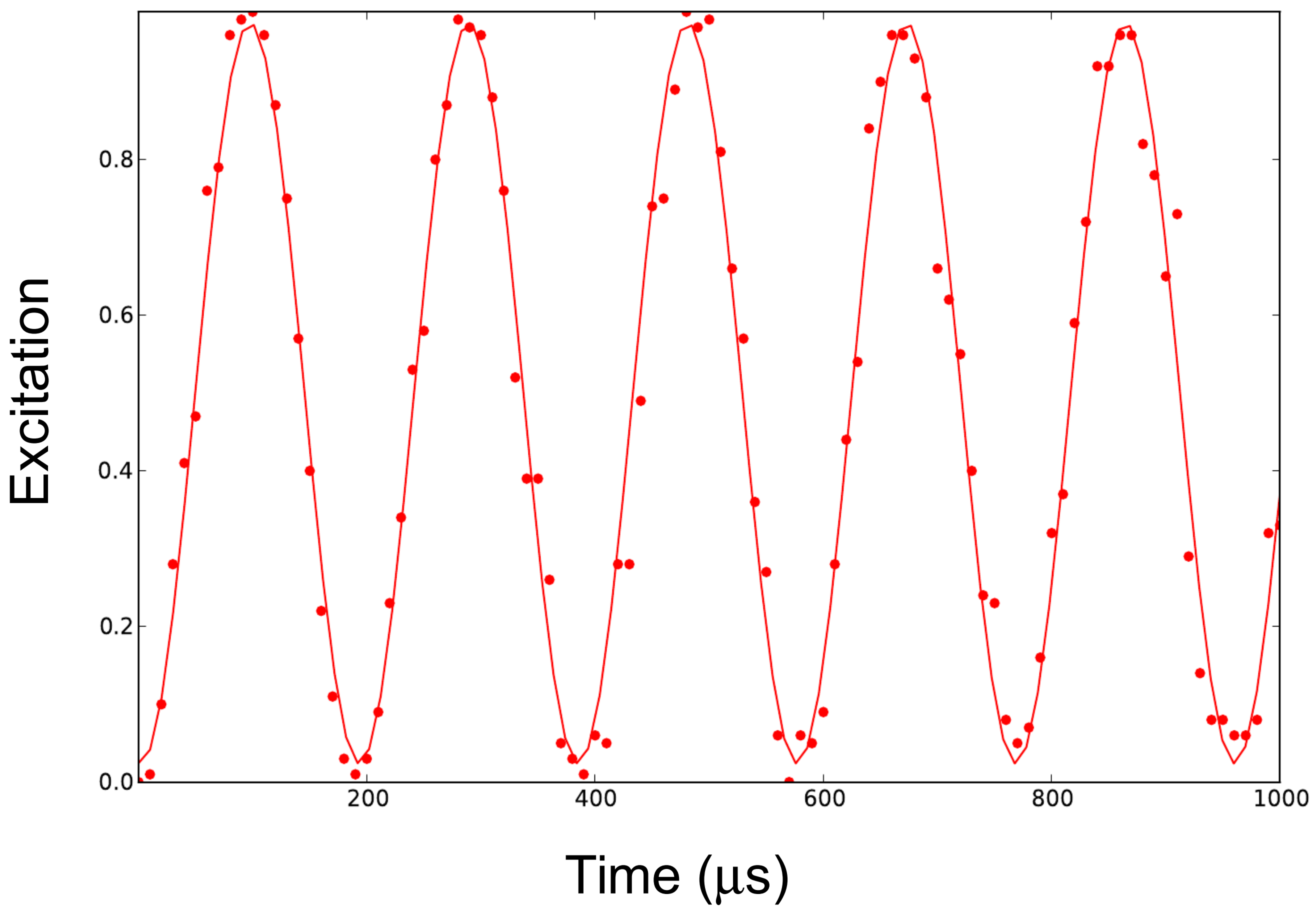
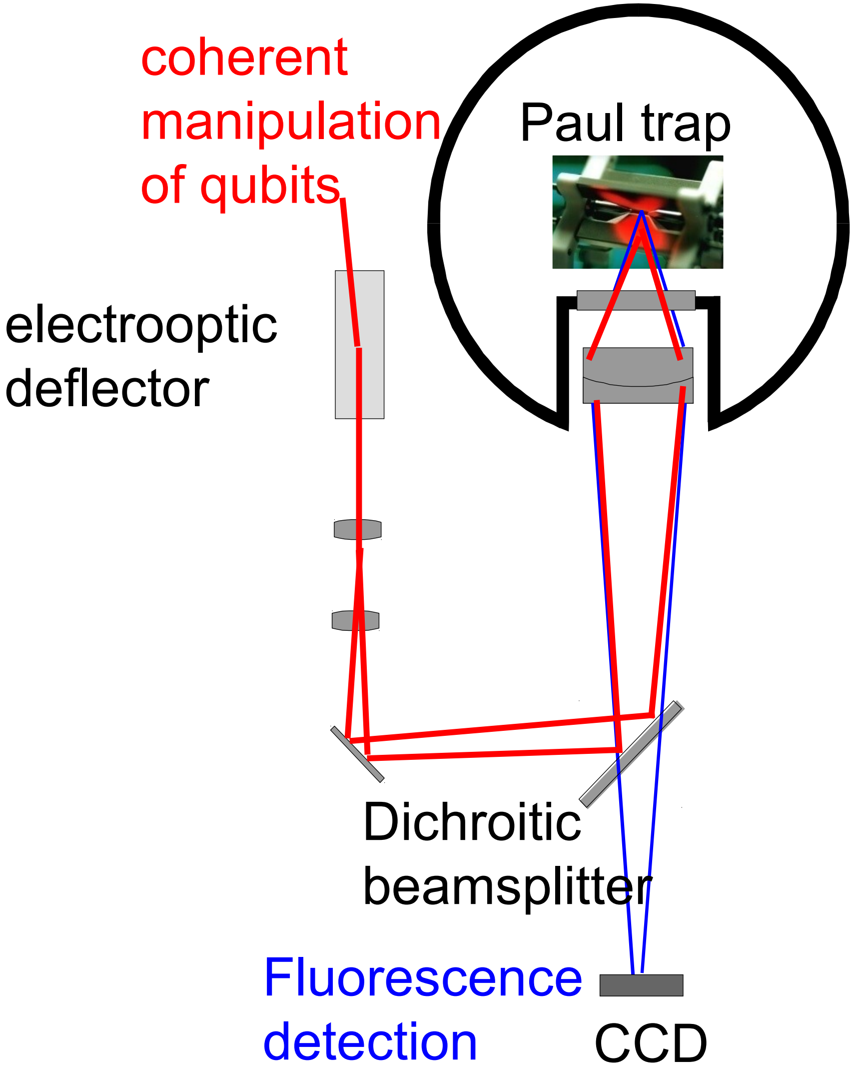
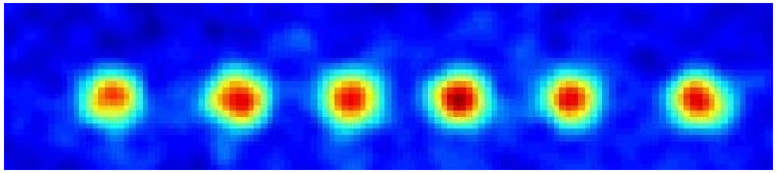
Single qubit operations

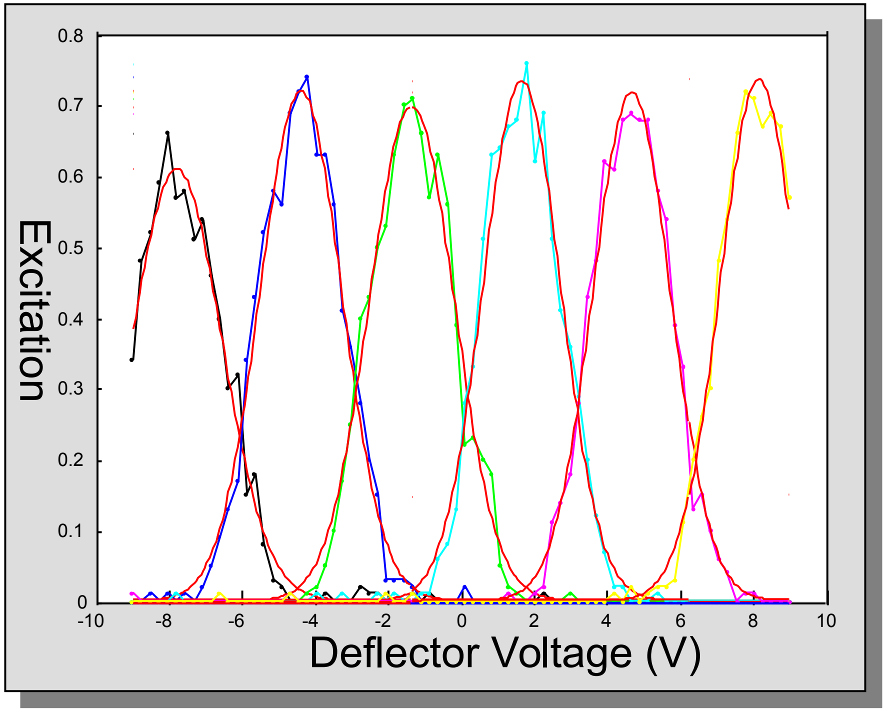


=> Laser intensity noise is about 1.5%

Adressing single qubits



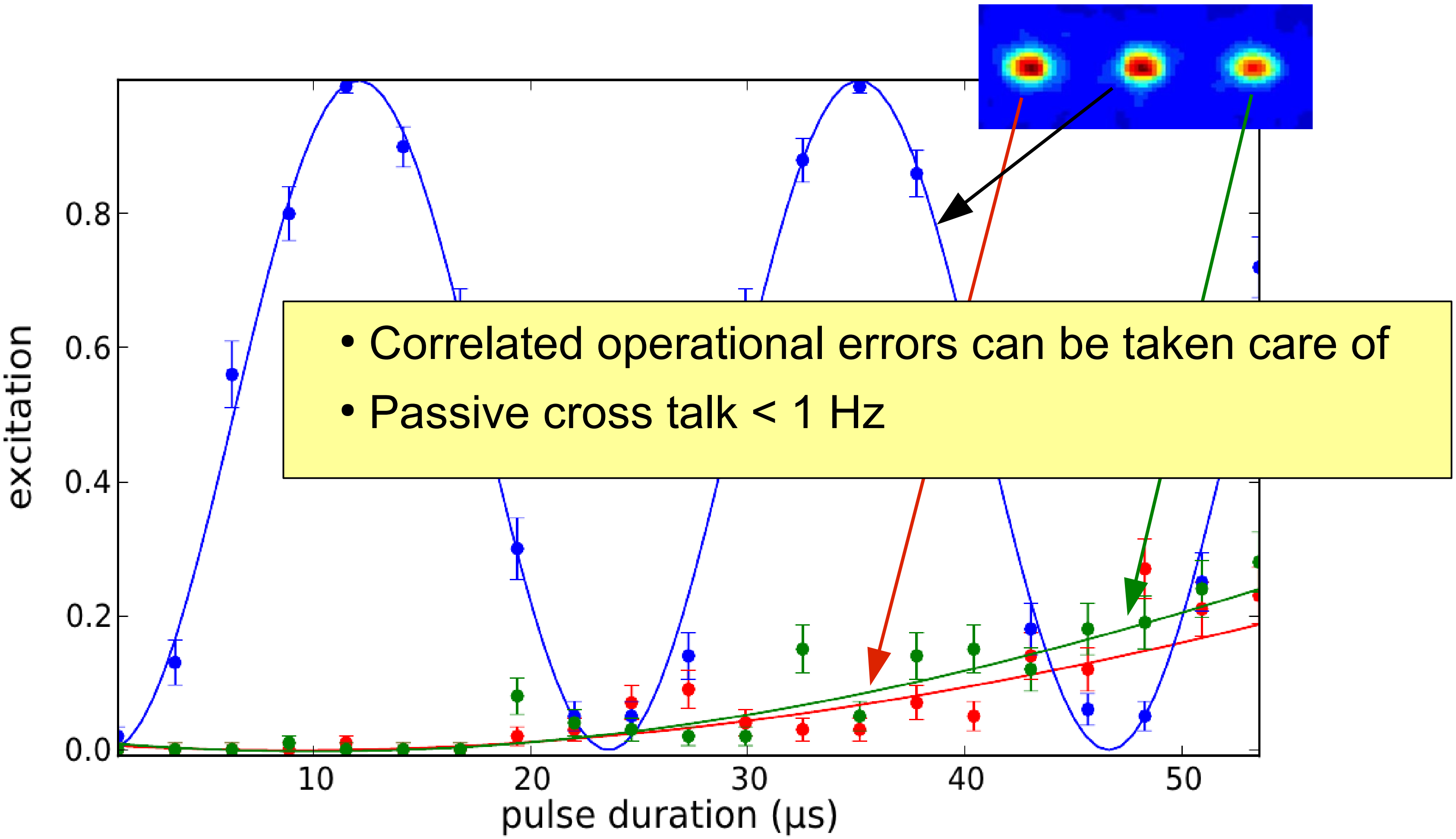




- inter ion distance: ~ 4 um
- addressing waist: ~ 2 um

< 0.1% intensity on neighbouring ions

Adressing single qubits



Drive on Resonance - 8% unwanted rotation

Use AC stark shift - addressing error < 1%

Innsbruck, 2010

Mølmer - Sørensen gate

$$|gg\rangle \rightarrow |ee\rangle, \quad |ge\rangle \rightarrow |eg\rangle$$

$$\omega_b = \omega_0 + (\nu - \varepsilon)$$
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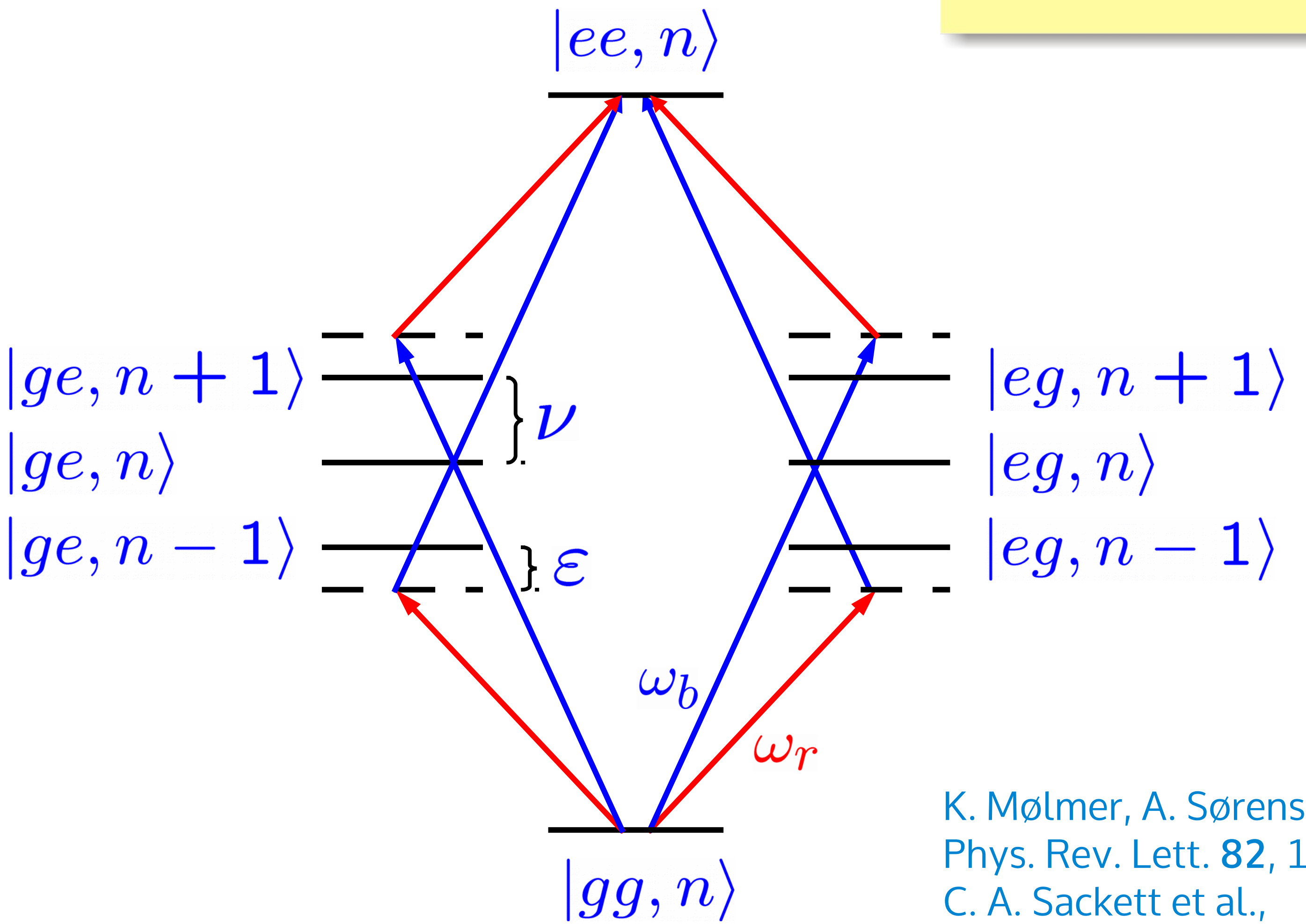

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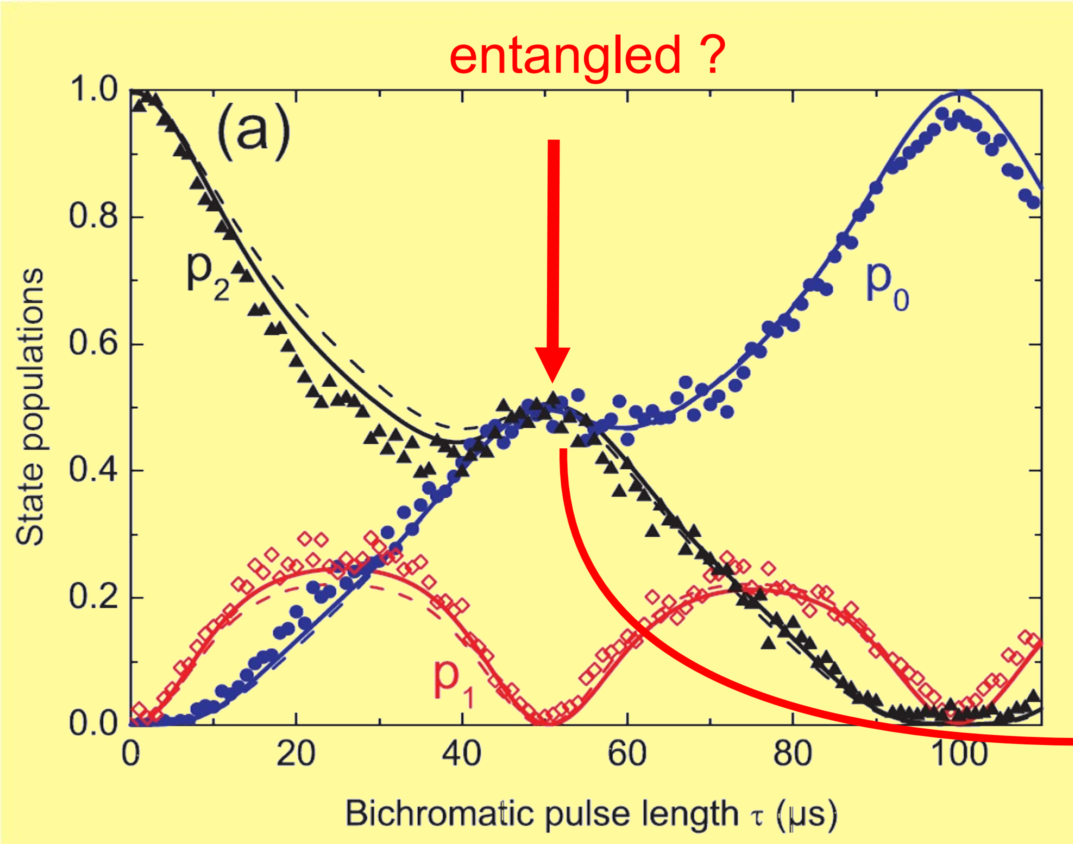
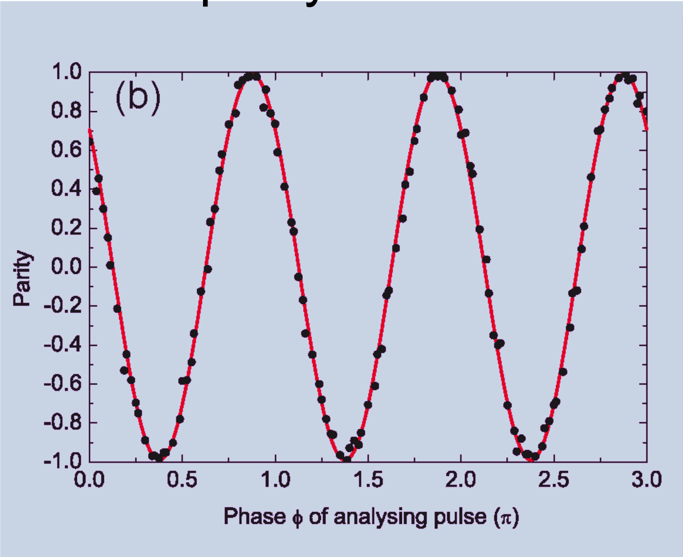


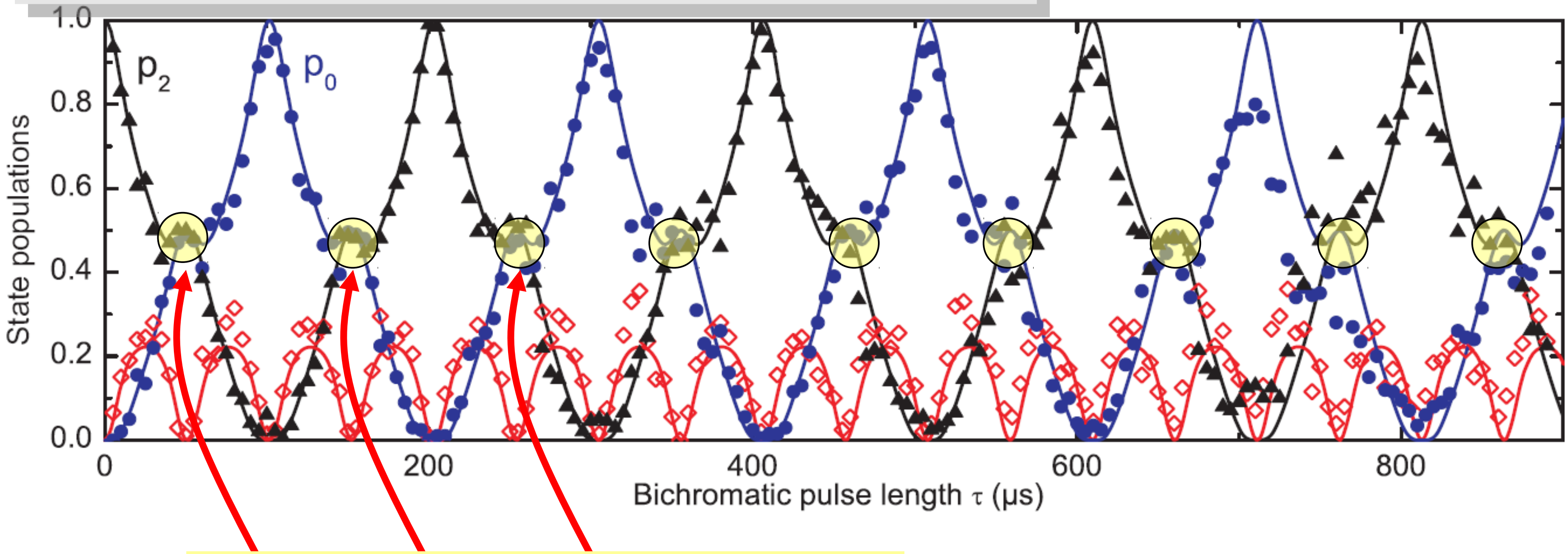
measure entanglement via parity oscillations



gate duration 50 μs

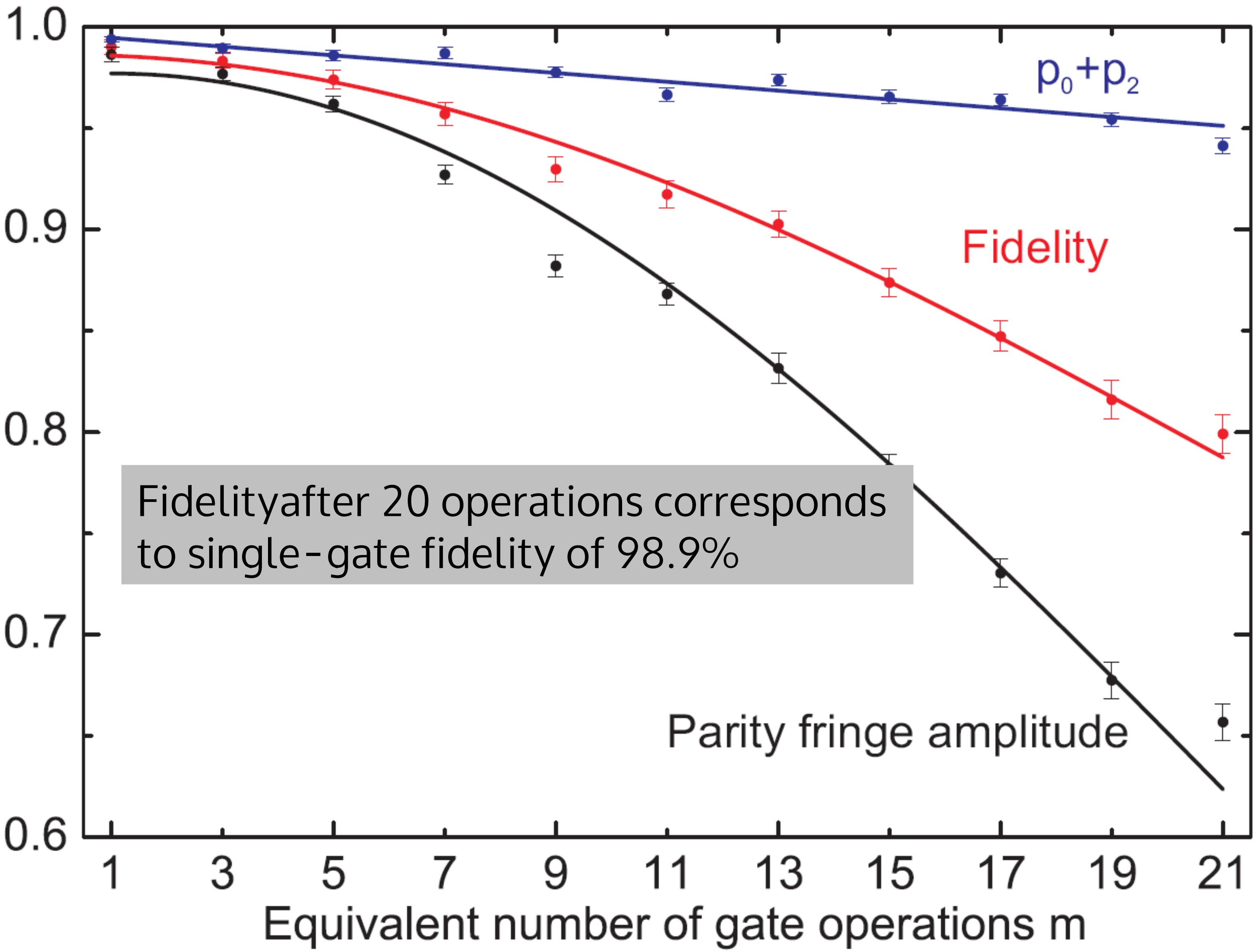
Multiple gates

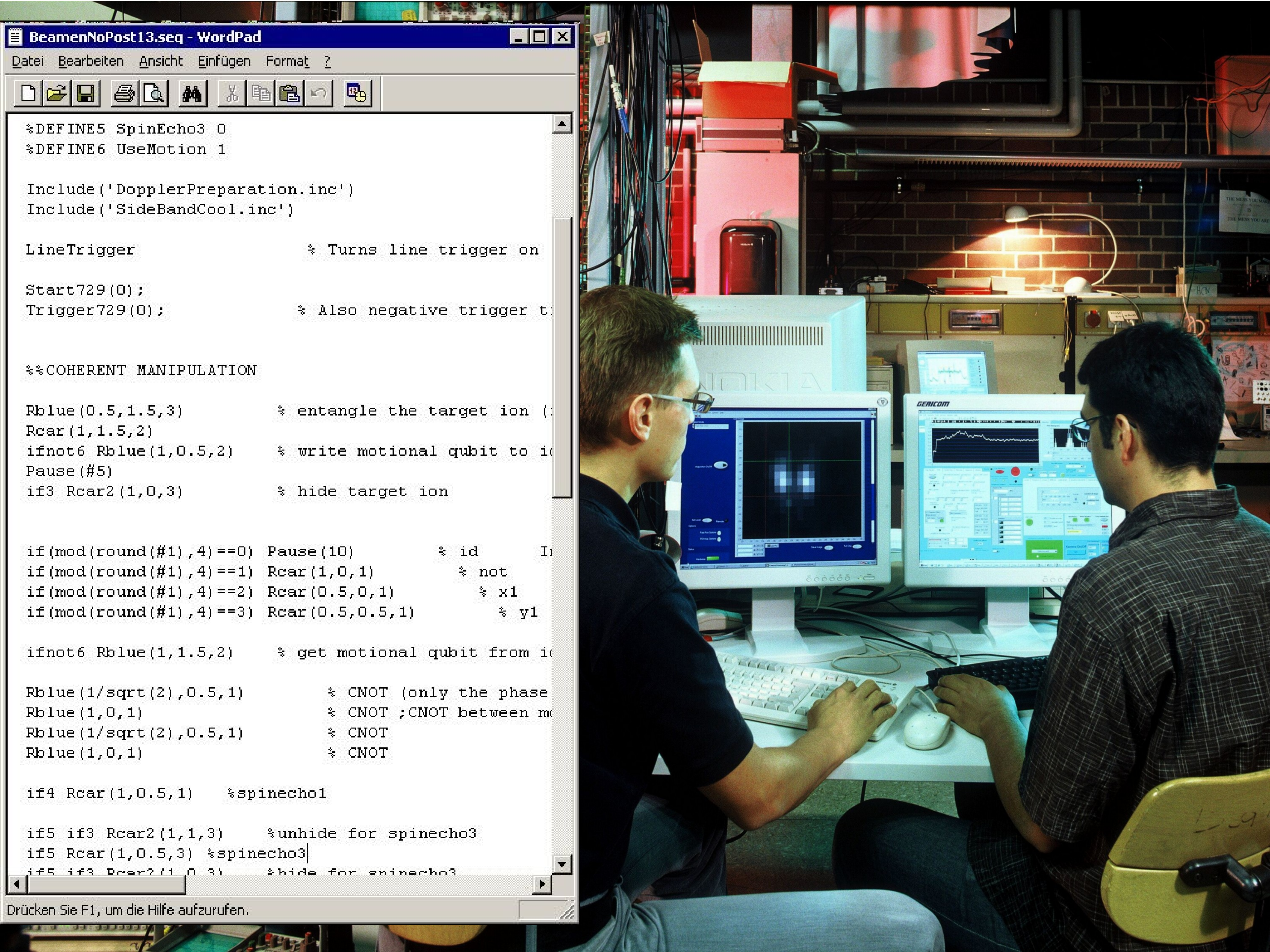
Infidelity:
- detection and initialization enter only once
- qubit dephasing
- trap frequency stability



maximally entangled states

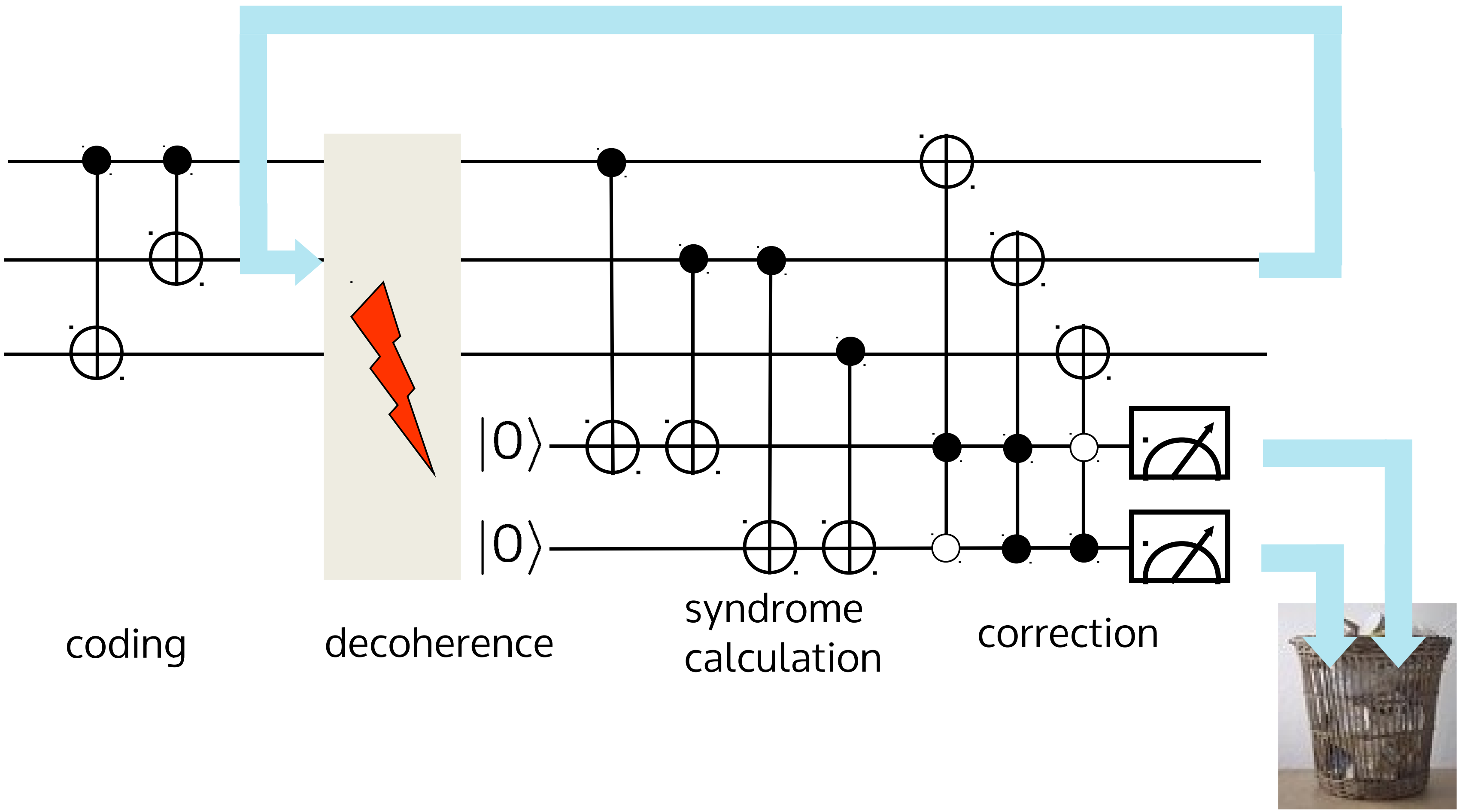
Multiple gates



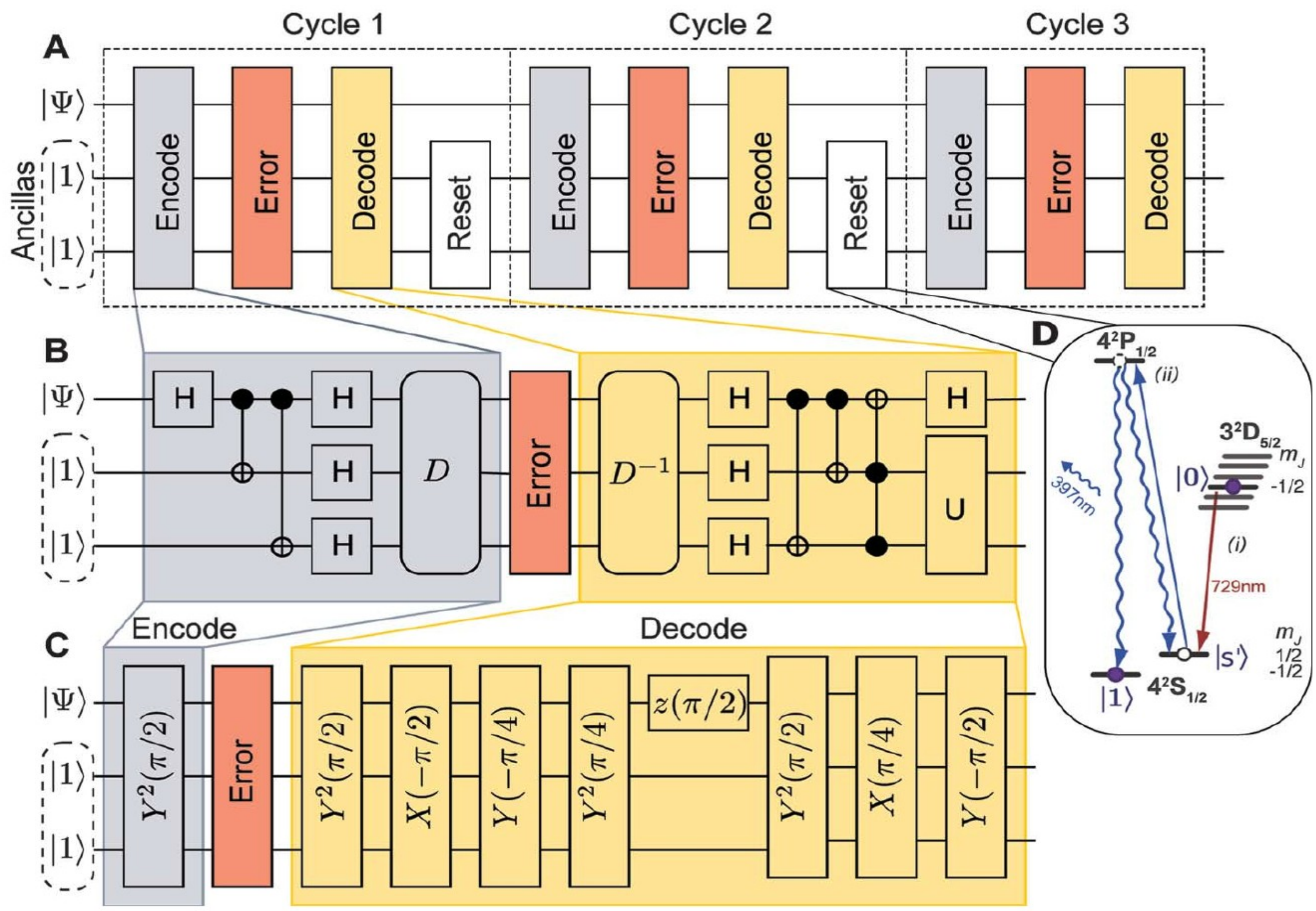


BeamenNoPost13.seq - WordPad
Datei Bearbeiten Ansicht Einfügen Format ?
%DEFINE5 SpinEcho3 0
%DEFINE6 UseMotion 1
Include('DopplerPreparation.inc')
Include('SideBandCool.inc')
LineTrigger % Turns line trigger on
Start729(0);
Trigger729(0); % Also negative trigger
%%COHERENT MANIPULATION
Rblue(0.5,1.5,3) % entangle the target ion
Rcar(1,1.5,2)
ifnot6 Rblue(1,0.5,2) % write motional qubit to i
Pause(#5)
if3 Rcar2(1,0,3) % hide target ion
if(mod(round(#1),4)==0) Pause(10) % id
if(mod(round(#1),4)==1) Rcar(1,0,1) % not
if(mod(round(#1),4)==2) Rcar(0.5,0,1) % x1
if(mod(round(#1),4)==3) Rcar(0.5,0.5,1) % y1
ifnot6 Rblue(1,1.5,2) % get motional qubit from i
Rblue(1/sqrt(2),0.5,1) % CNOT (only the phase
Rblue(1,0,1) % CNOT ;CNOT between m
Rblue(1/sqrt(2),0.5,1) % CNOT
Rblue(1,0,1) % CNOT
if4 Rcar(1,0.5,1) %spinecho1
if5 if3 Rcar2(1,1,3) %unhide for spinecho3
if5 Rcar(1,0.5,3) %spinecho3
Drücken Sie F1, um die Hilfe aufzurufen.
NOKIA
GERICOM

Quantum error correction



Error correction implementation



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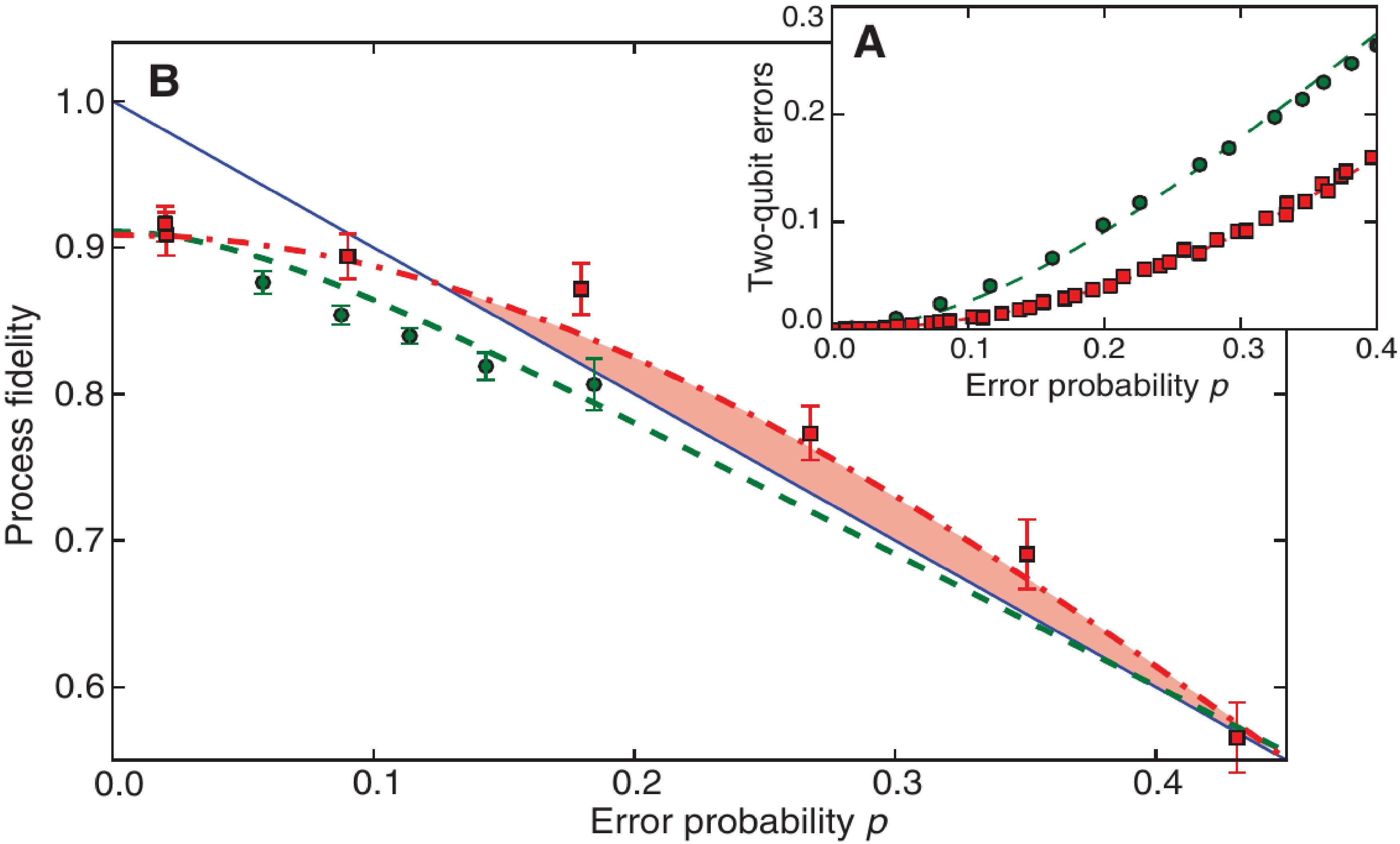
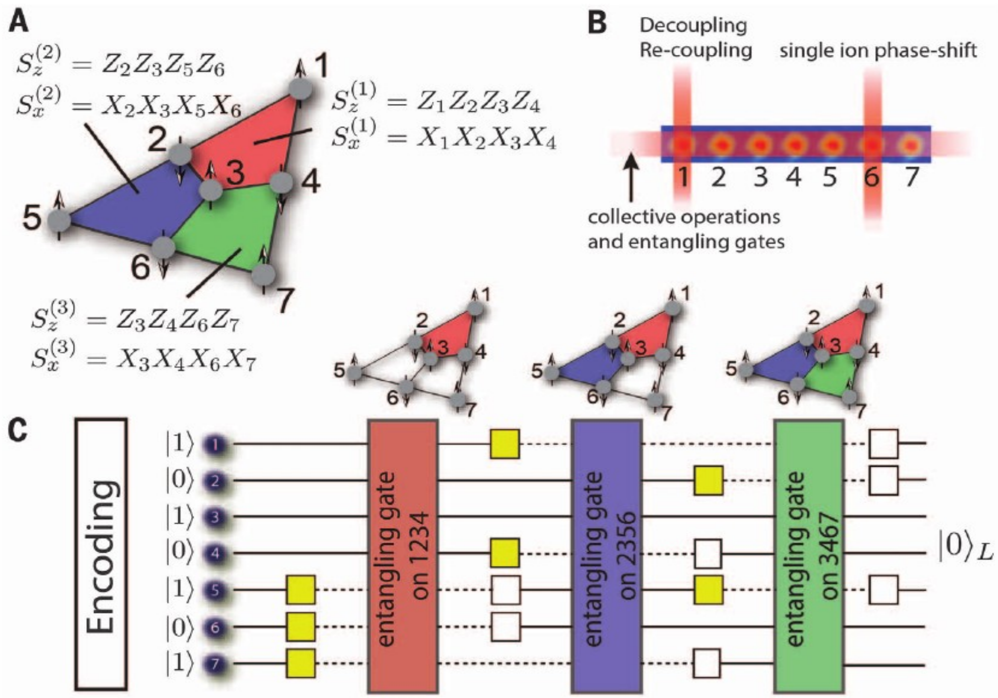
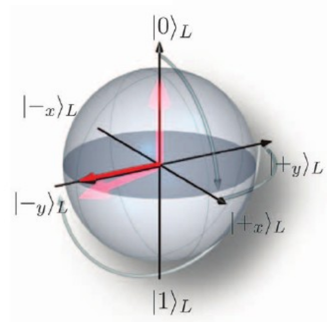


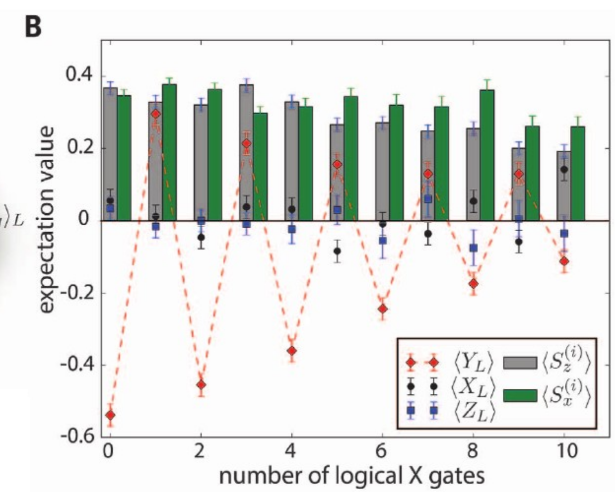
Repeatable quantum error correction:
P. Schindler et al, Science 332, 1059 (2011)

Operating on a topologically corrected qubit



Single qubit operations

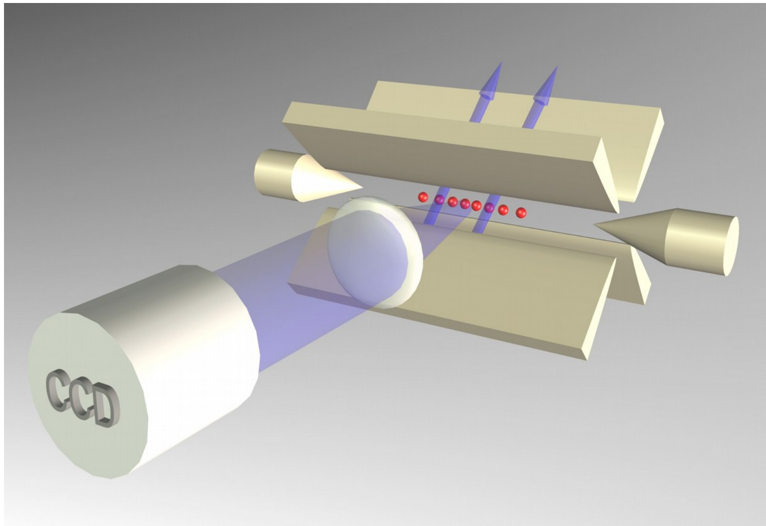




Fully protected qubit

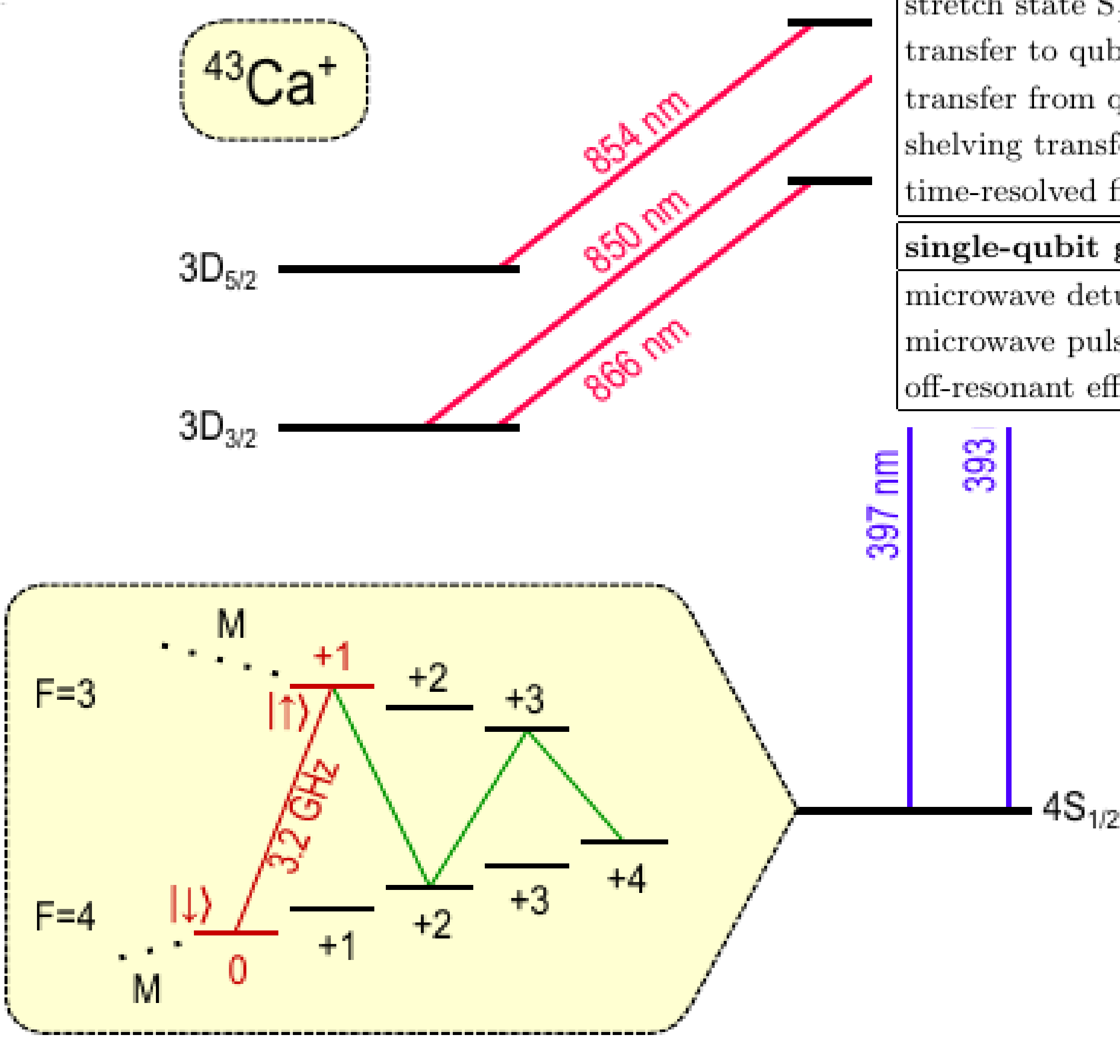
D. Nigg *et al.*, Science 345, 302 (2014)

Anticipated requirements for QEC



	Actual	Required
[illegible]	1.2 s	1 s
noise)	10 μG	1 μG
[illegible]	10 Hz	1 Hz
Laser intensity fluctuations	1.5 %	0.01 %
Cross talk	0.1 % / qubit	0.01 % / qubit
Initialization error	0.3 % / qubit	0.01 % / qubit
Read-out	0.5 % / qubit	0.01 % / qubit
Heating rate	3 quanta / s	10 quanta / s
Secular frequency stability in planar trap	~100 Hz	10 Hz

High-fidelity gates



preparation/readout operation	error
stretch state $S_{1/2}^{4,+4}$ preparation	$< 1 \times 10^{-4}$
transfer to qubit (3 or 4 m.w. π-pulses)	1.8×10^{-4}
transfer from qubit (4 m.w. π-pulses)	1.8×10^{-4}
shelving transfer $S_{1/2}^{4,+4} \rightarrow D_{5/2}$	1.7×10^{-4}
time-resolved fluorescence detection	1.5×10^{-4}

single-qubit gate error source	mean EPG
microwave detuning (4.5 Hz)	0.7×10^{-6}
microwave pulse area (5×10^{-4})	0.3×10^{-6}
off-resonant effects	0.1×10^{-6}

Harty *et al.*, arxiv.org:1403.1524 [quant-ph]

Mølmer - Sørensen gate

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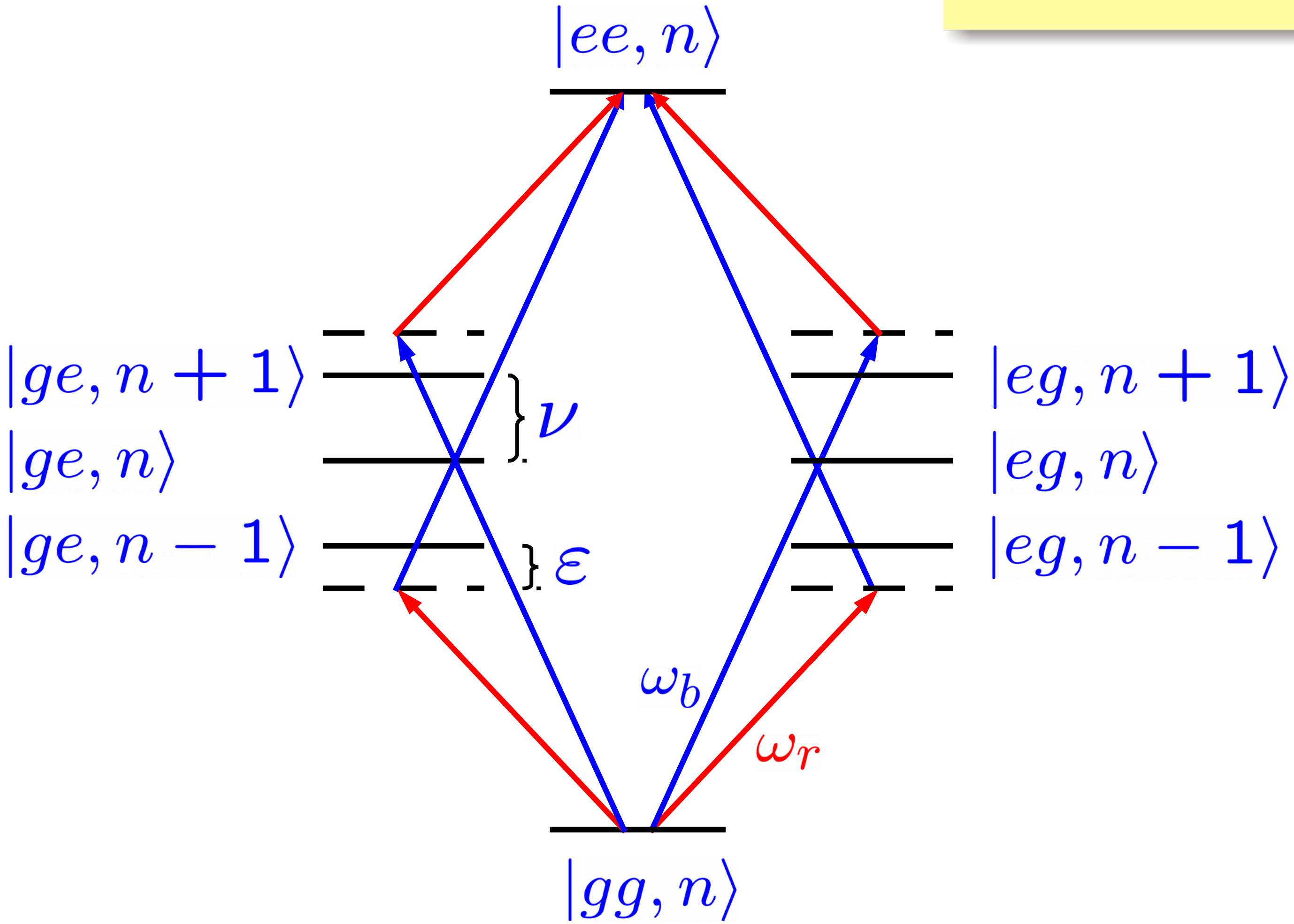

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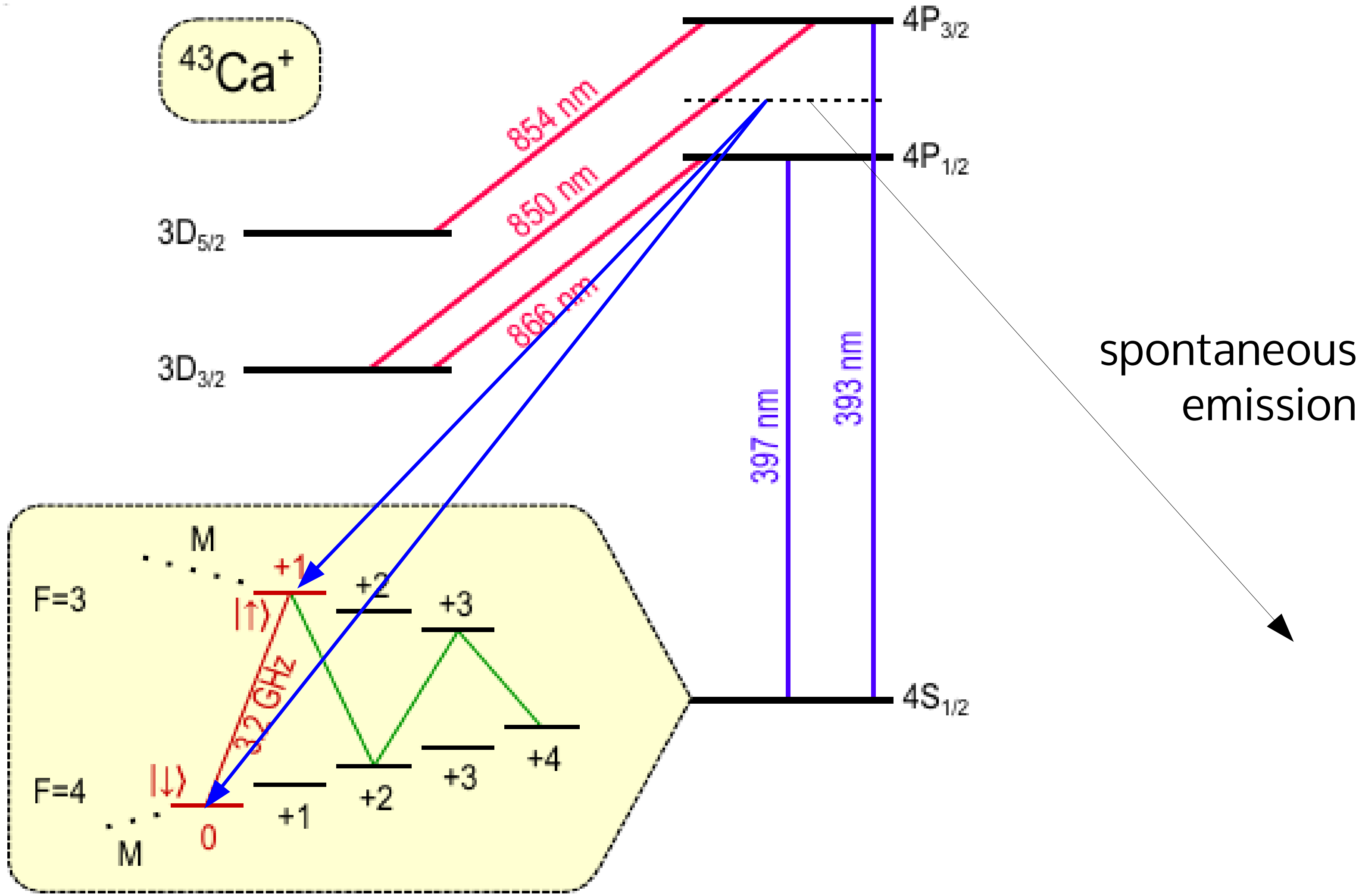
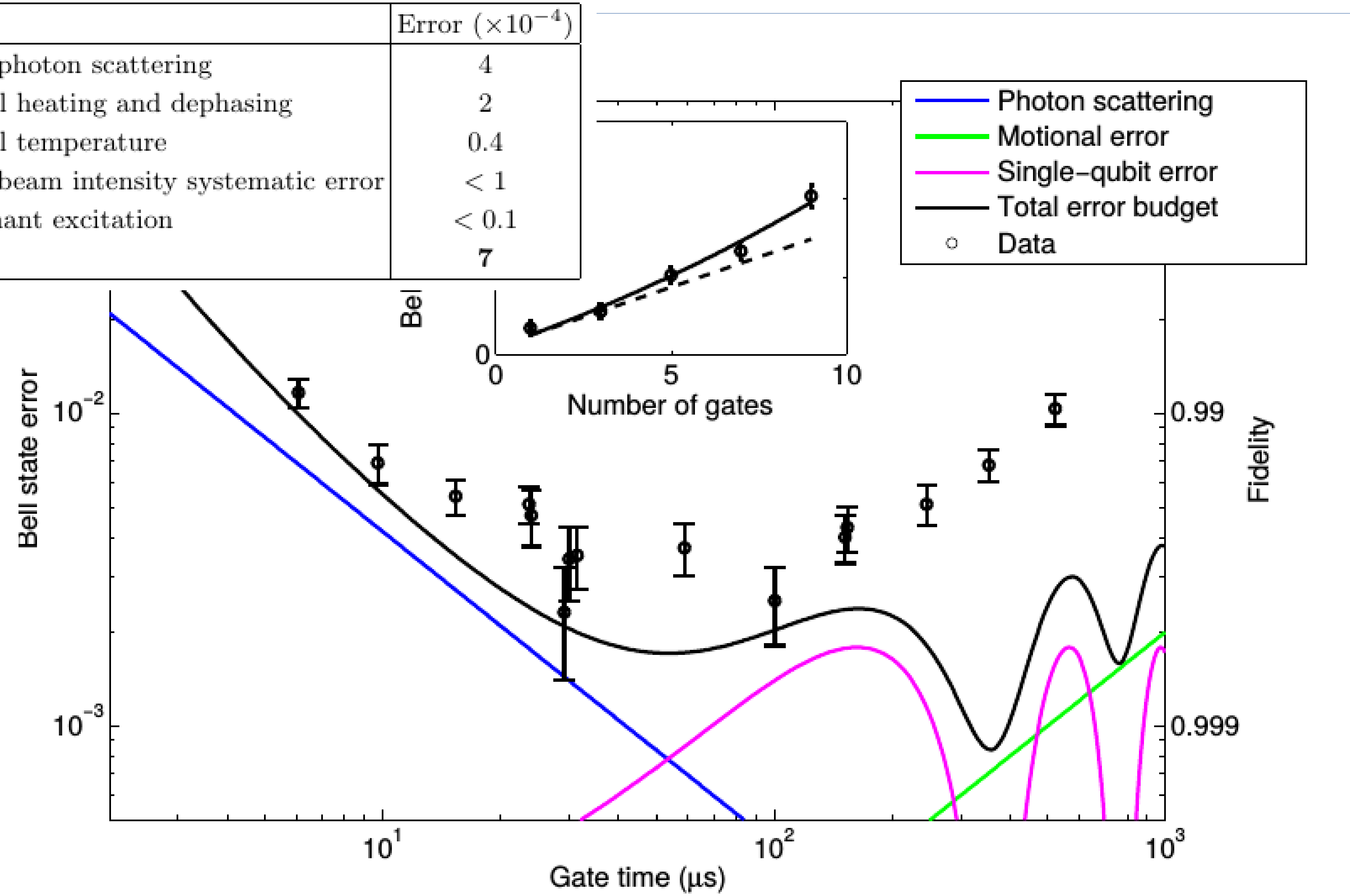


High-fidelity gates

Source	Error ($\times 10^{-4}$)
Raman photon scattering	4
motional heating and dephasing	2
motional temperature	0.4
Raman beam intensity systematic error	< 1
off-resonant excitation	< 0.1
Total	**7**



Ballance *et al.*, arxiv.org:1406.5473 [quant-ph]

Anticipated requirements for QEC

Harty *et al.*, arxiv.:1403.1524

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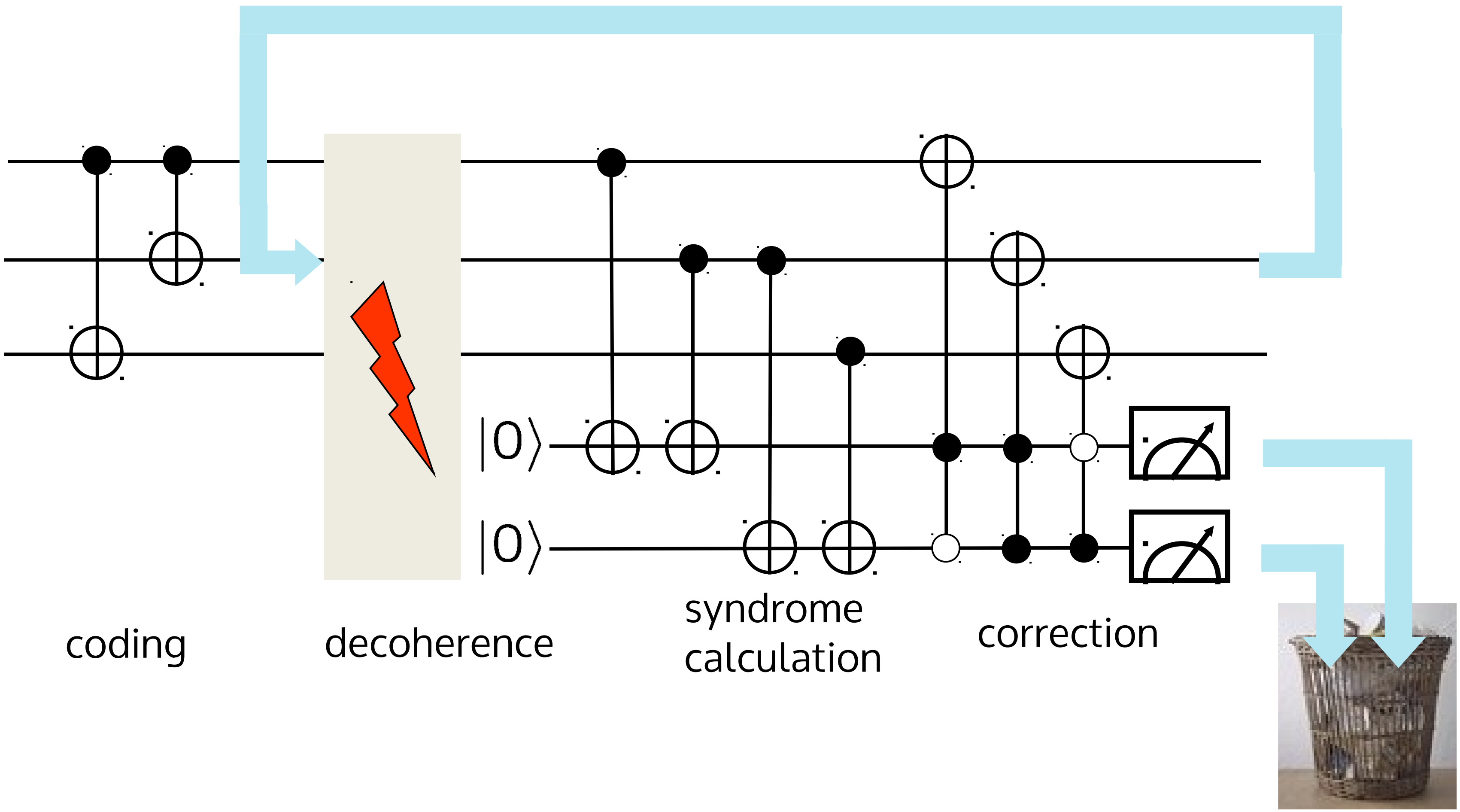
transfer to qubit (3 or 4 m.w. π-pulses)	1.8×10^{-4}
transfer from qubit (4 m.w. π-pulses)	1.8×10^{-4}
shelving transfer $S_{1/2}^{4,+4} \rightarrow D_{5/2}$	1.7×10^{-4}
time-resolved fluorescence detection	1.5×10^{-4}

single-qubit gate error source	**mean EPG**
microwave detuning (4.5 Hz)	0.7×10^{-6}
microwave pulse area (5×10^{-4})	0.3×10^{-6}
off-resonant effects	0.1×10^{-6}

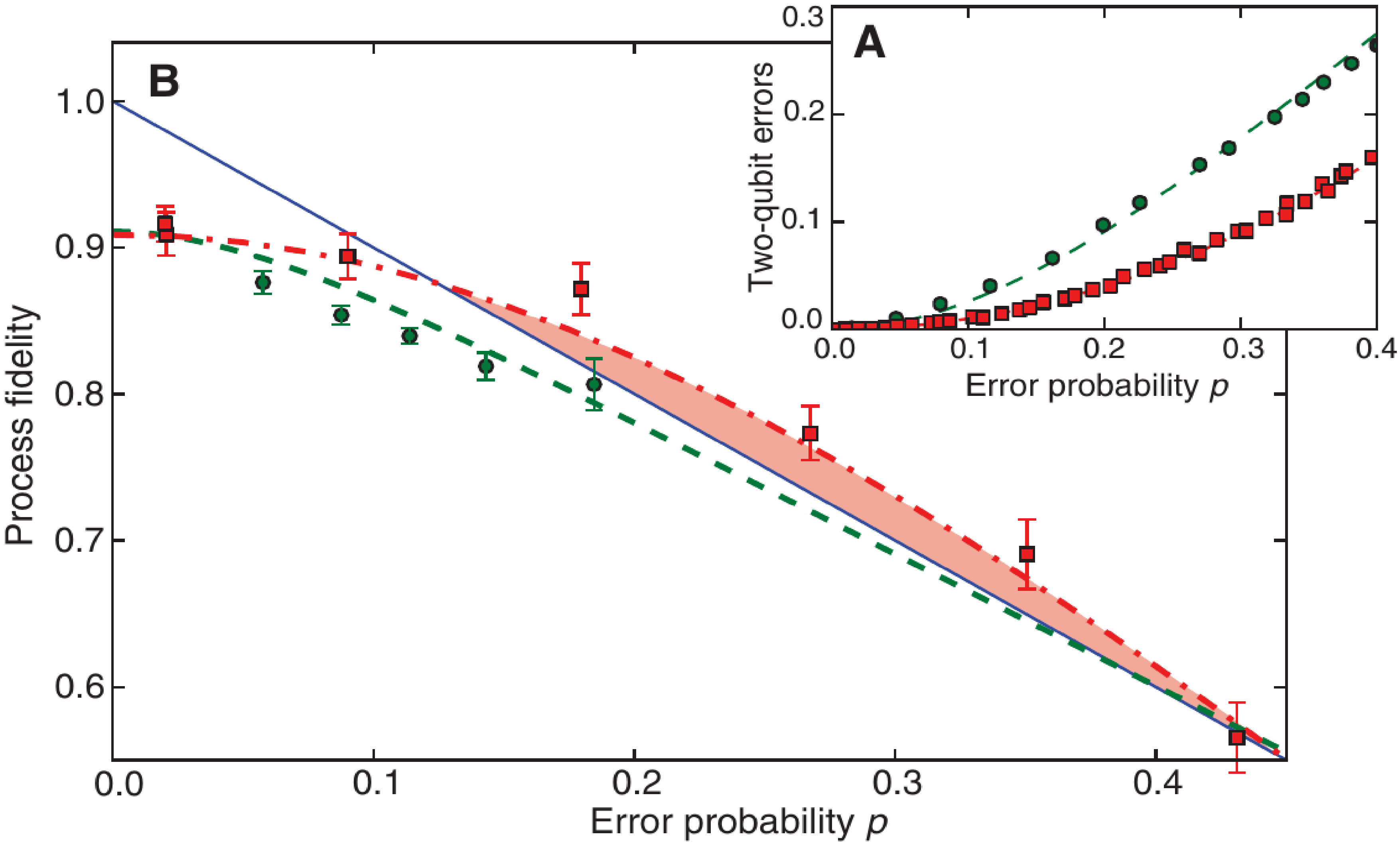
Ballance *et al.*, arxiv.org:1406.5473

Source	Error ($\times 10^{-4}$)
Raman photon scattering	4
motional heating and dephasing	2
motional temperature	0.4
Raman beam intensity systematic error	< 1
off-resonant excitation	< 0.1
Total	**7**

Quantum error correction



Error correction implementation



Repeatable quantum error correction:
P. Schindler et al, Science 332, 1059 (2011)

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- Paul traps
- Laser ion-interaction

Lecture #2: Quantum computing
- Quantum gates
- Quantum state tomography

Lecture #3: Decoherence
- Qubit decoherence
- Scaling

Lecture #4: Quantum simulation/emulation
- Scaling and anomalous heating
- Quantum simulation

Lecture #5: Applications
- Atomic clocks, quadrupole shifts
- Michelson-Morley experiment

The DiVincenzo criteria for quantum computing

I. Scalable physical system, well characterized qubits

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

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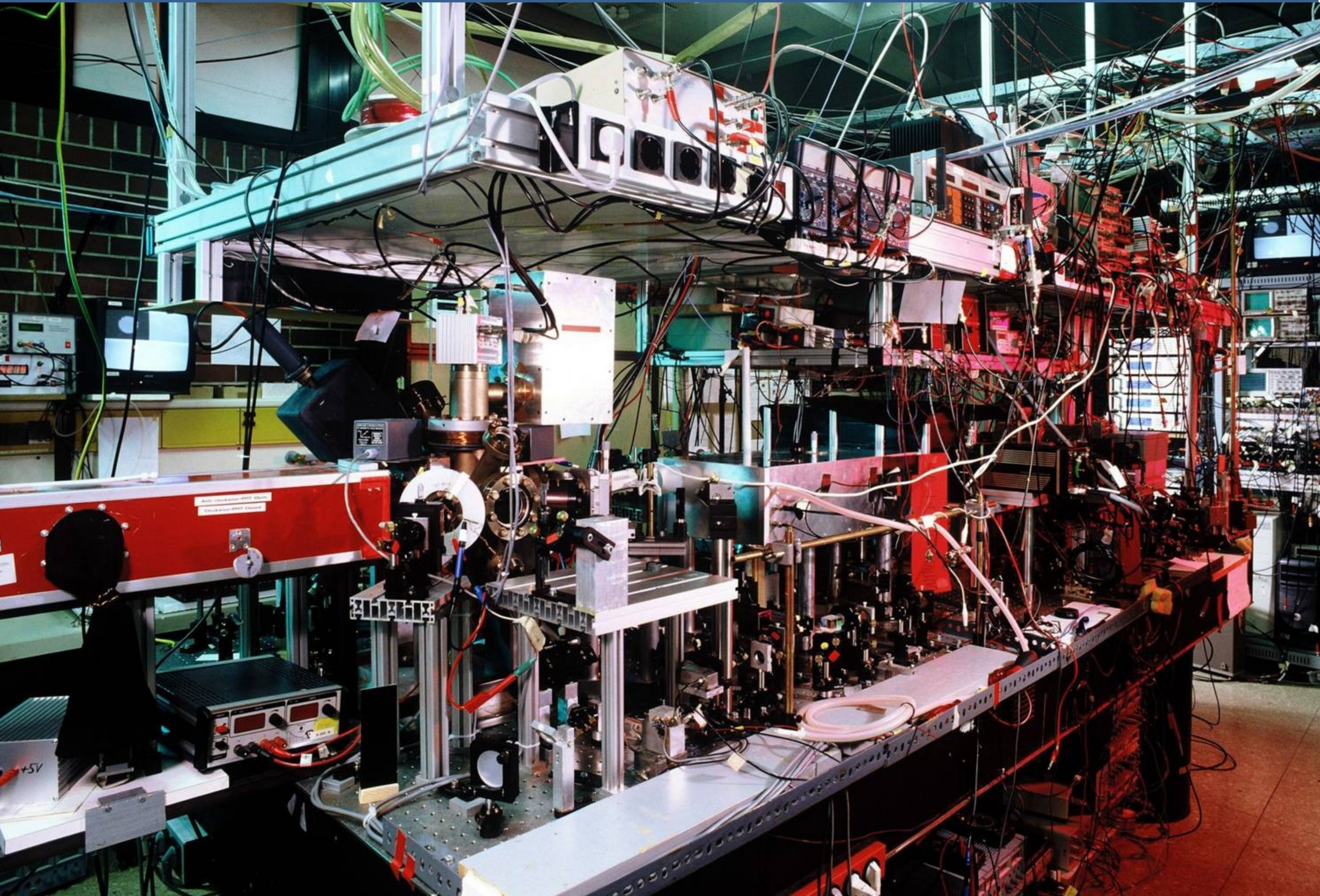
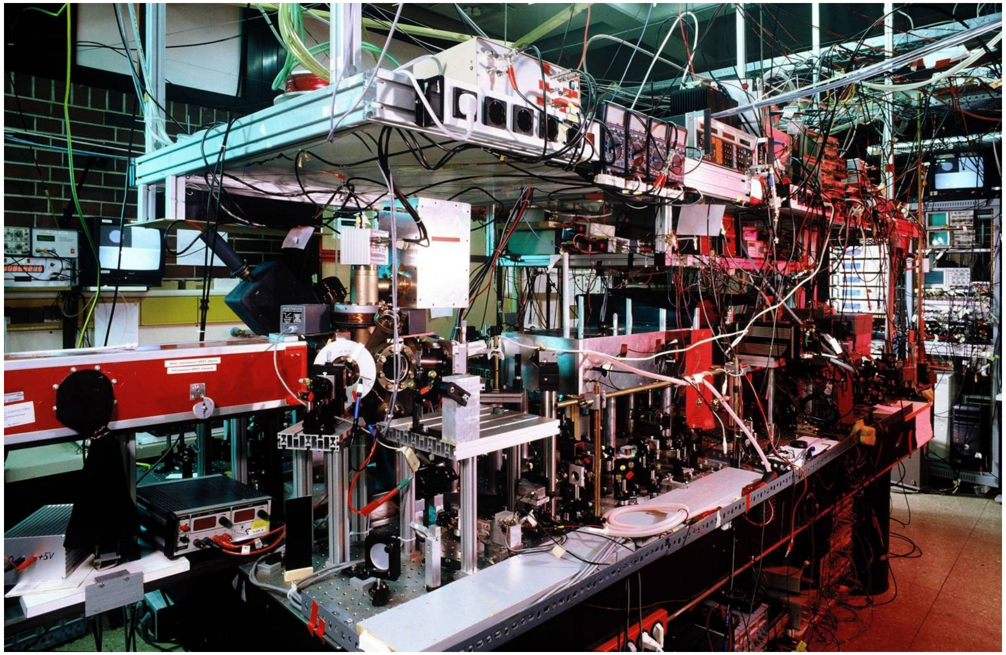
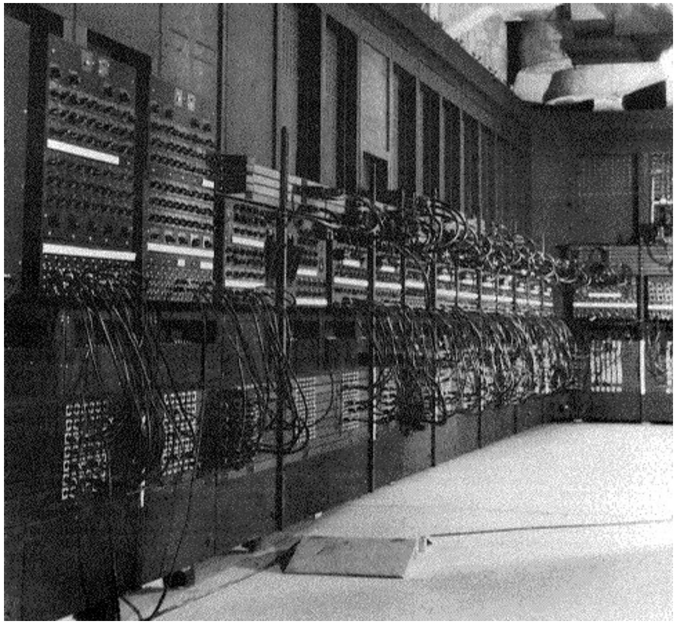
The hardware



The hardware

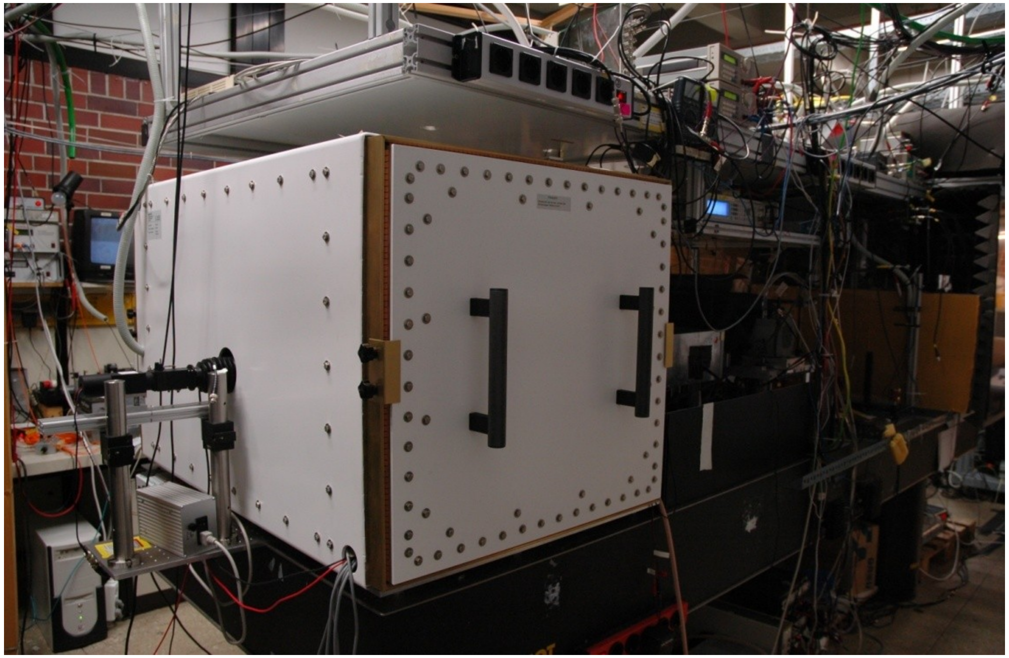


Quantum computer, 2005

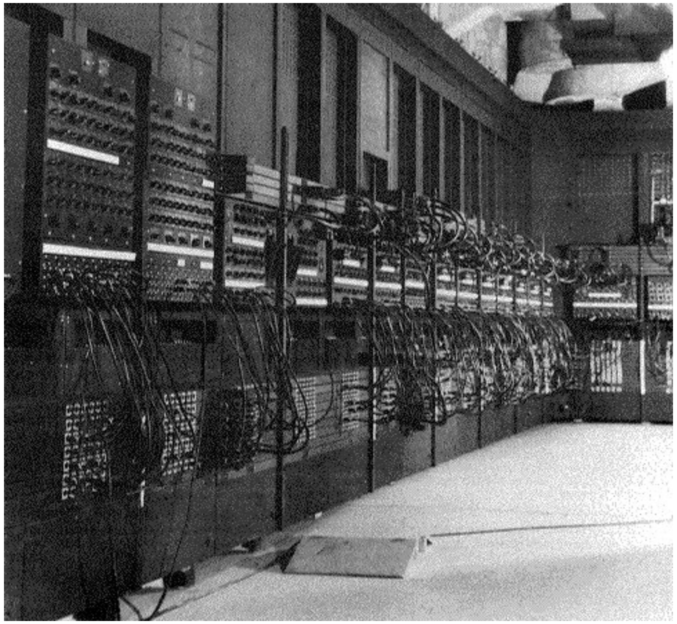


ENIAC, 1950

The hardware



Quantum computer, 2009



ENIAC, 1950

Scaling 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)

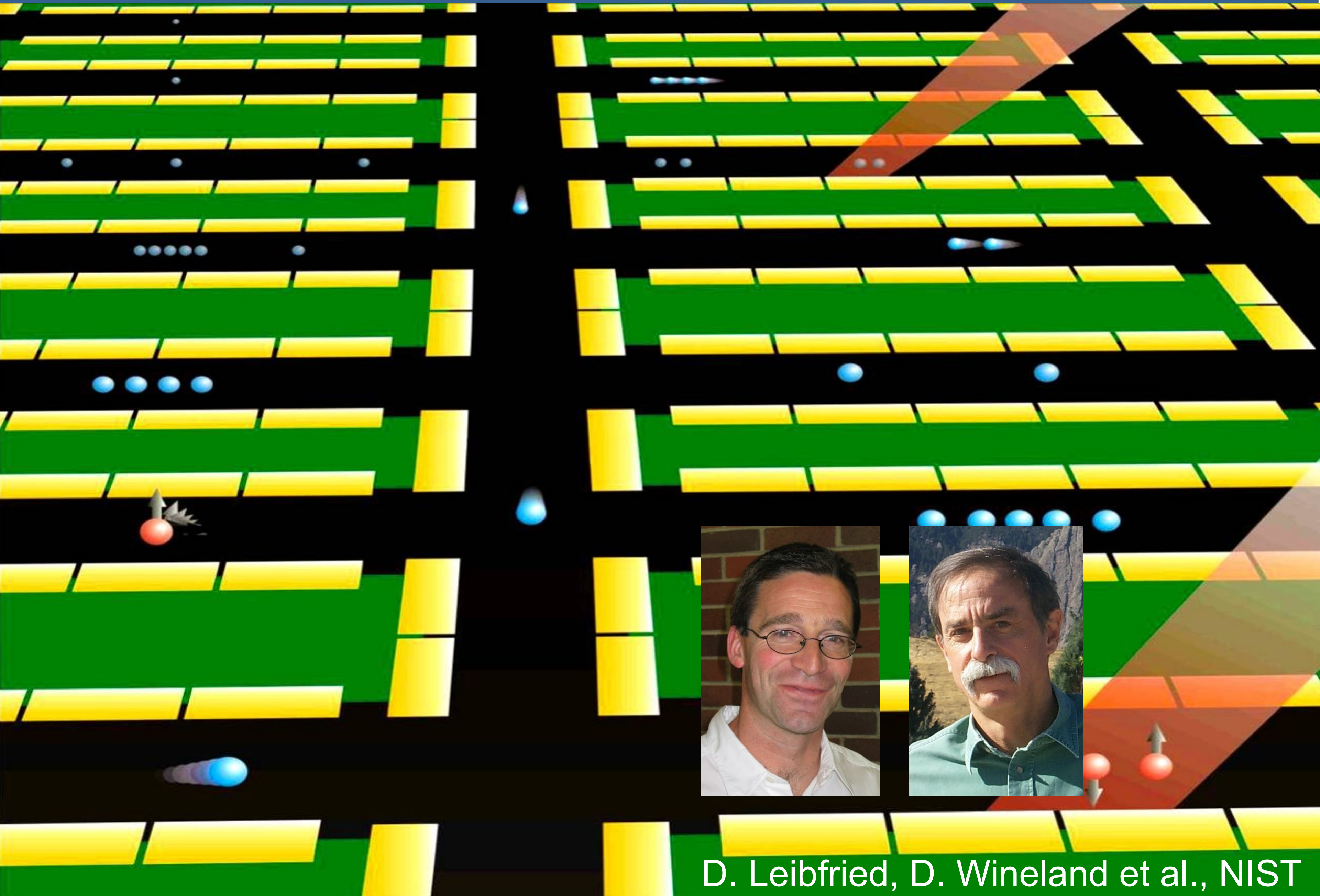
-> Gate operation speed slows down

- 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 ion trap quantum computers



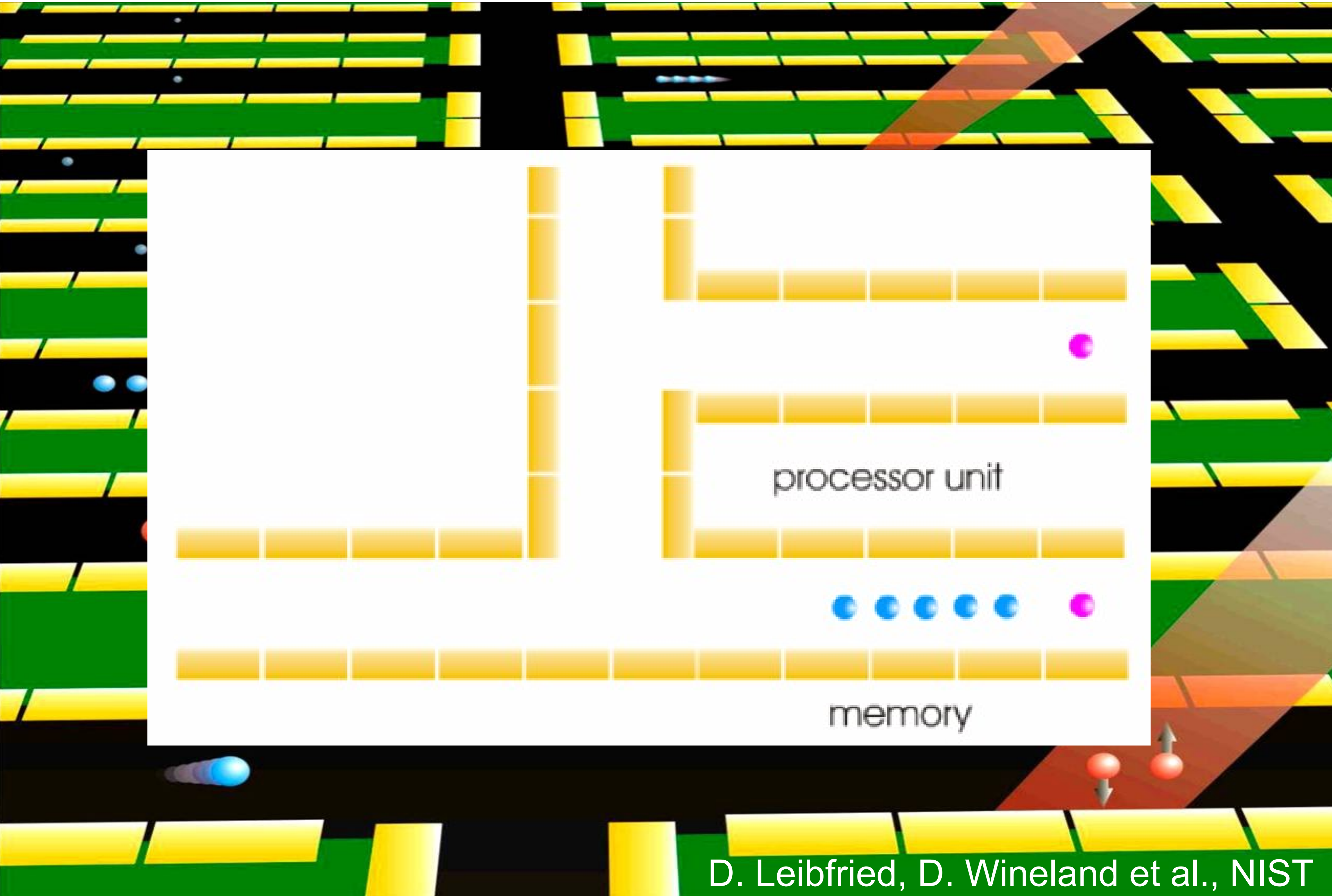
Scaling ion trap quantum computers

All ingredients for this approach have been shown to work together!

=> Home *et al.* , "Complete methods set for scalable ion trap quantum information processing," Science 325, 1227 (2009).

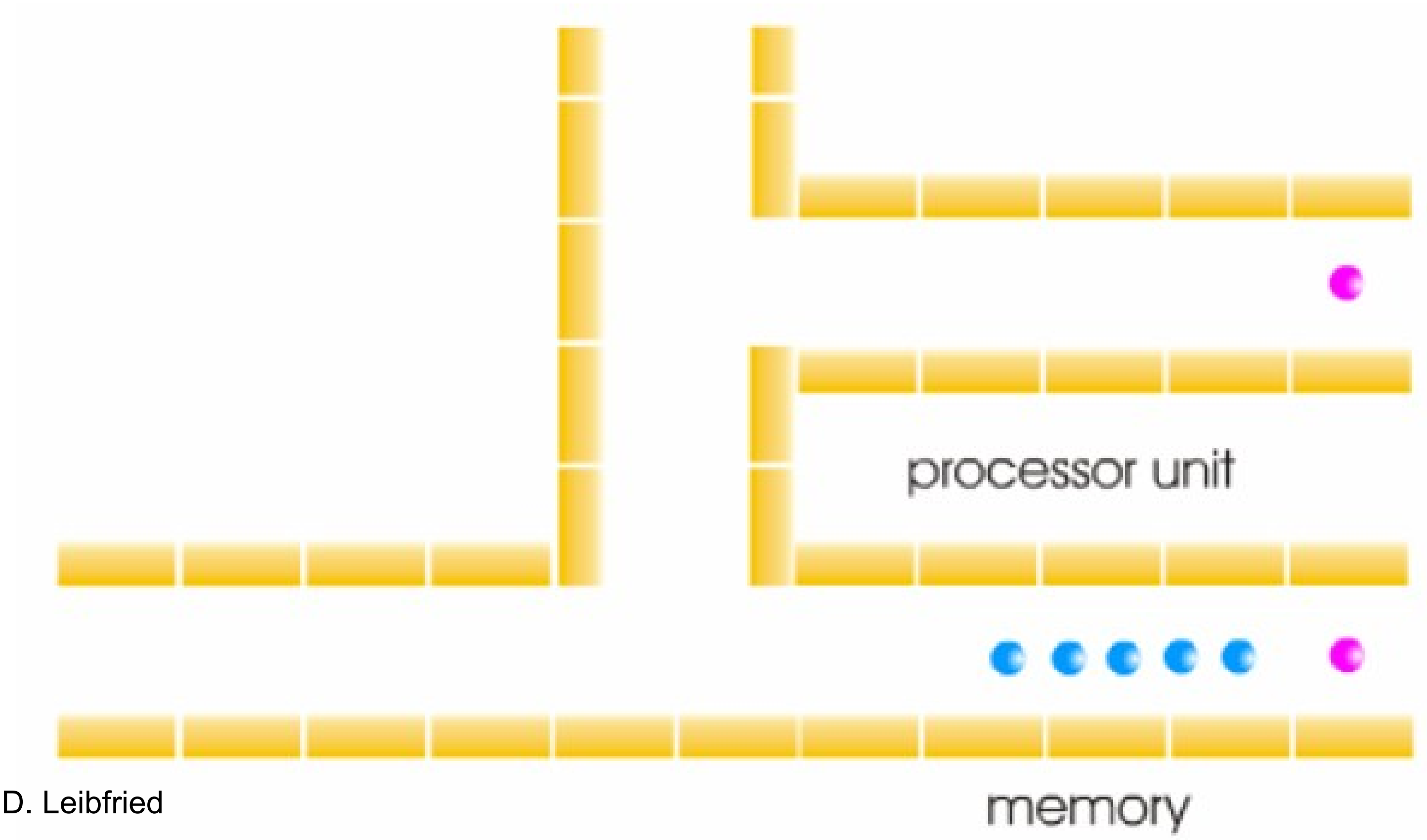
D. Leibfried, D. Wineland et al., NIST

Scaling ion trap quantum computers



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

Scaling ion trap quantum computers



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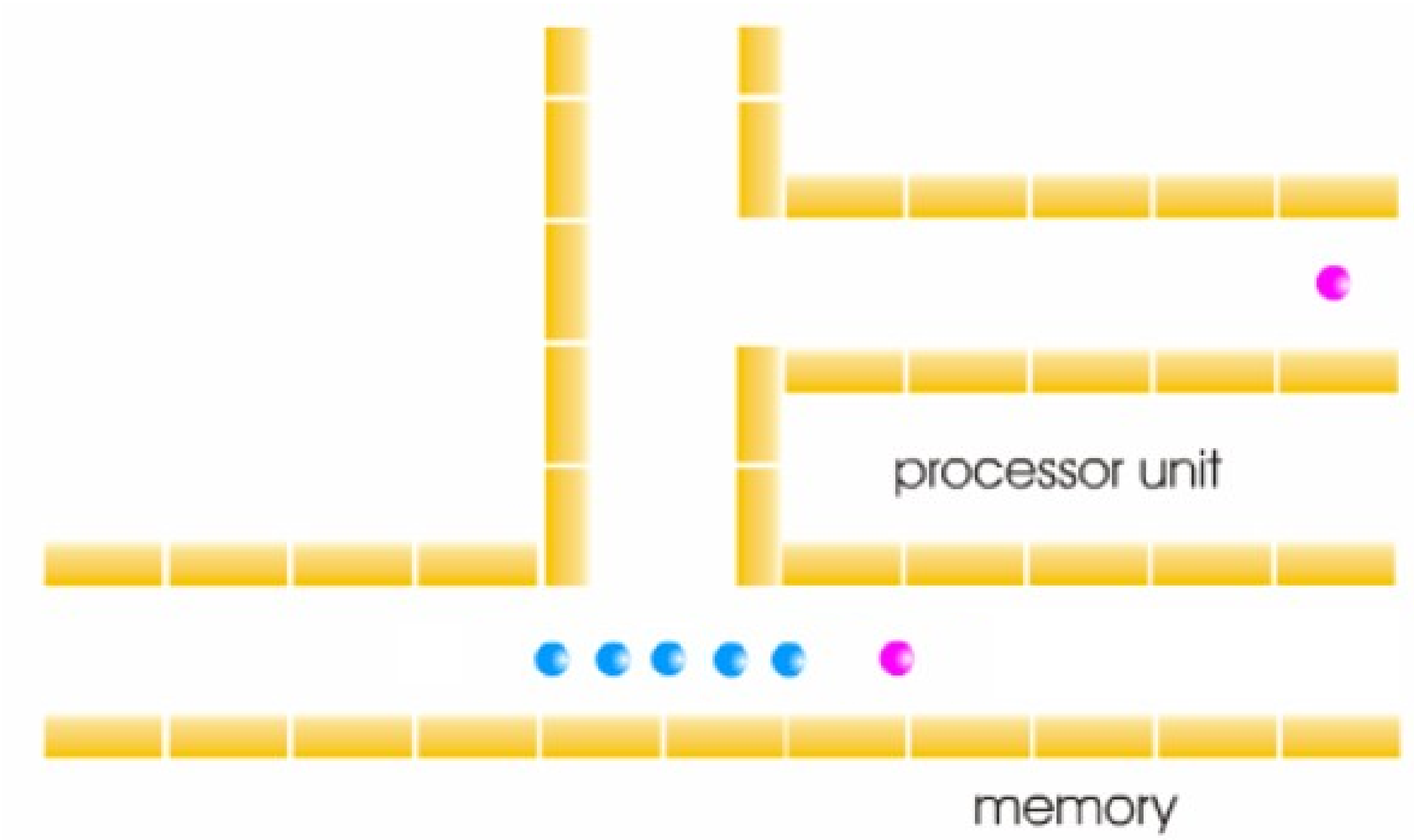
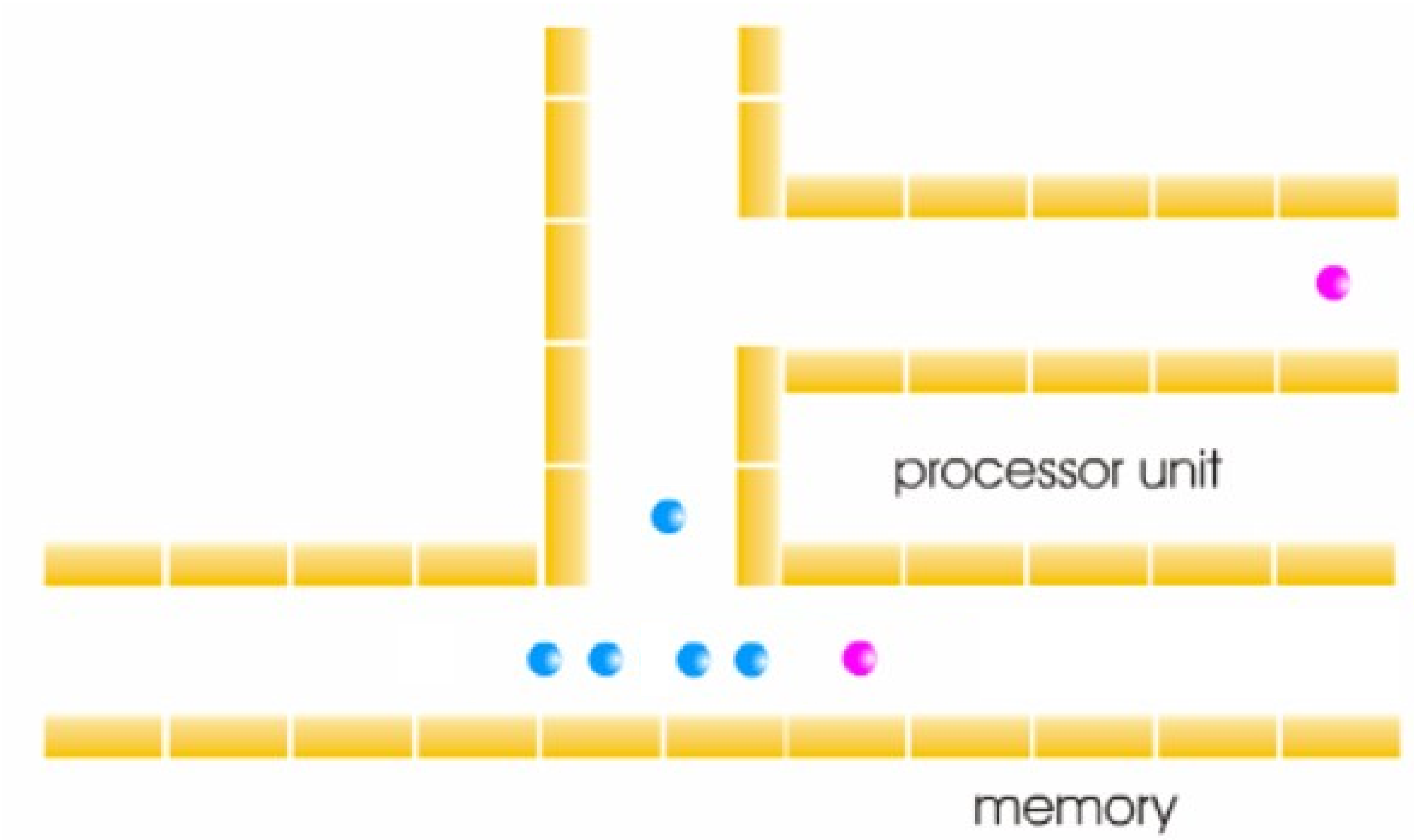
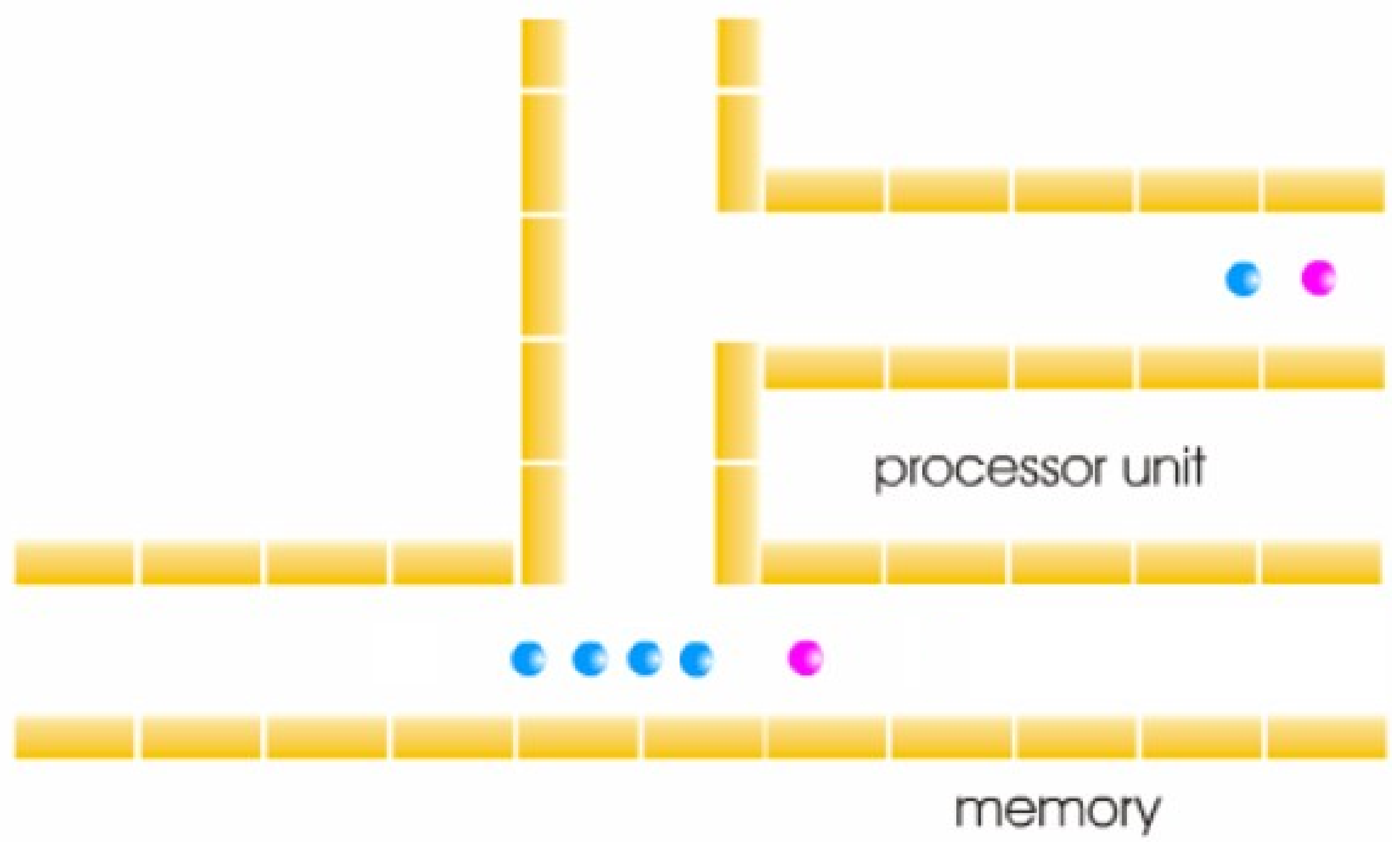


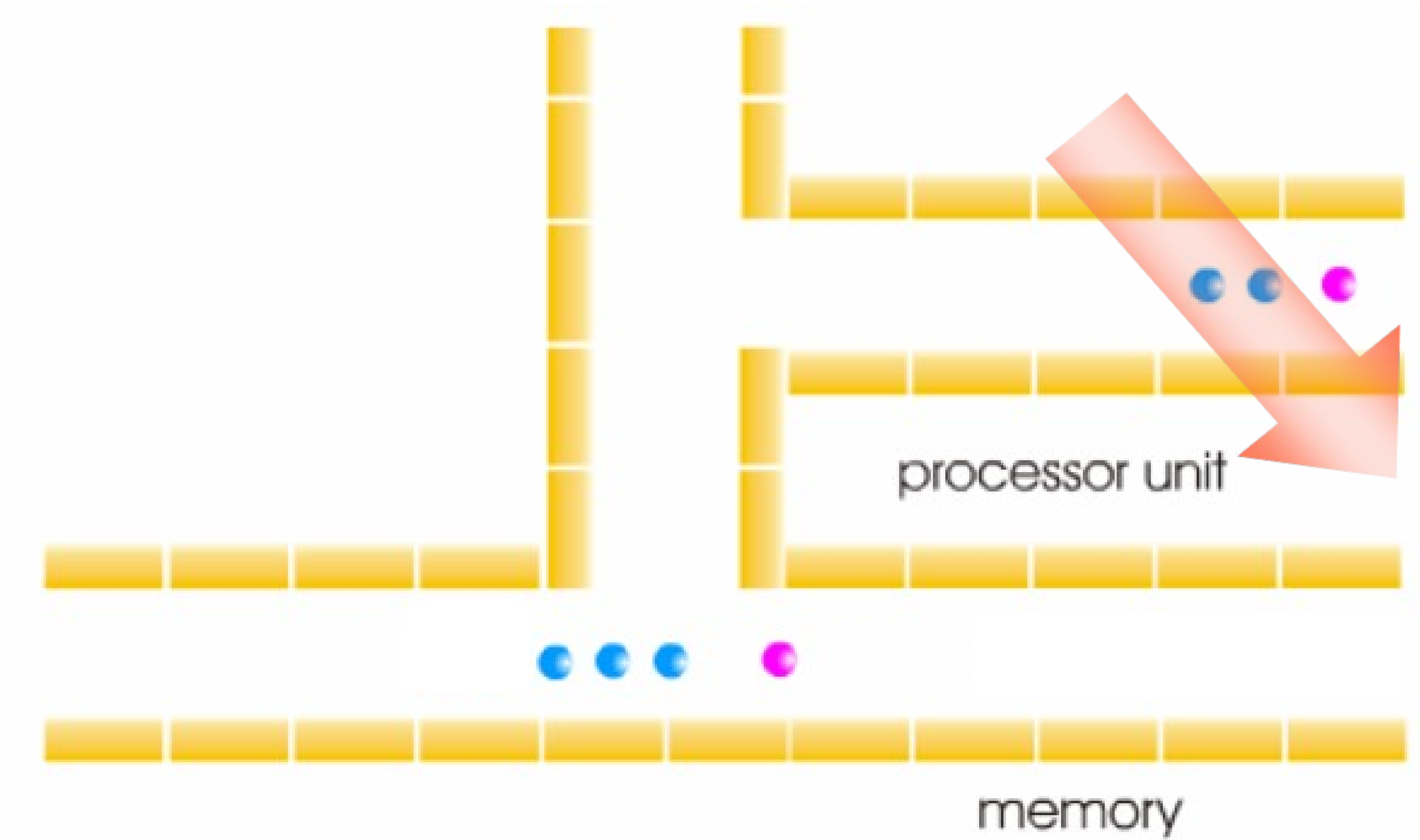
Scaling ion trap quantum computers



Scaling ion trap quantum computers

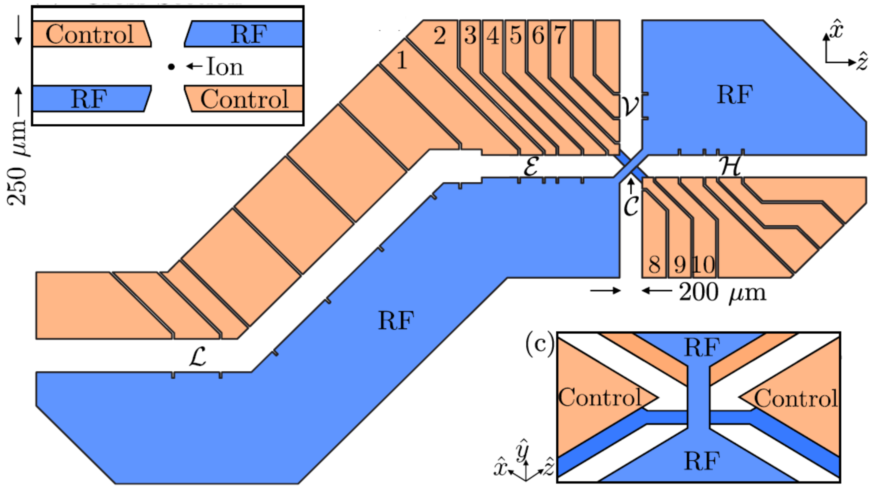


Scaling ion trap quantum computers

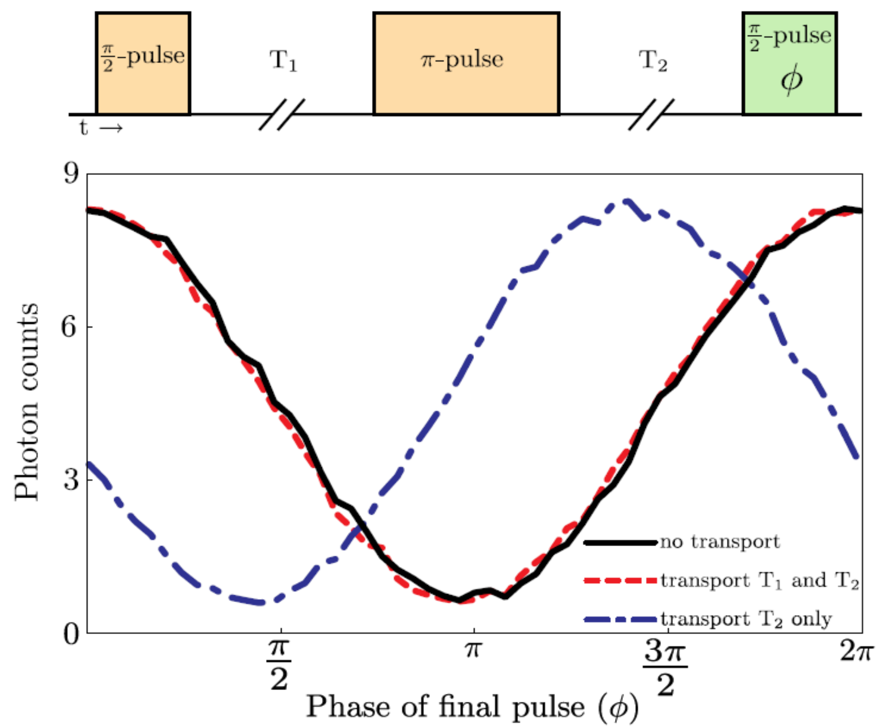


„Architecture for a large-scale ion-trap quantum computer“, D. Kielpinski et al., Nature **417**, 709 (2002).

Coherent transport through junctions

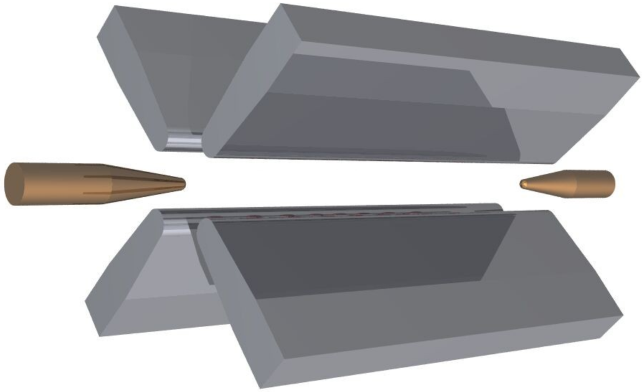


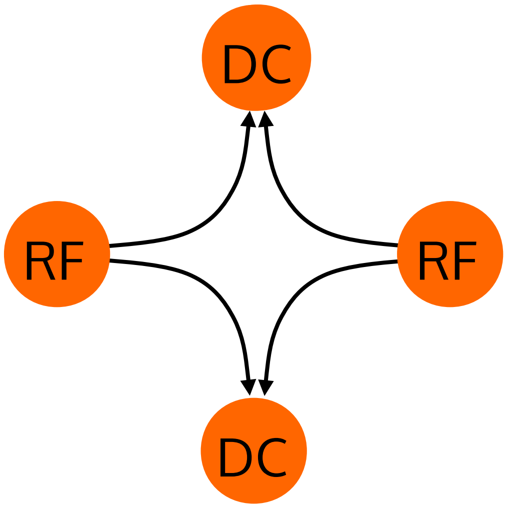
Transport		Energy Gain (recooling method) quanta/trip
$\mathcal{E}$-$\mathcal{C}$-$\mathcal{E}$	1 ion	3.2 ± 1.8
$\mathcal{E}$-$\mathcal{C}$-$\mathcal{H}$-$\mathcal{C}$-$\mathcal{E}$	1 ion	7.9 ± 1.5
$\mathcal{E}$-$\mathcal{C}$-$\mathcal{V}$-$\mathcal{C}$-$\mathcal{E}$	1 ion	14.5 ± 2.0
$\mathcal{E}$-$\mathcal{C}$-$\mathcal{E}$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



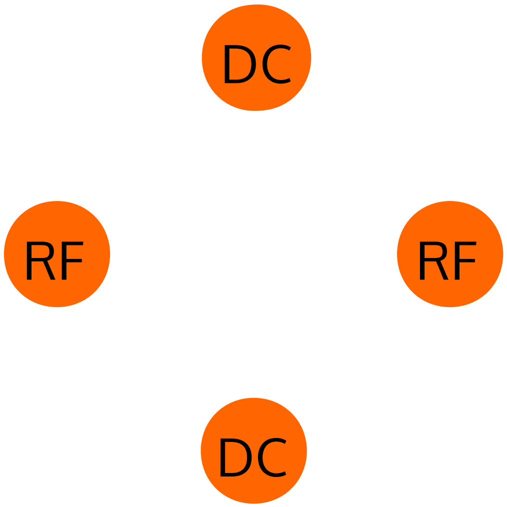
Blakestad, *et al.*, arXiv:0901.0533v1

"Classic" linear trap

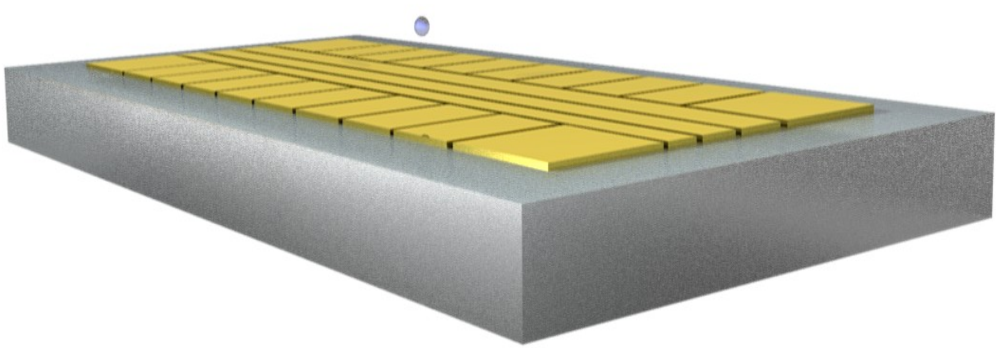


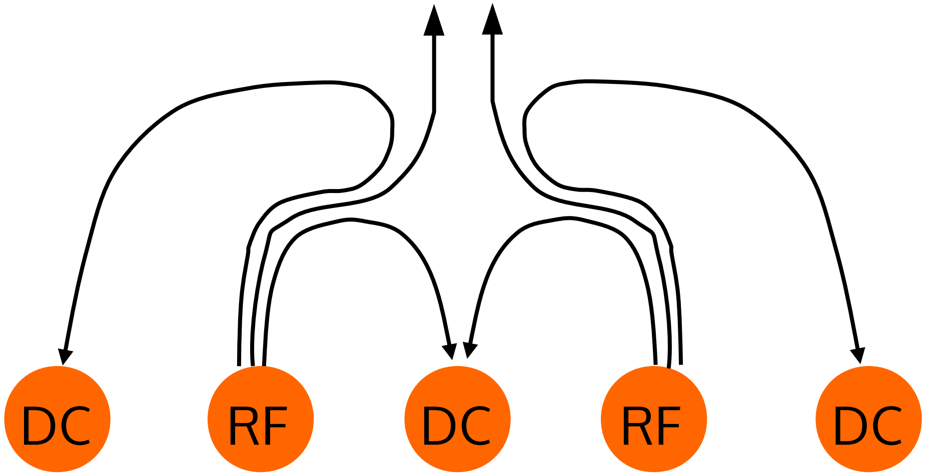


Surface traps



Microfabricated surface traps





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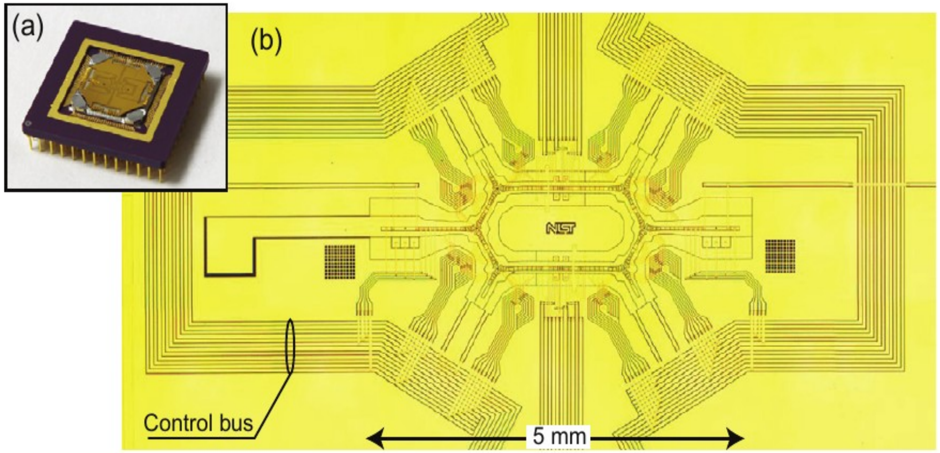
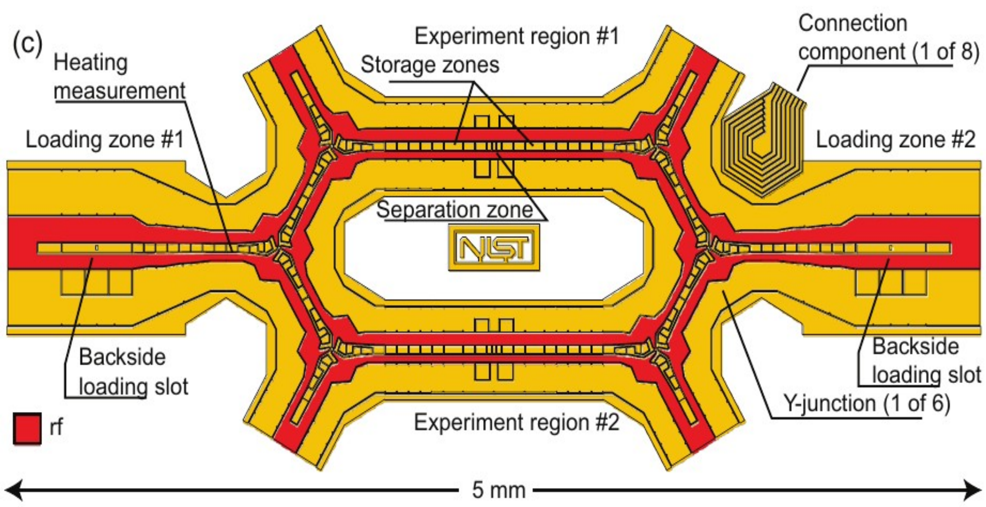
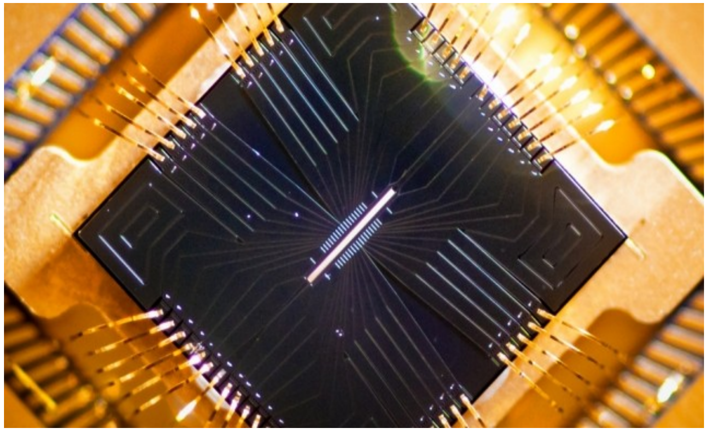




NIST, Amini *et al.*, NJP 2010



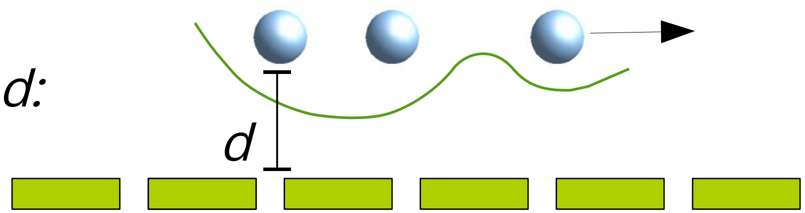
Sandia National Labs

Georgia Tech
Research Institute

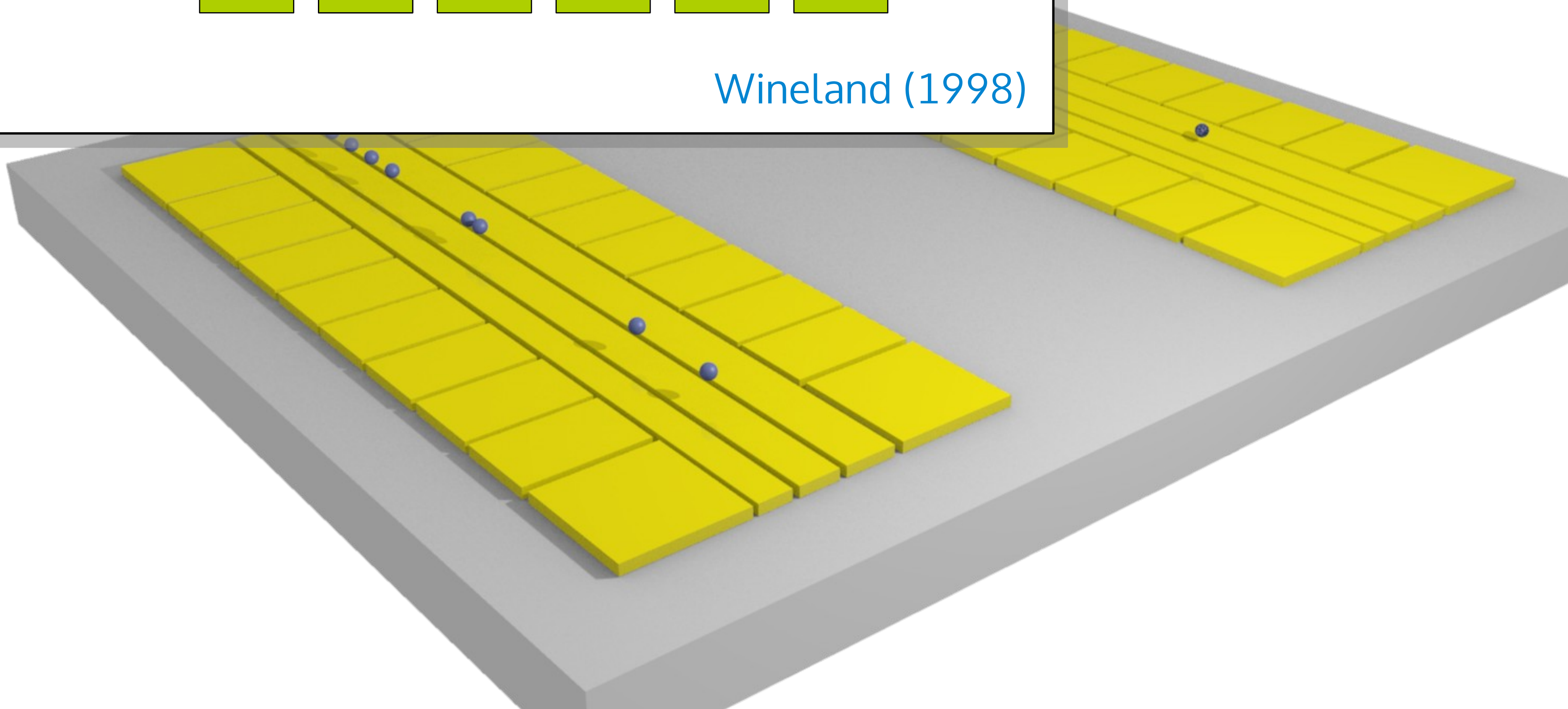
Ion trap quantum computing

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

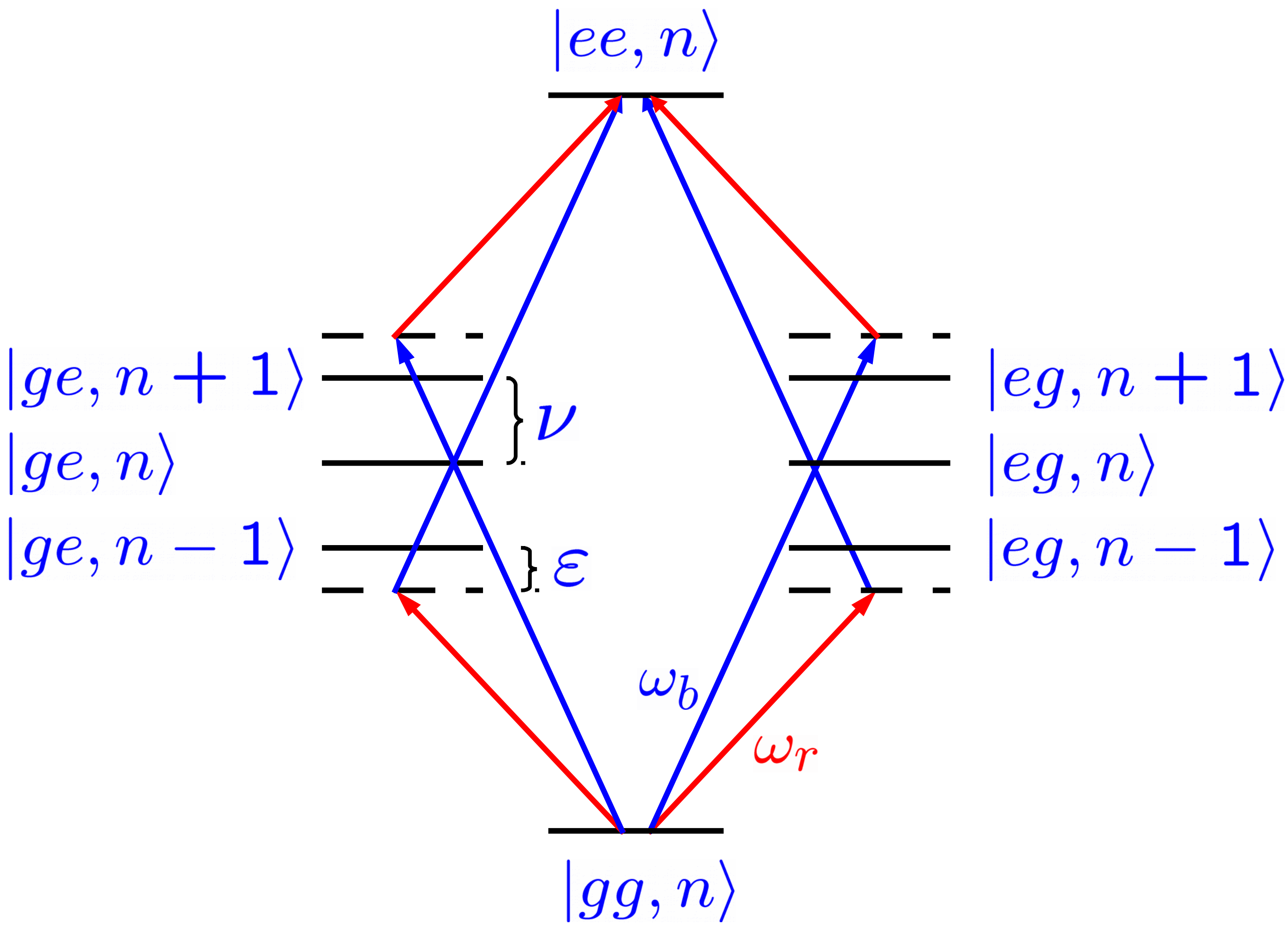
Speed ~ $1/d$:



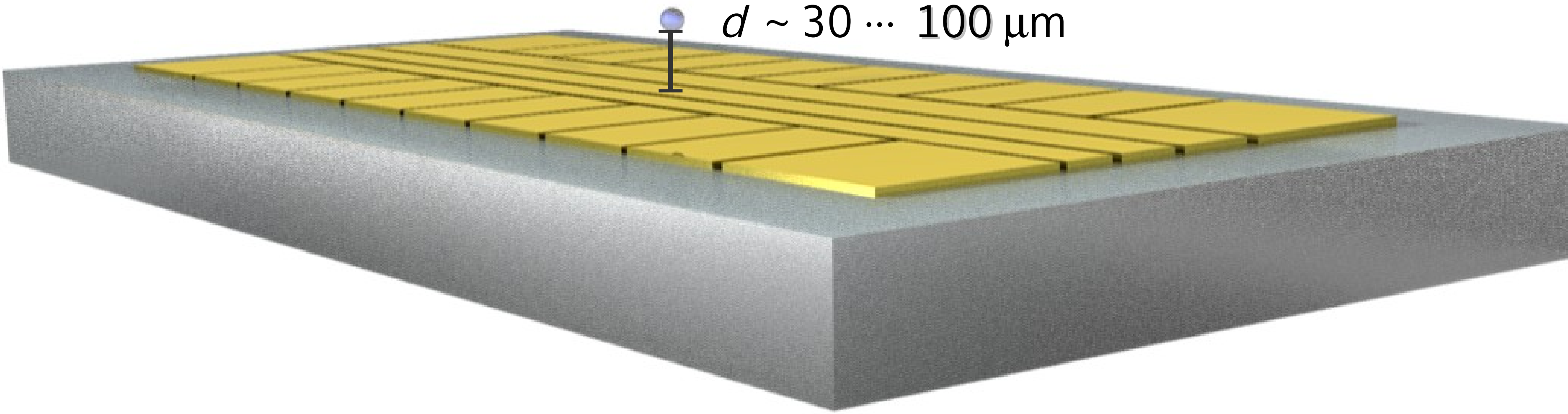
Wineland (1998)



Mølmer - Sørensen gate



Motional decoherence



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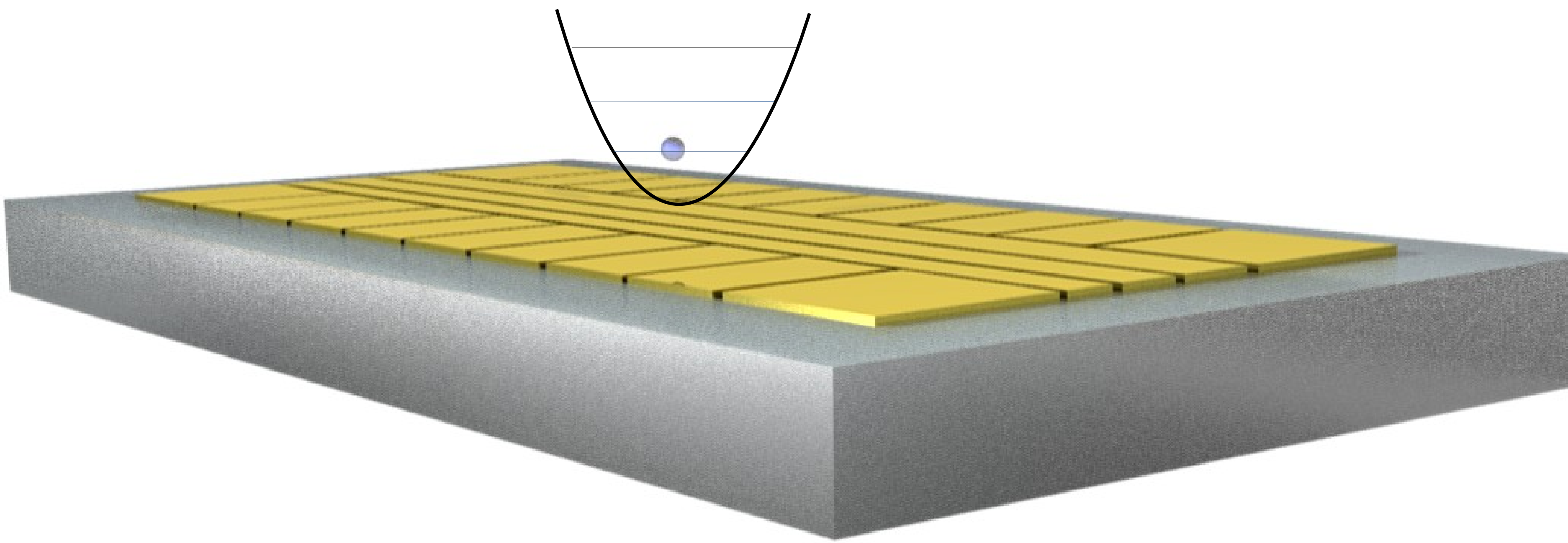
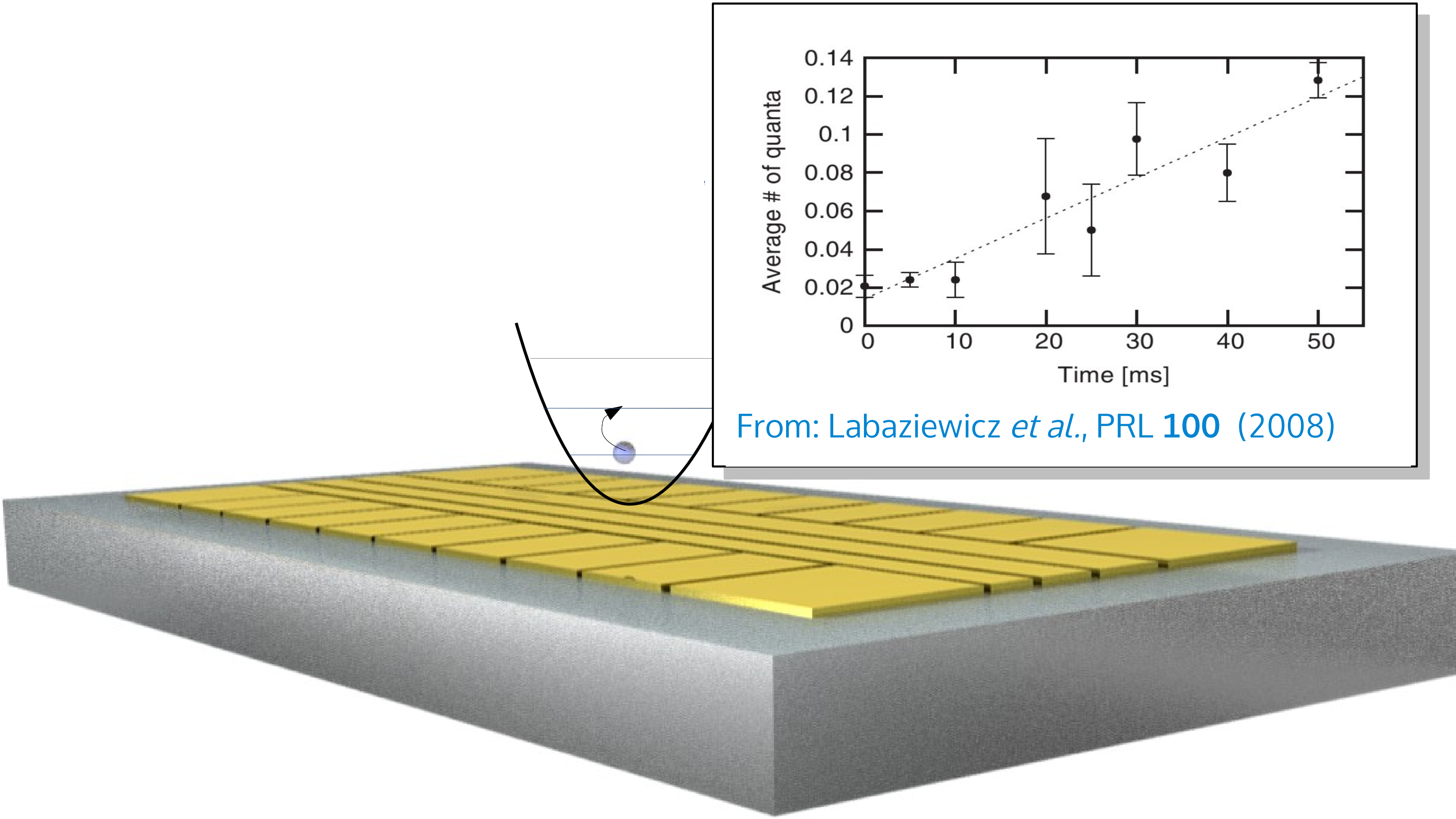


Motional decoherence

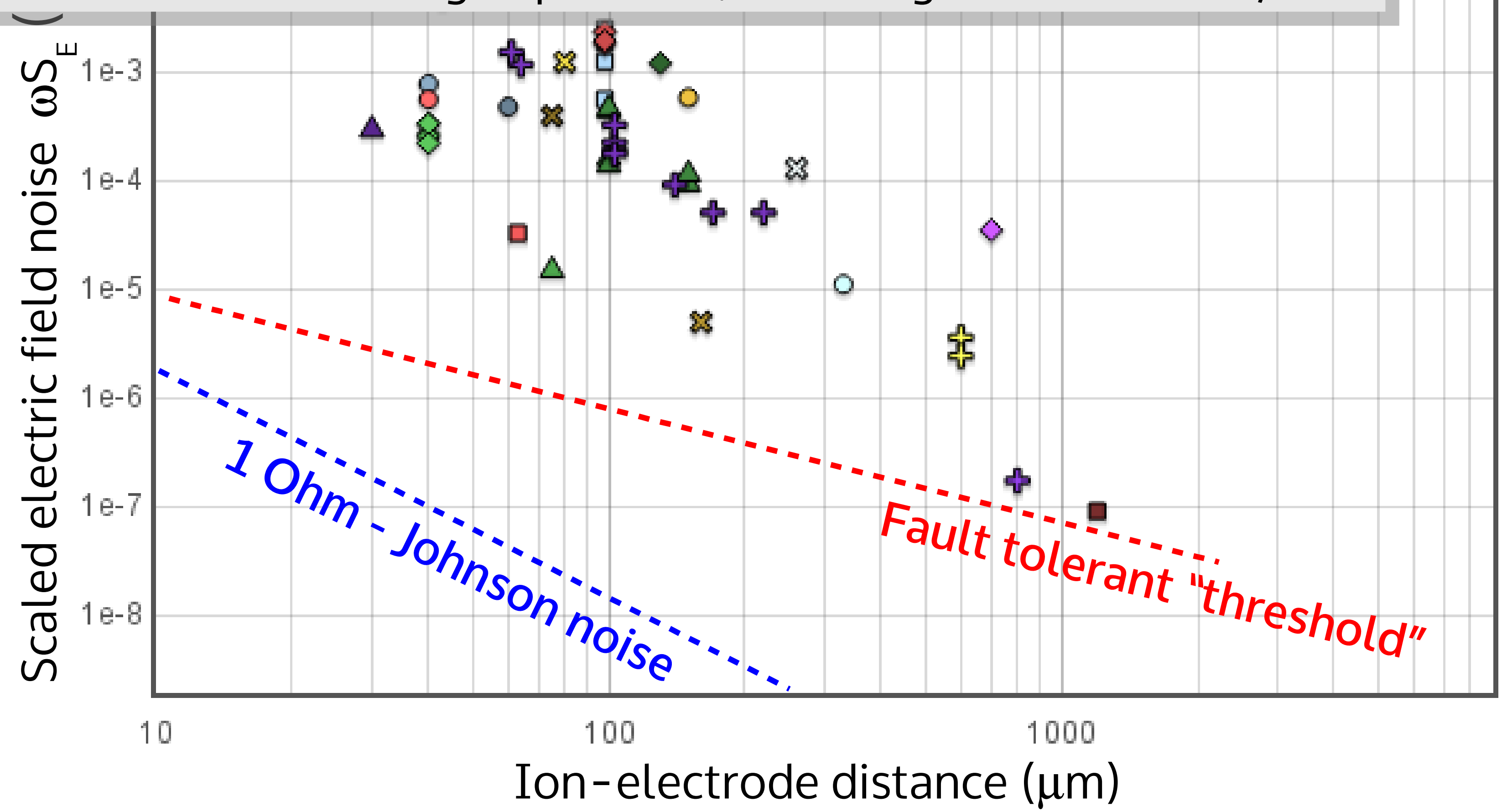


From: Labaziewicz *et al.*, PRL **100** (2008)

Excessive heating in ion traps

- Need to know what is causing it to deal with it

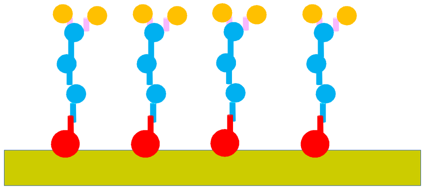
- Other technologies have similar problems:
  scanning probe microscopy, Casimir force measurements,
  free fall of charged particles, tests of general relativity



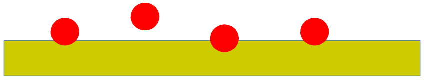
What is causing “the” anomalous heating ?

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

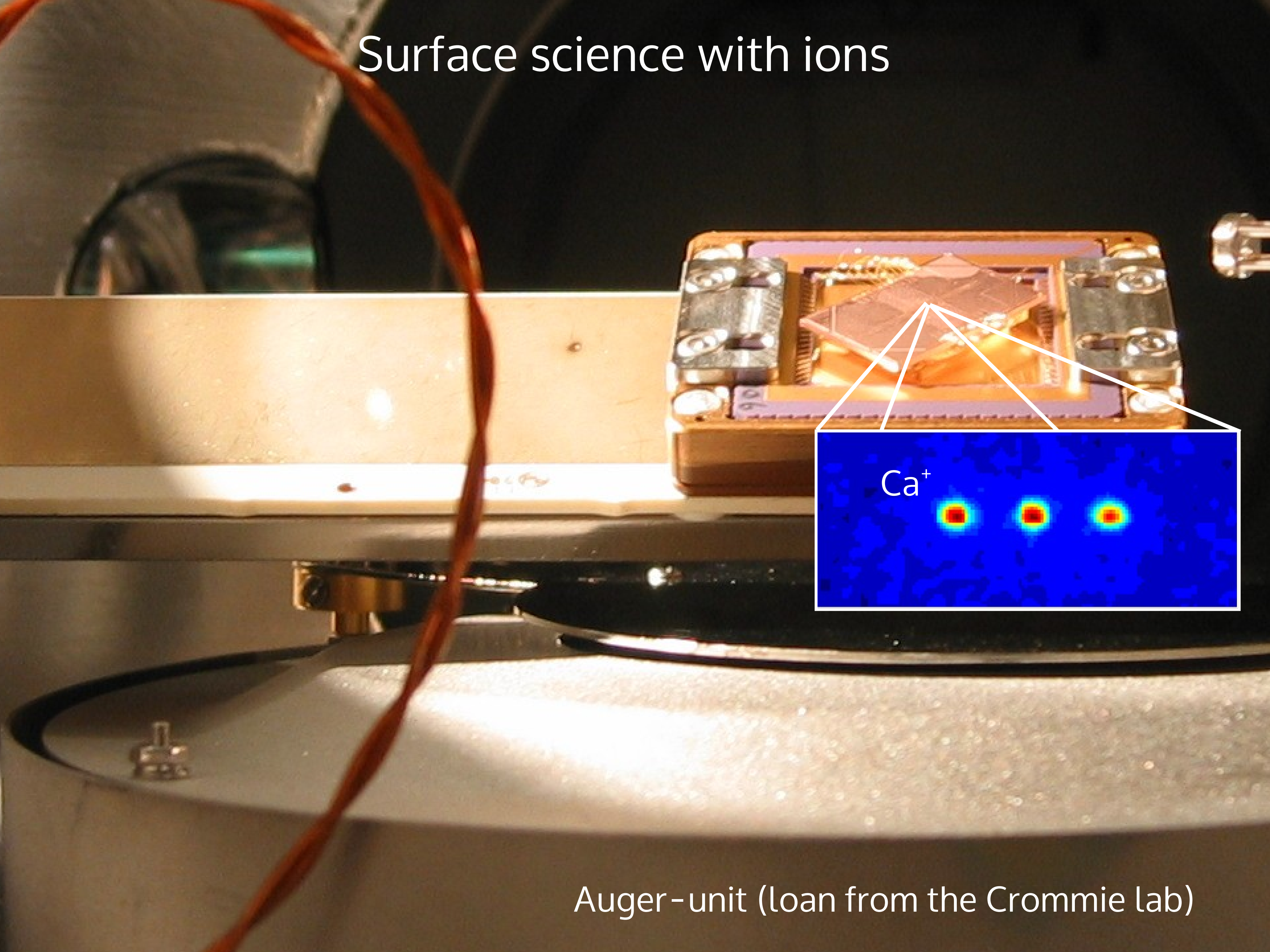
- independently fluctuating dipoles (Daniilidis 2010)



- fluctuating strength of dipoles (Safavi-Naini 2011, 2013)

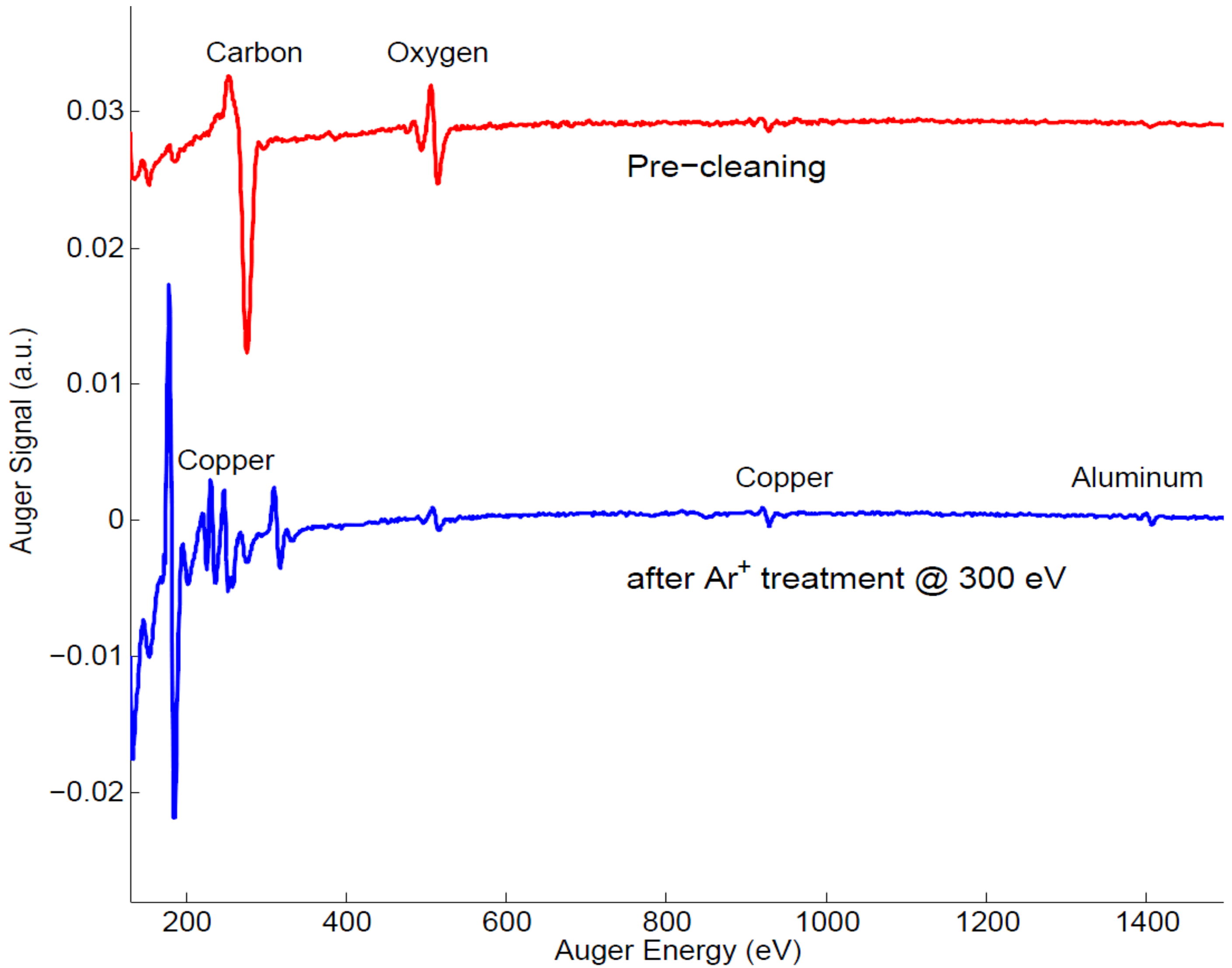


Surface science with ions

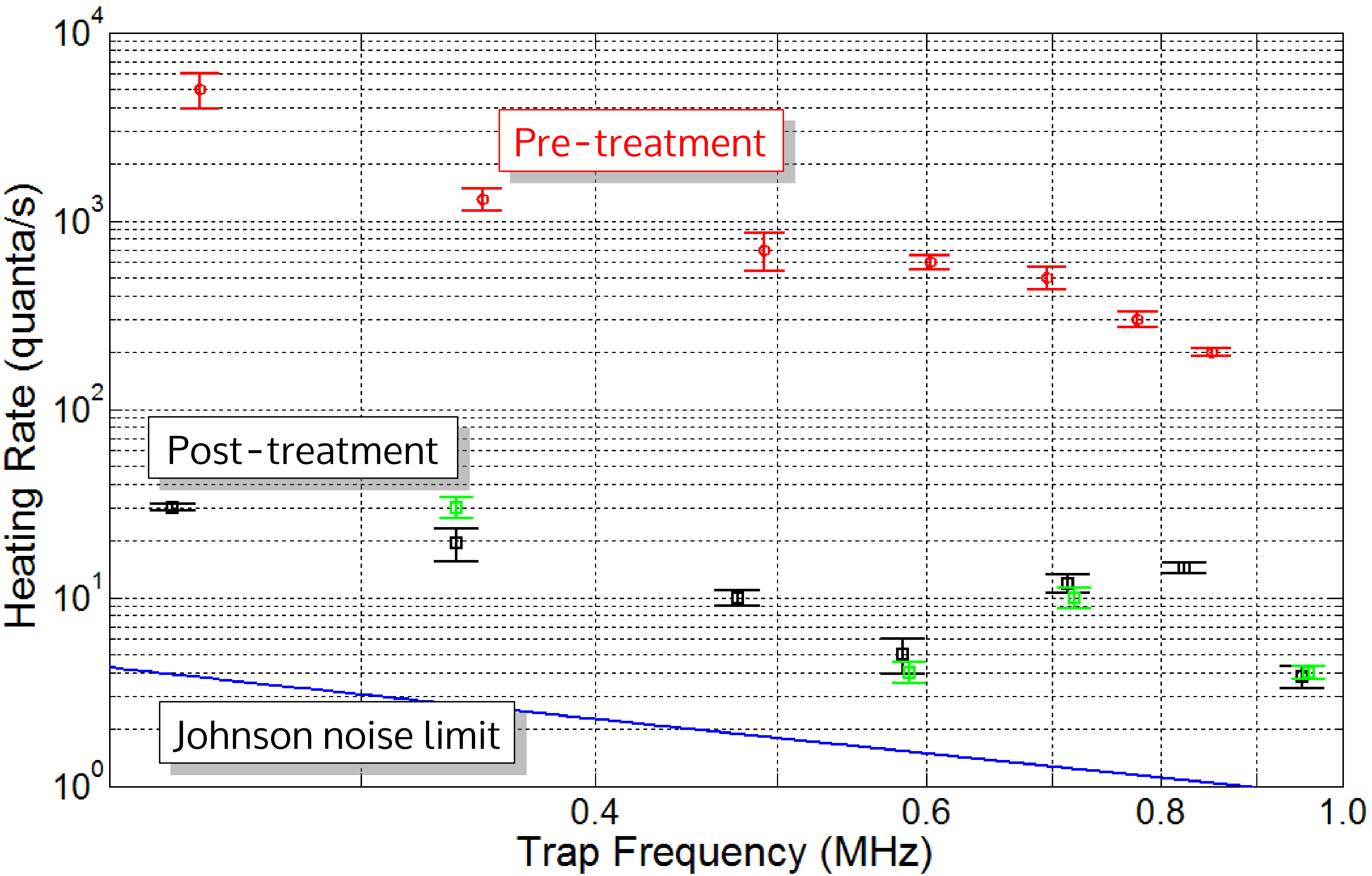


Auger-unit (loan from the Crommie lab)

Auger spectra of a Cu-Al surface

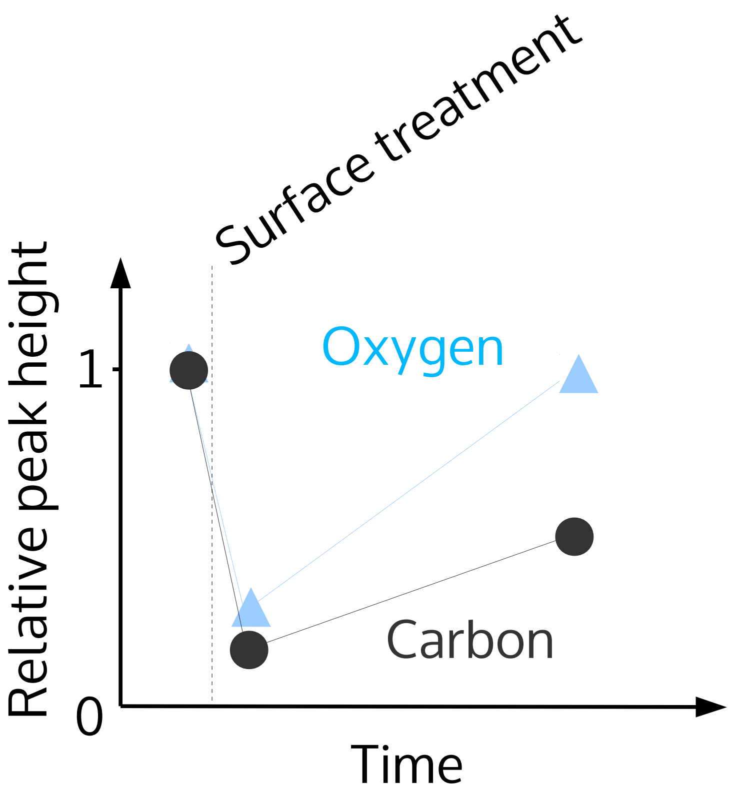


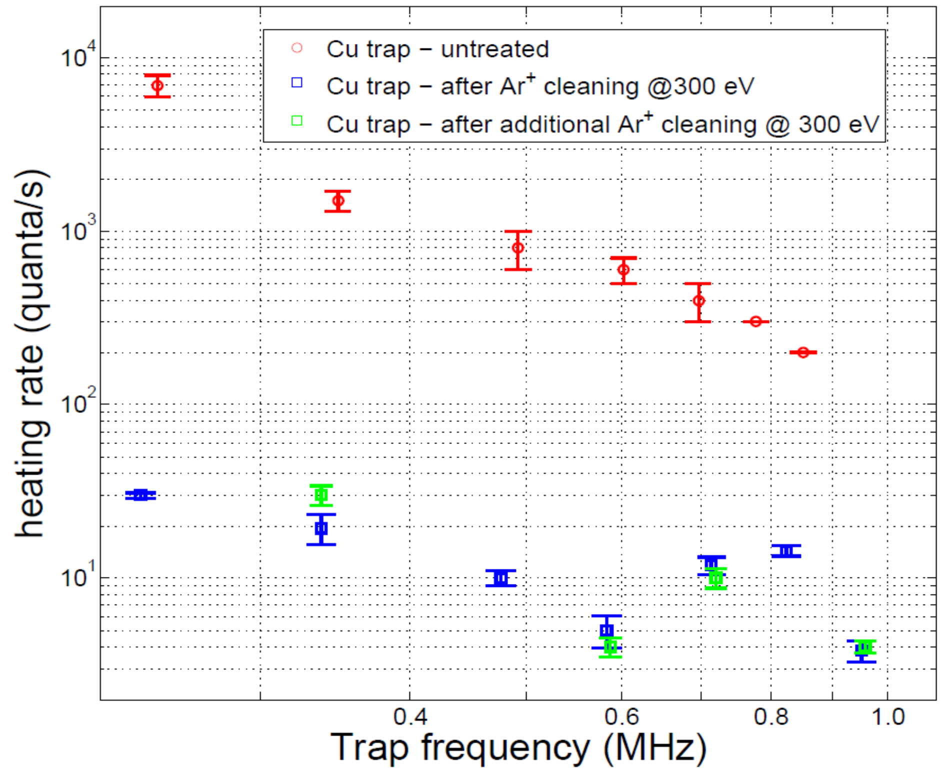
Heating rates



Findings

Structure of surface and/or contaminants matter



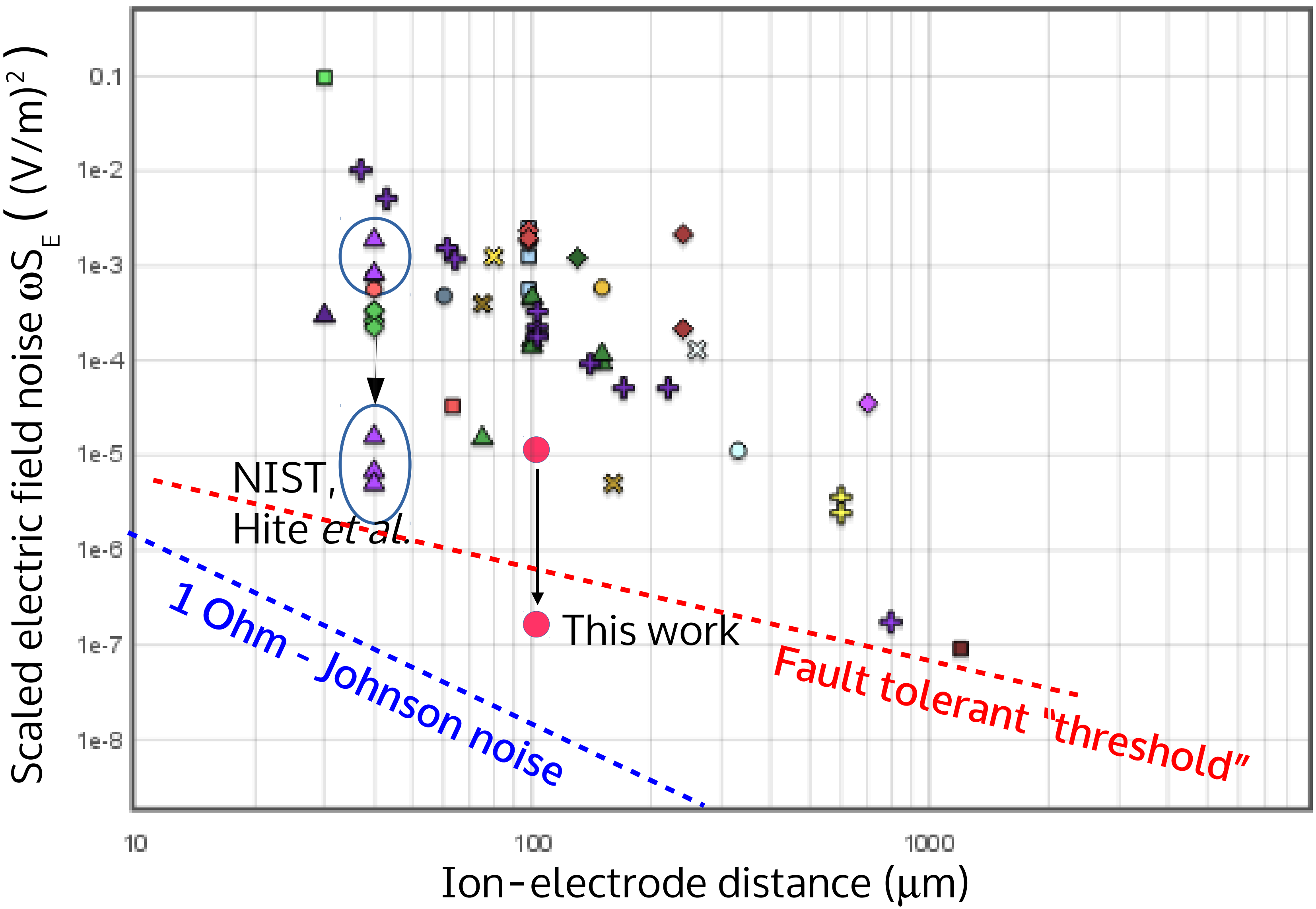


- Heating rate can be low despite full oxidation

- Heating rate low despite 50% of original Carbon level

Excessive heating in ion traps

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



Anticipated requirements for fault tolerant QIP

	Actual	Required
Spontaneous decay	1.2 s	1 s
Magnetic field fluctuations (slow noise)	10 μG	1 μG
Laser frequency (slow noise)	10 Hz	1 Hz
Laser intensity fluctuations	1.5 %	0.01 %
Cross talk	0.1 % / qubit	n.a.
Initialization error	0.3 % / qubit	0.01 % / qubit
Read-out	0.5 % / qubit	0.01 % / qubit
Heating rate	3 quanta / s	10 quanta / s
Secular frequency stability in planar trap	~100 Hz	10 Hz

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