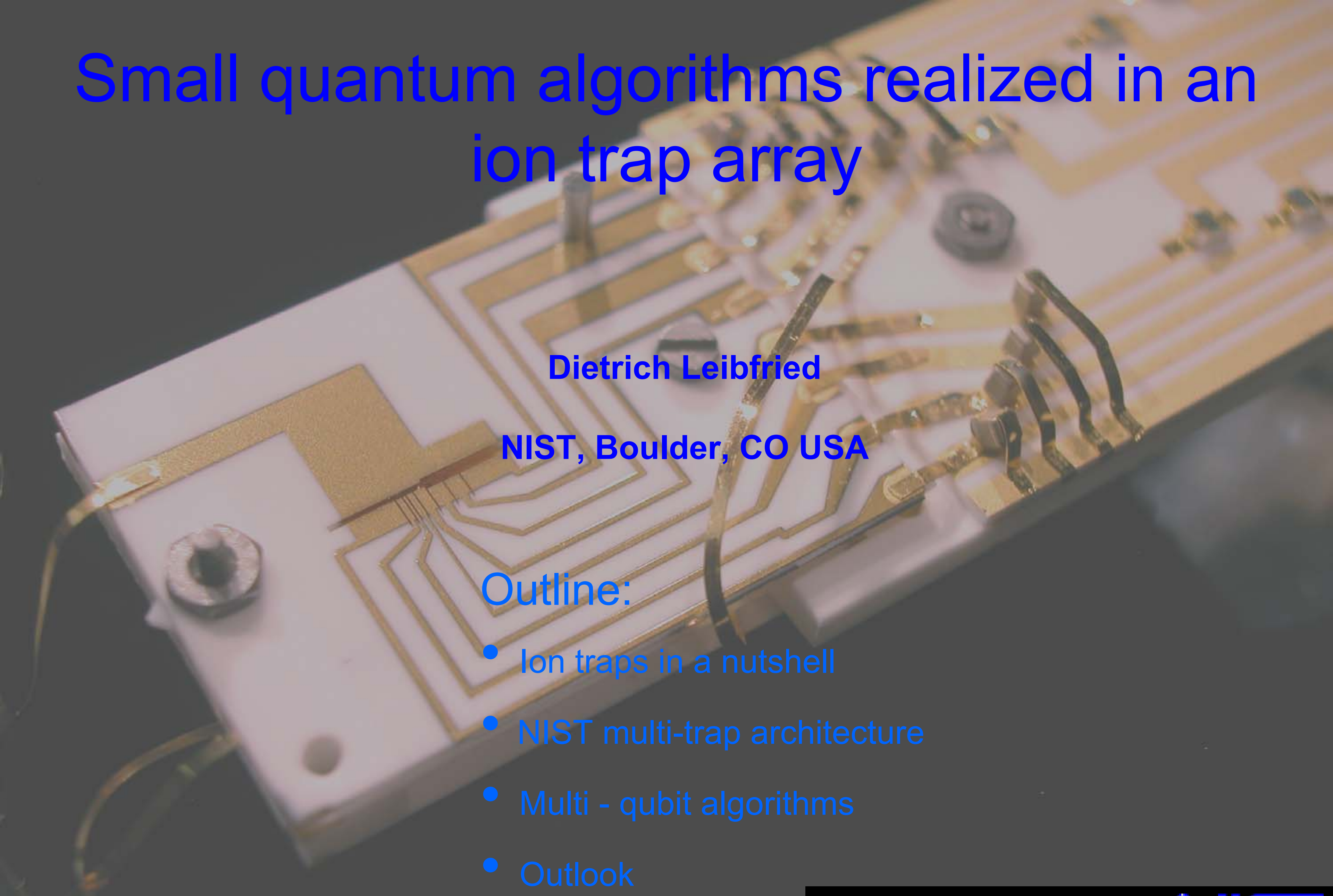


Small quantum algorithms realized in an ion trap array

Dietrich Leibfried

NIST, Boulder, CO USA

Outline:

- Ion traps in a nutshell
- NIST multi-trap architecture
- Multi - qubit algorithms
- Outlook

National Institute of Standards and Technology
Technology Administration, U.S. Department of Commerce

NIST quantum logic group

(April 26 2005)

Murray Barrett (postdoc, Otago)
Brad Blakestad (grad student, CU)
Jim Beall (NIST, Cryoelectronics)
Joe Britton (grad student, CU)
John Bollinger
John Chiaverini (postdoc, Stanford)
Wayne Itano
John Jost (grad student, CU)
Manny Knill (NIST, computer science)

Chris Langer (grad student, CU)
Dietrich Leibfried
Roee Ozeri (postdoc, Haifa)
Rainer Reichle (postdoc, Freiburg)
Till Rosenband (grad student, CU)
Tobias Schätz (postdoc, Munich)
Signe Seidelin (postdoc, Orsay)
Janus Wesenberg (postdoc, Aarhus)
David Wineland

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

optical pumping, ground-state cooling (99.9%) ✓

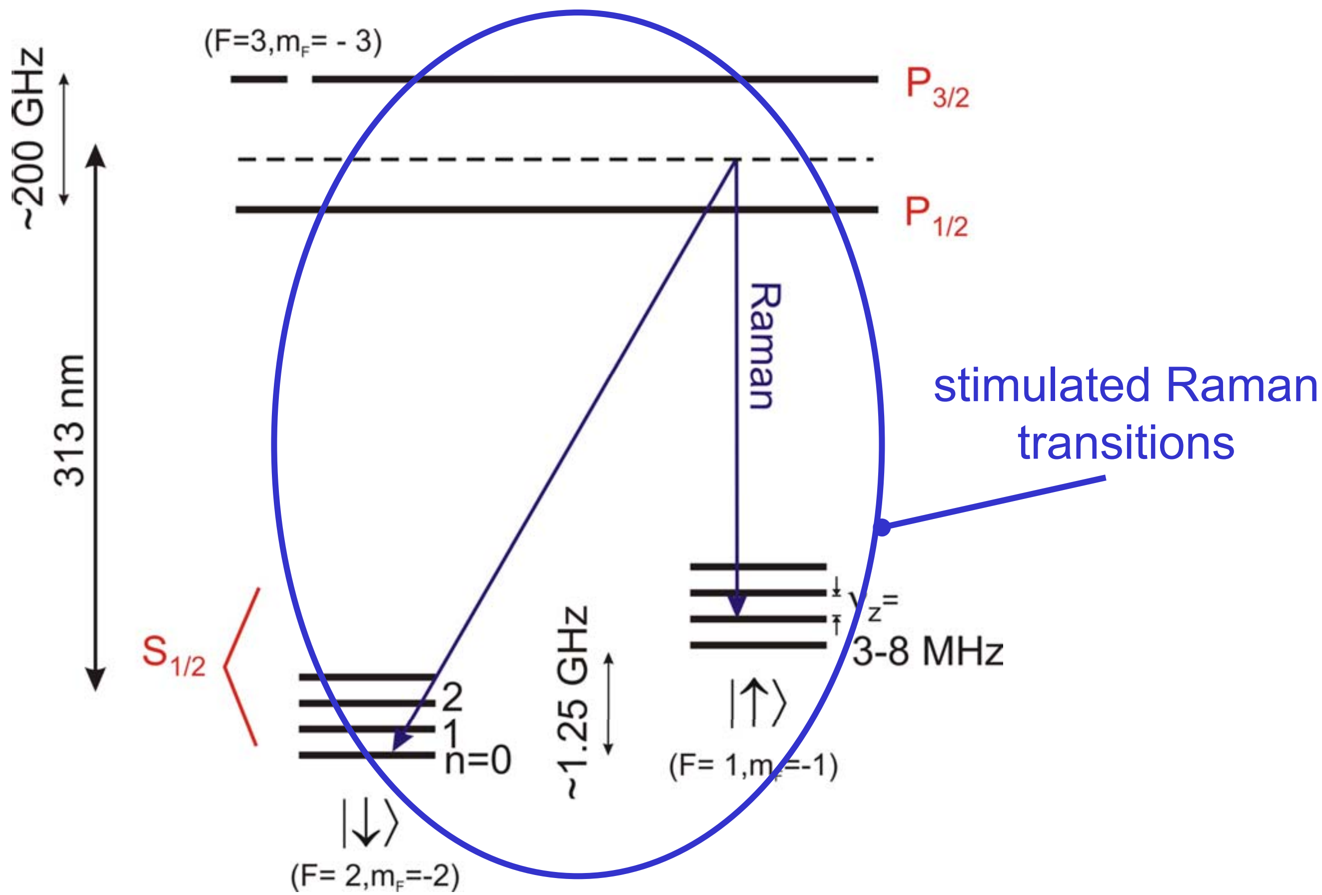
III. Long relevant decoherence times, much longer than the gate time

Hyperfine ground states T_{dec}> 10 **sec** demonstrated ✓

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

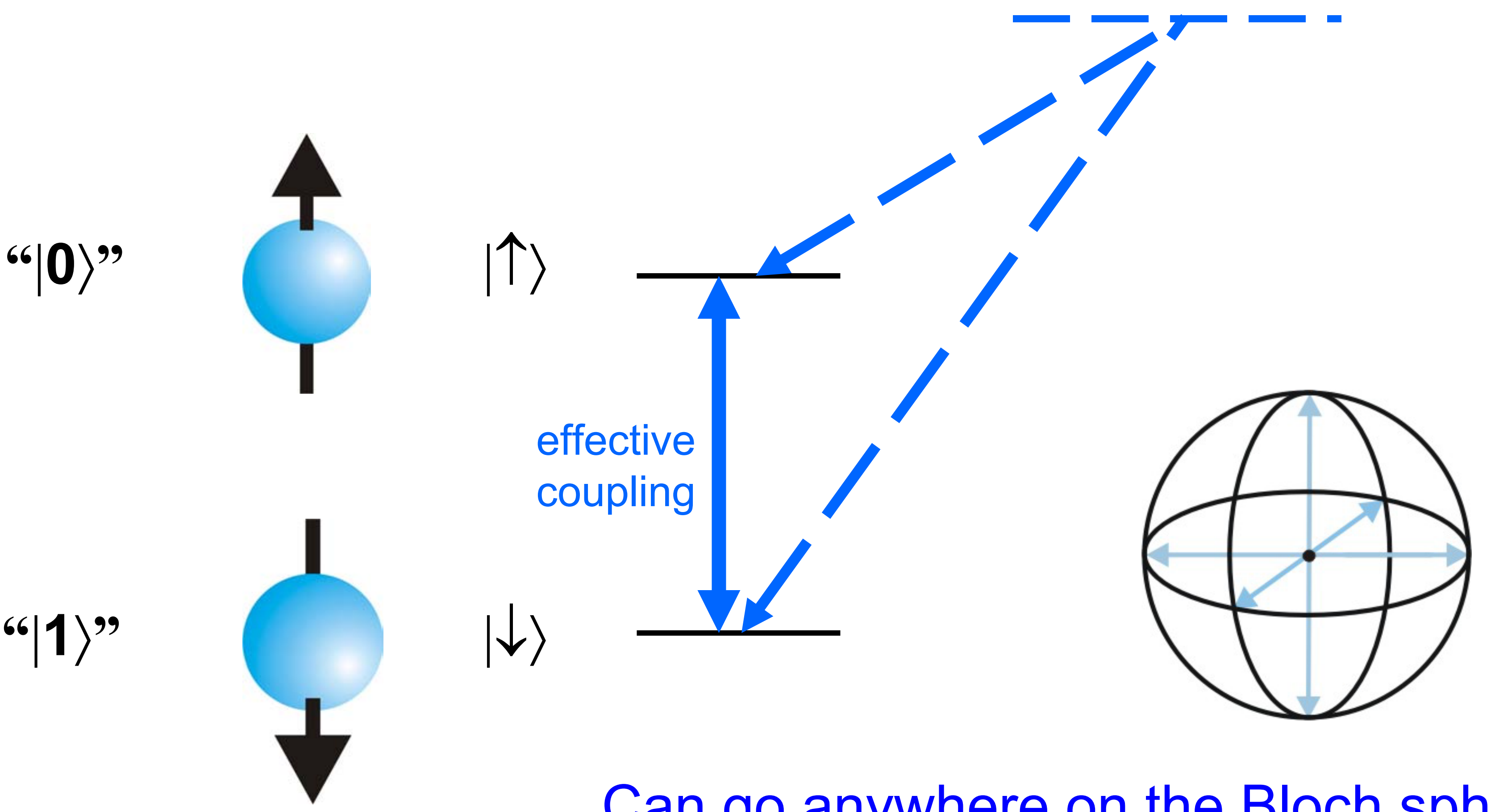
V. A qubit-specific read out capability

The qubit: $^9Be^+$



>10 sec decoherence time

Single qubit rotation: stimulated Raman transitions

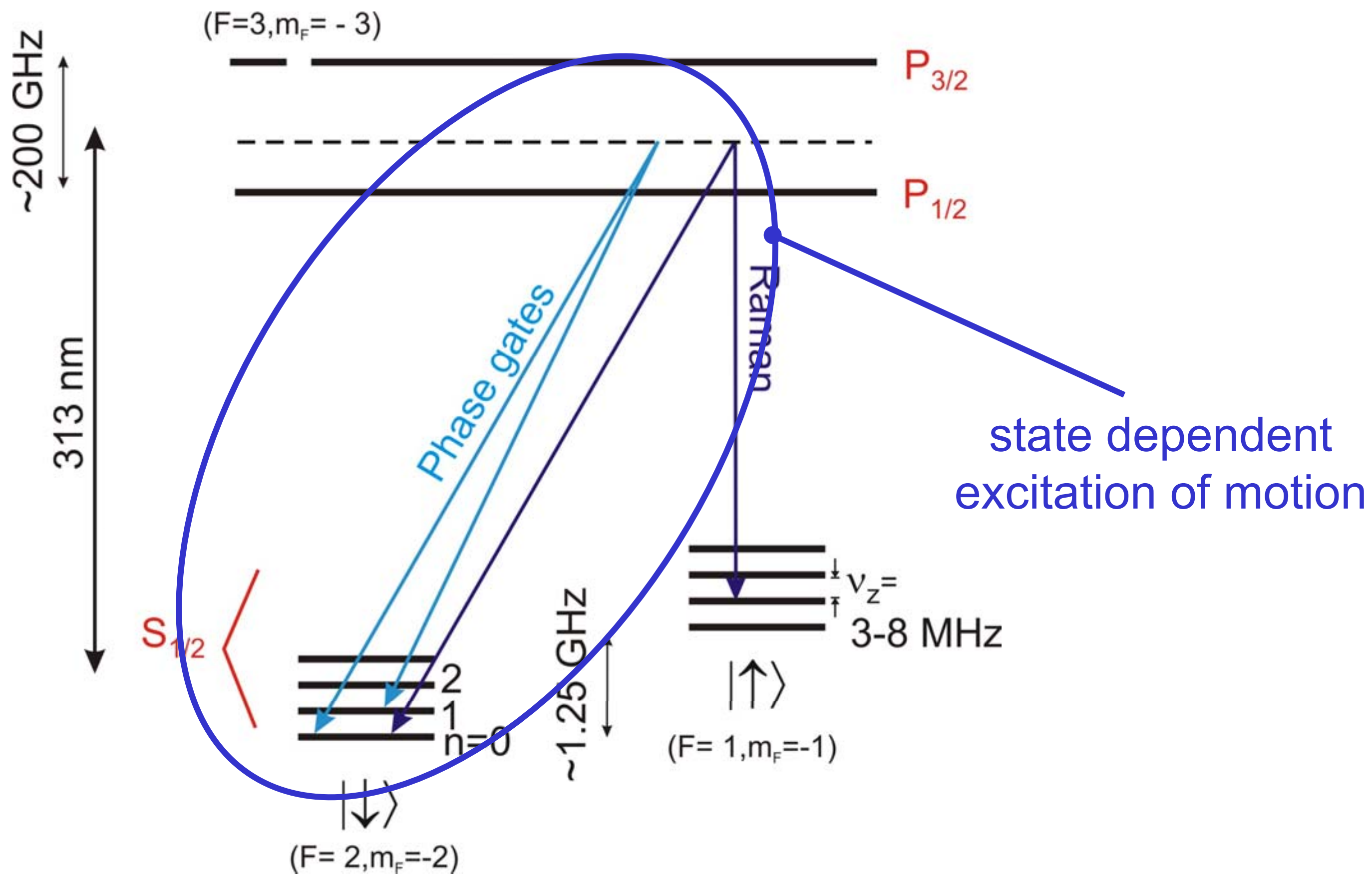


Can go anywhere on the Bloch sphere

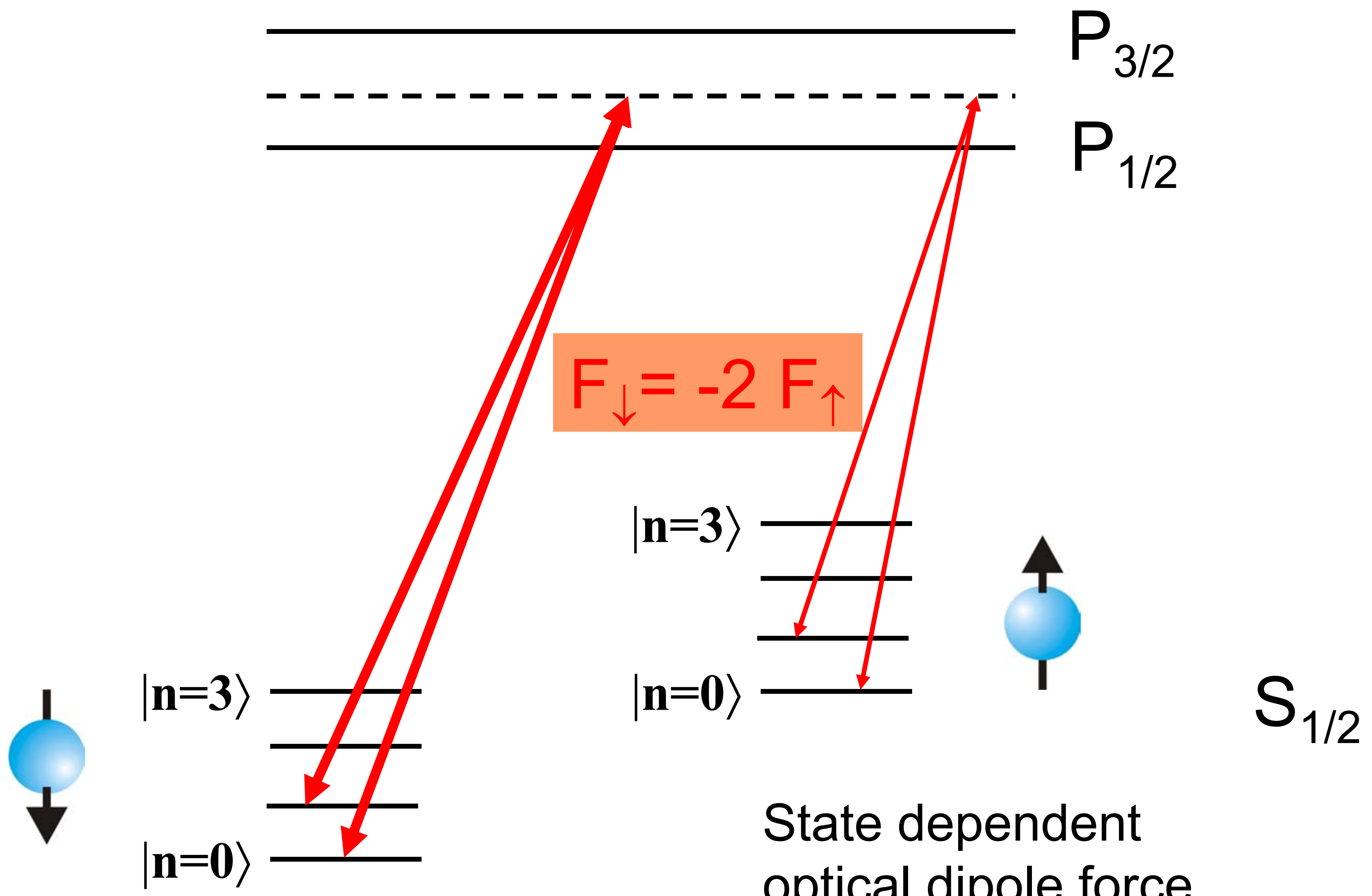
Typical π-pulse time:1 μs (Q=10^7)

Fidelity: >99.5%

The qubit: $^9Be^+$

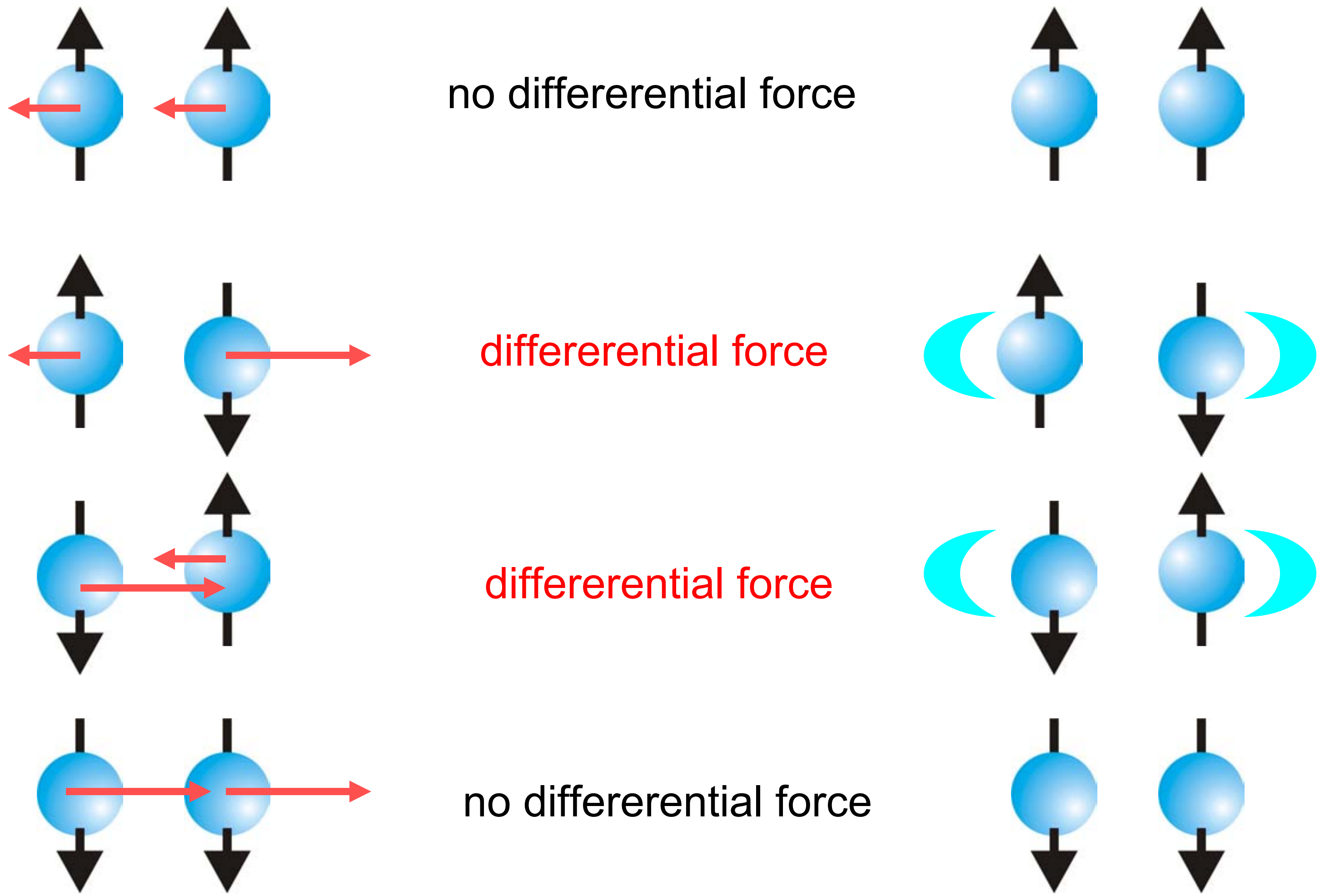


Motional excitation



State dependent optical dipole force

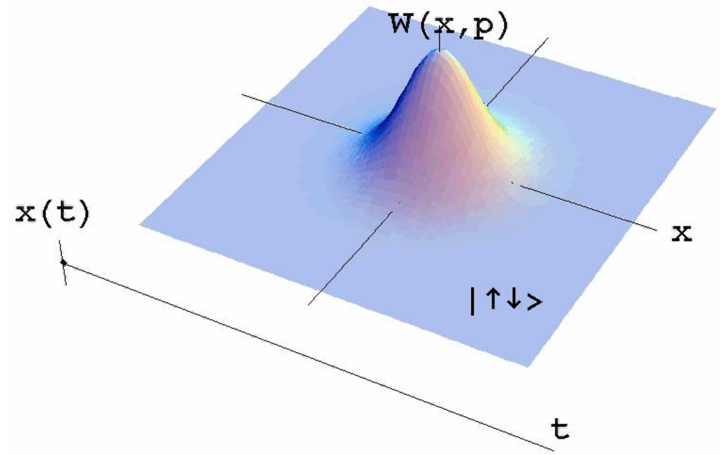
Stretch mode excitation



Phase space picture

Gate fidelity: 97%
Gate time: 7 μs (ca. 25/ν_{COM})

D. Leibfried *et al.*, Nature **422**, 414 (2003)
Theory: Milburn, Sørensen&Mølmer



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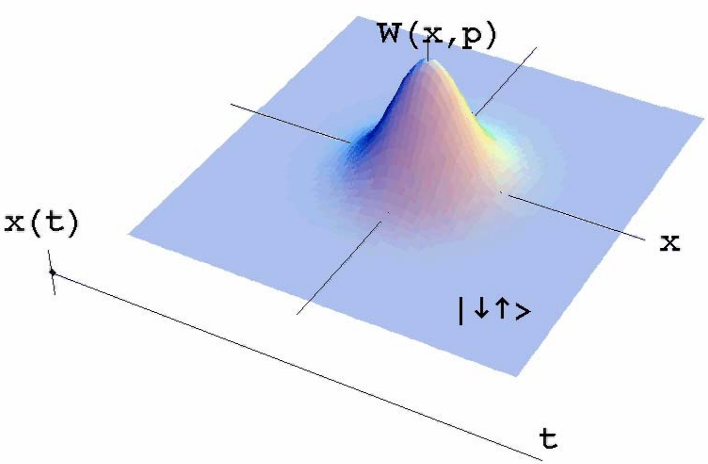

$$|\downarrow\downarrow\rangle \rightarrow |\downarrow\downarrow\rangle$$

$$|\downarrow\uparrow\rangle \rightarrow e^{i\phi}|\downarrow\uparrow\rangle$$

$$|\uparrow\downarrow\rangle \rightarrow e^{i\phi}|\uparrow\downarrow\rangle$$

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

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co-carrier rotations, phase gate

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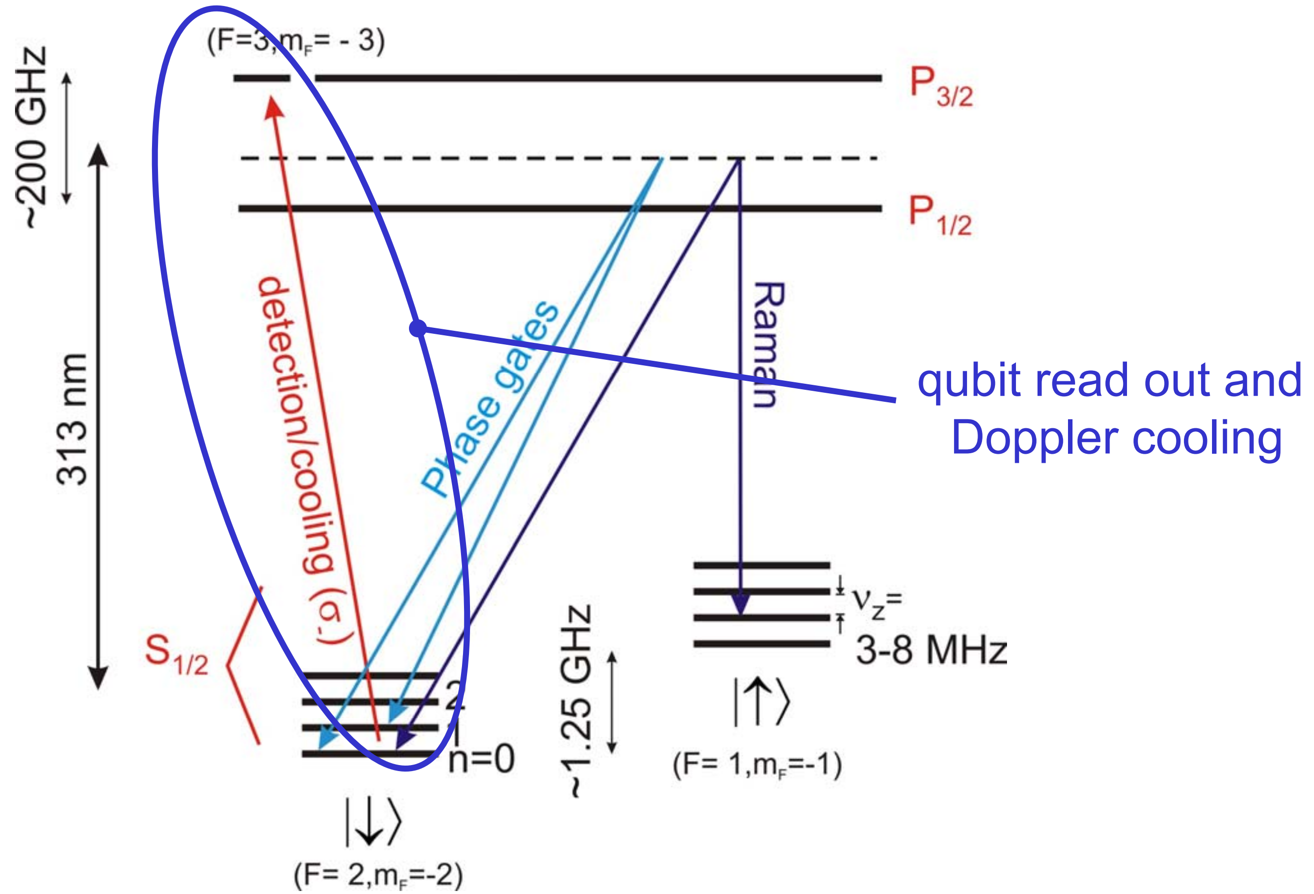
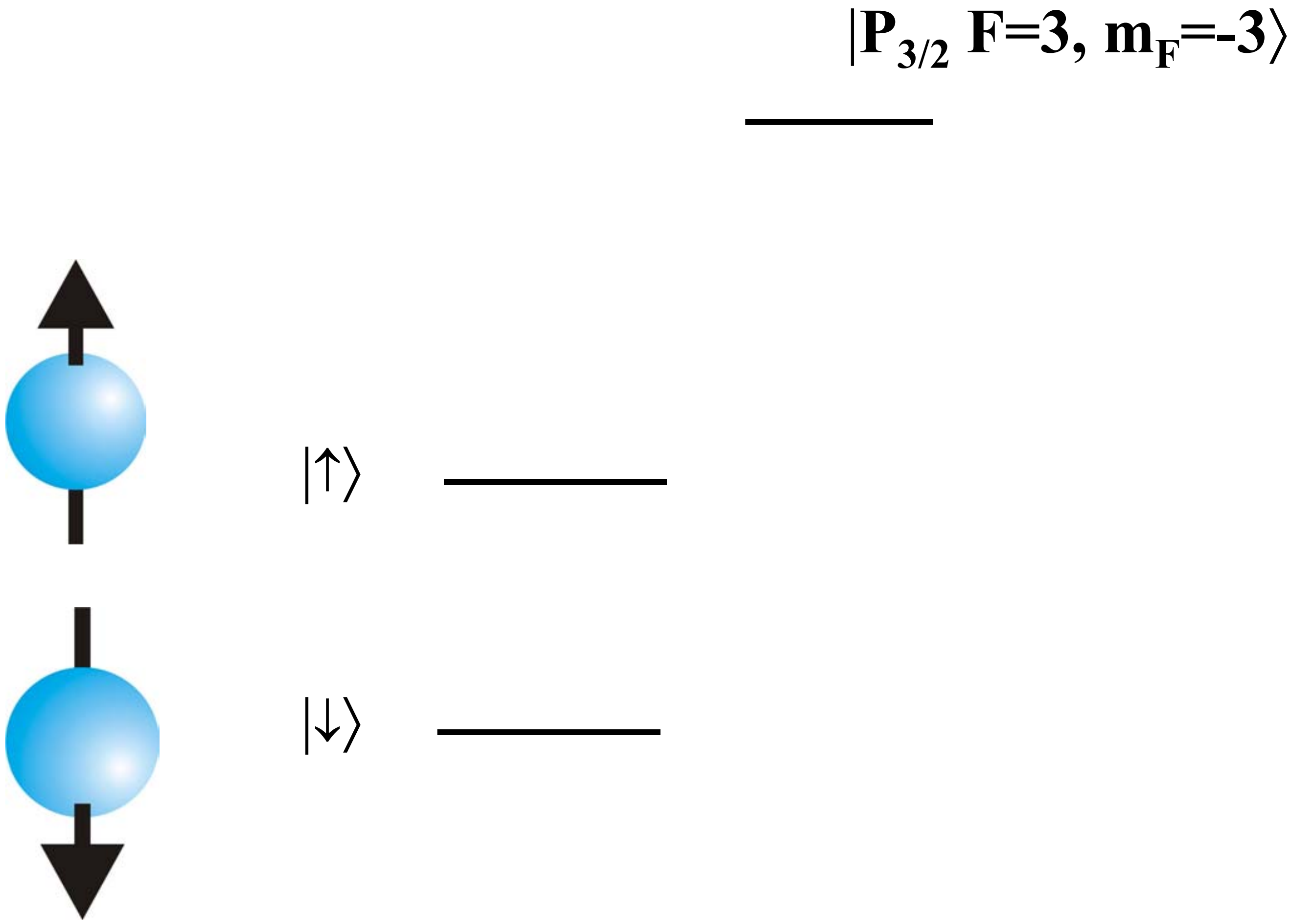
The qubit: $^{9}Be^{+}$

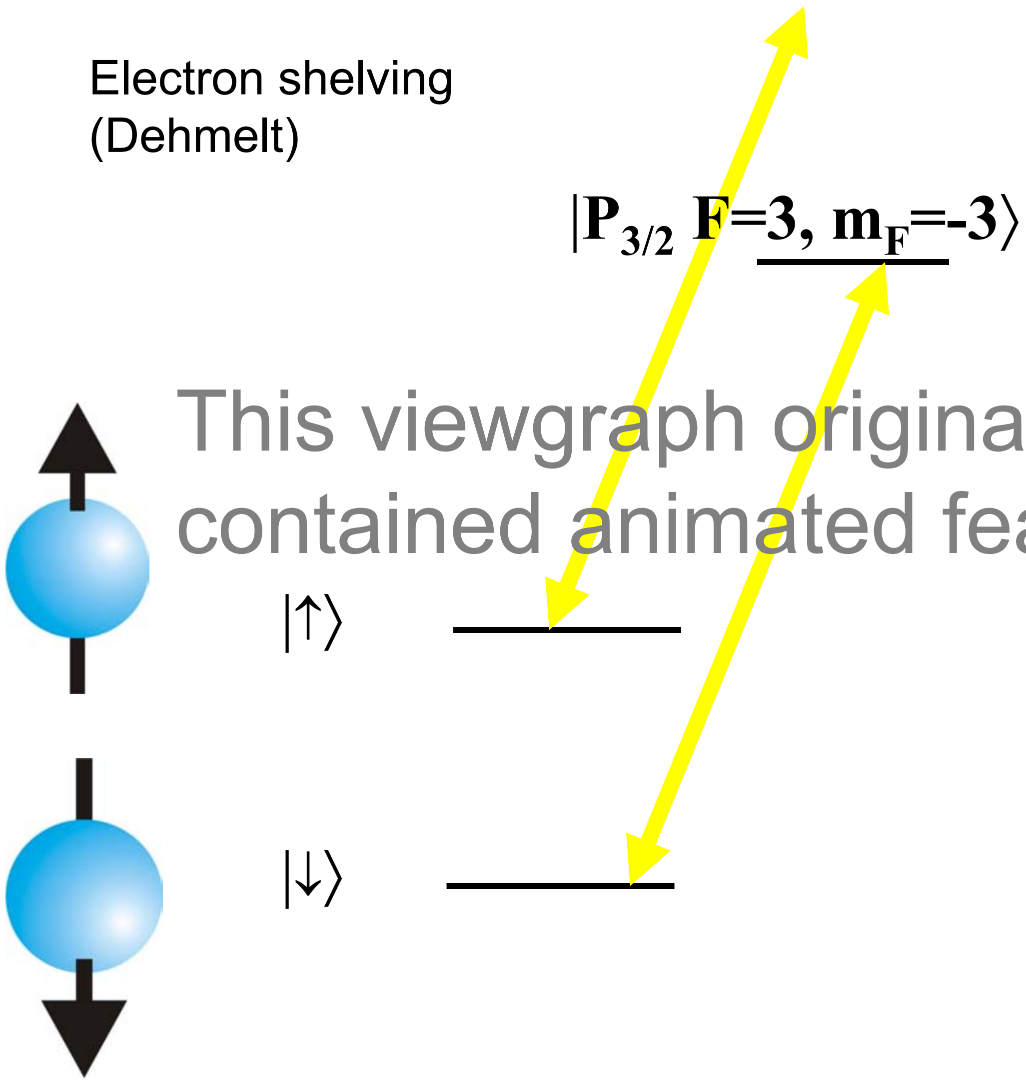


Qubit readout: electron shelving



Qubit readout

Electron shelving
(Dehmelt)



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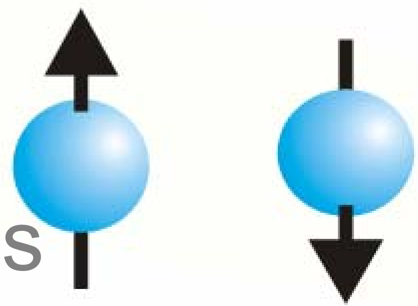


Be$^+$ (NIST):
200 μs detection period
10 counts in $|\downarrow\rangle$
0.1 counts in $|\uparrow\rangle$
>99% state discrimination

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

optical pumping, ground-state cooling (99.9%) $\Rightarrow |\downarrow\downarrow\downarrow\downarrow\ldots\rangle\ |0\rangle$ ✓

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

T_{dec}> 10 s, T_{gate}=10 μs, heating irrelevant ✓

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

co-carrier rotations, geometric-phase gate, heating tolerable ✓

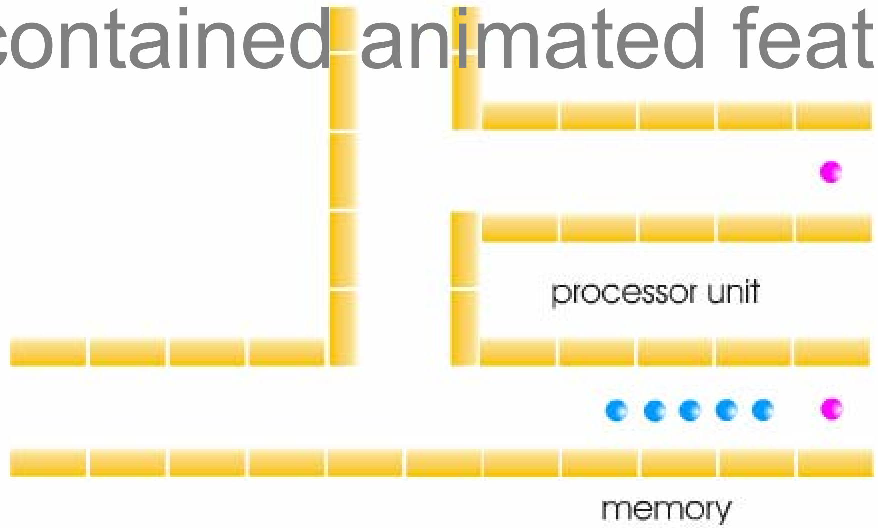
V. A qubit-specific read out capability

electron shelving method, 99% readout efficiency (100%) ✓

NIST Multiplexed trap architecture

extension of J. I. Cirac and P. Zoller, PRL **74,** 4091 (1995).

This viewgraph originally contained animated features



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) .

interconnected multi-trap structure
subtraps completely decoupled

routing of ions by controlling electrode voltages

processor sympathetically cooled
only need to cool three normal modes
no need for ground state cooling
in memory

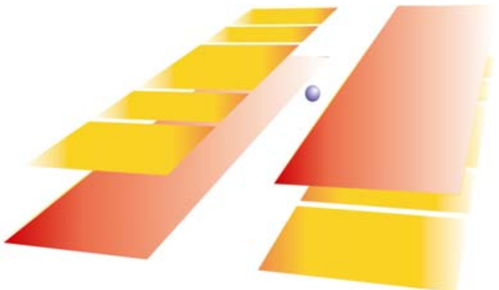
no individual optical addressing during two-qubit gates
can do gates in tight trap

one-qubit gates in extra subtrap
ion is strongly confined and
easily addressed

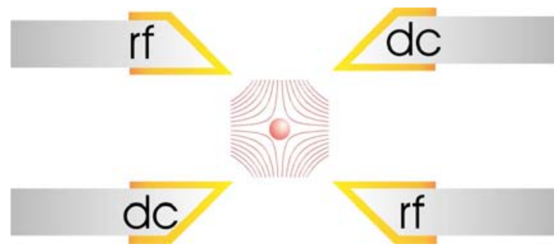
readout in extra subtrap
no rescattering of fluorescence

Two layer Paul trap

radial confinement:



radial cross section

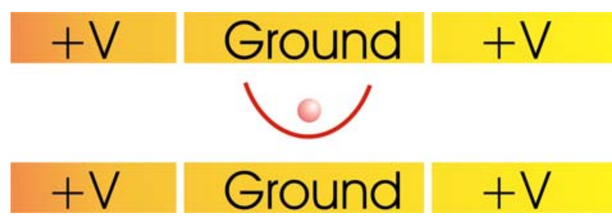


ac quadrupole field

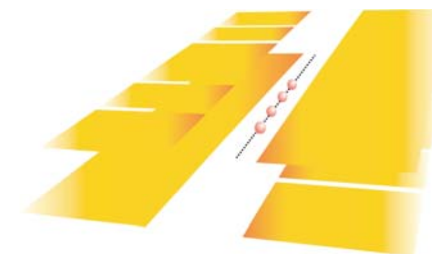
harmonic time averaged pseudo-potential

axial confinement:

axial cross section



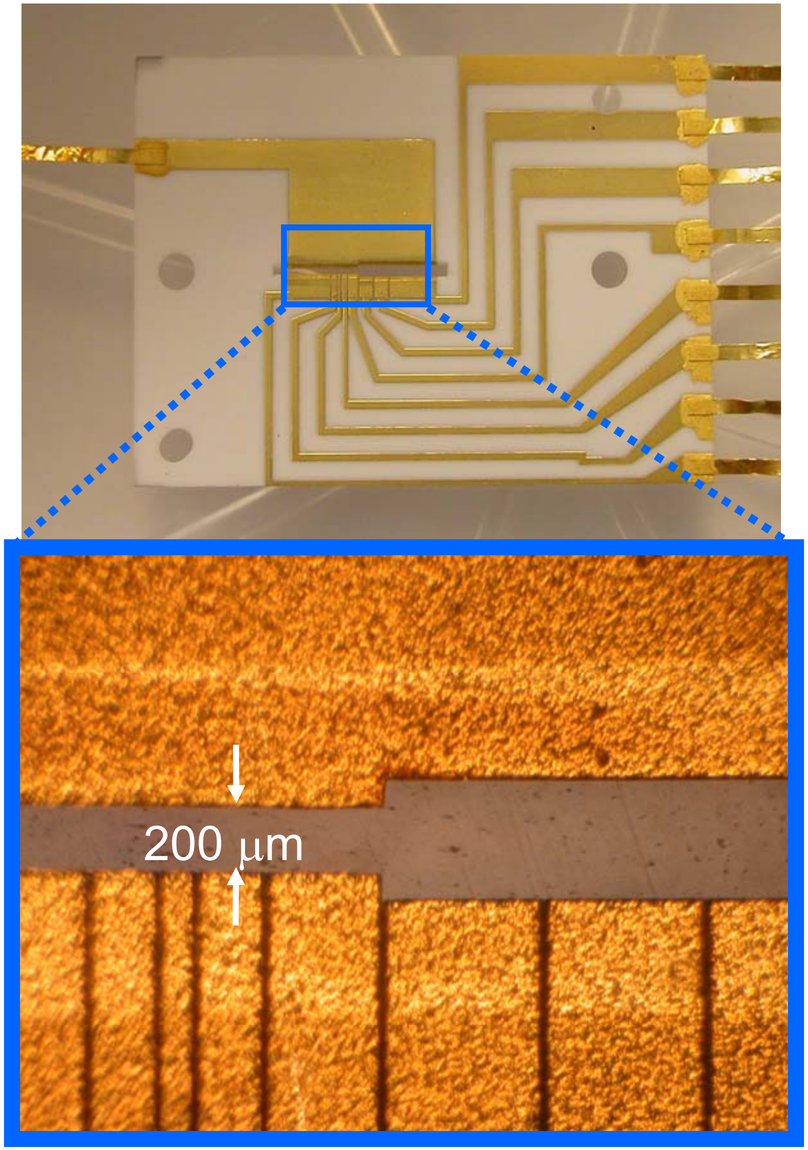
static harmonic axial potential



radial conf. >> axial conf.
$\Rightarrow$ ions align along trap axis

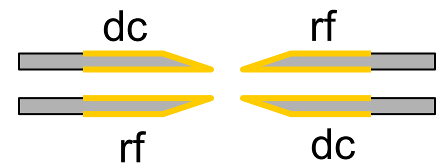
This viewgraph originally contained animated features

Two Layer Trap Technology

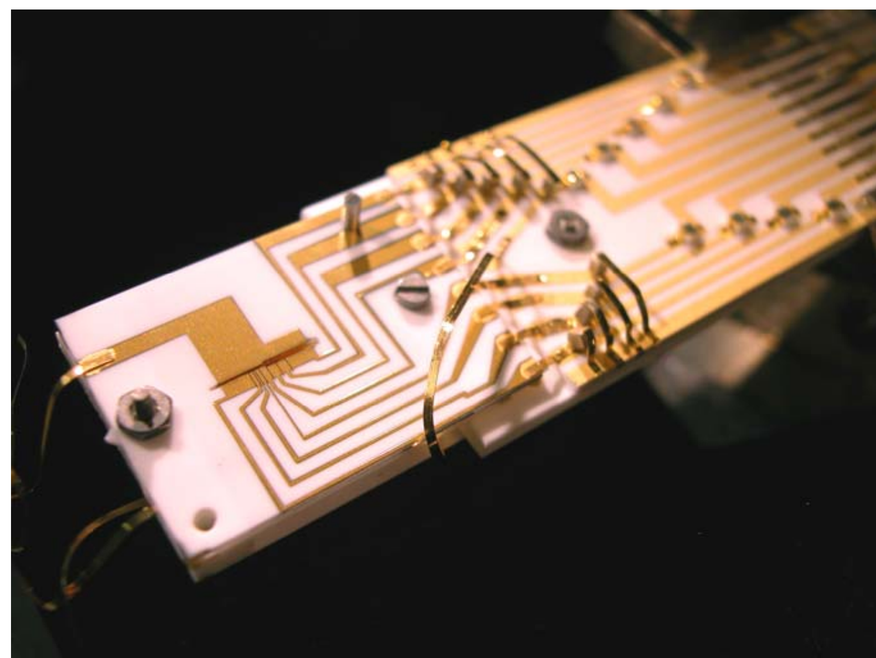


Murray Barrett/John Jost

2 wafers of alumina (0.2 mm thick)
gold conducting surfaces (2 μm)

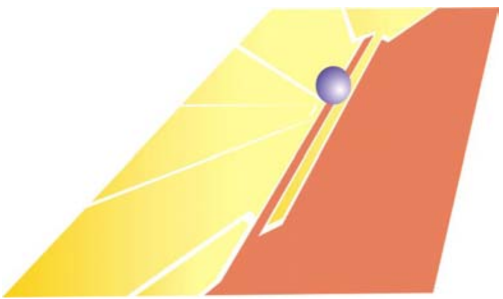


6 zones, dedicated loading zone

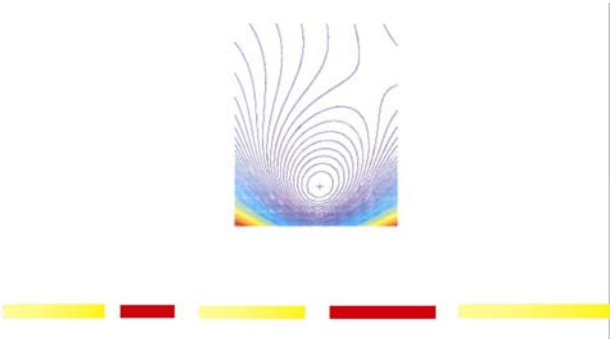


Surface trap

radial confinement:

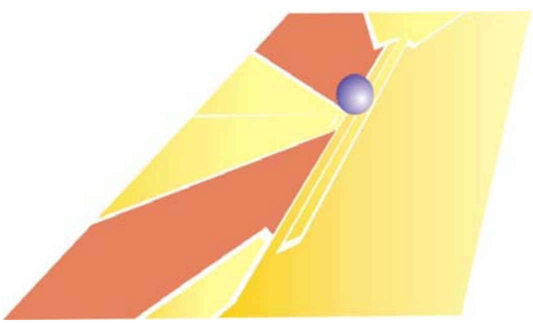


radial cross section



time averaged pseudo-potential

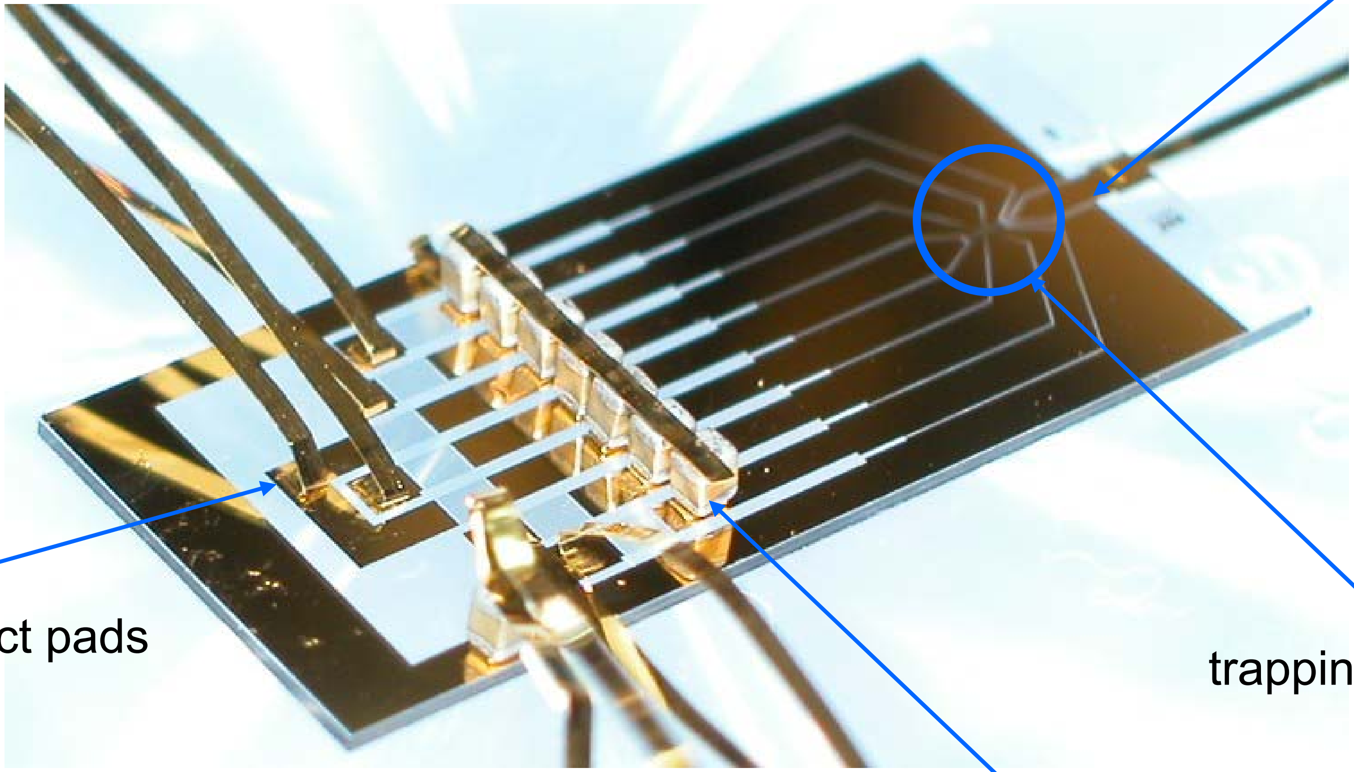
axial confinement:



axial cross section

Planar Trap Chip

Gold on fused silica



RF

DC Contact pads

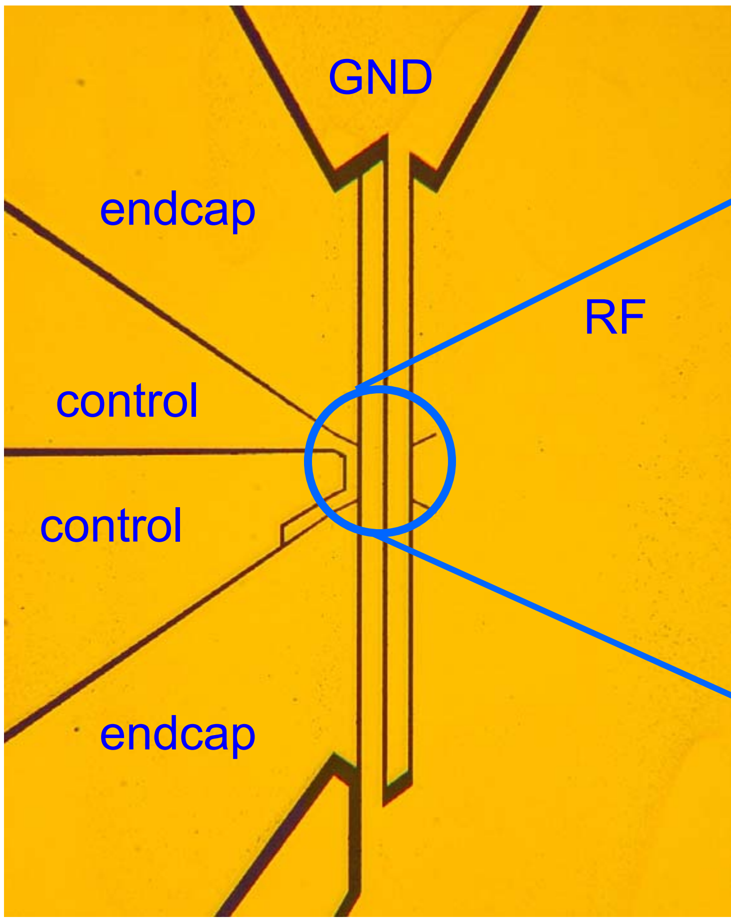
trapping region

low pass filters

John Chiaverini, Signe Seidelin

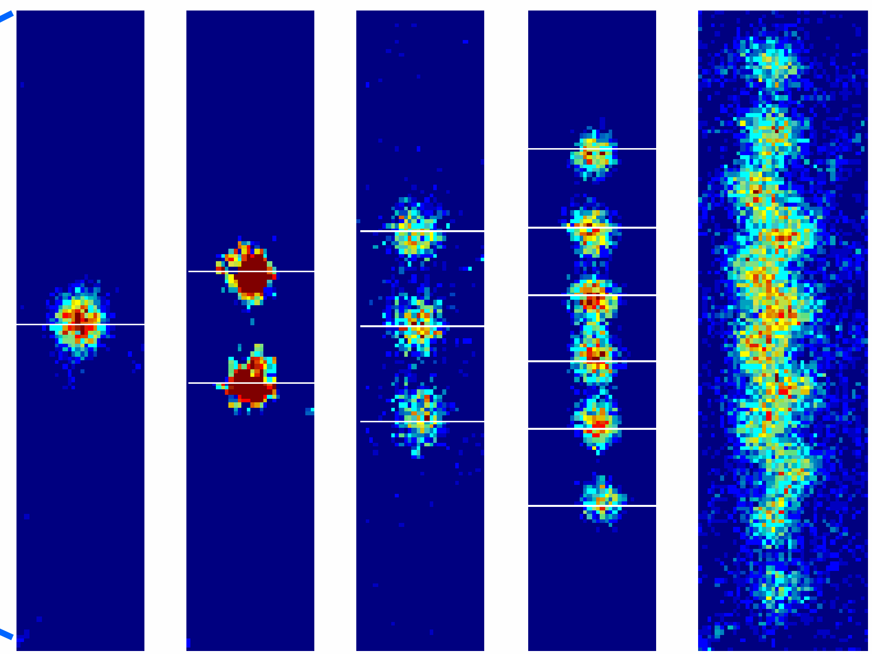
Planar Trap Chip

Magnified trap electrodes



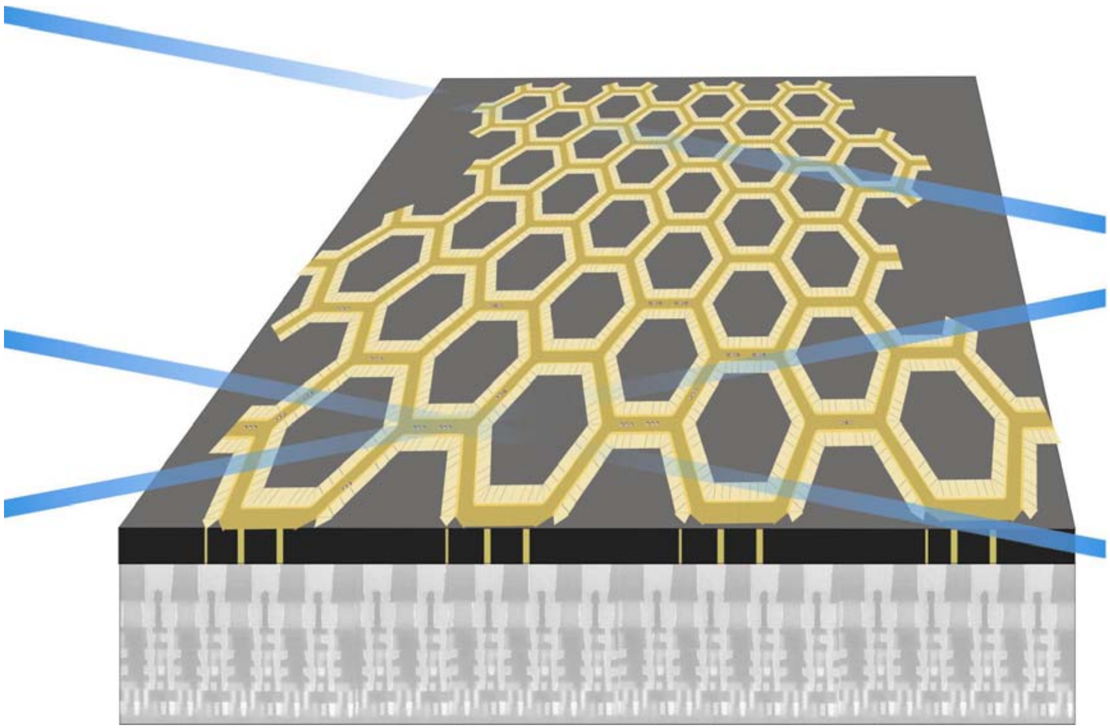
John Chiaverini, Signe Seidelin

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



Estimated heating rate <10 quanta/ms

The future: Integrated ion chips ?



“Solid state” with the bulk separated from qubits

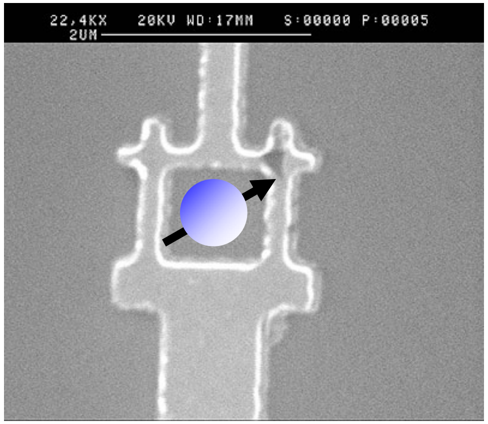
DTO/NSA Fabrication initiative:
Collaborations with Lucent Technology and Sandia Nat. Lab.

The future II: Hybrid systems ?

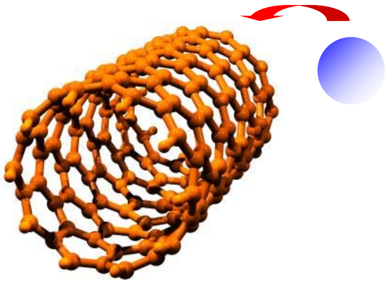
Ion/micro-cantilever:

(Wineland et al., 1998)

Ion/Josephson junctions:

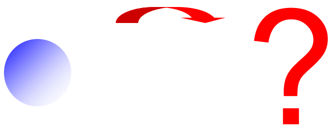


Ion/Carbon nanotubes:



(Tian, Zoller & Co. 2003)

Ion/(your micro-system here):



Cavity , microwave circuit …

Multi-Qubit Algorithms

Towards Heisenberg-Limited Spectroscopy with Multiparticle Entangled States,
Science **304**, 1476 (2004).

Deterministic quantum teleportation of atomic qubits,
Nature **429**, 737 (2004).

Quantum Dense Coding with Atomic Qubits,
Phys. Rev. Lett. **93**, 040505 (2004).

Realization of quantum error correction,
Nature **432**, 603 (2004).

Enhanced Quantum State Detection Efficiency through Quantum Information Processing,
Phys. Rev. Lett. **94**, 010501 (2005).

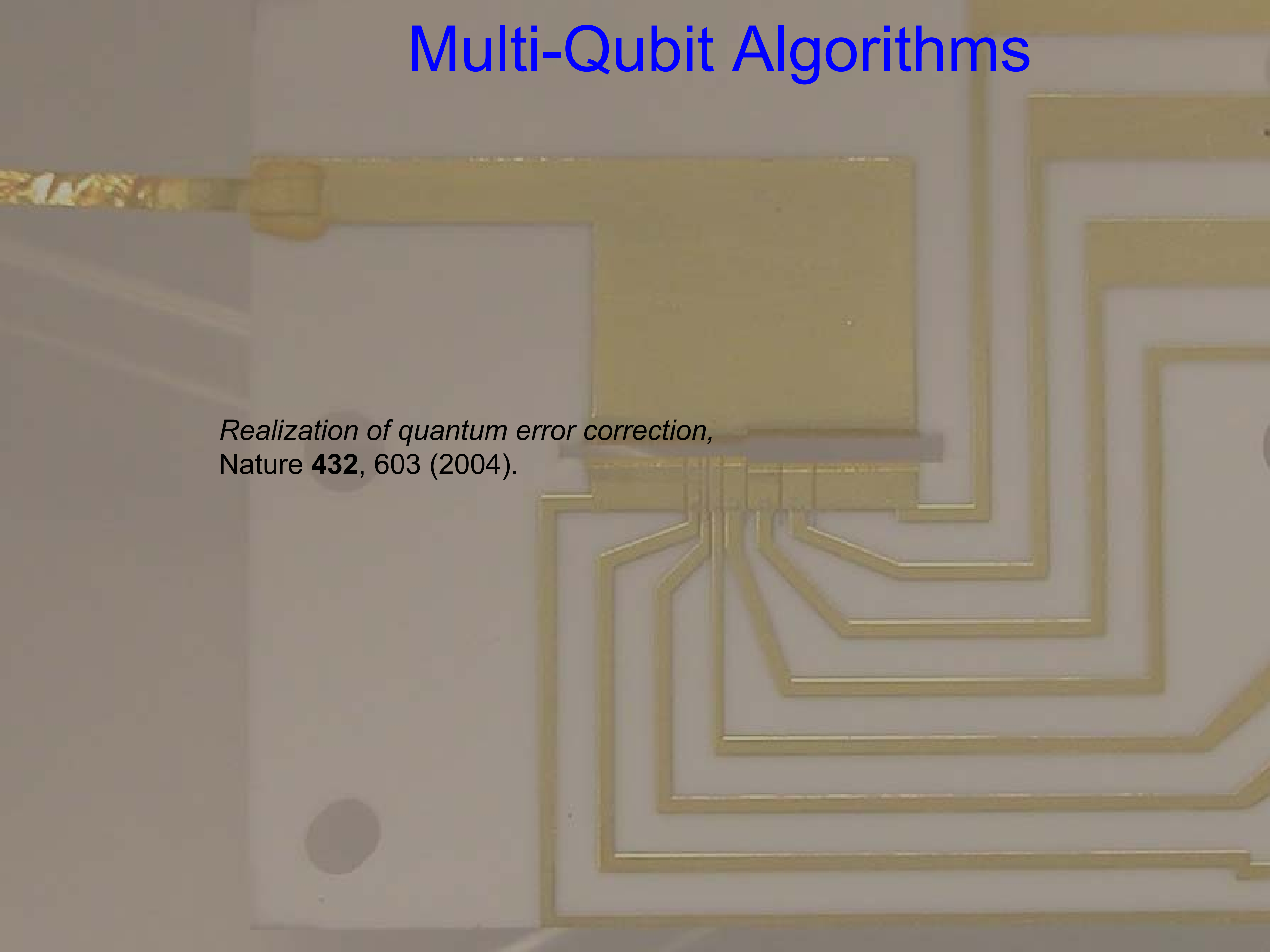
Implementation of the Semiclassical Quantum Fourier Transform in a Scalable System,
Science **308**, 997 (2005).

Hyperfine Coherence in the Presence of Spontaneous Photon Scattering,
Phys. Rev. Lett. **95**, 030403 (2005).

Long-lived qubit memory using atomic ions,
Phys. Rev. Lett. **95**, 060502 (2005).

Creation of a six-atom 'Schrödinger cat' state,
Nature **438**, 639 (2005).

Multi-Qubit Algorithms



Realization of quantum error correction,
Nature **432**, 603 (2004).

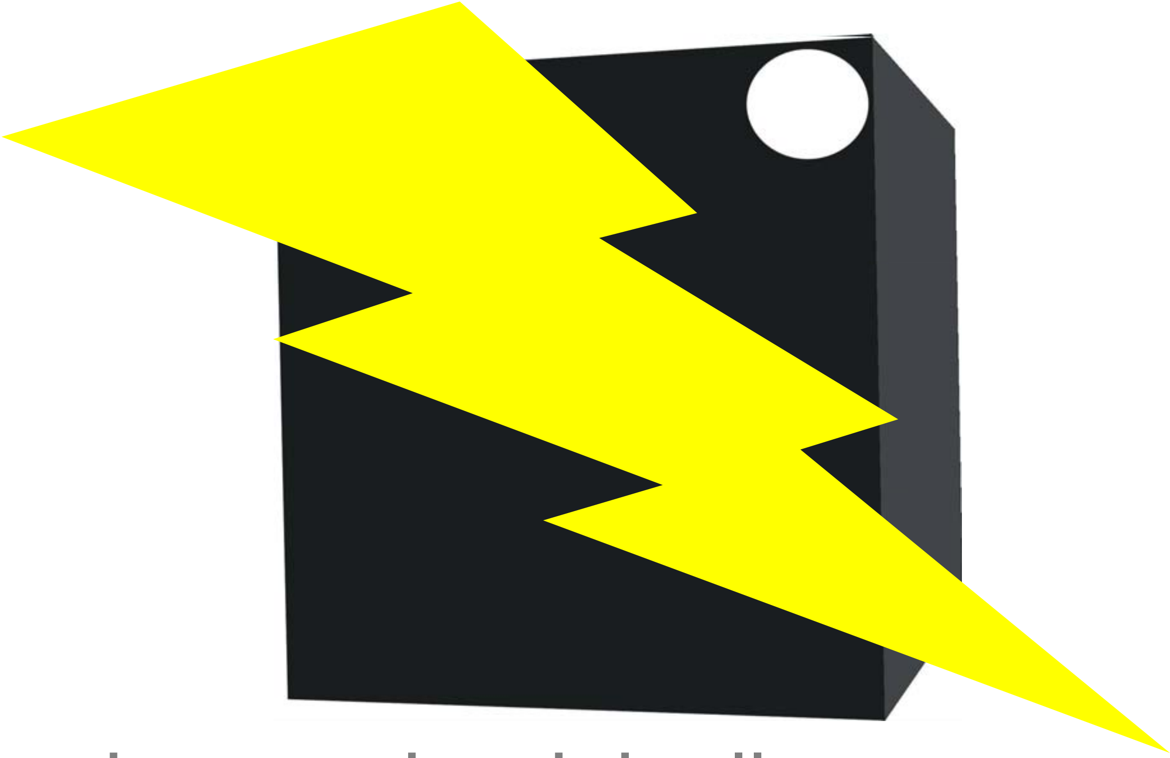
Why quantum error correction ?

Quantum error correction upgrades large scale quantum computing from
“Totally hopeless”
to
“Theoretically not hopeless”

Threshold theorem: If individual operation errors are sufficiently small we can do arbitrarily long calculations.

Analogy for quantum error correction

How can one correct a qubit without looking at it?



This viewgraph originally contained animated features

Analogy for quantum error correction

Ancilla measurement projects continuous errors to one of a few cases

Measured ancilla values reveal necessary correction

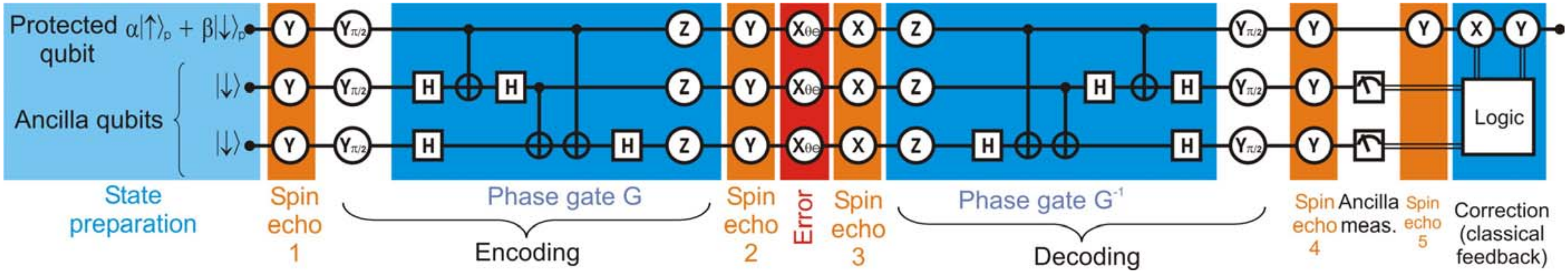
Correction conditional on ancilla values repairs damage without ever looking at the qubit

This viewgraph originally contained animated features

3 Qubit Bitflip Error-Correction

Motivation: Scaling will require fault tolerance and therefore error correction

- experimental error correction with classical feedback from *measured* ancillas
- based on new stabilizer code with generators {ZZX,ZXZ} (no classical analog)

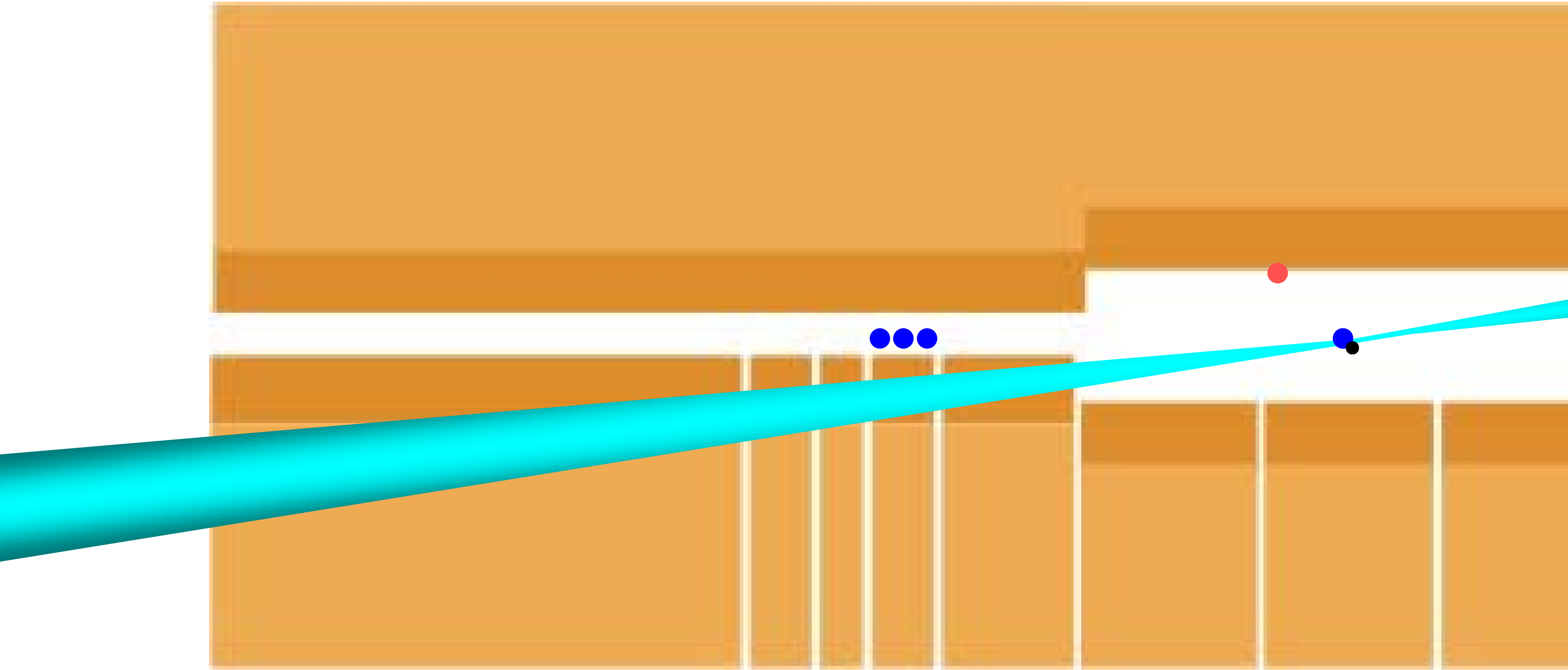


J. Chiaverini et al., *Nature,* **432**, 602 (2004)

Quantum Error Correction

This viewgraph originally contained animated features

Loading the trap



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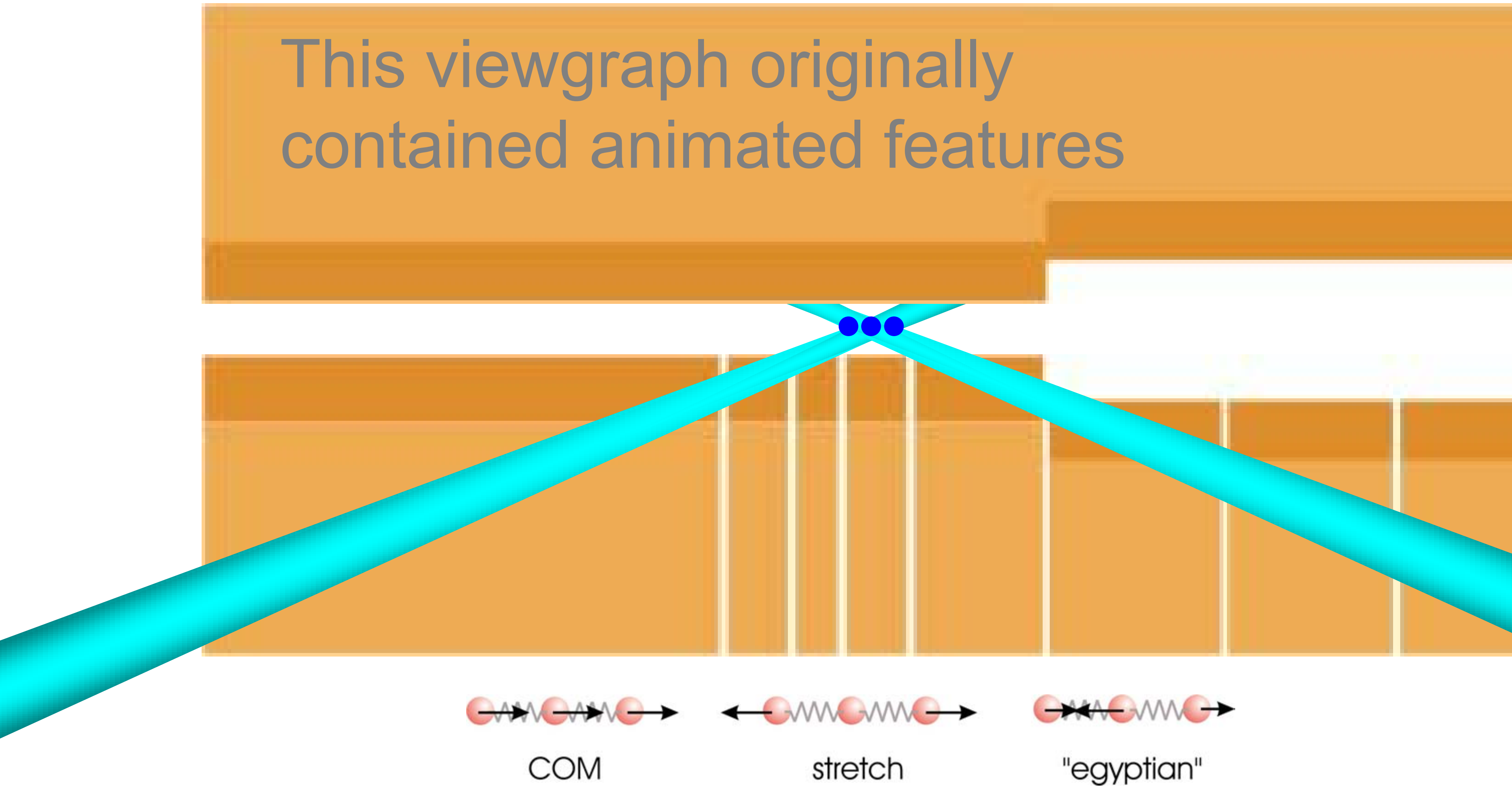
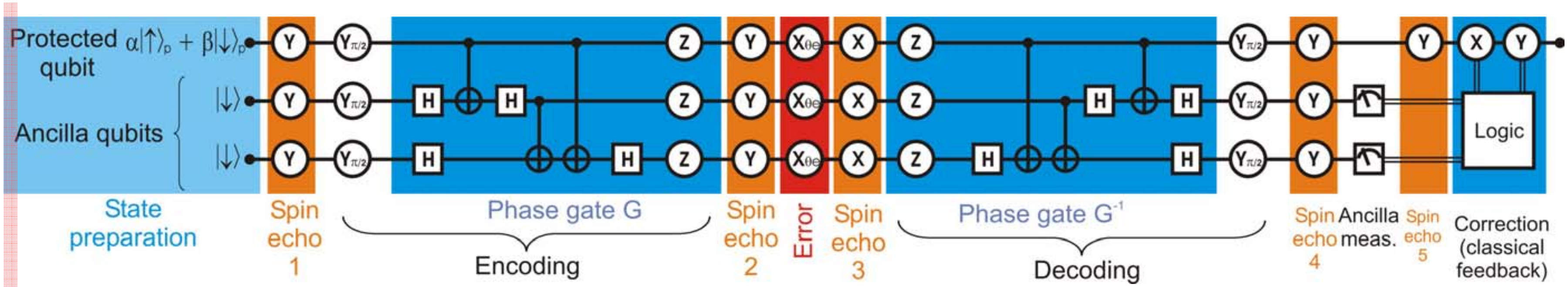
Ground state cooling



Quantum computer booted up !

Error correction implementation



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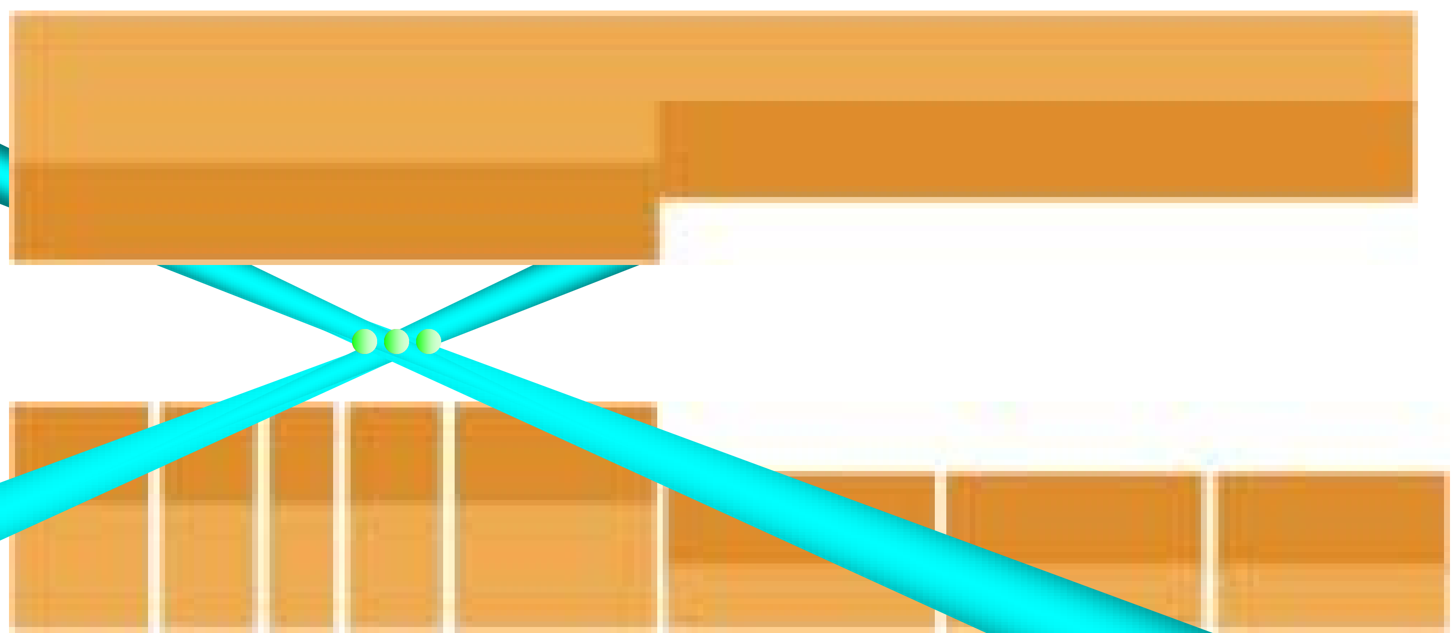
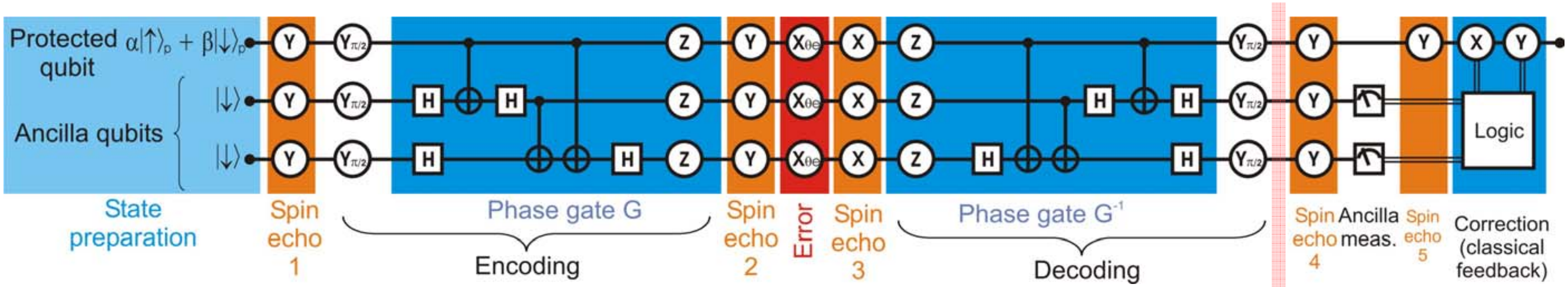


Error correction implementation



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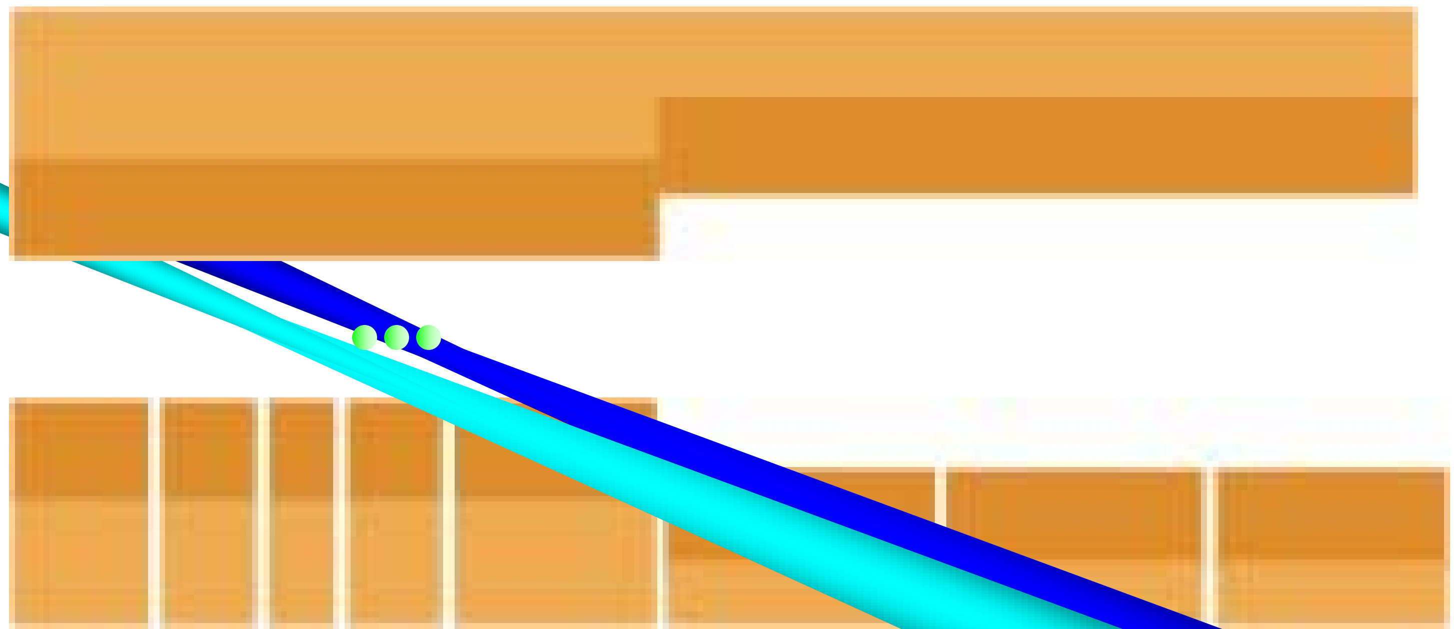
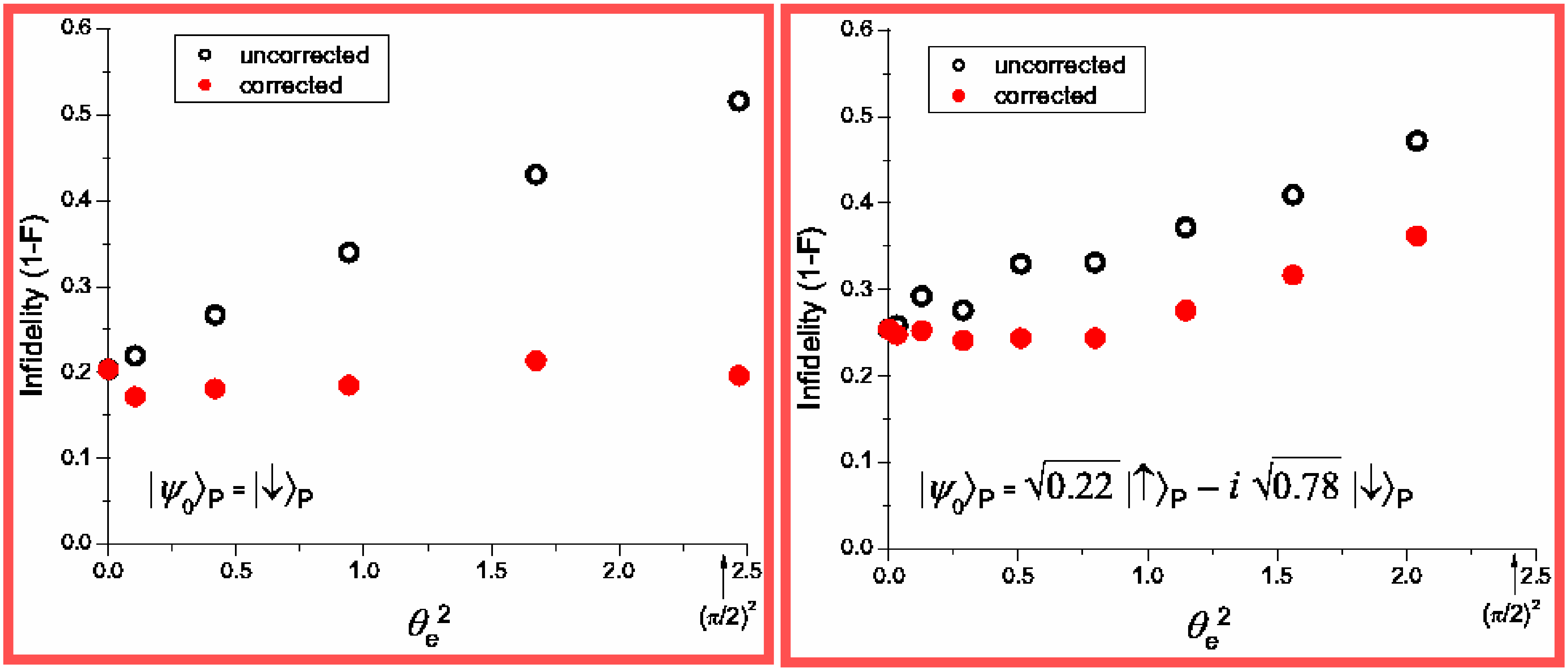


Error-Correction Results



- Uncorrected infid. $\sim \theta_e^2$, corrected infid. $\sim \theta_e^4$

J. Chiaverini et. al. *Nature* **432**, 602 (2004)

Entanglement purification

Motivation: Distribute good entangled pairs for communication and computation.

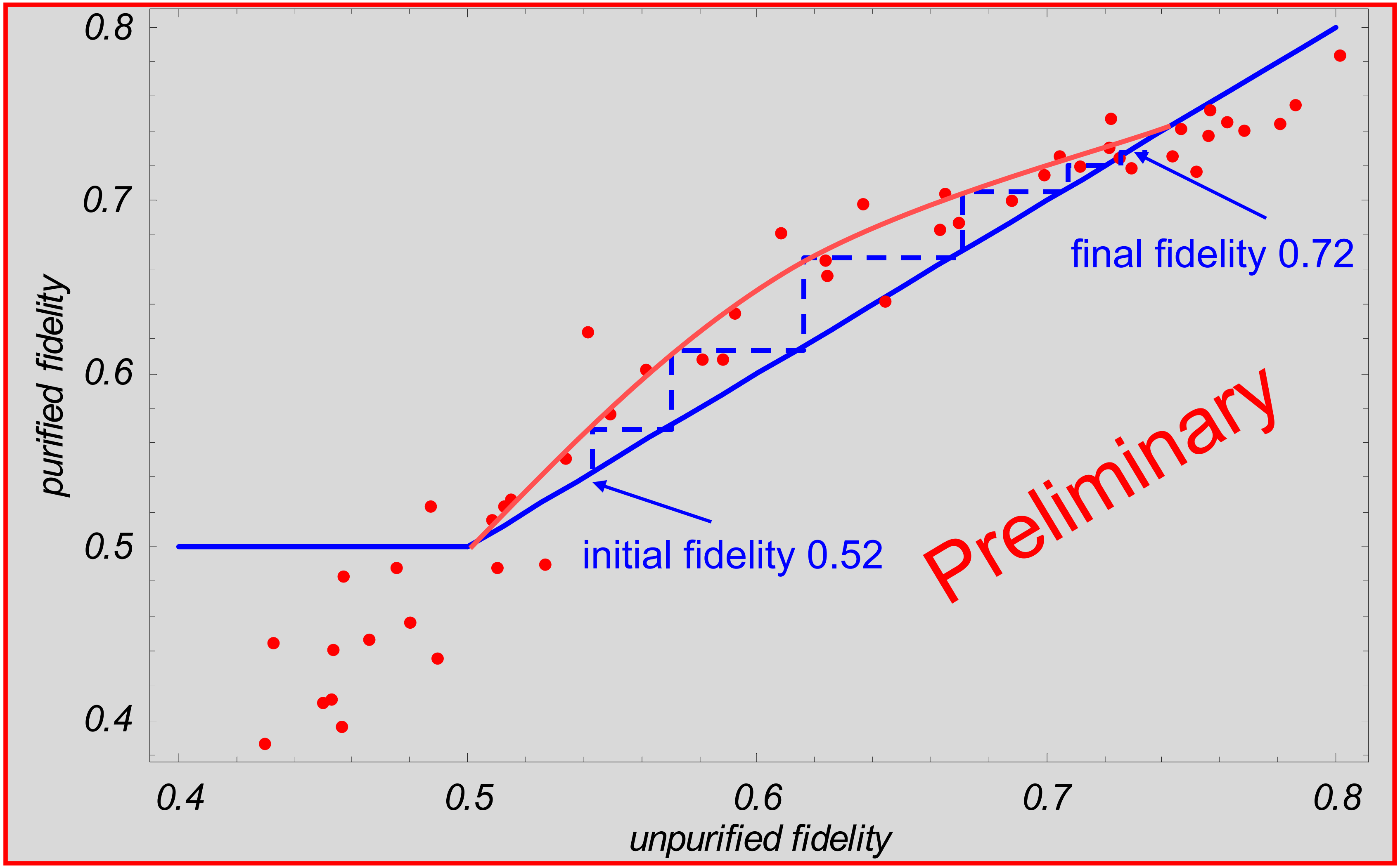
Increase maximum distance for quantum communication with modest effort (few qubit/few operations)

Goal: Produce one higher fidelity entangled pair out of two less entangled

Implemetation (following C. Bennett et al.):

Produce two entangled pairs
(two geometric phase gates)
Do controlled rotations between parts of the pairs
(two geometric phase gates)
Measure first pair, conditioned on outcome keep or discard first pair

Entanglement purification results



Gain would allow for entanglement pumping from F=0.53 to F=0.75

Present Status

DiVincenzo criteria demonstrated in individual experiments

Can control qubits with high operation fidelities
(97% two-qubit gate, 99% single qubit rotation)

Field independent qubits reduce memory error significantly.
Dec. times T1="∞"; T_2> 10 s.

Can do single qubit measurements (99.9% fidelity in 200 μs) and feed back on system well within decoherence time.

Studies of multiplexed traps, surface traps and micro-fabricaton (several groups).
Will try to scale to order 10 completely mobile qubits in the next 5 years

Achieving fault tolerance with high (0.9999) fidelity is *very hard* engineering job, but no known fundamental limits rule it out.

Quantum information at NIST

Further programs at NIST:

Neutral atoms (also Trey Porto's talk)

Quantum cryptography

Josephson junction qubits

Single photon resolving detectors

Overview in NIST brochure:

http://qubit.nist.gov