CQI Summer School
Aug. 21, 2009

J. Baugh

A BRIEF SURVEY OF IMPLEMENTATIONS

Some promising approaches for scaling up…

Cold atoms:

- Trapped ions
- Neutral atoms
- Optical lattices

Solid-state / nanoelectronics:

- Superconducting circuits (flux, phase, charge)
- Quantum dots (spin, charge)
- Kane-type devices

Optics

- LOQC

QIP paradigms…

Circuit-based QIP

- 'Standard' model
- Measurement-based (cluster states)
- Topological QC

Adiabatic QC

- E.g. D-wave approach

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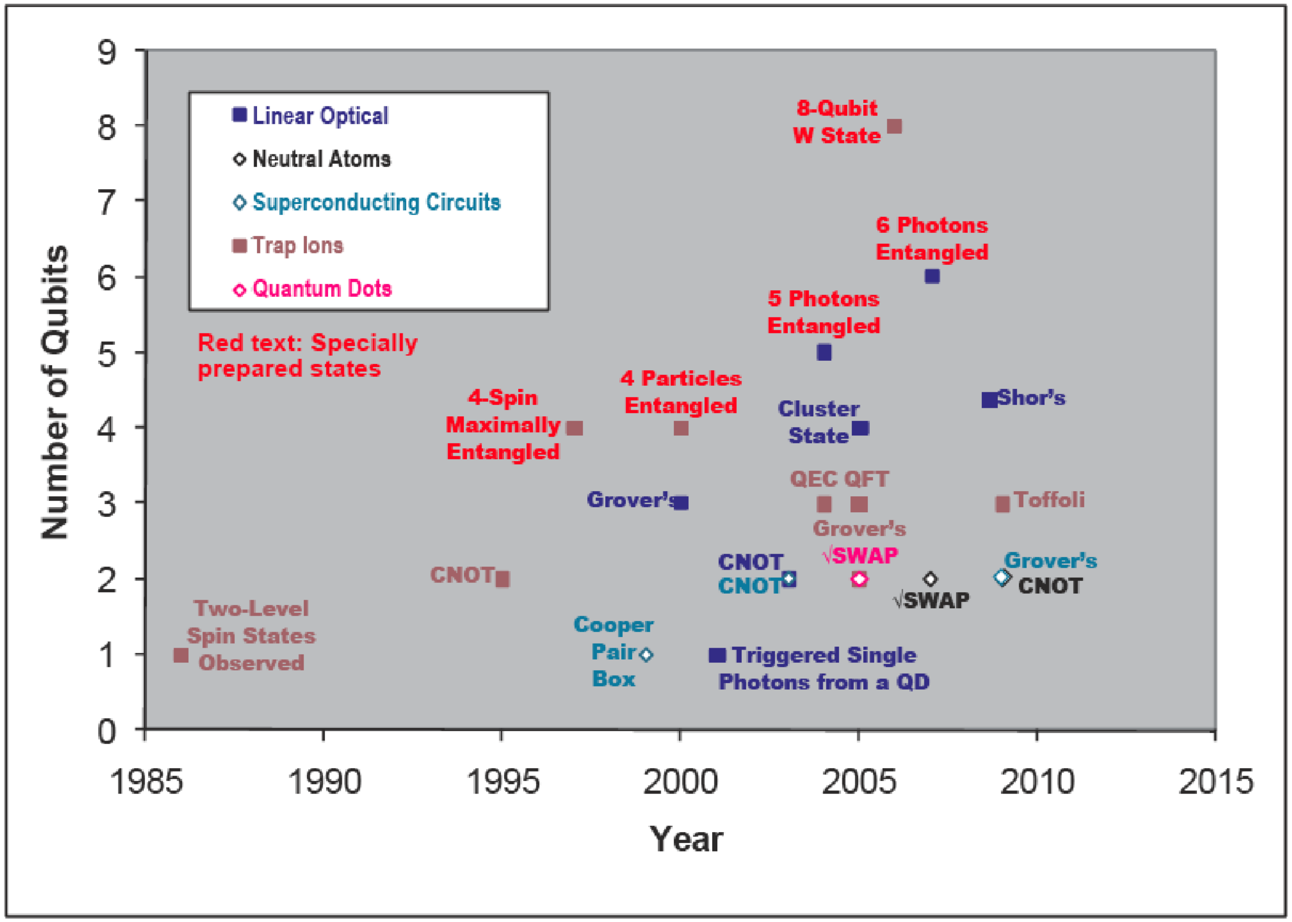
A BRIEF SURVEY OF IMPLEMENTATIONS

Progress of multi-qubit experimental demonstrations



From IARPA

Trapped ion slides courtesy D. J. Wineland, NIST

Trapped ion experimental groups pursuing Quantum Information Science:

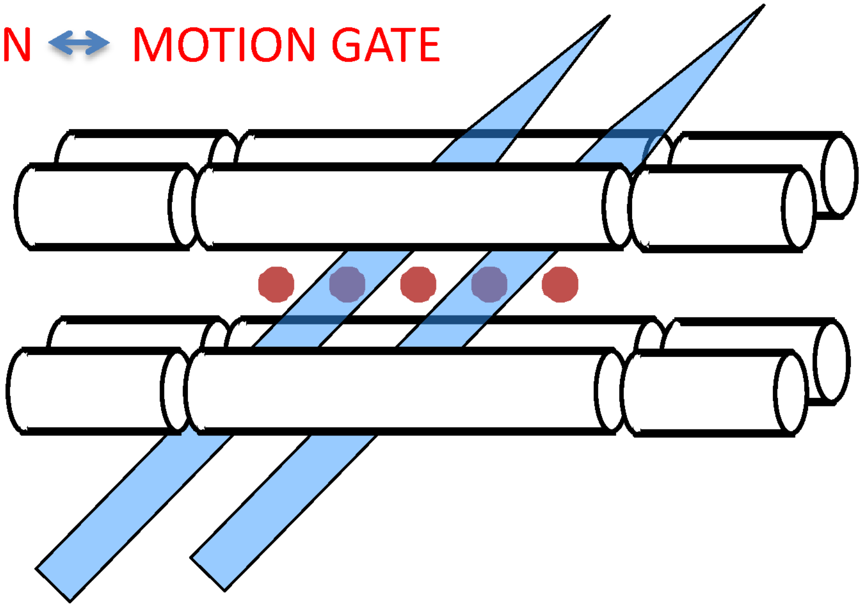
Aarhus
Barcelona
Berkeley
Garching, MPQ
Georgia Tech
Griffiths University
Innsbruck
LANL
London (Imperial)
U. Maryland
MIT
NIST
NPL, U.K.
Osaka University
Oxford
Paris (Université Paris)
PTB, Germany
Sandia National Lab
Siegen
Simon Fraser University
Singapore
Sussex
Ulm
U. Washington
Weizmann Institute

Atomic Ion QI processing:

basic scheme: J.I. Cirac, P. Zoller, ’95

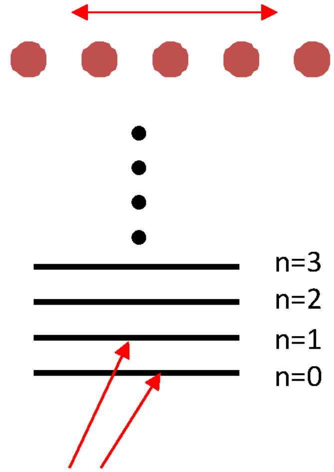
SPIN → MOTION MAP

SPIN ↔ MOTION GATE



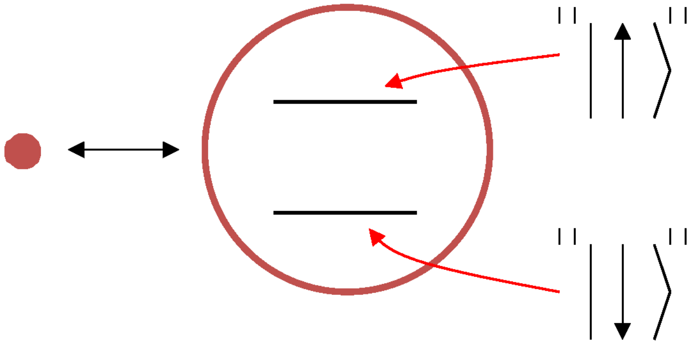
MOTION “DATA BUS”

(e.g., center-of-mass mode)



Motion qubit states

INTERNAL STATE QUBIT



Optical qubits (e.g. Ca$^+$, λ= 729 nm)

- radiative decay τ ~ 1 s

Hyperfine qubits

- τ→ ∞ ($\tau_{coherence}$ > 10 min observed)
- spontaneous emission decoherence during gates

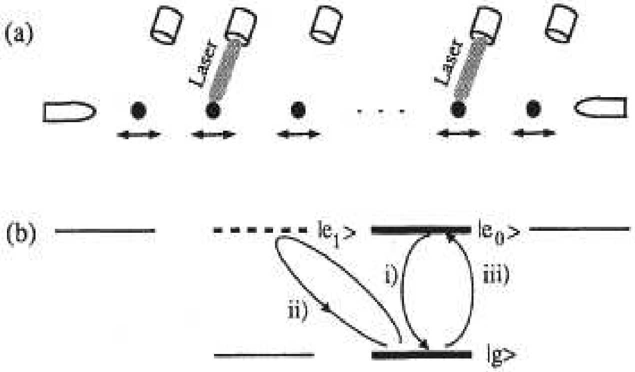
VOLUME 74, NUMBER 20 PHYSICAL REVIEW LETTERS 15 MAY 1995

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

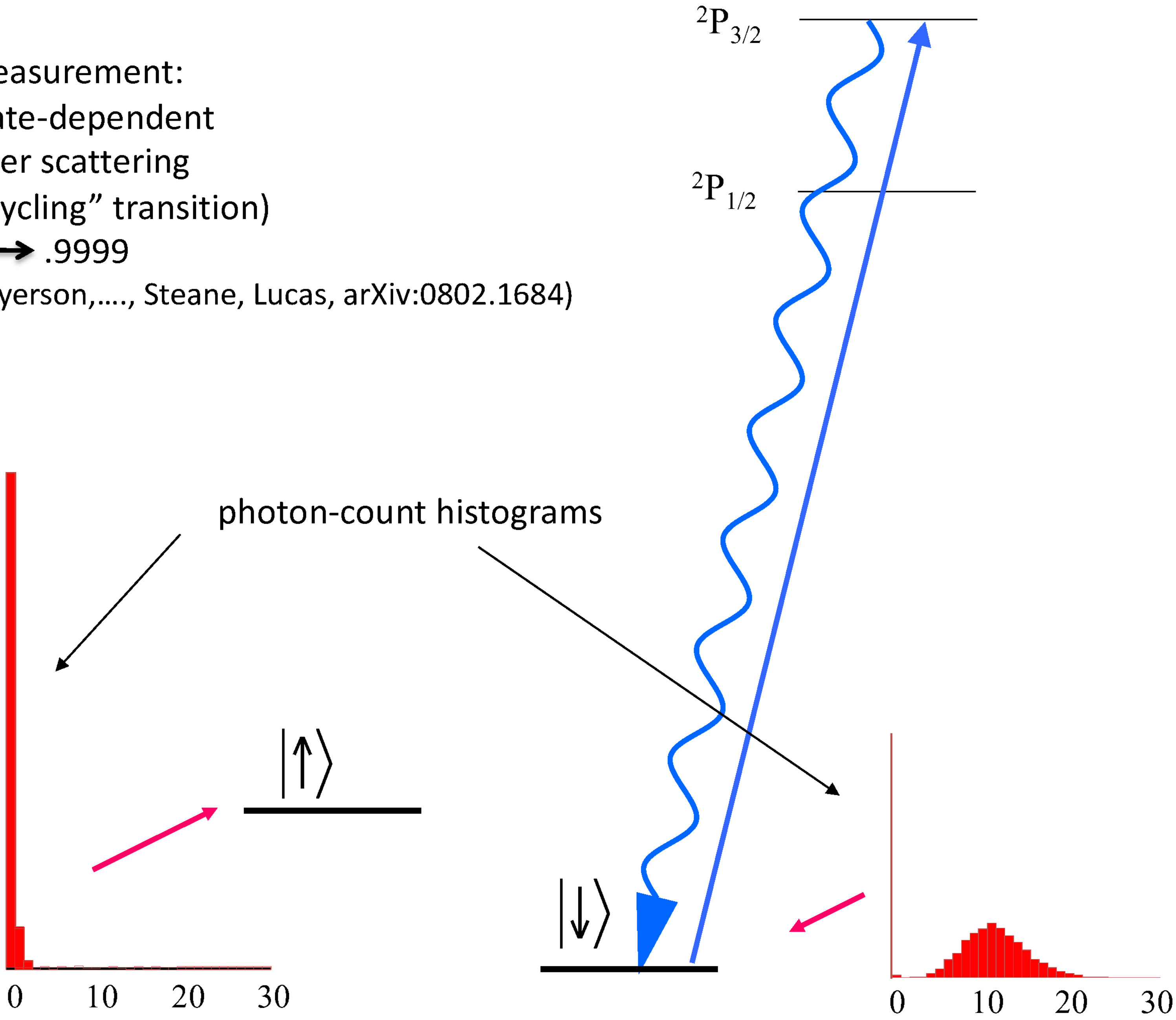


If the laser beam is on for a certain time $t = k\pi/(\Omega\eta/\sqrt{N})$ (i.e., using a $k\pi$ pulse), the evolution of the system will be described by the unitary operator

$$\hat{U}_n^{k,q}(\phi) = \exp\left[-ik\frac{\pi}{2}\left(|e_q\rangle_n\langle g|ae^{-i\phi} + \text{H.c.}\right)\right]. \quad (2)$$

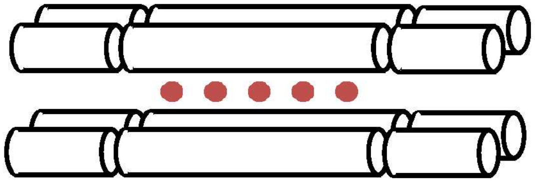
$$\begin{array}{lclclcl}
|g\rangle_m|g\rangle_n|0\rangle & \xrightarrow{\hat{U}_m^{1,0}} & |g\rangle_m|g\rangle_n|0\rangle & \xrightarrow{\hat{U}_n^{2,1}} & |g\rangle_m|g\rangle_n|0\rangle & \xrightarrow{\hat{U}_m^{1,0}} & |g\rangle_m|g\rangle_n|0\rangle\,, \\
|g\rangle_m|e_0\rangle_n|0\rangle & \longrightarrow & |g\rangle_m|e_0\rangle_n|0\rangle & \longrightarrow & |g\rangle_m|e_0\rangle_n|0\rangle & \longrightarrow & |g\rangle_m|e_0\rangle_n|0\rangle\,, \\
|e_0\rangle_m|g\rangle_n|0\rangle & \longrightarrow & -i|g\rangle_m|g\rangle_n|1\rangle & \longrightarrow & i|g\rangle_m|g\rangle_n|1\rangle & \longrightarrow & |e_0\rangle_m|g\rangle_n|0\rangle\,, \\
|e_0\rangle_m|e_0\rangle_n|0\rangle & \longrightarrow & -i|g\rangle_m|e_0\rangle_n|1\rangle & \longrightarrow & -i|g\rangle_m|e_0\rangle_n|1\rangle & \longrightarrow & -|e_0\rangle_m|e_0\rangle_n|0\rangle\,.
\end{array}$$

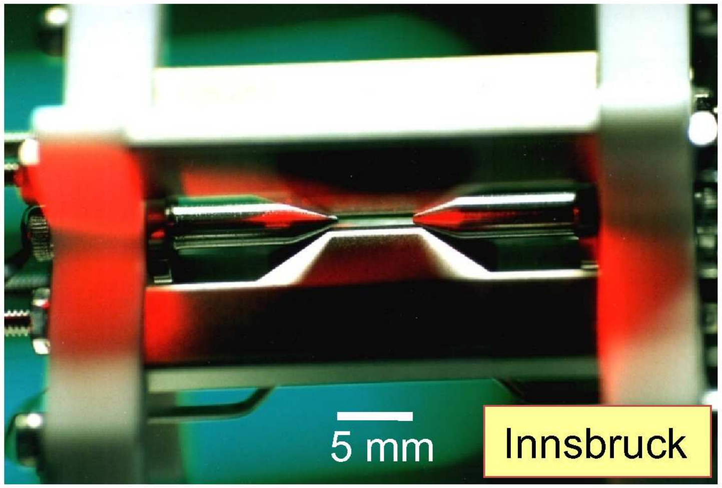
Measurement:
State-dependent
laser scattering
("cycling" transition)
F ⟶ .9999
(Myerson,…., Steane, Lucas, arXiv:0802.1684)

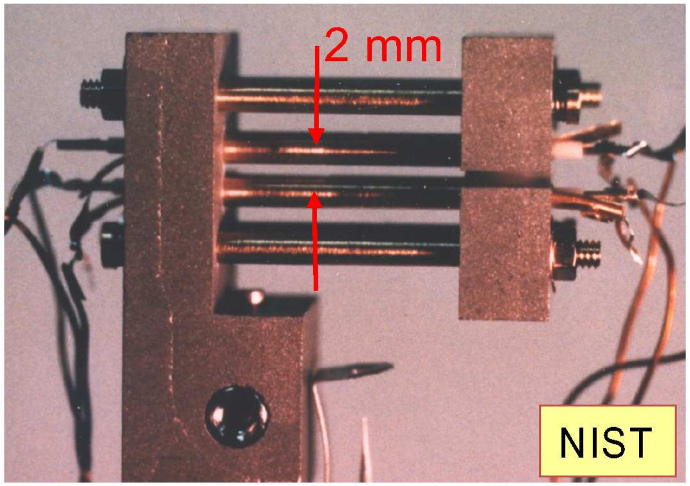


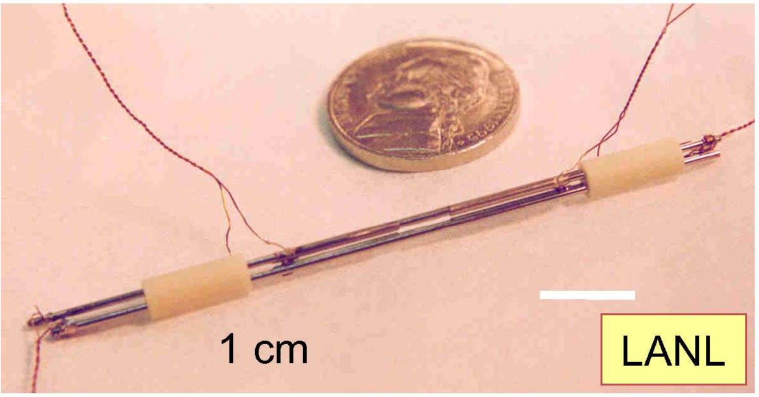
photon-count histograms

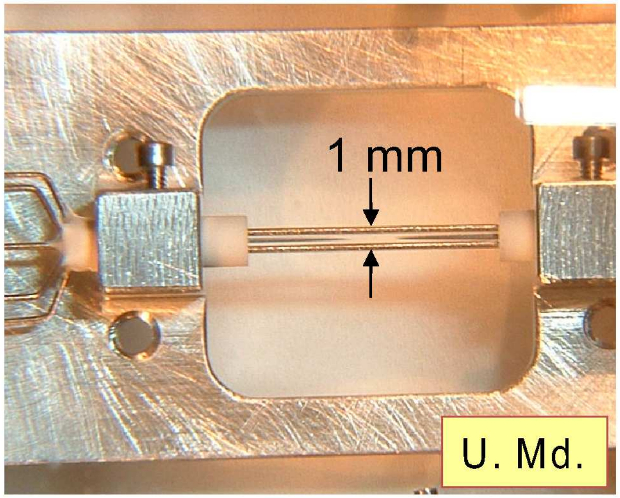
Traps:







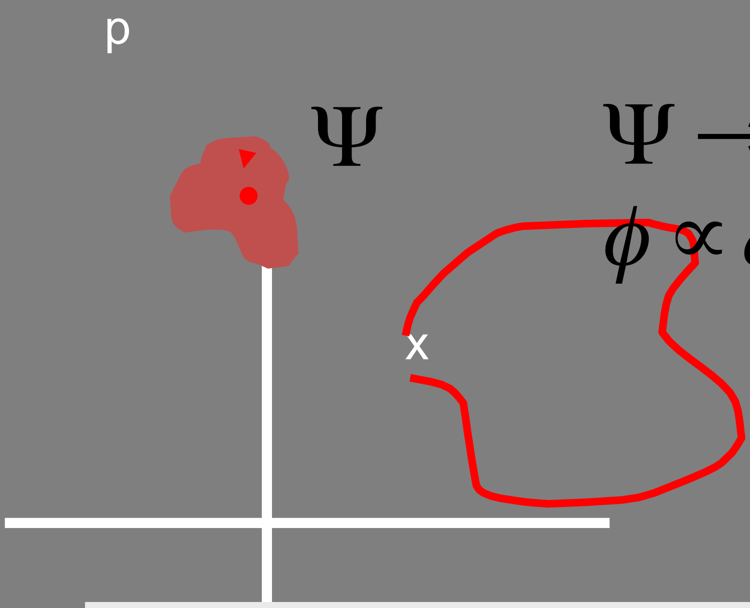




motion frequencies, gate speeds $\propto V_{RF}/md^2$ → make d small

multi-qubit phase gates

phase-space diagram for selected motional mode



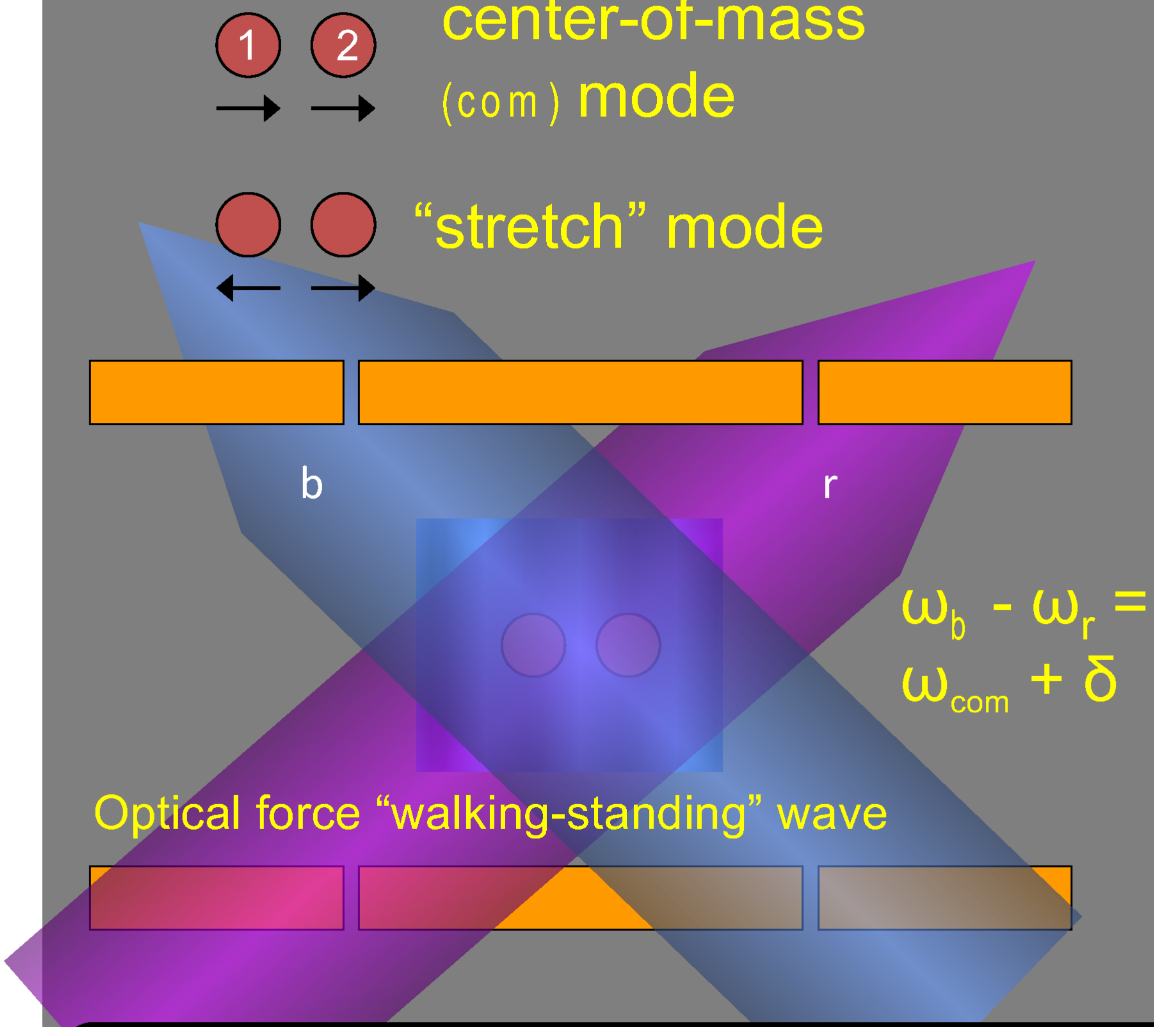
$$\Psi \rightarrow e^{i\phi}\Psi$$

$$\phi \propto enclosed \quad area$$

Phase gate:

- displacements with optical dipole forces
- make force spin dependent

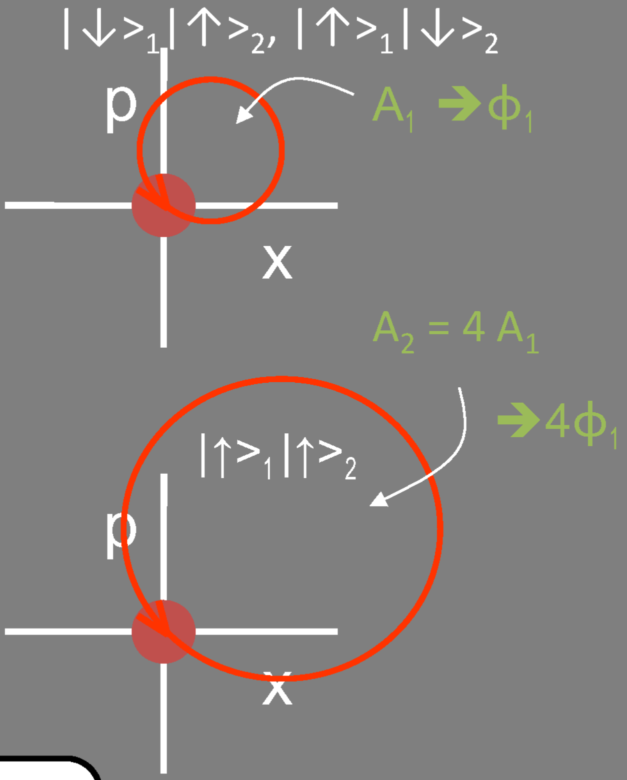
example: Z-basis phase gates



Assume dipole force

$F_{1\uparrow} = F_{2\uparrow} = F_{\uparrow}$

$F_{1\downarrow} = F_{2\downarrow} = 0$



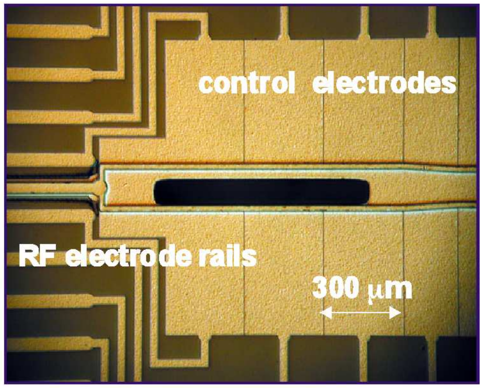
$$\Psi = \alpha|\downarrow\rangle|\downarrow\rangle + \beta|\downarrow\rangle|\uparrow\rangle + \gamma|\uparrow\rangle|\downarrow\rangle + \delta|\uparrow\rangle|\uparrow\rangle \rightarrow$$
$$\alpha|\downarrow\rangle|\downarrow\rangle + e^{i\phi_1}\beta|\downarrow\rangle|\uparrow\rangle + e^{i\phi_1}\gamma|\uparrow\rangle|\downarrow\rangle + e^{4i\phi_1}\delta|\uparrow\rangle|\uparrow\rangle$$

z rotations + phase gate

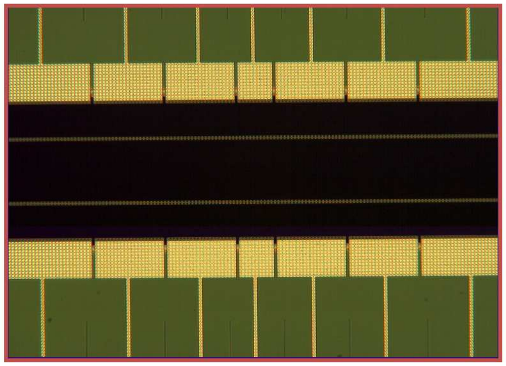
Experimental demonstrations of quantum computation primitives:

- Deutsch-Josza algorithm (Innsbruck)
- qubit teleportation (Innsbruck, NIST)
- quantum error correction (NIST)
- Grover search algorithm (U. Md.)
- Toffoli gate (Innsbruck)
- quantum Fourier transform (NIST)
- entangled state purification (NIST)
- entanglement swapping (Innsbruck)
- dense coding (NIST)
- entanglement assisted detection (NIST)
- eight-qubit W state (Innsbruck)
- six-qubit GHZ state (NIST)
- arbitrary motional state superpositions (NIST)

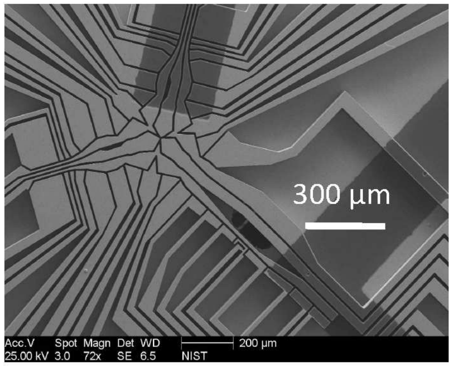
Surface-electrode trap examples



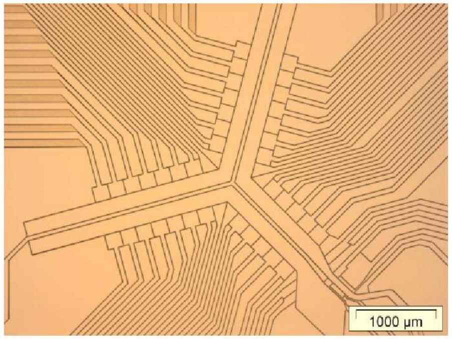
Lucent
Al on Si
17 zones



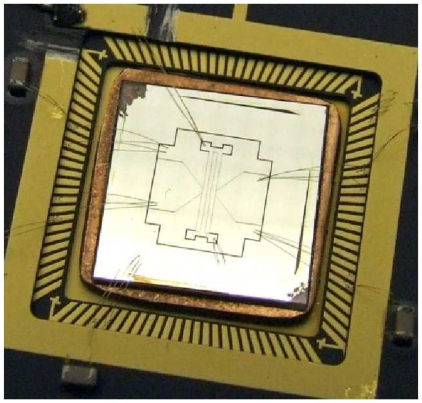
Sandia
W on Si
5 zones



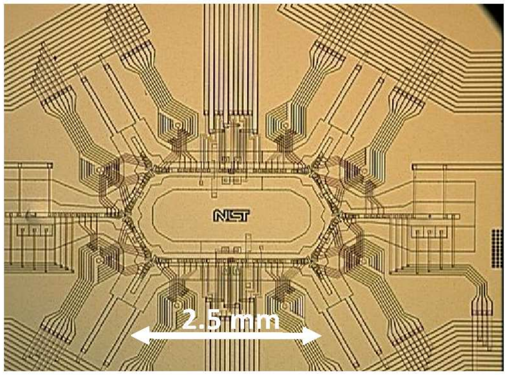
NIST
B-doped Si
23 zones



Ulm
Au on Al_2O_3
24 zones



MIT
Ag on
Sapphire
1 zone



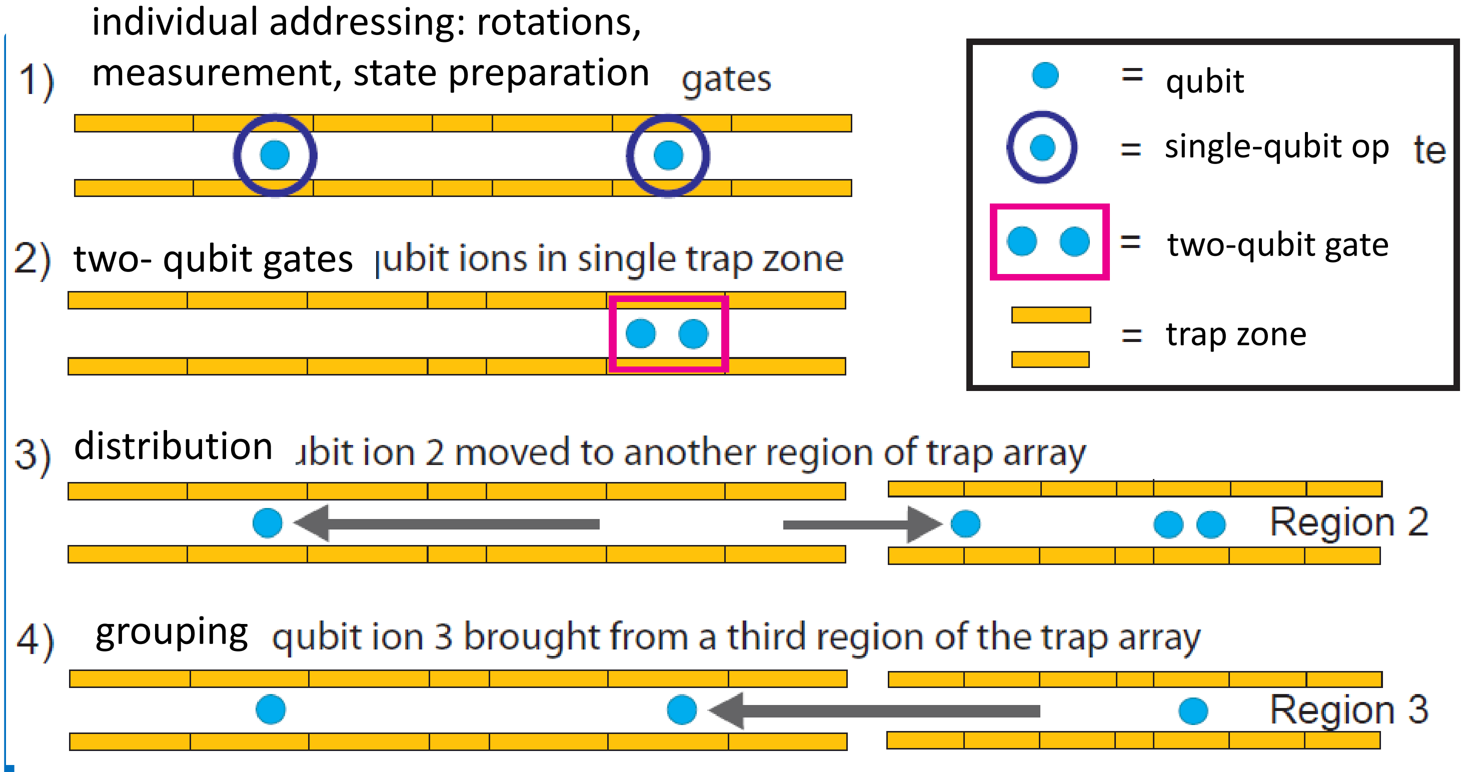
NIST
Au on quartz
~200 zone
“racetrack”

Towards large-scale processing

<u>General requirements:</u>

- transport qubit information between locations in processor
- repeated single- and multi-qubit gates on selected qubits
- detection and state preparation

Operation block for ions:



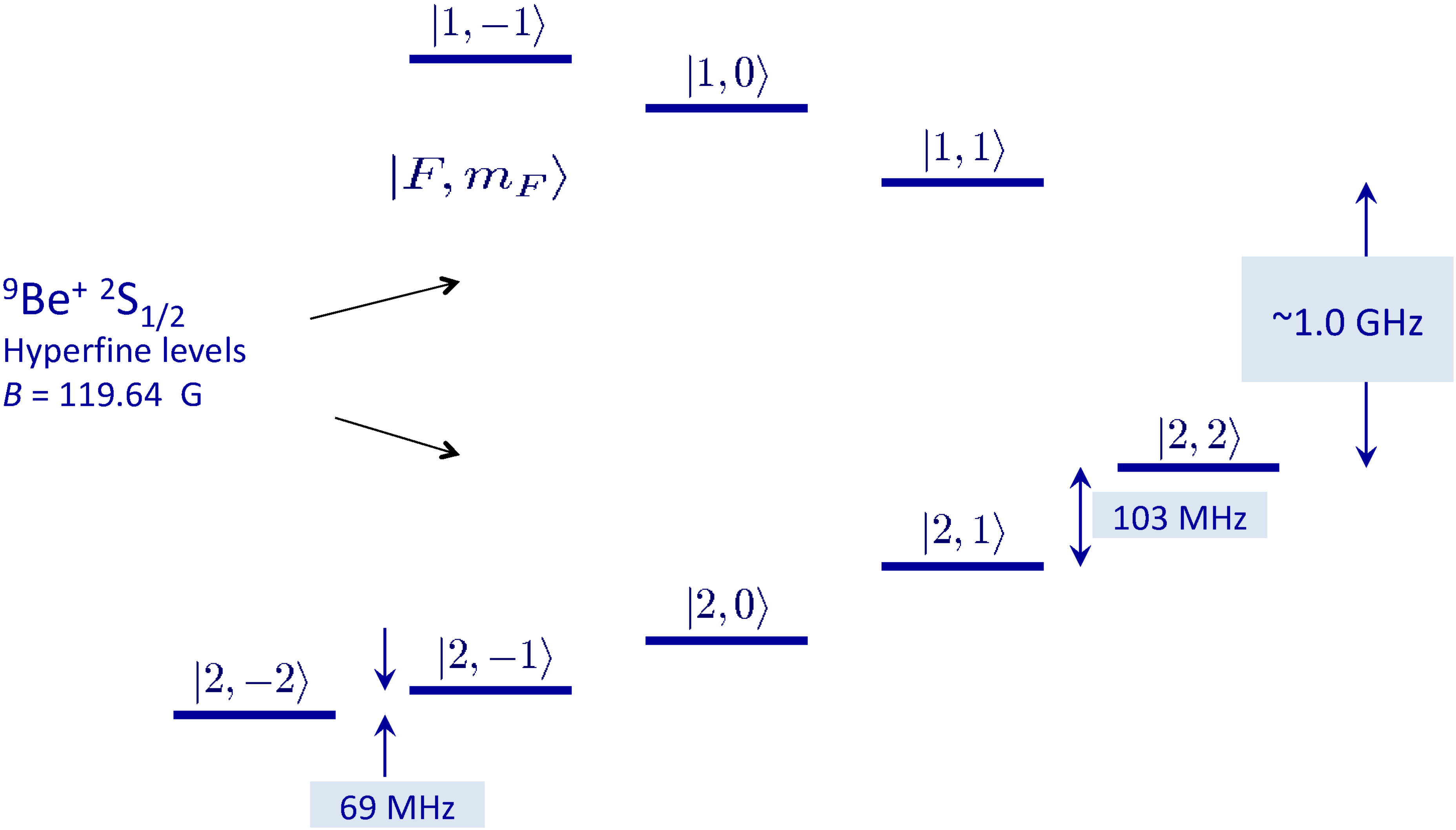
1) individual addressing: rotations, measurement, state preparation gates

2) two- qubit gates ubit ions in single trap zone

3) distribution bit ion 2 moved to another region of trap array

4) grouping qubit ion 3 brought from a third region of the trap array

Tool: hybrid qubit system



$^9\mathrm{Be}^+\ ^2S_{1/2}$
Hyperfine levels
B = 119.64 G

$|F, m_F\rangle$

$|1,-1\rangle$

$|1,0\rangle$

$|1,1\rangle$

~1.0 GHz

$|2,2\rangle$

103 MHz

$|2,1\rangle$

$|2,0\rangle$

$|2,-1\rangle$

$|2,-2\rangle$

69 MHz

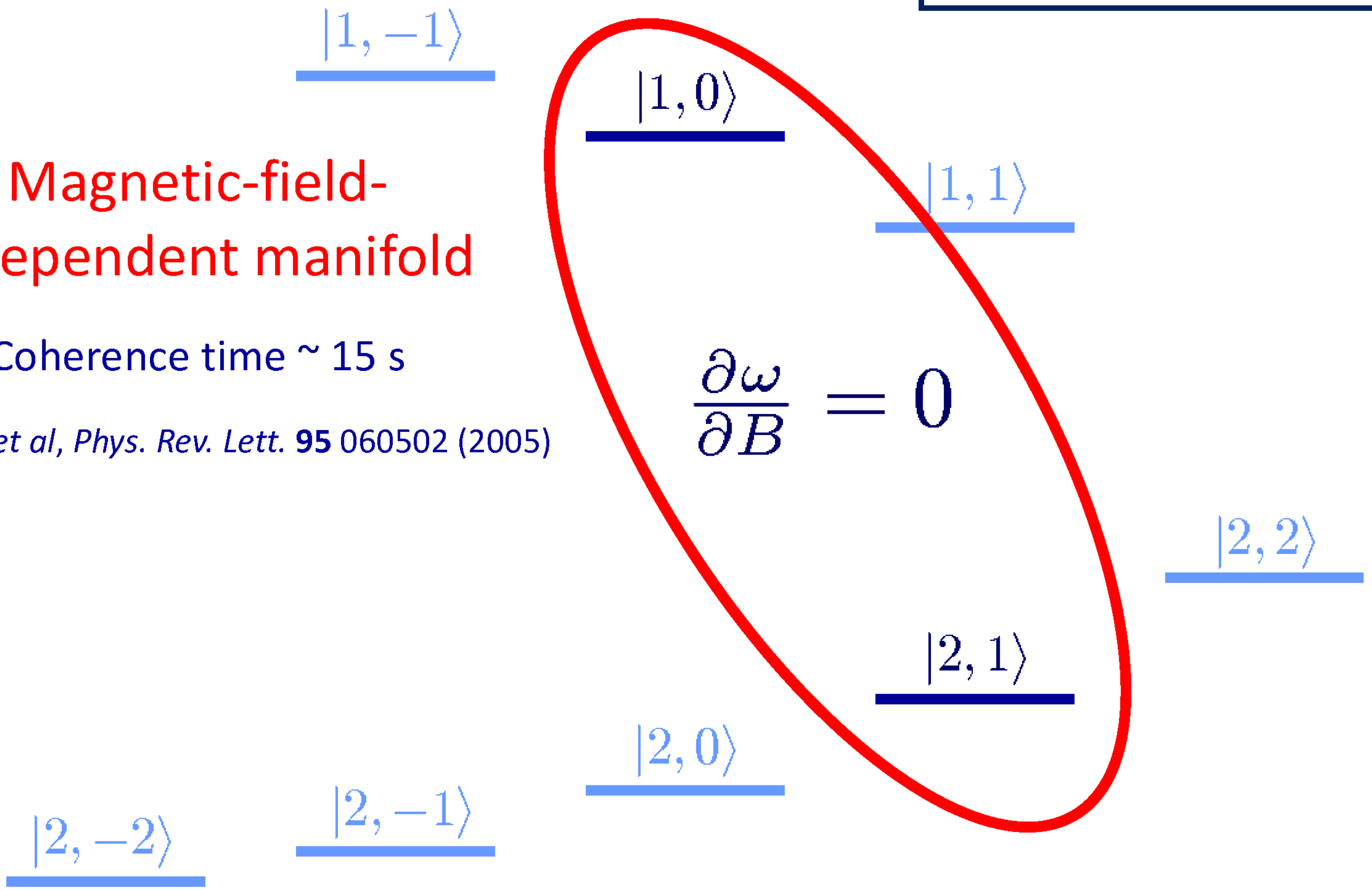
Tool: hybrid qubit system

qubit for memory,
transport, rotations

Magnetic-field-
independent manifold

Coherence time ~ 15 s

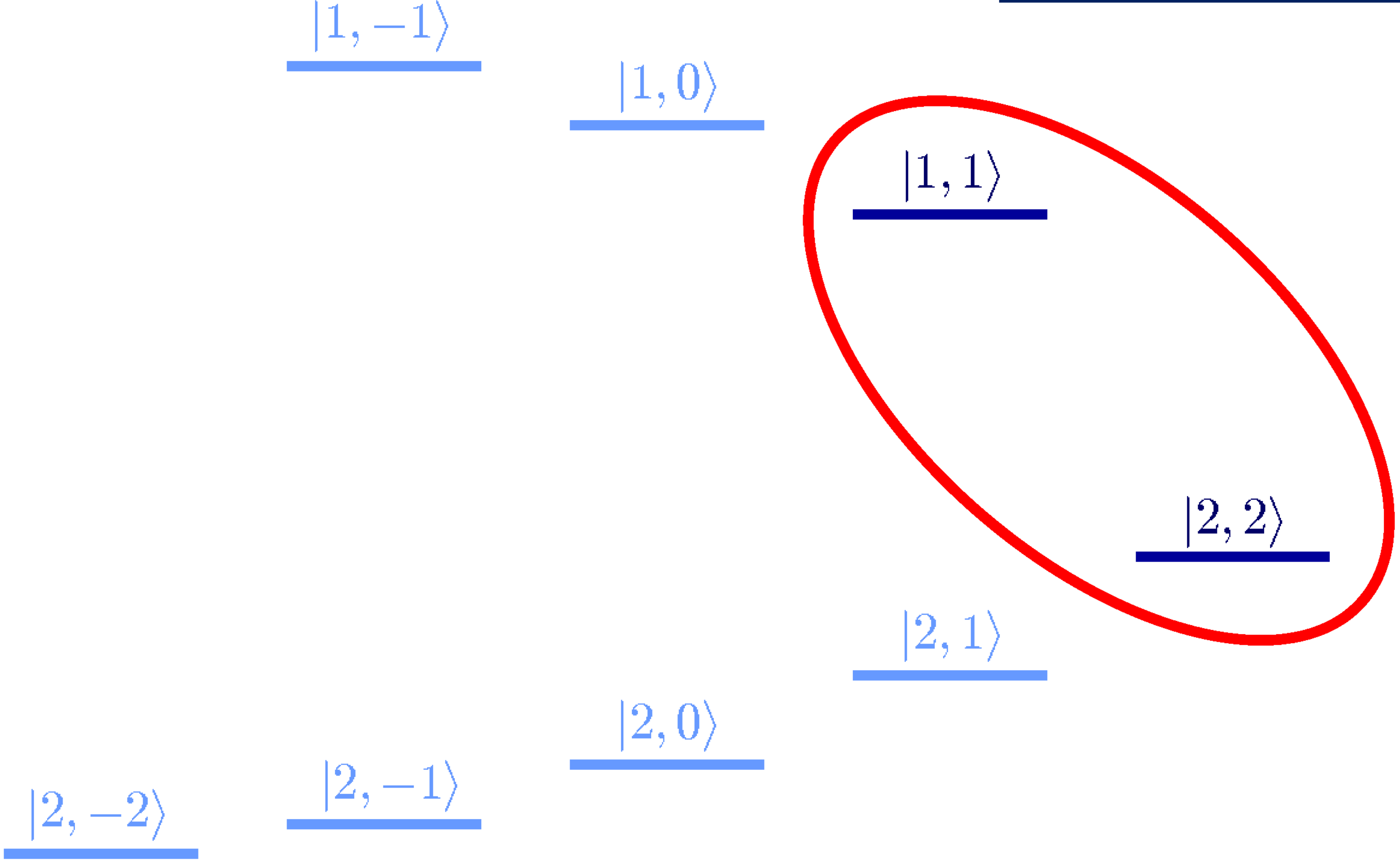
C. Langer, *et al*, *Phys. Rev. Lett.* **95** 060502 (2005)



$$\frac{\partial \omega}{\partial B} = 0$$

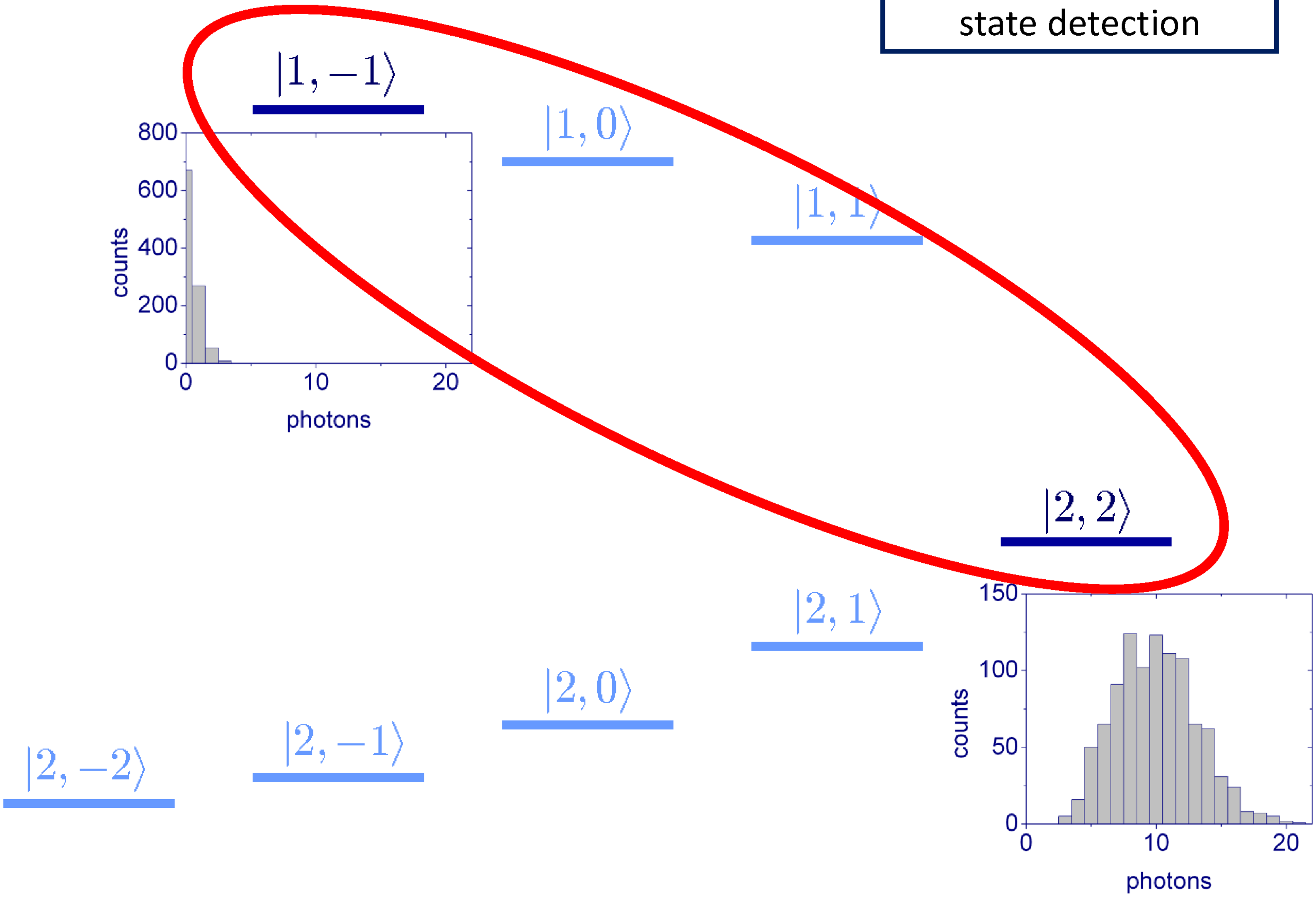
Tool: hybrid qubit system

qubit for
two-qubit gates

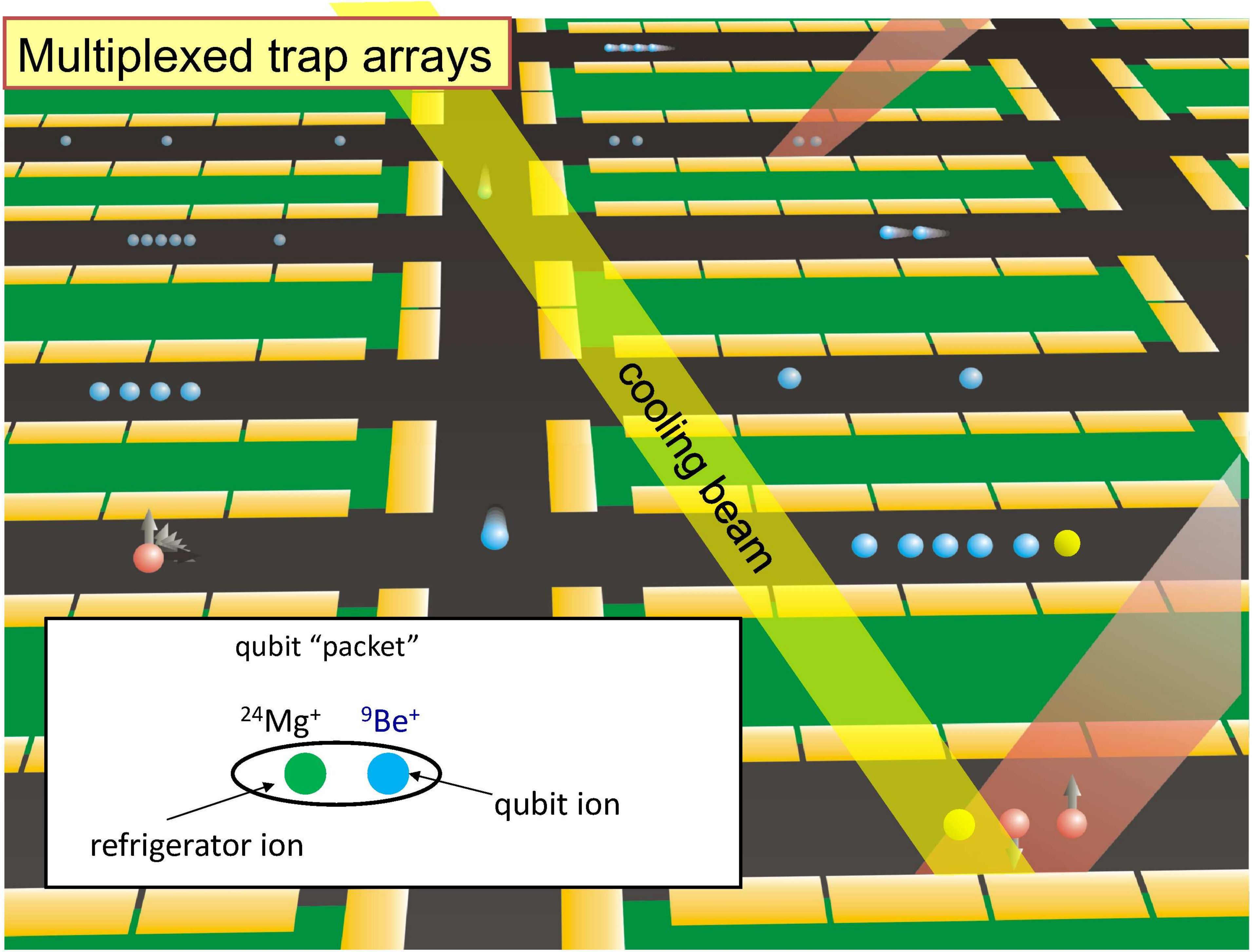


Tool: hybrid qubit system

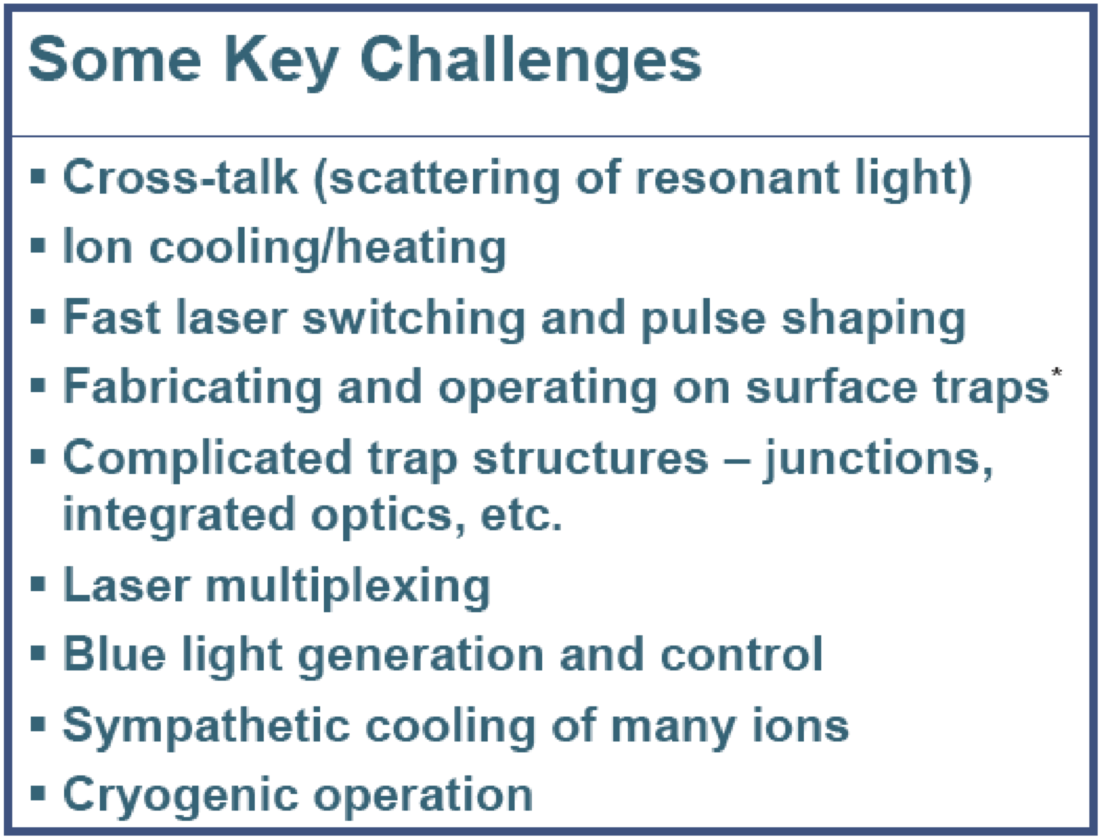
qubit for
state detection



Multiplexed trap arrays



Trapped ion challenges



Some Key Challenges

- Cross-talk (scattering of resonant light)
- Ion cooling/heating
- Fast laser switching and pulse shaping
- Fabricating and operating on surface traps*
- Complicated trap structures – junctions, integrated optics, etc.
- Laser multiplexing
- Blue light generation and control
- Sympathetic cooling of many ions
- Cryogenic operation

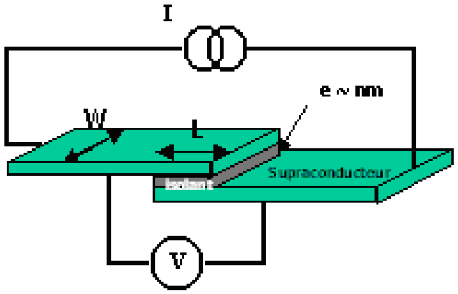
A BRIEF SURVEY OF IMPLEMENTATIONS

Some notable superconducting (SC) qubit research groups…

- Yale
- UC Santa Barbara
- Delft (Netherlands)
- NEC (Japan)
- CEA-Saclay (France)
- ENS Paris (France)
- IQC*
- …

*A. Lupascu's new research group

A BRIEF SURVEY OF IMPLEMENTATIONS



3 types of qubit formed from Josephson junctions:

- phase
- flux

$$\left.\begin{matrix}\text{phase}\\ \text{flux}\end{matrix}\right\} E_J >> E_C$$

E_J = Josephson energy

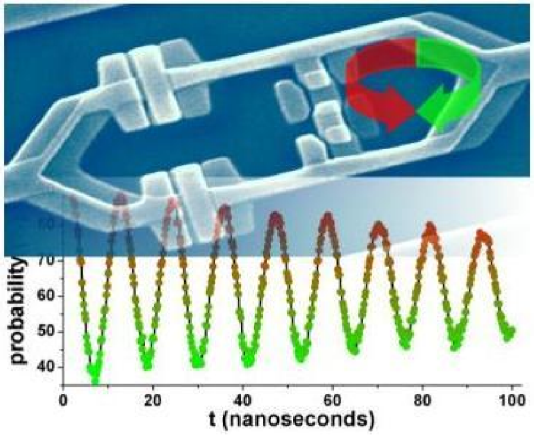
E_C = charging energy

- charge $E_C >> E_J$

Total energy of a Junction:

$$E = E_C(N_C - N_g)^2 - E_J\cos(\phi)$$

Flux qubit



$$H = \frac{-\varepsilon}{2}\sigma_z + \frac{\Delta}{2}\sigma_x$$

DC or RF single qubit control

‘quantronium’ and ‘transmon’ qubits = hybrid charge/phase (Saclay, Yale)

basics, see: “Superconducting qubits”, A. Zagoskin, A. Blais, arXiv: 0805.0164

Coupling two ‘transmon’ qubits via a cavity ‘bus’ (circuit QED)

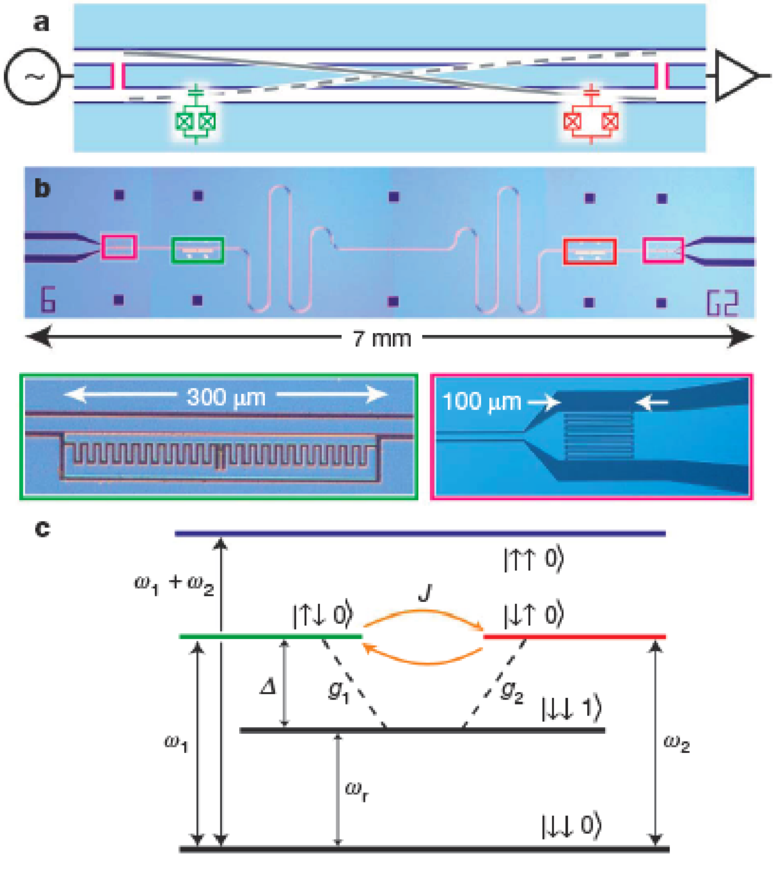
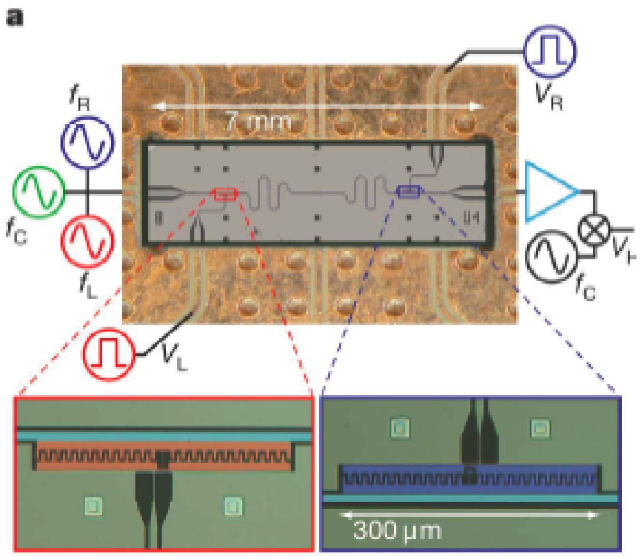


Figure 1 | Sample and scheme used to couple two qubits to an on-chip microwave cavity. Circuit (**a**) and optical micrograph (**b**) of the chip with two

J. Majer et al, *Nature* **449**, 443 (2007)

2-qubit Grover with c-QED coupled transmon qubits



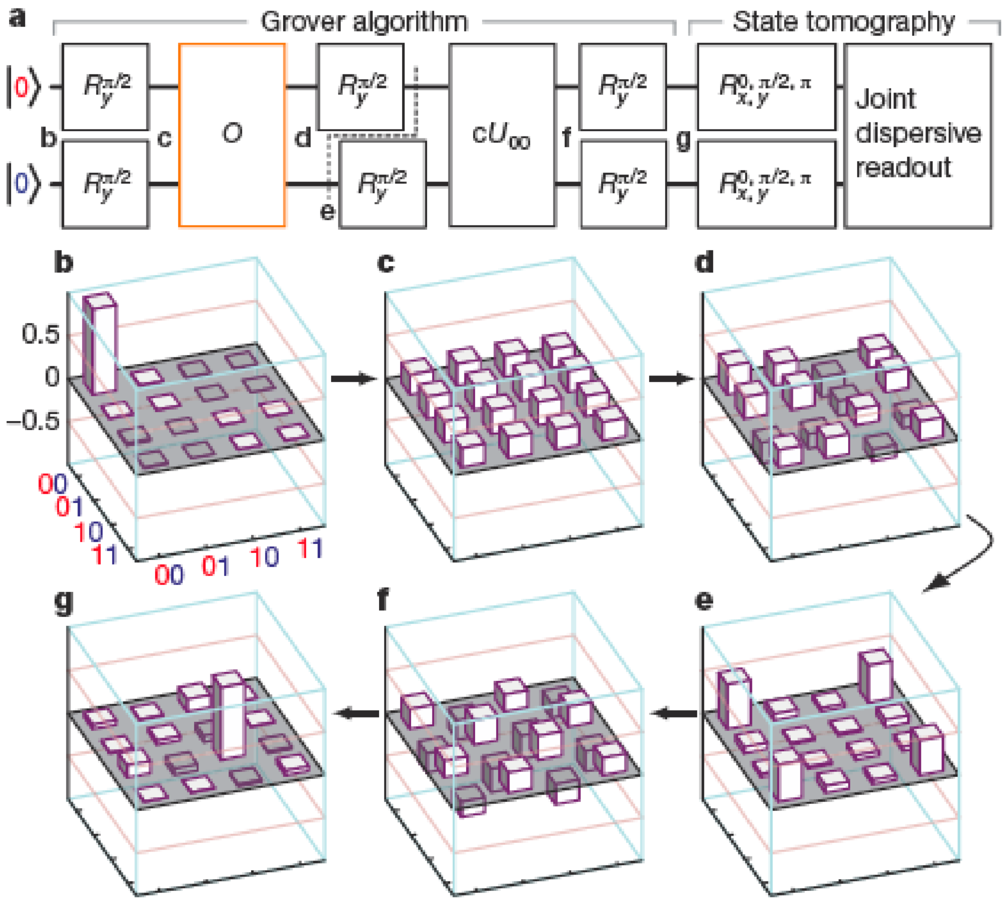
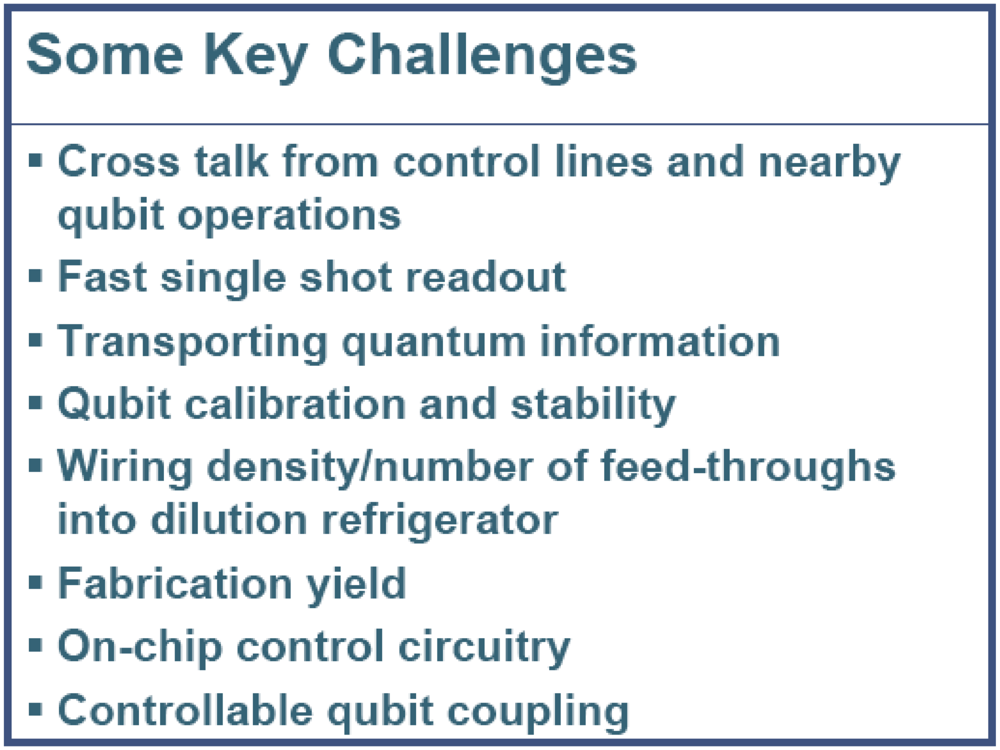


Figure 4 | Implementation of Grover's search algorithm. a, Concatenation

Fidelities ~ 80%; error completely due to relaxation (T_1)

L. DiCarlo et al, *Nature* **460**, 240 (2009)

Challenges for SC qubits



Some Key Challenges

- Cross talk from control lines and nearby qubit operations
- Fast single shot readout
- Transporting quantum information
- Qubit calibration and stability
- Wiring density/number of feed-throughs into dilution refrigerator
- Fabrication yield
- On-chip control circuitry
- Controllable qubit coupling

Increase T_1 & T_2;
essentially a materials problem
(charge defects in tunnel
barriers?)

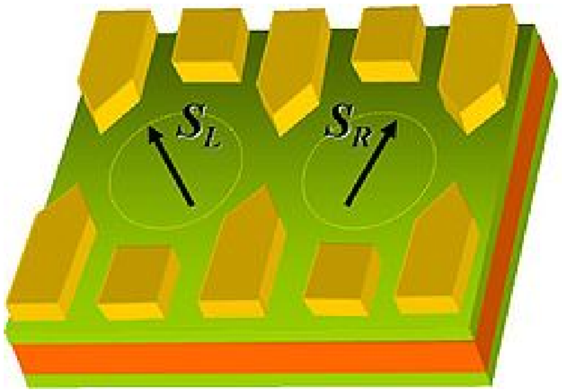
A BRIEF SURVEY OF IMPLEMENTATIONS

Some notable quantum dot / spin-qubit research groups…

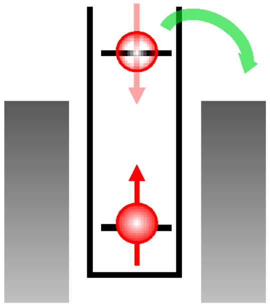
- Harvard
- Delft (Netherlands)
- U. Tokyo (Japan)
- ETH Zurich (Switzerland)
- Lund (Sweden)
- Wisconsin
- Michigan
- NRC Ottawa
- Sherbrooke
- UBC
- IQC*
- …

*My new research group

Loss-Divincenzo QD spin-qubit proposal (1997)

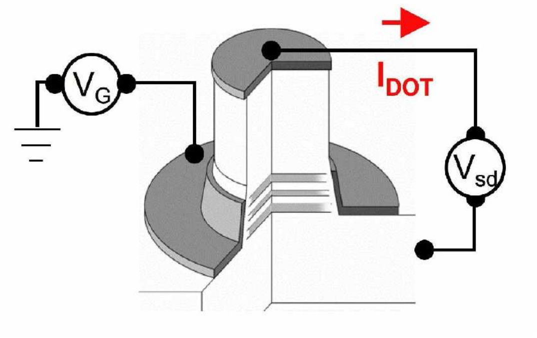


- Array of singly charged QDs (e.g. 2-D electron gas structure)
- Single electron spin resonance → single qubit gates
- Gate-controlled n. n. exchange interaction → two-qubit gates $J(V_g)\vec{S}_1 \bullet \vec{S}_2$
- Spin-dependent tunneling readout
- Low temp / magnetic field → initialization $\hbar\omega_{Zeeman} >> kT$

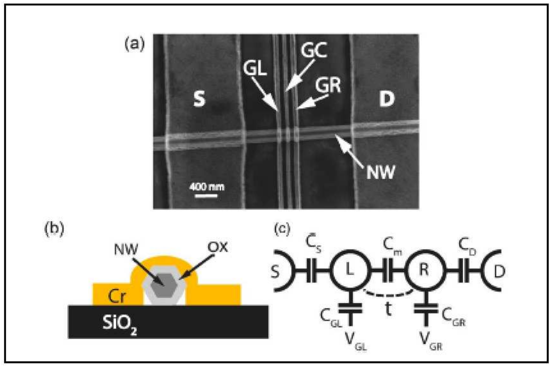


Solid-state, builds on semiconductor fabrication technologies; Quantum confinement suppresses spin-orbit relaxation → millisecond T_1's (compared to *ps*, *ns* gate ops)

Few-electron quantum dots

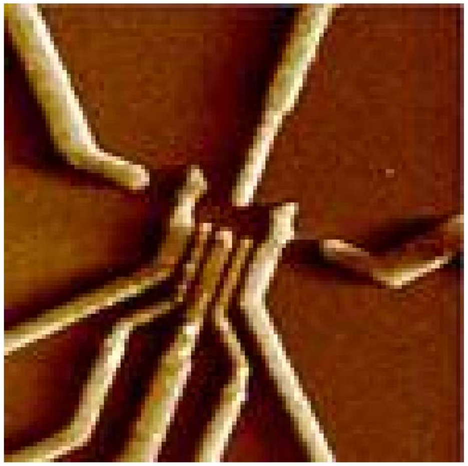


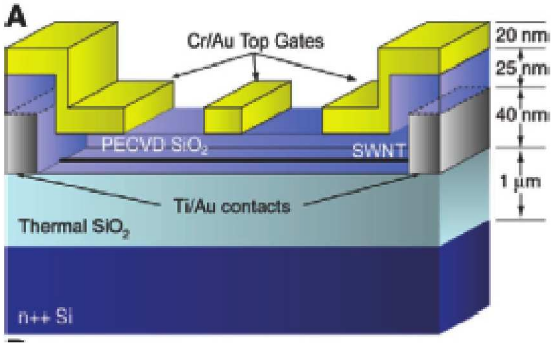
Vertical devices (Japan)



Gated 2DEGs (Harvard, Delft, NRC, ETH,…)

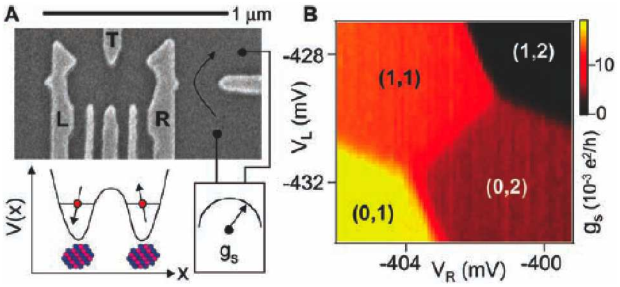
nanowire devices (Lund, ETH)



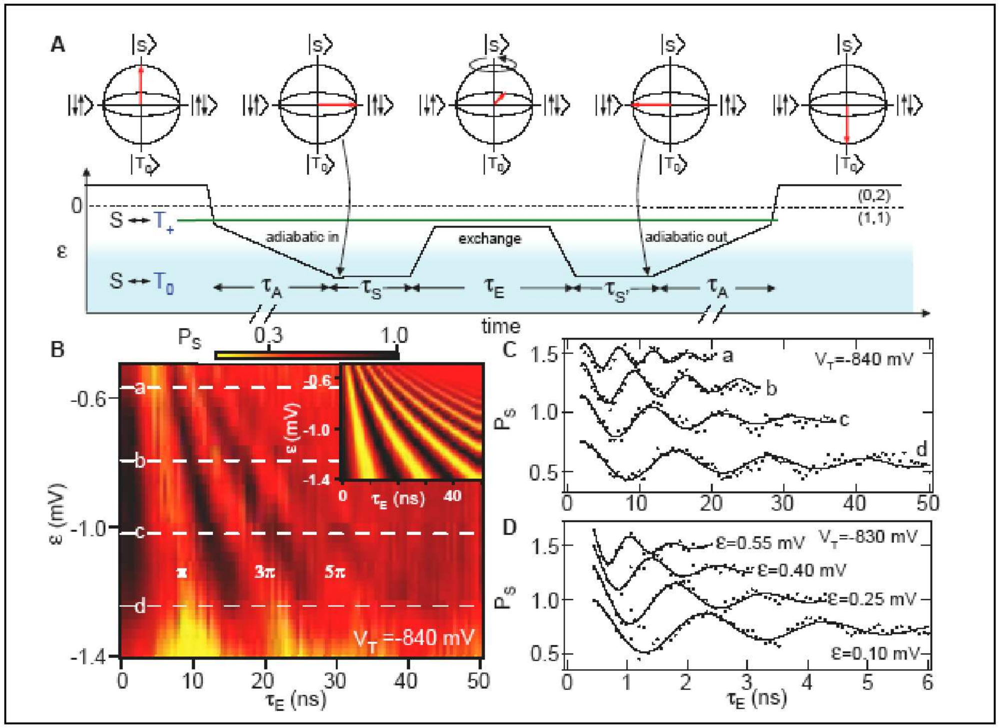


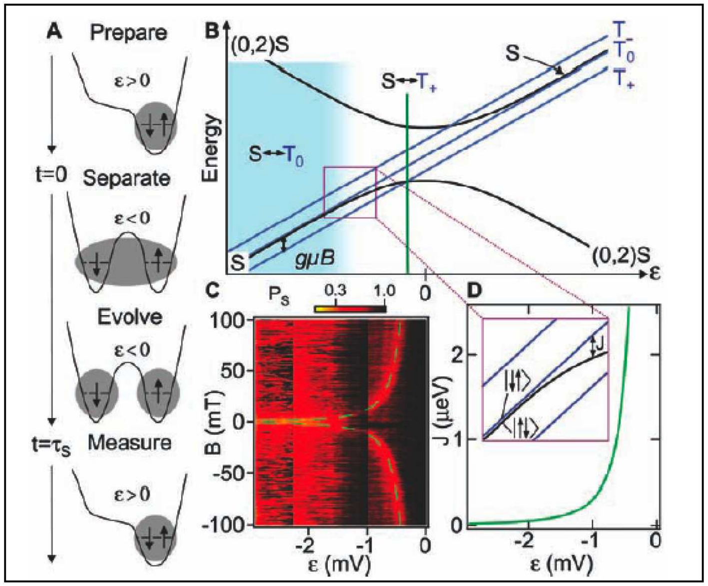
carbon nanotube devices (Harvard)

Coherent control of the exchange interaction



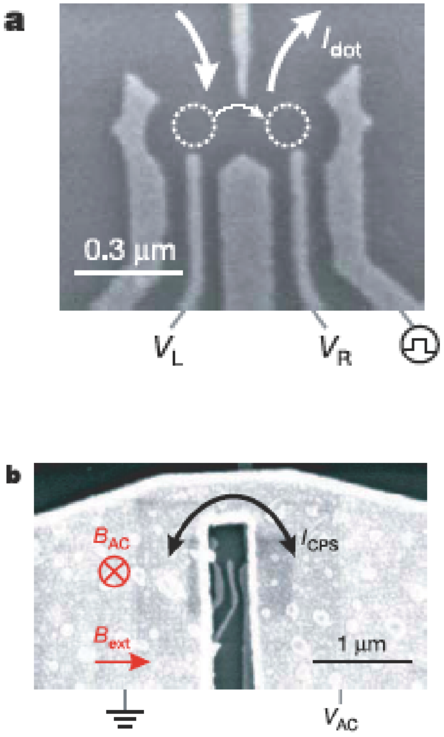
$$\sqrt{SWAP} \sim 180\,ps$$

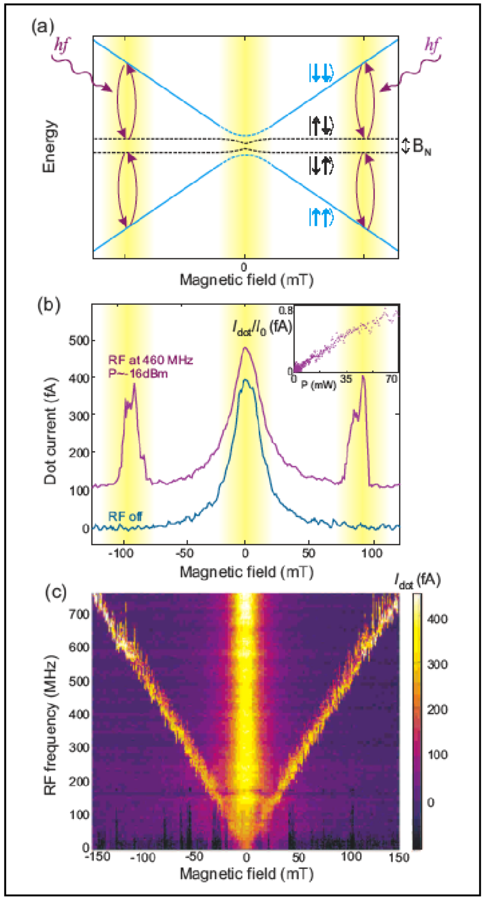


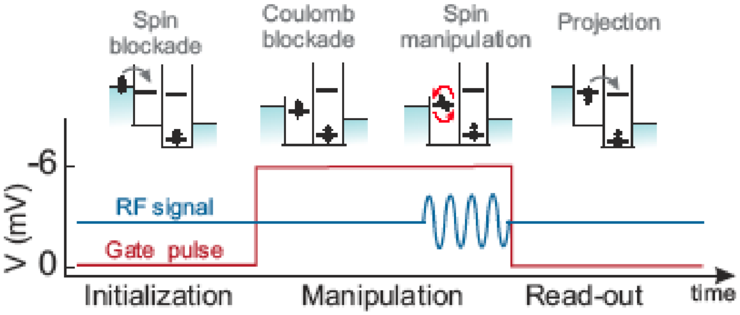


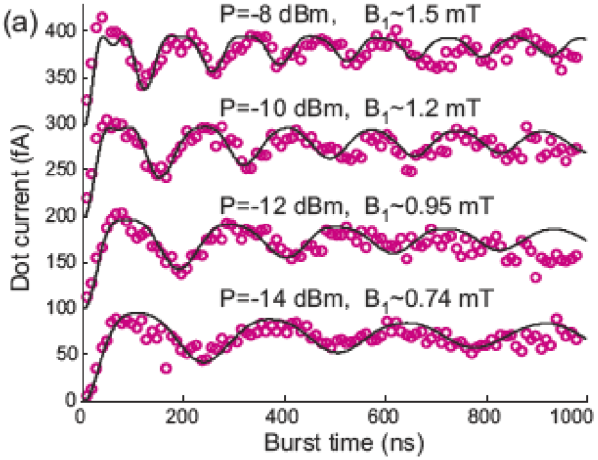
J. R. Petta et al, *Science* **309**, 2180 (2005)

Single electron spin resonance (Delft)



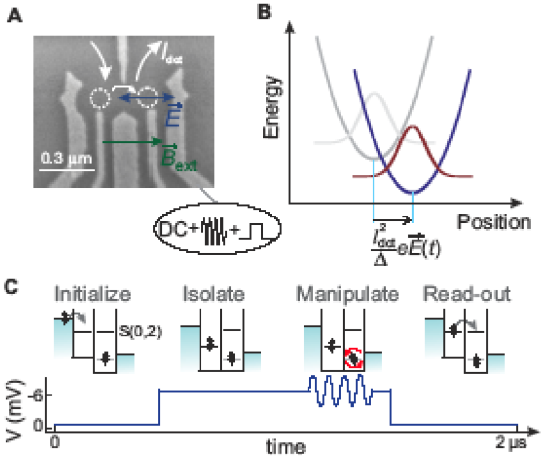


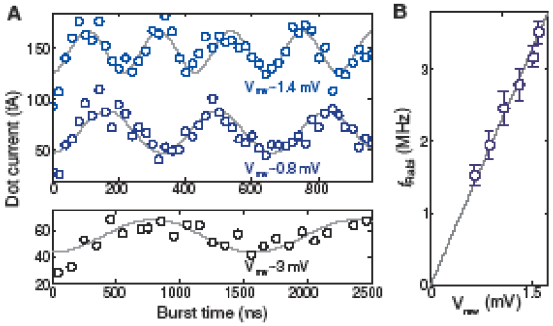


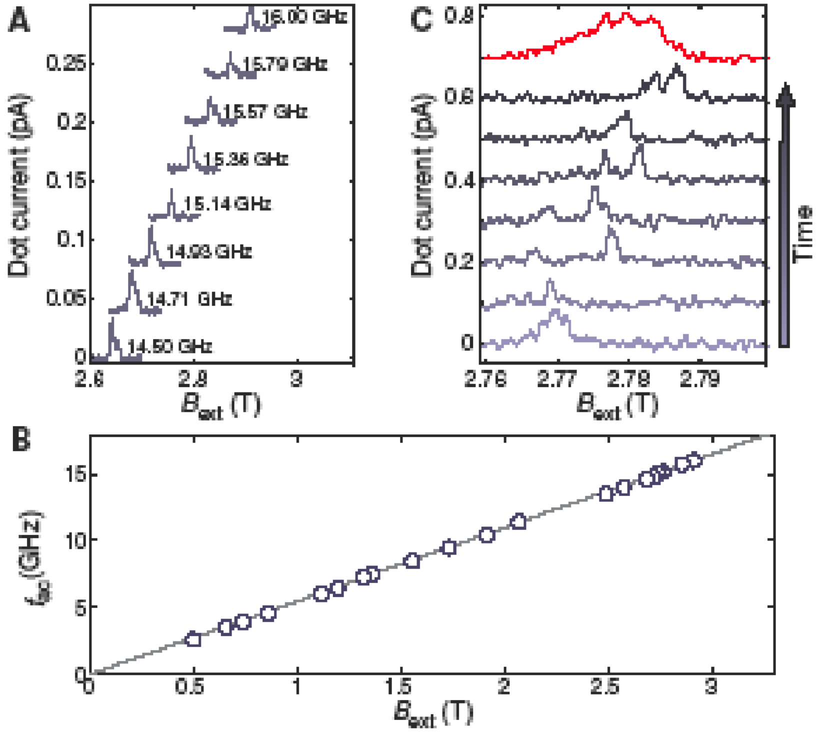


F. H. L. Koppens et al, *Nature* **446**, 766 (2006)

Single electron *electric dipole* spin resonance (Delft)

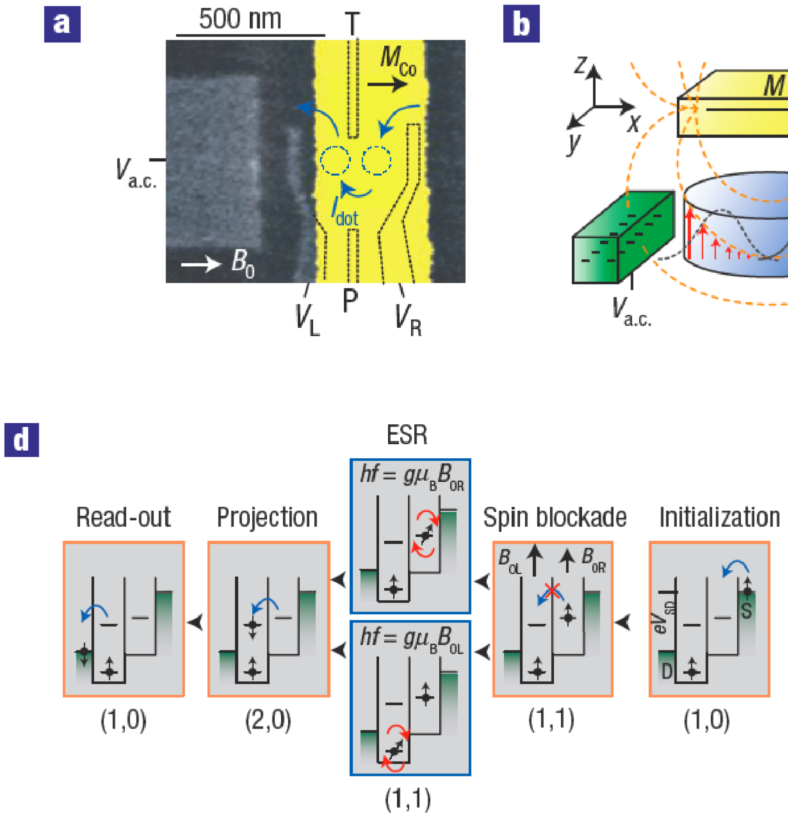


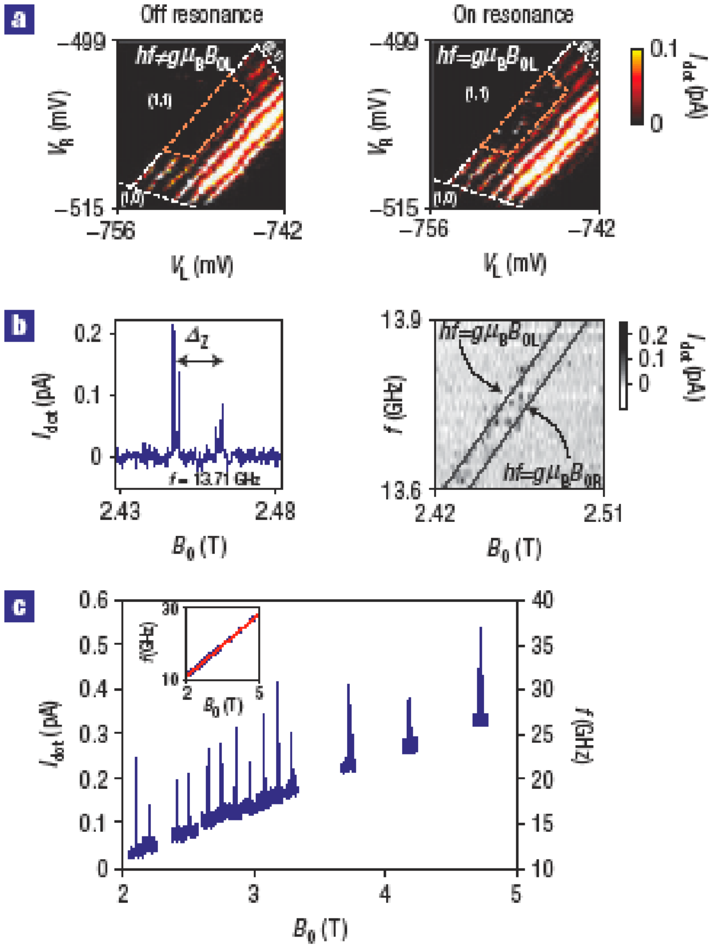




K. C. Nowack et al, *Science* **318**, 1430(2007)

Electric dipole spin resonance with a micromagnet (ICORP-Japan)

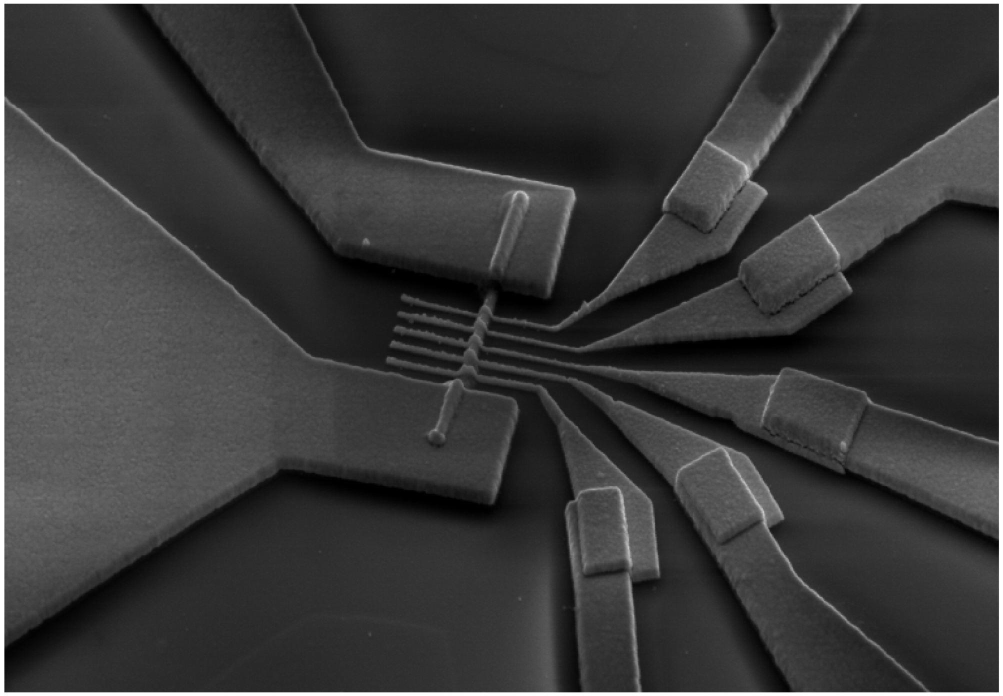




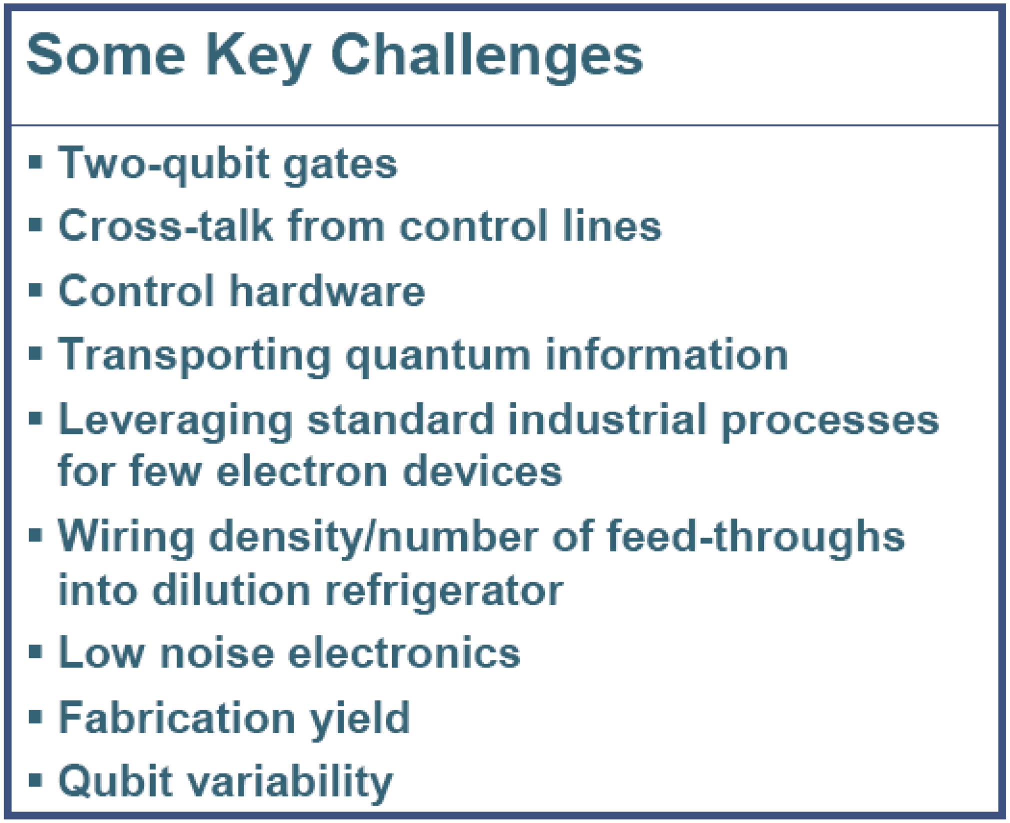
M. Pioro-Ladriere et al, *Nat. Phys.* **4**, 776 (2008)

A BRIEF SURVEY OF IMPLEMENTATIONS

Nanowire-based gate-defined quantum dot device recently fabricated in my group @ Waterloo…



Challenges for QD spin qubits



Some Key Challenges

- Two-qubit gates
- Cross-talk from control lines
- Control hardware
- Transporting quantum information
- Leveraging standard industrial processes for few electron devices
- Wiring density/number of feed-throughs into dilution refrigerator
- Low noise electronics
- Fabrication yield
- Qubit variability

Controlling nuclear spin induced decoherence (III-V semiconductors, which are nice electronically), or developing nuclear spin-free devices (CNT, graphene, Si, etc)

The latter are more challenging in terms of well-defined spin-qubits and electronic gating, etc.

THE END!

Many useful QI-related tutorials (some on implementations) can be found here:
https://www.iqc.ca/publications/tutorials.php

Further questions: baugh@iqc.ca