Quantum computing hardware

aka Experimental Aspects of Quantum Computation

PHYS 576

Class format

1st hour: introduction by BB

2nd and 3rd hour: two student presentations,
about 40 minutes each
followed by discussions

Coffee break(s) in between

What you do:

- Choose a topic
- Research literature
- Put together title and the abstract
- Prepare and give a talk

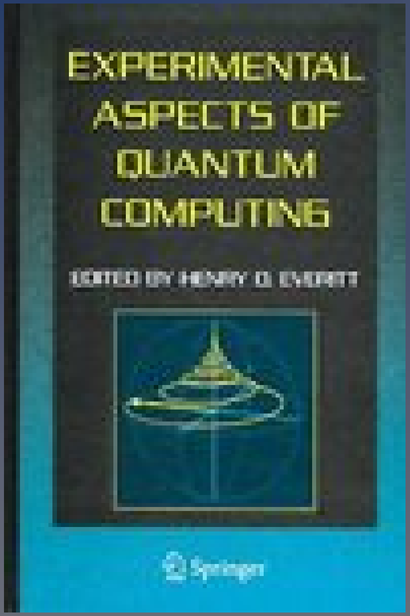
Hopefully, by the third half of today's class
a few of you can decide on the topic and sign up.

Workshops themes (generic)

1. ~~**NMR** (quantum computer in a vial)~~
2. **Ion Trap** ("vacuum tubes")
3. **Neutral Atom** (catching up)
4. **Cavity QED** (0.01 atoms interacting with 0.01 photons)
5. **Optical** (fiber… and more fiber)
6. **Solid State** (what real computers are made of)
7. **Superconducting** (the cool)
8. **"Unique"** (really crazy stuff)

Class schedule

January 5	Introduction
January 12	Short class (1 hour)
January 19	Workshop 1 SC
January 26	Workshop 2 SC
February 2	Workshop 3
February 9	Workshop 4
February 16	No Class (SQuInT meeting)
February 23	Workshop 5
March 2	Workshop 6
March 9	Workshop 7



EXPERIMENTAL
ASPECTS OF
QUANTUM
COMPUTING

EDITED BY HENRY O. EVERITT

Springer

Reprinted from
Quantum Information Processing 3 (2004).

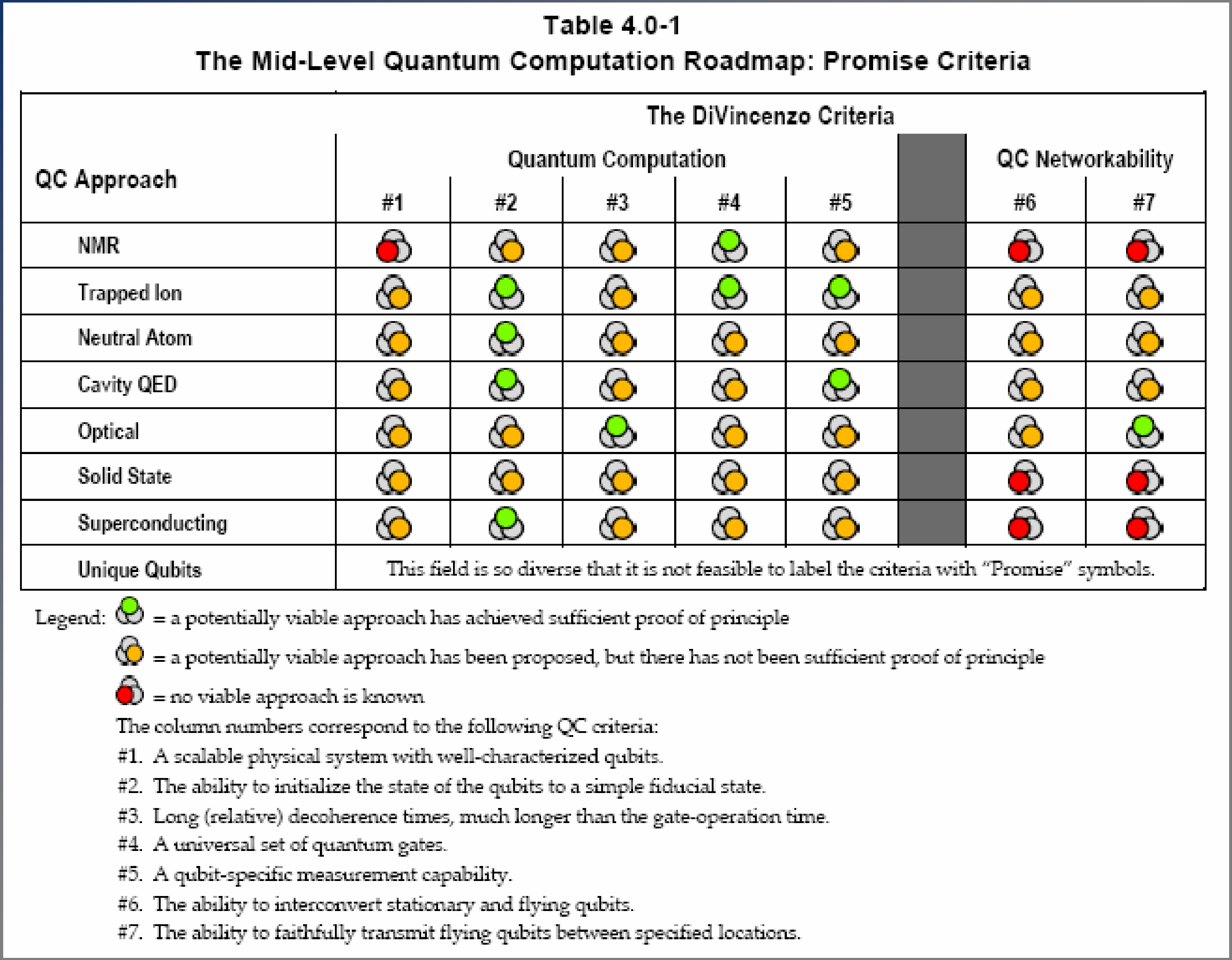


Table 4.0-1
The Mid-Level Quantum Computation Roadmap: Promise Criteria

QC Approach	The DiVincenzo Criteria						
	Quantum Computation					QC Networkability	
	#1	#2	#3	#4	#5	#6	#7
NMR	🔴	🟡	🟡	🟢	🟡	🔴	🔴
Trapped Ion	🟡	🟢	🟡	🟢	🟢	🟡	🟡
Neutral Atom	🟡	🟢	🟡	🟡	🟡	🟡	🟡
Cavity QED	🟡	🟢	🟡	🟡	🟢	🟡	🟡
Optical	🟡	🟡	🟢	🟡	🟡	🟡	🟢
Solid State	🟡	🟡	🟡	🟡	🟡	🔴	🔴
Superconducting	🟡	🟢	🟡	🟡	🟡	🔴	🔴
Unique Qubits	This field is so diverse that it is not feasible to label the criteria with "Promise" symbols.						

Legend: 🟢 = a potentially viable approach has achieved sufficient proof of principle

🟡 = a potentially viable approach has been proposed, but there has not been sufficient proof of principle

🔴 = no viable approach is known

The column numbers correspond to the following QC criteria:

#1. A scalable physical system with well-characterized qubits.
#2. The ability to initialize the state of the qubits to a simple fiducial state.
#3. Long (relative) decoherence times, much longer than the gate-operation time.
#4. A universal set of quantum gates.
#5. A qubit-specific measurement capability.
#6. The ability to interconvert stationary and flying qubits.
#7. The ability to faithfully transmit flying qubits between specified locations.

http://qist.lanl.gov/qcomp_map.shtml

"Approaches"

NMR (obsolete?) – David Cory, Ike Chuang (MIT)

Ion Trap – David Wineland (NIST), Chris Monroe (Michigan), Rainer Blatt (Innsbruck), …

Neutral Atom – Phillipe Grangier (Orsay), Poul Jessen (Arizona)

Cavity QED – Jeff Kimble (Caltech), Michael Chapman (GATech)

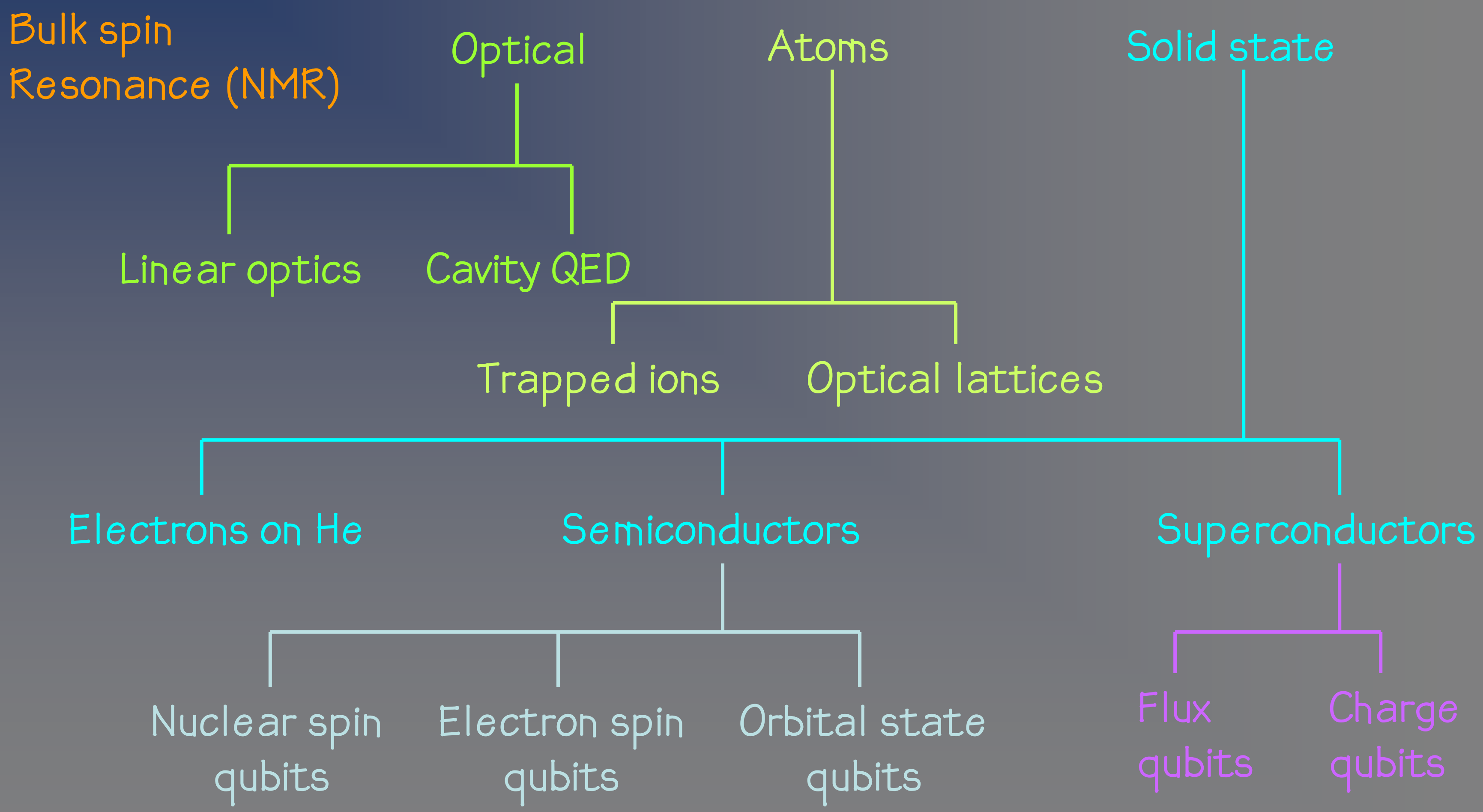
Optical – Paul Kwiat (Illinois)

Solid State – too many to mention a few? David Awschalom (UCSB), Duncan Steel (Michigan)

Superconducting – Michel Devoret (Yale), John Martinis (UCSB)

"Unique" – Phil Platzman (Bell Labs)

QC implementation proposals



Bulk spin
Resonance (NMR)

Optical

Linear optics

Cavity QED

Atoms

Trapped ions

Optical lattices

Solid state

Electrons on He

Semiconductors

Nuclear spin
qubits

Electron spin
qubits

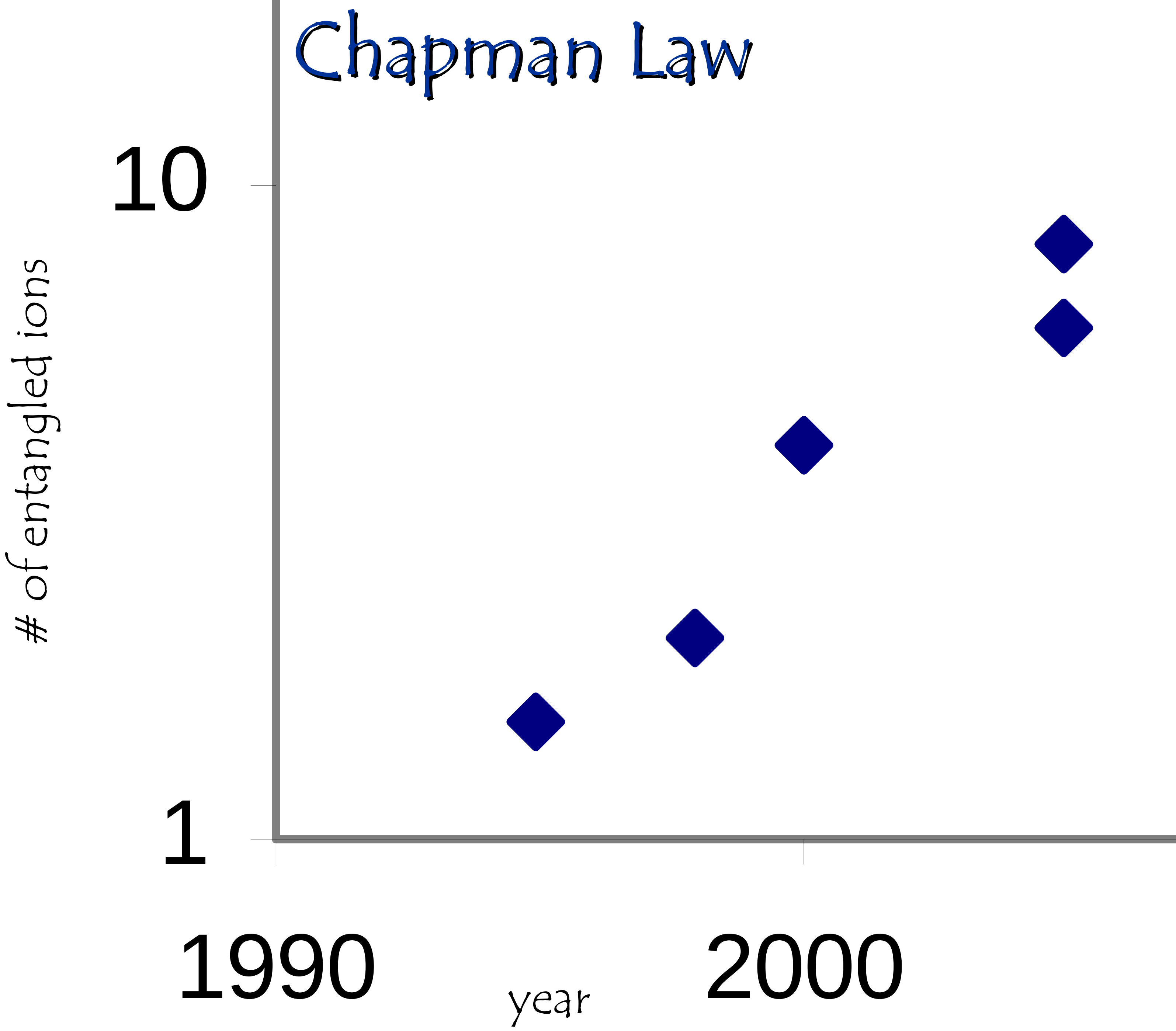
Orbital state
qubits

Superconductors

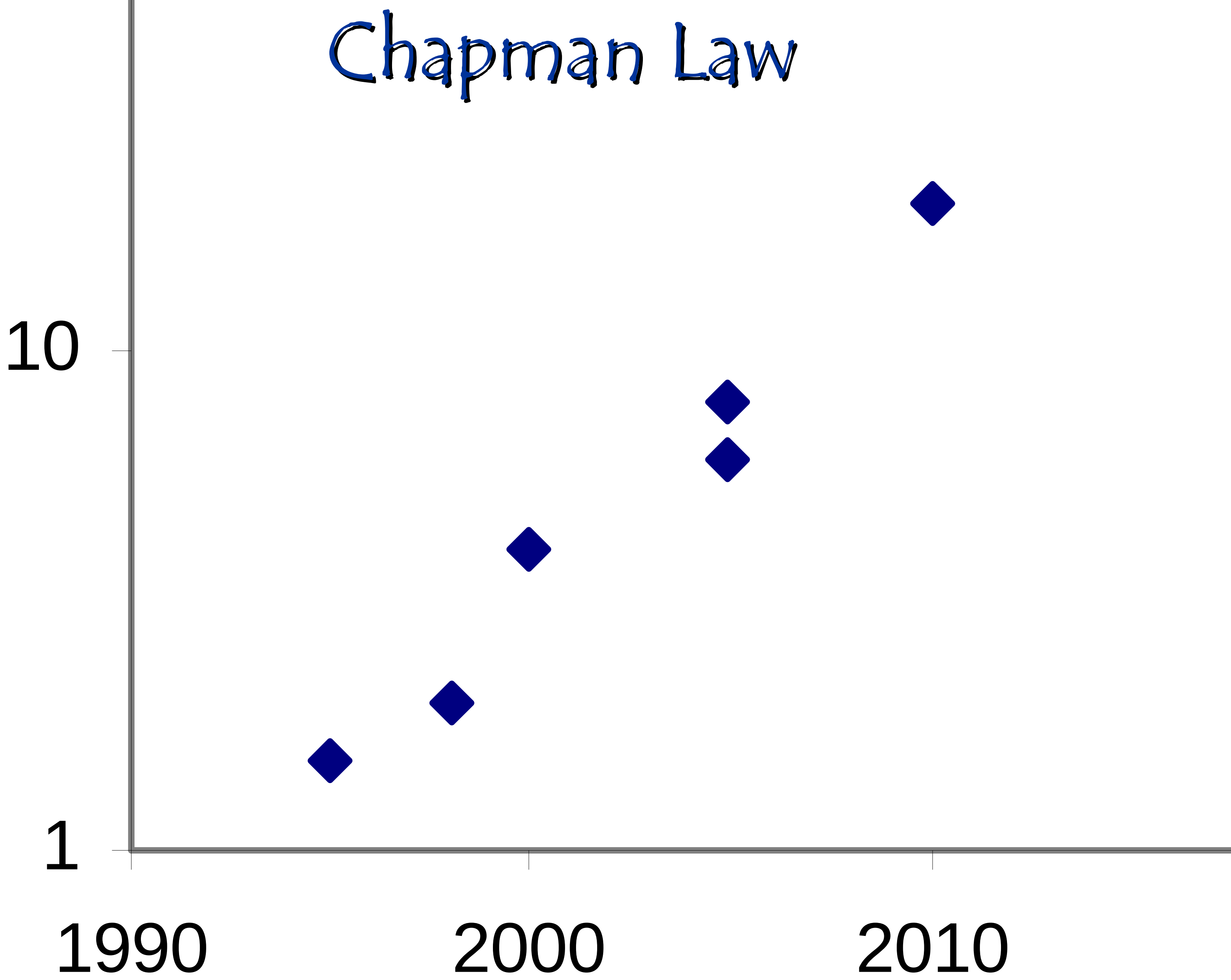
Flux
qubits

Charge
qubits

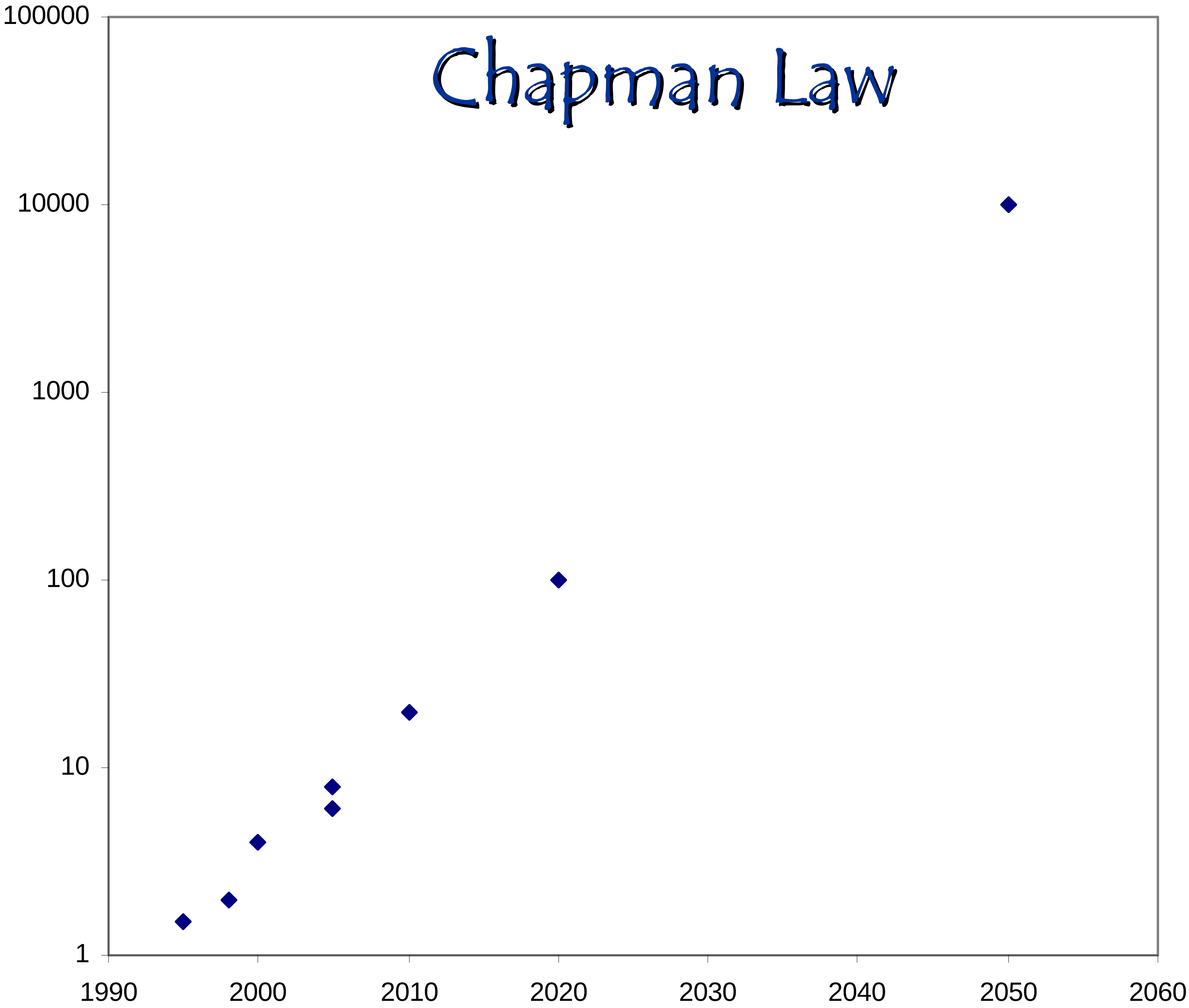
Chapman Law



Chapman Law



Chapman Law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2020
2030
2040
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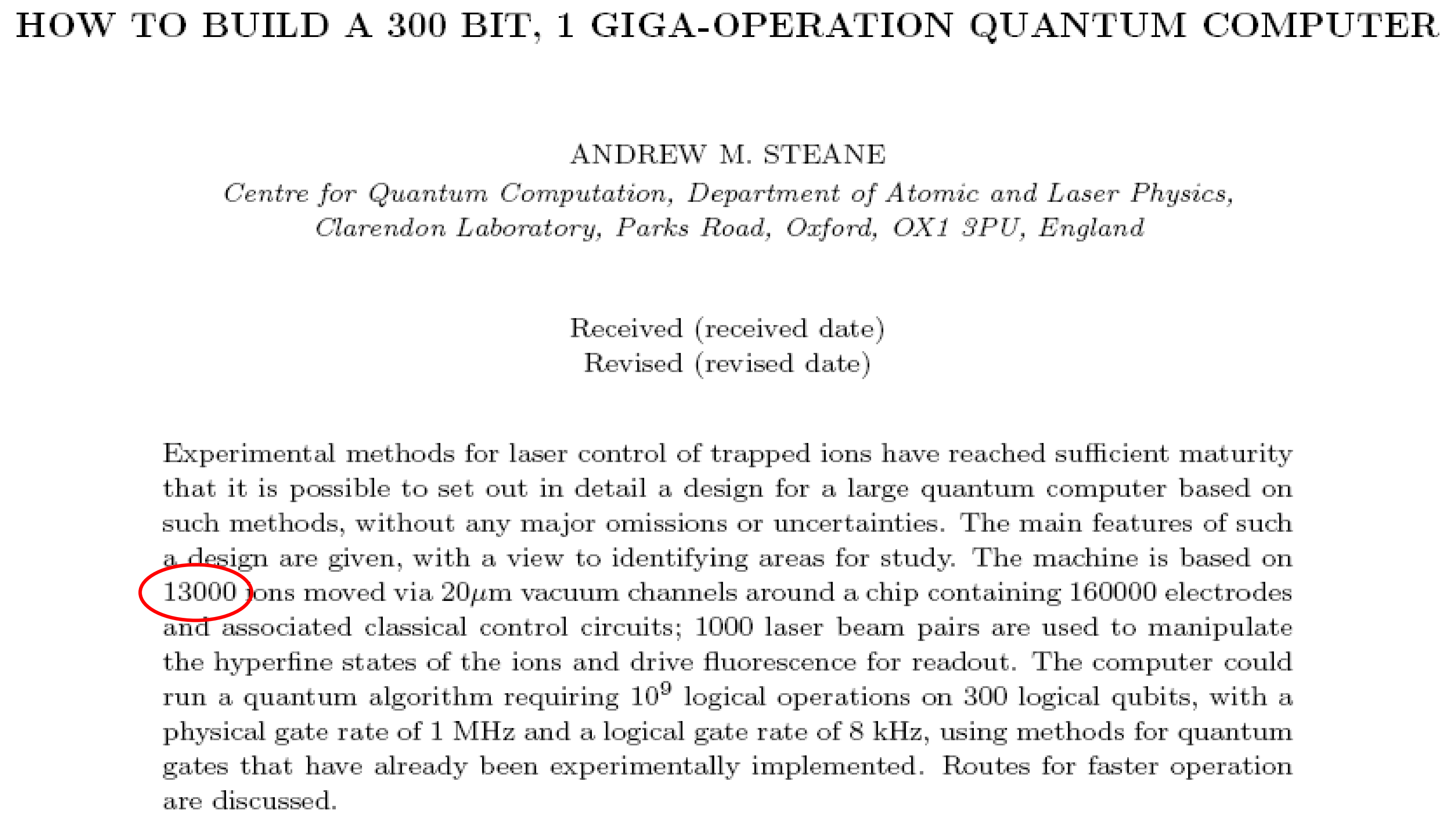
2060



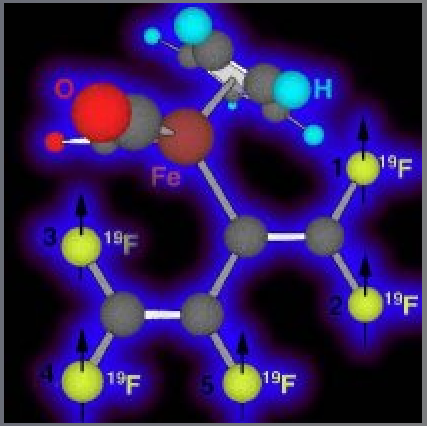
HOW TO BUILD A 300 BIT, 1 GIGA-OPERATION QUANTUM COMPUTER

ANDREW M. STEANE
Centre for Quantum Computation, Department of Atomic and Laser Physics,
Clarendon Laboratory, Parks Road, Oxford, OX1 3PU, England

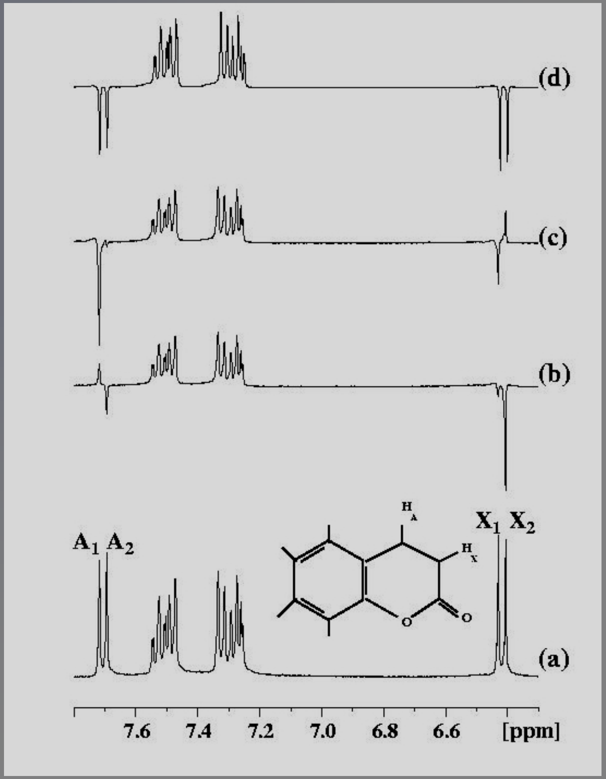
Received (received date)
Revised (revised date)

Experimental methods for laser control of trapped ions have reached sufficient maturity that it is possible to set out in detail a design for a large quantum computer based on such methods, without any major omissions or uncertainties. The main features of such a design are given, with a view to identifying areas for study. The machine is based on 13000 ions moved via 20μm vacuum channels around a chip containing 160000 electrodes and associated classical control circuits; 1000 laser beam pairs are used to manipulate the hyperfine states of the ions and drive fluorescence for readout. The computer could run a quantum algorithm requiring 10^9 logical operations on 300 logical qubits, with a physical gate rate of 1 MHz and a logical gate rate of 8 kHz, using methods for quantum gates that have already been experimentally implemented. Routes for faster operation are discussed.

NMR



http://www.org.chemie.tu-muenchen.de/glaser/NMR.jpg



http://www.physics.iitm.ac.in/~kavita/qc.jpg

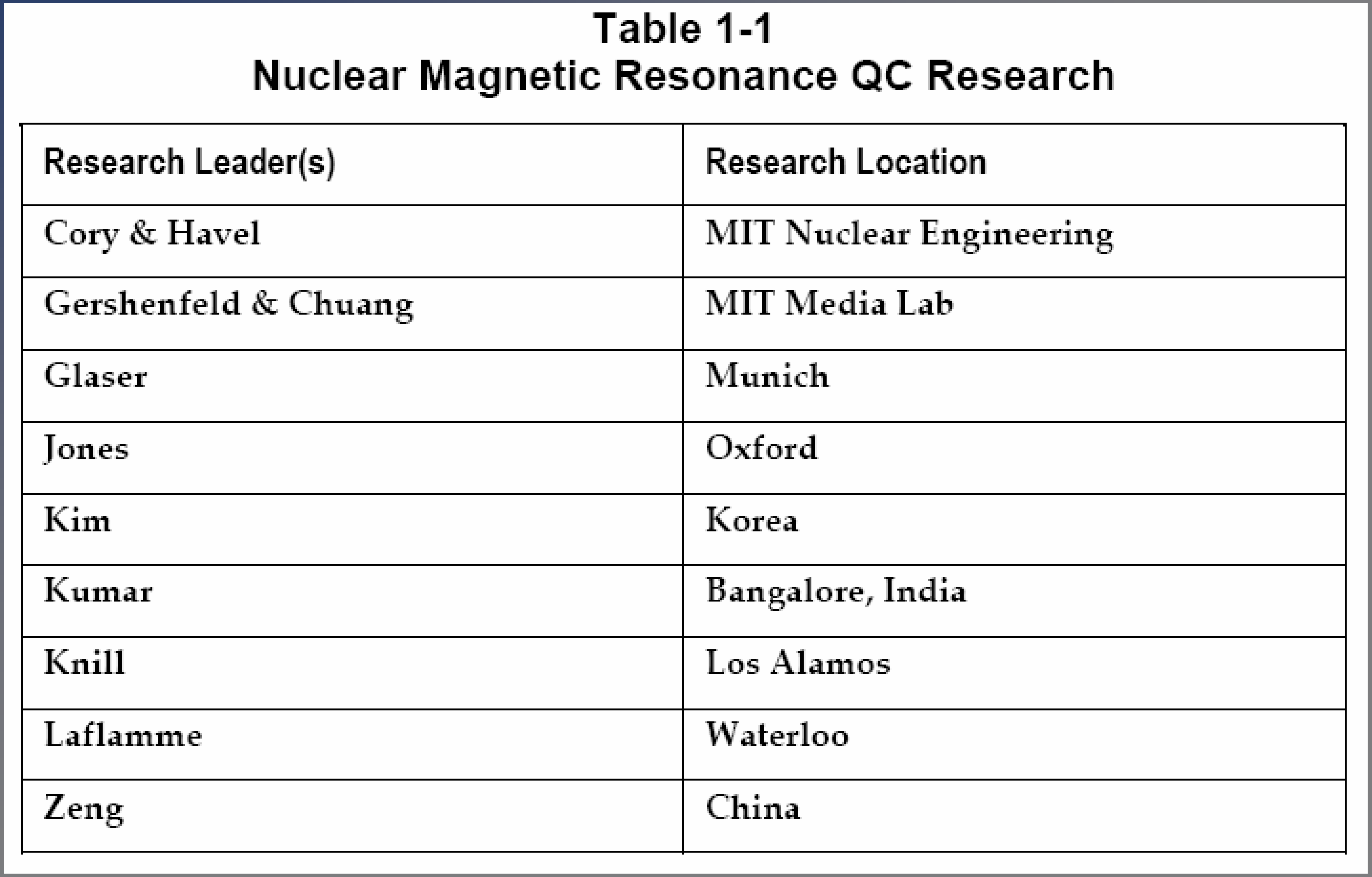


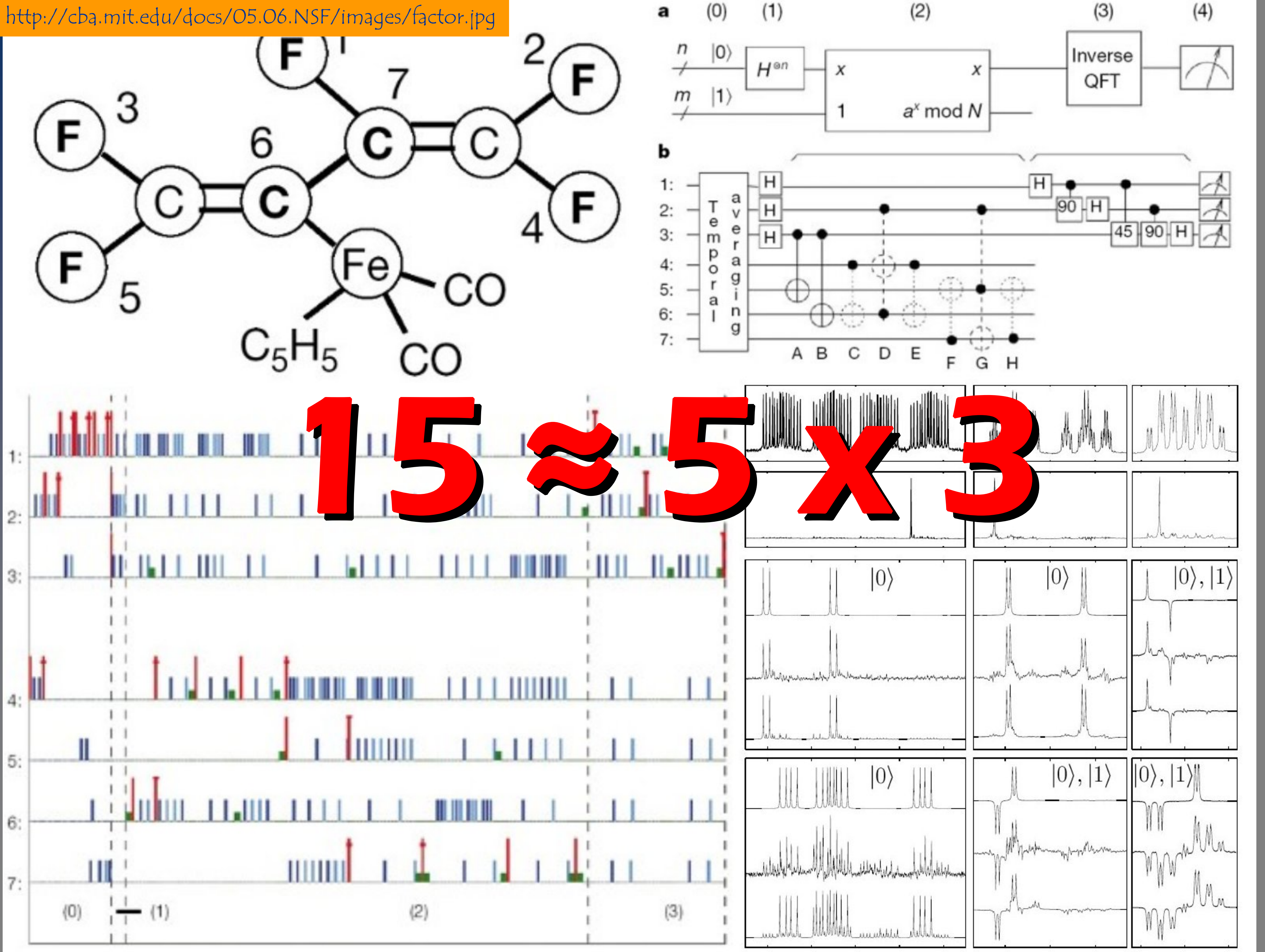
Table 1-1

Nuclear Magnetic Resonance QC Research

Research Leader(s)	Research Location
Cory & Havel	MIT Nuclear Engineering
Gershenfeld & Chuang	MIT Media Lab
Glaser	Munich
Jones	Oxford
Kim	Korea
Kumar	Bangalore, India
Knill	Los Alamos
Laflamme	Waterloo
Zeng	China

http://qist.lanl.gov/qcomp_map.shtml

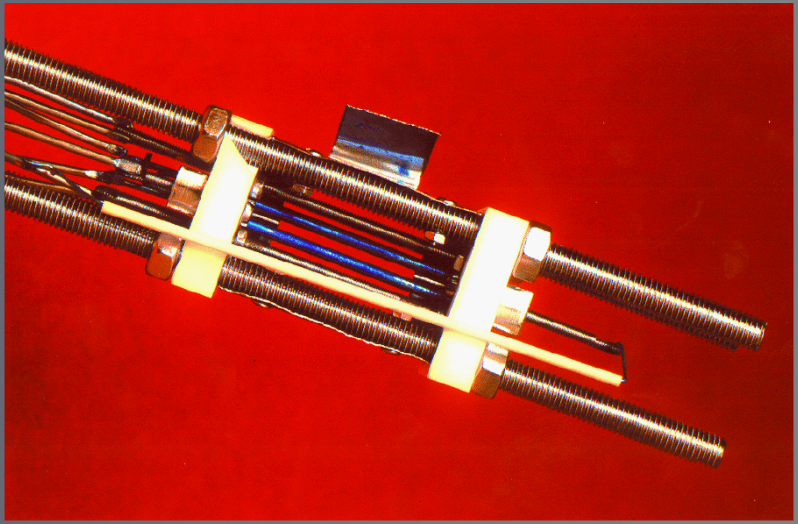
http://cba.mit.edu/docs/05.06.NSF/images/factor.jpg

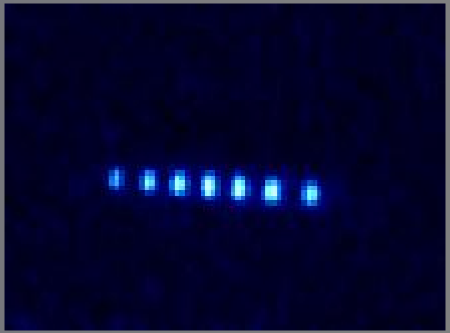


15 ≈ 5 x 3

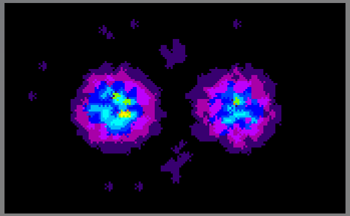
Ion Traps

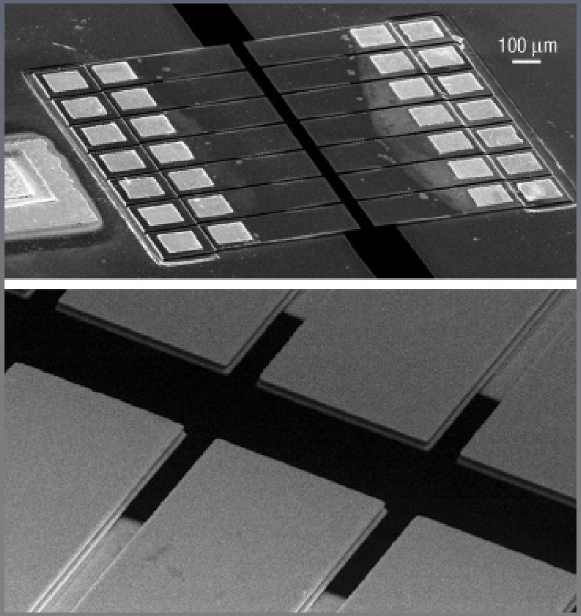
http://nodens.physics.ox.ac.uk/~mcdonnell/wardPres/wardPres.html





http://www.physics.gatech.edu/ultracool/Ions/7ions.jpg





http://www.nature.com/nphys/journal/v2/n1/images/nphys171-f2.jpg

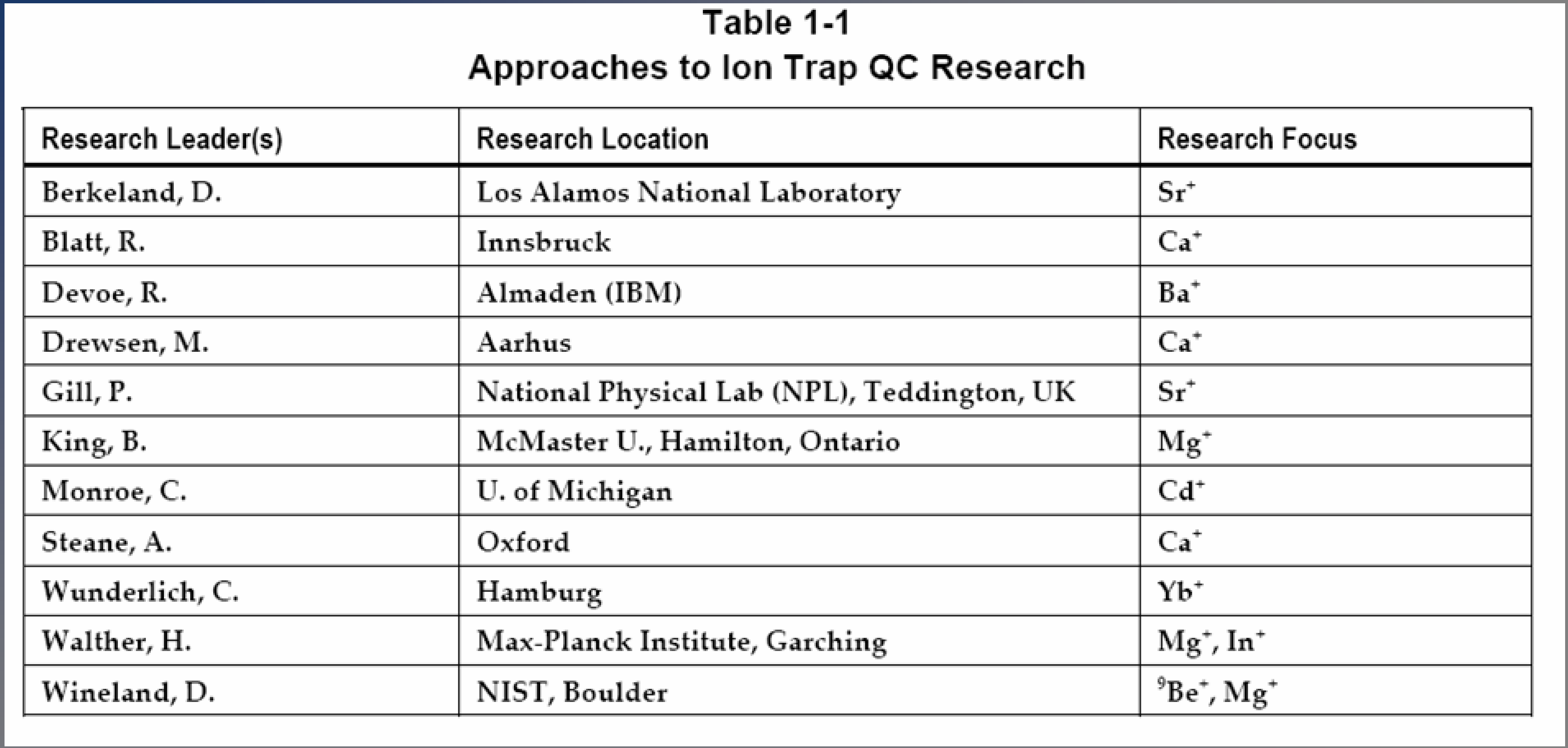
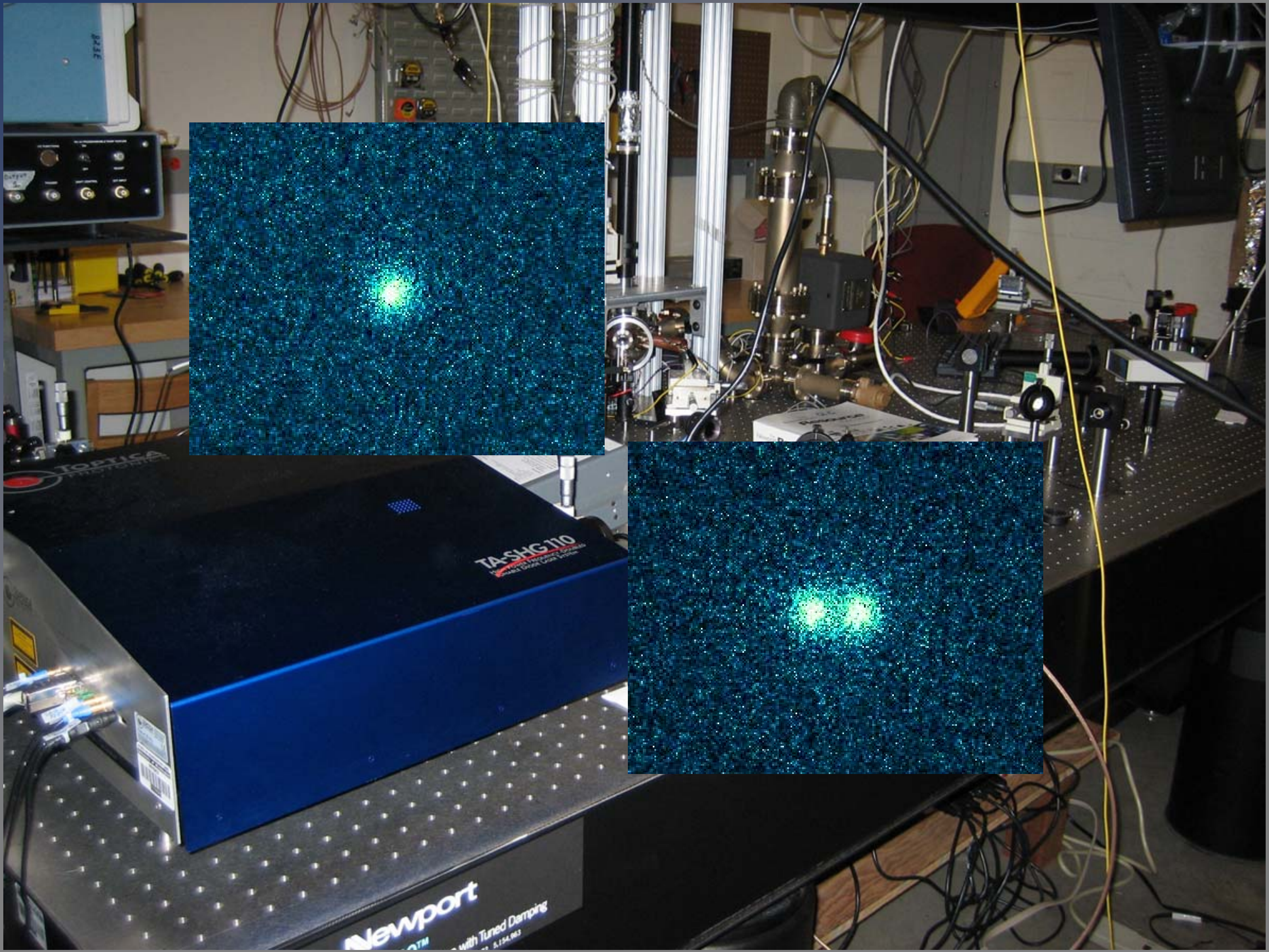


Table 1-1
Approaches to Ion Trap QC Research

Research Leader(s)	Research Location	Research Focus
Berkeland, D.	Los Alamos National Laboratory	Sr$^+$
Blatt, R.	Innsbruck	Ca$^+$
Devoe, R.	Almaden (IBM)	Ba$^+$
Drewsen, M.	Aarhus	Ca$^+$
Gill, P.	National Physical Lab (NPL), Teddington, UK	Sr$^+$
King, B.	McMaster U., Hamilton, Ontario	Mg$^+$
Monroe, C.	U. of Michigan	Cd$^+$
Steane, A.	Oxford	Ca$^+$
Wunderlich, C.	Hamburg	Yb$^+$
Walther, H.	Max-Planck Institute, Garching	Mg$^+$, In$^+$
Wineland, D.	NIST, Boulder	^{9}Be$^+$, Mg$^+$

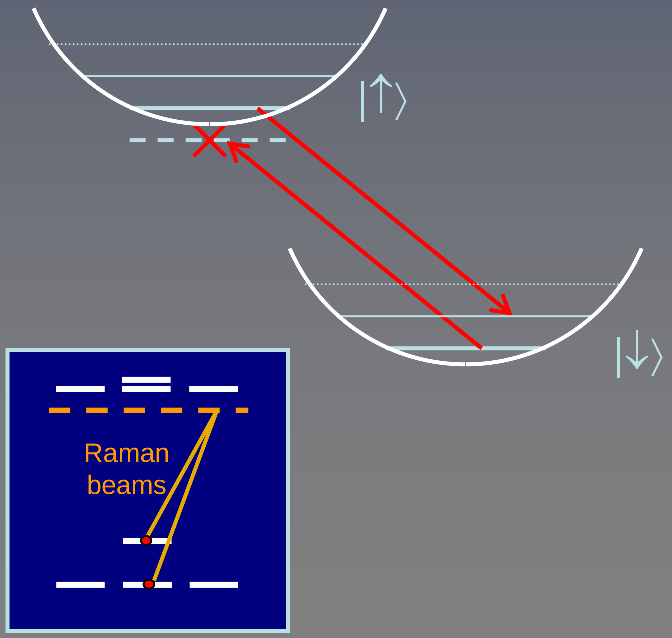
Blinov, B	U. of Washington	Ba$^+$
Haljan, P	Simon Fraser U.	Yb$^+$
Hensinger, W	U. of Sussex	Ca$^+$
Madsen, M	Wabash College	Ca$^+$

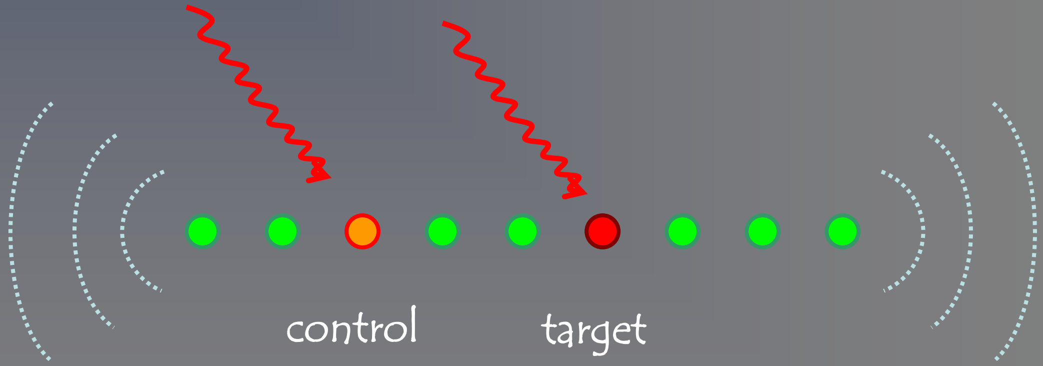
UW ion trap QC lab



Cirac-Zoller CNOT gate – the classic trapped ion gate

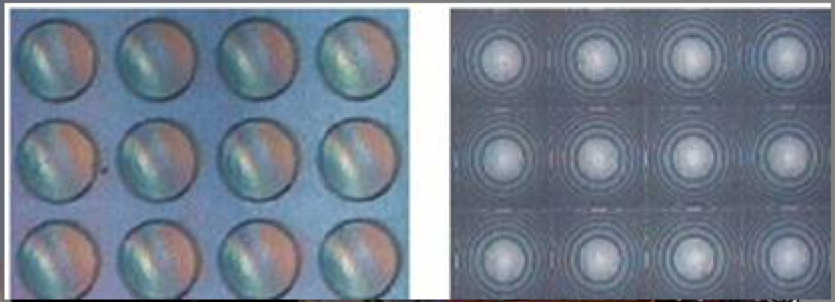
To create an effective spin-spin coupling, "control" spin state is mapped on to the motional "bus" state, the target spin is flipped according to its motion state, then motion is remapped onto the control qubit.

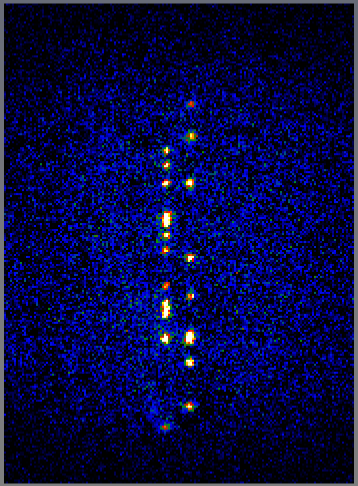




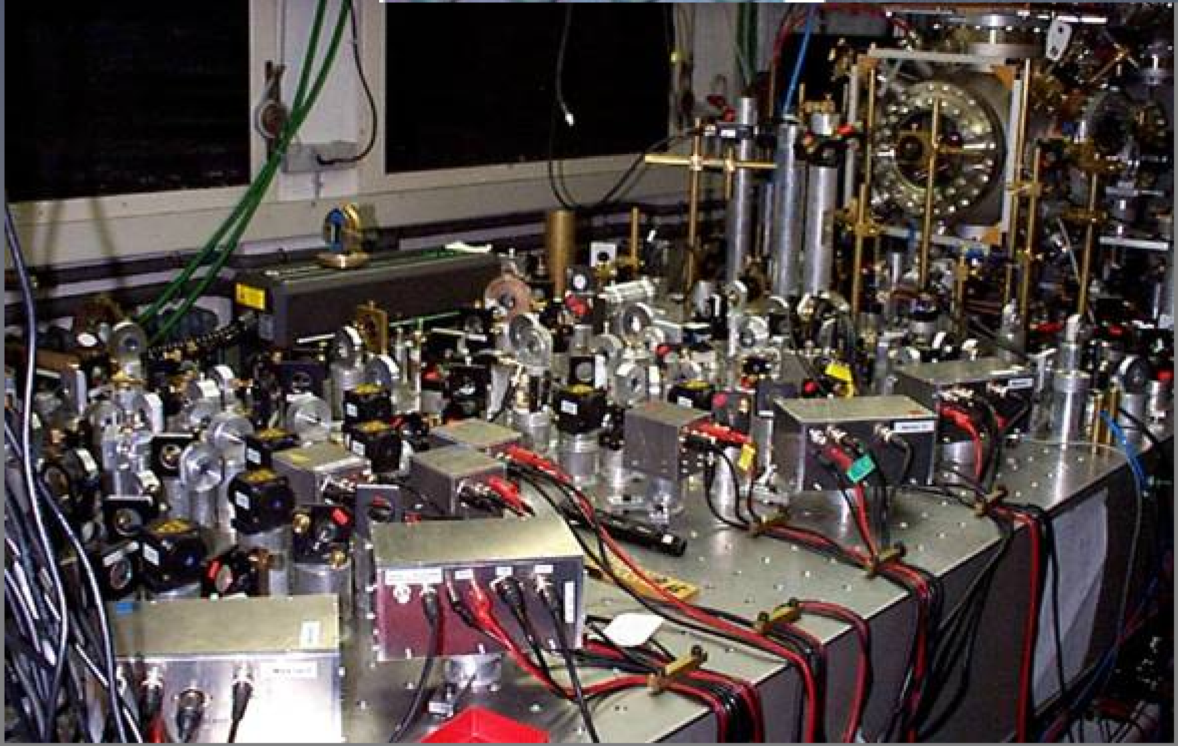
Cirac and Zoller, *Phys. Rev. Lett.* **74**, 4091 (1995)

Neutral atoms





http://www.physics.gatech.edu/ultracool/



http://www.iqo.uni-hannover.de/ertmer/atoindex/

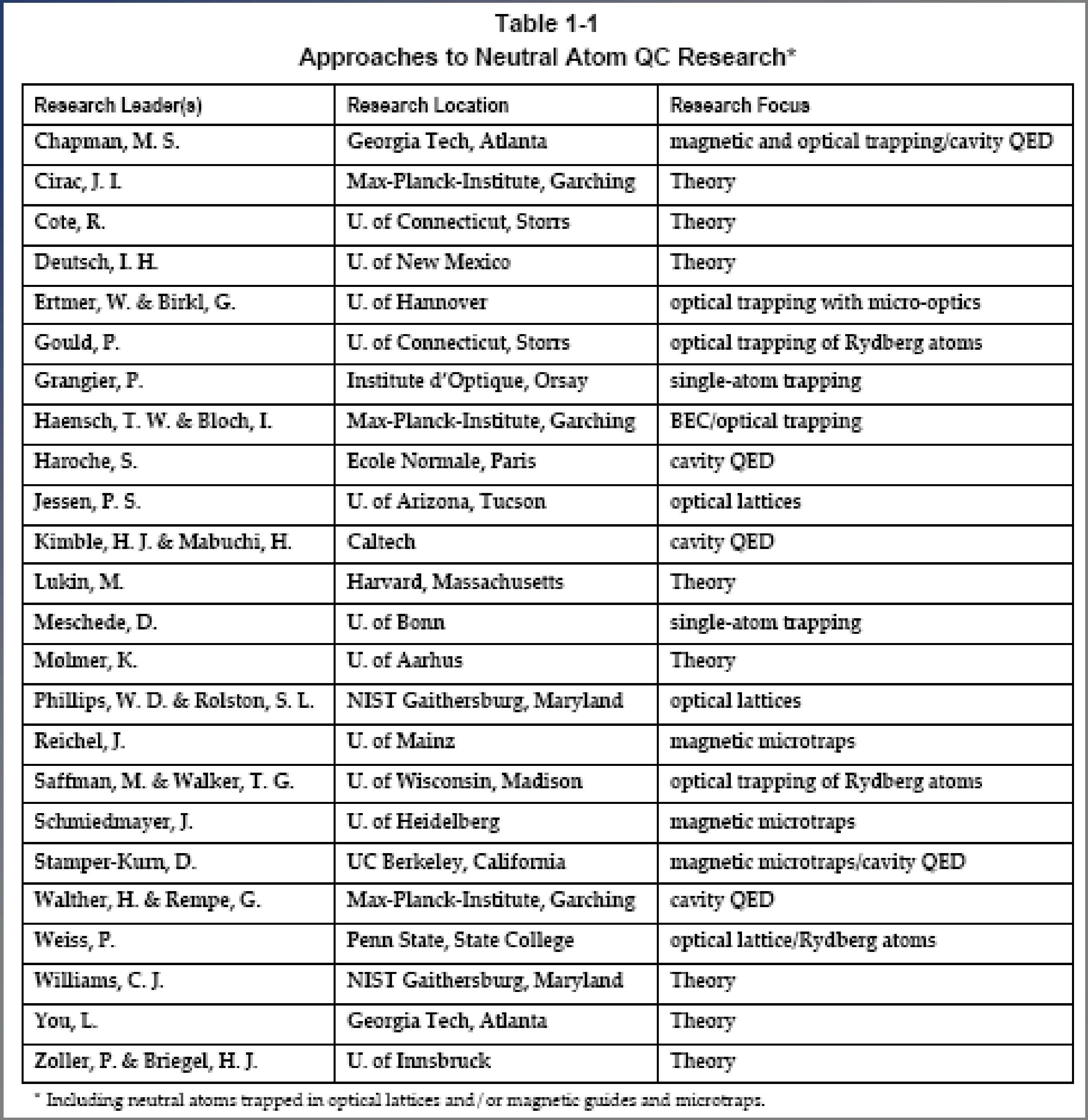


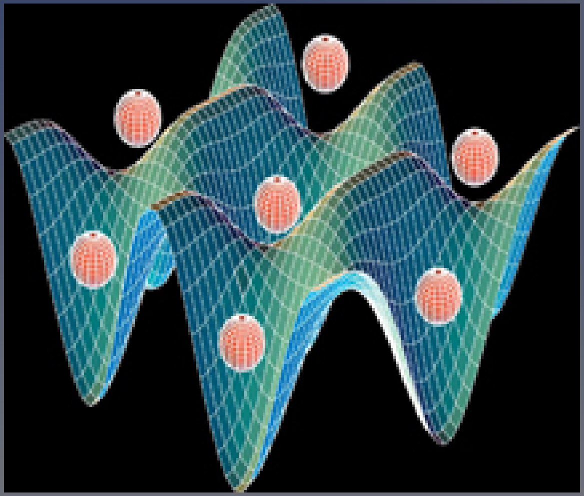
Table 1-1
Approaches to Neutral Atom QC Research*

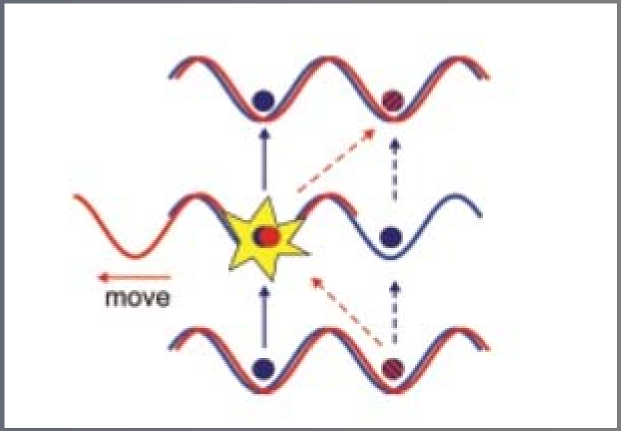
Research Leader(s)	Research Location	Research Focus
Chapman, M. S.	Georgia Tech, Atlanta	magnetic and optical trapping/cavity QED
Cirac, J. I.	Max-Planck-Institute, Garching	Theory
Cote, R.	U. of Connecticut, Storrs	Theory
Deutsch, I. H.	U. of New Mexico	Theory
Ertmer, W. & Birkl, G.	U. of Hannover	optical trapping with micro-optics
Gould, P.	U. of Connecticut, Storrs	optical trapping of Rydberg atoms
Grangier, P.	Institute d'Optique, Orsay	single-atom trapping
Haensch, T. W. & Bloch, I.	Max-Planck-Institute, Garching	BEC/optical trapping
Haroche, S.	Ecole Normale, Paris	cavity QED
Jessen, P. S.	U. of Arizona, Tucson	optical lattices
Kimble, H. J. & Mabuchi, H.	Caltech	cavity QED
Lukin, M.	Harvard, Massachusetts	Theory
Meschede, D.	U. of Bonn	single-atom trapping
Molmer, K.	U. of Aarhus	Theory
Phillips, W. D. & Rolston, S. L.	NIST Gaithersburg, Maryland	optical lattices
Reichel, J.	U. of Mainz	magnetic microtraps
Saffman, M. & Walker, T. G.	U. of Wisconsin, Madison	optical trapping of Rydberg atoms
Schmiedmayer, J.	U. of Heidelberg	magnetic microtraps
Stamper-Kurn, D.	UC Berkeley, California	magnetic microtraps/cavity QED
Walther, H. & Rempe, G.	Max-Planck-Institute, Garching	cavity QED
Weiss, P.	Penn State, State College	optical lattice/Rydberg atoms
Williams, C. J.	NIST Gaithersburg, Maryland	Theory
You, L.	Georgia Tech, Atlanta	Theory
Zoller, P. & Briegel, H. J.	U. of Innsbruck	Theory

* Including neutral atoms trapped in optical lattices and/or magnetic guides and microtraps.

"Cold collision" gates

Atoms trapped in optical lattices

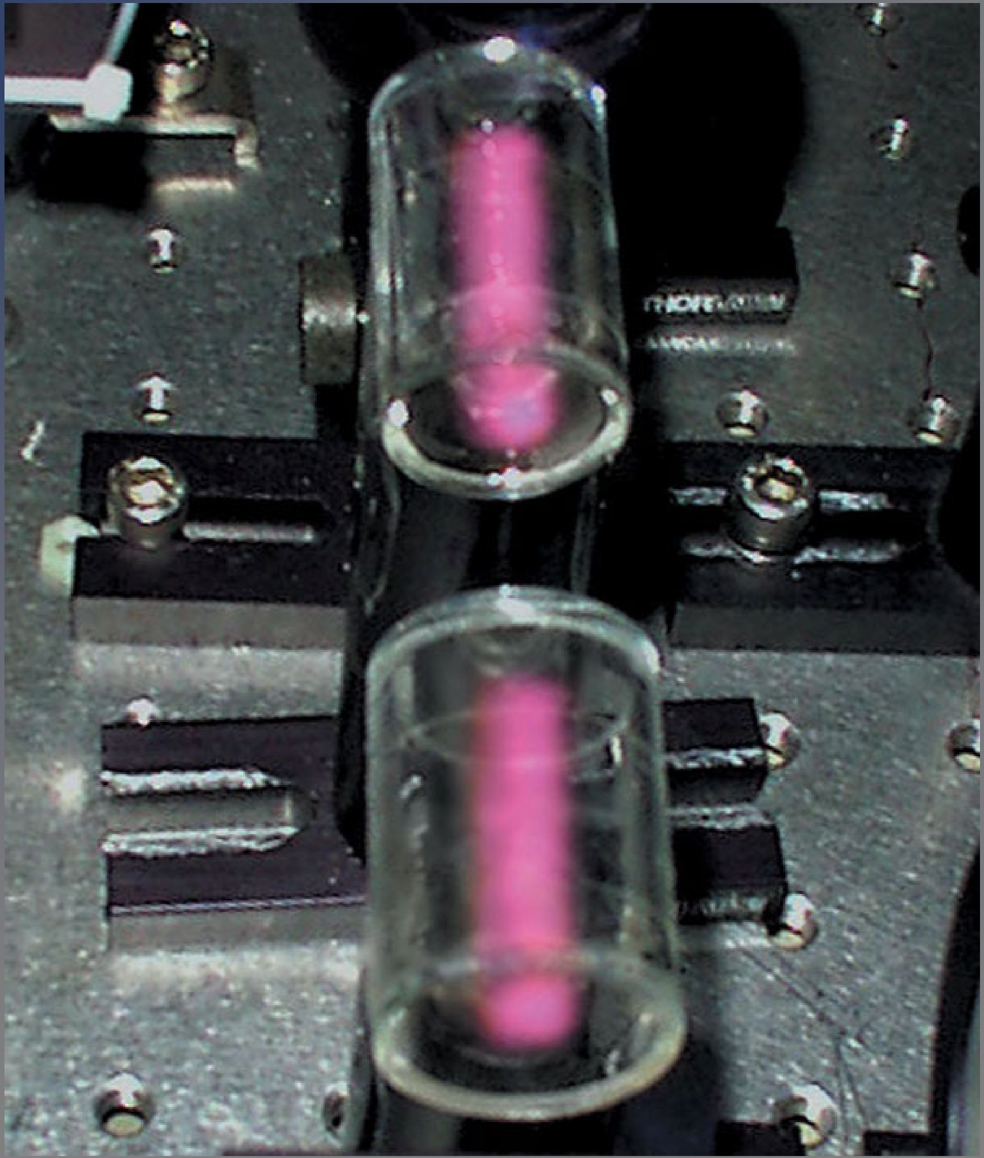




Lattices move, atoms collide

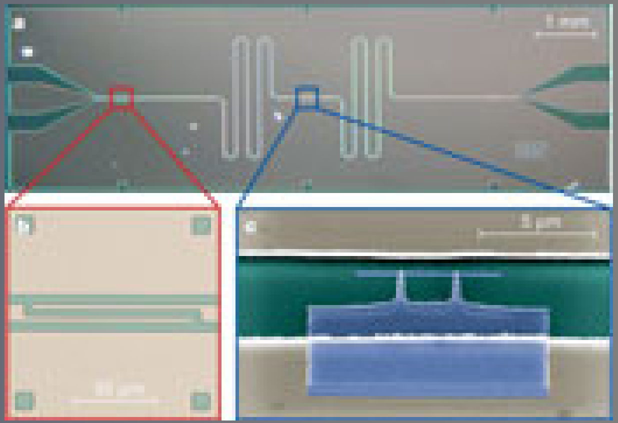
Massively parallel operation: gates on all pairs of neighboring qubits at once... but no individual addressability.
Good for quantum simulators

Entanglement of atomic ensembles

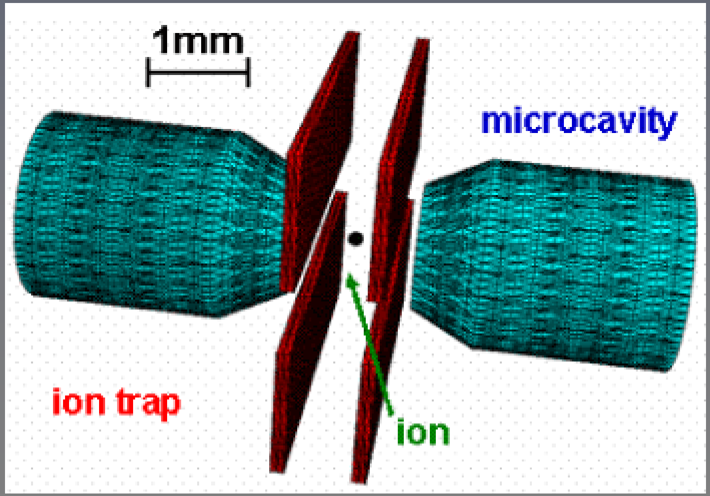


E. Polzik, University of Aarhus

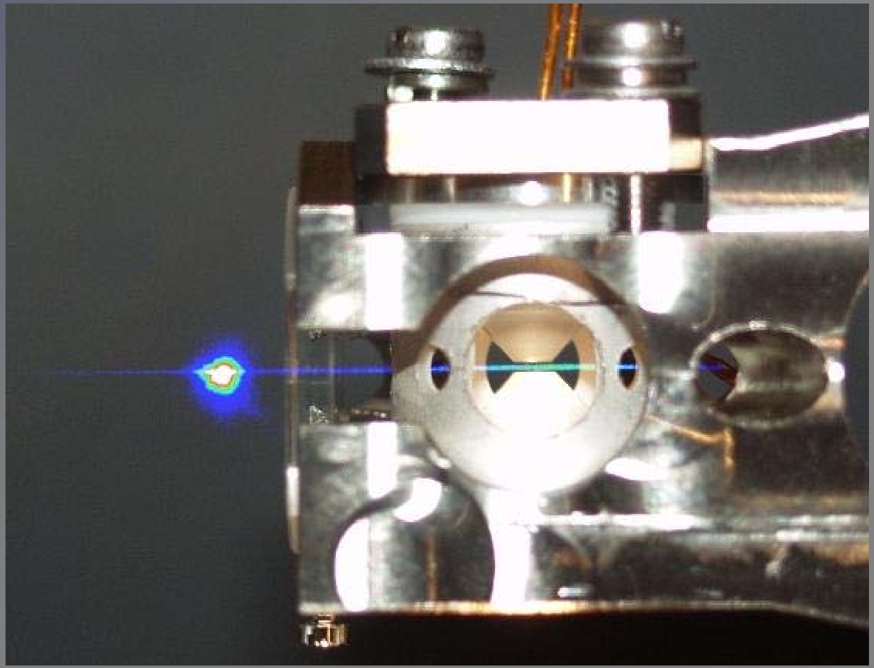
Cavity QED



http://www.nature.com/



http://www2.nict.go.jp/



http://www.wmi.badw.de/SFB631/tps/dipoletrap_and_cavity.jpg

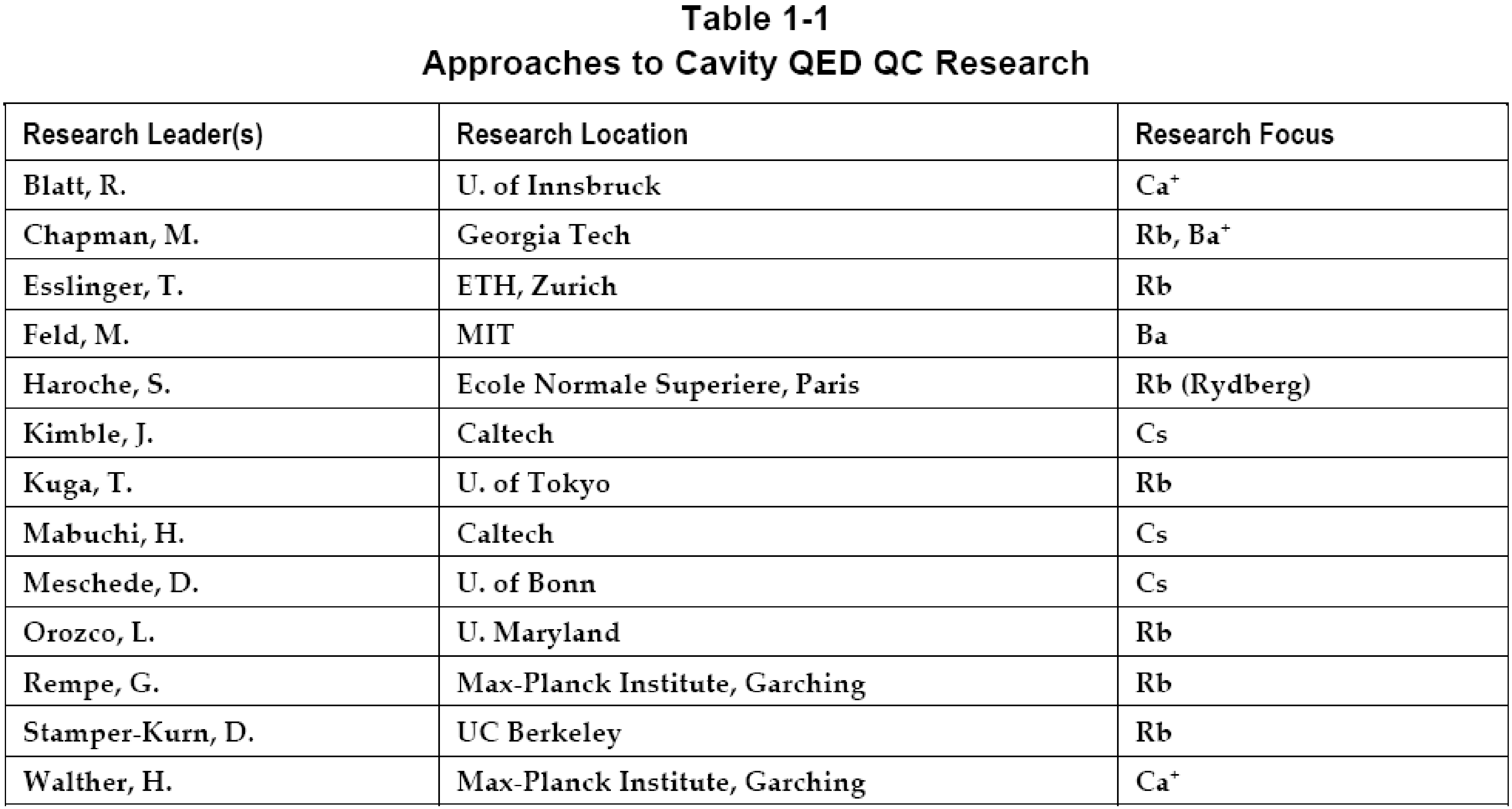
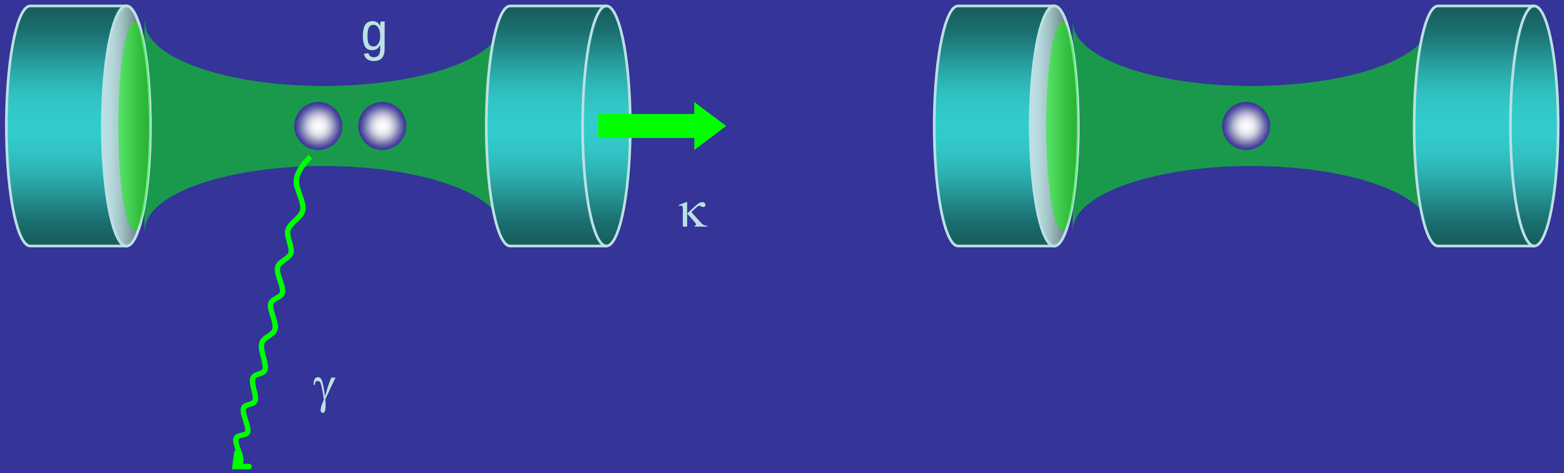


Table 1-1
Approaches to Cavity QED QC Research

Research Leader(s)	Research Location	Research Focus
Blatt, R.	U. of Innsbruck	Ca$^+$
Chapman, M.	Georgia Tech	Rb, Ba$^+$
Esslinger, T.	ETH, Zurich	Rb
Feld, M.	MIT	Ba
Haroche, S.	Ecole Normale Superiere, Paris	Rb (Rydberg)
Kimble, J.	Caltech	Cs
Kuga, T.	U. of Tokyo	Rb
Mabuchi, H.	Caltech	Cs
Meschede, D.	U. of Bonn	Cs
Orozco, L.	U. Maryland	Rb
Rempe, G.	Max-Planck Institute, Garching	Rb
Stamper-Kurn, D.	UC Berkeley	Rb
Walther, H.	Max-Planck Institute, Garching	Ca$^+$

Photon-mediated entanglement

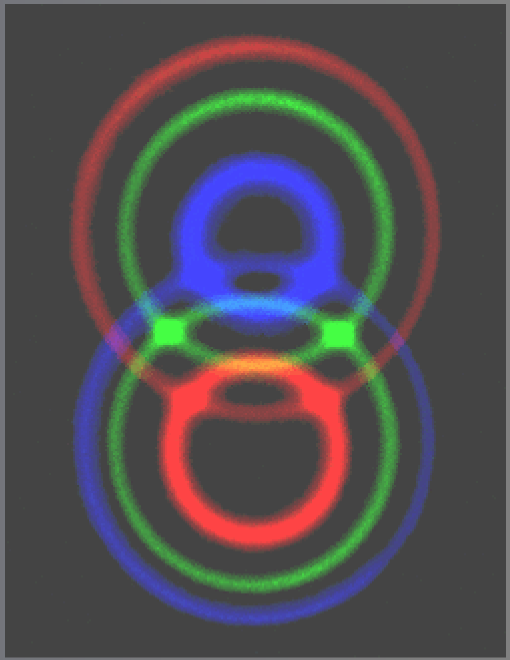


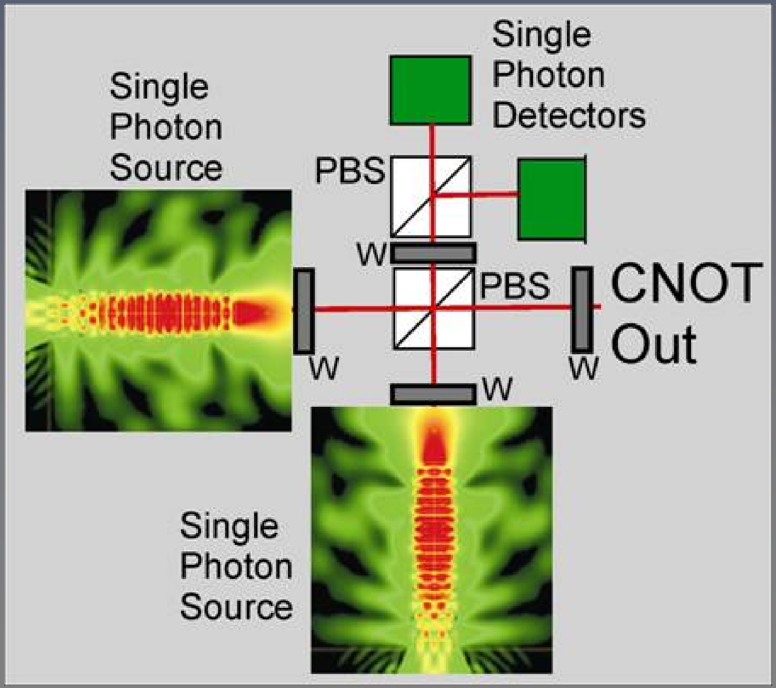
Strong coupling:

$$\frac{g^2}{\kappa\,\gamma} \gg 1$$

Optical

http://focus.aps.org/





http://www.qipirc.org/images/projects/image018.jpg

http://www.quantum.at/

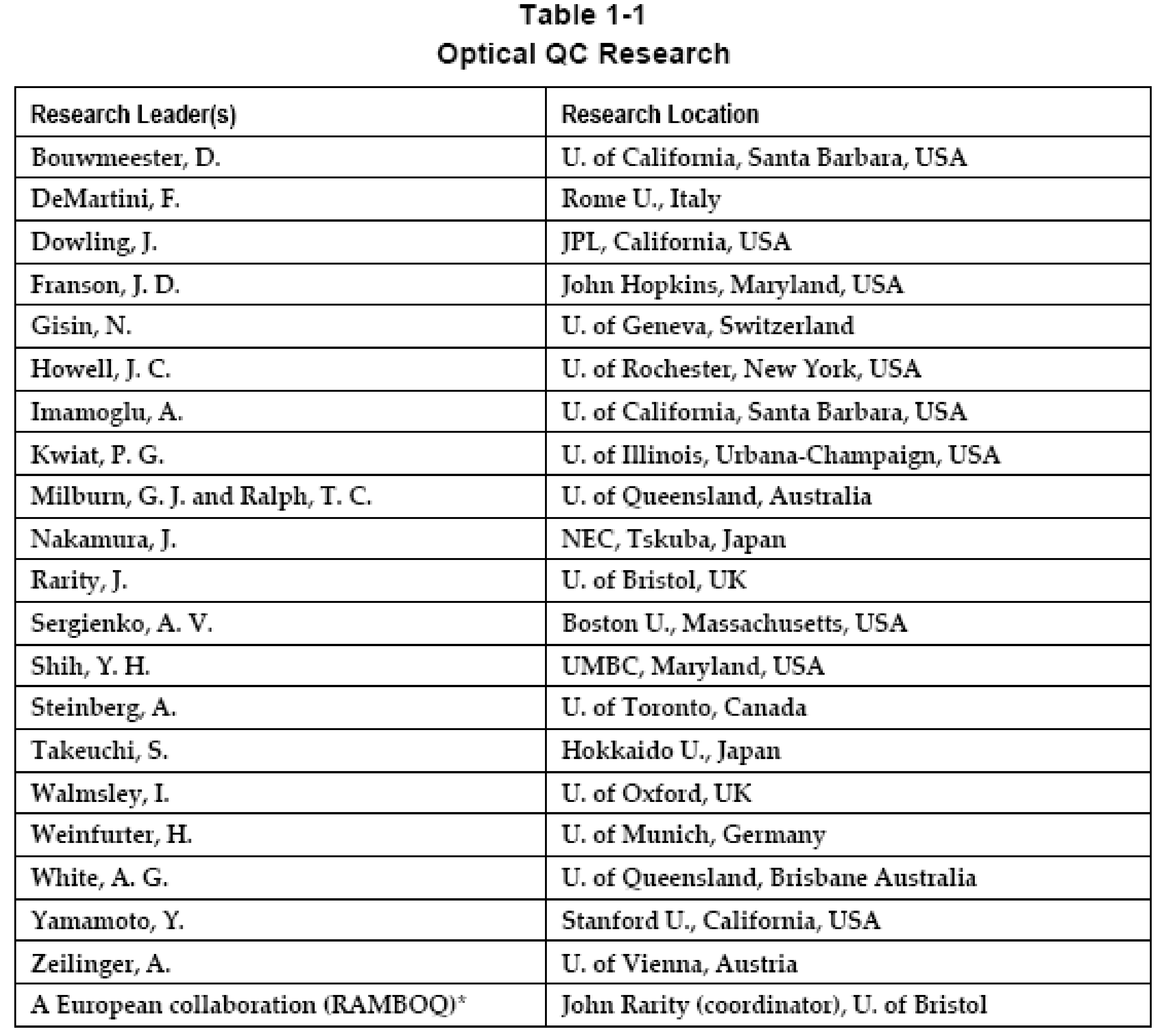
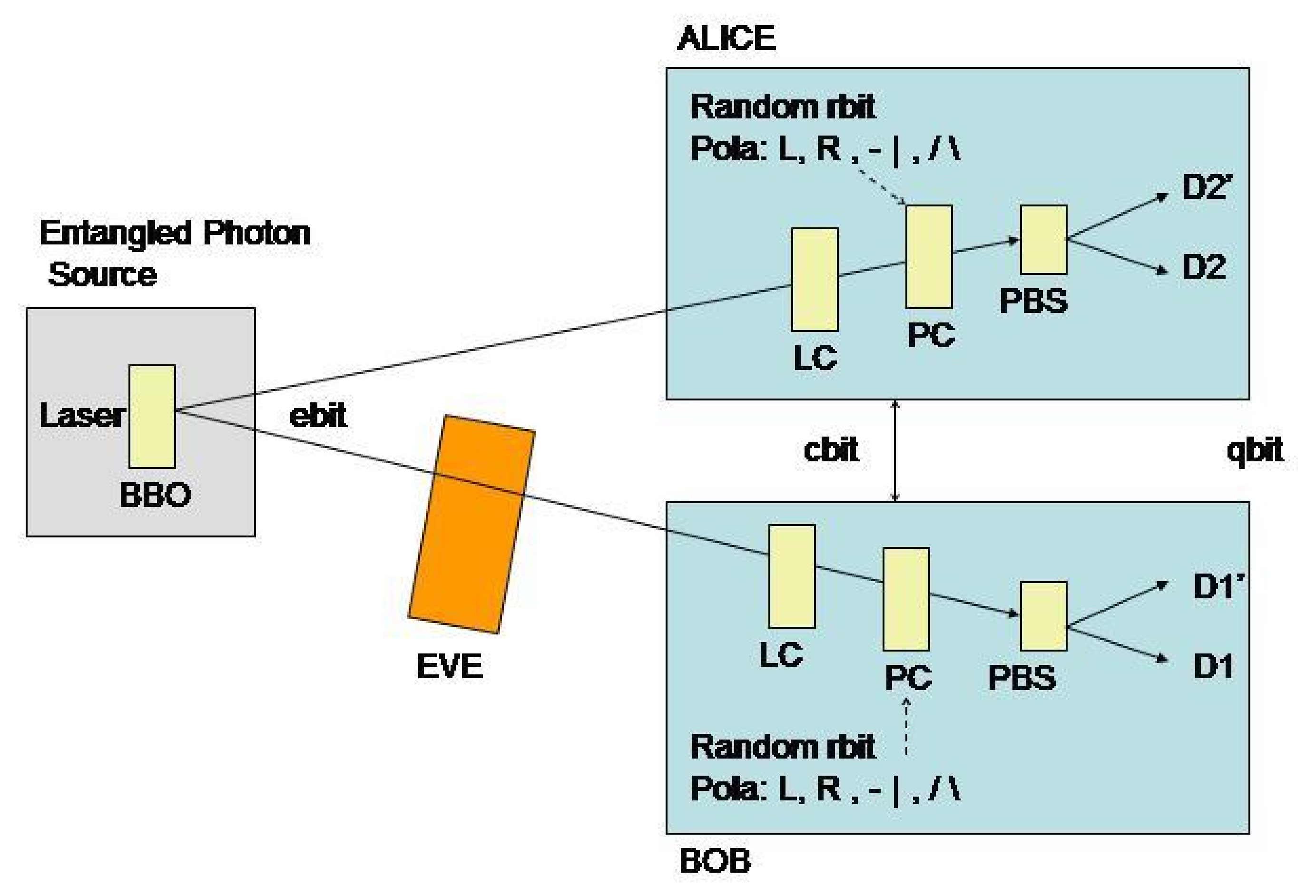


Table 1-1
Optical QC Research

Research Leader(s)	Research Location
Bouwmeester, D.	U. of California, Santa Barbara, USA
DeMartini, F.	Rome U., Italy
Dowling, J.	JPL, California, USA
Franson, J. D.	John Hopkins, Maryland, USA
Gisin, N.	U. of Geneva, Switzerland
Howell, J. C.	U. of Rochester, New York, USA
Imamoglu, A.	U. of California, Santa Barbara, USA
Kwiat, P. G.	U. of Illinois, Urbana-Champaign, USA
Milburn, G. J. and Ralph, T. C.	U. of Queensland, Australia
Nakamura, J.	NEC, Tskuba, Japan
Rarity, J.	U. of Bristol, UK
Sergienko, A. V.	Boston U., Massachusetts, USA
Shih, Y. H.	UMBC, Maryland, USA
Steinberg, A.	U. of Toronto, Canada
Takeuchi, S.	Hokkaido U., Japan
Walmsley, I.	U. of Oxford, UK
Weinfurter, H.	U. of Munich, Germany
White, A. G.	U. of Queensland, Brisbane Australia
Yamamoto, Y.	Stanford U., California, USA
Zeilinger, A.	U. of Vienna, Austria
A European collaboration (RAMBOQ)*	John Rarity (coordinator), U. of Bristol

Entangled-photon six-state quantum cryptography (Paul G Kwiat)



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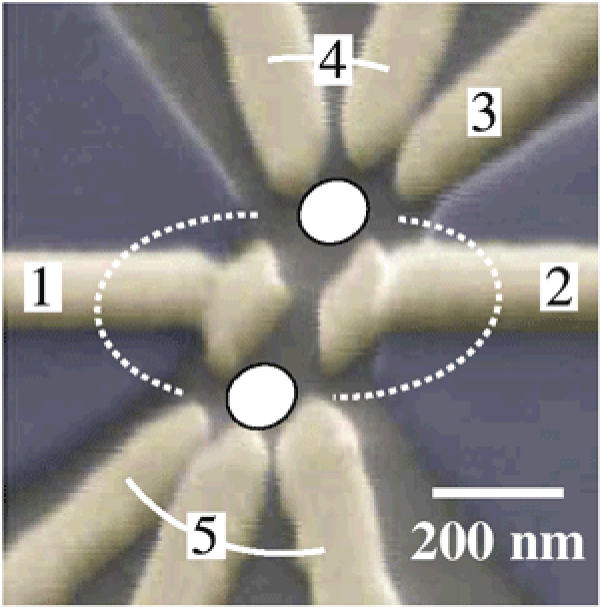
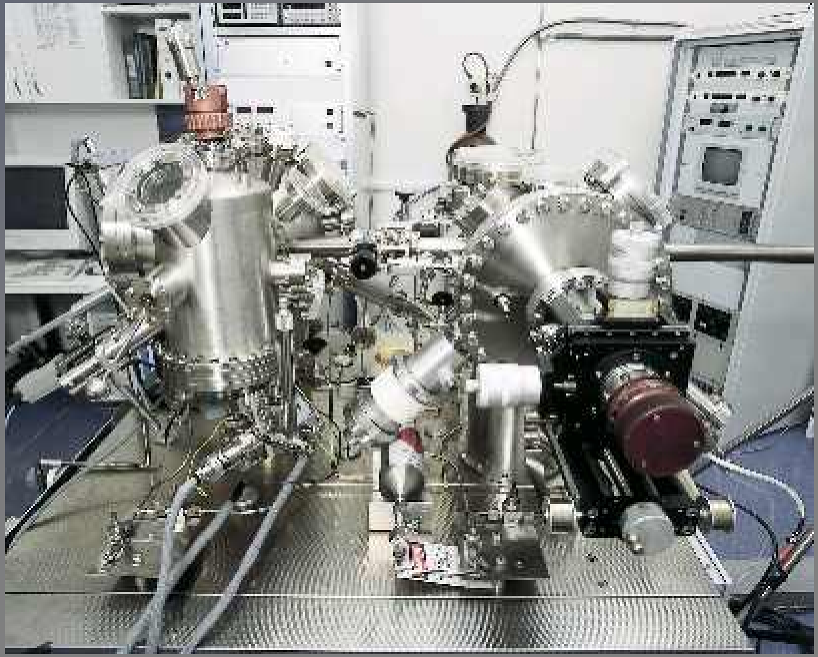


Solid state

http://groups.mrl.uiuc.edu/



http://mcba2.phys.unsw.edu.au/~mcba/hons02-1-12-figb.jpg

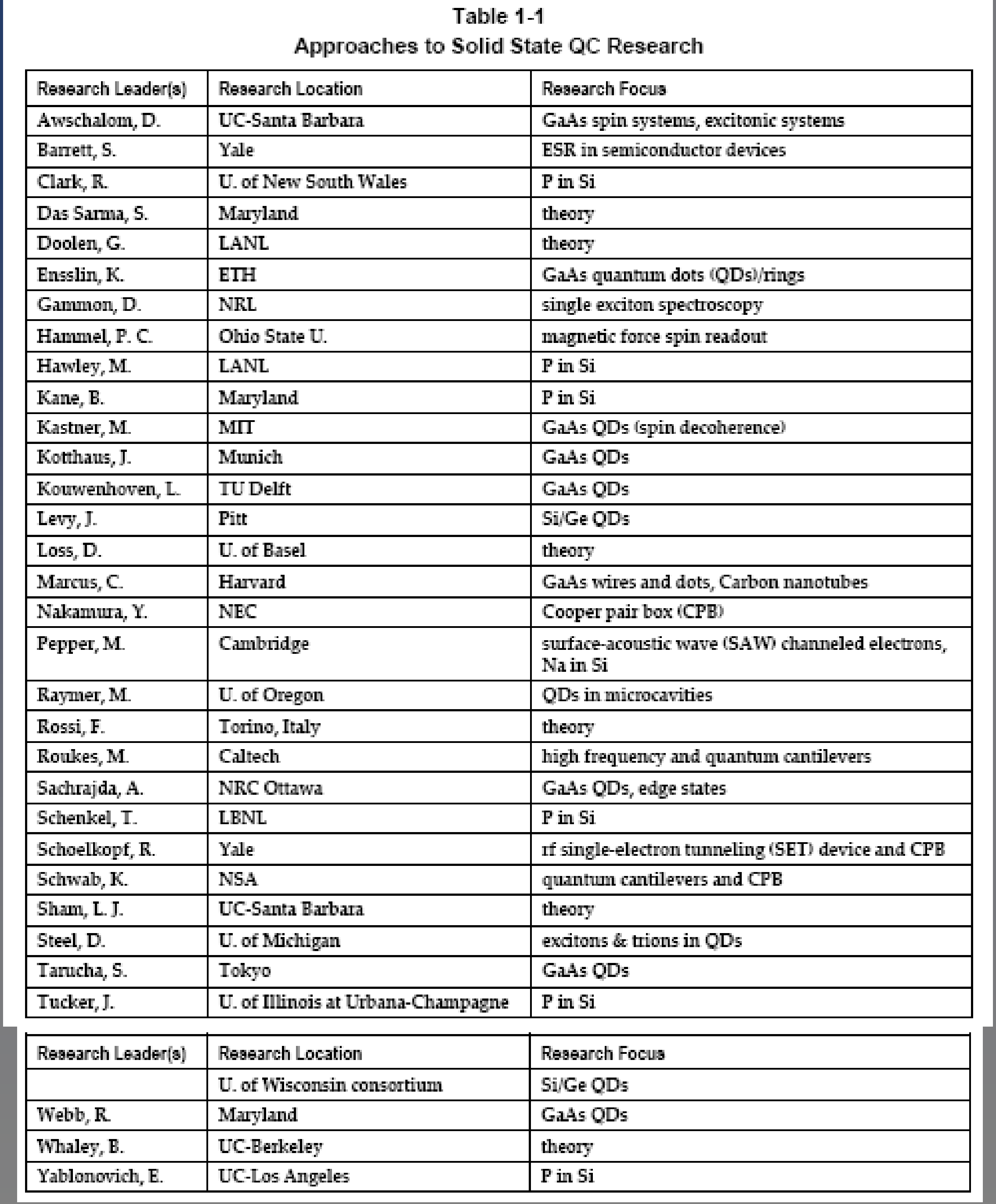
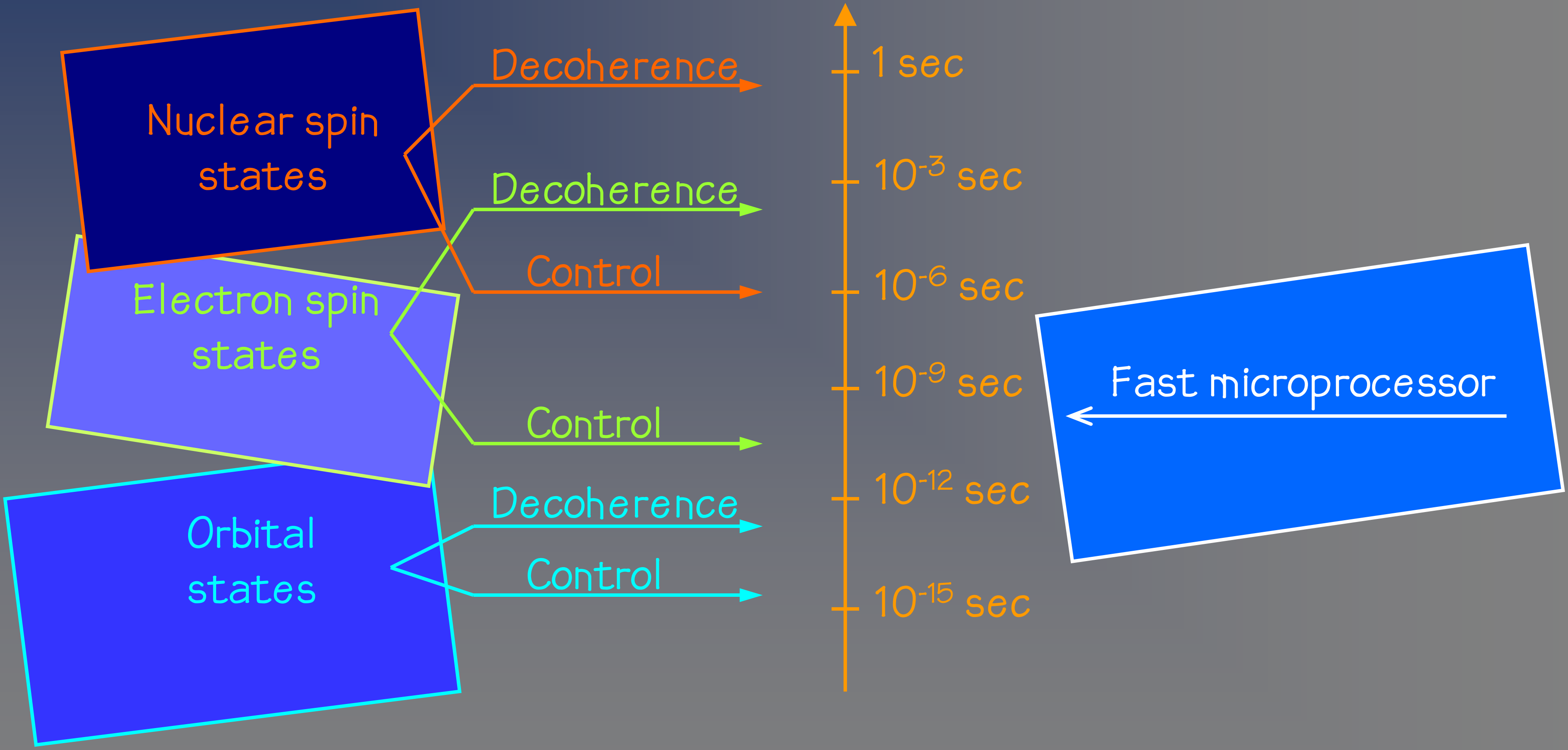


Table 1-1
Approaches to Solid State QC Research

Research Leader(s)	Research Location	Research Focus
Awschalom, D.	UC-Santa Barbara	GaAs spin systems, excitonic systems
Barrett, S.	Yale	ESR in semiconductor devices
Clark, R.	U. of New South Wales	P in Si
Das Sarma, S.	Maryland	theory
Doolen, G.	LANL	theory
Ensslin, K.	ETH	GaAs quantum dots (QDs)/rings
Gammon, D.	NRL	single exciton spectroscopy
Hammel, P. C.	Ohio State U.	magnetic force spin readout
Hawley, M.	LANL	P in Si
Kane, B.	Maryland	P in Si
Kastner, M.	MIT	GaAs QDs (spin decoherence)
Kotthaus, J.	Munich	GaAs QDs
Kouwenhoven, L.	TU Delft	GaAs QDs
Levy, J.	Pitt	Si/Ge QDs
Loss, D.	U. of Basel	theory
Marcus, C.	Harvard	GaAs wires and dots, Carbon nanotubes
Nakamura, Y.	NEC	Cooper pair box (CPB)
Pepper, M.	Cambridge	surface-acoustic wave (SAW) channeled electrons, Na in Si
Raymer, M.	U. of Oregon	QDs in microcavities
Rossi, F.	Torino, Italy	theory
Roukes, M.	Caltech	high frequency and quantum cantilevers
Sachrajda, A.	NRC Ottawa	GaAs QDs, edge states
Schenkel, T.	LBNL	P in Si
Schoelkopf, R.	Yale	rf single-electron tunneling (SET) device and CPB
Schwab, K.	NSA	quantum cantilevers and CPB
Sham, L. J.	UC-Santa Barbara	theory
Steel, D.	U. of Michigan	excitons & trions in QDs
Tarucha, S.	Tokyo	GaAs QDs
Tucker, J.	U. of Illinois at Urbana-Champagne	P in Si
	U. of Wisconsin consortium	Si/Ge QDs
Webb, R.	Maryland	GaAs QDs
Whaley, B.	UC-Berkeley	theory
Yablonovich, E.	UC-Los Angeles	P in Si

Semiconductor qubits



Nuclear spin states

Decoherence

Control

Electron spin states

Decoherence

Control

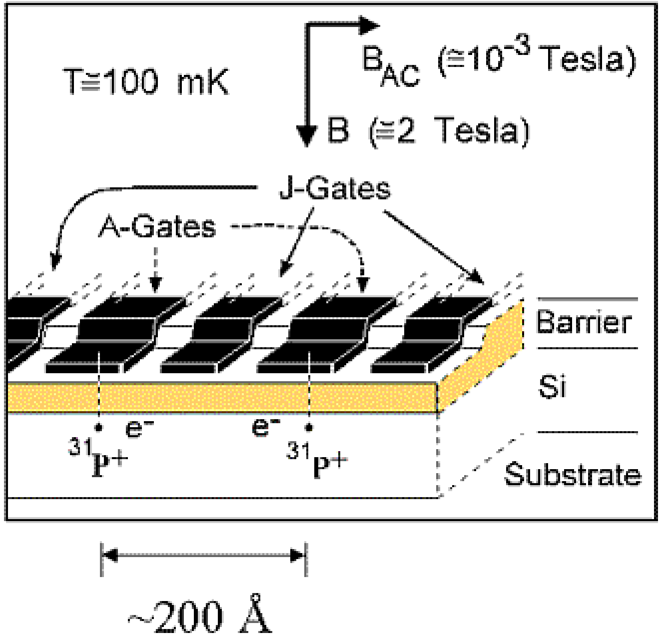
Orbital states

Decoherence

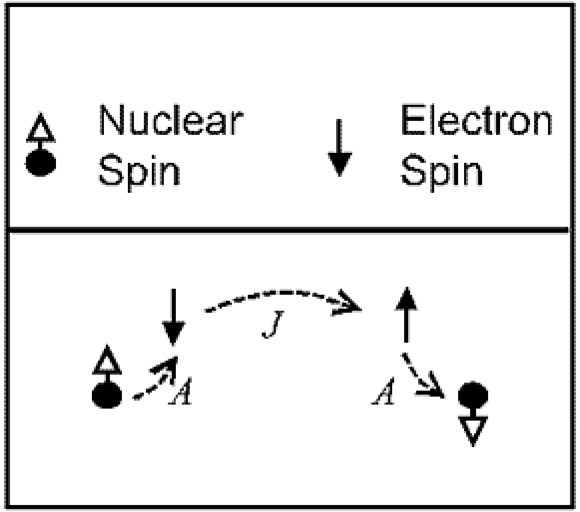
Control

Fast microprocessor

“Kane proposal”



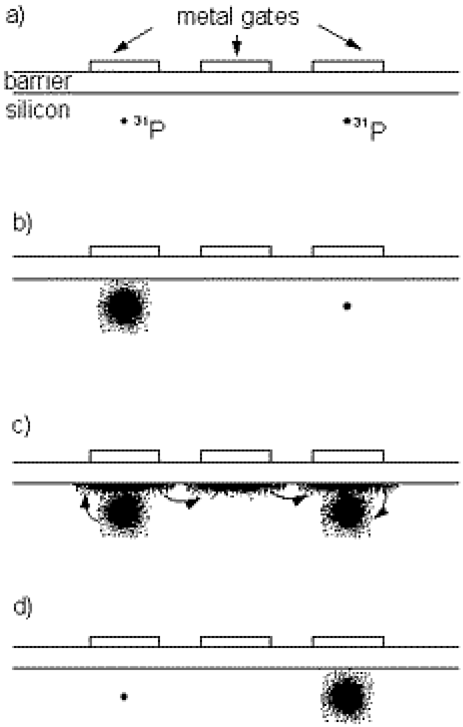
“A Silicon-based nuclear spin quantum computer”
B. E. Kane, *Nature*, May 14, 1998
also, quant-ph/0003031

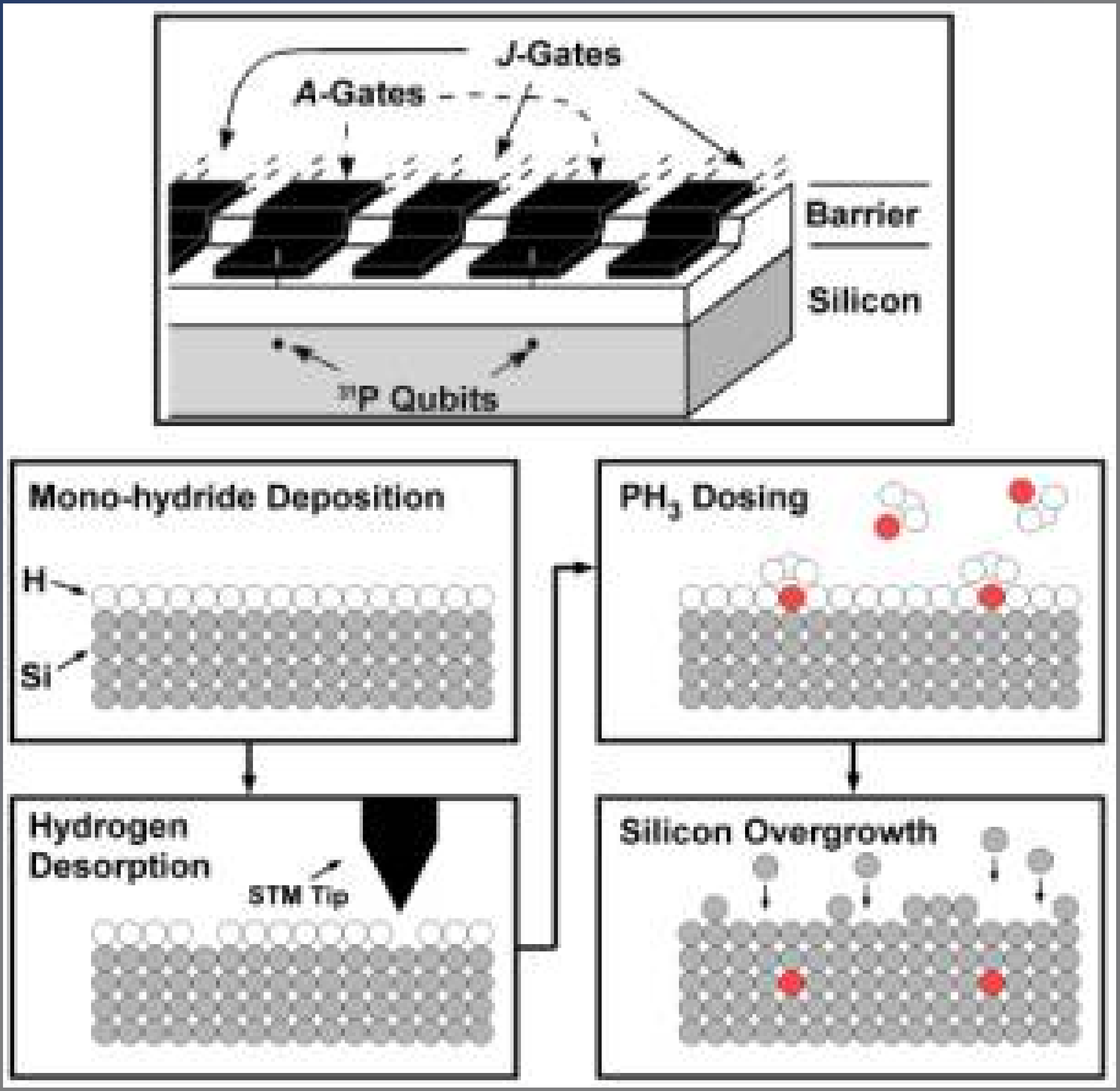


Recipe for Quantum Computing:

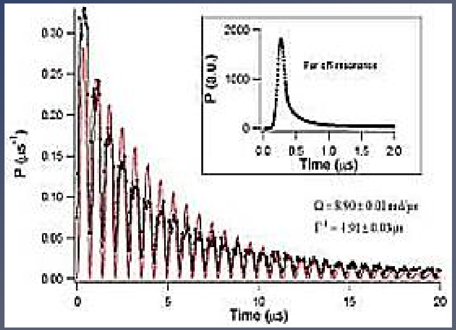
1. Do SWAPs and fractional SWAPs between electron and nuclear spins by accurately controlling the *time* electrons reside on donor states

2. Move electrons between nuclear sites to transmit quantum information.

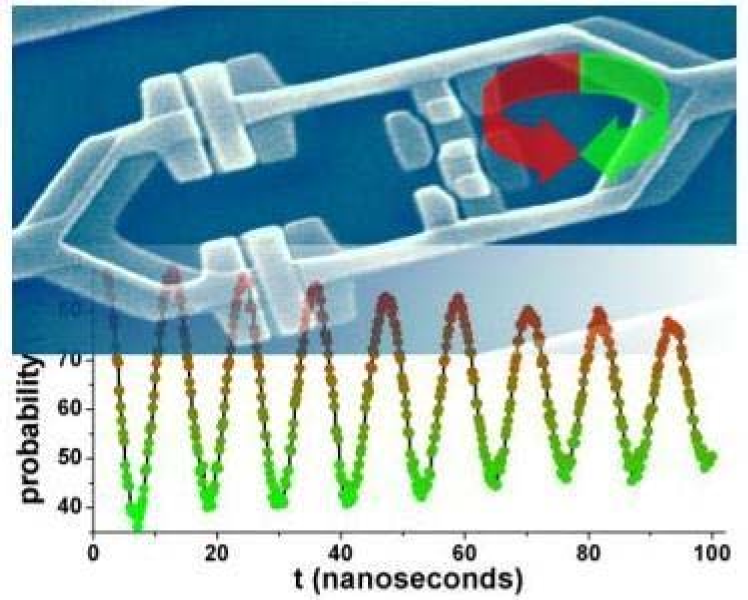



J-Gates
A-Gates
Barrier
Silicon
^{31}P Qubits
Mono-hydride Deposition
H
Si
Hydrogen Desorption
STM Tip
PH_3 Dosing
Silicon Overgrowth

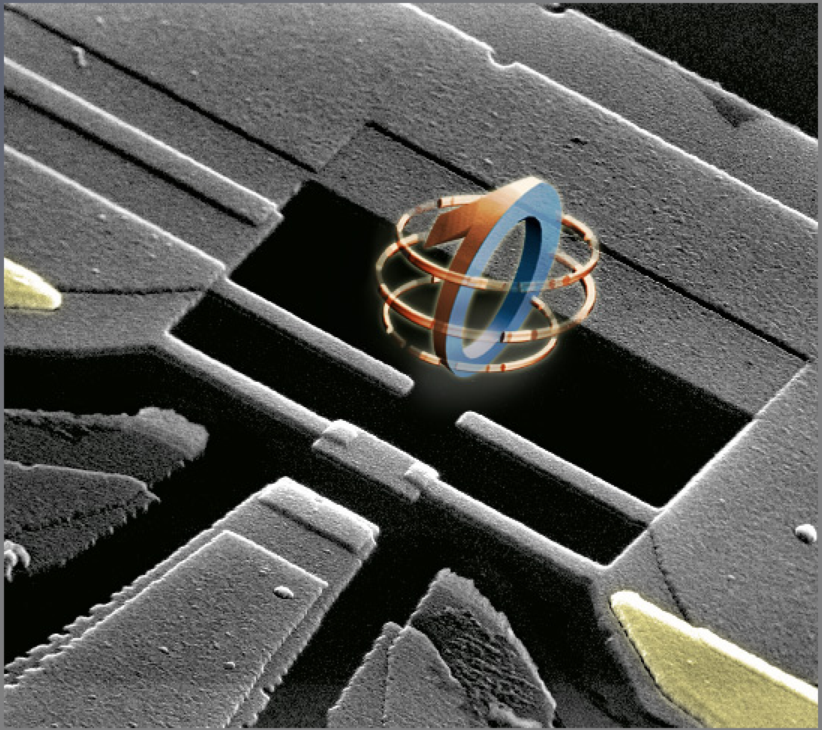
Superconductors



www.physics.ku.edu



http://qt.tn.tudelft.nl/research/fluxqubit/qubit_rabi.jpg



http://www-drecam.cea.fr/

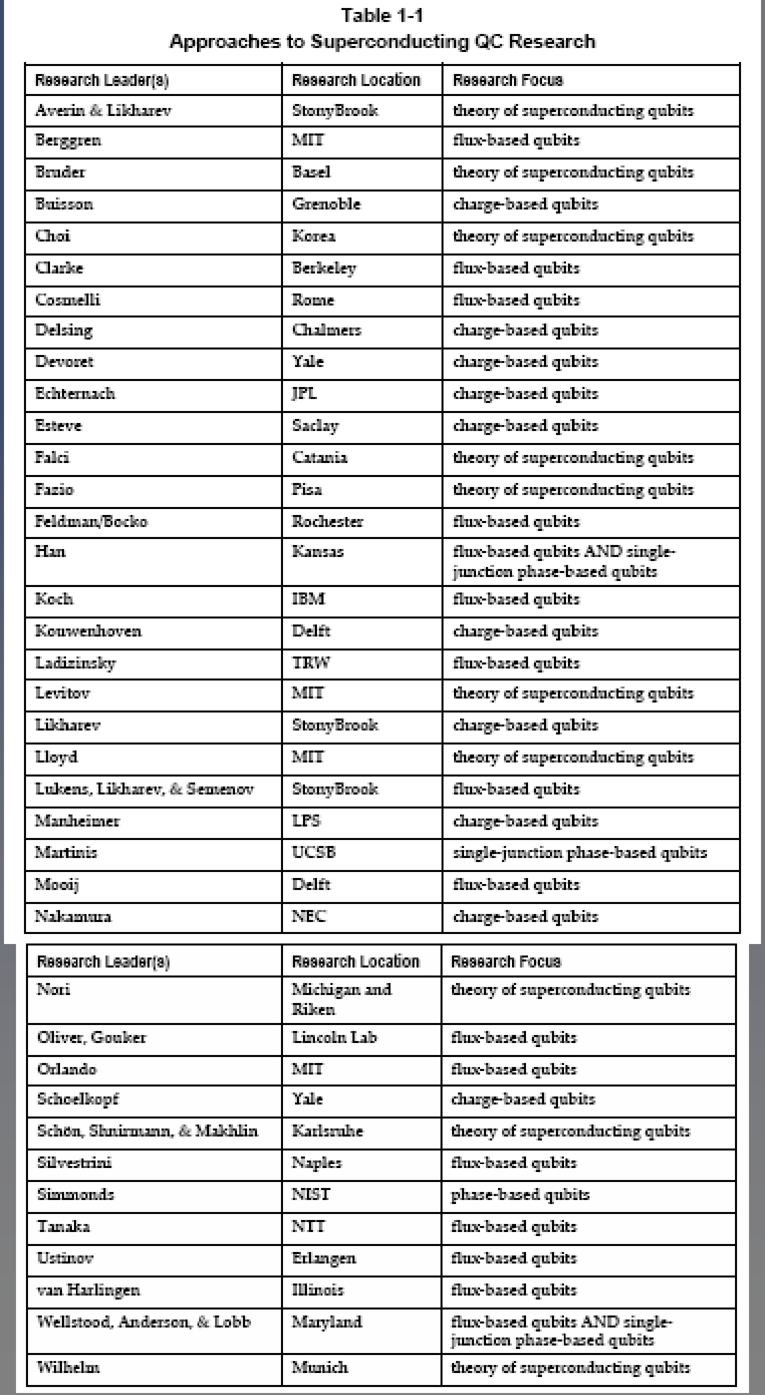
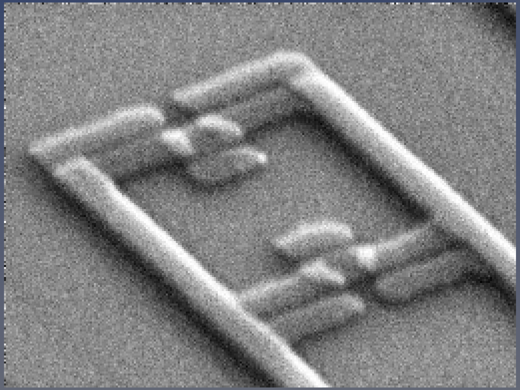


Table 1-1
Approaches to Superconducting QC Research

Research Leader(s)	Research Location	Research Focus
Averin & Likharev	StonyBrook	theory of superconducting qubits
Berggren	MIT	flux-based qubits
Bruder	Basel	theory of superconducting qubits
Buisson	Grenoble	charge-based qubits
Choi	Korea	theory of superconducting qubits
Clarke	Berkeley	flux-based qubits
Cosmelli	Rome	flux-based qubits
Delsing	Chalmers	charge-based qubits
Devoret	Yale	charge-based qubits
Echternach	JPL	charge-based qubits
Esteve	Saclay	charge-based qubits
Falci	Catania	theory of superconducting qubits
Fazio	Pisa	theory of superconducting qubits
Feldman/Bocko	Rochester	flux-based qubits
Han	Kansas	flux-based qubits AND single-junction phase-based qubits
Koch	IBM	flux-based qubits
Kouwenhoven	Delft	charge-based qubits
Ladizinsky	TRW	flux-based qubits
Levitov	MIT	theory of superconducting qubits
Likharev	StonyBrook	charge-based qubits
Lloyd	MIT	theory of superconducting qubits
Lukens, Likharev, & Semenov	StonyBrook	flux-based qubits
Manheimer	LPS	charge-based qubits
Martinis	UCSB	single-junction phase-based qubits
Mooij	Delft	flux-based qubits
Nakamura	NEC	charge-based qubits
Nori	Michigan and Riken	theory of superconducting qubits
Oliver, Gouker	Lincoln Lab	flux-based qubits
Orlando	MIT	flux-based qubits
Schoelkopf	Yale	charge-based qubits
Schön, Shnirmann, & Makhlin	Karlsruhe	theory of superconducting qubits
Silvestrini	Naples	flux-based qubits
Simmonds	NIST	phase-based qubits
Tanaka	NTT	flux-based qubits
Ustinov	Erlangen	flux-based qubits
van Harlingen	Illinois	flux-based qubits
Wellstood, Anderson, & Lobb	Maryland	flux-based qubits AND single-junction phase-based qubits
Wilhelm	Munich	theory of superconducting qubits

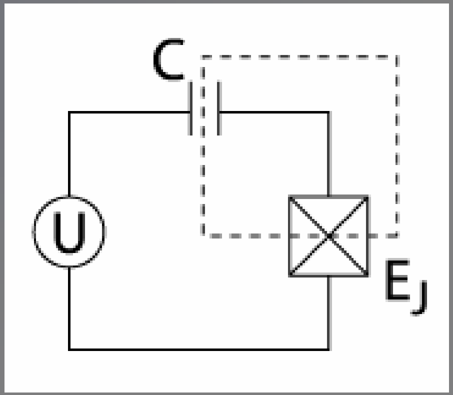
Josephson junction qubits

Flux qubit



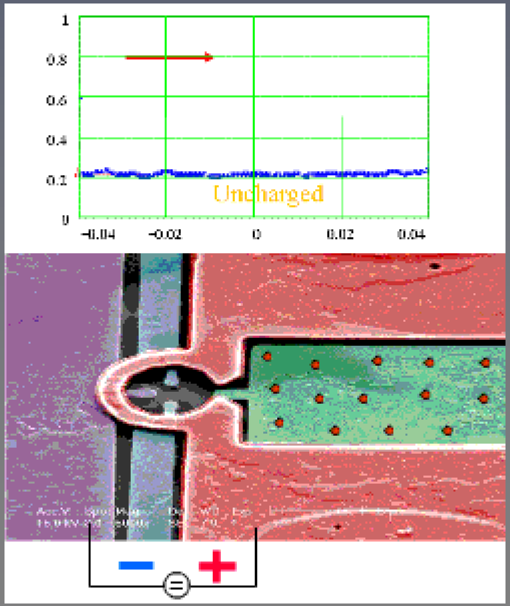
Quantization of magnetic field flux inside the loop containing several JJs

Quantization of electric charge (number of Cooper pairs) trapped on an island sealed off by a JJ. (|0› and |1› states are 1000000 Cooper pairs vs. 1000001 Cooper pairs)



Cooper pair box (charge qubit)

Unique



http://www-drecam.cea.fr/Images/astImg/375_1.gif

Any other wild ideas???

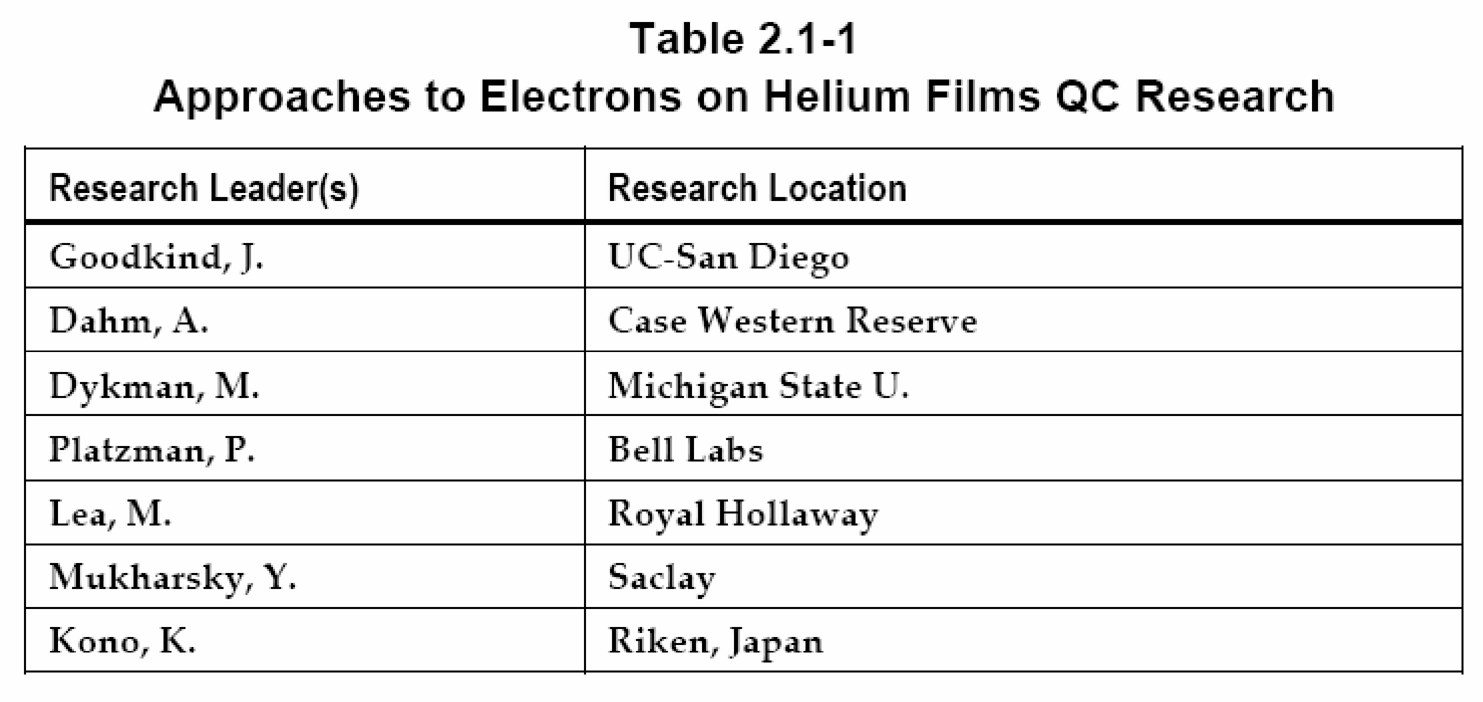


Table 2.1-1

Approaches to Electrons on Helium Films QC Research

Research Leader(s)	Research Location
Goodkind, J.	UC-San Diego
Dahm, A.	Case Western Reserve
Dykman, M.	Michigan State U.
Platzman, P.	Bell Labs
Lea, M.	Royal Hollaway
Mukharsky, Y.	Saclay
Kono, K.	Riken, Japan

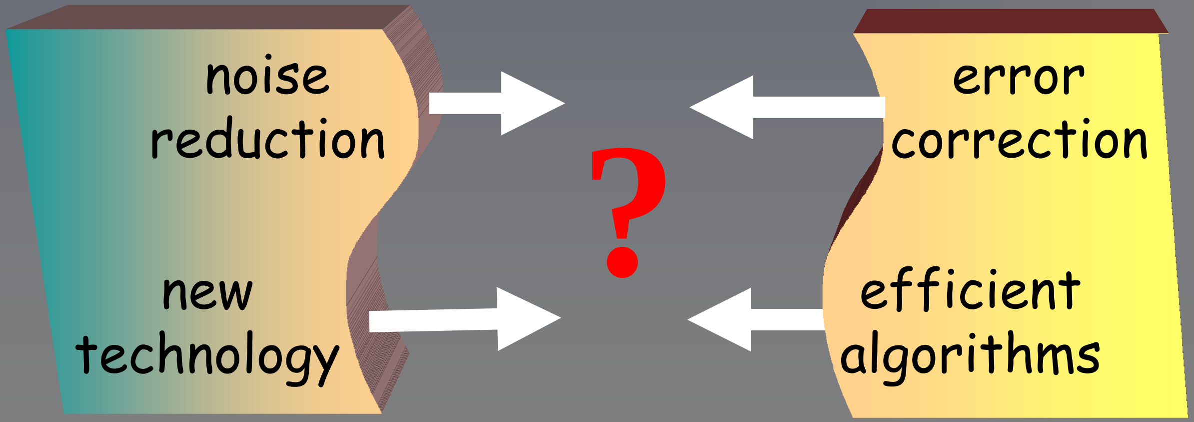
Quantum Computing Abyss
(after D. Wineland)

state-of-the-art experiments

theoretical requirements for “useful” QC

~ 5 # quantum bits >1000

<100 # logic gates $>10^9$



noise reduction

new technology

?

error correction

efficient algorithms