Physical implementations of quantum computing

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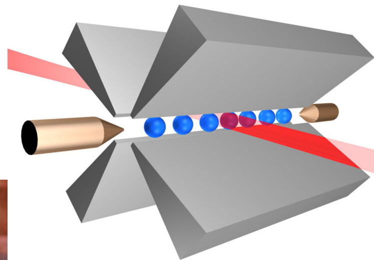
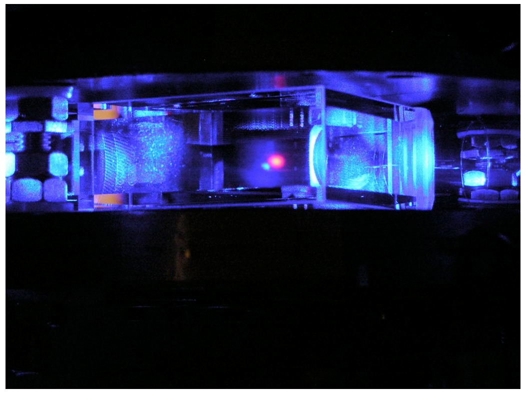
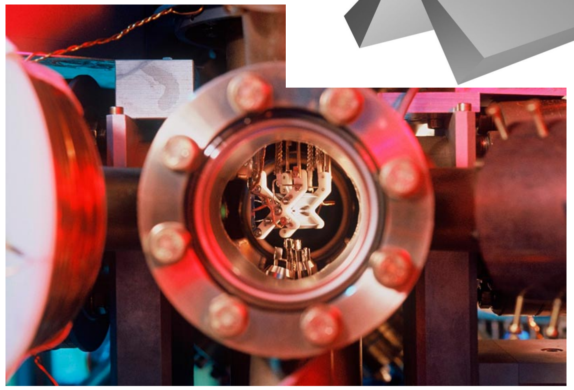
Overview (Review)



Introduction

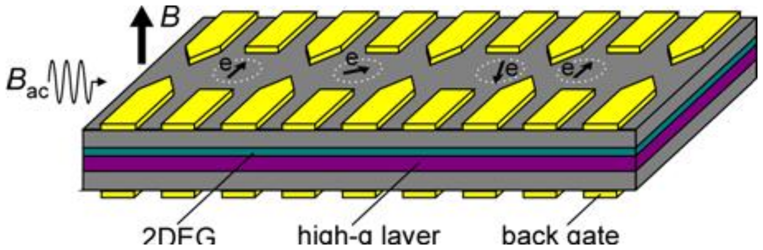
- DiVincenzo Criteria
- Characterising coherence times



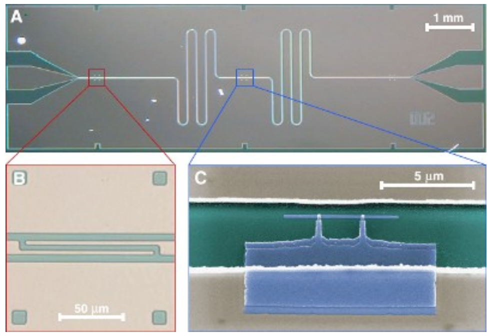


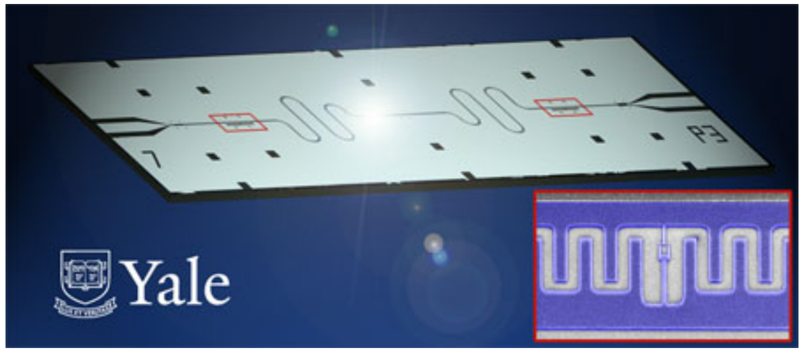
Survey of possible qubits and implementations

- Neutral atoms
- Trapped ions

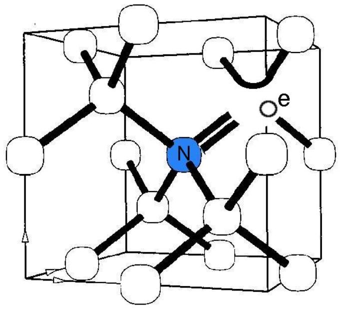


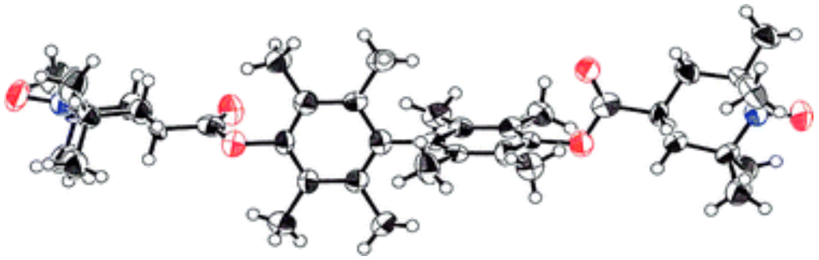
- Colour centres (e.g., NV-centers in diamond)
- Electron spins (e.g,. quantum dots)
- Superconducting qubits (charge, phase, flux)





- NMR
- Optical qubits
- Topological qubits

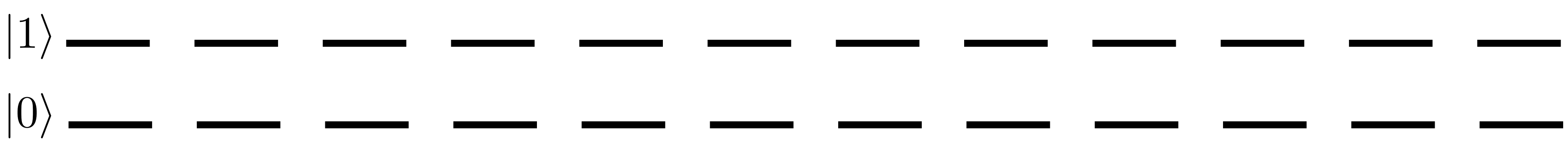




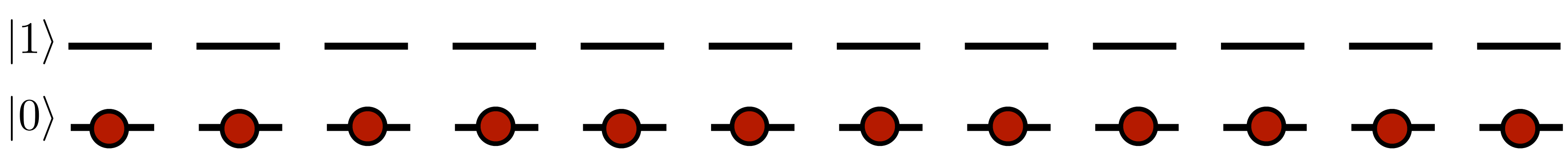
Back to the DiVincenzo Criteria:

Requirements for the implementation of quantum computation

1. A scalable physical system with well characterized qubits

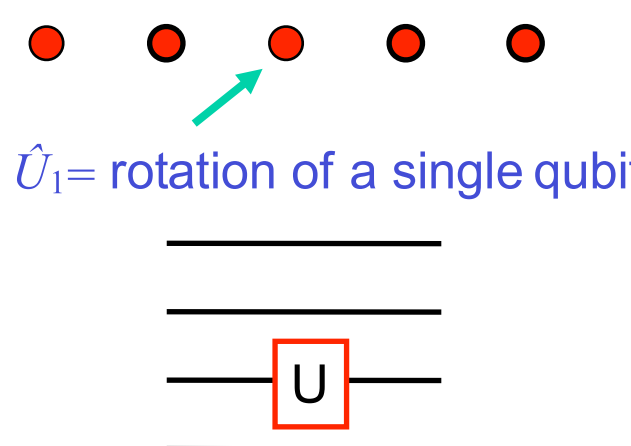


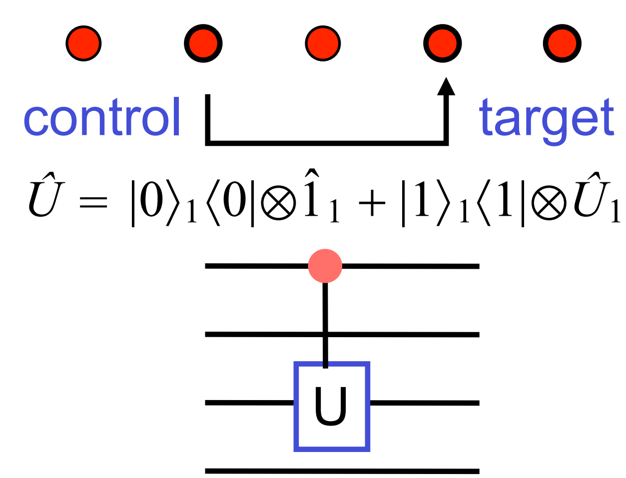
2. The ability to initialize the state of the qubits to a simple fiducial state, such as $|000...\rangle$



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

4. A "universal" set of quantum gates
   (single qubit rotations
   + C-Not / C-Phase / ....)





5. A qubit-specific measurement capability

D. P. DiVincenzo "The Physical Implementation of Quantum Computation", Fortschritte der Physik **48**, p. 771 (2000)
arXiv:quant-ph/0002077

Neutral atoms

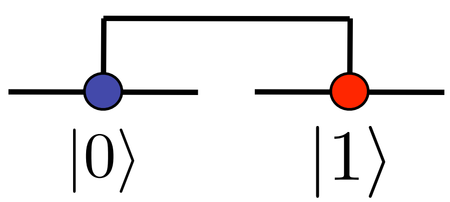
Advantages:

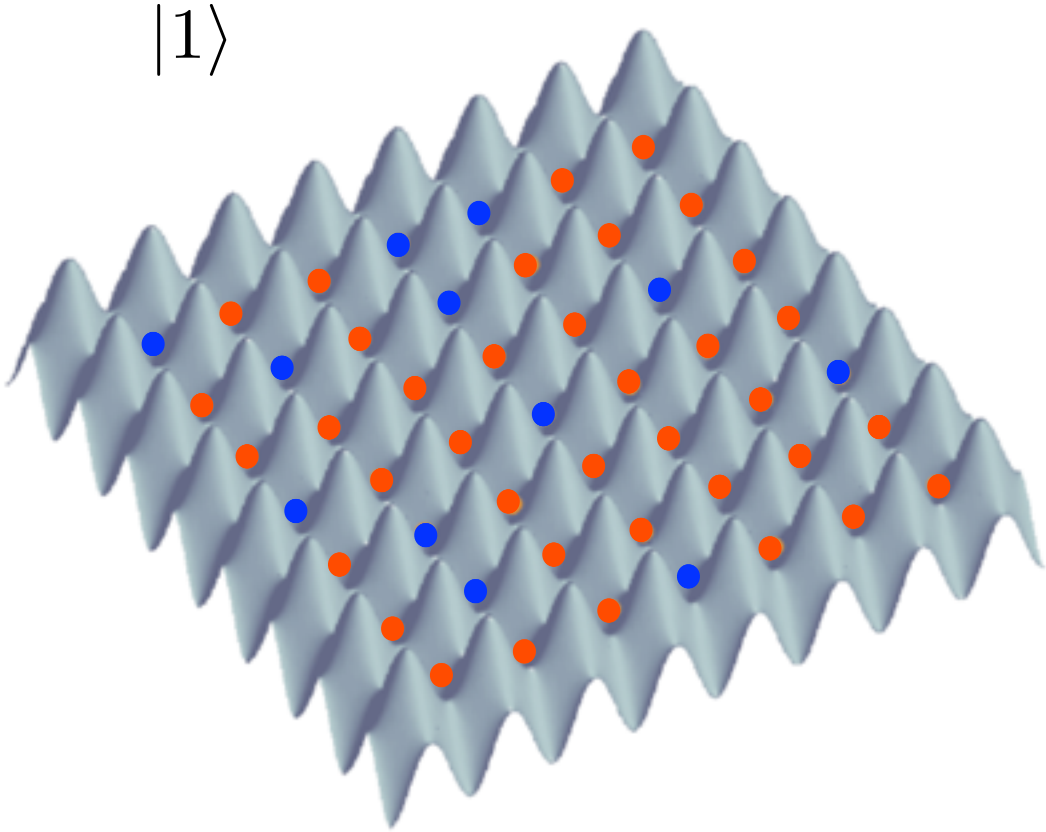
- Production of large quantum registers
- Massive parallelism in gate operations
- Long coherence times (>20s)

Difficulties:

- Gates typically slower than other implementations (~ms for collisional gates)
  (Rydberg gates can be somewhat faster)
- Individual addressing (but recently achieved)

Quantum Register with neutral atoms in an optical lattice

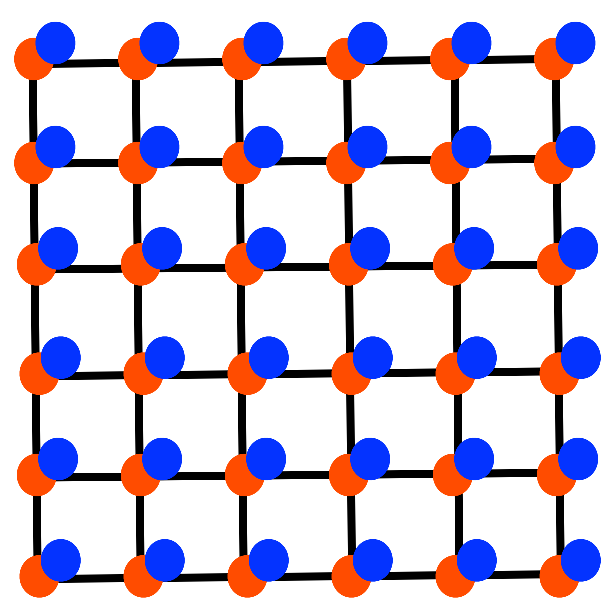


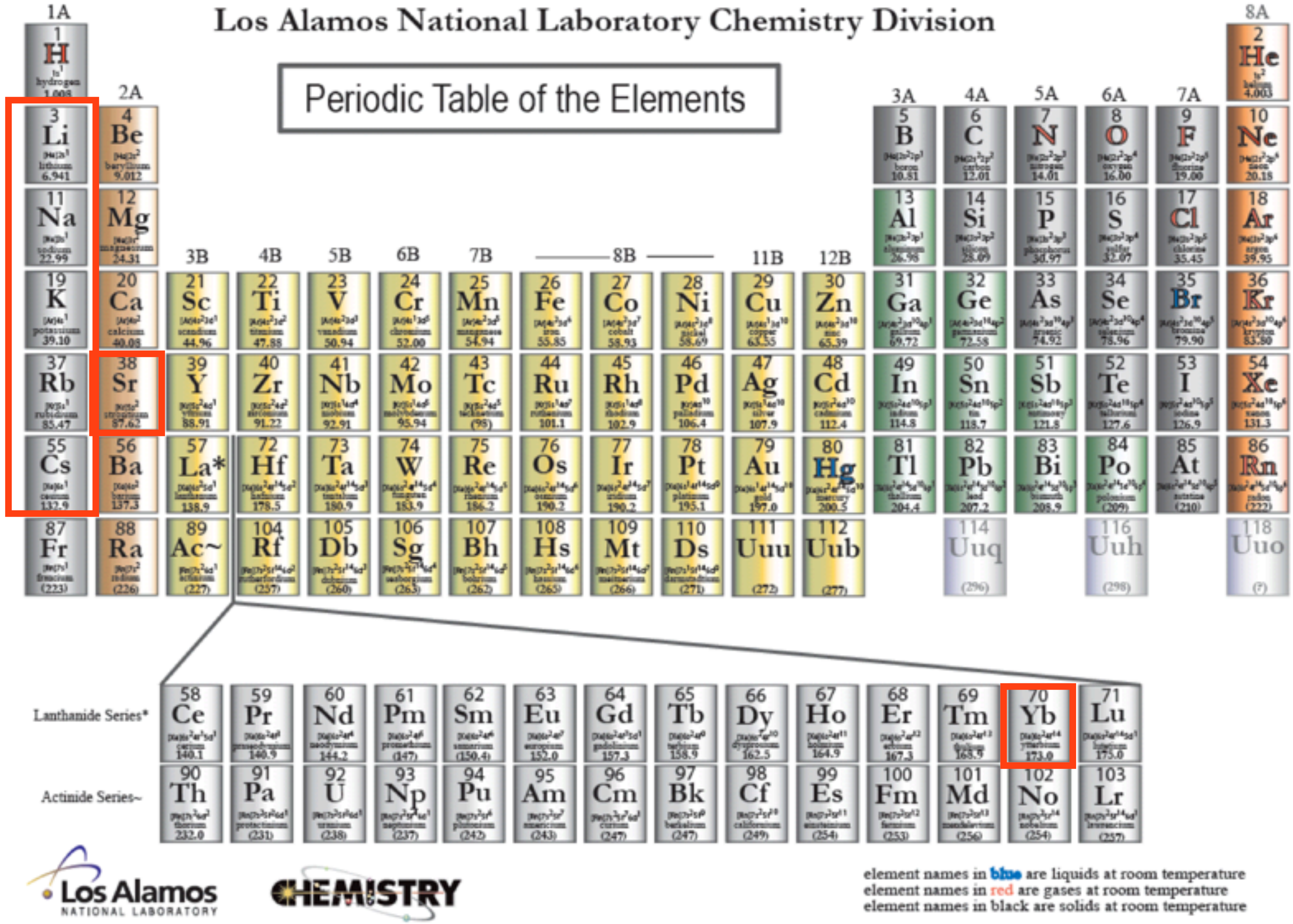


Requirements:

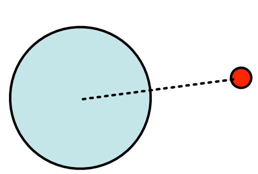
- Long lived storage of qubits
- Addressing of individual qubits
- Single and two-qubit gate operations

- Array of singly occupied sites
- Qubits encoded in long-lived internal states (alkali atoms - electronic states, e.g., hyperfine)
- Single-qubit via laser/RF field coupling
- Entanglement via Rydberg gates or via controlled collisions in a spin-dependent lattice





Rb:



Electron outside closed shell

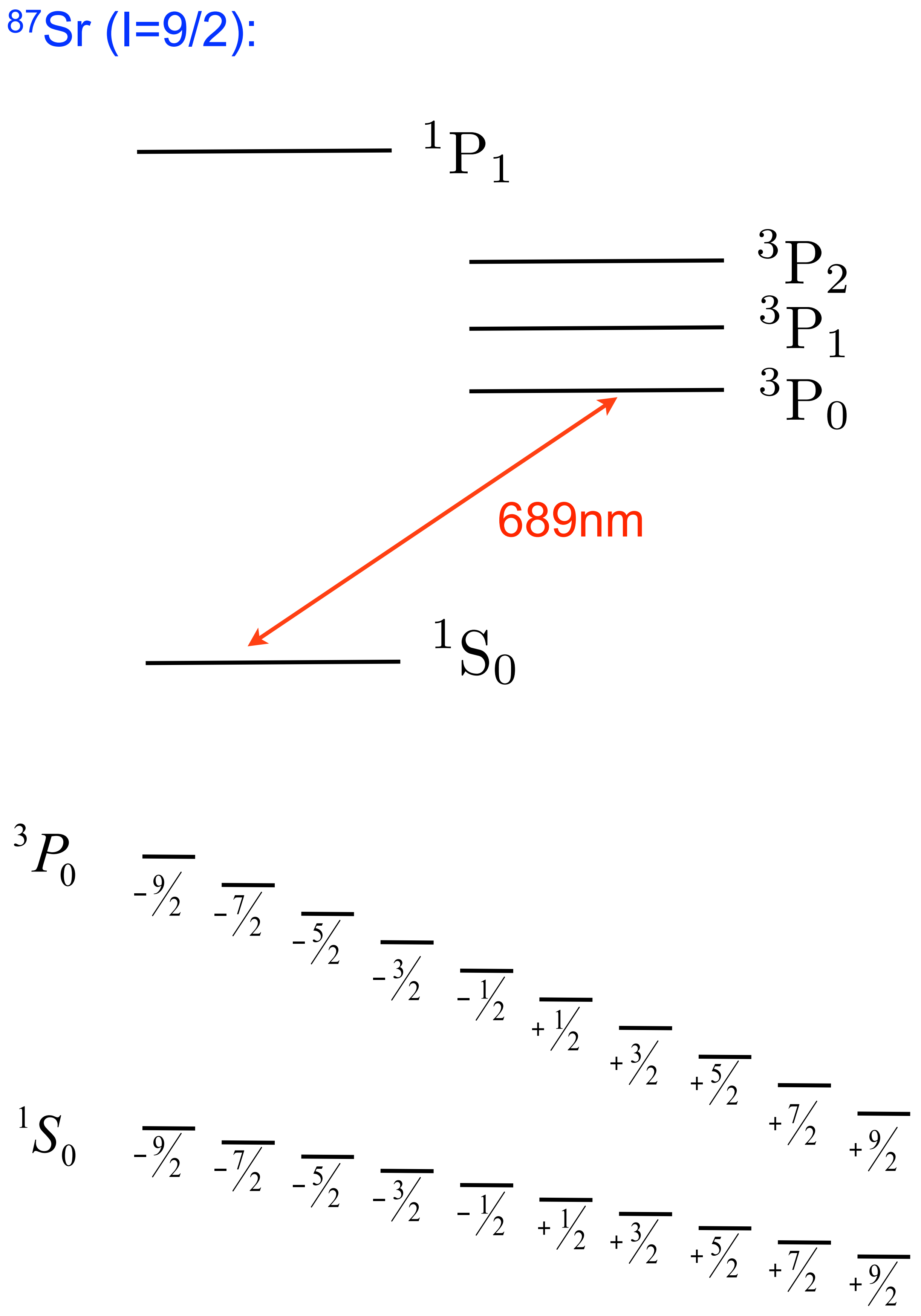
Quantum numbers: $n, l, m_l,$

$m_l = -l, \ldots l$

$1s^2 2s^2 2p^6 3s^2 3p^6 3d^{10} 4s^2 4p^6$ core

Group II Atoms

- Extensively developed, e.g., optical clocks
- Degenerate gases of Yb, Ca,...
- Stable lasers, especially for clock transition frequency

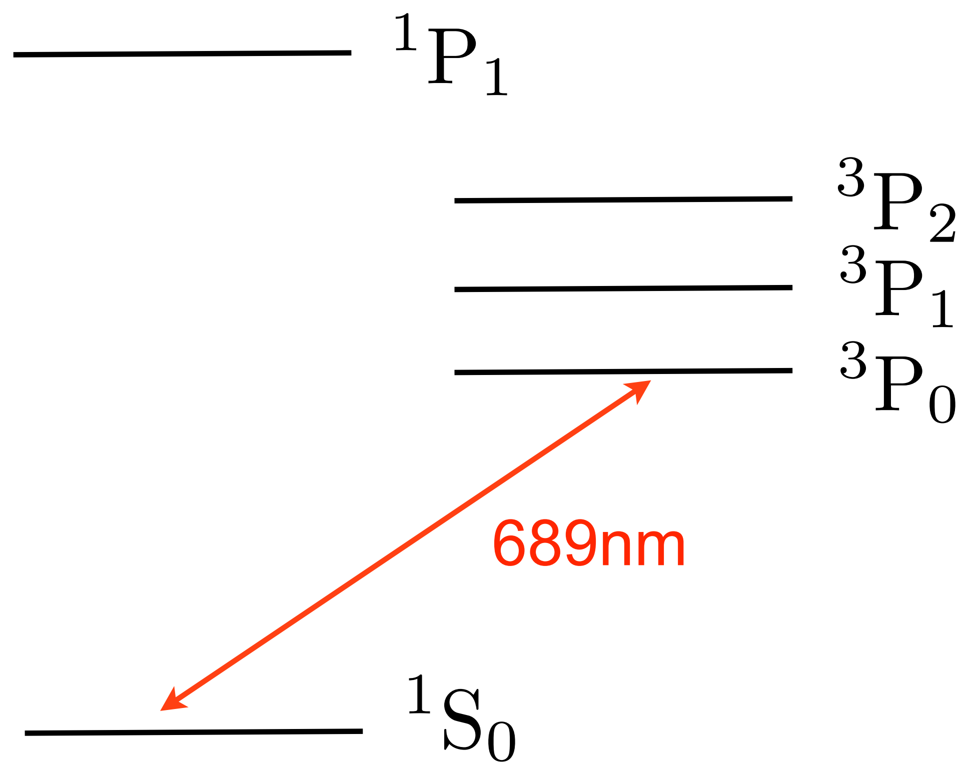


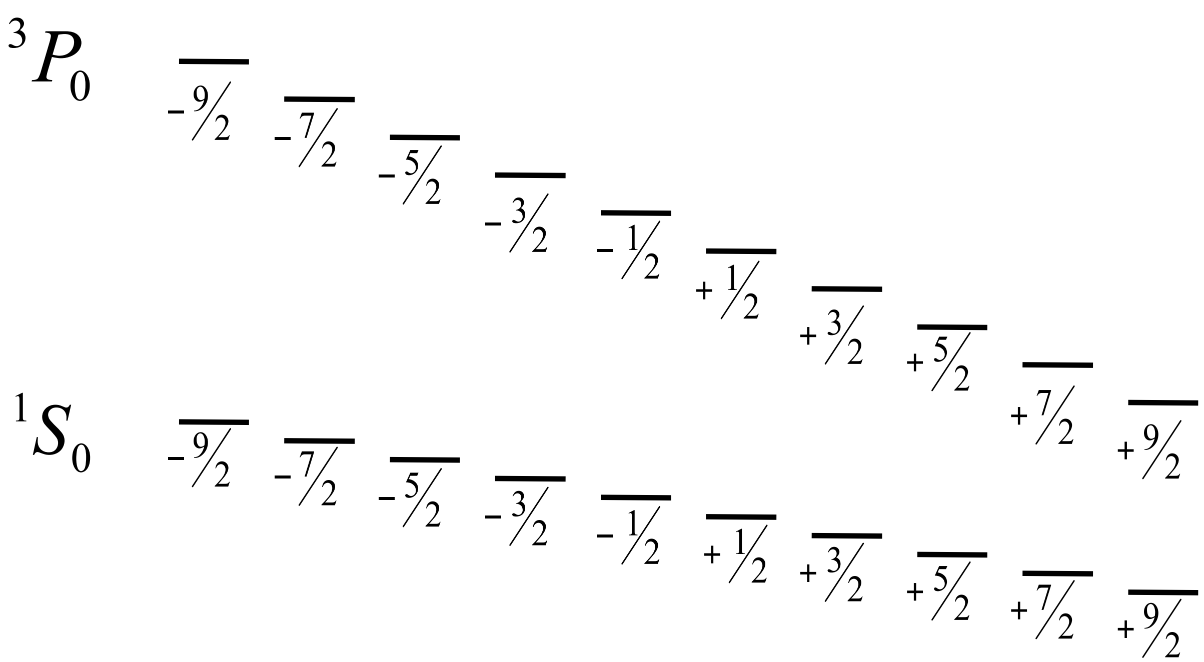
Key properties

- Metastable triplet states:
  - $^3P_0$ Lifetimes >150s (Fermions)
  - $^3P_1$ linewidth ~ kHz
  - $^3P_2$ lifetime >>150s
- Many nuclear spin levels for fermionic isotopes
- Nuclear spin states decoupled from electronic state on clock transition

Quantum Computing with Alkaline Earth Atoms

^{87}Sr (I=9/2):





Implementation of Quantum Computing:

- Nuclear spin states for qubit storage (insensitive to magnetic field fluctuations)

  D. Hayes, P. S. Julienne, and I. H. Deutsch, PRL 98, 070501 (2007)

  I. Reichenbach and I. H. Deutsch, PRL 99, 123001 (2007).

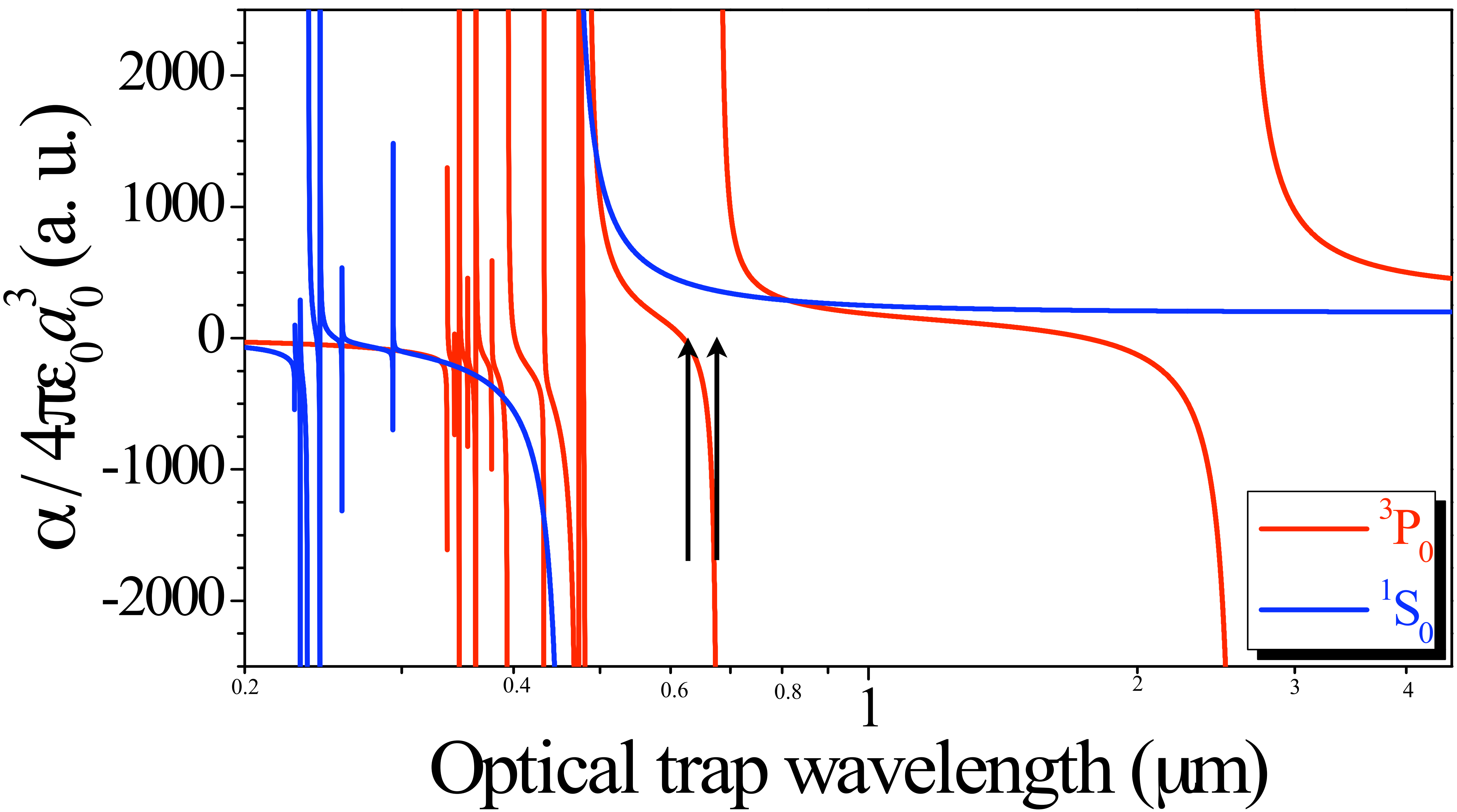
- Electronic state for:
  - Access to qubits
  - Gate operations

HERE: Via state-dependent lattices

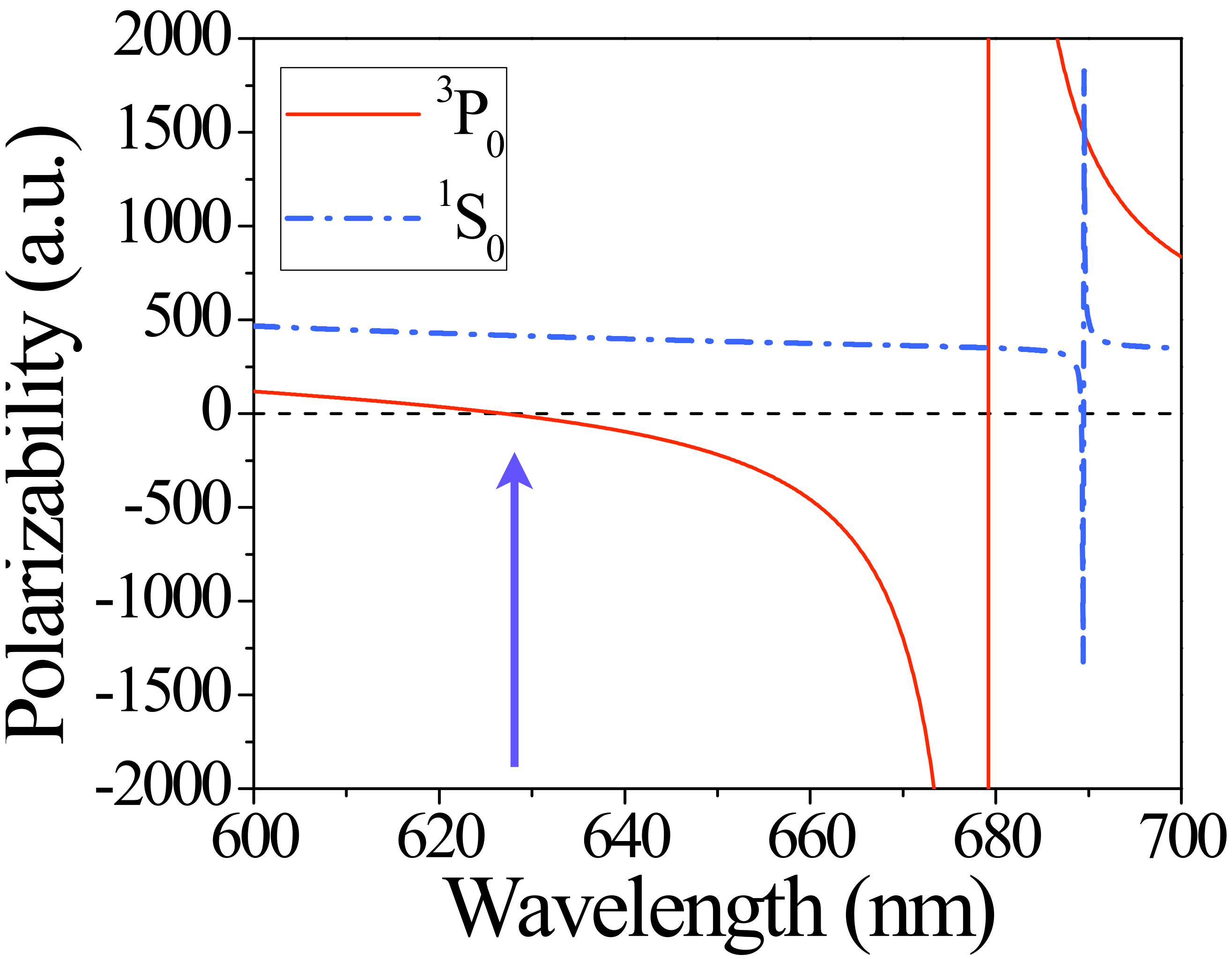
A. J. Daley, M. M. Boyd, J. Ye, and P. Zoller, Phys. Rev. Lett. **101**, 170504 (2008)

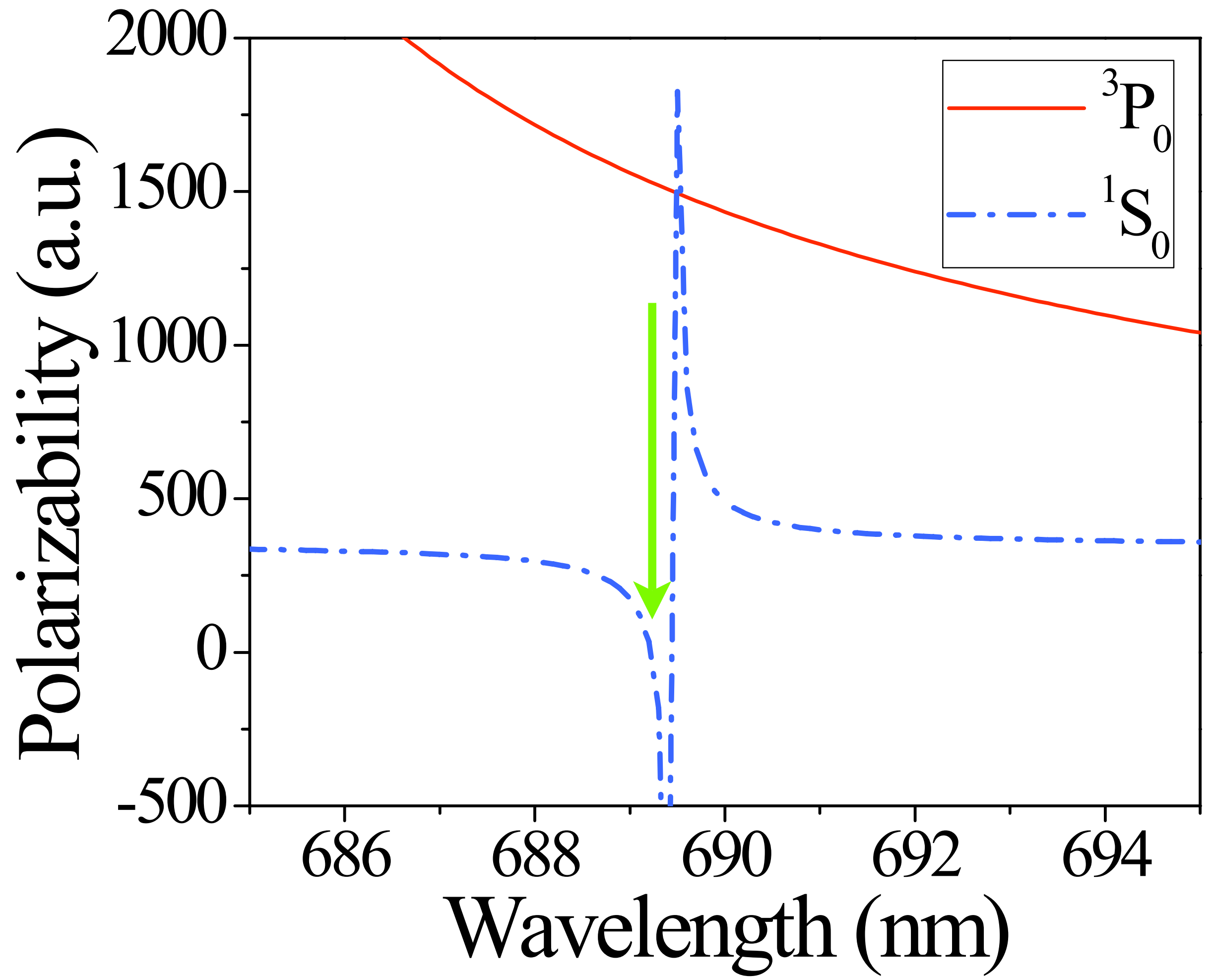
AC Polarisability (AC-Stark Shift per intensity) for ^{87}Sr

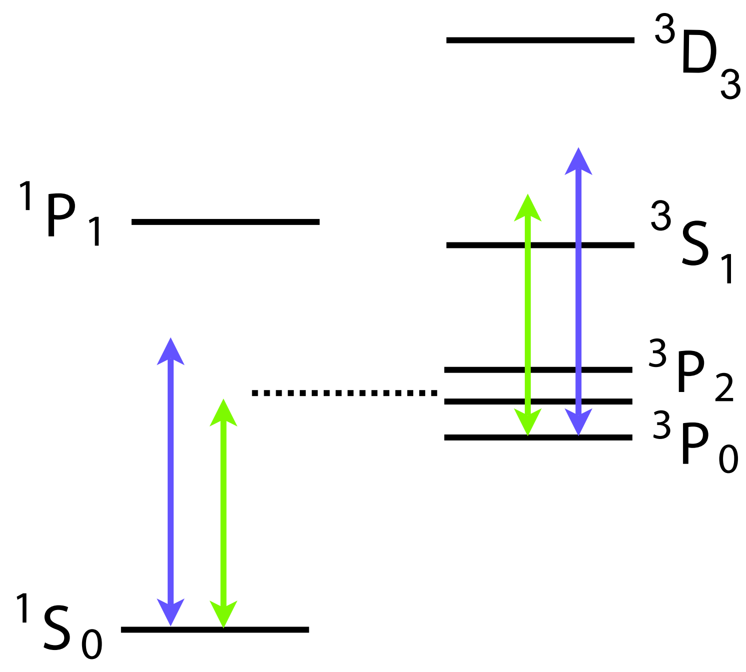
Ye, Kimble, & Katori, Science 320, 1734 (2008).

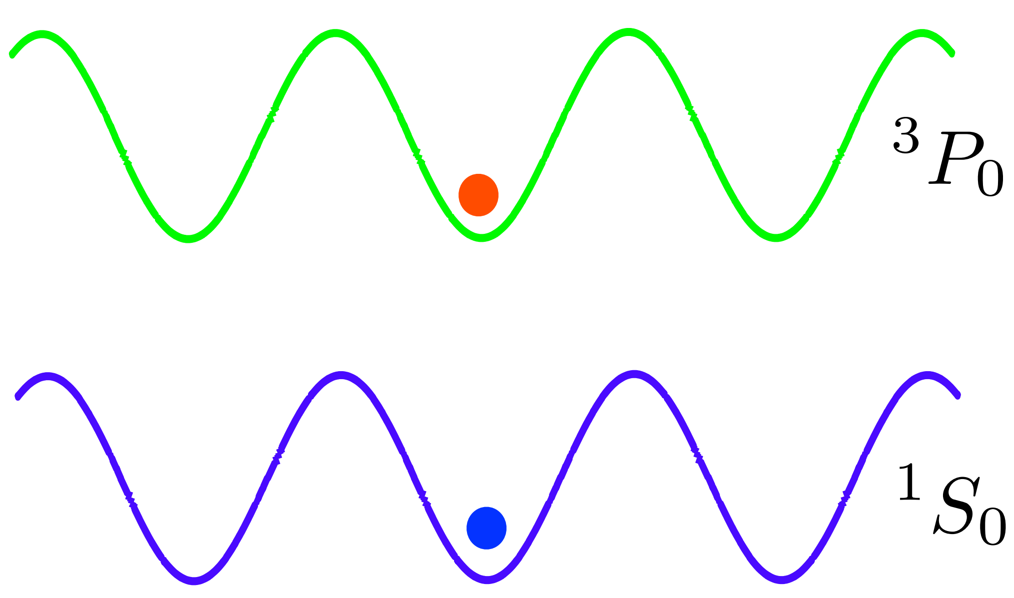


Polarizability and State-dependent lattices:

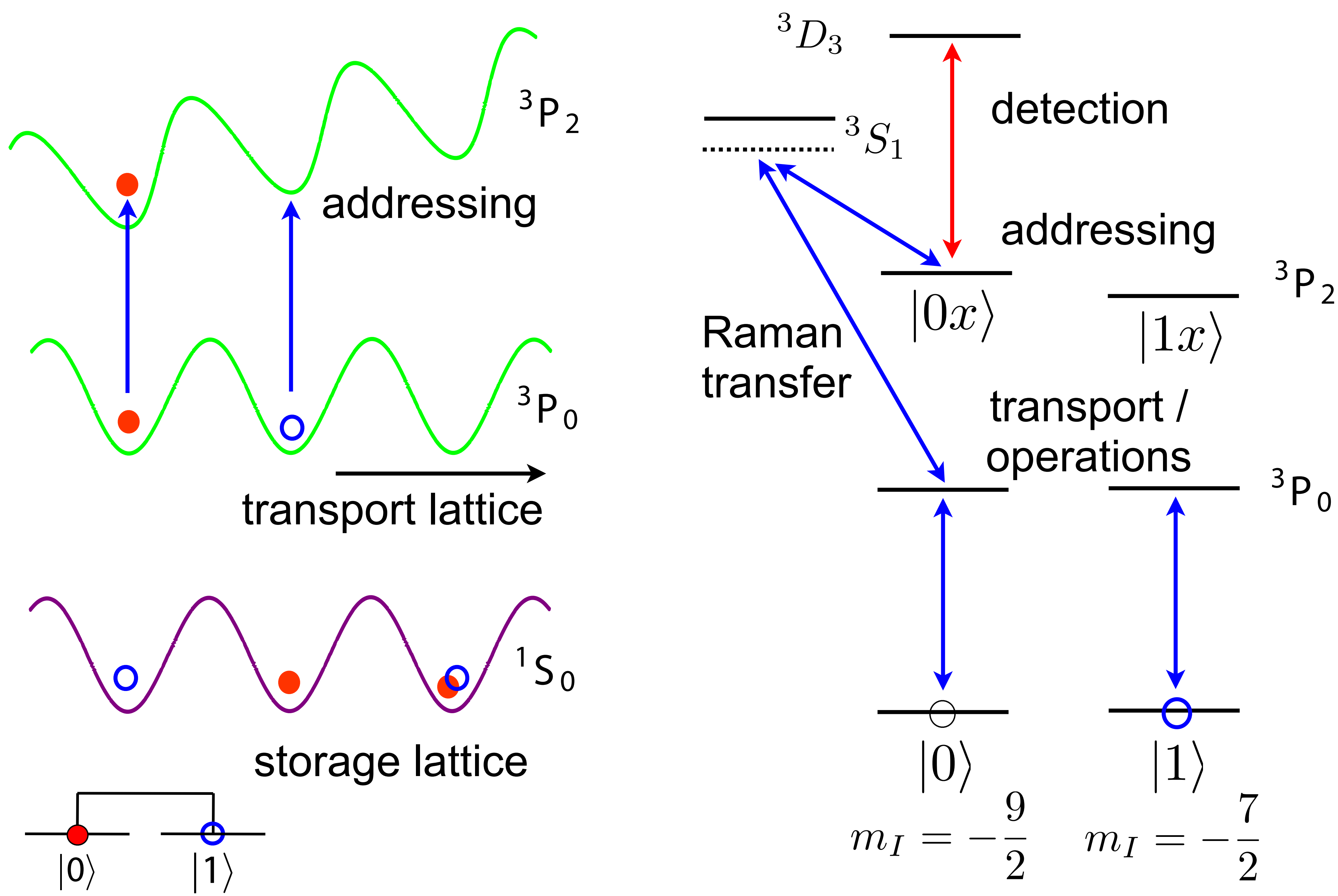








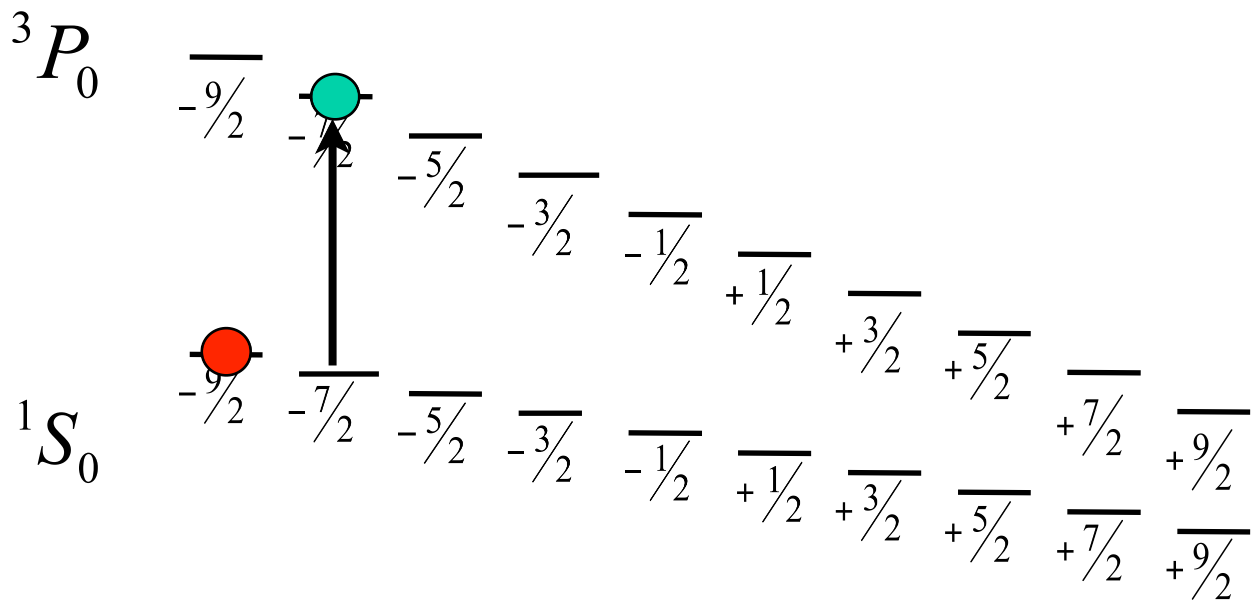
Quantum computing with Alkaline Earth Atoms



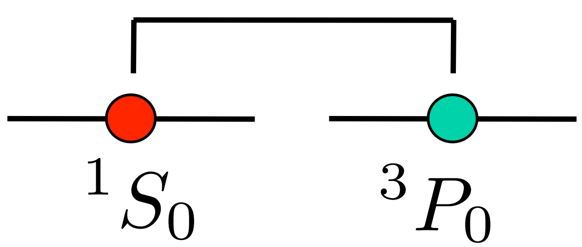
Key ideas:

- Independent Lattices for $^3P_0$ and $^1S_0$ states: storage and transport
- Qubits encoded on nuclear spin states, relatively insensitive to magnetic fields
- Local addressing via $^3P_2$ level, which shifts in a gradient field (100 G/cm - 410 MHz/cm, 15 kHz shift between neighbouring sites)

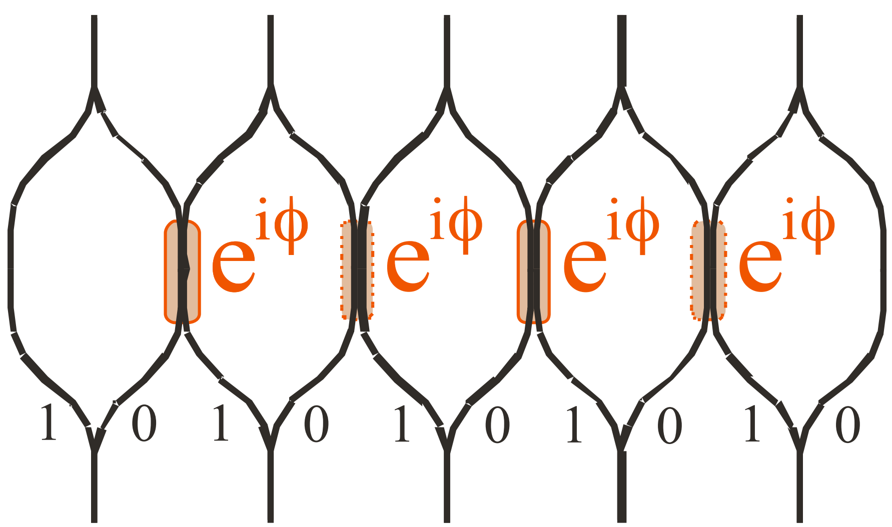
Collisional Gates (simple example):

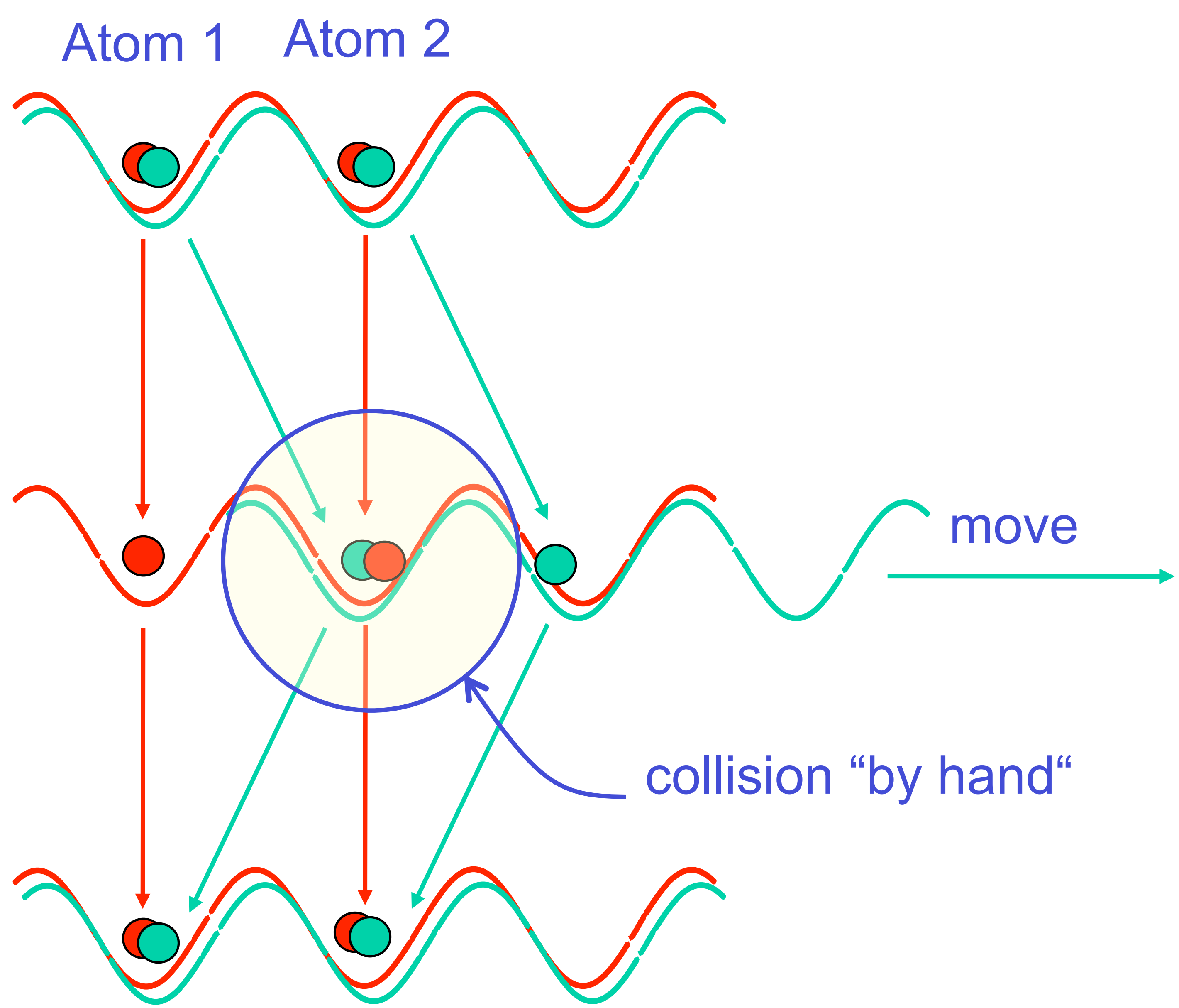


- Gate: controlled collisions
  D. Jaksch et al., PRL 82, 1975 ('99)
- Operation performed in parallel for whole system
- Simple preparation of a cluster state
- Ideal setup for measurement-based quantum computing.



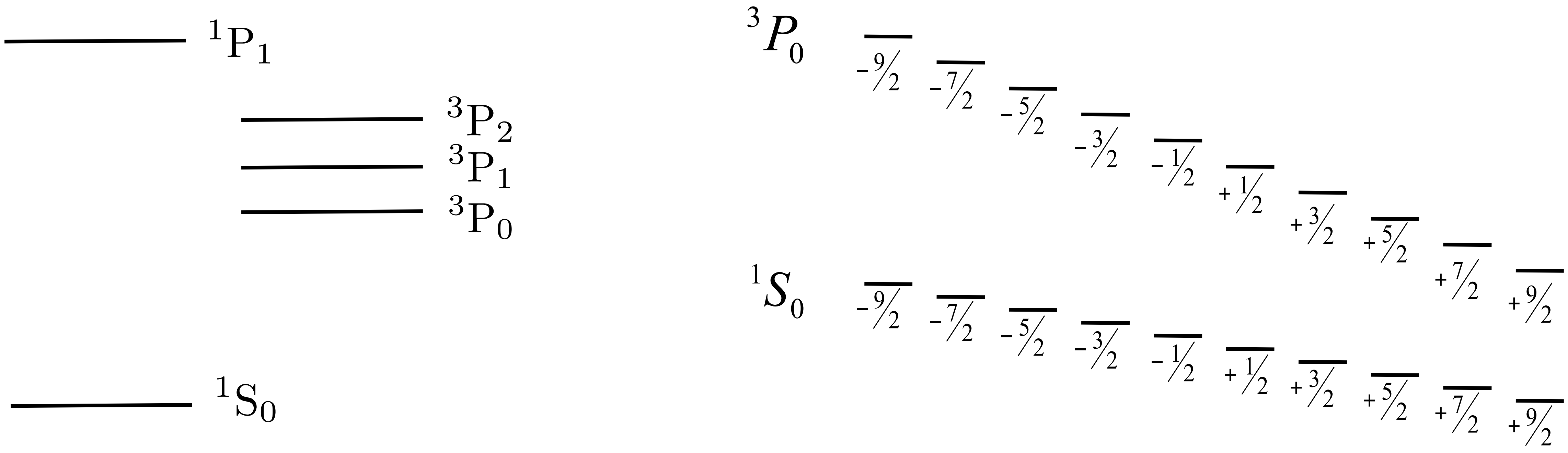
internal states





Extensions:

- Use additional nuclear spins: Quantum register encoded on a single atom



- Flying qubits, e.g., coupling to an optical cavity

Requirements:

- Scalable physical system, well-defined qubits
- Initialisable to a fiducial state such as |000...>
- Long coherence times
- Universal set of quantum gates
- High efficiency, Qubit-specific measurements

Selected numbers:

Gate/readout Timescales:

- Lattice trapping frequency: 25 - 100 kHz / collisional gate limit

Addressing

- $^3P_2$ Shift m_F=-13/2: 100 G/cm: 410 MHz / cm (ca. 15kHz per lattice site)
- $^1S_0$/$^3P_0$ Shifts: 100 G/cm: ca. 1Hz / m_I per lattice site

Spontaneous emission lifetime T_1 (25kHz trap frequency lattices for $^1S_0$ and $^3P_0$):

- Storage $^1S_0$: 20s
- Operations $^3P_0$ / $^3P_2$: 2s / 1s

Decoherence from Magnetic field fluctuations (T_2)

- $^1S_0$ shift: -185 Hz/G - Decoherence in mG fluctuations <<1 Hz,
- $^3P_0$ shift: -195 Hz/G

Lossy blockade gates:

- $^3P_2$-$^3P_2$ loss: 20 kHz

Realisations underway: Kyoto (in lattices)
Innsbruck, Houston (degenerate gases)

Ion traps

Advantages:

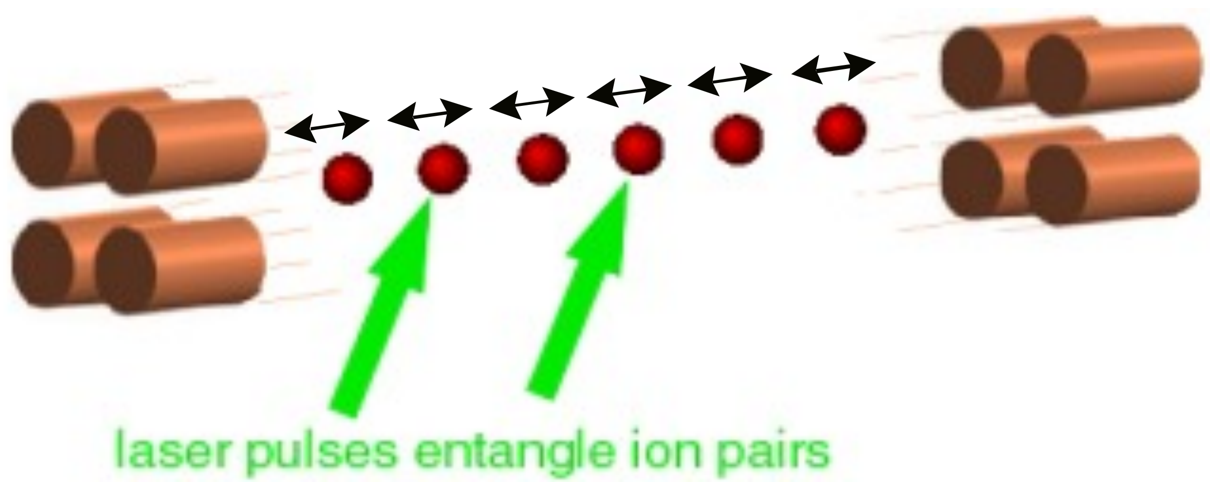
- Long coherence times (>20s for nuclear spins)
- Basic gates somewhat faster than neutral atoms (~0.01 ms)
- Individual addressing straightforward
- High-precision experiments already commonplace (also optical clocks)

Difficulties:

- Scaling to many qubits requires complicated traps
- Slower gates than many solid state implementations

Ion Trap Quantum Computer '95

- Cold ions in a linear trap



Qubits: internal atomic states

1-qubit gates: addressing ions with a laser

2-qubit gates: entanglement via exchange of phonons of quantized collective mode

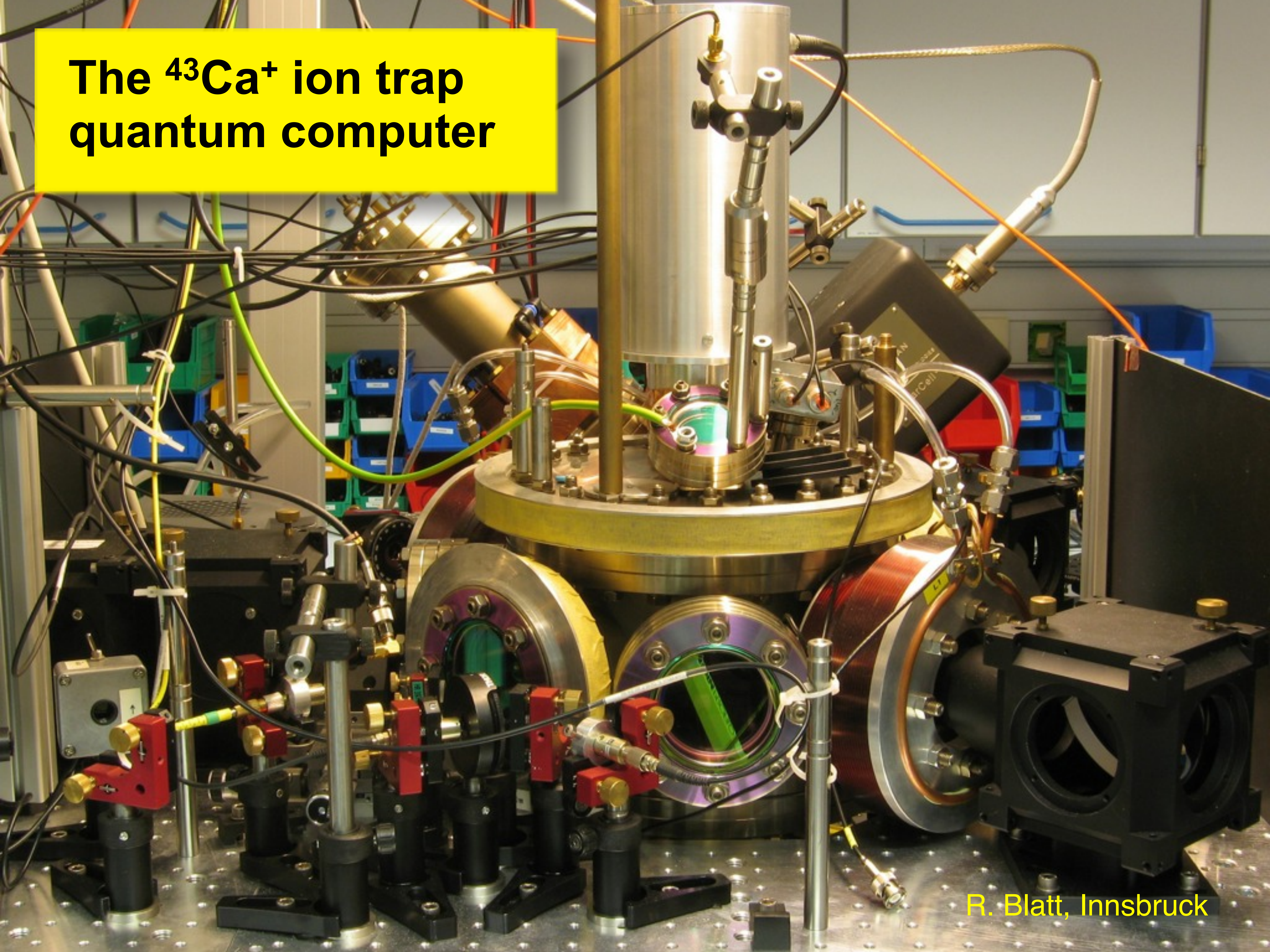
- State vector

$$|\Psi\rangle = \sum c_x |x_{N-1}, \ldots, x_0\rangle_{\text{atom}} \quad |0\rangle_{\text{phonon}}$$

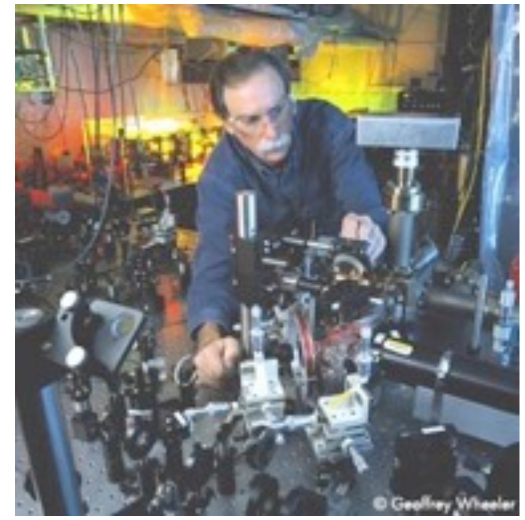
quantum register — data bus

- QC as a time sequence of laser pulses
- Read out by quantum jumps

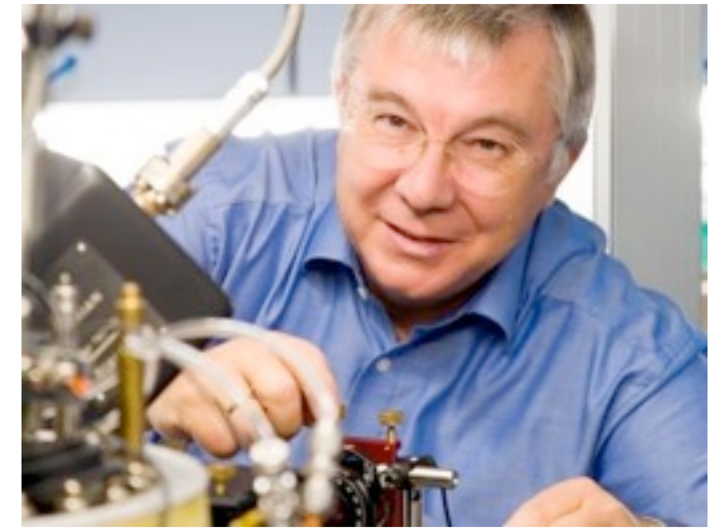
The $^{43}Ca^{+}$ ion trap quantum computer



R. Blatt, Innsbruck



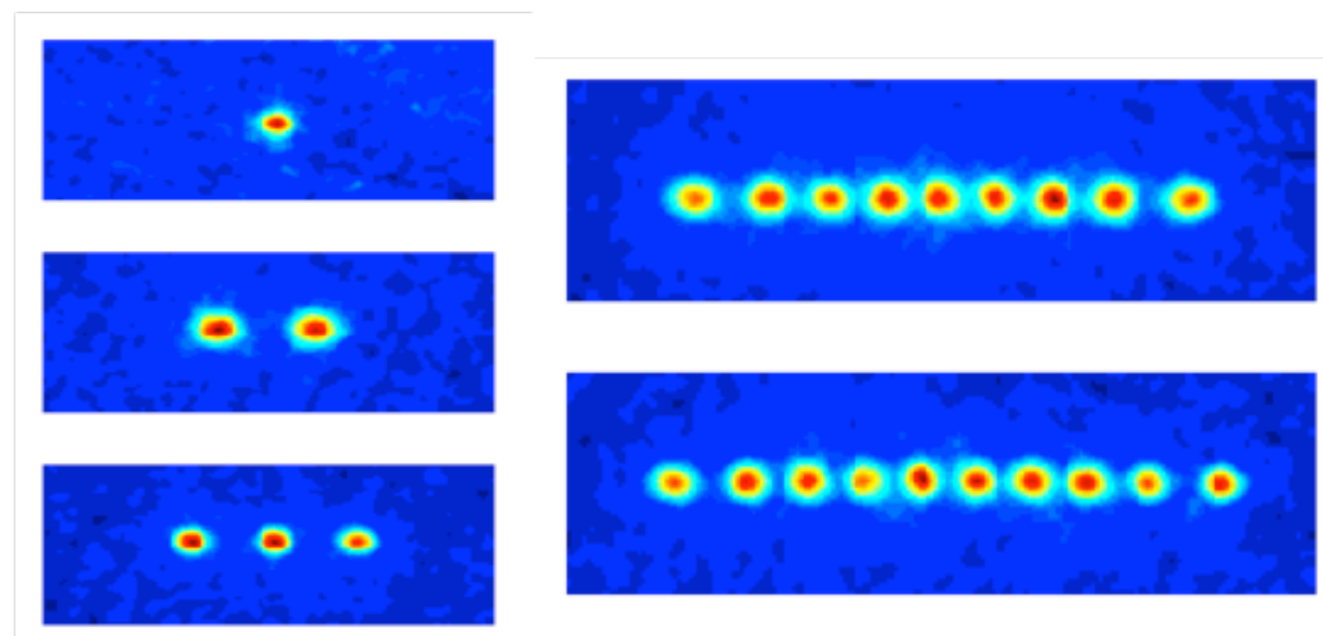
D.Wineland
NIST



R.Blatt
Innsbruck

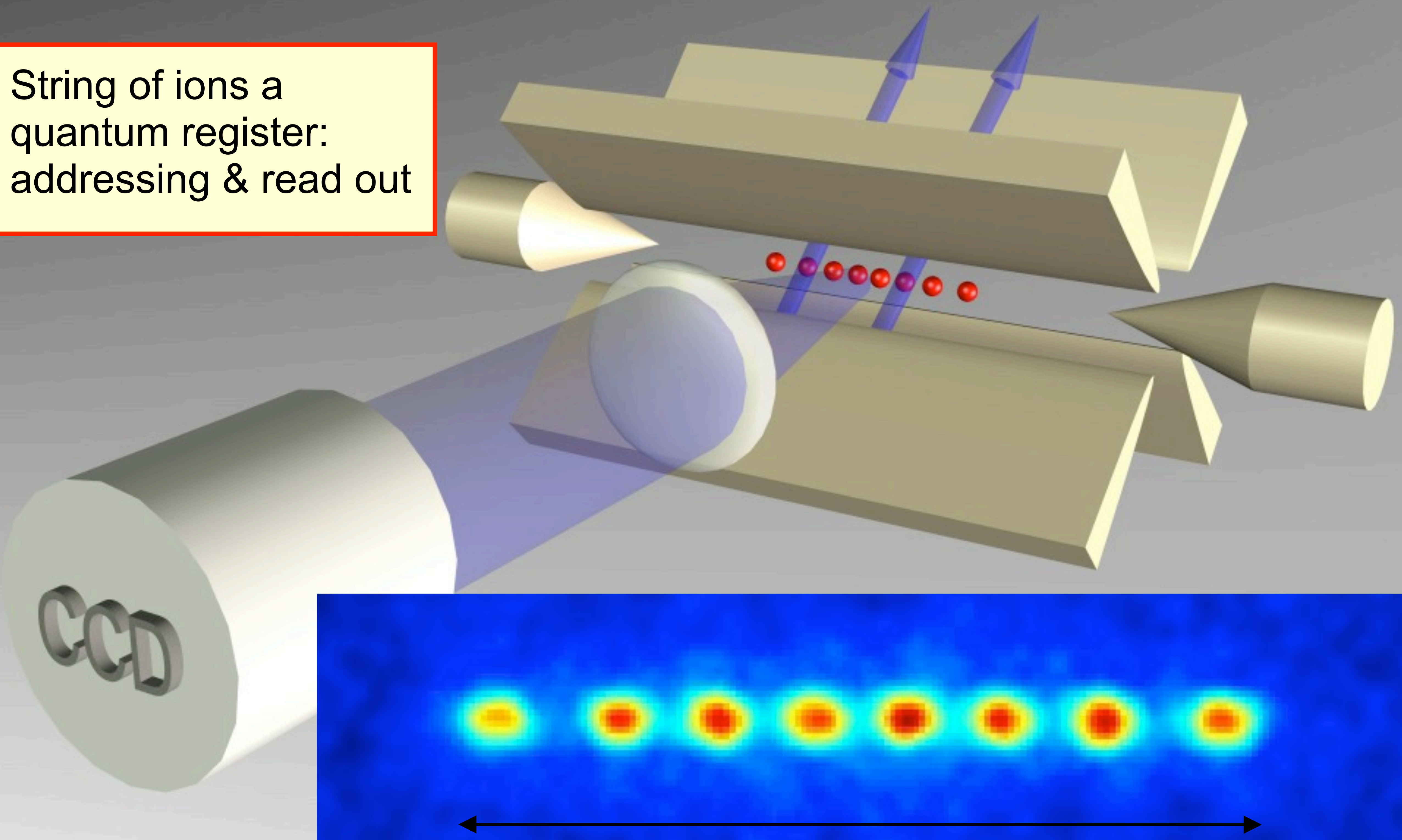
What has been achieved in the laboratory

- 2 … 15 ions / qubits
  - high fidelity quantum gates
  - simple algorithms
  - teleportation (within a trap)
  - error correction
  - quantum simulation algorithms



String of $^{40}Ca^{+}$ Ions in a Linear Paul Trap

String of ions a quantum register: addressing & read out



R. Blatt@Innsbruck

Addressable Cirac-Zoller 2-ion Controlled-NOT

truth table CNOT:

$\|0\rangle\|0\rangle$	$\rightarrow$	$\|0\rangle\|0\rangle$
$\|0\rangle\|1\rangle$	$\rightarrow$	$\|0\rangle\|1\rangle$
$\|1\rangle\|0\rangle$	$\rightarrow$	$\|1\rangle\|1\rangle$
$\|1\rangle\|1\rangle$	$\rightarrow$	$\|1\rangle\|0\rangle$

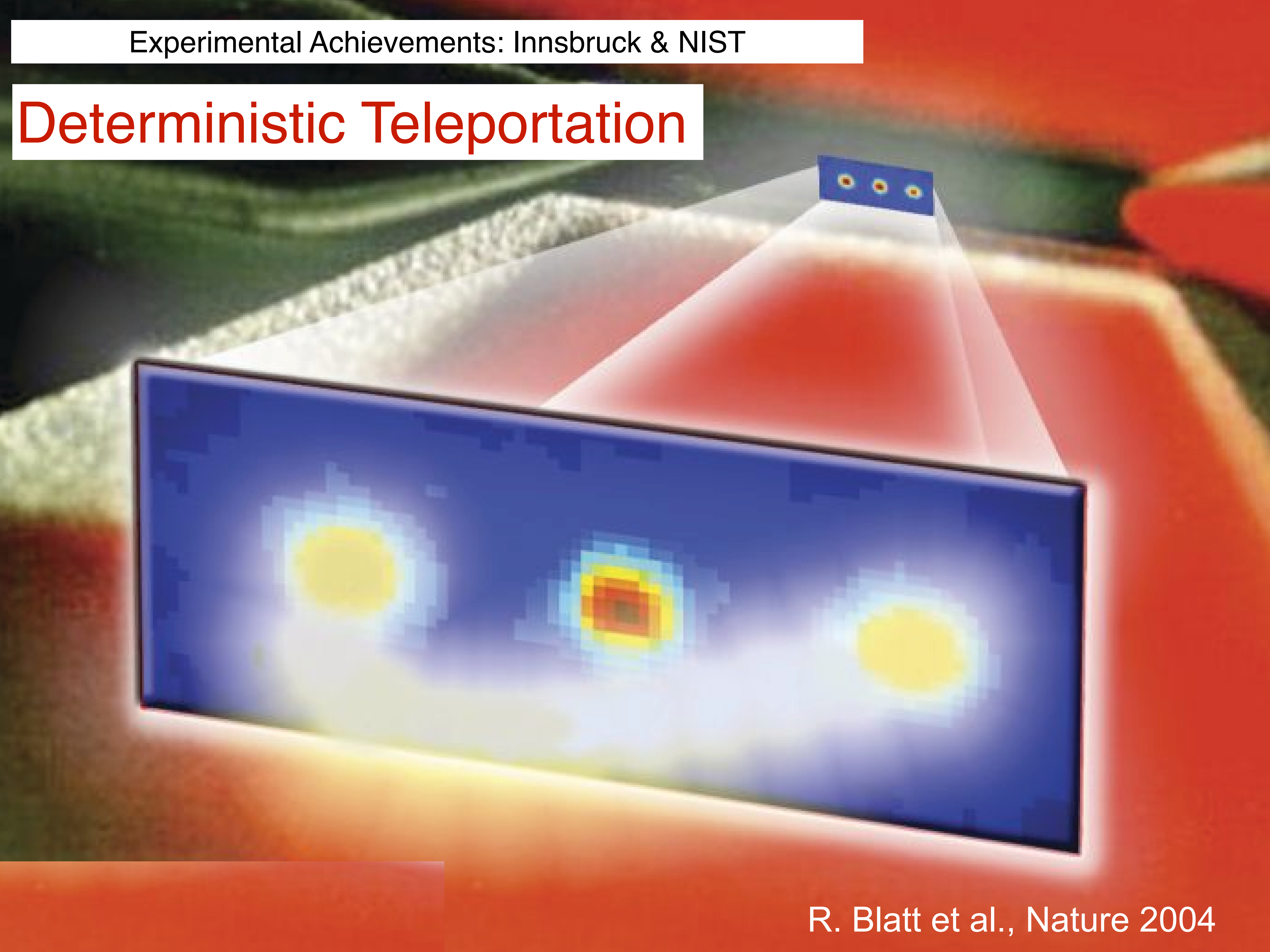
Control   Target

fidelity F=0.993

R. Blatt et al., Nature 2003;
Nature Physics 2008

Experimental Achievements: Innsbruck & NIST

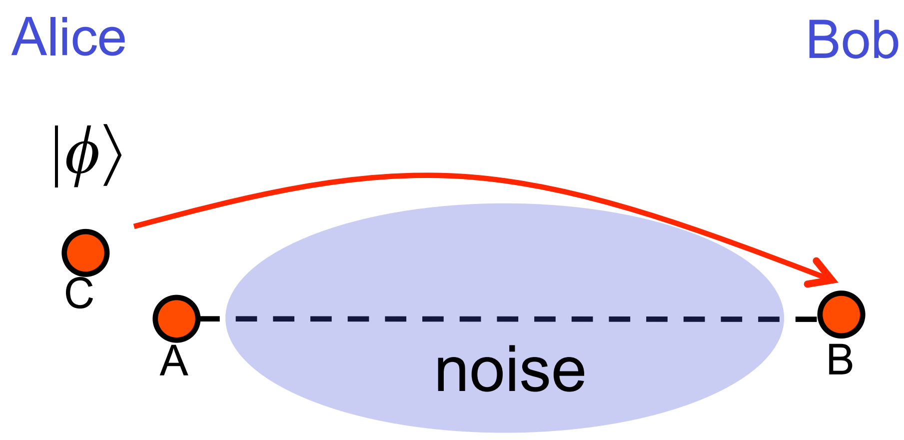
Deterministic Teleportation



R. Blatt et al., Nature 2004

Deterministic Teleportation

If Alice and Bob share a singlet (EPR) pair as a resource, we can teleport the unknown quantum state

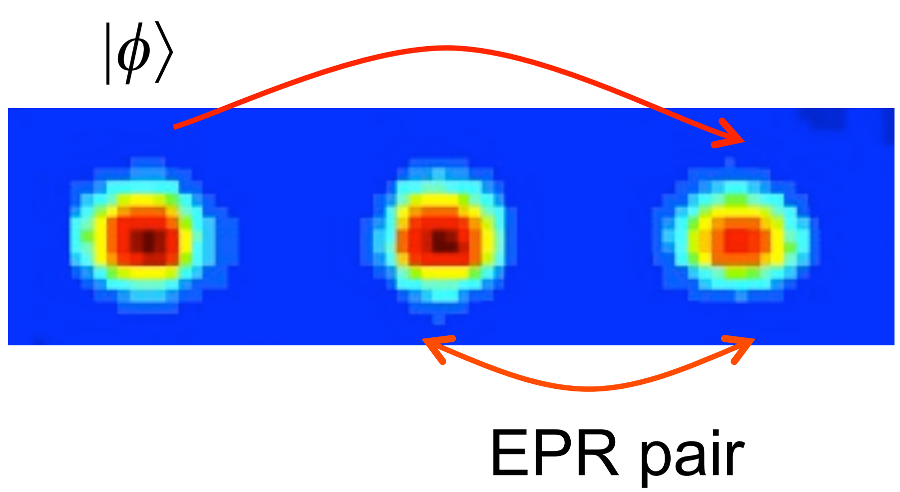


$$|\text{EPR}\rangle \sim |0\rangle_A|1\rangle_B - |1\rangle_A|0\rangle_B$$

Protocol:

- ✓ CNOT between A&C
- ✓ measure A&C
- ✓ classical communication Alice to Bob
- ✓ rotate B

- **Innsbruck ion trap experiment:**



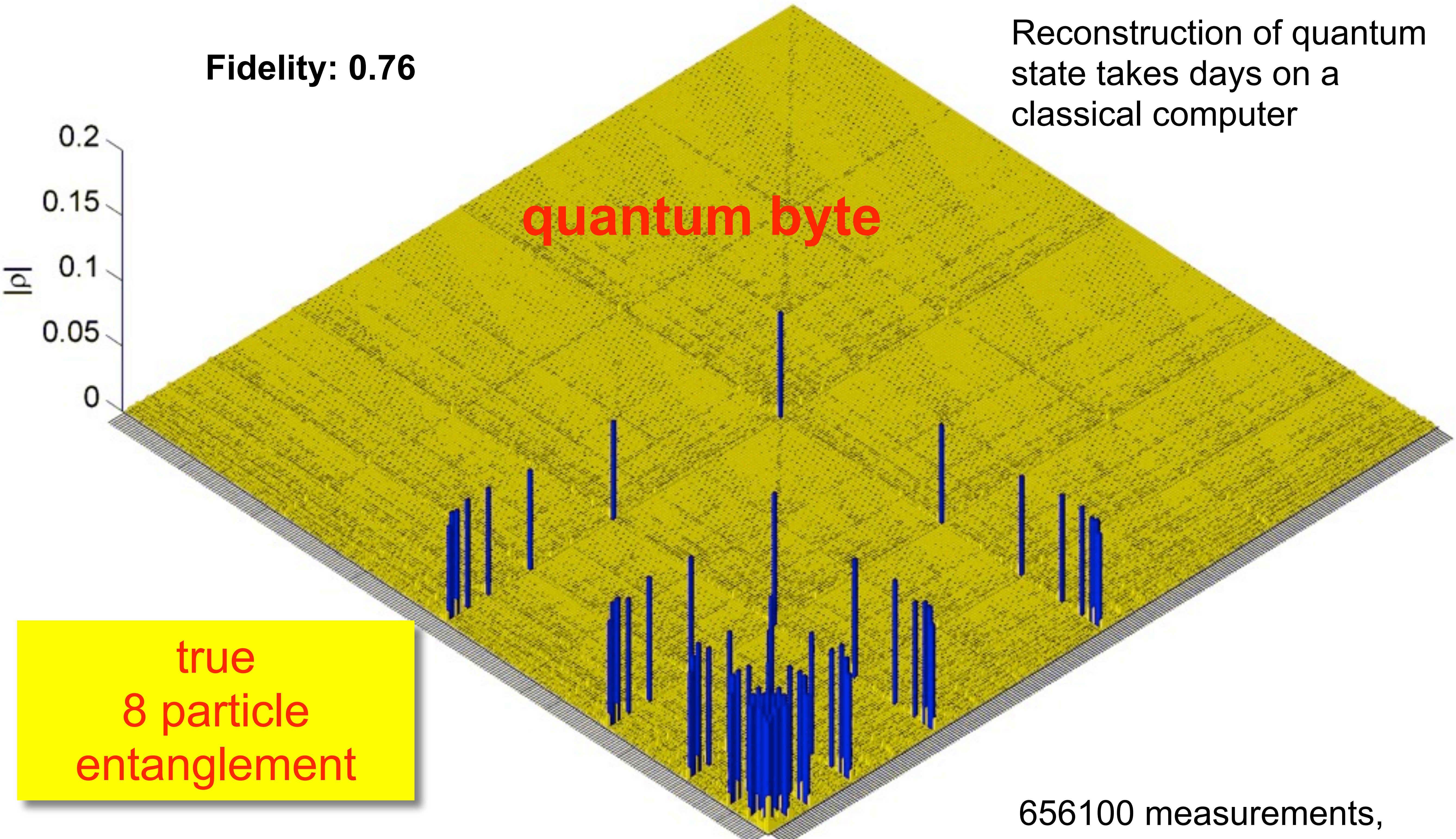
deterministic teleportation:

- ✓ no postselection
- ✓ complete Bell measurement
- ✓ on demand
- ✓ only 10 μm ☹

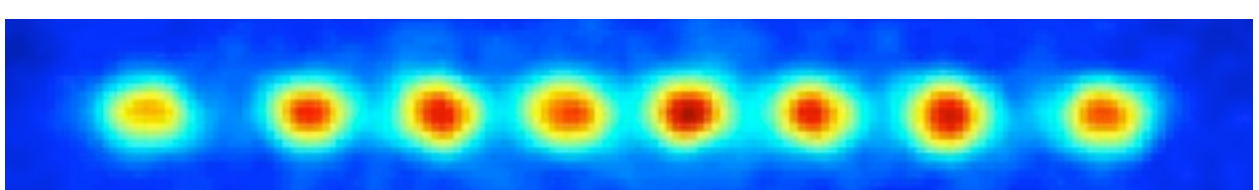
Quantum Byte

Fidelity: 0.76

Reconstruction of quantum state takes days on a classical computer



true
8 particle
entanglement



656100 measurements,
~ 10 h measurement time total

R. Blatt et al., Nature 2006

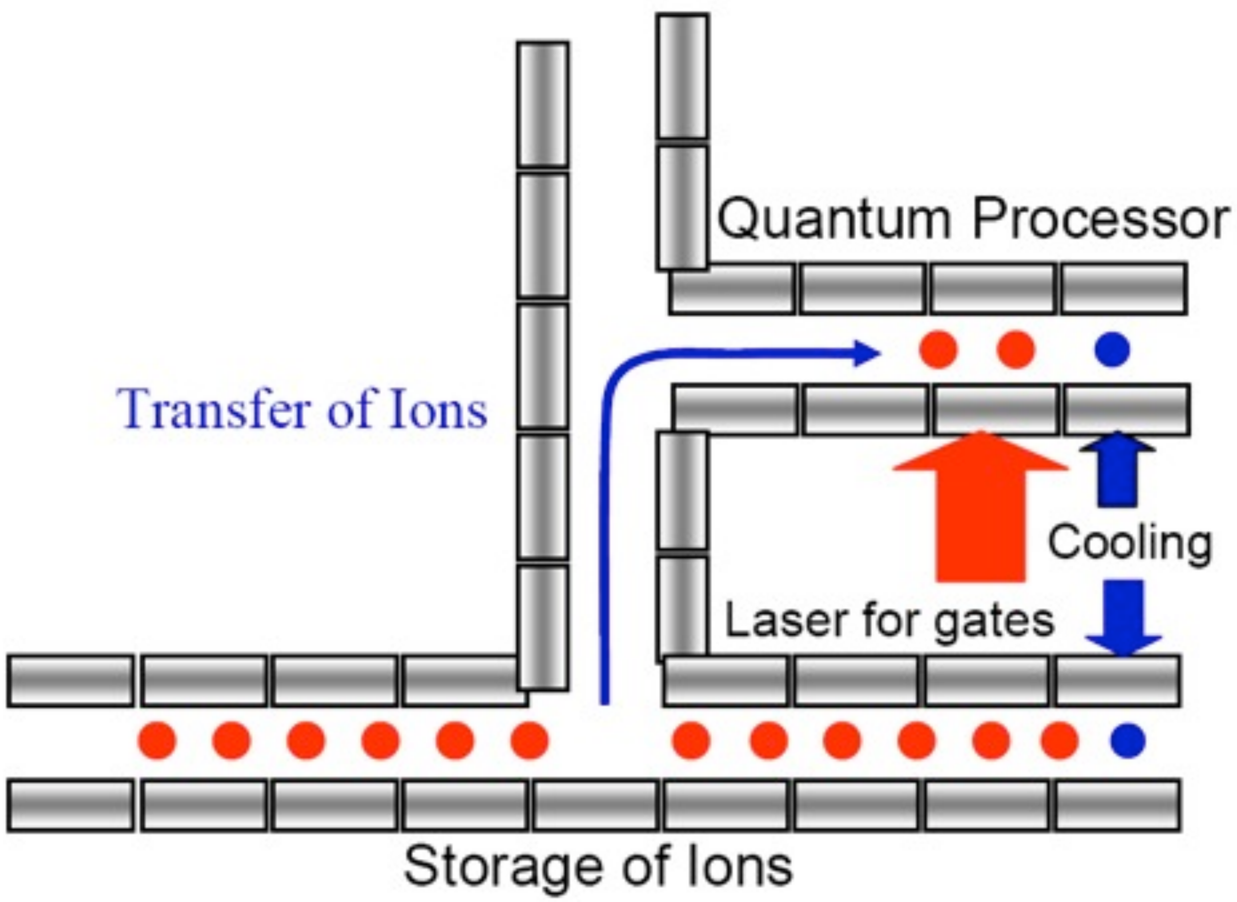
Scalability: Multizone Traps

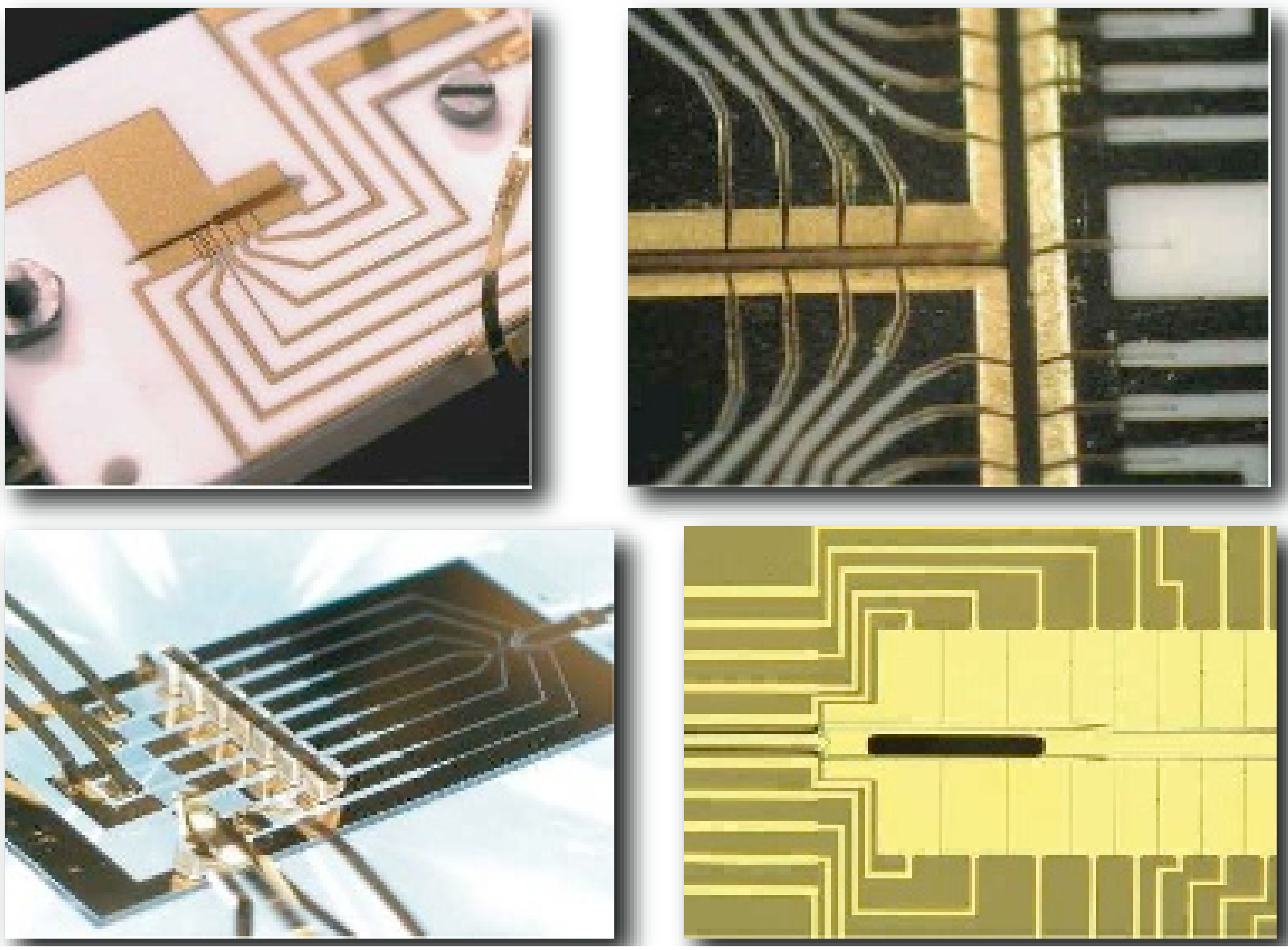
idea: Wineland et al.

exp.: Innsbruck, NIST Boulder, Michigan, Oxford,...

- **implementation:** physically sending the qubit

ion trap quantum computer





R. Slusher, Georgia Tech

Nitrogen-Vacancy Centers

Advantages:

- Combine advantages of atomic systems with solid state
- Faster gate times (<μs) but faster decoherence (~2ms)
- Room-temperature operation

Difficulties:

- Lack of uniformity in qubit frequency
- Coupling qubits is more difficult (e.g., optical processes)

Pitt: Experiments in group of G. Dutt

NV-center in diamond

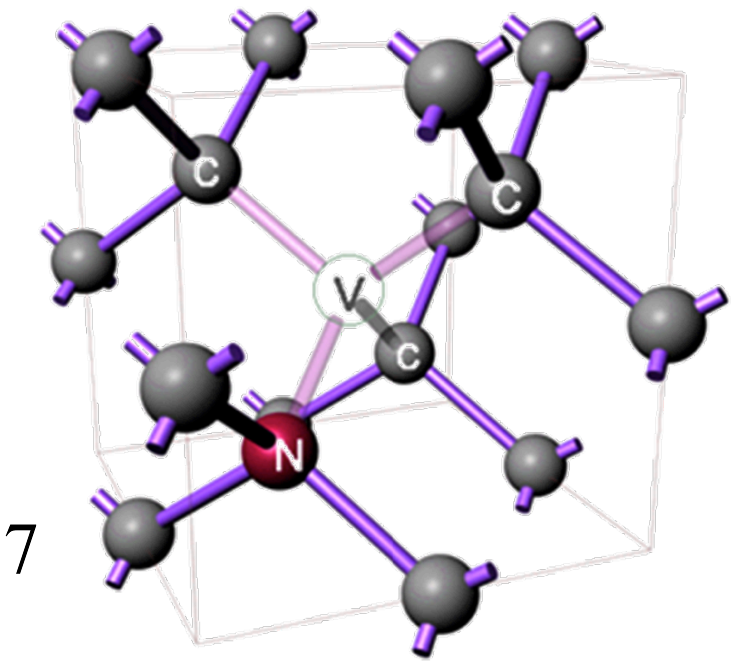
- Substitutional nitrogen atom replaces a single carbon atom in the lattice.
  - P1 centers (S=1/2)

- Vacancy (missing carbon in the lattice) becomes mobile at 450°C, but forms a stable NV center when pairing with N

- Two flavors (NV^0 and NV^-) have different optical properties.

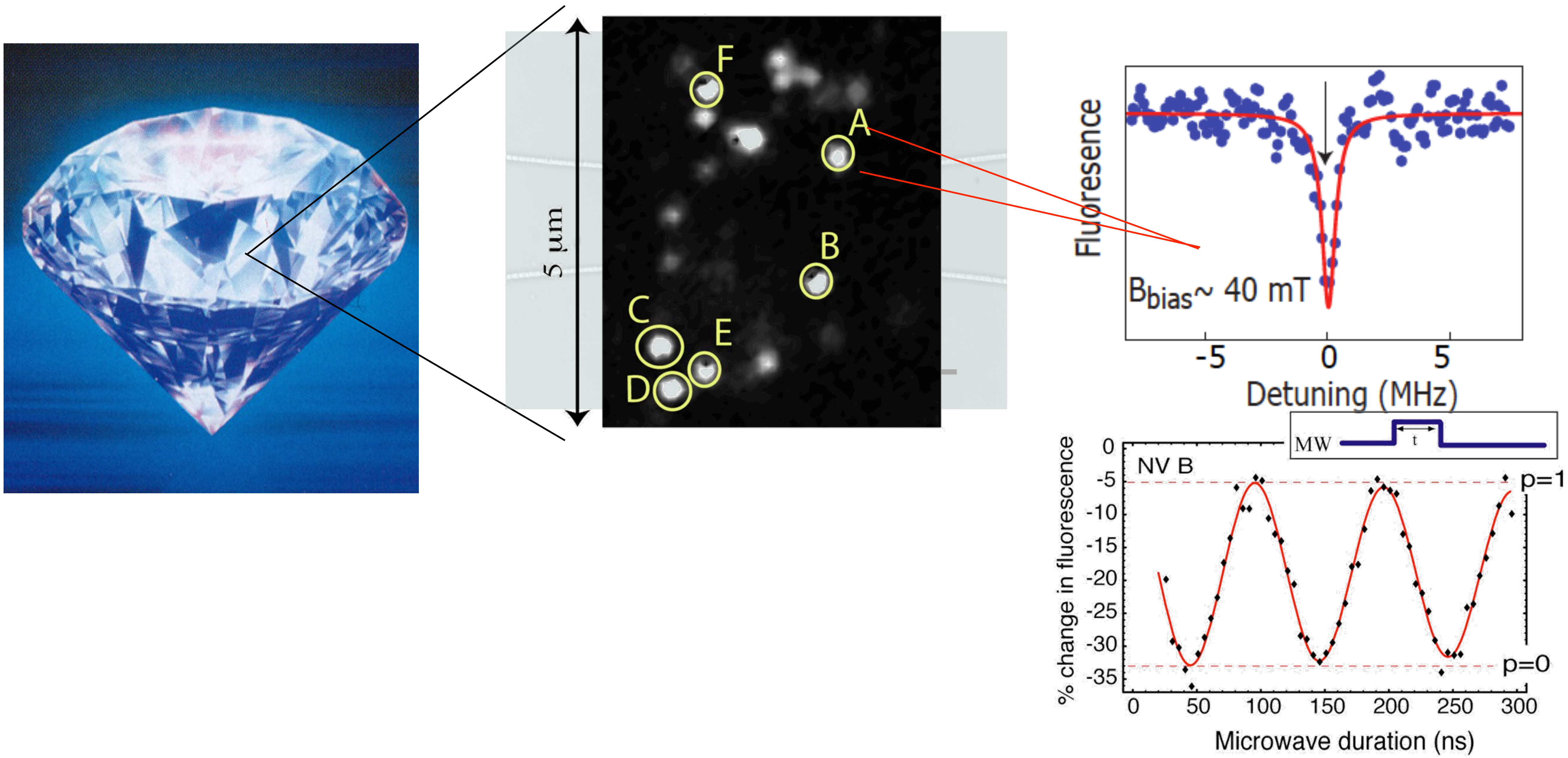
- NV^-: Excite with 532 nm off-resonantly or resonantly with 637 nm, emission at 637 nm (ZPL) or 638 – 720 nm (PSB).

- Good single photon emitter.



Early work:
S.Rand, N.Manson

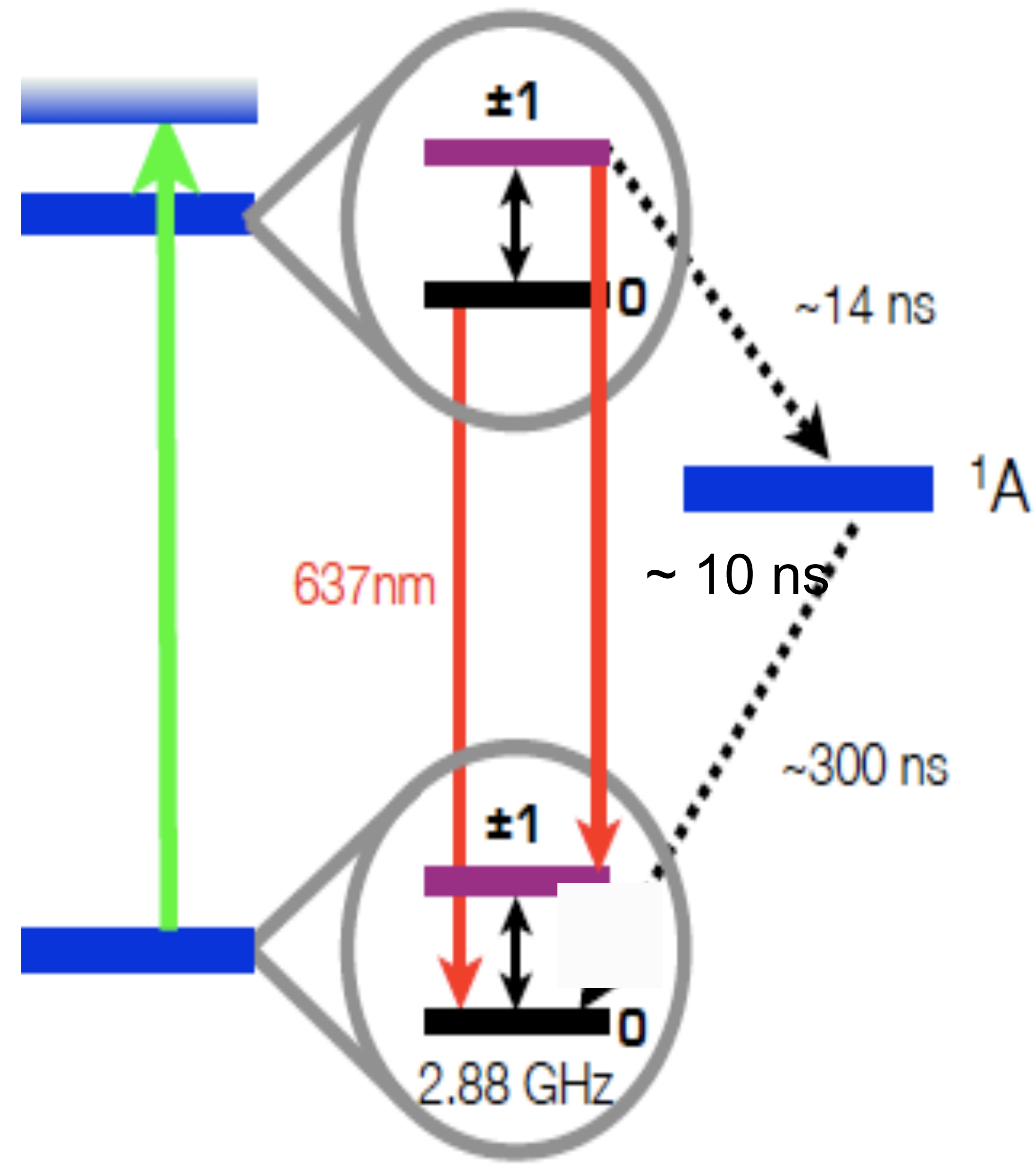
Isolating a single spin by laser spectroscopy



- Long T_1 (~ 10ms – 4 sec) and T_2 (~ 0.3 - 2 ms) times

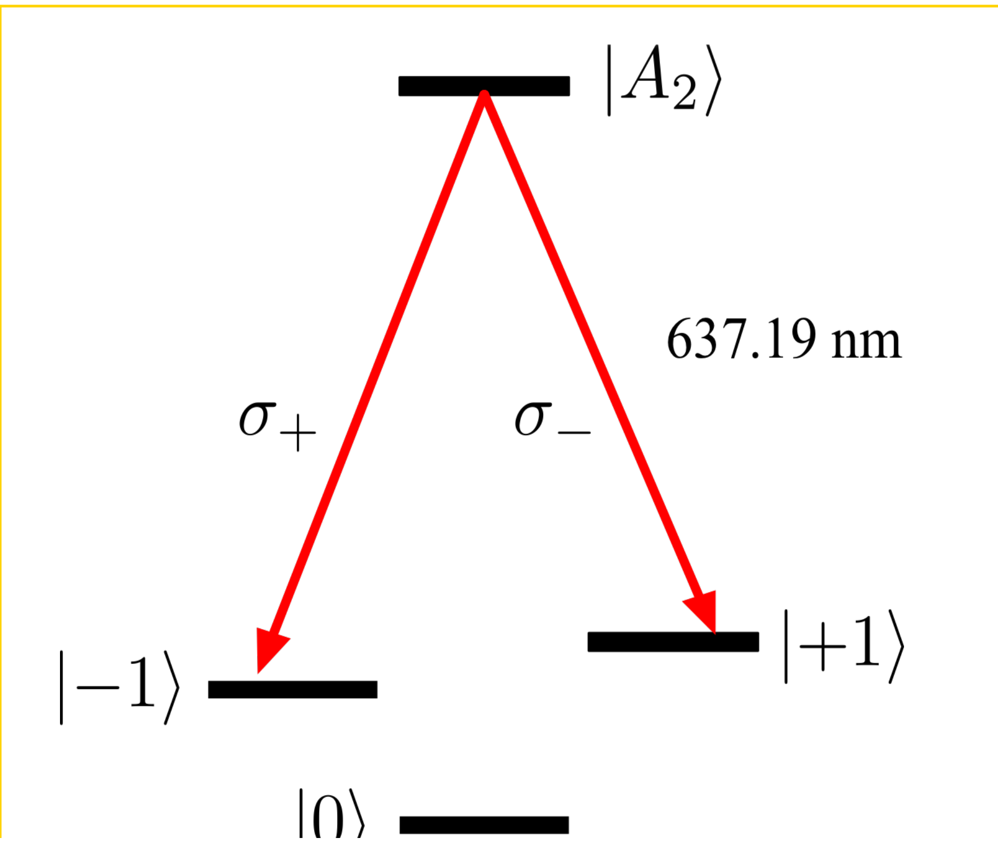
- Spin-state dependent fluorescence allows for spin detection at room temp, also allows spin pumping.

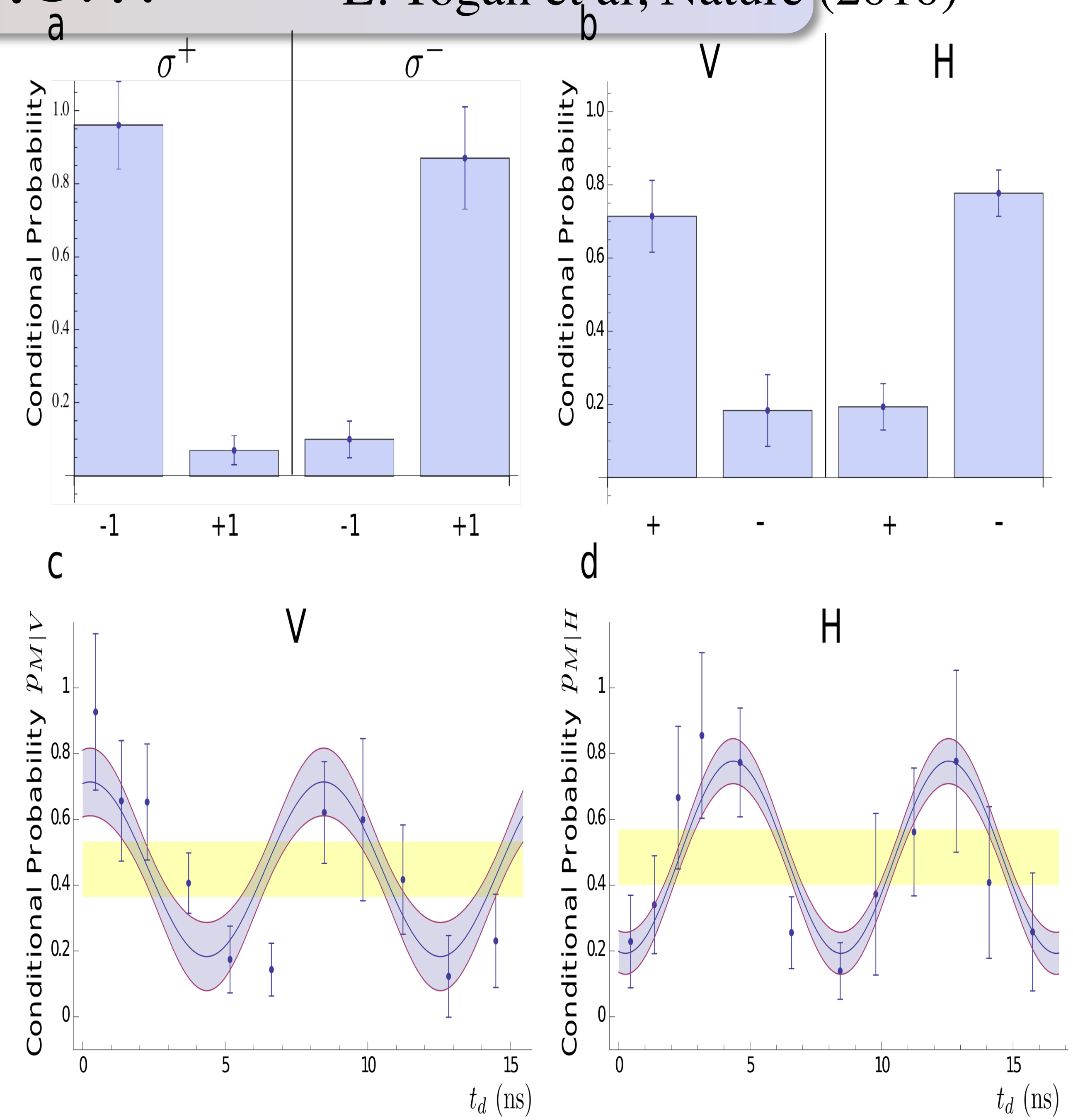
- Proximal nuclear spins (T_2 ~ 100s of ms) can be controlled and measured.
    - F. Jelezko et al, PRL 2004
    - L. Childress et al, Science 2006
    - G. Dutt et al, Science 2007
    - Neumann et al, Science 2008
    - Balasubramanian et al, N. Mat. 2009



Spin-Photon Entanglement

E. Togan et al, Nature (2010)





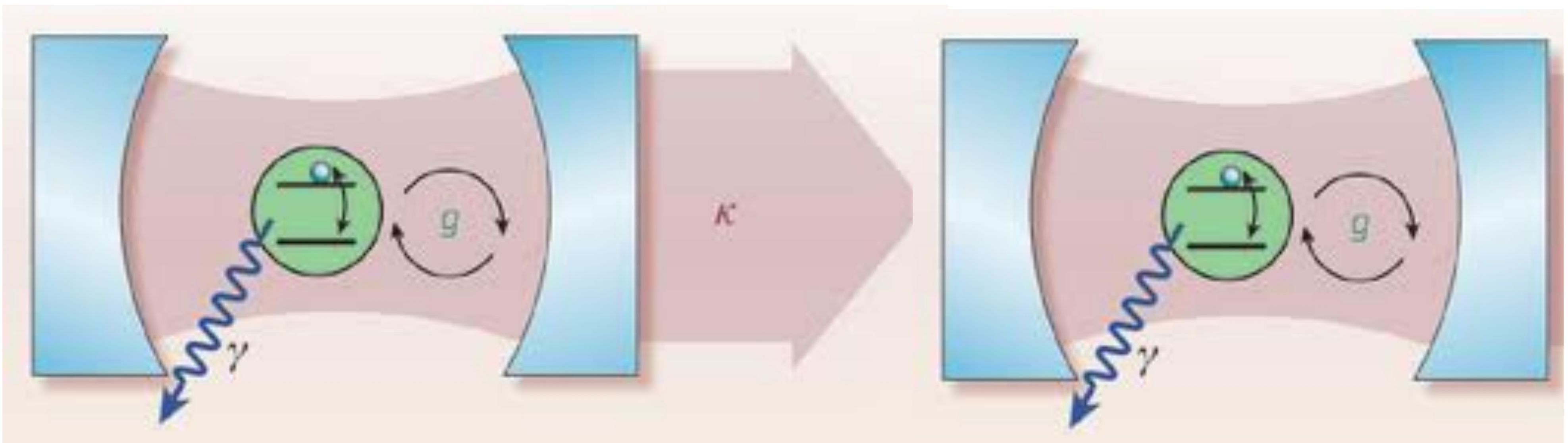
$$|A_2\rangle = \frac{1}{\sqrt{2}}(|E_-\rangle\,|+1\rangle + |E_+\rangle\,|-1\rangle)$$

$$|\sigma_-\rangle|+1\rangle + |\sigma_+\rangle|-1\rangle$$

✓ Fidelity F=69 ± 7 %, Probability of entanglement = 99.7%

Slide: G. Dutt

Cavity-QED for Optical Interconnects



• Photons mediate entangled states of atoms (spins) at remote locations

• Strong coupling results in deterministic interactions

• Weak coupling allows for great improvement in probabilistic entanglement creation – loophole-free tests of Bell inequalities

Slide: G. Dutt

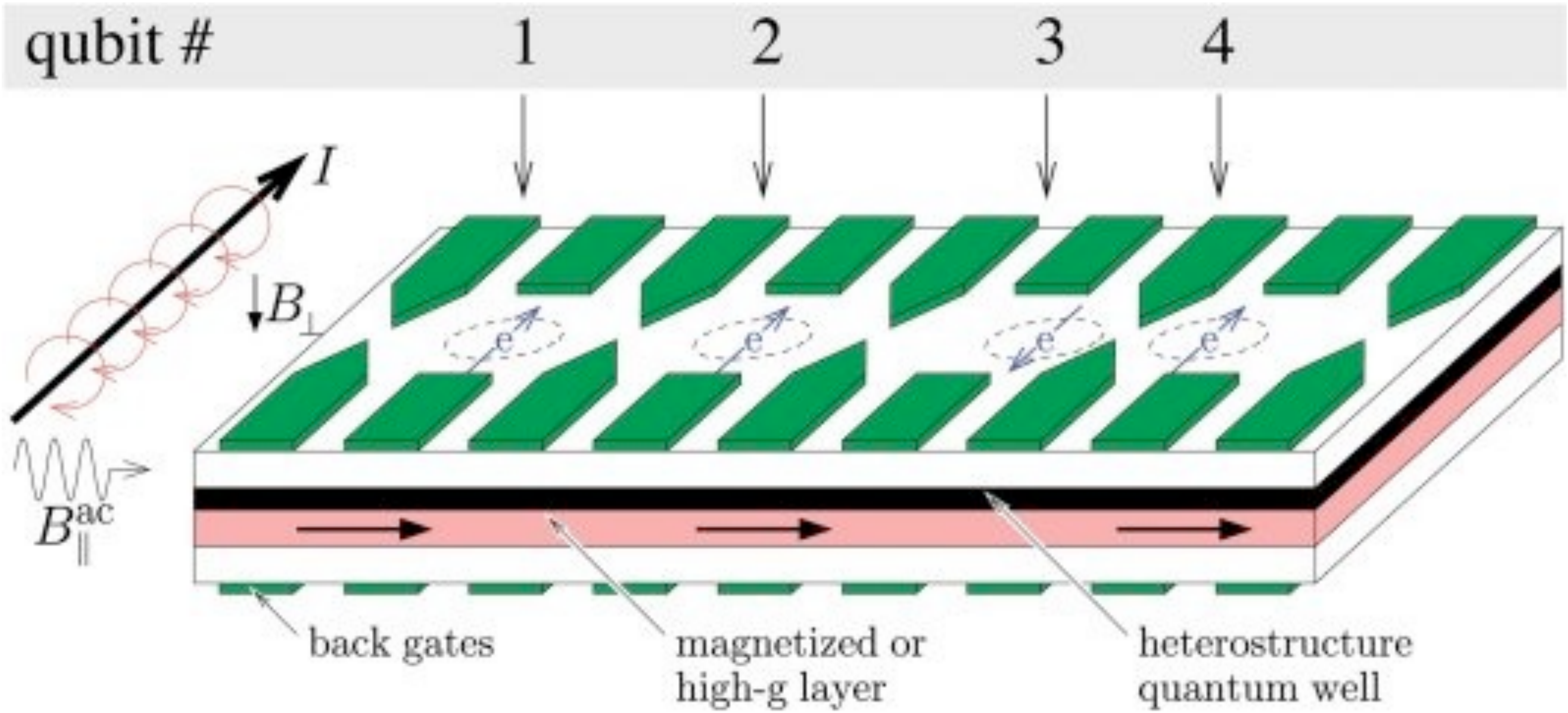
Electron Spins

Advantages:

- Faster gate times (~ns) but faster decoherence (~30μs)

Difficulties:

- Production of regular arrays of, e.g., quantum dots is non-trivial



- Qubits are electron spins, e.g., in electrically gated quantum dots
- Single qubits can be manipulated via electrode potentials, microwave fields

- Two-qubit gates based on spin-exchange interaction. Can be switched with electrical gates.

$$H = -J\vec{S}_1.\vec{S}_2$$

Superconducting qubits

Advantages:

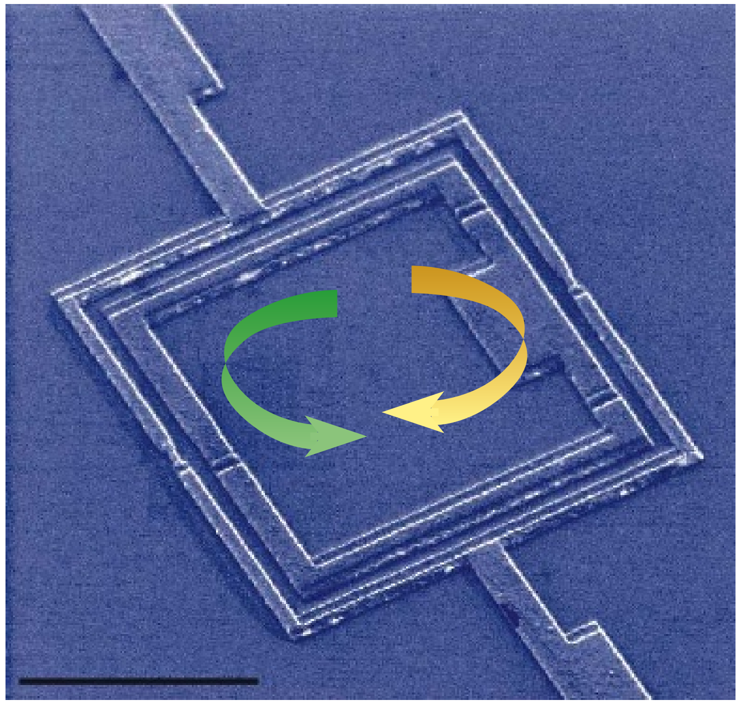
- Faster gate times (~ns) but faster decoherence (~0.5-9.6μs)
- Many possibilities for coupling to AMO systems (microwave/optical photons, atoms/ions/molecules)

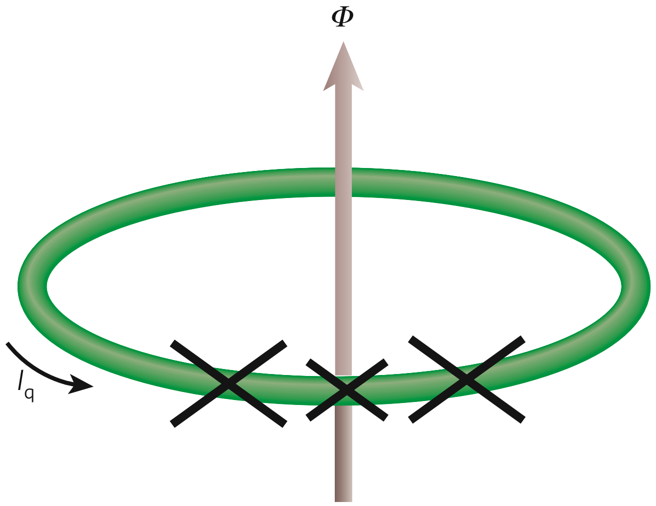
Difficulties:

- Production of regular arrays of qubits is non-trivial

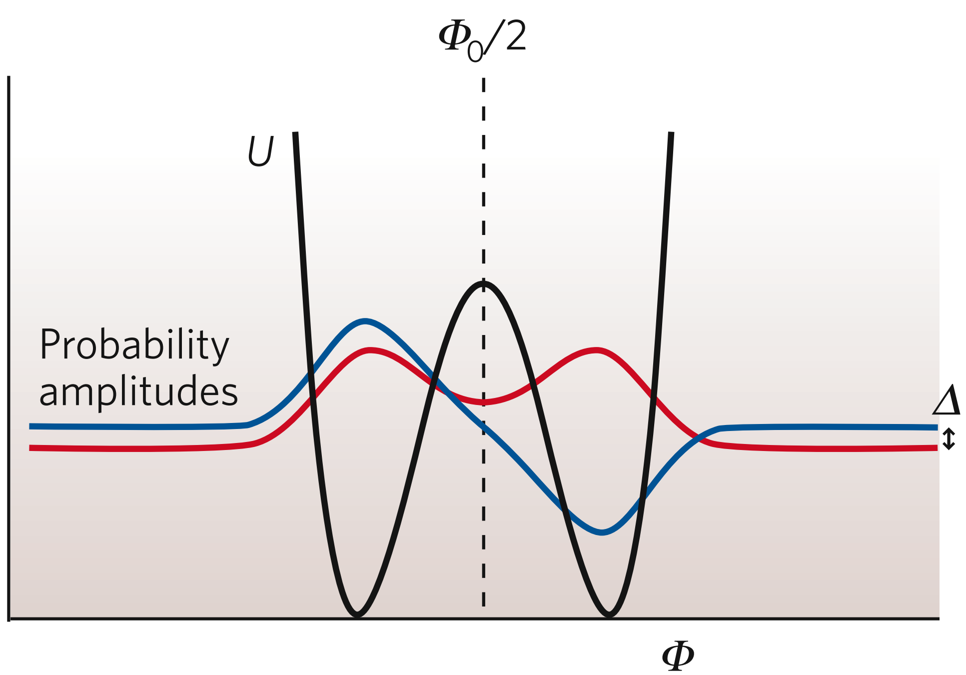
Pitt: Experiments J. Levy / S. Frolov

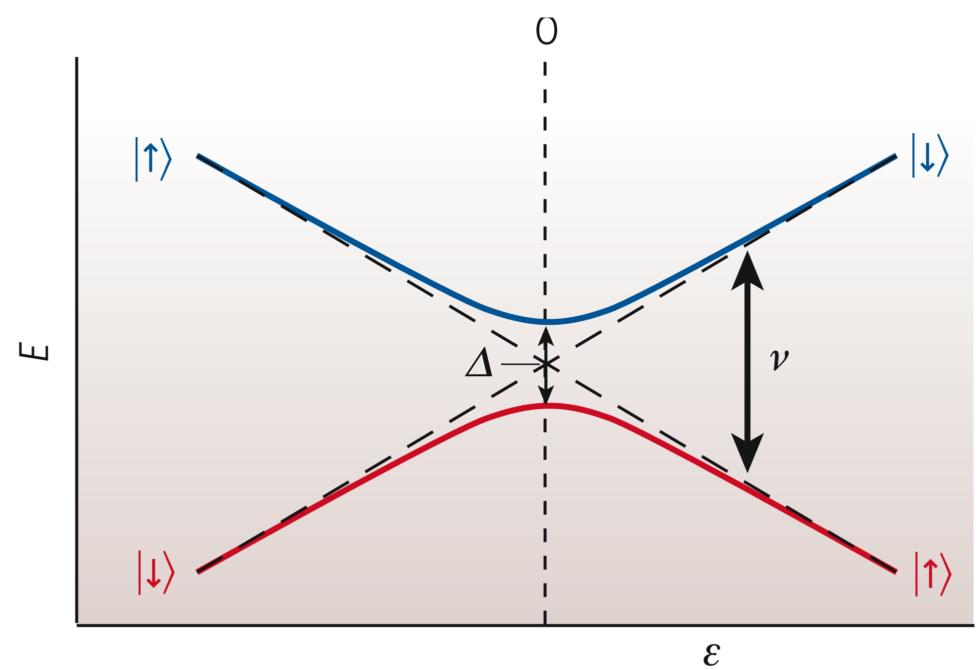
Flux qubit





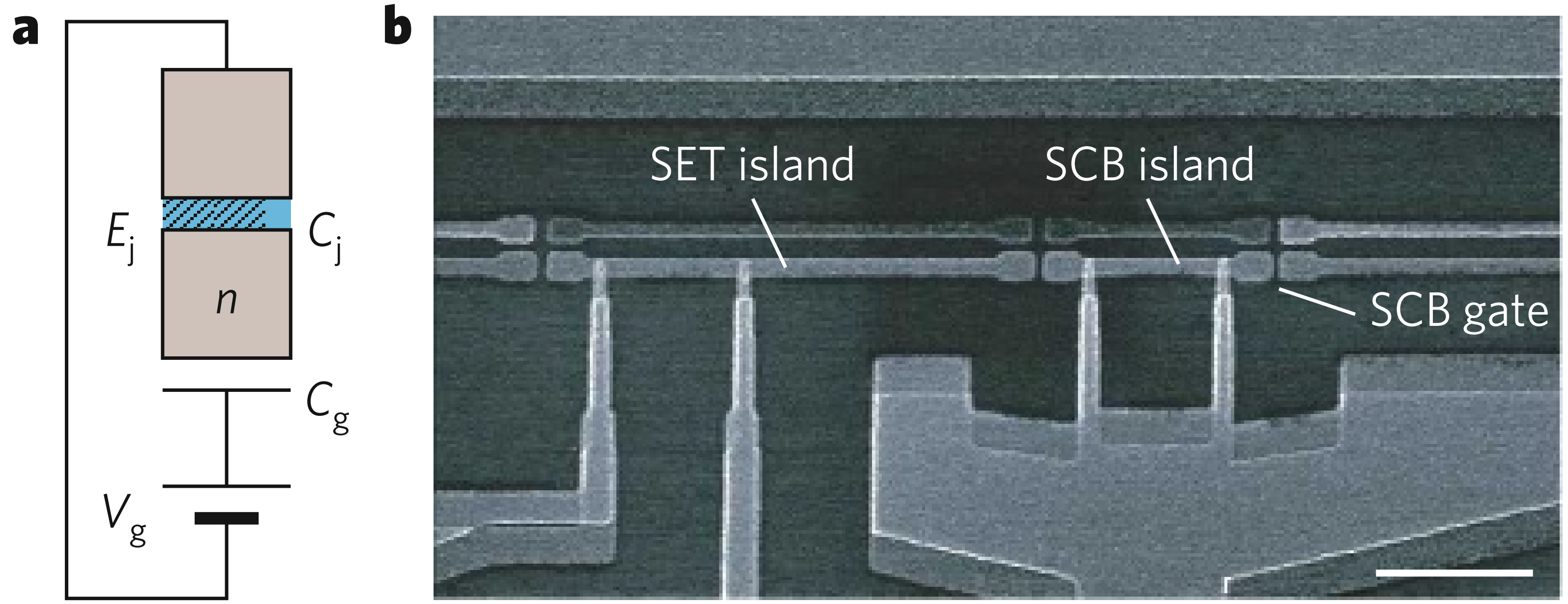
- Superconducting loop interrupted by Josephson junctions
- Quantum states of electron current in two directions (with different magnetic flux) constitute a qubit



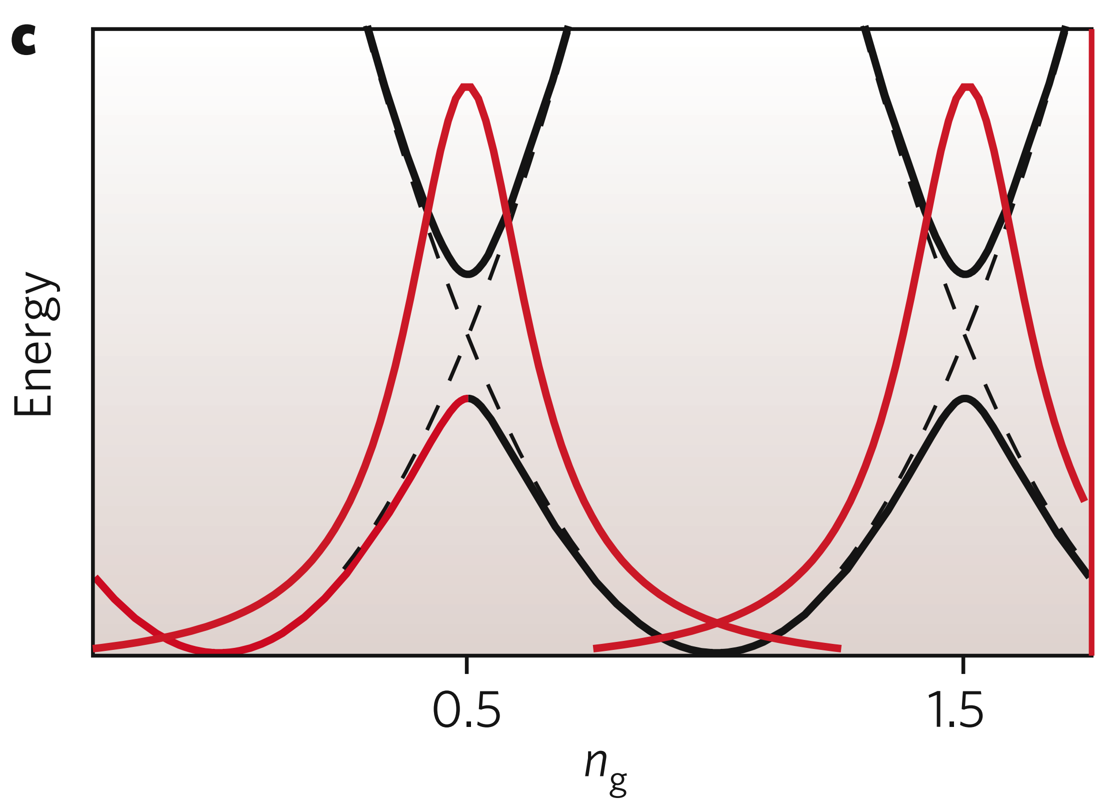


- Measurements via sensitive magnetic field detection (SQUIDs)
- Control via applied microwave fields
- Coupling e.g., via magnetic fields

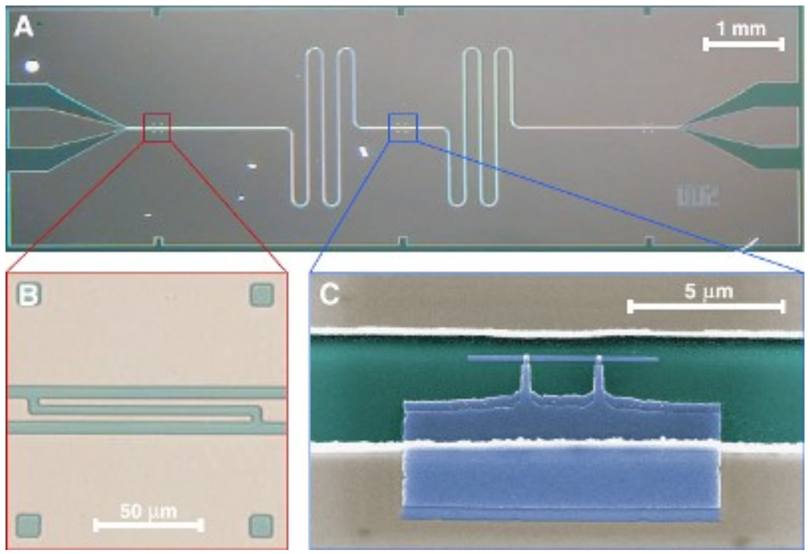
Charge qubit



- Superconductor connected to a Cooper pair box
- Qubit state is determined by the (quantised) number of cooper pairs in the box
- Control via electrical gating



- Readout via a single electron transistor
- Also coupling to microwave fields (cavity QED)



Coherence measurements

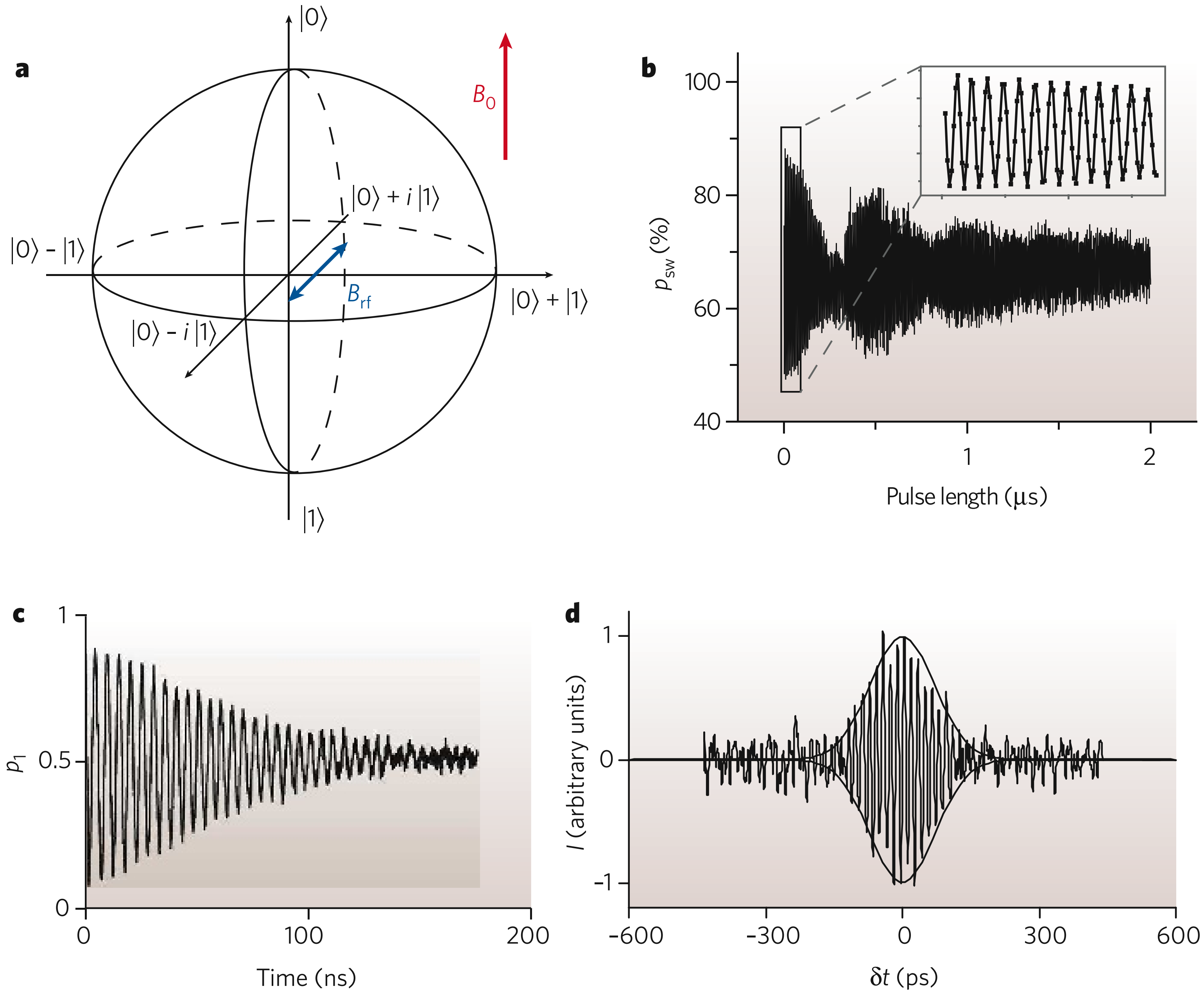


Figure 6 | Qubit manipulation in the time domain. a, The Bloch sphere is depicted, with an applied static magnetic field B_0 and a radio-frequency magnetic field B_{rf}. Any given superposition of the six states shown is represented by a unique point on the surface of the sphere. **b**, Rabi oscillations in a flux qubit are shown. The probability p_{sw} that the detector (SQUID) switches to the normal state versus pulse length is shown, and the inset is a magnification of the boxed region, showing that the dense traces are sinusoidal oscillations. As expected, the excited-state population oscillates under resonant driving. (Panel reproduced, with permission, from ref. 40.) **c**, Ramsey fringes in a phase qubit are shown. Coherent oscillations of the switching probability p_1 between two detuned π/2 pulses is shown as a function of pulse separation. (Panel reproduced, with permission, from ref. 31.) **d**, The charge echo in a Cooper-pair box is shown as a function of the time difference $\delta t = t_1 - t_2$, where t_1 is the time between the initial π/2 pulse and the π pulse, and t_2 is the time between the π pulse and the second π/2 pulse. The echo peaks at $\delta t = 0$. (Panel reproduced, with permission, from ref. 39.)

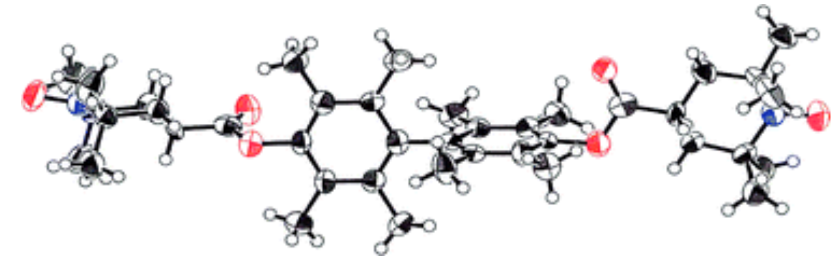
Table 1 | Highest reported values of T_1, $T_2^\star$ and T_2

Qubit	T_1 (μs)	$T_2^\star$ (μs)	T_2 (μs)	Source
Flux	4.6	1.2	9.6	Y. Nakamura, personal communication
Charge	2.0	2.0	2.0	ref. 77
Phase	0.5	0.3	0.5	J. Martinis, personal communication

For a review, see
J. Clarke and F. K. Wilhelm,
Nature 453, 1031 (2008)

Other systems / hybrid systems

NMR:

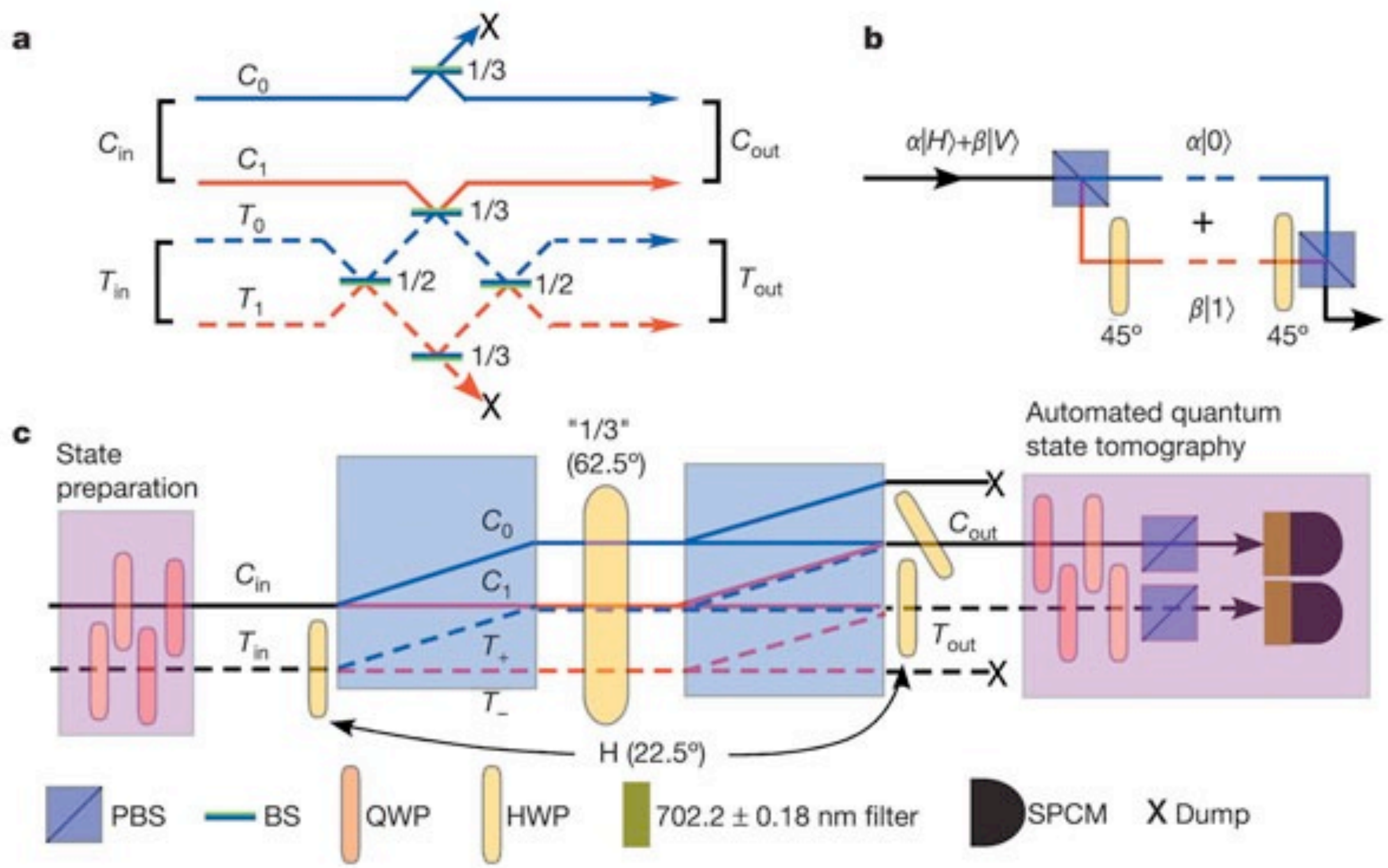


- First system with gate operations on multiple qubits
- Demonstrated factorization of 15 with Shor's algorithm
- Difficulties in scaling for liquid phase (limited by molecule size)
- Somewhat replaced by NMR in solid state qubits

- See Nielsen & Chuang for a detailed summary

Optical qubits

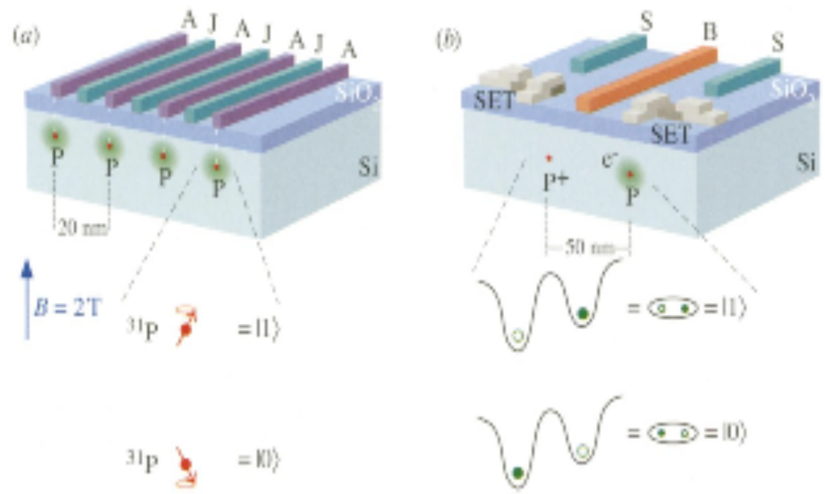
- Polarisation or two-rail encoding, single qubit gates by linear elements
- Probabalistic quantum gates, measurement-based entanglement
- Optical C-Not gate (O'Brien et al, Nature 2003)



Hybrid systems

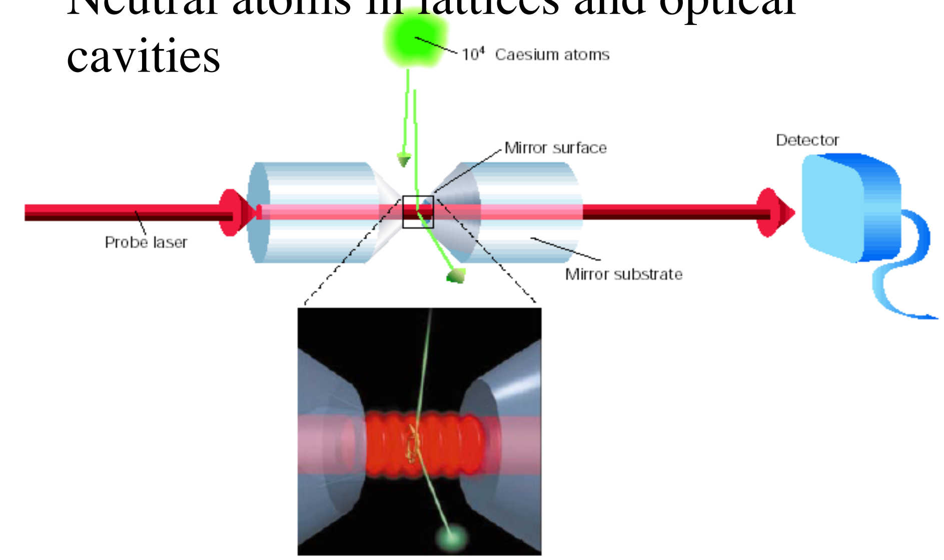
Combine advantages of different physical quantum systems, e.g. fast (but decohering) qubits with slow (but protected) qubits; or matter qubits (robust, strongly interacting) with flying qubits (fragile, weakly interacting)

Electron and nuclear spins in semiconductors

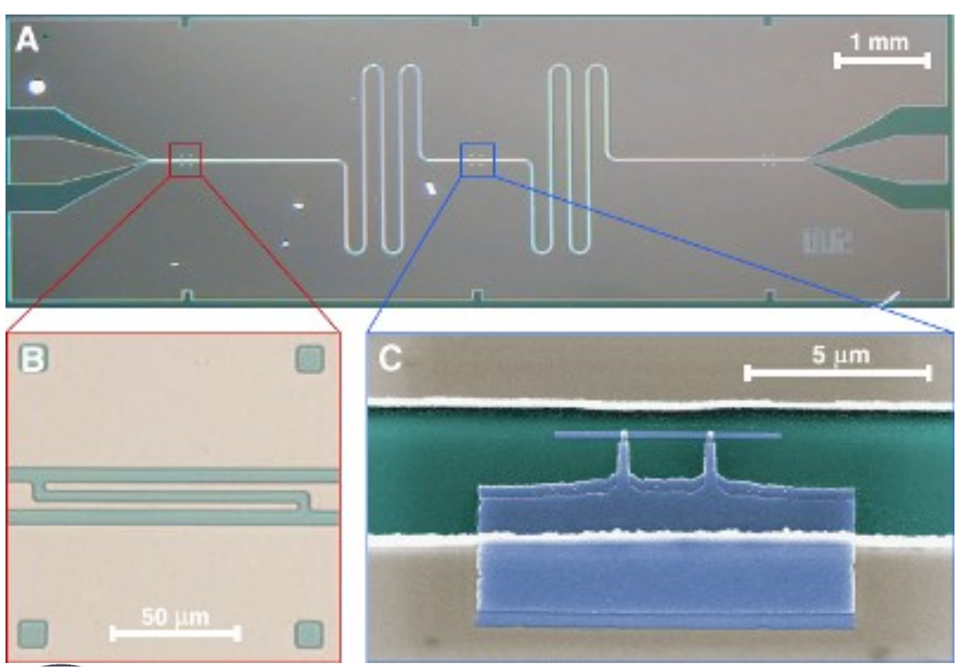


B. E. Kane, Nature (1998)

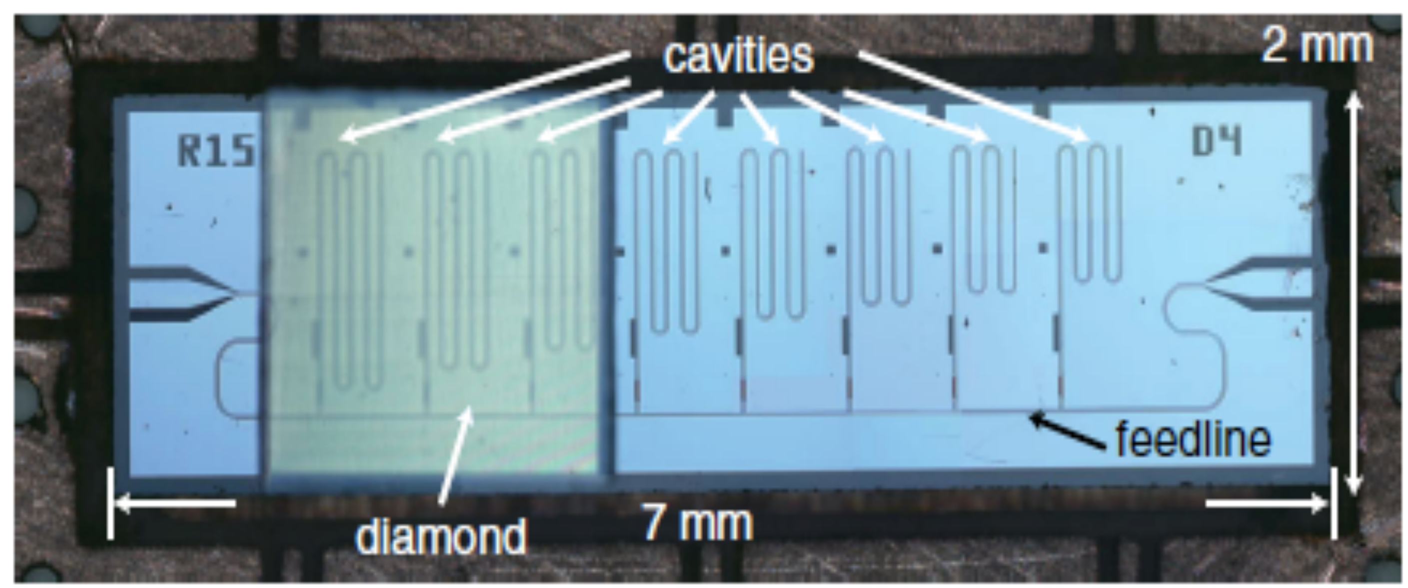
Neutral atoms in lattices and optical cavities



Superconducting qubits with microwave cavity photons



Diamond color centers with microwave cavity photons



Topological qubits

- Protected quantum memories based on non-trivial state topology (solid state, e.g., groups of J. Levy/S. Frolov at Pitt)