Atomic Physics Realizations of Quantum Logic Elements in Dissipative Environments

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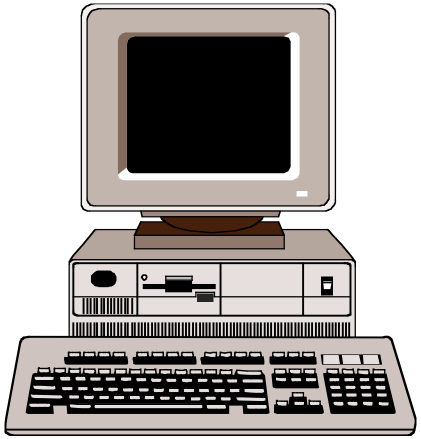
- Quantum resources
- Amo
- Ions
- Cavities
- Lattices
- decoherence

QUBITS EU Network: the Gang of 11

- Munich: Rempe, Walther, Weitz
- Paris: Haroche, Grangier
- Innsbruck: Blatt
- London: ICSTM
- Oxford: Steane
- NPL: Gill
- Ulm: Schleich
- Bratislava: Buzek

Computation = physical process

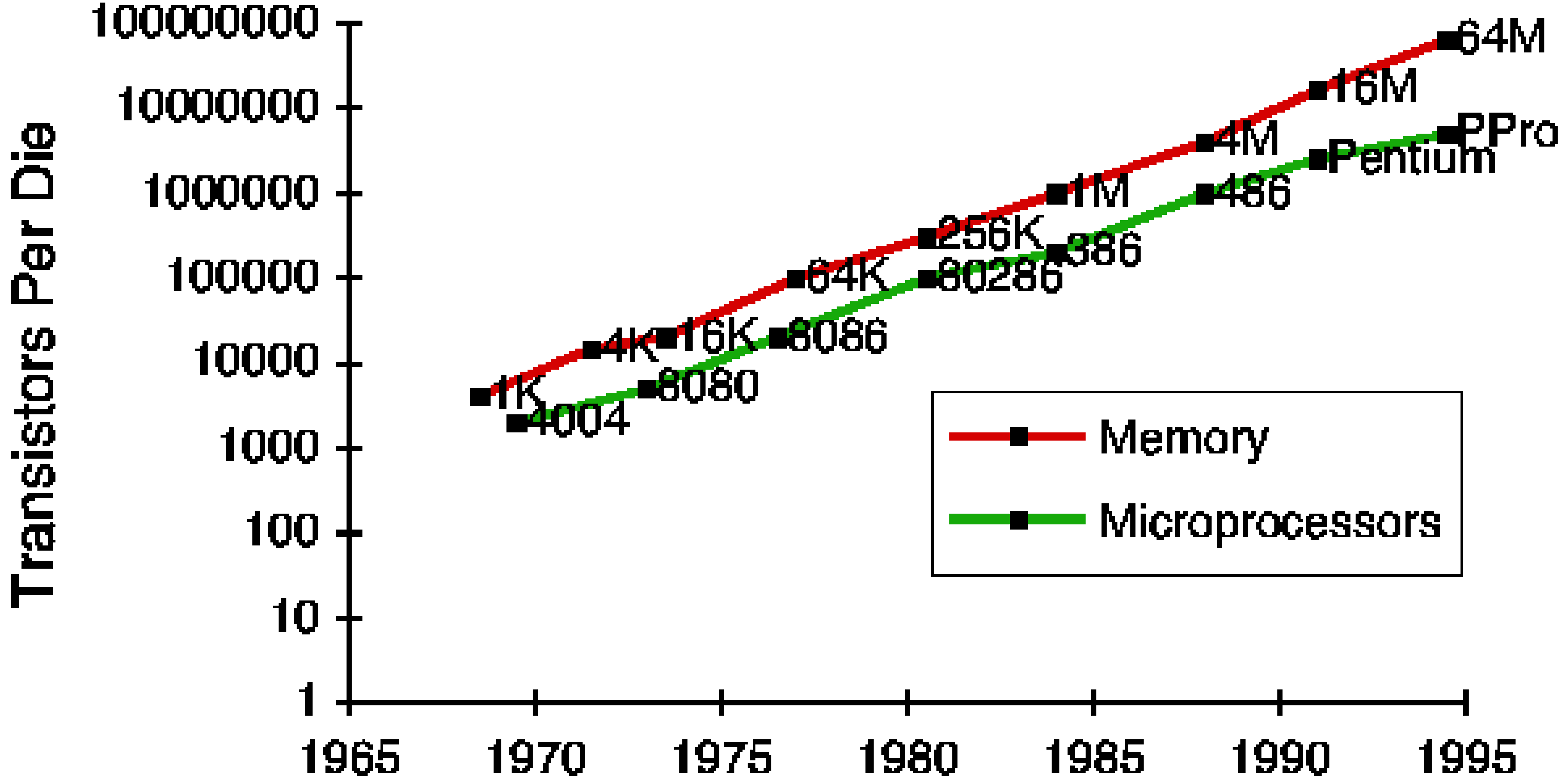


Hardware obeys the laws of physics-
but nature is quantum mechanical

So what would a quantum computer
look like?

“Computers of the future may weigh no more than 1.5 tons”

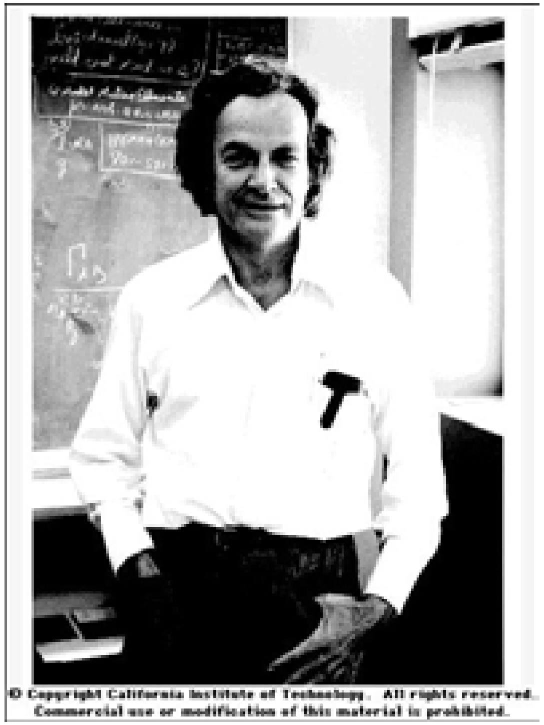
Popular mechanics, 1949!



Moore's Law: Growth in chips and shrinking space. What when/if get to one electron/gate?

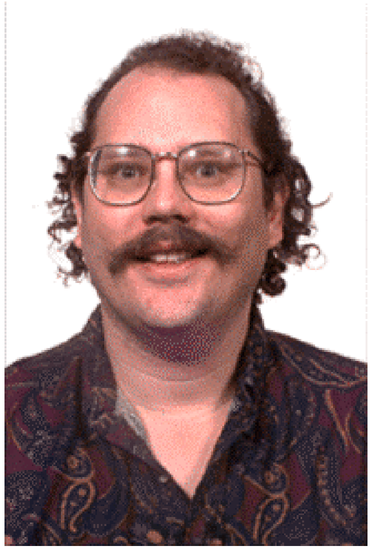
Pioneers of the Physics of Information

Alan Turing



Richard Feynman

David Deutsch



Peter Shor

Quantum Computing History

Initial Ideas - *quantum more powerful than classical*
Benioff - 1982, Feynman - 1984

Quantum Parallelism - *oracles, Hadamards...*
Deutsch-Jozsa (92)/ Bernstein-Vazirani (93) / Simon (93)

Quantum Factoring- *explosion of interest*
Shor (94), Ekert (94) brings it to physics

Implementations- *hardware, gates, decoherence*
Cirac-Zoller (94)
Wineland, Kimble, Haroche, Hughes, Blatt,….

Error Correction- *the conquest of decoherence*
Shor, Steane

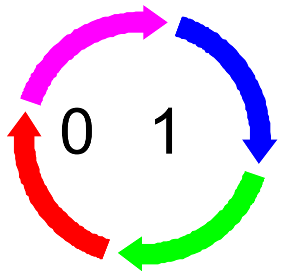
Qubits & Quantum Registers

Classical Bit

0 or 1

Quantum Bit

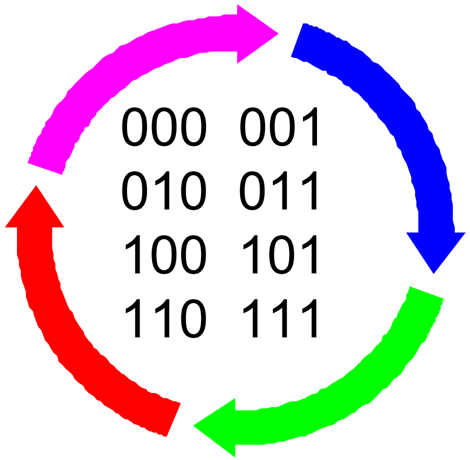
0 or 1 or



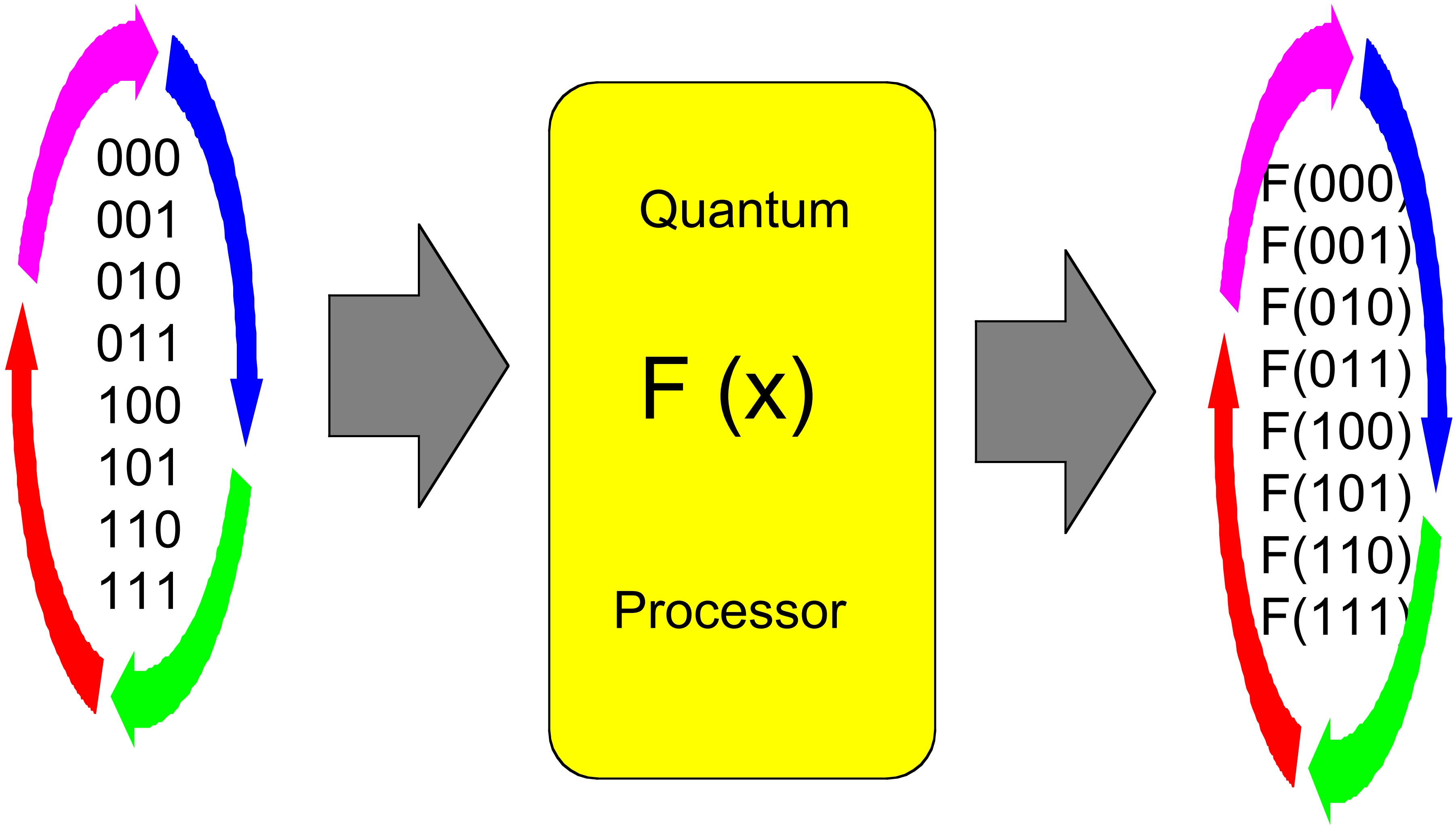
Classical register

101

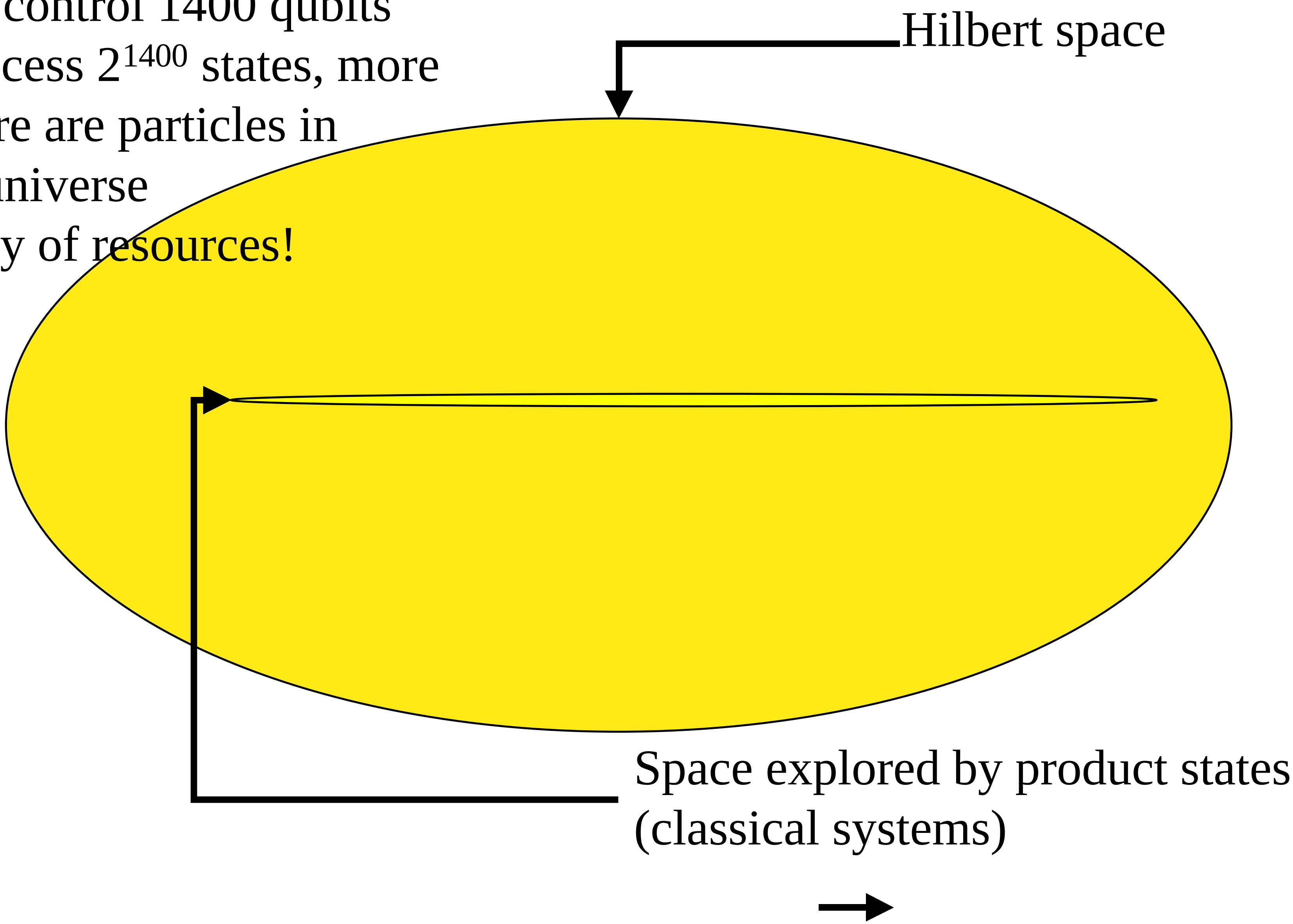
Quantum register



Quantum parallel processing

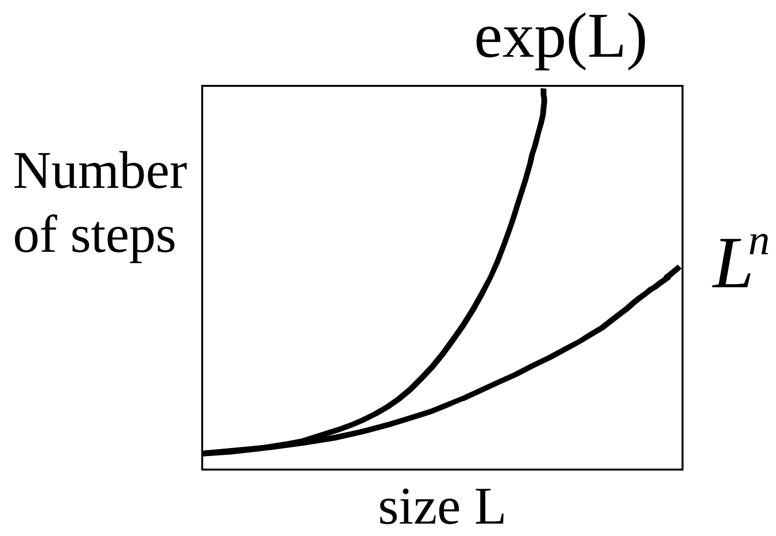


If could control 1400 qubits
could access 2^{1400} states, more
than there are particles in
visible universe
Economy of resources!



Quantum system explores whole Hilbert space- big, isn’t it!
Really really big

Complexity Classes
Tractable and Intractable problems



Input size ~ number of bits required to specify input: 15 1111 in binary -> 4 bit input

Then evaluate number of steps needed as f(size)

- **'P': Solution can be found in polynomial time.**
  Multiplication of two numbers scales quadratically with the input size!

Input size	Comp. Time
10	10 ns
100	1000 ns
1000	100000 ns

- **‘NP’: Solution can be checked in polynomial time, but finding it may require non-polynomial time.**

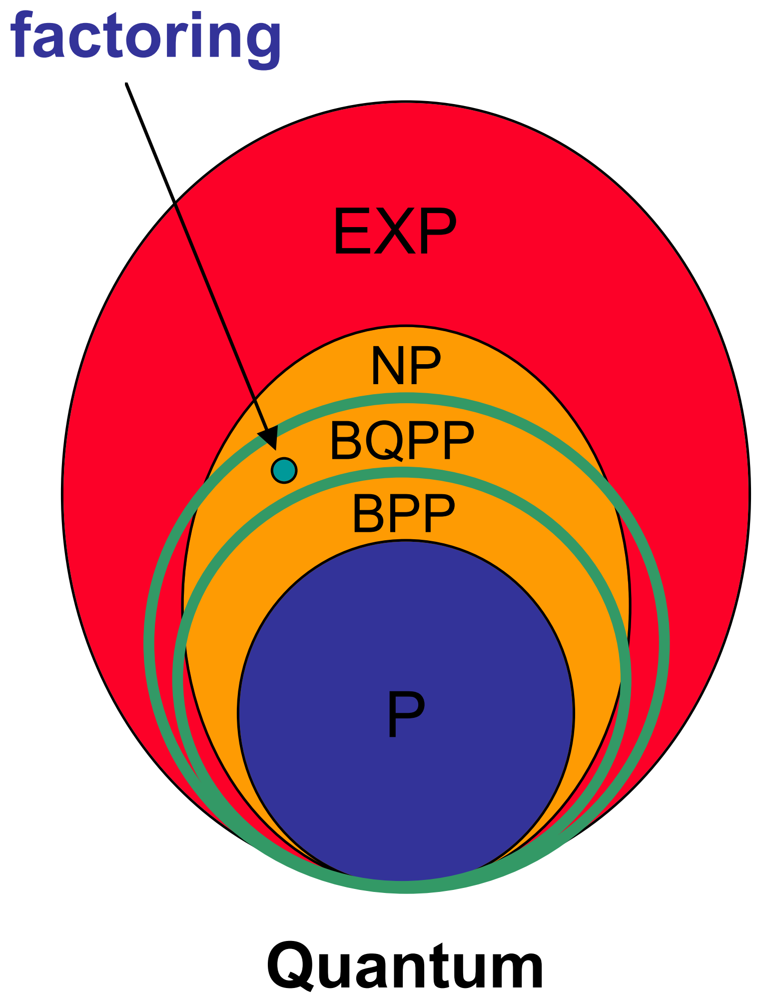
Finding the factors of a product of two large prime numbers is <u>exponential</u> in the number of digits!

Input size	Computation time
10	1 s
100	8103 s
1000	990 0000000000 0000000000 0000000000 0000000000 s

In 1985 David Deutsch (generalization in 1992 with Jozsa) proved that in quantum mechanics the complexity of some problems can change dramatically!
Then in 1994 Peter Shor discovered a quantum algorithm that allows to factor large numbers in polynomial time, ie factoring is essentially as easy as multiplying!

Power of quantum algorithms

Complexity class changed!



Why is irreversibility a problem?

Remember: Quantum mechanics is reversible!

$$|\Psi(t)>=U(t,0)|\Psi(0)>$$

Final state at time t

Initial state at t=0

Unitary time evolution according to the Schroedinger equation

In QM you can always reverse time evolution:

$$|\Psi(0)>=U^{-1}(t,0)|\Psi(t)>$$

From the final state we can always come back to the initial state!

Quantum Logic I

Define a quantum XOR => Quantum **CNOT** gate

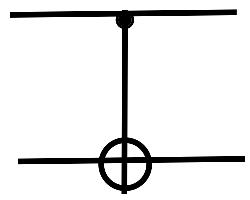
State 1	State 2	Out 1	Out 2
$\vert 0\rangle$	$\vert 0\rangle$	$\vert 0\rangle$	$\vert 0\rangle$
$\vert 0\rangle$	$\vert 1\rangle$	$\vert 0\rangle$	$\vert 1\rangle$
$\vert 1\rangle$	$\vert 0\rangle$	$\vert 1\rangle$	$\vert 1\rangle$
$\vert 1\rangle$	$\vert 1\rangle$	$\vert 1\rangle$	$\vert 0\rangle$

Basic input |0> and |1>
unit called **qubit**

Quantum Mechanics allows
for **superpositions** of states!

Map superpositions of states into entangled states!

$$(|0\rangle + |1\rangle)\,|0\rangle \rightarrow |00\rangle + |11\rangle$$



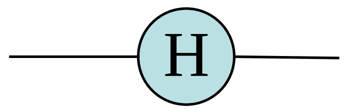
gates and networks

Quantum Logic

We need gates that make quantum superpositions.

The Hadamard gate

$H|0\rangle \rightarrow (|0\rangle + |1\rangle) / \sqrt{2}$
$H|1\rangle \rightarrow (|0\rangle - |1\rangle) / \sqrt{2}$



General single qubit rotations

$|0\rangle \longrightarrow \cos x\,|0\rangle + \exp(iy)\,\sin x\,|1\rangle$

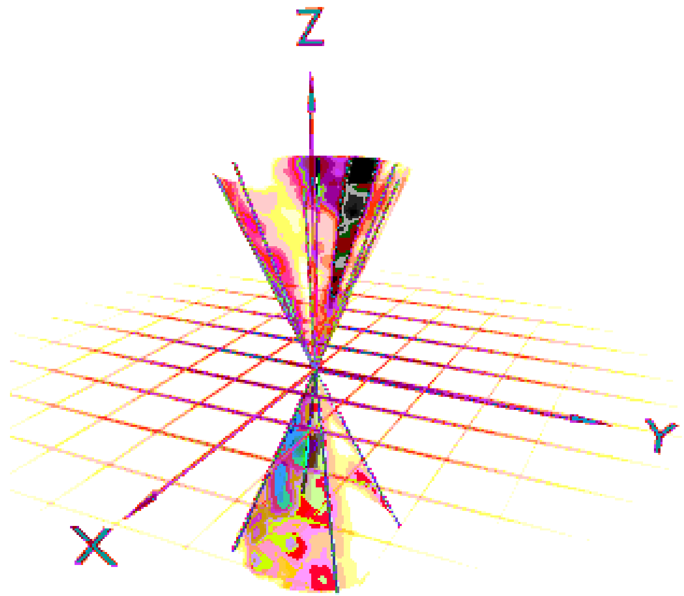
$|1\rangle \longrightarrow -\sin x\,|0\rangle + \exp(-iy)\,\cos x\,|1\rangle$

Quantum Parallelism

Consider a k-bit string: $|0\rangle|0\rangle....|0\rangle$

Apply one bit (Hadamard) rotation S to each bit

$$S = (1/\sqrt{2})\begin{bmatrix} 1 & -1 \\ 1 & 1 \end{bmatrix}$$



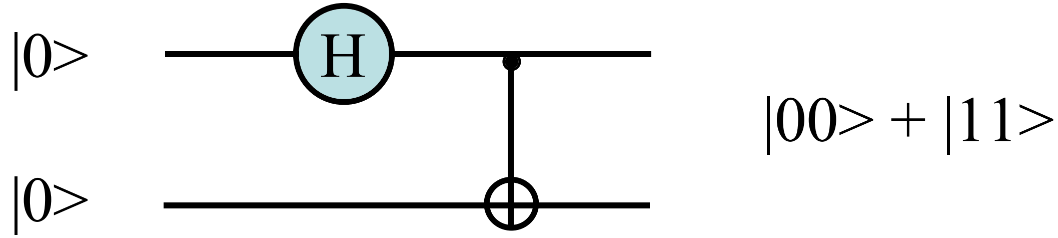
$$(2^{-k/2})(|0\rangle + |1\rangle)(|0\rangle + |1\rangle)....(|0$$

$$= (2^{-k/2})\sum_i |i\rangle$$ sum over all 2^k k-bit strings

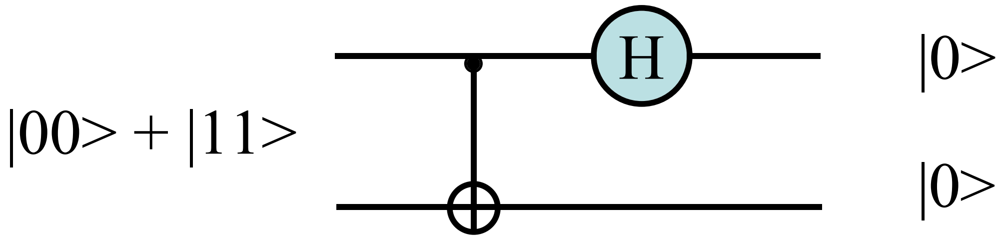
Quantum parallelism- 2^k states after only k operations

Quantum Logic II

Make entanglement

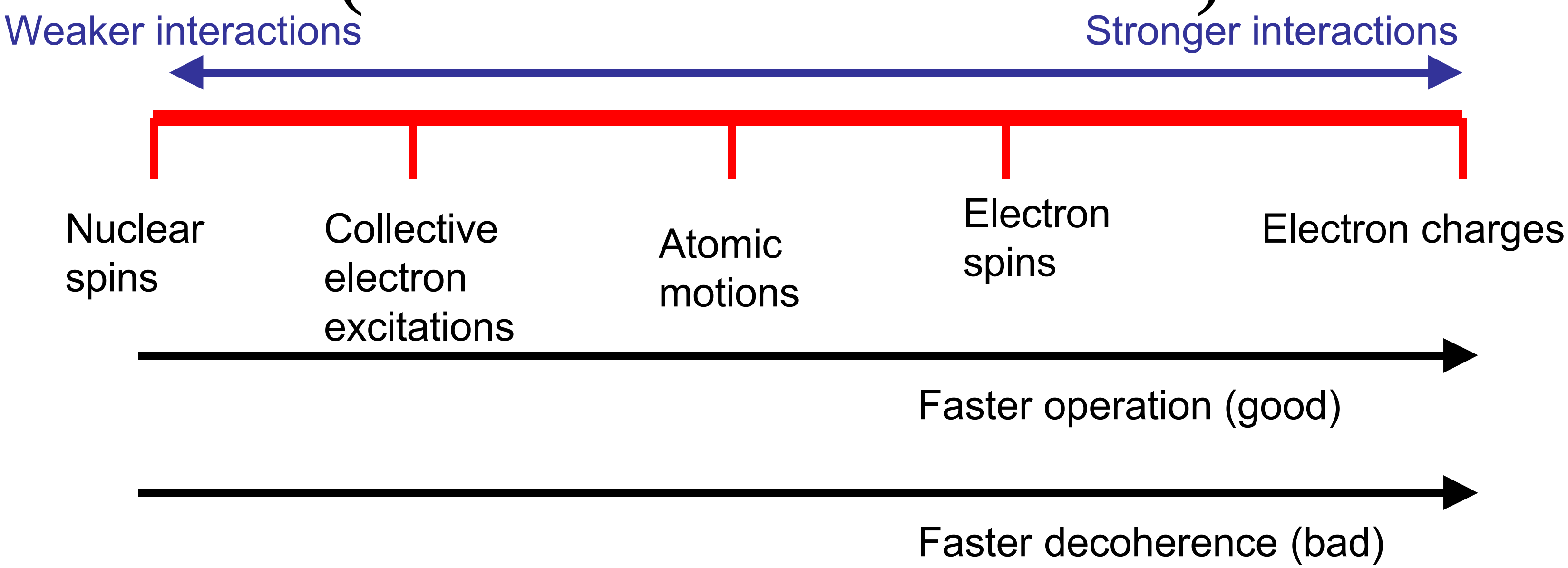


Measure entanglement



Timescales

- Can arrange these roughly according to strength of the qubit interactions with one another (and with the environment)



The ‘DiVincenzo Checklist’

Must be able to

- Characterise well-defined set of quantum states to use as qubits
- Prepare suitable pure states within this set
- Carry out desired quantum evolution
- Avoid decoherence for long enough to compute
- Read out the results

AMO successes

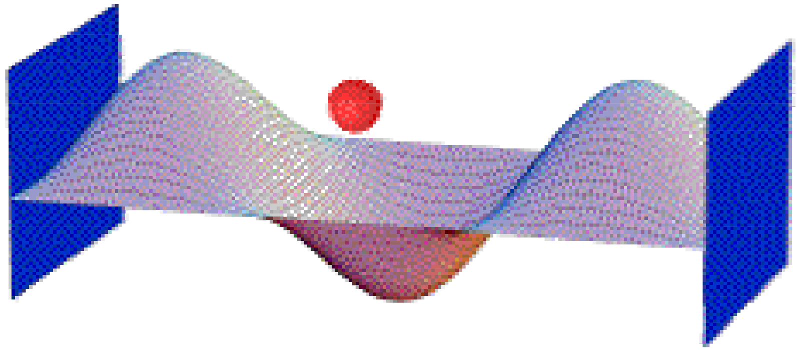
- Ions: isolated qubits; arrays; gates, 4 ion entanglement; decoherence
- Cavity qed: single particle manipulation; atom-atom entanglement, nonlocality
- Atoms in lattices: loading, interaction
- Atom chips: guided; coherence?

amo realizations?

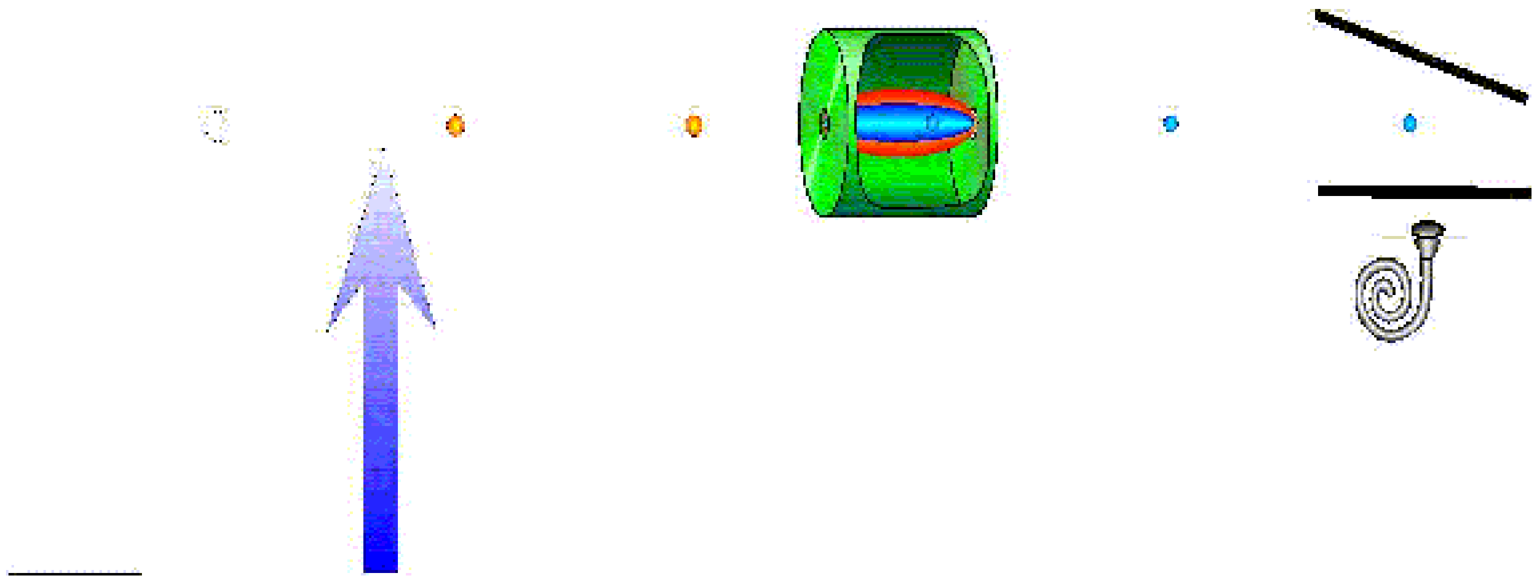
chunky but they work!

Cavity qed: trapped photons

- Haroche group: Rydberg atoms & microwave cavities
- Walther group: micromasers & Rydberg atoms
- Rempe group: optical transitions and single photon switches
- Also use trapped ions: NPL, Innsbruck, MPQ as prototype quantum communicator, mapping quantum states of a memory on to the output of a quantum radiation channel.



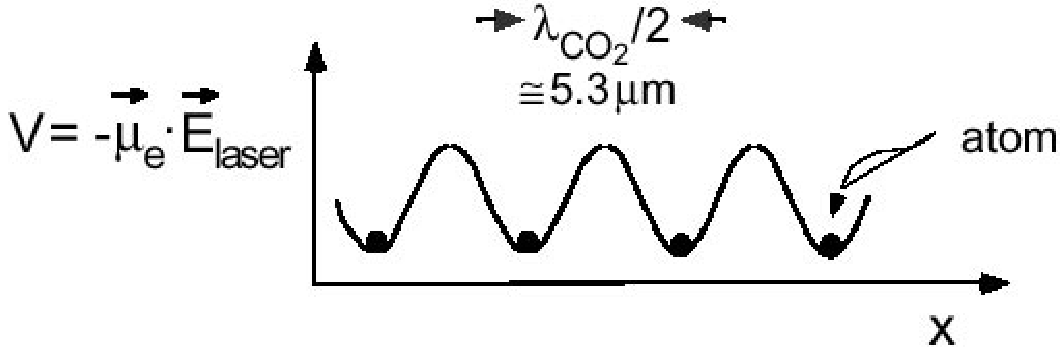
Atom-field entanglement



Prepare atoms, inject into cavity, atom-field interaction entangles atoms

Quantum Logic in a CO_2-Laser Optical Lattice

Martin Weitz, LMU Munich



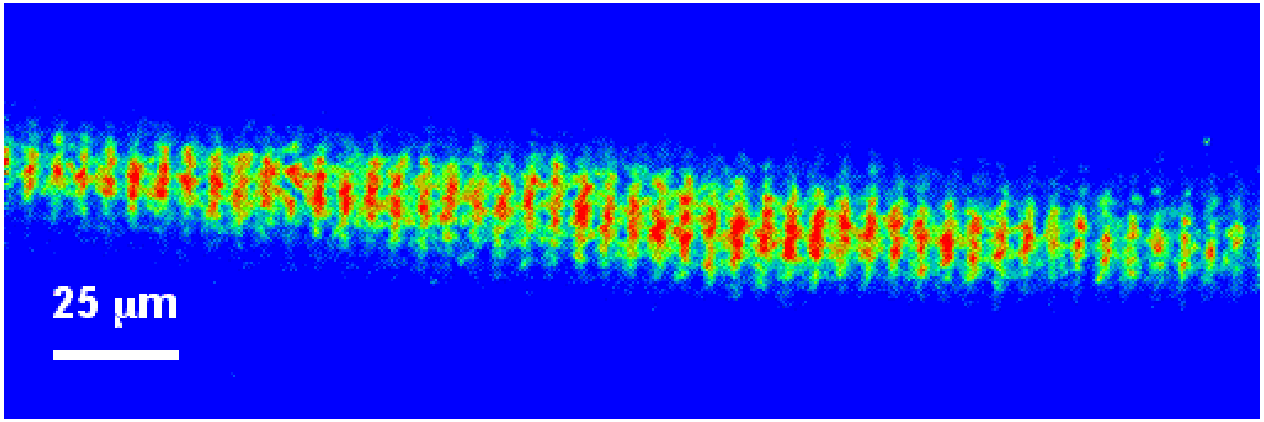
atoms trapped by the ac Stark shift in a standing wave near 10.6 μm

- storage of a qubit per atom in internal atomic states

Project funded by the Future and Emerging Technologies arm of the IST Programme
FET-QIPC

Image of Rubidium Atoms in a CO_2-Laser Optical Lattice

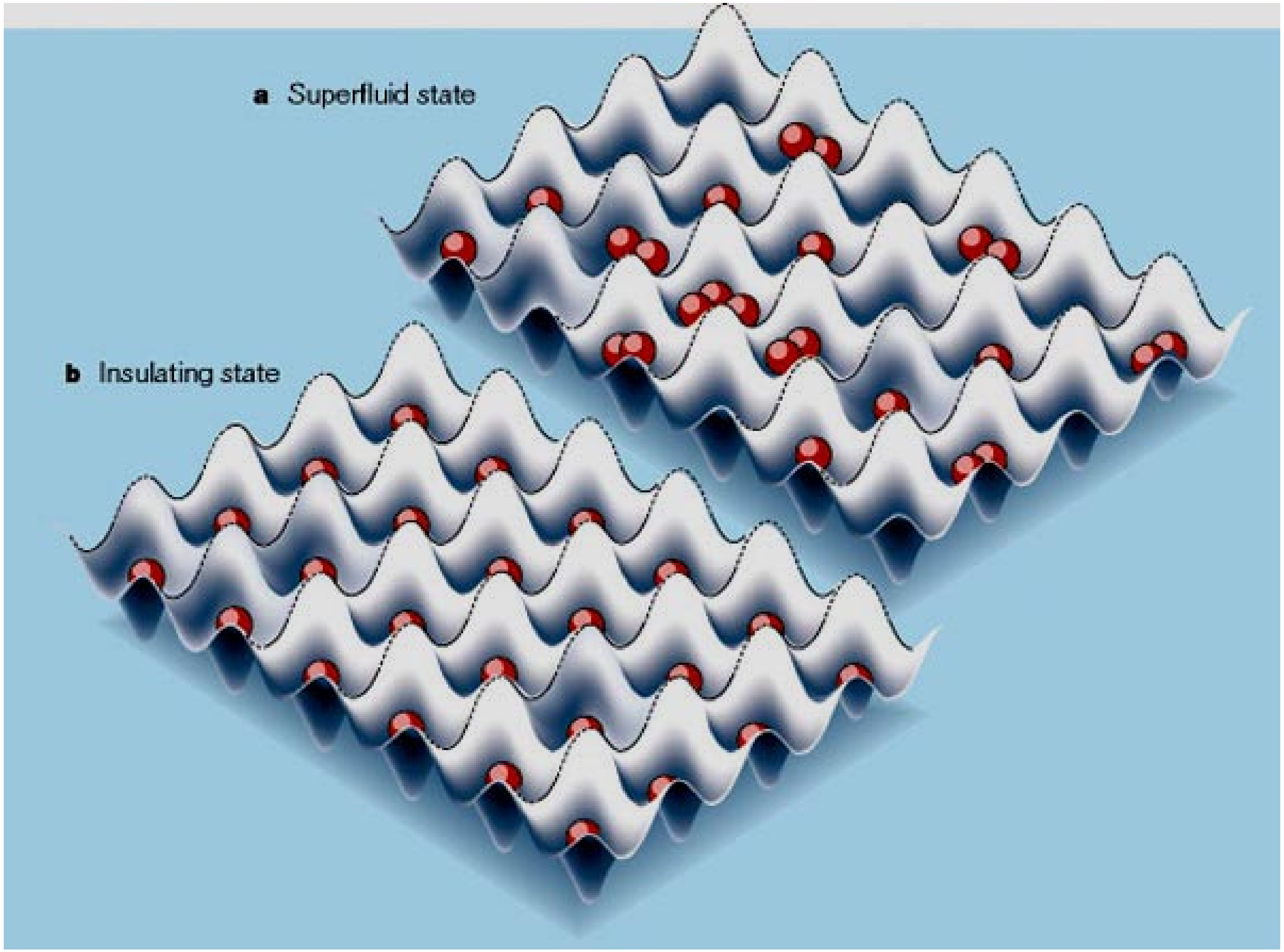
Martin Weitz, LMU Munich



R. Scheunemann, F. Cataliotti, T. W. Hänsch, and M. Weitz, Phys. Rev. A **62**, 051801 (R) (2000).

Project funded by the Future and Emerging Technologies arm of the IST Programme
FET-QIPC

Mott transition in Lattices: Hansch last week in Nature



Atom chips

- Guided atoms
- Interferometer
- EU presence: Sussex, Hannover, Heidelberg…

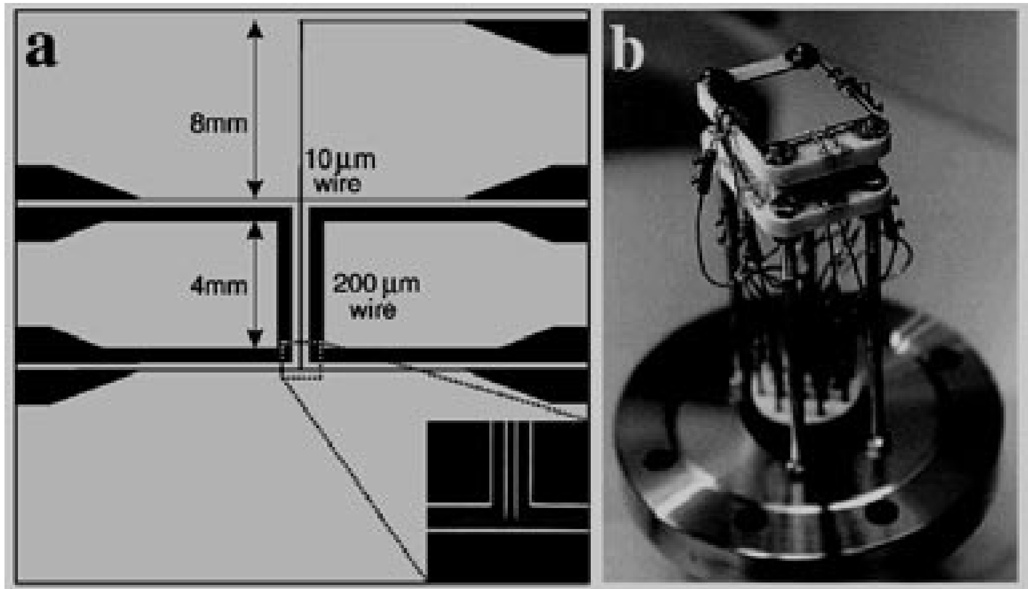
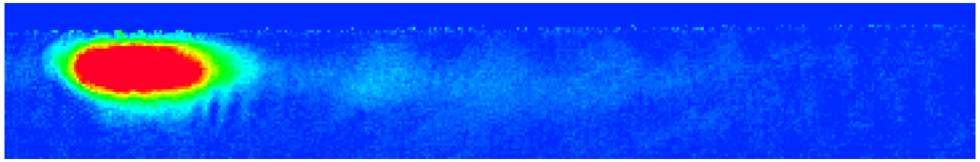
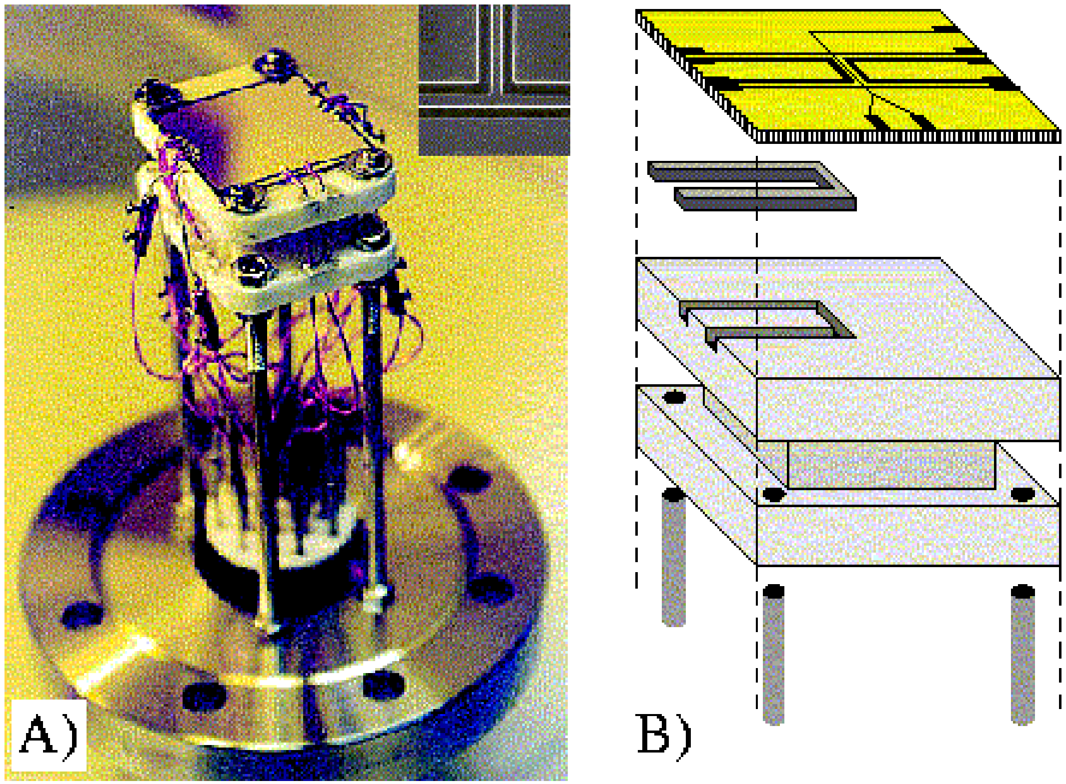


FIG. 1. (a) A schematic of the chip surface design. For simplicity, only wires used in the experiment are shown. The wide wires are 200 μm wide while the thin wires are 10 μm wide.

Atoms can be trapped and guided using nanofabricated wires on surfaces, achieving the scales required by quantum information proposals. These *atom chips* form the basis for robust and widespread applications of cold atoms ranging from atom optics to fundamental questions in mesoscopic physics, and possibly quantum information systems.

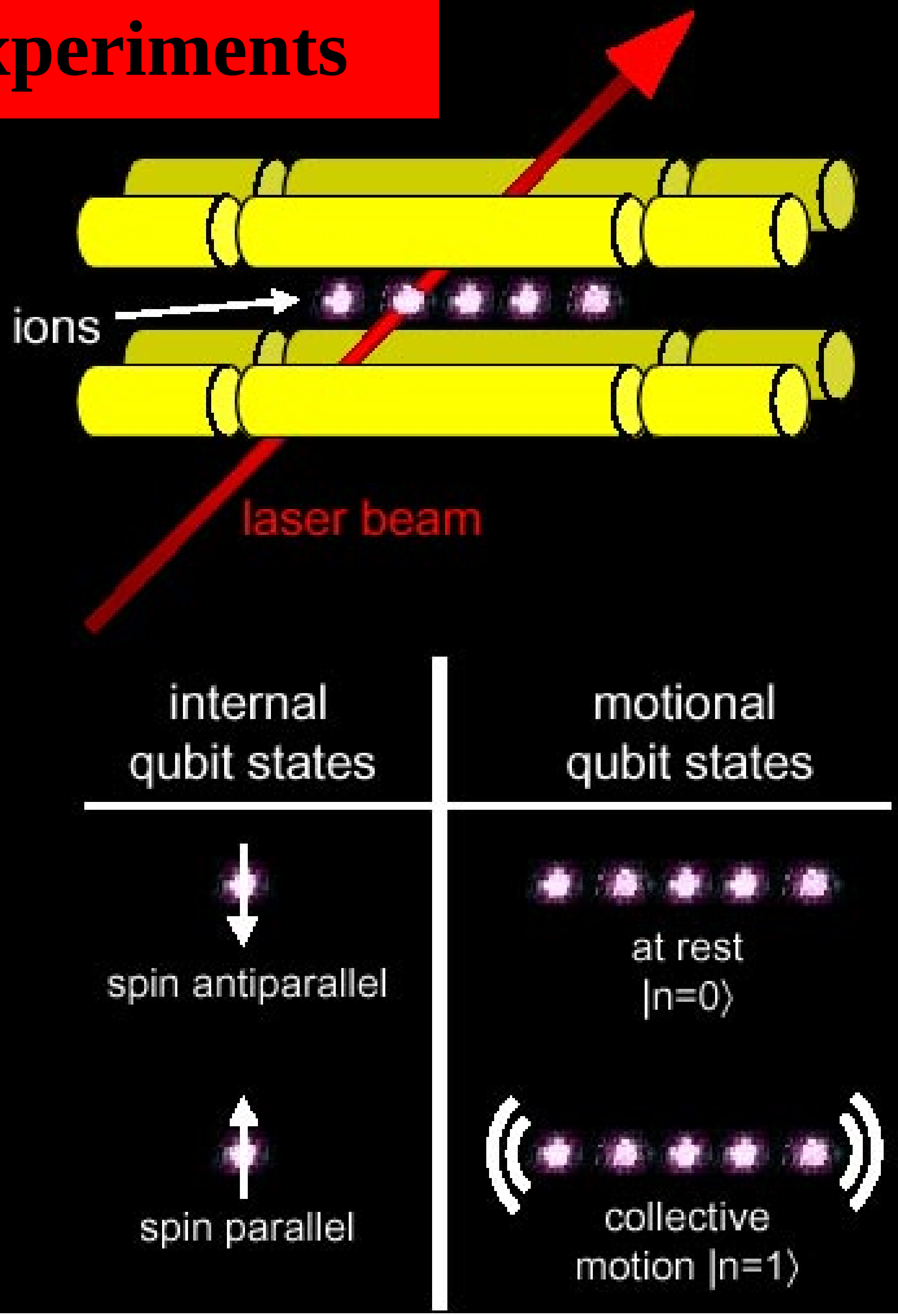
Atomic Conveyor Belt



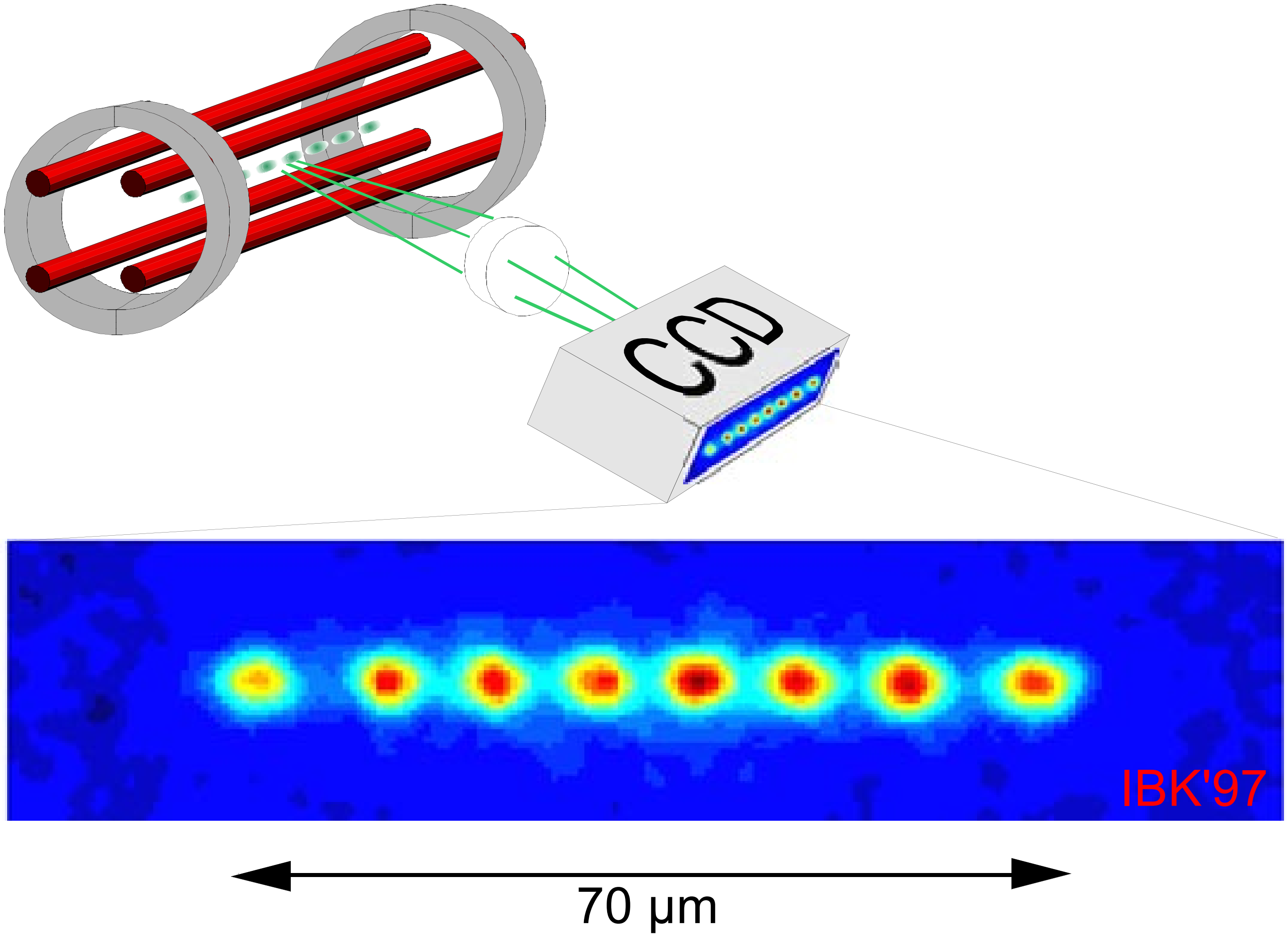


ions - my favourite!

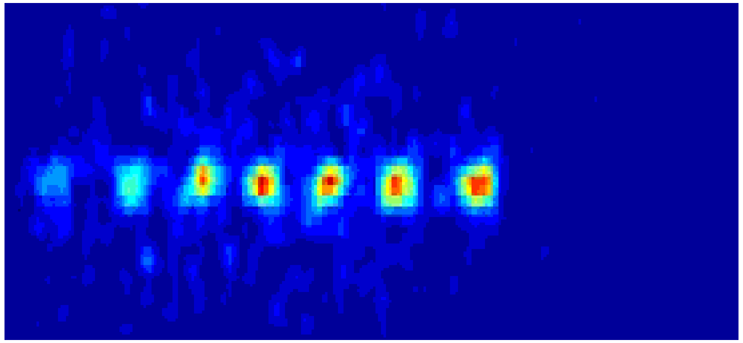
Ion experiments



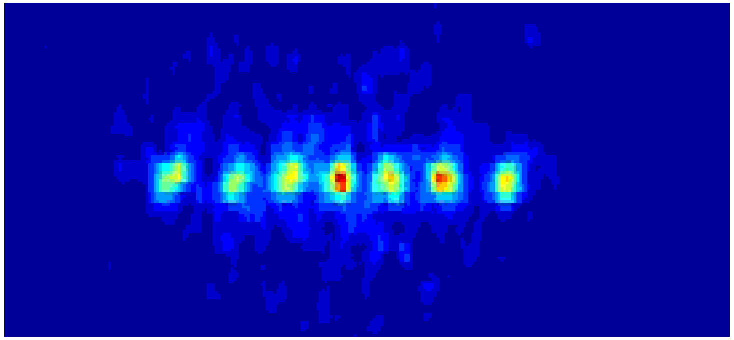
String of Ca^+ ions in a linear Paul trap



Collective motion of ions



Centre of mass motion

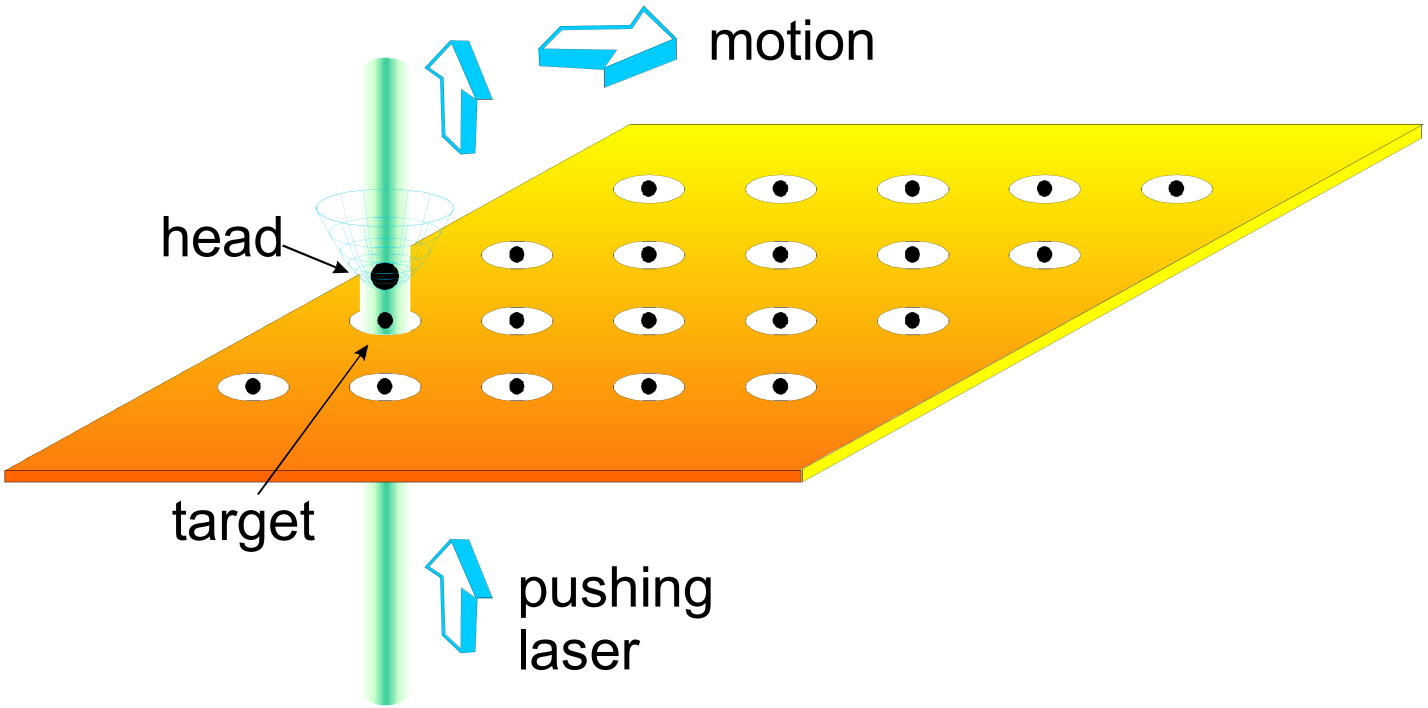


Stretch motion

Quantum computer with ion traps- a vision

I. Cirac and P. Zoller, Nature 404, 579, (2000)

• quantum optics and nano-technology: scalability



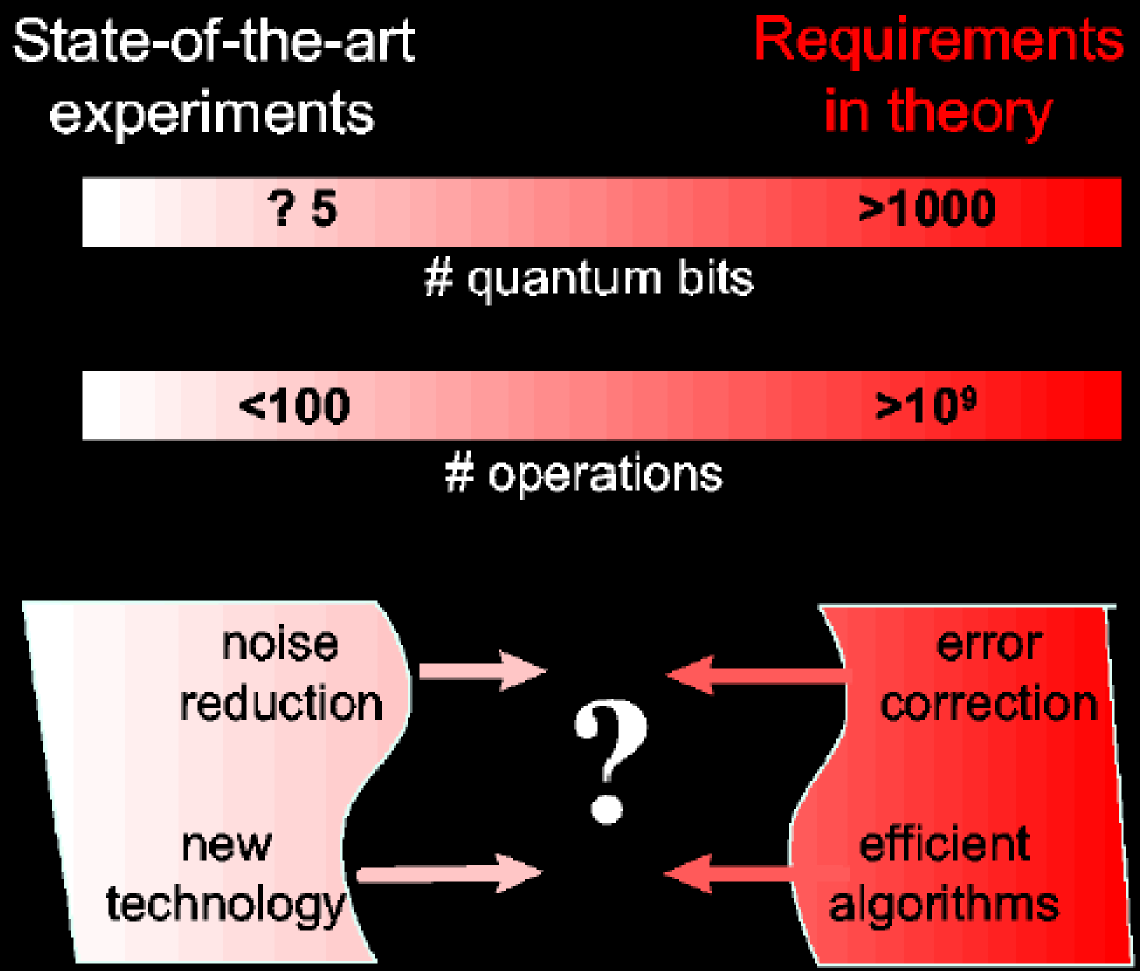
The solid state: pros and cons for quantum computing

- Potential advantages:
  - Scalability
  - Silicon compatibility
  - Microfabrication (and nanofabrication)
  - Possibility of ‘engineering’ structures
  - Interaction with light (quantum *communication*)
- Potential disadvantage:
  - Much stronger contact of qubits with environment, so (usually) much more rapid decoherence

Solid State qubits?

- Many different particles in solids (electrons *and* nuclei) whose states can be used
- There are also collective excitations that *only* occur in many-particle systems
- Possible systems for qubits include:
  - Nuclear spins
  - Nuclear (atomic) displacements
  - Electron spins
  - Electron charges
  - Correlated many-electron states

Quantum Computing Abyss



hard, isn't it?