Quantum Computing: Implementation

Peter Zoller
Institute for Theoretical Physics
University of Innsbruck
Austria

- There has been significant experimental progress over the last year
  - good candiates, but no clear winner(s)
  - strong European presence in theory and experiment
- US ROADMAP for quantum computing Dec 2002 on www.qist.lanl.gov
- DISCLAIMER: this is not a (complete) review / pedagogical talk, or a talk to promote a specific field

Why implement a quantum computer?

- implement quantum hardware for ...
  - quantum algorithms (large resources / long term)
  - ...
  - quantum simulations (specialized hardware / short term)
  - [quantum communications]

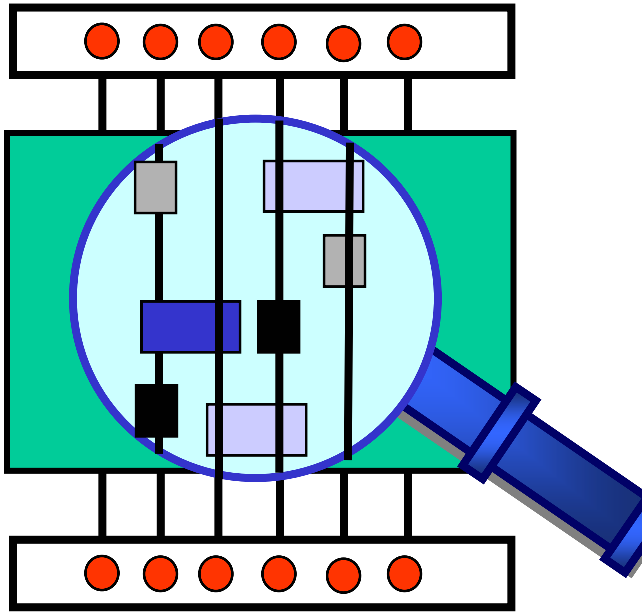
GOAL: outperform a classical computer (on a useful problem)

- the bigger picture & spin-offs
  - precision measurements beyond Standard Quantum Limit: atomic clocks, ...
  - ....

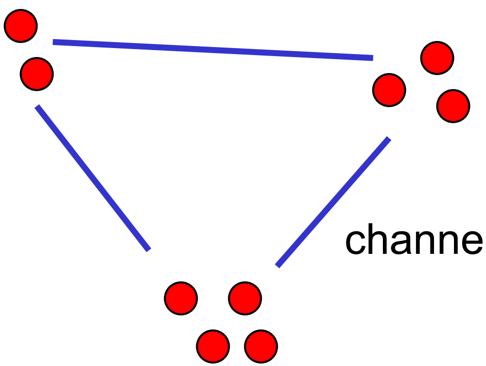
GOAL: develop quantum *technologies*

Quantum Computing Models / Scenarios

- standard quantum computing paradigm
  – quantum bit / register
  – quantum gate
  – initialize / read out
  – [no decoherence]



- quantum networking and quantum communications



- Nodes: local quantum computing
  - store quantum information
  - local quantum processing
- Channels: quantum communication
  - transmit quantum information

... other versions

- one way quantum computer (Briegel)

- continuous variable quantum computing (Braunstein & Lloyd)
- [and cv quantum communications]

- finite temperature (NMR)

How? The Beauty Contest

- AMO
  - ions, neutral atoms, cavity QED (single quanta / ensembles)
  - linear optics qc
- Solid State
  - Josephson junction
  - Quantum dots
  - Solid State NMR (Kane, Fullerenes)
- other
  - electrons on He surfaces
  - spectral hole burning
- NMR
  - liquid state / high temperature
  - ...

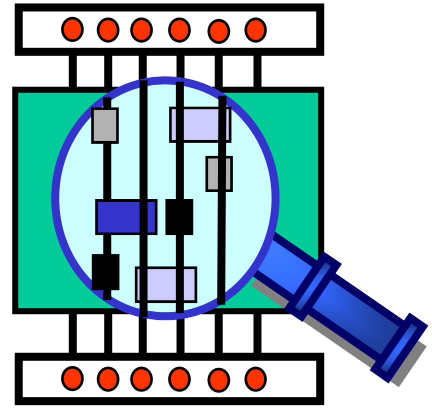
- the role of theory

US ROADMAP (Dec 2002)

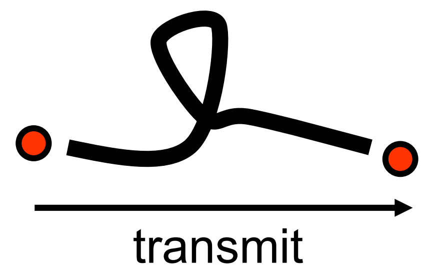
(as starting point and reference)

DiVincenzo Criteria

1. scalable system of well-characterized qubits
2. initialize qubits
3. long decoherence times
4. universal set of quantum gates
5. qubit readout



6. interconvert stationary and flying qubits
7. faithful transmission of qubits between specified locations



GOAL: satisfy requirements of fault tolerant quantum computing

Questions and Answers

- Q.: are there fundamental obstacles to implement fault tolerant quantum computing?

  NO, but technological challenge

- Q.: Is there a best approach?

  NO, but a few top candidates

QC Approach	#1 scalable physical system / qubit	#2 initialize	#3 decoherence	#4 qugates	#5 readout		#6 <-> flying qubit	#7 transmiss
NMR	red	orange	orange	green	orange		red	red
Trapped Ion	orange	green	orange	green	green		orange	orange
Neutral Atom	orange	green	orange	orange	orange		orange	orange
Optical	green	orange	green	orange	orange		orange	green
Solid State	orange	orange	orange	orange	orange		red	red
Superconducting	orange	green	orange	orange	orange		red	red
Unique Qubits								
e-Helium	orange	green	orange	orange	orange		red	red
Spectral Hole Burning	orange	green	orange	orange	green		orange	orange

Legend: (green) = a potentially viable approach has achieved sufficient proof of principle

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

(red) = no viable approach is known

December 2002

QC ROADMAP

time

- (physical) qubit
  - creation and readout
- single qubit operations
  - Rabi flops, decoherence
- two-qubit operations
  - two qubit gate, decoherence, gate tomography, [Bell]
- operations 3-10 qubits
  - simple quantum algorithms, error correction, decoherence free subspace, [GHZ, teleportation]

2007

- one logical qubit
- 3-10 logical qubits
  - fault tolerant operations

2012

criteria:

✓achieved in lab

✓ expected to work

✓ not know how to (road block)

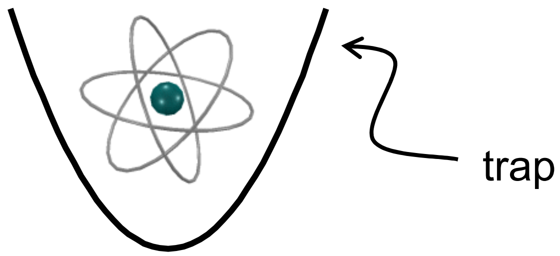
AMO = Atoms, (Molecules) and Optics

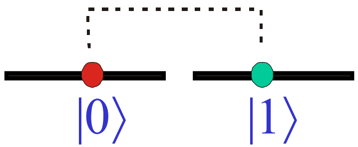
- atoms and ions (as qubits)
- photons (as flying qubits)

Cold atoms as quantum memory

- cold atoms, ions [and molecules]

single trapped atom:





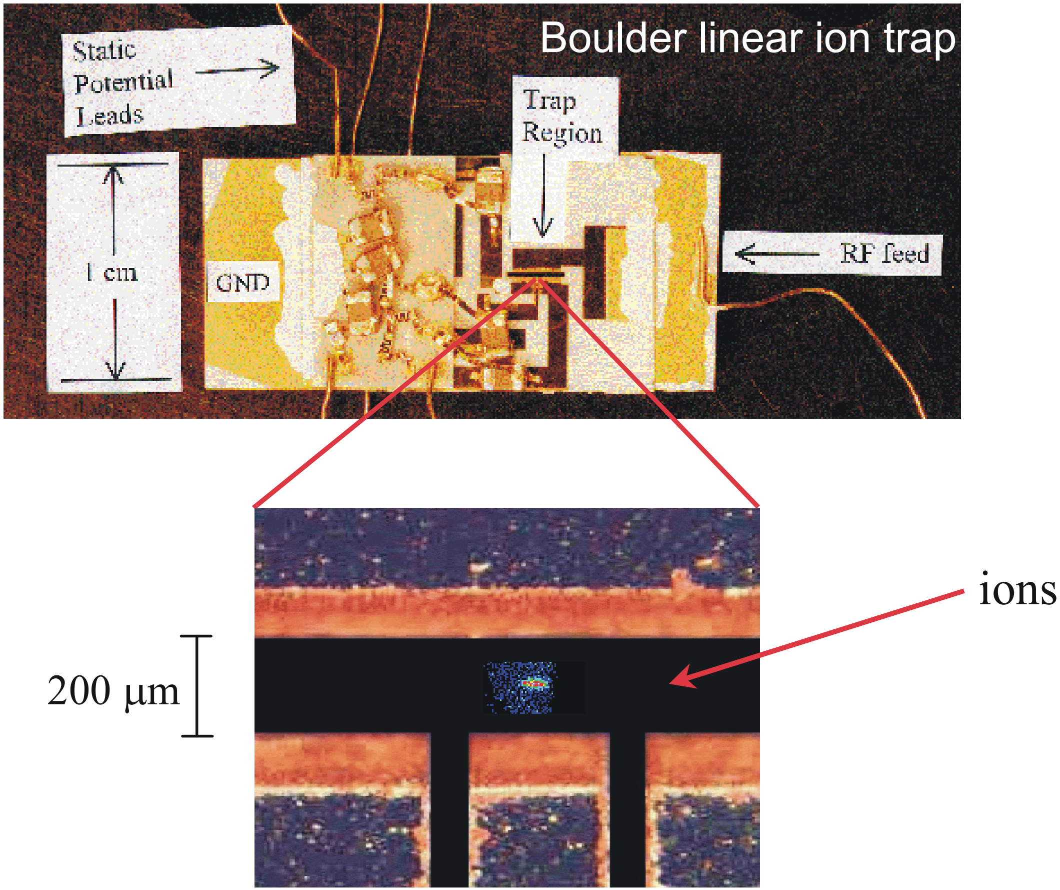
qubit in *longlived* internal states

DiVincenzo criteria:

- preparation of the qubit
  - trapping
  - cooling
- single qubit operations
- two qubit operations
  - requirements
  - timescales
- decoherence
- initialization and read out

Ion traps ... preparation of qubits

- ion traps



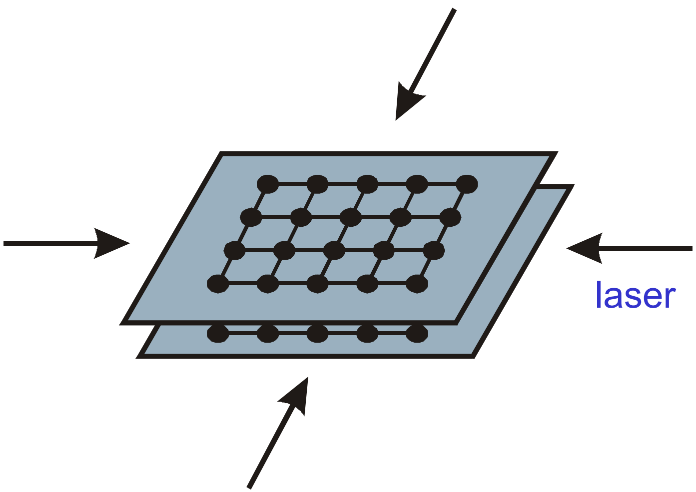
issues:

- ✓ conservative potential ν_{trap} ~ 0.3 – 10 MHz
- ✓ single atom loading
- ✓ laser cooling to ground state
- ✓ decoherence: heating [problem solved!?]

NIST Boulder, Innsbruck, Munich, Hamburg, Aarhus, Oxford, London, ...

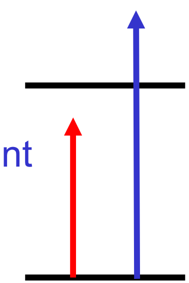
Neutral atom traps & cooling

- far-offresonance optical lattice

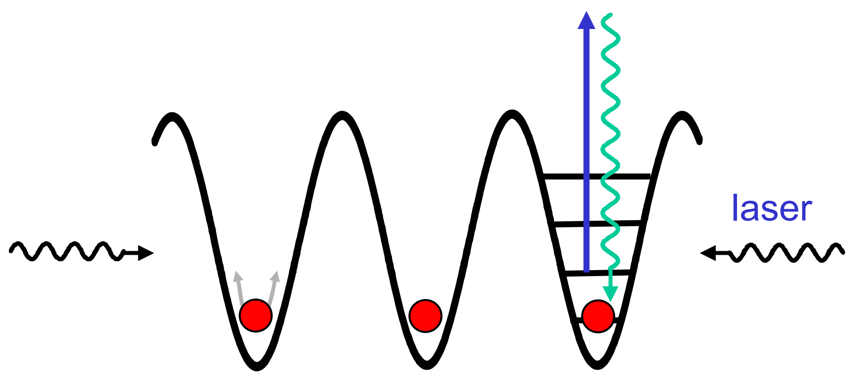


issues:

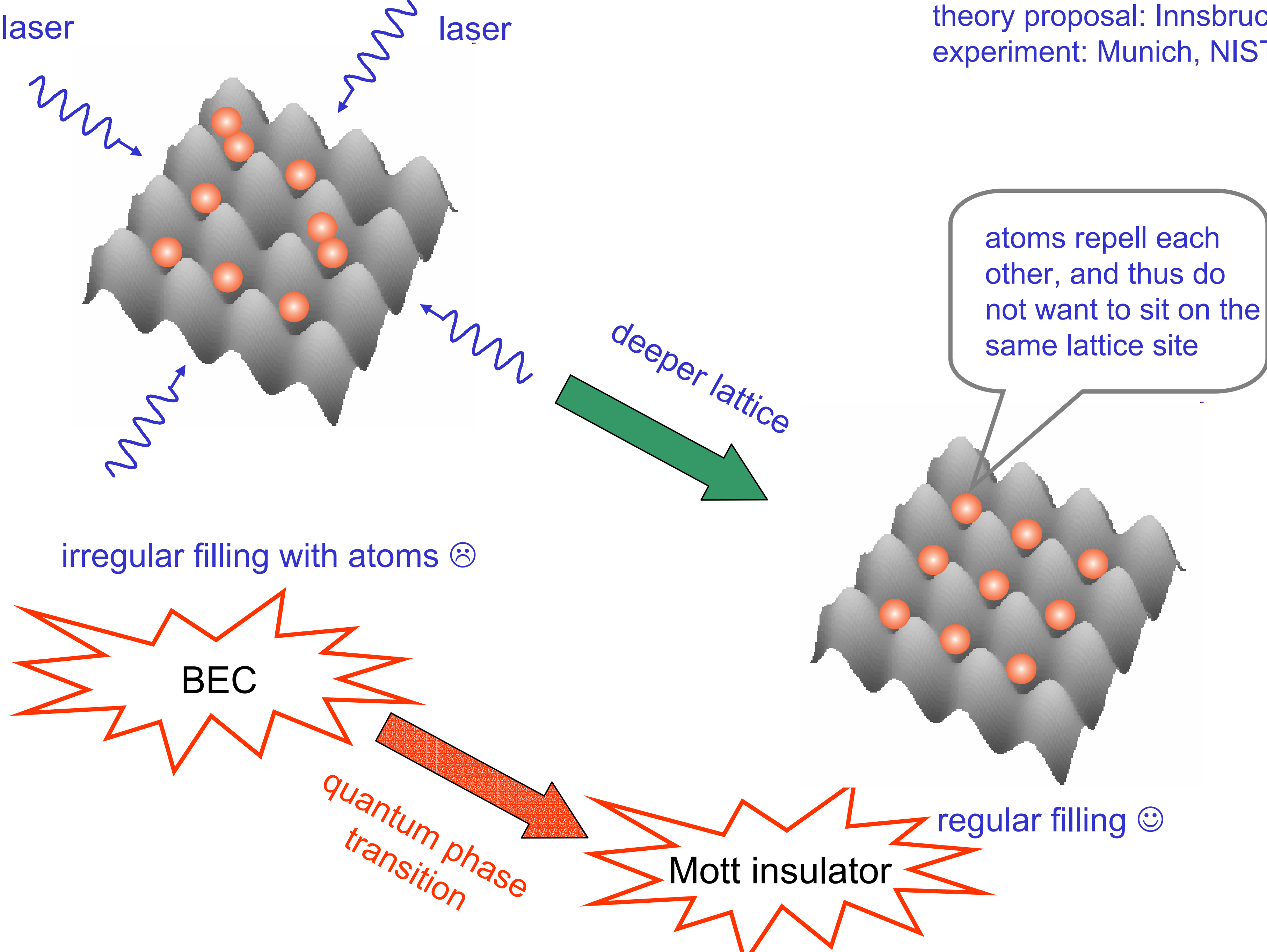
- ✓ conservative potential
- ✓ single atom loading of large arrays (?!)
  [problem solved via Mott insulator loading from a BEC]
- ✓ laser cooling
- ✓ decoherence: spontaneous emission ~ sec
- ✓ LARGE # of atoms >10^4



AC Stark shift

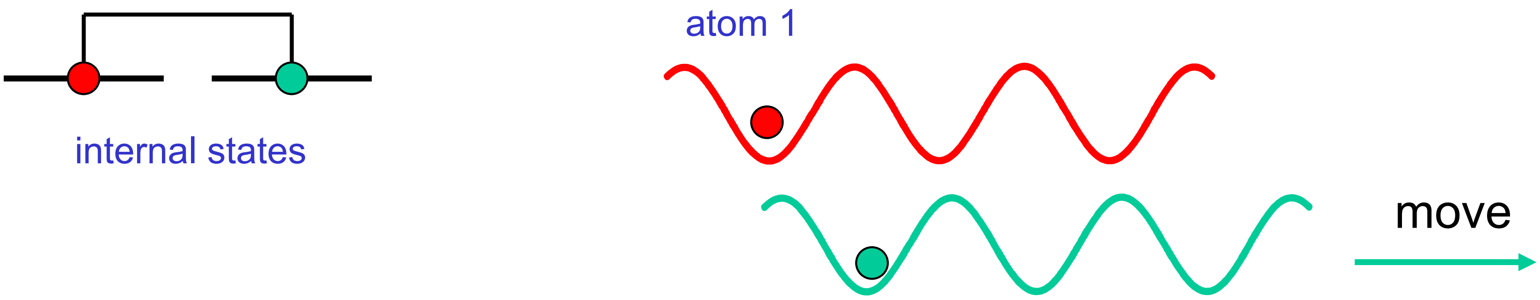


optical lattice

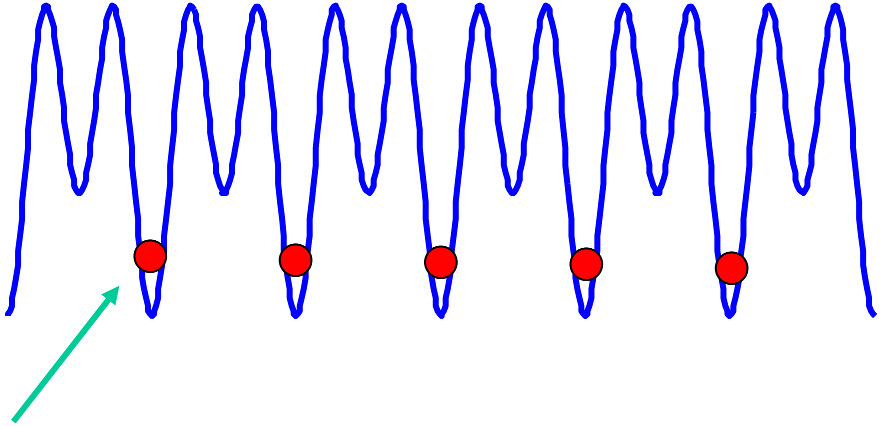


laser
laser
theory proposal: Innsbruc
experiment: Munich, NIST
atoms repell each other, and thus do not want to sit on the same lattice site
deeper lattice
irregular filling with atoms ☹
BEC
quantum phase transition
regular filling ☺
Mott insulator

- spin dependent optical potentials



- addressing (?): super lattices, gradients

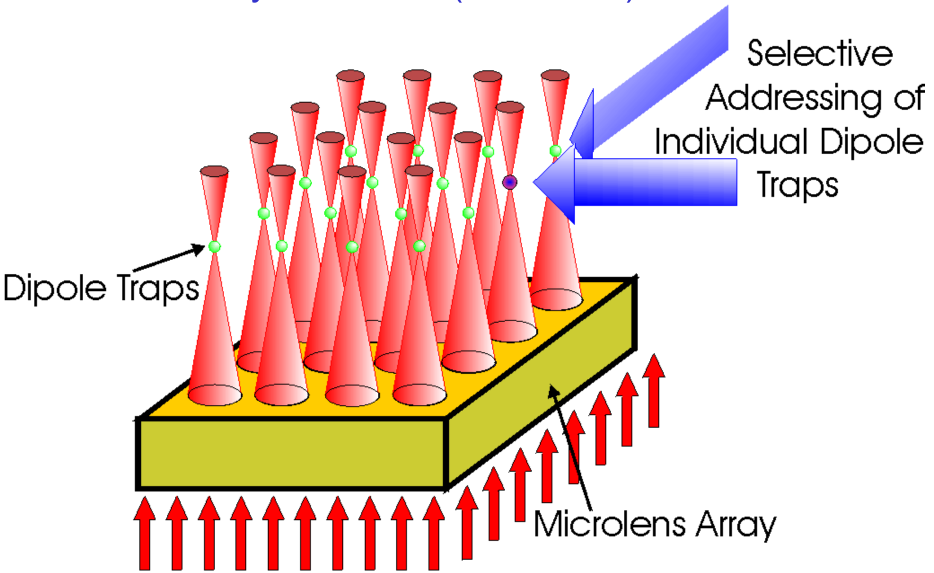


Note: some interesting applications like quantum simulations do not need individual addressing

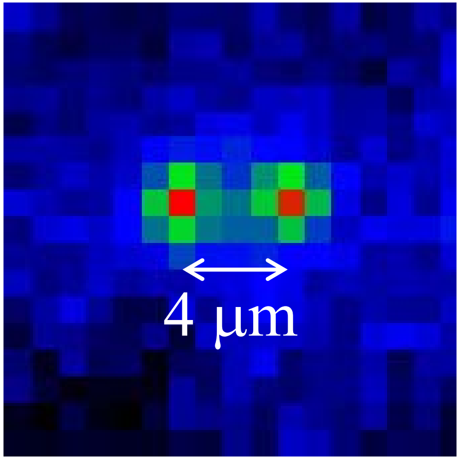
Neutral atoms traps

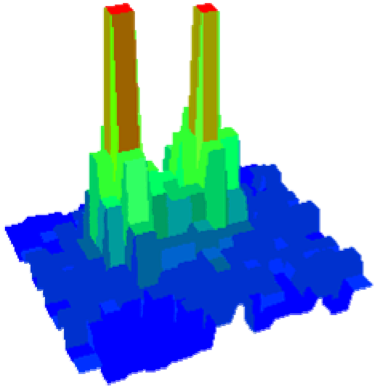
- single atom FORTs

array of FORTs (Hannover)

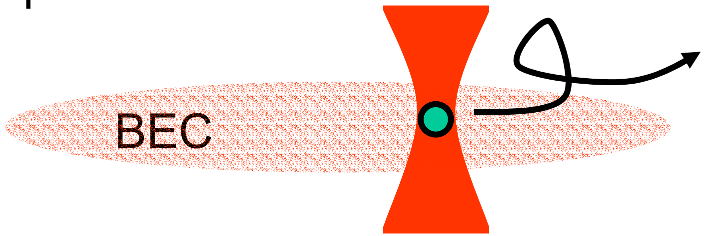


two movable single-atom FORTs (Orsay)



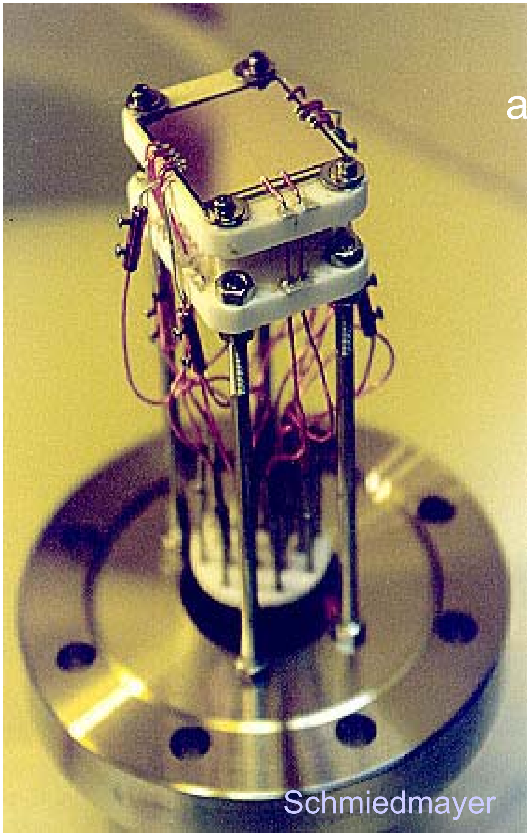


- grab an atom from a BEC: “quantum dot“



Magnetic traps

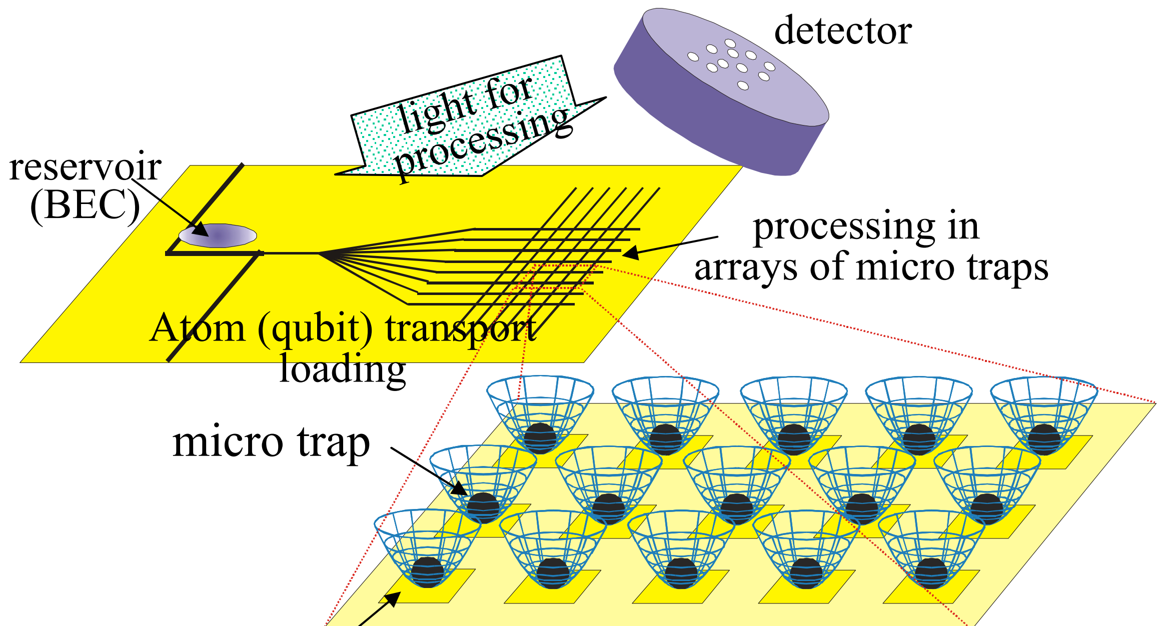
- magnetic traps



Heidelberg, Munich, Harvard, Orsay

issues:

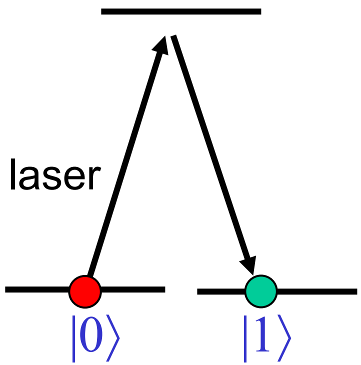
- ✓ conservative potential surface effects (?)
- ✓ single atom loading (?)
- ✓ laser cooling (?)
- ✓ loading from a BEC! Mott insulator loading?



© Schmiedmayer

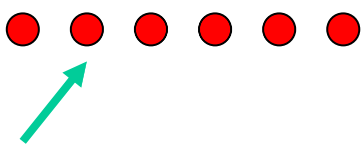
Single qubit gates

- single qubit gates



exp: high fidelity Rabi osc are standard

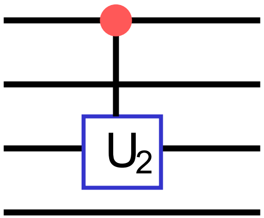
addressing single qubit



requirement: spatial separation

Entanglement: two-qubit gates

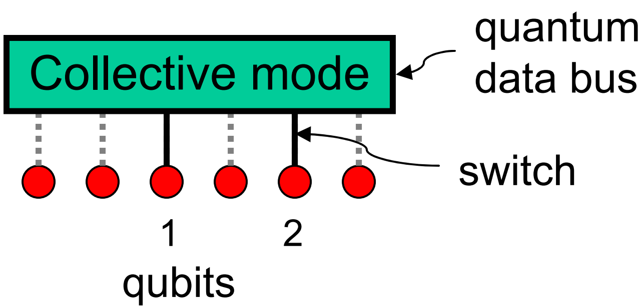
- implement entanglement of two qubits



example:
phase gate

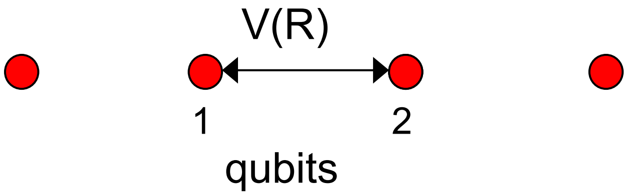
$$
\begin{aligned}
|00\rangle &\to |00\rangle \\
|01\rangle &\to |01\rangle \\
|10\rangle &\to |10\rangle \\
|11\rangle &\to e^{i\phi}|11\rangle
\end{aligned}
$$

- How?
  - ✓ auxiliary collective mode as data bus: ions, CQED, ...



  - ✓ controllable two body interactions: collisions, ...

    (dynamical phases, geometric phases)

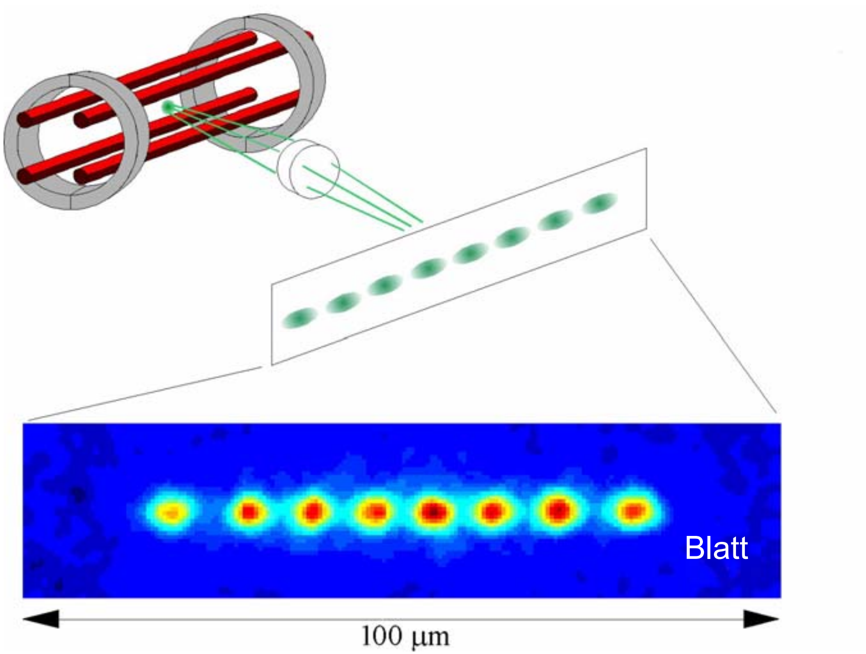


Ion Trap Quantum Computer

theory: Innsbruck, Aarhus, London, Brisbane ..

exp: NIST Boulder, Innsbruck, Munich, Oxford

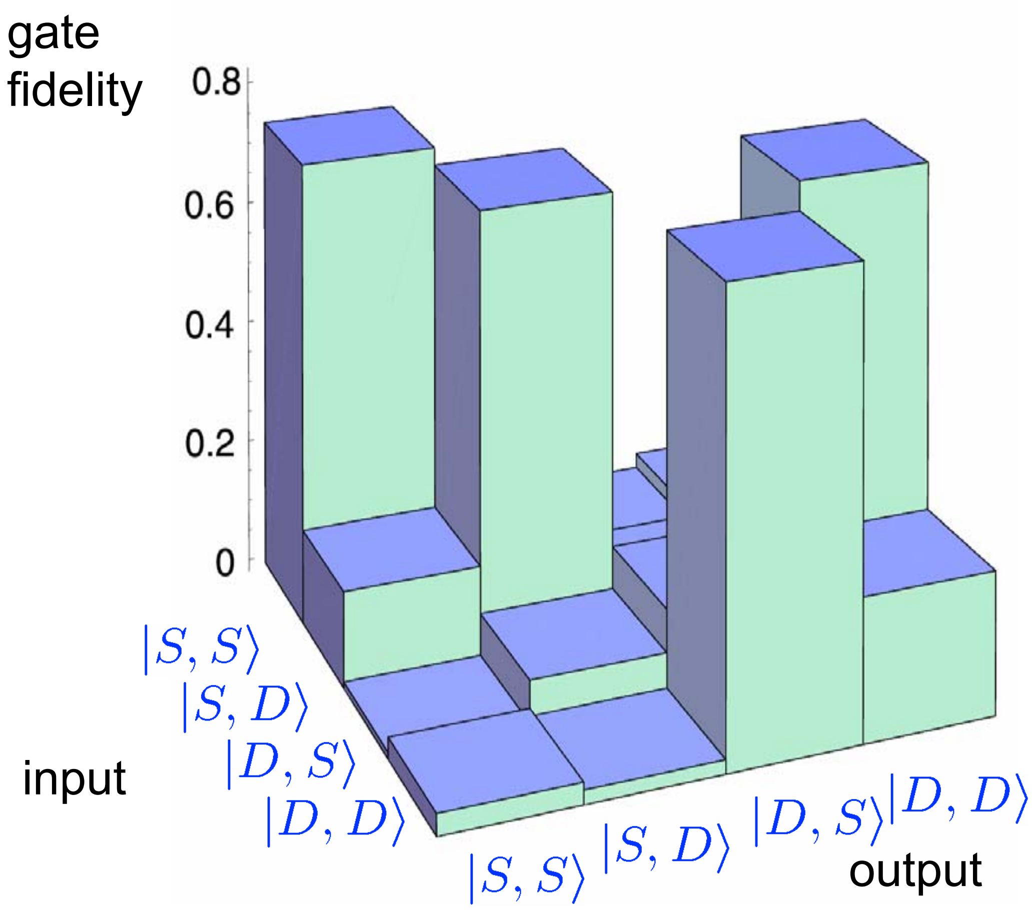
- Cold ions in a linear trap



- Qubits: internal atomic states
- Quantum gates: entanglement via exchange of phonons of quantized center-of-mass mode

- Achievements:
  - entanglement of four ions
  - single & two qubit gates with and without individual addressing

- addressable 2 ion controlled-NOT (R. Blatt et al., Nature 2003)



truth table CNOT

- 2 ion controlled NOT (Wineland et al., Nature 2003)

Limits?

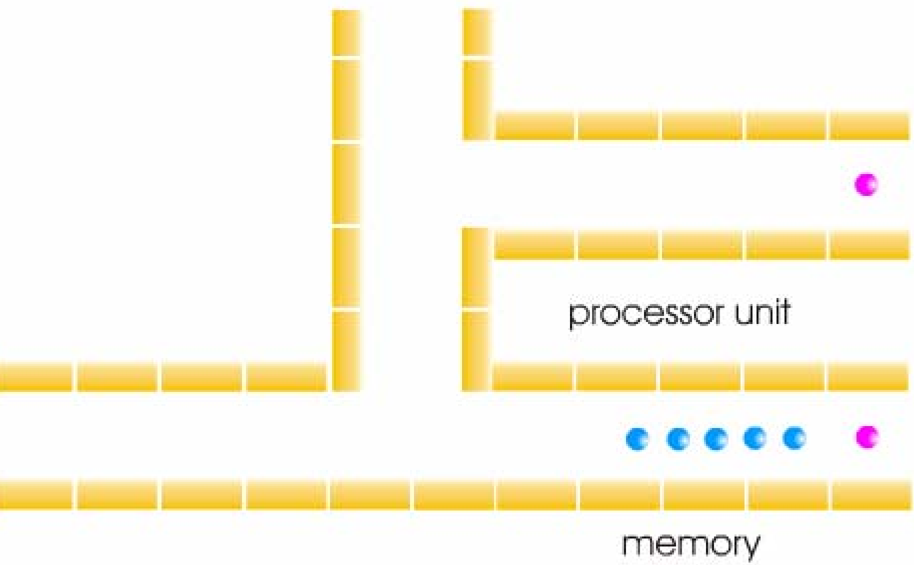
- new gate designs overcome limits …
  - NO ground state cooling
  - NO individual addressing required (of two ions)
  - gate time NOT limited by the trap period (very fast gates)
  - NO Lamb Dicke requirements

- optimizing gate operation and fidelities, and simplify requirements by coherent control techniques (quantum engineering)

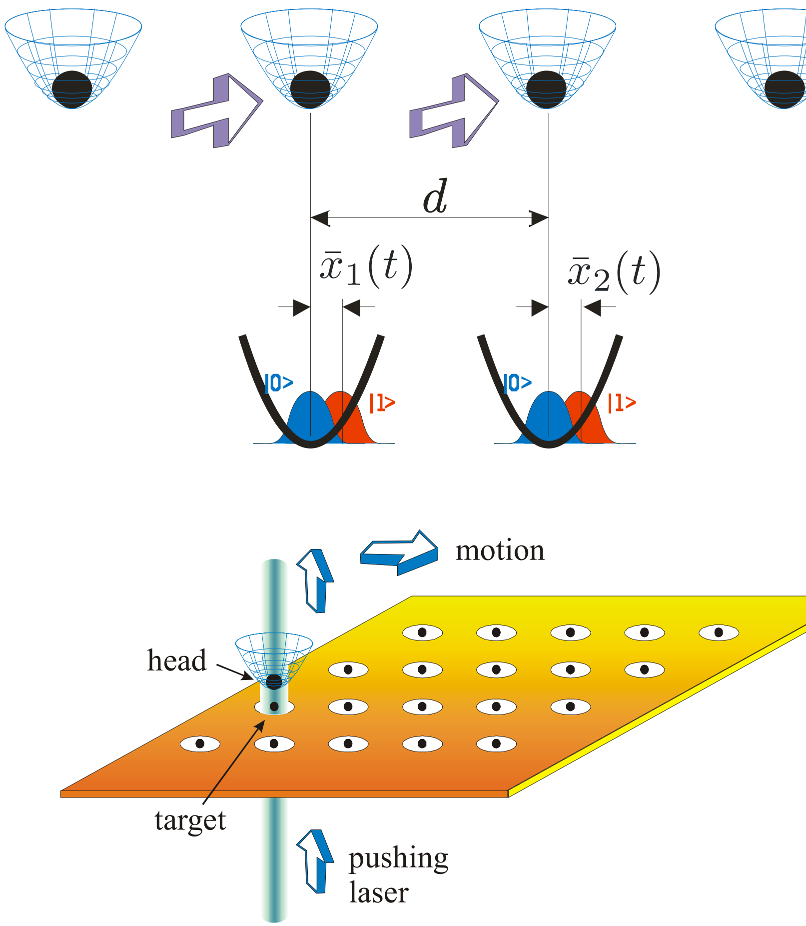
no limits!

Scalability: moving ions

- NIST Boulder © D. Leibfried



- Cirac-Zoller 2000: “moving head”



Summary (DiVincenco requirements)

I. multiplexed trap architecture, hyperfine ground states ✓

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

III. T_{dec}=1 ms (>100 s), T_{heat}=10 ms (1 s), T_{gate}=32 μs (500 ns) ✓

IV. single and two qubit gates ✓

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

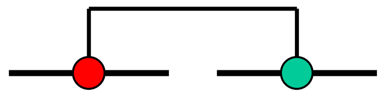
All requirements met *experimentally!*

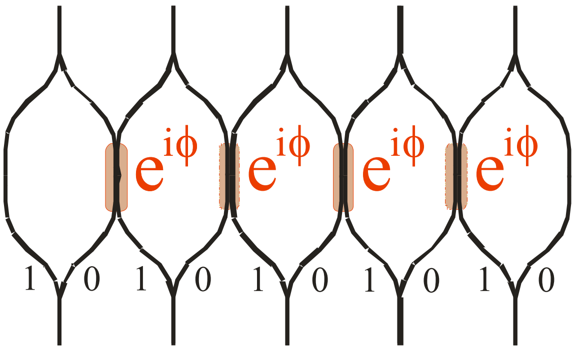
No fundamental limits in sight!

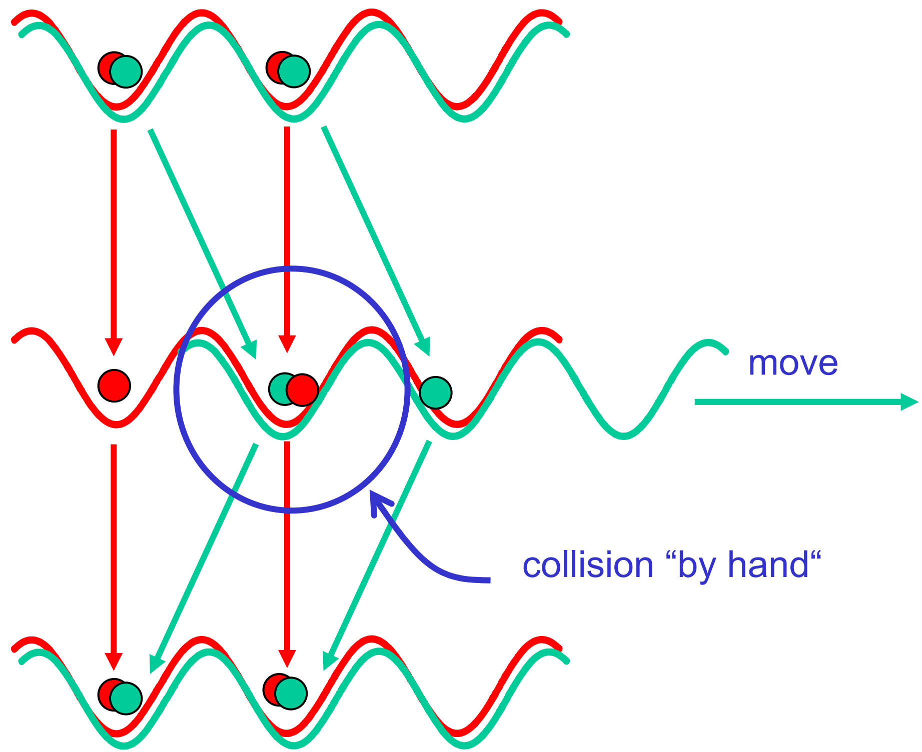
Entanglement via collisions in an optical lattice

theory: Innsbru
Albuquerque
exp.: Munich

- interactions by moving the lattice + colliding the atoms “by hand”







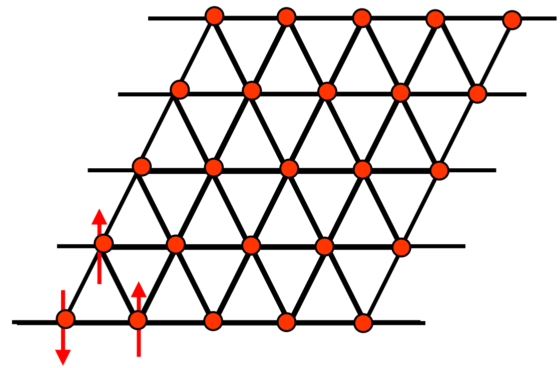
- Ising type interaction as the building block of the UQS

$$H = -\frac{J}{2} \sum_{\langle a,b \rangle} \sigma_z^{(a)} \otimes \sigma_z^{(b)}$$

Feynman's Universal Quantum Simulator (specialized quantum computing)

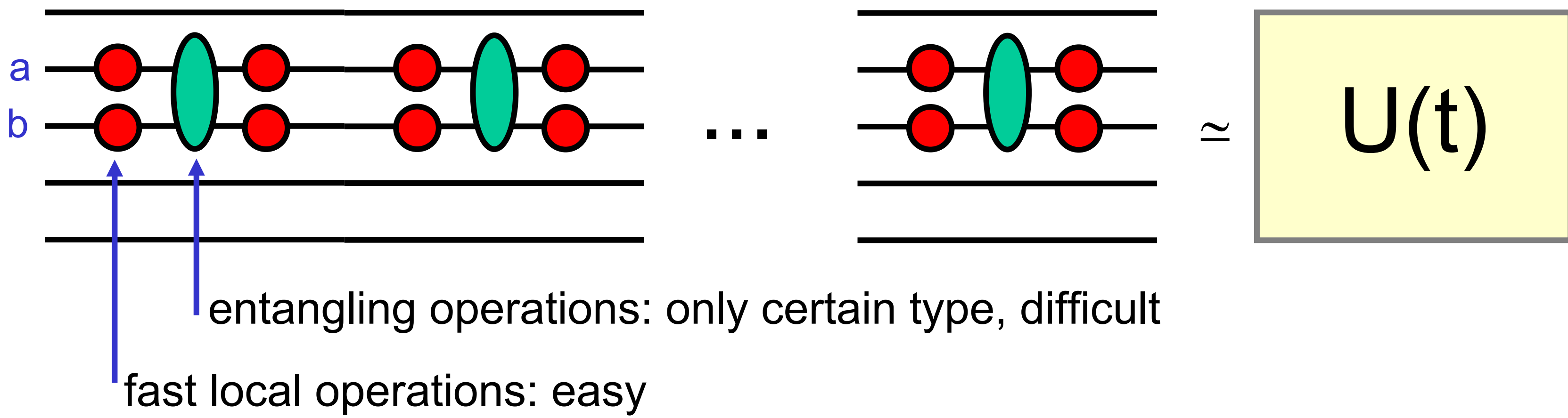
Feynman, Lloyd, ...

- Example: condensed matter
  - spin models
  - Hubbard models



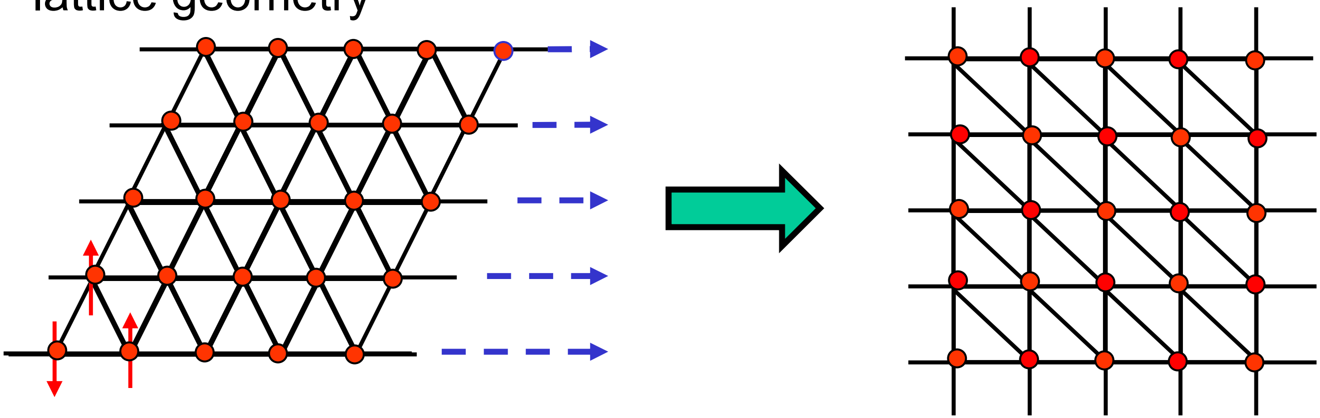
$$|\psi\rangle = \sum_{\tilde{\sigma}} c_{\tilde{\sigma}} |\sigma_1 \sigma_2 \ldots \sigma_N\rangle$$

- idea: effective Hamiltonian H_{eff} evolves as time average over other Hamiltonian H



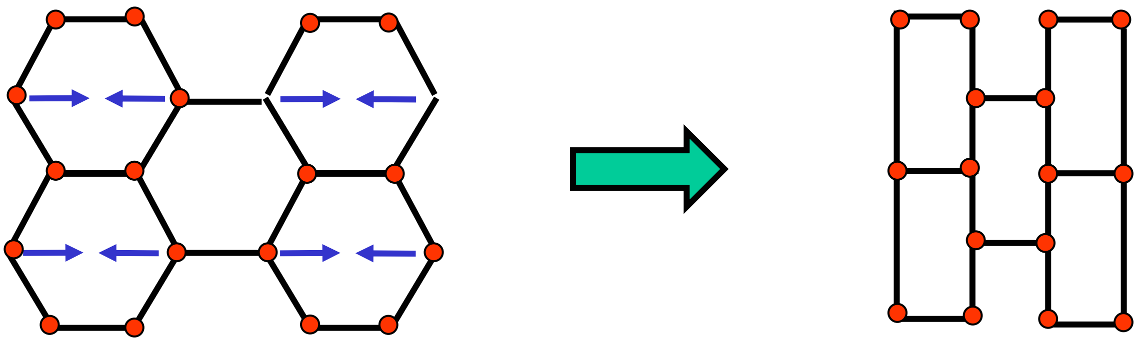
- implementation: optical lattice

- lattice geometry



triangular lattice

square lattice



hexagonal lattice

square lattice

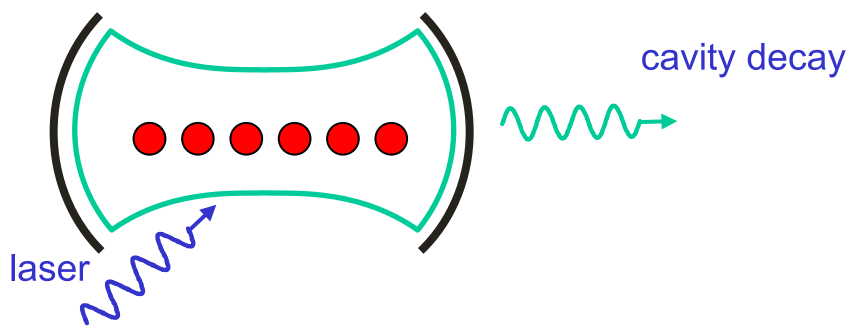
... requires individu
addressing

- solving high-T_c superconductivity models, … ?

Optical Cavity QED

optical: Munich, Caltech, Georgia Tech, Bonn, Innsbruck
microwave: ENS, Munich

- *optical / microwave* photons in a high-Q cavity as "data bus„: FAST



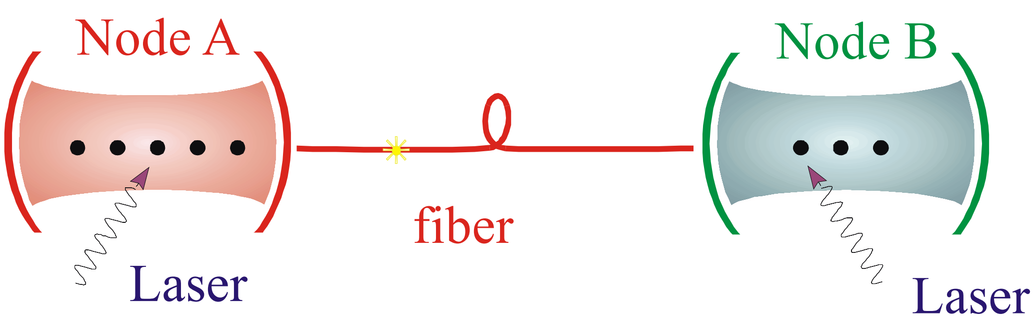
problem in the past:
storage of atoms

also:

✓single photon source

✓entangled photon source

- quantum transmission between nodes

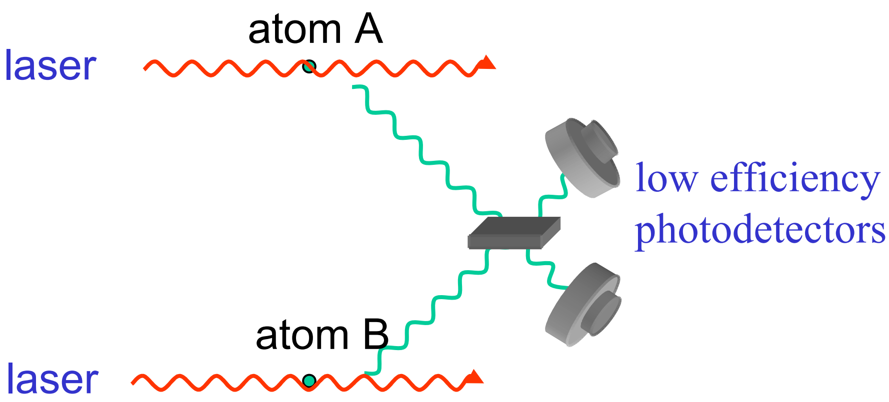


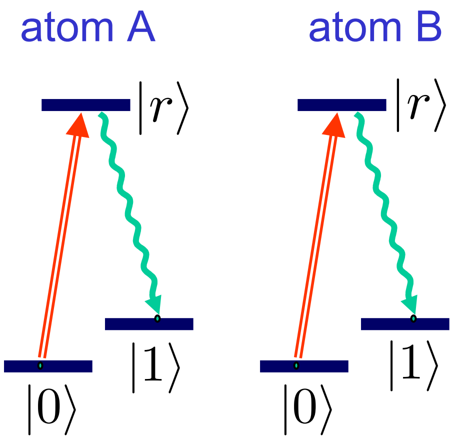
• memory: atoms → • databus: photons → • memory: atoms

Cabrillo et al. `99

Probabilistic Entanglement: example ... single atoms / ensembles / quantum dots

- entanglement generation





- Weak (short) laser pulse, so that the excitation probability is small.

- If no detection, pump back and start again.

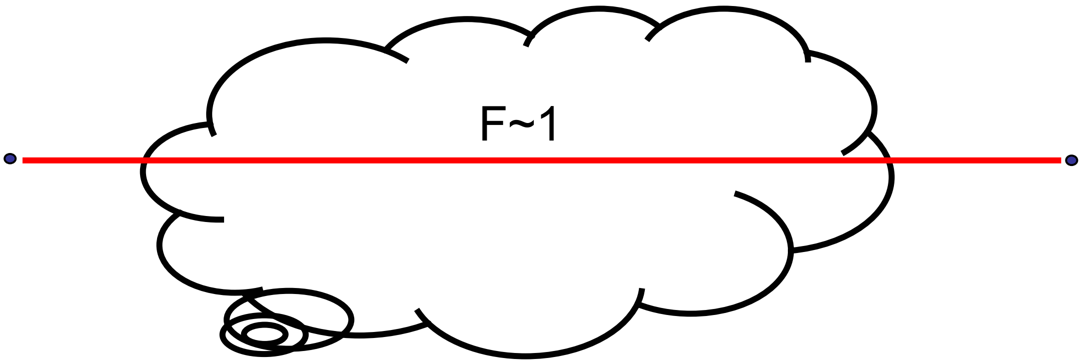
- If detection, an entangled state is created

$$\sim |0,1\rangle + |1,0\rangle$$

... which allows us to build a quantum repeater

- we can do long distance quantum communication if we have a high fidelity EPR pair

- quantum repeater protocol = generate *long distance entangled pairs* with fidelity *F ~ 1* in a small number of trials $\sim L^{\eta}$ in the presence of noise



$$|\mathrm{EPR}\rangle = |0,1\rangle + |1,0\rangle$$

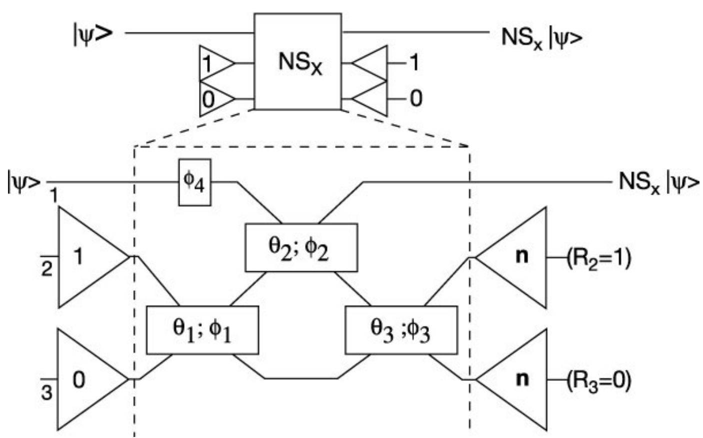
Optics

- qubits = photons
- quantum communication and networking [see cavity QED]

- optical (only) quantum computing
  - single photon nonlinearities

✓slow light

  - *linear optics* quantum computing (Knill, Laflamme, Milburn)



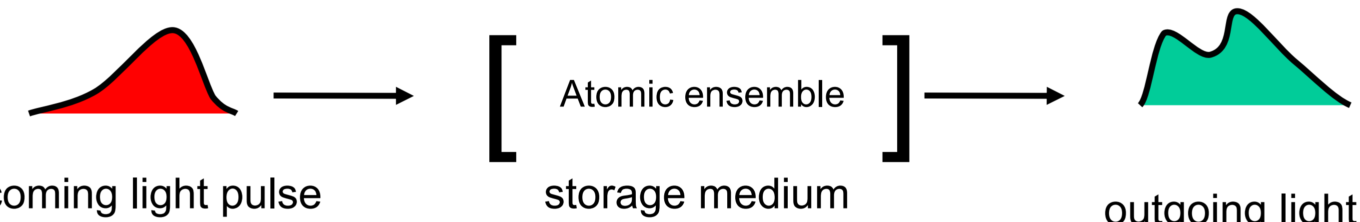
✓photodetection as a nonlinearity

✓single photon sources

✓efficient photo detectors

Atomic ensembles: quantum memory for light

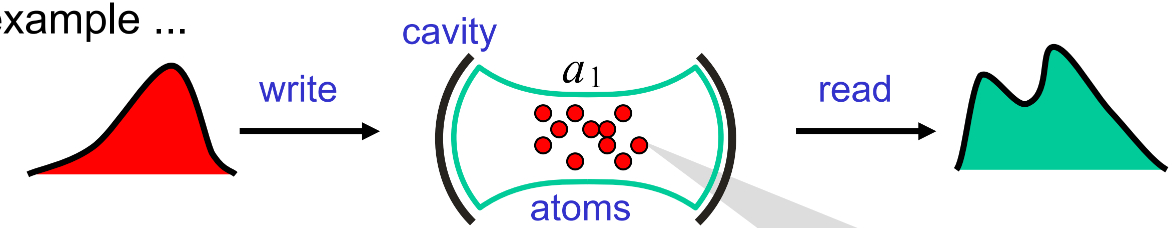
- purpose

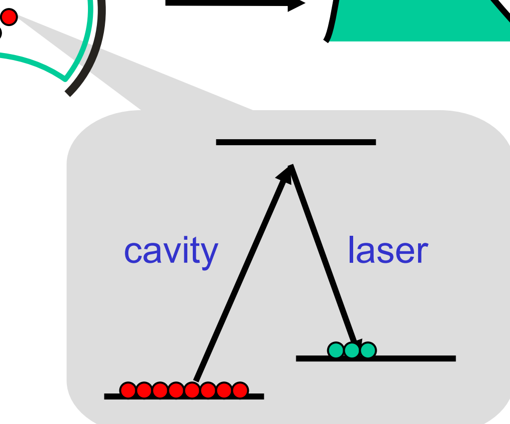


✓unknown (arbitrary) state
✓known shape of wave packet

✓same state
✓reshaping

- how? example ...

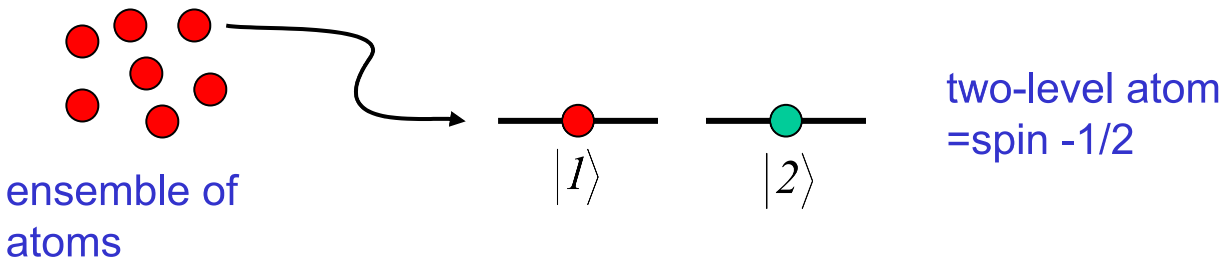




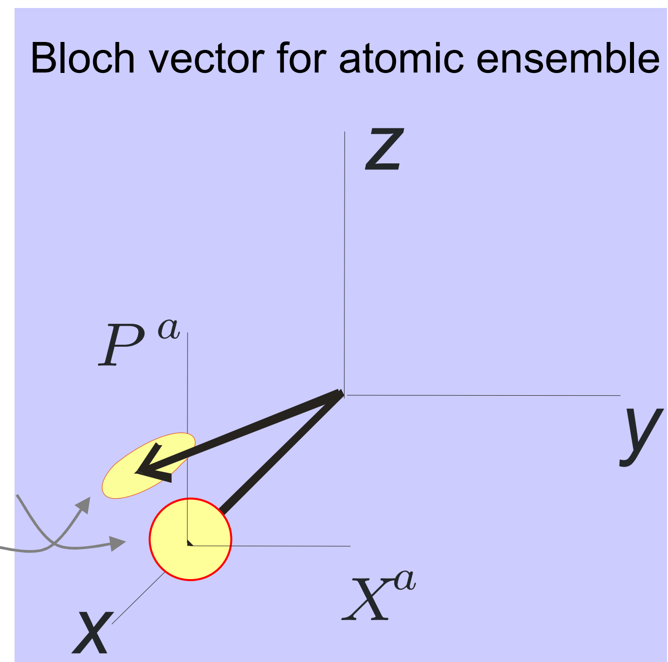
theory Harvard, Aarhus
exp: Harvard

Atomic ensembles as quantum memory

- We consider an ensemble of N atoms

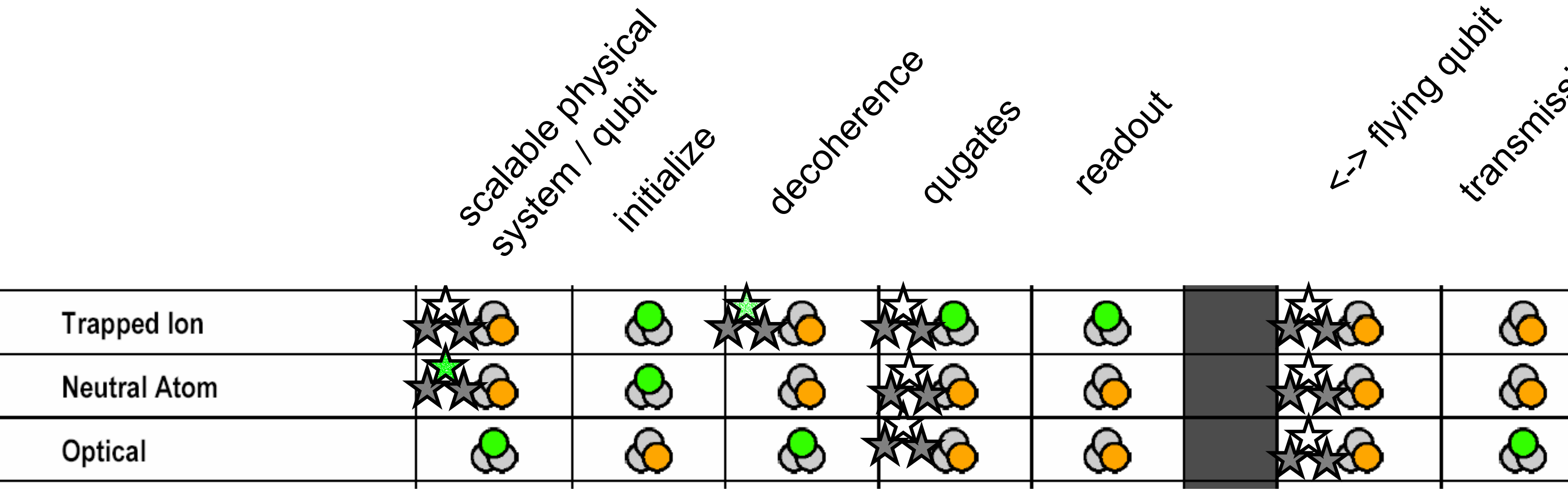


- storing qubits ...
- storing continuous variable states, teleportation (Aarhus)



✓ coherent spin state =vacuum state

✓ there are *many* cv quantum states around it:



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

my evaluation

Solid State

- ... comes in many flavors

- systems
  - spins, excitons in quantum dots, impurities, ...
  - solid state NMR (Kane, Fullerenes,…)
  - Josephson Junctions
  - spectral hole burning

+ in line with existing fabrication / technologies
+ "switch on and it is there"

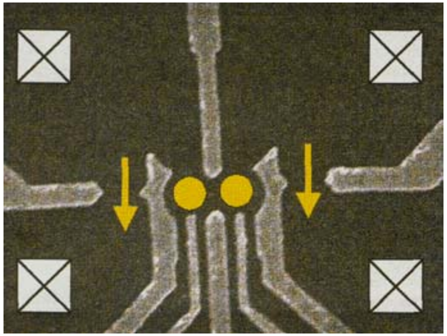
solid state $\longrightarrow$ scalable

~~not solid state $\longrightarrow$ not scalable~~

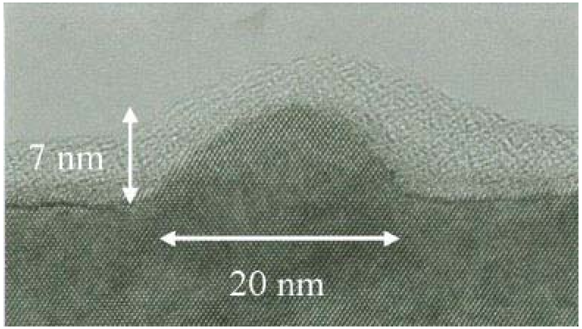
- [black art of] material science: decoherence (fundamental limits?)

Electron spins in semiconductor quantum dots

- spin in spatially confined structures (e.g. quantum dot)
- quantum dots:
  - electrically gated quantum dots: ↔ electronics

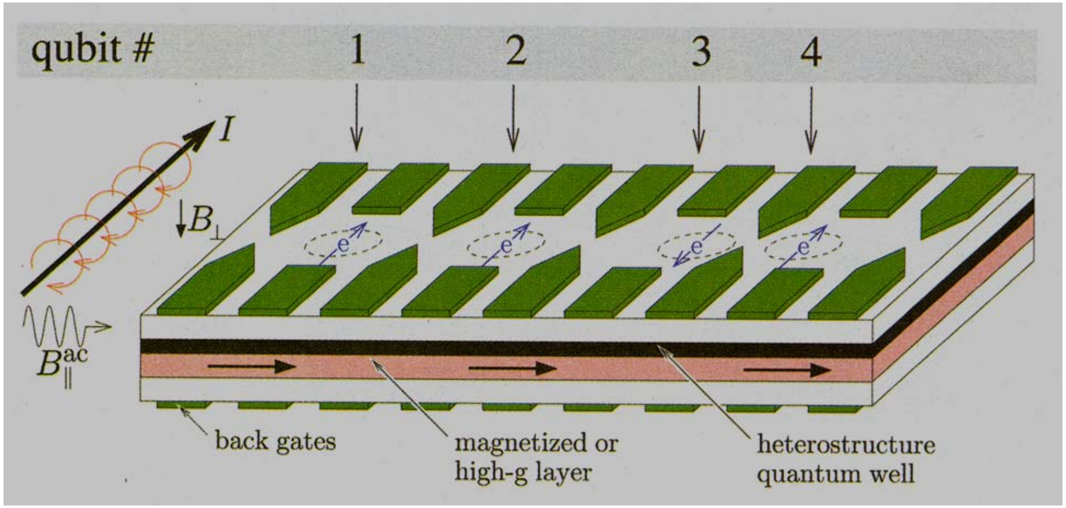


  - self-assembled etc quantum dots: ↔ optics



Electronics: electrically gates quantum dots

- Loss DiVincenzo proposal



300 mKelvin,

B ~ Tesla

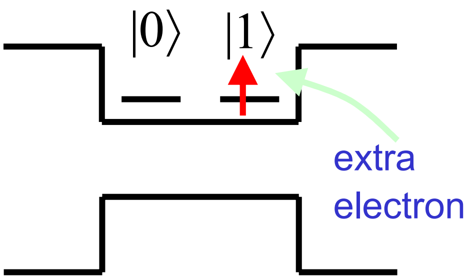
- qubit: electron spin [decoherence: hyperfine, ... , ~ μs]
- interactions:
  - 2 qubit: exchange interaction spin-charge [speed ~ tens of *ps*]
  - 1 qubit: g-factor
- measurement: SET

- achievements ... (?)

“artificial atoms”
$\leftrightarrow$ AMO

Optics: self-assembled quantum dots *etc.*

- charged QD: electron spin as qubit



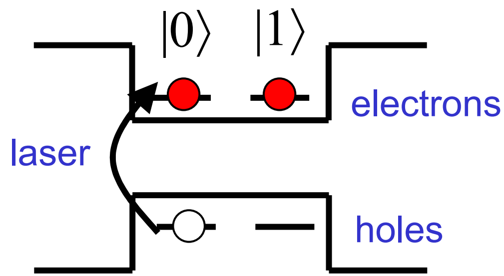
decoherence: μs (hyperfine)

[size fluctuations]

preparation: optical pumping

measurement: quantum jumps

- excitons, and spin charge conversion



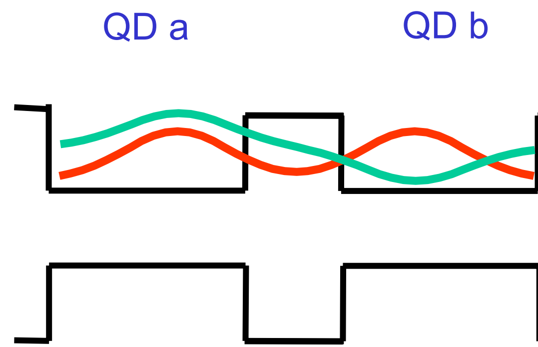
decoherence: spontaneous emission (and phonons)

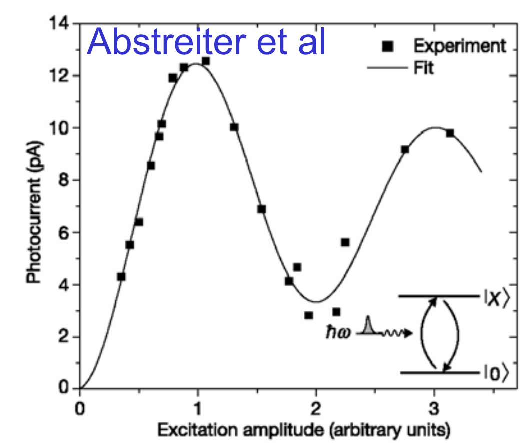
interactions:

spin $\xrightarrow{\text{laser}}$ charge

- exp.: exciton Rabi oscillations (5 groups)
- exp.: spectroscopy – single dot, molecules

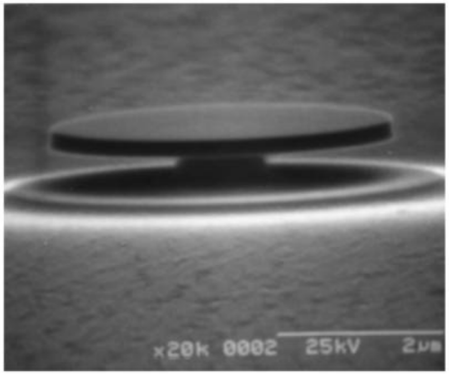
- QD molecules



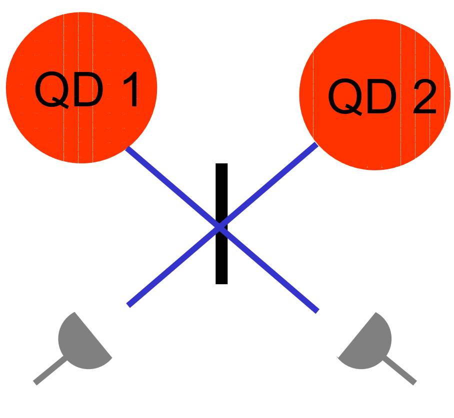


... natural connection with:

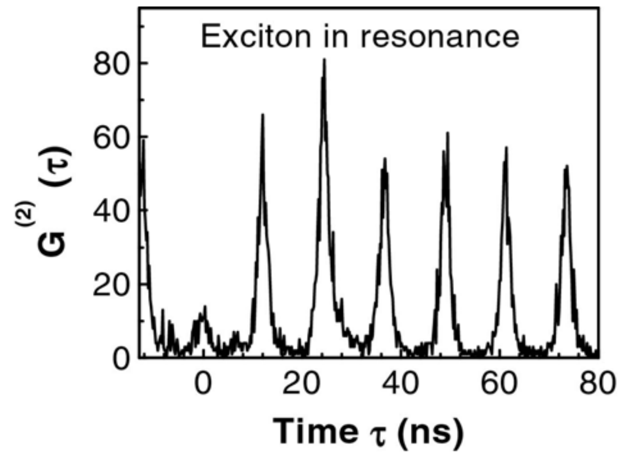
- CQED



- probabilistic entanglement



- single photon sources



(Immamoglu, Yamomoto)

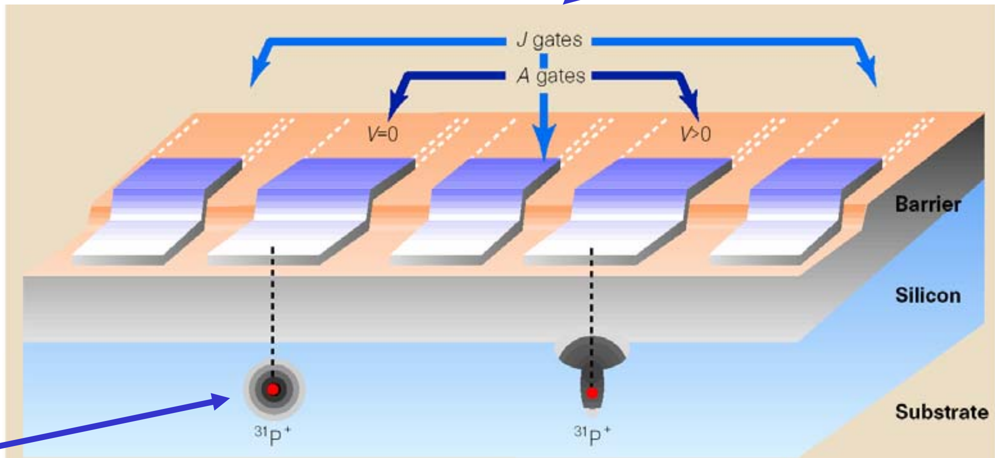
- see also: CQED with atoms, Nitrogen vacancies

- $\leftrightarrow$ linear optics quantum computation

Solid State NMR: Kane

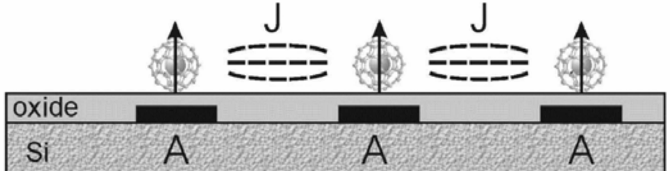
A & J gates control hyperfine & exchange interaction

- **Kane proposal**



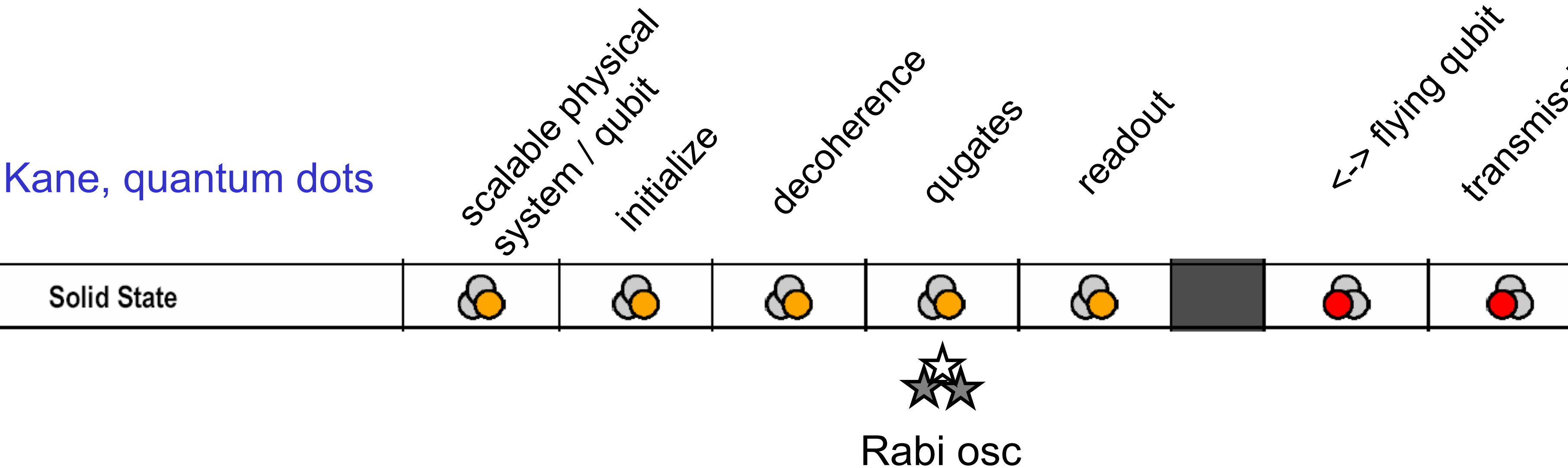
- qubit: nuclear spin of P donors in Si
- interactions: donor electron – nuclear spin, exchange interaction
- read out: SET
- decoherence: qubit – electron interaction
- gate time: ~second
- status: P implanted (Australia), ... ?

- **Fullerenes**



N in cage

Kane, quantum dots



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

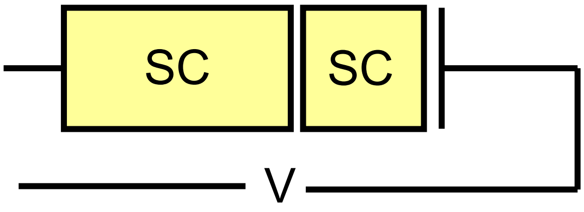
= a potentially viable approach has been proposed, but there has not been sufficient proof of principle

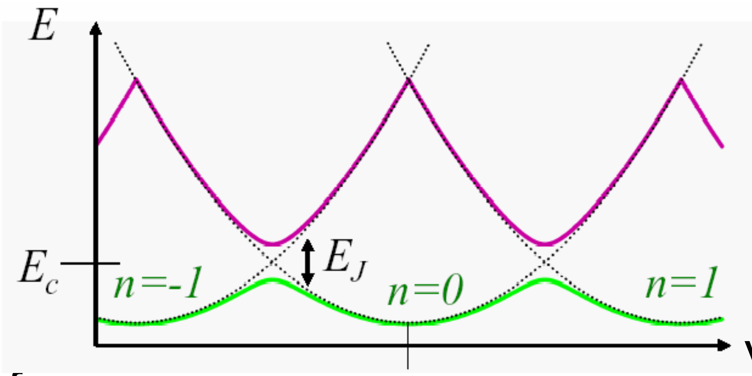
= no viable approach is known

December 2002

Josephson Junctions

example: charge qubit
(Cooper pair box)





- qubits = superconducting circuits @ mKelvin
  - charge
  - flux, energy
  - levels
- interactions:
  - charge: capacitive
  - flux: inductive
- energy scales 1 – 10 GHz, clock speed of ~ns
- preparation: cooling
- manipulation: rf pulses
- measurement: (rf) SET, SQUID (projective measurements?)
- decoherence: theory ~ms, exp ~μs [charge hopping? 1/f noise]

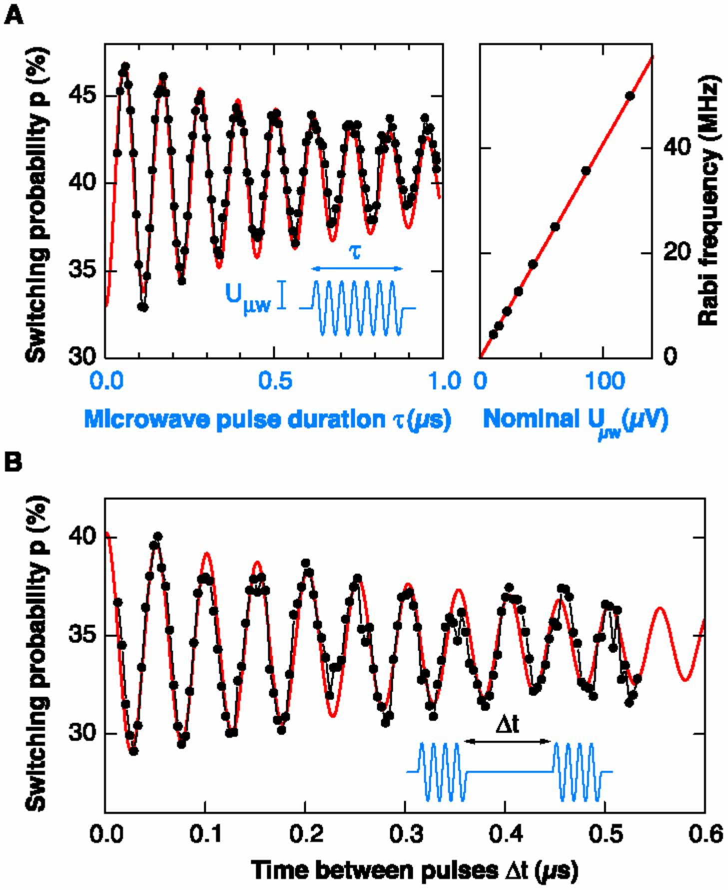
- theoretical proposals for gates etc.

- qubit
  - ½ charge + ½ flux qubit

charge qubit:
Rabioscillations

Esteve, Devoret
et al.

charge qubit:
Ramsey



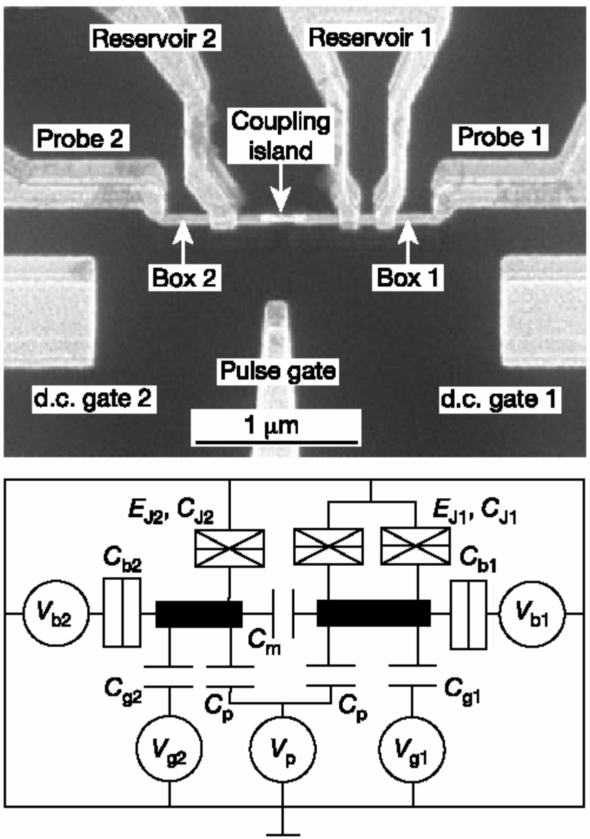
  - flux qubits: spectroscopy

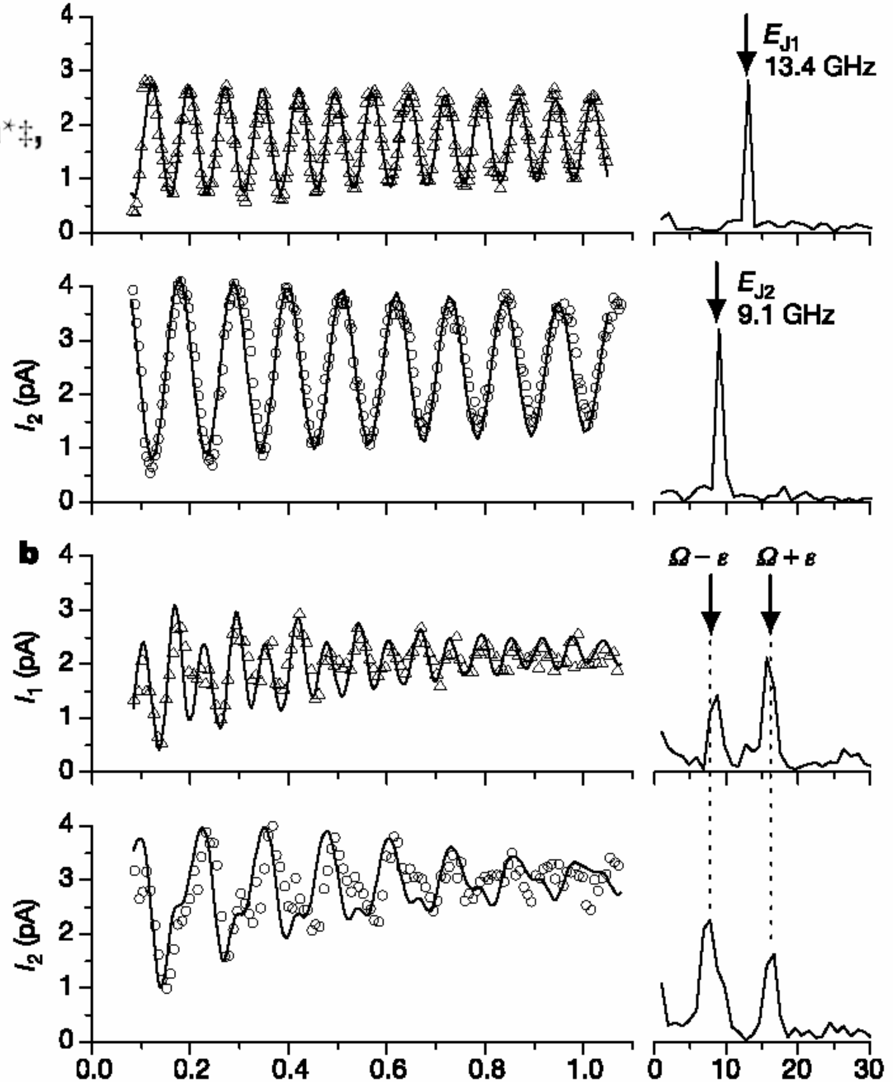
Mooij et al, ...

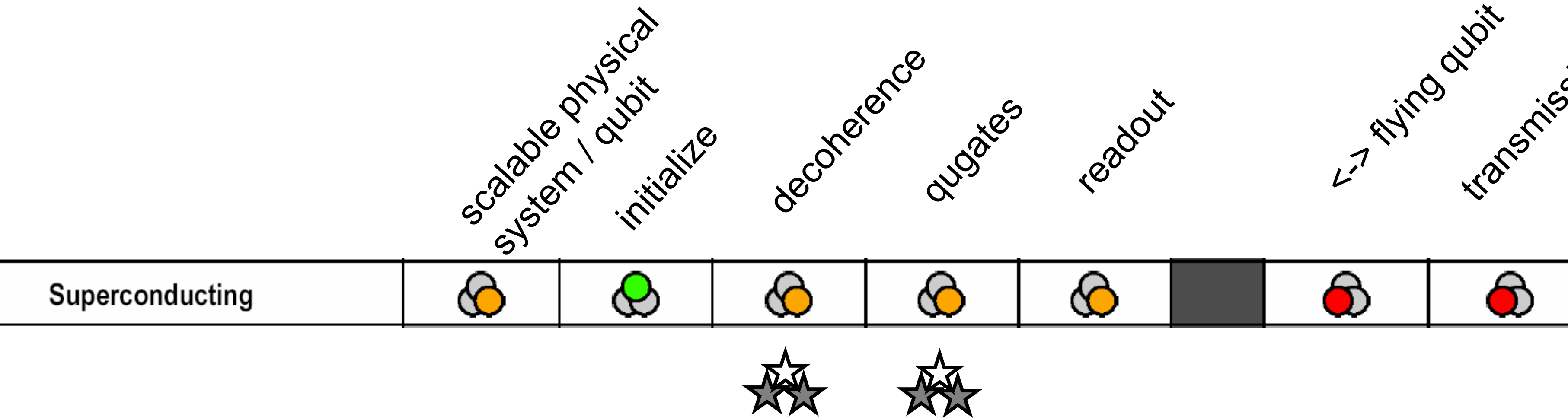
- coupled qubits: coupled Josephson Junctions (2003)

Quantum oscillations in two coupled charge qubits

Yu. A. Pashkin*†, T. Yamamoto*‡, O. Astafiev*, Y. Nakamura*‡, D. V. Averin§ & J. S. Tsai*‡







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

December 2002

Facts & Opinions 1

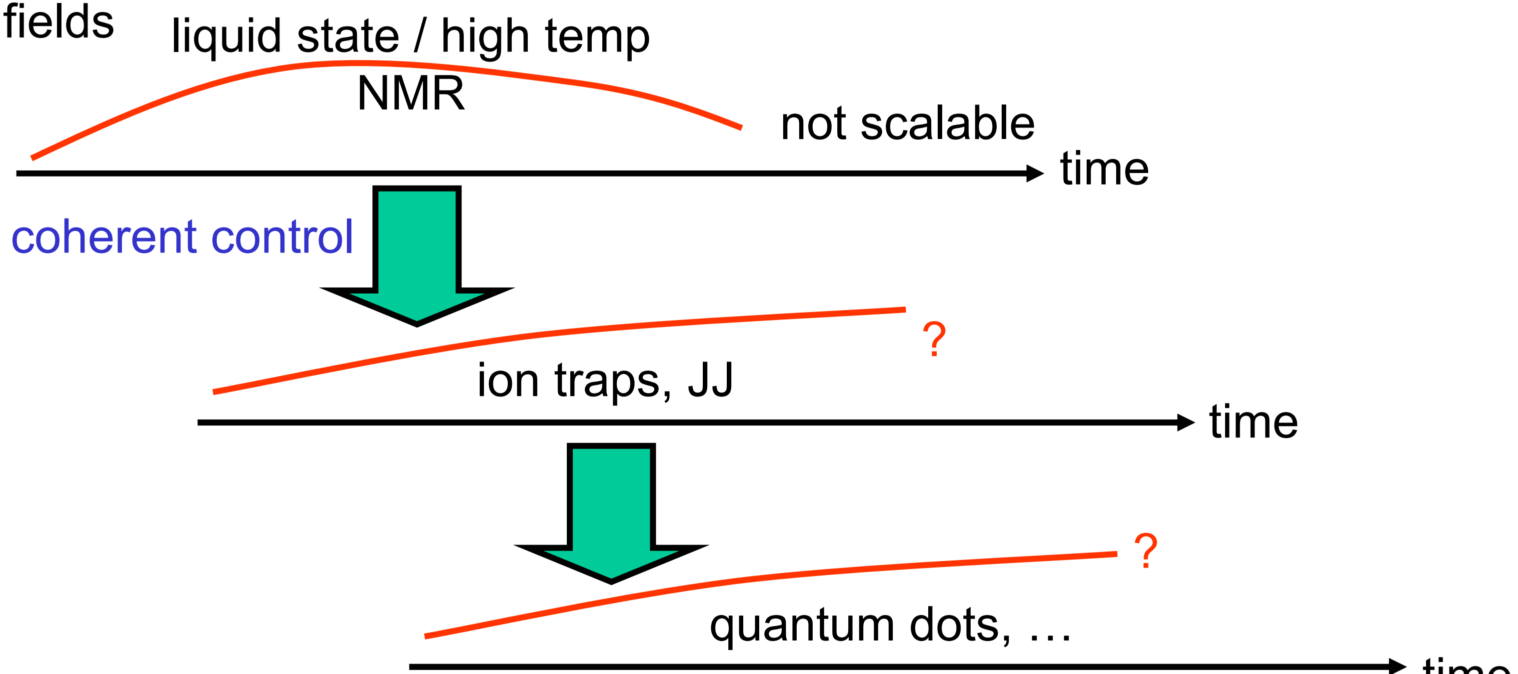
- FACT: quantum jump in experimental progress during last ~ 1 year
- FACT: Europe is very strong, both in theory, and experiment.
- FACT/OPINION : no fundamental physical obstacles, but a significant technological challenge
- => OPINION quantum computing (in some form) is likely to happen. [Q.: will it happen in Europe?]

Facts & Opinions 2

- FACT there are no clear winners at the moment, but hot candidates: identified by
  (i) theory: complete qc model [scalability], and
  (ii) an experimental program on the way of demonstrating these ideas

no road block in sight

- FACT / OPINION Ideas have there life time, but interact with other fields

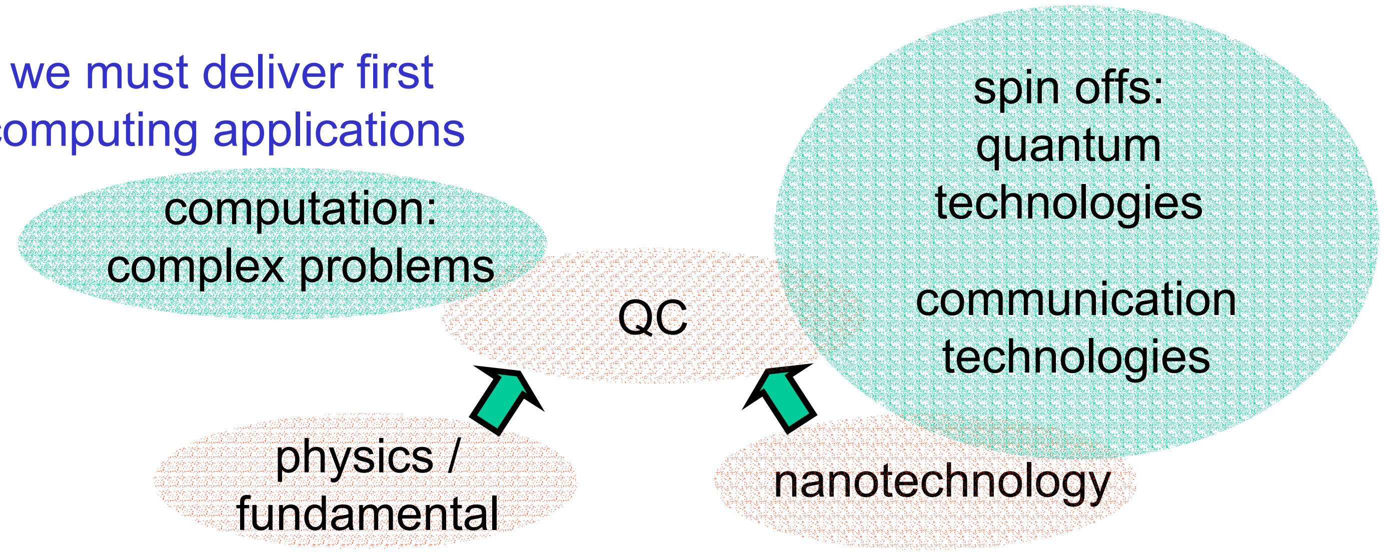


CONCLUSION: funding only what is hot right now is a mistake

Facts & Opinions 3

- Quantum computing is developing more and more a technological component = limited at present by technological progress

we must deliver first computing applications



funding of exp programs must develop a second leg: *technology*

- OPINION do not disentangle theory and experiment