

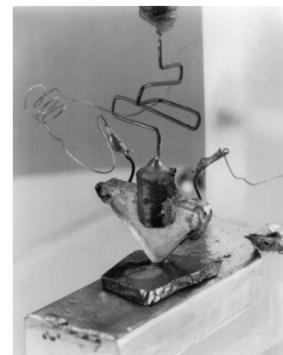
**MIT QUANTEN
KANN MAN RECHNEN**



- bit \leftrightarrow qubit
- neue Algorithmen
- experimentelle Umsetzung

bit 0, 1

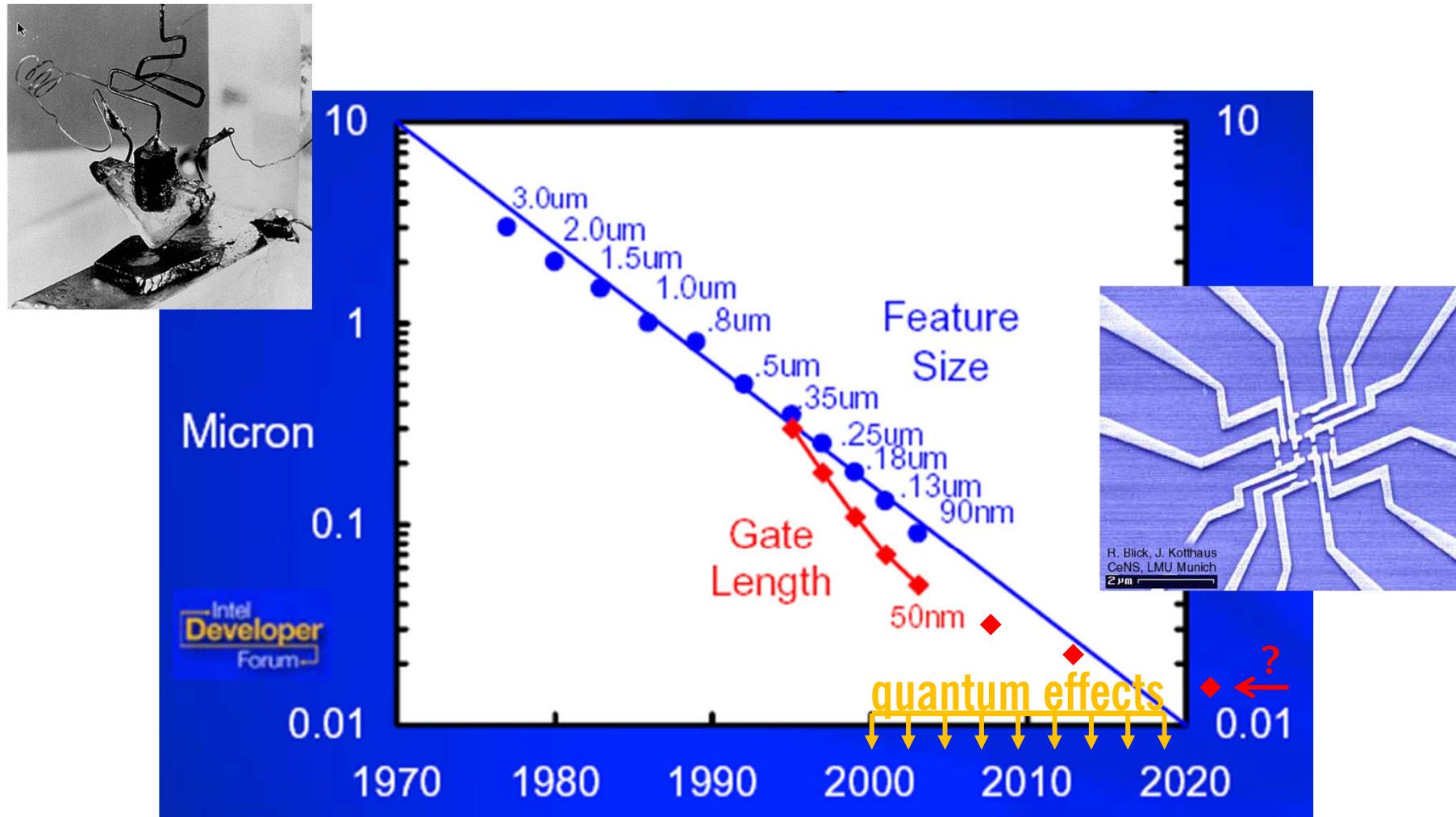
Informationsträger: Lichtpuls, Strom, Spannung,
Ladung, Magnetisierung....



stetige Steigerung der Rechenleistung durch
fortschreitende Miniaturisierung

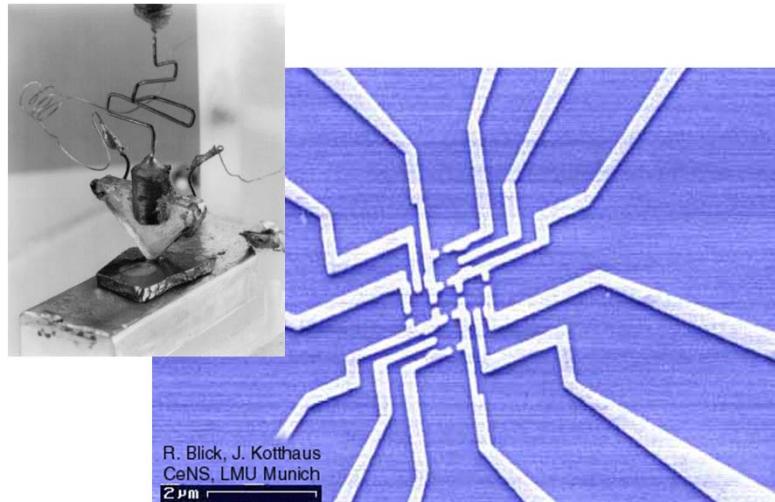


Moore's Law



**bit 0, 1**

Informationsträger :
Lichtpuls, Strom,
Spannung, Ladung ...

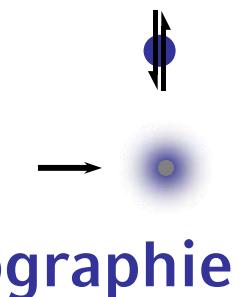


Miniaturisierung
→ Quanteneffekte
vermeiden ? **VERWENDEN!**

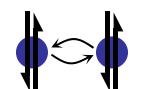
qubit $|\Psi\rangle = a_0|0\rangle + a_1|1\rangle$

Informationsträger:
Photonen, Atome,
Elektronen,...

- Superposition
- Unschärfeprinzip

Zufallszahlen**Quantenkryptographie**

- Verschränkung

**Quantenteleportation**
Quantencomputer



bit \leftrightarrow qubit



bit



qubit



- bit 0, 1
zwei möglicher Werte
- qubit $|0\rangle, |1\rangle$
beliebige Superpositionen
der beiden Zustände

$$|\Psi\rangle = a_0|0\rangle + a_1|1\rangle$$



bit → qubit

Informationsträger



"0"	"1"	bit
		CD: <i>pattern</i>
		Pixel <i>brightness</i>
		hard disk <i>magnetic orientation</i>
		TTL-signals <i>voltage level</i>
		high speed glass fiber connection <i>light</i>
		RAM-memory <i>charge of capacitance</i>

"0"	"1"	qubit
		photon: <i>linear polarization</i>
		superconducting current: <i>orientation</i>
		electron, neutron, atomic nucleus: <i>spin</i>
		atom, ion: <i>internal states</i>
		quantum dots: <i>energy levels</i>
		any particle: <i>directions at beam splitter</i>



bit

Rechnen mit

 \leftrightarrow

qubit



- bit 0, 1
zwei möglicher Werte
- strings 0, 1, 1, 0
- Berechnung irreversibel
(reversibel \leftrightarrow Permutation)
- Ergebnis auslesen “r”
- qubit $|0\rangle, |1\rangle$
- beliebige Superpositionen der beiden Zustände
$$|\Psi\rangle = a_0|0\rangle + a_1|1\rangle$$
- qubit strings $|0,1,1,0\rangle$
in beliebiger Superposition
$$|\Psi\rangle = \sum_{i=0...00,...1..11} a_i|i\rangle$$
- Berechnung reversibel
$$|\Psi\rangle \xrightarrow{\text{calculation}} U|\Psi\rangle$$
- Messung “r” \rightarrow ein Resultat
ein einziges !?!



- QC kann die Komplexität eines Problems reduzieren
 - Komplexität bezüglich Zahl der Operationen, Speicherbedarf (abhängig von Zahl der Eingabestellen)
 - z.B.: Summe $11+23=?$ $O(n)$
Produkt $11*23=?$ $O(n^2)$
Faktorisieren $253=a*b$ $O(\exp(n^{1/3}))$
- Vorteil, wenn gemeinsame Eigenschaften der Resultate gesucht sind
(z.B. Eigenschaft, Parameter einer Funktion)
 - Faktorisierung, (Suche)
 - nutze Quantenparallelismus !

Reviews zu Quantenalgorithmen:

A. Ekert, R. Jozsa, RMP 68, 733 (1996), A. Montanaro, NPJ Quantum Information 2, 15023 (2015)
M-H Yung et. al, arXiv:1203.1331 (Adv. Chem. Phys. 157, 67 (2014))



- qubit $|\Psi\rangle = a_0|0\rangle + a_1|1\rangle$ entspricht: $\begin{pmatrix} a_0 \\ a_1 \end{pmatrix}$
- single qubit gates

▪ Einheitsoperation $\begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$

▪ NOT

▪ Hadamard

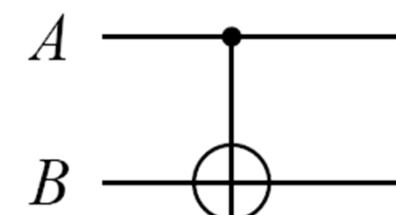
$$\mathbf{H} = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 & 1 \\ 1 & -1 \end{pmatrix} \quad \text{--- H ---}$$

e.g.: $\mathbf{H} \begin{pmatrix} a_0 \\ a_1 \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} a_0 + a_1 \\ a_0 - a_1 \end{pmatrix}$ $\mathbf{H}|0\rangle = \frac{1}{\sqrt{2}}(|0\rangle + |1\rangle)$ $\mathbf{H}|1\rangle = \frac{1}{\sqrt{2}}(|0\rangle - |1\rangle)$

- two qubit gates

▪ CNOT

$$\begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{pmatrix} \begin{pmatrix} a_0 b_0 \\ a_0 b_1 \\ a_1 b_0 \\ a_1 b_1 \end{pmatrix}$$



▪ erzeugt Verschränkung $\mathbf{CNOT} \left[\frac{1}{\sqrt{2}}(|0\rangle + |1\rangle) \otimes |0\rangle \right] = \frac{1}{\sqrt{2}}(|0\rangle|0\rangle + |1\rangle|1\rangle)$

- genügt für alle n-qubit gates !



Algorithmen



Deutsch-Josza algorithm



- are the two sides of a coin equal ?
- i.e., determine, whether function is constant or balanced

$$f_1(0)=0$$

$$f_1(1)=0$$

$$f_2(0)=1$$

$$f_2(1)=1$$

$$f_3(0)=0$$

$$f_3(1)=1$$

$$f_4(0)=1$$

$$f_4(1)=0$$

constant

balanced

- classical solution: calculate function 2x



Deutsch-Josza, quantum solution

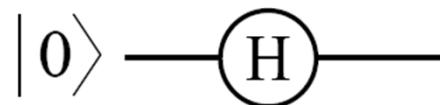


- use two qubits, initially in state $|0,1\rangle$

- define function: $U_f|x,y\rangle = |x,y \oplus f(x)\rangle$

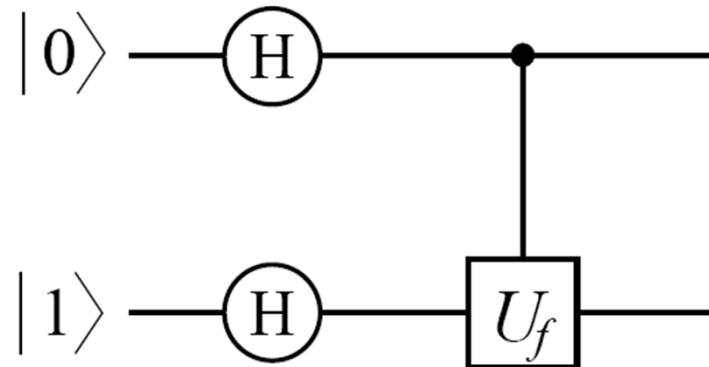
- apply Hadamard on both:

$$|\psi_1\rangle = \mathbf{H}_a \mathbf{H}_b |0,1\rangle = \frac{1}{2}(|0\rangle + |1\rangle)(|0\rangle - |1\rangle) = \frac{1}{2}(|0,0\rangle + |0,1\rangle - |1,0\rangle - |1,1\rangle)$$





- use two qubits, initially in state $|0,1\rangle$
- define function: $U_f |x,y\rangle = |x,y \oplus f(x)\rangle$
- apply Hadamard on both:
$$|\psi_1\rangle = \mathbf{H}_a \mathbf{H}_b |0,1\rangle = \frac{1}{2}(|0\rangle + |1\rangle)(|0\rangle - |1\rangle) = \frac{1}{2}(|0,0\rangle + |0,1\rangle - |1,0\rangle - |1,1\rangle)$$
- evaluate function
$$|\psi_2\rangle = \mathbf{U}_f |\psi_1\rangle = \frac{1}{2}(|0,f(0)\rangle + |0,f(1)\rangle - |1,1 \oplus f(0)\rangle + |1,1 \oplus f(1)\rangle)$$

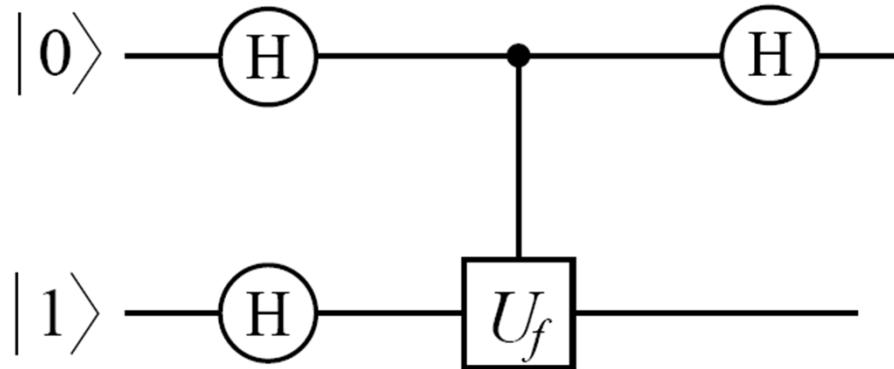




Deutsch-Josza, quantum solution



- use two qubits, initially in state $|0,1\rangle$
- define function: $U_f |x,y\rangle = |x,y \oplus f(x)\rangle$
- apply Hadamard on both:
$$|\psi_1\rangle = \mathbf{H}_a \mathbf{H}_b |0,1\rangle = \frac{1}{2}(|0\rangle + |1\rangle)(|0\rangle - |1\rangle) = \frac{1}{2}(|0,0\rangle + |0,1\rangle - |1,0\rangle - |1,1\rangle)$$
- evaluate function
$$|\psi_2\rangle = \mathbf{U}_f |\psi_1\rangle = \frac{1}{2}(|0,f(0)\rangle + |0,f(1)\rangle - |1,1 \oplus f(0)\rangle + |1,1 \oplus f(1)\rangle)$$
- two cases: **constant** $f(1) = f(0)$
$$|\psi_2\rangle = \frac{1}{2}(|0,f(0)\rangle + |0,f(0)\rangle - |1,1 \oplus f(0)\rangle + |1,1 \oplus f(0)\rangle) =$$
$$= \frac{1}{2}(|0\rangle + |1\rangle)(|f(0)\rangle - |1 \oplus f(0)\rangle)$$



- evaluate function

$$|\psi_2\rangle = \mathbf{U}_f |\psi_1\rangle = \frac{1}{2} (|0, f(0)\rangle + |0, f(1)\rangle - |1, 1 \oplus f(0)\rangle + |1, 1 \oplus f(1)\rangle)$$

- two cases: **constant** $f(1) = f(0)$

$$\begin{aligned} |\psi_2\rangle &= \frac{1}{2} (|0, f(0)\rangle + |0, f(0)\rangle - |1, 1 \oplus f(0)\rangle + |1, 1 \oplus f(0)\rangle) = \\ &= \frac{1}{2} (|0\rangle + |1\rangle) (|f(0)\rangle - |1 \oplus f(0)\rangle) \end{aligned}$$

- balanced**

$$\begin{aligned} f(1) &= 1 \oplus f(0) \\ |\psi_2\rangle &= \frac{1}{2} (|0, f(0)\rangle + |1, 1 \oplus f(0)\rangle - |0, 1 \oplus f(0)\rangle - |1, f(0)\rangle) = \\ &= \frac{1}{2} (|0\rangle - |1\rangle) (|f(0)\rangle - |1 \oplus f(0)\rangle) \end{aligned}$$

→ to measure first qubit solves the question

(only one evaluation, also for many qubits)



search algorithm (Grover)



- unsorted database “oracle” $f(x_s) = 1$ (if x_s solution), $f(x) = 0$ otherwise
- manipulate amplitude of all possible data-elements (a_i), such that the correct one dominates at a certain time

1. prepare superposition of all elements

$$|\psi_1\rangle = \mathbf{H}^{\otimes n} |00\dots 0\rangle = N^{-1/2} \sum_{x=0..N-1} |x\rangle \quad (N = 2^n)$$

2. apply oracle \mathbf{I}_{x_s} : $\mathbf{U}_{f(x)}|x\rangle = (-1)^{f(x)}|x\rangle$

3. apply inversion around the average

$$|\psi'\rangle = \mathbf{H}^{\otimes n} \mathbf{I}_0 \mathbf{H}^{\otimes n} |\psi\rangle$$

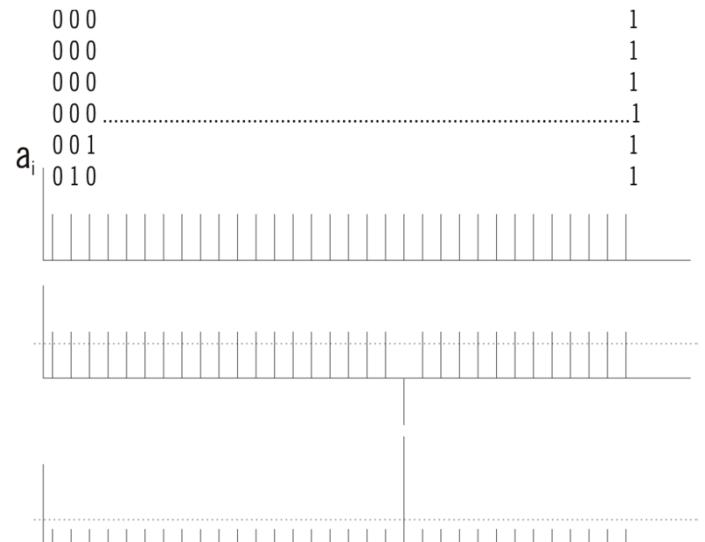
$$\mathbf{I}_0|x\rangle = -(-1)^{\delta_{0,x}}|x\rangle$$

- repeat 2.,3.,

$$|\psi_k\rangle = (\mathbf{H}^{\otimes n} \mathbf{I}_0 \mathbf{H}^{\otimes n} \mathbf{0})^k |\psi_1\rangle = \cos \frac{2k+1}{2}\theta |x_s\rangle + \sin \frac{2k+1}{2}\theta |x_{others}\rangle$$

- stop after about $\frac{\pi}{4}\sqrt{N}$ iterations

with $|\psi_1\rangle = \cos \frac{\theta}{2} |x_s\rangle + \sin \frac{\theta}{2} |x_{others}\rangle$, if only 1 solution





factorization of N



- difficult problem, best known classical algorithm $O(\exp(n^{1/3}))$
- fact that factorization is difficult, is used to warrant security of public-key encryption
- a (not very fast) **factoring algorithm**:
 - choose y , coprime with N ; evaluate $F_N(a) = y^a \pmod{N}$
 - **find period** r of $F_N(a) \Rightarrow y^r \equiv 1 \pmod{N}$
$$(y^r = kN + 1 \Rightarrow y^{r+1} = kNy + y \Rightarrow \\ \Rightarrow y^{r+1} \pmod{N} = y \pmod{N} \Rightarrow r \text{ period of } F_N)$$
 - if r even, set $x = y^{r/2} \Rightarrow x^2 \equiv 1 \pmod{N} \Rightarrow \\ \Rightarrow x^2 - 1 = (x - 1)(x + 1) \equiv 0 \pmod{N}$
 - $x - 1$ or $x + 1$ cannot be multiples of N , thus they must have a common factor
 $\Rightarrow p, q = \gcd(x \pm 1, N)$ are **factors of N**
- all tasks can be calculated efficiently except finding the period F_N
 \Rightarrow Shor: use quantum Fourier transform



quantum Fourier transform



- use quantum parallelism to calculate $F_N(a)$ for many a
 - use Fourier transform to calculate period r
 - two registers: source register with K qubits, where $N^2 \leq Q := 2^K \leq 2N^2$
target register with $L \geq \log_2 N$
1. initialize: $|\psi_1\rangle = H^{\otimes K} |0\rangle |0\rangle = \frac{1}{\sqrt{Q}} \sum_{q=0..Q-1} |q\rangle |0\rangle$
 2. calculate $F_N(q)$: $|\psi_2\rangle = \frac{1}{\sqrt{Q}} \sum_{q=0..Q-1} |q\rangle |y^q \bmod N\rangle$
all values are calculated in parallel and available for the next step
 3. measure target register, suppose result Z , where $z = y^r \bmod N$.
Since $y^r \equiv y^{jr+l} \bmod N$ source register is in state

$$|\phi_l\rangle = \frac{1}{\sqrt{A+1}} \sum_{j=0..A} |jr+l\rangle$$

measurement gives one value of $kr+l$,
but, l random, different in every run, not useful.



quantum Fourier transform II



4. Fourier transform to extract r : $\mathbf{U}_{F_q} : |q\rangle \mapsto \frac{1}{\sqrt{Q}} \sum_{q'=0..Q-1} \exp\left(2\pi i \frac{q'q}{Q}\right) |q'\rangle$

$$\begin{aligned} \Rightarrow |\phi'_l\rangle &= \frac{1}{\sqrt{Q(A+1)}} \sum_{q'=0..Q-1} \sum_{j=1..A} \exp\left(2\pi i \frac{q'(jr+l)}{Q}\right) |q'\rangle = \\ &= \frac{1}{\sqrt{Q(A+1)}} \sum_{q'=0..Q-1} \exp\left(2\pi i \frac{q'l}{Q}\right) \underbrace{\sum_{j=1..A} \exp\left(2\pi i \frac{q'jr}{Q}\right)}_{Q/r \text{ for } q' \text{ multiple of } Q/r; 0 \text{ otherwise}} |q'\rangle \end{aligned}$$

$$U_{F_q} |\phi_l\rangle = \frac{1}{\sqrt{r}} \sum_{j=0..r-1} \exp\left(2\pi i \frac{l j}{r}\right) |j \frac{Q}{r}\rangle$$

5. measure source register, result $\lambda Q/r$, independent of l

6. repeat 1...5, several values of $\lambda_i Q/r \rightarrow$ determine r



example: factor $N=15$



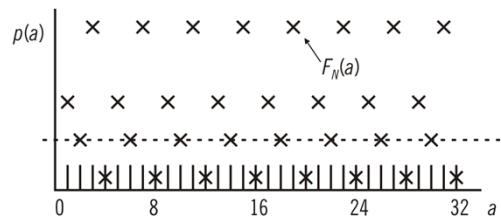
- choose y , coprime with N , e.g. $y=7$, evaluate $F_N(a) \equiv 4 \Rightarrow x = 7^2 = 49$

a	1	2	3	4	5	6	7
$F_N(a)$	7	4	13	1	7	4	13

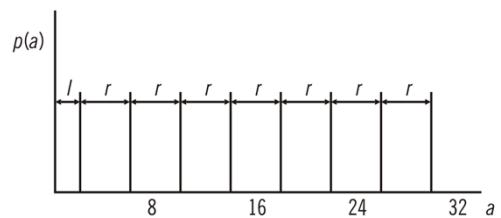
$$p = \gcd(49 - 1, N) = 3$$

$$q = \gcd(49 + 1, N) = 5$$

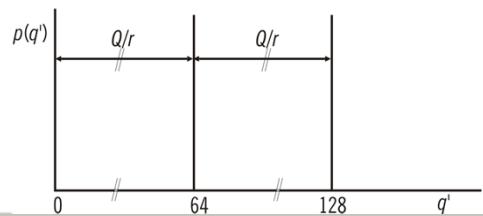
- quantum Fourier transform to find r :



initialize, evaluate $F_N(a)$



measure 2nd register, superposition in 1st register
random shift by I_i



QFT, measure first register \Rightarrow period $Q/r \Rightarrow r$



example: factor $N=15$



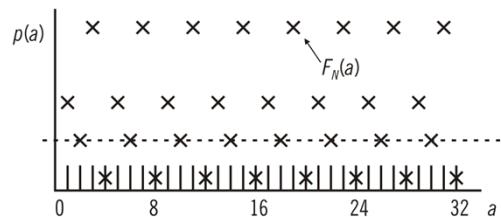
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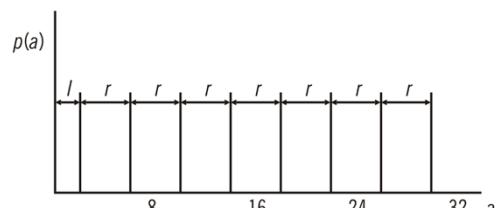
$$q = \gcd(49 + 1, N) = 5$$

- quantum Fourier transform to find r :



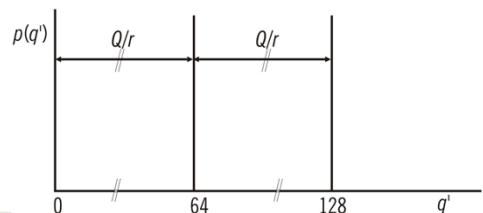
initialize, evaluate $F_N(a)$

$$F_N(q) : |\psi_2\rangle = \frac{1}{\sqrt{Q}} \sum_{q=0..Q-1} |q\rangle |y^q \bmod N\rangle$$



measure 2nd register, superposition in 1st register
random shift by l ,

$$|\phi_l\rangle = \frac{1}{\sqrt{A+1}} \sum_{j=0..A} |jr + l\rangle$$



QFT, measure first register \Rightarrow period $Q/r \Rightarrow r$



Feynman:

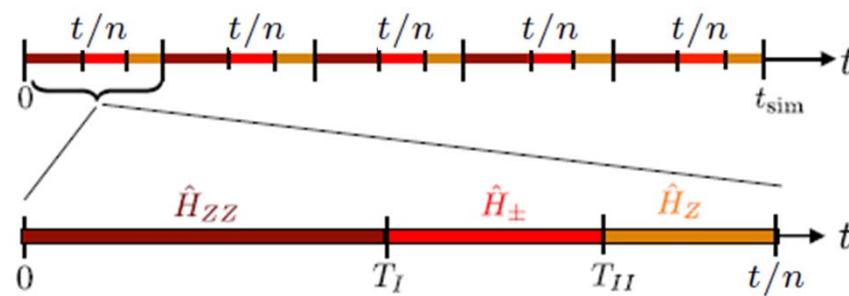
- Ein Quantensystem auf einem Computer zu simulieren ist exponentiell aufwändig
- Ein Quantensystem evolviert in Echtzeit, d.h., es kann sich selbst in Echtzeit simulieren
- Kann diese Quantensystem derart manipuiert werden, dass es ein anderes Quantensystem (in Echtzeit) simuliert?

- Digitale Quantensimulation
 - Evolution durch Hamiltonoperator bestimmt

$$H = T + V$$

- T und V gleichzeitig in Ort/Impulsbasis diagonalisieren

$$e^{-iHt} \approx \left(U_{\text{QFT}}^\dagger e^{-iTt/n} U_{\text{QFT}} e^{-iVt/n} \right)^n$$



- effizient – Aufwand polynomial

- Analog Quantensimulation
 - Kopplung der qubits (atome, Xmon, ...) entspricht der Kopplung von Spins o. Elektronen in Festkörper o. Molekülen, in Gittermodell für Feldtheorie, etc.
 - gleiche Geometrie (aber nicht notwendig)
 - verfolge direkte Evolution
 - manipuliere Parameter (Gitterkonstante, Kopplungen etc.)
- Adiabatische Optimierung
 - suche Lösung bei geg. Randbedingungen
 - beginne bei bekanntem H – variiere H “langsam”, sodass RB abgebildet werden – Grundzustand von H ist Lösung.



Umsetzung



Anforderungen für “qubit” in experimenteller Umsetzung



- qubits definiere 2 unterscheidbare Zustände
- Initialisierung Möglichkeit, die qubits (auf 0) zu setzen
- Quantengatter Operationen zur Erzeugung verschränkter Zustände (starke Kopplung notwendig)
- Auslesen Messung einzelner qubits nach Operation
- (De-) Kohärenz Zeit während der Quanteneigenschaften überwiegen muss ausreichend lang sein



NMR – quantum computer

- nuclear magnetic resonance
- spin $1/2$ $^1\text{H}, ^{13}\text{C}, ^{15}\text{N}, ^{19}\text{F}, ^{29}\text{Si}$

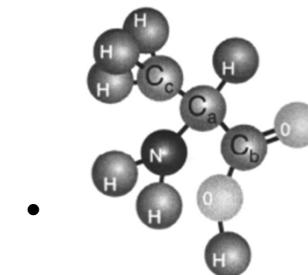
$$\Delta E = \mu \cdot \hbar B_0$$

liquids – individual processors
(weak coupling: $2\pi J_{ij} \ll |\omega_i - \omega_j|$):

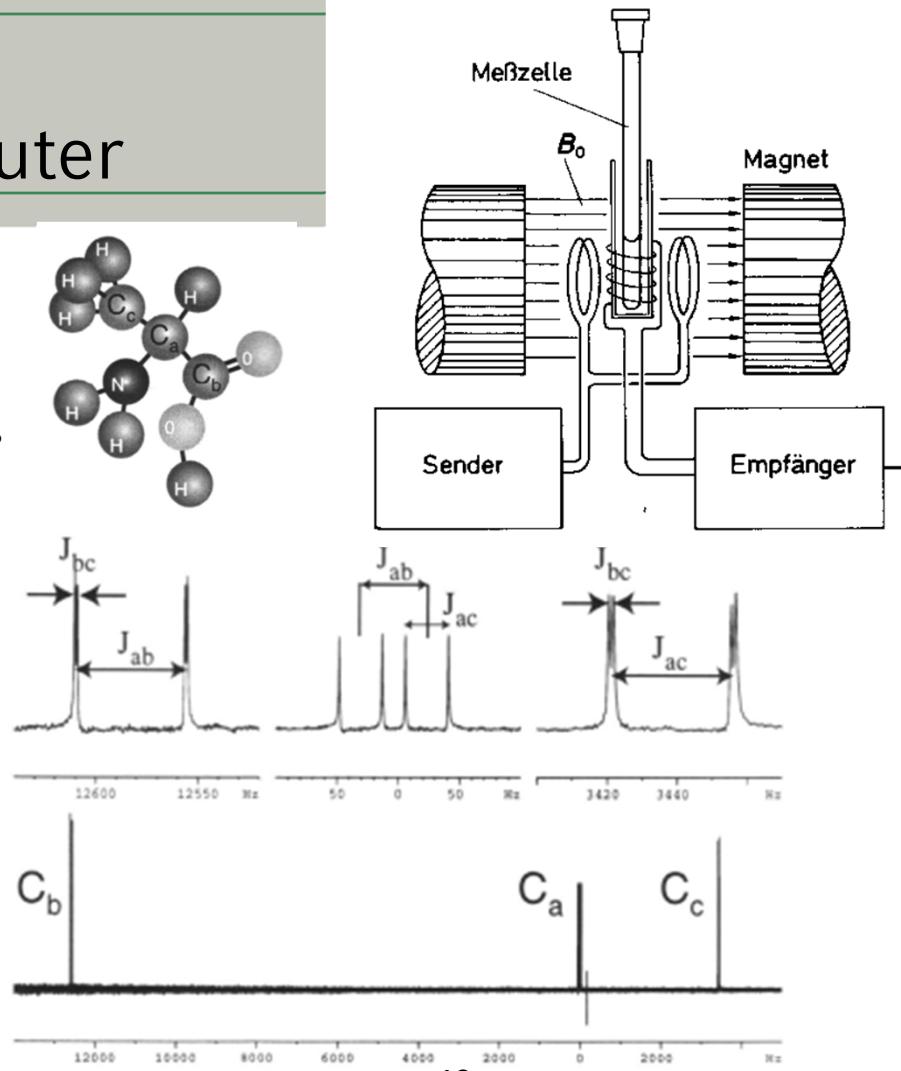
$$H = \frac{1}{2} \sum_i \omega_i \sigma_i^z + \frac{\pi}{2} \sum_{i \neq j} J_{ij} \sigma_i^z \sigma_j^z$$

energy of single spins
→ identification

spin-spin interaction
→ 2-qubit gate



-



- spectra for three ^{13}C -nuclei at 9.4T

$$H = \pi[10^8(\sigma_z^a + \sigma_z^b + \sigma_z^c) - 12580 \sigma_z^b + 3440 \sigma_z^c] + (\pi/2)[53 \sigma_z^a \sigma_z^b + 38 \sigma_z^a \sigma_z^c + 1.2 \sigma_z^b \sigma_z^c]$$

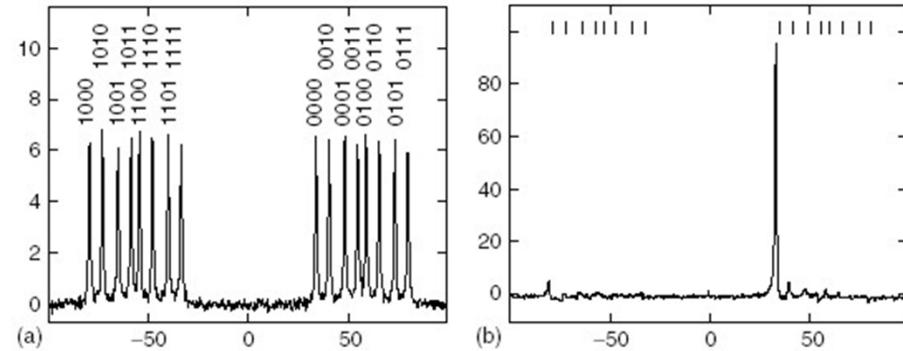


NMR – quantum computer

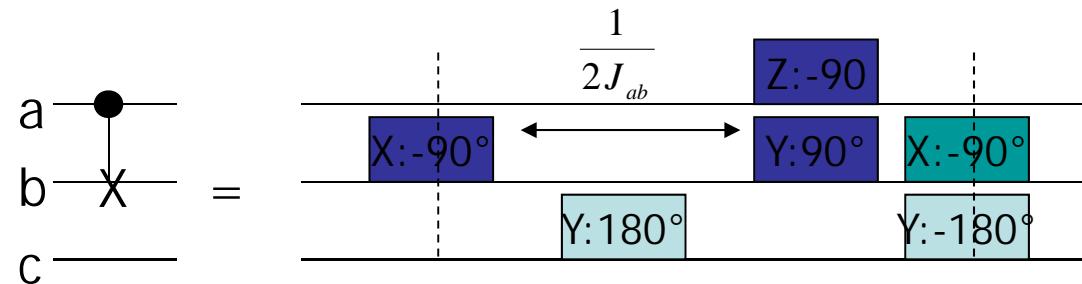


- pseudo-pure states

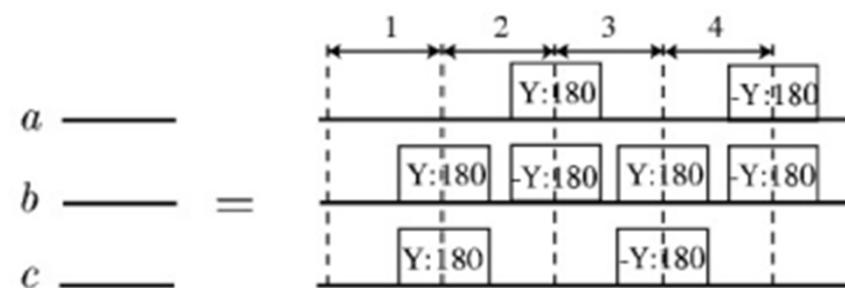
$$\rho \approx \frac{1}{2^n} (1 - \varepsilon) \cdot \mathbb{I} + \varepsilon \prod_i |\psi\rangle_i \langle \psi|_i$$



- CNOT-gate



- refocussing

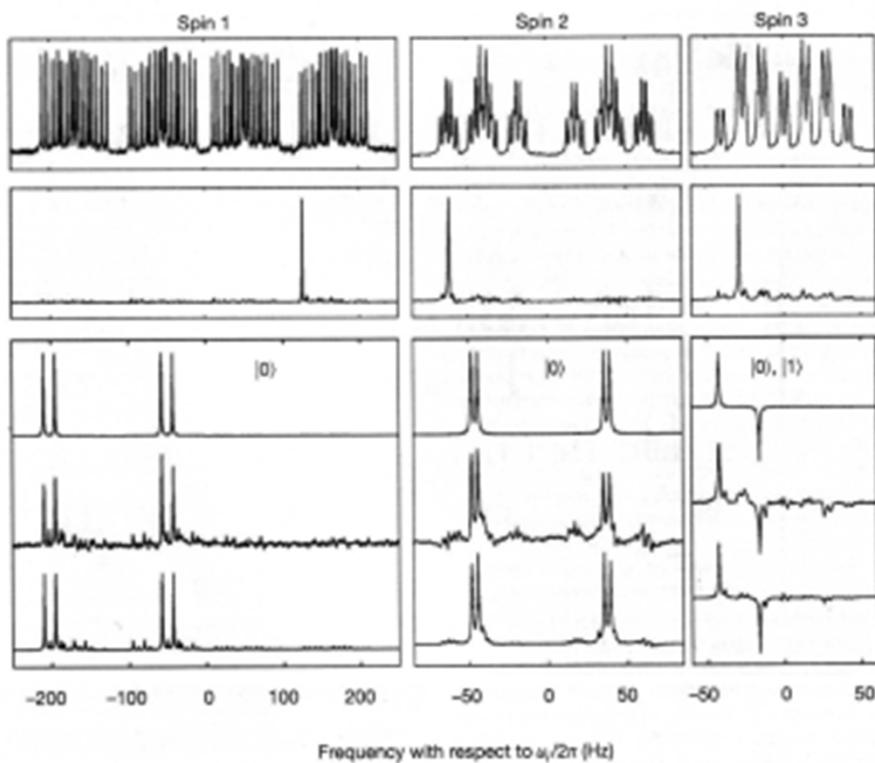
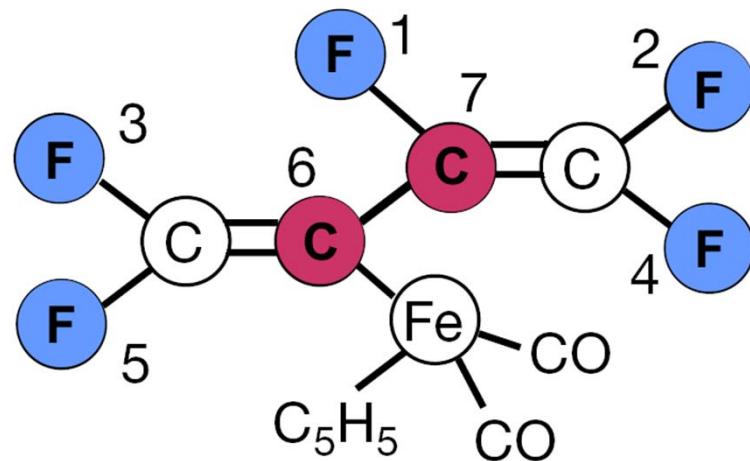




NMR – quantum computer



- nuclear magnetic resonance
- factorize 15



- 7 qubits
- 11.4T, 470MHz (^{19}F) und 125MHz (^{13}C)
- ~300 pulses, 720ms total time

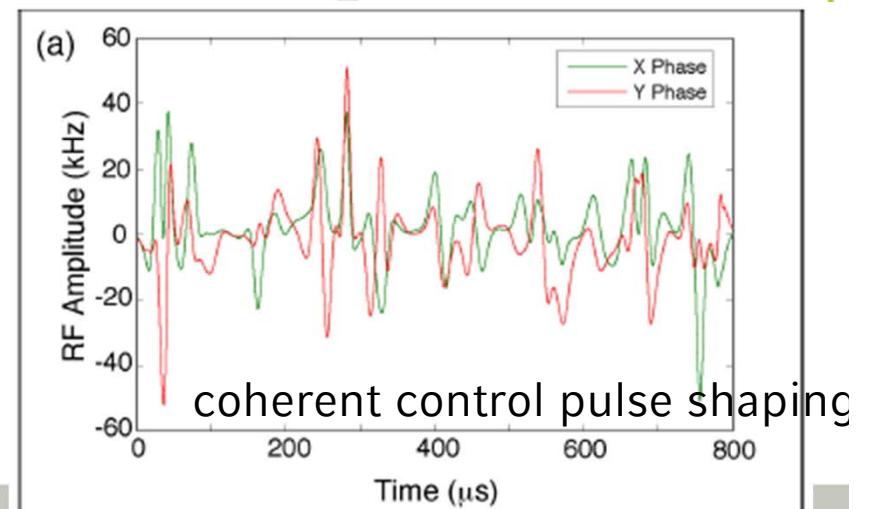
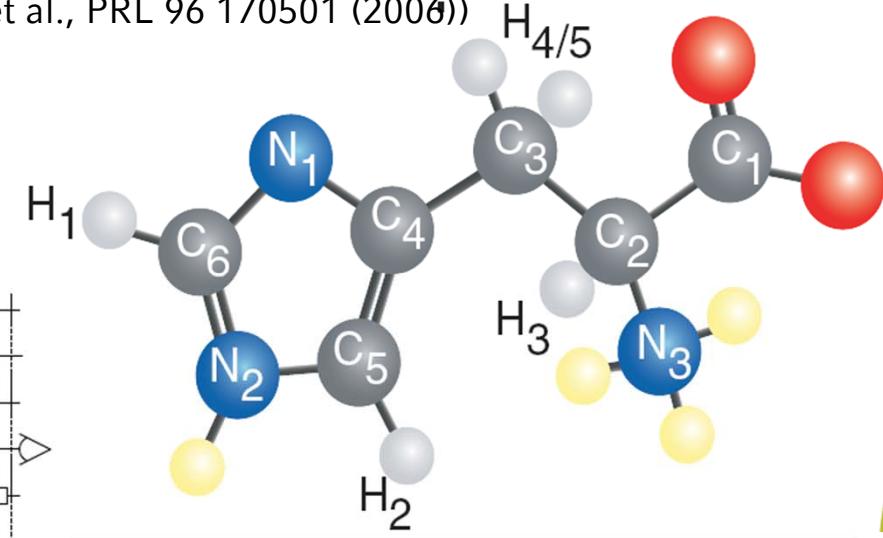
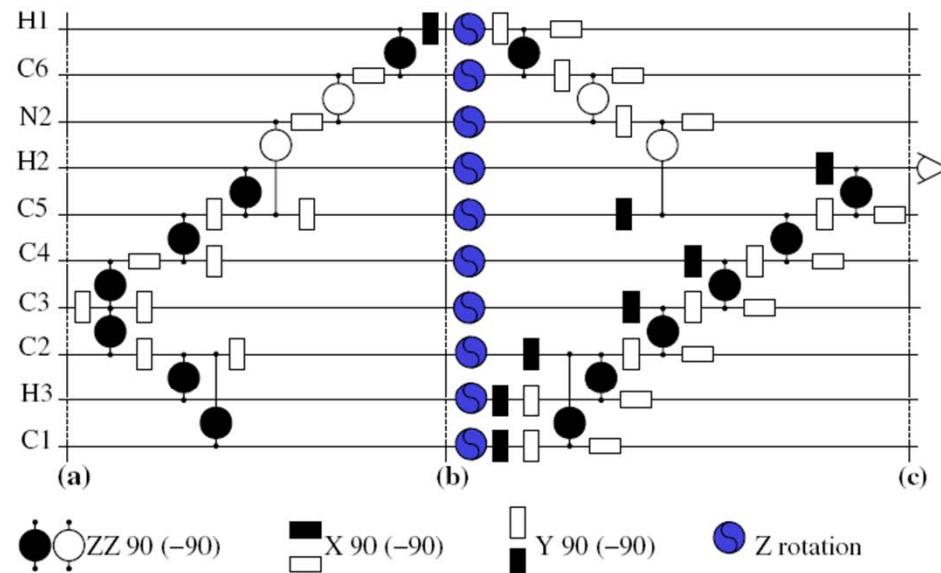
L. M. K. Vandersypen, et al., Nature 414, 883 (2001).



- 12-Qubit System (Negrevergne et al., PRL 96 170501 (2006))

I-Histidine molecule

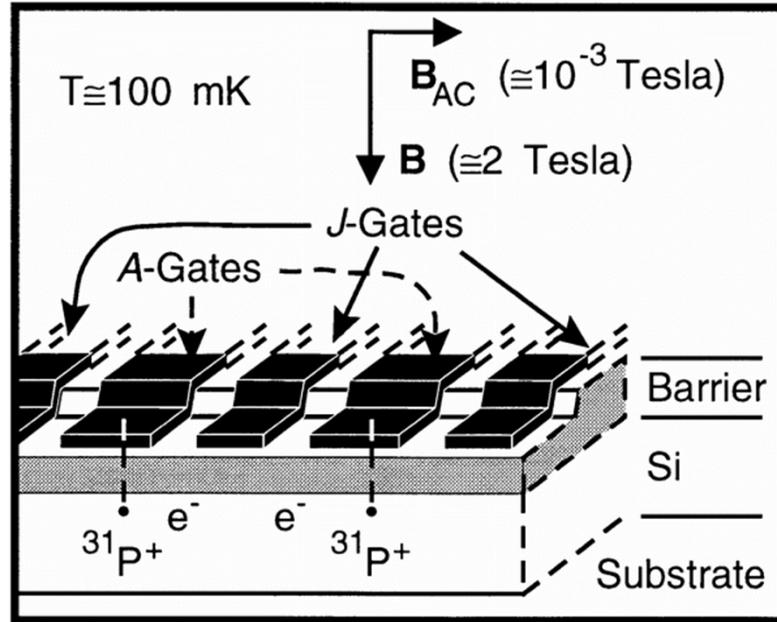
- GHZ-state



- Decoherence during calculation

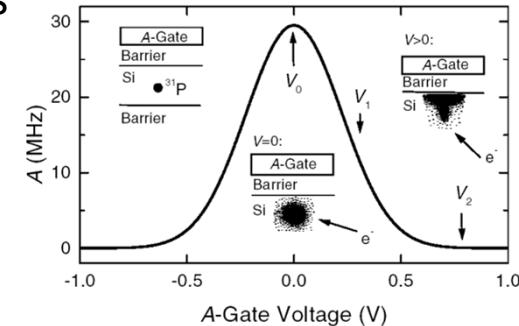


- NMR in semiconductors
- single Phosphor atoms
- coupling controlled via gate voltages
- P-P: 10-20nm

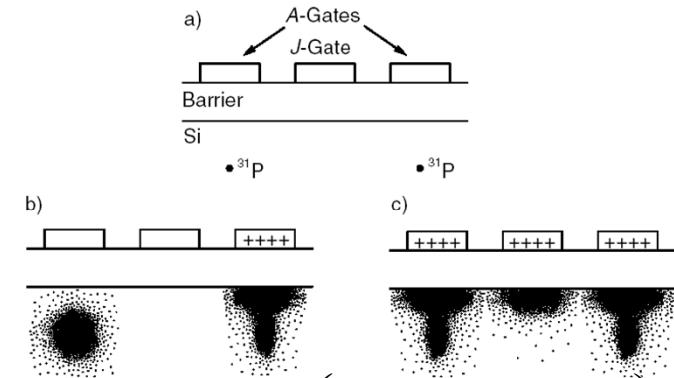


B.E. Kane, Nature 393, 133 (1998)

- manipulate e- wavefunction with A gates



- couple qubits via J-gates: SWAP-gate



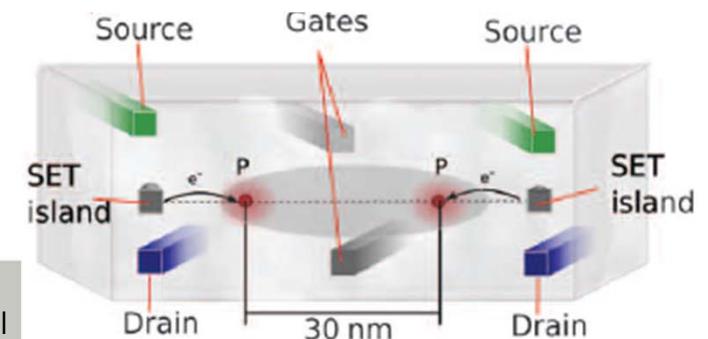
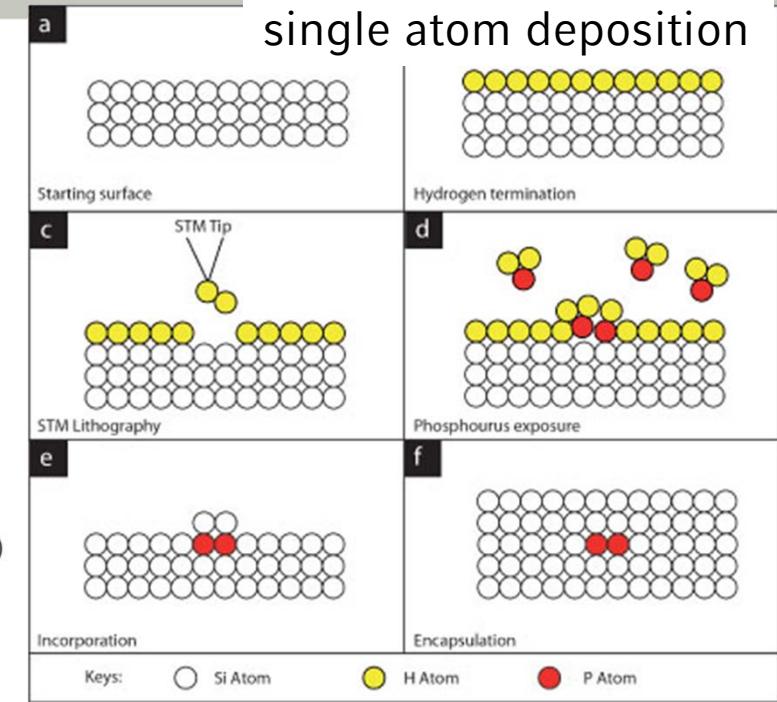
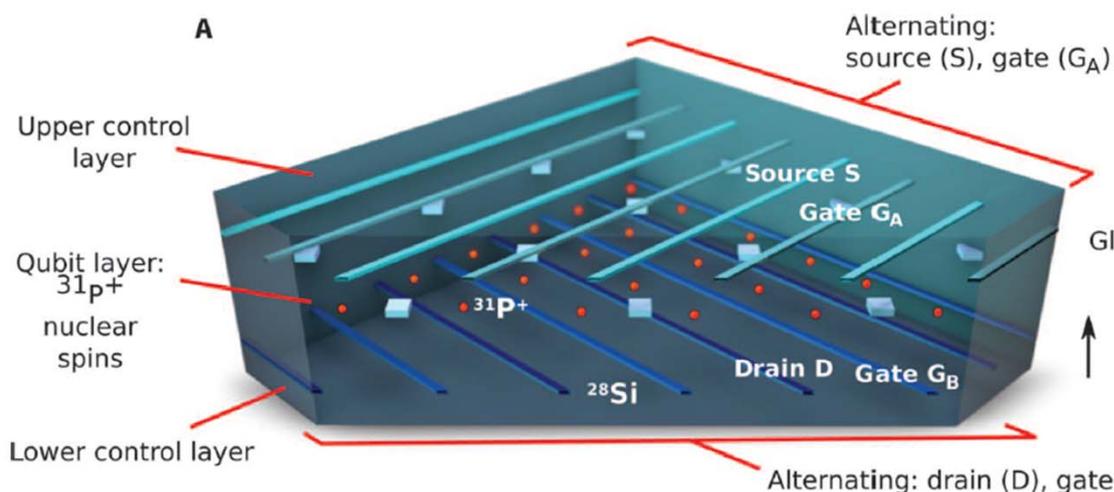
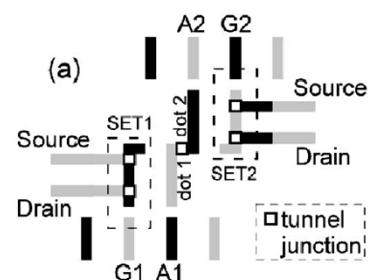
$$h\nu_J = 2A^2 \left(\frac{1}{\mu_B B - 2J} - \frac{1}{\mu_B B} \right)$$



solid state NMR – quantum computer



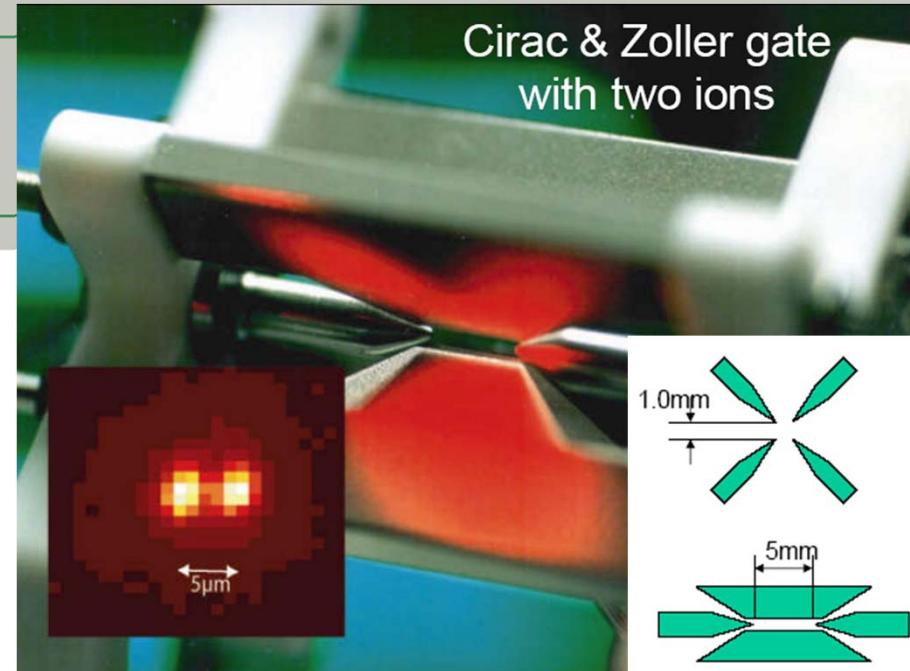
- readout: single-electron transistor (SET)
- 3D configuration



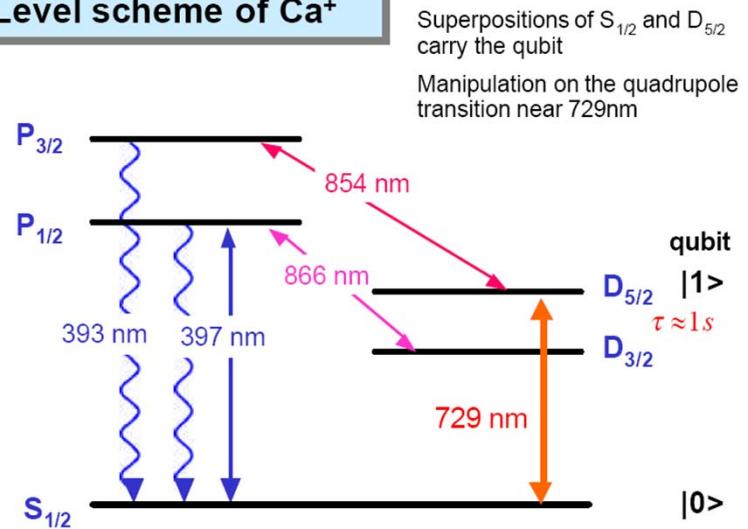


trapped ions

- ions trapped by rf-fields
- linear trap ($\omega_{\text{ax}} \sim 0.7\text{-}2\text{Mhz}$.
 $\omega_{\text{rad}} \sim 5\text{MHz}$)
- effective two level system



Level scheme of Ca^+

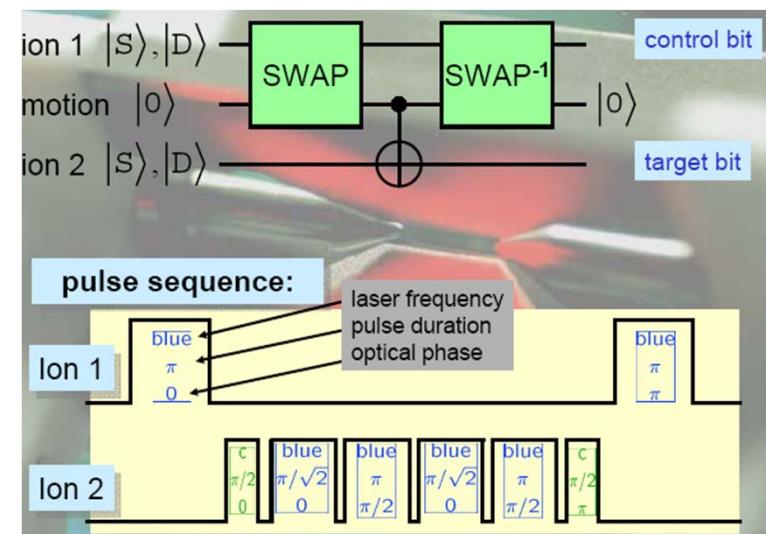
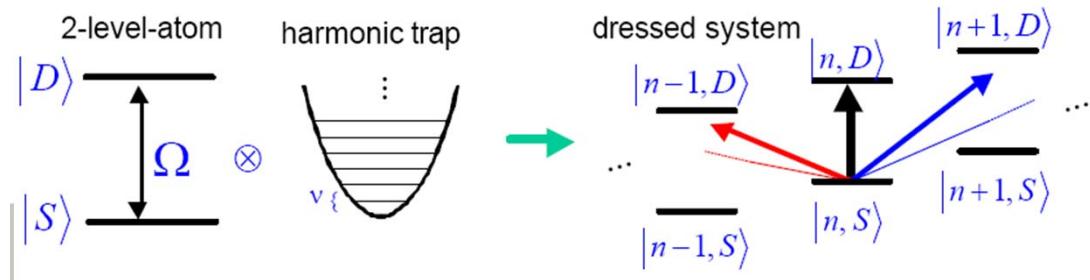




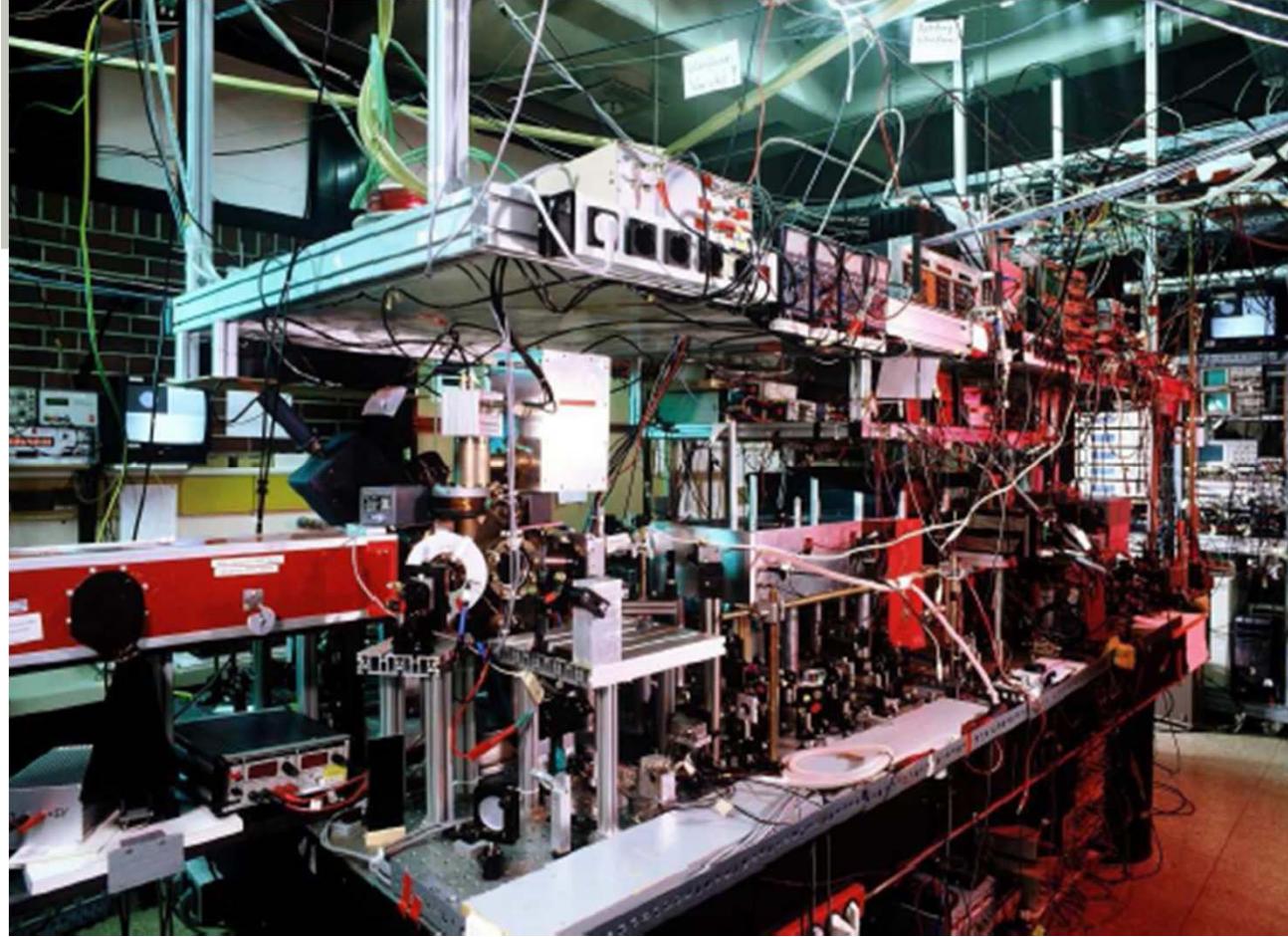
trapped ions



- motional states of the ion chain in harmonic potential
⇒ qubit states "dressed" with motional states
 - possible also for distant ions:
 - state of the atom can be transferred to the motional state of the chain and back
 - phase shift on a single ion, depending on its ion-phonon state (CPhase)
 - transfer state of first ion back to the ion
- perform CNOT operation for the two ions



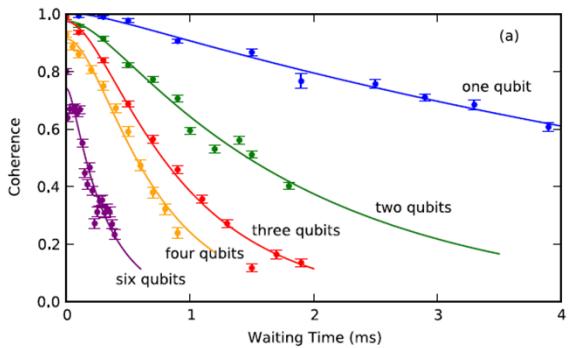
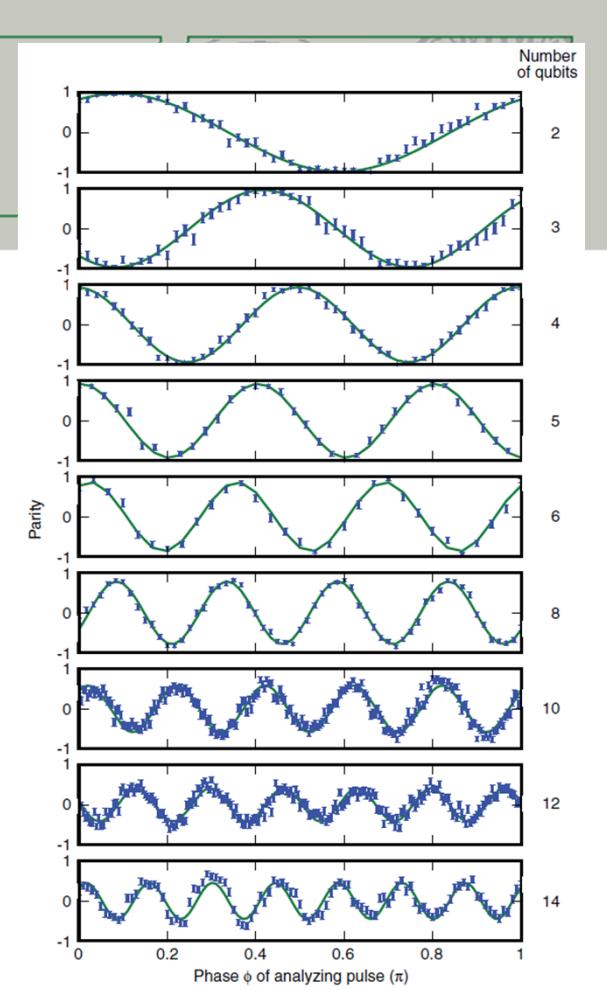
interaction with laser light depends also on the motional state of atoms



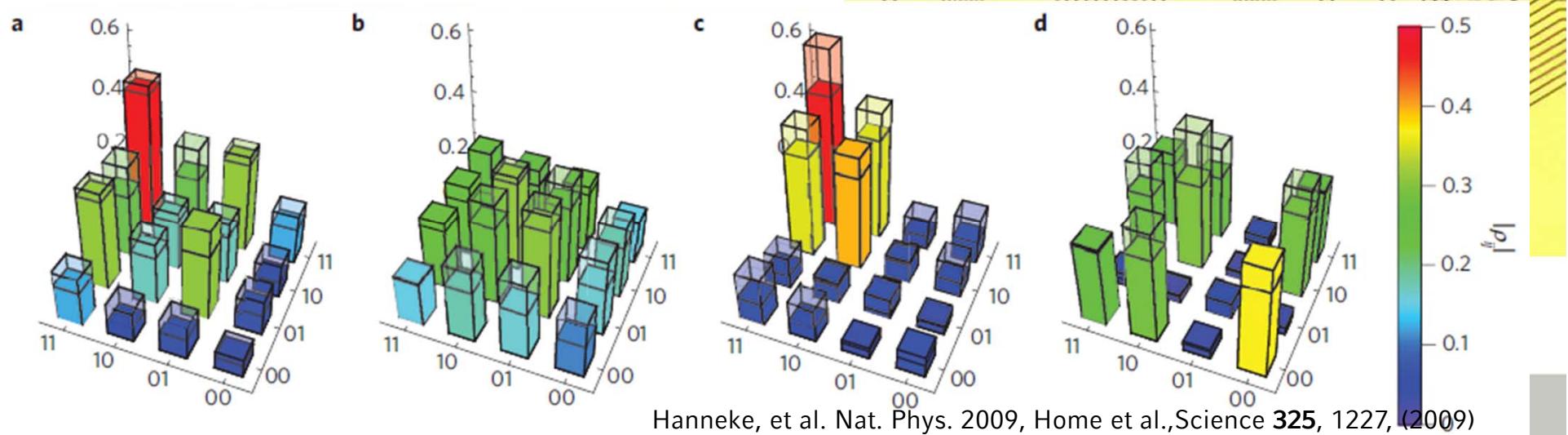
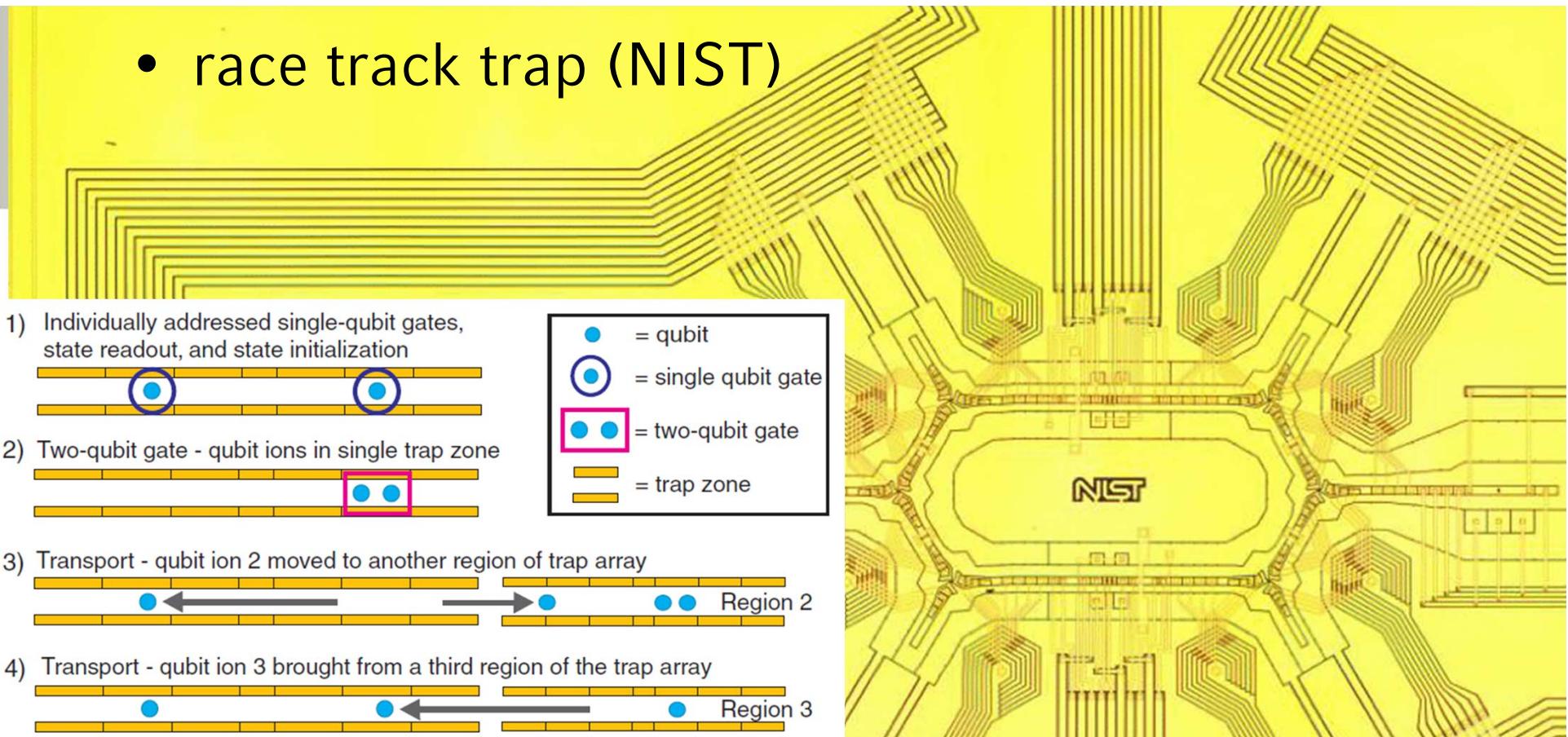
- 14 ion GHZ-state

TABLE I. Populations, coherence, and fidelity with a N -qubit GHZ state of experimentally prepared states. Entanglement criteria supported by σ standard deviations. All errors in parenthesis, 1 standard deviation.

Number of ions	2	3	4	5	6	8	10	12	14
Populations, %	99.50(7)	97.6(2)	97.5(2)	96.0(4)	91.6(4)	84.7(4)	67.0(8)	53.3(9)	56.2(11)
Coherence, %	97.8(3)	96.5(6)	93.9(5)	92.9(8)	86.8(8)	78.7(7)	58.2(9)	41.6(10)	45.4(13)
Fidelity, %	98.6(2)	97.0(3)	95.7(3)	94.4(5)	89.2(4)	81.7(4)	62.6(6)	47.4(7)	50.8(9)
Distillability criterion [14], σ	283	151	181	100	95	96	40	18	17
Entanglement criterion [15], σ	265	143	167	101	96	92	25	-6	0.7



- race track trap (NIST)

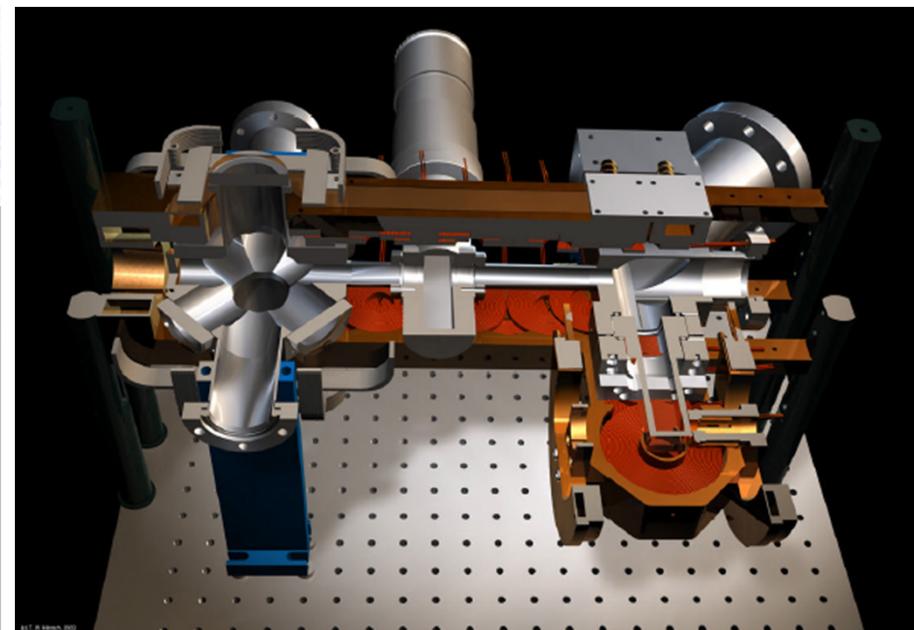
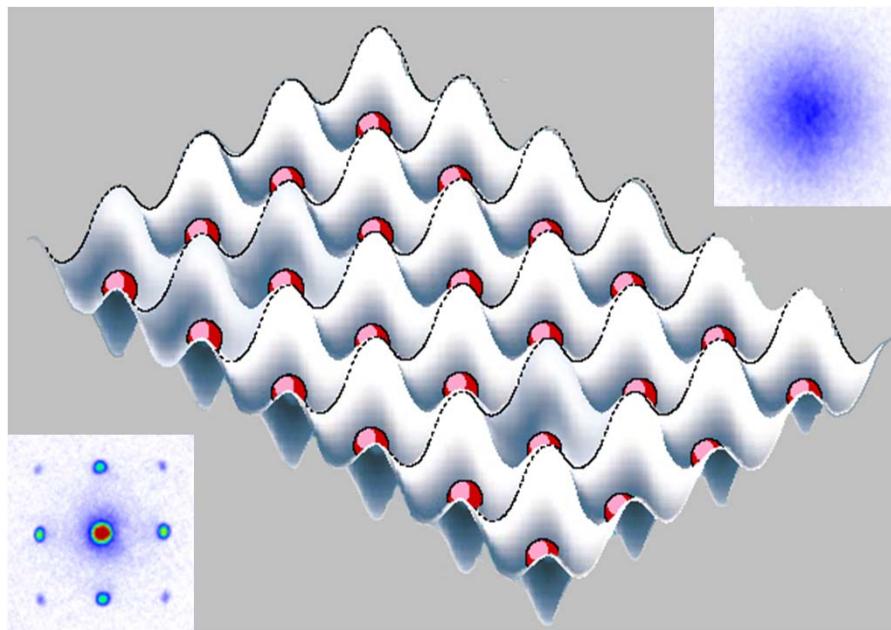
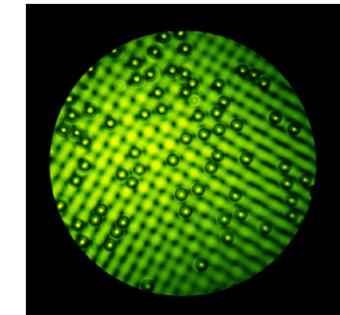




neutral atoms

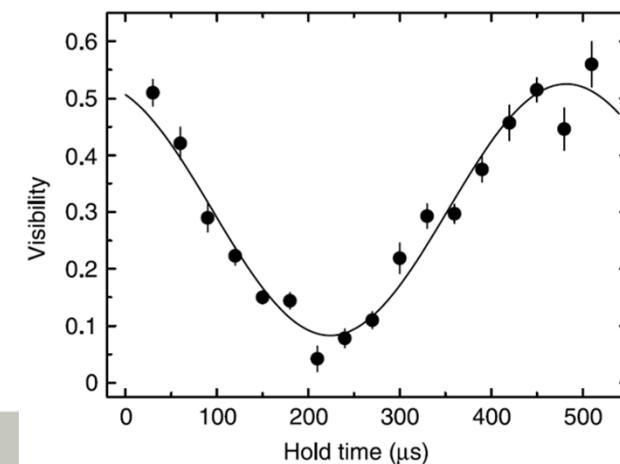
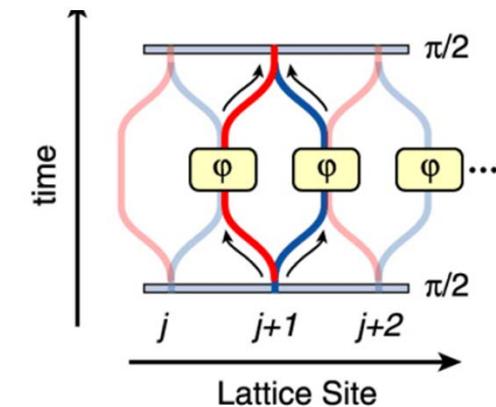
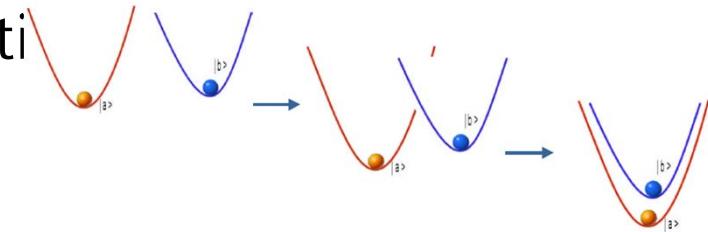


- atoms trapped in optical lattice
- first Bose-Einstein condensate to ensure high density
- ramp up optical lattice to transfer atoms

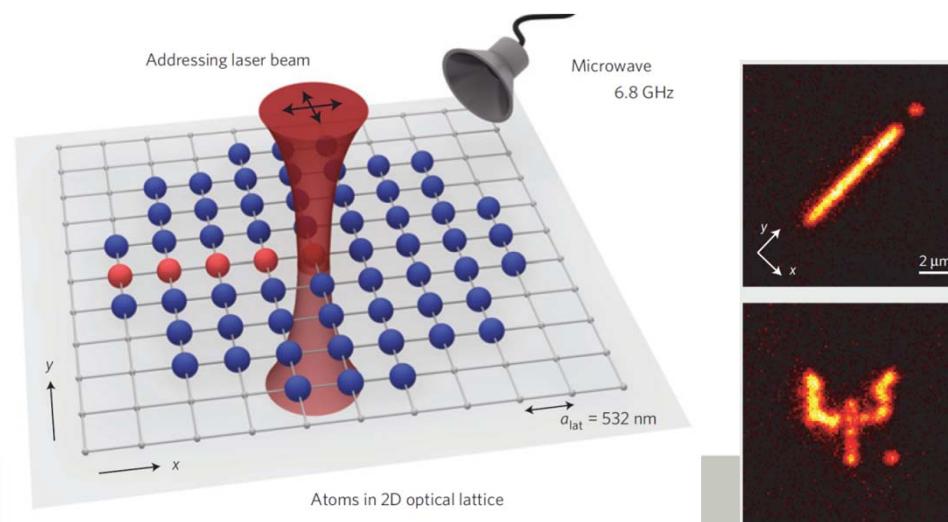
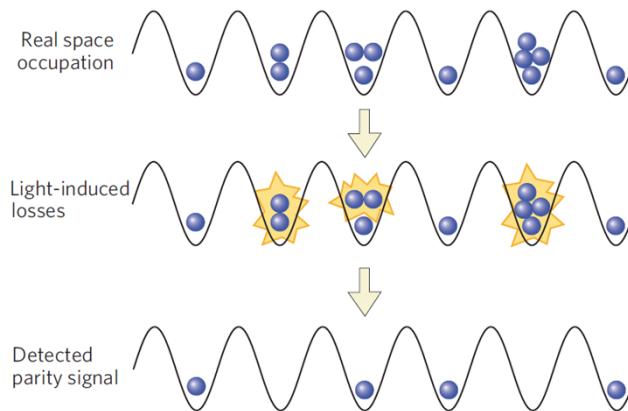
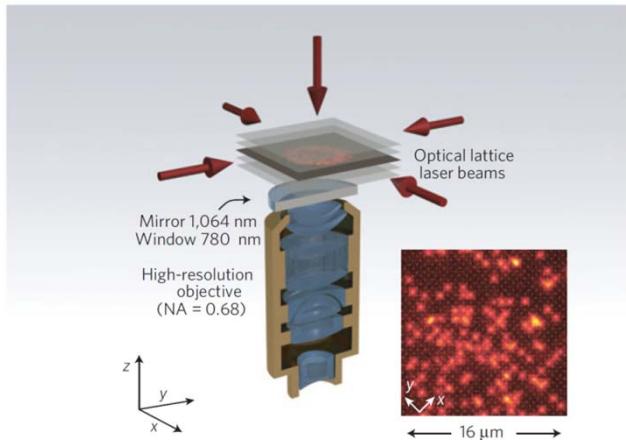




- atoms can be moved, when shifting the standing light fields
- phase shift for (s-wave) scattering of atoms
- state dependent traps
 - state dependent phase shift
 - between all neighbouring atoms entangle more than 10 atoms
- individual readout difficult
- "cluster-state" one-way quantum computing



- read out via single atom imaging



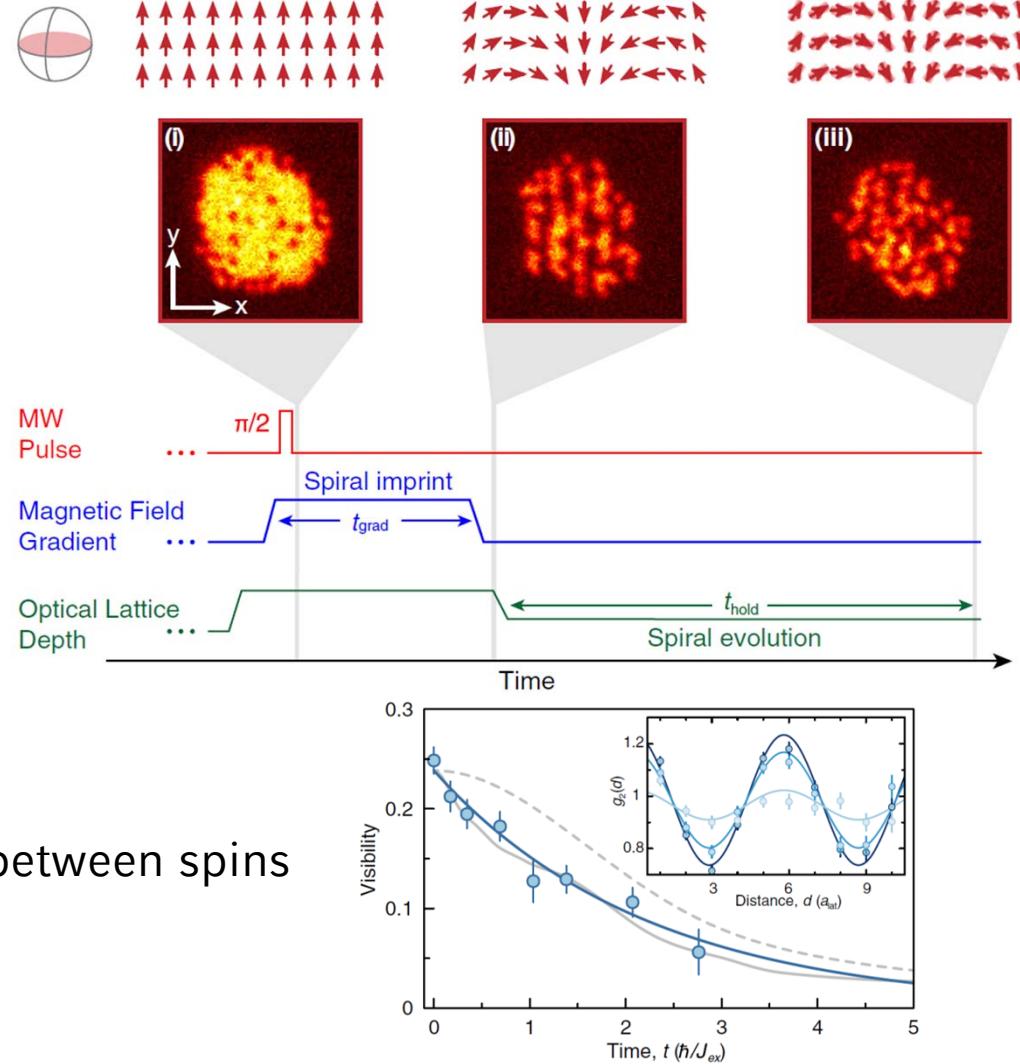
Quantum Simulation: Spin Transport in Heisenberg Quantum Magnets



$$\hat{H} = -J_{\text{ex}} \sum_i \left[\frac{1}{2} (\hat{S}_i^+ \hat{S}_{i+1}^- + \hat{S}_i^- \hat{S}_{i+1}^+) + \Delta \hat{S}_i^z \hat{S}_{i+1}^z \right]$$

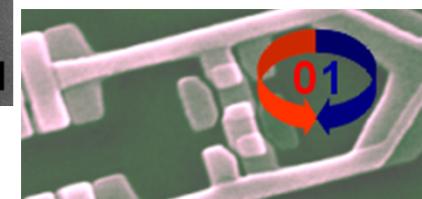
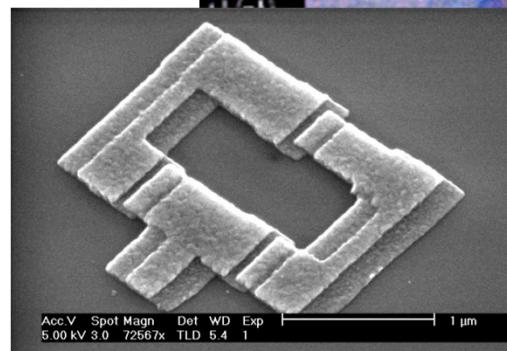
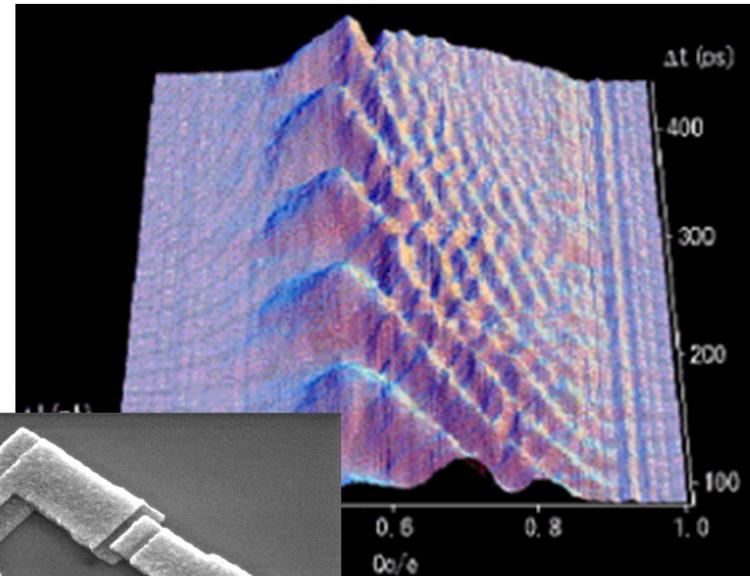
study change of spin orientation for $J > 0$

- initialize atoms from BEC in 2D lattice in ground state
- $\pi/2$ pulse + field gradient to generate spin-spiral
- evolution for varying J
- single-site read out + correlation analysis
- observe decay of correlations between spins





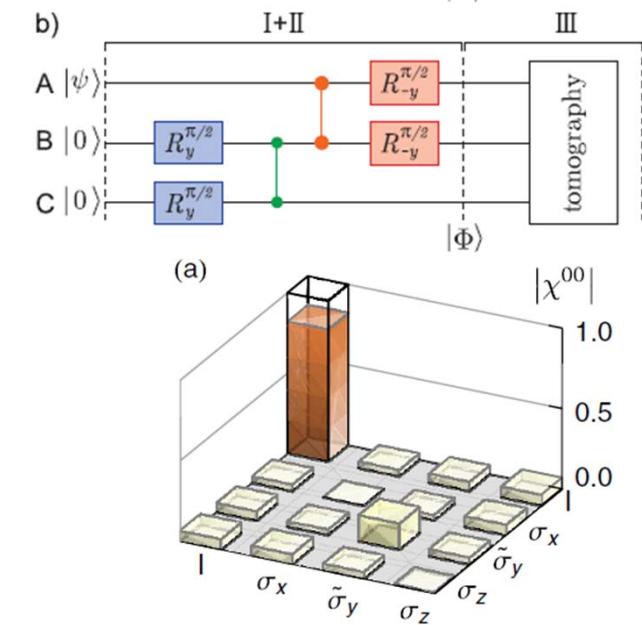
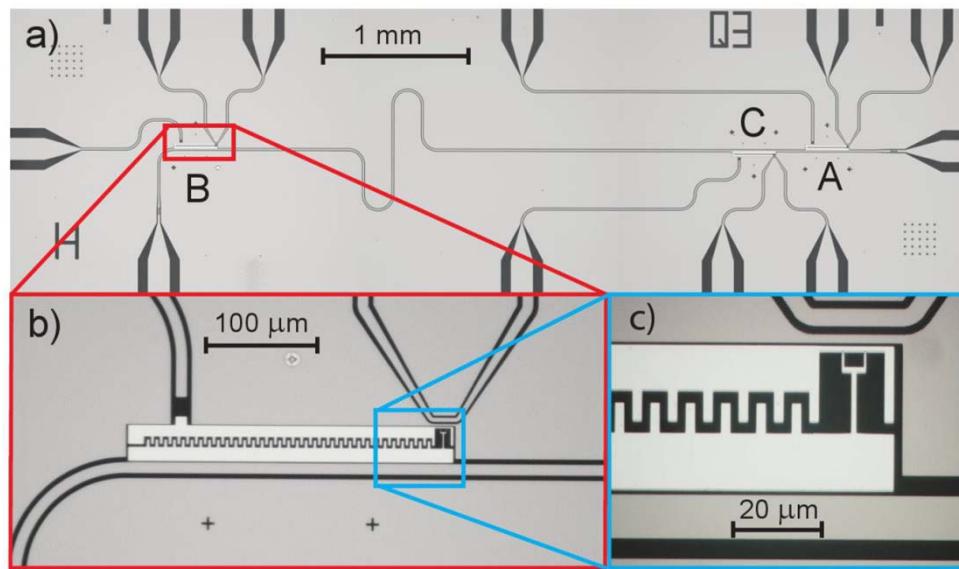
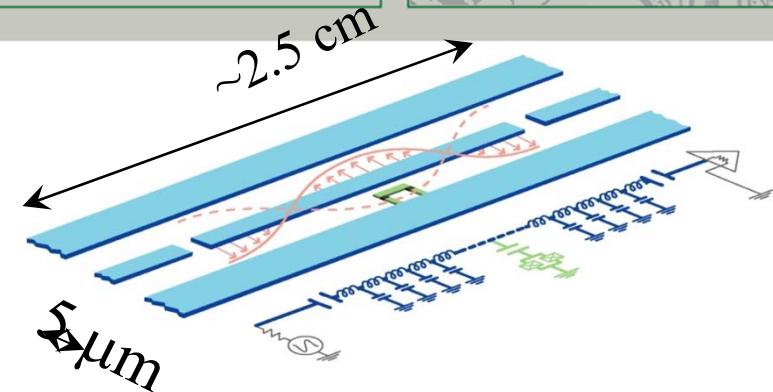
- superconducting qubits
- quantized current/charge in loop with Josephson-junctions:
qubits demonstrated ("entanglement")
- anharmonisches Potential
Übergänge mit unterschiedlicher Frequenz
- adressierbar





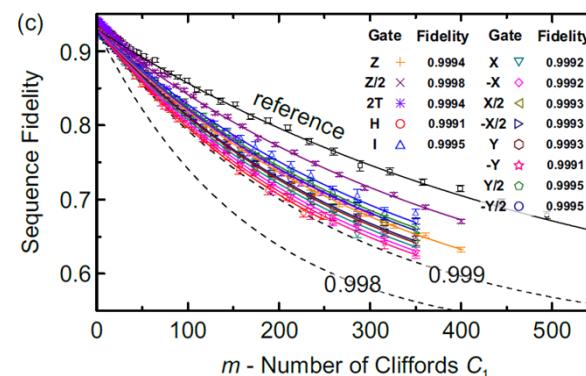
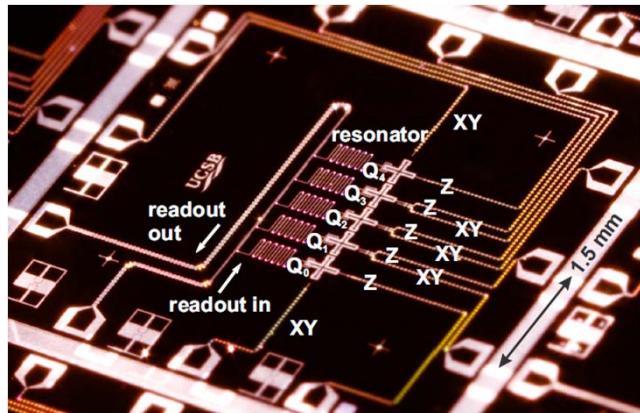
- coupling of sc-qubits via μ -wave resonators

- 3 qubit experiments, 2 CPhase operations

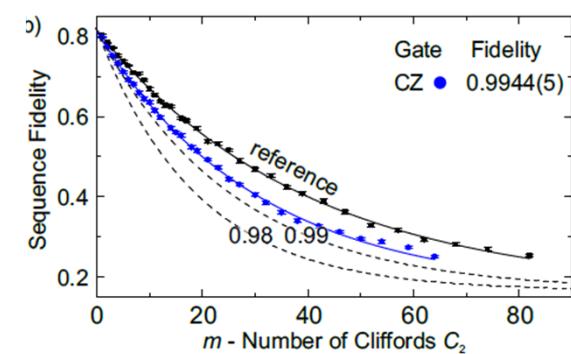




- quantum gates at fault tollerant threshold

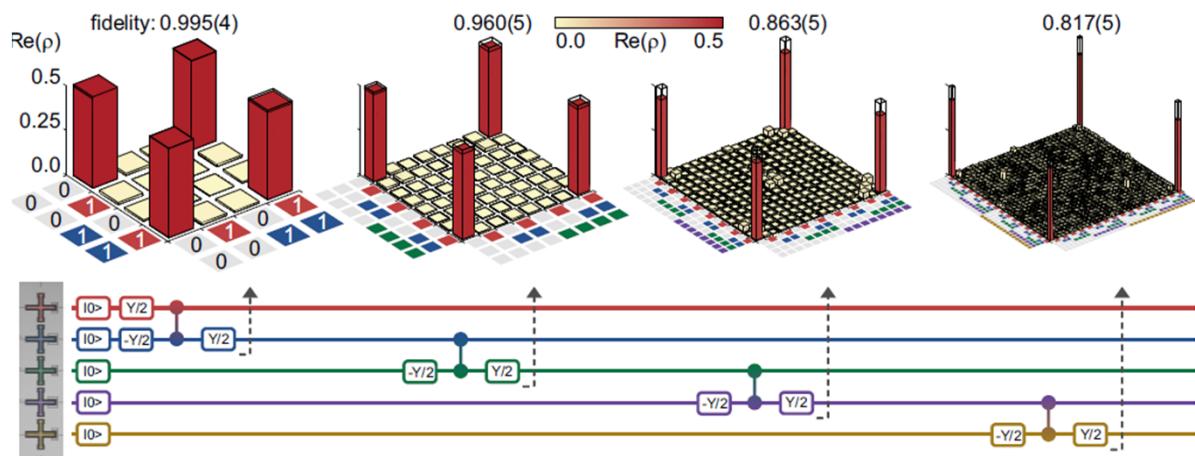


1-qubit gates



2-qubit gates

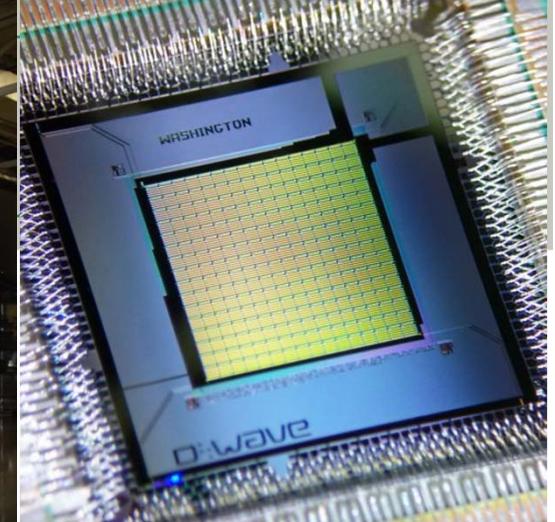
randomized benchmarking:
sequence of m gate operations
to determine fidelity





Industry!

- D-Wave
 - adiabatic solver
- Google
 - supraleitende qubits, playground, AI
- NASA
 - QuAIL mit D-Wave Rechner
- Microsoft
 - Quantum Architectures and Computation (QArC)
 - Anwendungen in Chemie (Fe_2S_2)
- NTT, IBM
 - superconducting qubit architectures





Zusammenfassung

- Quantenparallelismus $|\Psi\rangle = a_0|0\rangle + a_1|1\rangle$
- Neue Algorithmen $|\Psi\rangle \xrightarrow{\text{calculation}} U|\Psi\rangle$
 - Faktorisieren
 - Quantensimulation
- Quantengatter durch Wechselwirkung
- Algorithmen mit wenigen qubits
- Unterschiedliche experimentelle Umsetzungen

