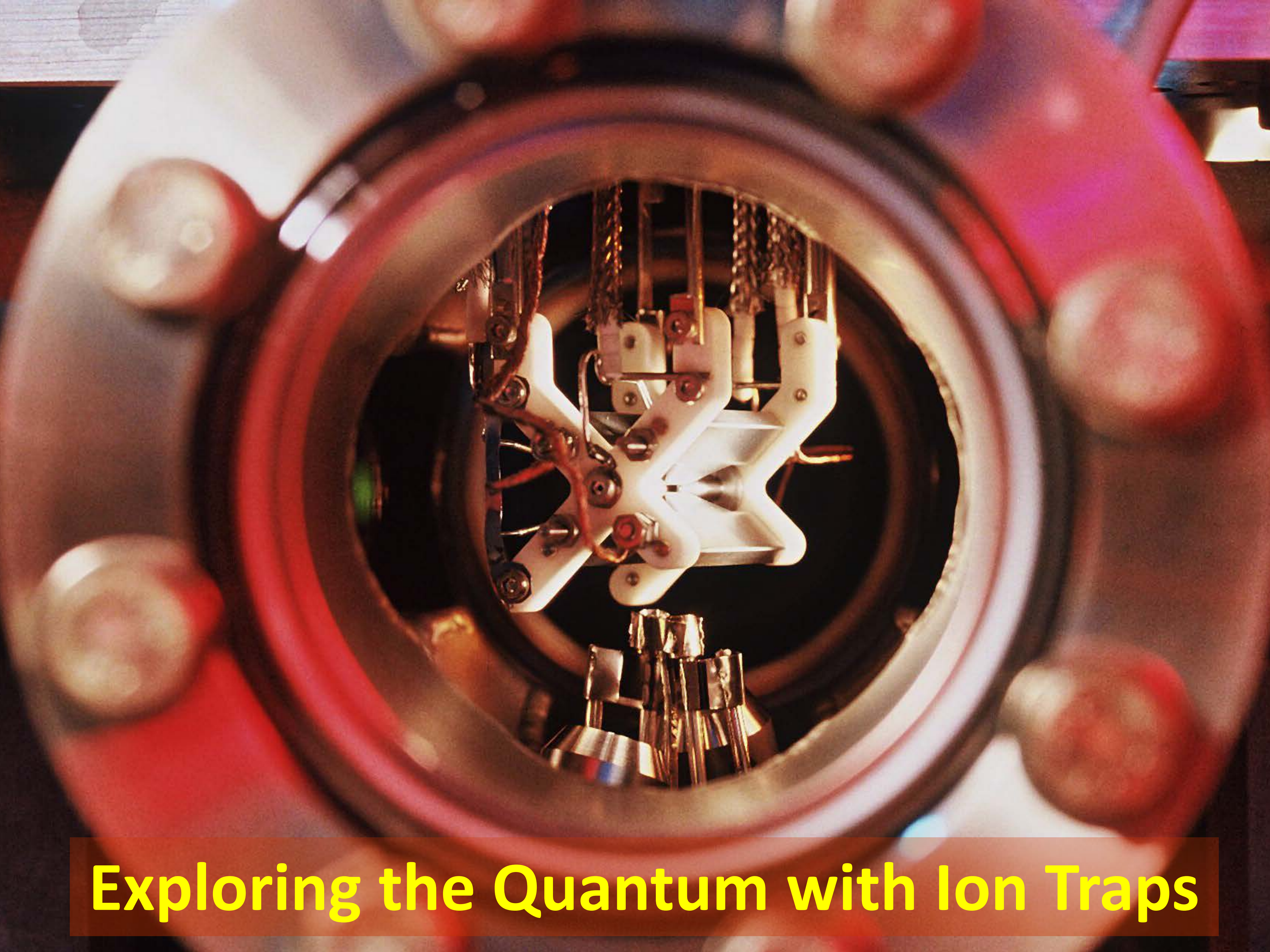


Exploring the Quantum with Ion Traps

Exploring the Quantum with Ion Traps

- Ion Traps: A Tool for Quantum Optics and Spectroscopy
- The Paul trap and its application to quantum physics
- Why quantum computers ?
- Quantum bits, Q-registers, Q-gates
- Exploring Quantum Computation with Trapped Ions
- Quantum Toolbox with Ions
- Quantum Simulations, analog and digital
- Scaling the ion trap quantum computer

Rainer Blatt

Institute for Experimental Physics, University of Innsbruck,
Institute for Quantum Optics and Quantum Information,
Innsbruck, Austrian Academy of Sciences

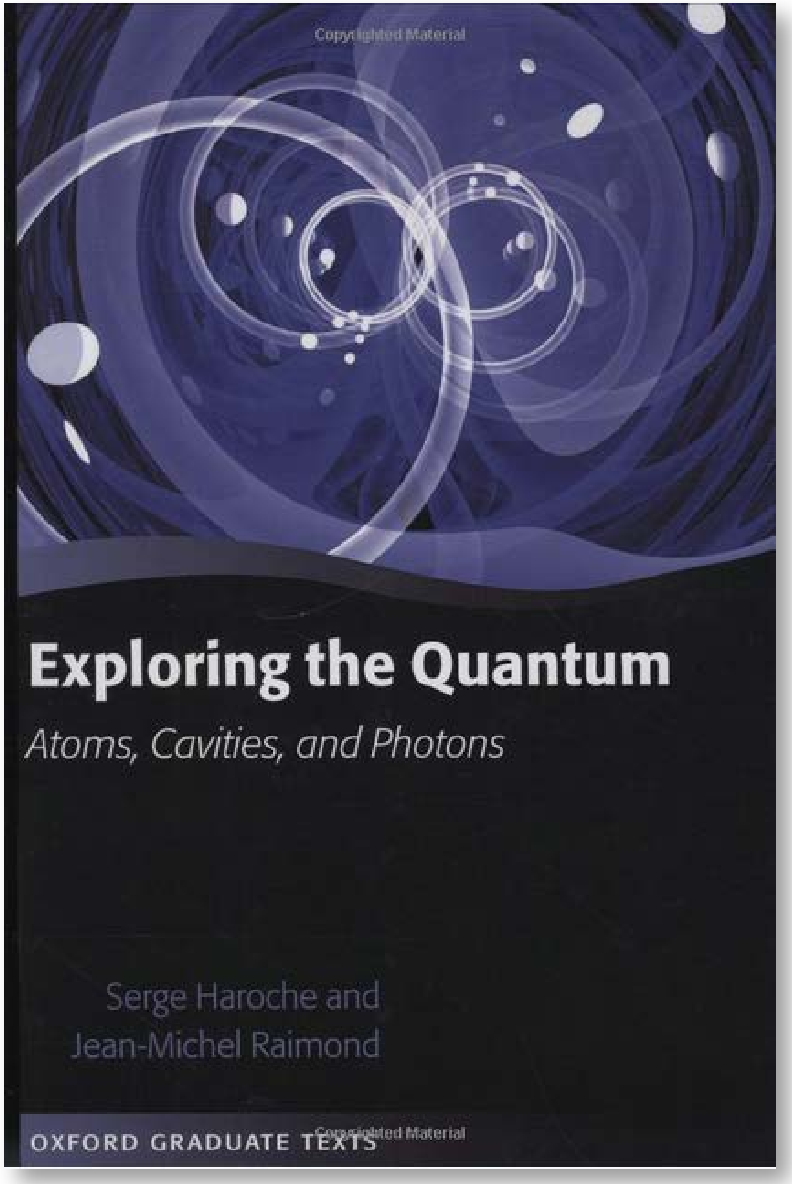
universität innsbruck

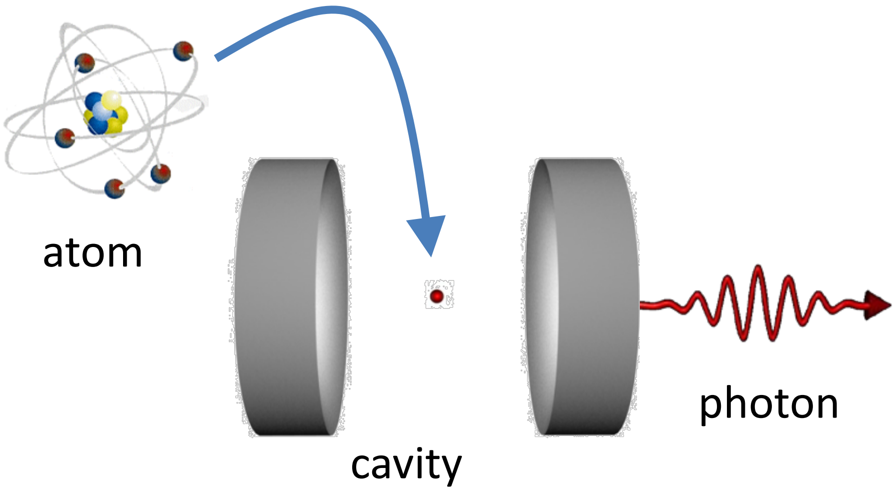
AG Quantenoptik
und Spektroskopie

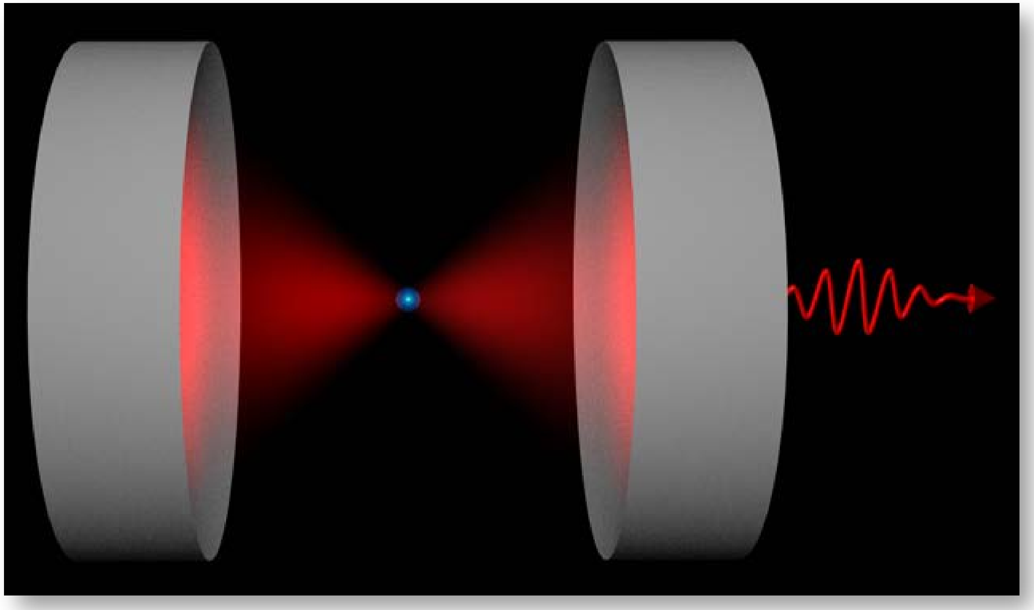
IQOQI

ÖAW
Österreichische Akademie
der Wissenschaften

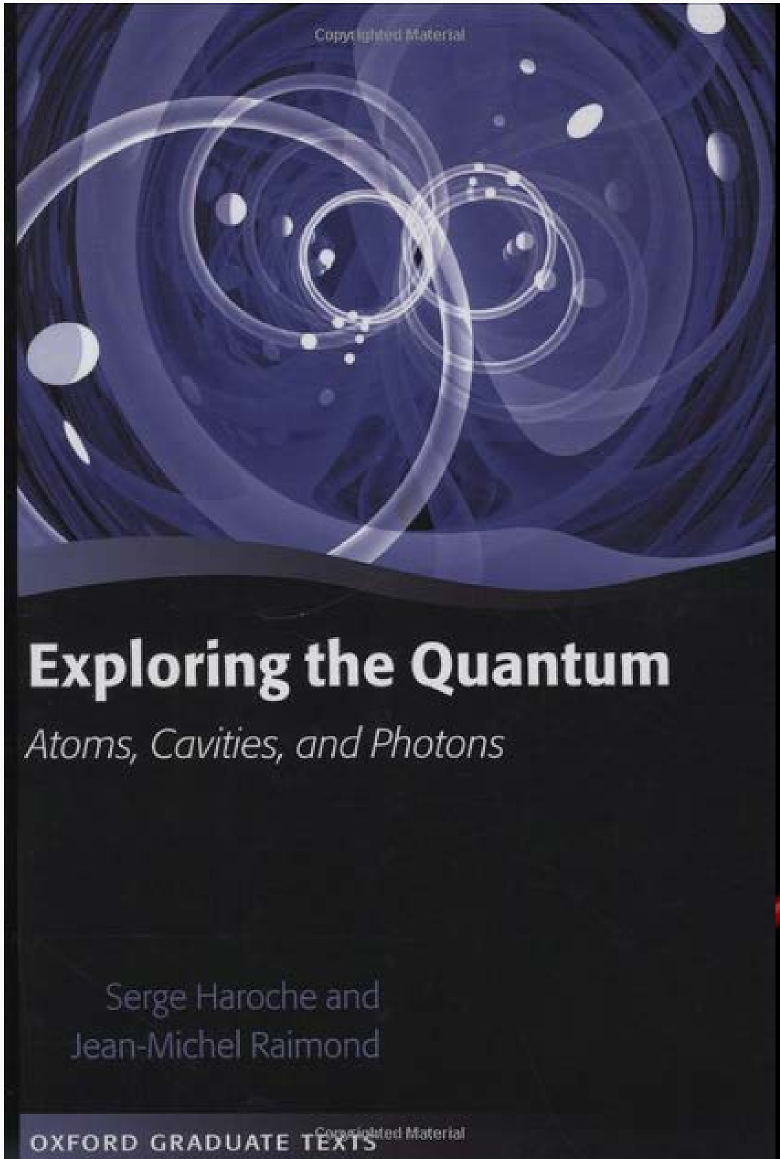
Exploring Quanta ...

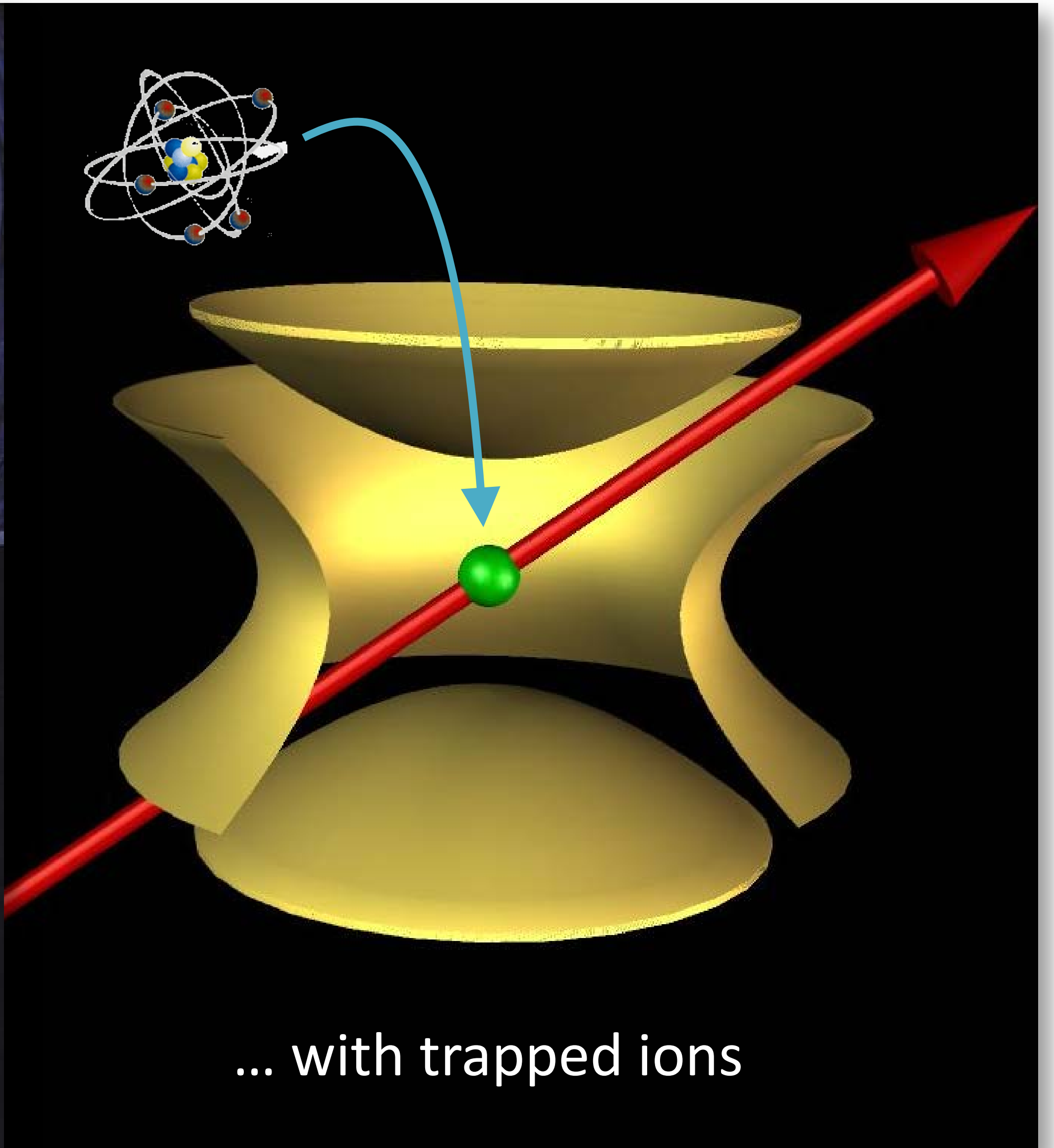






Exploring Quanta ...





The development of the ion trap (W. Paul, 1956)

DK 537.534.3 535.336.2

FORSCHUNGSBERICHTE
DES WIRTSCHAFTS- UND VERKEHRSMINISTERIUMS
NORDRHEIN-WESTFALEN

Herausgegeben von Staatssekretär Prof. Dr. h. c. Dr. E. h. Leo Brandt

Nr. 415

Prof. Dr.-Ing. Wolfgang Paul
Dr. rer. nat. Otto Osberghaus
Dipl.-Phys. Erhardt Fischer
Physikalisches Institut der Universität Bonn

Ein Ionenkäfig

Als Manuskript gedruckt

WESTDEUTSCHER VERLAG / KÖLN UND OPLADEN
1958

Prof. Dr.-Ing. Wolfgang Paul
Dr. rer. nat. Otto Osberghaus
Dipl.-Phys. Erhardt Fischer
Physikalisches Institut der Universität Bonn

Ein Ionenkäfig

The development of the ion trap (W. Paul, 1956)

DK 537.534.3 535.336.2

$$\varphi = (U + V\cos\omega_0 t)\,\frac{x^2 + y^2 - 2z^2}{2r_0^2}$$

WESTDEUTSCHER VERLAG / KÖLN UND OPLADEN

1958

Prof. Dr.-Ing. Wolfgang Paul

Dr. rer. nat. Otto Osberghaus

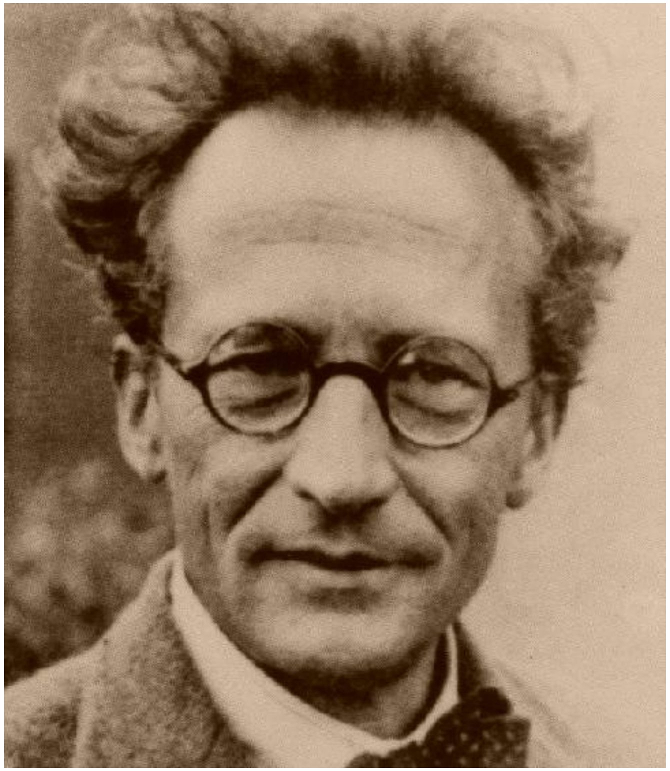
Dipl.-Phys. Erhardt Fischer

Physikalisches Institut der Universität Bonn

Ein Ionenkäfig

Experimenting with Single Atoms ?

In the first place it is fair to state that we are not *experimenting* with single particles, anymore than we can raise Ichtyosauria in the zoo.



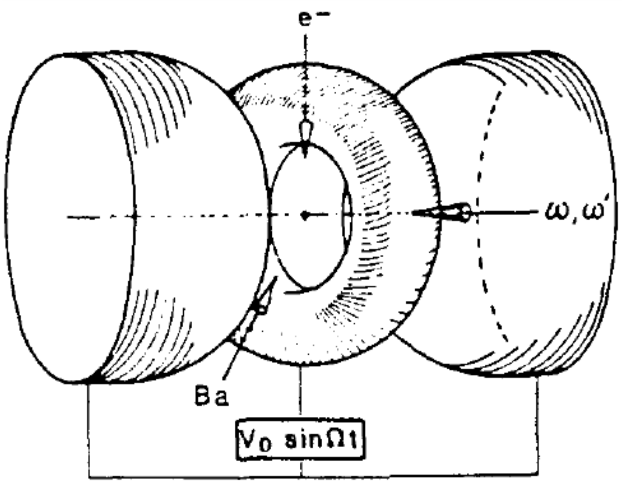
...., this is the obvious way of registering the fact, that we *never* experiment with just *one* electron or atom or (small) molecule. In thought-experiments we sometimes assume that we do; this envariably entails ridiculous consequences.

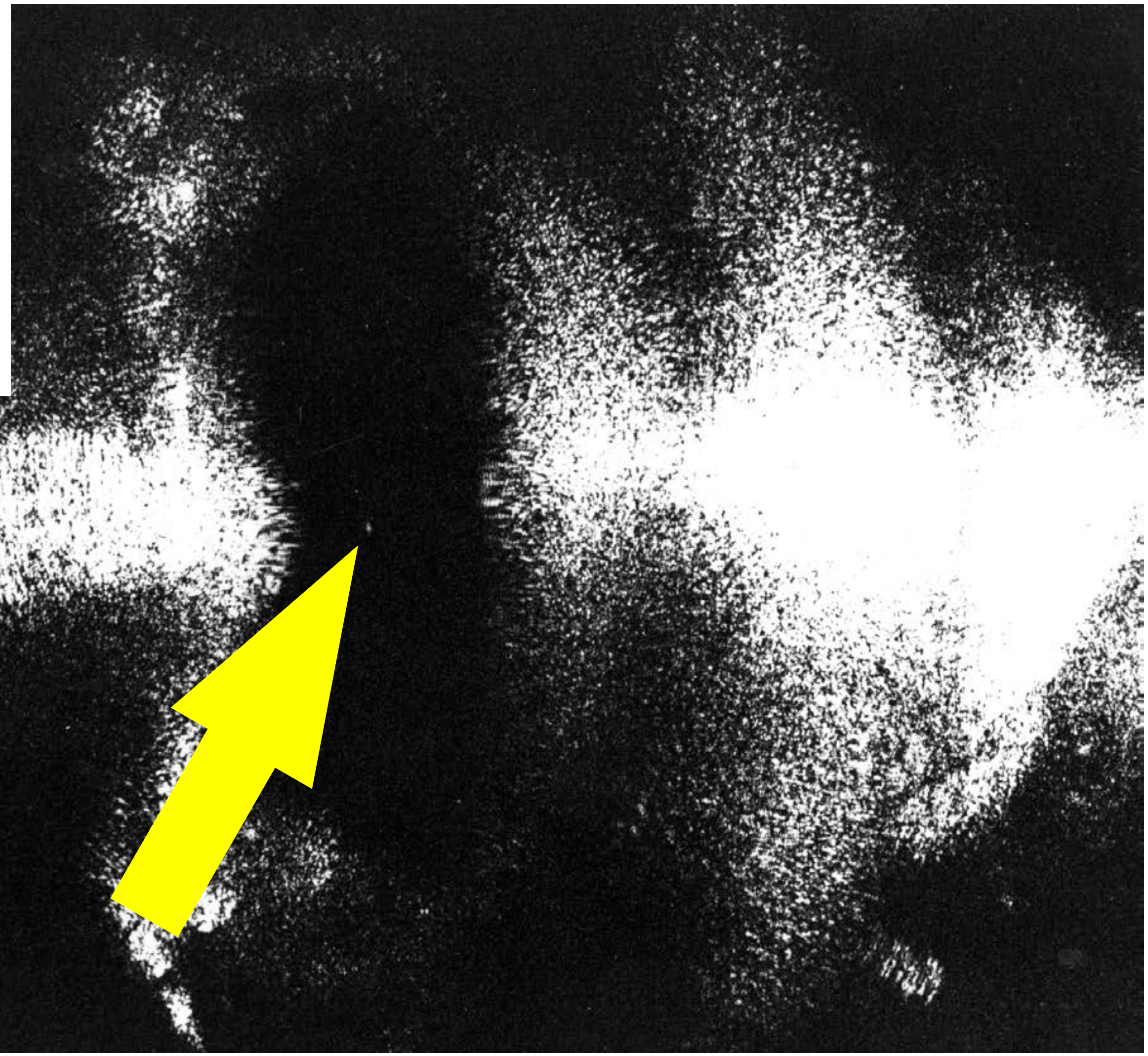
E. Schrödinger

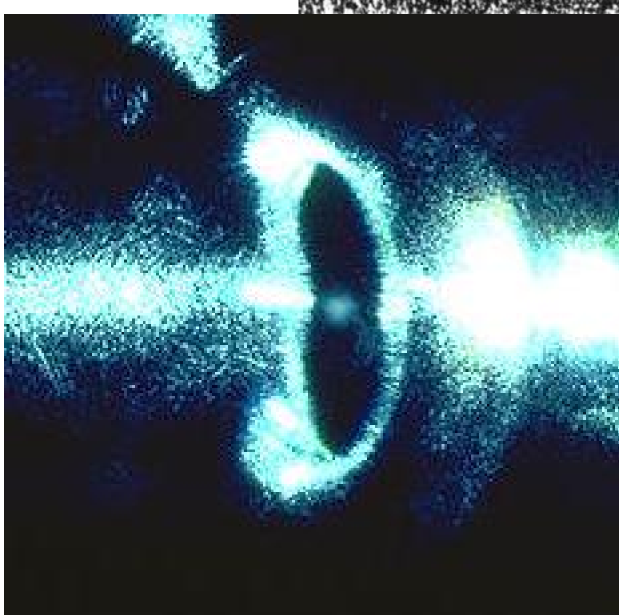
British Journal of the Philosophy of Science III (10), (1952)

Paul trap in the 70s: a single laser-cooled ion

W. Neuhauser, M. Hohenstatt, P. Toschek, H. Dehmelt
Phys. Rev. Lett. **41**, 233 (1978), PRA (1980)

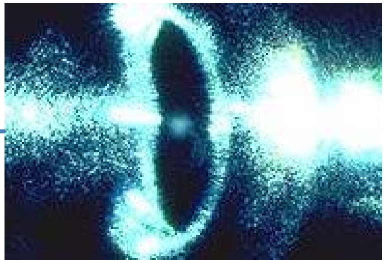






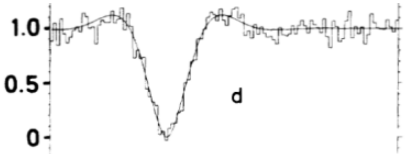
Applying the Paul trap in the 80s…

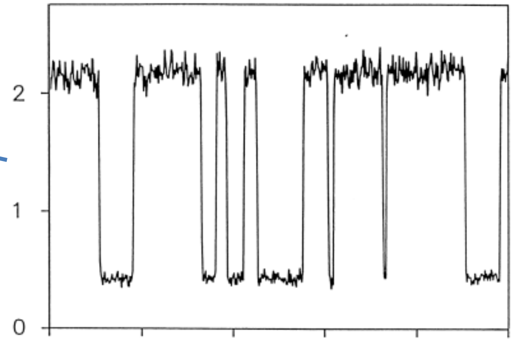
… a major breakthrough for quantum optics and spectroscopy

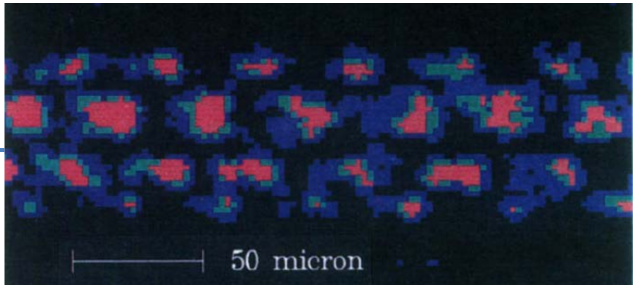


- Single ions, laser cooling
- Precision spectroscopy
- Quantum optics ($g^2(\tau)$, dark resonances)
- Quantum jumps
- Ion crystals
- Nonlinear dynamics
- Dynamics of clouds
- Multipole traps
- Theory advances
- Sideband cooling

… and more



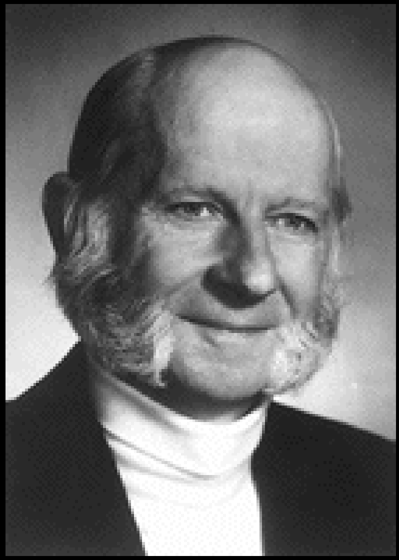




The Nobel prize in 1989

„for the development of the ion trap technique“

W. Paul



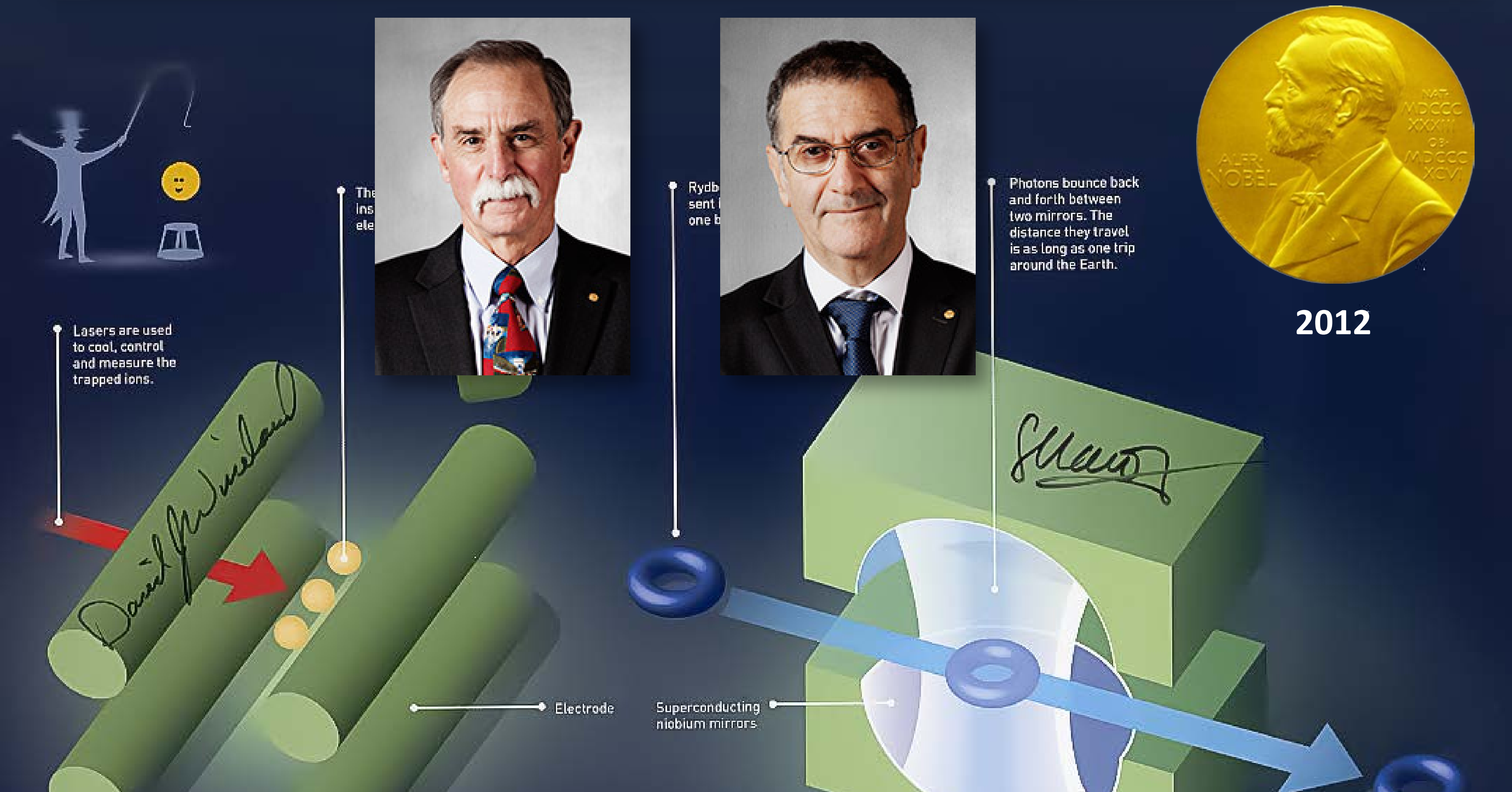
H. Dehmelt

Exploring the quantum with ion traps in the 90s …

Theory and experimental progress….

- Quantum optics, correlation functions, new treatment of cooling in traps,
  I.Cirac, R. Blatt, P. Zoller, W. Phillips, Phys. Rev. **A 46**, 2668 (1992)
- Equivalence: **ion trap <=> cavity QED system** ("CQED without a cavity")
  C. Blockley, D. Walls, H. Risken, Europhys. Lett. **17**, 509 (1992)
- 1994: ICAP Boulder – quantum information talk (A. Ekert),
  -> Paul trap application for quantum information processing
- 1995: Cirac-Zoller proposal, **quantum computation** with trapped ions
  I. Cirac, P. Zoller, Phys. Rev. Lett. **74**, 4091 (1995)
- Quantum optics and quantum information experiments
  Boulder, Innsbruck, Oxford, C. Monroe et al., Phys. Rev. Lett. **75**, 4714 (1995)
- **Development of tools and methods for measuring and manipulating individual quantum systems**

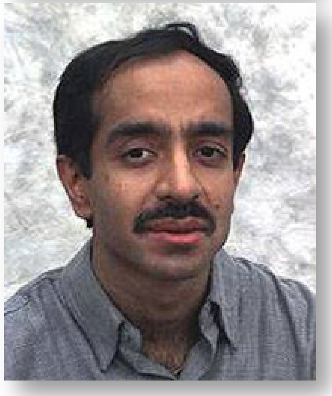
Exploring the quantum with cavities and ion traps



Nobel Prize 2012
"for ground-breaking experimental methods that enable measuring and manipulation of individual quantum systems"

Why Exploring Quantum Computers … ?

applications in physics and mathematics



- factorization of large numbers (P. Shor, 1994) can be achieved much faster on a quantum computer than with a classical computer

  factorization of number with L digits:

  classical computer: $\sim\exp(L^{1/3})$, quantum computer: $\sim L^2$

- fast database search (L. Grover, 1997)

  search data base with N entries:

  classical computer: O(N), quantum computer: $O(N^{1/2})$

- simulation of Schrödinger equations **hot topic !**

- spectroscopy: quantum computer as atomic “state synthesizer“

  D. M. Meekhof et al., Phys. Rev. Lett. **76**, 1796 (1996)

- quantum physics with “information guided eye“

The requirements for quantum computation

D. P. DiVincenzo, Quant. Inf. Comp. **1** (Special), 1 (2001)

I. Scalable physical system, well characterized qubits

II. Ability to initialize the state of the qubits

III. Long relevant coherence times, much longer than gate operation time

IV. "Universal" set of quantum gates

V. Measurement capability specific to implementation

VI. Ability to interconvert stationary and flying qubits

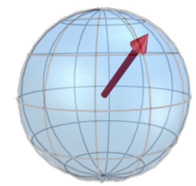
VII. Ability to faithfully transmit flying qubits between specified locations

The seven commandments for QC !!

Quantum bits and registers

- classical bit: physical object in state 0  or in state 1 
- register: bit rows 0 1 1 . . .
- quantum bit (qubit): superposition of two orthogonal quantum states

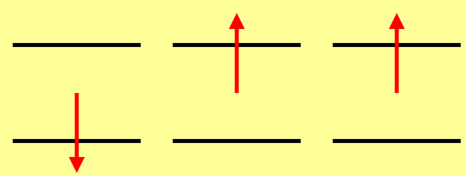
$$|\Psi\rangle = c_0|0\rangle + c_1|1\rangle$$



- quantum register: L 2-level atoms, 2^L quantum states

  2^L states correspond

  to numbers $0,\ldots\ldots,2^L-1$



$$|0\rangle \otimes |1\rangle \otimes |1\rangle$$

- most general state of the register is the superposition

$$\begin{aligned} |\Psi\rangle &= c_{000}|000\rangle + c_{001}|001\rangle + \cdots + c_{110}|110\rangle + c_{111}|111\rangle \quad \text{(binary)} \\ &= c_0|0\rangle + c_1|1\rangle + \cdots + c_6|6\rangle + c_7|7\rangle \quad \text{(decimal)} \end{aligned}$$

Superpositions -> Quantum Parallelism

… many computational paths "interfere" and produce the result

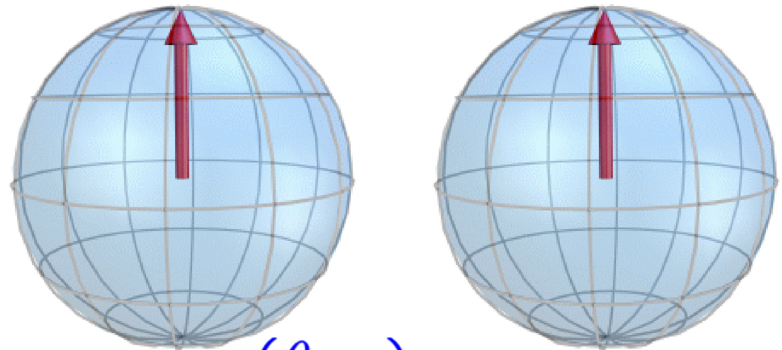
computational space :

# Qubits n	# comp. paths 2^n
1	2
2	4
4	16
8	256
16	65536
32	4.29×10^9
64	1.84×10^{19}

With 300 qubits, the number of computational paths exceeds the number of atoms in the universe …!

Universal quantum gate operations

Operations with single qubit:
(1-bit rotations)



$(\theta, \varphi) =$

$(\pi, 0)$ $\quad$ $2/3(\pi, \pi)$

together universal !

Operations with two qubits:
(2-bit rotations)

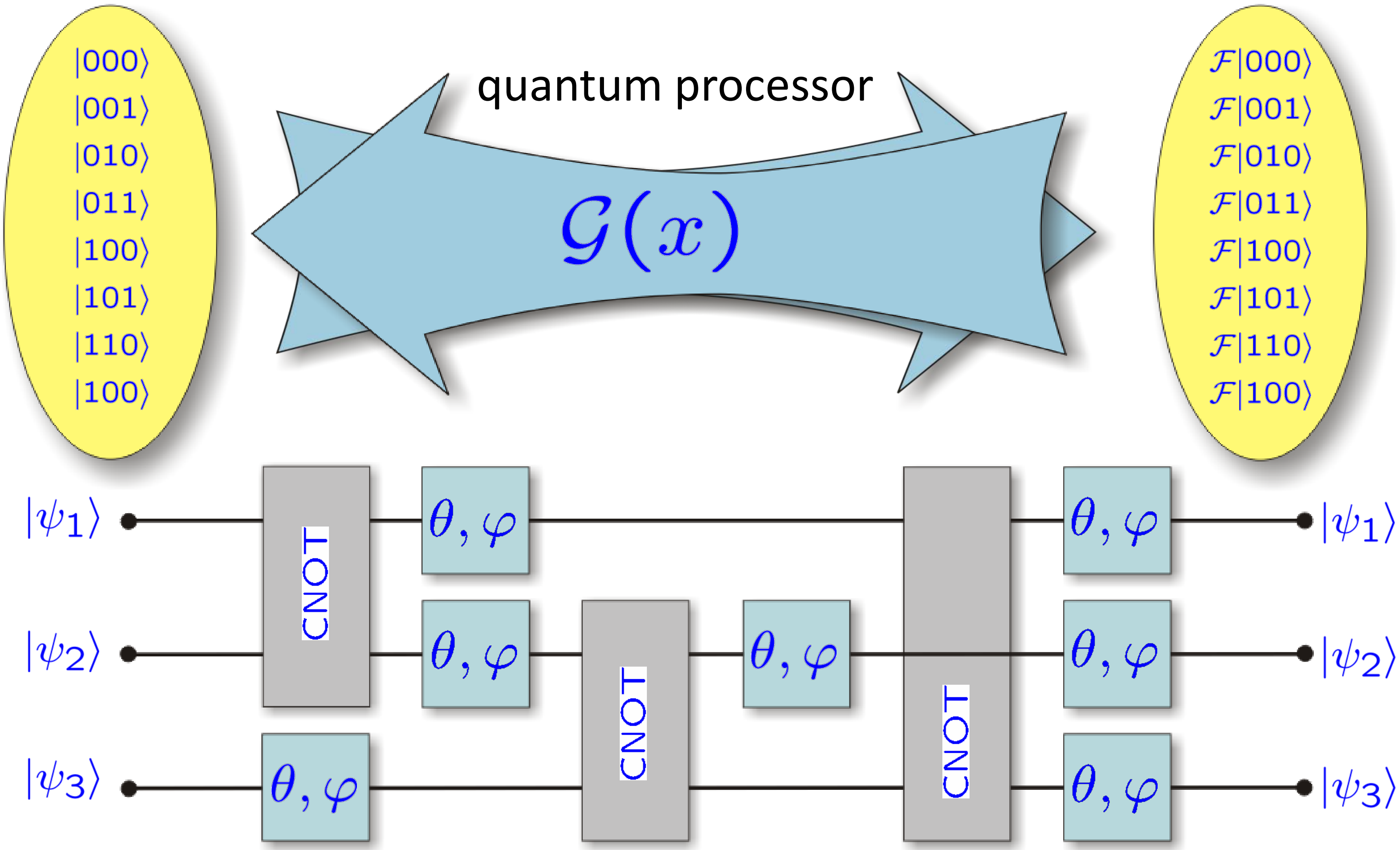
CNOT – gate operation
(controlled-NOT)

analogous to classical XOR

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

control bit $\quad$ target bit

How quantum information processing works



Input ⇨ computation: sequence of quantum gates ⇨ output

Quantum Computation with Trapped Ions

VOLUME 74, NUMBER 20 PHYSICAL REVIEW LETTERS 15 MAY 1995

Quantum Computations with Cold Trapped Ions

J. I. Cirac and P. Zoller*

Institut für Theoretische Physik, Universiät Innsbruck, Technikerstrasse 25, A-6020 Innsbruck, Austria

(Received 30 November 1994)

A quantum computer can be implemented with cold ions confined in a linear trap and interacting with laser beams. Quantum gates involving any pair, triplet, or subset of ions can be realized by coupling the ions through the collective quantized motion. In this system decoherence is negligible, and the measurement (readout of the quantum register) can be carried out with a high efficiency.

PACS numbers: 89.80.+h, 03.65.Bz, 12.20.Fv, 32.80.Pj

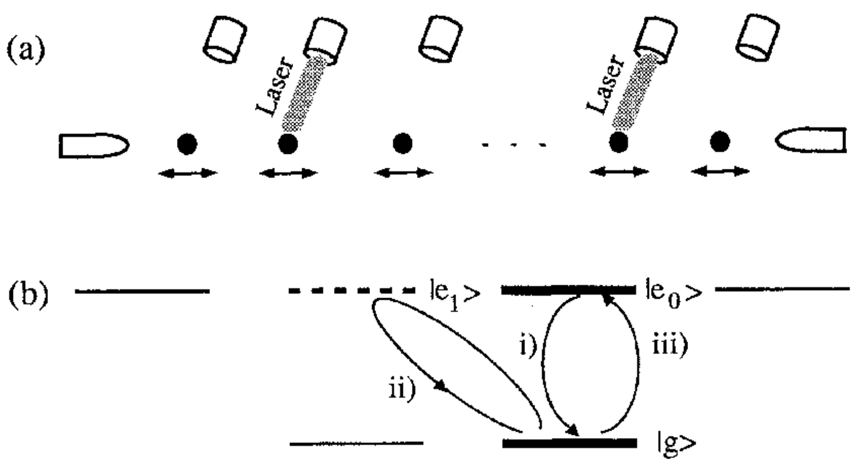


FIG. 1. (a) N ions in a linear trap interacting with N different laser beams; (b) atomic level scheme.

J. I. Cirac

P. Zoller

other gate proposals (and more):

- Cirac & Zoller
- Mølmer & Sørensen,
- Milburn, Zagury, Solano
- Jonathan & Plenio & Knight
- Geometric phases
- Leibfried & Wineland

Quantum Computation with Trapped Ions

VOLUME 74, NUMBER 20 PHYSICAL REVIEW LETTERS 15 MAY 1995

Quantum Computations with Cold Trapped Ions

J. I. Cirac and P. Zoller*
Institut für Theoretische Physik, Universiät Innsbruck, Technikerstrasse 25, A-6020 Innsbruck, Austria
(Received 30 November 1994)

A quantum computer can be implemented with cold ions confined in a linear trap and interacting with laser beams. Quantum gates involving any pair, triplet, or subset of ions can be realized by coupling the ions through the collective quantized motion. In this system decoherence is negligible, and the measurement (readout of the quantum register) can be carried out with a high efficiency.

PACS numbers: 89.80.+h, 03.65.Bz, 12.20.Fv, 32.80.Pj

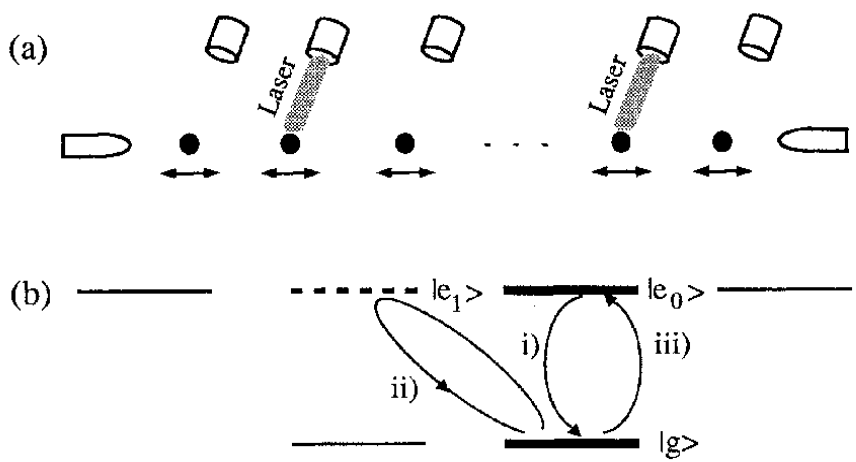


FIG. 1. (a) N ions in a linear trap interacting with N different laser beams; (b) atomic level scheme.

controlled – NOT :

$$|\varepsilon_1\rangle|\varepsilon_2\rangle \rightarrow |\varepsilon_1\rangle|\varepsilon_1 \oplus \varepsilon_2\rangle$$

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

control bit — target bit

other gate proposals (and more):

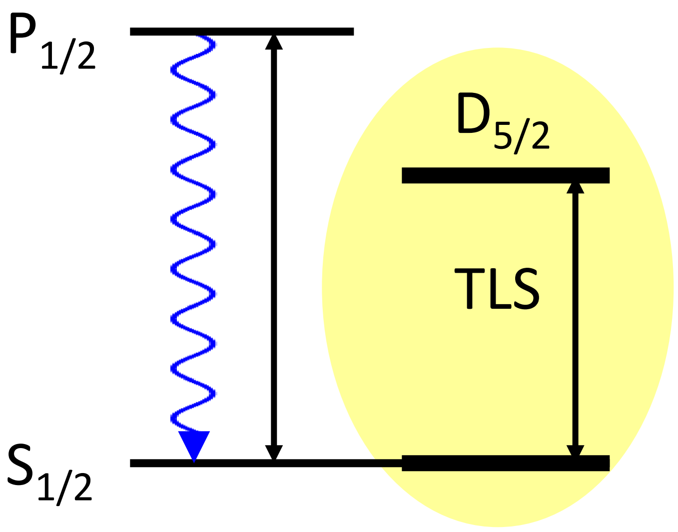
- Cirac & Zoller
- Mølmer & Sørensen,
- Milburn, Zagury, Solano
- Jonathan & Plenio & Knight
- Geometric phases
- Leibfried & Wineland

Qubits with Trapped Ions

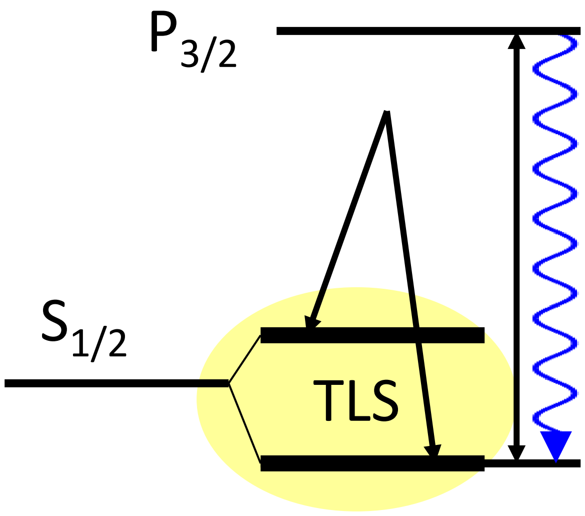
Storing and keeping quantum information requires long-lived atomic states:

- optical transition frequencies (forbidden transitions, intercombination lines)
  S – D transitions in alkaline earths:
  Ca^+, Sr^+, Ba^+, Ra^+, (Yb^+, Hg^+) etc.

- microwave transitions (hyperfine transitions, Zeeman transitions)
  alkaline earths:
  $^{9}Be^+$, $^{25}Mg^+$, $^{43}Ca^+$, $^{87}Sr^+$, $^{137}Ba^+$, $^{111}Cd^+$, $^{171}Yb^+$

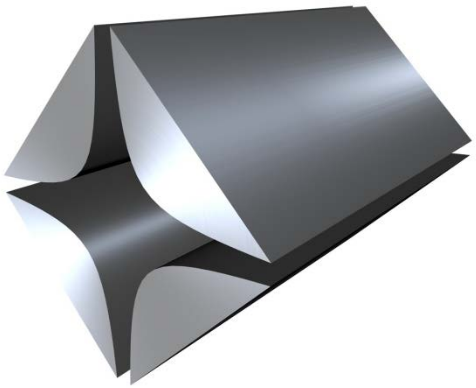


Innsbruck $^{40}Ca^+$

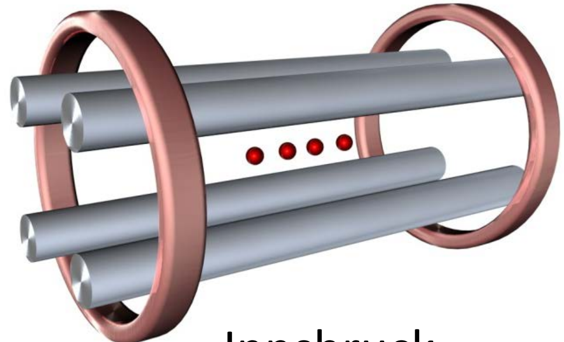


Boulder $^{9}Be^+$; Michigan $^{111}Cd^+$; Innsbruck $^{43}Ca^+$, Oxford $^{43}Ca^+$; Maryland $^{171}Yb^+$;

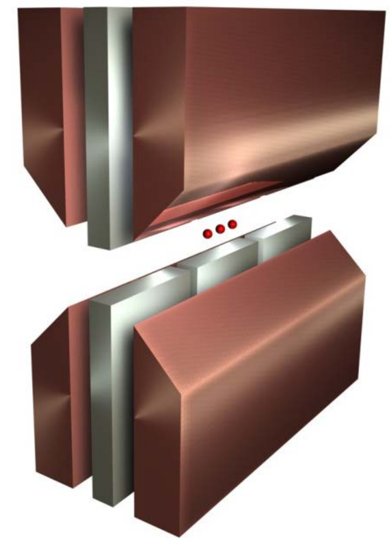
Linear Ion Traps



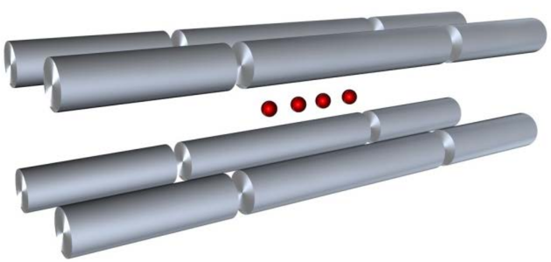
Paul mass filter



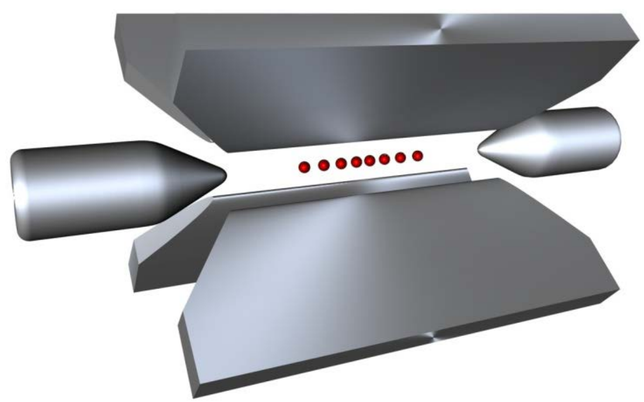
Innsbruck
Ann Arbor



München,
Sussex

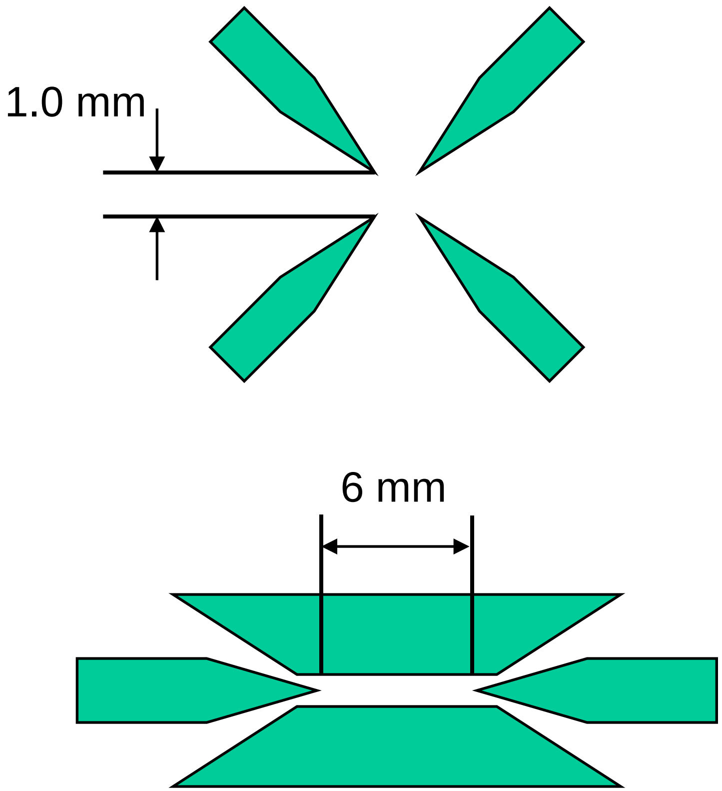


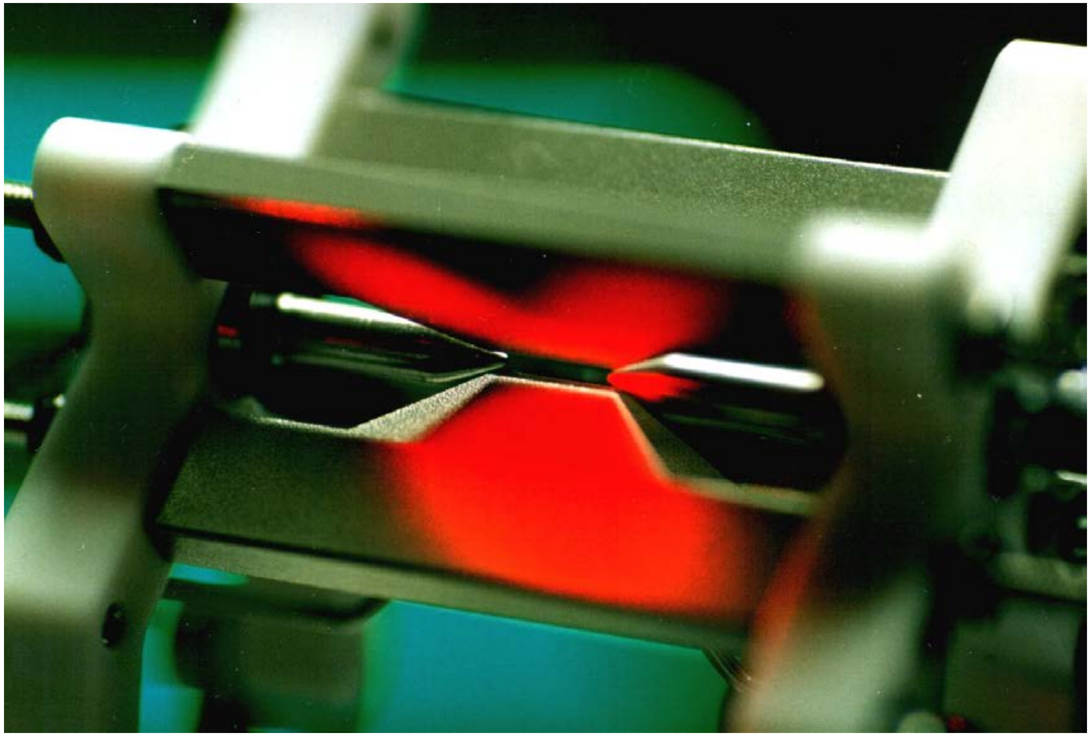
Boulder, Mainz, Aarhus



Innsbruck, Oxford

Innsbruck linear ion trap (2000)





$$\omega_z \approx 0.7 - 2\,\mathrm{MHz} \qquad \omega_{x,y} \approx 1.5 - 4\,\mathrm{MHz}$$

Quantum Computer with Trapped Ions

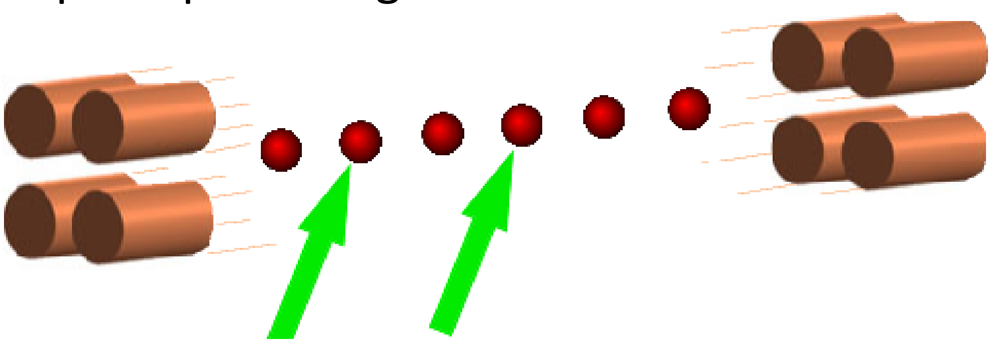
J. I. Cirac, P. Zoller; Phys. Rev. Lett. **74**, 4091 (1995)

L Ions in linear trap

- quantum bits, quantum register
  - narrow optical transitions
  - groundstate Zeeman coherences
- state vector of quantum computer

$$|\Psi\rangle = \sum_{\underline{x}} c_{\underline{x}} |x_{L-1}, \ldots, x_0\rangle \otimes |0\rangle_{\mathrm{CM}}$$

- 2-qubit quantum gate



laser pulses entangle pairs of ions

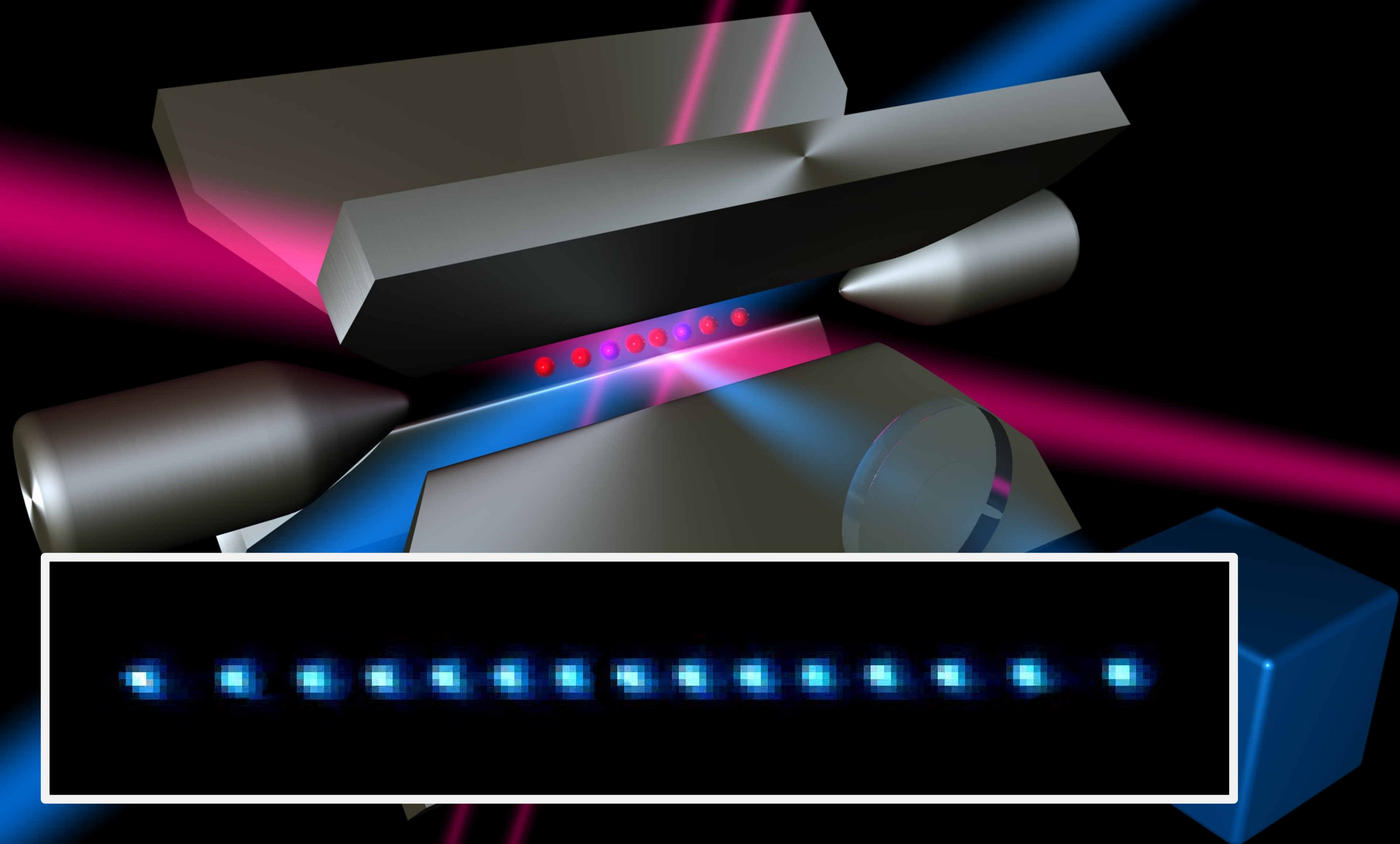
$$\begin{aligned} |0\rangle|0\rangle &\rightarrow |0\rangle|0\rangle \\ |0\rangle|1\rangle &\rightarrow |0\rangle|1\rangle \\ |1\rangle|0\rangle &\rightarrow |1\rangle|1\rangle \\ |1\rangle|1\rangle &\rightarrow |1\rangle|0\rangle \end{aligned}$$

control bit

target bit

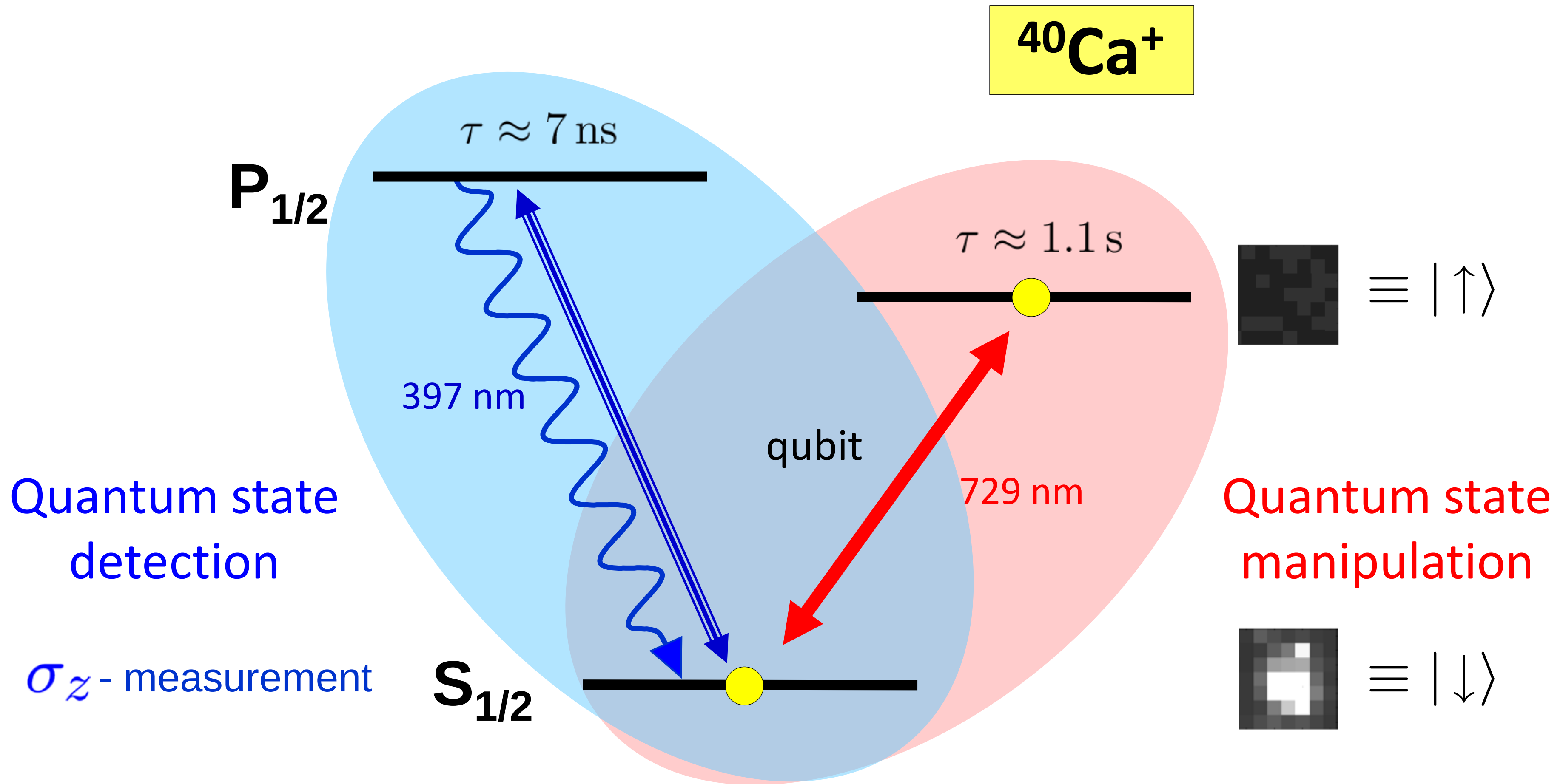
- needs individual addressing, efficient single qubit operations
- small decoherence of internal and motional states
- quantum computer as series of gate operations (sequence of laser pulses)

The Quantum Information Processor with Trapped Ca^+ Ions

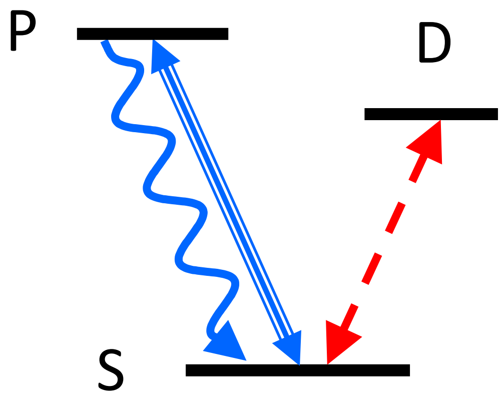


P. Schindler et al., New. J. Phys. 15, 123012 (2013)

Experiments with trapped Ca^+ ions

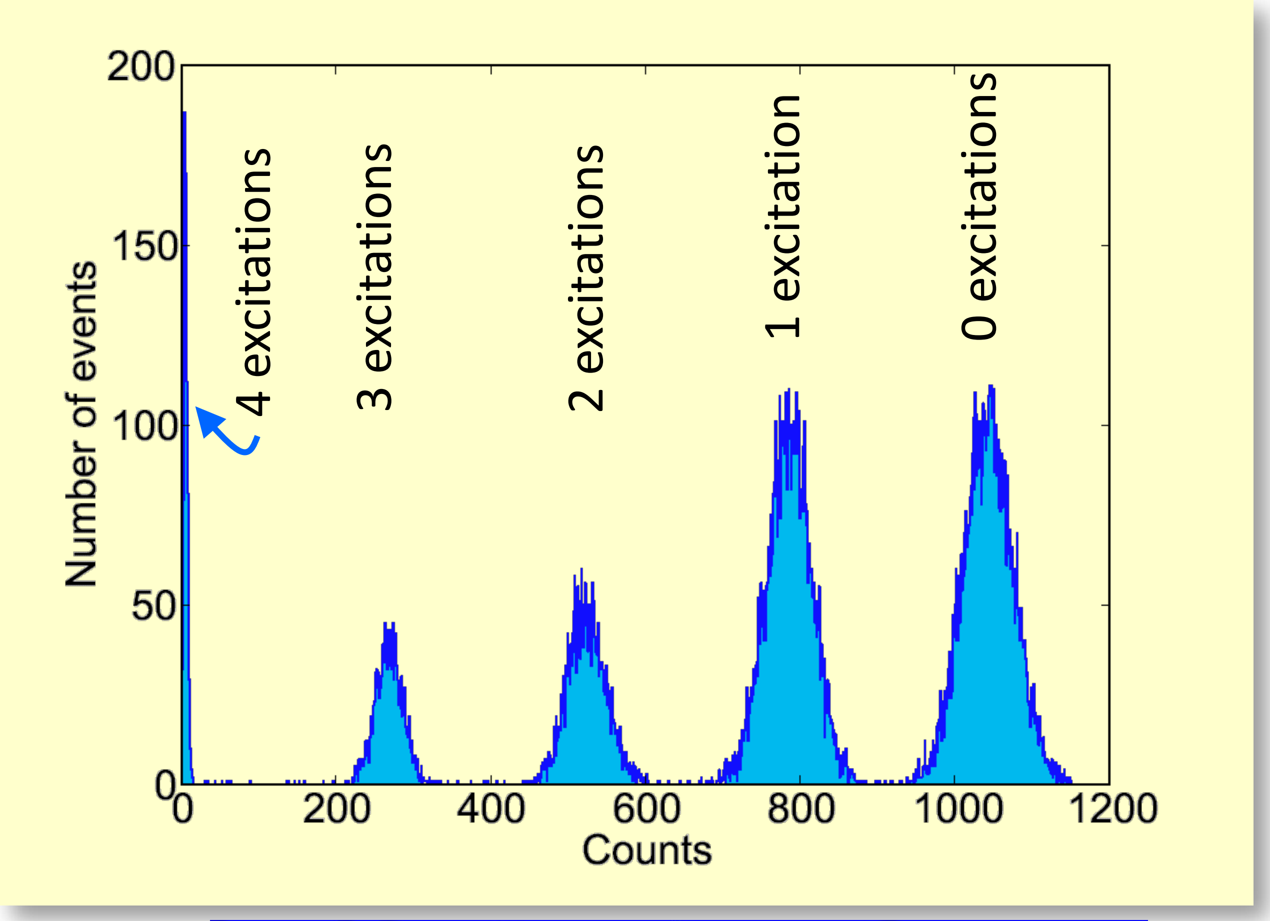


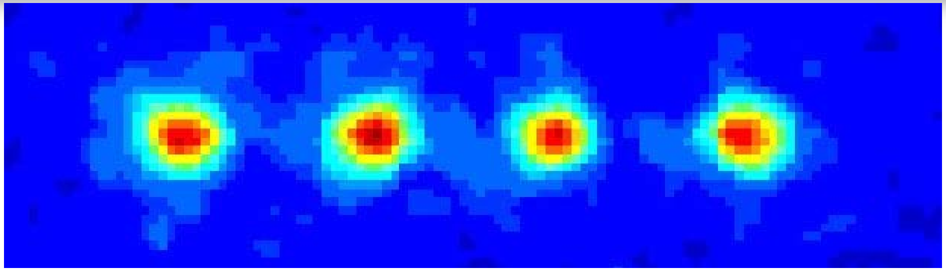
Quantized Fluorescence Detection of an Ion String



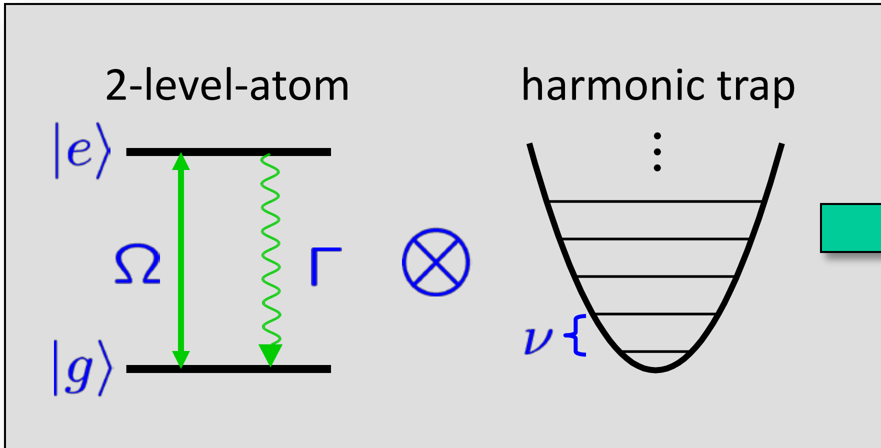
Detection:
Doing Quantum Jumps

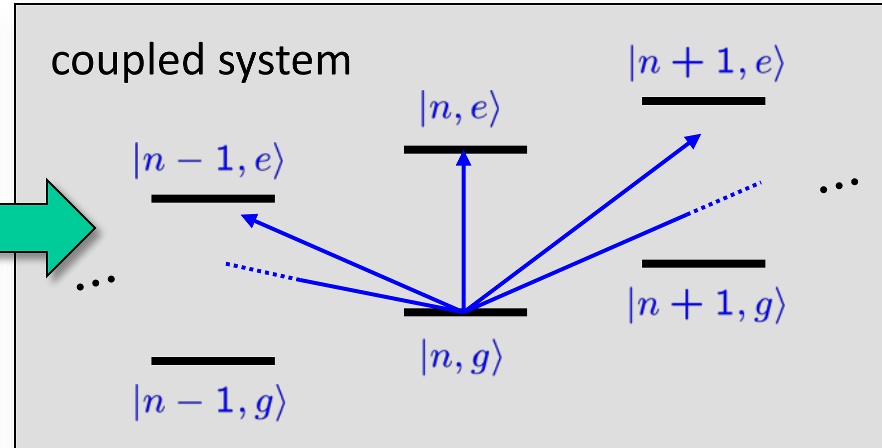
- Projection of ions to either S or D states,
- Coherences are destroyed

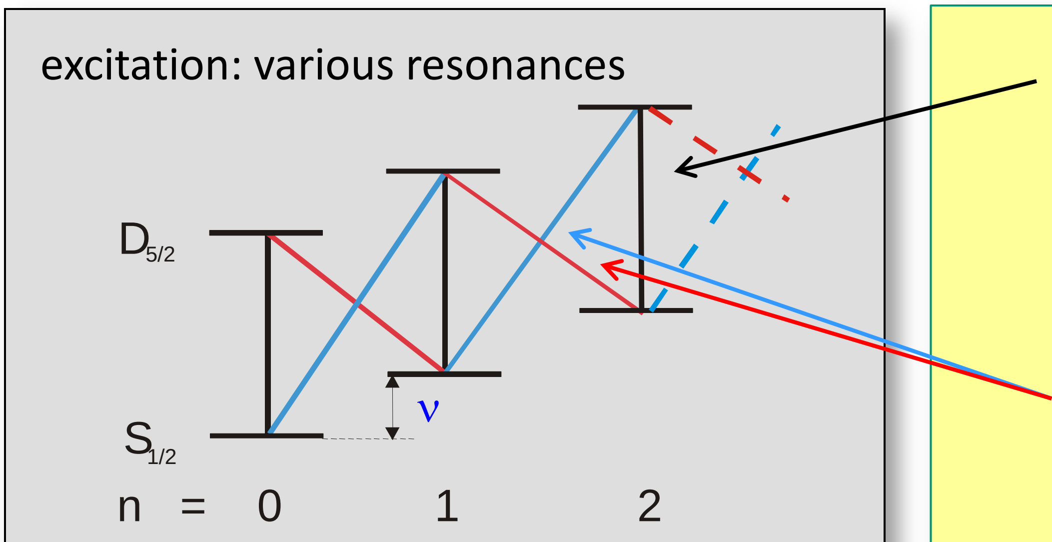




Quantized ion motion: superpositions and entanglement



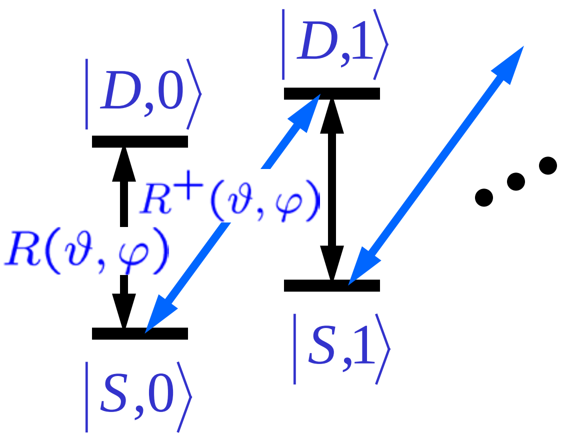


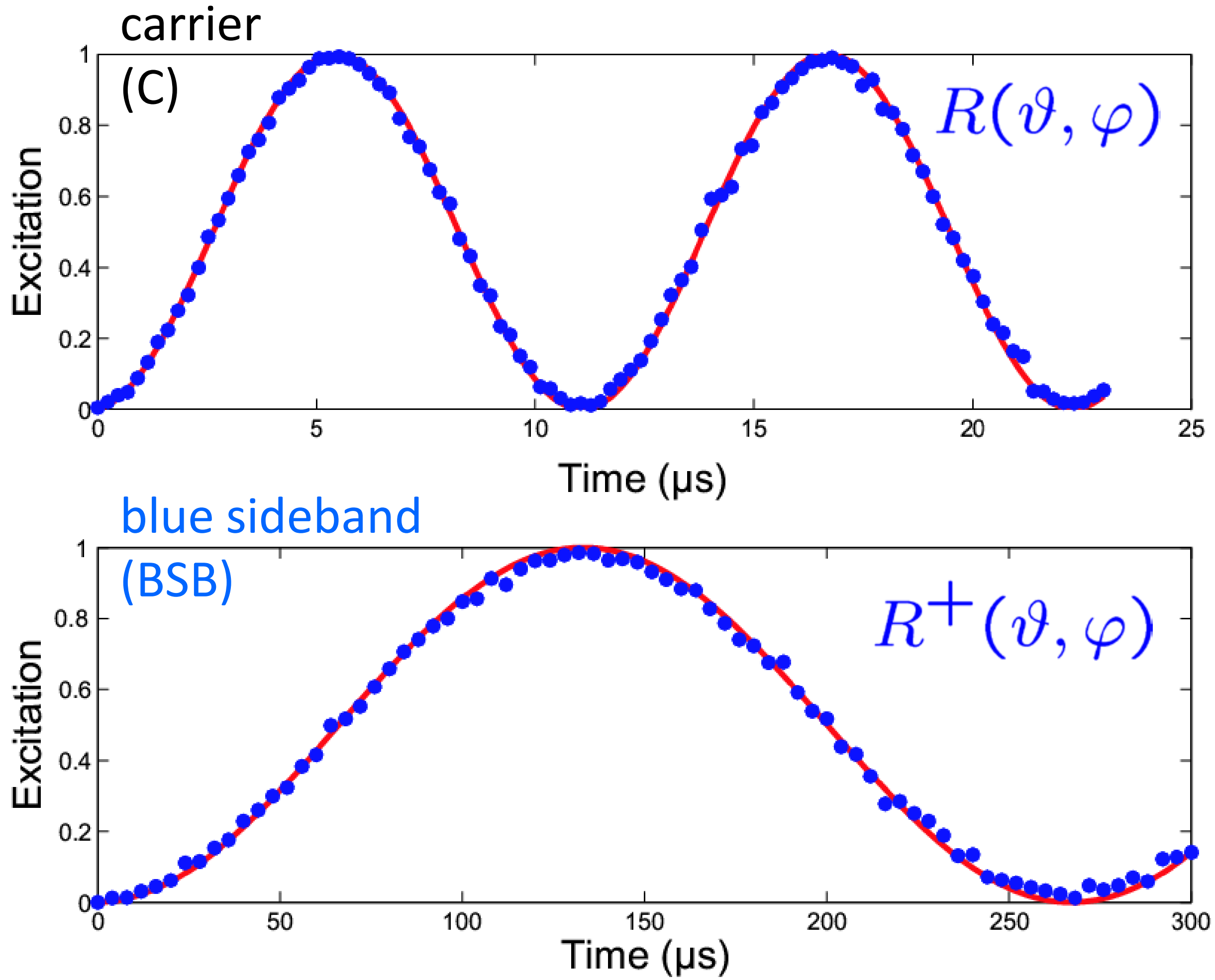


Carrier:
manipulate qubit
→ internal superpositions

Sidebands:
manipulate motion and qubit
→ create entanglement

Coherent state manipulation





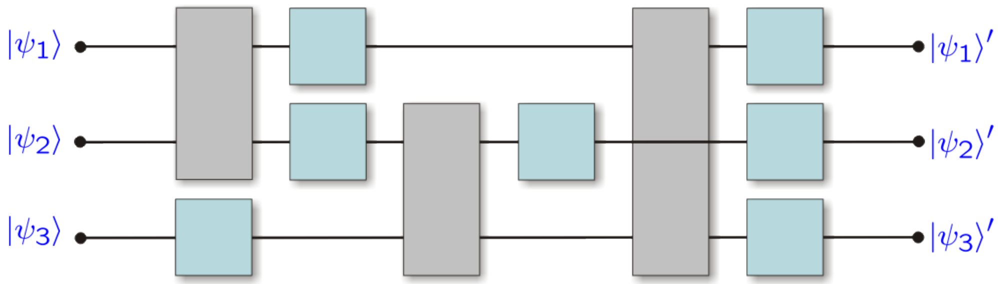
carrier and sideband
Rabi oscillations
with Rabi frequencies

$$\Omega, \quad \eta\Omega\sqrt{n+1}$$

$\eta = kx_0$ Lamb-Dicke parameter

Quantum information processing with trapped ions

- **algorithms**:
  sequence of single qubit and two-qubit gate operations



- **gate operations**:
  sequences of laser pulses (carrier and/or sideband pulses)

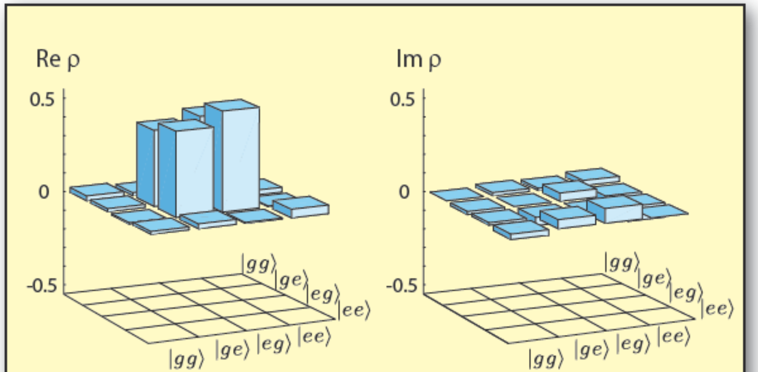
$R(\vartheta, \varphi)$, $R^+(\vartheta, \varphi)$

carrier sideband

- **analysis**:

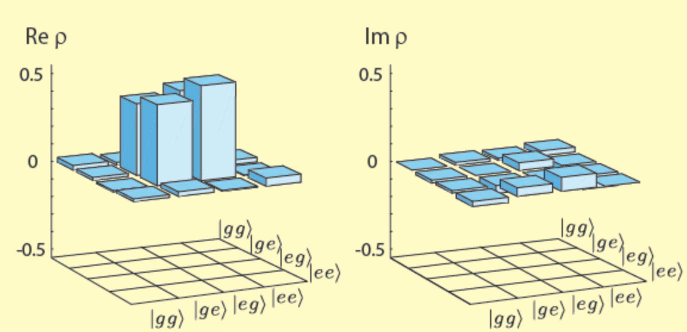
  measure density matrix of state or process (**tomography**)

  measure entanglement via **parity oscillations**

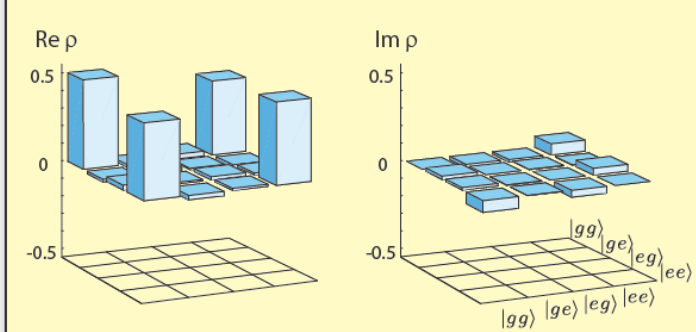


$$|\Psi^+\rangle = \frac{1}{\sqrt{2}}(|ge\rangle + |eg\rangle)$$

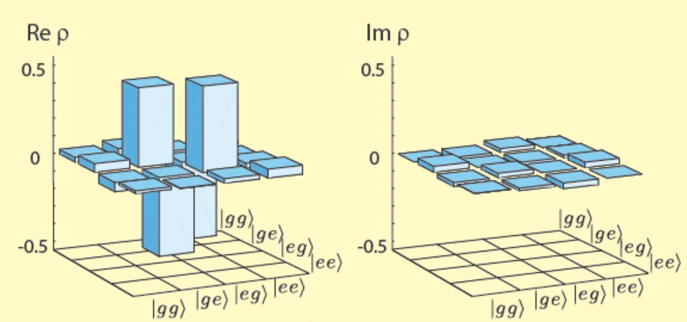
Push-button preparation and tomography of Bell states



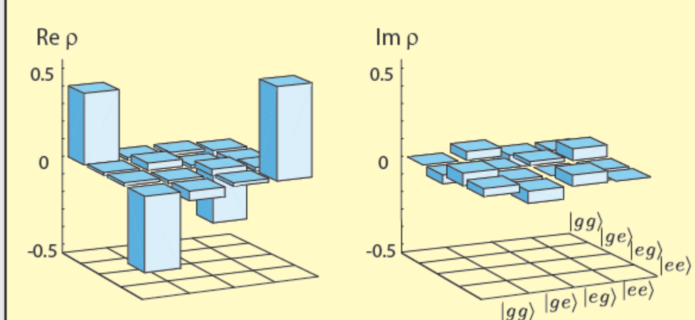
$$|\Psi^+\rangle = \frac{1}{\sqrt{2}}(|ge\rangle + |eg\rangle)$$



$$|\Phi^+\rangle = \frac{1}{\sqrt{2}}(|gg\rangle + |ee\rangle)$$



$$|\Psi^-\rangle = \frac{1}{\sqrt{2}}(|ge\rangle - |eg\rangle)$$



$$|\Phi^-\rangle = \frac{1}{\sqrt{2}}(|gg\rangle - |ee\rangle)$$

Fidelity:

F = 0.91

Entanglement of formation:

$E(\rho_{exp}) = 0.79$

Violation of Bell inequality:

$S(\rho_{exp}) = 2.53(6)$
> 2

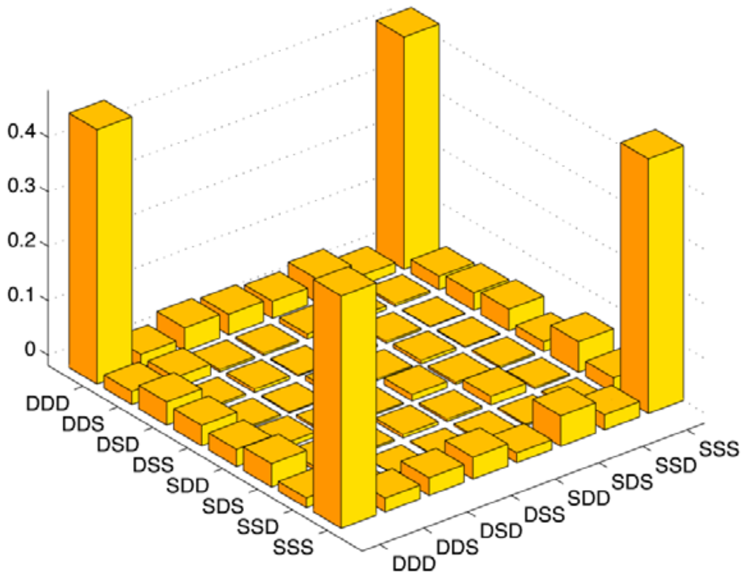
C. Roos et al., Phys. Rev. Lett. **92**, 220402 (2004)

Scalable push-button generation of GHZ states

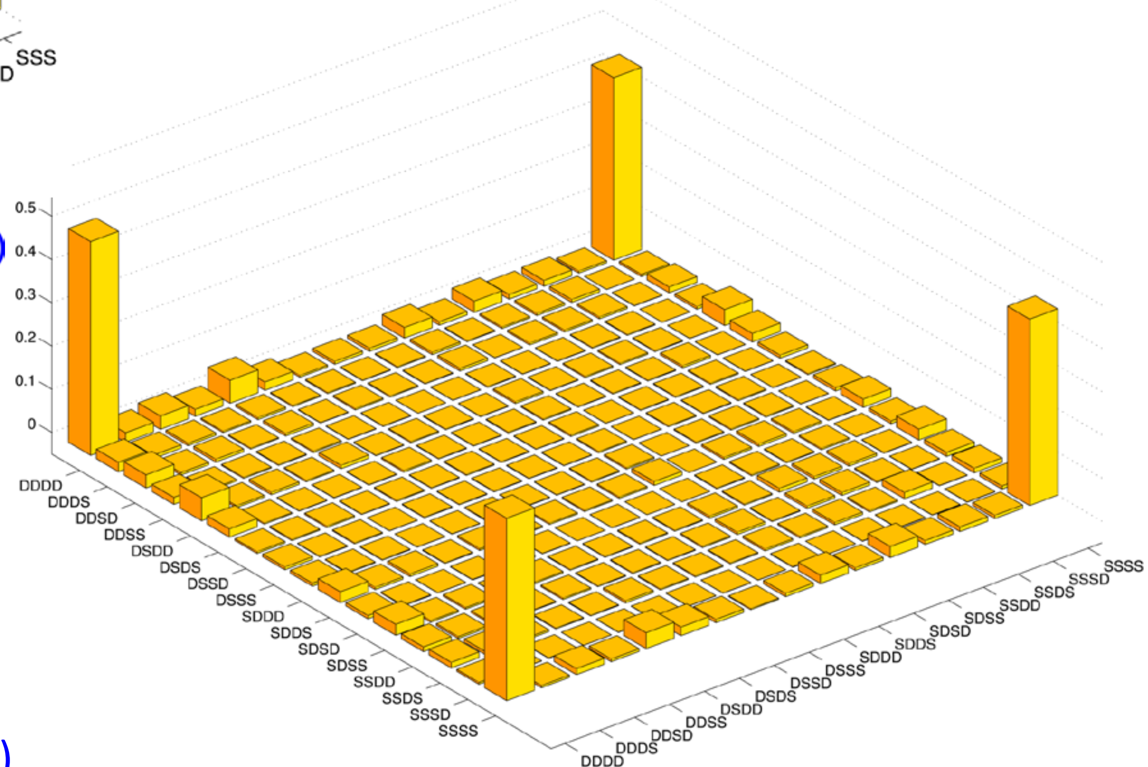
$$|\Psi\rangle_{\mathrm{GHZ}_4} = \frac{1}{\sqrt{2}}(|SSSS\rangle + |DDDD\rangle)$$

Fidelity

$$F_{\mathrm{GHZ}_4} = 88(1)\%$$



$$|\Psi\rangle_{\mathrm{GHZ}_3} = \frac{1}{\sqrt{2}}(|SSS\rangle + |DDD\rangle)$$



Fidelity

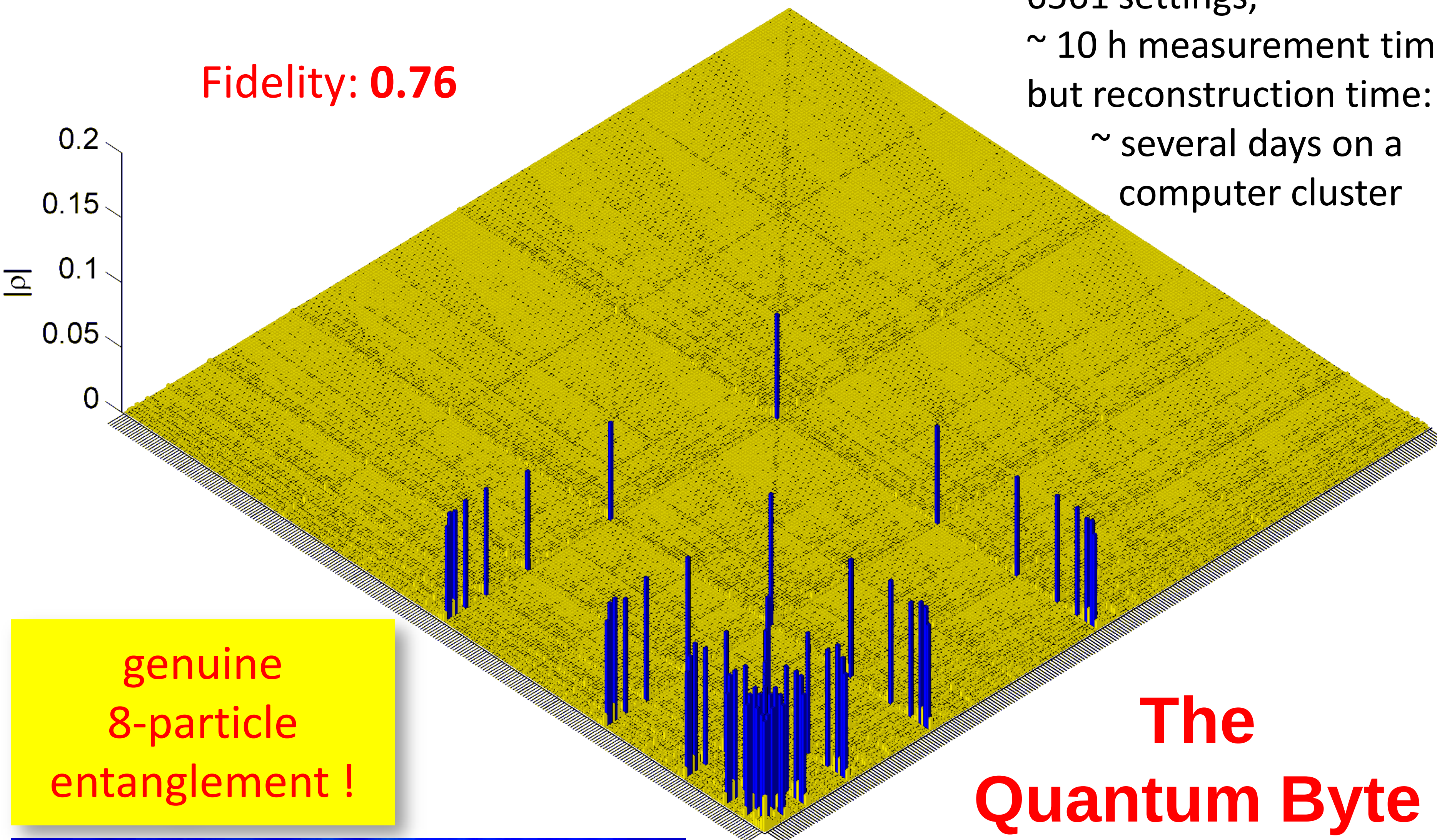
$$F_{\mathrm{GHZ}_3} = 89(1)\%$$

C. Roos et al., Science **304**, 1478 (2004)

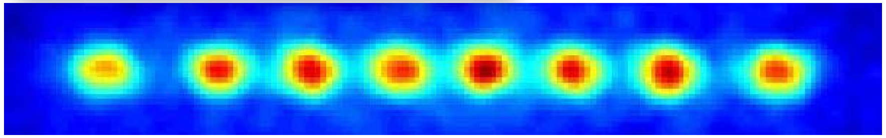
Eight – Ion W-state

6561 settings,
~ 10 h measurement time,
but reconstruction time:
~ several days on a computer cluster

Fidelity: **0.76**



genuine 8-particle entanglement !



The Quantum Byte

H. Häffner et al., Nature **438**, 643 (2005)

Quantum procedures and fidelities

▶ single qubit operations	$\vert\psi\rangle = \alpha\vert g\rangle + \beta\vert e\rangle$	> 99 %
▶ 2-qubit CNOT gate	$\vert\varepsilon_1\rangle\vert\varepsilon_2\rangle \rightarrow \vert\varepsilon_1\rangle\vert\varepsilon_1 \oplus \varepsilon_2\rangle$	~ 93 %
▶ Bell states	$\Psi_- = \frac{1}{\sqrt{2}}(\vert SD\rangle - \vert DS\rangle)$	93-95 %
▶ W and GHZ states	$\vert\psi\rangle_{GHZ} = \vert SSS + DDD\rangle$	85-90 %
▶ Quantum teleportation	$\vert\Psi\rangle_A \longrightarrow \vert\Psi\rangle_B$	83 %
▶ Entanglement swapping	$\vert Bell\rangle_{ab}, \vert Bell\rangle_{cd} \longrightarrow \vert Bell\rangle_{ad,bc}$	~ 80 %
▶ Toffoli gate operation	$\vert a\rangle\vert b\rangle\vert c\rangle \rightarrow \vert a\rangle\vert b\rangle\vert c \oplus ab\rangle$	71 %

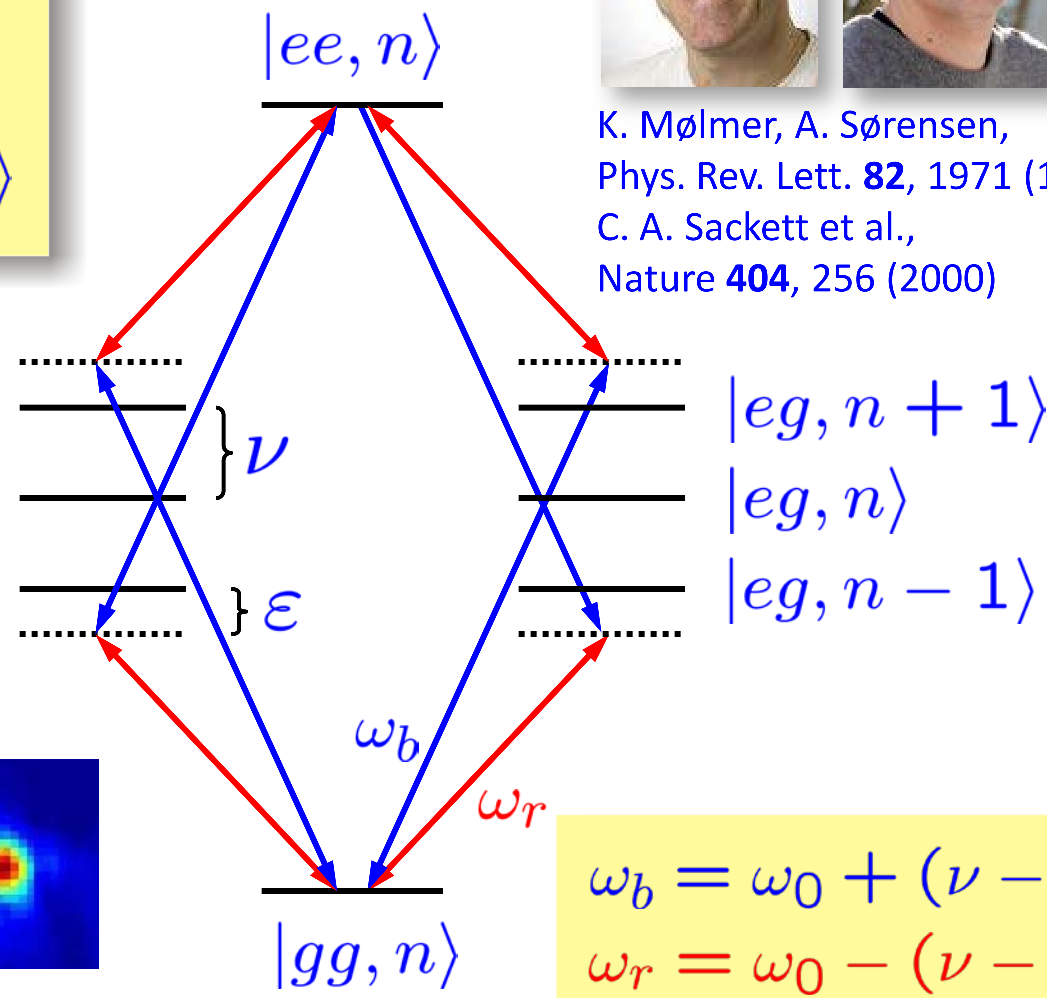
BUT: for fault-tolerant operation needed > 99 % !

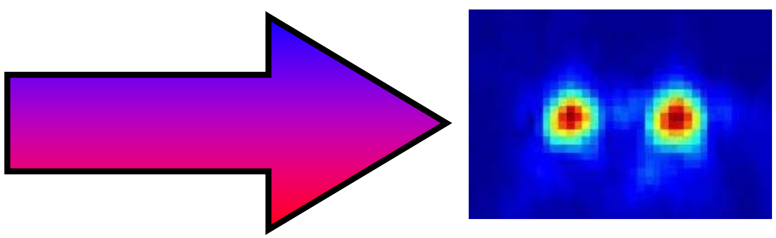
Mølmer – Sørensen gate operation

bichromatic laser excitation close to upper and lower sidebands induces collective state changes (spin flips)

$$|gg\rangle \rightarrow |ee\rangle, \quad |ge\rangle \rightarrow |eg\rangle$$

K. Mølmer, A. Sørensen,
Phys. Rev. Lett. **82**, 1971 (1999)
C. A. Sackett et al.,
Nature **404**, 256 (2000)





$$\omega_b = \omega_0 + (\nu - \varepsilon)$$
$$\omega_r = \omega_0 - (\nu - \varepsilon)$$

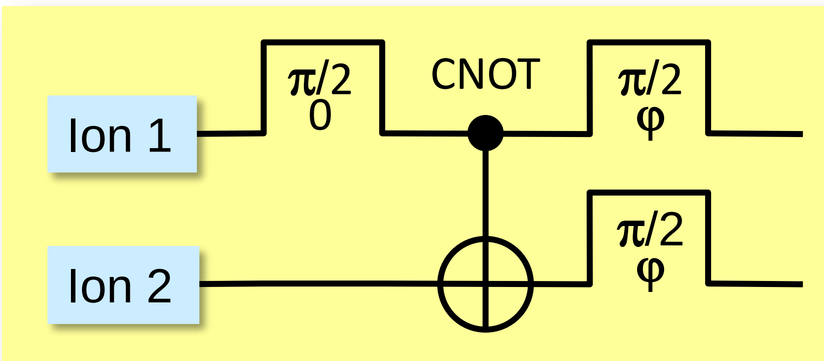
Measuring entanglement

C. A. Sackett et al., Nature **404**, 256 (2000)

entangling operation: $|SS\rangle \longrightarrow |SS \pm DD\rangle$ correlates states

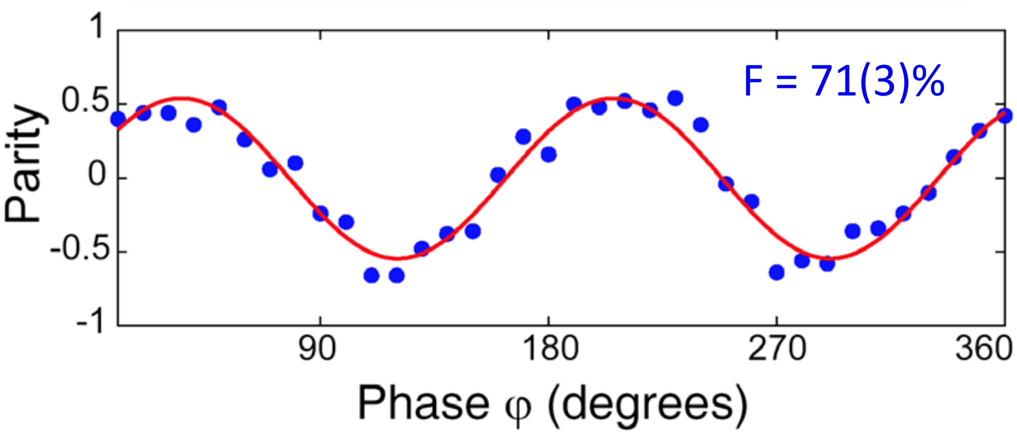
parity Π witnesses entanglement:

Π oscillates with 2φ !



$$\Pi = \sum_{j=0}^{2} (-1)^j P_j$$

$P_0 \equiv P_{DD}, P_1 \equiv P_{SD,DS}, P_2 \equiv P_{SS}$

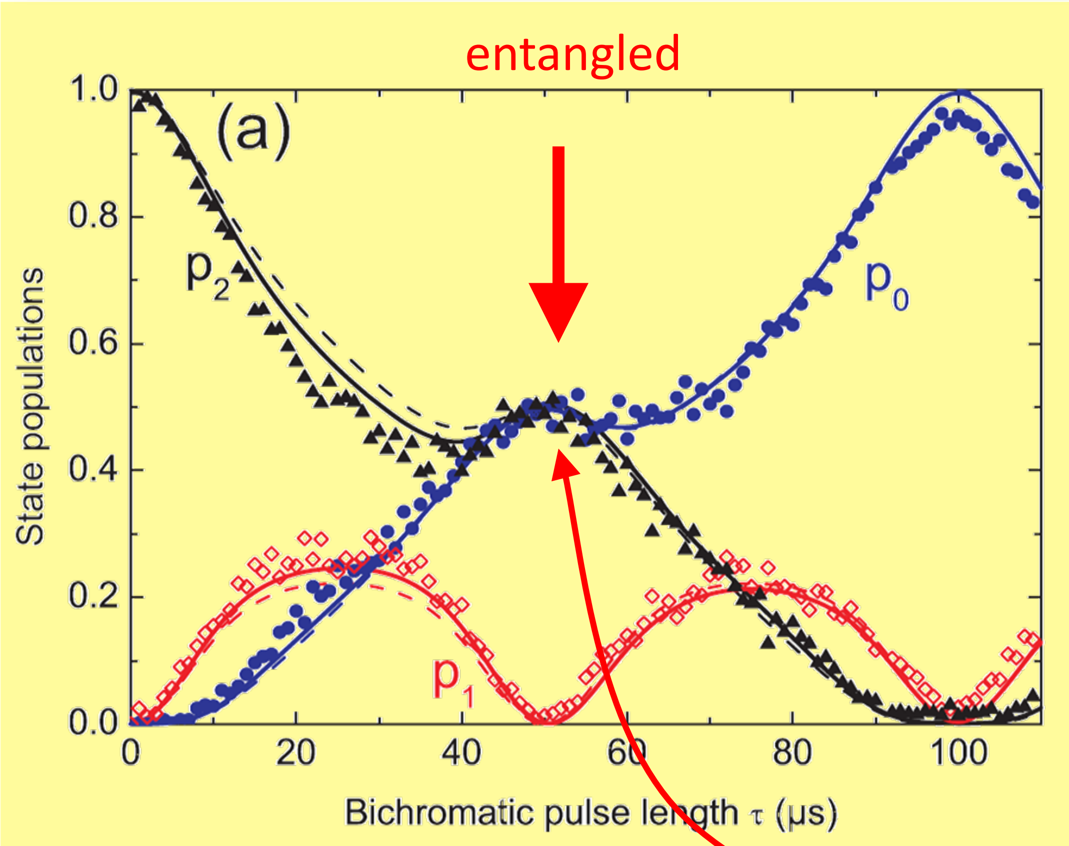


Fidelity =

0.5 (P_{SS}+P_{DD}+visibility)

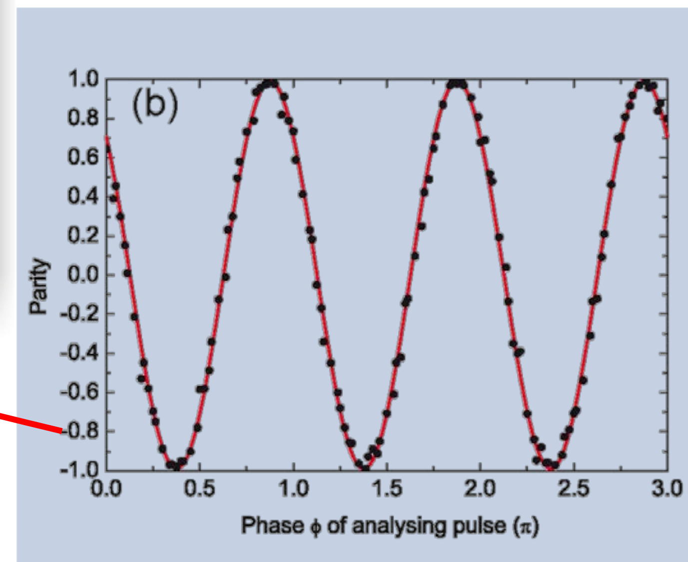
F. Schmidt-Kaler et al., Nature **422**, 408 (2003)

Deterministic Bell states using the Mølmer-Sørensen gate



J. Benhelm, G. Kirchmair, C. Roos
Theory: C. Roos,
New Journ. of Physics **10,** 013002 (2008)

measure entanglement via parity oscillations



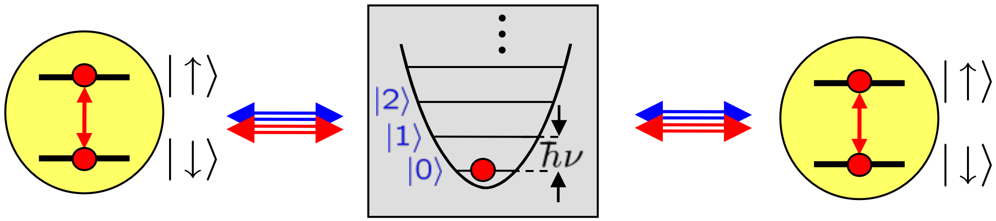
gate duration $51\mu s$

average fidelity

$$F_{\mathrm{MS}} = 99.3(0.2)\%$$

Entangling gates with more than two ions

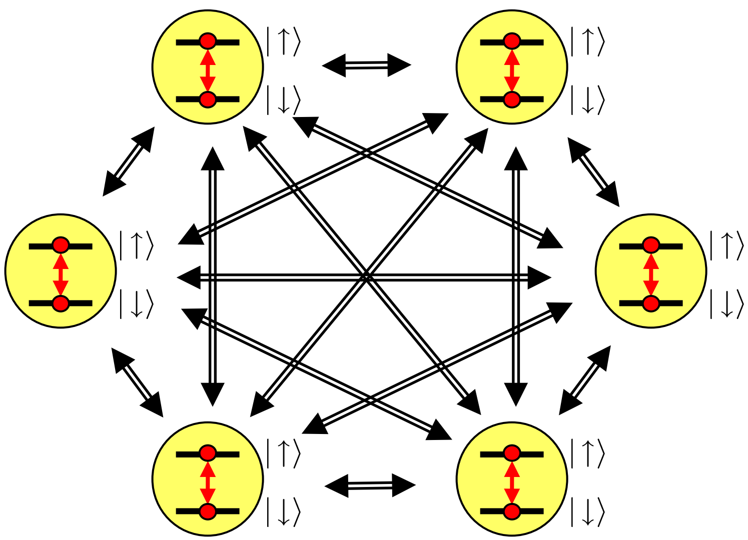
Two-body interaction by off-resonant spin-motion coupling



Effective spin-spin interaction

$$H_{\mathrm{eff}} \propto \sigma_x^{(1)} \sigma_x^{(2)}$$

Many ions:



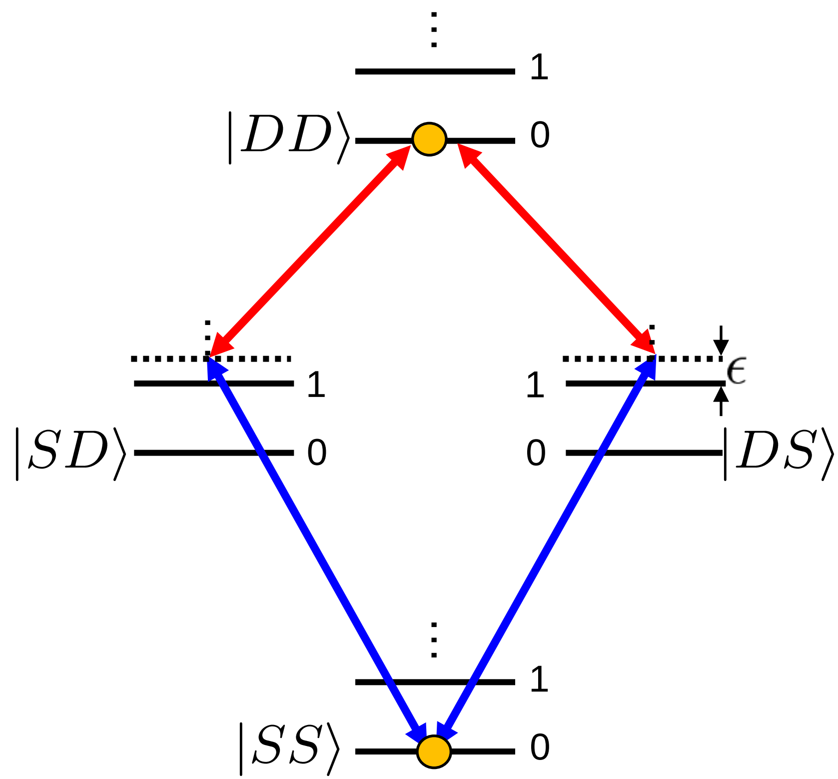
$$H_{\mathrm{eff}} \propto \sum_{i \neq j} \sigma_x^{(i)} \sigma_x^{(j)}$$

→ Creation of GHZ states

C. Roos, New J. Phys. **10,** 013002 (2008), J. Benhelm et al., Nature Phys. **4**, 463 (2008)

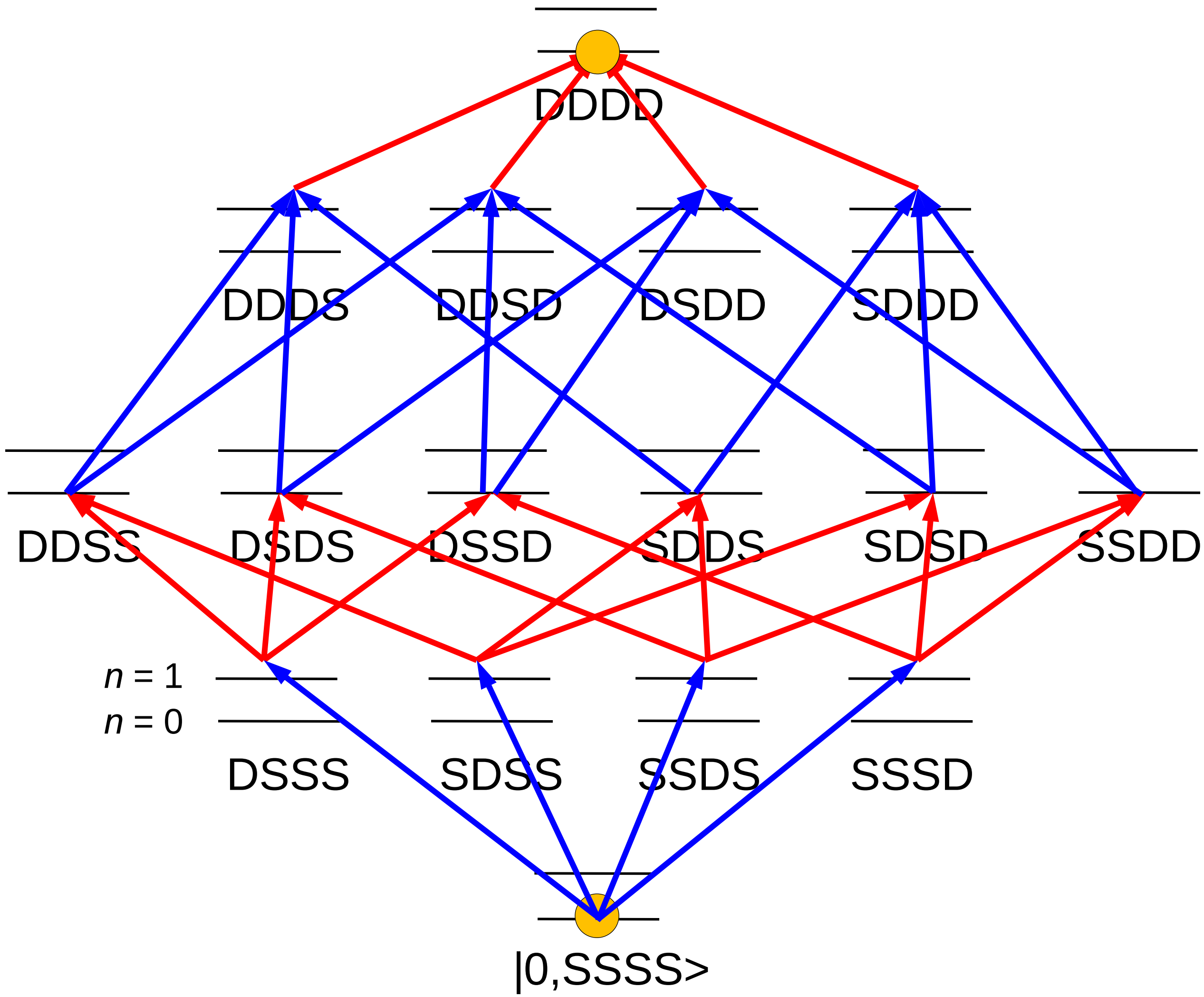
Mølmer-Sørensen gate with two ions: Bell states

A. Sørensen, K. Mølmer, PRL **82**, 1971 (1999)



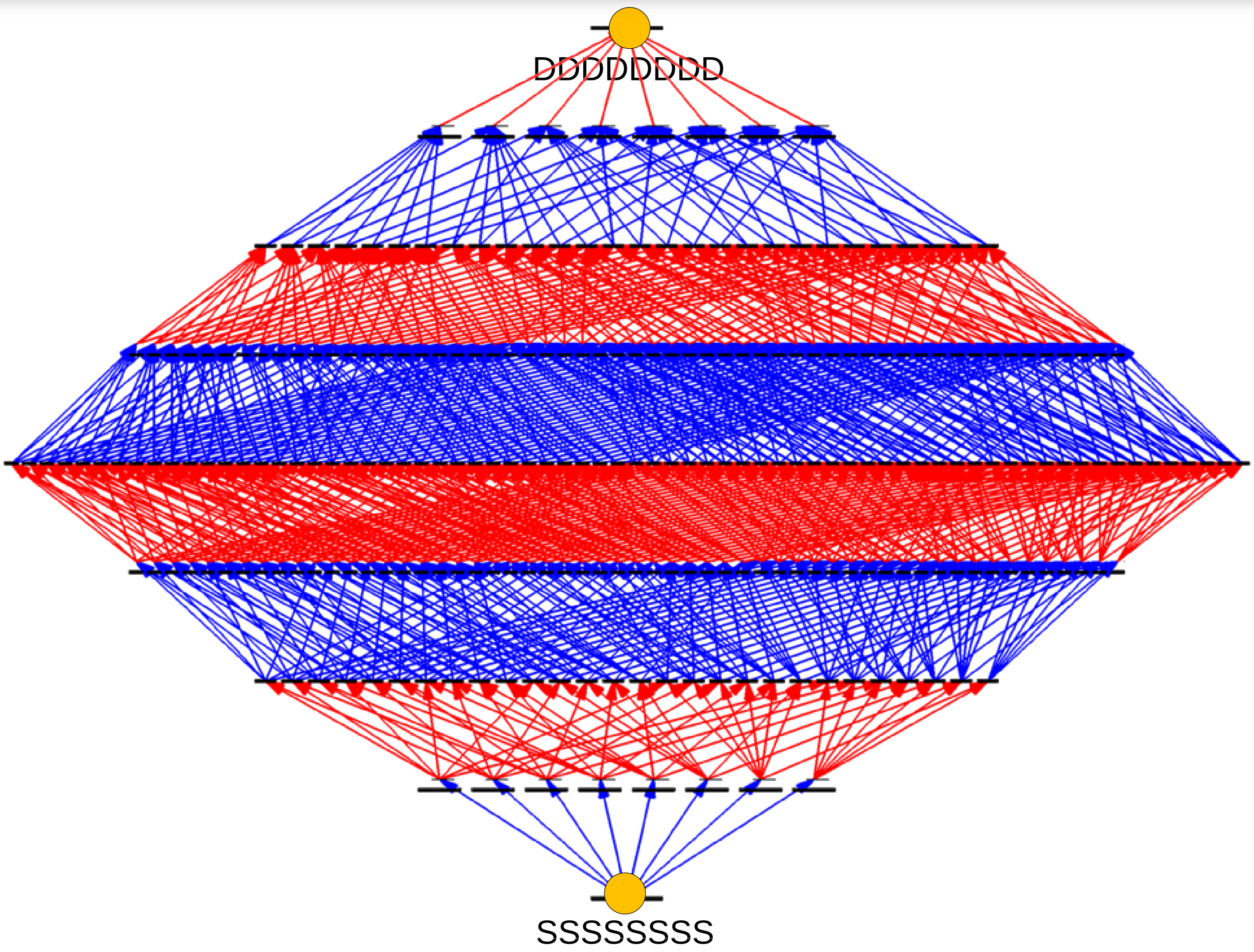
$$|SS\rangle \longrightarrow (|SS\rangle + i|DD\rangle)/\sqrt{2}$$

Creating GHZ-states with 4 ions



$$|SSSS\rangle \longrightarrow (|SSSS\rangle + |DDDD\rangle)/\sqrt{2}$$

Creating GHZ-states with 8 ions

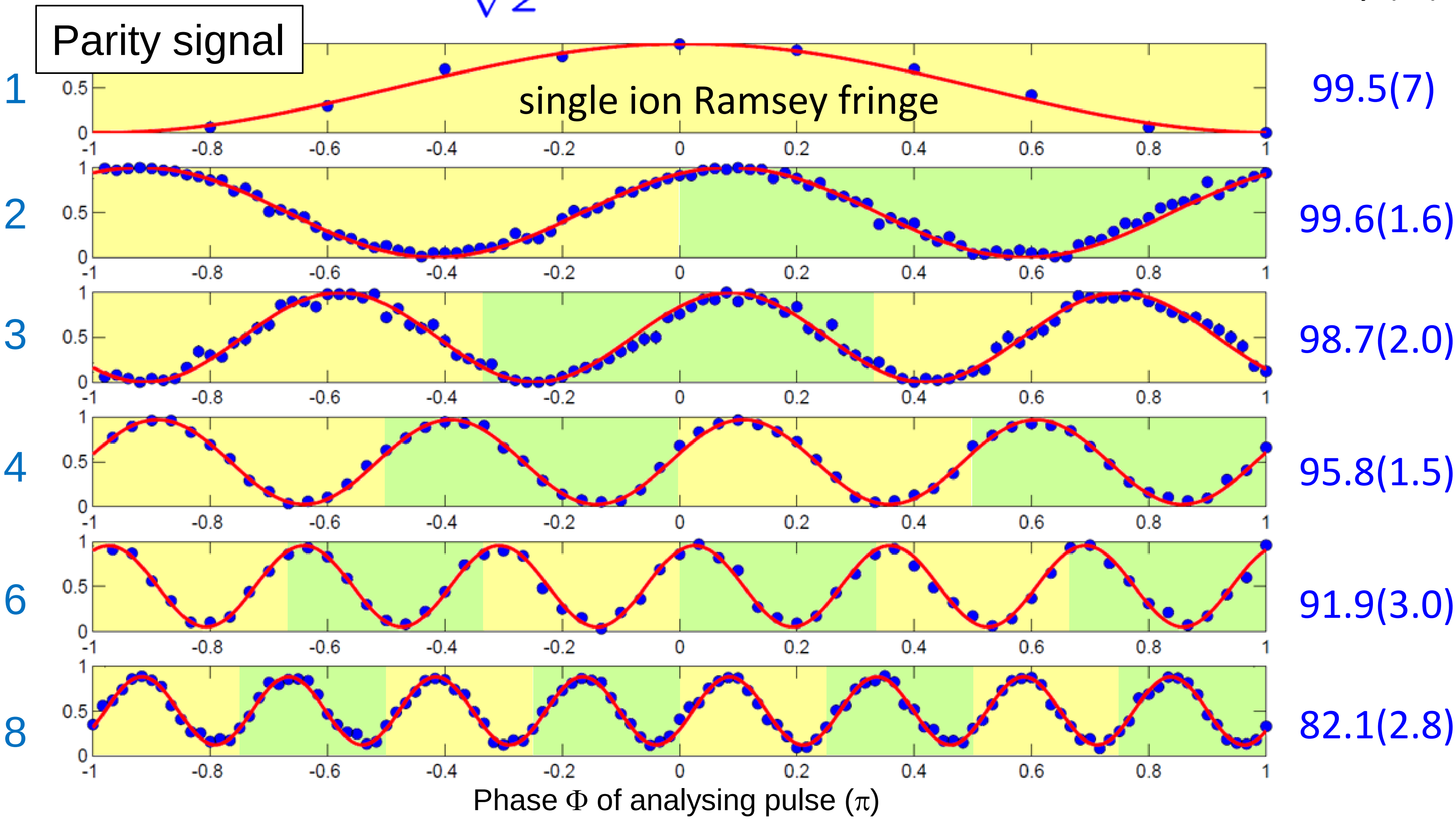


$$|SSSSSSSS\rangle \longrightarrow (|SSSSSSSS\rangle + |DDDDDDDD\rangle)/\sqrt{2}$$

n - qubit GHZ state generation with global MS gates

$n =$

$$\Psi = \frac{1}{\sqrt{2}}(|gg\ldots g\rangle + |ee\ldots e\rangle)$$



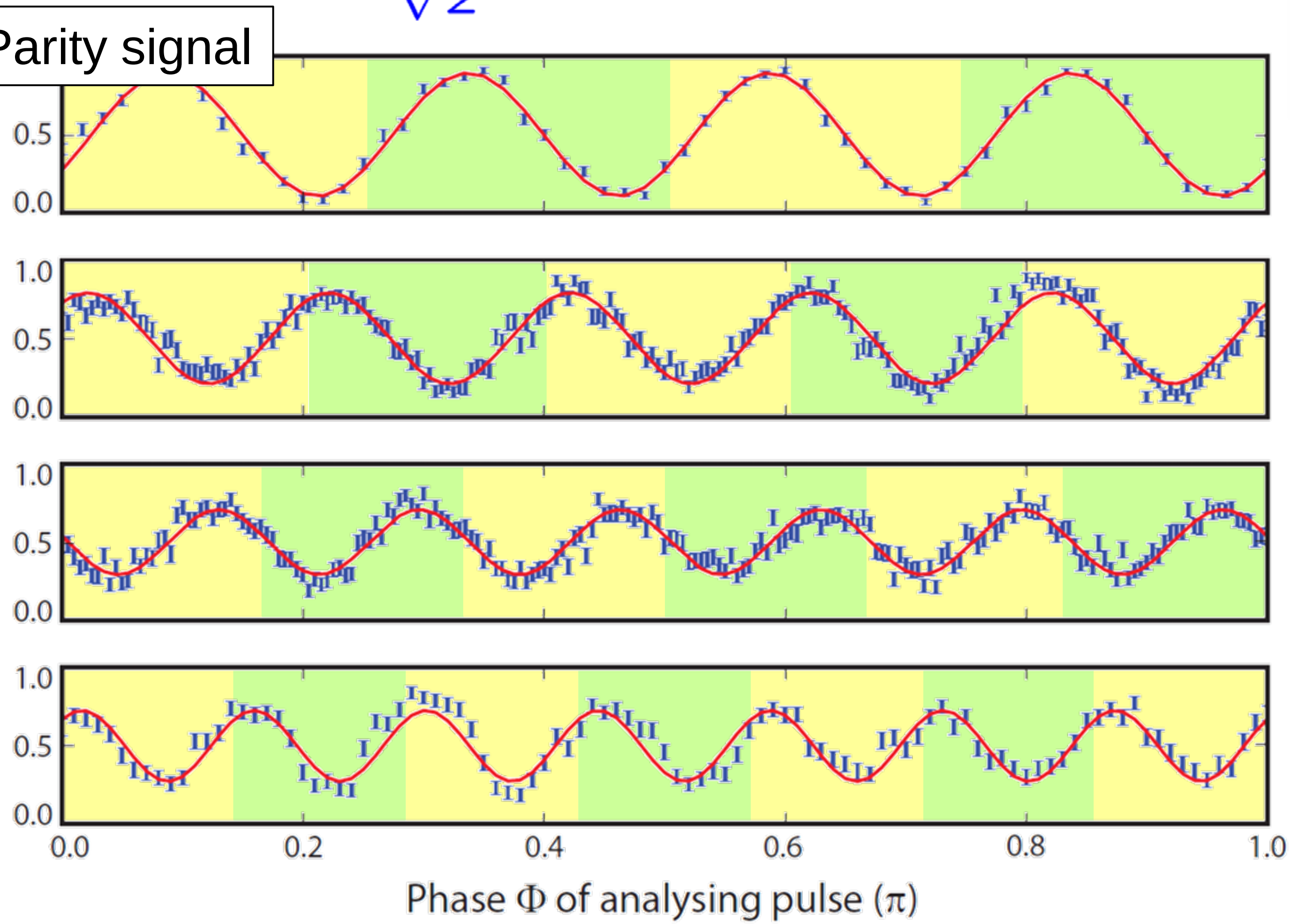
T. Monz, P. Schindler, J. Barreiro et al., Phys. Rev. Lett. **106**, 130506 (2011)

n - qubit GHZ state generation with global MS gates

$N =$

$$\Psi = \frac{1}{\sqrt{2}}(|gg\ldots g\rangle + |ee\ldots e\rangle)$$

genuine
N-particle
Entanglement
by

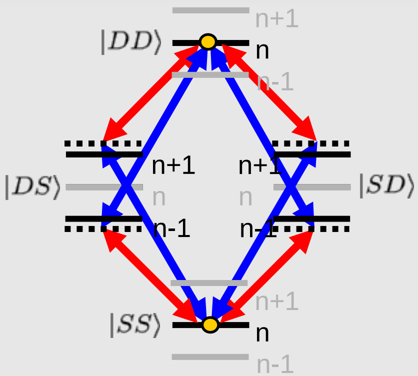


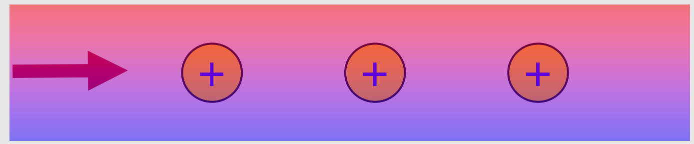
N	
8	96σ
10	40σ
12	18σ
14	17σ

W. Dür, I. Cirac
J. Phys A 34,
6837, (2001)

T. Monz, P. Schindler, J. Barreiro et al., Phys. Rev. Lett. **106**, 130506 (2011)

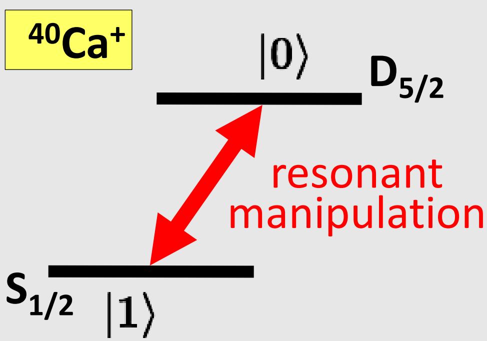
Quantum computing with global and local operations

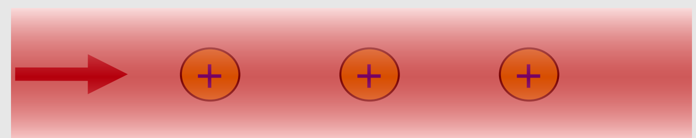




$$S^2_{x,y}(\theta)$$

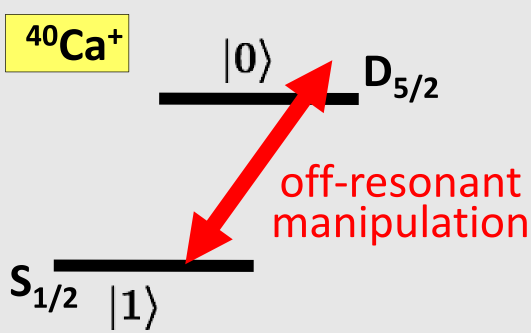
Bichromatic excitation: entangling operations

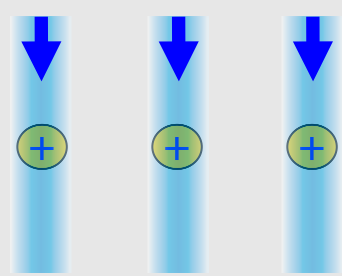




$$S_{x,y}(\theta)$$

Resonant excitation: collective local operations

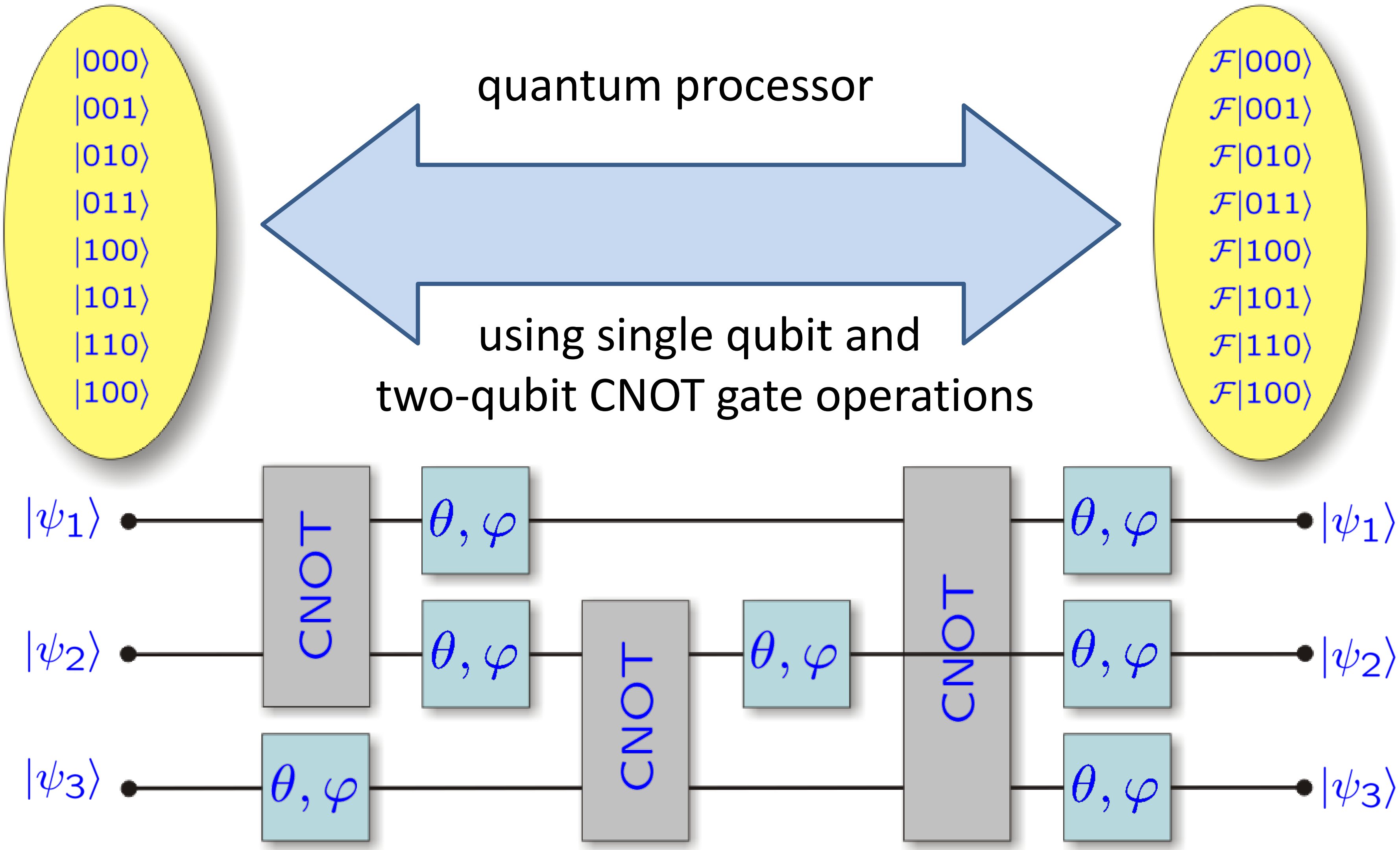




off-resonant excitation:
individual local operations
(AC Stark shifts)

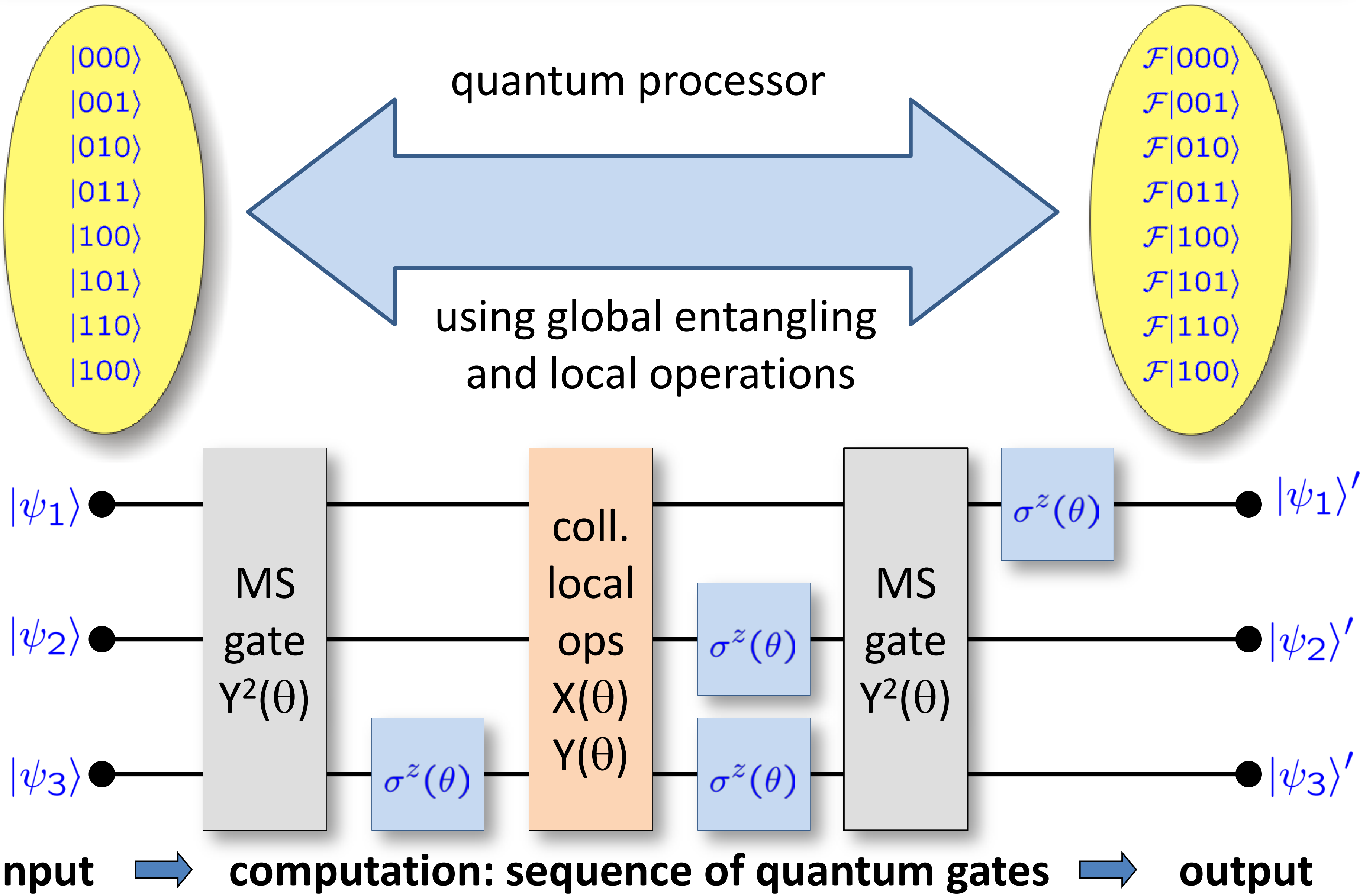
$$\sigma_z^{(i)}(\theta)$$

Quantum information processing with CNOT gate ops.

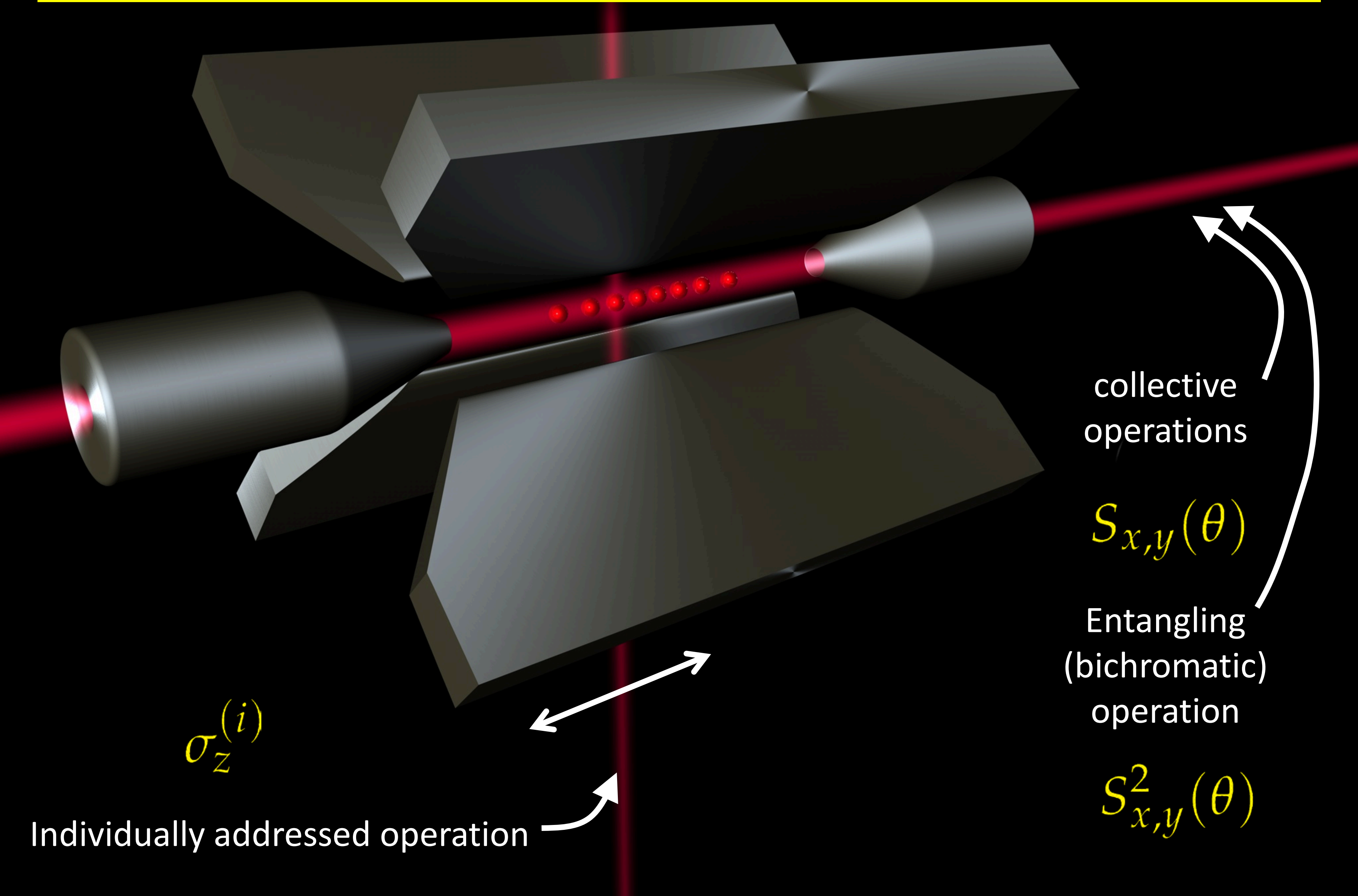


Input ➡ computation: sequence of quantum gates ➡ output

Quantum computation with global and local operations



Laser-ion interactions: Geometry



An optimizing compiler for quantum code

N ions

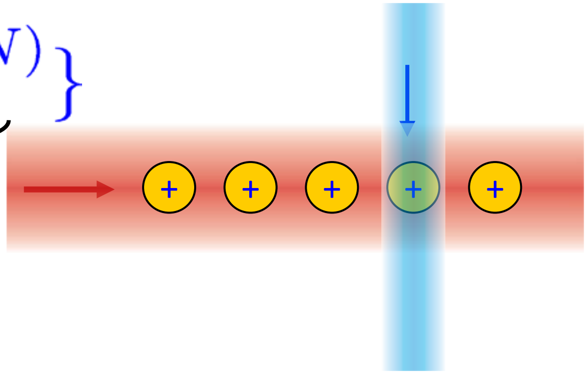
Basic set of operations:

$$H_i \in \{S^2_{x,y}, S_{x,y}, \underbrace{\sigma_z^{(1)}, \sigma_z^{(2)} \ldots \sigma_z^{(N)}}\}$$

Mølmer-Sørensen gate

collective spin flips

individual light shift gates



Optimal control

Quantum optimal control:

$$H(t) = \sum_{k=1}^{n} \alpha_k(t) H_k$$

V. Nebendahl et al., Phys. Rev. A **79**, 012312 (2009)

Find $\{\alpha_k(t), k = 1 \ldots n\}$ such that $U_{gate} \stackrel{!}{=} \mathcal{T} \int_0^{T} dt\, e^{-\frac{i}{\hbar} \sum_k \alpha_k(t) H_k}$

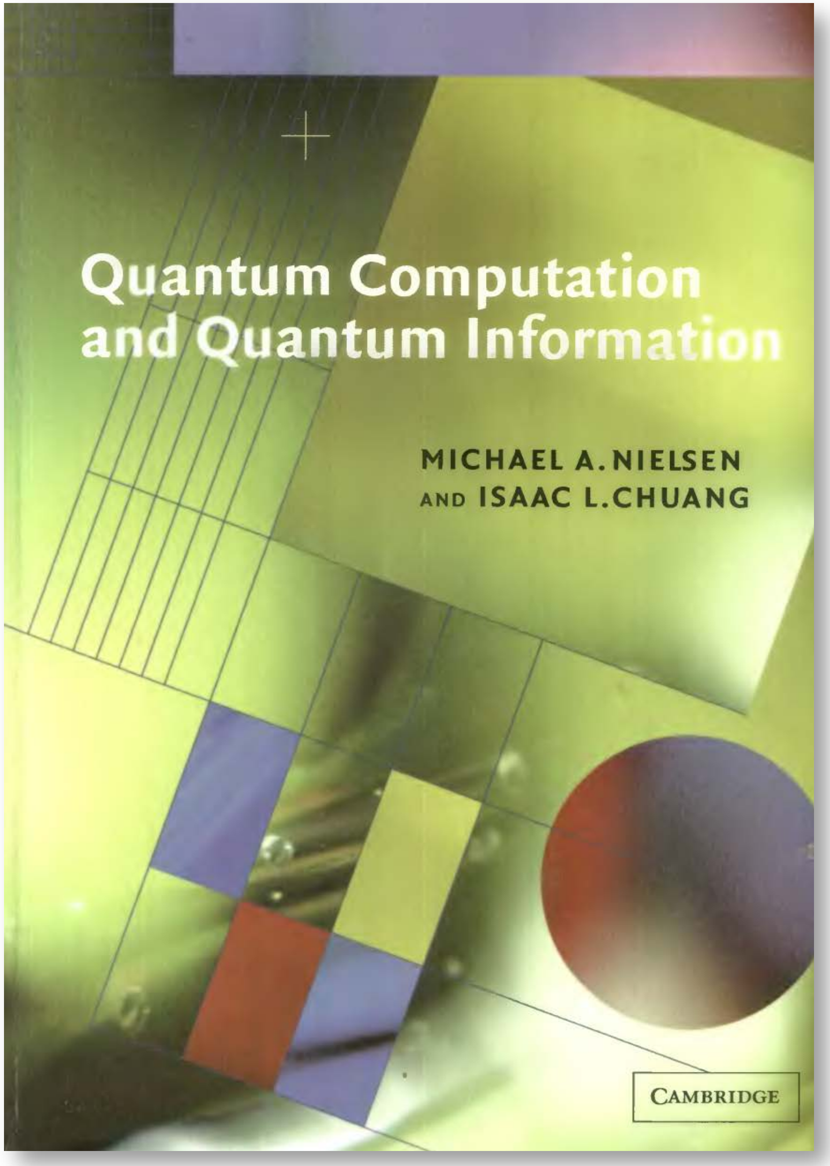
Gradient ascent algorithm:
(GRAPE - algorithm)

N. Khaneja *et al.*, J. Magn. Res. **172**, 296 (2005)

The Quantum Way of Doing Computations

Algorithms to implement:

- Grover algorithm
- Quantum Fourier Transform
- Phase estimation algorithm
- Shor algorithm
- Order finding
- Quantum error correction
- Analog quantum simulations
- Digital quantum simulations
- etc. ...



Analog quantum simulator

Goal

Simulate the physics of a quantum system of interest by another system that is easier to control and to measure.

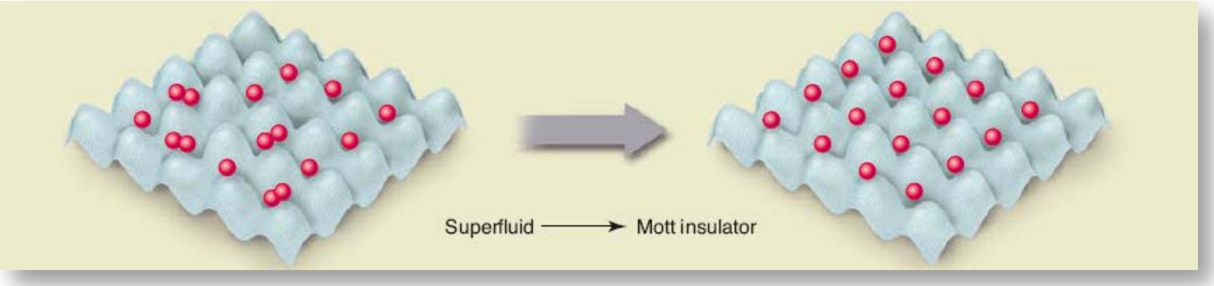
Approach

Engineer a Hamiltonian H_{sim} exactly matching the system Hamiltonian H_{sys}

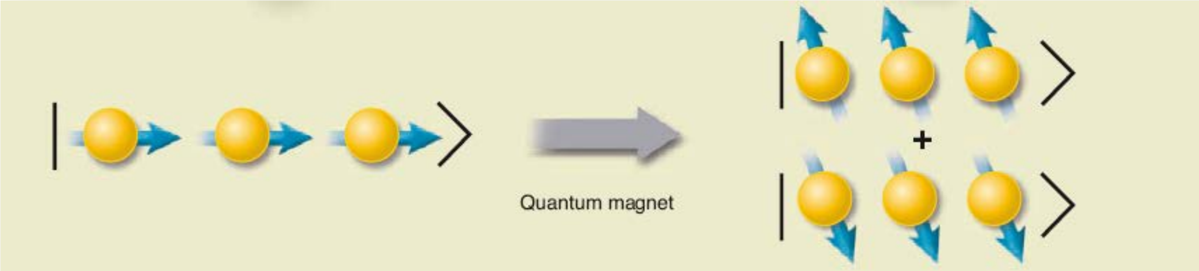
$$H_{\rm sim} \propto H_{\rm sys}(\lambda_1, \lambda_2, \ldots)$$

Examples:

- Ultracold atoms in optical lattices (MIT, Harvard, MPQ, NIST,...)

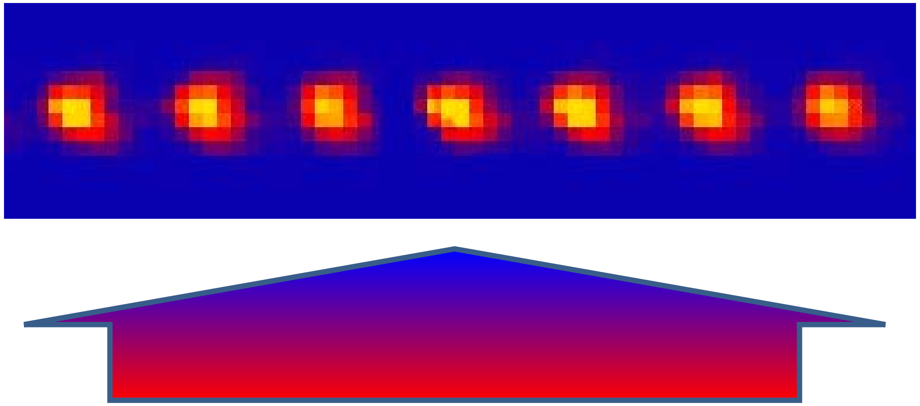


- Ion crystals (JQI, MPQ, IQOQI ...)



I. Buluta, F. Nori, Science **326**, 108 (2009)

Quantum simulations with spin chains



N ions interacting with a transverse bichromatic beam simulating the Hamiltonian

$$H_{Ising} = \hbar \sum_{i<j} J_{ij} \sigma_i^x \sigma_j^x + \hbar B \sum_i \sigma_i^z$$

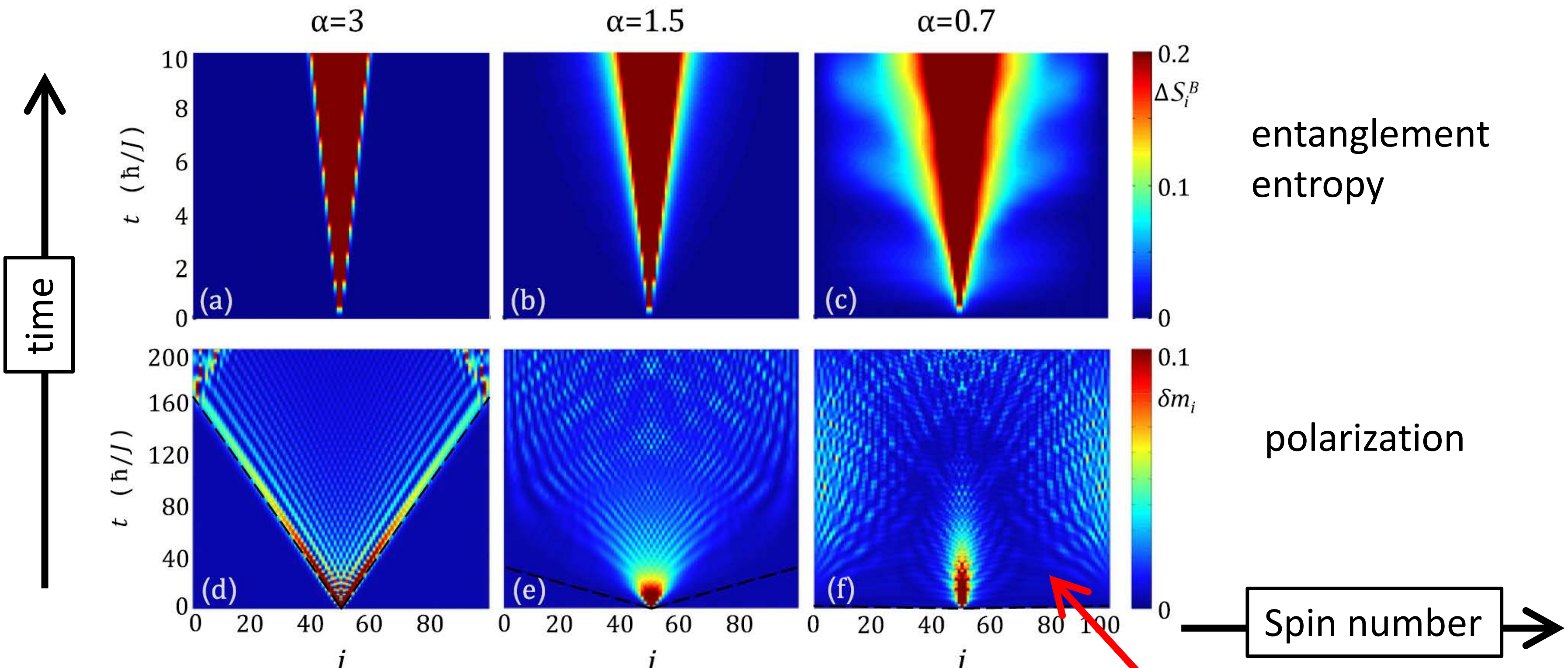
Coupling matrix J_{ij} has an approximate power law dependence with a tunable exponent α

$$J_{ij} \sim \frac{1}{|i-j|^\alpha} \begin{cases} \alpha = 0 & \text{infinite range interactions} \\ \alpha = 1 & \text{Coulomb interactions} \\ \vdots & \\ \alpha = 3 & \text{dipole-dipole interactions} \end{cases}$$

for $B \gg max(|J_{ij}|)$ hopping hardcore bosons $H_{XY} = \hbar \sum_{i<j} J_{ij} (\sigma_i^+ \sigma_j^- + \sigma_i^- \sigma_j^+)$

Spread of correlations in interacting quantum systems

P. Hauke, L. Tagliacozzo, Phys. Rev. Lett. **111**, 207202 (2013)



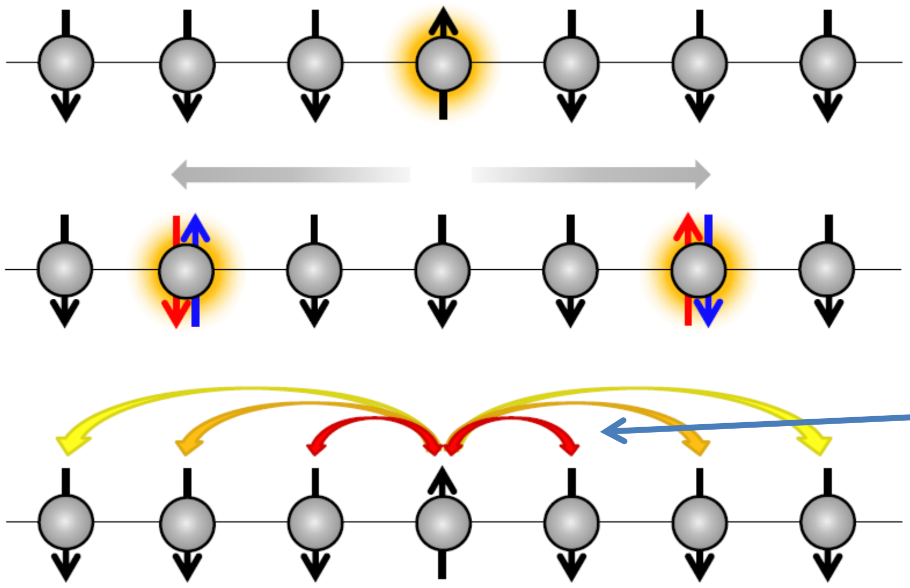
Short range
$\alpha > 2$
excitation spreads like a light-cone

$2 > \alpha > 1$
no well-defined wave front

Long range
$\alpha < 1$
excitation spreads fast over entire system

group velocity becomes large

Quantum simulations with spin chains



- prepare ground state,
- flip one spin (local quench),
- simulate interaction,
- measure quasiparticle dynamics

Interactions J_{ij} can be adjusted

K. Kim et al., PRL **103**, 120502 (2009)

$$J_{ij} = \Omega_i \Omega_j \frac{\hbar k^2}{2m} \sum_n \frac{\eta_{i,n}\, \eta_{j,n}}{\Delta^2 - \omega_n^2}$$

Ω_i Rabi frequency

$k = 2\pi/\lambda$ wavenumber

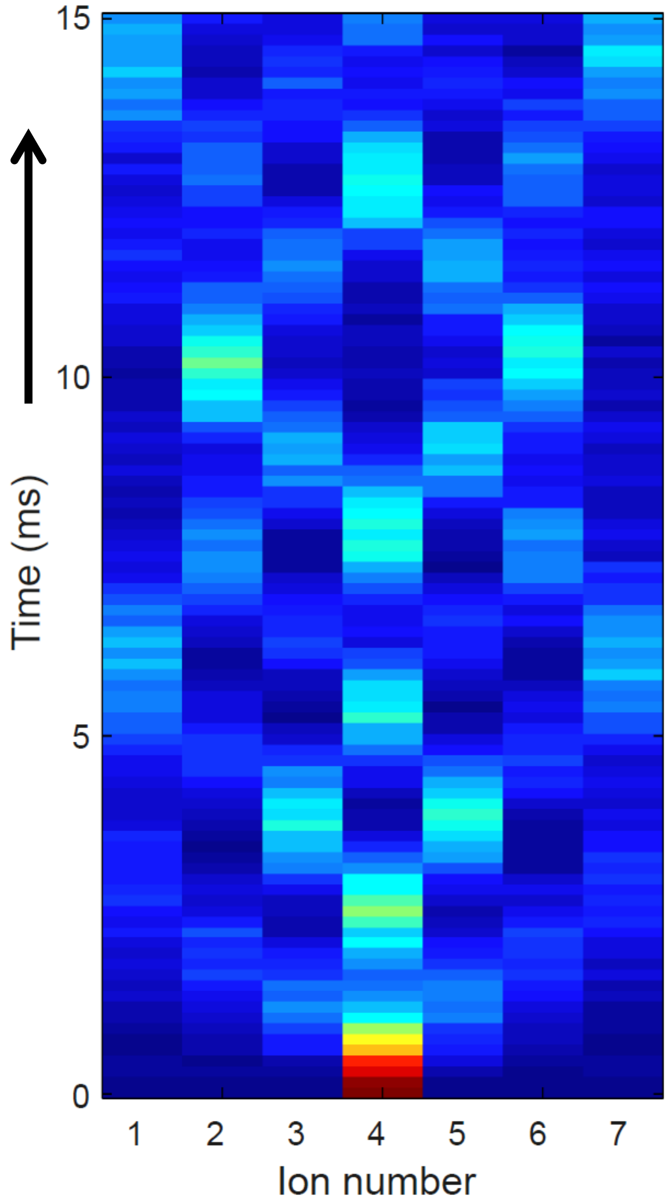
ω_n transverse mode frequency

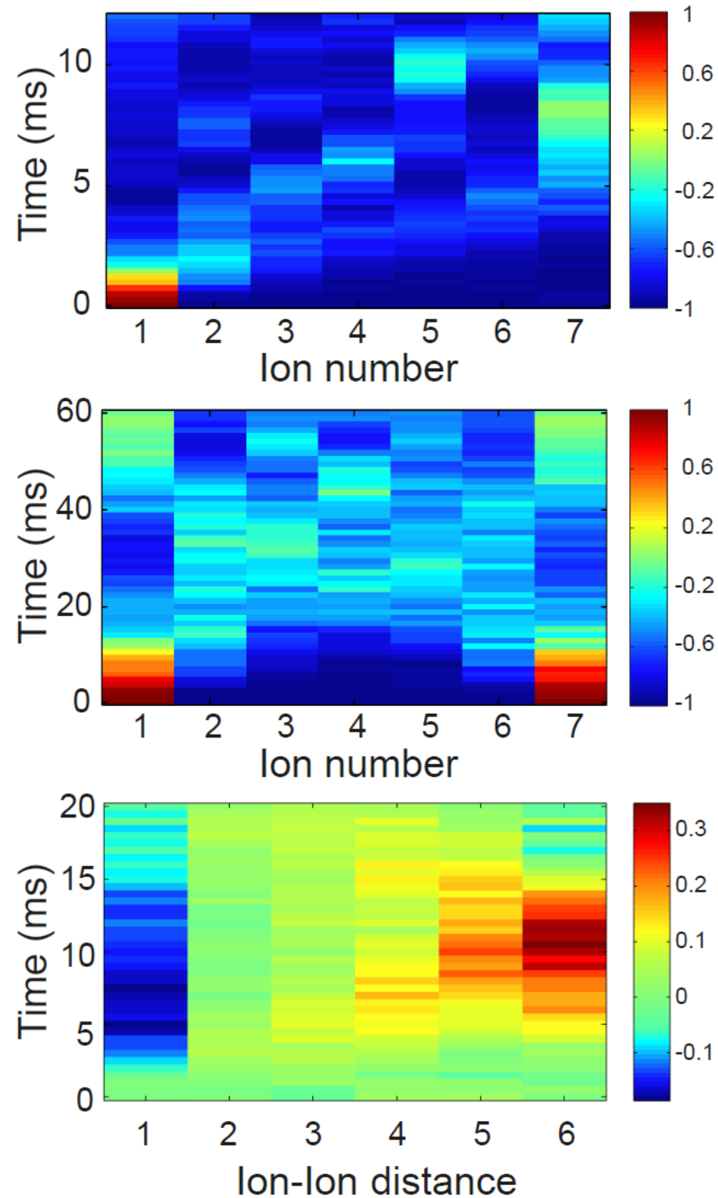
m Ion mass

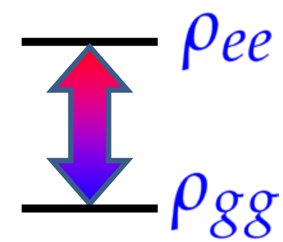
Δ detuning

$\eta_{i,n}$ Lamb-Dicke factor of ith ion in nth mode

Quasiparticle dynamics following quenches







local quench

global quench

correlation function

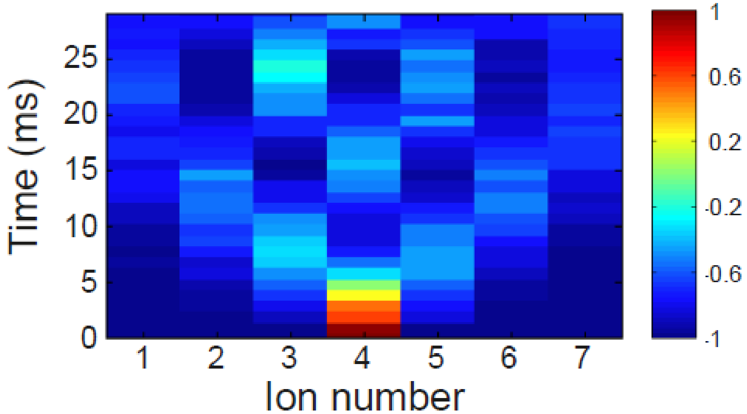
$$C_{ij} = \langle \sigma_i^z \sigma_j^z \rangle - \langle \sigma_i^z \rangle \langle \sigma_j^z \rangle$$

P. Richerme et al., Nature **511**, 198 (2014)

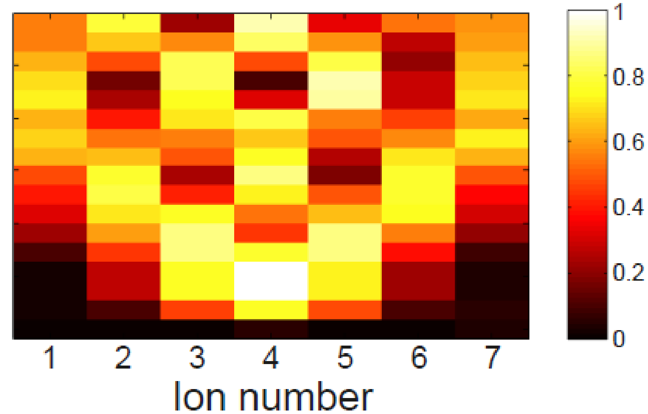
P. Jurcevic et al., Nature **511**, 202 (2014)

Entanglement distribution following a local quench

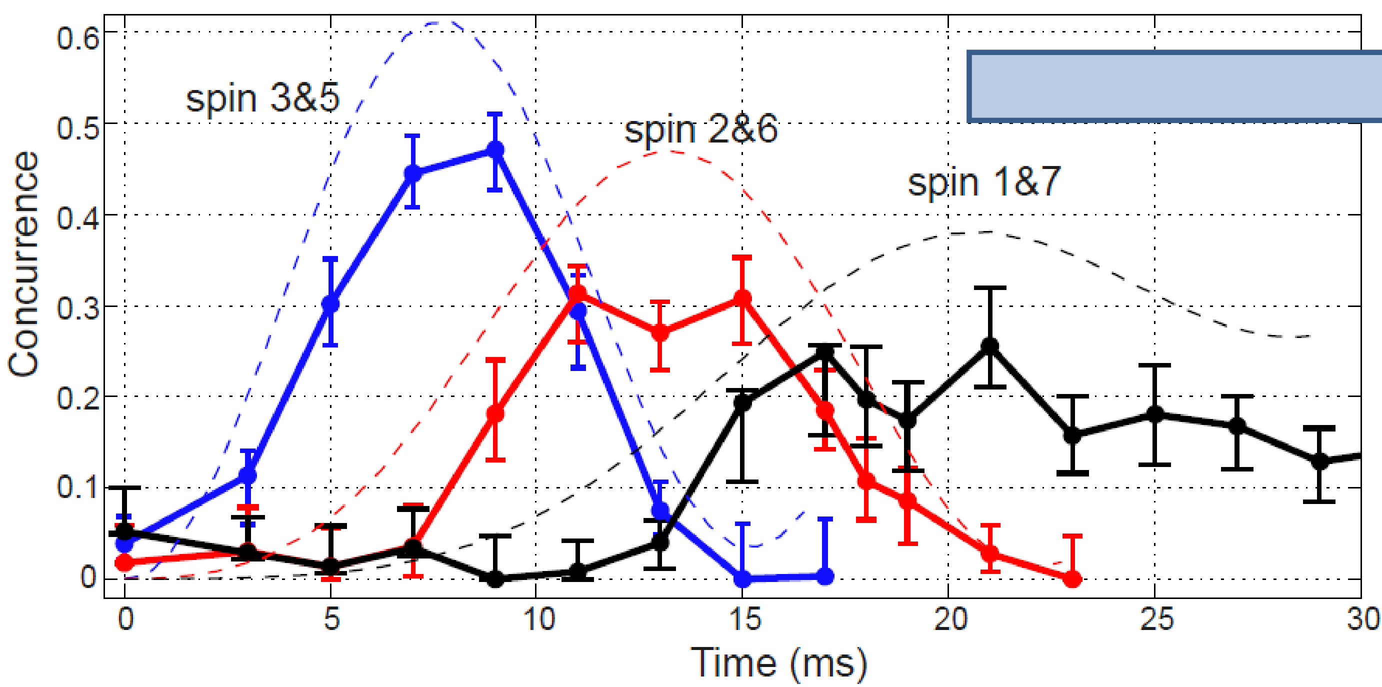
single-spin magnetization



entropy $Tr(\rho \log(\rho)) / \log(2)$



high-entropy states due to correlations with other spins

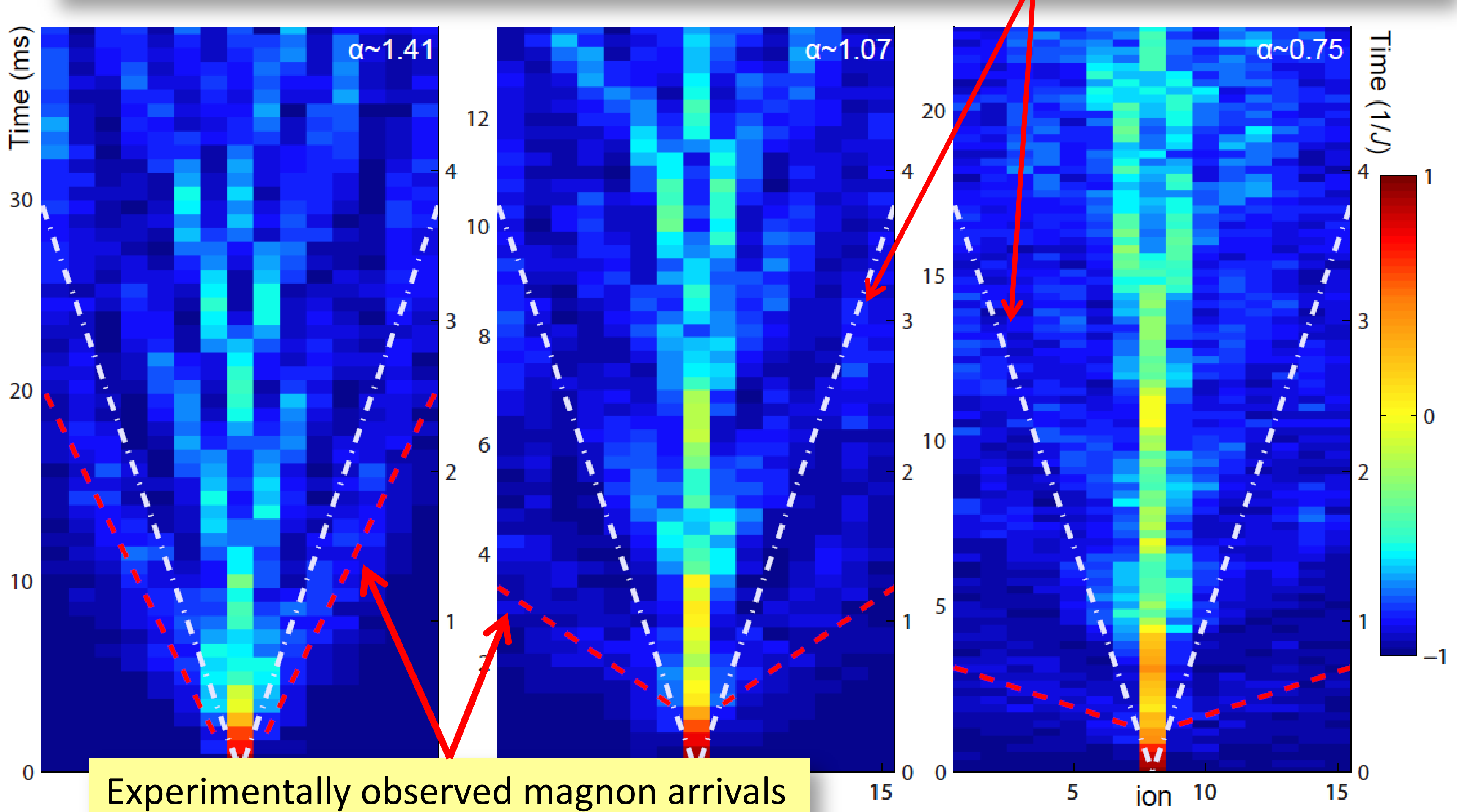


Spin-waves: propagation of entanglement

P. Jurcevic et al., Nature **511**, 202 (2014)

Break-down of the light-cone picture

With increasing interaction range($\alpha \to 0$) the spin waves propagate faster than what is allowed by the nearest-neighbour light-cone (**Lieb-Robinson** bound)



Increasing interaction range

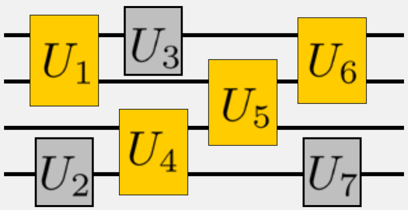
Digital Quantum Simulator

Goal

Simulate the physics of a quantum system of interest by another system that is easier to control and to measure.

Approach

Use a quantum computer as a quantum simulator



Decompose dynamics induced by system Hamiltonian into sequence of quantum gates

$$U_{\mathrm{sim}} = \prod_{j=1}^{N} U_j \qquad U_{\mathrm{sim}} \propto U_{\mathrm{sys}} \qquad U_{\mathrm{sys}} = e^{-\frac{i}{\hbar} H_{\mathrm{sys}} \tau}$$

Example:

$$H = H_1 + H_2 + \ldots + H_k$$

$$e^{-\frac{i}{\hbar} H t} = \left(e^{-\frac{i}{\hbar} H_1 t/n} e^{-\frac{i}{\hbar} H_2 t/n} \ldots e^{-\frac{i}{\hbar} H_k t/n} \right)^n$$

RB, C. Roos, Nature Physics **8**, 277 (2012)

Digital Simulation: Universal Quantum Simulator

$$H = \sum_k h_k$$ ← model of some local system to be simulated for a time t

0. have a universal set on 'encoding' degrees of freedom

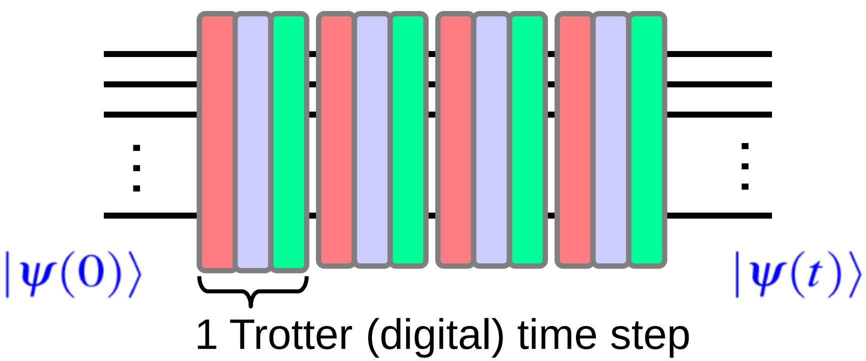
1. build each local evolution operator separately, for small time steps, using operation set

$$u_k = e^{-ih_k t/n}$$

2. approximate global evolution operator using the Trotter approximation

$$Et/h = \theta$$

$$U = e^{-iHt} \approx \left(e^{-ih_1 \frac{t}{n}} e^{-ih_2 \frac{t}{n}} e^{-ih_3 \frac{t}{n}} \ldots e^{-ih_k \frac{t}{n}} \right)^n$$



"Efficient for local quantum systems"

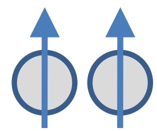
S. Lloyd,
Science **273**, 1073 (1996)

Proof-of-principle demonstration

B. Lanyon et al., Science **334**, 6052 (2011)

2-spin Ising system

$$H = J\sigma_x^1\sigma_x^2 + B(\sigma_z^1 + \sigma_z^2)$$



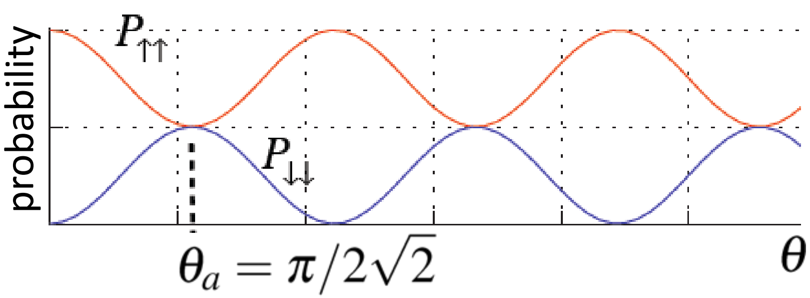
$$\tilde{H} = \sigma_x^1\sigma_x^2 + R(\sigma_z^1 + \sigma_z^2) \qquad R = B/J$$

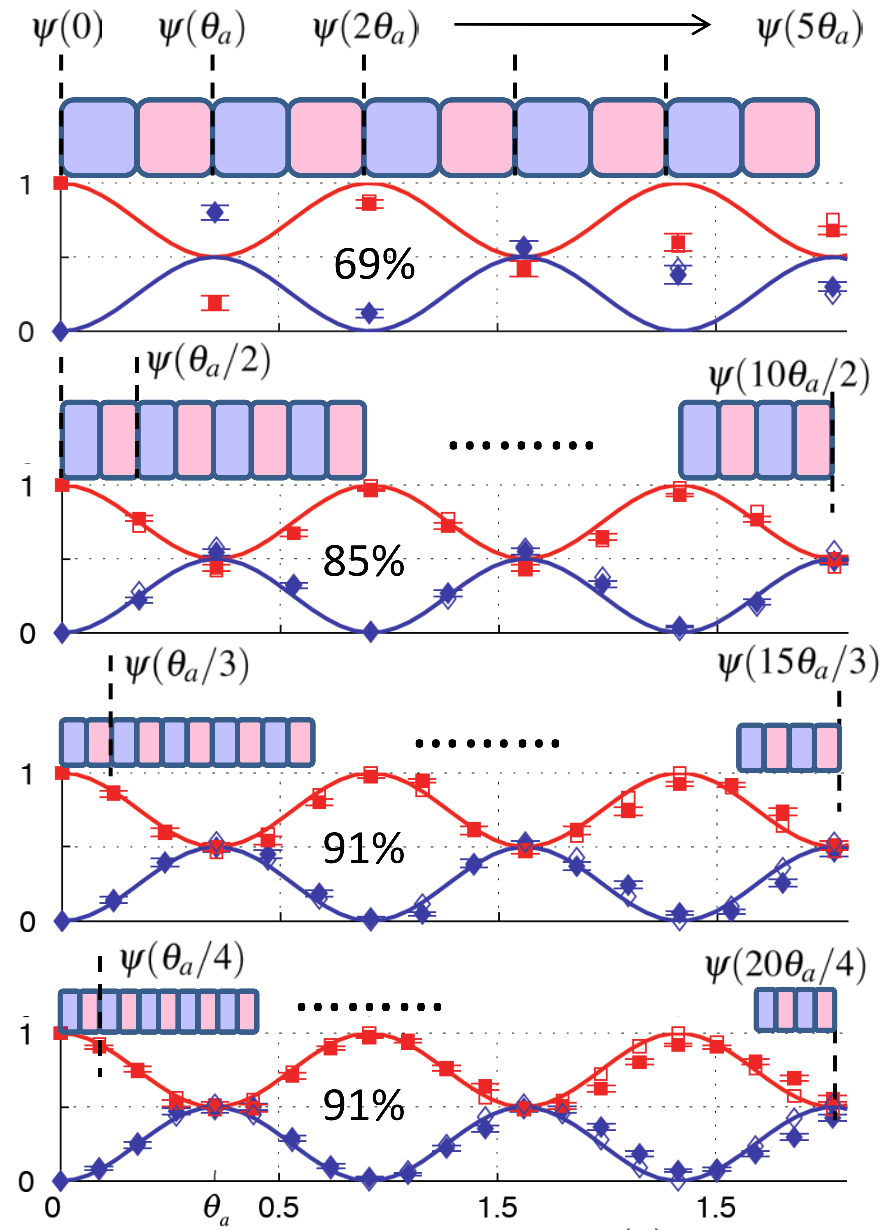
$$U(\theta) \simeq \left(e^{-i\sigma_x^j\sigma_x^k \frac{\theta}{n}} \, e^{-i\sum_j \sigma_z^j R \frac{\theta}{n}} \right)^n$$

Mølmer-Sørensen gate

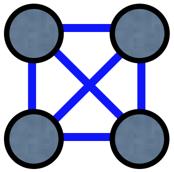
AC-Stark gate

dynamics to simulate: $e^{-iH\theta}|\uparrow\uparrow\rangle, \; R = 0.5$

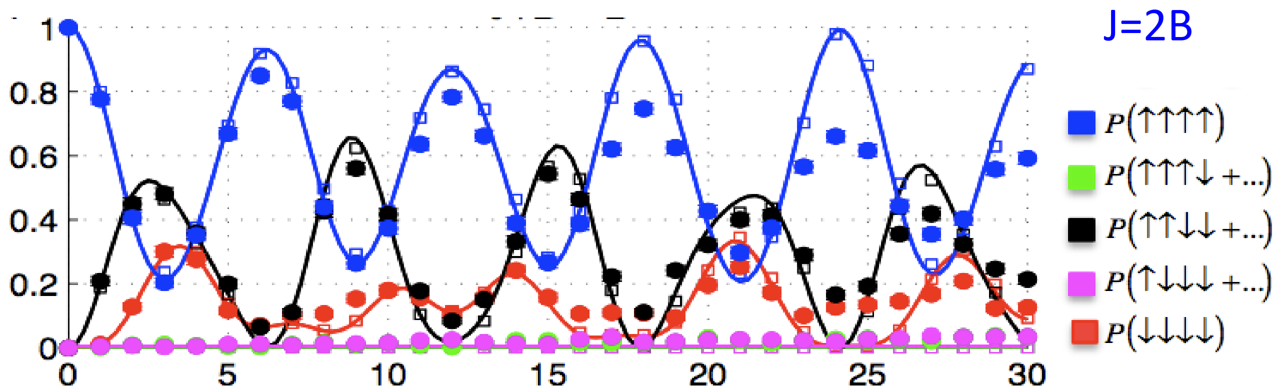




Outlook and future work



$$J\sum_{i\neq j}\sigma_x^i\sigma_x^j + B\sum_{i=1}^{n}\sigma_z^i$$



- **Time dependent dynamics** allows preparation of complex eigenstates, exploration of ground state properties and quantum phase changes

- **Frequencies tell you about spectrum:**
  Fourier transform the data and get the energy gaps in the simulated Hamiltonian

- **Energy eigenvalues could be extracted** by embedding into phase estimation algorithm

- **Current limiting source of error:**
  thought to be laser intensity fluctuations limiting possible simulation size and complexity

- **Inclusion of error correction and error protection**

Scaling the ion trap quantum computer ...

- more ions, larger traps, phonons carry quantum information

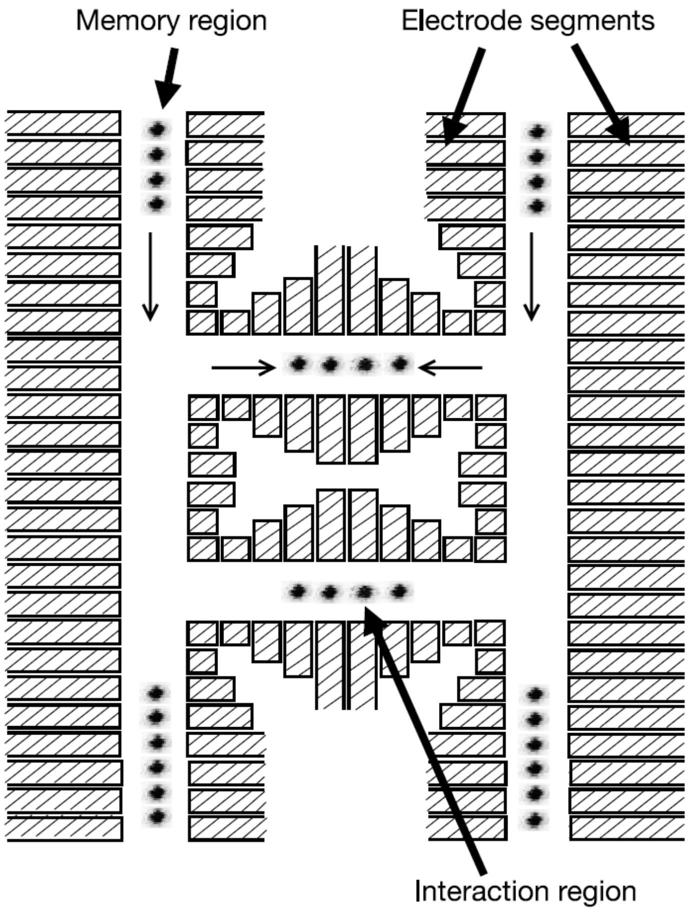
  Cirac-Zoller, slow for many ions (few 10 ions maybe possible)

- move ions, carry quantum information around

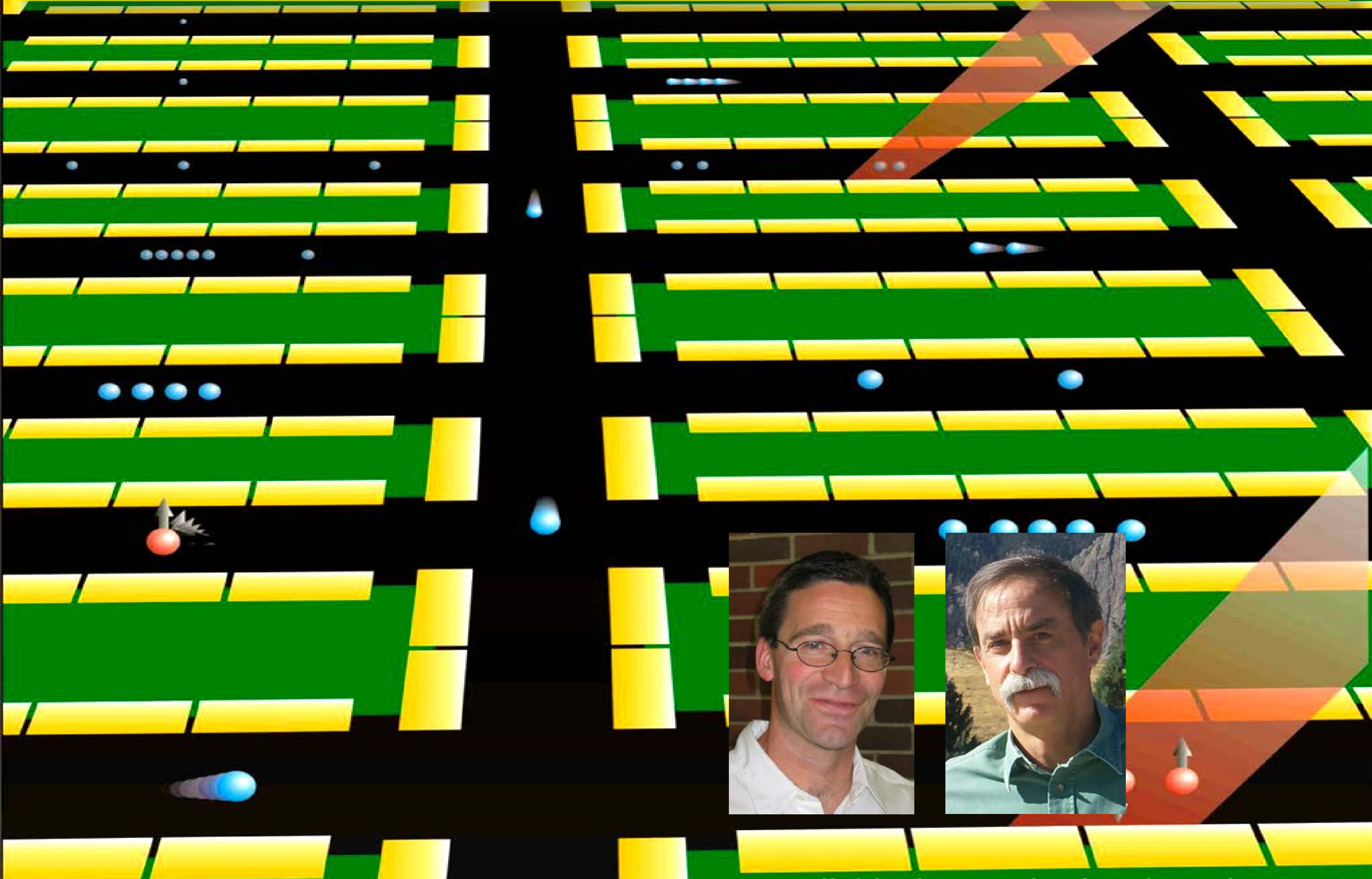
  Kielpinski et al.,
  Nature **417**, 709 (2002)

  requires small,
  integrated trap structures,

  miniaturized optics
  and electronics

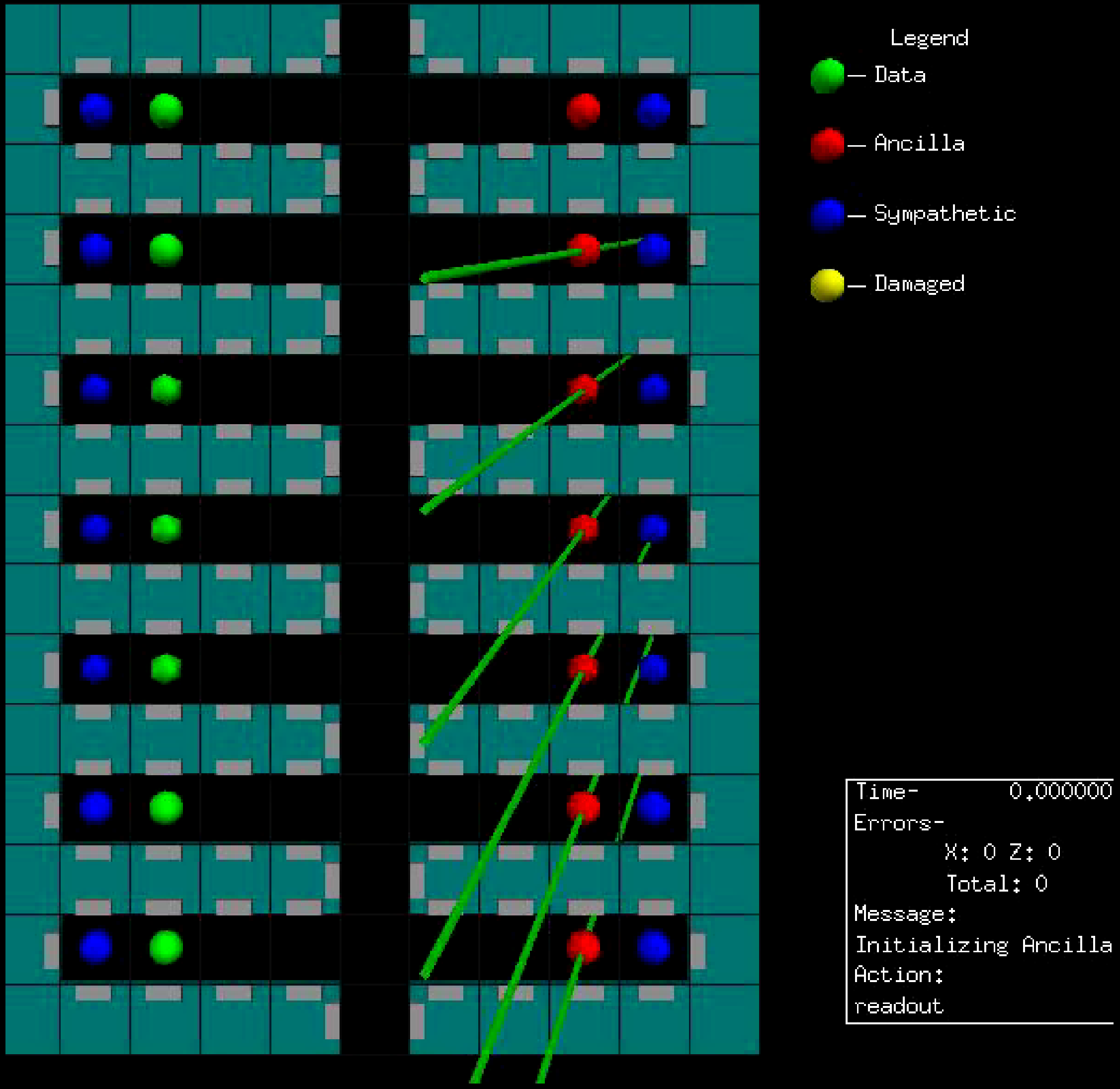


Multiplexed trap structure: NIST Boulder



D. Leibfried, D. Wineland et al., NIST

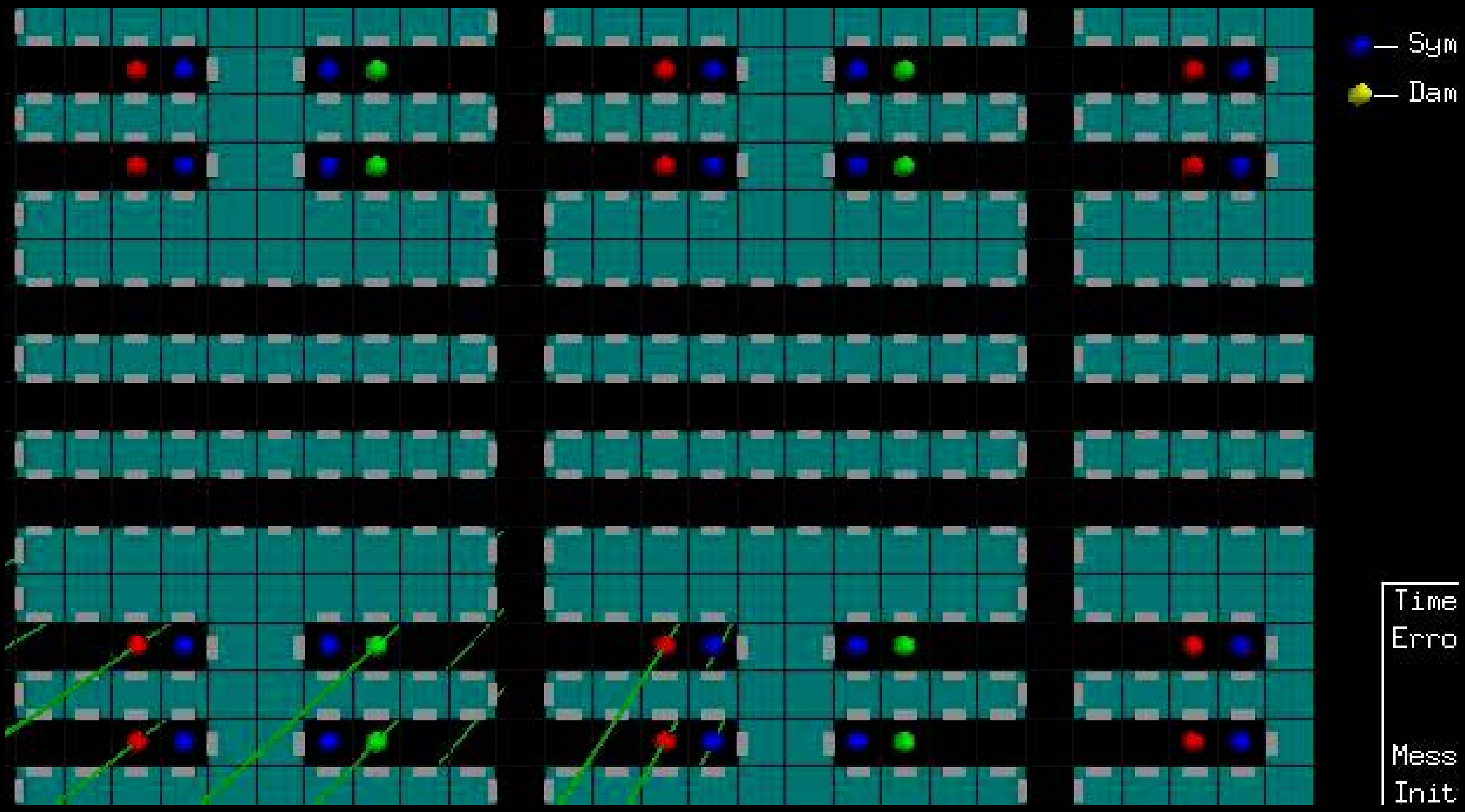
Operating a quantum algorithm on an ion chip



Isaac Chuang, MIT

Movie: © Isaac Chuang, MIT

Operating a quantum algorithm on an ion chip

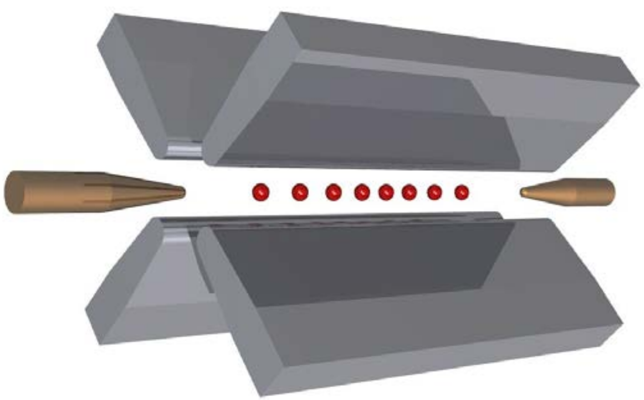


Movie: © Isaac Chuang, MIT

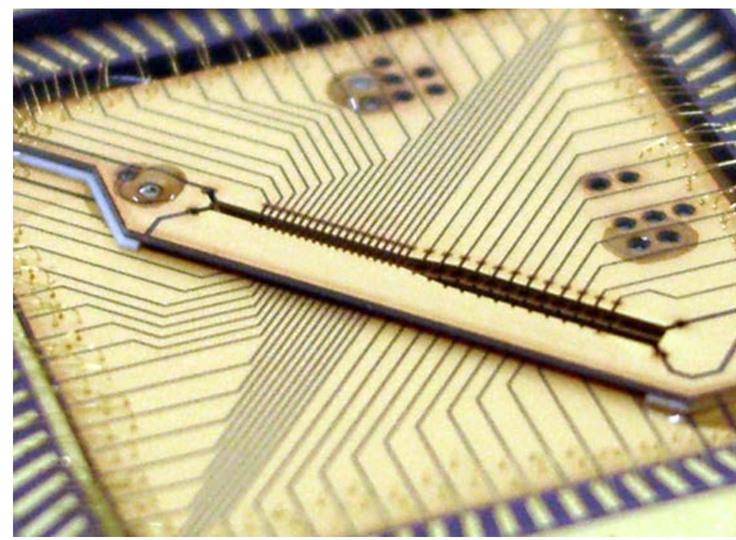
The development of a quantum microprocessor

scala

Microtrap



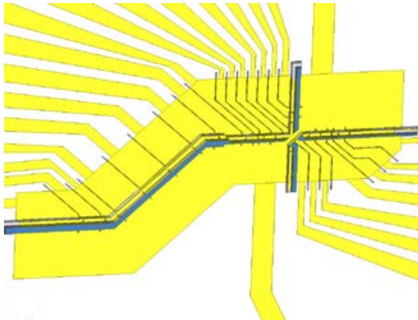
Innsbruck ion trap since 2000

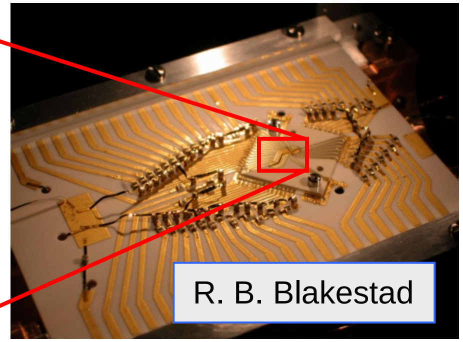


ion trap chip 2008, microtrap

Advanced chip traps at NIST

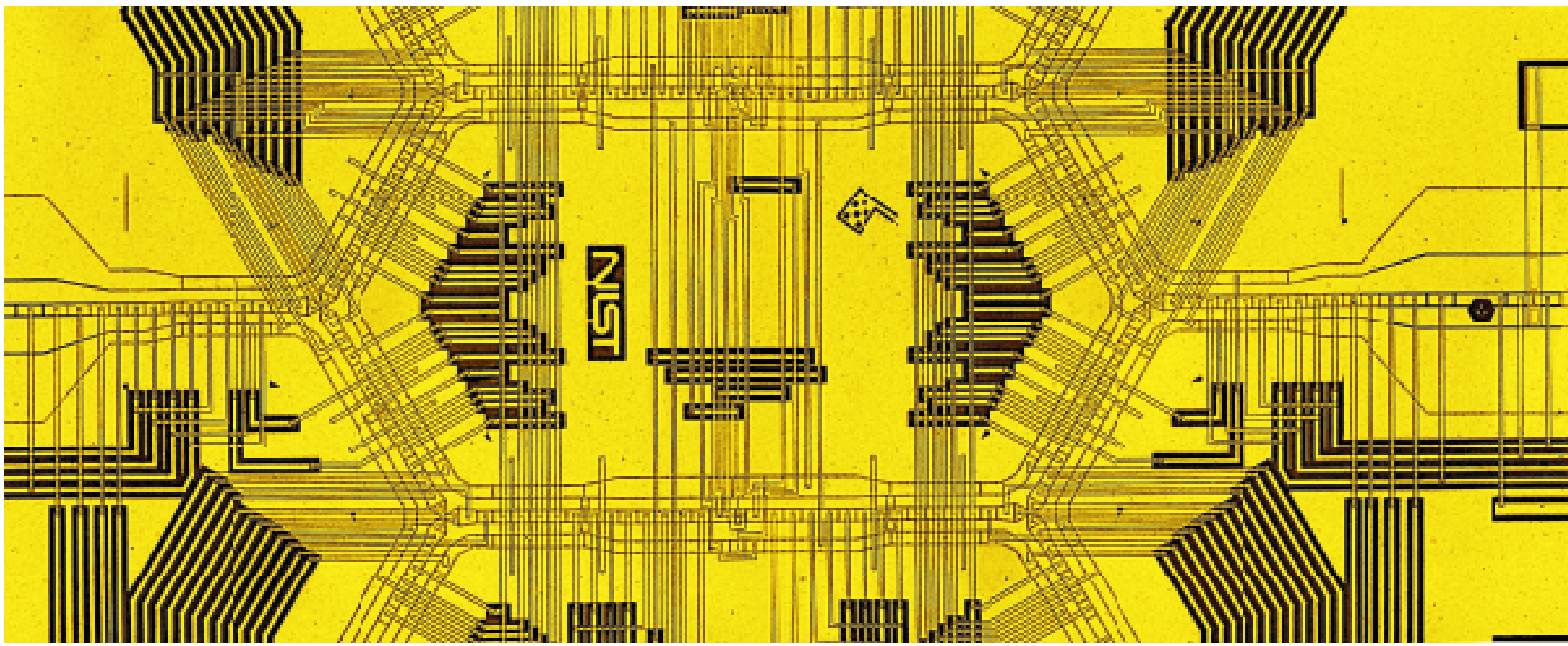
2-layer, 2-D, X-junction, 18 zones (Au on Al_2O_3)





- Transport through junction ($^9Be^+$,$^{24}Mg^+$)
  - ◊ minimal heating ~ 20 quanta
  - ◊ transport error < 3 x 10^{-6}

t

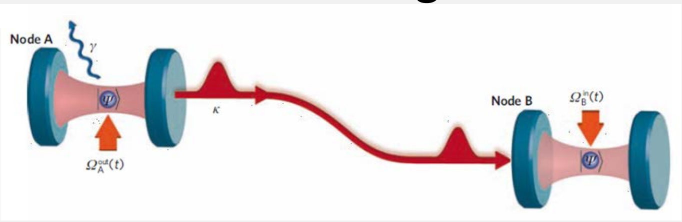


Scaling the ion trap quantum computer

- cavity QED: atom – photon interface, use photons for networking

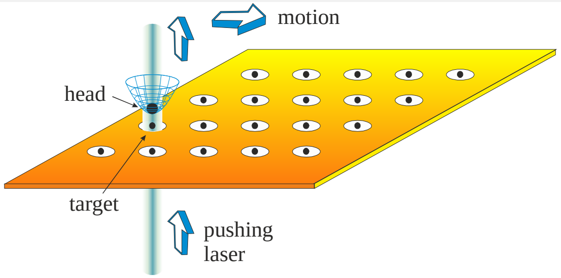
  J. I. Cirac et al., PRL **78**, 3221 (1997)

  T. Northup et al., Univ. Innsbruck



- trap arrays, using single ion as moving head

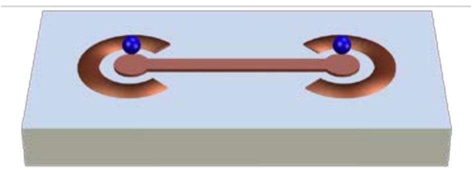
  I. Cirac und P. Zoller, Nature **404**, 579 (2000)

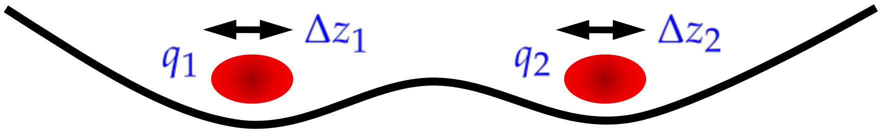


- ion – wire – solid state qubits (e.g. charge qubit)

  L. Tian et al., PRL **92**, 247902 (2004)

  H. Häffner et al., UC Berkeley





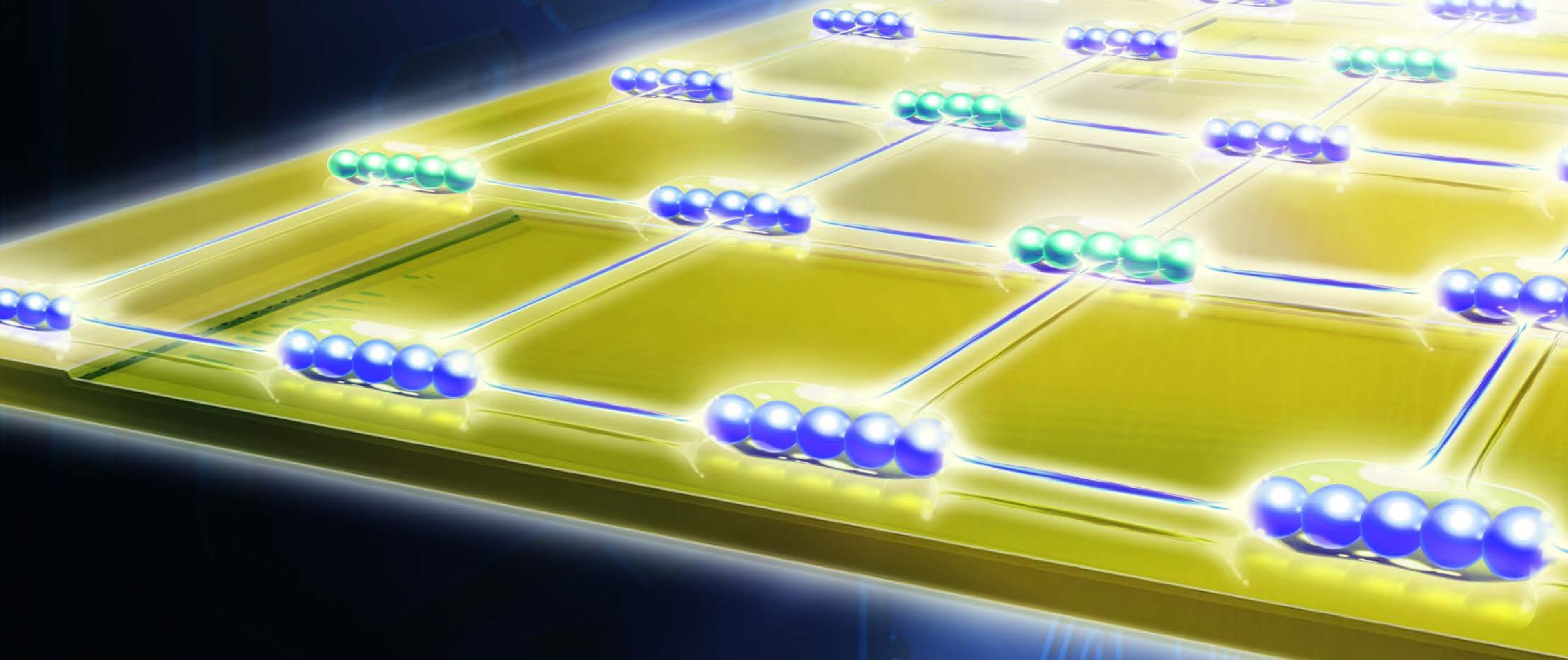
- dipole – dipole coupling

  K. Brown et al., Nature **471**, 196 (2011),

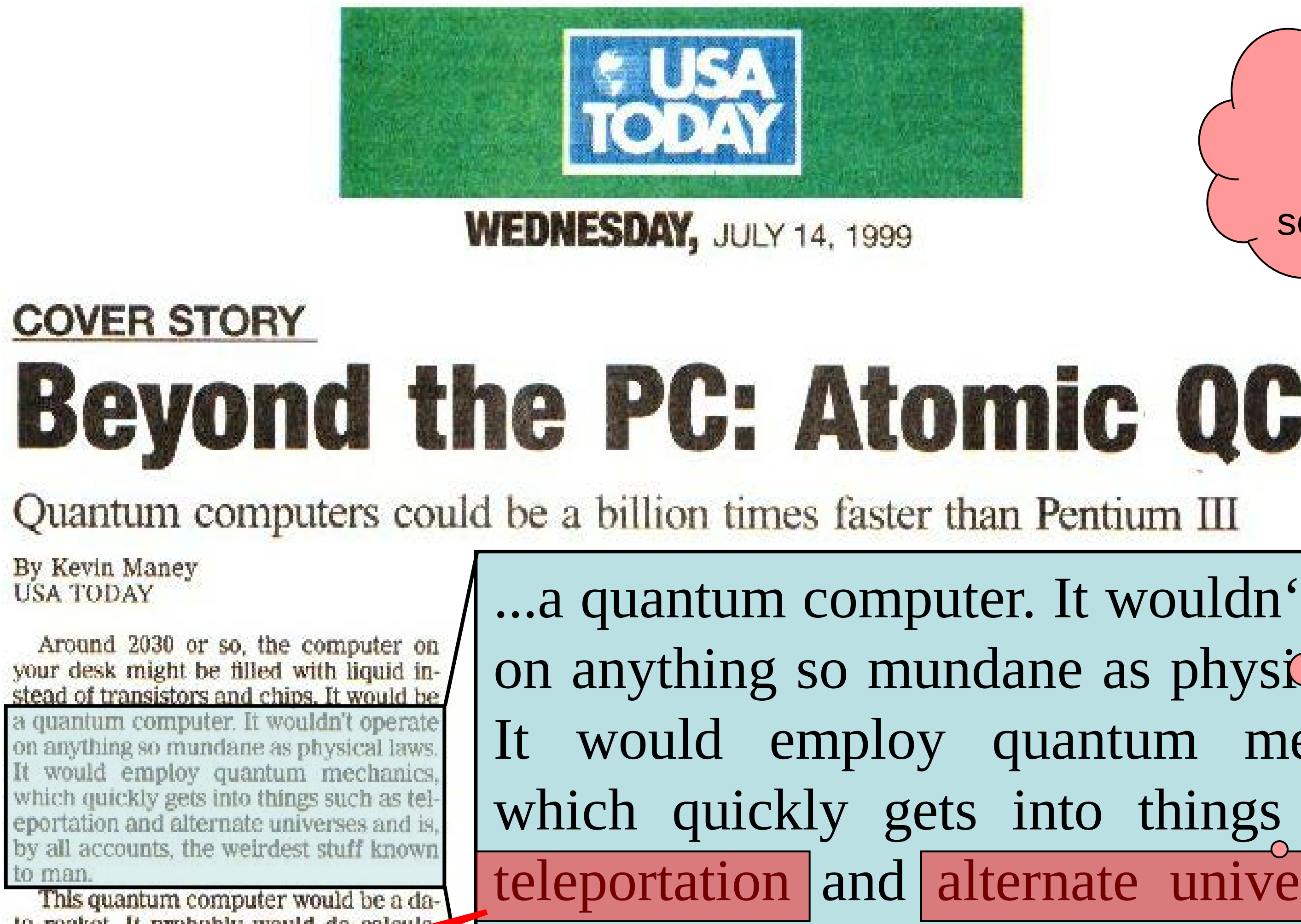
  M. Harlander et al., Nature **471**, 200 (2011)

The Dream (and vision):

- local logical qubits,
- protected by error correction,
- interconnected via
  dipole-dipole interaction (on chip)
  ion-cavity interfaces (network)



Exploring Quantum Computations



USA TODAY

WEDNESDAY, JULY 14, 1999

COVER STORY

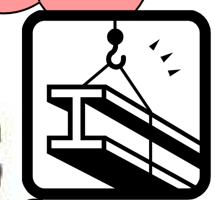
Beyond the PC: Atomic QC

Quantum computers could be a billion times faster than Pentium III

By Kevin Maney
USA TODAY

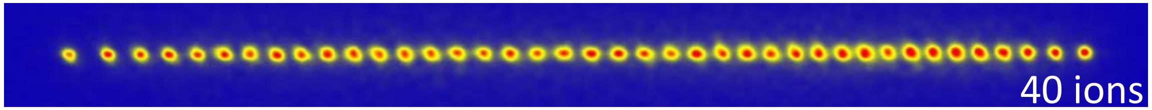
Around 2030 or so, the computer on your desk might be filled with liquid instead of transistors and chips. It would be a quantum computer. It wouldn't operate on anything so mundane as physical laws. It would employ quantum mechanics, which quickly gets into things such as teleportation and alternate universes and is, by all accounts, the weirdest stuff known to man.

This quantum computer would be a data rocket. It probably would do calcula-



...a quantum computer. It wouldn't operate on anything so mundane as physical laws. It would employ quantum mechanics, which quickly gets into things such as teleportation and alternate universes and is, by all accounts, the weirdest stuff known to man.

Future goals and developments



- more qubits (~20 – 50)
- better fidelities
- faster gate operations
- faster detection

} cryogenic trap, micro-structured traps

- development of 2-d trap arrays, onboard addressing, electronics etc.
- entangling of large(r) systems: characterization ?
- implementation of error correction
- applications

„qubit alive“

  - small scale QIP (e.g. **repeaters**)
  - quantum **metrology**, enhanced S/N, tailored atoms and states
  - quantum **simulations** (Dirac equation, Klein paradox, spin Hamiltonians etc.)
  - quantum **computation** (period finding, quantum Fourier transform, factoring)

AG Quantenoptik und Spektroskopie

The International Team 2014

universität innsbruck

€ SFB FoQuS FWF SFB SIQS

erc Industrie Tirol IQI GmbH

FWF bm:bwk

IQI $ IARPA

AG Quantenoptik und Spektroskopie

The International Team 2014

universität innsbruck

C. Roos
M. Hennrich
M. Brownnutt
T. Northup
T. Monz
B. Lanyon

Y. Colombe
R. Rothganger
F. Ong
M. Lee

D. Nigg
E. Martinez
B. Casabone
M.Guggemos
D. Heinrich
D. Higginbottom
C. Hempel
M. Niedermayr
C. Mayer
M. van Mourik

M. Kumph
R. Lechner
B. Ames
M. Brandl
P. Jurcevic
K. Friebe
P. Holz
K. Lakhmansky
K. Schüppert
G. Araneda

L. Postler
A. Erhard
M. Meraner
A. Nolf
J. Ghetta
D. Fioretto
S. Schunke

Theory collaboration:
P. Zoller, P. Hauke, M. Müller, M.A. Martin-Delgado

€ SFB FoQuS FWF SFB SIQS

erc Industrie Tirol IQI GmbH

FWF bm:bwk IQI $ IARPA