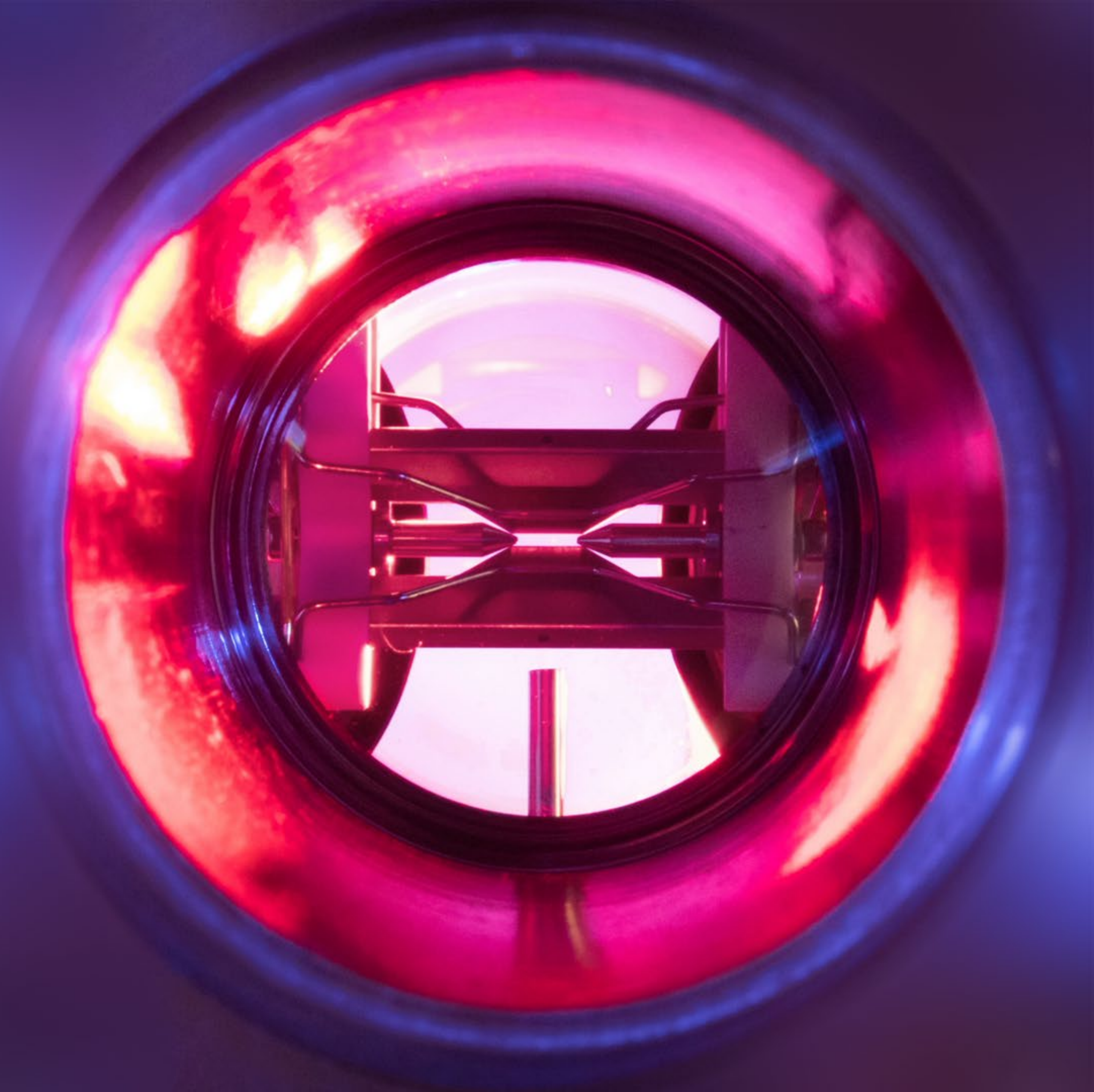
The Quantum Way of Doing Computations, Simulations and Measurements



The Quantum Way of Doing Computations, Simulations and Measurements

- Why quantum computers ?
- Quantum bits, Q-registers, Q-gates and realization concepts
- Quantum computation with trapped ions
- Quantum toolbox with ions
- Quantum computations, simulations and measurements
- Scaling the ion trap quantum computer

Rainer Blatt
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IQI
ÖAW ÖSTERREICHISCHE AKADEMIE DER WISSENSCHAFTEN
AQT

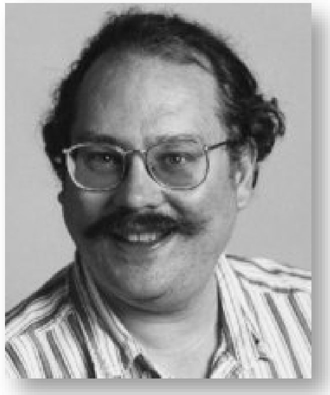
Why Quantum Computers … ?

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

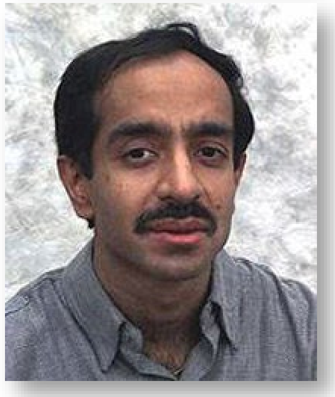


Peter Shor

- fast database search (L. Grover, 1997)

  search data base with N entries:

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



Luv Grover

- simulation of Schrödinger equations   Hot topic !

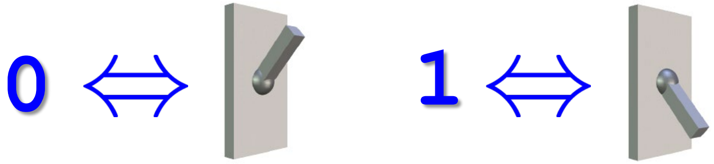
- spectroscopy: quantum computer as atomic "state synthesizer"

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

- quantum physics with "information guided eye"

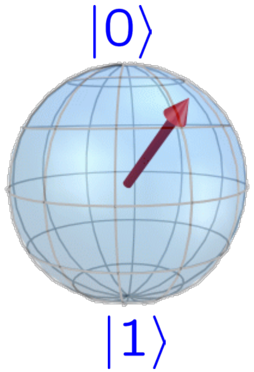
Elementary building blocks: Quantum Bits and Quantum Registers

- 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

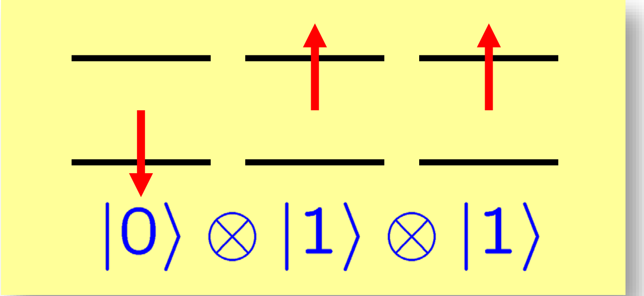
$$|\Psi\rangle = c_0|0\rangle + c_1|1\rangle$$

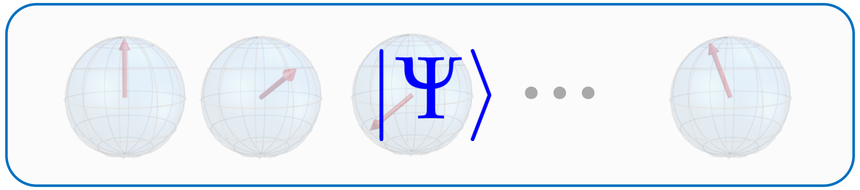


- quantum register: L 2-level atoms, 2^L quantum states

  2^L states correspond

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



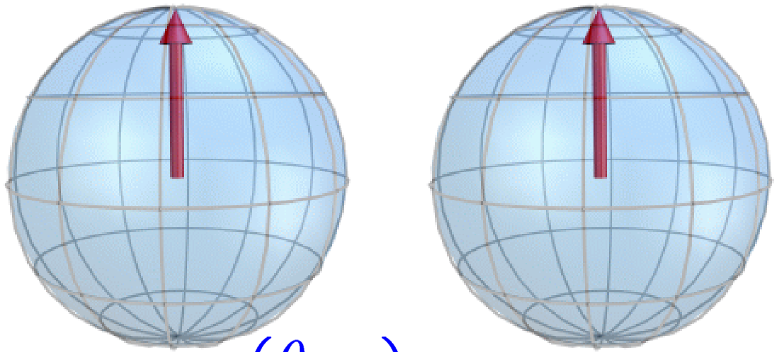


- most general state of the register is the superposition

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

Universal quantum gate operations

Operations with single qubit:
(1-bit rotations)



$(\theta, \varphi) =$

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

Operations with two qubits:
(2-bit rotations)

CNOT – gate operation
(controlled-NOT)

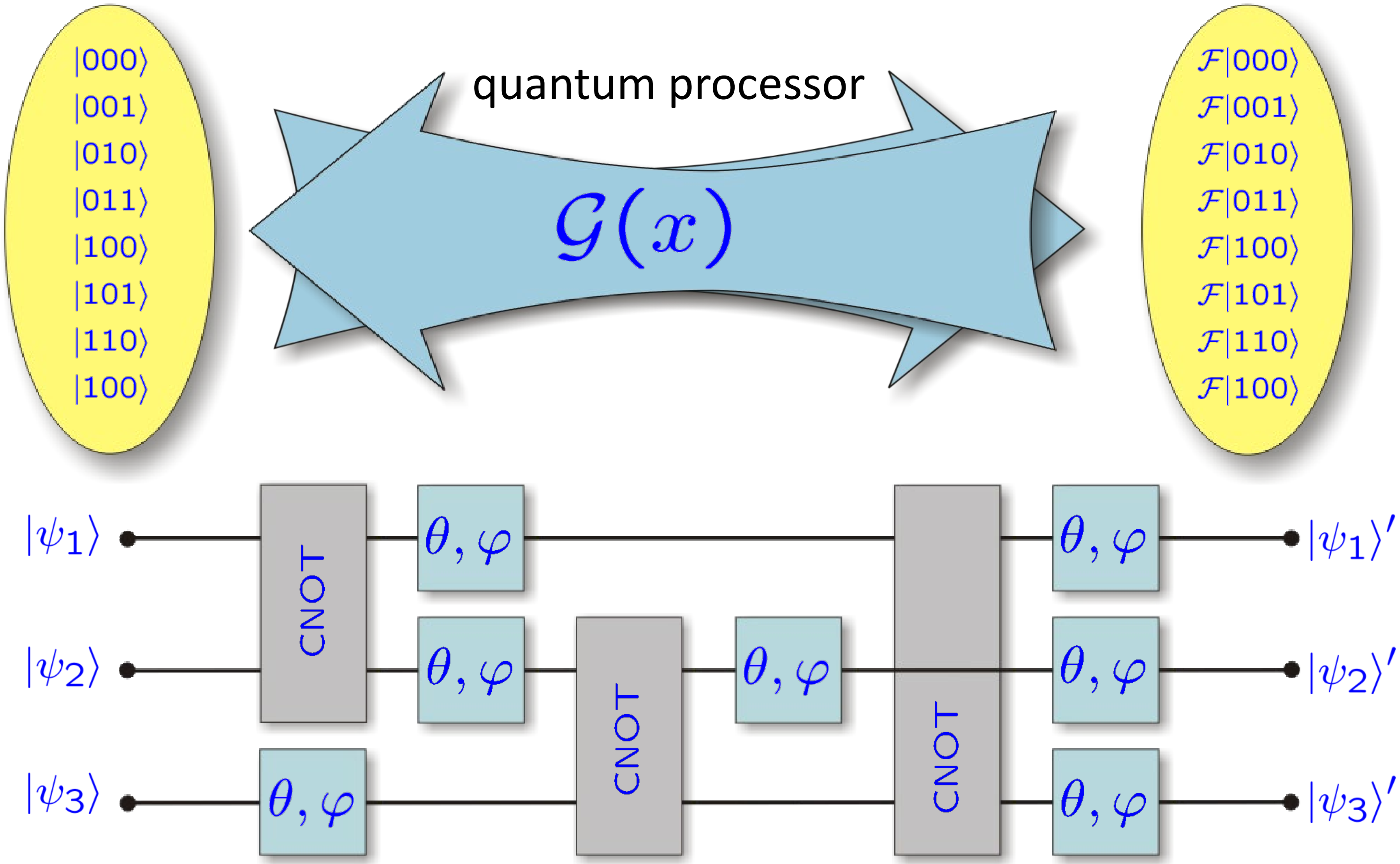
analogous to classical XOR

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

control bit — target bit

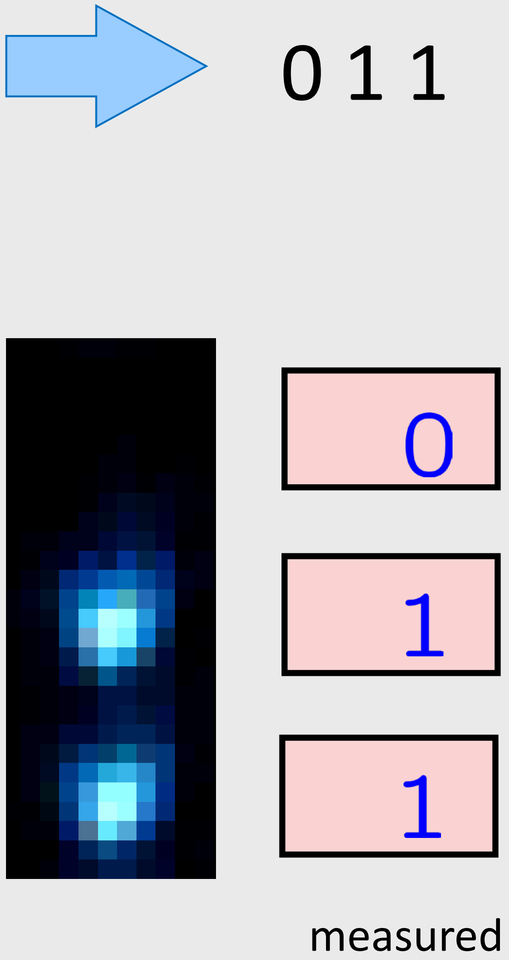
Together: universal set of gate operations

How quantum information processing works



Input ➡ computation: sequence of quantum gates ➡ output

Measurement



Realization concepts

Quantum Information Science and Technology Roadmaps:
US – http://qist.lanl.gov/
EU – http://qurope.eu/content/Roadmap

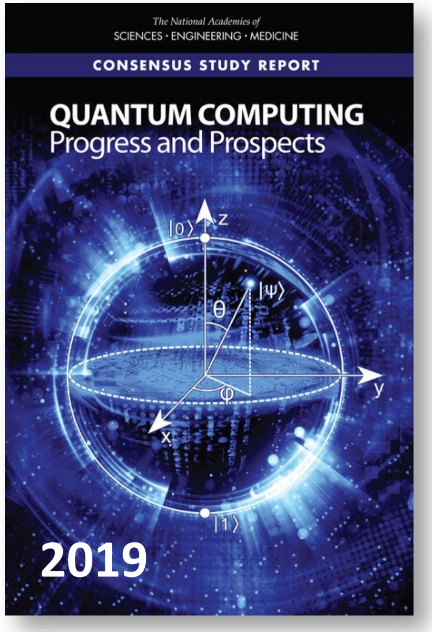
The European Roadmap
New J. Phys. **20**, 080201 (2018)

- Ion traps
- Neutral atoms in traps (opt. traps, opt. lattices, microtraps)
- Neutral atoms and cavity QED
- NMR (in liquids)
- Superconducting qubits (charge-, flux-qubits)
- Solid state concepts (spin systems, quantum dots, etc.)
- Optical qubits and LOQC (linear optics quantum computation)
- Electrons on L-He surfaces
- Spectral hole burning
- …and more new ideas

Quantum Systems

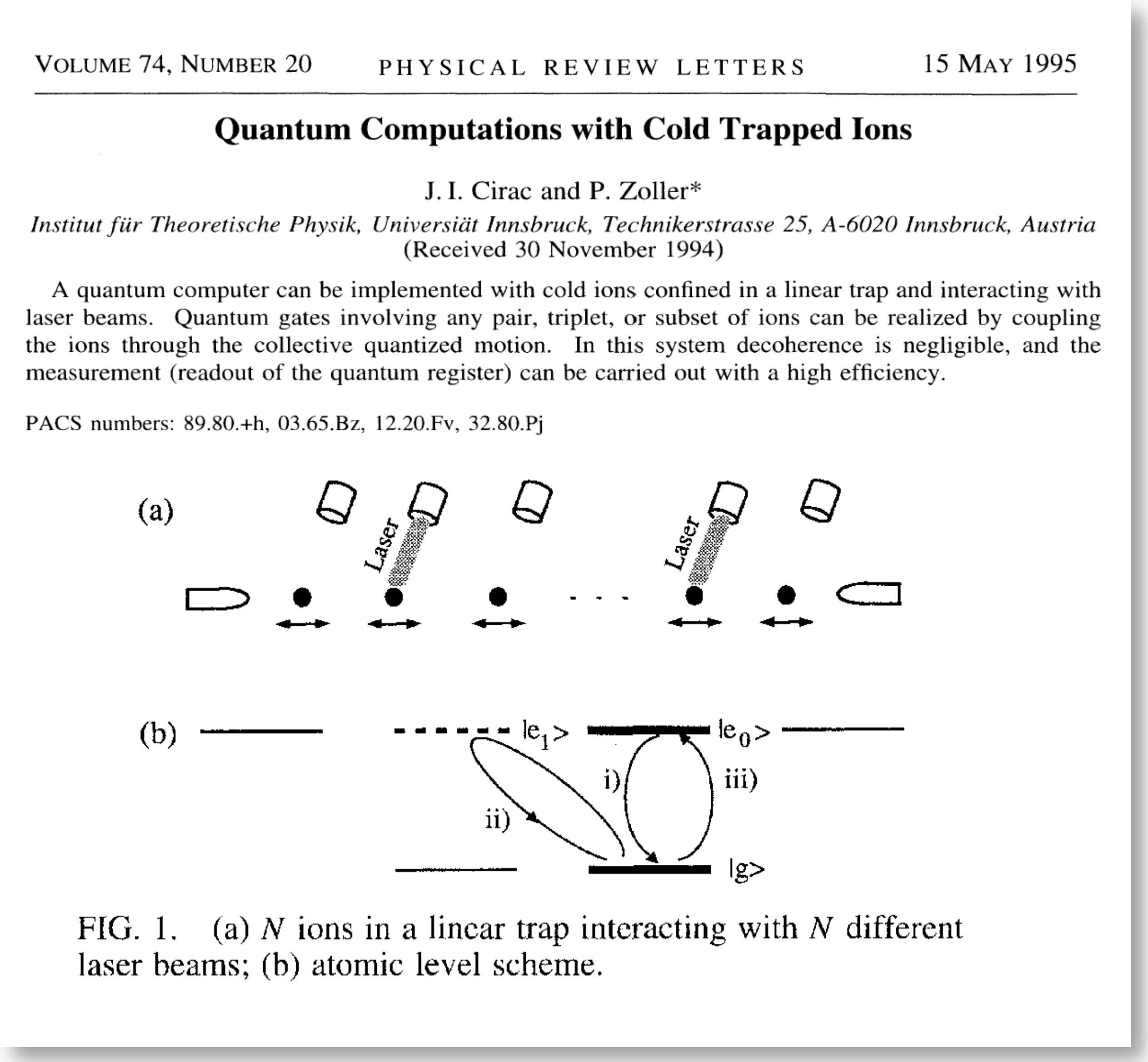
that can be **controlled** and **manipulated**

http://qurope.eu/manifesto



http://nap.edu/25196

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.

- single ions as qubits
- addressed lasers for gate operation

Idea:

- use common motion to create entanglement

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 qubit

target qubit

J. I. Cirac

P. Zoller

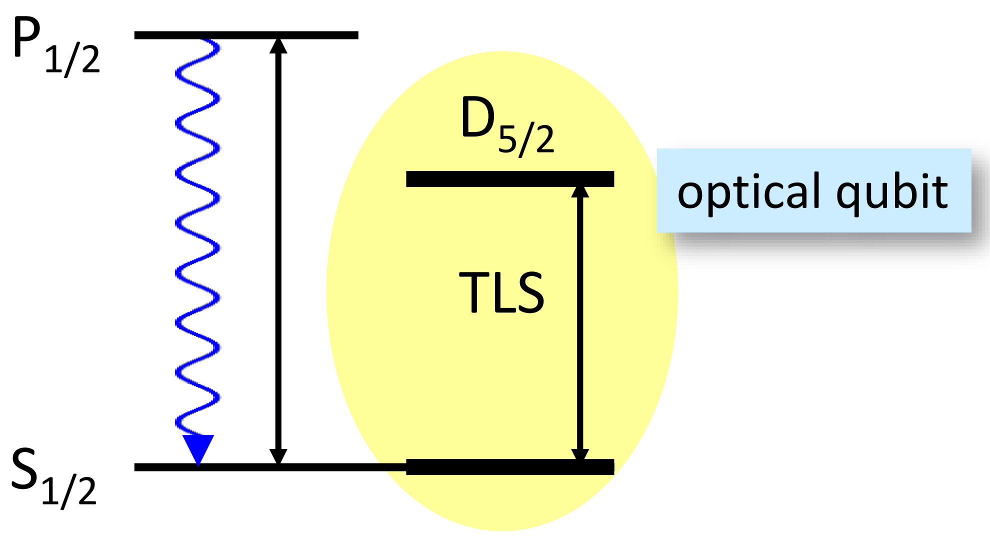
1995

Qubits with Trapped Ions

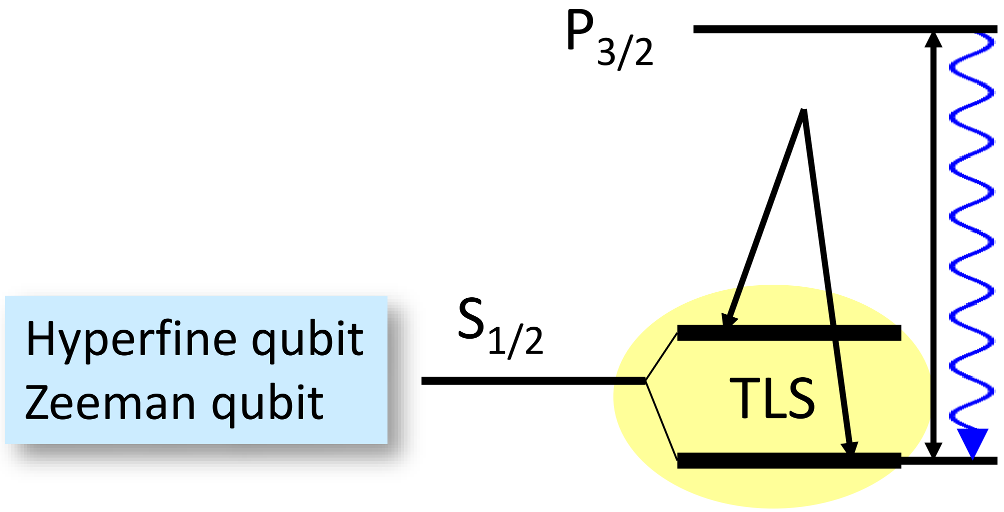
Storing and keeping quantum information requires long-lived atomic states:

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

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

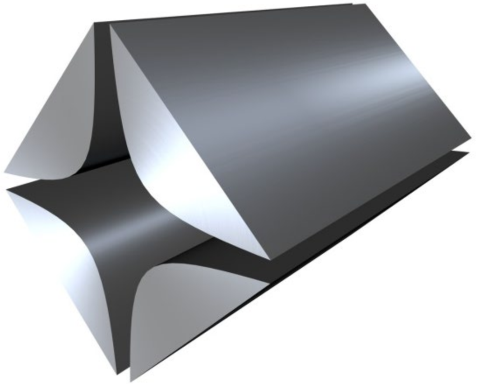


Innsbruck, $^{40}Ca^+$ a.o.

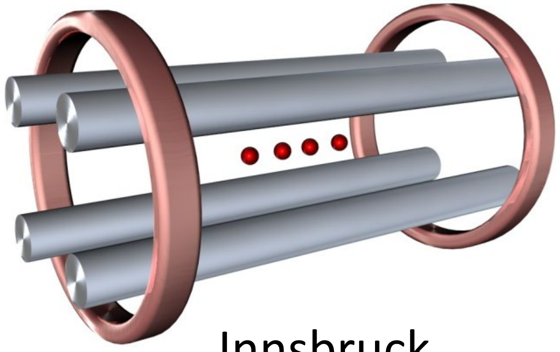


Boulder $^{9}Be^+$; Innsbruck, Oxford $^{43}Ca^+$; Michigan $^{111}Cd^+$; Maryland $^{171}Yb^+$; a.o.

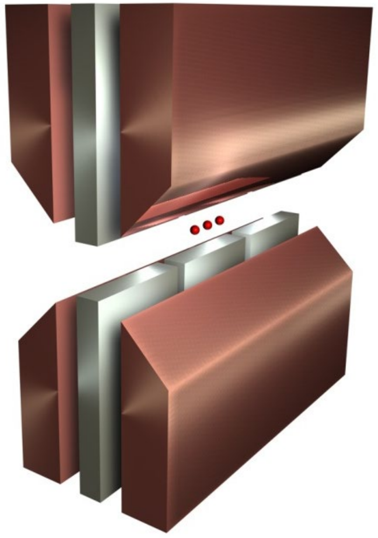
Linear Ion Traps



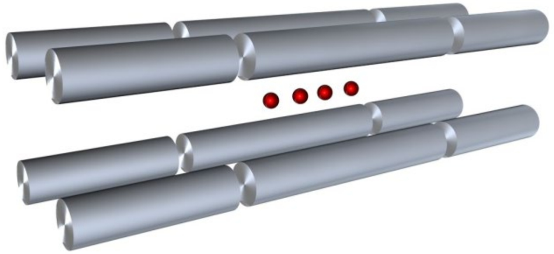
Paul mass filter



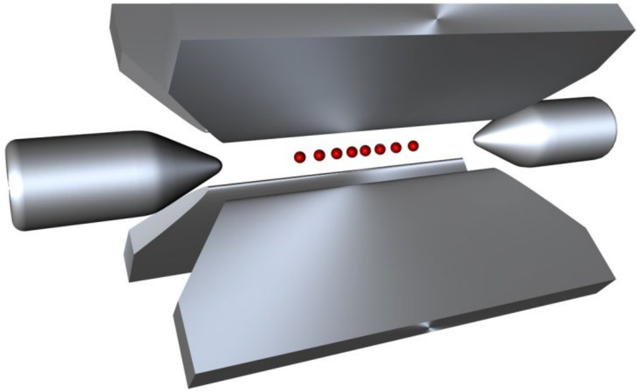
Innsbruck
Ann Arbor



München,
Sussex

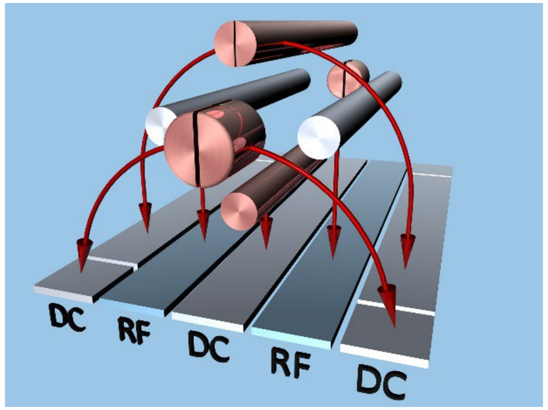


Boulder, Mainz, Aarhus

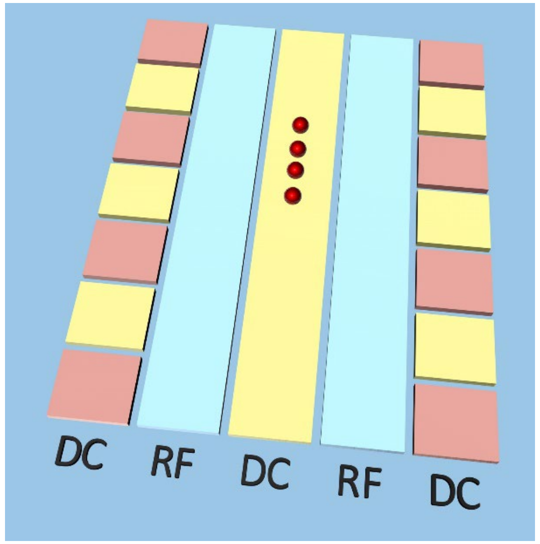


Innsbruck, Oxford

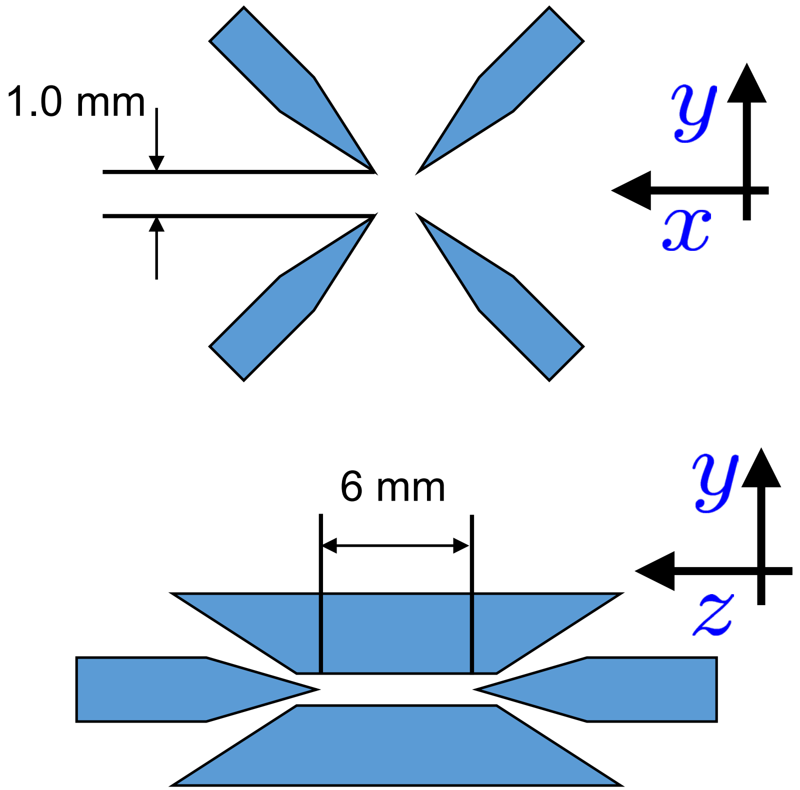
Surface Traps

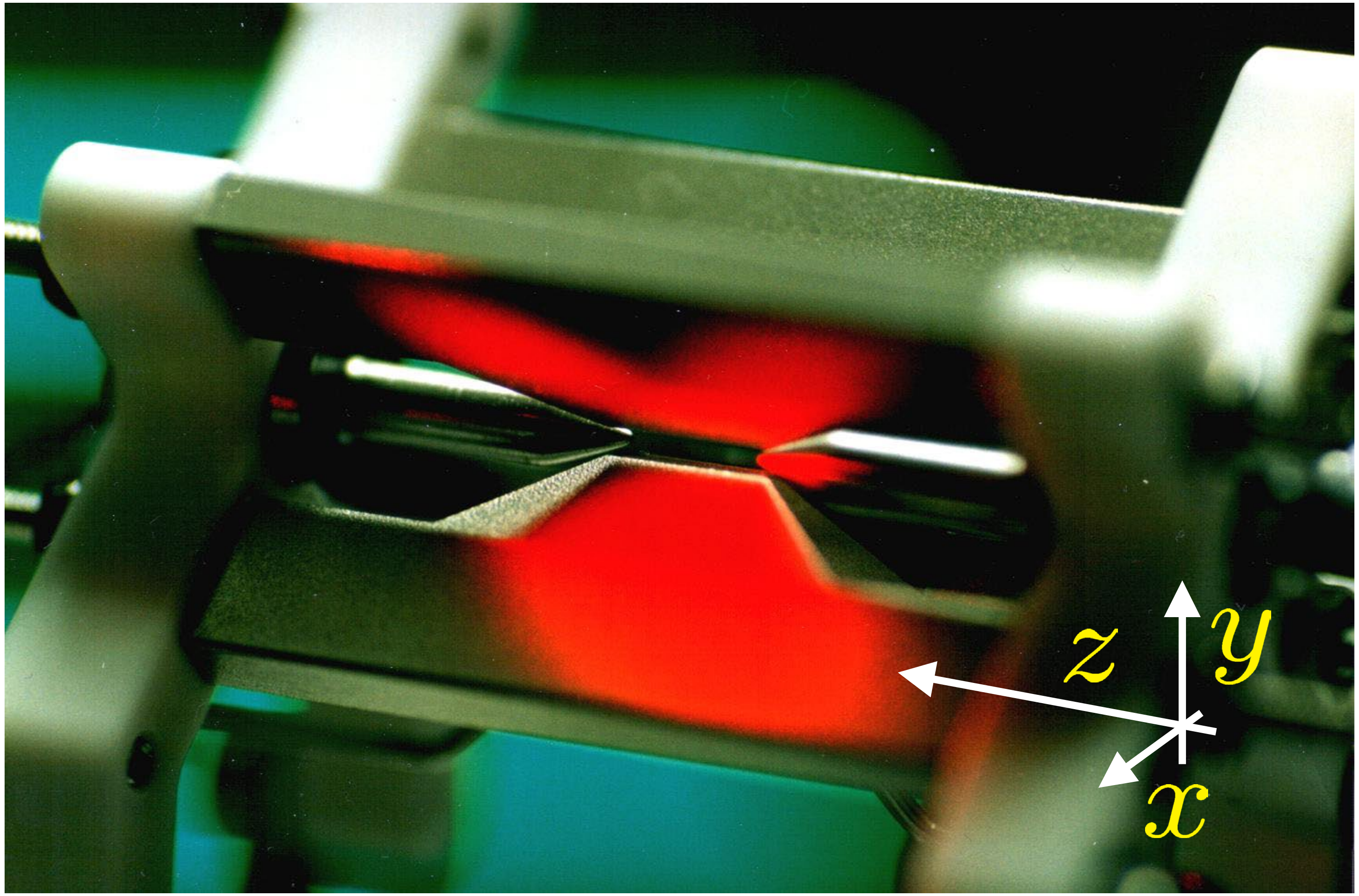


Boulder



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

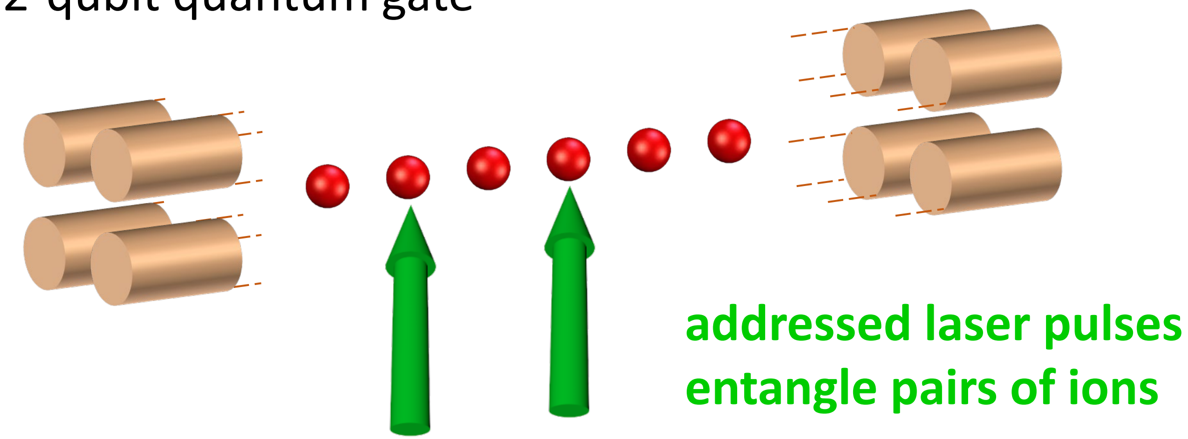
J. I. Cirac, P. Zoller; Phys. Rev. Lett. **74**, 4091 (1995)

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



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

control qubit

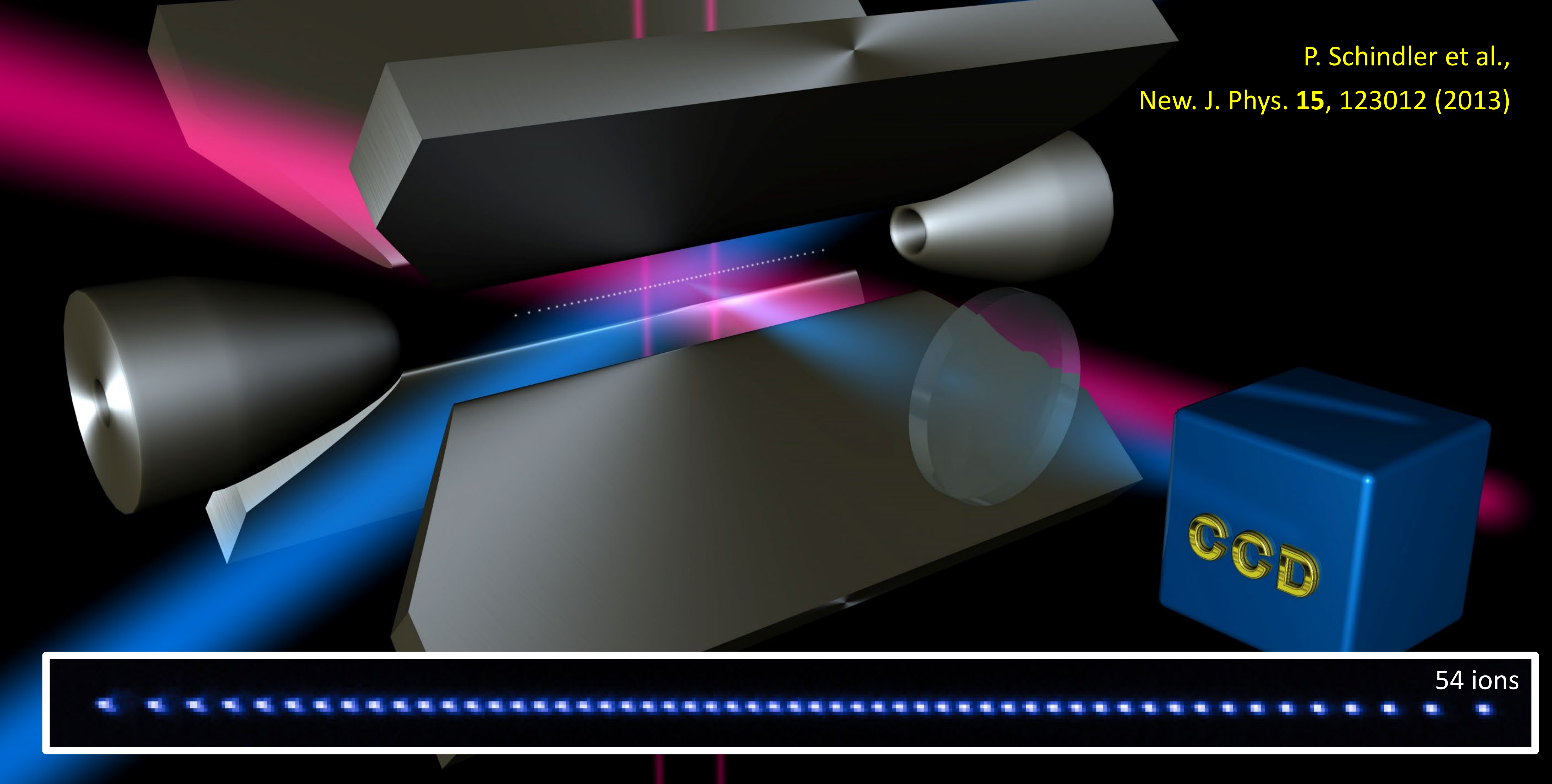
target qubit

- 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)

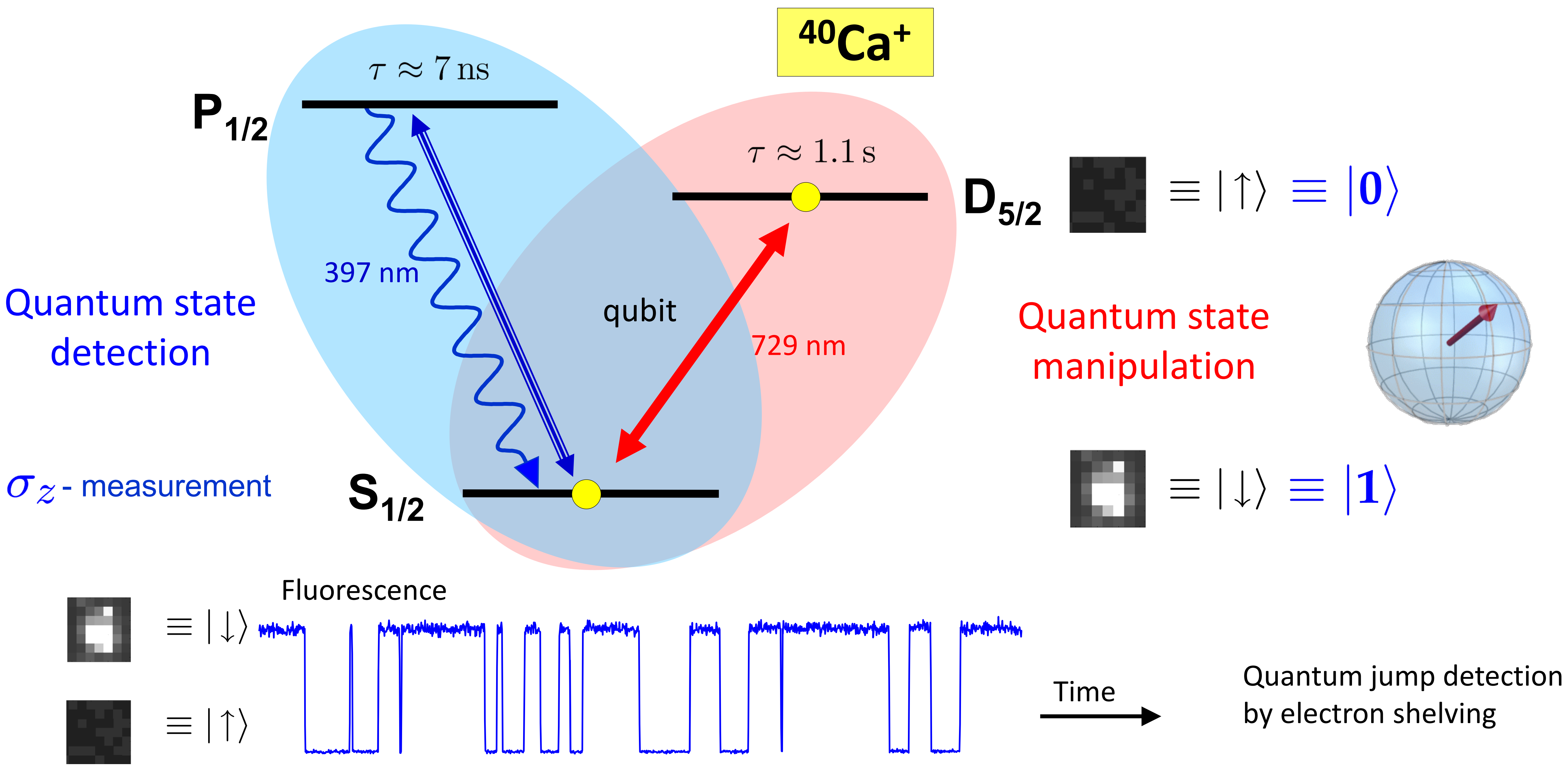
The Quantum Information Processor with Trapped Ca^+ Ions

P. Schindler et al.,

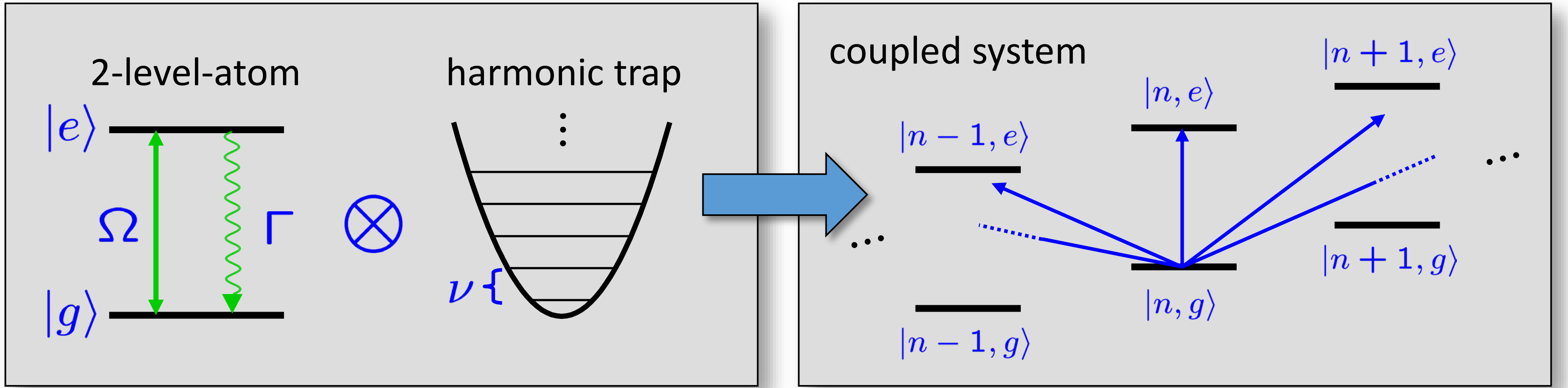
New. J. Phys. **15**, 123012 (2013)

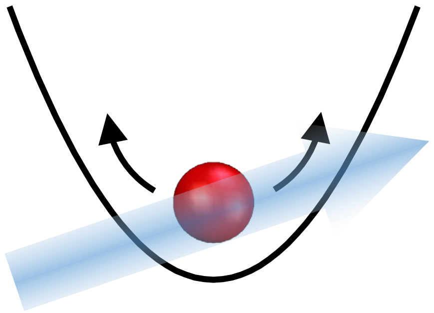


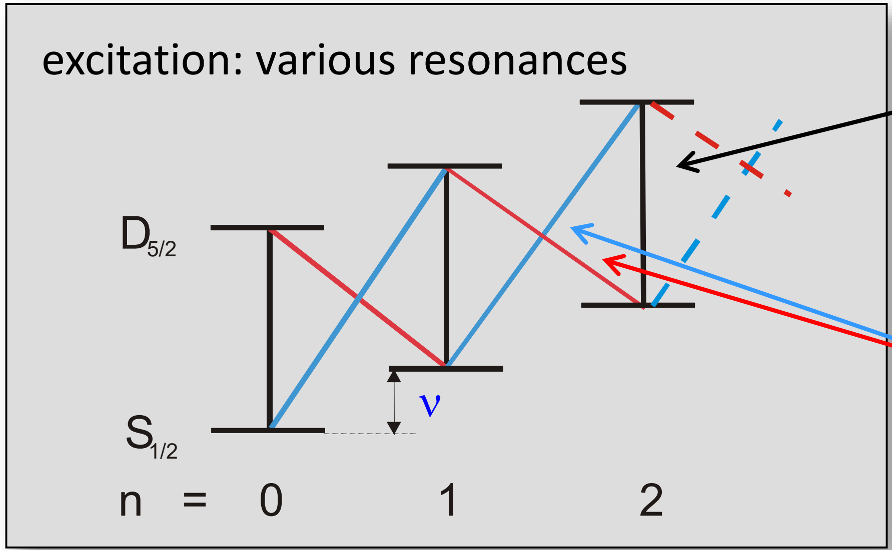
Experiments with trapped Ca^+ ions



Quantum state manipulation: carrier and sidebands







Carrier:
manipulate qubit
→ internal superpositions

Sidebands:
manipulate motion and qubit
→ create entanglement

S. Stenholm,
RMP **58**, 699 (1986)

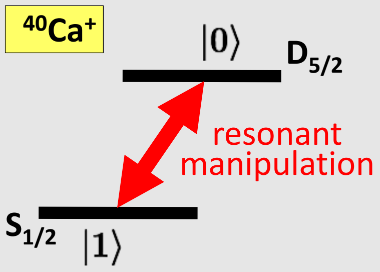
J. I. Cirac, P. Zoller;
PRL **74**, 4091 (1995)

D. Leibfried, R. Blatt,
C. Monroe, D. Wineland
RMP **75**, 281 (2003)

Quantum computing with global and local operations

Global

Collective Local Operations

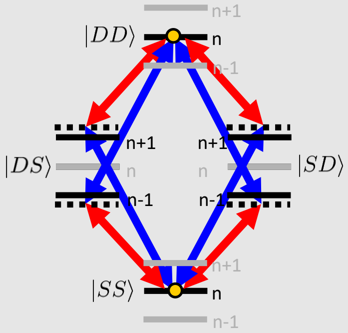


$S_{x,y}(\theta)$

τ = 20µs

F > 99.5%

Global Mølmer-Sørensen entangling gate



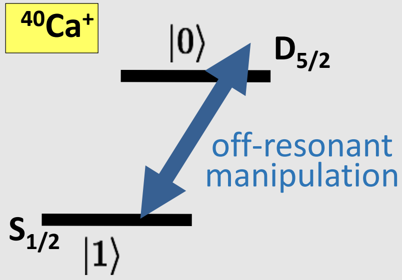
$S^2_{x,y}(\theta)$

τ = 50µs

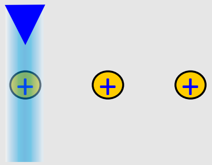
F_2 > 99%

Local

Individual local operations



$S_z(\theta)$



τ = 20µs

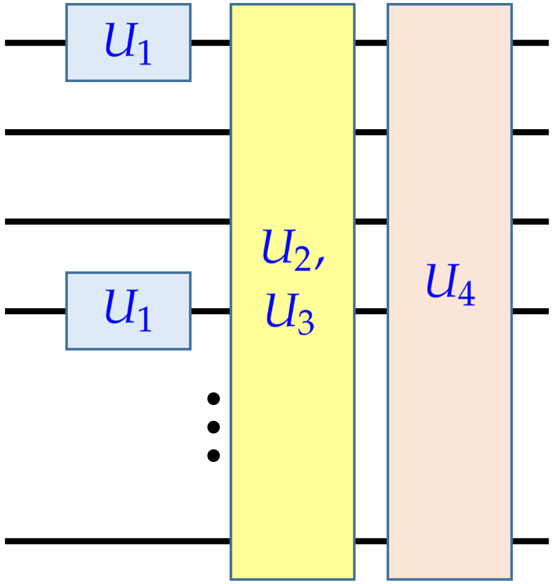
F > 99%

All three blocks combined realize a **universal gate set** for arbitrary quantum computation

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

Quantum gate operations – unitaries

Quantum circuits:



$$U_1(\theta, j) = e^{-i\theta\sigma_z^j}$$

$\sigma_z^{(i)}(\theta)$
local Stark shifts

$$U_2(\theta) = e^{-i\theta\sum_i \sigma_z^i}$$

$S_z(\theta)$
collective Stark shifts

$$U_3(\theta, \phi) = e^{-i\theta\sum_i \sigma_\phi^i}$$

$S_\phi(\theta)$
collective local ops.

$$U_4(\theta, \phi) = e^{-i\theta\sum_{i<j} \sigma_\phi^i \sigma_\phi^j}$$

$S_\phi^2(\theta)$
entangling MS ops.

$$\sigma_\phi = \cos\phi\sigma_x + \sin\phi\sigma_y$$

σ_k^j *k*-th Pauli matrix acting on *j*-th qubit

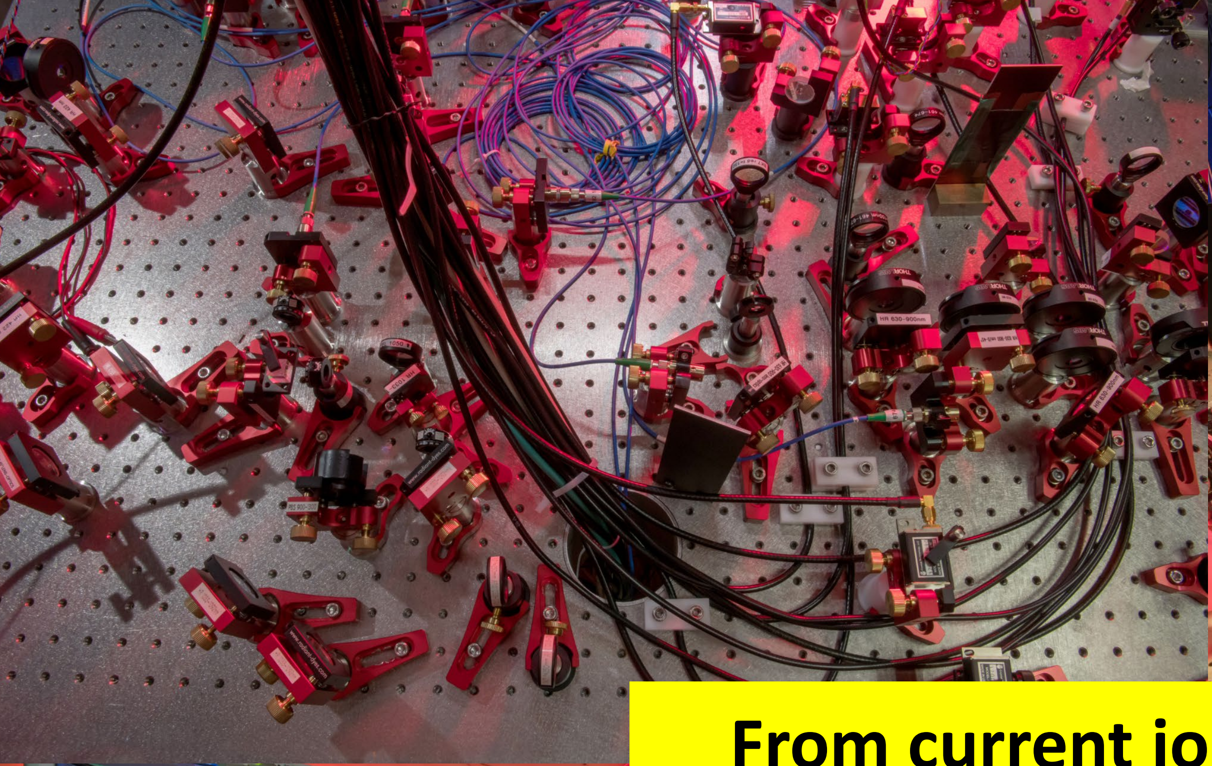
additional operations:

- hiding operations (reduce/enlarge computat. subspace)
- dephasing operations (open systems)
- initialization/reset operation
- quantum (cache) memory

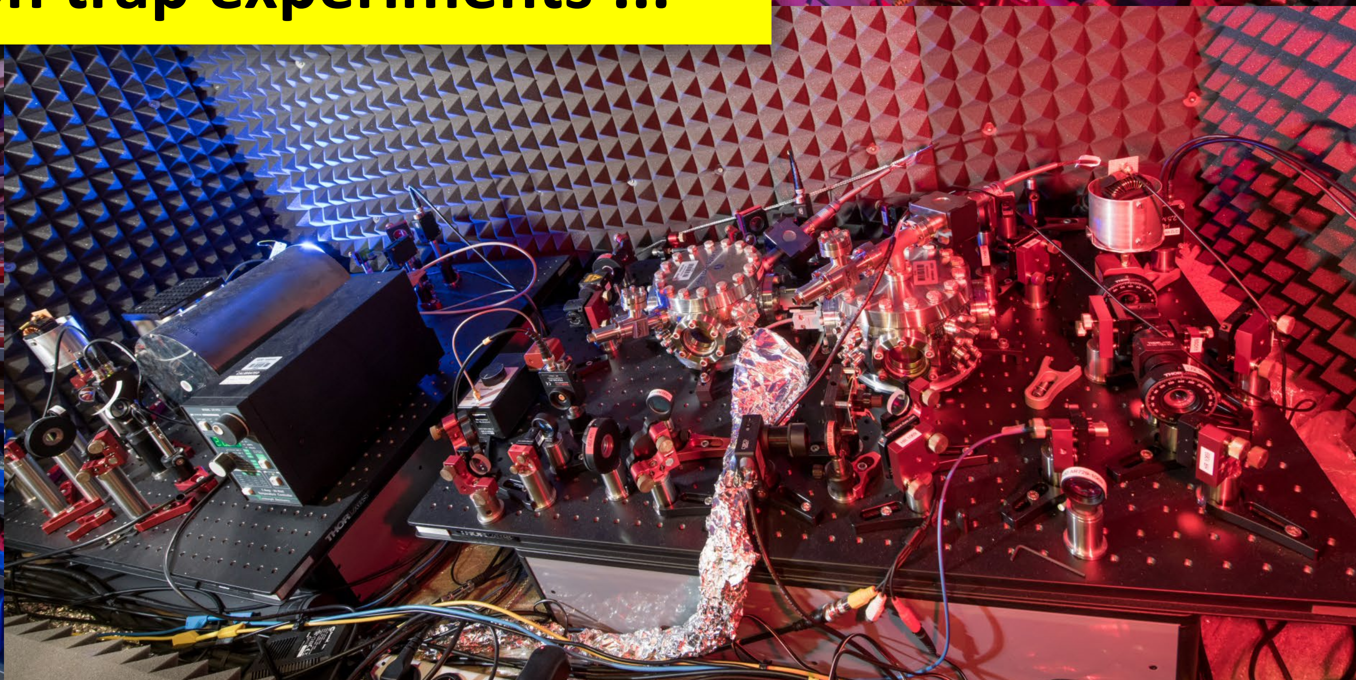
The Quantum Way of Doing Computation (with trapped ions)

Algorithms:

- Teleportation
- Grover Algorithm (Optimization)
- Quantum-Fourier-Transformation
- Phase estimation
- Shor algorithm
- „Order finding“ Algorithm
- Quantum Error Correction
- Analog quantum simulation
- Digital quantum simulation
- Quantum metrology
- etc. …




From current ion trap experiments ...

… to a compact modular quantum computing demonstrator

AQTION

consortium

universität innsbruck

TOPTICA PHOTONICS

Atos

JOHANNES GUTENBERG UNIVERSITÄT MAINZ

JG|U

Swansea University Prifysgol Abertawe

UNIVERSITY OF OXFORD

ETH zürich

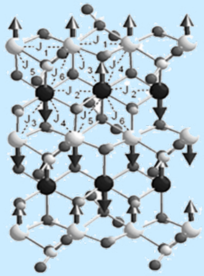
AKKA Digital

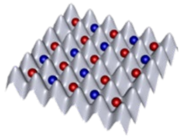
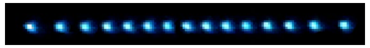
C. Marciniak I. Pogorelov

trap module

QUANTUM FLAGSHIP

Quantum Simulation Approaches

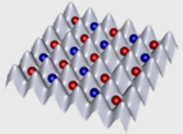
problem to compute  → $\hat{H}$ → ✗  classical computer

→ Quantum Simulator  or 

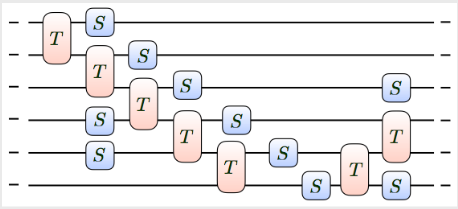
Analog simulation:

$$|\psi(0)\rangle \; e^{-\frac{i}{\hbar}\hat{H}t} \; |\psi(t)\rangle$$

requires match between engineerable interactions and model

 ,  , SC-QS ....

Digital simulation (computation):

$|\psi(0)\rangle$  $|\psi(t)\rangle$

can simulate any model $\hat{H}$,
but requires many gate operations

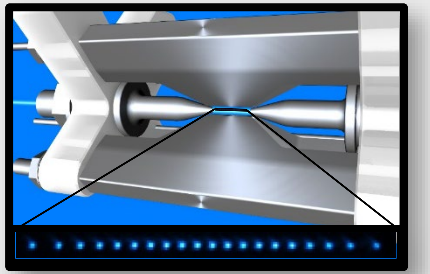
$$U_N(\delta(t))\ldots U_2(\delta(t))U_1(\delta(t))$$

Hybrid simulation:

Classical computer

Θ

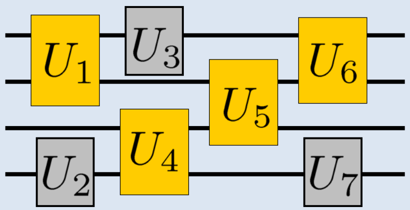
$\langle \hat{H}_T(\Theta)\rangle$



analog quantum simulator

Quantum Simulations with Trapped Ions

digital approach



$$U_{\mathrm{sim}} = \prod_{j=1}^{N} U_j = U_1 U_2 U_3 \cdots U_N$$

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

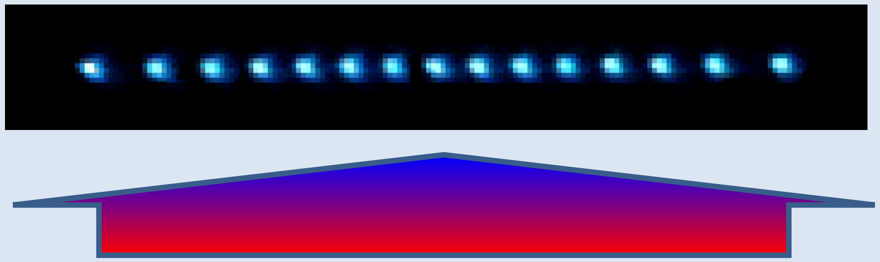
$$U = e^{-\frac{i}{\hbar} H\, t}$$

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

gate_1 gate_2 gate_k

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

analog approach



N ions interacting with a transverse bichromatic beam

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

Interactions J_{ij} can be adjusted with

trap parameters (mode frequency)
interaction parameters (Rabi frequency, detuning)
ion mass

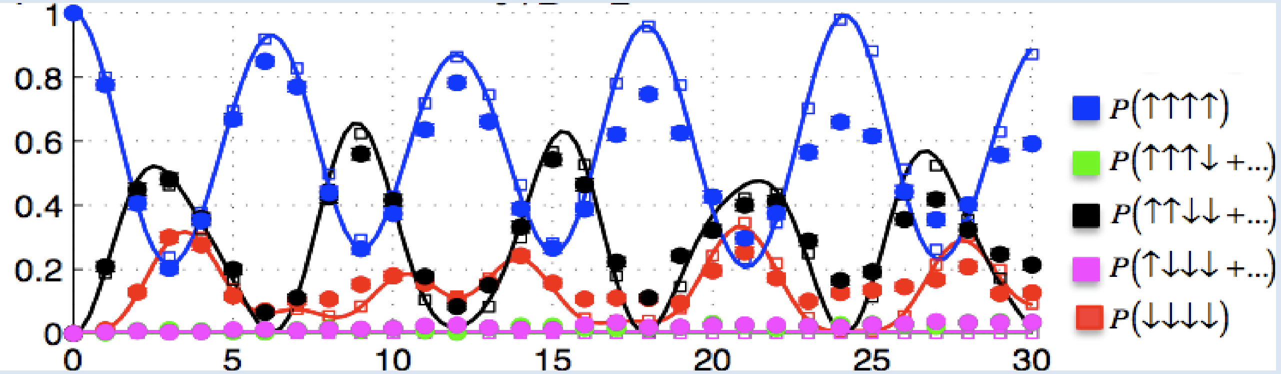
C. Monroe et al., Rev. Mod. Phys. **93**, 025001 (2021)

Digital Quantum Simulations with Trapped Ions

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

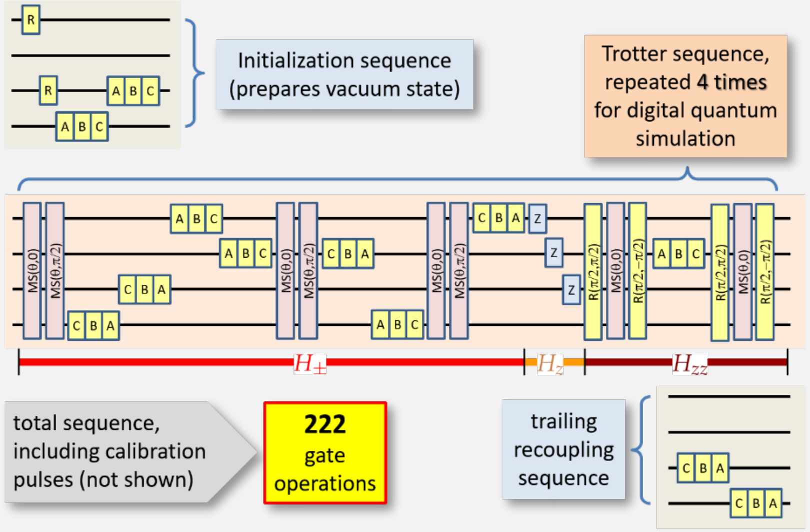
- Open system simulations
- Ising, XY, XYZ Hamiltonians
- Many-body Hamiltonians

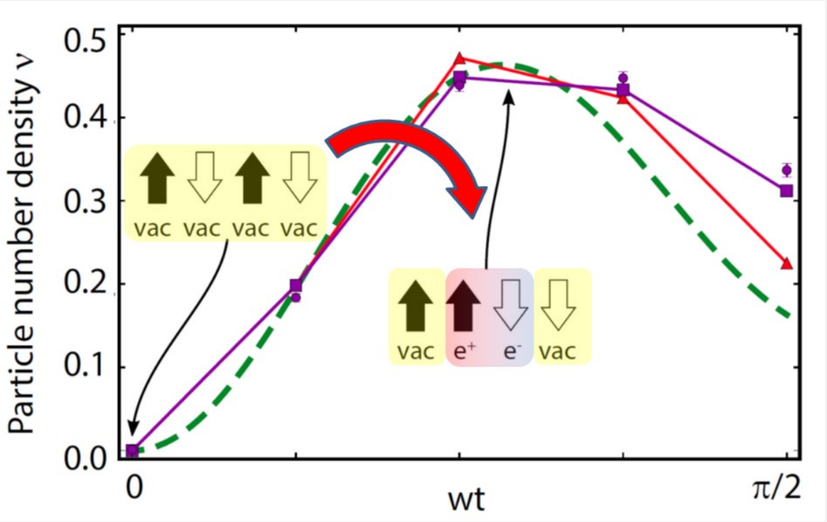
$$J\sum_{i\neq j}\sigma_x^i\sigma_x^j + B\sum_{i=1}^{n}\sigma_z^i$$



- 1-D lattice gauge theory (Schwinger model)

$$H = J\sum_{i<j} c_{ij}\sigma_i^z\sigma_j^z + w\sum_i(\sigma_i^+\sigma_{i+1}^- + \sigma_{i+1}^+\sigma_i^-) + m\sum_i c_i\sigma_i^z + J\sum_i \tilde{c}_i\sigma_i^z$$



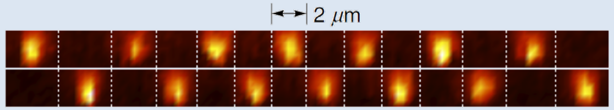


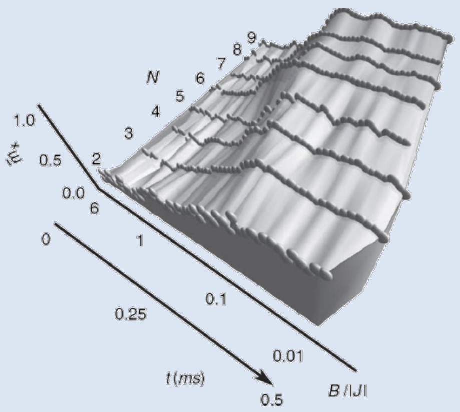
E. Martinez, C. Muschik et al.,
Nature **534**, 516-519 (2016)
C. Muschik et al.,
New J. Phys. 19, 113038 (2017)

Analog Quantum Simulations with Trapped Ions

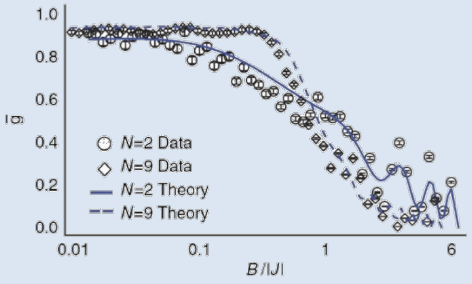
- transverse Ising Hamiltonian $H_{TI} = \sum_{i<j} J_{ij}\sigma_x^i\sigma_x^j + B_y \sum_i \sigma_y^i$

paramagnetic-to-ferromagnetic crossover,
Néel ordering





C. Monroe et al.,
Rev. Mod. Phys. **93**, 025001 (2021)



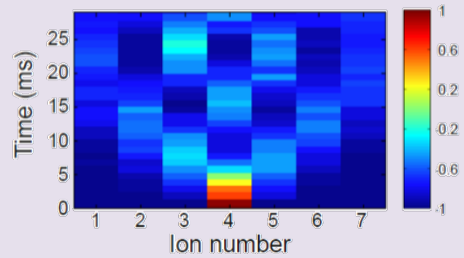
- Ising, XY, XYZ Hamiltonians
- Many-body Hamiltonians

$$H_{XY} = \sum_{i<j} \frac{J_0}{|i-j|^\alpha}(\sigma_i^+\sigma_j^- + \sigma_i^-\sigma_j^+)$$

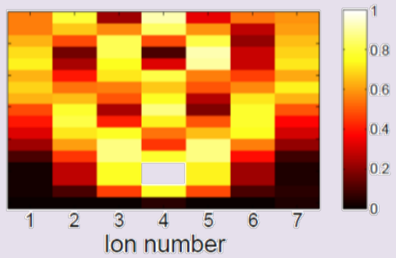
$0 < \alpha < 3$ tunable

P. Jurcevic et al., Nature **511**, 202 (2014)
P. Richerme et al., Nature **511**, 198 (2014)

single-spin magnetization



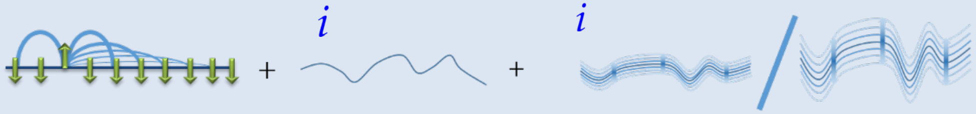
entropy $Tr(\rho\log(\rho))/\log(2)$



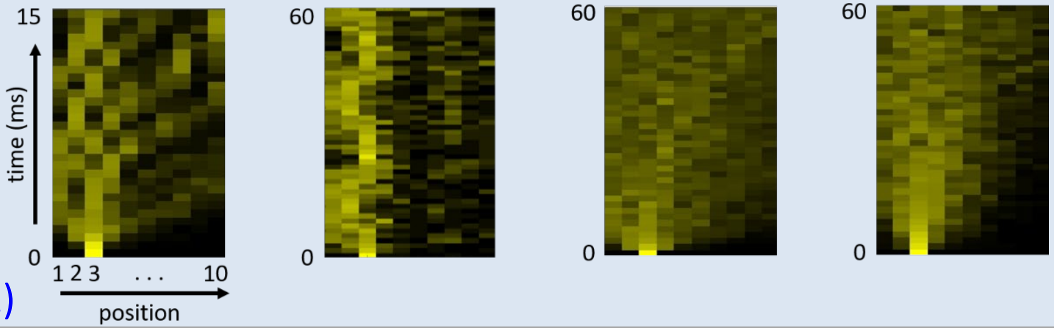
- Quantum transport simulations

programmable **disorder** **noise**

$$H_{XY} + \sum_i B_i\sigma_i^z + \sum_i W_i(t)\sigma_i^z$$



ballistic, coherent transport | Anderson localization | diffusive, enhanced transport | diffusive, suppressed transport

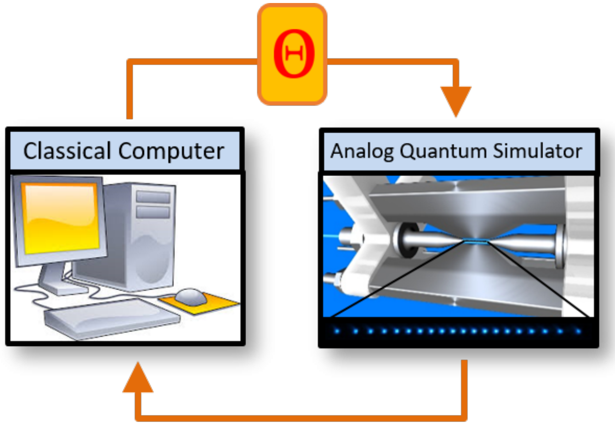


C. Maier et al.; PRL **122**, 050501 (2019), M. Joshi et al., Science **376**, 720 (2022)

Variational Quantum Simulations with Trapped Ions

- Finding the ground state of a Hamiltonian

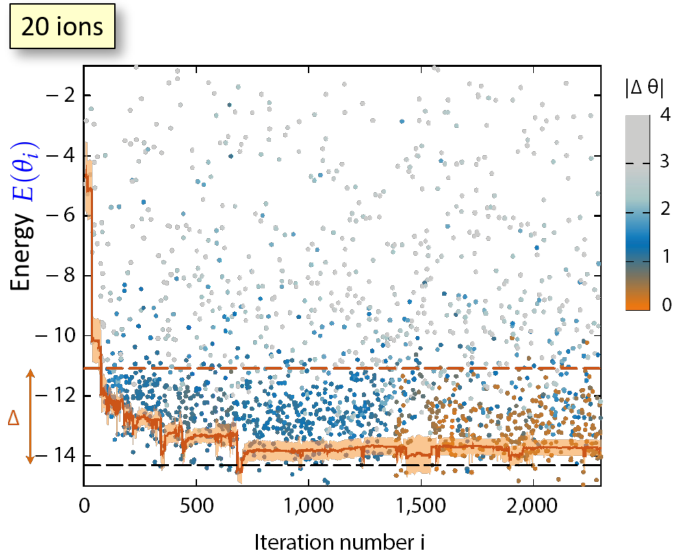
$$\langle \hat{H} \rangle = \sum_i \langle \hat{h}_i \rangle$$



$$\hat{H} = \omega \sum_{n=1}^{N} [\sigma_n^+ \sigma_{n+1}^- + \text{h.c.}] + \frac{m}{2} \sum_{n=1}^{N} (-1)^n \sigma_n^z + \sum_{n,l=1}^{N-1} J_{nl}\, \sigma_n^z \sigma_l^z$$

Lattice Schwinger model

C. Kokail, C. Maier et al., Nature **569**, 355-360 (2019)



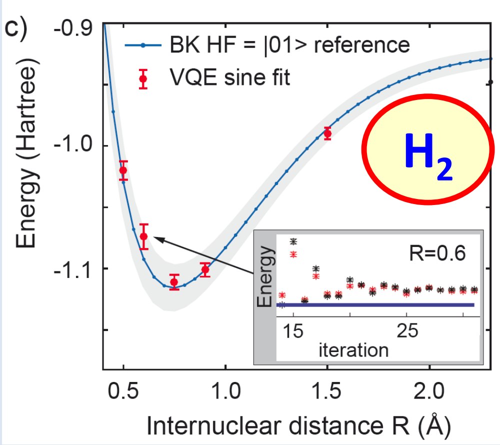
- Iteratively determine energies $\langle \hat{H}_T(\Theta) \rangle$
- Iteratively determine error bars from variances

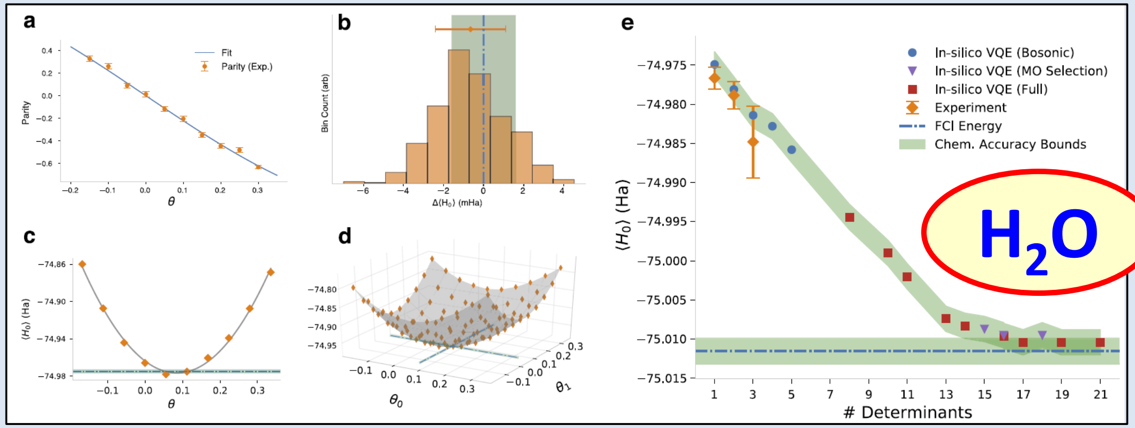
$$\langle (\hat{H}_T(\Theta) - E_0^{\Theta})^2 \rangle$$

- Quantum chemistry calculations

C. Hempel et al., Phys. Rev. **X 8**, 031022 (2018) — H_2

J. Kim et al., npj Quantum Inf. **6**, 33 (2020) — H_2O



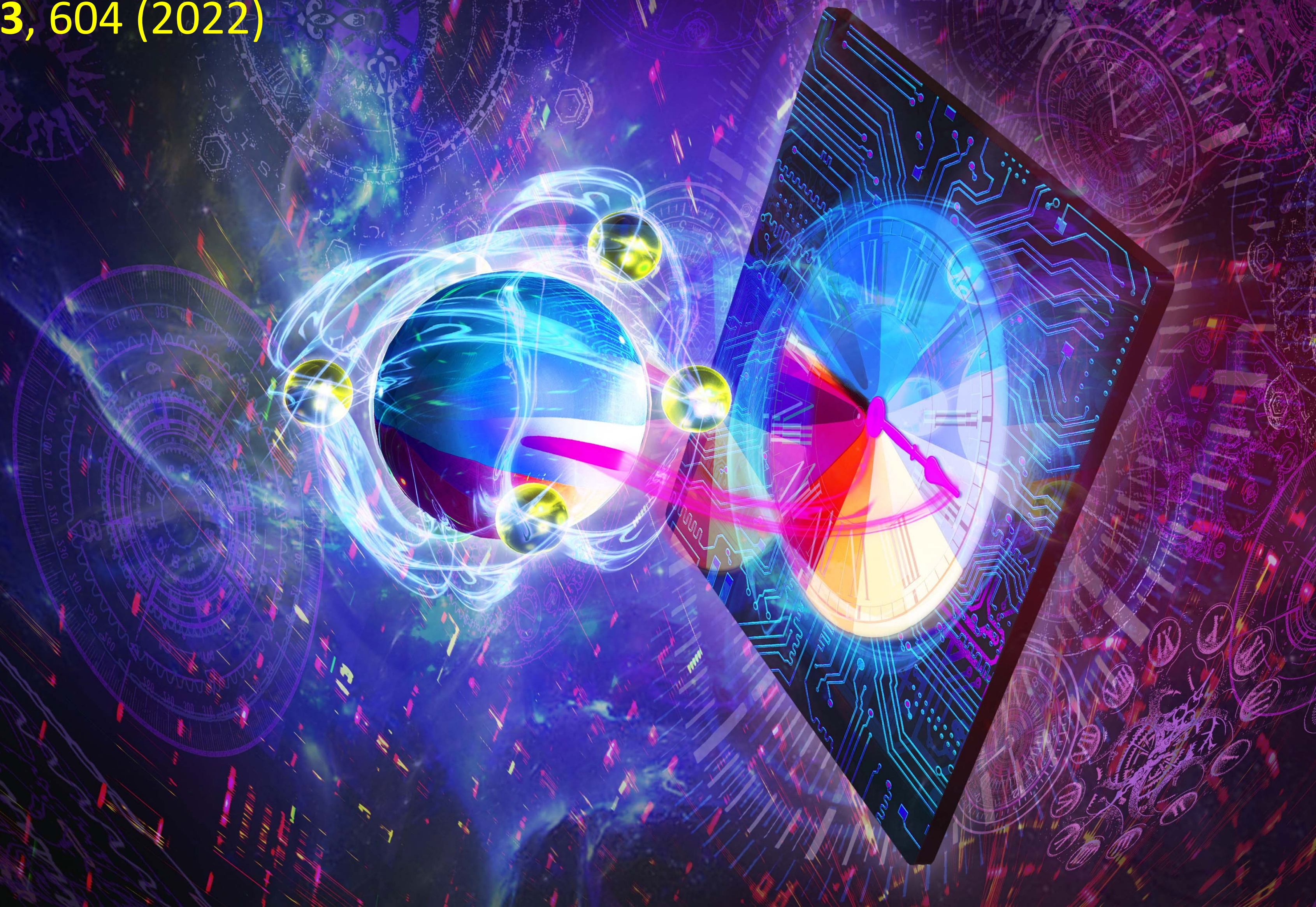


Optimal Metrology with Variational Quantum Circuits

C. Marciniak et al., Nature **603**, 604 (2022)

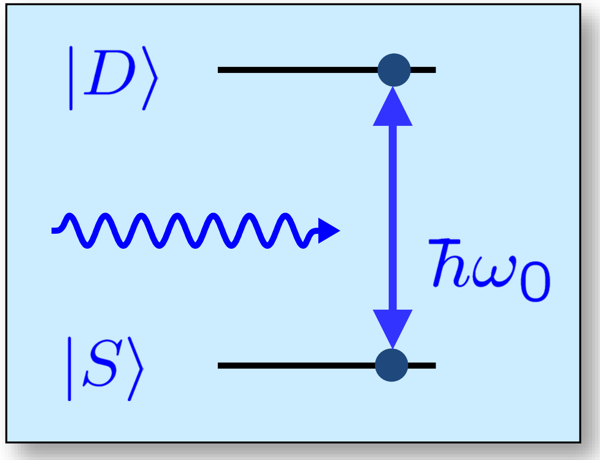
C. Marciniak R. Kaubrügger

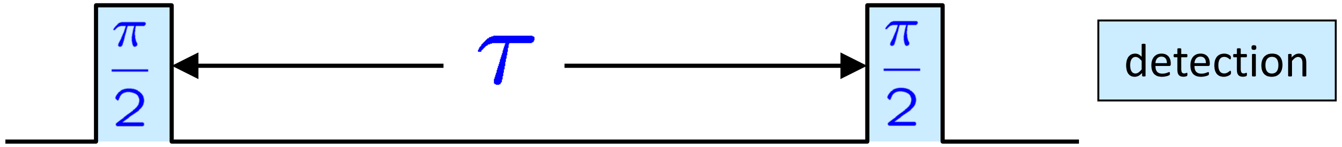
T. Feldker P. Zoller



Frequency Standard with Trapped Ca^+ Ions

Ramsey spectroscopy with interrogation time τ

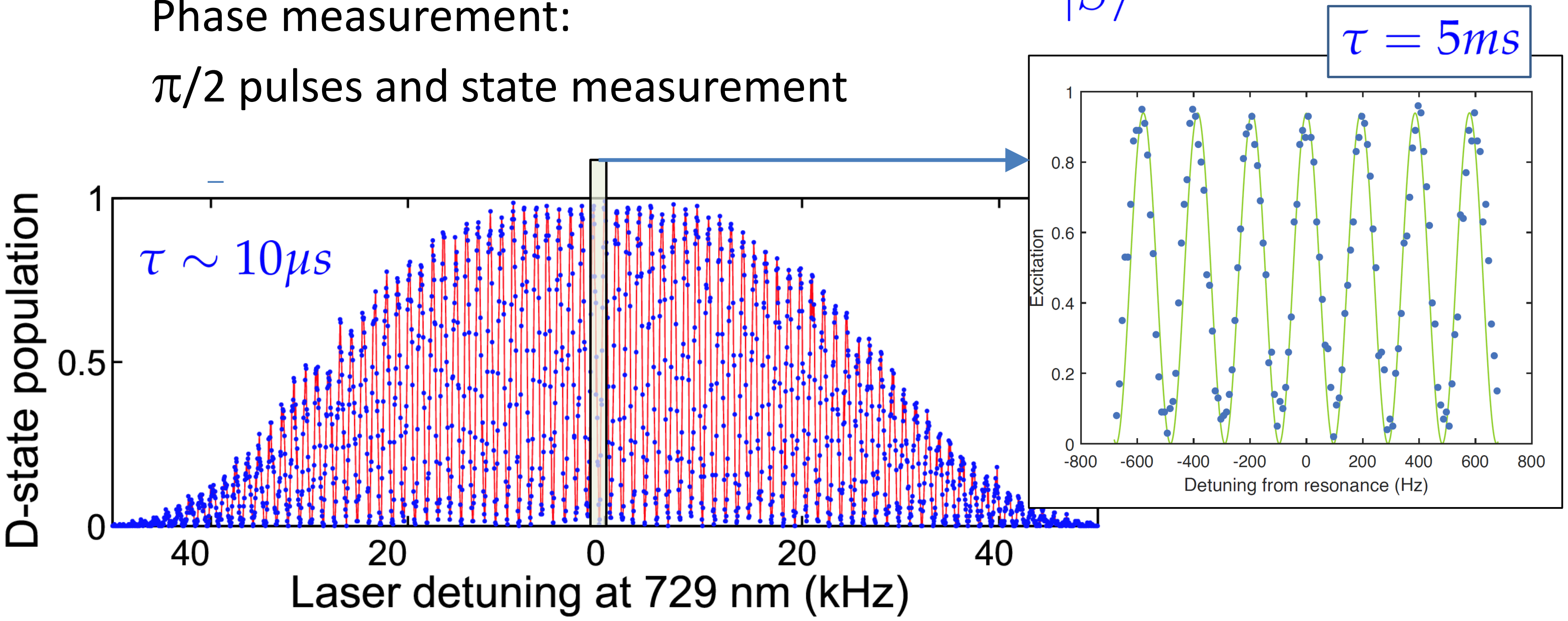




$$|S\rangle \longrightarrow |S\rangle + |D\rangle \xrightarrow{\tau} |S\rangle + e^{-i\Delta\tau}|D\rangle \rightarrow |D\rangle,\ |S\rangle$$

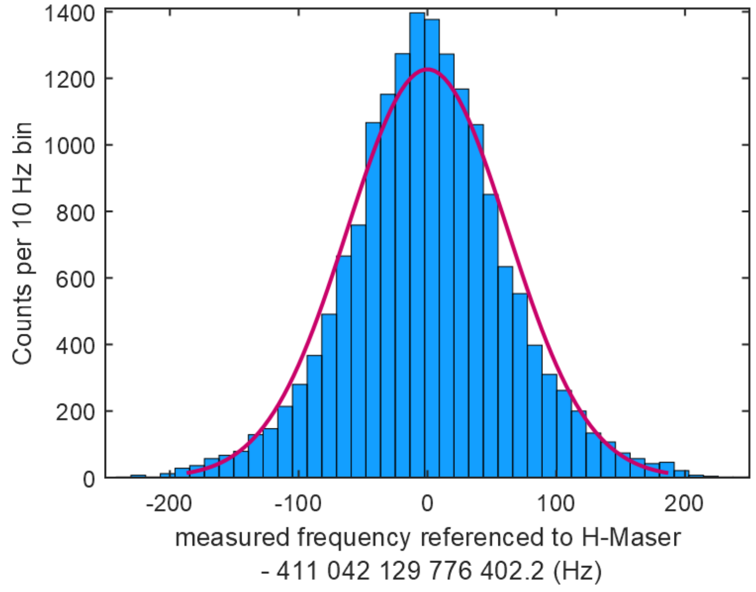
Phase measurement:

π/2 pulses and state measurement



M. Chwalla et al.,
PRL **102**, 023002 (2009)

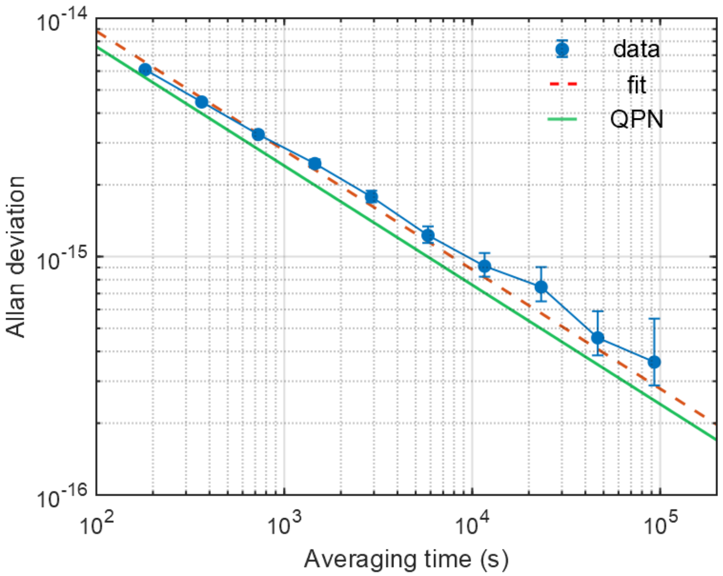
Frequency Standard with Trapped Ca^{+} Ions

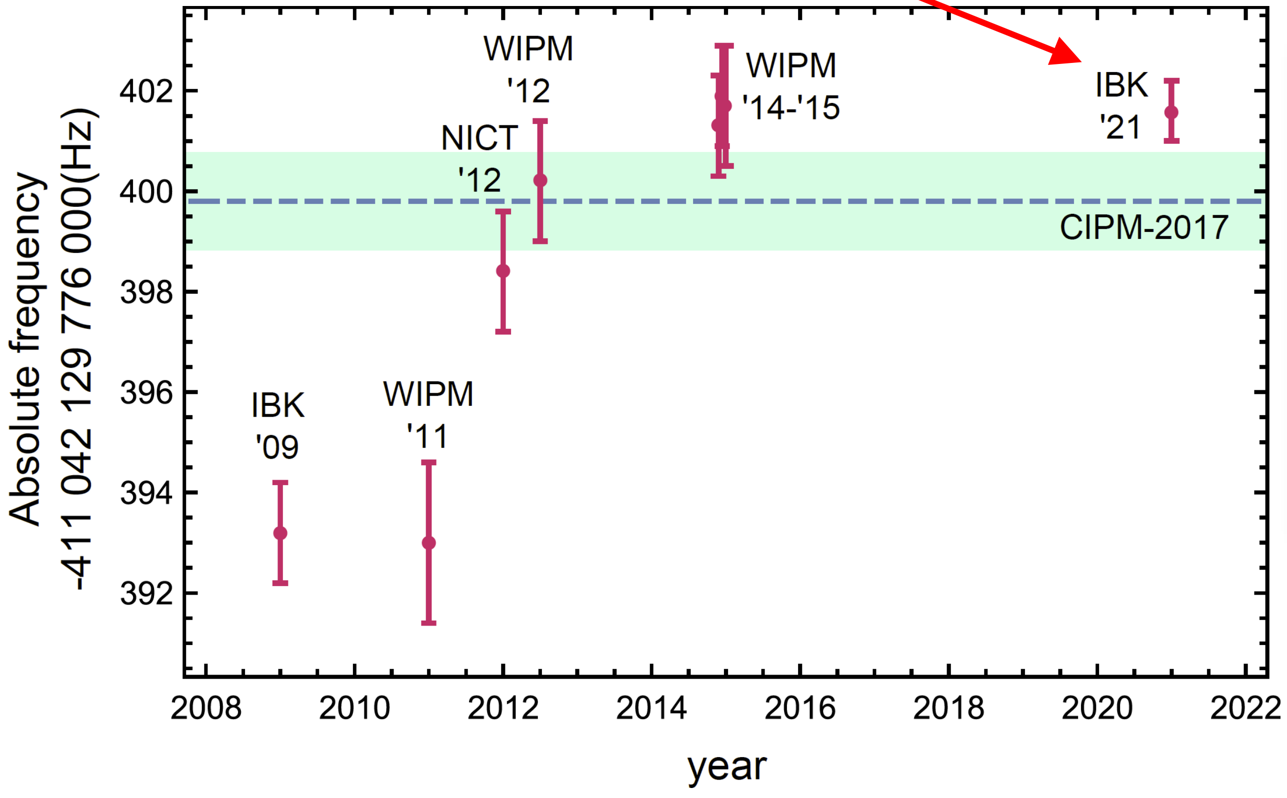


$$f_{S-D} = 411\ 042\ 129\ 776\ 401.3\ (0.6)\ (0.14)\,Hz$$

current statistics

current systematics

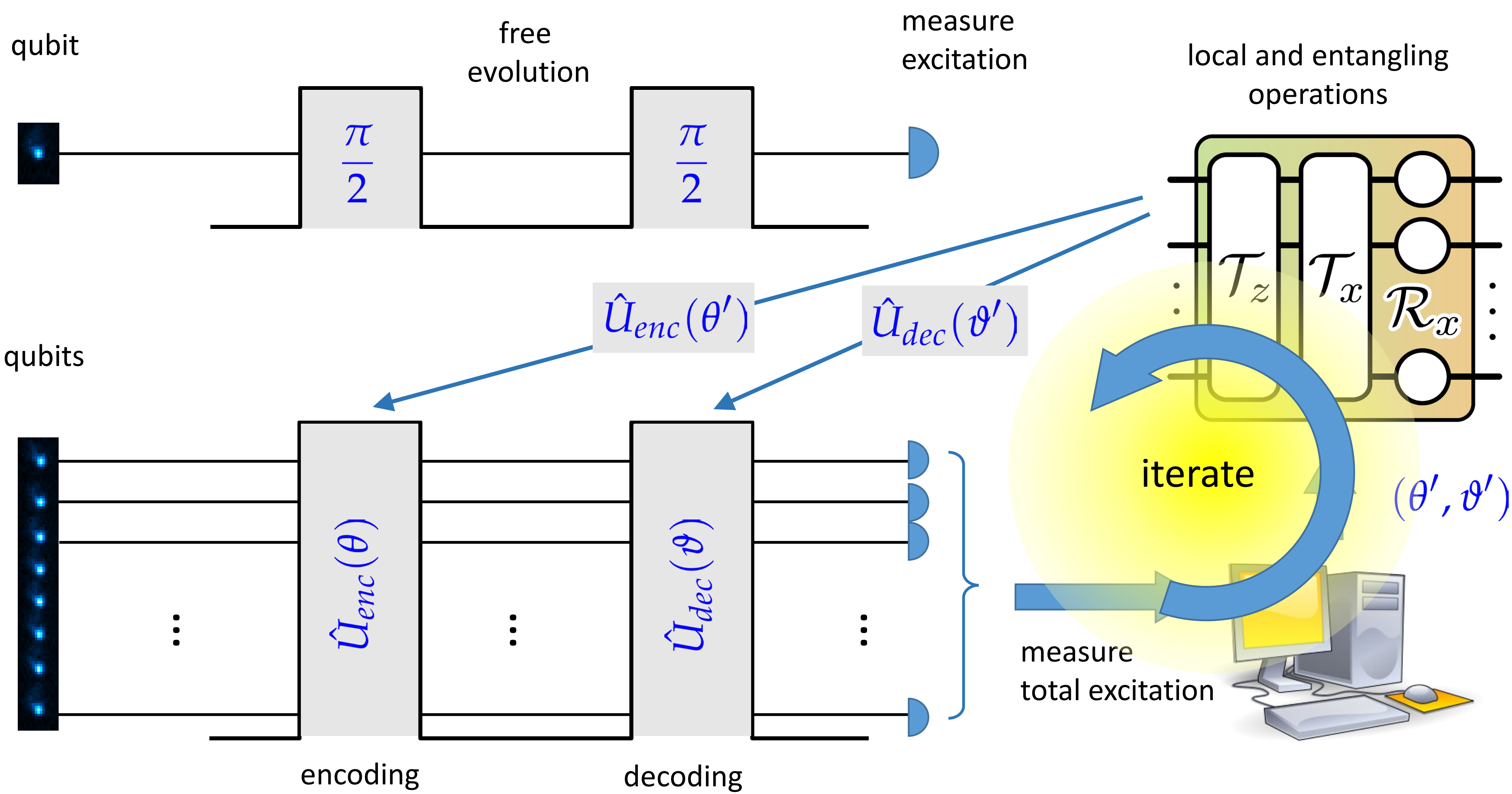




M. Guevara-Bertsch

IBK 2021

Optimal Metrology with Quantum Circuits: Generalized Ramsey Spectroscopy

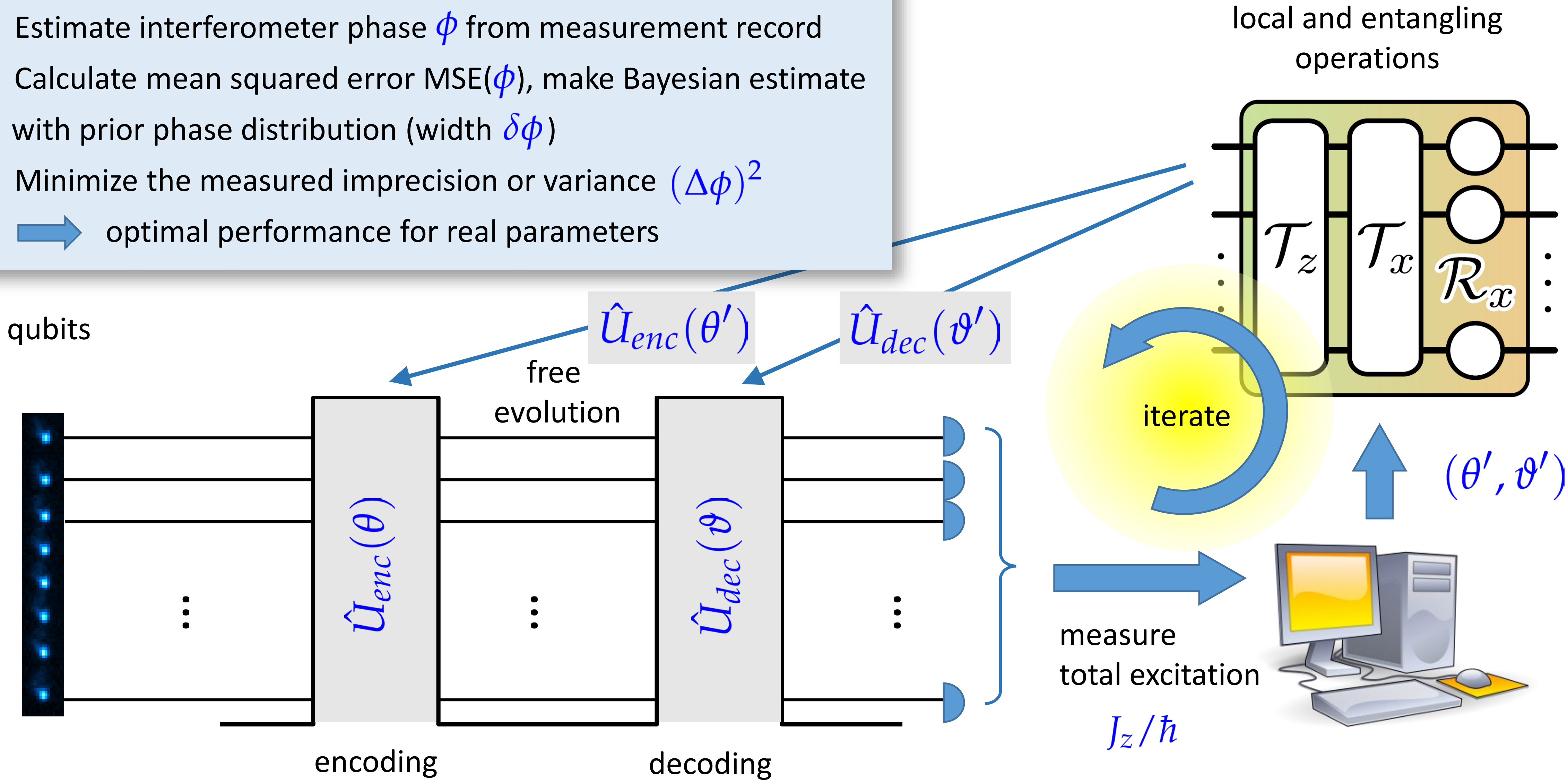


Optimal Metrology with Quantum Circuits: Optimal Ramsey Interferometry

Goal:

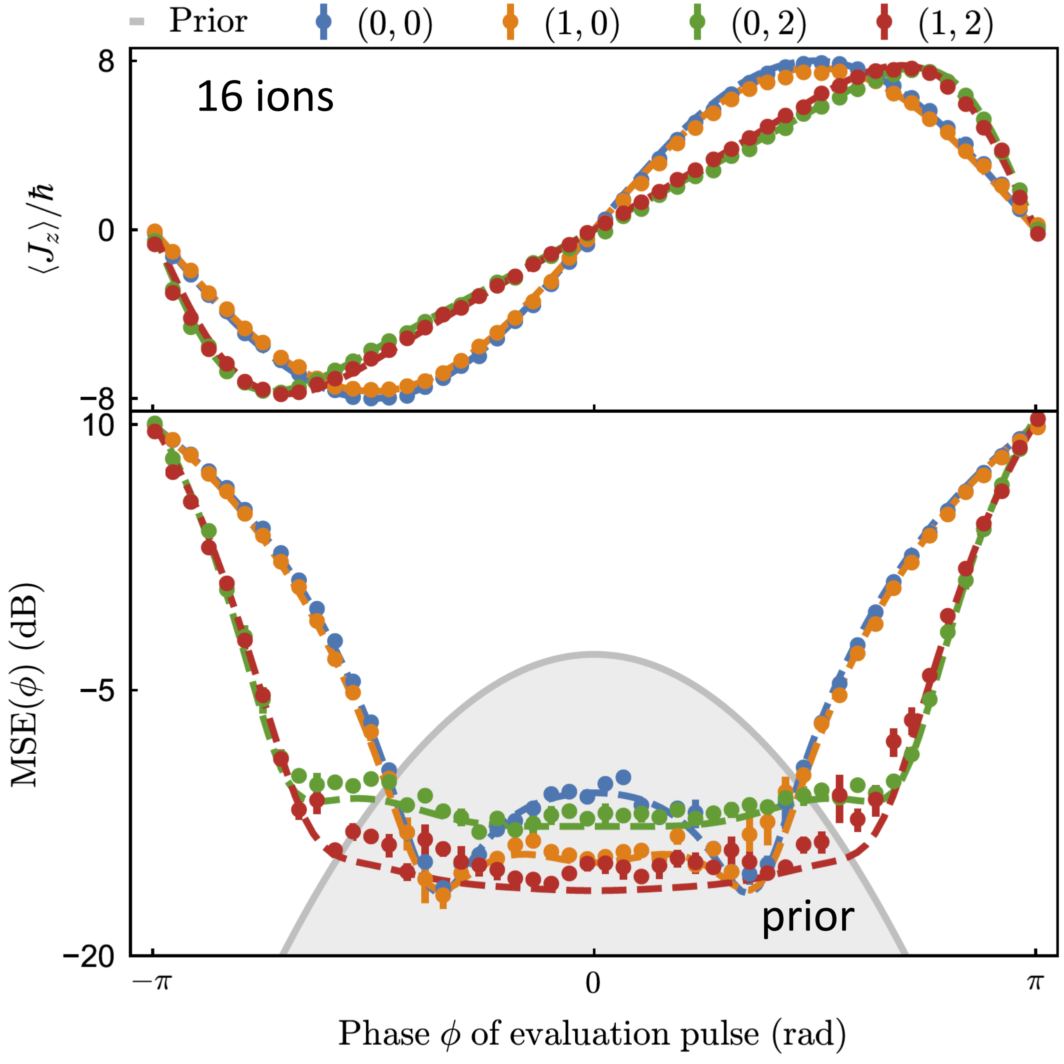
- Estimate interferometer phase ϕ from measurement record
- Calculate mean squared error MSE(ϕ), make Bayesian estimate with prior phase distribution (width $\delta\phi$)
- Minimize the measured imprecision or variance $(\Delta\phi)^2$

→ optimal performance for real parameters



Performance of variationally optimized Ramsey sequences

$(n_{enc}, n_{dec}) =$



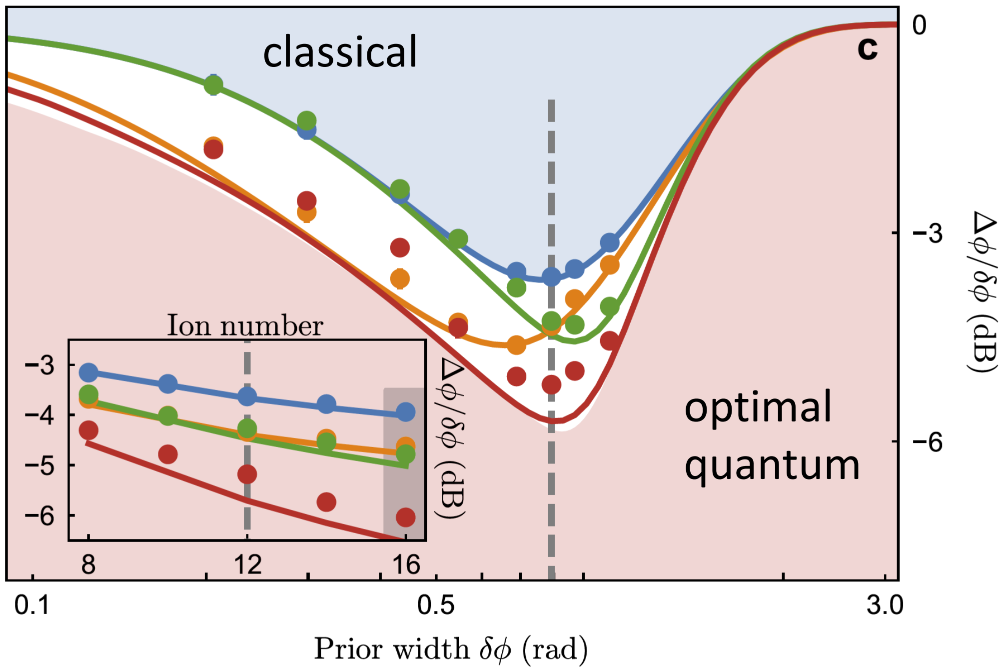
Four cases - encoding/decoding layer depth - four circuits

$(0,0)$ CSS: classical coherent spin state (standard Ramsey)

$(1,0)$ SSS: squeezed spin state

$(0,2)$ CSS input and tailored measurement

$(1,2)$ Both tailored input and measurement

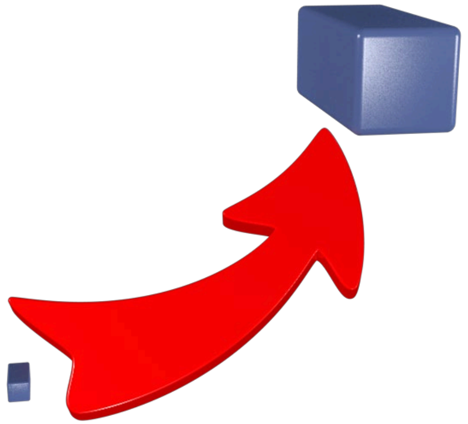


C. Marciniak, T. Feldker et al., Nature **603**, 604 (2022)

Scaling the Ion Trap Quantum Computer: Goals and Strategies

Scaling UP needs more

- qubits → traps (1D, 2D)
- operations → better control, quantum error correction
- comput. power → quantum software, solving a key problem
- predictability → component performance to system performance

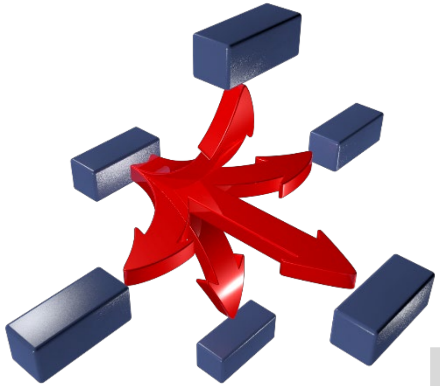


Scaling DOWN needs less

- space → miniaturize control hardware
- errors → protection schemes (passive), correction (active)
- time → fast(er) gate operations

Scaling OUT needs

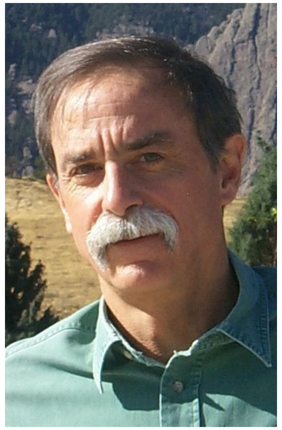
- interconnectivity → modular design, optical interfaces (hardware)
- distributivity → quantum parallel processing (software)



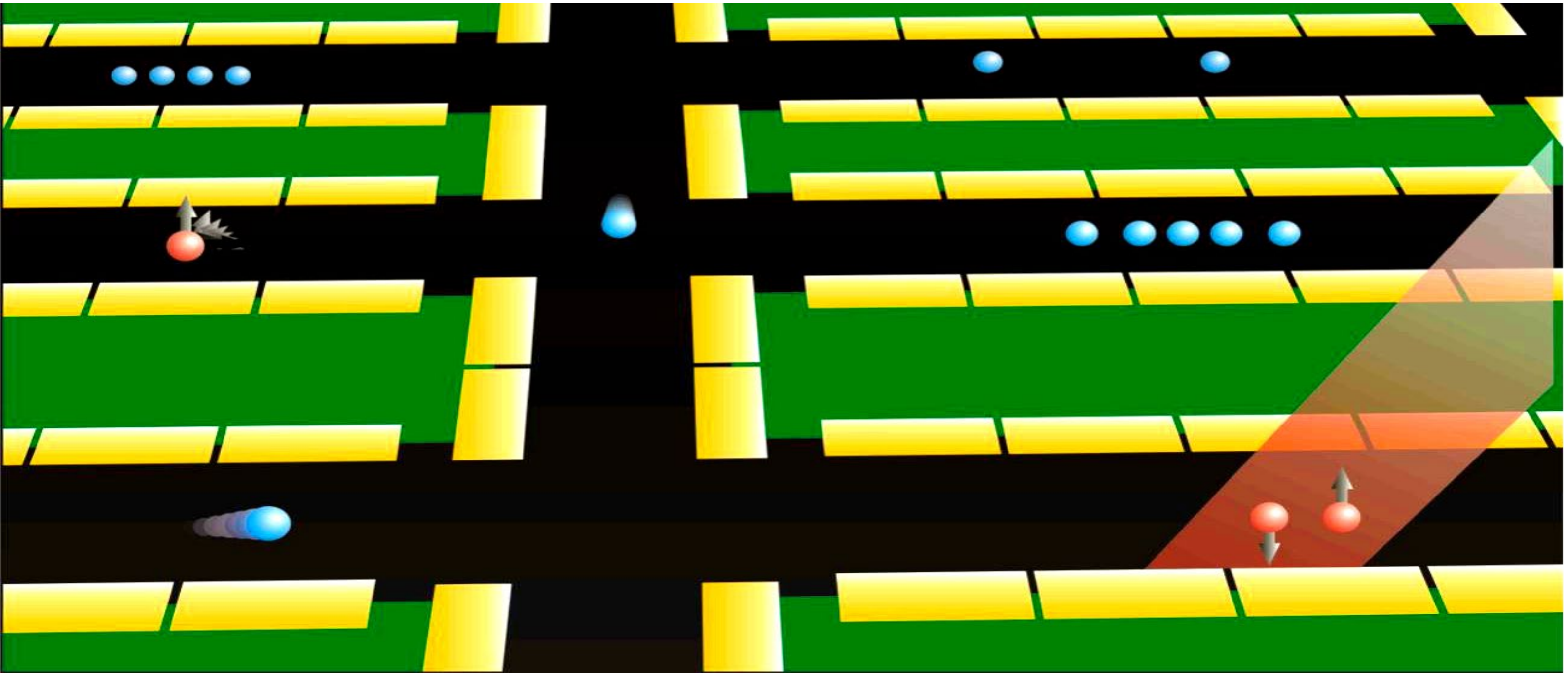
Scaling the ion trap quantum computer …

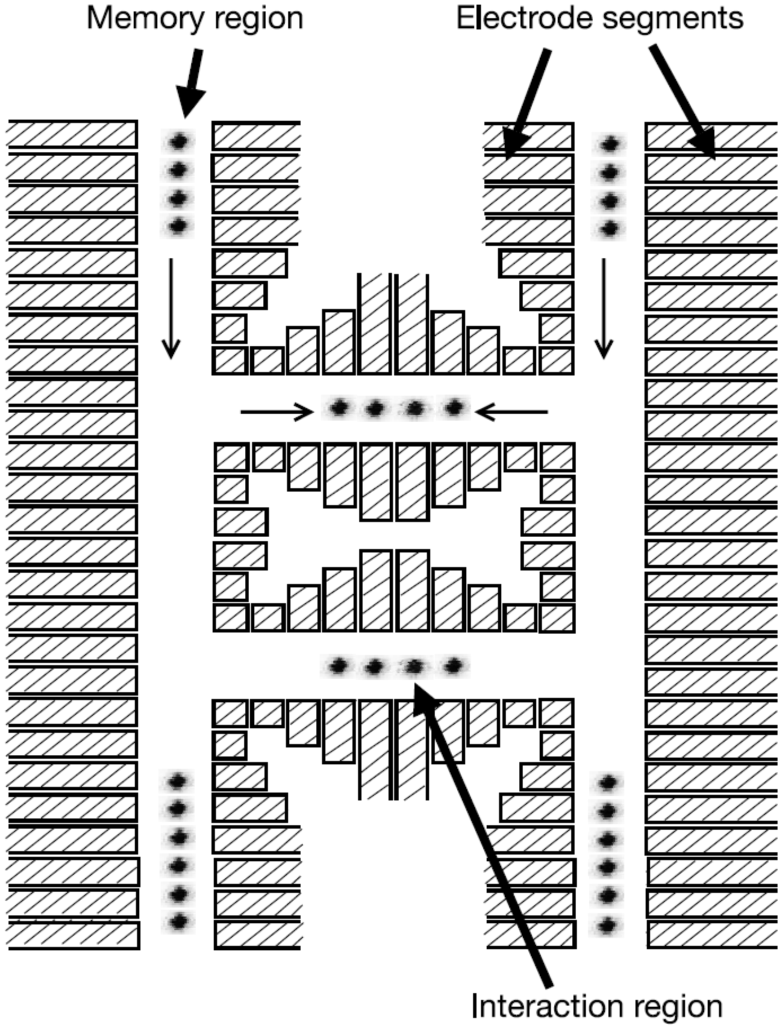
- more ions, **carry quantum information with phonons**:
  Cirac-Zoller, slow for many ions
- move ions, **carry quantum information with ions**:
  Kielpinski et al., Nature **417**, 709 (2002)

→ chip-traps, micro-structured traps



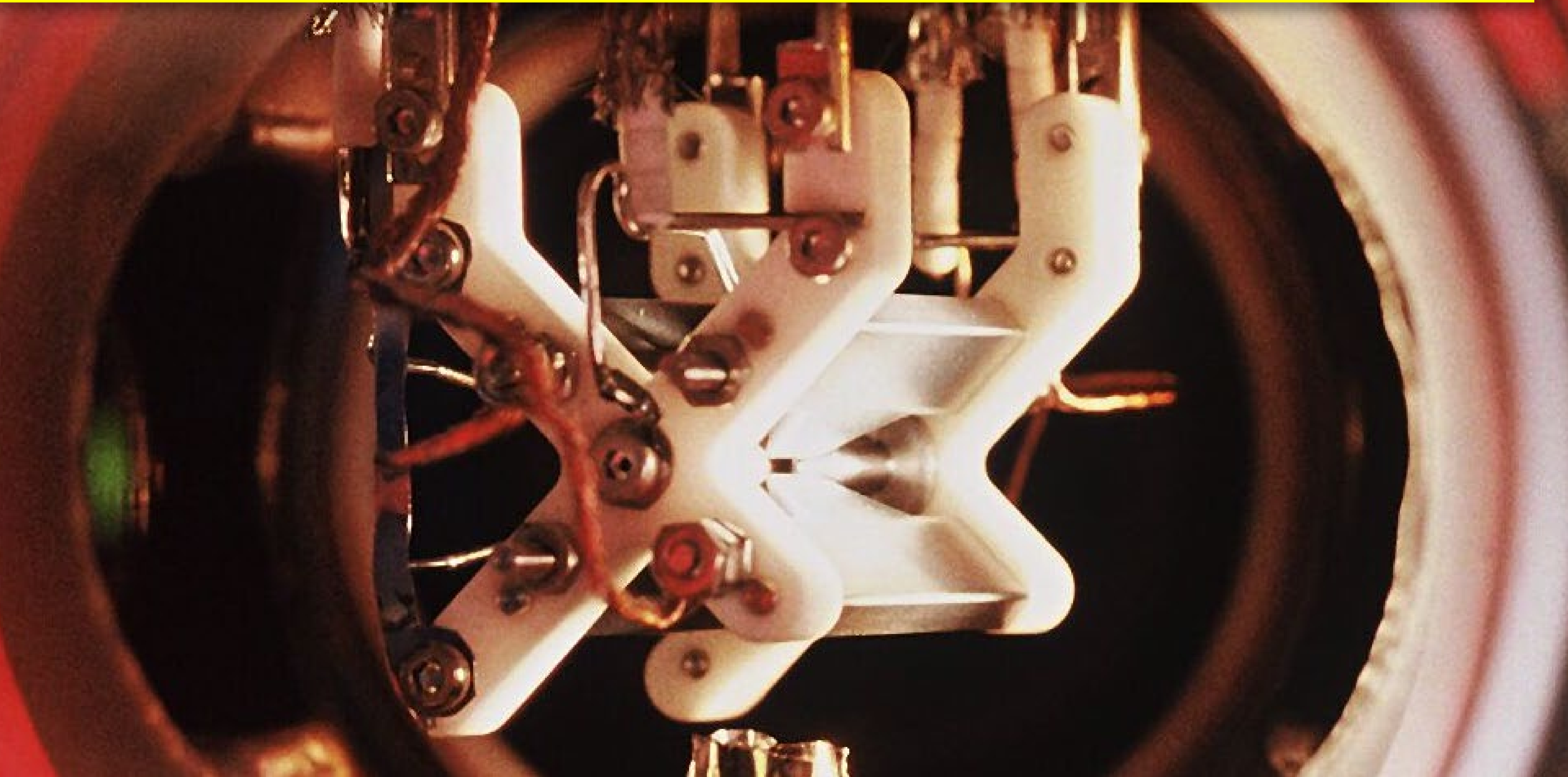
D. Wineland



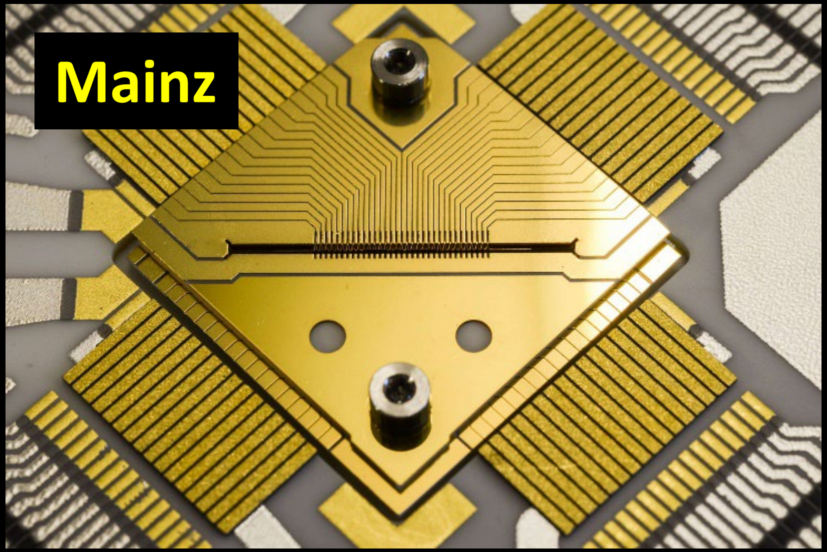


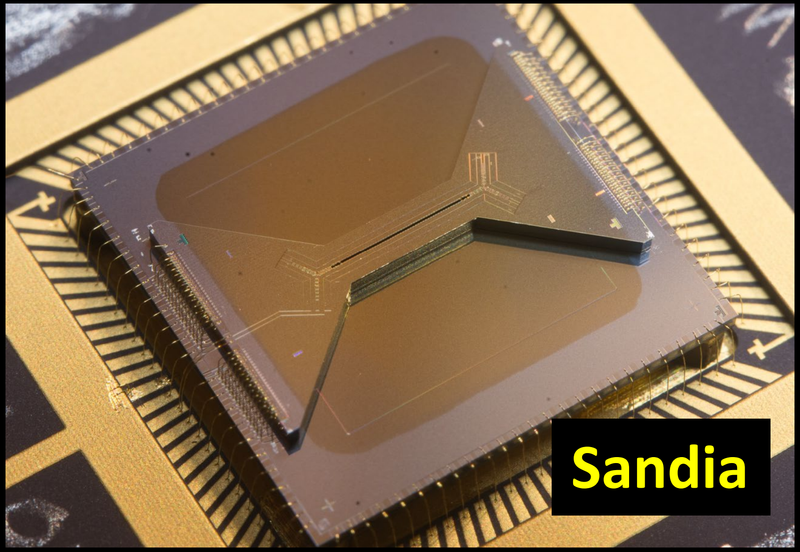
pioneered and developed by the Wineland group at NIST

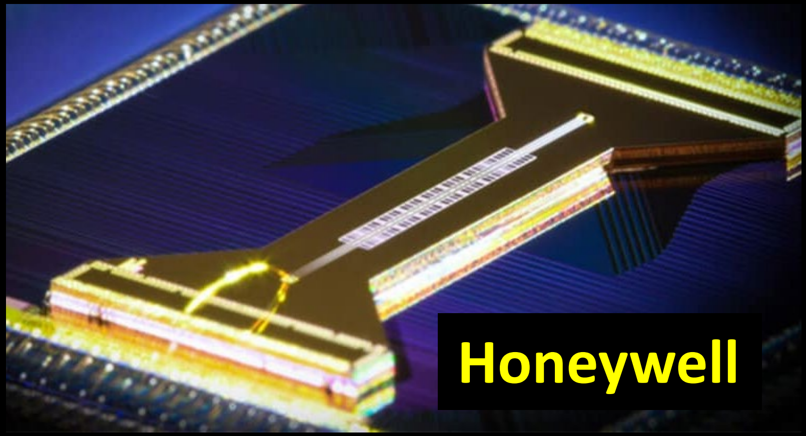
Ion trap 2000 - 2010

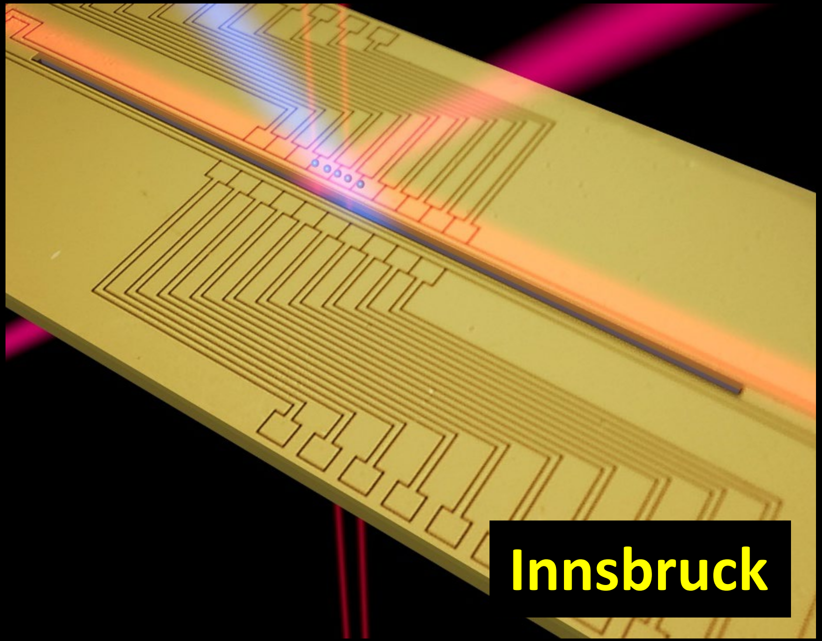


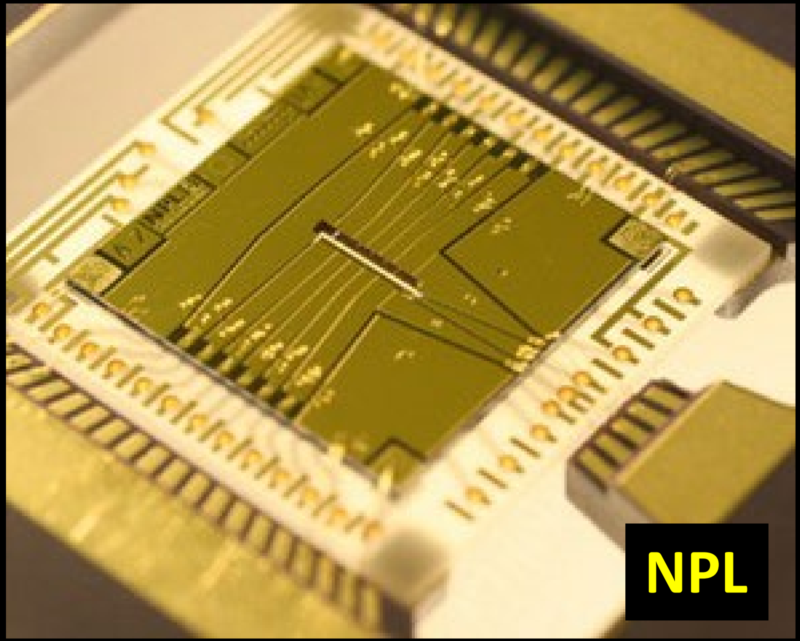
2010 – 2020 Chip Trap Quantum Processors

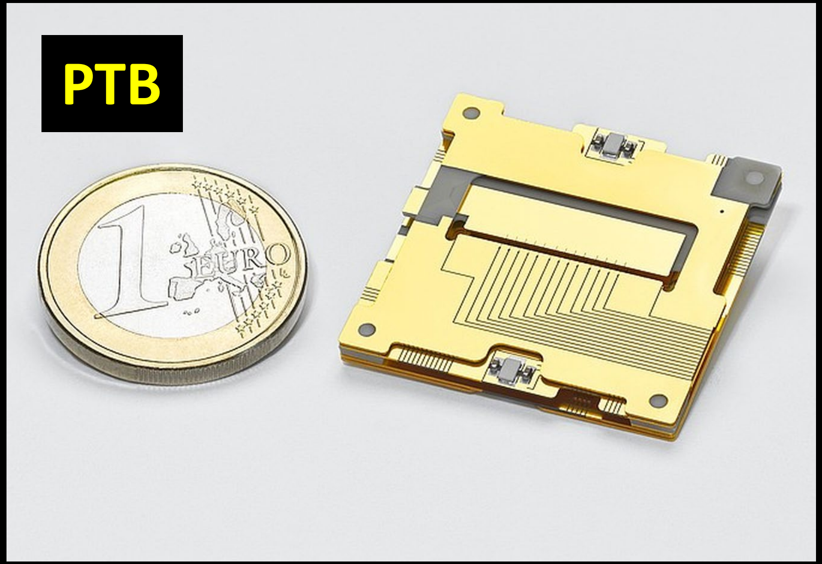




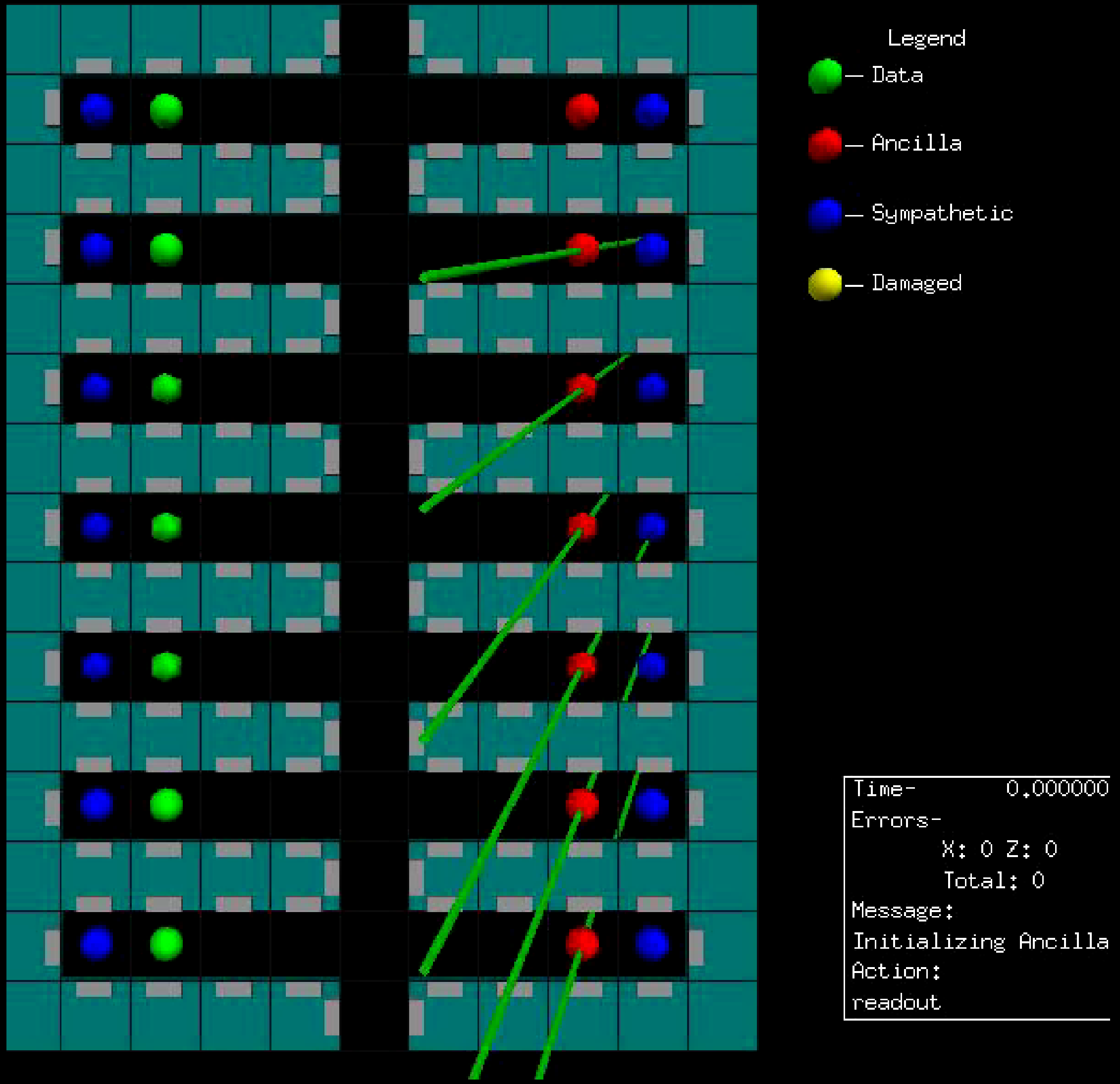








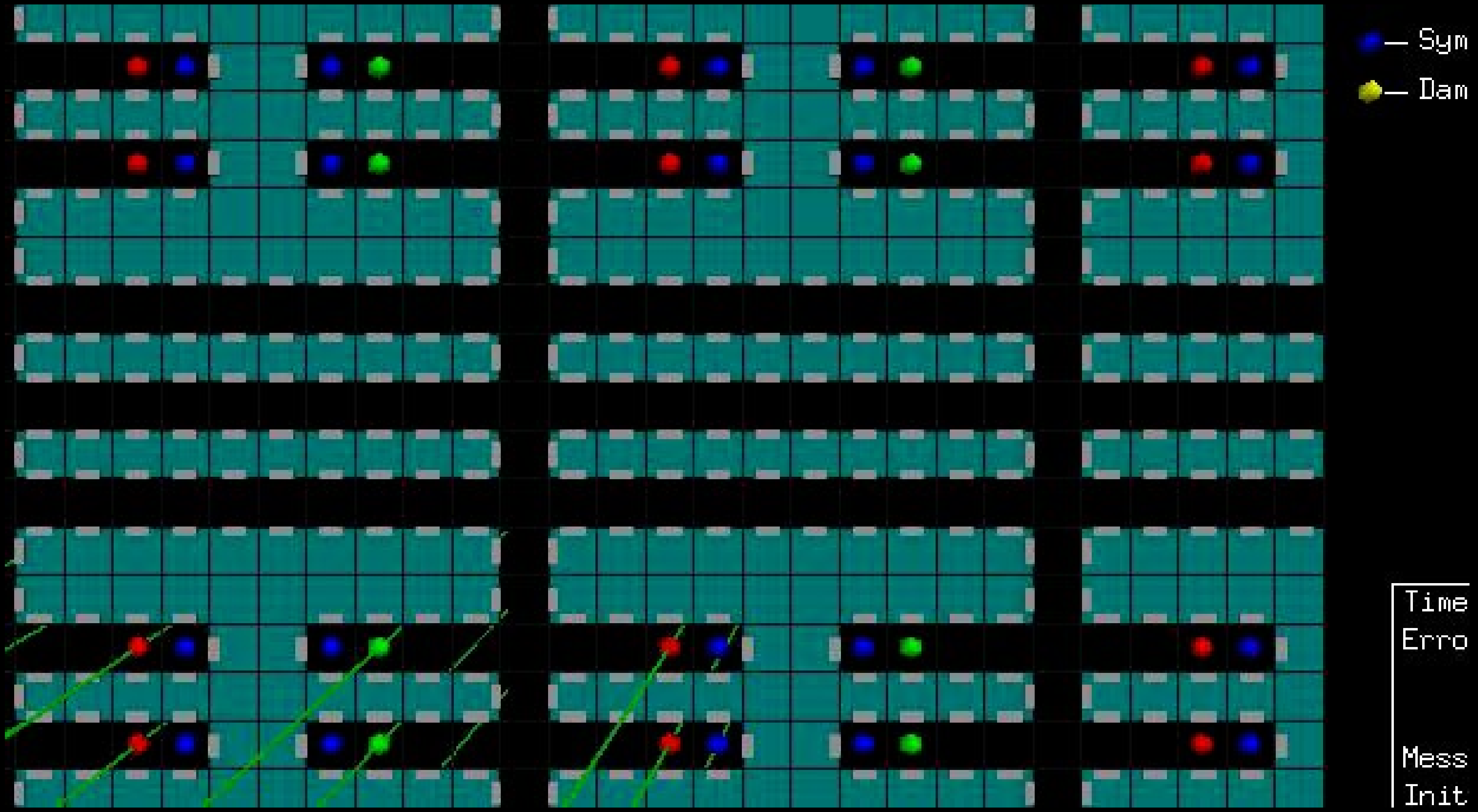
Operating a quantum algorithm on an ion chip



Isaac Chuang, MIT

Movie: © Isaac Chuang, MIT

Operating a quantum algorithm on an ion chip



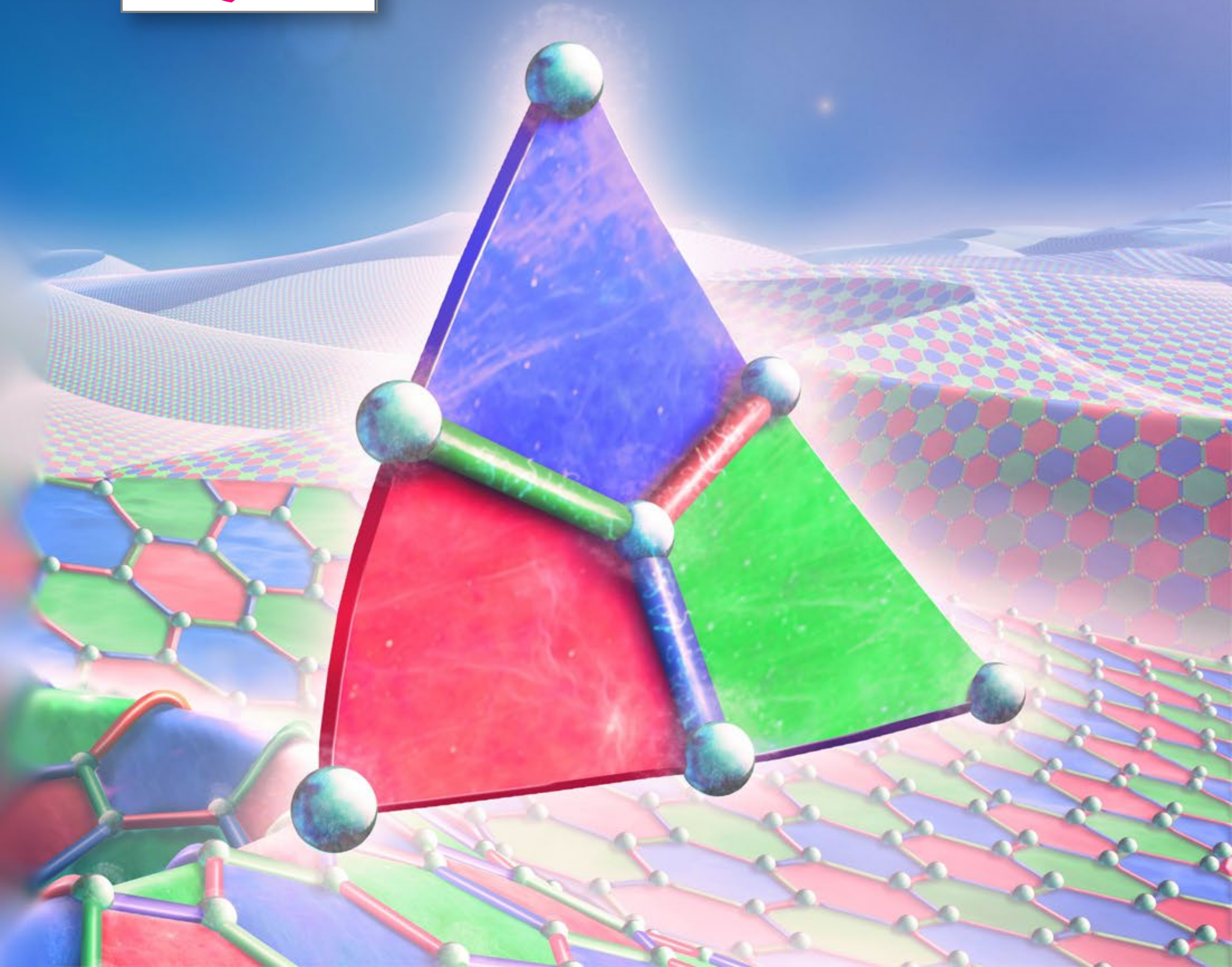
Movie: © Isaac Chuang, MIT

Keeping a Qubit Alive
and
The Quest for a Scalable Ion Trap Quantum Computer

eQual

D. Nigg, M. Müller et al., Science **345**, 302 (2014)

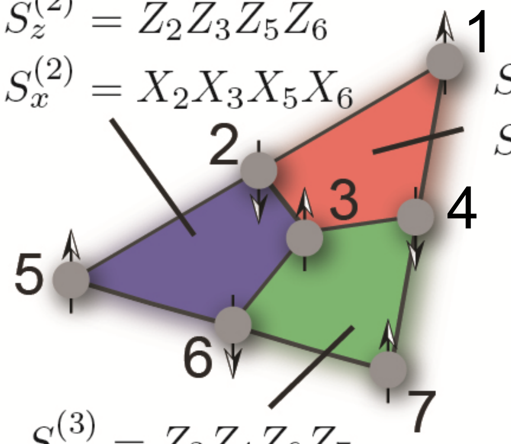
Th. Monz M. Müller



Encoding a Logical Qubit: Color Code Qubit

$S_z^{(2)} = Z_2 Z_3 Z_5 Z_6$

$S_x^{(2)} = X_2 X_3 X_5 X_6$



$S_z^{(1)} = Z_1 Z_2 Z_3 Z_4$

$S_x^{(1)} = X_1 X_2 X_3 X_4$

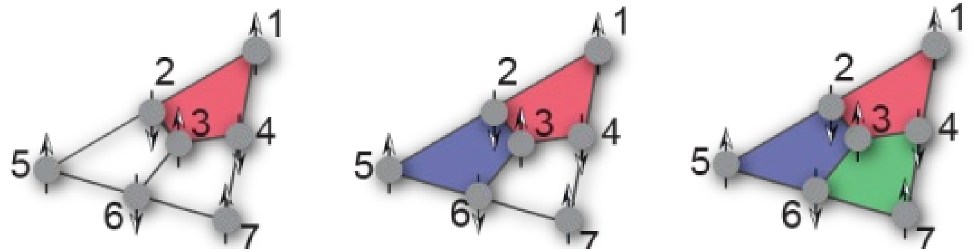
$S_z^{(3)} = Z_3 Z_4 Z_6 Z_7$

$S_x^{(3)} = X_3 X_4 X_6 X_7$

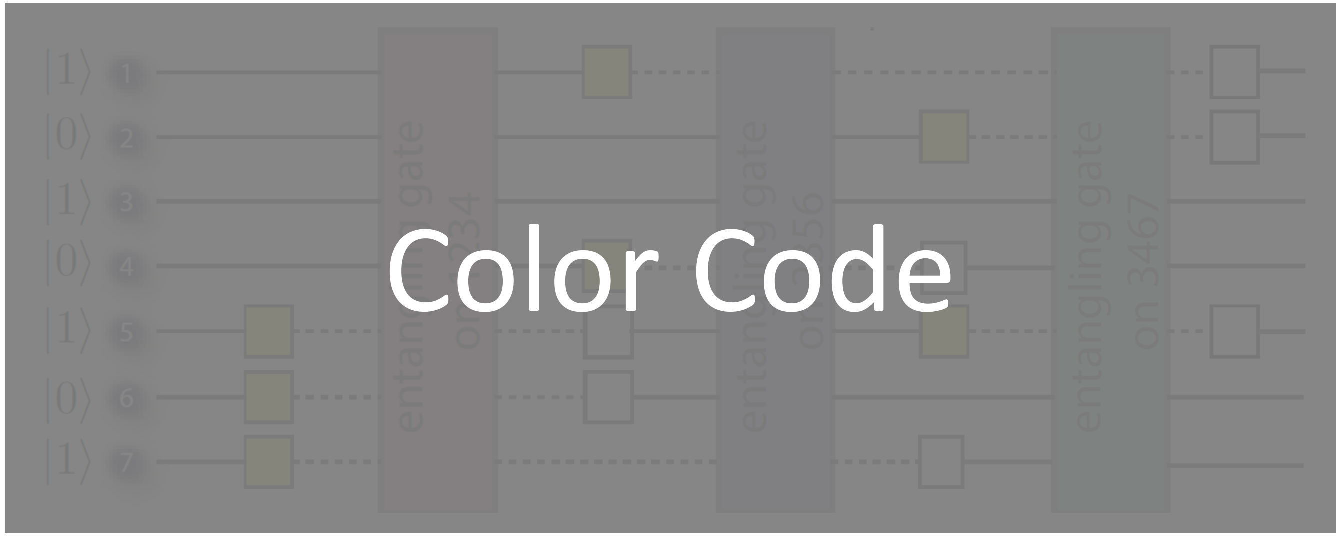
Stabilizers:

$S_x^{(j)}, S_z^{(j)}, j = 1,2,3$

- Encoding: Prepare in +1 eigenspace
- |1010101> : already fulfills Z requirements
- plaquette-wise entanglement for X cond.



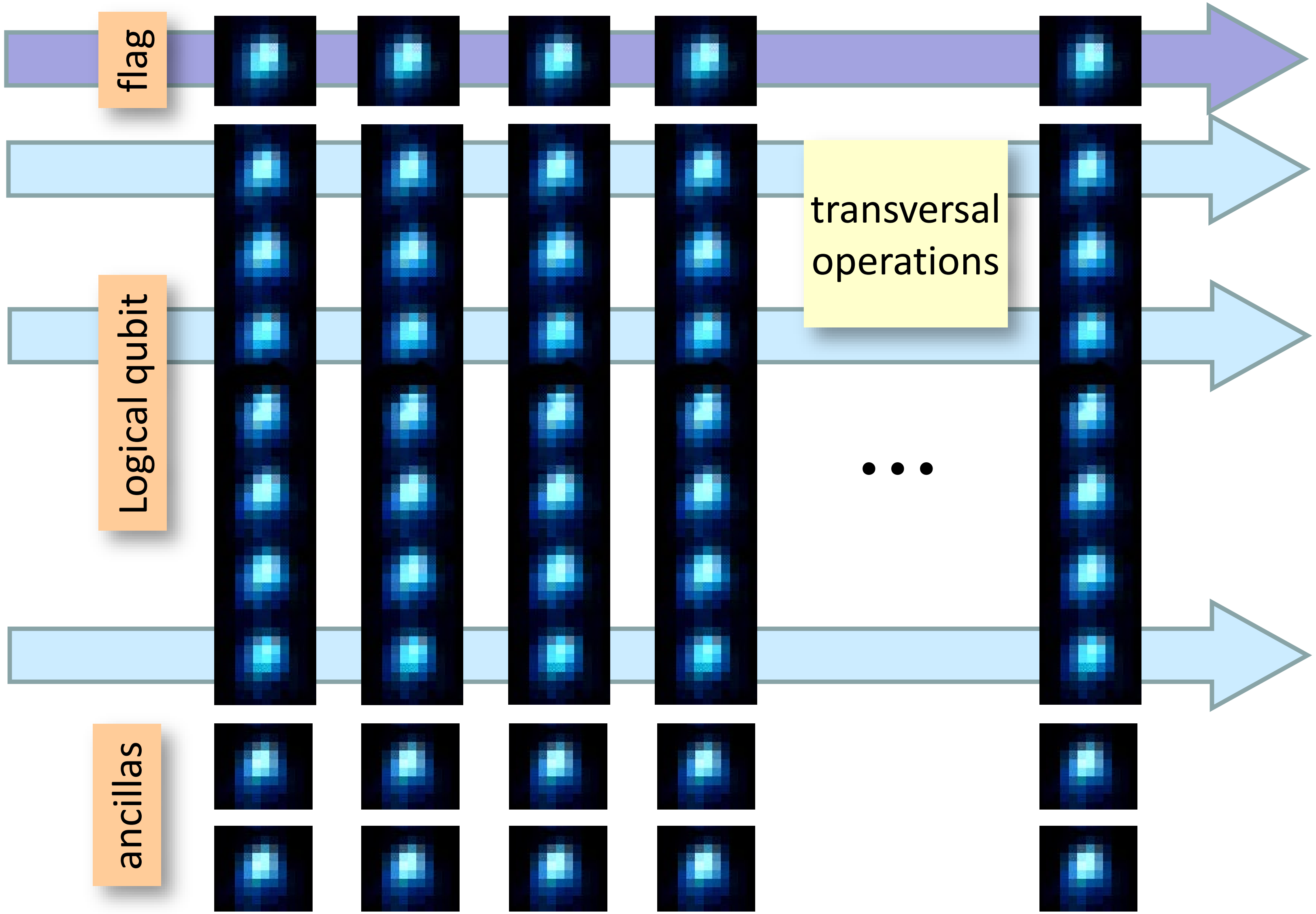
Encoding



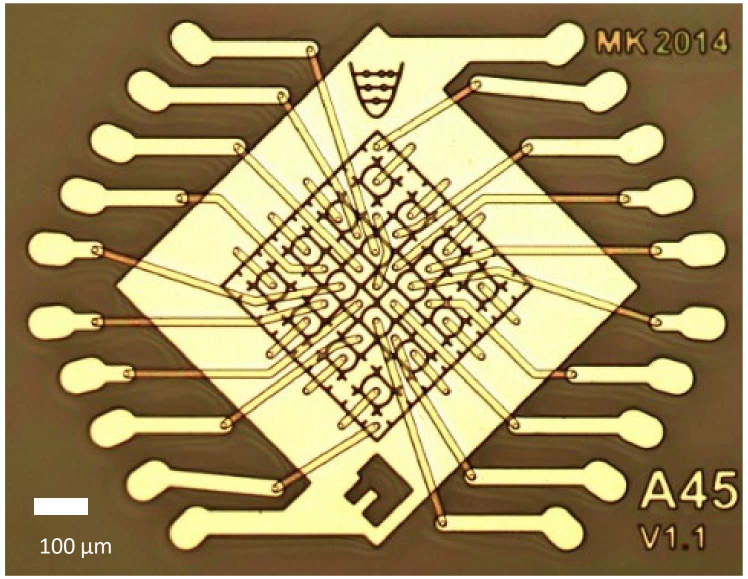
$|0\rangle_L$

logical qubit

A long-term vision: a 2D ion trap architecture



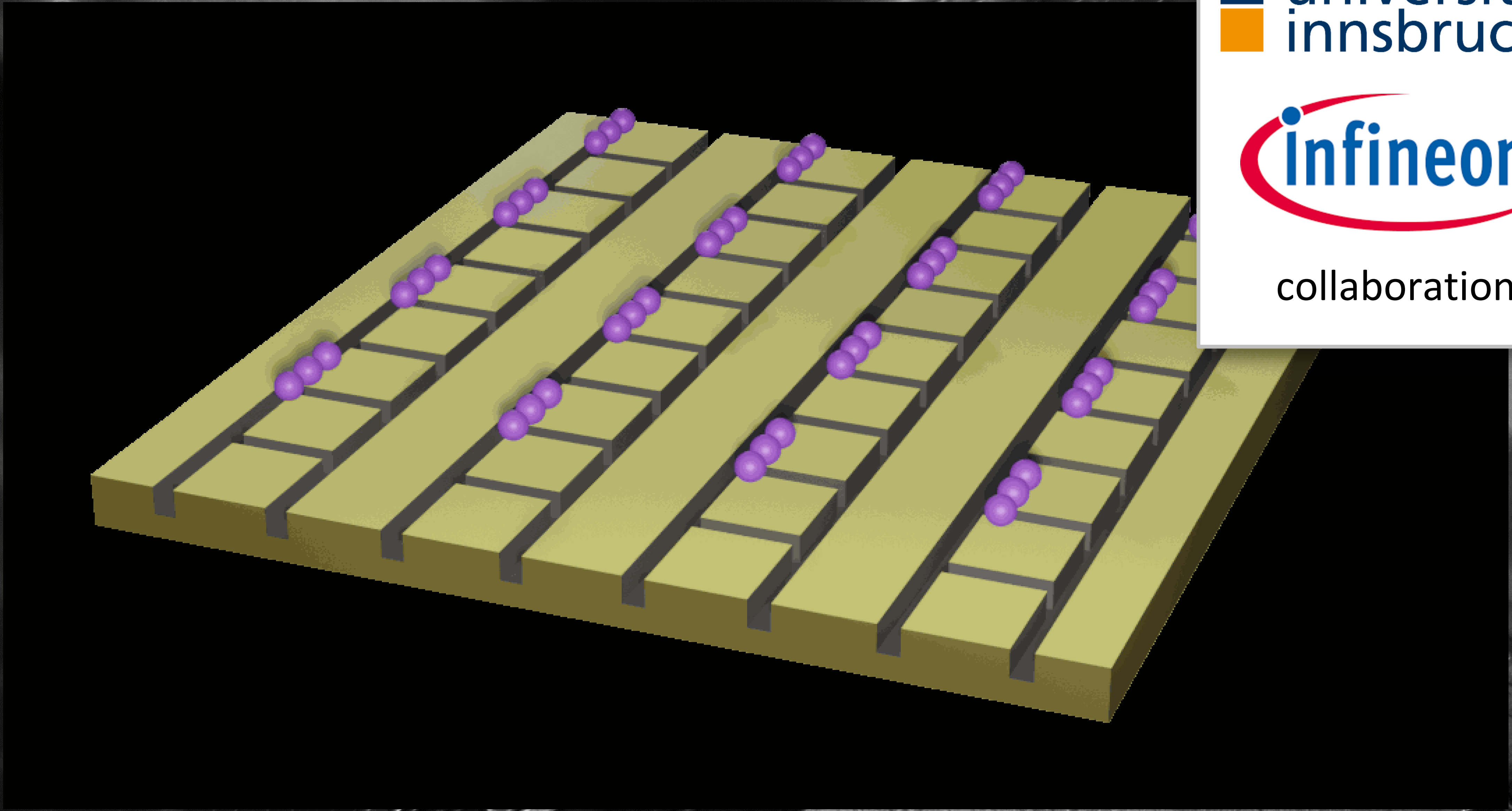
Requires the construction of ion traps that provide **ion arrays**



Innsbruck: 2D trap 2014

universität innsbruck

2D ion trap arrays



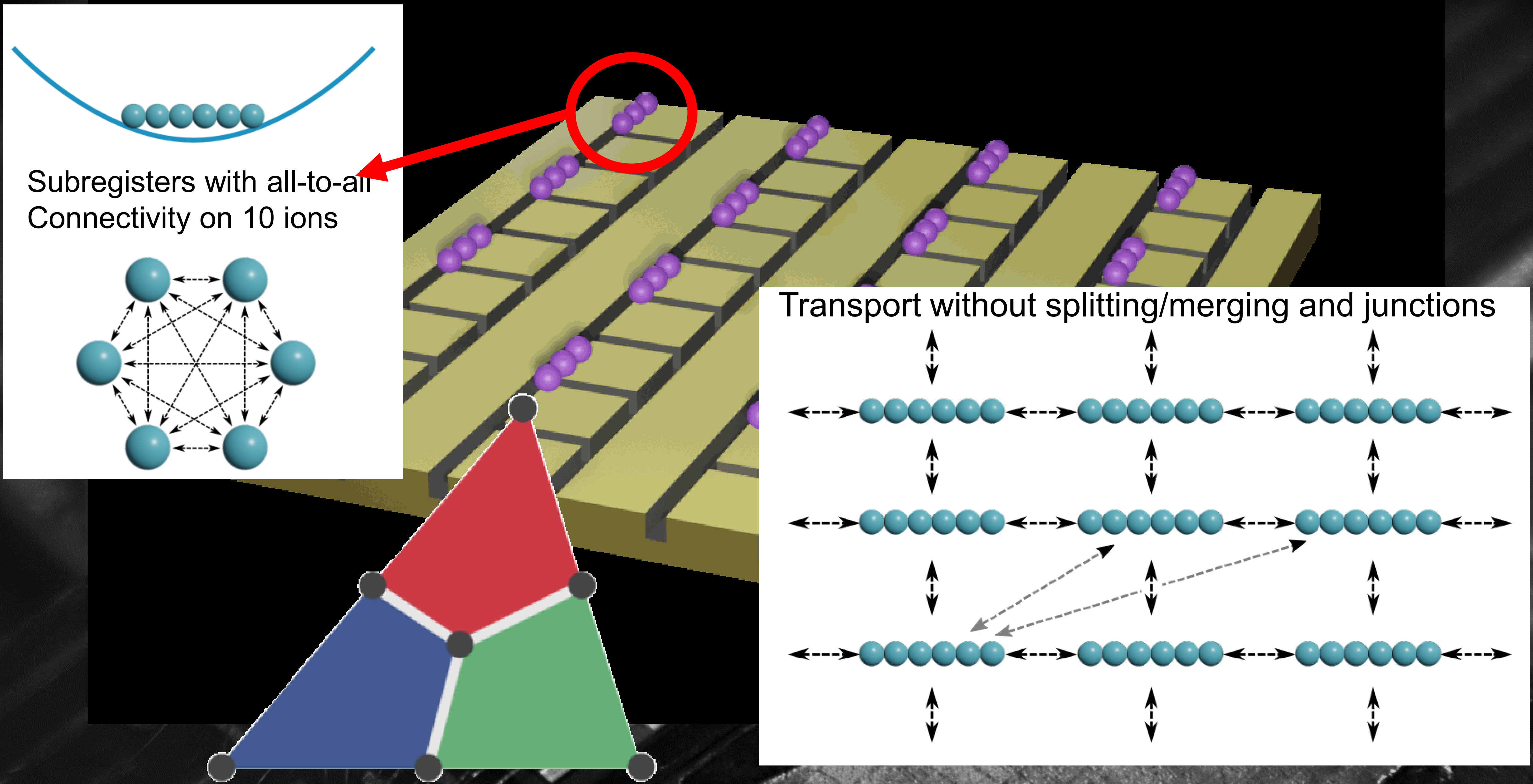
universität innsbruck

Infineon

collaboration

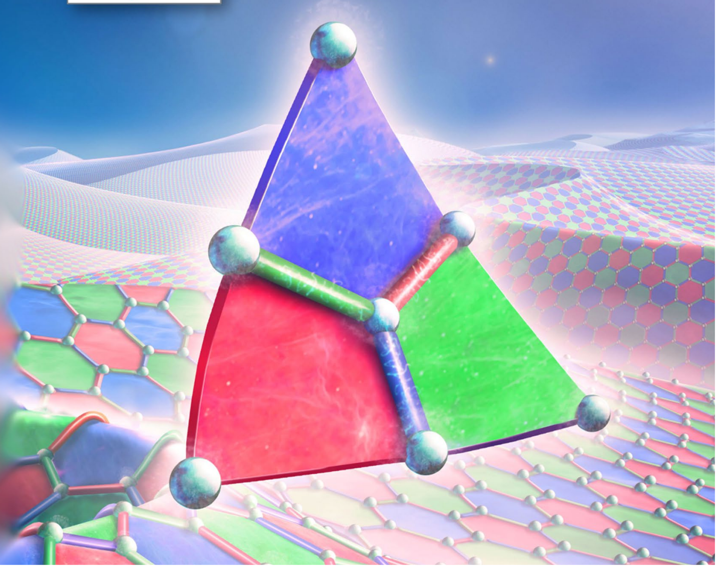
arXiv:2406.0240

Motivation for architecture

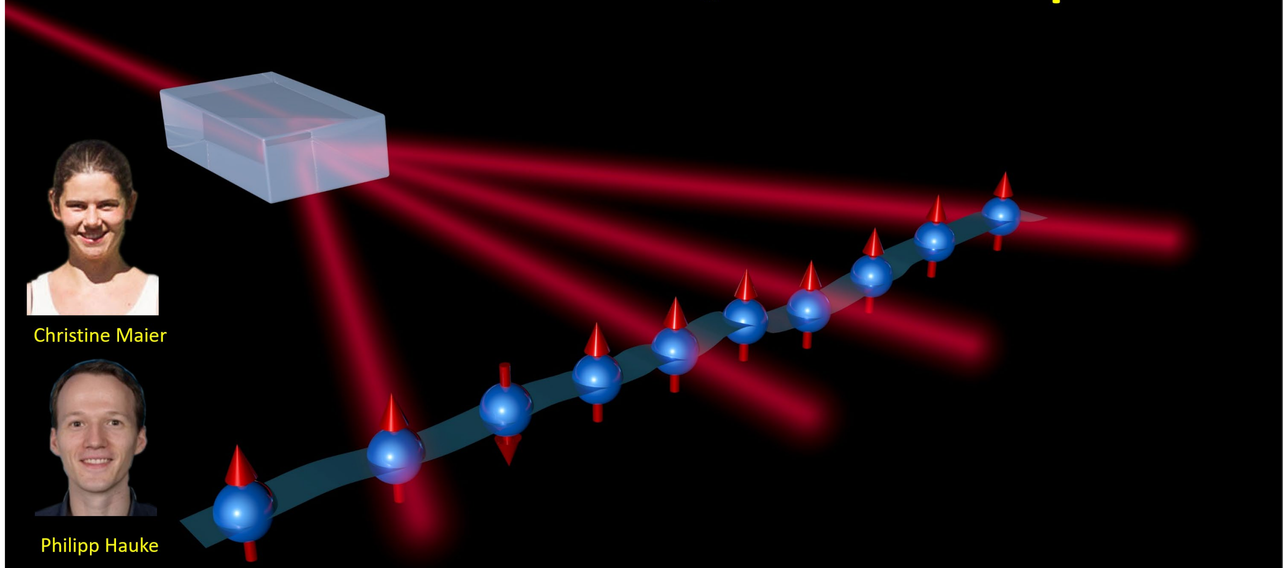


Keeping a Qubit Alive
and
The Quest for a Scalable Ion Trap Quantum Computer

D. Nigg, M. Müller et al., Science **345**, 302 (2014)

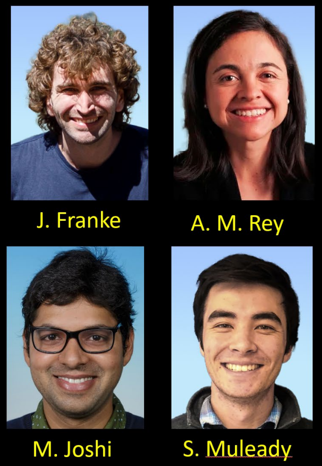


Environment Assisted Quantum Transport

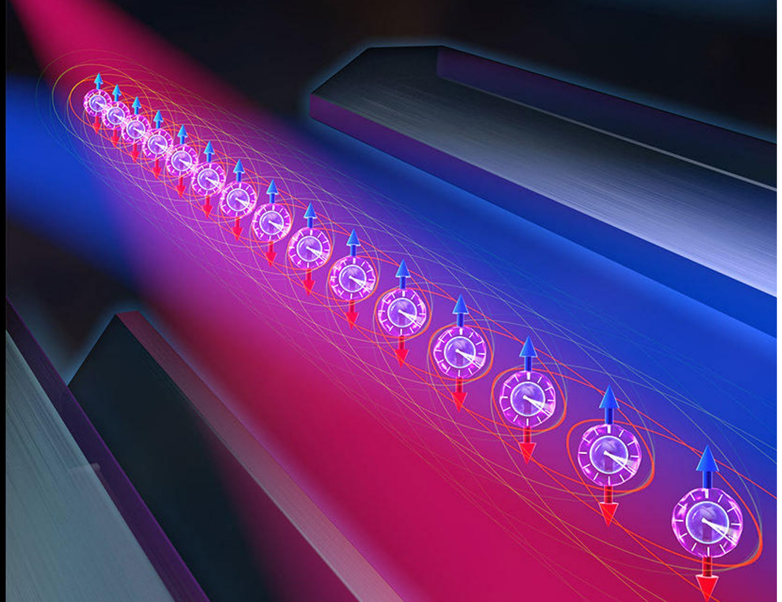


Phys. Rev. Lett. **122**, 050501 (2019)

Spin-squeezing with finite-range interactions



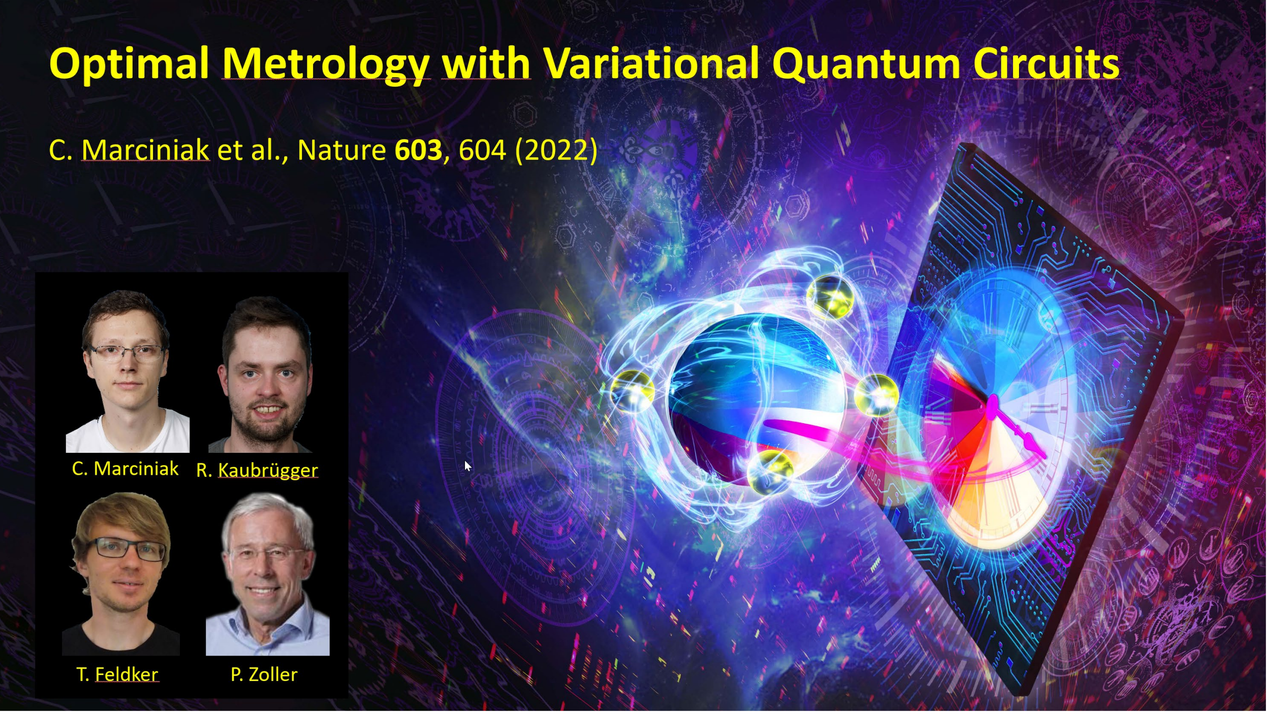
J. Franke et al., Nature **621**, 740 (2023)

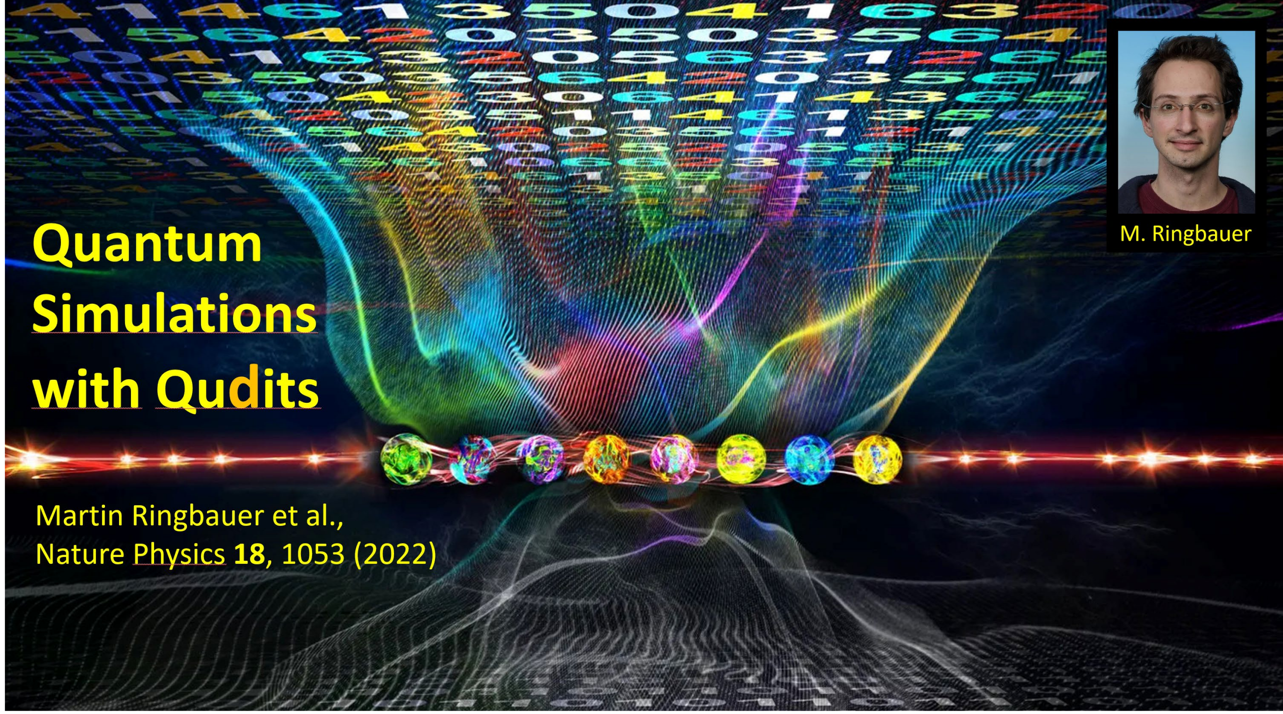


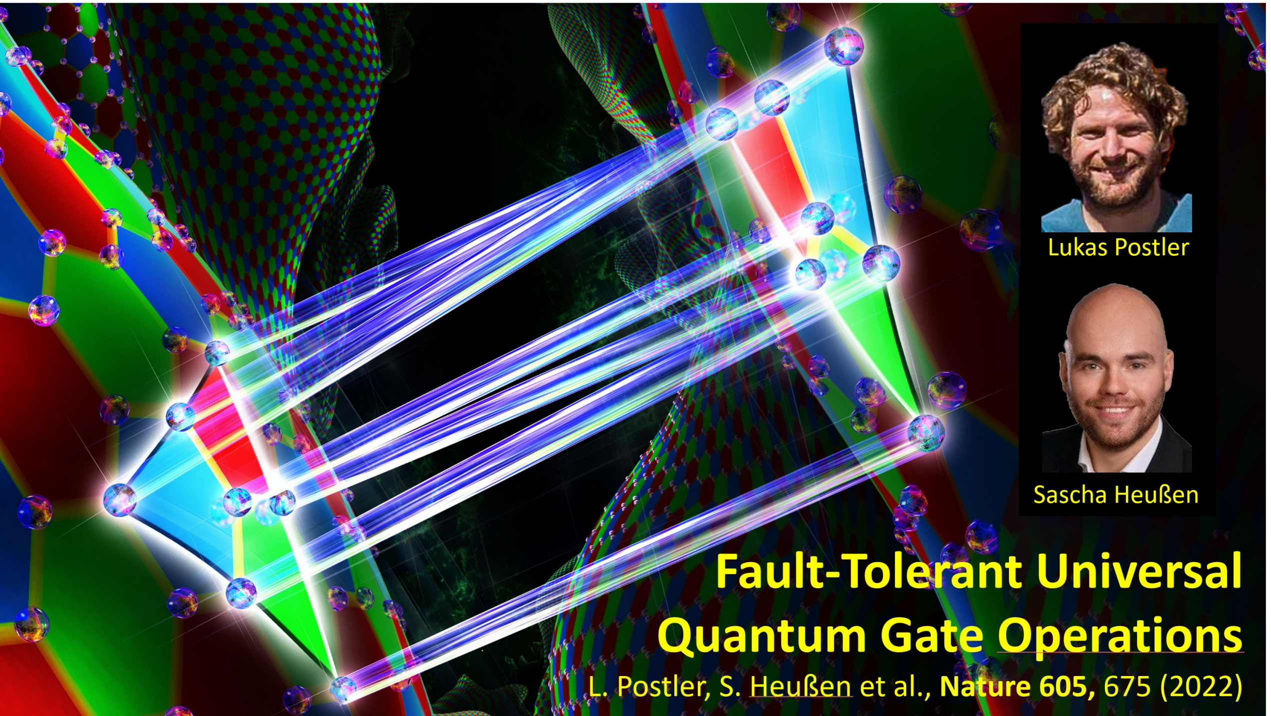
IQOQI – JILA collaboration

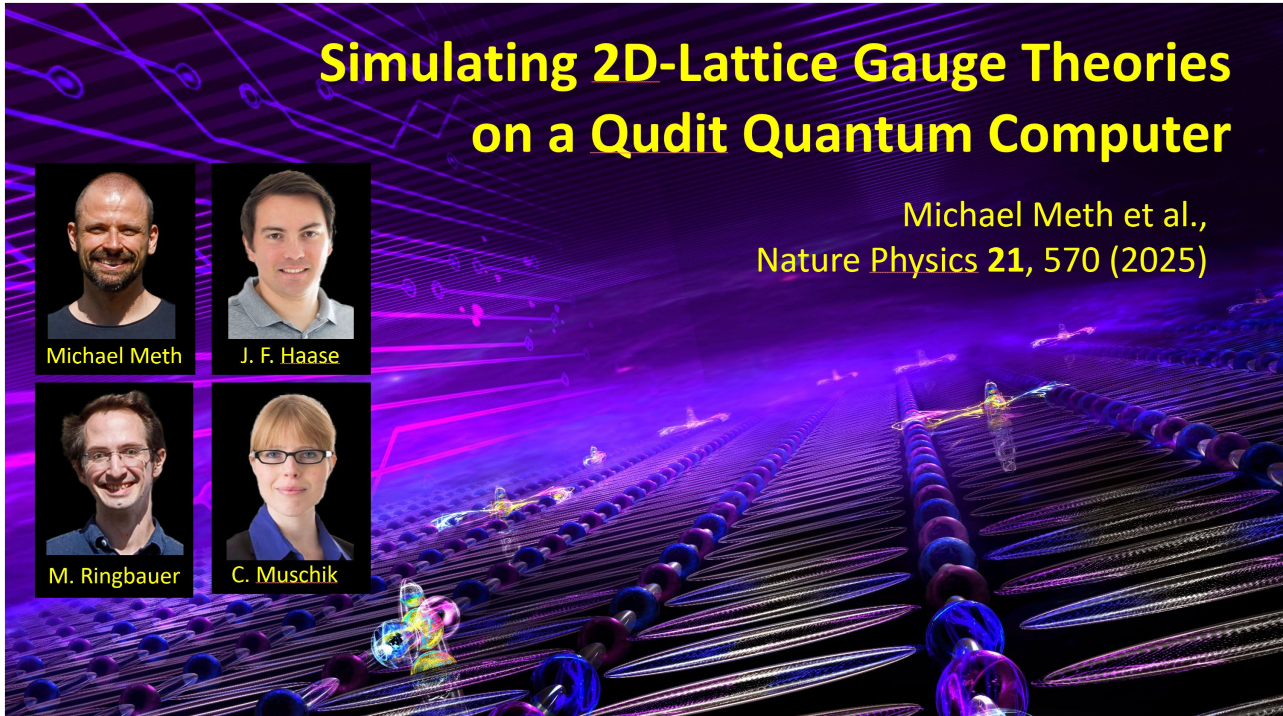
Exploring large-scale entanglement in quantum simulation

M. Joshi, C. Kokail et al.,
Nature **624**, 539 (2023)


Optimal Metrology with Variational Quantum Circuits
C. Marciniak et al., Nature 603, 604 (2022)
C. Marciniak
R. Kaubrügger
T. Feldker
P. Zoller


Quantum Simulations with Qudits
M. Ringbauer
Martin Ringbauer et al.,
Nature Physics 18, 1053 (2022)

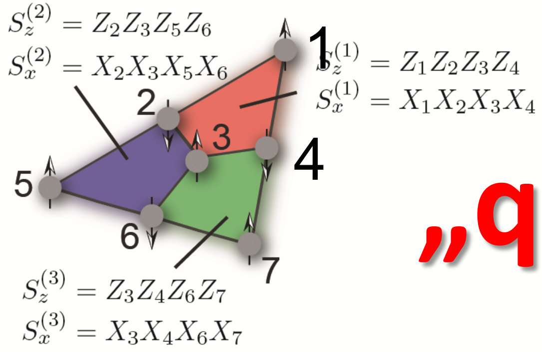

Lukas Postler
Sascha Heußen
Fault-Tolerant Universal Quantum Gate Operations
L. Postler, S. Heußen et al., Nature 605, 675 (2022)


Simulating 2D-Lattice Gauge Theories on a Qudit Quantum Computer
Michael Meth et al.,
Nature Physics 21, 570 (2025)
Michael Meth
J. F. Haase
M. Ringbauer
C. Muschik

Current work and new developments

Quantum error correction (QEC)

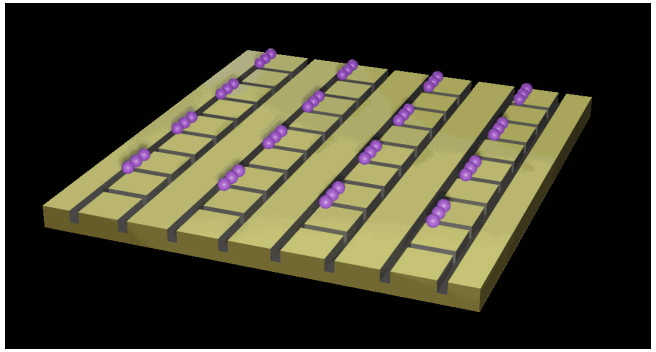
- **Logical qubits** (comprised of several physical qubits)
- QEC **protocols** (syndrome detection and correction)
- **Fault-Tolerance** (suppress error propagation)
- Correcting for **qubit loss** (internal degrees of freedom)



„qubit alive“

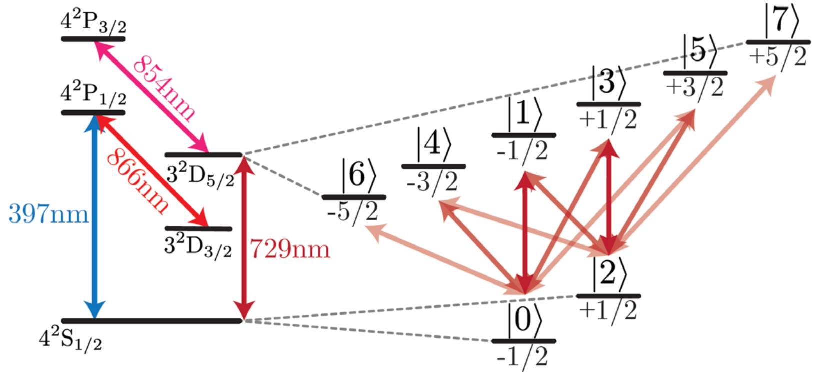
Scalability issues

- Design and **architecture** (traps, shuttling, measurement s)
- **Integration** of traps with electronic and photonic structures
- **Interfacing** ion qubits and photons (flying qubits)
- Use of ion trap systems for **quantum networking**



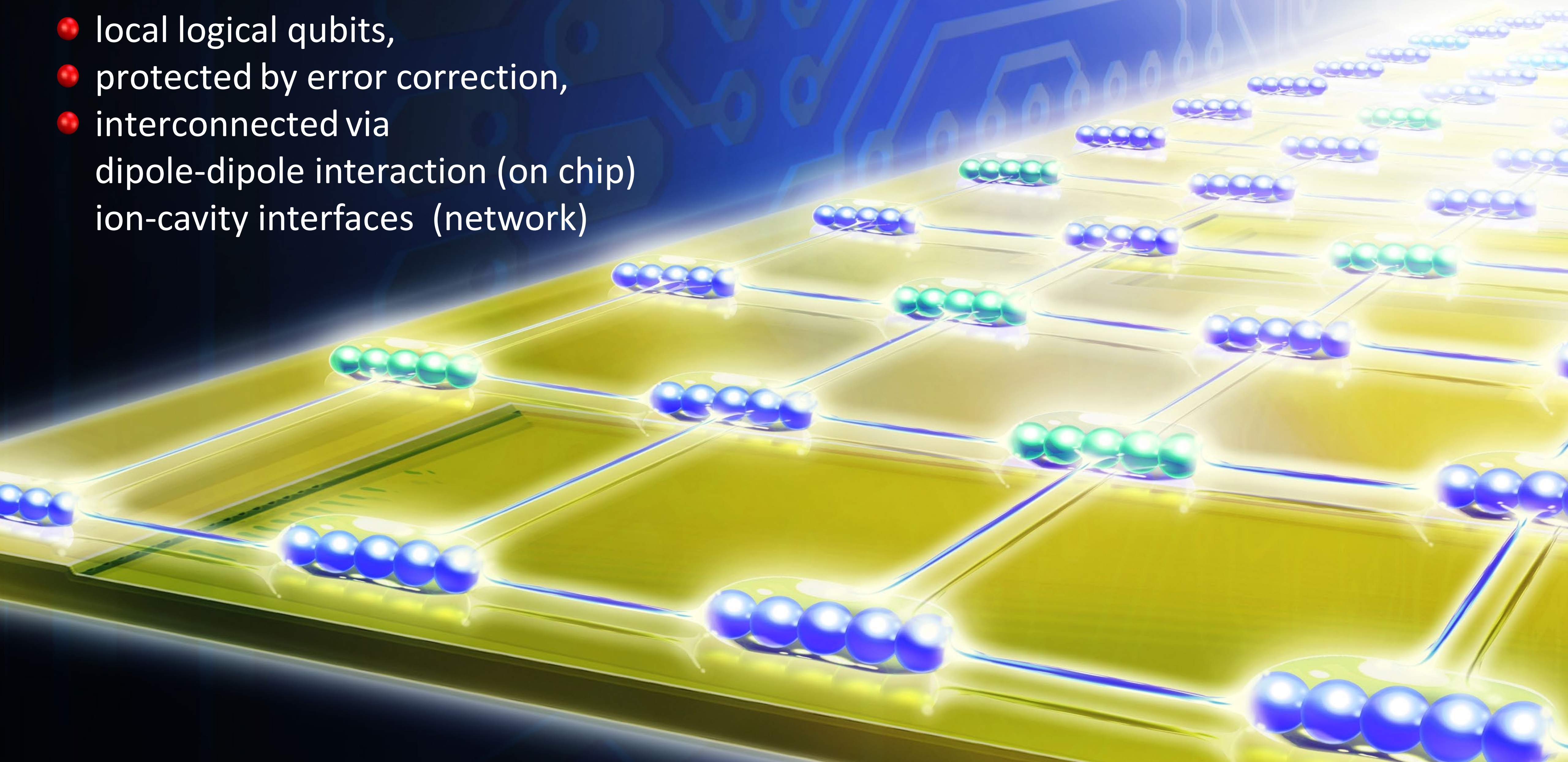
New developments

- Use of **qudits** for quantum information processing (d>2)
- Explore **molecular ions** for QIP applications
- **Hamiltonian Learning** and entanglement characterization



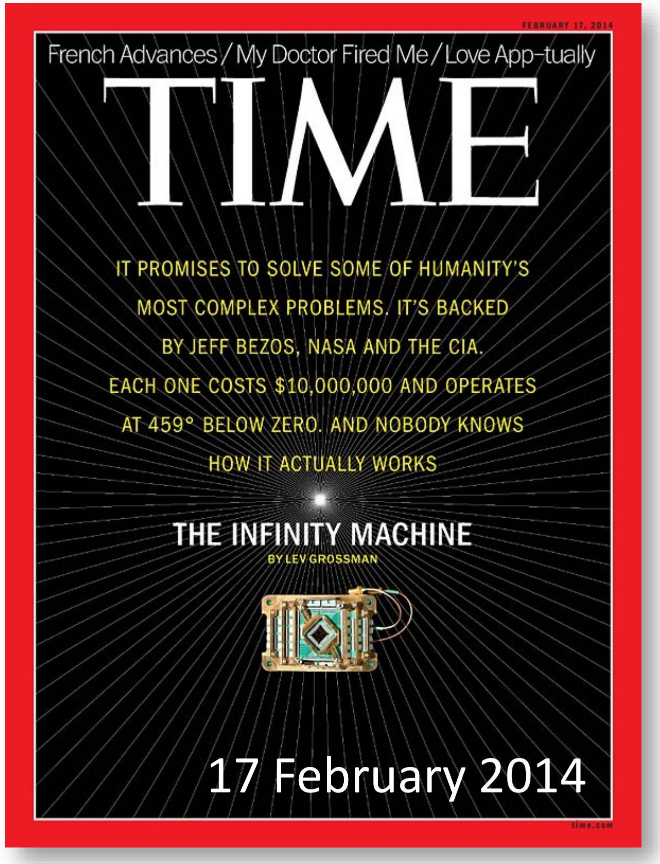
The Dream (and vision):

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



Quantum Computer (QC): Fiction

- QCs will replace classical computers ?
- QCs are better than classical computers ?
- QCs are always faster than classical computers ?



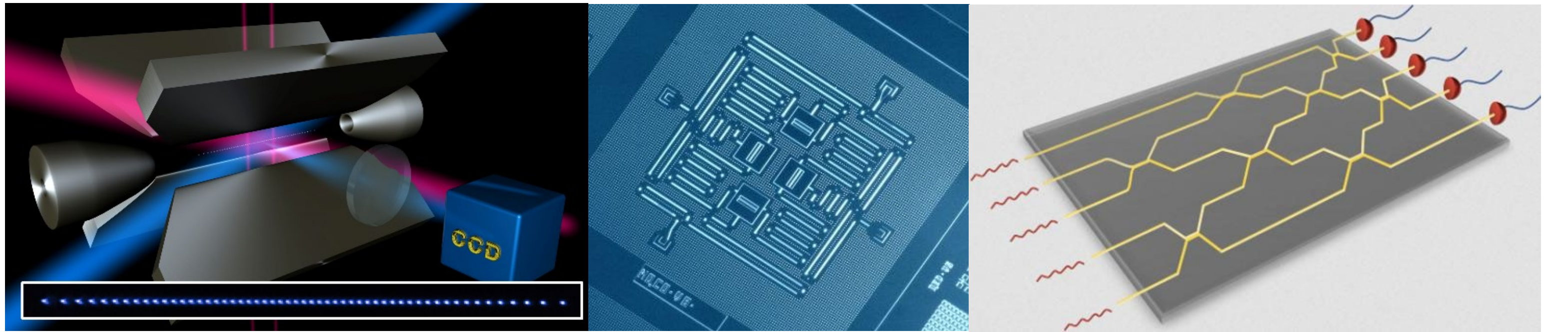
?

Quantum Computer (QC): **Facts**

- Quantum computers are universal computers ✓
- QCs work completely differently from classical computers ✓

  (superpositions, entanglement)
- Quantum information is more volatile than classical information ✓
- Error correction works in the quantum world ✓
- Quantum computers are faster than classical computers ✓
- Quantum computers are already reality ✓

  (ions/atoms in traps, superconducting circuits, photons)



But also: **Fact**

currently:

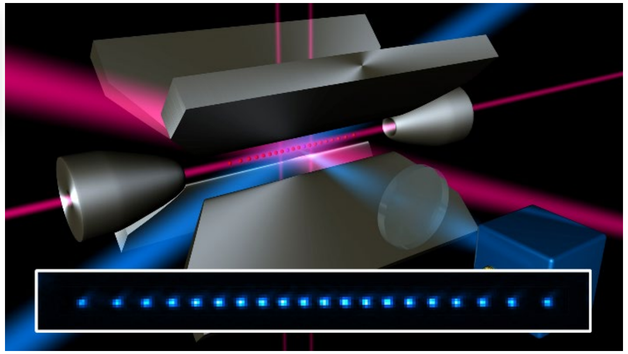
~100 qubits available
~500 – 1000 gate ops.

competitive applications need

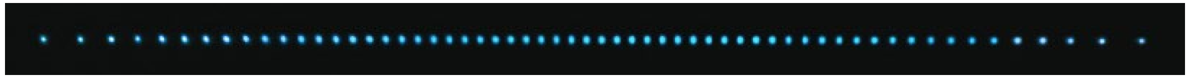
~ 10^5 – 10^6 qubits
~ 10^6 -10^9 gate ops.

currently: NISQ computer (noisy intermediate scale quantum)

QIP with ions: Future goals and developments

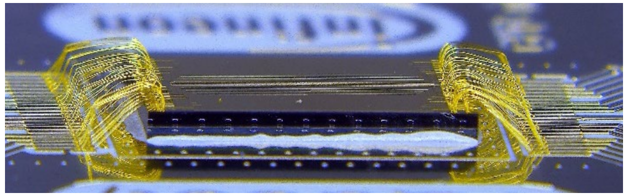


- more qubits (~50 – 100)



59 ions

- better fidelities
- faster gate operations } cryogenic trap, micro-structured traps
- faster detection



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

„qubit alive“

Quantum eQual

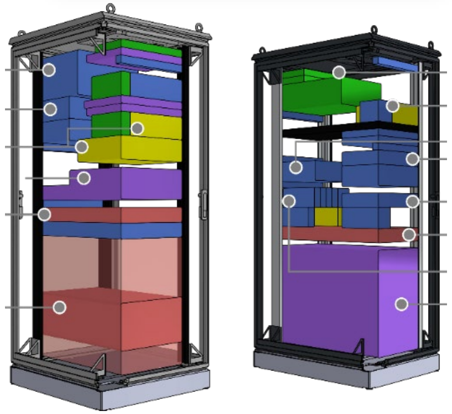
- applications

  - small scale QIP (e.g. **repeaters**)

  - quantum **metrology**, enhanced S/N, tailored atoms and states

  - quantum **simulations** (spin Hamiltonians, 2-dimensional systems)

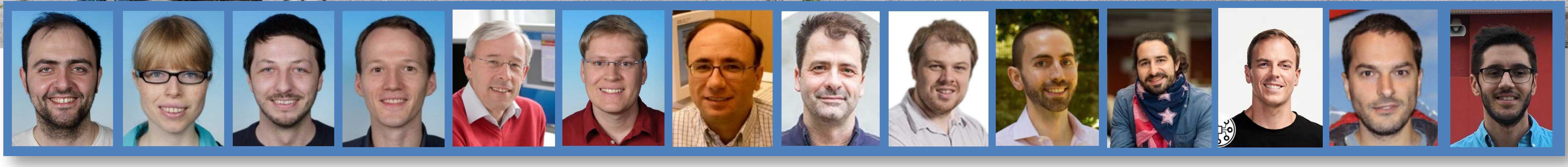
  - quantum **computation** (optimization, quantum chemistry, quantum simulations)



Quantum Optics & Spectroscopy

The international Team 2024

universität innsbruck



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