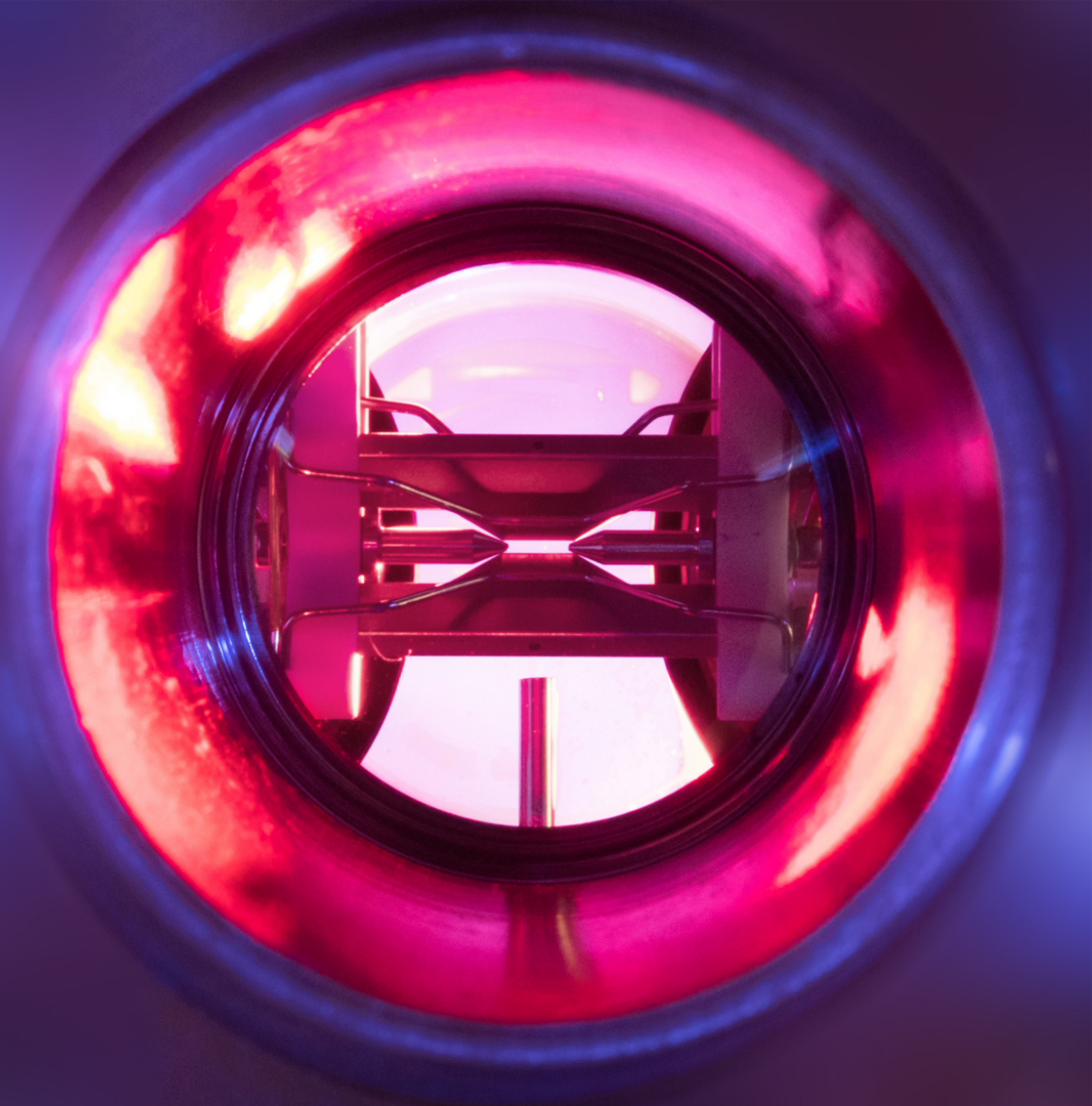
The Trapped-Ion Platform for Quantum Information Processing



The Trapped-Ion Platform for Quantum Information Processing

- Atomic platforms for quantum information processing
- Qubits, interactions and quantum gate operations
- Quantum information processing with Trapped Ions (toolbox)
- Quantum computation, simulation and characterization
- Scaling the ion trap quantum platform
- Logical qubits, quantum error correction and FT-operation

Rainer Blatt

universität innsbruck

Quantum Optics & Spectroscopy

IQOQI

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ÖSTERREICHISCHE AKADEMIE DER WISSENSCHAFTEN

€ FWF SFB BEYOND C AQTION erc FFG PASQuanS IQOQI $ IARPA

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and the trapped-ion community

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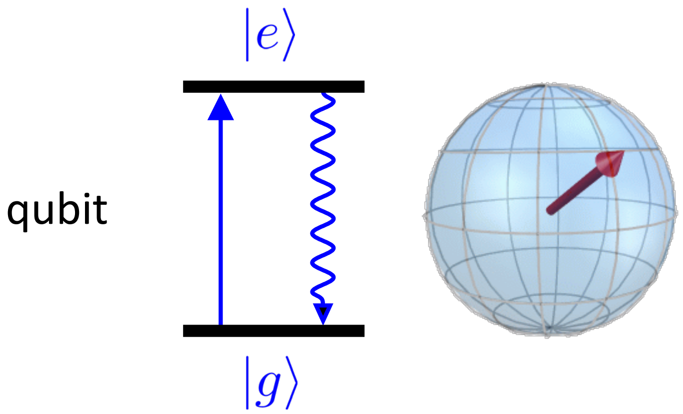
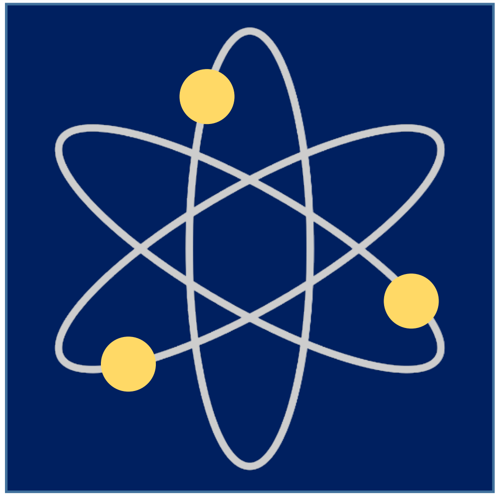
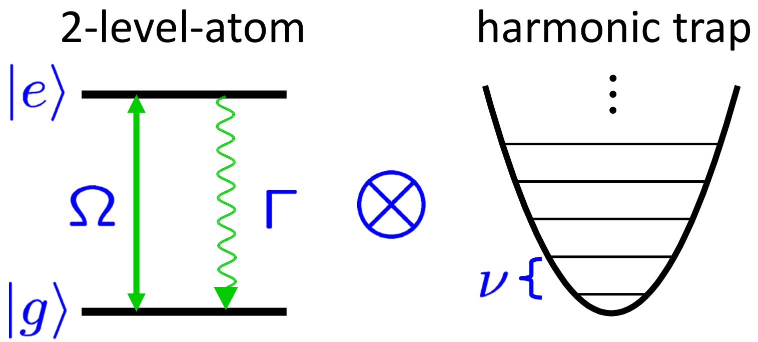
Atomic Platforms for Quantum Information Processing (QIP)





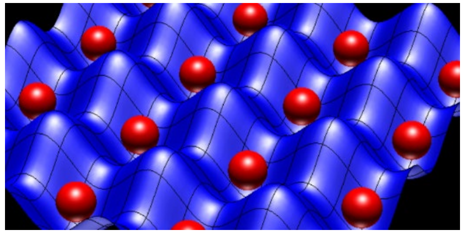


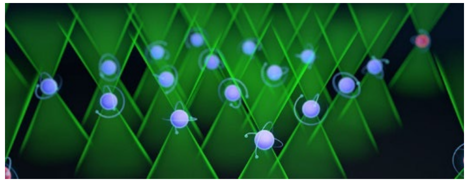
QIP requires qubits with

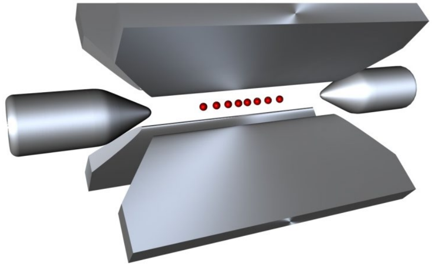
- a scalable physical system
- initializable input states
- long coherence times
- a universal set of gates
- close to perfect measurements
- interfacing technology
- distribution capabilities

Atomic platforms offer

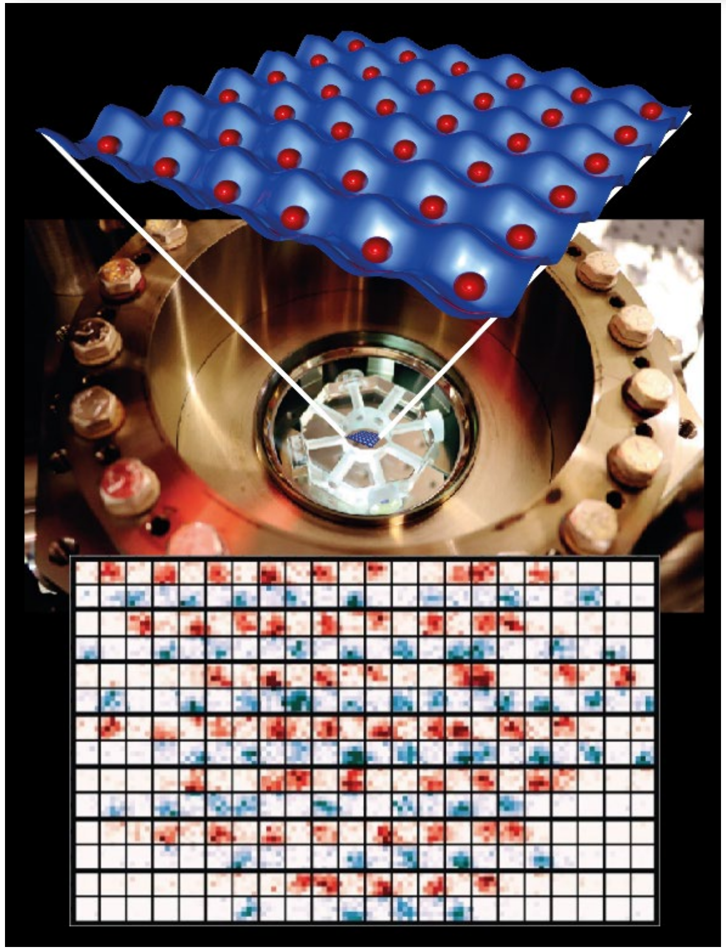
- Identical atoms at rest in free space
- Optically pumped and manipulated
- Long-lived atomic states
- Coulomb and dipole-dipole interactions
- Electron shelving for detection
- Shuttling and/or cavity QED techniques
- Single photons in optical fibers





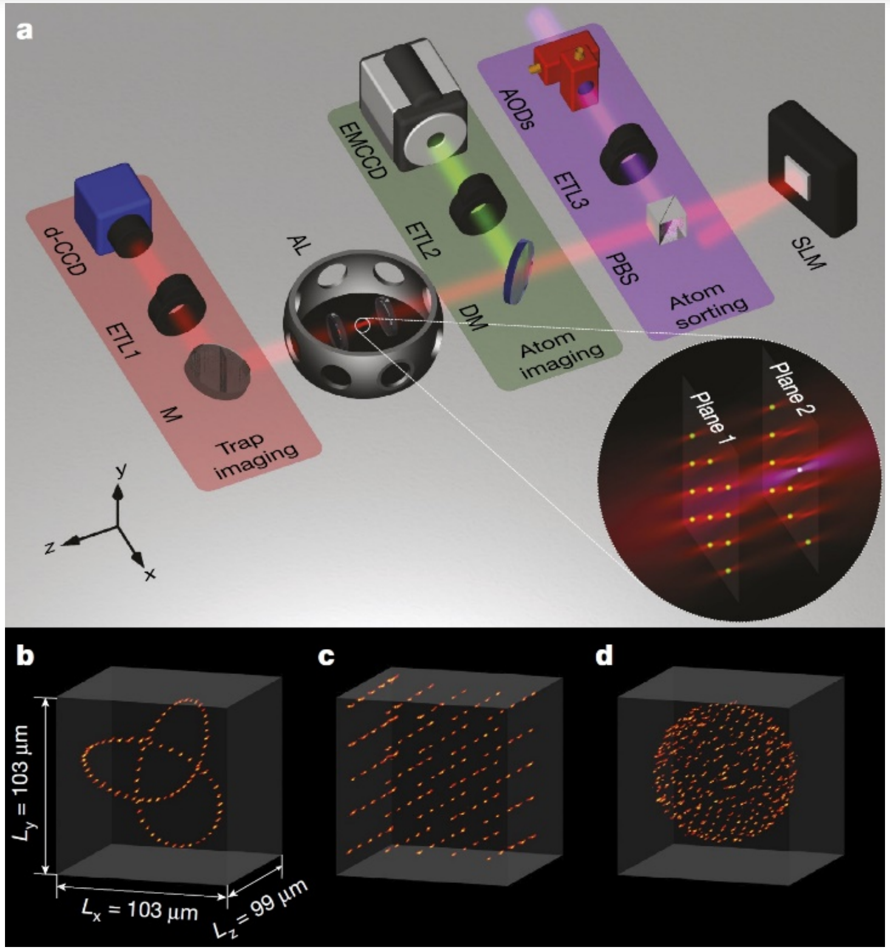


Atomic Platforms for Quantum Information Processing (QIP)



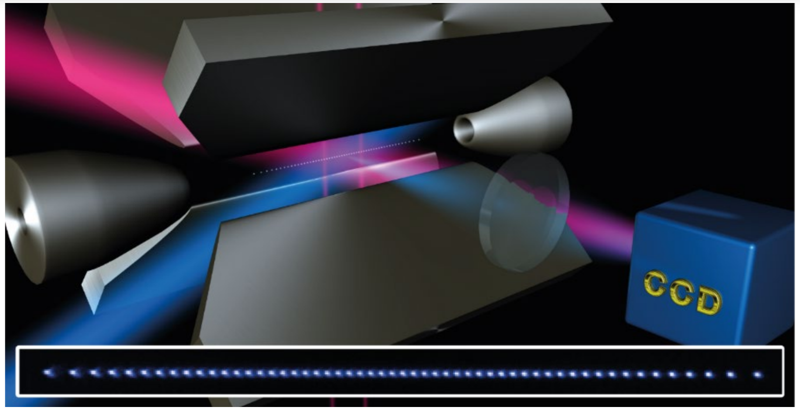
atoms in an optical lattice

I. Bloch et al., Garching

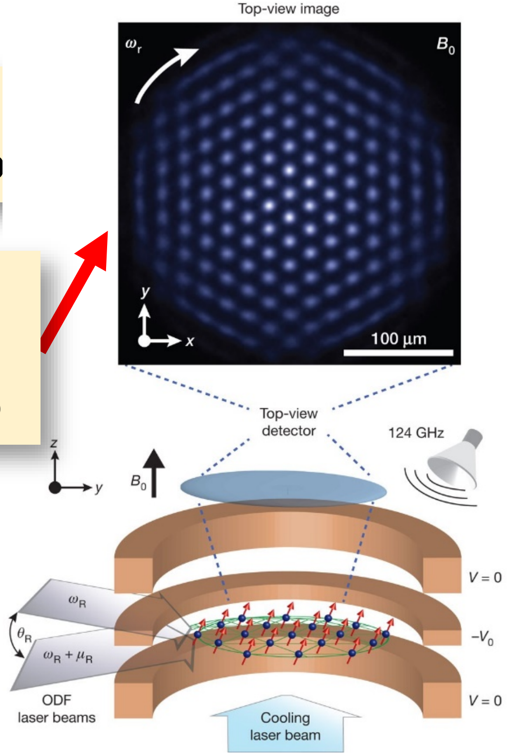


atoms in optical tweezers

A. Browaeys et al., Paris



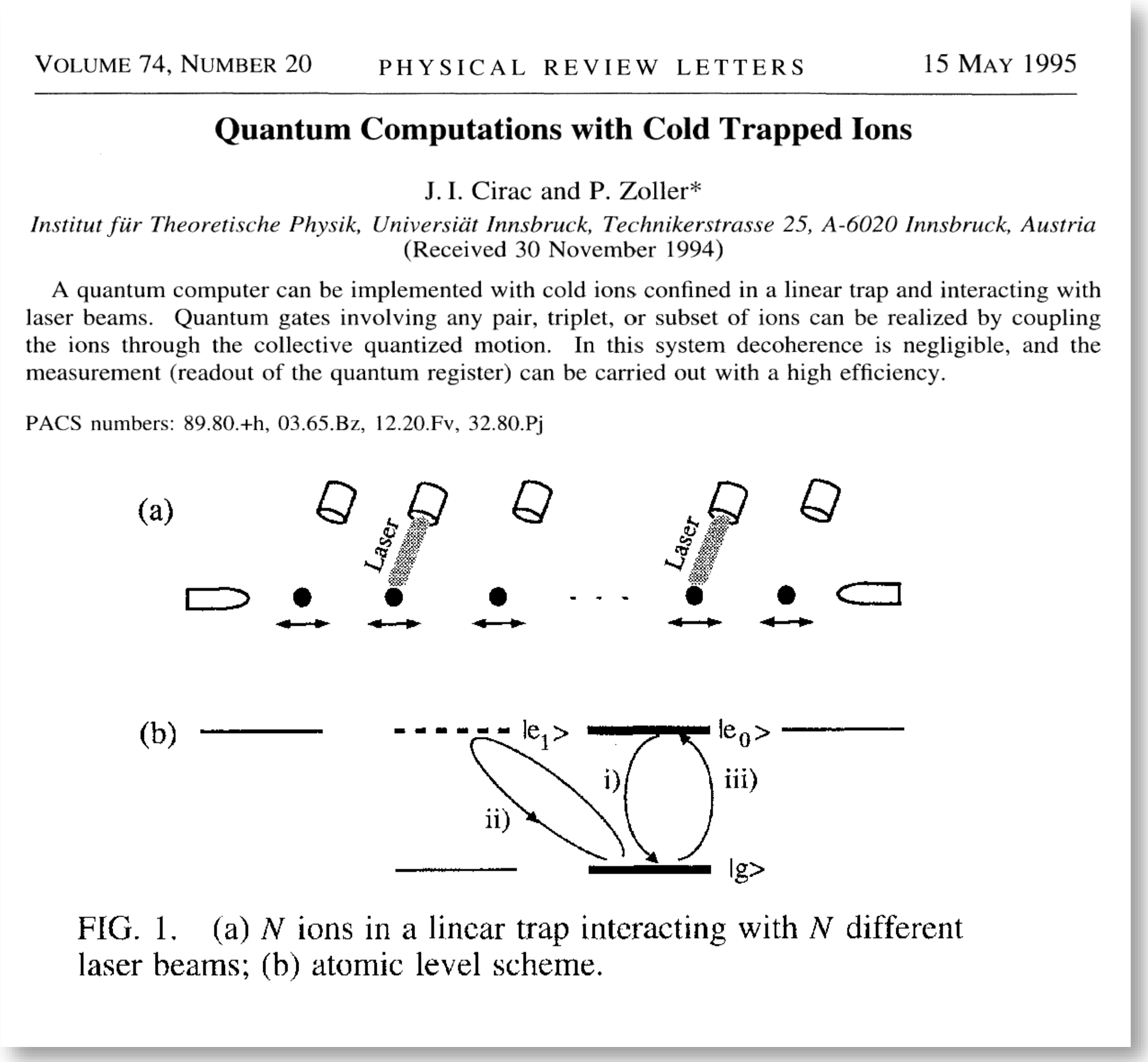
atomic ions in a Paul trap



atomic ions in a Penning trap

J. Bollinger et al., Boulder

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

other gate proposals (and more):

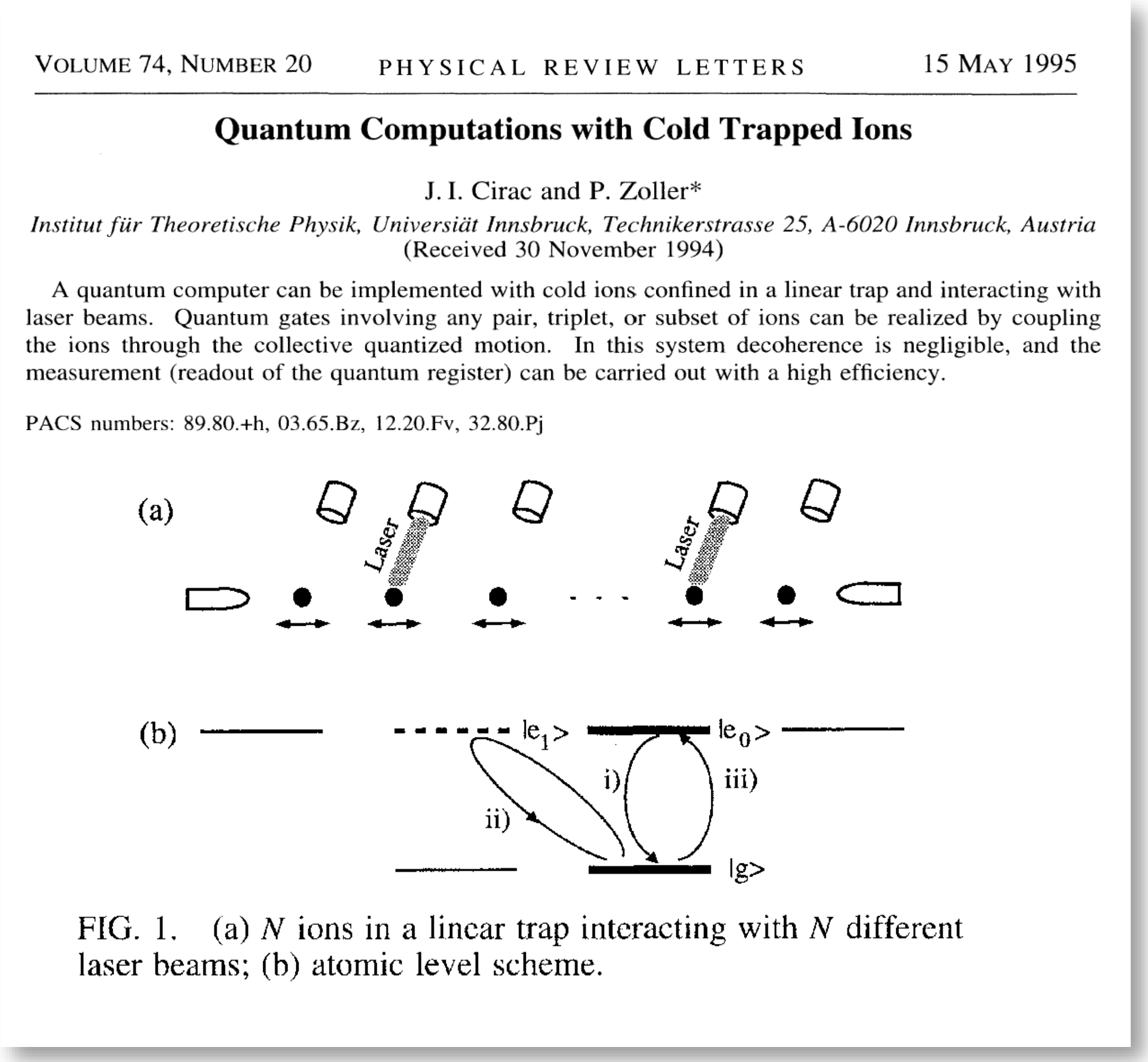
- Cirac & Zoller
- Mølmer & Sørensen,
- Milburn, Zagury, Solano
- Jonathan & Plenio & Knight
- Geometric phases
- Leibfried & Wineland

J. I. Cirac

P. Zoller

1995

Quantum Computation with Trapped Ions



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- use common motion to create entanglement

$$\text{controlled} - \text{NOT}:$$

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

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

control qubit

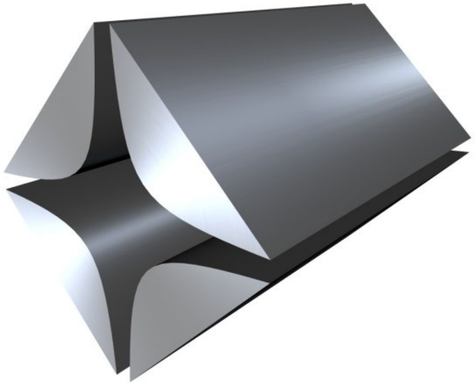
target qubit

J. I. Cirac

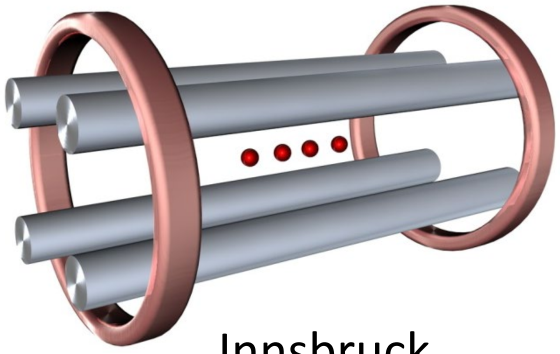
P. Zoller

1995

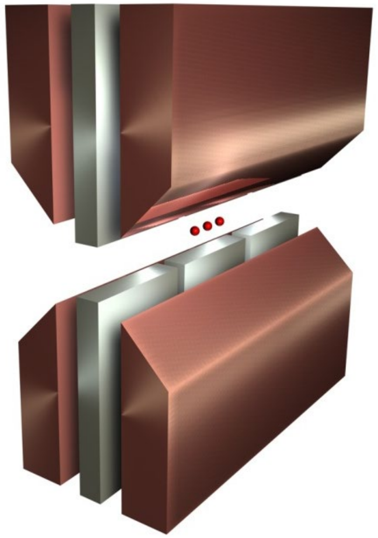
The Traps: Linear Paul Traps



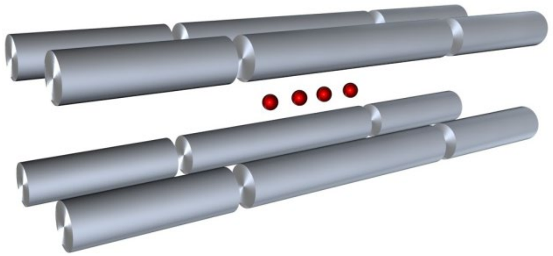
Paul mass filter



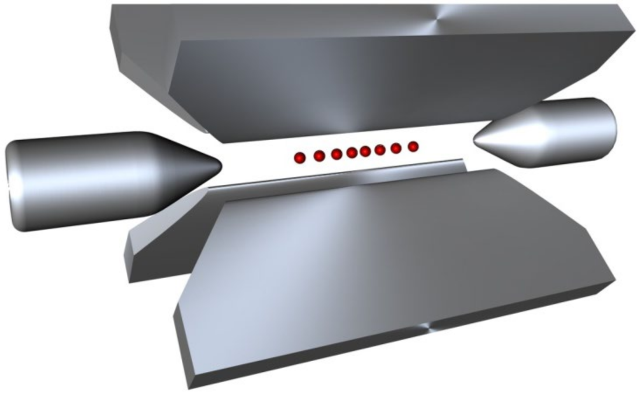
Innsbruck
Ann Arbor



München,
Sussex

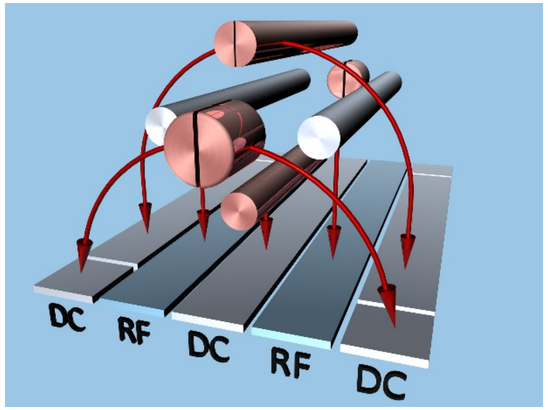


Boulder, Mainz, Aarhus

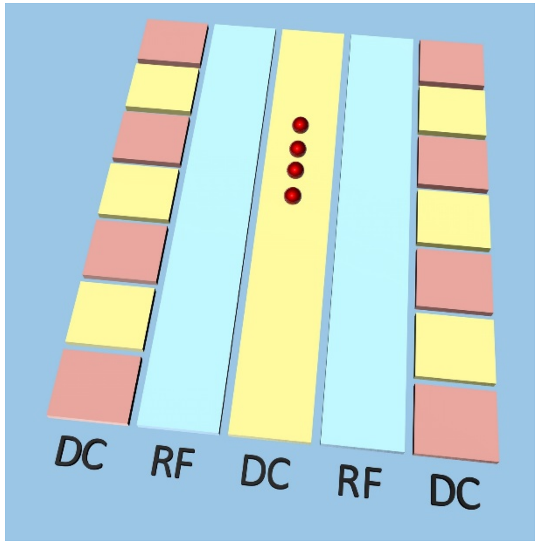


Innsbruck, Oxford

Surface Traps



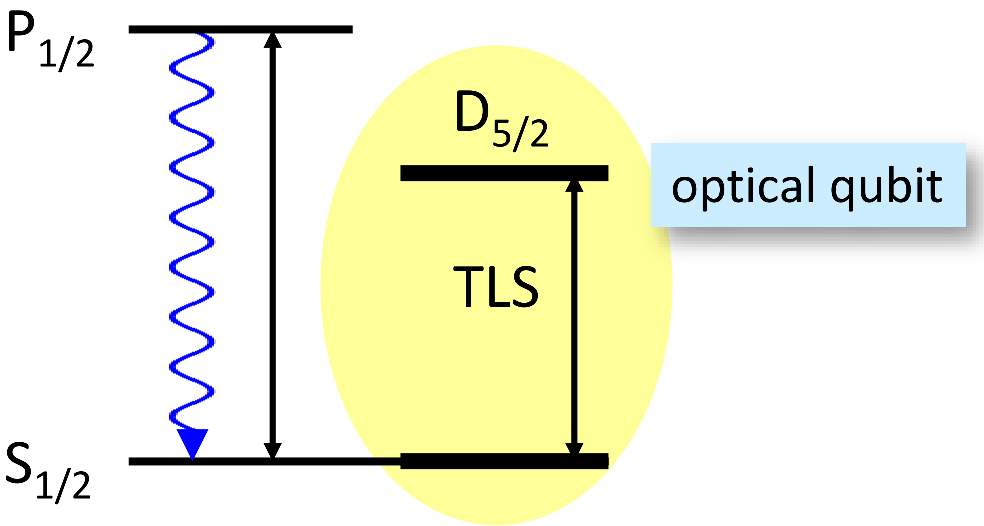
Boulder



The Qubits with Trapped Ions

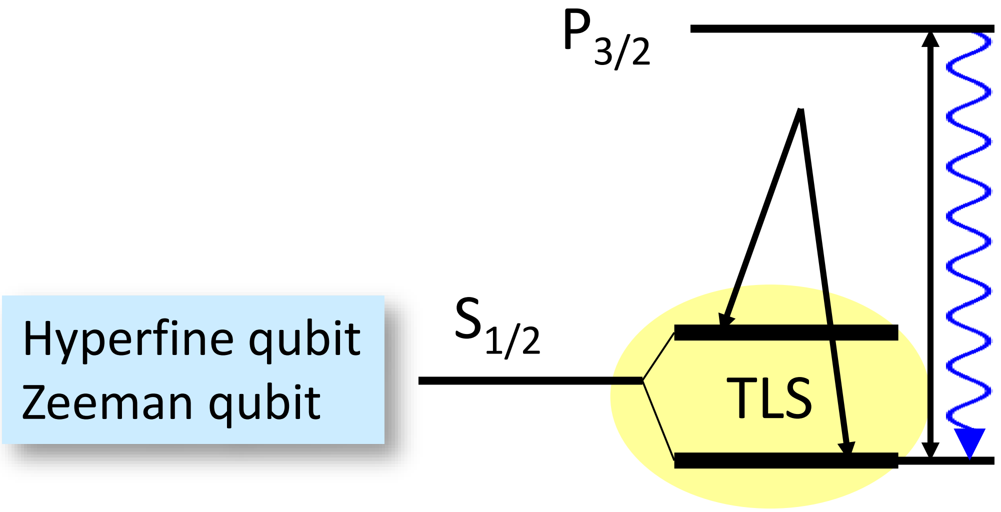
Storing and keeping quantum information requires long-lived atomic states:

- 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$^+$, ^{133}Ba$^+$



optical qubit

Innsbruck, ^{40}Ca$^+$; (many places now)
MIT, Weizmann ^{88}Sr$^+$ (a.o.),

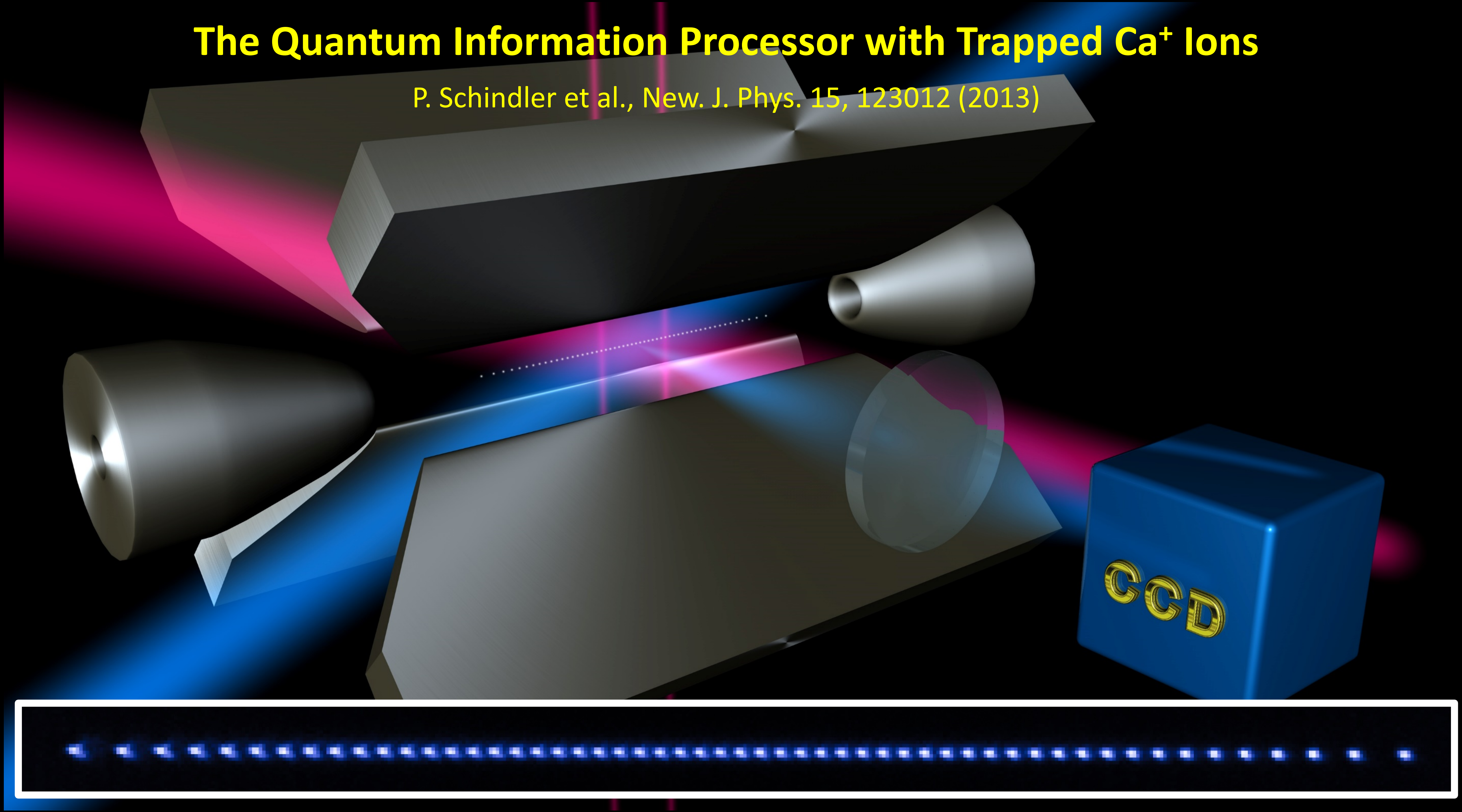


Hyperfine qubit
Zeeman qubit

Boulder ^{9}Be$^+$; Innsbruck, Oxford ^{43}Ca$^+$;
Michigan ^{111}Cd$^+$; Maryland ^{171}Yb$^+$; a.o.
UCLA ^{133}Ba$^+$;

The Quantum Information Processor with Trapped Ca^+ Ions

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

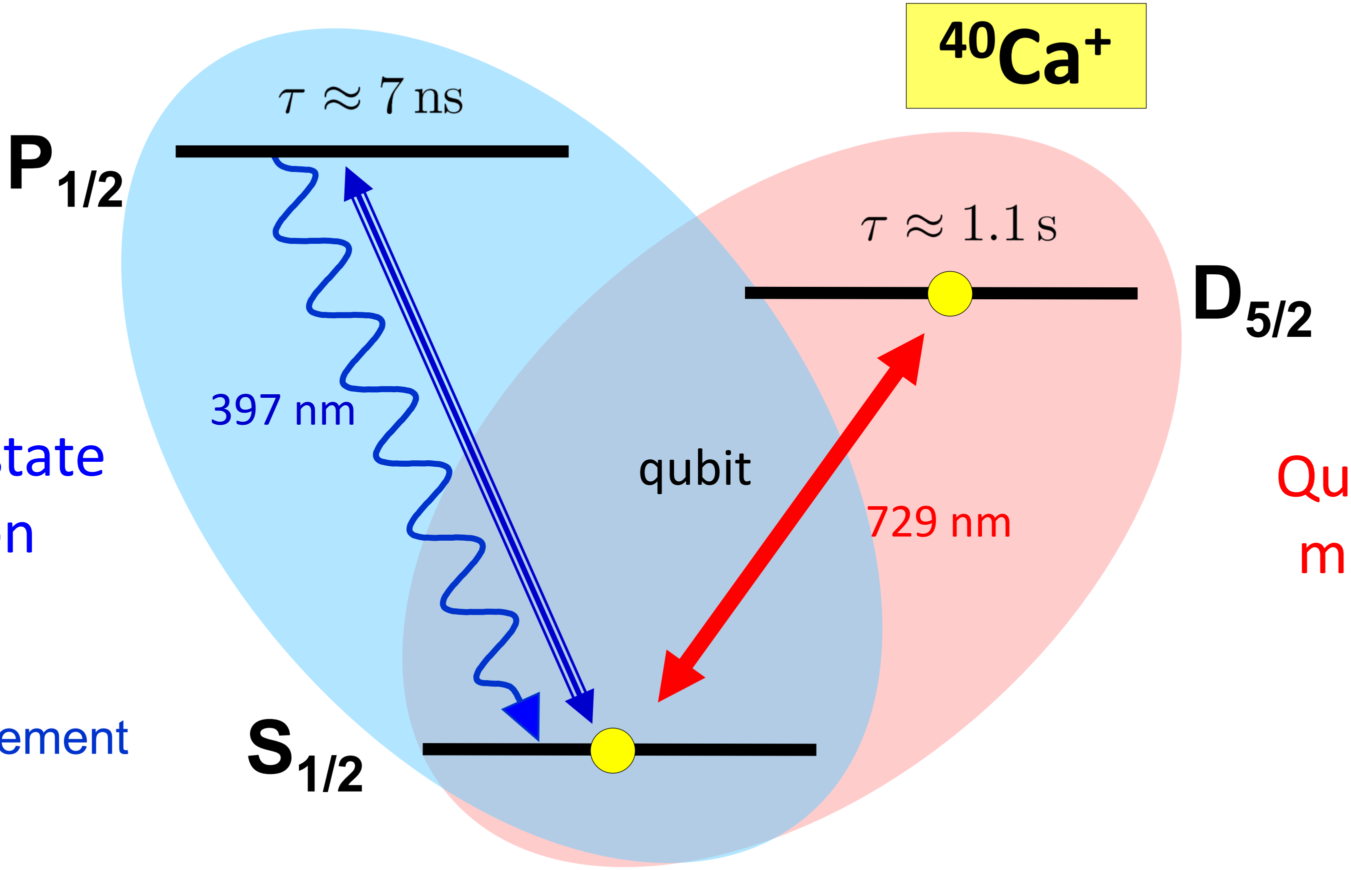


Qubit Detection (Readout) with trapped ions: Electron Shelving

^{40}Ca^{+}

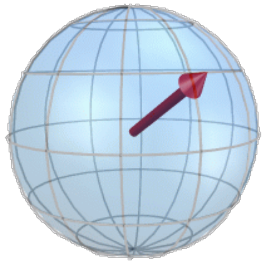
Quantum state detection

σ_z - measurement

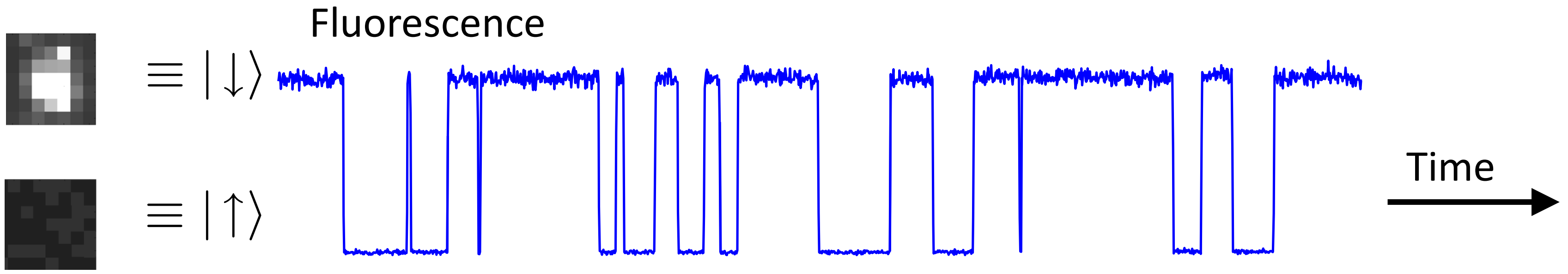


$\equiv |\uparrow\rangle \equiv |0\rangle$

Quantum state manipulation

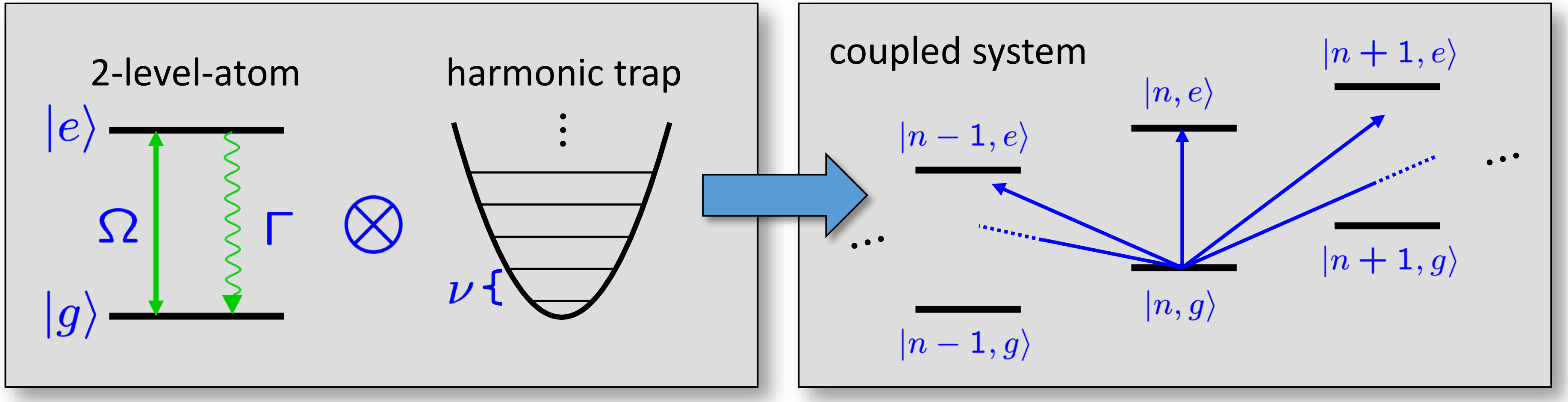


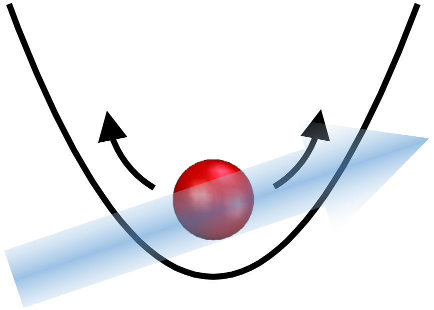
$\equiv |\downarrow\rangle \equiv |1\rangle$



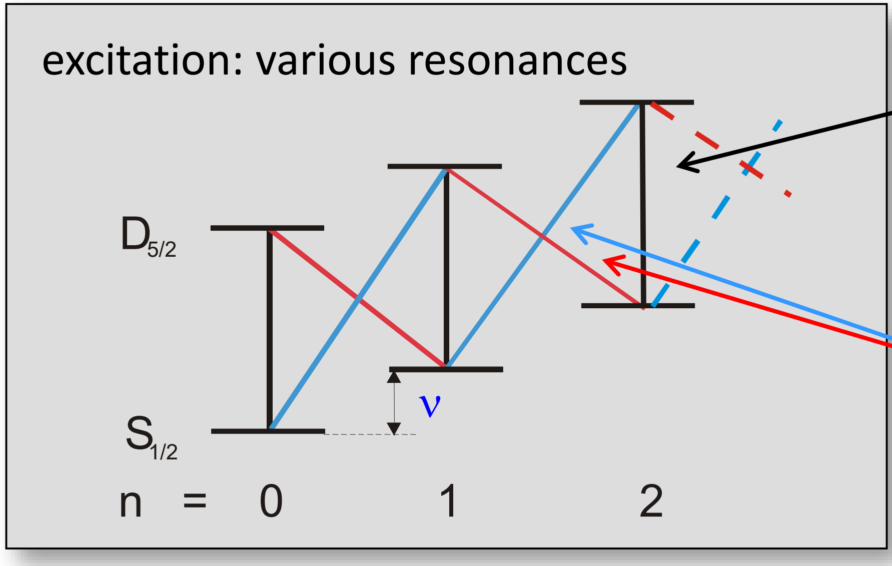
Quantum jump detection
by electron shelving

Quantum state manipulation: carrier and sidebands





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



Carrier:
manipulate qubit
→ internal superpositions

Sidebands:
manipulate motion and qubit
→ create entanglement

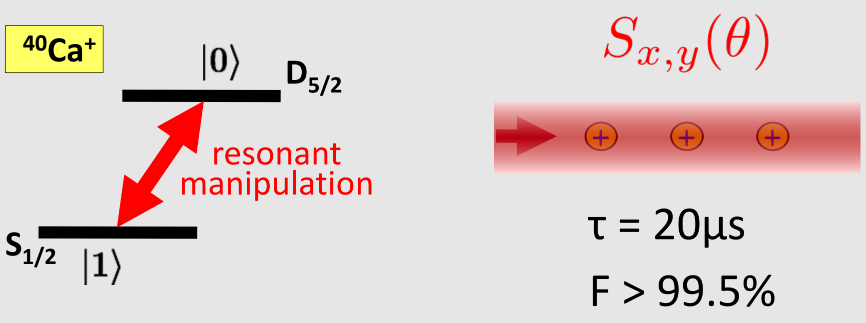
J. I. Cirac, P. Zoller;
PRL **74**, 4091 (1995)

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

Quantum computing with global and local operations

Global

Collective Local Operations

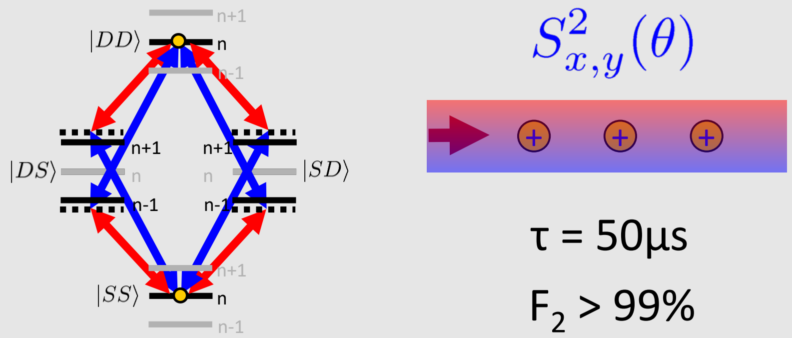


$S_{x,y}(\theta)$

τ = 20µs

F > 99.5%

Global Mølmer-Sørensen entangling gate



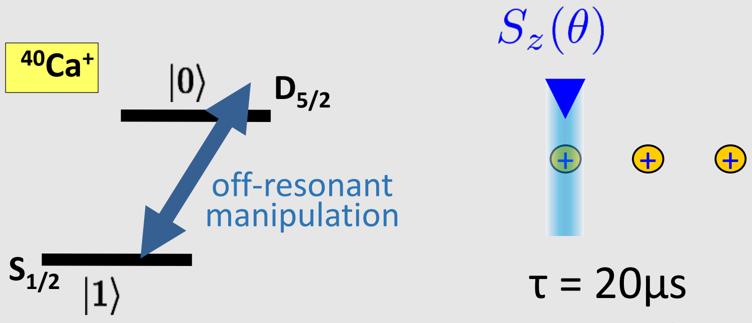
$S^2_{x,y}(\theta)$

τ = 50µs

F_2 > 99%

Local

Individual local operations



$S_z(\theta)$

τ = 20µs

F > 99%

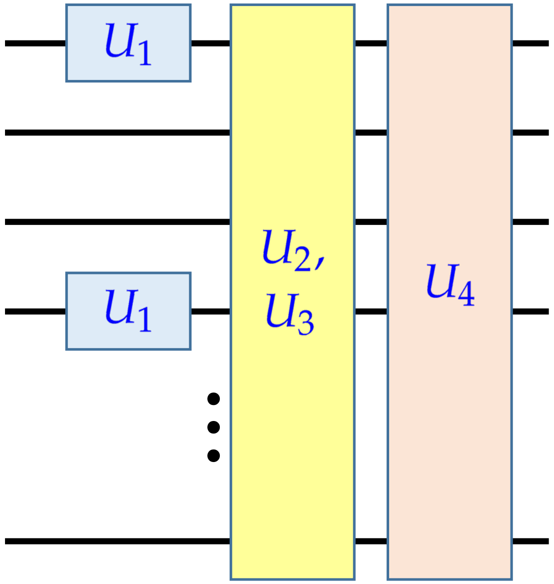
All three blocks combined realize a **universal gate set** for arbitrary quantum computation

Entangling gate operation involves common motion:
all-to-all connectivity

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

Trapped Ion Quantum Computing

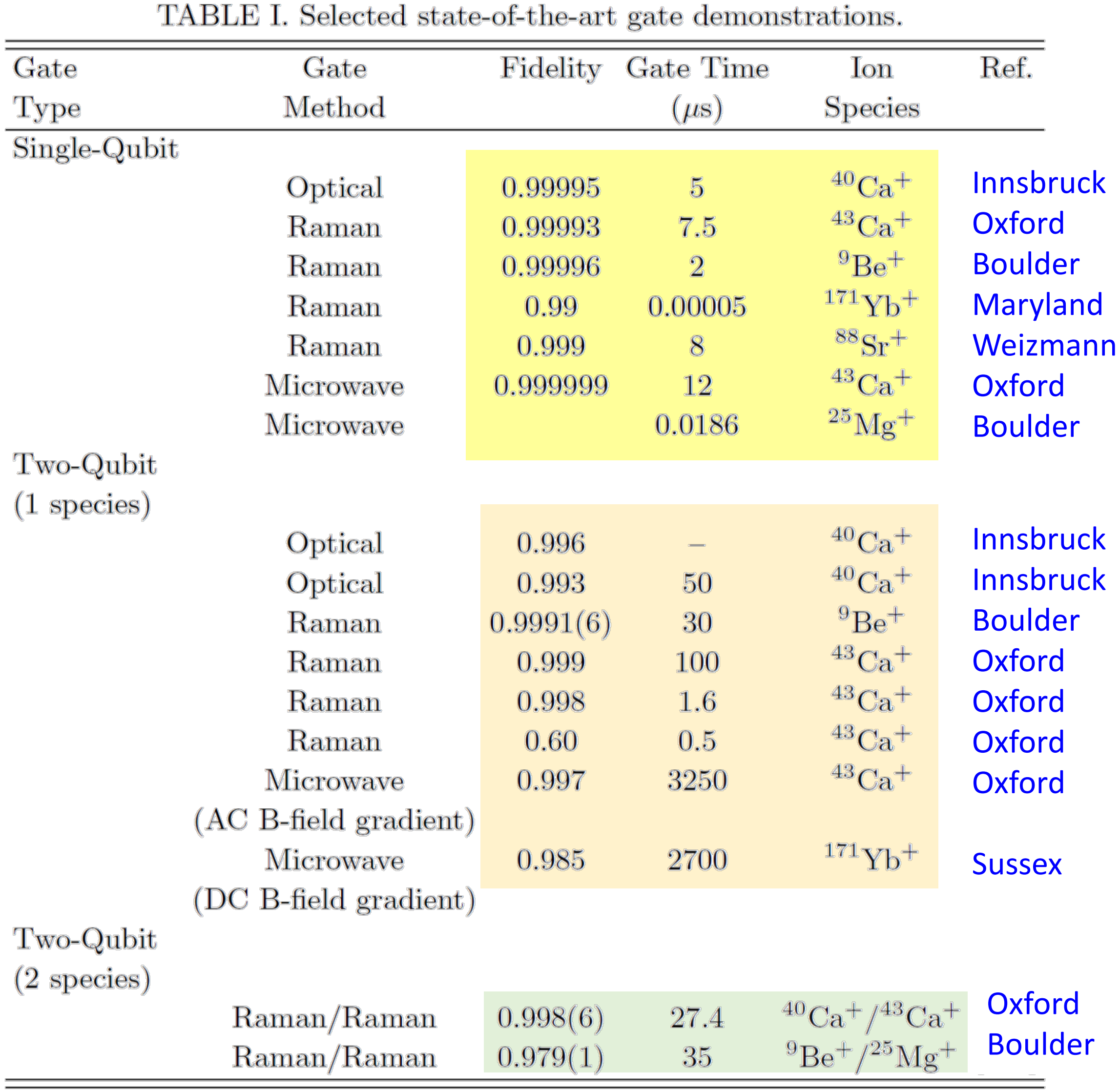


TABLE I. Selected state-of-the-art gate demonstrations.

Gate Type	Gate Method	Fidelity	Gate Time (μs)	Ion Species	Ref.
Single-Qubit					
	Optical	0.99995	5	^{40}Ca$^+$	Innsbruck
	Raman	0.99993	7.5	^{43}Ca$^+$	Oxford
	Raman	0.99996	2	^{9}Be$^+$	Boulder
	Raman	0.99	0.00005	^{171}Yb$^+$	Maryland
	Raman	0.999	8	^{88}Sr$^+$	Weizmann
	Microwave	0.999999	12	^{43}Ca$^+$	Oxford
	Microwave		0.0186	^{25}Mg$^+$	Boulder
Two-Qubit (1 species)					
	Optical	0.996	–	^{40}Ca$^+$	Innsbruck
	Optical	0.993	50	^{40}Ca$^+$	Innsbruck
	Raman	0.9991(6)	30	^{9}Be$^+$	Boulder
	Raman	0.999	100	^{43}Ca$^+$	Oxford
	Raman	0.998	1.6	^{43}Ca$^+$	Oxford
	Raman	0.60	0.5	^{43}Ca$^+$	Oxford
	Microwave (AC B-field gradient)	0.997	3250	^{43}Ca$^+$	Oxford
	Microwave (DC B-field gradient)	0.985	2700	^{171}Yb$^+$	Sussex
Two-Qubit (2 species)					
	Raman/Raman	0.998(6)	27.4	^{40}Ca$^+$/^{43}Ca$^+$	Oxford
	Raman/Raman	0.979(1)	35	^{9}Be$^+$/^{25}Mg$^+$	Boulder

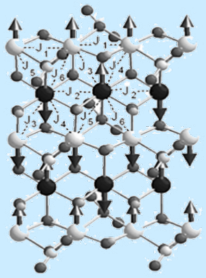
Algorithms demonstrated (some examples)

- Deutsch-Josza (Innsbruck)
- Order-Finding (Innsbruck)
- Shor algorithm (Innsbruck)
- Grover algorithm (Maryland)
- Bernstein-Vazirani (Georgia-Tec, Maryland)
- Quantum Fourier-transform (Boulder, Innsbruck, Maryland)
- Quantum error correction (Boulder, Innsbruck, Maryland)
- …
- …
- and more

C. D. Bruzewicz et al., Appl. Phys. Rev. **6**, 021314 (2019)

Quantum Simulation Approaches

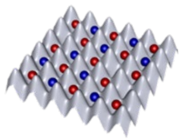
problem
to
compute



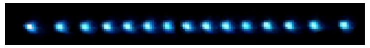
$\hat{H}$

classical computer

Quantum
Simulator

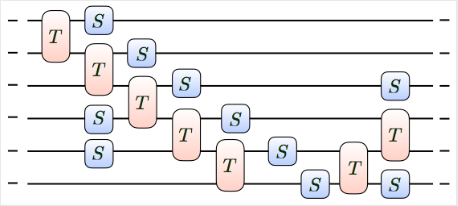


or



Digital simulation (computation):

$|\psi(0)\rangle$



$|\psi(t)\rangle$

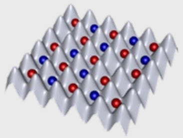
can simulate any model $\hat{H}$,
but requires many gate operations

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

Analog simulation:

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

requires match between
engineerable interactions and model

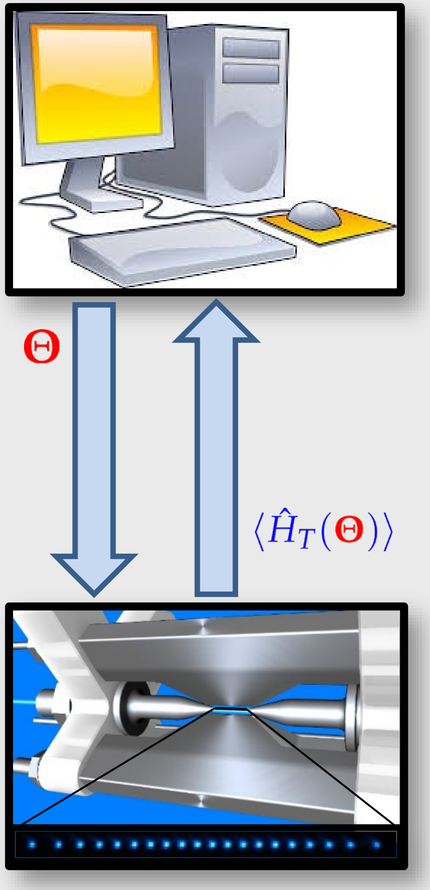


,

, SC-QS ....

Hybrid simulation:

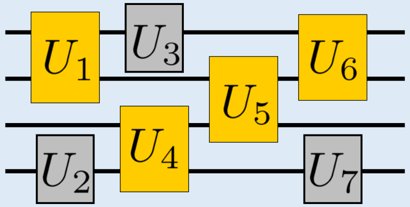
Classical computer



analog quantum
simulator

Quantum Simulations with Trapped Ions

digital approach



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

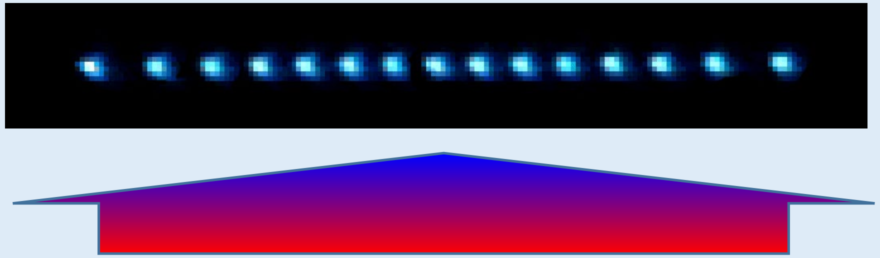
$$H = H_1 + H_2 + \ldots + H_k$$

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

$$\approx \Big(\underbrace{e^{-\frac{i}{\hbar} H_1\, t/n}}_{\text{gate}_1} \underbrace{e^{-\frac{i}{\hbar} H_2\, t/n}}_{\text{gate}_2} \ldots \underbrace{e^{-\frac{i}{\hbar} H_k\, t/n}}_{\text{gate}_k} \Big)^n$$

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

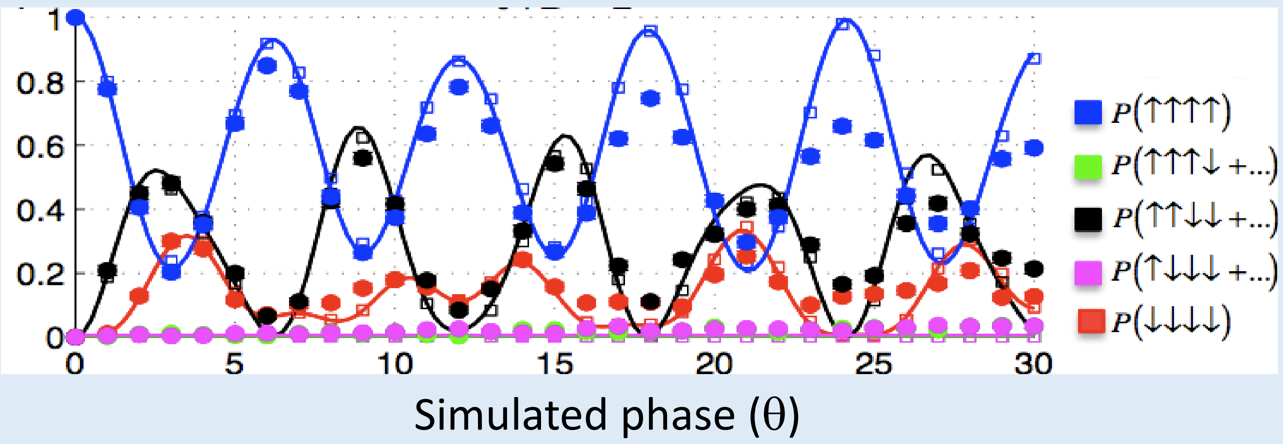
C. Monroe et al., Rev. Mod. Phys. **93**, 025001 (2021)

Digital Quantum Simulations with Trapped Ions

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

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

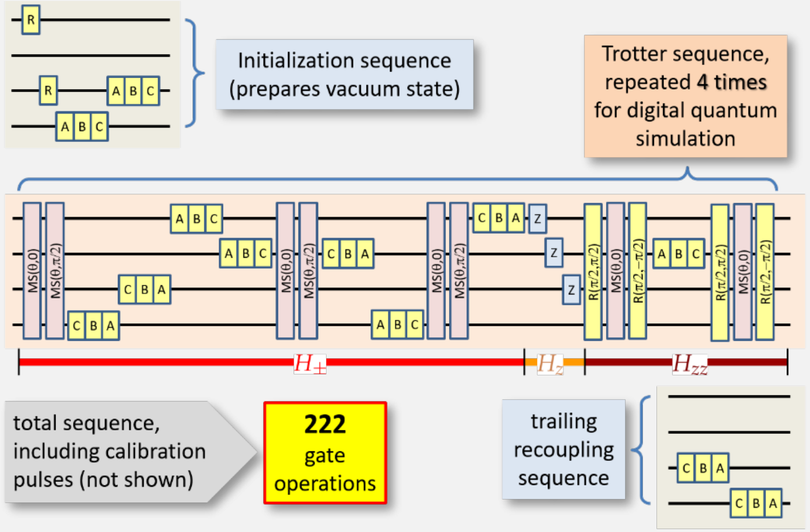
$$J\sum_{i\neq j}\sigma_x^i\sigma_x^j + B\sum_{i=1}^{n}\sigma_z^i$$



- 1-D lattice gauge theory (Schwinger model)

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

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



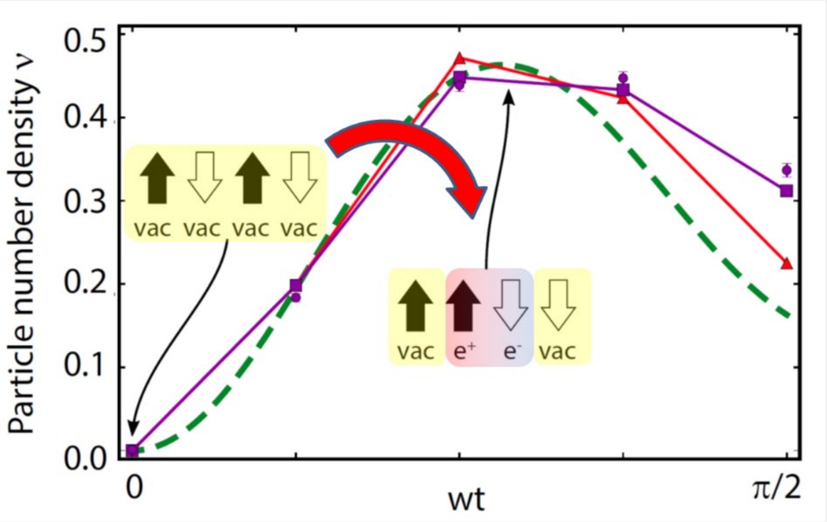
Initialization sequence (prepares vacuum state)

Trotter sequence, repeated **4** times for digital quantum simulation

total sequence, including calibration pulses (not shown)

222 gate operations

trailing recoupling sequence

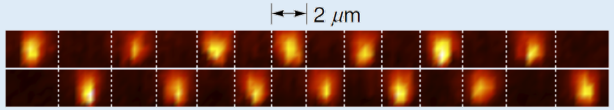


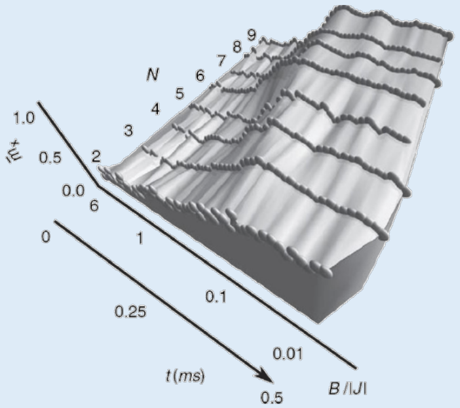
Analog Quantum Simulations with Trapped Ions

- transverse Ising Hamiltonian

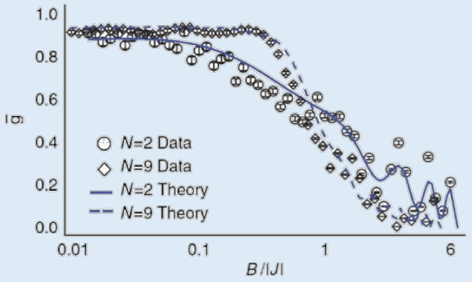
$$H_{TI} = \sum_{i<j} J_{ij}\sigma_x^i\sigma_x^j + B_y\sum_i \sigma_y^i$$

paramagnetic-to-ferromagnetic crossover,
Néel ordering





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



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

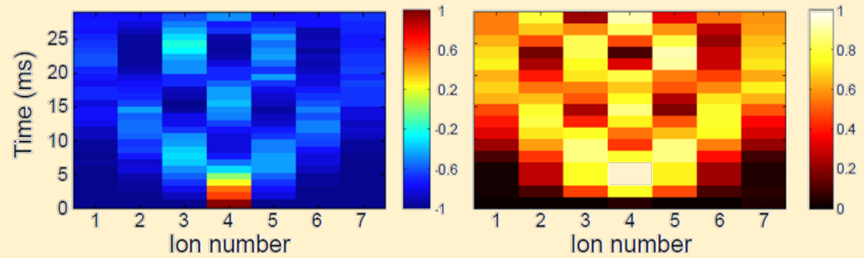
$$H_{XY} = \sum_{i<j}\frac{J_0}{|i-j|^{\alpha}}(\sigma_i^+\sigma_j^- + \sigma_i^-\sigma_j^+)$$

$0 < \alpha < 3$ 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**

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

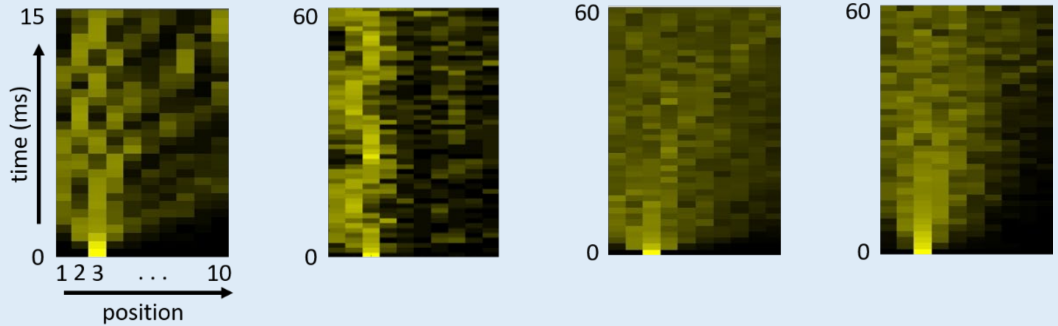
C. Maier et al.; PRL **122**, 050501 (2019)

ballistic, coherent transport

Anderson localization

diffusive, enhanced transport

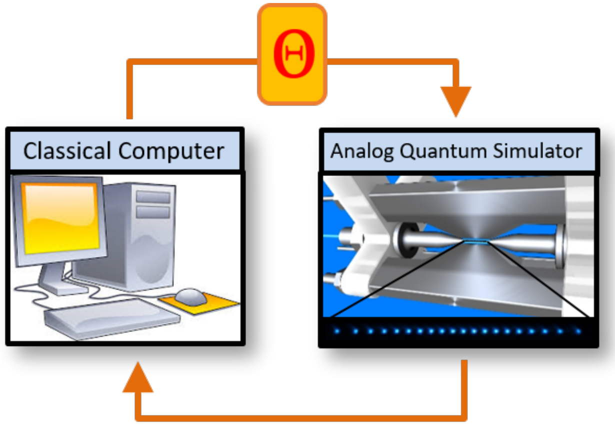
diffusive, suppressed transport



Variational Quantum Simulations with Trapped Ions

- Finding the ground state of a Hamiltonian

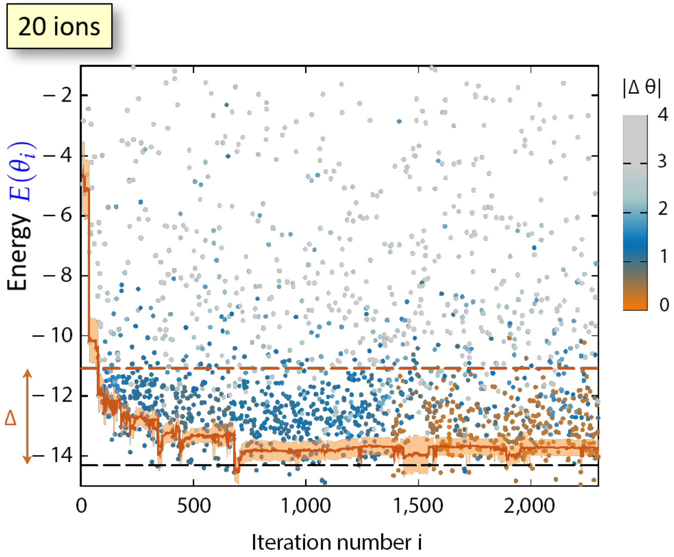
$$\langle \hat{H} \rangle = \sum_i \langle \hat{h}_i \rangle$$



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

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

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

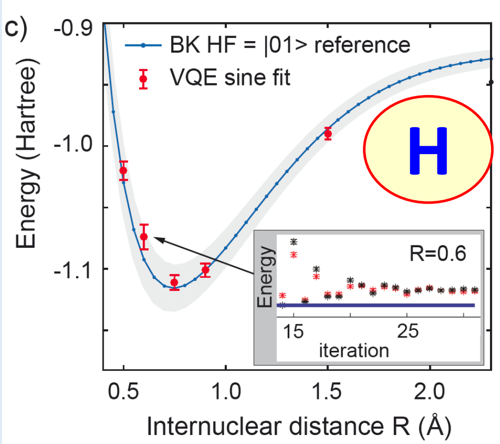
- Quantum chemistry calculations

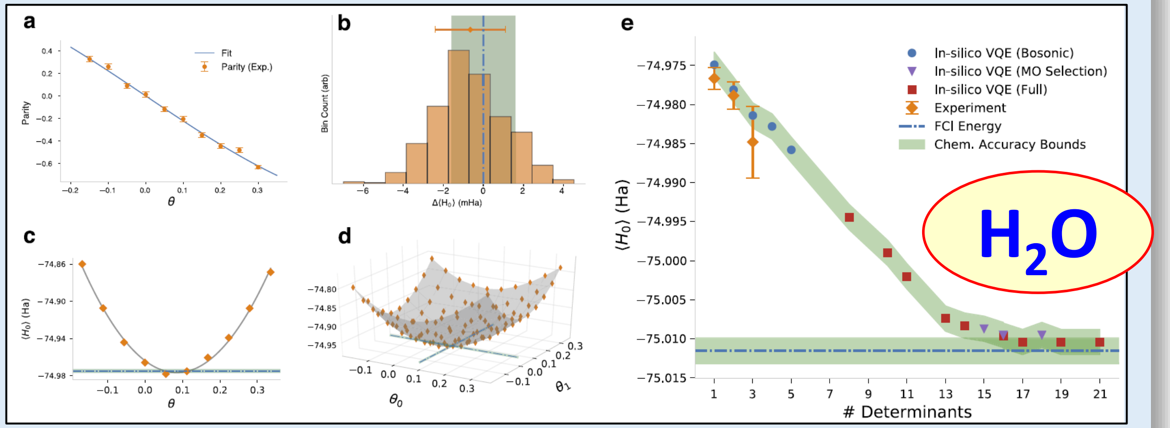
C. Hempel et al.,
Phys. Rev. **X 8**, 031022 (2018)

H

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

H_2O





Trapped Ions: Scalability Goals and Strategies

Scaling UP needs more

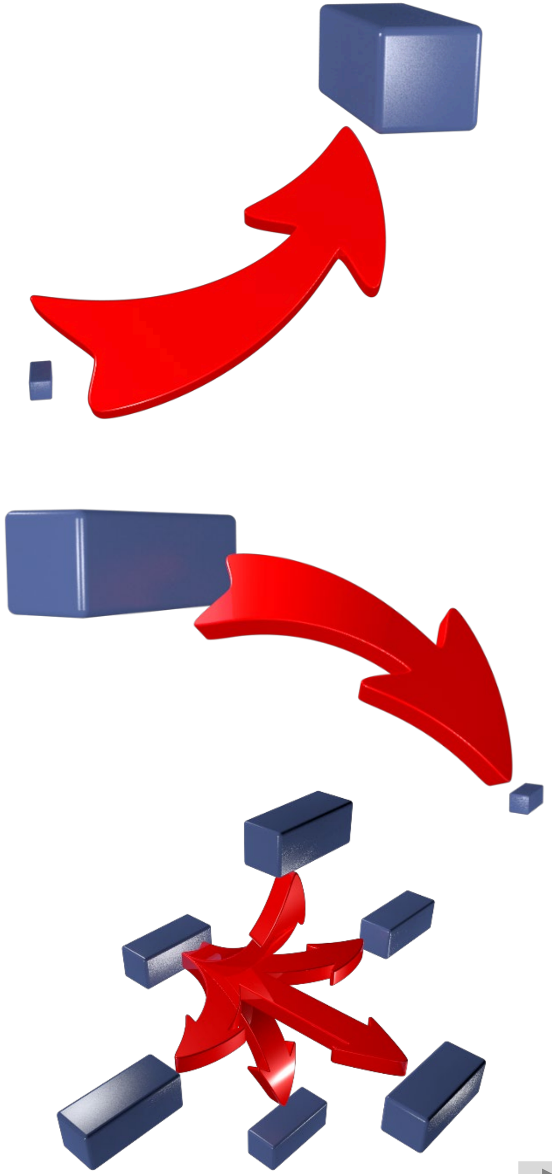
- qubits → traps (1D, 2D)
- operations → better control, quantum error correction
- comput. power → quantum software, solving a key problem
- predictability → component performance to system performance

Scaling DOWN needs less

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

Scaling OUT needs

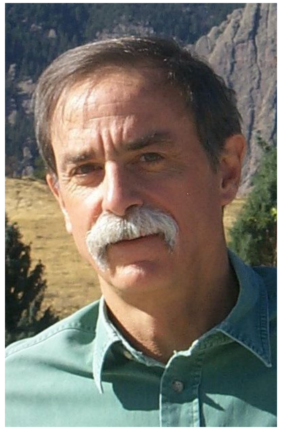
- interconnectivity → modular design, optical interfaces (hardware)
- distributivity → quantum parallel processing (software)



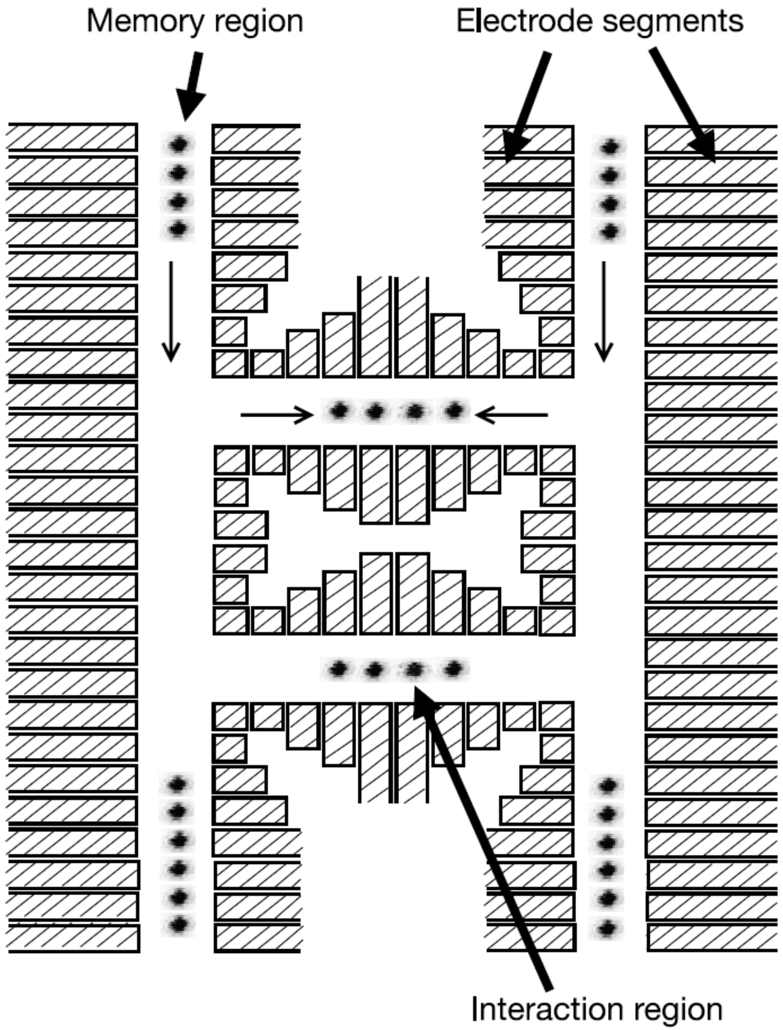
Scaling the ion trap quantum computer …

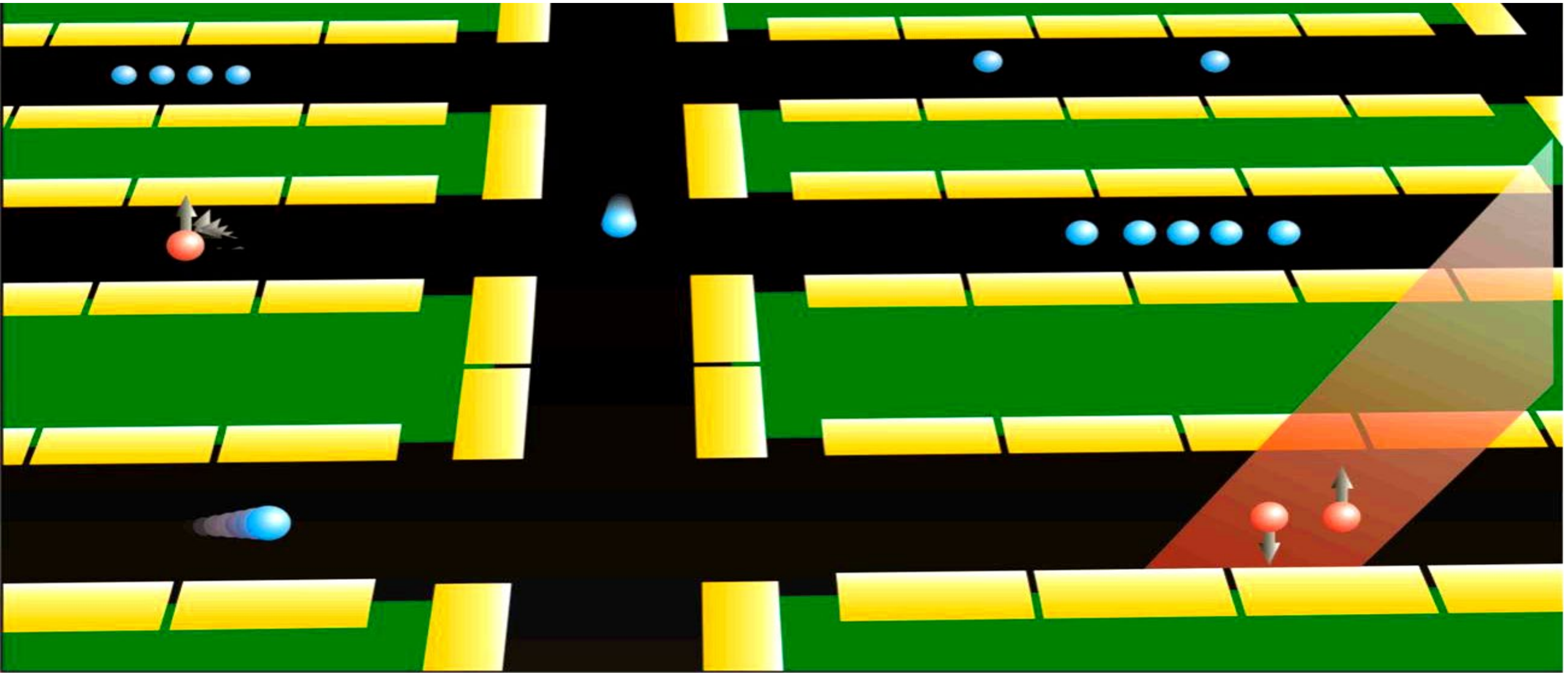
- more ions, **carry quantum information with phonons**:
  Cirac-Zoller, slow for many ions
- move ions, **carry quantum information with ions**:
  Kielpinski et al., Nature **417**, 709 (2002)

→ chip-traps, micro-structured traps



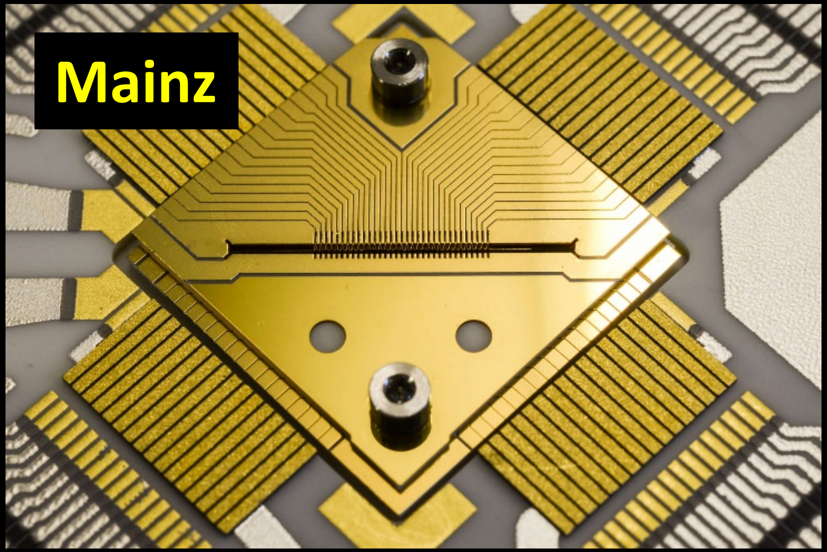
D. Wineland

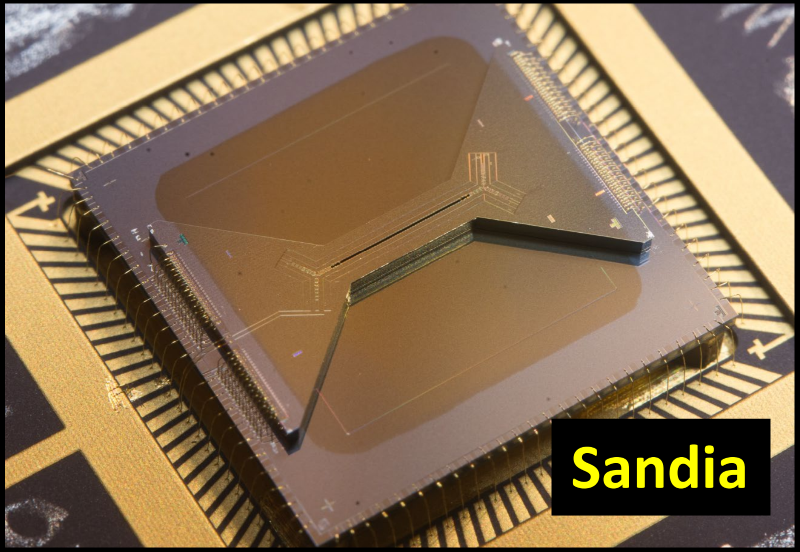


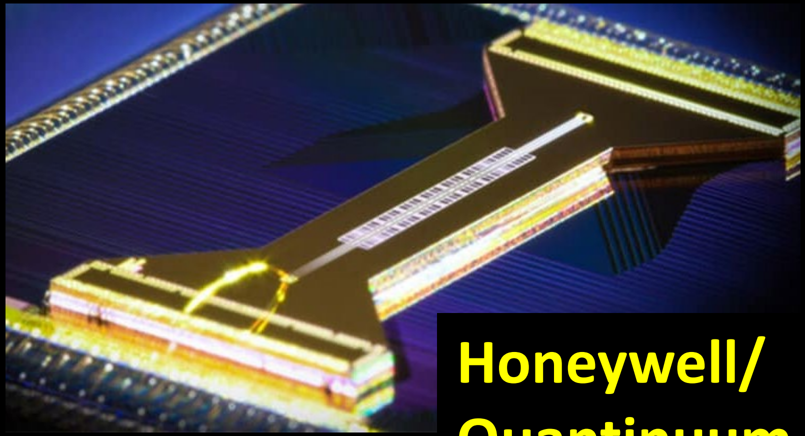


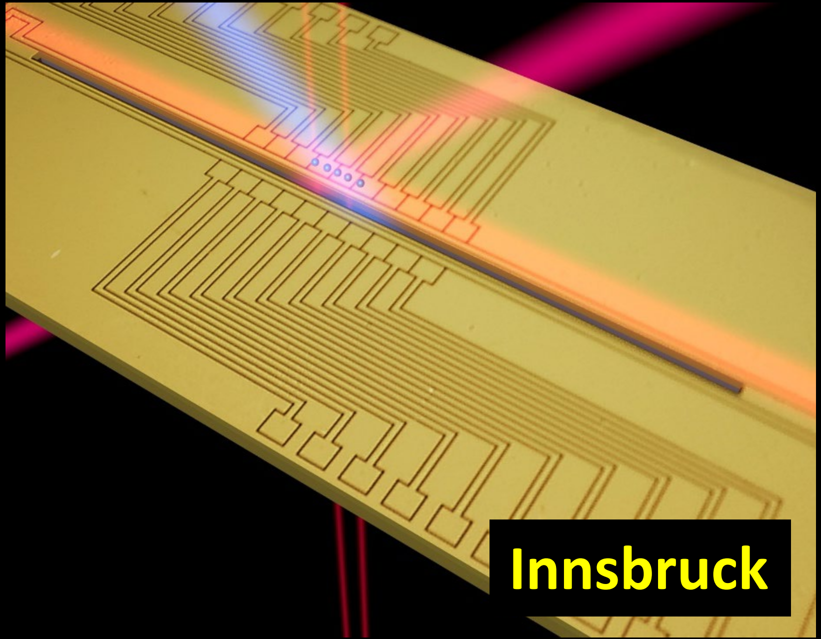
pioneered and developed by the Wineland group at NIST

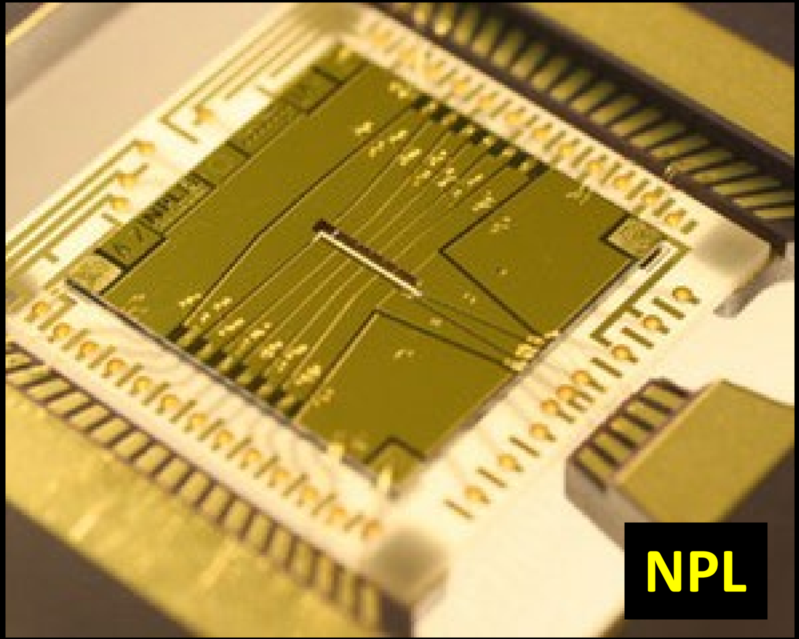
2010 – 2022 Chip Trap Quantum Processors

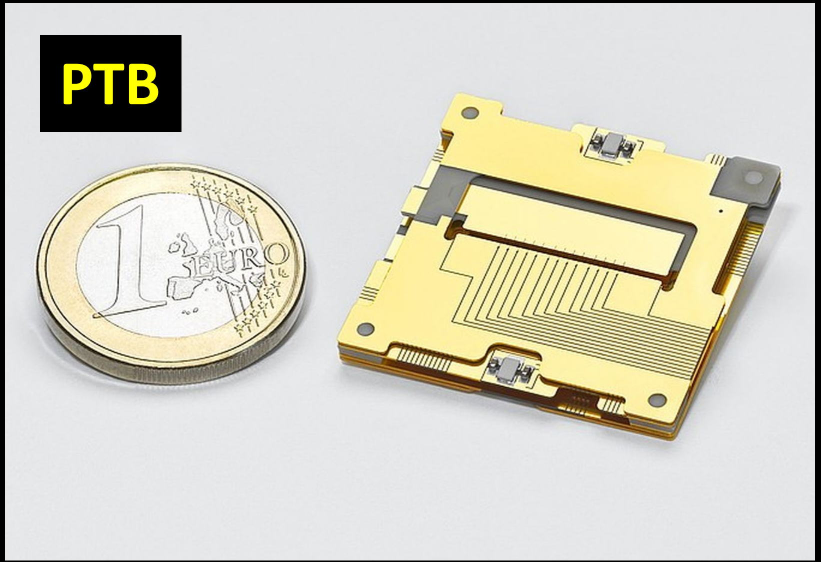

Mainz


Sandia


Honeywell/
Quantinuum

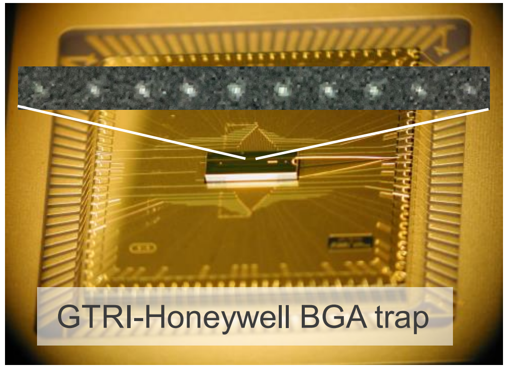

Innsbruck


NPL


PTB

Trapology

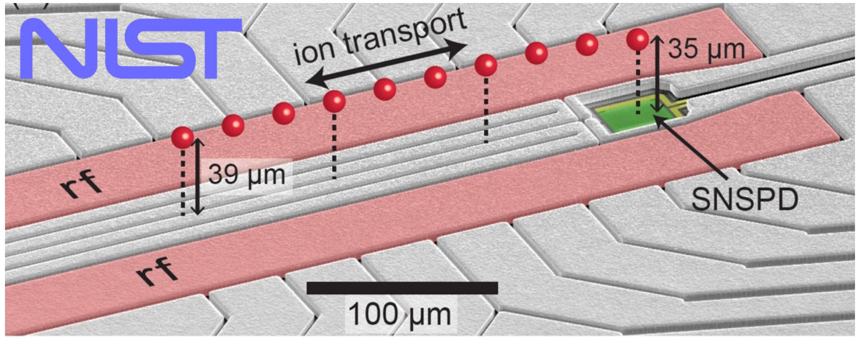
Georgia Tech
Research Institute



Ball-grid-array surface electrode trap for high-N.A. optical access and versatile control electrode signal routing. Inset shows 10 Yb^+ ions trapped in a chain.

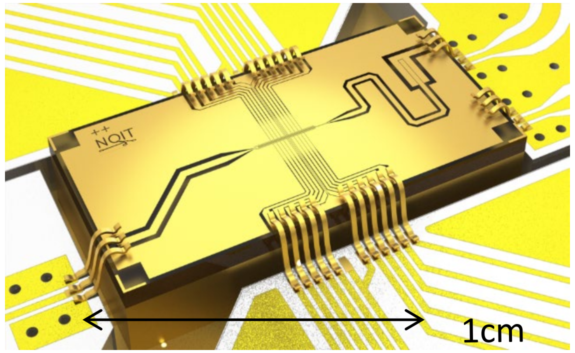
Guise, N. D. *et al.*, Ball-grid Array Architecture for Microfabricated Ion Traps, JAP **117**, 174901 (2015).

NIST

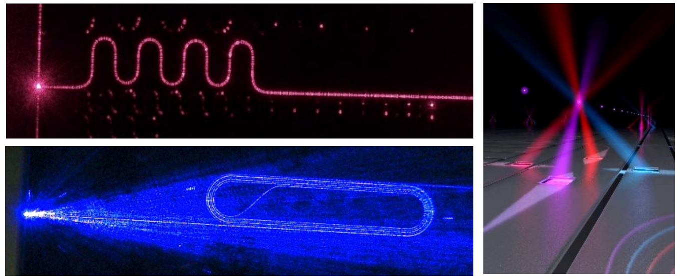


- scalable, trap-integrated photon detection
- highly parallelizable
- no optical elements, alignment free
- detection error 9 x 10^{-4} in 43 µs

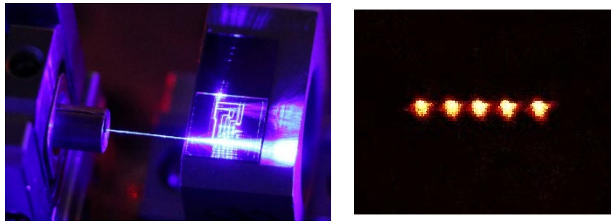
Univ. Oxford
µ-wave chip trap



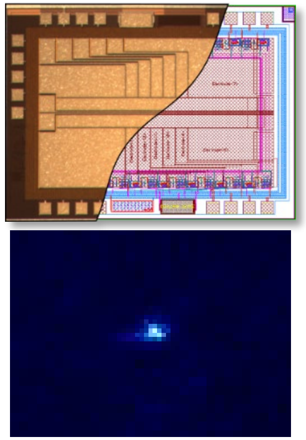
MIT Center for QuantumEngineering
MIT



On-chip waveguides and optics for multi-wavelength ion control

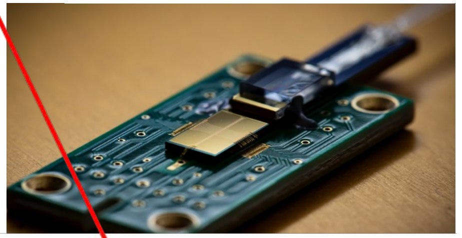


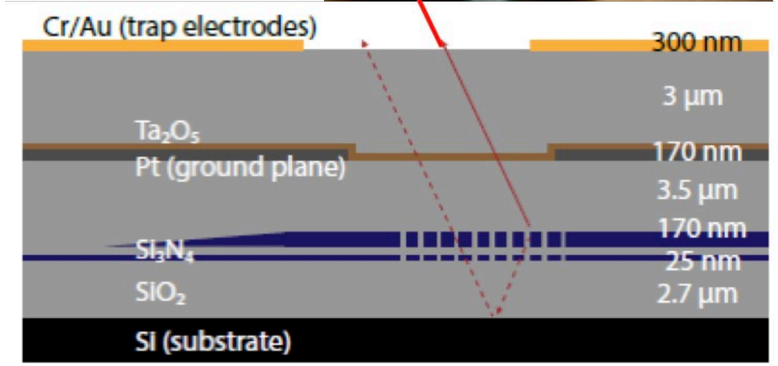
Programmable, trap-integrated voltage sources

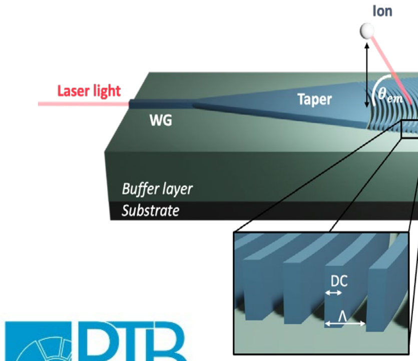


ETH zürich

Light to ion
50 micron above
surface



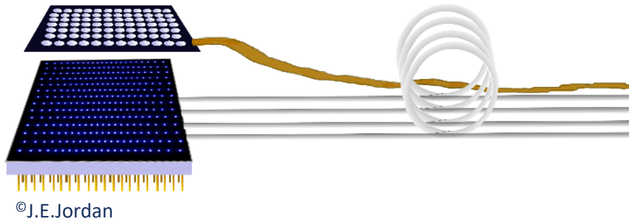




Integrated
optical
grating

PTB

Array of detectors



Array of ions

Predictability: component performance to system performance

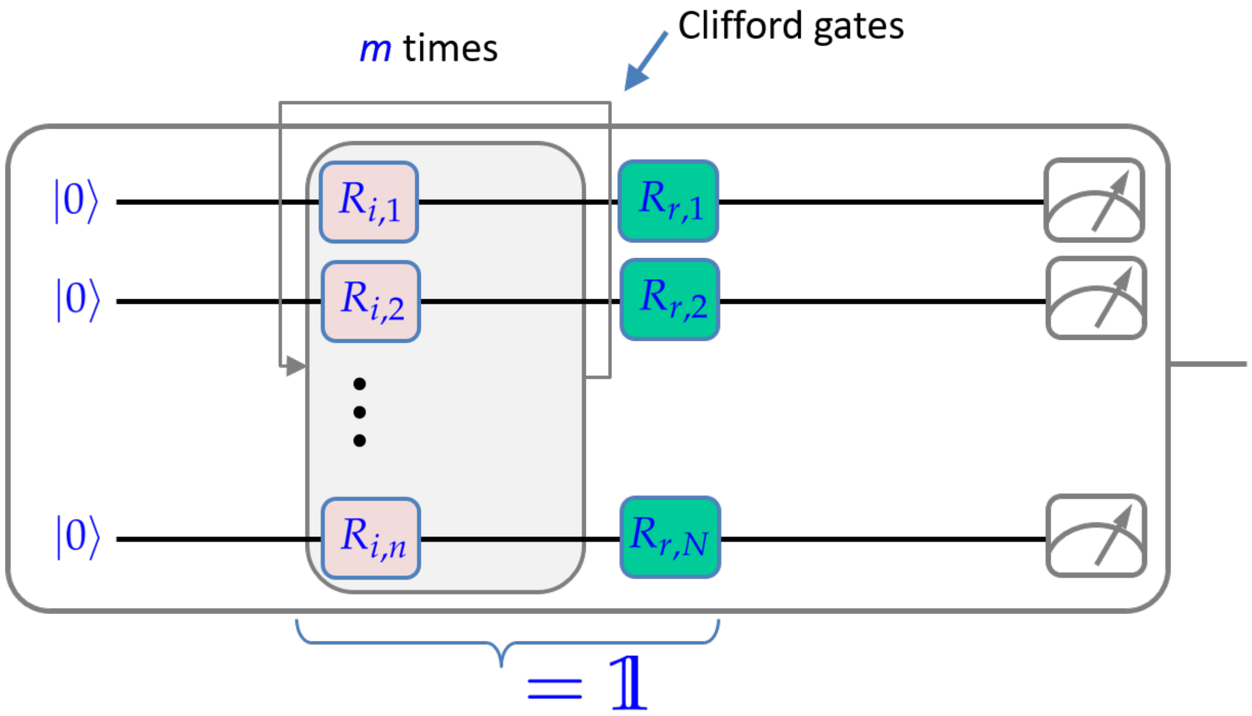
Benchmarking:
qubits, gate operations, processes, algorithms

- randomized benchmarking
  (qubits, gate operations)
- tomography
  (quantum states, quantum processes)
- GST – gate set tomography
  (metric)
- verification and validation protocols
  (algorithms)

System Performance

(Local) Randomized Benchmarking

Experimental protocol:



- characterizes local gates

Predictability: component performance to system performance

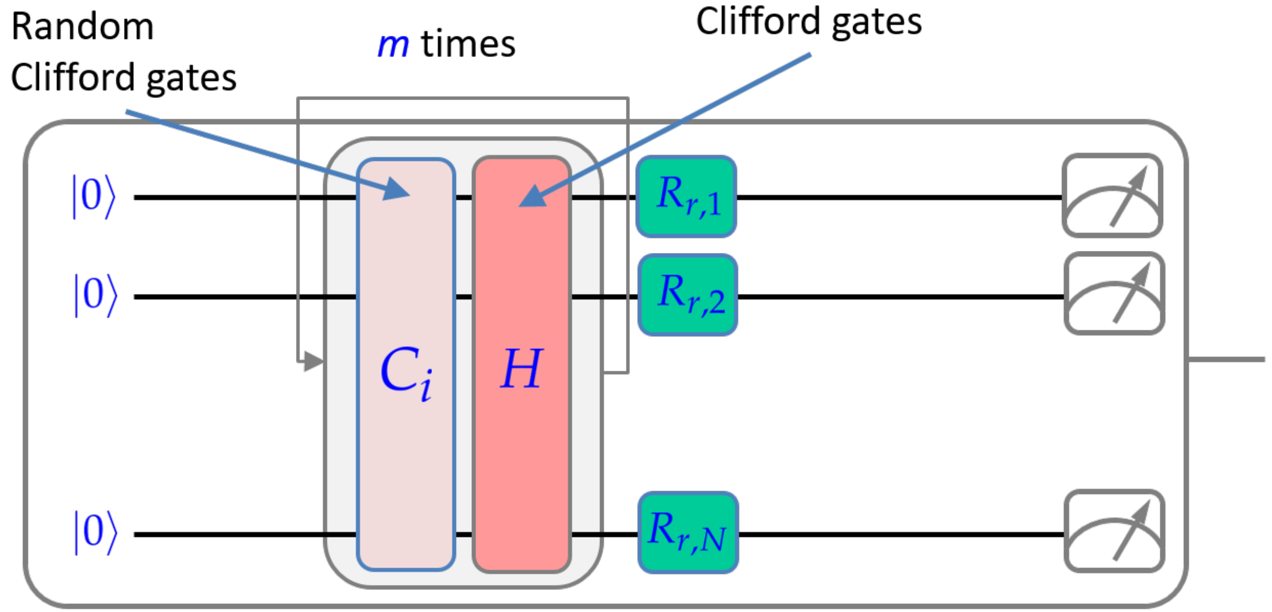
Benchmarking:
qubits, gate operations, processes, algorithms

- randomized benchmarking
(qubits, gate operations)
- tomography
(quantum states, quantum processes)
- GST – gate set tomography
(metric)
- verification and validation protocols
(algorithms)

System Performance

Interleaved Randomized Benchmarking

Experimental protocol:



- Characterizes arbitrary gate (H), for instance entangling gate (MS-gate)
- Needs n^2 entangling operations, thus impractical for large registers

Predictability: component performance to system performance

Benchmarking:
qubits, gate operations, processes, algorithms

- randomized benchmarking (qubits, gate operations)
- tomography (quantum states, quantum processes)
- GST – gate set tomography (metric)
- verification and validation protocols (algorithms)

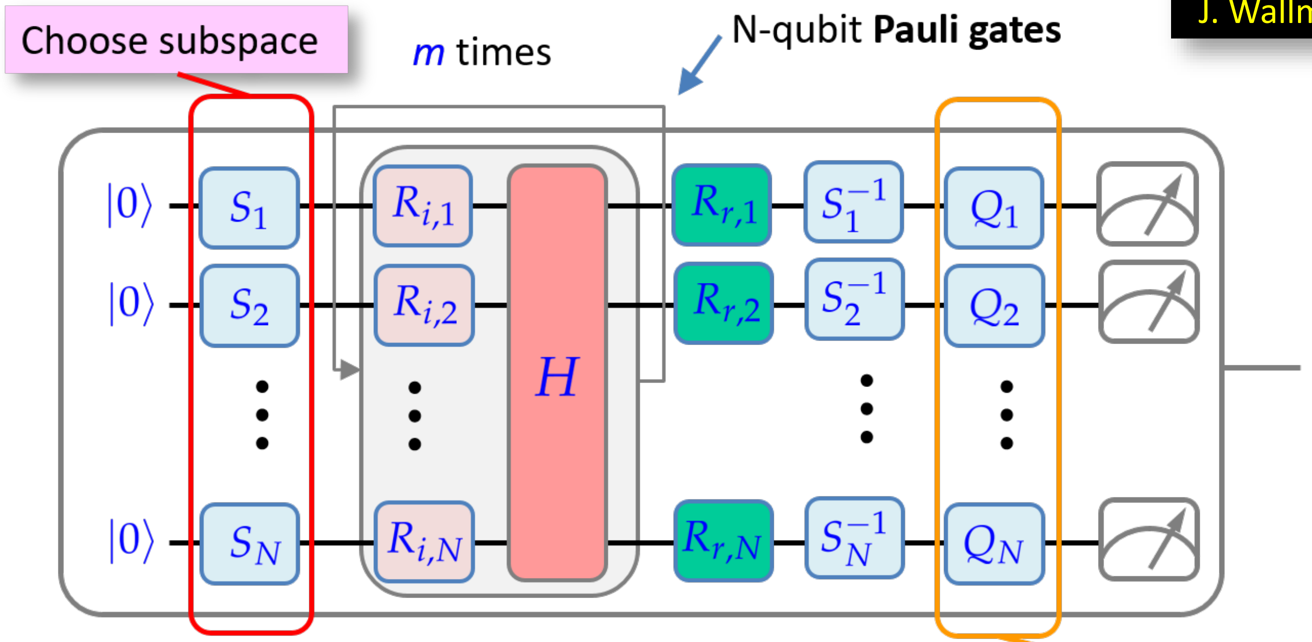
?

System Performance

Cycle Benchmarking (CB)


J. Wallman

Experimental protocol:


Choose subspace

m times

N-qubit **Pauli gates**

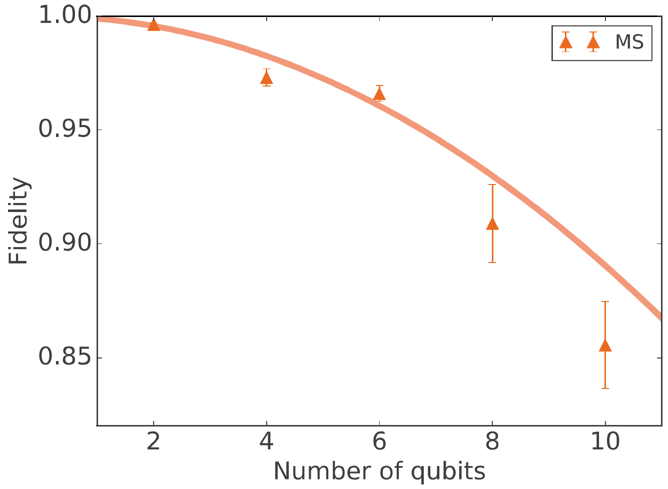
- Study several independent measurement bases
- Captures global errors
- Improved scaling properties

Random Pauli ops.: Robust against measurement errors.

A. Erhard, J. Wallman et al., Nat. Commun. **10**, 5347 (2019)

Cycle Benchmarking: The Mølmer-Sørensen Gate

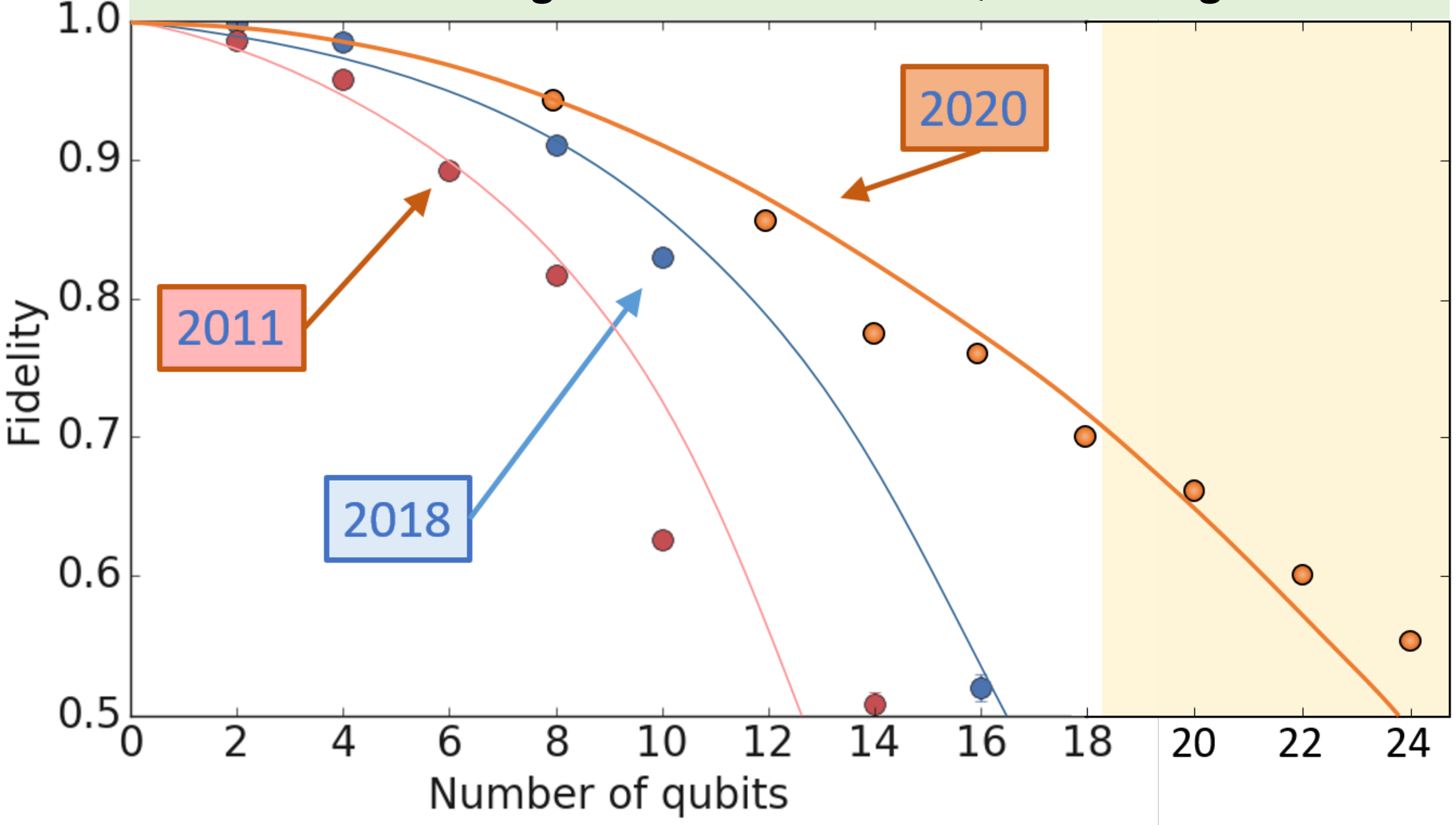
MS gate fidelity vs. number of qubits in register



Cycle benchmarking result:

error rate per single-qubit gate
and per two-qubit coupling
does not increase with
increasing system size

Generating and Characterizing GHZ States:
Benchmarking the Coherence of a Quantum Register



C. Marciniak, I. Pogorelov et al.,
PRX Quantum **2**, 020343 (2021)

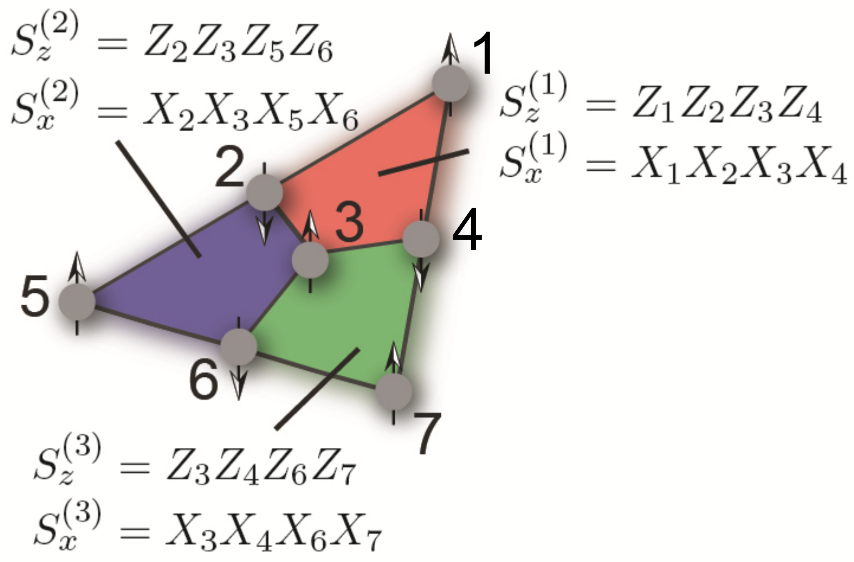
Quantum Error Correction with Trapped Ions

Qubit codes:

- delocalized entangled states of many qubits
- local errors, low probability

color code:
(Innsbruck)

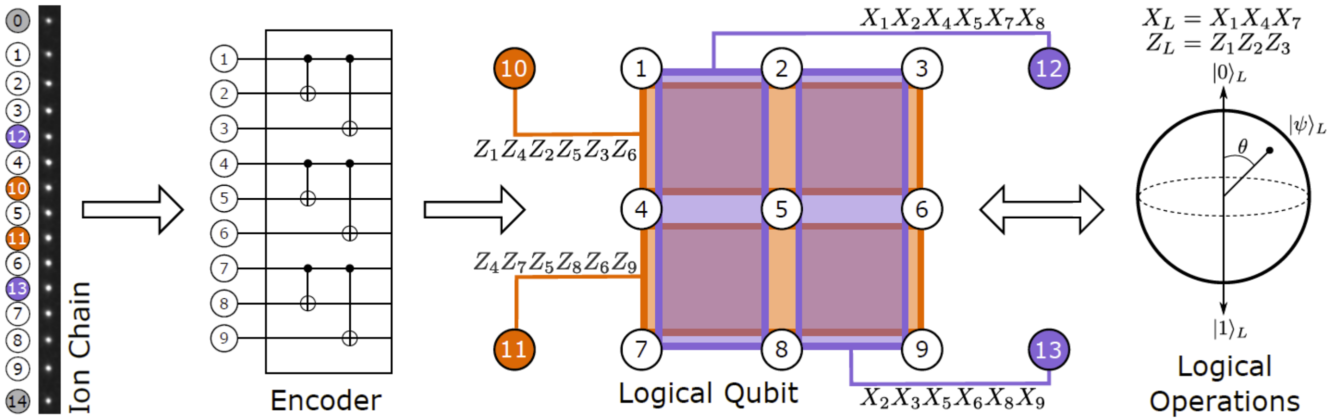
stabilizers S_x, S_z



$$S_z^{(2)} = Z_2 Z_3 Z_5 Z_6$$
$$S_x^{(2)} = X_2 X_3 X_5 X_6$$
$$S_z^{(1)} = Z_1 Z_2 Z_3 Z_4$$
$$S_x^{(1)} = X_1 X_2 X_3 X_4$$
$$S_z^{(3)} = Z_3 Z_4 Z_6 Z_7$$
$$S_x^{(3)} = X_3 X_4 X_6 X_7$$

Bacon-Shor code:
(Maryland)

stabilizers



$X_1X_2X_4X_5X_7X_8$

$X_2X_3X_5X_6X_8X_9$

$Z_1Z_4Z_2Z_5Z_3Z_6$

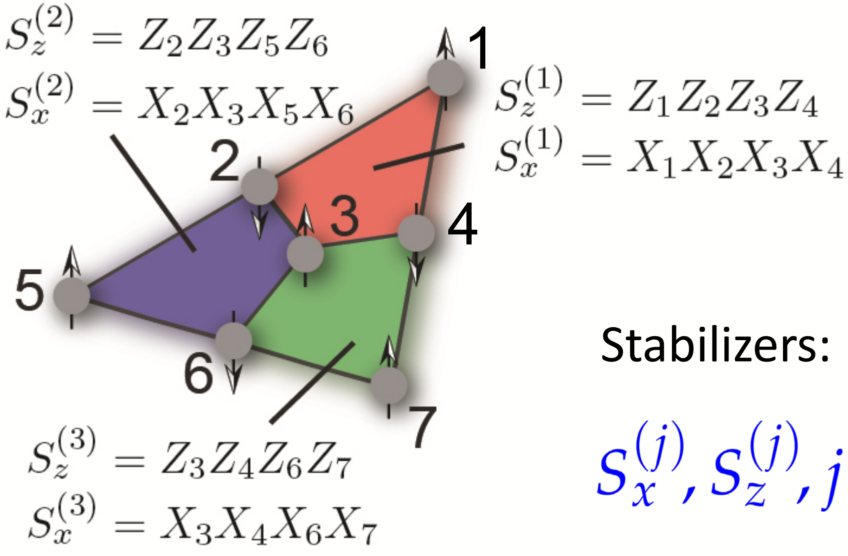
$Z_4Z_7Z_5Z_8Z_6Z_9$

$X_L = X_1X_4X_7$
$Z_L = Z_1Z_2Z_3$

H. Bombin, M. A. Martin-Delgado, PRL **97** , 180501 (2006)
D. Nigg, M. Müller et al., Science **345**, 302 (2014)

D. Bacon, Phys. Rev. A 73, 012340 (2006)
N.H. Nguyen et al., Phys. Rev. Appl. **16**, 024057 (2021)
L. Egan, et al., Nature **598**, 281 (2021)

Quantum Error Correction: Encoding a Logical Qubit



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

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

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

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

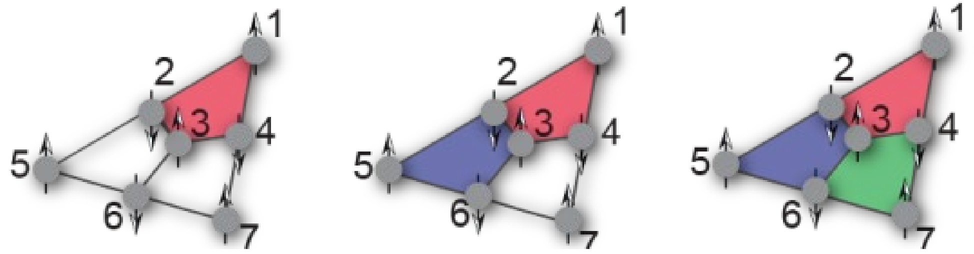
$S_z^{(3)} = Z_3 Z_4 Z_6 Z_7$

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

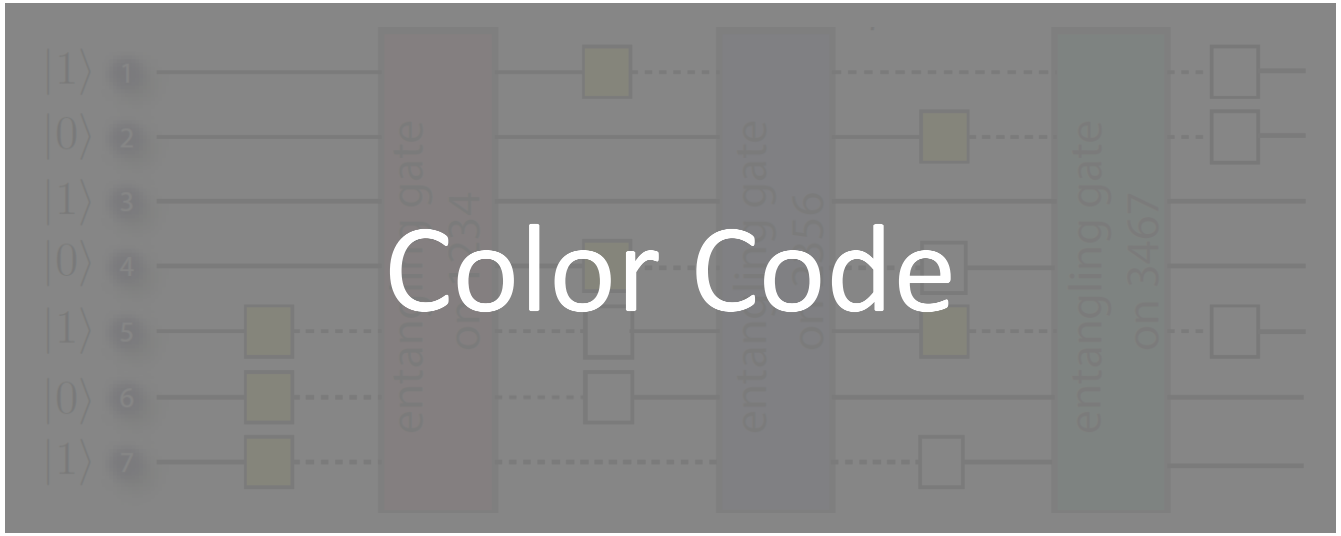
Stabilizers:

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

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



Encoding

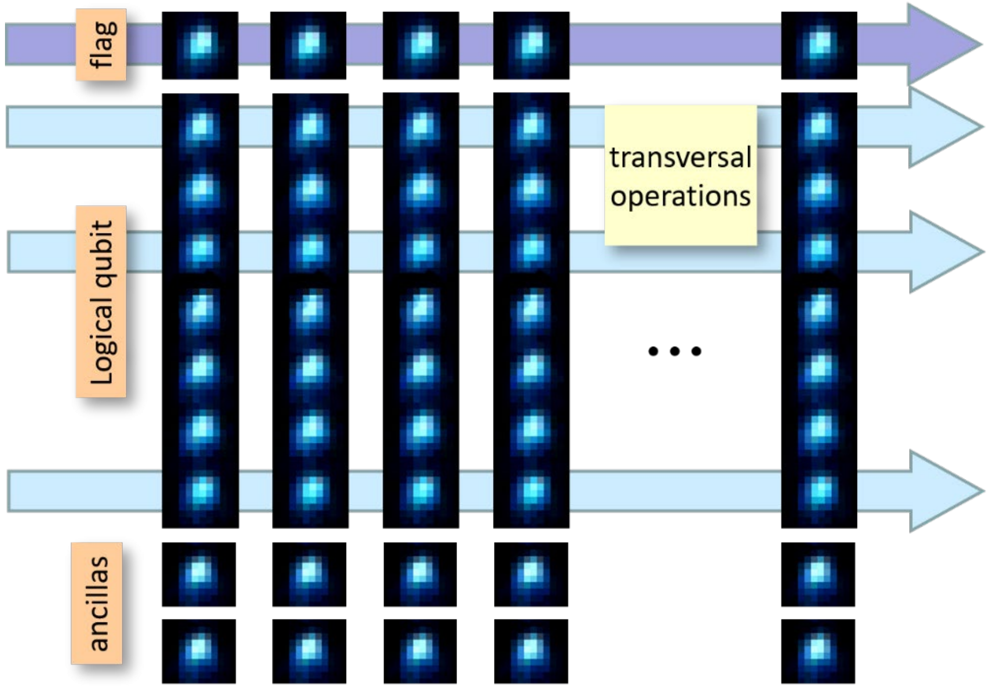


$\Big\} \; |0\rangle_L$

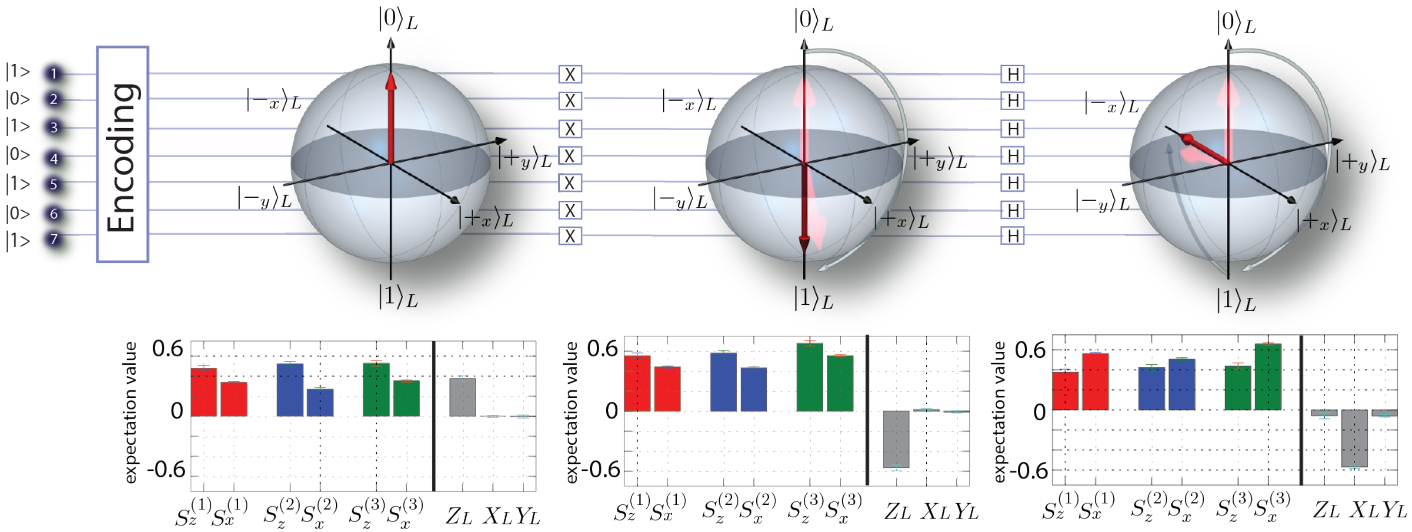
logical qubit

Gate operations with logical qubits

architecture for QC with logical qubits



apply {X, H} gate operations to map |0> onto |1> and $|-_x>$



Fidelity within codespace: F_{cs} = {95(2), 85(3), 87(2)} %

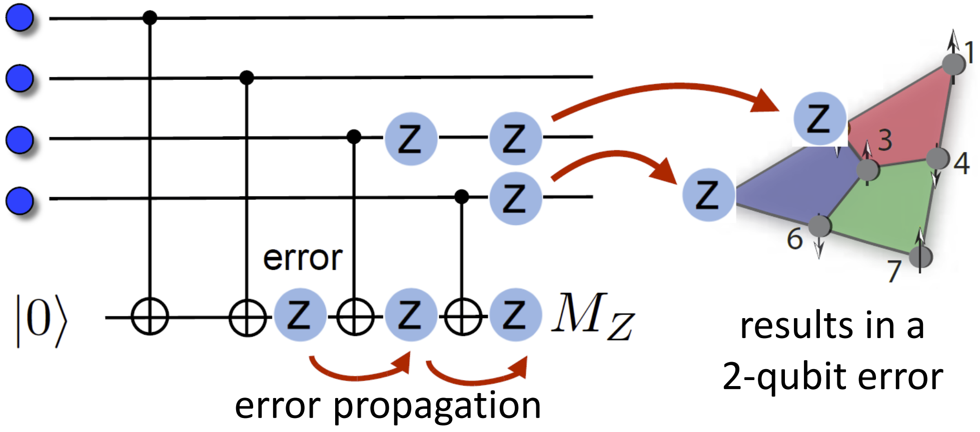
similarly:
{H, K, X} gate operations to map |0> onto $|+_x>$, $|+_y>$ and $|-_y>$
T-gate can be injected using an ancilla ion

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

Fault-Tolerant (FT) operation with trapped ions

FT requires control of error propagation

stabilizer measurement circuit for $S_z = Z_2 Z_3 Z_5 Z_6$

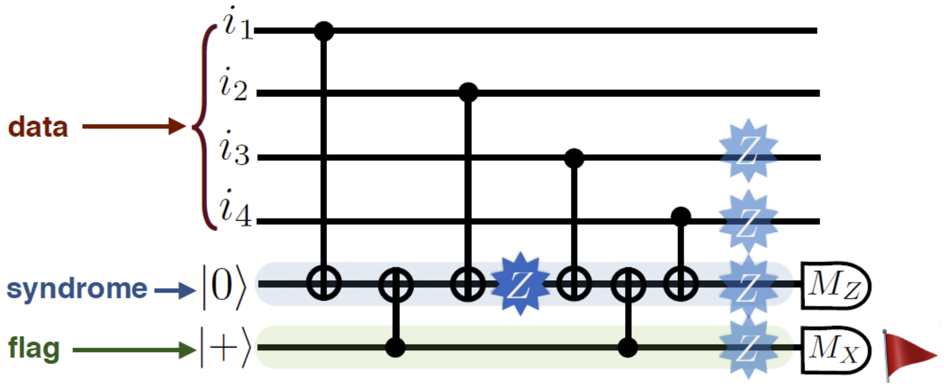


error

error propagation

results in a
2-qubit error

can be prevented using an **additional flag qubit**



R. Chao, B. Reichardt, PRL **121**, 050502 (2018)

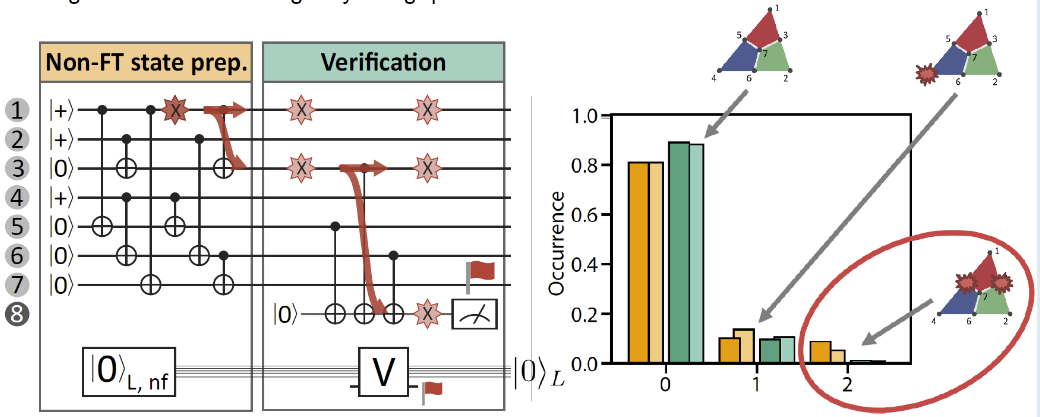
recent work done on FT operation with trapped ions:

- FT protocols and assessment (Innsbruck eQual collaboration)
  A. Bermudez et al., Phys. Rev. **X7**, 041061 (2017)
- FT-readout with 4 qubits (Maryland)
  N. Linke et al., Sci. Adv. **3**, e1701074, (2017)
- FT-control of an error-corrected qubit, (Maryland)
  L. Egan, et al., Nature **598**, 281 (2021)
- Realization of Real-Time FT Quantum Error Correction (Quantinuum)
  C. Ryan-Anderson et al., Phys. Rev. **X11**, 041058 (2021)
- FT-Parity Readout on a Shuttling-Based Trapped-Ion QC, (Mainz)
  J. Hilder et al., Phys. Rev. **X12**, 011032 (2022)
- Demonstration of FT universal quantum gate operations (Innsbruck)
  L. Postler et al., Nature **604**, (2022)

- Entangling logical qubits with **lattice surgery** (Innsbruck)
- Experimental **deterministic correction of qubit loss** (Innsbruck)

Fault-Tolerant Universal Quantum Gate Operations

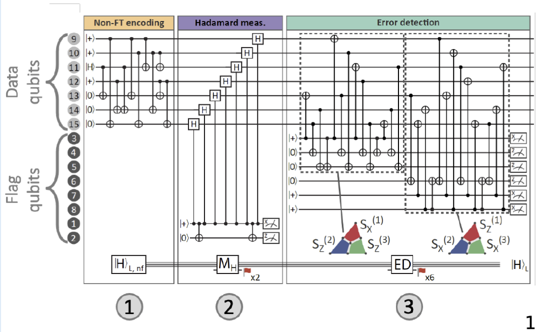
Fault-tolerant encoding:
Dangerous errors are caught by a flag qubit



- If dangerous error is detected, restart encoding

Uncorrectable fraction significantly reduced

- FT magic-state preparation

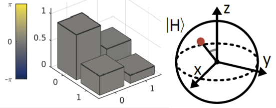


① Non-FT prepare magic state

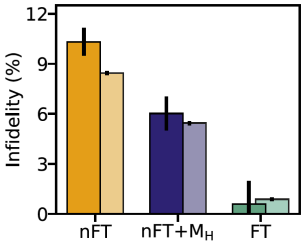
② Measure Hadamard: Magic state is +1-eigenstate

③ Error detection

- **Magic state** $|H\rangle_L = \cos(\pi/8)\,|0\rangle_L + \sin(\pi/8)\,|1\rangle_L$



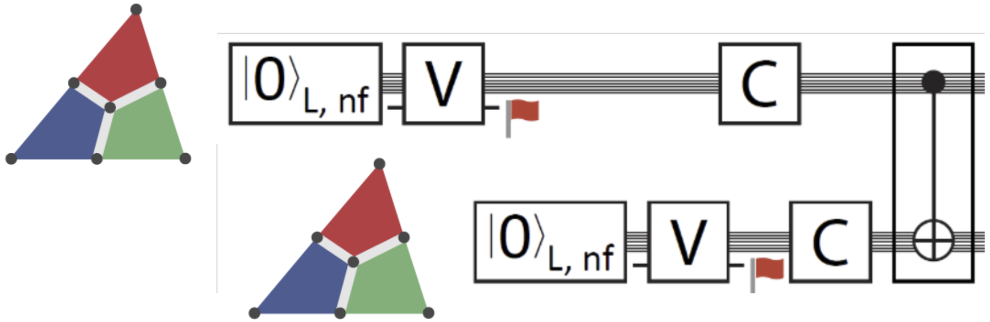
$\mathcal{F}_{\rm FT} = 0.994^{+5}_{-14}$



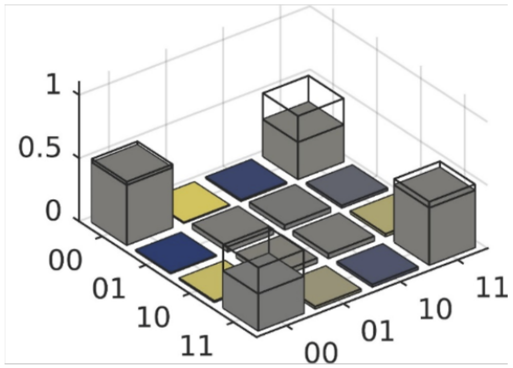
Fidelity:

$\mathcal{F}_{\mathcal{H}} = 0.994^{+5}_{-14}$

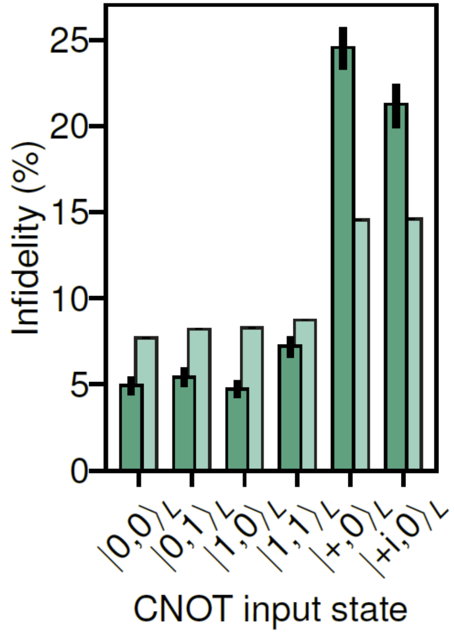
Experimental Fault-Tolerant CNOT gate operation



- **Logical Bell state (2 x 7 qubits)**



$\mathcal{F}_{\rm Bell} = 0.754(9)$



Ongoing work with trapped ions as a platform for QIP

● microwave driven gate operations	Boulder, Braunschweig, Siegen, Sussex, Oregon
● quantum metrology with entangled ions	
correlation spectroscopy,	Innsbruck, Boulder
frequency standards, variationally improved	Innsbruck
quantum logic spectroscopy (mixed species)	Boulder, Innsbruck, Braunschweig, Oxford, Zürich
● ion – photon entanglement (interfaces)	Innsbruck, Maryland, Oxford
● quantum repeaters with ions for quantum communication	Innsbruck
● entangling ions across distances (networking)	
photonic coupling	Innsbruck, Maryland
shuttling	Boulder, Mainz, Quantinuum, MIT
dipole-dipole interactions	Boulder, Innsbruck
● quantum thermodynamics with ions	Mainz
● gate operations using Rydberg blockade	Stockholm
● molecular ions for QIP	Boulder, Braunschweig, Los Angeles
● qubits with trapped electrons	Berkeley
● quDits with trapped ions (up to D=7, full gate set)	Innsbruck
● 2D simulations with trapped ions (Penning, Paul)	Boulder, Tsinghua, Indiana, Washington, Innsbruck

Strengths and Weaknesses of the Trapped-Ion (TI) Platform

Strengths of the TI Platform

- all-to-all connectivity
- indistinguishable atoms/ions
- isolated, at rest in free space
- long coherence times
- near perfect readout (99.99…%)
- flexible toolbox (local/global…)
- interfaces available
- NISQ – room temperature devices

Weaknesses of the TI Platform

- anomalous heating issue
- comparatively slow
- scalability technically involved
- cryo-techniques for large(r) ion numbers
- micromotion in 2D approaches
- rotating frame in Penning traps
- sensitivity to stray charges

Opportunities of the TI Platform

(similar to M. Lukins slide)

- creating/probing entanglement
- far-from equilibrium ent. dynamics
- quantum error correction – break-even, keeping qubit alive
- quantum sensing, metrology
- explore qu. algorithms/simulations eg. Hamiltonian learning
- scalability studies

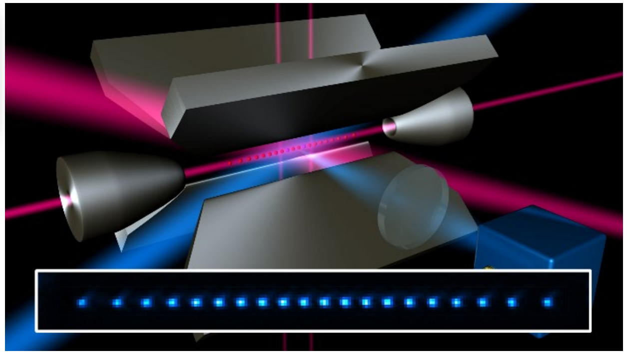
… and

there is room for improvements !

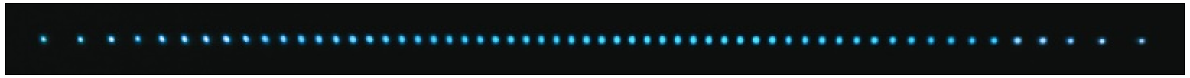
Threats to the TI Platform

- current hype discussion
- excellent science

QIP with Trapped Ions: Future Goals and Developments



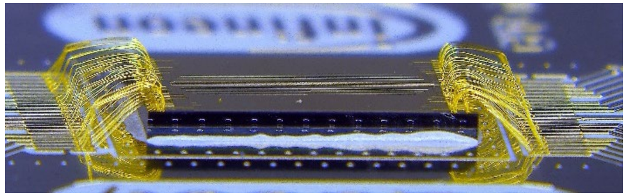
- more qubits (~50 – 100)



59 ions

- better fidelities (10^{-4} – 10^{-5} infidelity)
- faster gate operations
- faster detection

} cryogenic trap, micro-structured traps

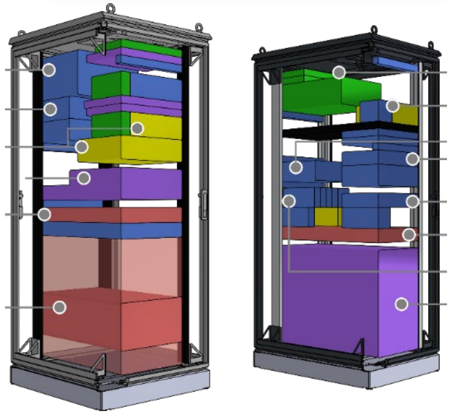


- development of 2-d trap arrays, onboard addressing, onboard electronics etc.
- entangling of large(r) systems: characterization ?
- implementation of error correction

„qubit alive“

- 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)

eQual



The Ion Trap Community Worldwide

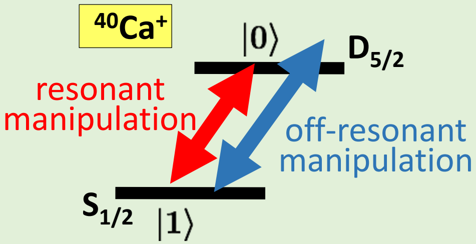
~ 70 ion trapping groups working on quantum information with trapped ions

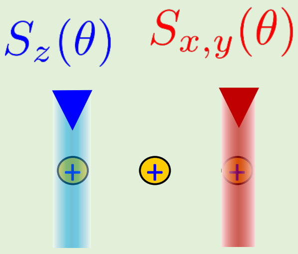
Ion Trapping Groups Worldwide (102 today and counting),
https://quantumoptics.at/en/links/ion-trapping-worldwide.html

Thank you on behalf of the ion trap community

The workhorse at UIBK …

Individual (and parallel) local operations





τ = 20µs

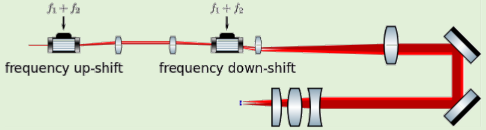
F > 99%

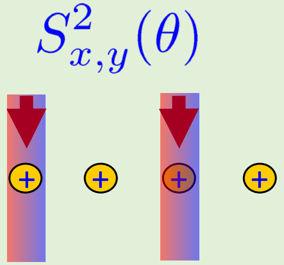
Control capabilities

- T1 approx 1s
- T2 approx 500 ms
- Routinely work with 20+ ions
- Demonstrated 24q-GHZ state
- Supports Qiskit/Cirq/…

Local Mølmer- Sørensen entangling gate

Simultaneous addressing of multiple ions



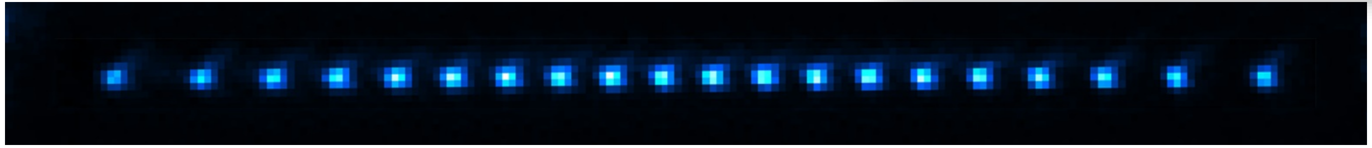


τ = 100µs

F ~ 99%

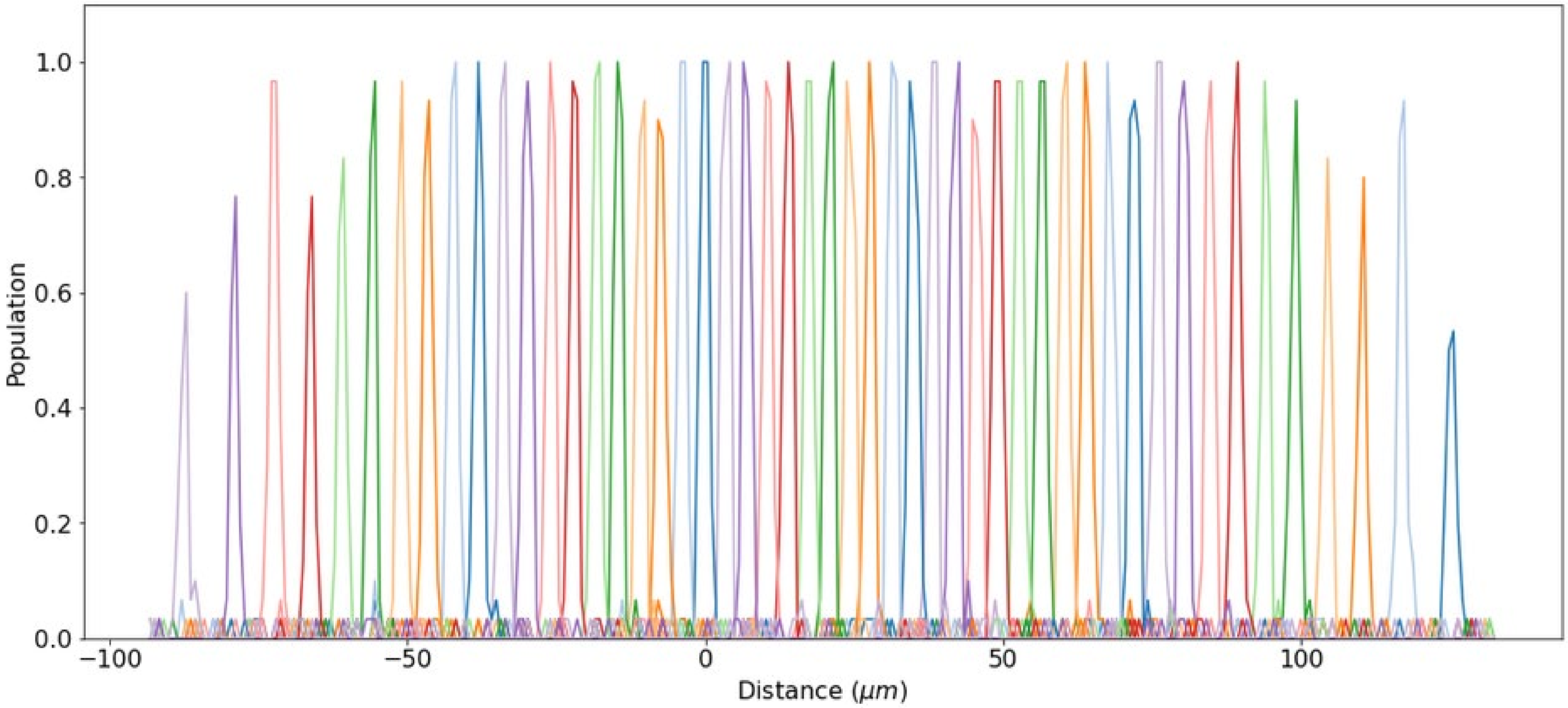
Automated tune-up

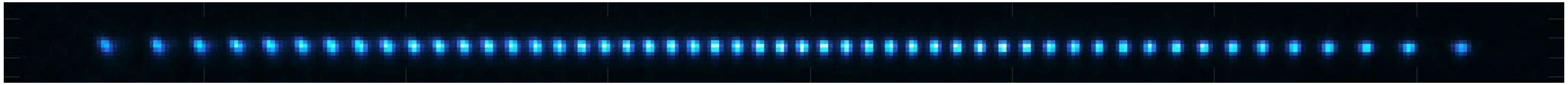
- Single-qubit control
- Single-setting MS up to 20 q with full connectivity
- N^2 calibration speed-up
- Tune-up to > 99% in 30 sec



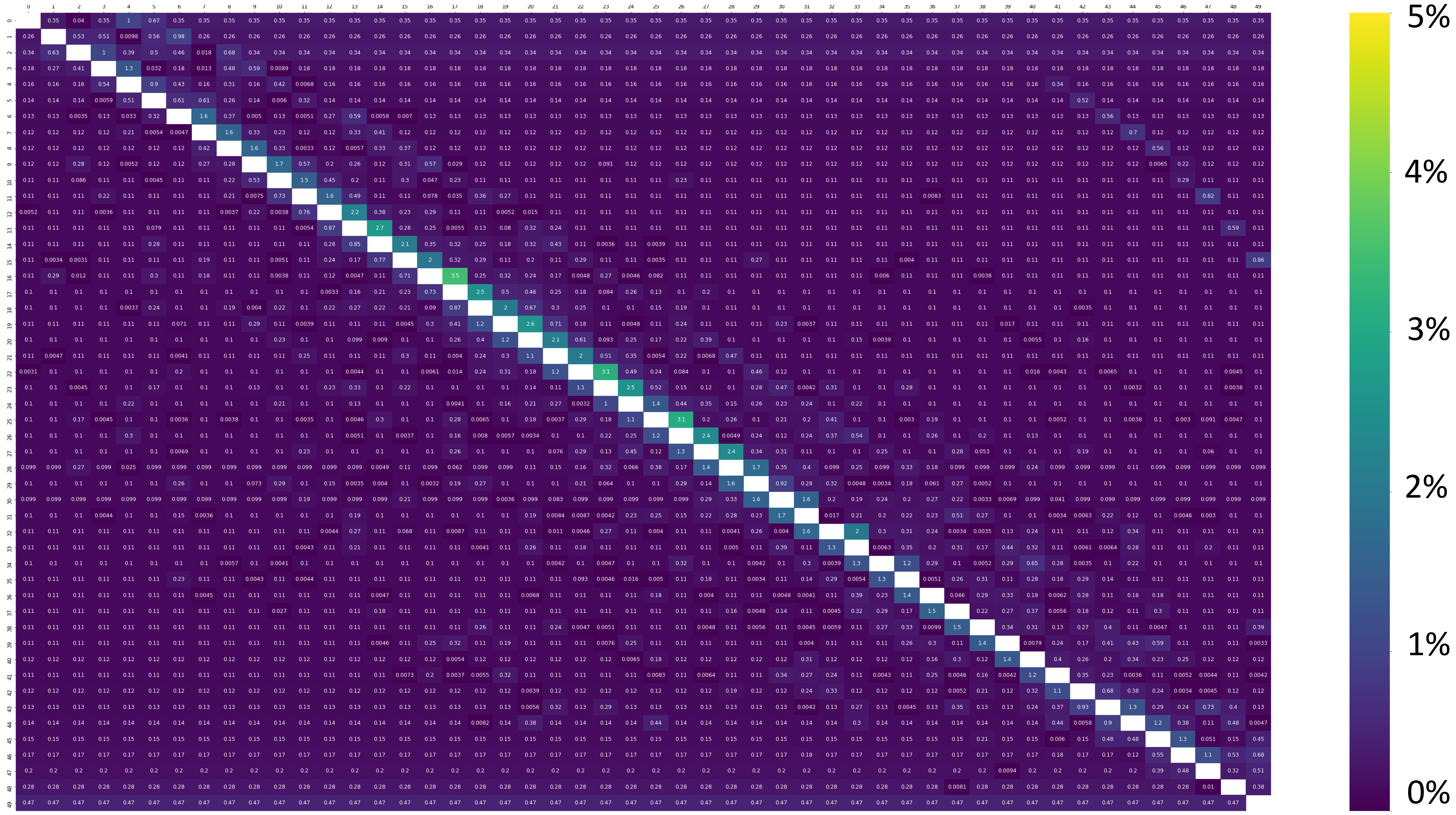
PRX Quantum **2**, 020343 (2021)

State-of-the-art: addressing 50 qubits





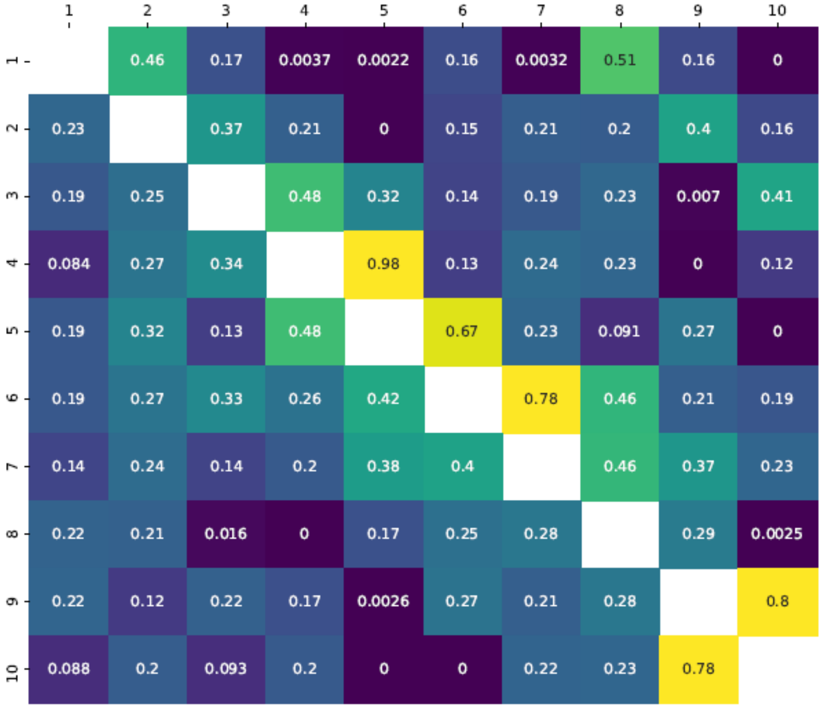
Cross-talk: 50 qubits, resonant excitation



Maxium cross-talk 3.5%; avg. NN cross-talk 1.2%, avg. cross-talk <0.2%

Cross-talk using addressing error correction

Resonant

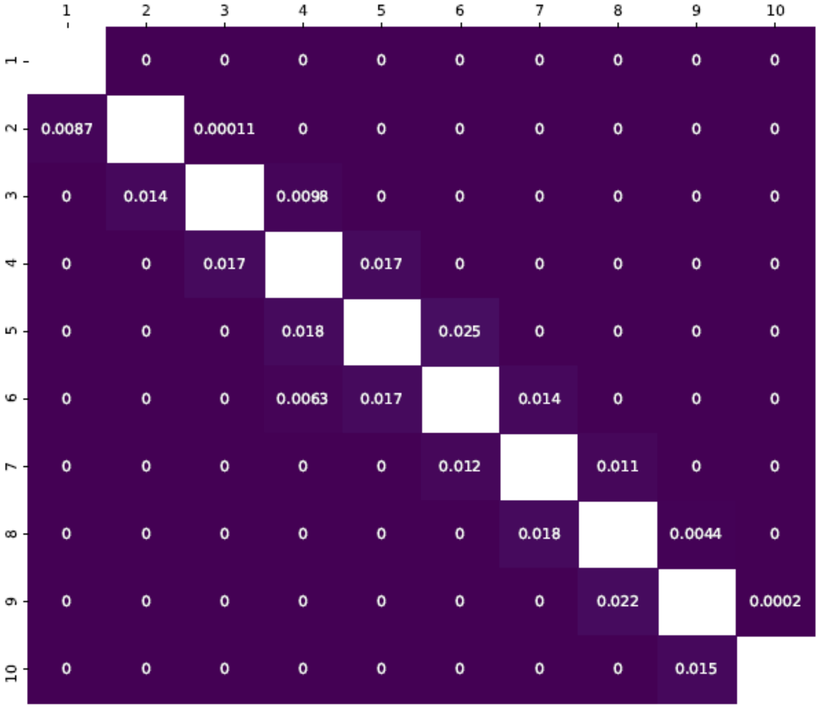


	1	2	3	4	5	6	7	8	9	10
1		0.46	0.17	0.0037	0.0022	0.16	0.0032	0.51	0.16	0
2	0.23		0.37	0.21	0	0.15	0.21	0.2	0.4	0.16
3	0.19	0.25		0.48	0.32	0.14	0.19	0.23	0.007	0.41
4	0.084	0.27	0.34		0.98	0.13	0.24	0.23	0	0.12
5	0.19	0.32	0.13	0.48		0.67	0.23	0.091	0.27	0
6	0.19	0.27	0.33	0.26	0.42		0.78	0.46	0.21	0.19
7	0.14	0.24	0.14	0.2	0.38	0.4		0.46	0.37	0.23
8	0.22	0.21	0.016	0	0.17	0.25	0.28		0.29	0.0025
9	0.22	0.12	0.22	0.17	0.0026	0.27	0.21	0.28		0.8
10	0.088	0.2	0.093	0.2	0	0	0.22	0.23	0.78	

max = 0.98%
min < 0.1%
avg. on all = 0.22%
avg. on NN = 0.49%

Correctable

Off-resonant

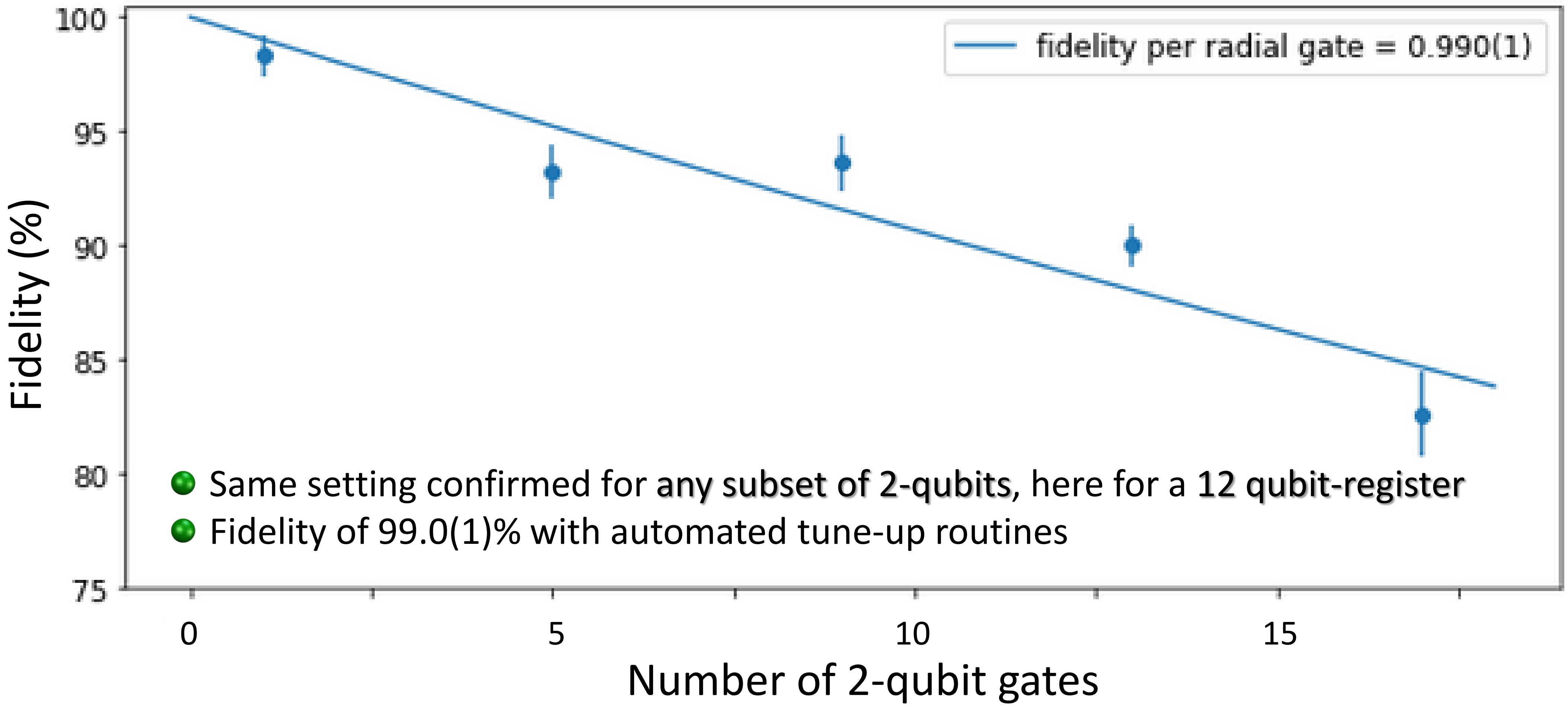


	1	2	3	4	5	6	7	8	9	10
1		0	0	0	0	0	0	0	0	0
2	0.0087		0.00011	0	0	0	0	0	0	0
3	0	0.014		0.0098	0	0	0	0	0	0
4	0	0	0.017		0.017	0	0	0	0	0
5	0	0	0	0.018		0.025	0	0	0	0
6	0	0	0	0.0063	0.017		0.014	0	0	0
7	0	0	0	0	0	0.012		0.011	0	0
8	0	0	0	0	0	0	0.018		0.0044	0
9	0	0	0	0	0	0	0	0.022		0.0002
10	0	0	0	0	0	0	0	0	0.015	

max = $2.5*10^{-4}$
min < $5*10^{-5}$
avg on NN = $1.25*10^{-4}$
or **10^{-8} error rate**

Negligible errors @ 10^{-6}

2-qubit gate performance

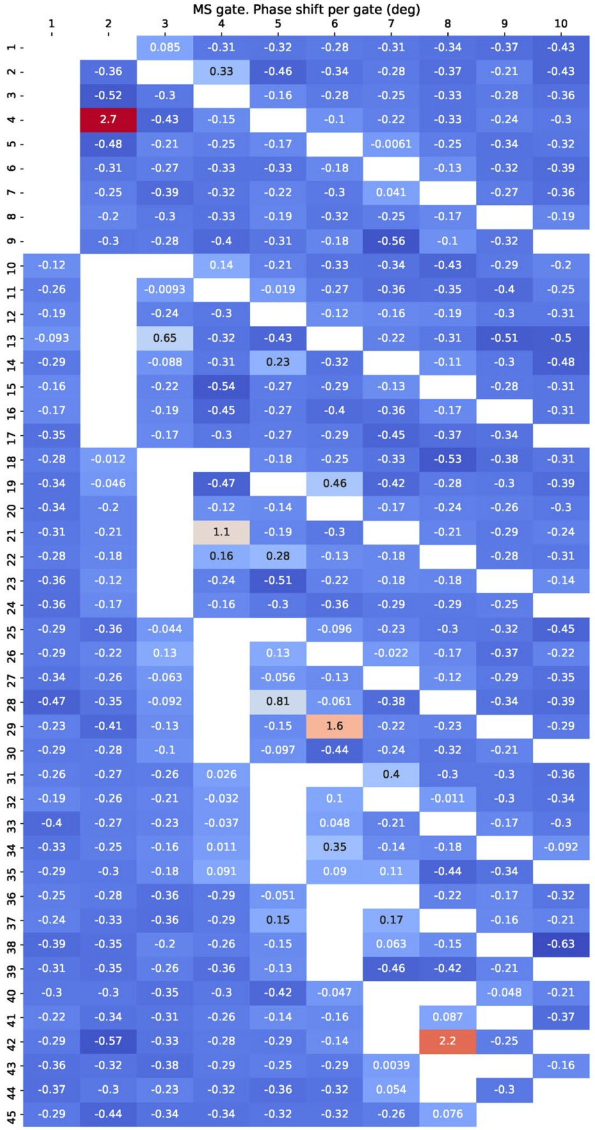


- Same setting confirmed for **any subset of 2-qubits**, here for a **12 qubit-register**
- Fidelity of 99.0(1)% with automated tune-up routines

Good gates w/o cross-talk

Cross-talk with 2-qubit gates (in a 10-qubit register)

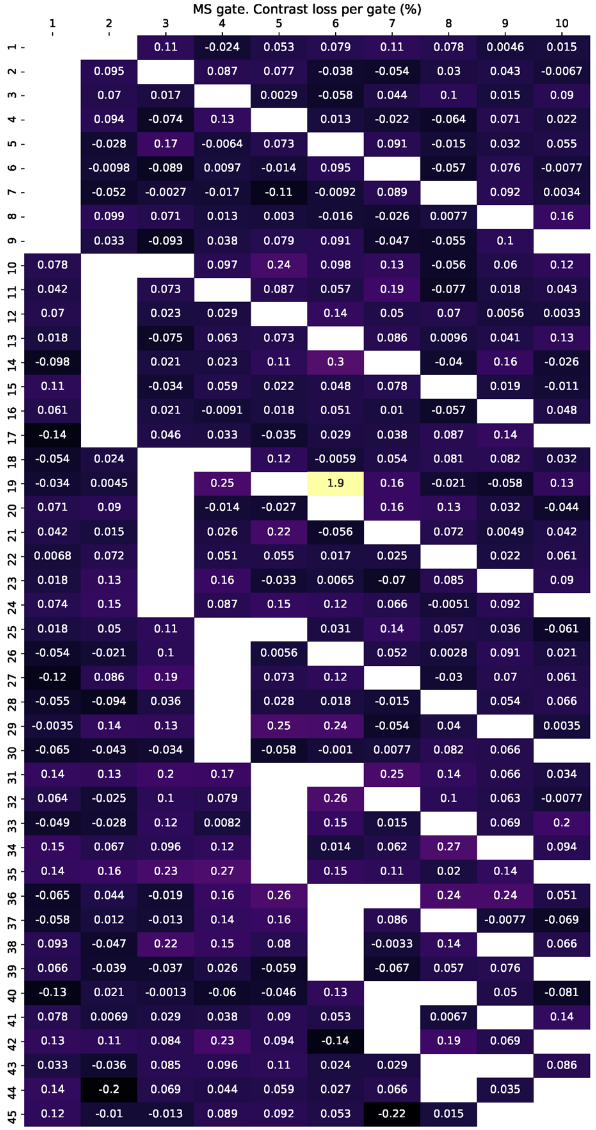
MS phase shift



MS gate. Phase shift per gate (deg)

	1	2	3	4	5	6	7	8	9	10
1			0.085	-0.31	-0.32	-0.28	-0.31	-0.34	-0.37	-0.43
2		-0.36		0.33	-0.46	-0.34	-0.28	-0.37	-0.21	-0.43
3		-0.52	-0.3		-0.16	-0.28	-0.25	-0.33	-0.28	-0.36
4		2.7	-0.43	-0.15		-0.1	-0.22	-0.33	-0.24	-0.3
5		-0.48	-0.21	-0.25	-0.17		-0.0061	-0.25	-0.34	-0.32
6		-0.31	-0.27	-0.33	-0.33	-0.18		-0.13	-0.32	-0.39
7		-0.25	-0.39	-0.32	-0.22	-0.3	0.041		-0.27	-0.36
8		-0.2	-0.3	-0.33	-0.19	-0.32	-0.25	-0.17		-0.19
9		-0.3	-0.28	-0.4	-0.31	-0.18	-0.56	-0.1	-0.32	
10	-0.12			0.14	-0.21	-0.33	-0.34	-0.43	-0.29	-0.2
11	-0.26		-0.0093		-0.019	-0.27	-0.36	-0.35	-0.4	-0.25
12	-0.19		-0.24	-0.3		-0.12	-0.16	-0.19	-0.3	-0.31
13	-0.093		0.65	-0.32	-0.43		-0.22	-0.31	-0.51	-0.5
14	-0.29		-0.088	-0.31	0.23	-0.32		-0.11	-0.3	-0.48
15	-0.16		-0.22	-0.54	-0.27	-0.29	-0.13		-0.28	-0.31
16	-0.17		-0.19	-0.45	-0.27	-0.4	-0.36	-0.17		-0.31
17	-0.35		-0.17	-0.3	-0.27	-0.29	-0.45	-0.37	-0.34	
18	-0.28	-0.012			-0.18	-0.25	-0.33	-0.53	-0.38	-0.31
19	-0.34	-0.046		-0.47		0.46	-0.42	-0.28	-0.3	-0.39
20	-0.34	-0.2		-0.12	-0.14		-0.17	-0.24	-0.26	-0.3
21	-0.31	-0.21		1.1	-0.19	-0.3		-0.21	-0.29	-0.24
22	-0.28	-0.18		0.16	0.28	-0.13	-0.18		-0.28	-0.31
23	-0.36	-0.12		-0.24	-0.51	-0.22	-0.18	-0.18		-0.14
24	-0.36	-0.17		-0.16	-0.3	-0.36	-0.29	-0.29	-0.25	
25	-0.29	-0.36	-0.044			-0.096	-0.23	-0.3	-0.32	-0.45
26	-0.29	-0.22	0.13		0.13		-0.022	-0.17	-0.37	-0.22
27	-0.34	-0.26	-0.063		-0.056	-0.13		-0.12	-0.29	-0.35
28	-0.47	-0.35	-0.092		0.81	-0.061	-0.38		-0.34	-0.39
29	-0.23	-0.41	-0.13		-0.15	1.6	-0.22	-0.23		-0.29
30	-0.29	-0.28	-0.1		-0.097	-0.44	-0.24	-0.32	-0.21	
31	-0.26	-0.27	-0.26	0.026			0.4	-0.3	-0.3	-0.36
32	-0.19	-0.26	-0.21	-0.032		0.1		-0.011	-0.3	-0.34
33	-0.4	-0.27	-0.23	-0.037		0.048	-0.21		-0.17	-0.3
34	-0.33	-0.25	-0.16	0.011		0.35	-0.14	-0.18		-0.092
35	-0.29	-0.3	-0.18	0.091		0.09	0.11	-0.44	-0.34	
36	-0.25	-0.28	-0.36	-0.29	-0.051			-0.22	-0.17	-0.32
37	-0.24	-0.33	-0.36	-0.29	0.15		0.17		-0.16	-0.21
38	-0.39	-0.35	-0.2	-0.26	-0.15		0.063	-0.15		-0.63
39	-0.31	-0.35	-0.26	-0.36	-0.13		-0.46	-0.42	-0.21	
40	-0.3	-0.3	-0.35	-0.3	-0.42	-0.047			-0.048	-0.21
41	-0.22	-0.34	-0.31	-0.26	-0.14	-0.16		0.087		-0.37
42	-0.29	-0.57	-0.33	-0.28	-0.29	-0.14		2.2	-0.25	
43	-0.36	-0.32	-0.38	-0.29	-0.25	-0.29	0.0039			-0.16
44	-0.37	-0.3	-0.23	-0.32	-0.36	-0.32	0.054		-0.3	
45	-0.29	-0.44	-0.34	-0.34	-0.32	-0.32	-0.26	0.076		

MS dephasing



MS gate. Contrast loss per gate (%)

	1	2	3	4	5	6	7	8	9	10
1			0.11	-0.024	0.053	0.079	0.11	0.078	0.0046	0.015
2		0.095		0.087	0.077	-0.038	-0.054	0.03	0.043	-0.0067
3		0.07	0.017		0.0029	-0.058	0.044	0.1	0.015	0.09
4		0.094	-0.074	0.13		0.013	-0.022	-0.064	0.071	0.022
5		-0.028	0.17	-0.0064	0.073		0.091	-0.015	0.032	0.055
6		-0.0098	-0.089	0.0097	-0.014	0.095		-0.057	0.076	-0.0077
7		-0.052	-0.0027	-0.017	-0.11	-0.0092	0.089		0.092	0.0034
8		0.099	0.071	0.013	0.003	-0.016	-0.026	0.0077		0.16
9		0.033	-0.093	0.038	0.079	0.091	-0.047	-0.055	0.1	
10	0.078			0.097	0.24	0.098	0.13	-0.056	0.06	0.12
11	0.042		0.073		0.087	0.057	0.19	-0.077	0.018	0.043
12	0.07		0.023	0.029		0.14	0.05	0.07	0.0056	0.0033
13	0.018		-0.075	0.063	0.073		0.086	0.0096	0.041	0.13
14	-0.098		0.021	0.023	0.11	0.3		-0.04	0.16	-0.026
15	0.11		-0.034	0.059	0.022	0.048	0.078		0.019	-0.011
16	0.061		0.021	-0.0091	0.018	0.051	0.01	-0.057		0.048
17	-0.14		0.046	0.033	-0.035	0.029	0.038	0.087	0.14	
18	-0.054	0.024			0.12	-0.0059	0.054	0.081	0.082	0.032
19	-0.034	0.0045		0.25		1.9	0.16	-0.021	-0.058	0.13
20	0.071	0.09		-0.014	-0.027		0.16	0.13	0.032	-0.044
21	0.042	0.015		0.026	0.22	-0.056		0.072	0.0049	0.042
22	0.0068	0.072		0.051	0.055	0.017	0.025		0.022	0.061
23	0.018	0.13		0.16	-0.033	0.0065	-0.07	0.085		0.09
24	0.074	0.15		0.087	0.15	0.12	0.066	-0.0051	0.092	
25	0.018	0.05	0.11			0.031	0.14	0.057	0.036	-0.061
26	-0.054	-0.021	0.1		0.0056		0.052	0.0028	0.091	0.021
27	-0.12	0.086	0.19		0.073	0.12		-0.03	0.07	0.061
28	-0.055	-0.094	0.036		0.028	0.018	-0.015		0.054	0.066
29	-0.0035	0.14	0.13		0.25	0.24	-0.054	0.04		0.0035
30	-0.065	-0.043	-0.034		-0.058	-0.001	0.0077	0.082	0.066	
31	0.14	0.13	0.2	0.17			0.25	0.14	0.066	0.034
32	0.064	-0.025	0.1	0.079		0.26		0.1	0.063	-0.0077
33	-0.049	-0.028	0.12	0.0082		0.15	0.015		0.069	0.2
34	0.15	0.067	0.096	0.12		0.014	0.062	0.27		0.094
35	0.14	0.16	0.23	0.27		0.15	0.11	0.02	0.14	
36	-0.065	0.044	-0.019	0.16	0.26			0.24	0.24	0.051
37	-0.058	0.012	-0.013	0.14	0.16		0.086		-0.0077	-0.069
38	0.093	-0.047	0.22	0.15	0.08		-0.0033	0.14		0.066
39	0.066	-0.039	-0.037	0.026	-0.059		-0.067	0.057	0.076	
40	-0.13	0.021	-0.0013	-0.06	-0.046	0.13			0.05	-0.081
41	0.078	0.0069	0.029	0.038	0.09	0.053		0.0067		0.14
42	0.13	0.11	0.084	0.23	0.094	-0.14		0.19	0.069	
43	0.033	-0.036	0.085	0.096	0.11	0.024	0.029			0.086
44	0.14	-0.2	0.069	0.044	0.059	0.027	0.066		0.035	
45	0.12	-0.01	-0.013	0.089	0.092	0.053	-0.22	0.015		

Single-qubit phase shift
on spectator ions
max = 2.7°
min = 0.01°
avg = 0.23°

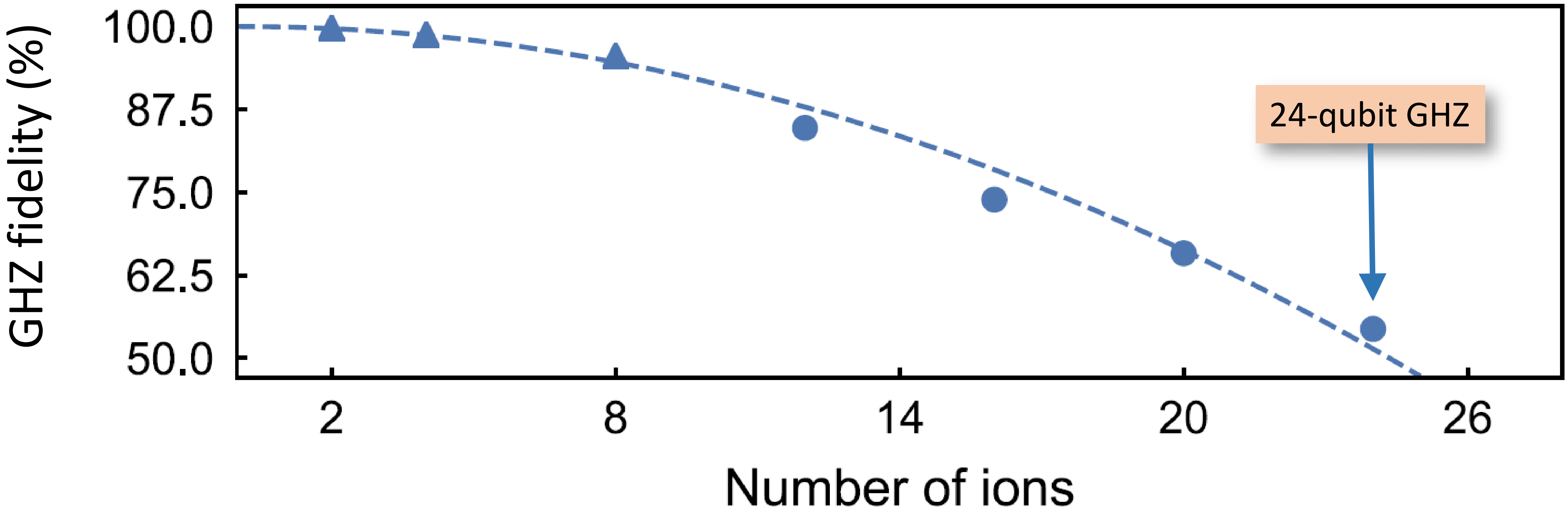
Correctable
or **10^{-6} error rate** ✓

Dephasing on spectator ions
max = $2*10^{-2}$
min < 10^{-4}
avg. on all = $6.3*10^{-4}$

Threshold @ 10^{-4} - 10^{-5}

Highly connected quantum register

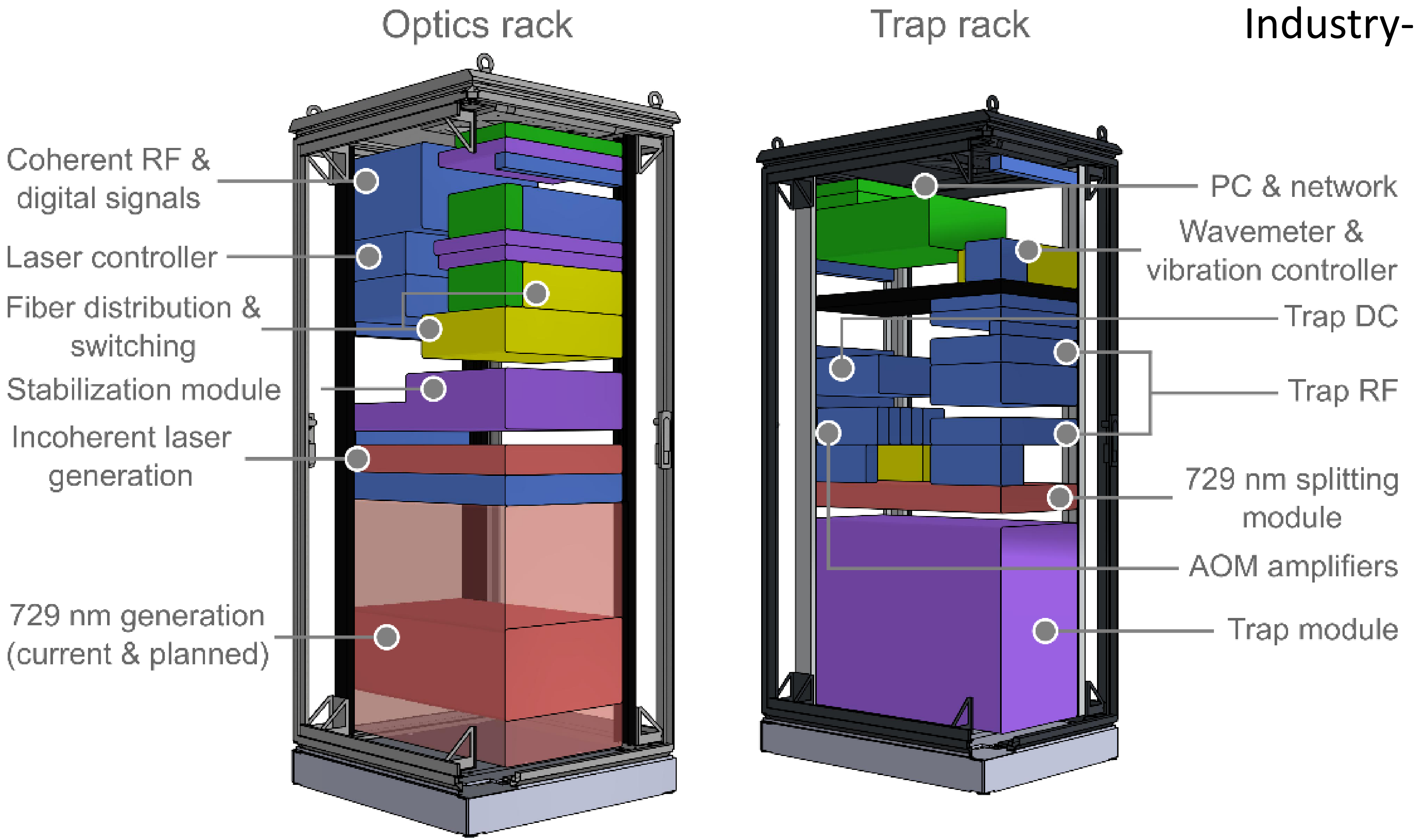
GHZ state generation w/ global interactions



Quantum register with > 20 entangled qubits

PRX Quantum **2**, 020343 (2021)

Compact ion-trap quantum computing demonstrator



Industry-Standard 19’’ Rack

I. Pogorelov, et al., PRX Quantum **2**, 020343 (2021)

Compact ion-trap quantum computing demonstrator

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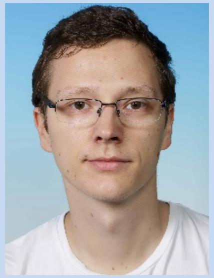
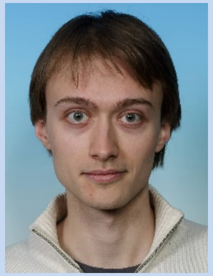

C. Marciniak


I. Pogorelov

Compact ion-trap quantum computing demonstrator

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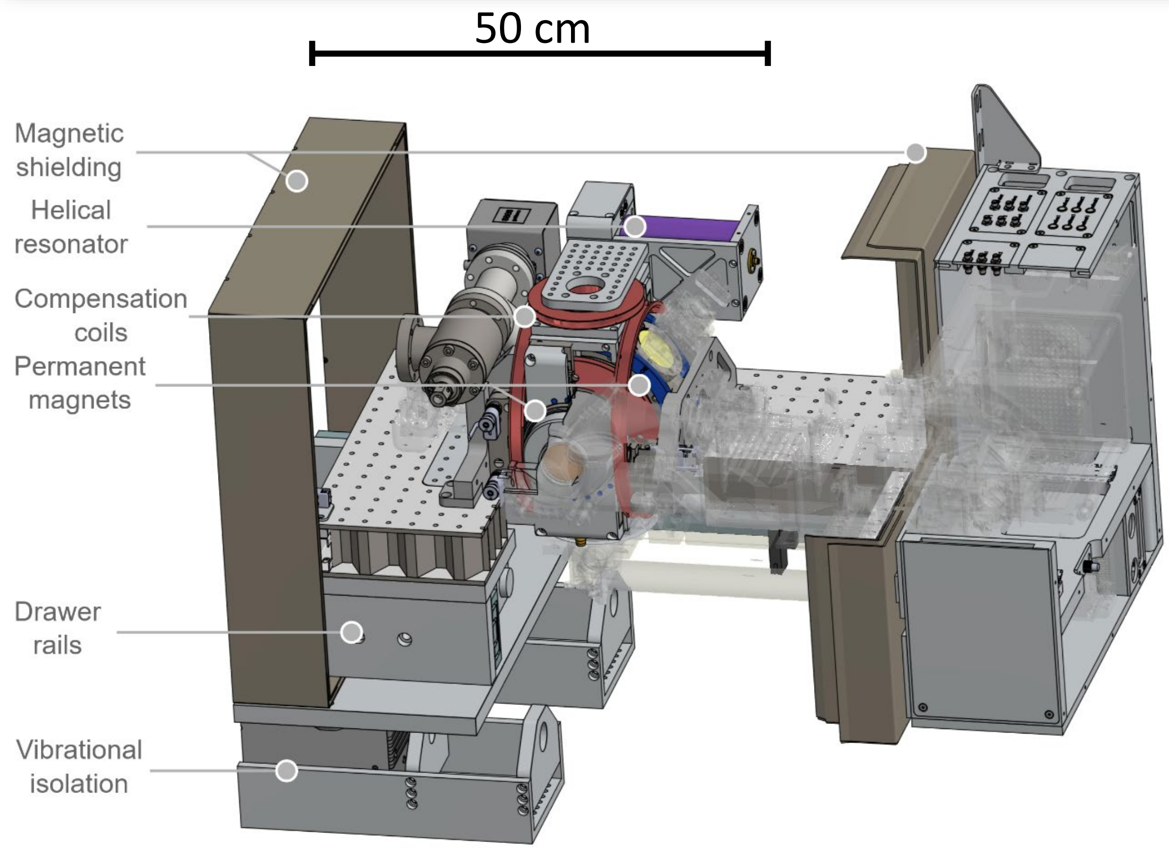
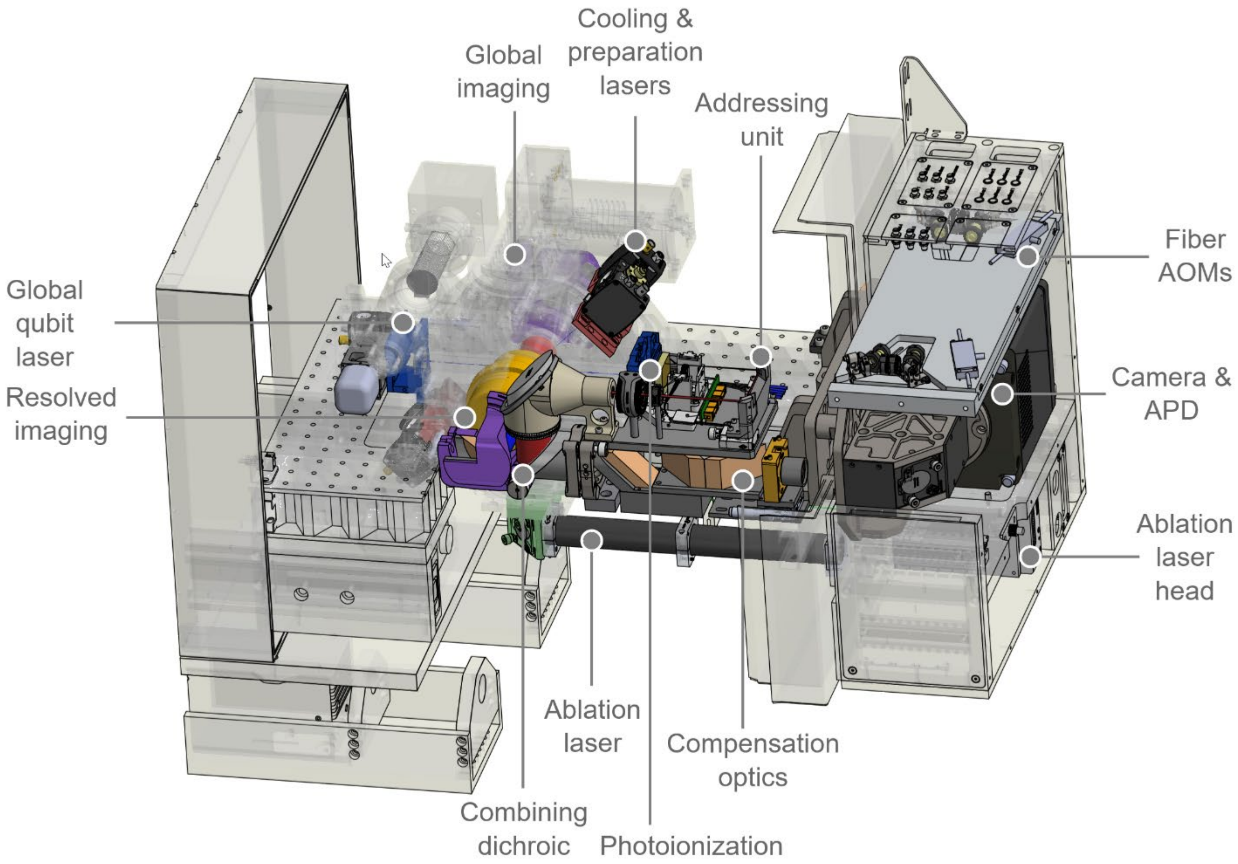


Ion trap module, mechanical

Ion trap module, optical



I. Pogorelov, T. Feldker et al.,
PRX Quantum **2**, 020343 (2021)