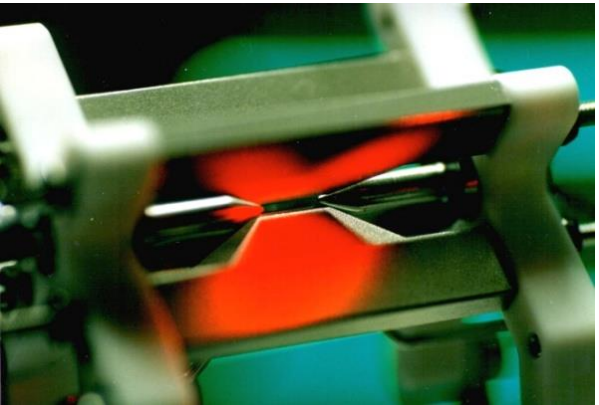
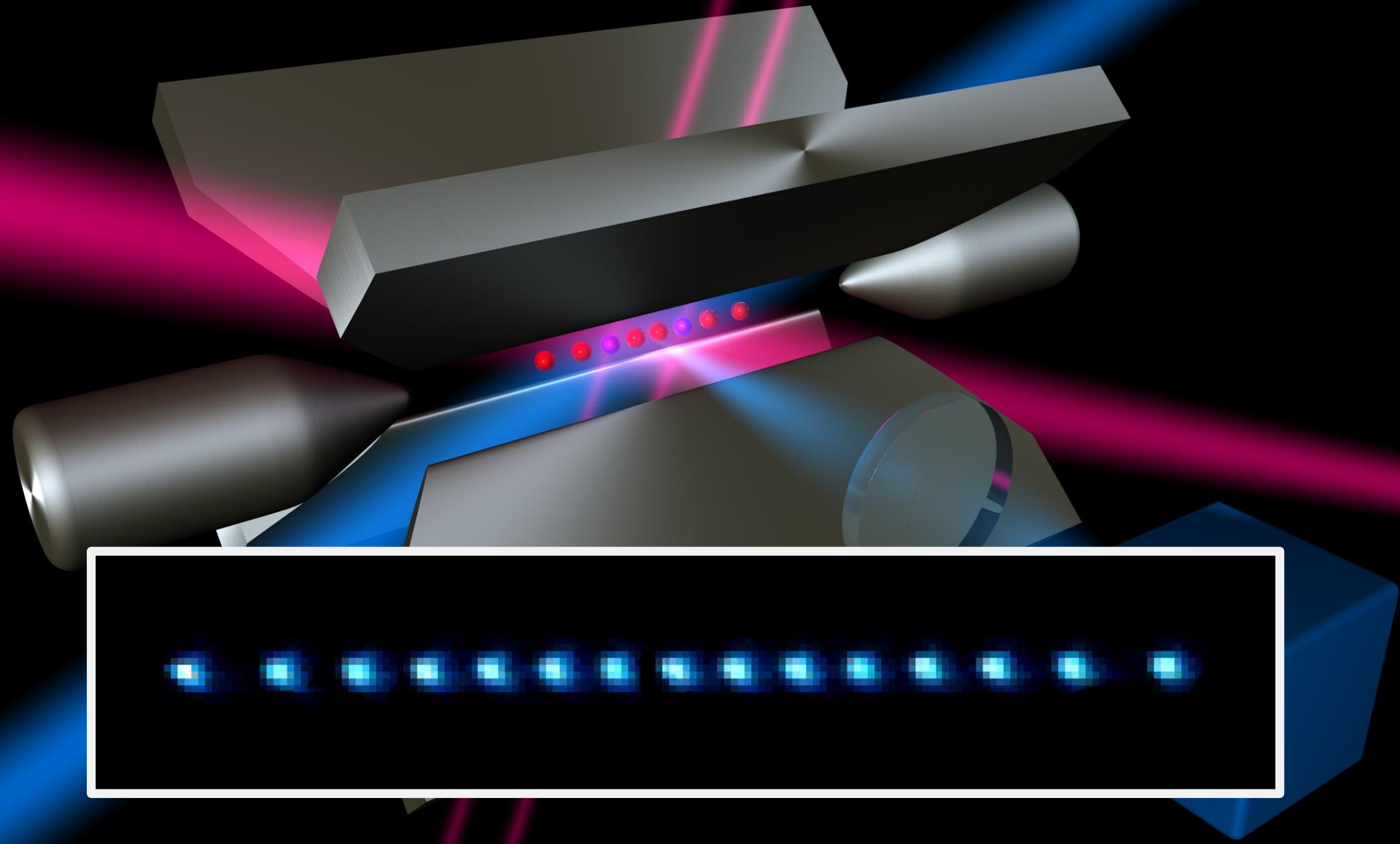


Quantum science with trapped ions

Philipp Schindler

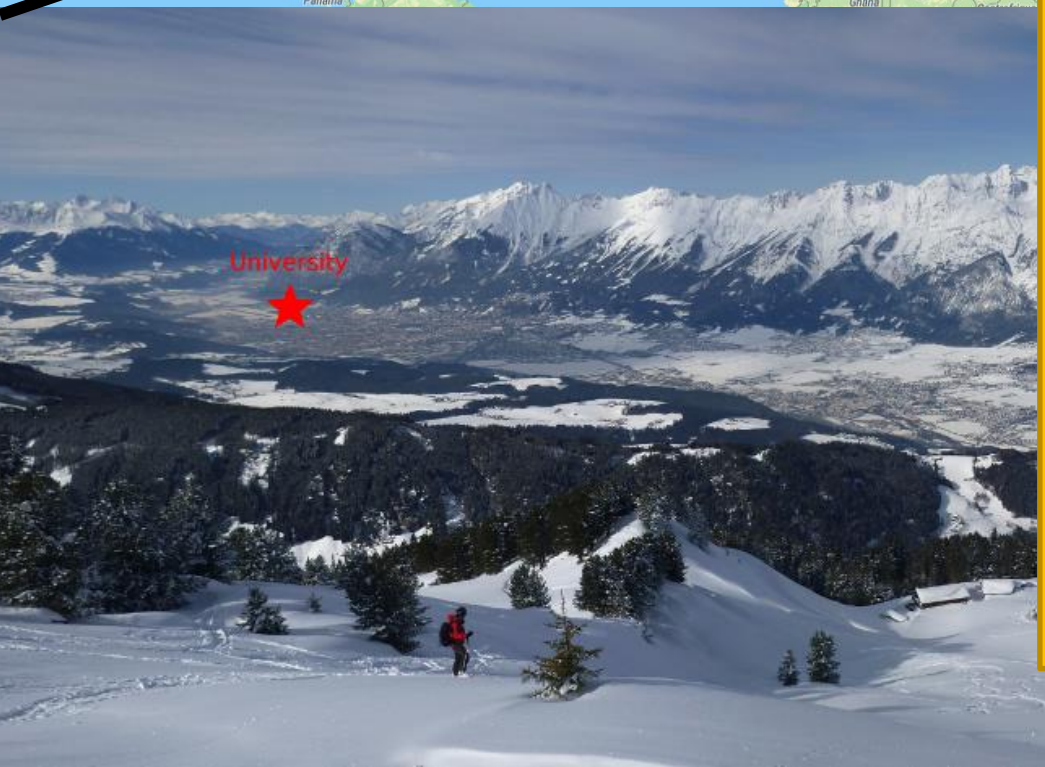
Universität Innsbruck

The Quantum Information Processor with Trapped Ca^+ Ions



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

Ion trap QC around the globe



Ion traps at this workshop:


NL, Fri

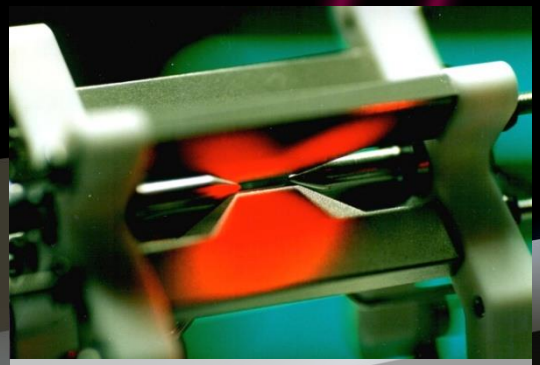

FSK, Thu


PM, Thu

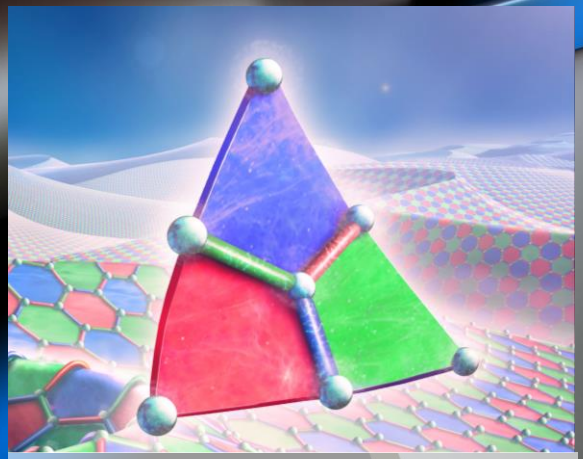

WH, Wed


MJ, Wed

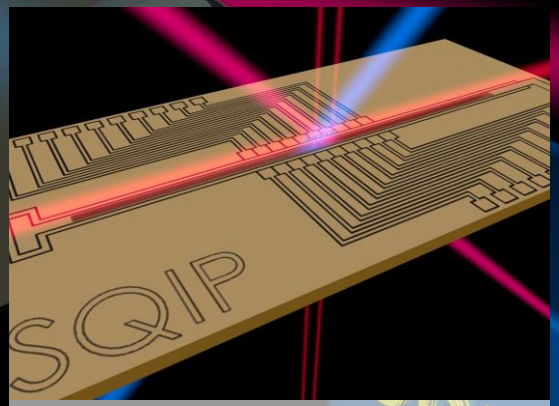

CO, Thu



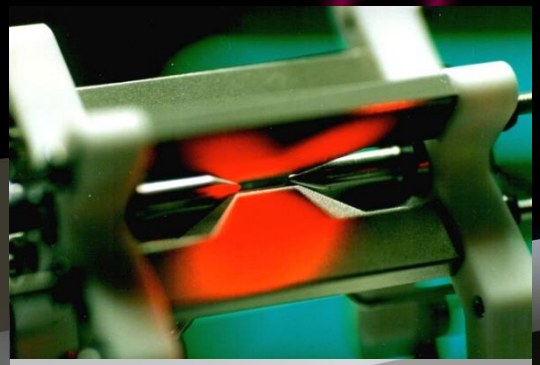
Ion trapping basics



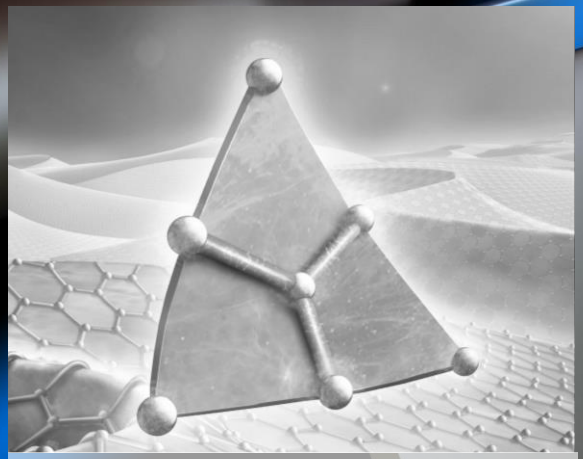
Gates and Algorithms



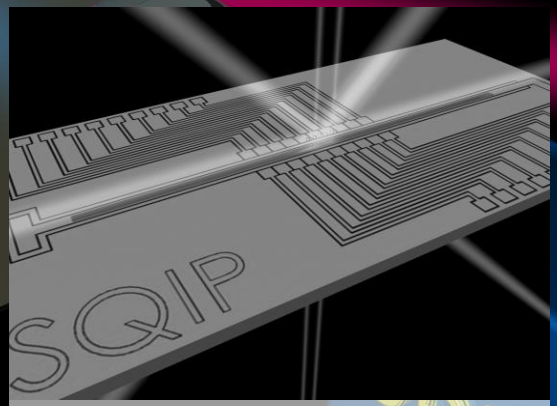
Scalable devices &
Engineering challenges



Ion trapping basics



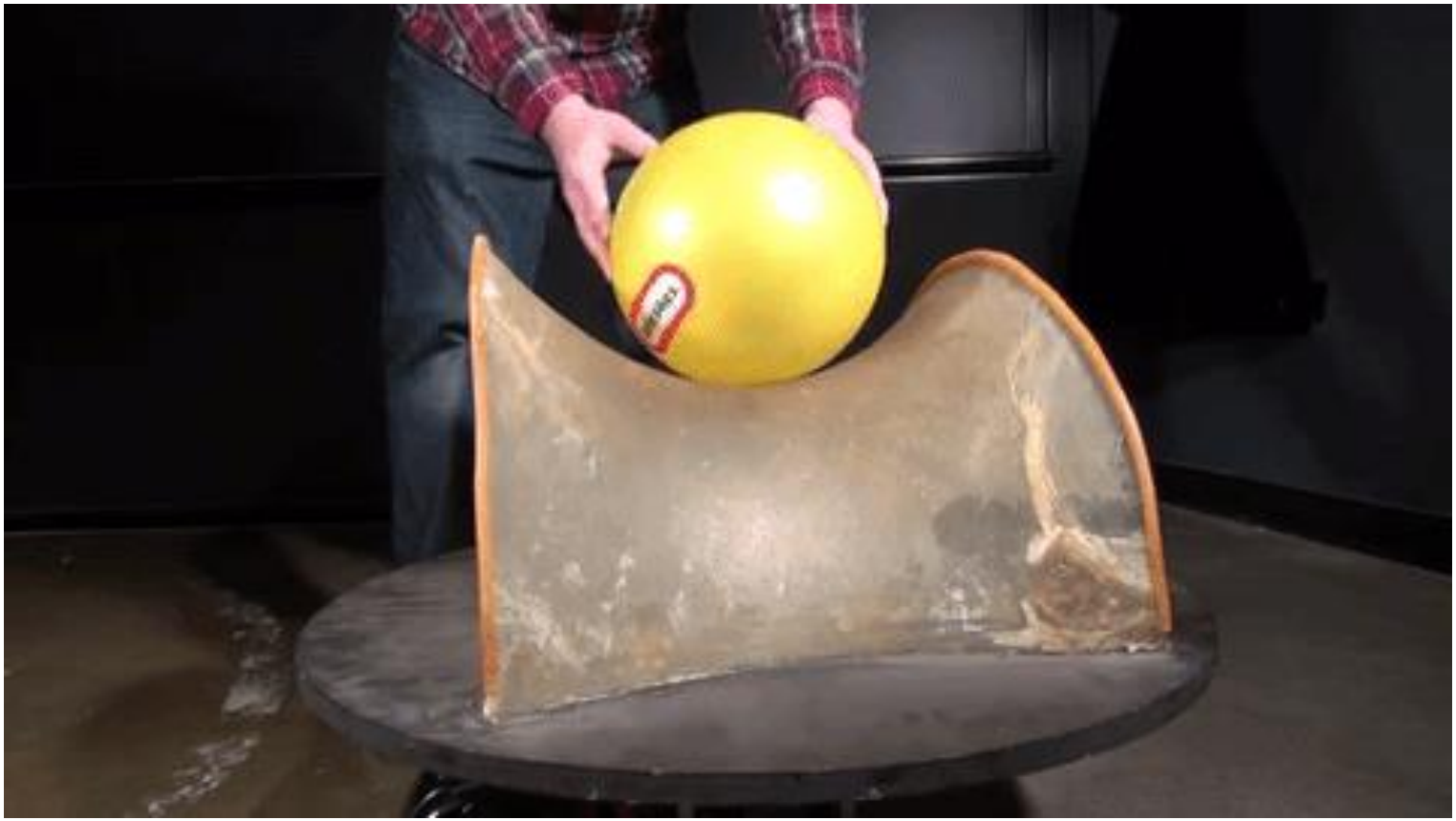
Gates and Algorithms



Scalable devices &
Engineering challenges

Ion trapping – how does it work?

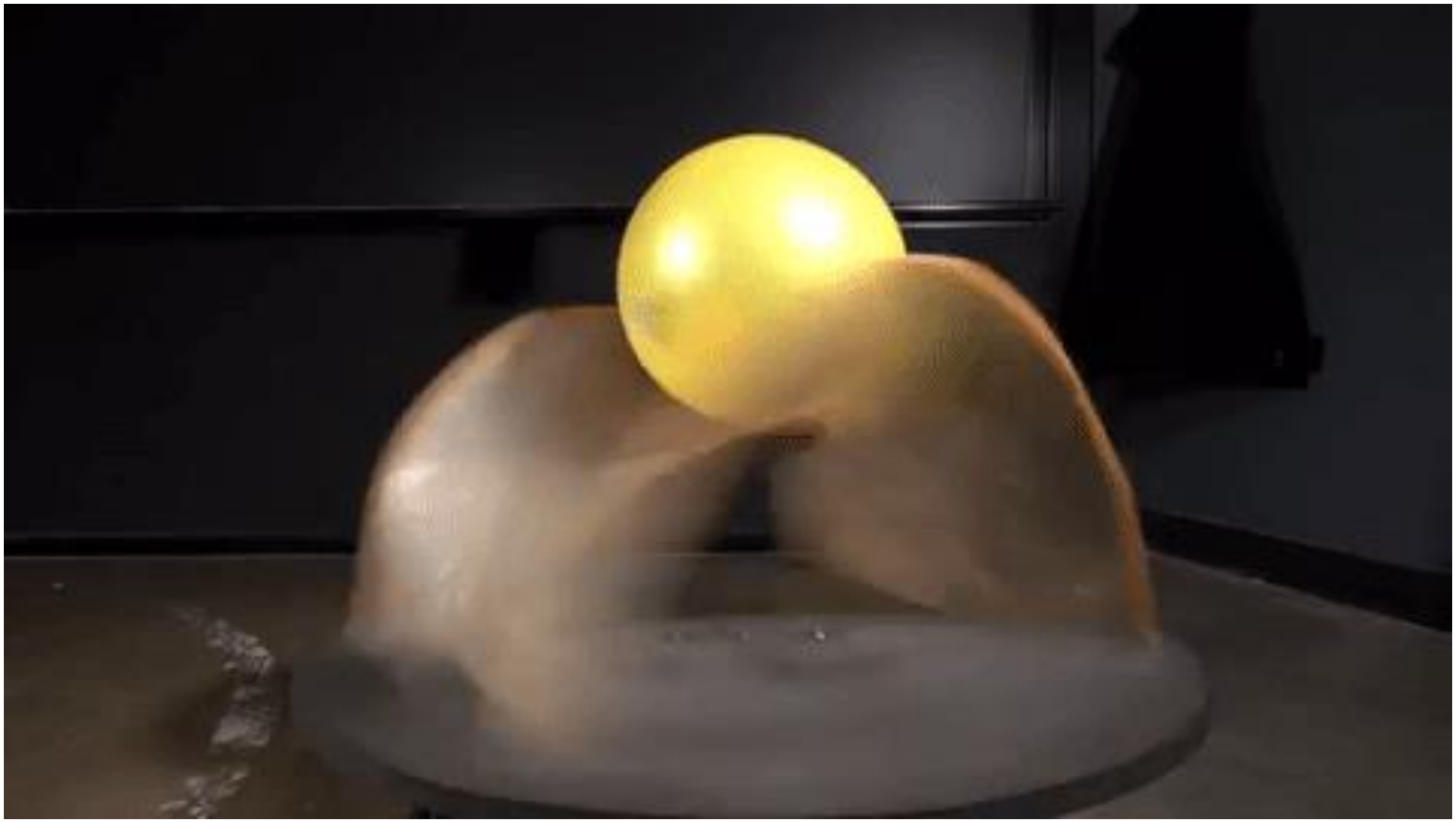
Static electric fields generate potential that is anti-confining in one dimension



Video: Harvard Natural Sciences Lecture Demonstrations

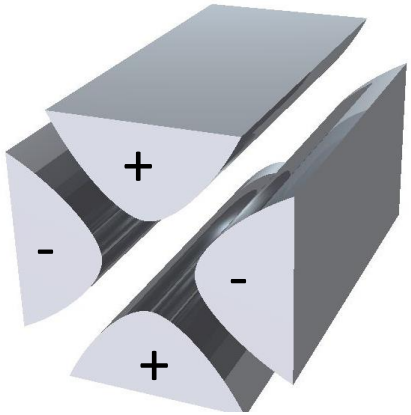
Ion trapping – how does it work?

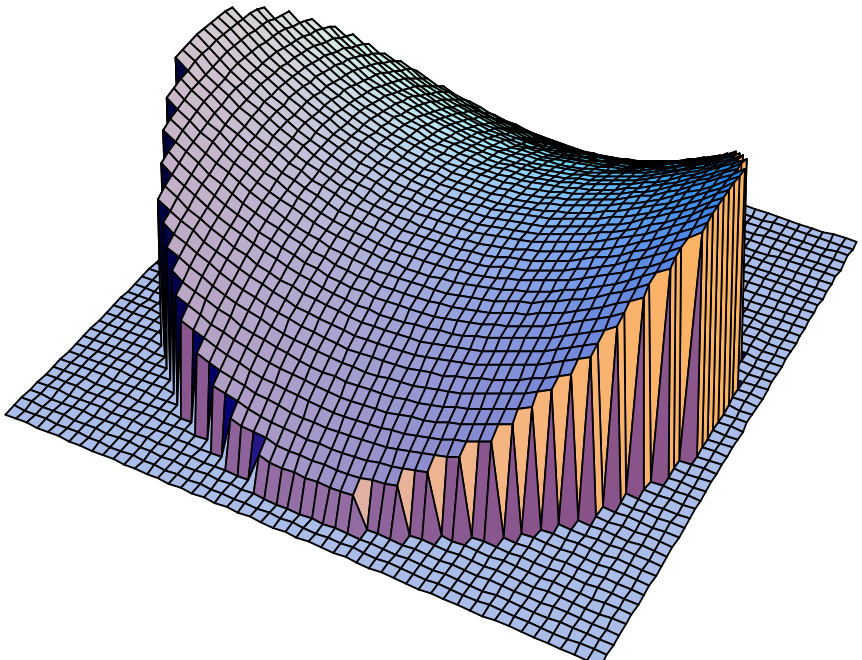
Use oscillating fields to generate an effective confining potential.

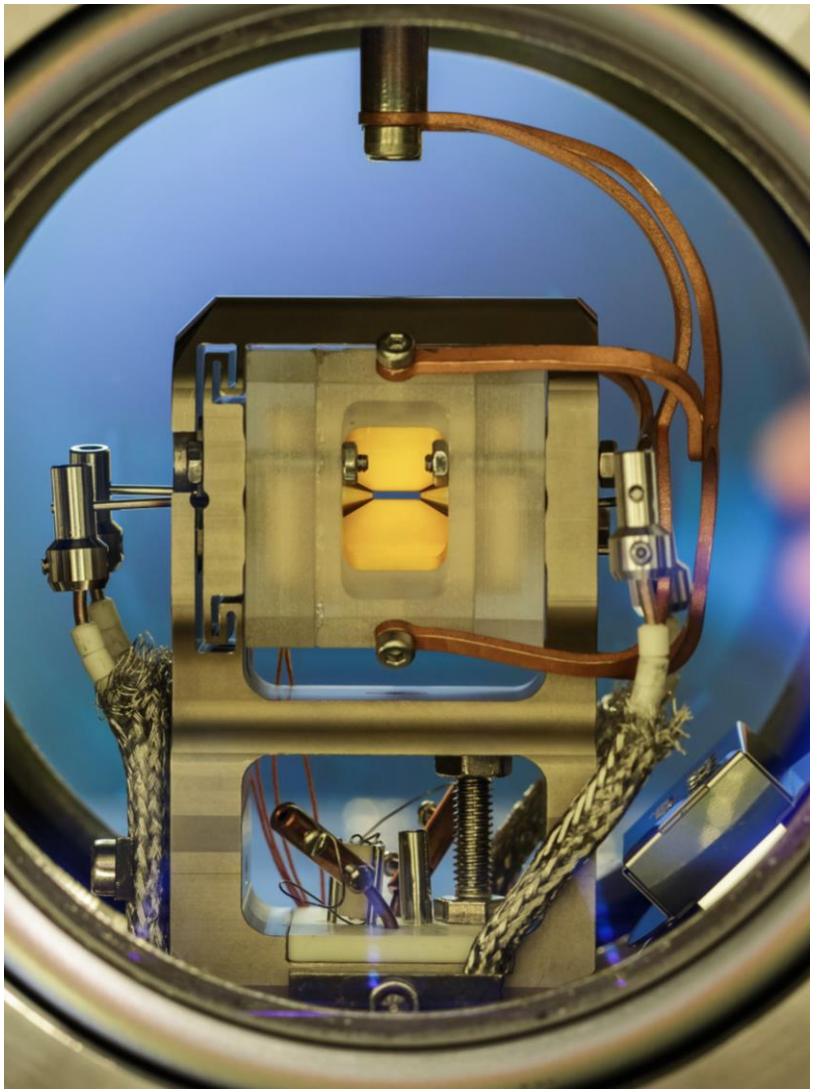


Video: Harvard Natural Sciences Lecture Demonstrations

The linear Paul trap



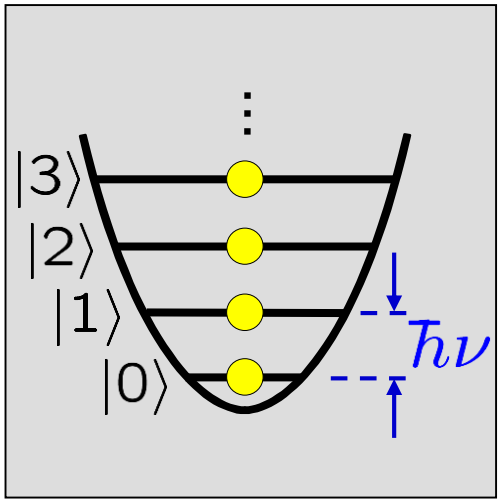


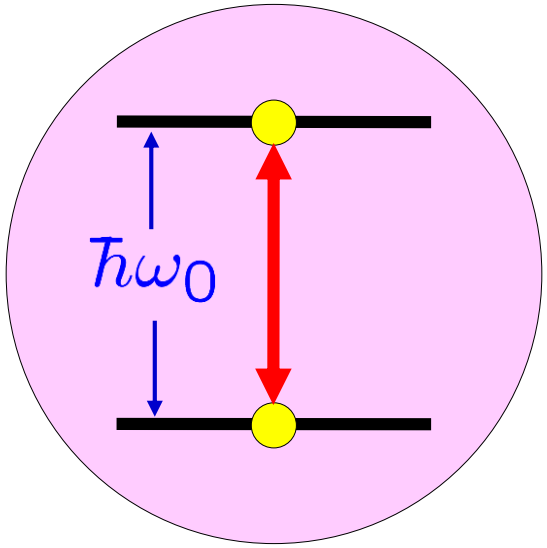


The ideal ion trap QC

Harmonic oscillator

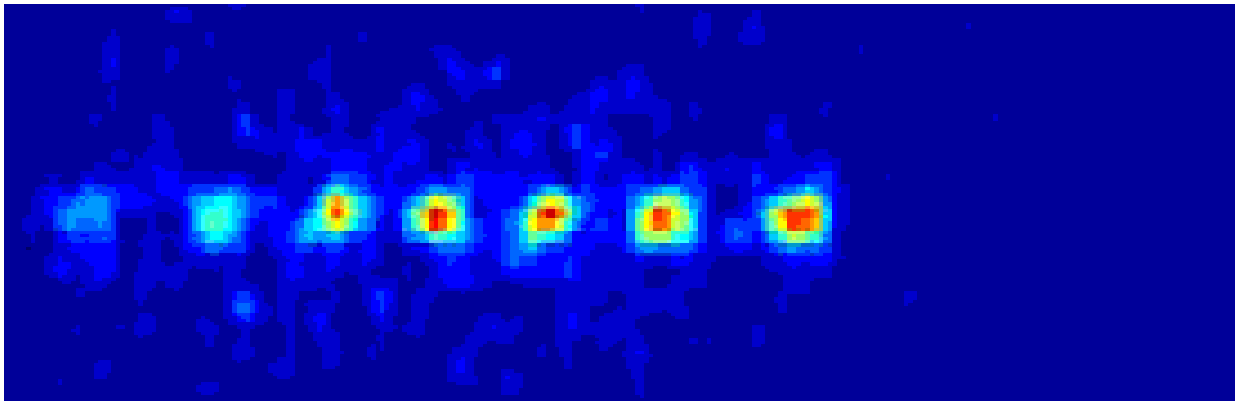
Quantum bit



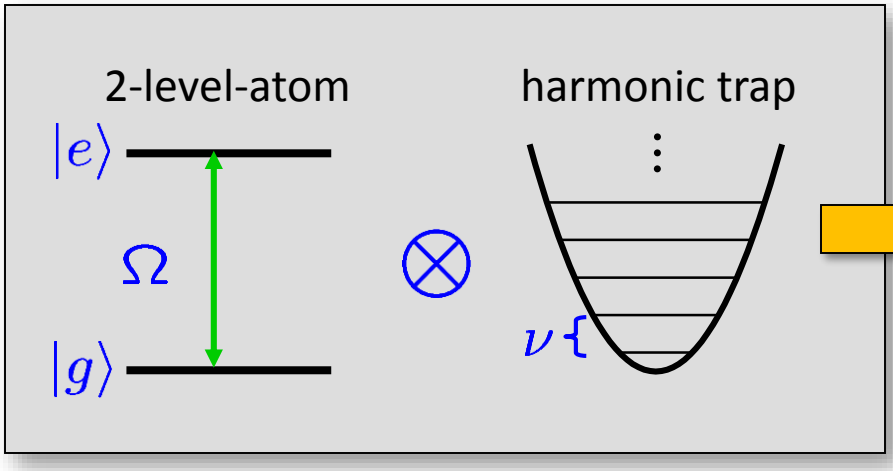


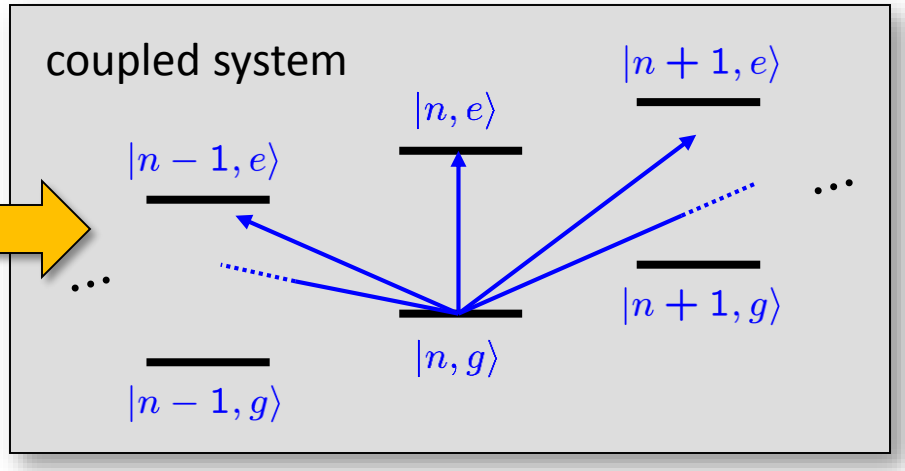
Motion in the trap

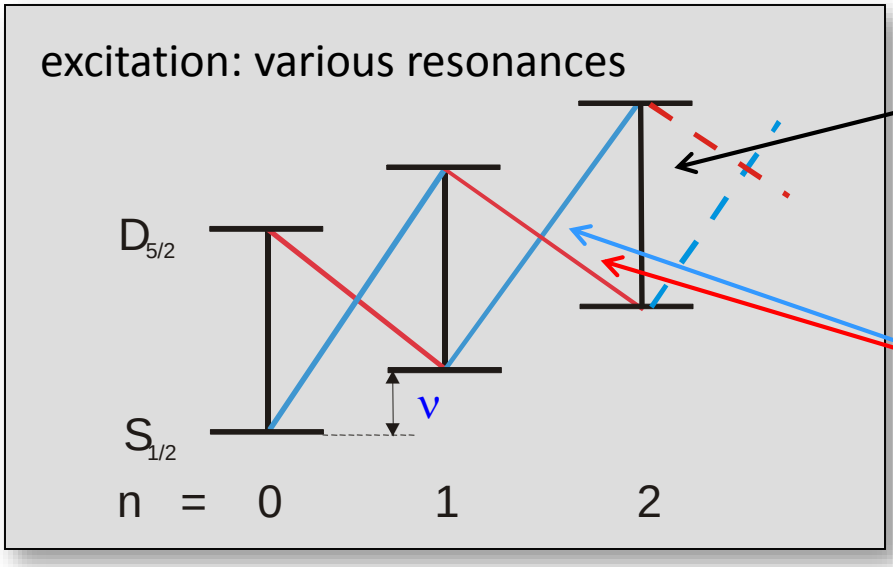
The atom



Qubit manipulation



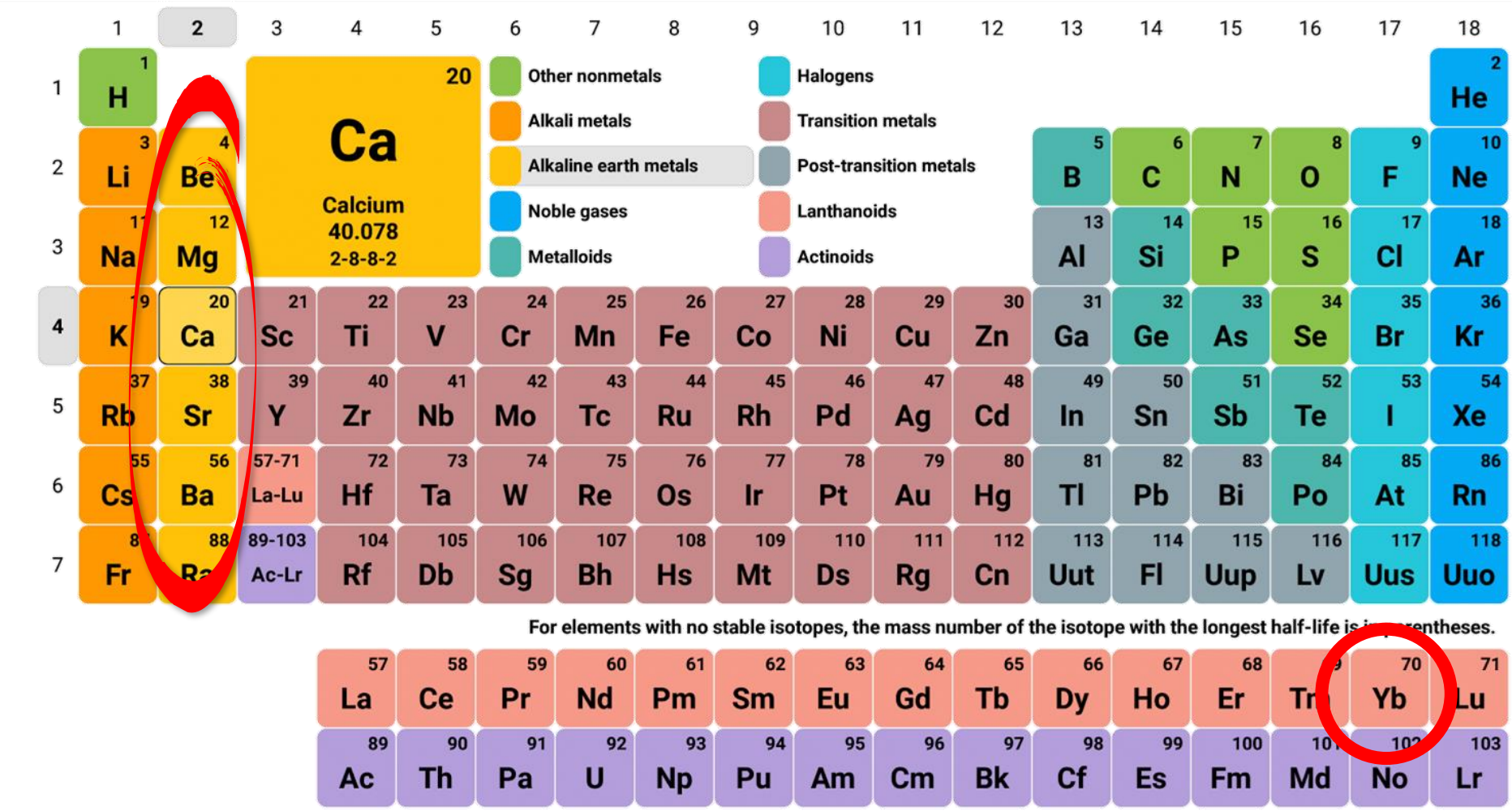




Carrier:
manipulate qubit
→ internal superpositions

Sidebands:
manipulate motion and qubit
→ create entanglement

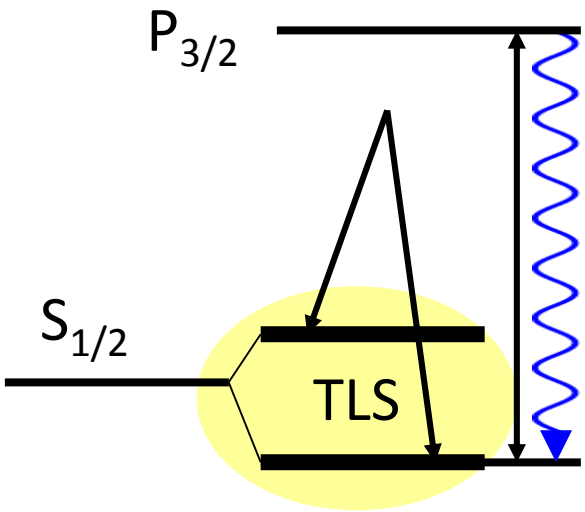
Ion trappers favorites



Possible qubits

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

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



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

- optical transition frequencies (forbidden transitions, intercombination lines)

Qubit manipulation technology:

Laser:

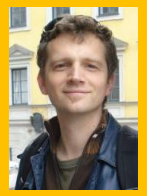

NL, Fri


FSK, Thu


PM, Thu

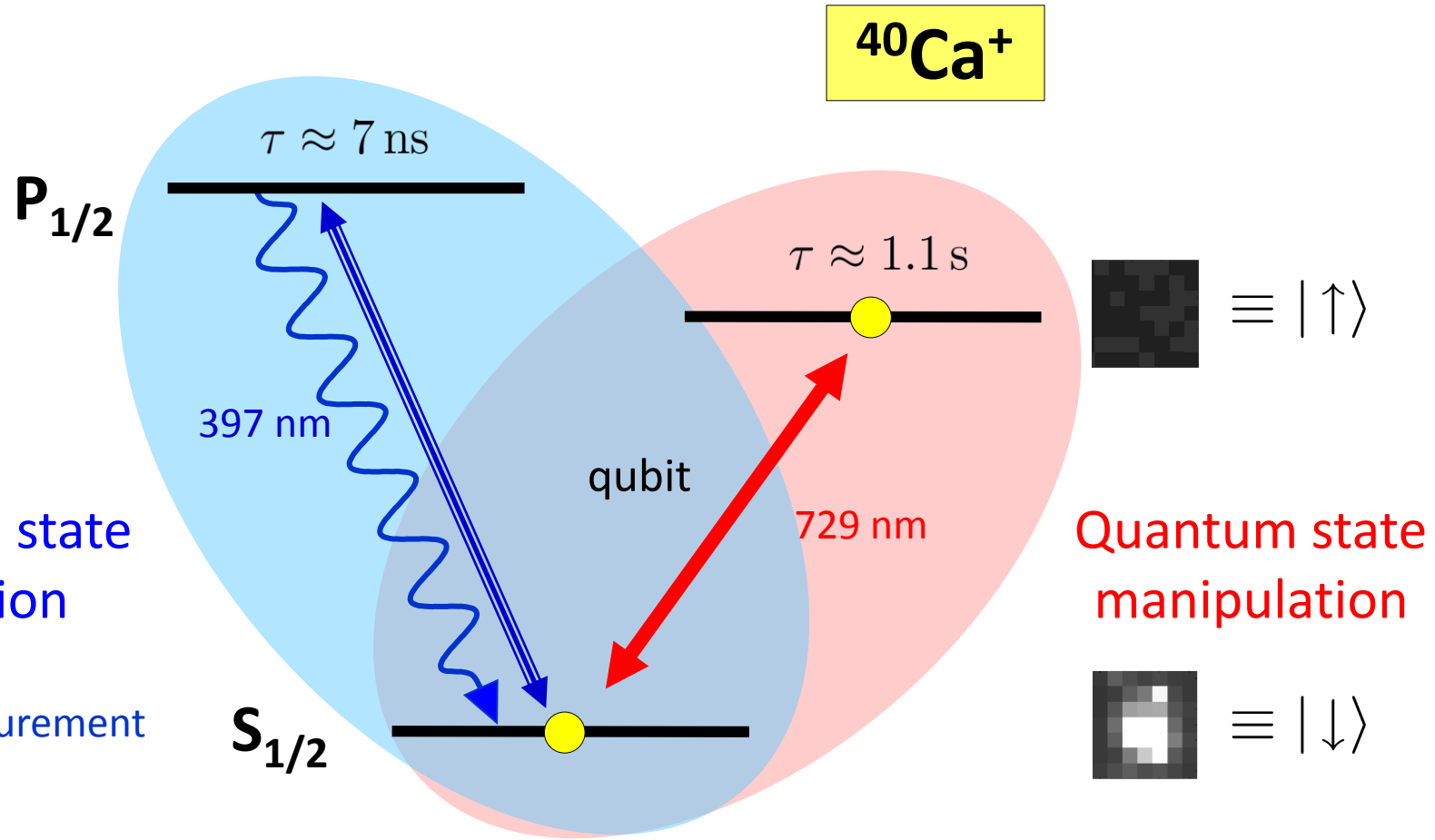
μ-wave:


WH, Wed

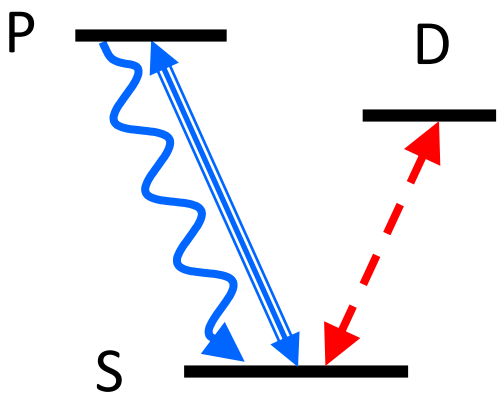

MJ, Wed


CO, Thu

Our ion of choice

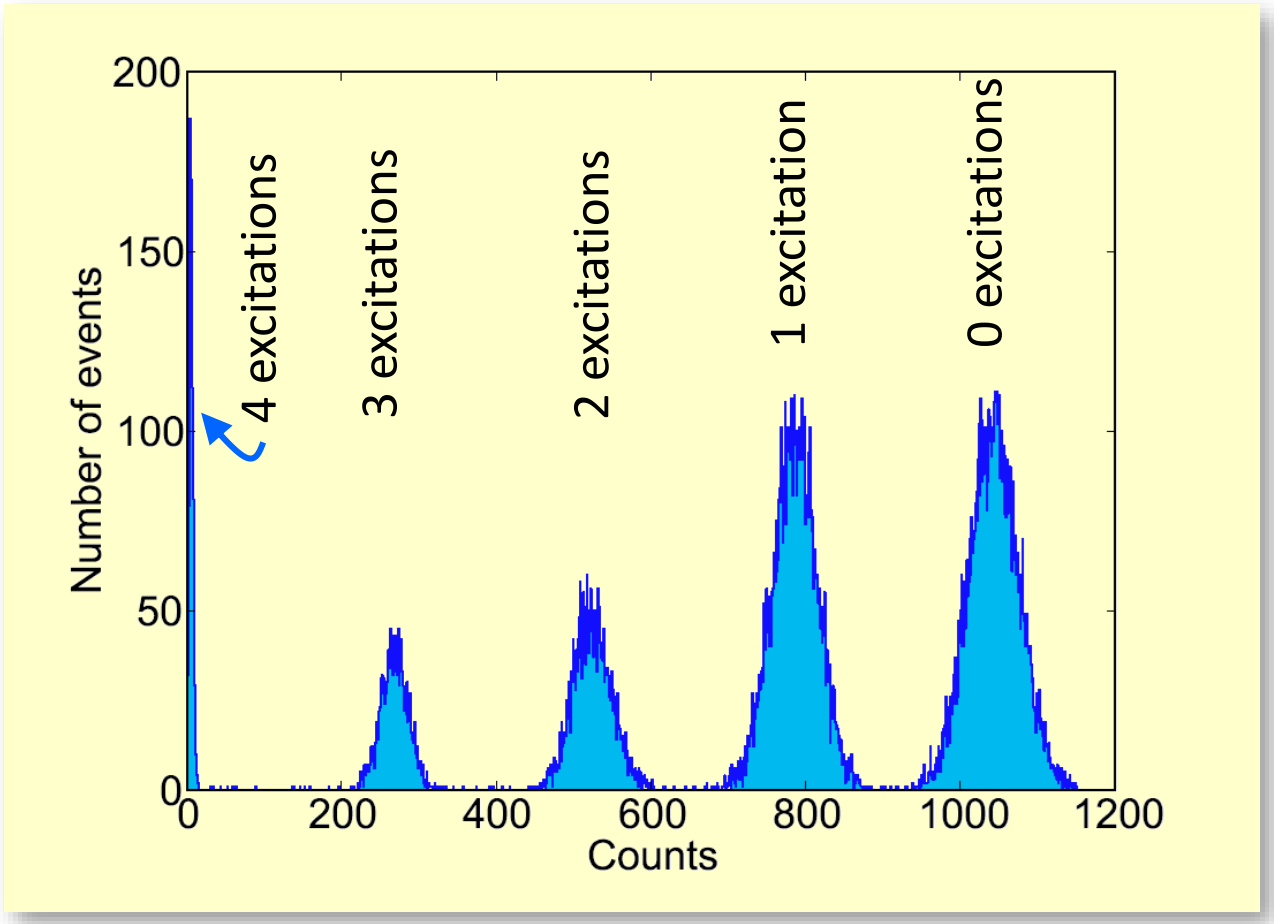


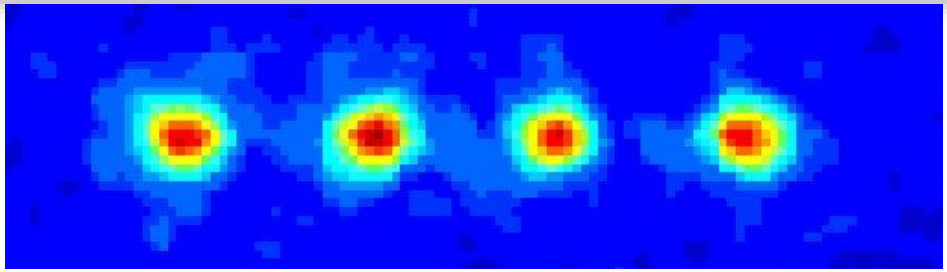
Qubit measurement

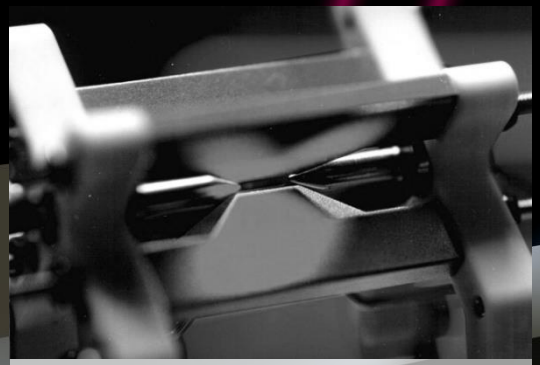


Detection:
Quantum Jumps

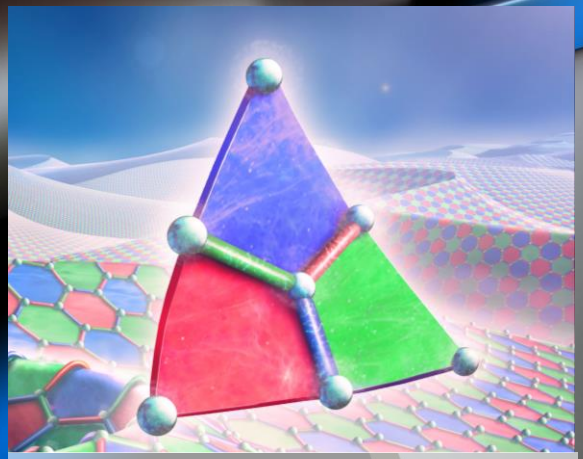
- Projection of ions to either S or D states,



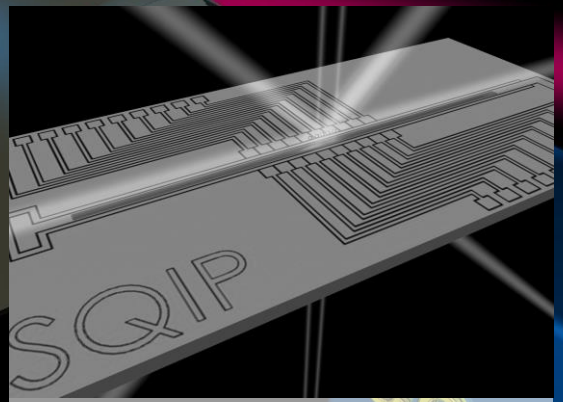




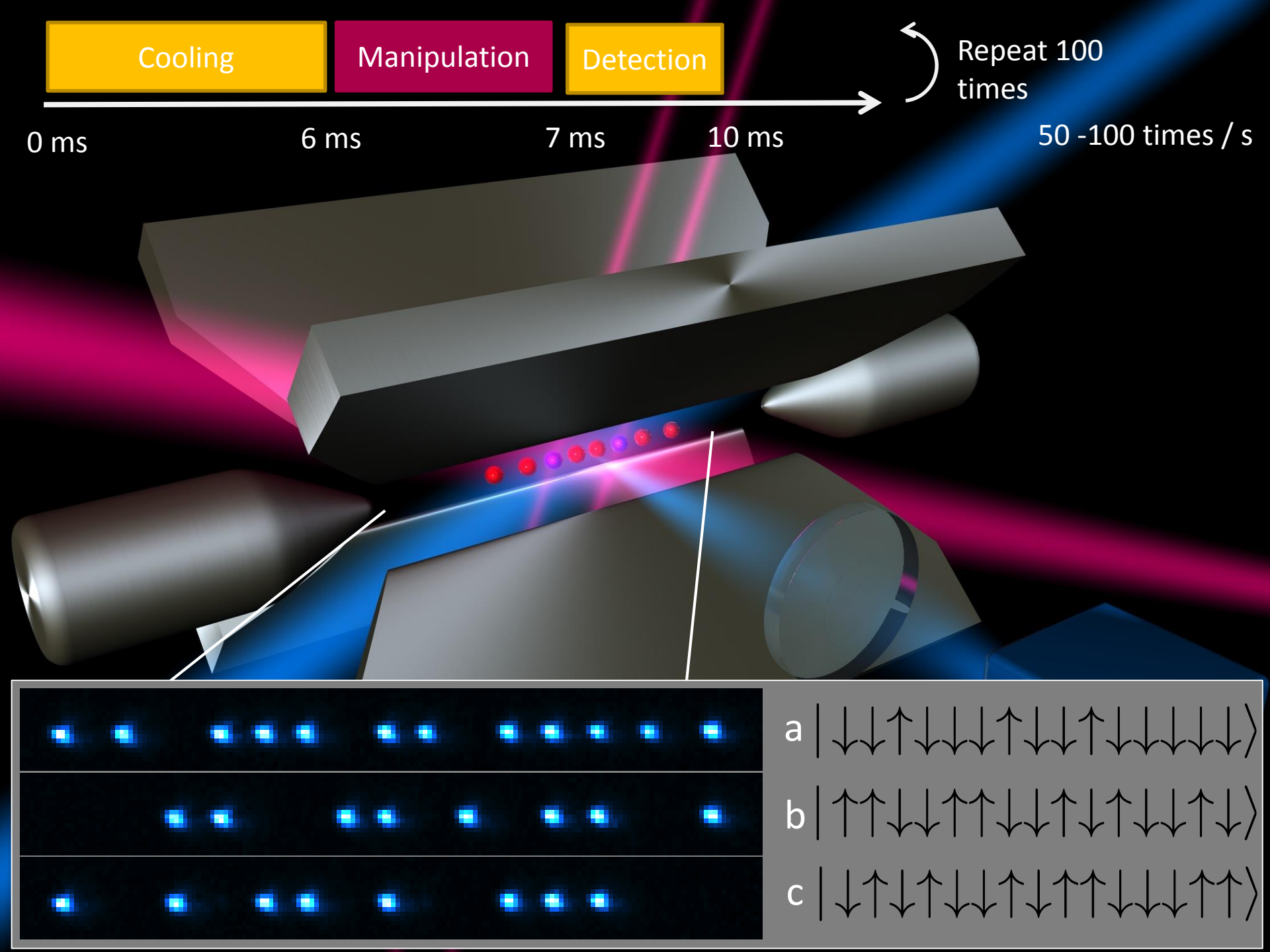
Ion trapping basics



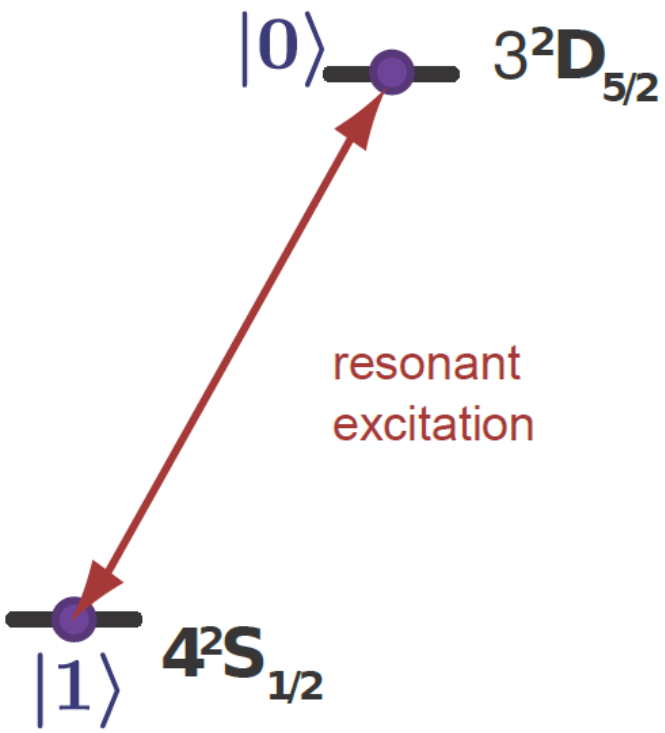
Gates and Algorithms

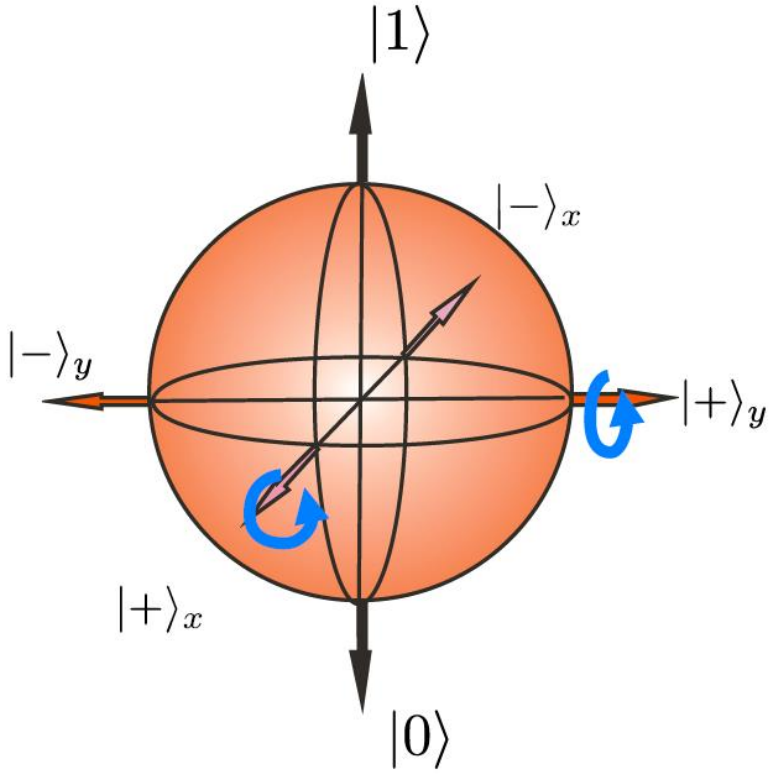


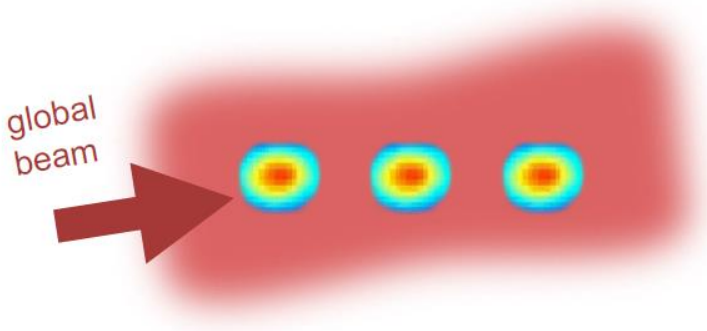
Scalable devices &
Engineering challenges


Cooling
Manipulation
Detection
Repeat 100 times
0 ms
6 ms
7 ms
10 ms
50 -100 times / s
a
b
c

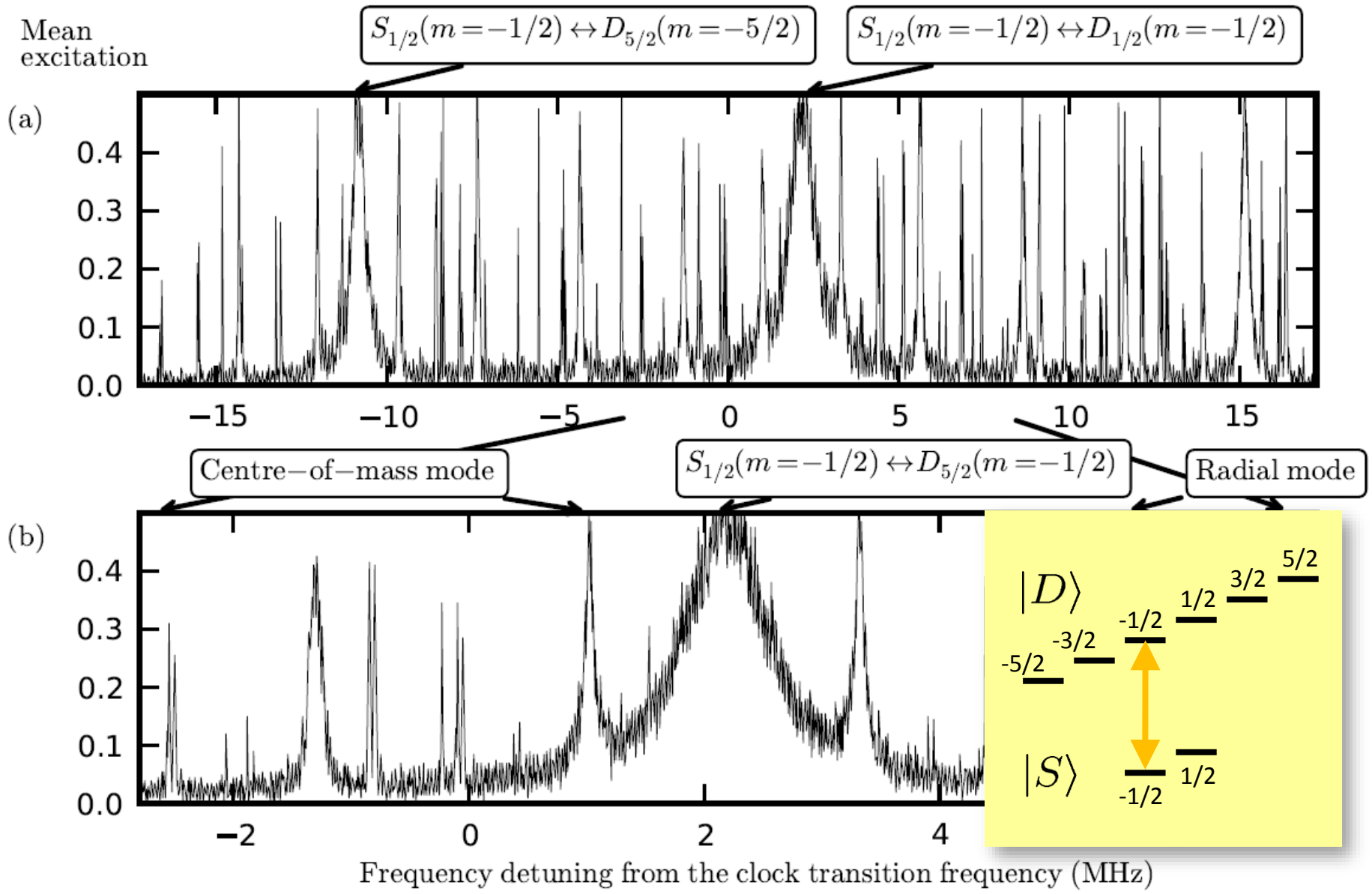
Single-qubit operations





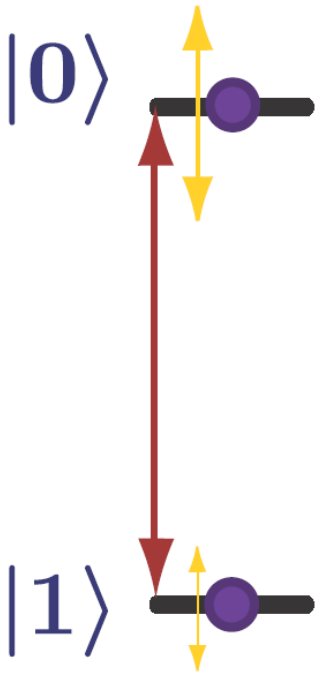


The real world - It's a two-level system?

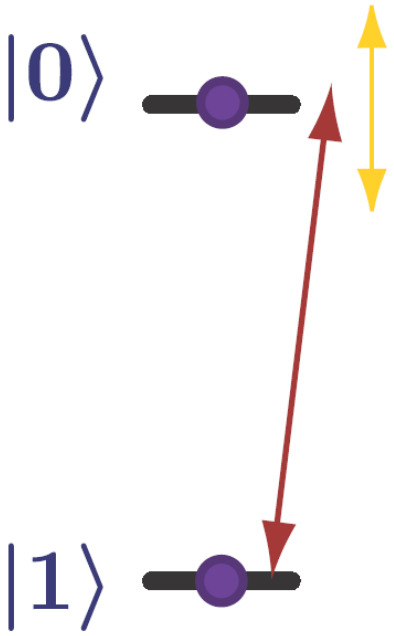


Decoherence – phase damping (T2)

To keep the “quantumness” of the qubit, the phase of the driving laser and the two-level system needs to be preserved.



Level spacing fluctuations
(B-field)



Local oscillator fluctuations
(Laser, RF source)

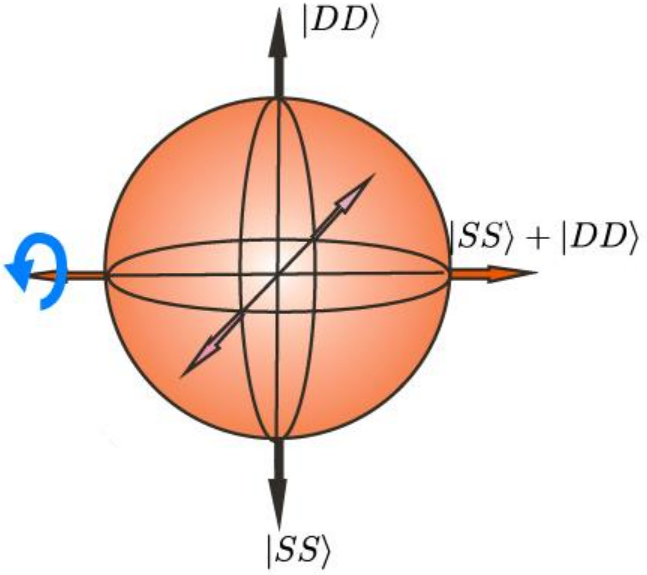
Mølmer-Sørensen entangling operation

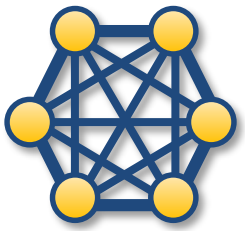
Based on state-dependent light forces.

Works for any number of qubits

Effective infinite range 2-body interaction.

Independent of motional state





WH, Wed

PM, Thu

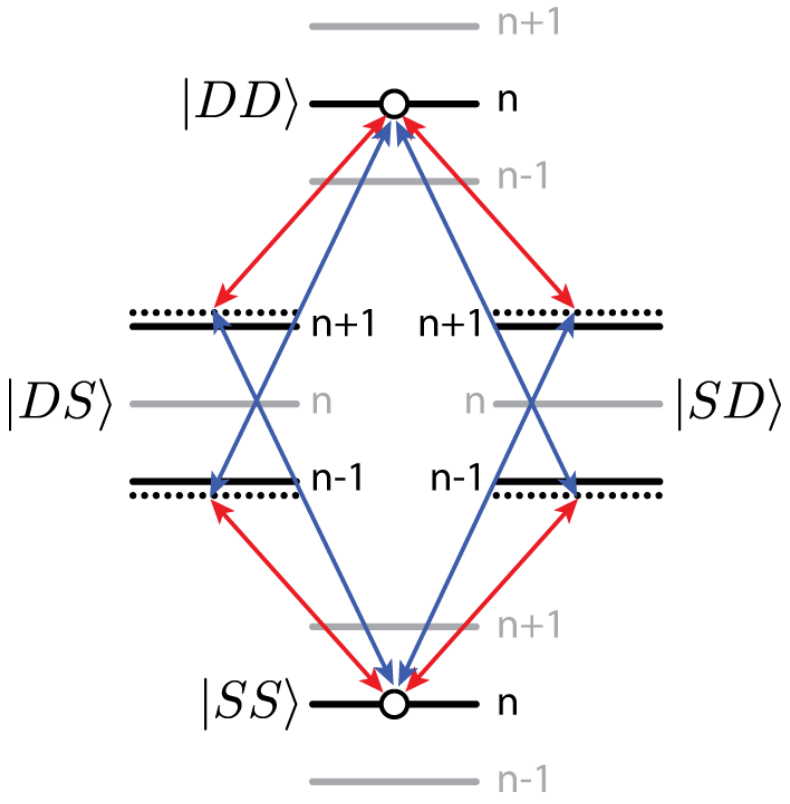
NL, Fri

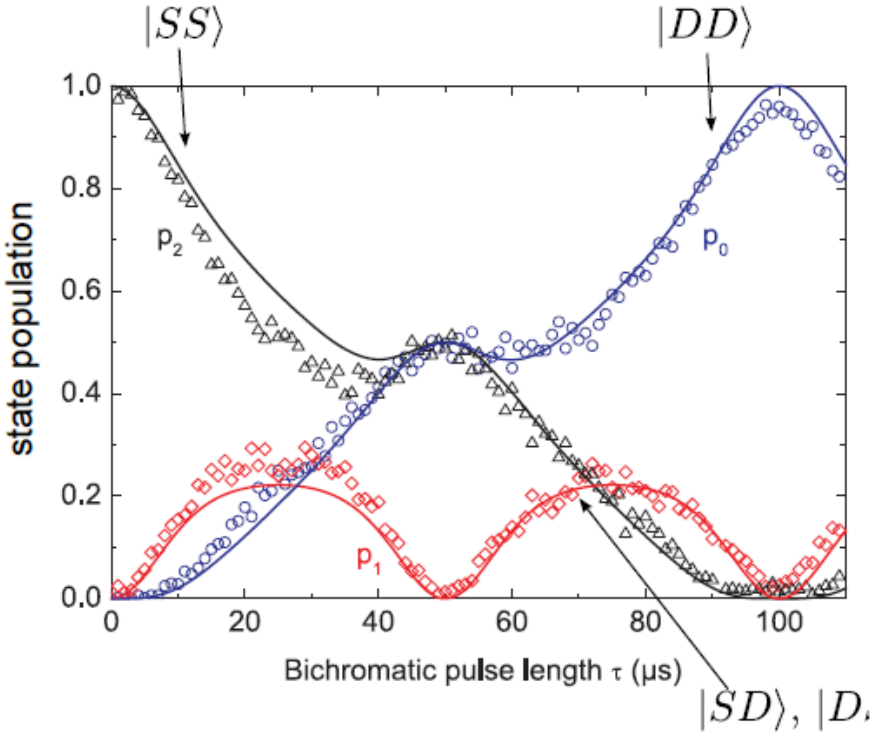
MJ, Wed

T. Monz et al., *PRL.* **106**, 130506 (2011).

K. Mølmer and A. Sørensen, PRL 82, 1835 (1999).

Mølmer-Sørensen entangling operation



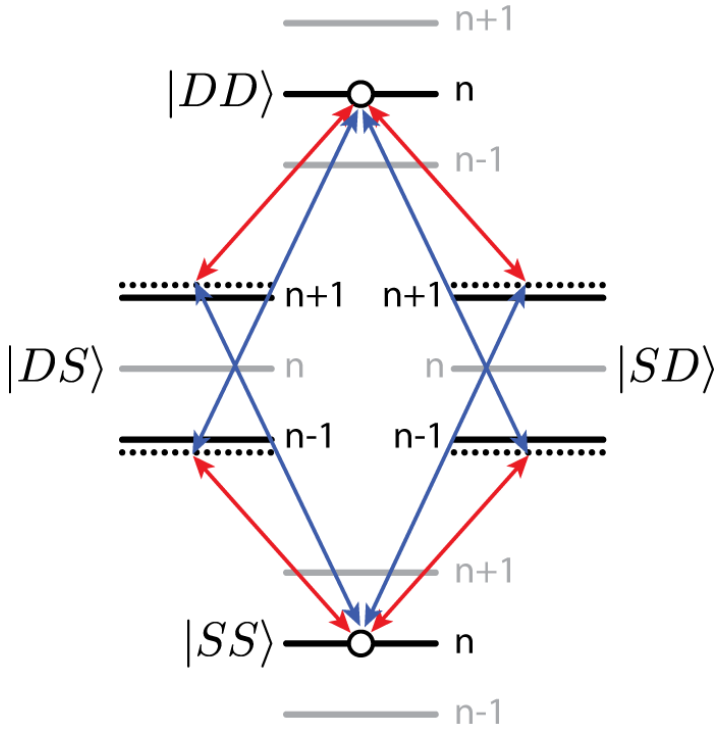


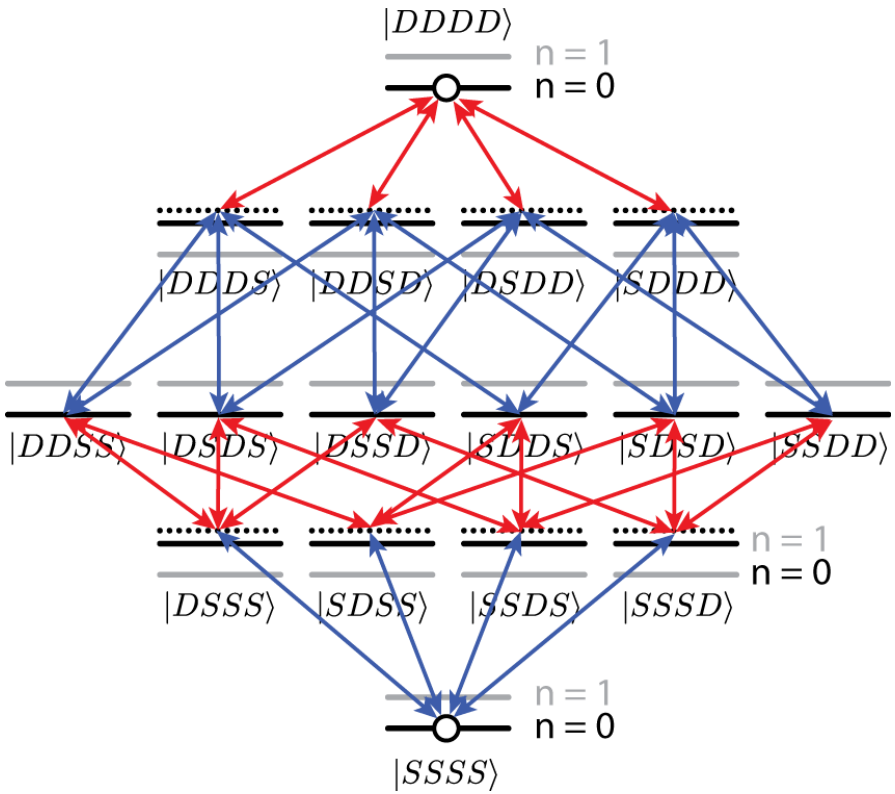
- Off-resonant coupling to the sidebands
- Unwanted populations interfere destructively

G. Kirchmair, et. al. New. J. Phys. 11, 023002 (2009)

K. Mølmer and A. Sørensen, PRL 82, 1835 (1999).

Multi path interferometer

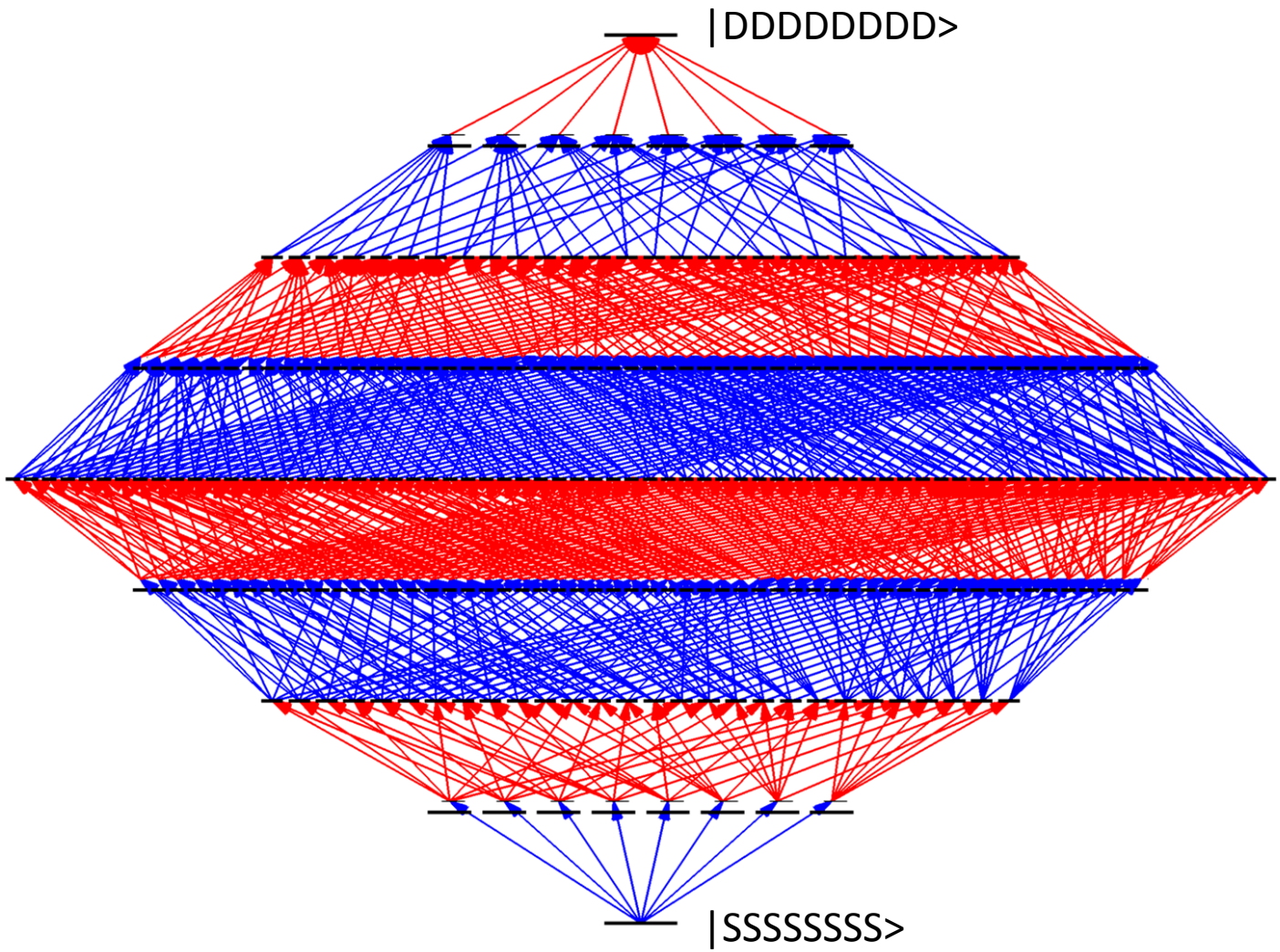




2 qubits

4 qubits

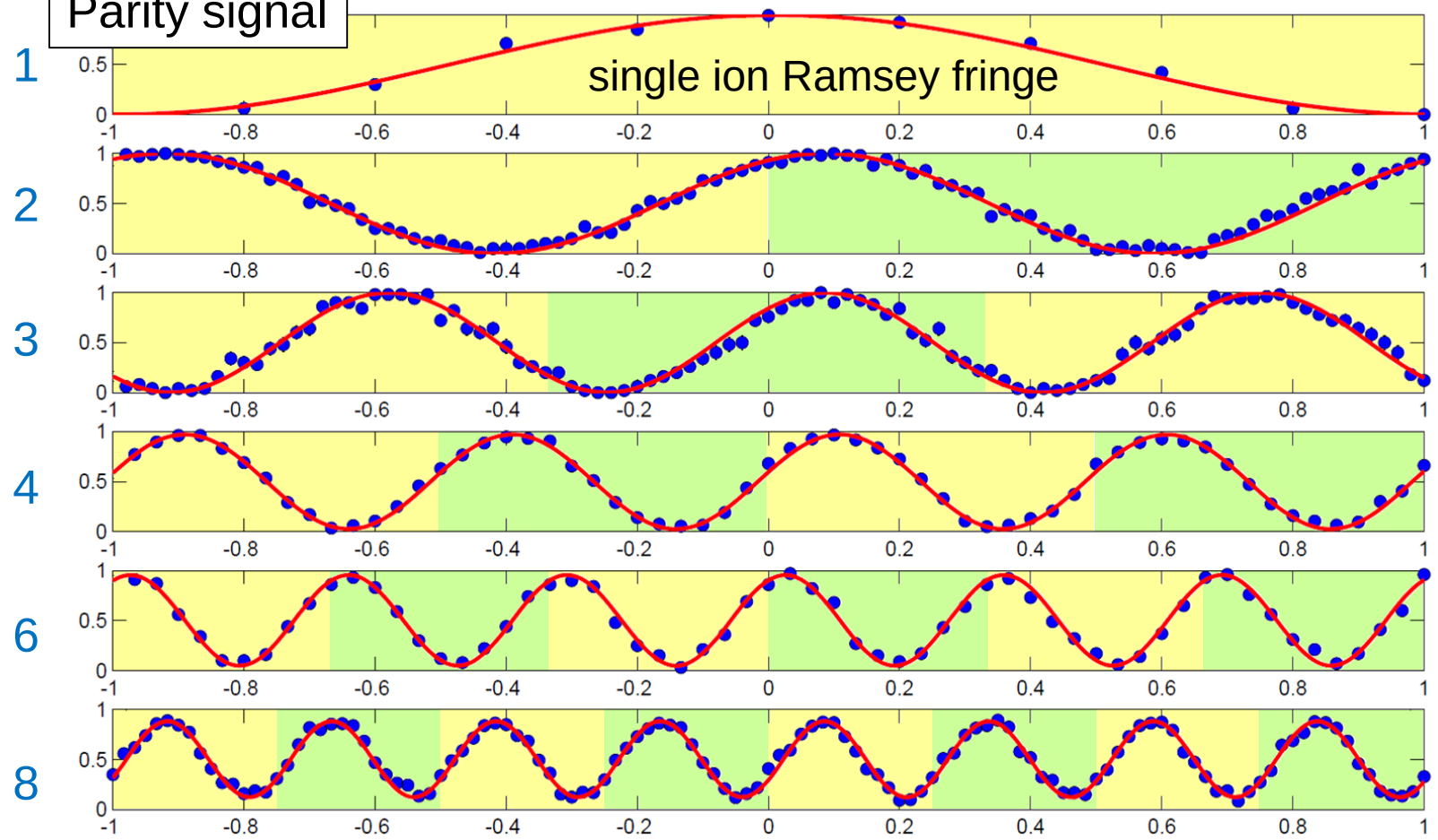
Multi path interferometer – 8 ions



GHZ state fidelity

$N =$ $\Psi = \frac{1}{\sqrt{2}}(|SS\ldots S\rangle + |DD\ldots D\rangle)$

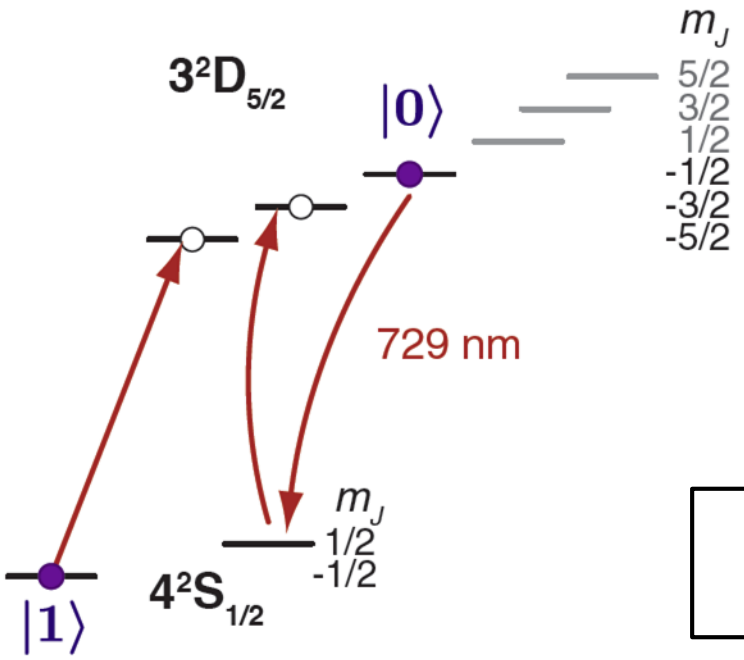
Fidelity (%)



T. Monz et al., *PRL.* **106**, 130506 (2011).

Changing connectivity

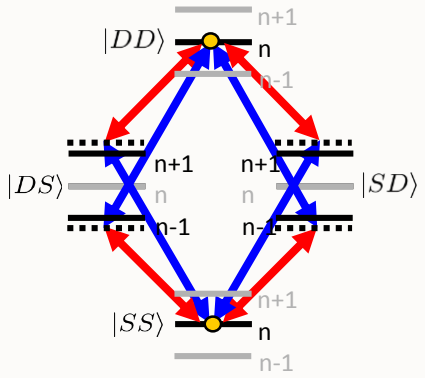
Spectroscopic decoupling

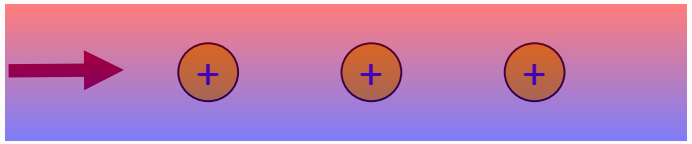


Removes ions from interaction with lasers

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

Set of operations





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

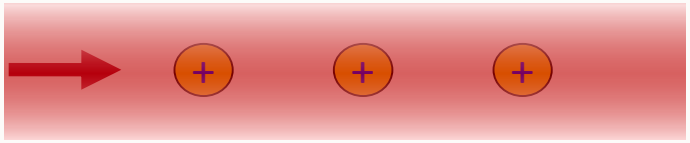
Bichromatic excitation: entangling operations

$^{40}Ca^+$

$|0\rangle$ $D_{5/2}$

resonant manipulation

$S_{1/2}$ $|1\rangle$



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

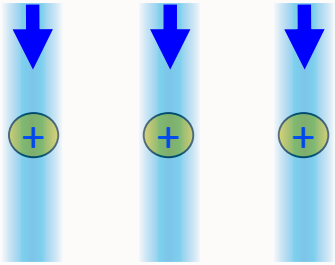
Resonant excitation: collective local operations

$^{40}Ca^+$

$|0\rangle$ $D_{5/2}$

off-resonant manipulation

$S_{1/2}$ $|1\rangle$

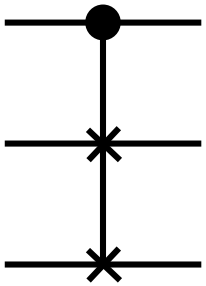


off-resonant excitation: individual local operations (AC Stark shifts)

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

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

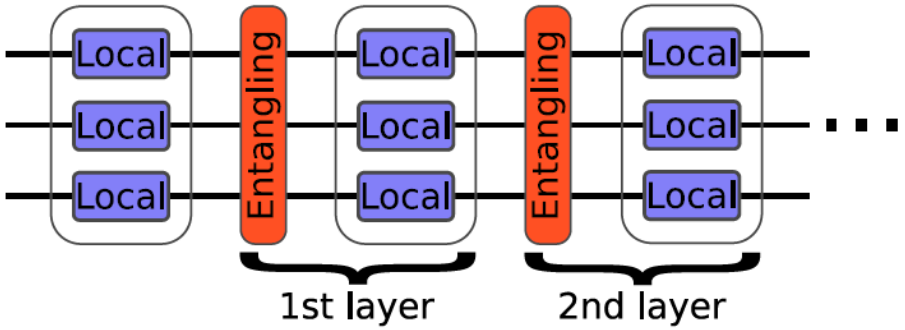
Quantum compiling: Fredkin gate



=

Pulse Nr.	Pulse	Pulse Nr.	Pulse
1	$R(1/2, 1/2)$	10	$R(1/2, 1)$
2	$S_z(3/2, 3)$	11	$S_z(1/4, 2)$
3	$MS(4/8)$	12	$S_z(3/2, 3)$
4	$S_z(3/2, 2)$	13	$MS(4/8)$
5	$S_z(1/2, 3)$	14	$S_z(3/2, 2)$
6	$R(3/4, 0)$	15	$S_z(3/2, 1)$
7	$MS(6/8)$	16	$R(1/2, 1)$
8	$S_z(3/2, 2)$	17	$S_z(3/2, 1)$
9	$MS(4/8)$	18	$S_z(3/2, 2)$

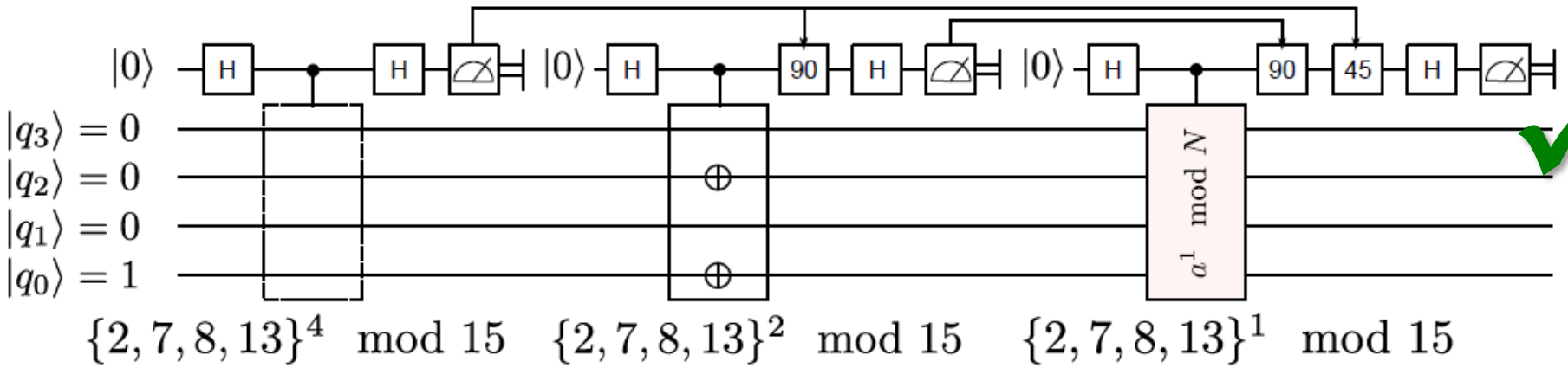
Find optimal pulse sequence with a quantum “compiler”

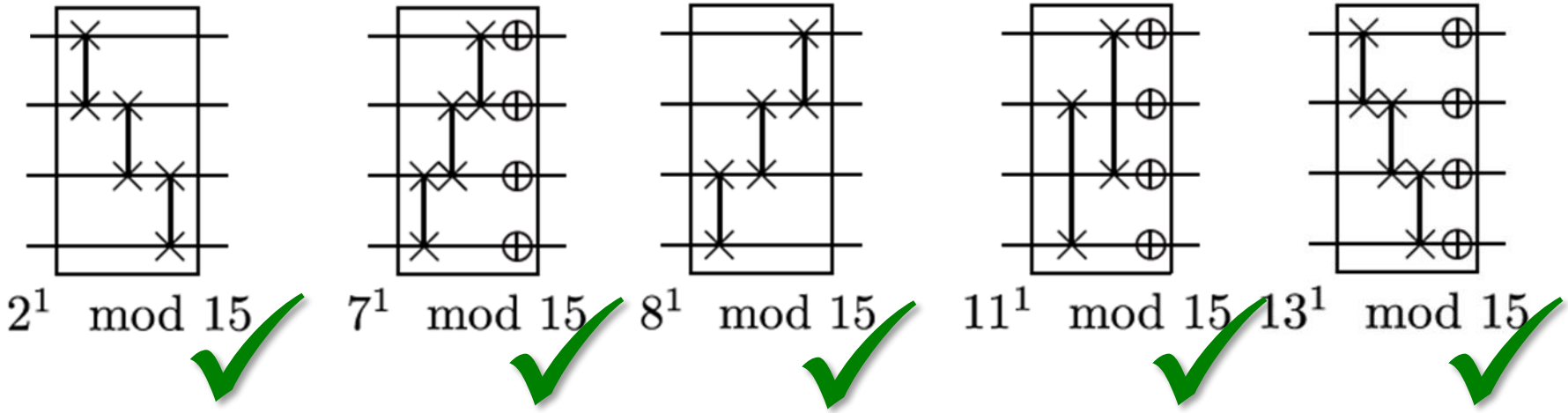


Find sequence with the fewest layers

E. Martinez, New J. Phys. 18, 063029 (2016)

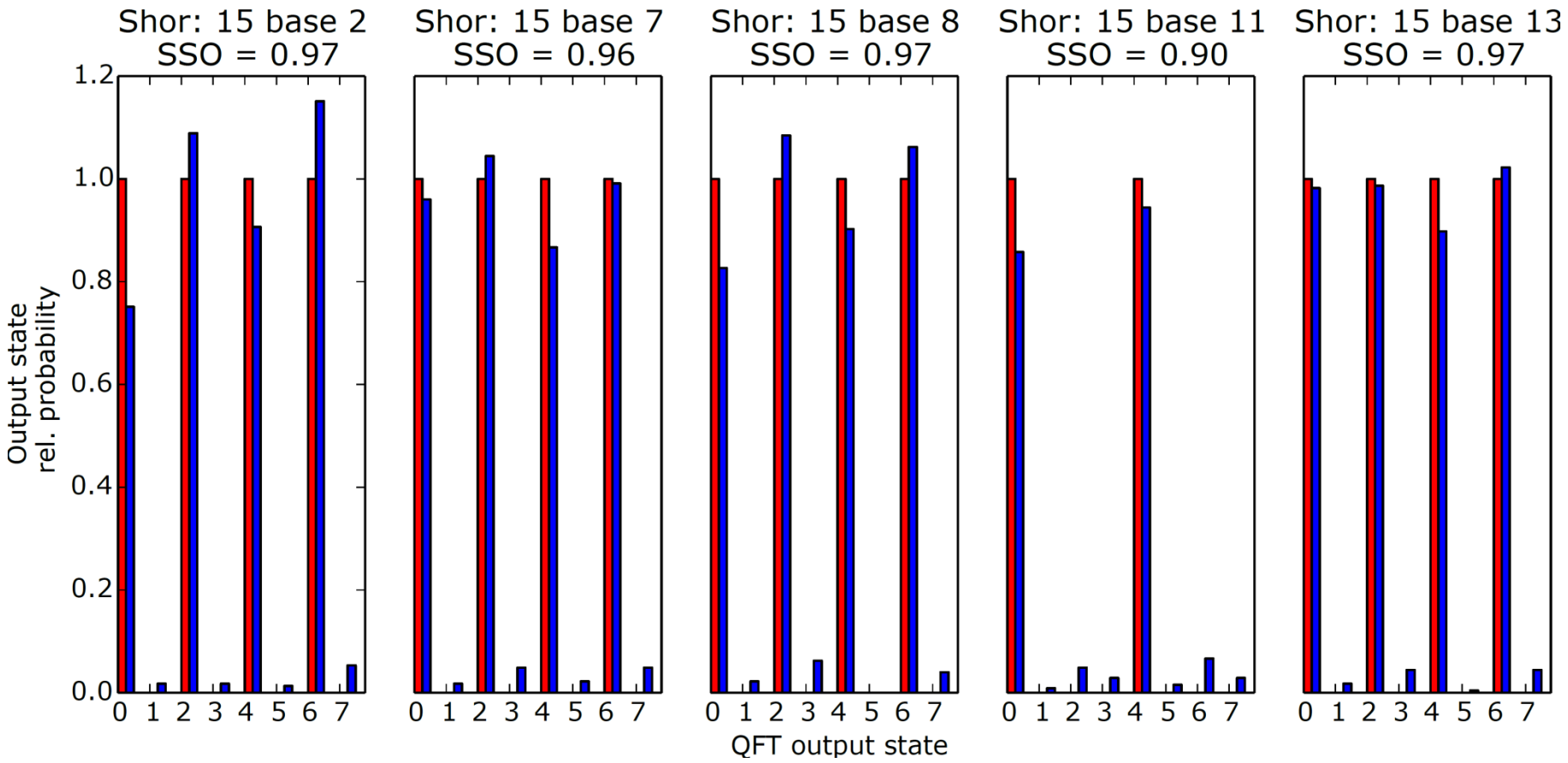
Shor's algorithm – 15 = 3*5





T. Monz et al, Science 351, 1068 (2016)

Experimental results – Shor's algorithm



SSO = {0.968(1), 0.964(1), 0.966(1), 0.901(1), 0.972(1)}

Confidence @ 99% to obtain correct factors after 8 single-shots.

T. Monz et al, Science 351, 1068 (2016)

Benchmarking quantum operations

We want to characterize the errors that occur during a quantum algorithm.

- Number of parameters to describe a quantum process scales exponentially with the register size
- Find a rigorous way to approximate the quantum process with fewer parameters.
- Estimate the performance with a reasonable signal-to noise ratio

J. Wallman,NJP 16, 103032 (2014), PRL 115, 060501 (2015)
J. Wallman, arXiv:1511.00727, arXiv: 1412.4126
A Dugas, PRA 92, 060302 (2015)
A. Rivas, NJP 17, 062001 (2015)
L. Postler, A.Rivas , Quantum 2, 90 (2018)
A. Erhard, J. Wallman, arXiv:1902.08543

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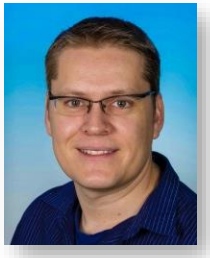
Swansea University
Prifysgol Abertawe



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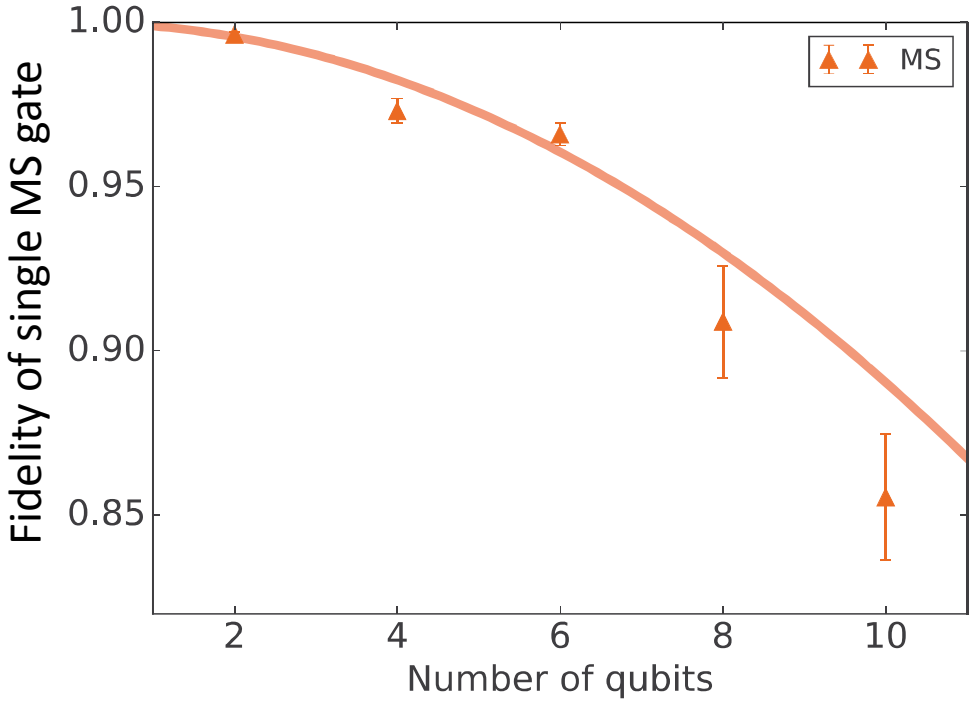
IQC Institute for Quantum Computing

Benchmarking of medium sized registers

Perform rigorous benchmarking with local randomizing operations



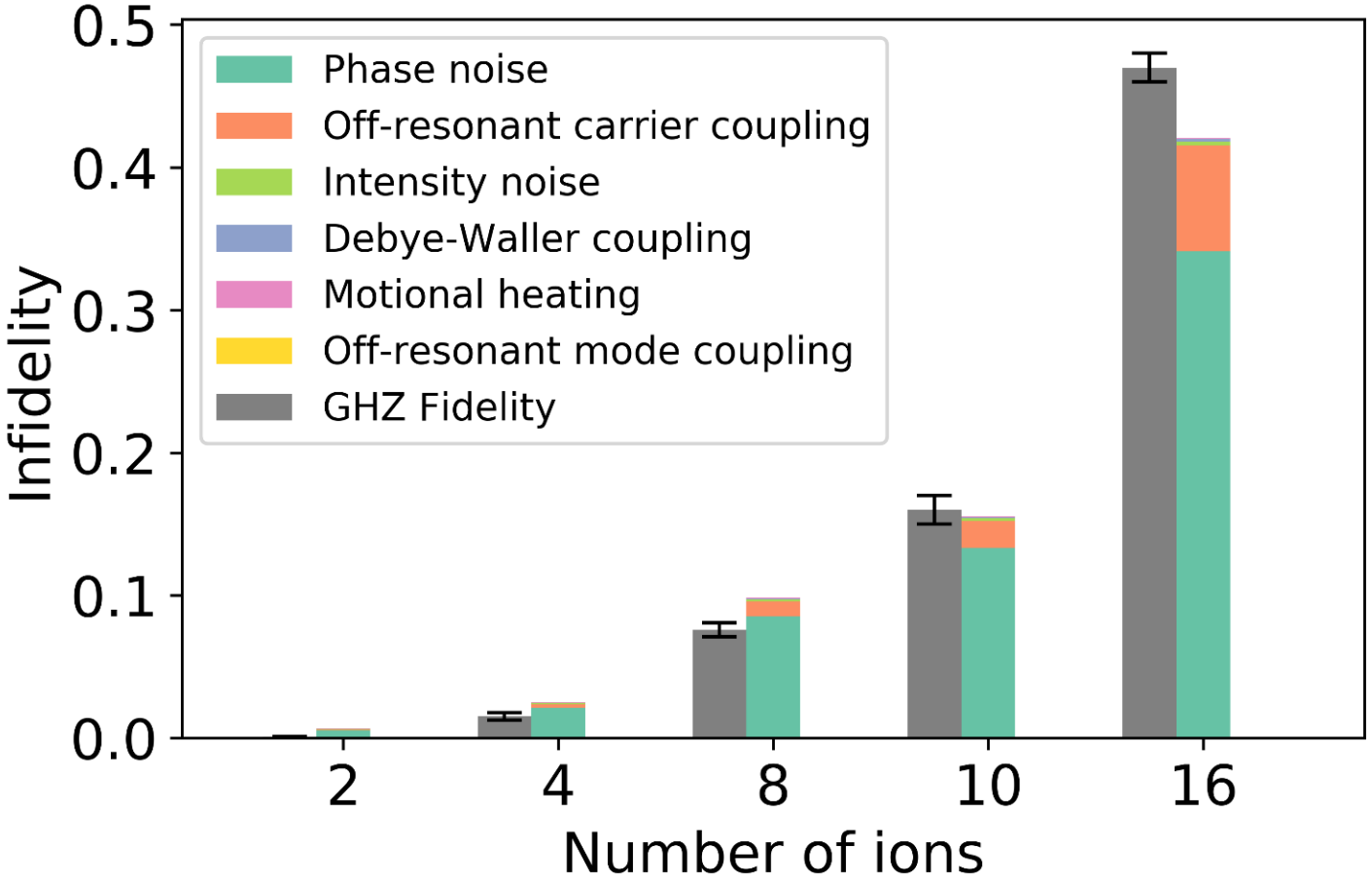
J. Wallman

Scaling by MS-gate limitations
due to full connectivity
→ quadratic dependence on qubit #

$$\#\text{conn} \propto N(N-1)$$

A. Erhard, J. Wallman et al, arXiv:1902.08543

Entangling operation error model



Independently measured parameters

Analytic error model, adapted from A. Sørensen, K. Mølmer, PRA **63** 022311 (2000)

The next step: Keeping a qubit alive

Improve gate p

Use advanced t

Develop suitab

encoding

e models

specific noise

Markus Müller:
Thursday 9:20

F Schmidt-Kaler
Thursday 10:00

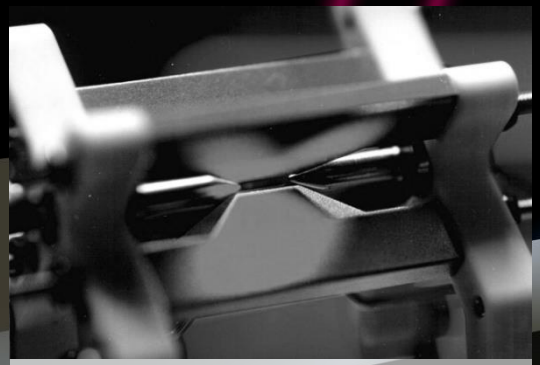
ETH zürich

THE UNIVERSITY OF SYDNEY

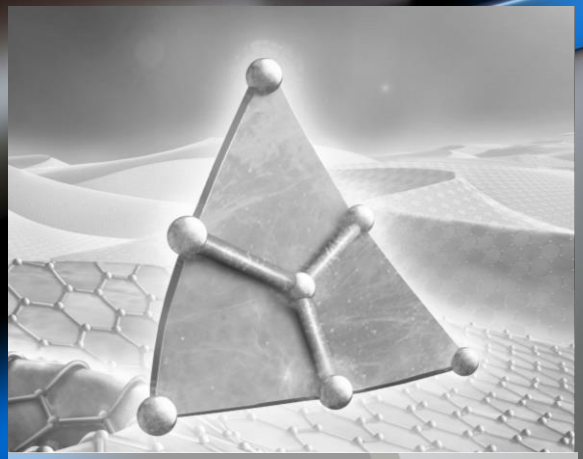
JOHANNES GUTENBERG UNIVERSITÄT MAINZ

Swansea University
Prifysgol Abertawe

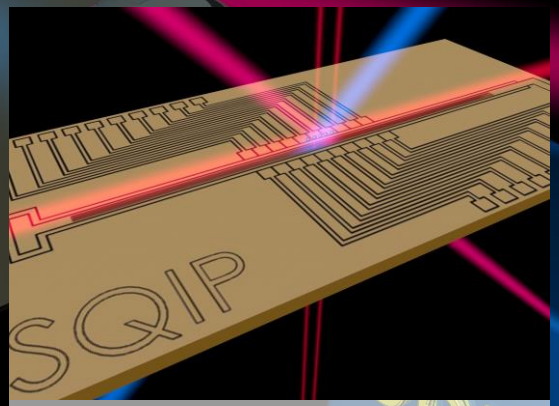
eQual



Ion trapping basics

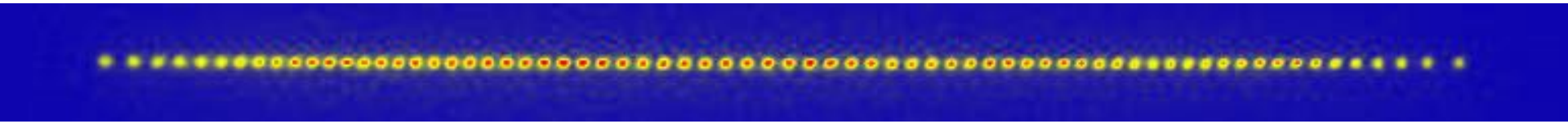


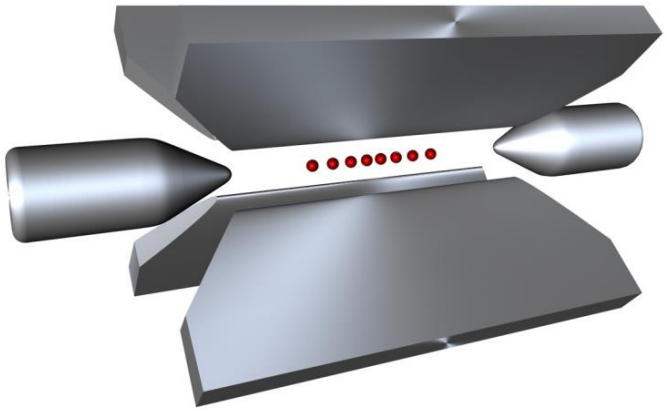
Gates and Algorithms



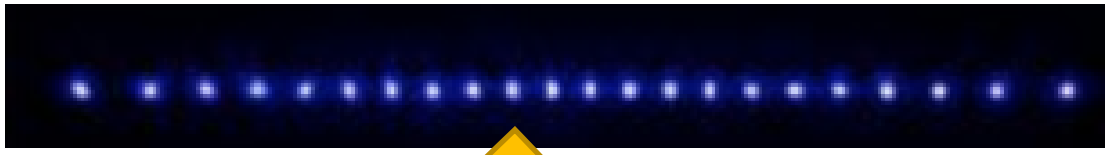
Scalable devices &
Engineering challenges

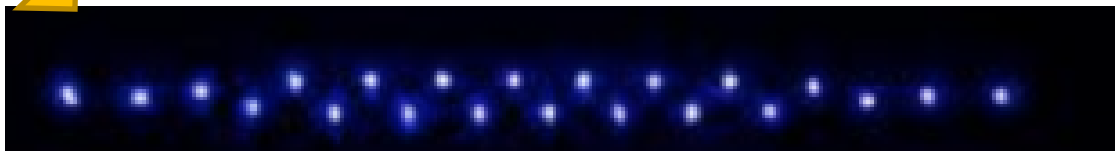
Are ion traps scalable?

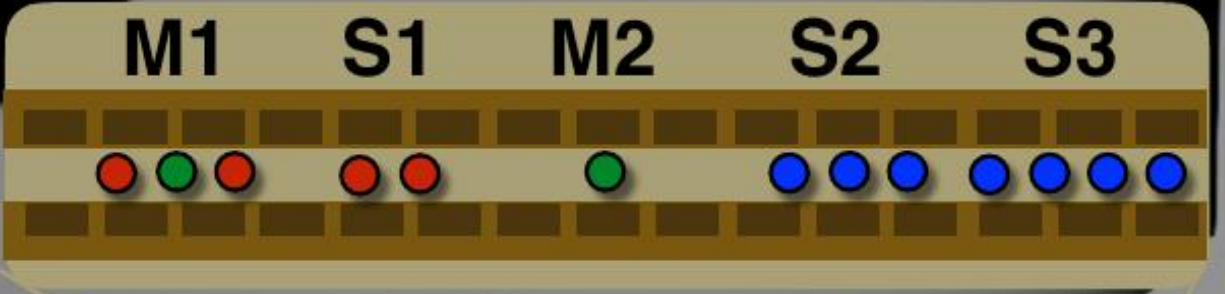




Ion strings for QIP cannot be created for >100 ions.







data ions
ancilla ions
cooling ions

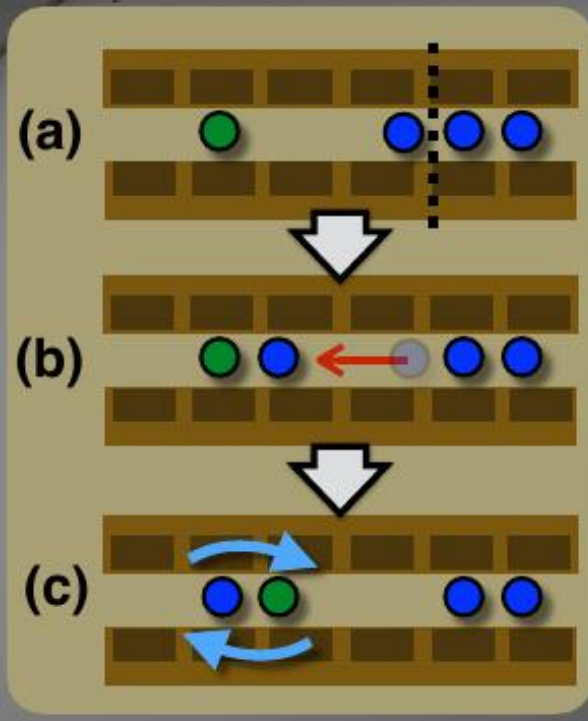
WH, Wed

Idea: split trap into multiple smaller trapping regions.

Requires trap geometry with 100µm features

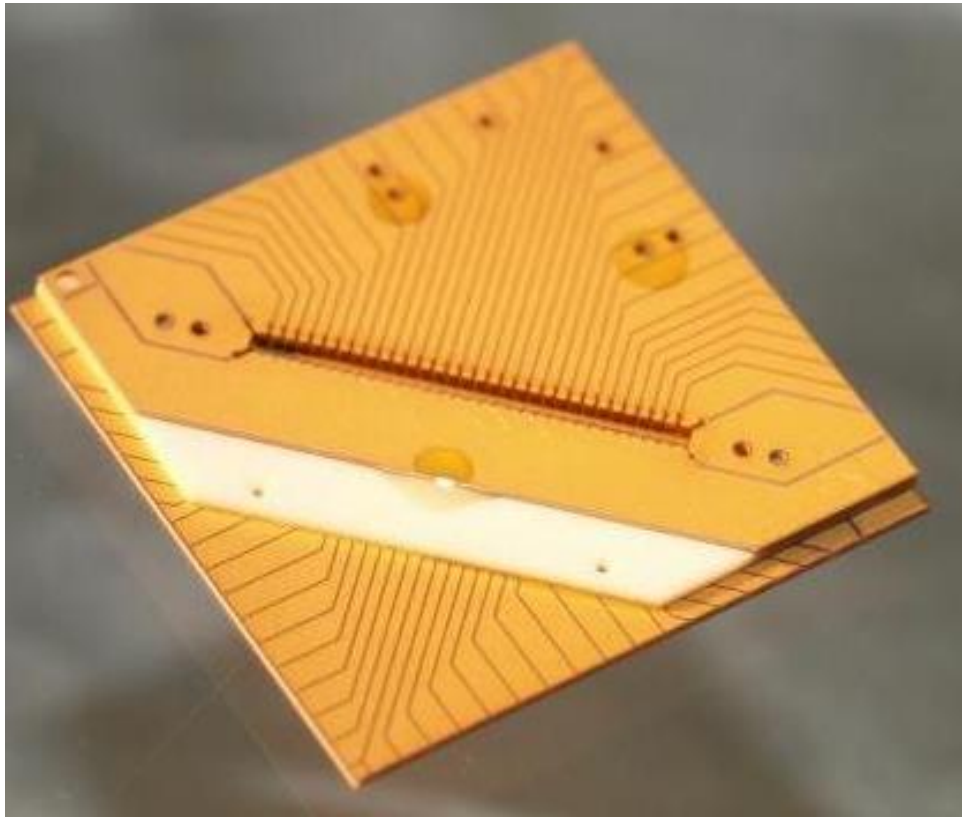
-

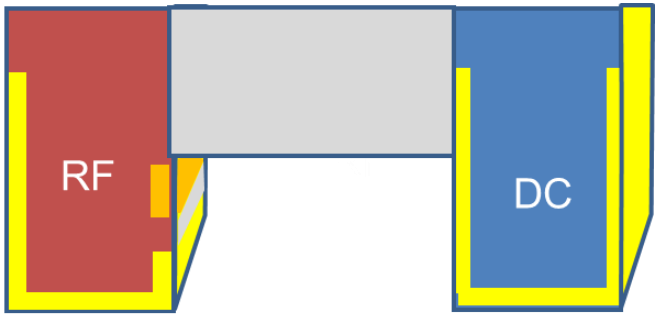
Reduced motional coherence (heating rates)

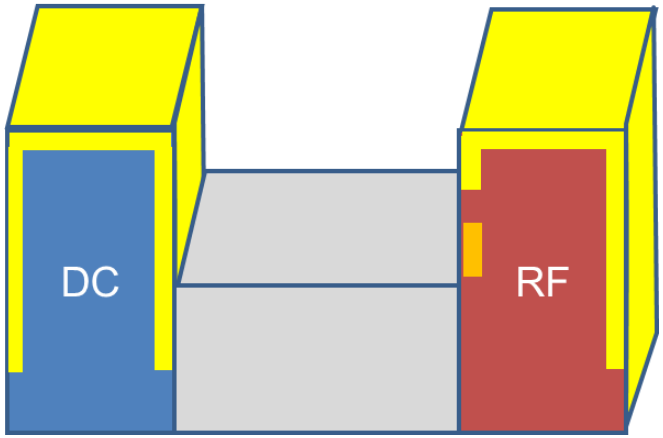


S3400 10.0kV 30.1mm x19 SE 3/30/2015 3.00mm

3D micro-traps



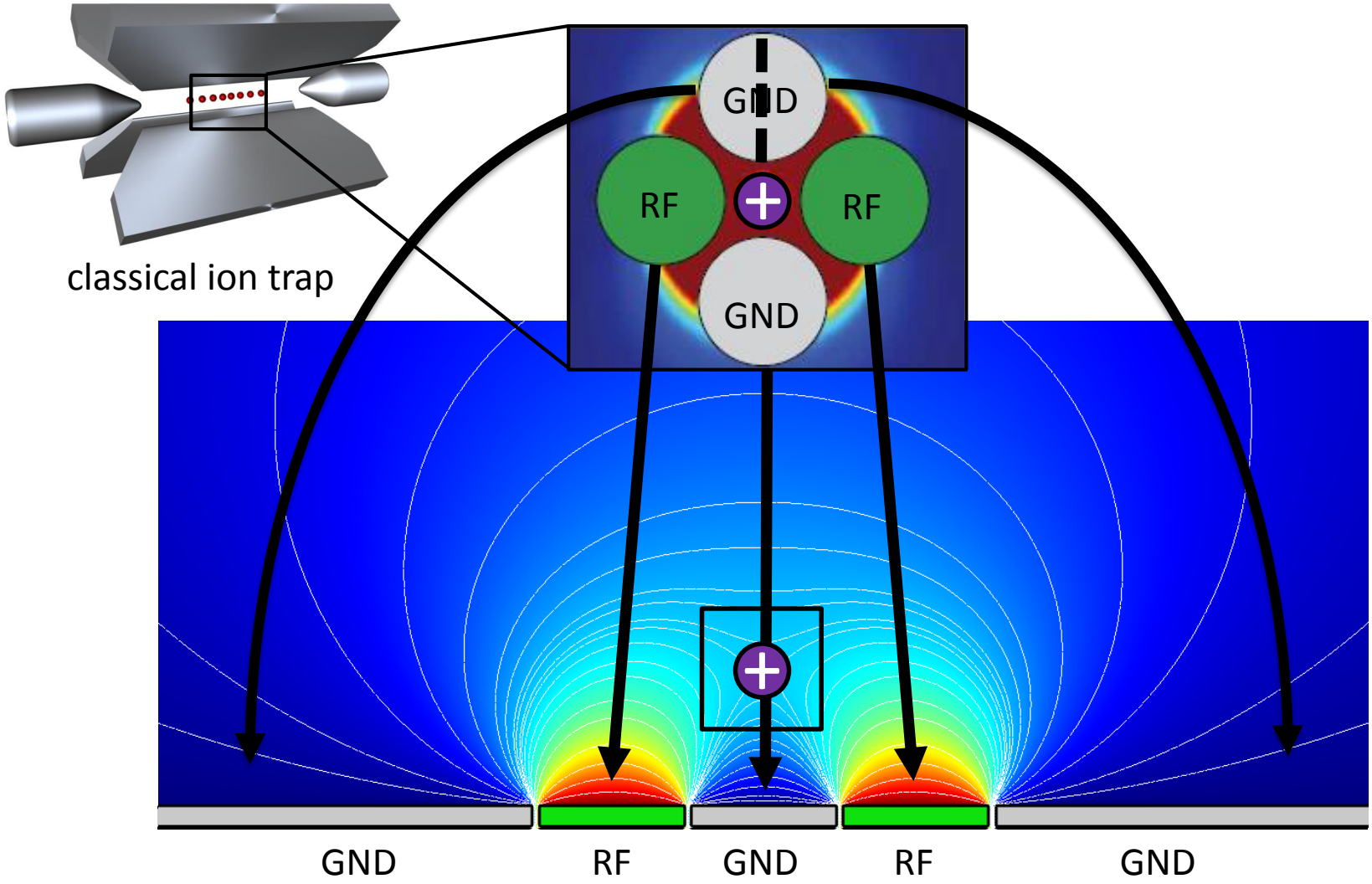




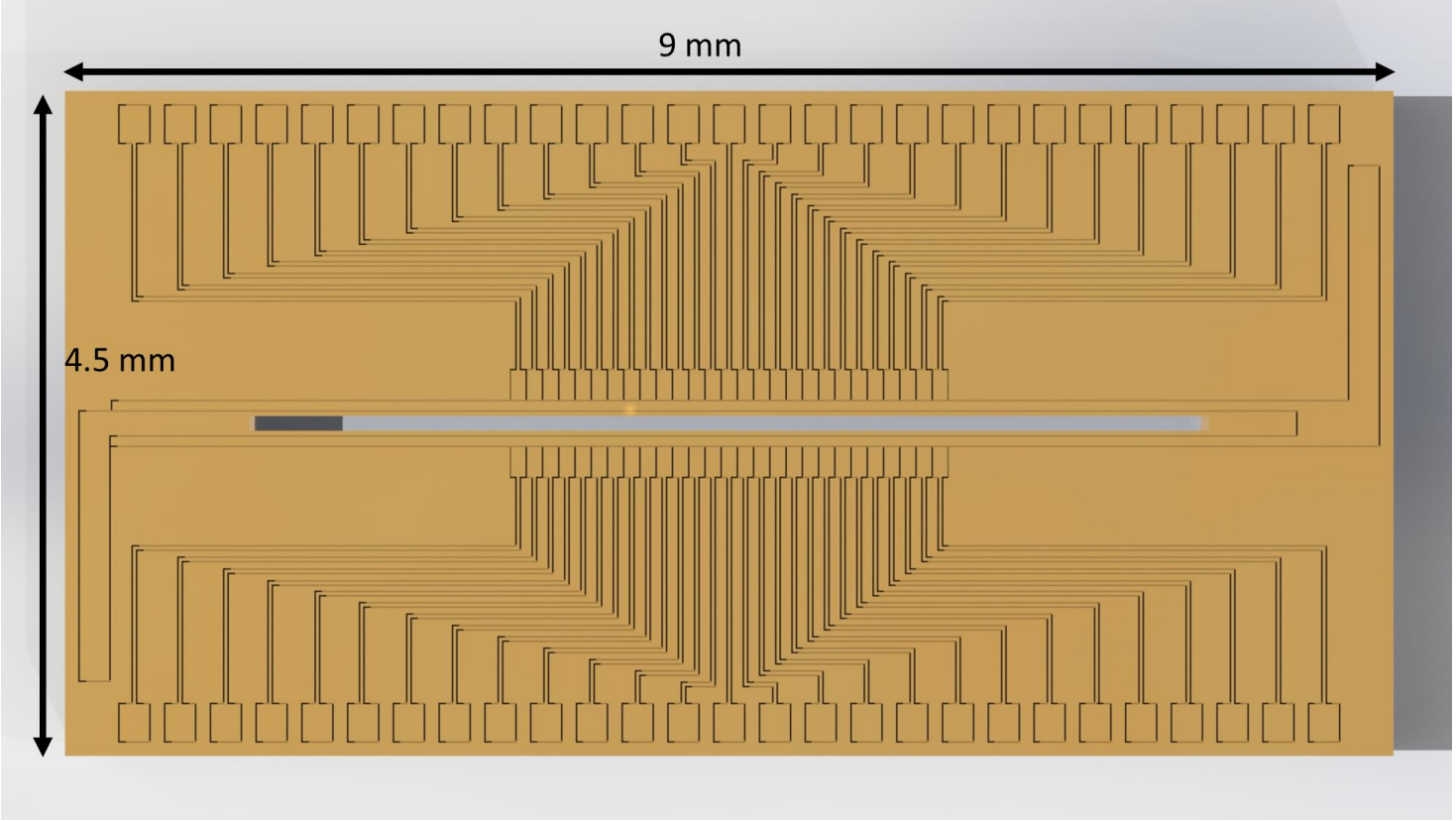
Sandwiched design
Challenges:
- Waver alignment
- Fabrication

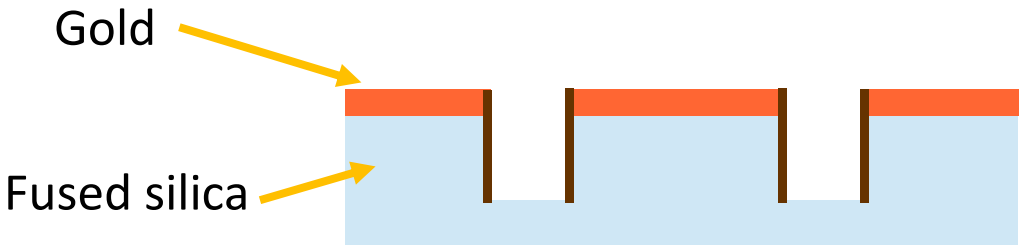
FSK, Thu

Planar ion traps



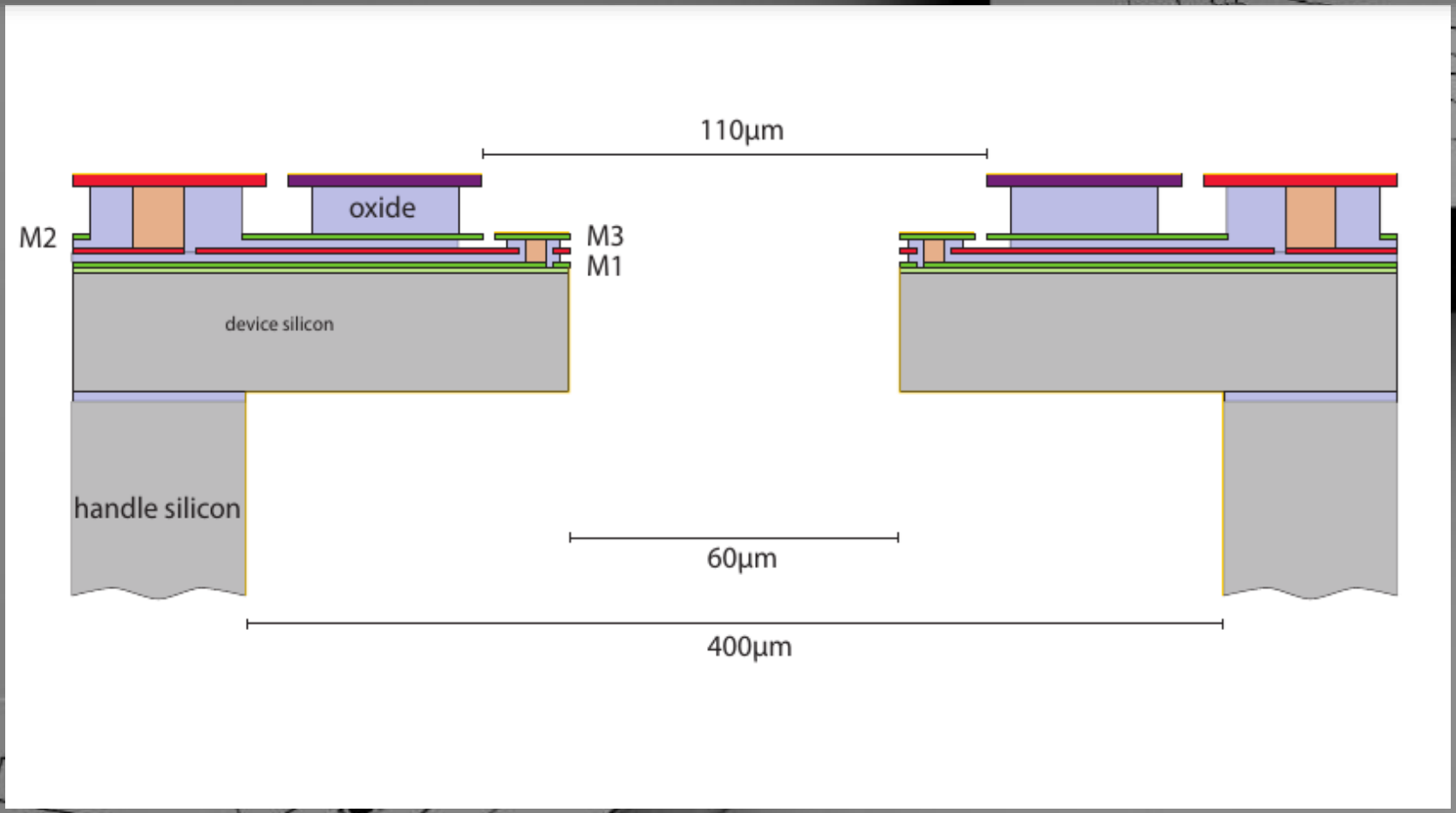
Single layer fused silica traps





- Simple and clean procedure
- Only single layer routing possible

Multi layer silicon traps – HOA 2

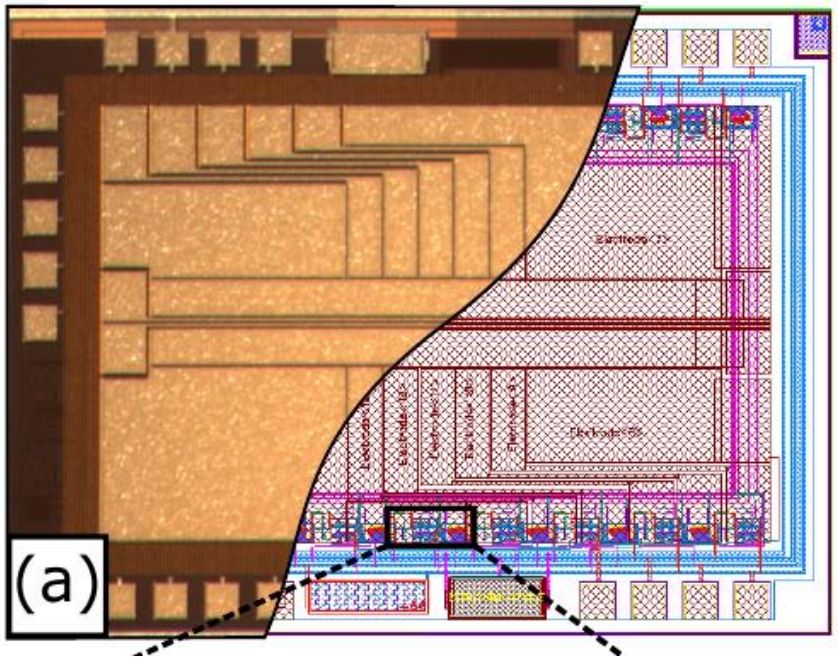


PM, Thu

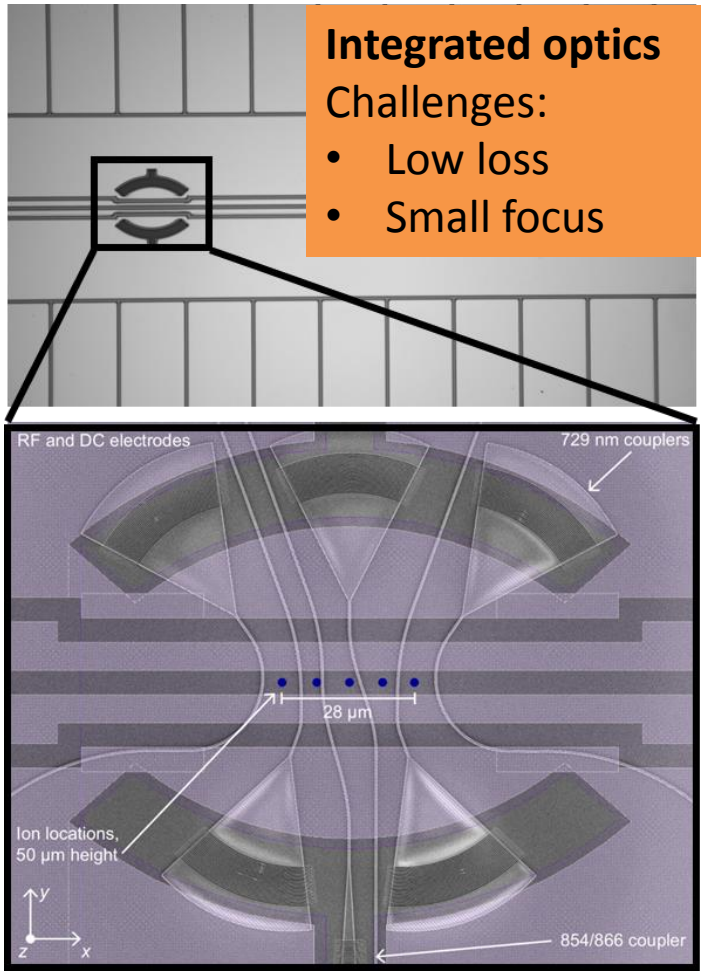
CO, Thu

Sandia National Laboratories

Integrated components



Integrated DAC
Challenges:
- Low noise
- High voltage
- High update rate
- 10 … 100 outputs

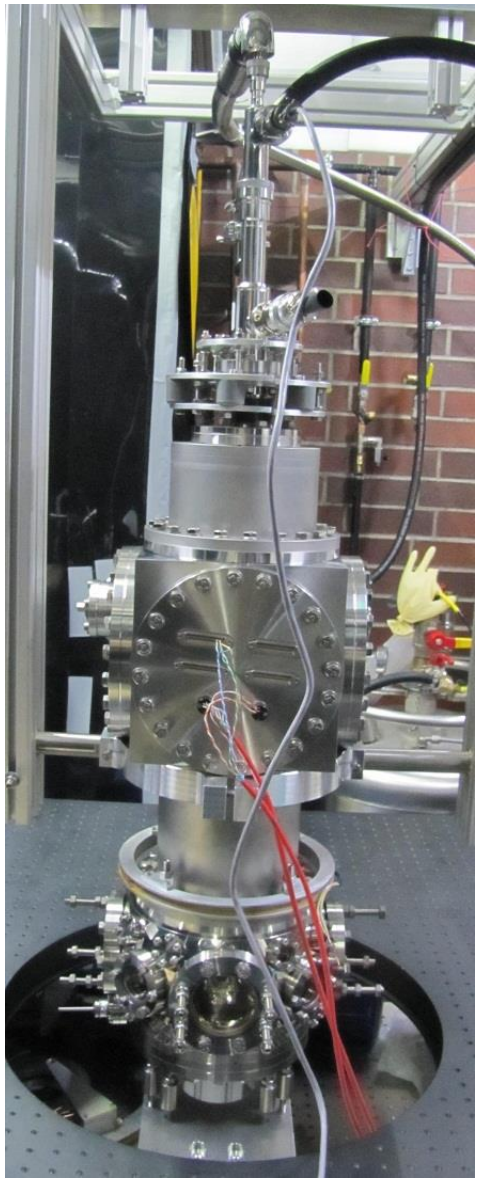


Integrated optics
Challenges:
- Low loss
- Small focus

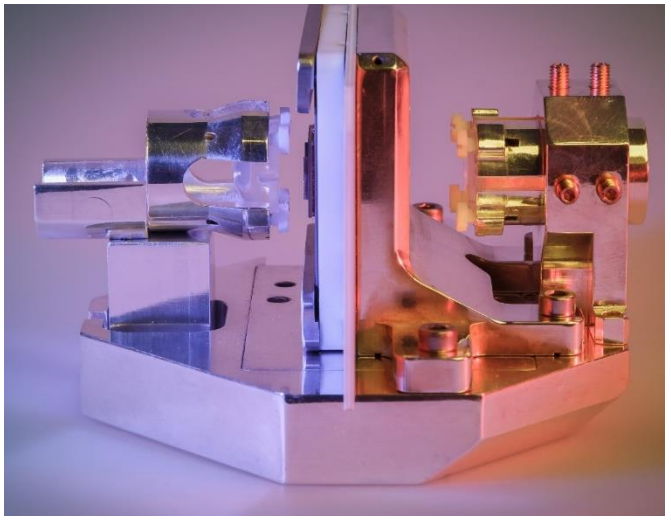
J. Stuart et al, PR Applied 11, 024010 (2019)
Also: ETH, UIBK, Infineon

K. Mehta et al, Nature Nano **11**, 1066 (2016)
Image: K. Mehta, J. Home, ETH

System engineering – Cryogenic system



Vibrational decoupling



High collection efficiency in-vacuum optics

Cryogenic systems (4K):

- Increased motional coherence
- Improved vacuum
- Magnetic shielding
- Heat load (DC lines, RF drive)
- Vibrational decoupling

CO, Thu

FSK, Thu

M. Brandl et al, Rev. Sci. Instrum. 87, 113103 (2016)

System engineering - control system

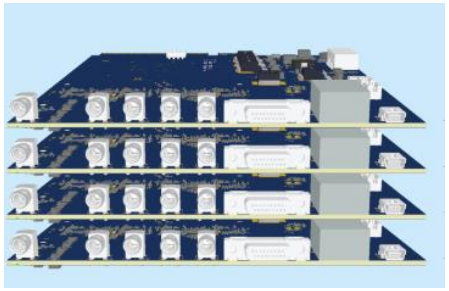
Local oscillator (Laser)

Light modulation (Acousto Optic Modulators)

Focusing optics

Digital signal (FPGA)

RF-signal (DDS)



AQTION – Flagship initiative

MM, Thu

FSK, Thu

AQTION

ETH zürich

Atos

UNIVERSITY OF OXFORD

Fraunhofer IOF

Swansea University
Prifysgol Abertawe

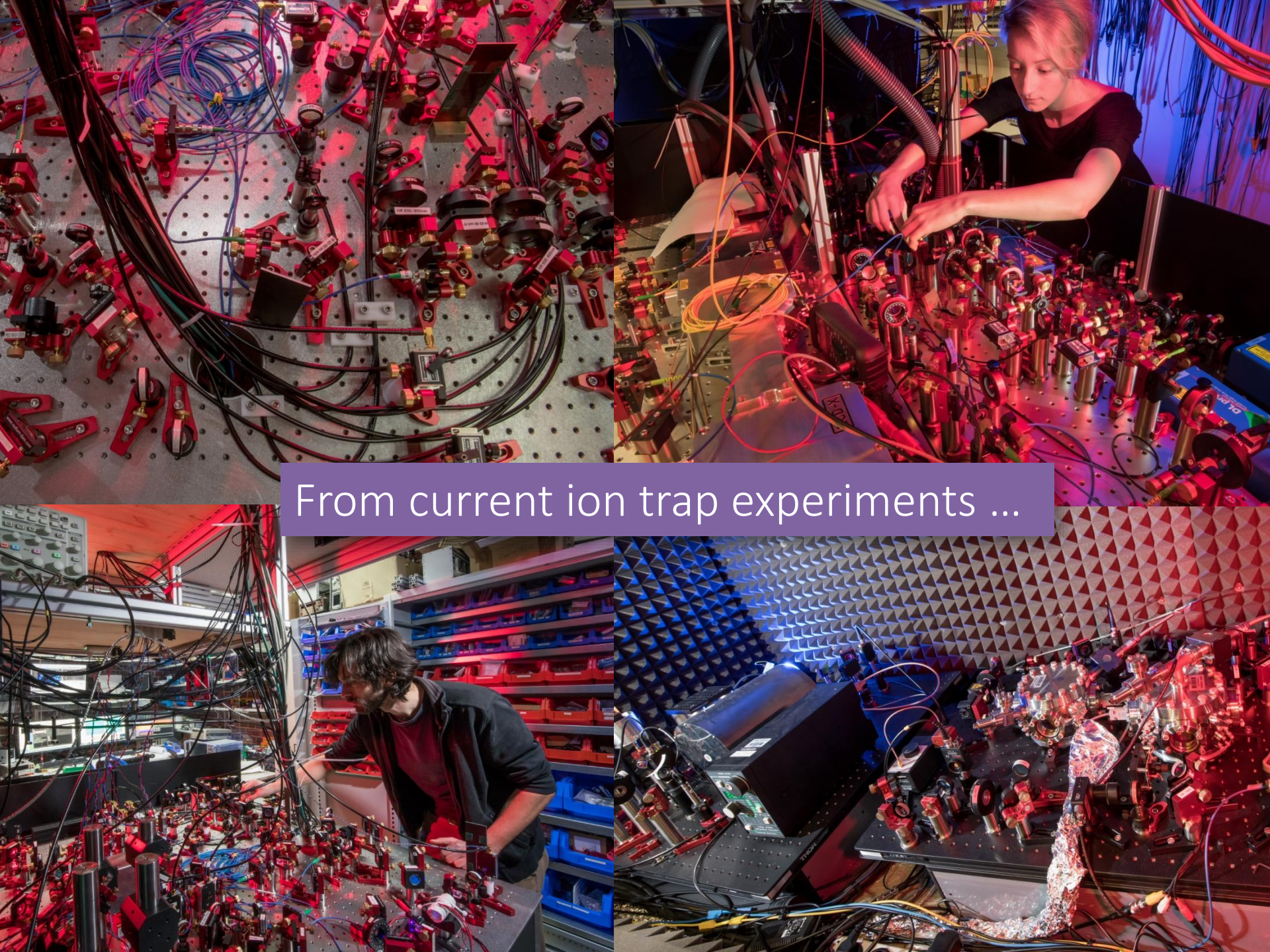
universität innsbruck

TOPTICA PHOTONICS

JG|U

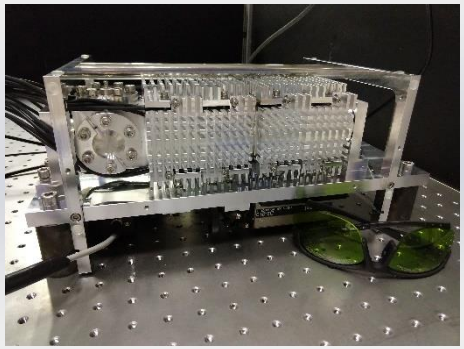
JOHANNES GUTENBERG UNIVERSITÄT MAINZ

AKKA



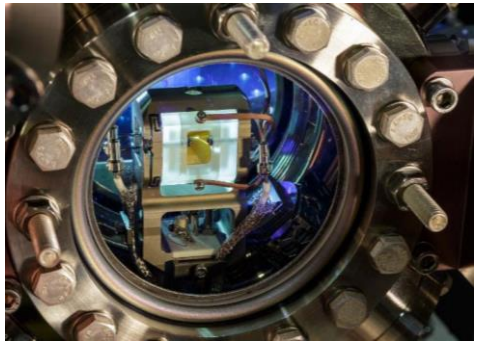
From current ion trap experiments …

… to a compact and robust ion trap QC

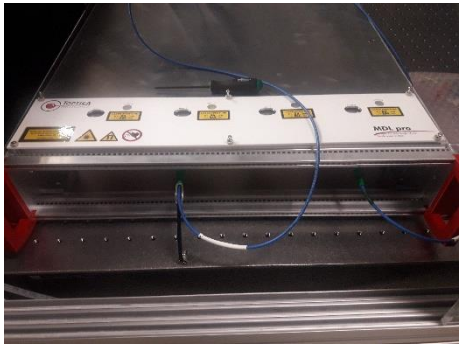


Compact optical reference

Advanced ion traps

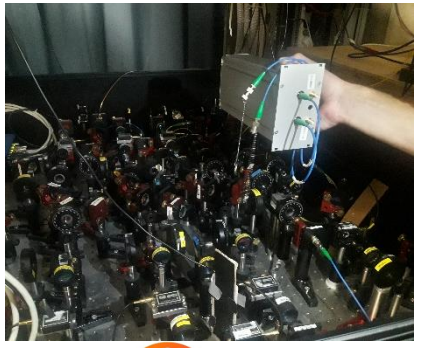


Compact lasers



Control electronics

Optics



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AQT

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AG Quantenoptik
und Spektroskopie

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