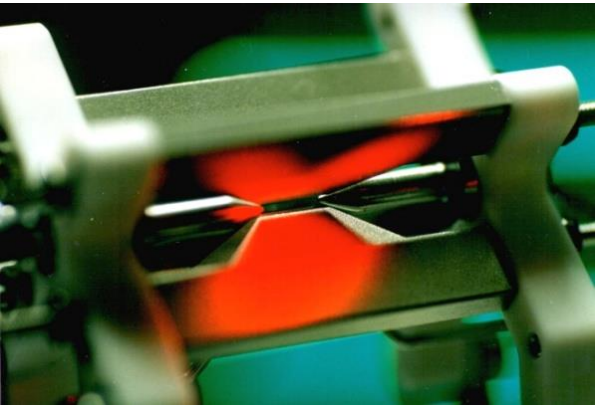
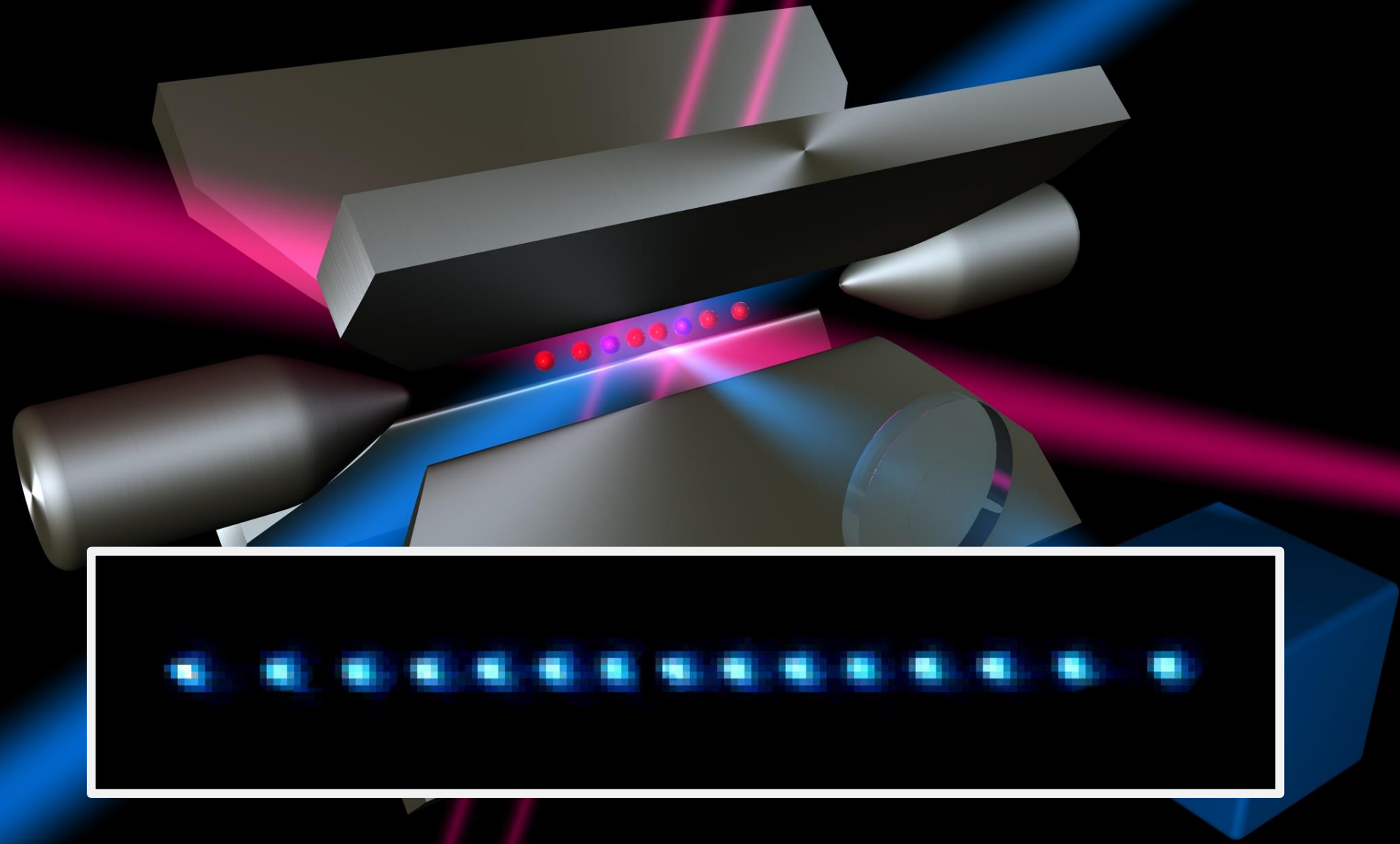


Quantum science with trapped ions

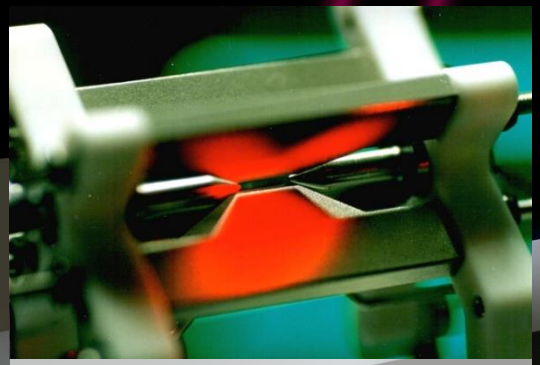
Philipp Schindler

Universität Innsbruck

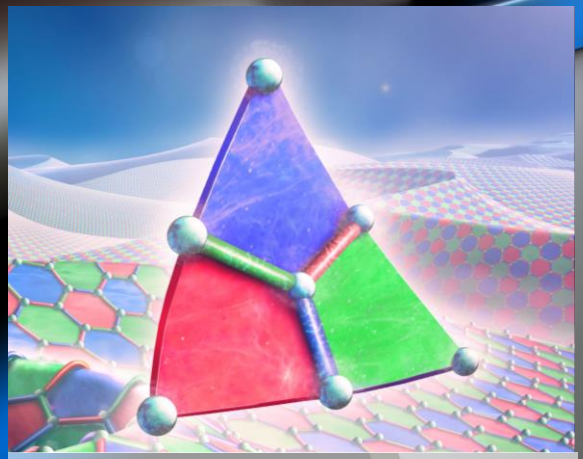
The Quantum Information Processor with Trapped Ca^+ Ions



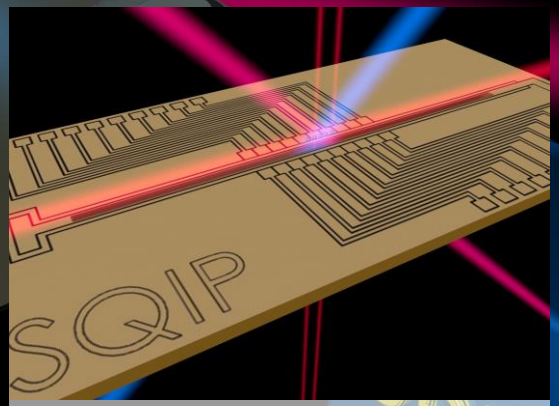
P. Schindler et al., New. J. Phys. 15, 123012 (2013)



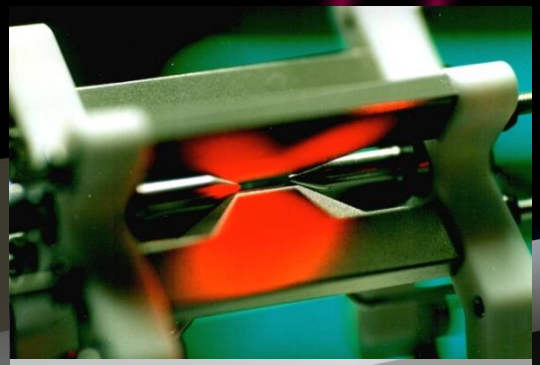
Ion trapping basics



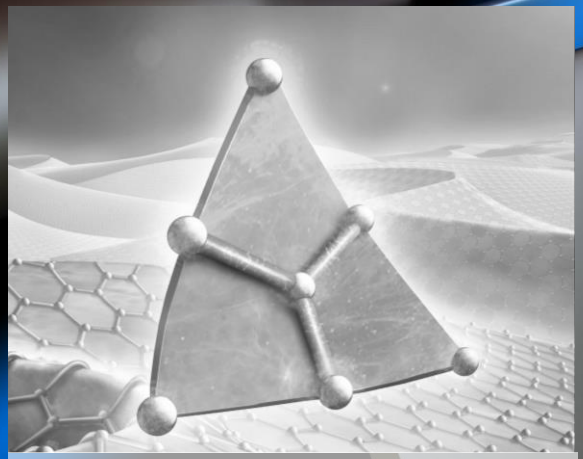
Gates and Algorithms



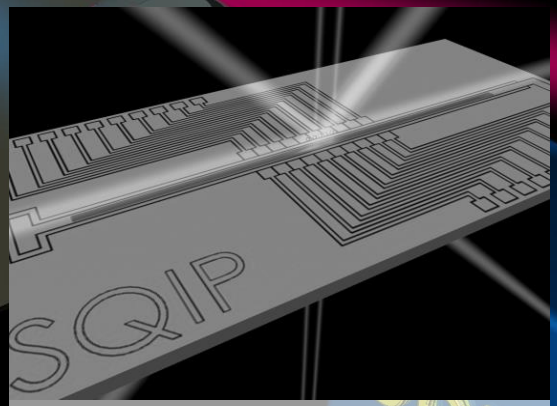
Scalable devices &
Engineering challenges



Ion trapping basics



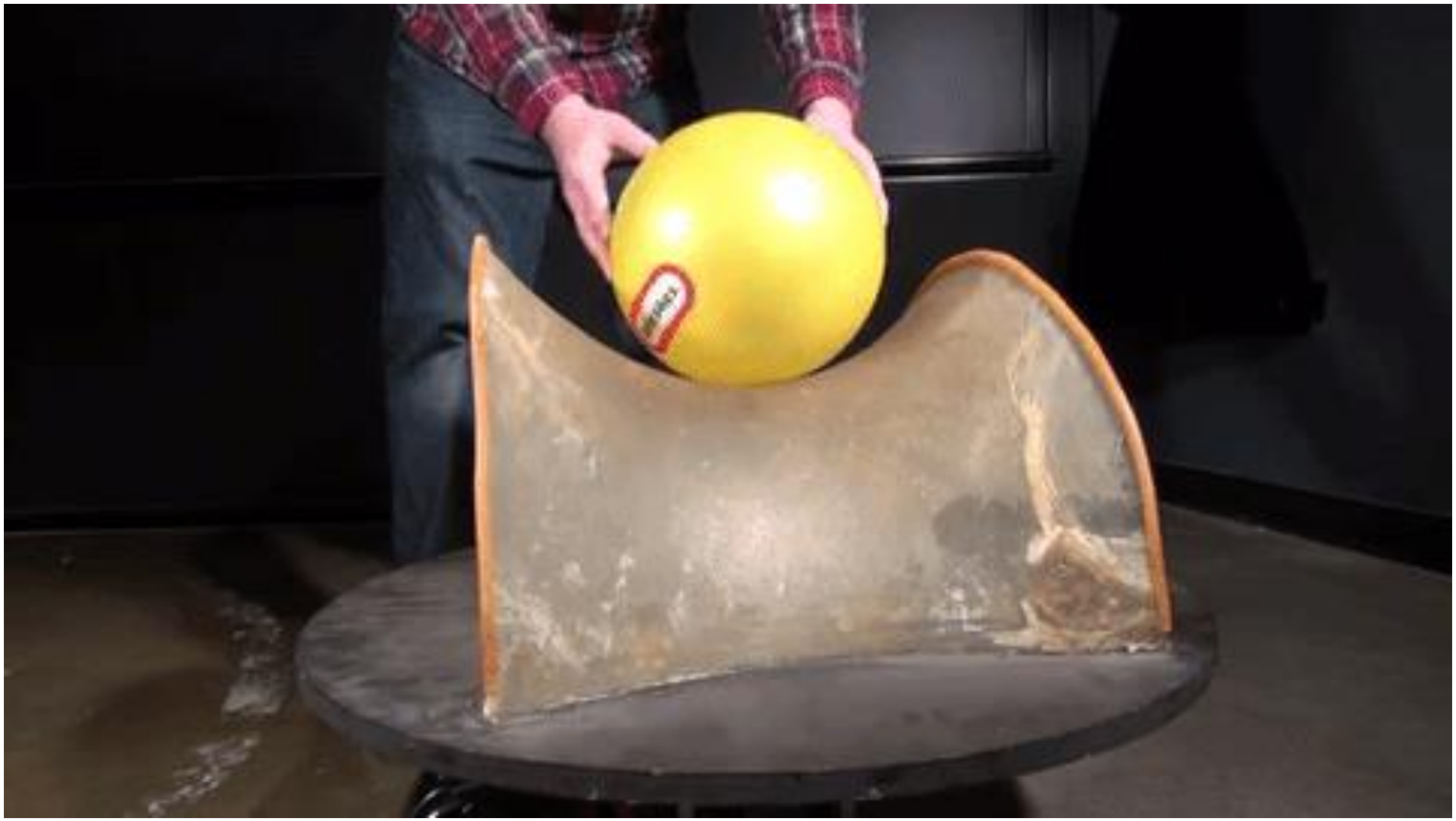
Gates and Algorithms



Scalable devices &
Engineering challenges

Ion trapping – how does it work?

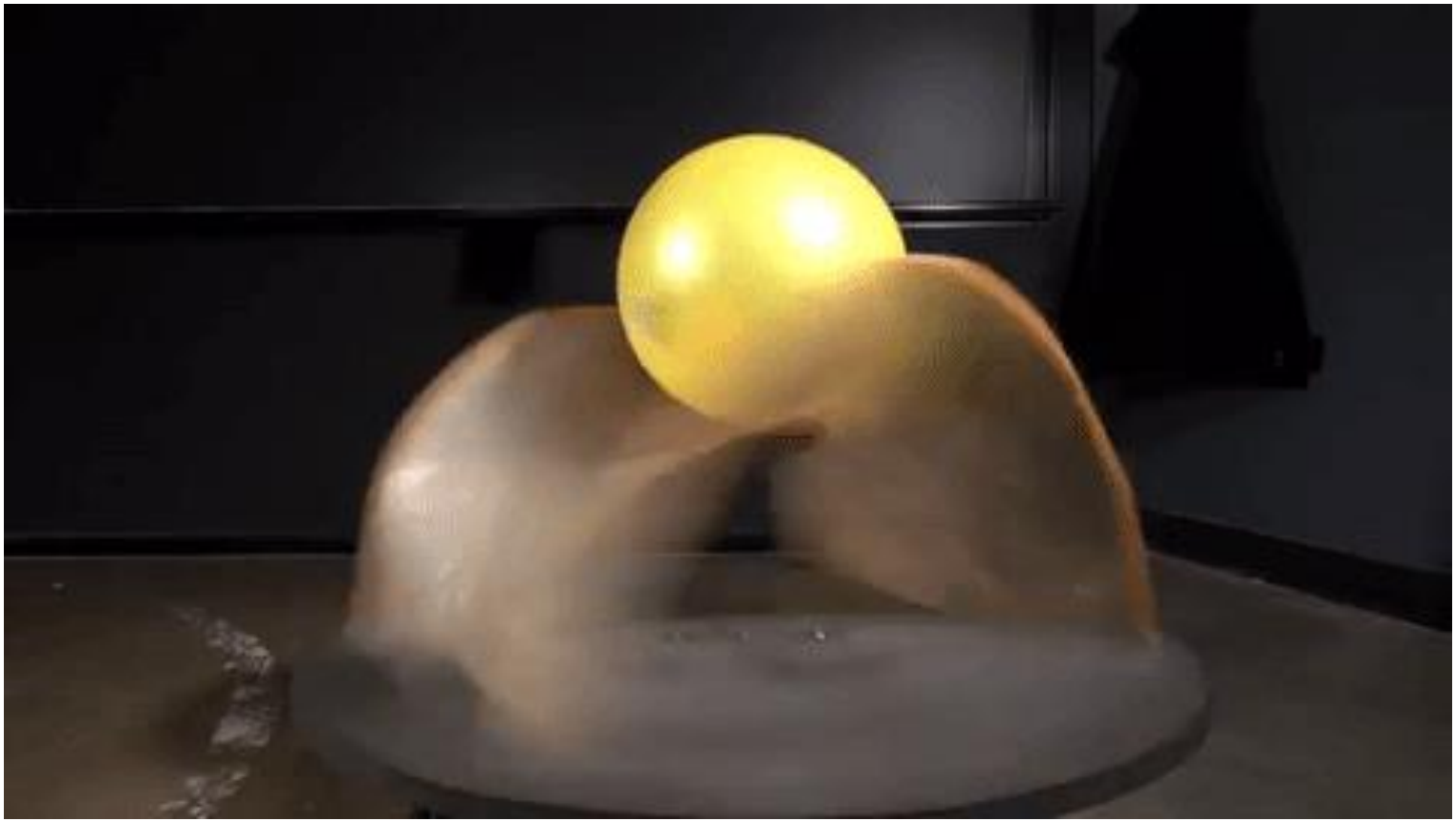
Static electric fields generate potential that is anti-confining in one dimension



Video: Harvard Natural Sciences Lecture Demonstrations

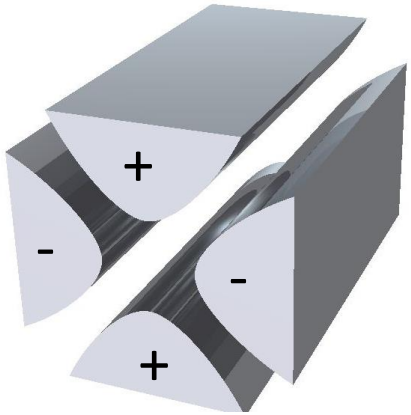
Ion trapping – how does it work?

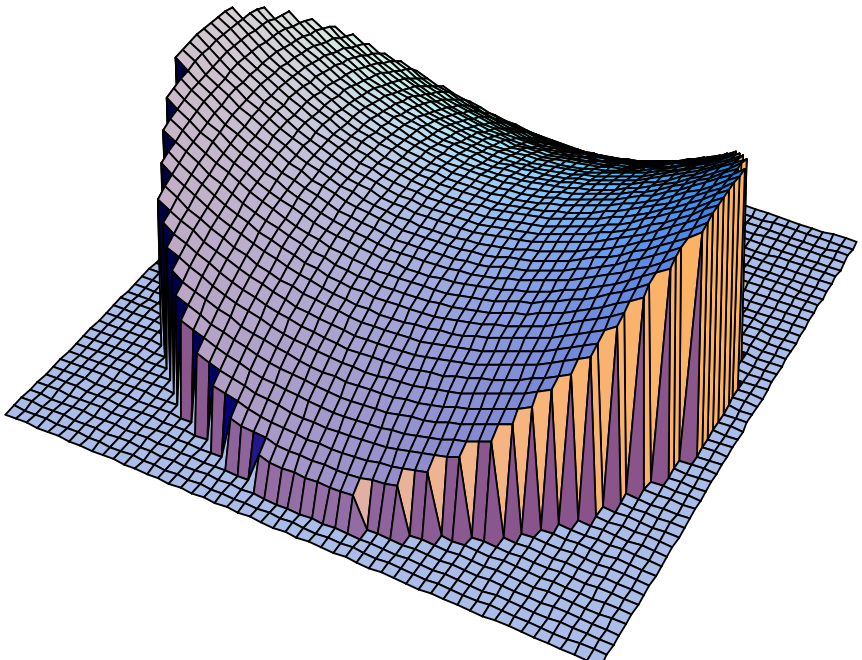
Use oscillating fields to generate an effective confining potential.

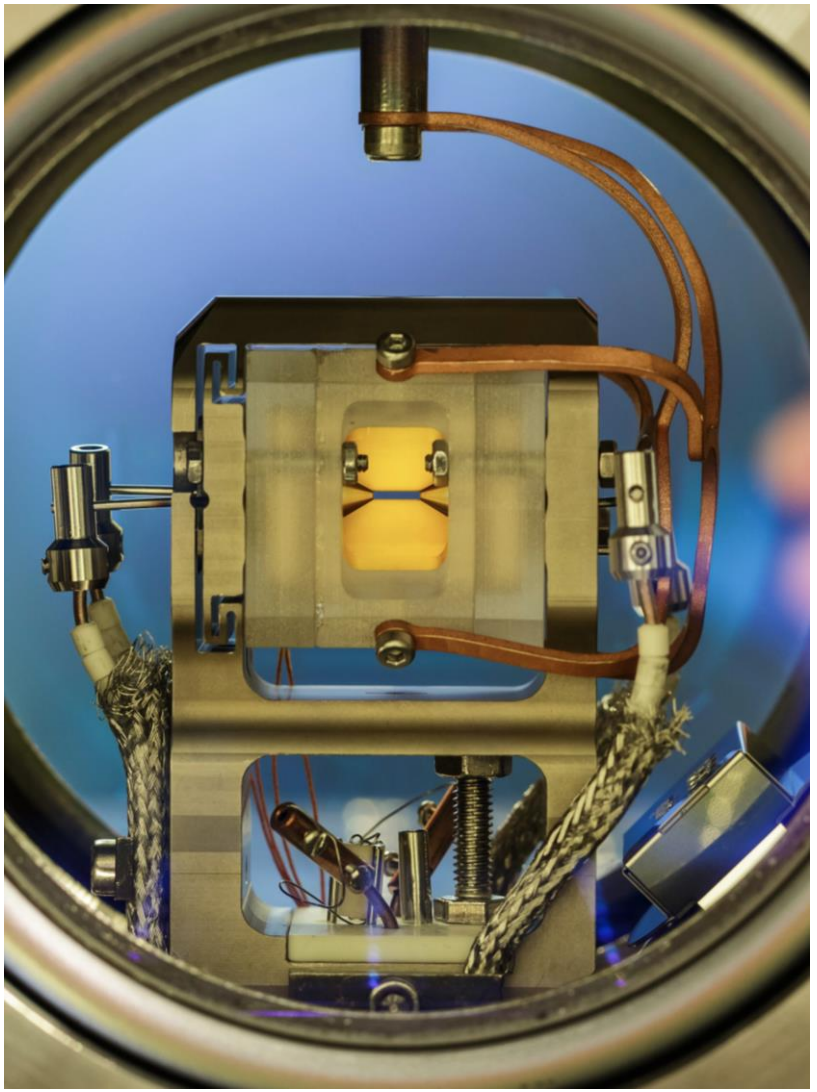


Video: Harvard Natural Sciences Lecture Demonstrations

The linear Paul trap



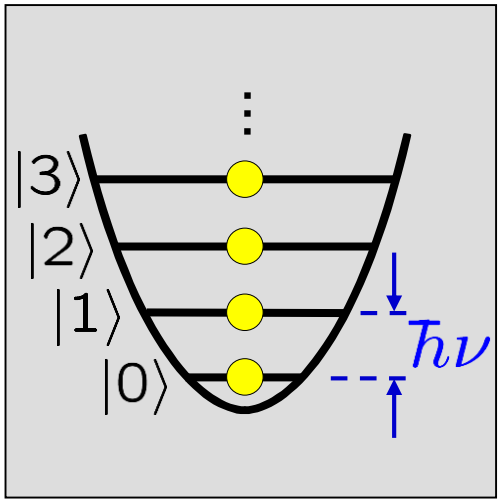


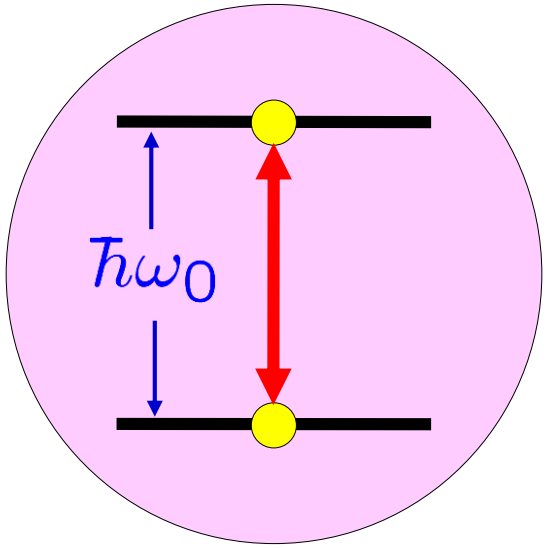


The ideal ion trap QC

Harmonic oscillator

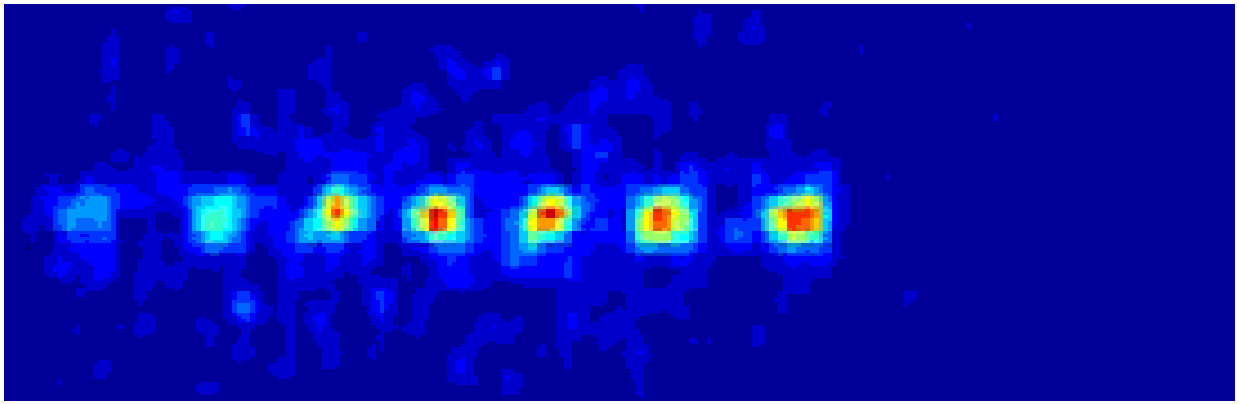
Quantum bit



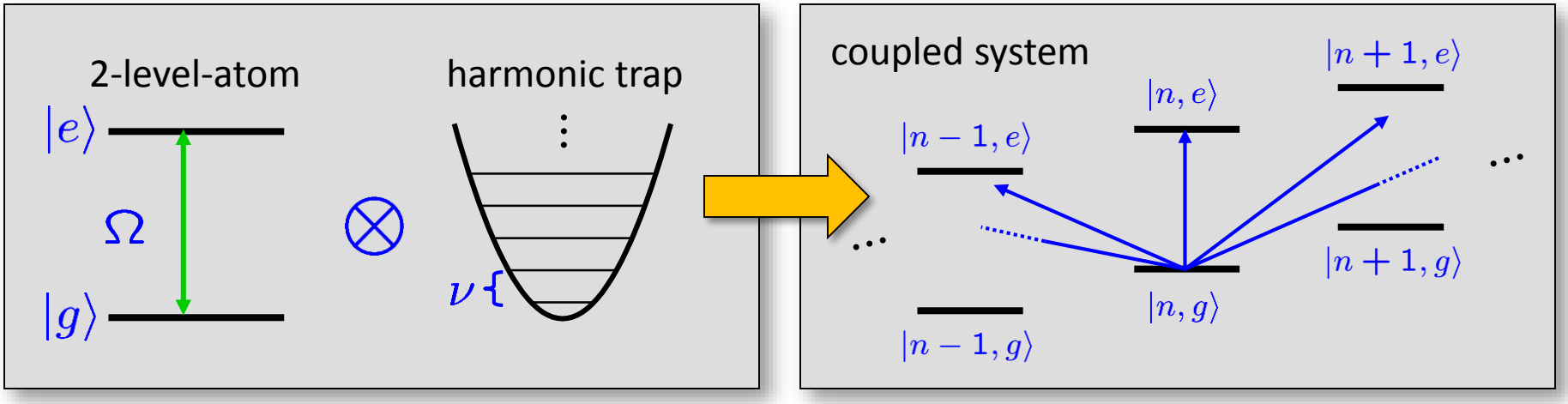


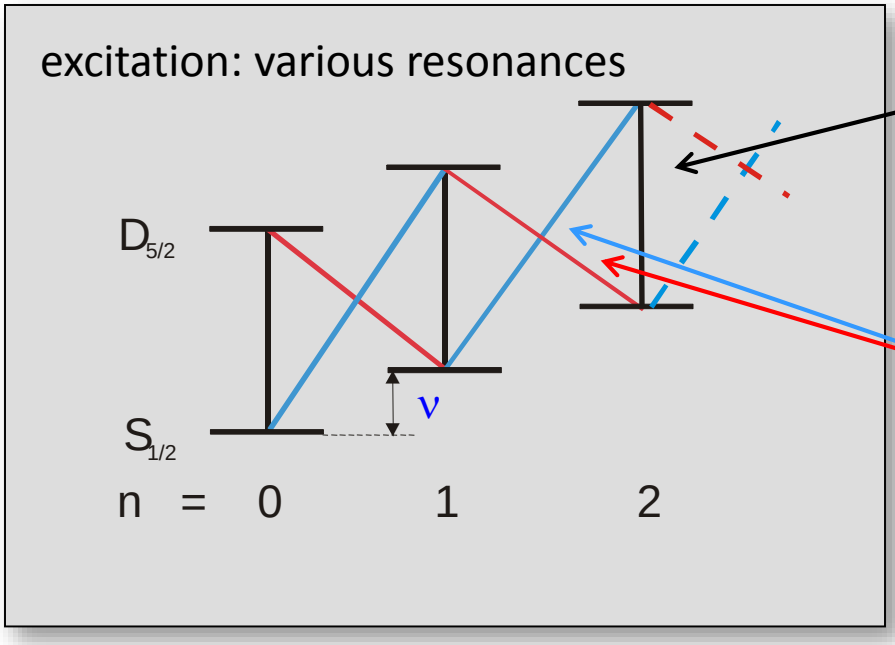
Motion in the trap

The atom



Qubit manipulation

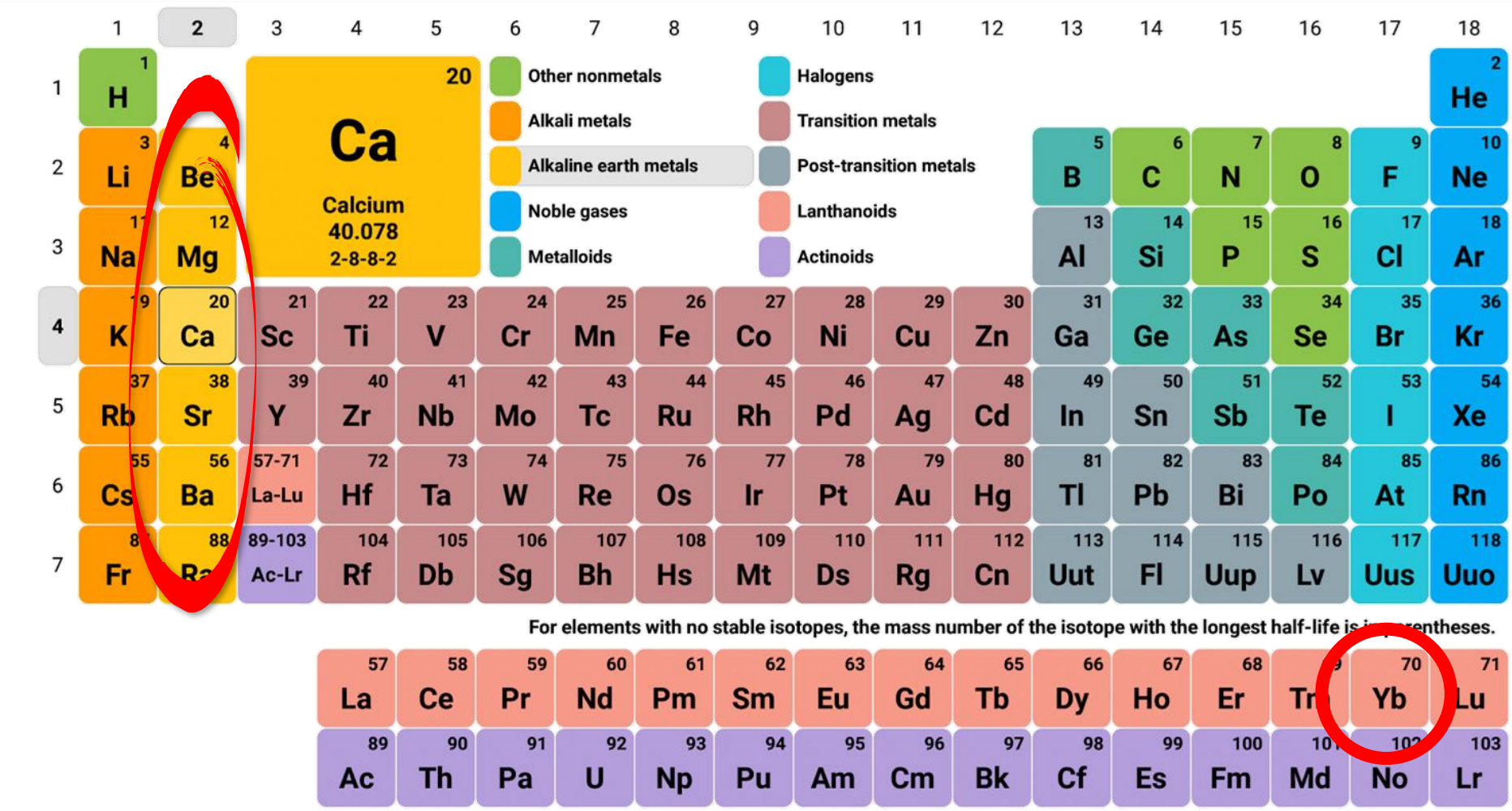




Carrier:
manipulate qubit
Strong transition
→ internal superpositions

Sidebands:
manipulate motion and qubit.
Weak transition
→ create entanglement

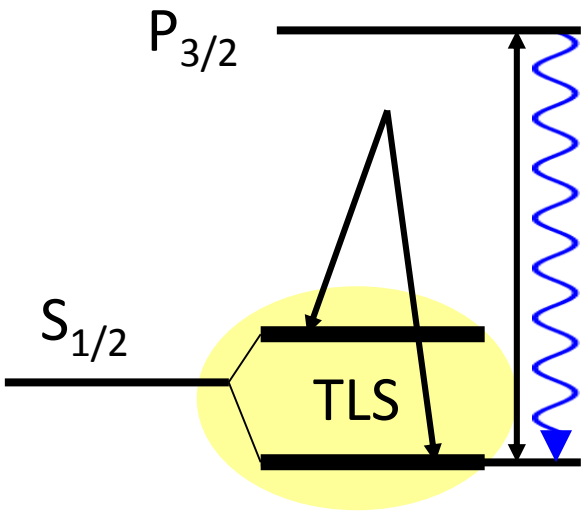
Ion trappers favorites



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)

Ion trapping at this workshop:

Laser:

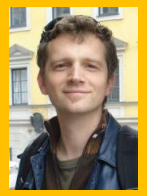

NL, Fri


FSK, Thu


PM, Thu

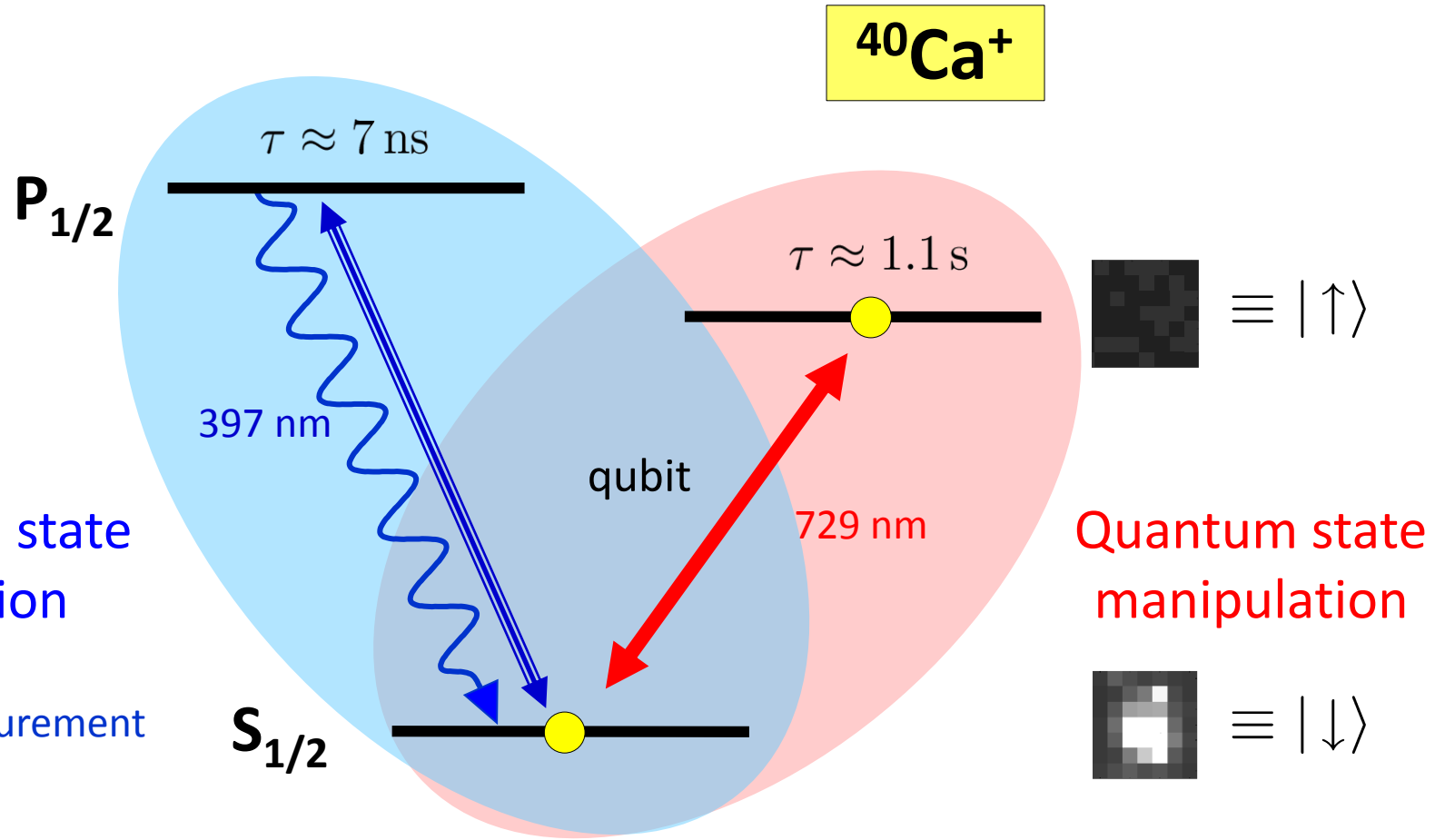
μ-wave:


WH, Wed

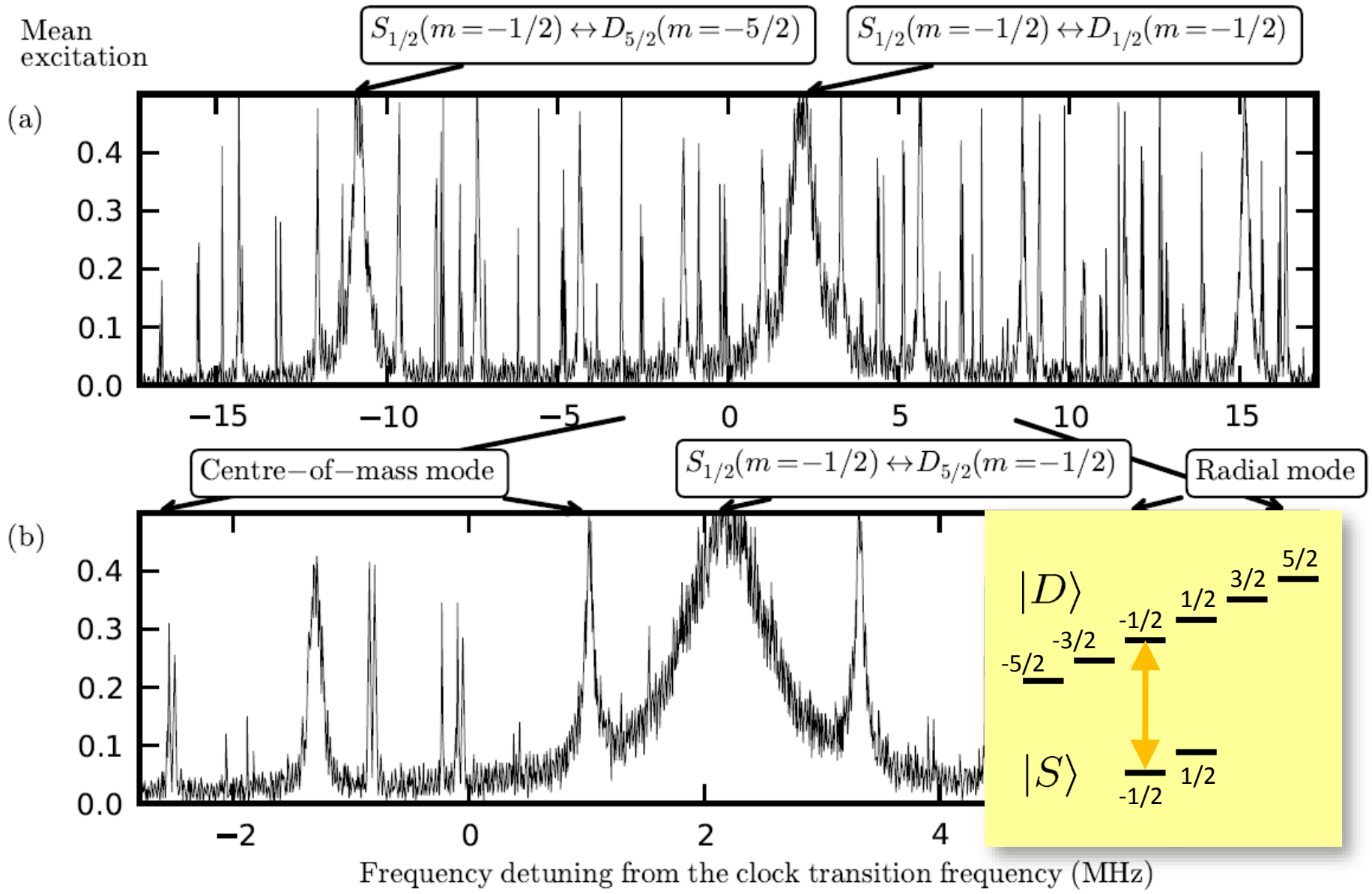

MJ, Wed


CO, Thu

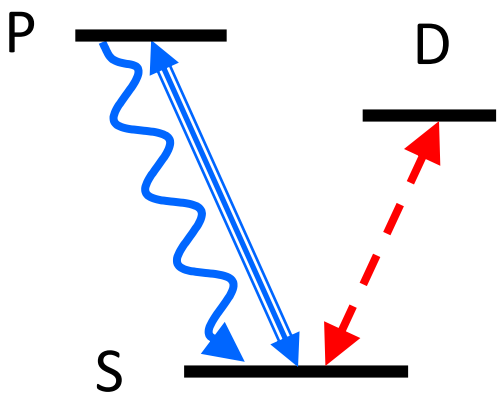
Our ion of choice



It’s a two-level system?

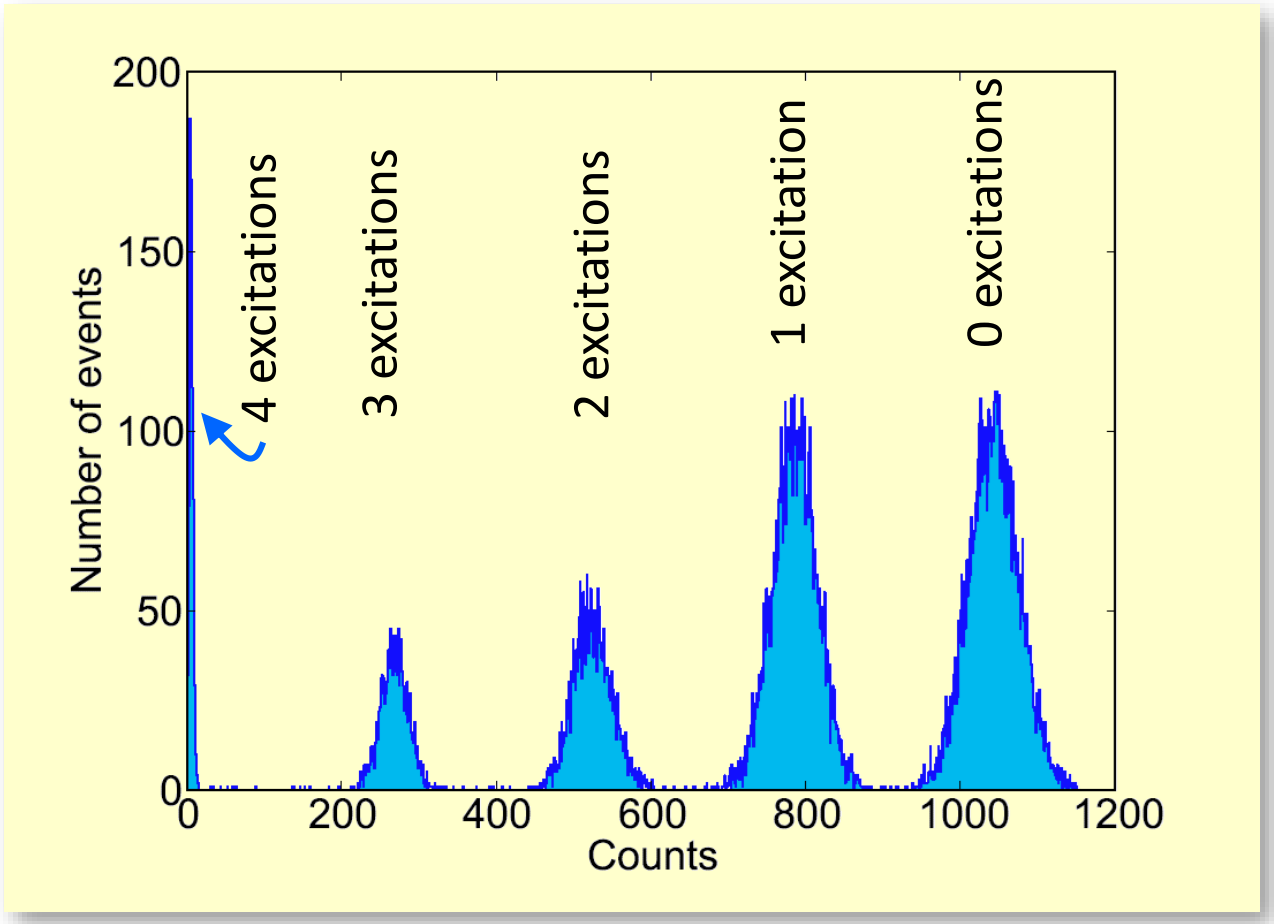


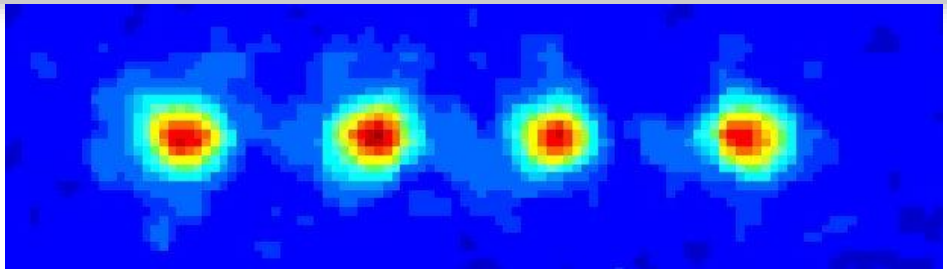
Qubit measurement

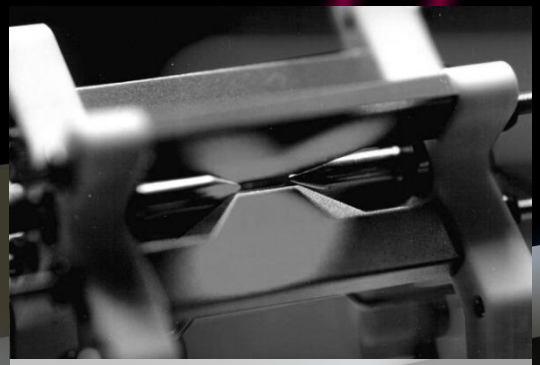


Detection:
Quantum Jumps

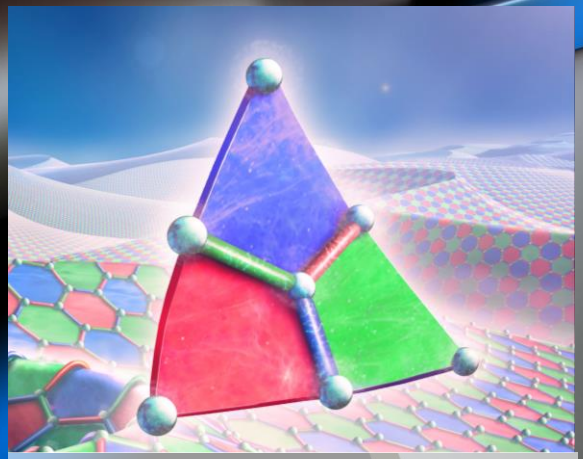
- Projection of ions to either S or D states,



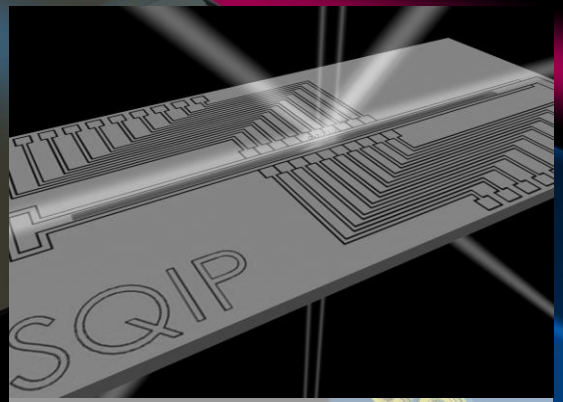




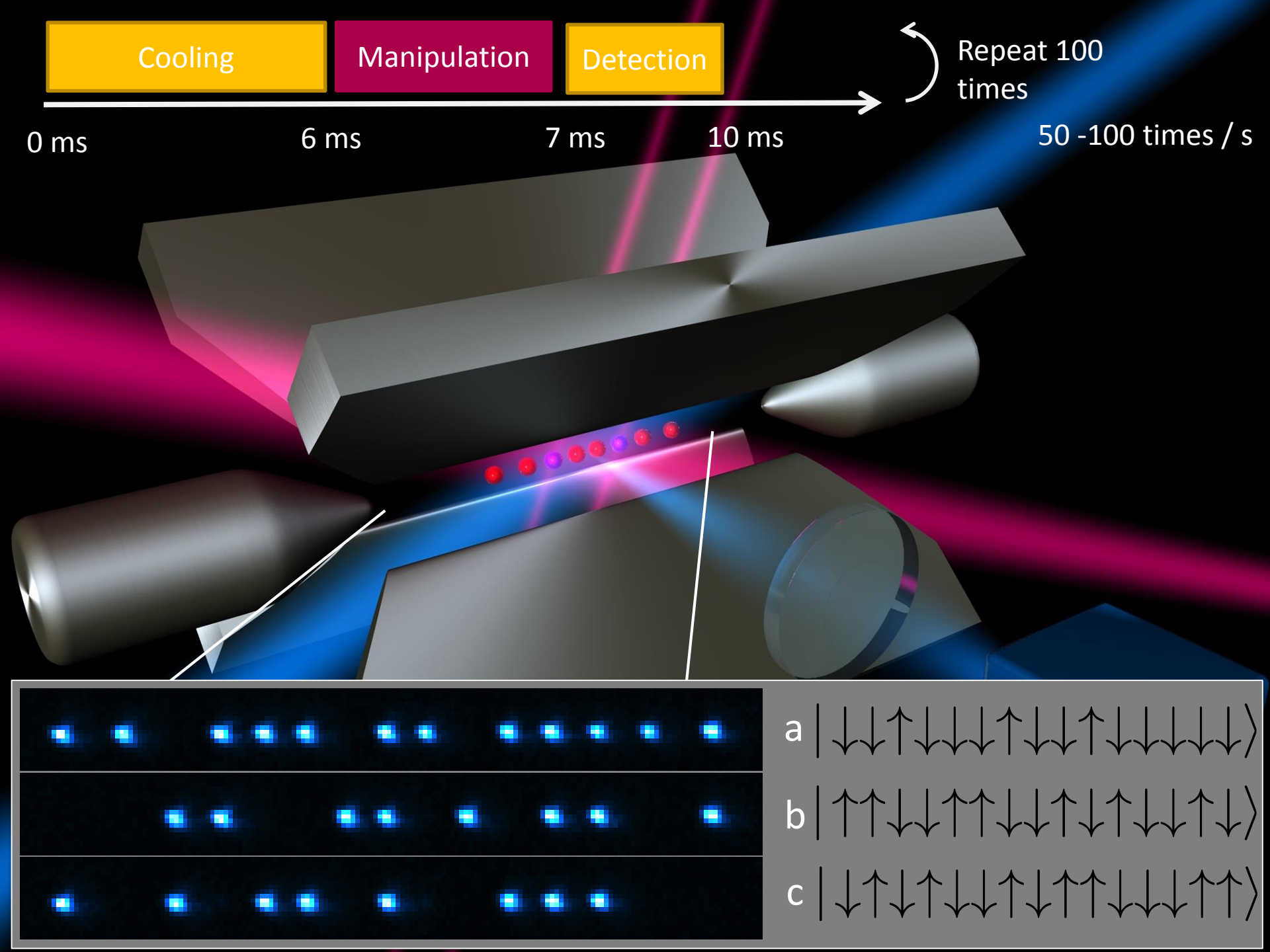
Ion trapping basics



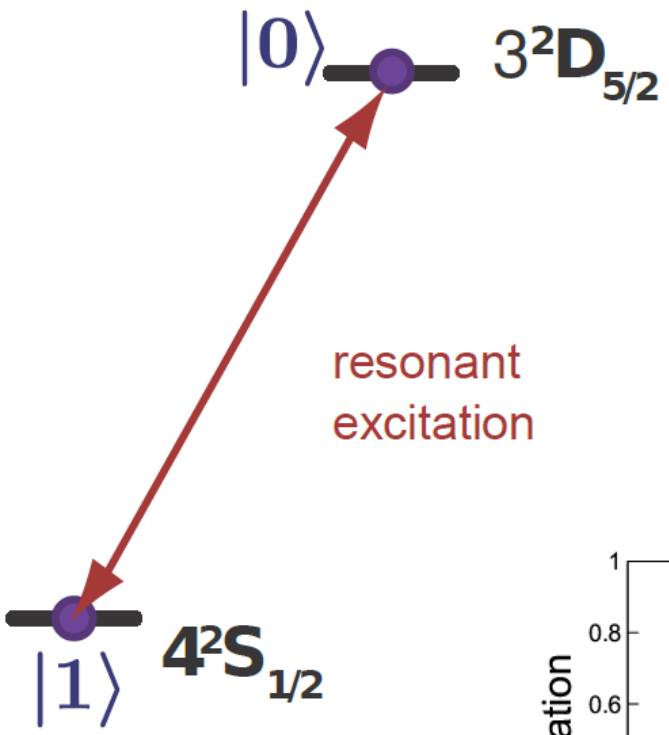
Gates and Algorithms

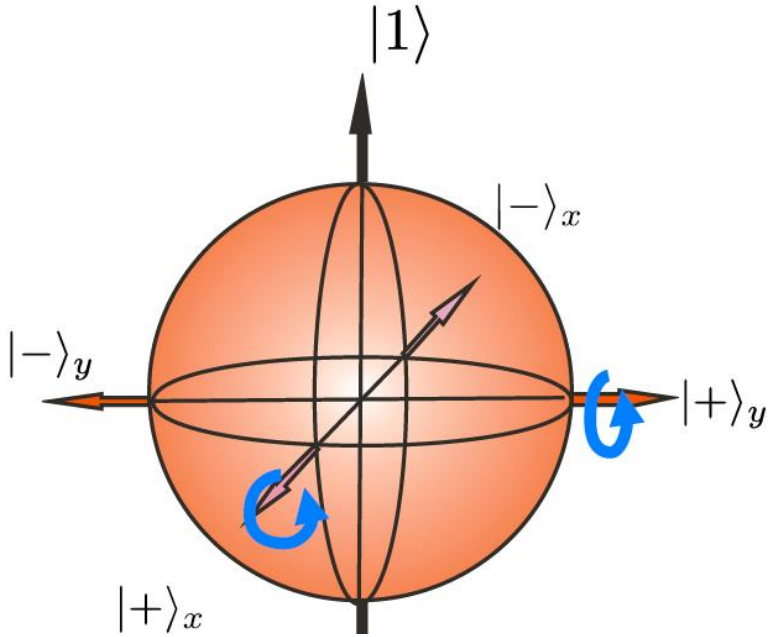


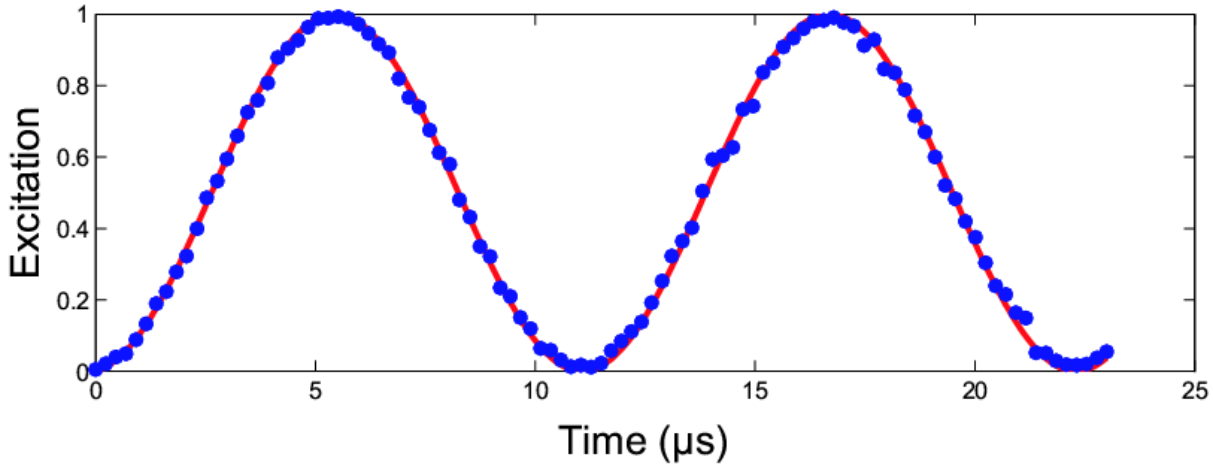
Scalable devices &
Engineering challenges


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

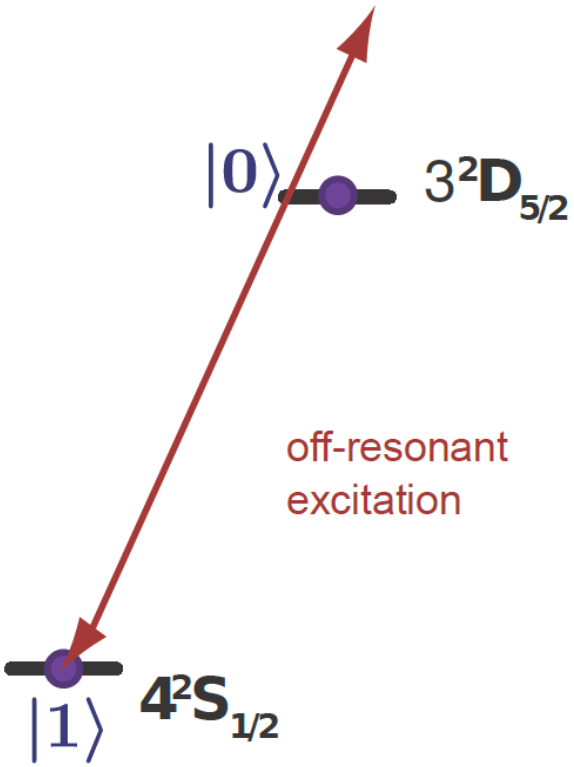
Single-qubit operations

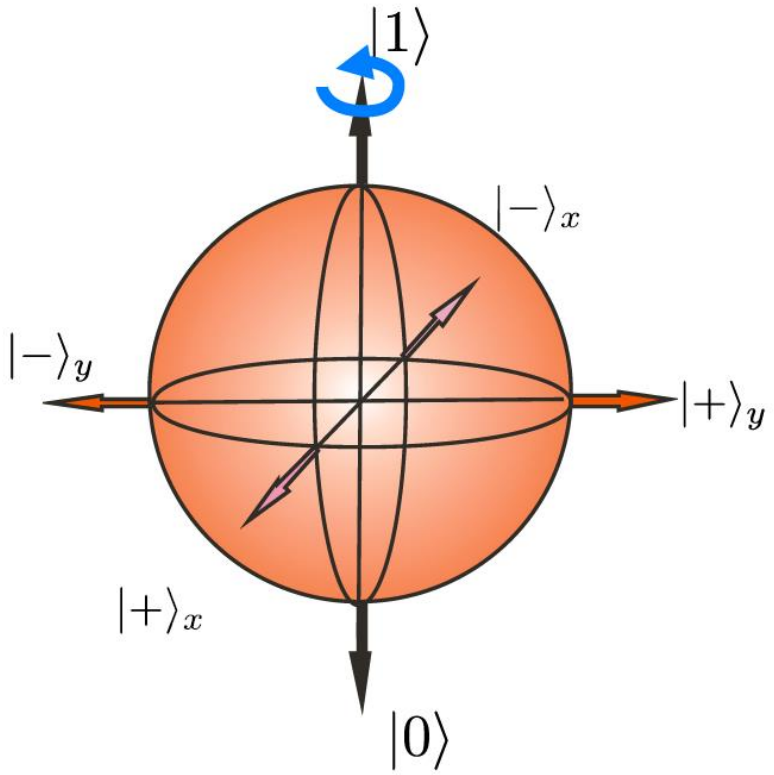




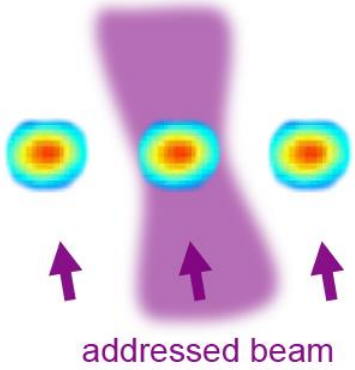


Single qubit operations





Off resonant light field induces AC-Stark shift



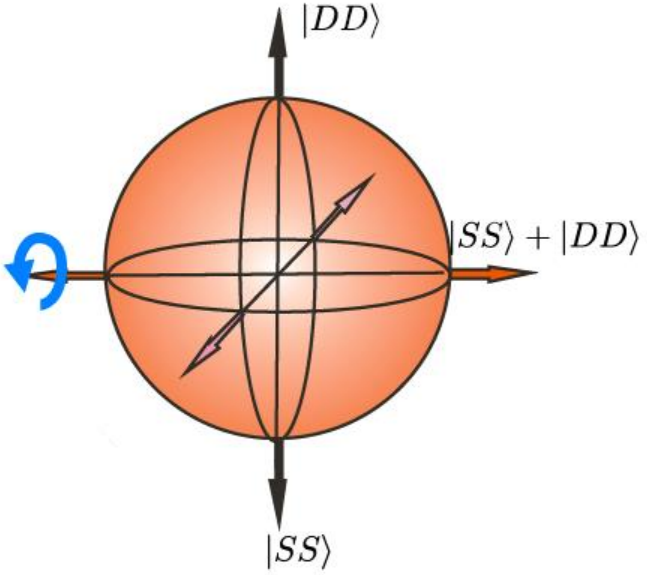
Mølmer-Sørensen entangling operation

Based on state-dependent light forces.

Works for any number of qubits

Effective infinite range 2-body interaction.

Independent of motional state



WH, Wed

MJ, Wed

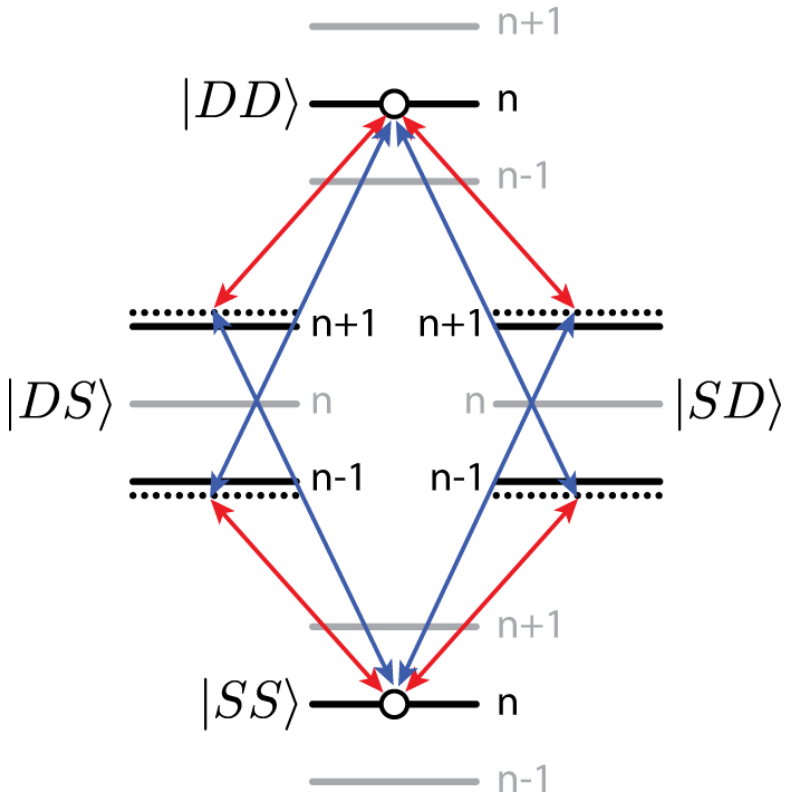
PM, Thu

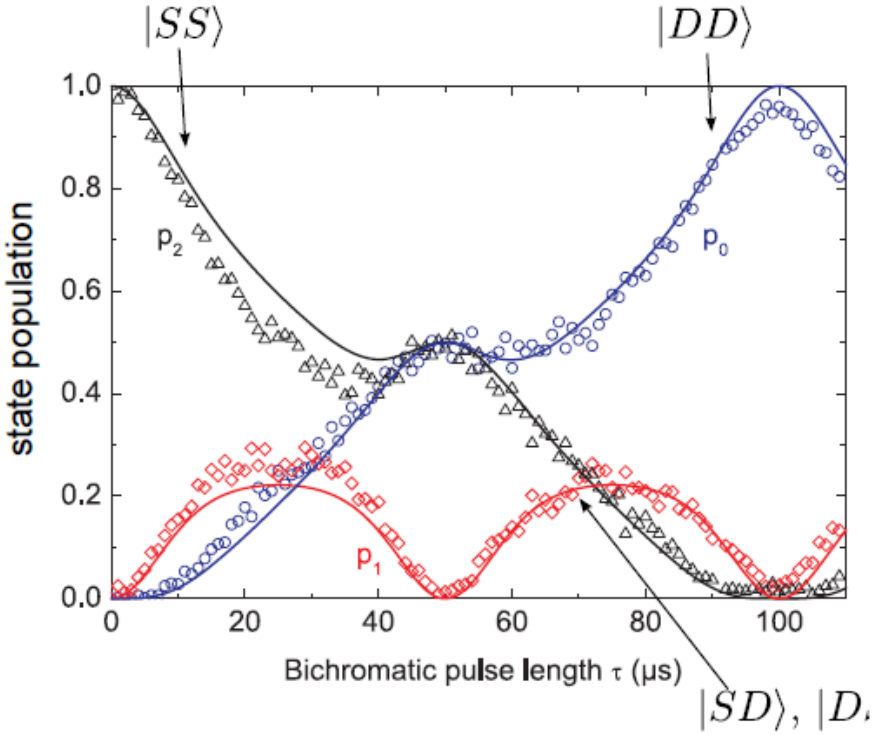
NL, Fri

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

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

Mølmer-Sørensen entangling operation



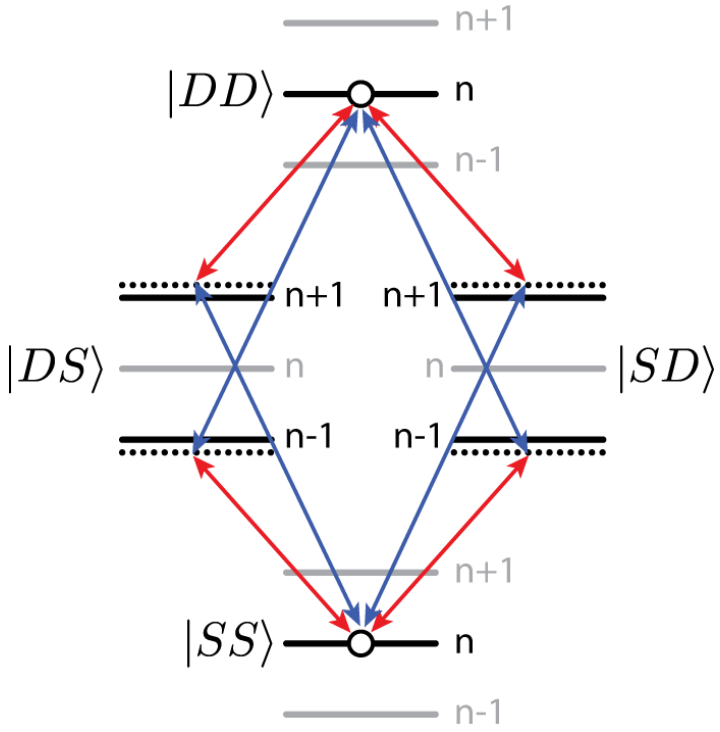


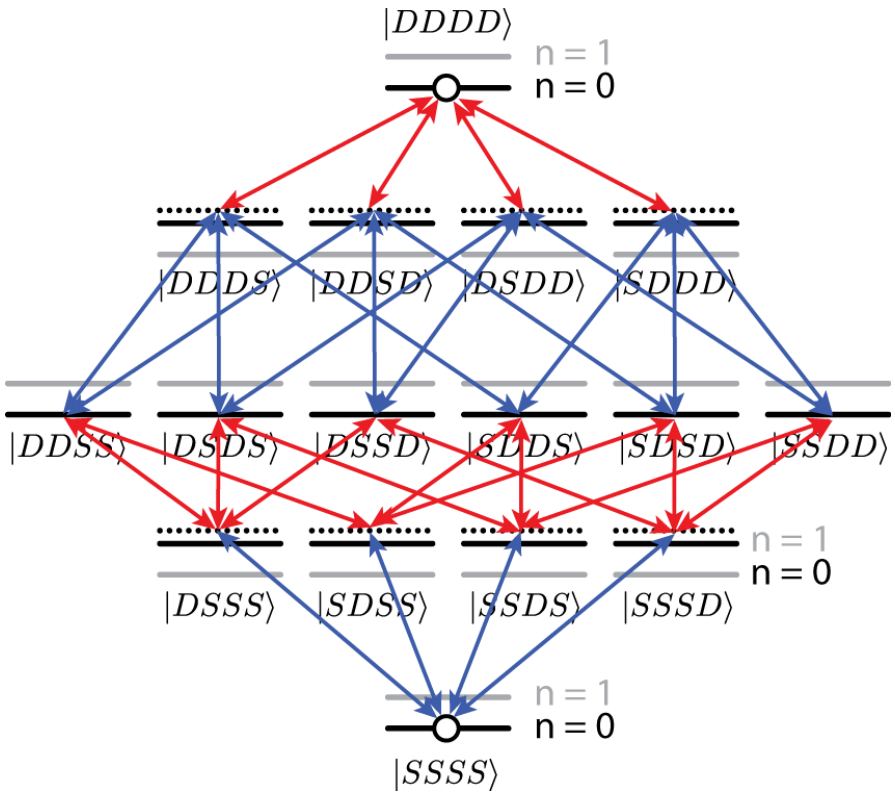
- Off-resonant coupling to the sidebands
- Unwanted populations interfere destructively

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

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

Multi path interferometer

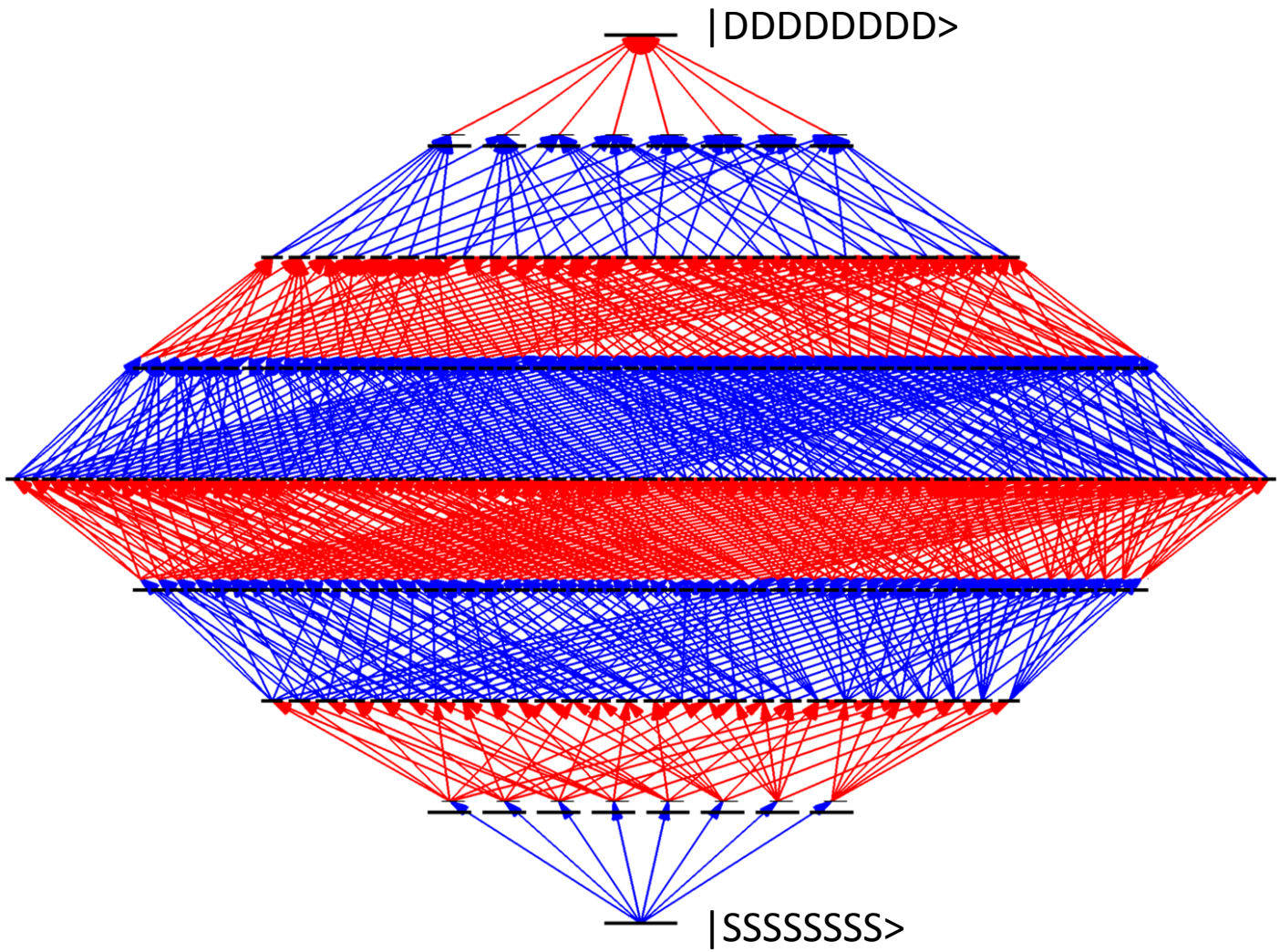




2 qubits

4 qubits

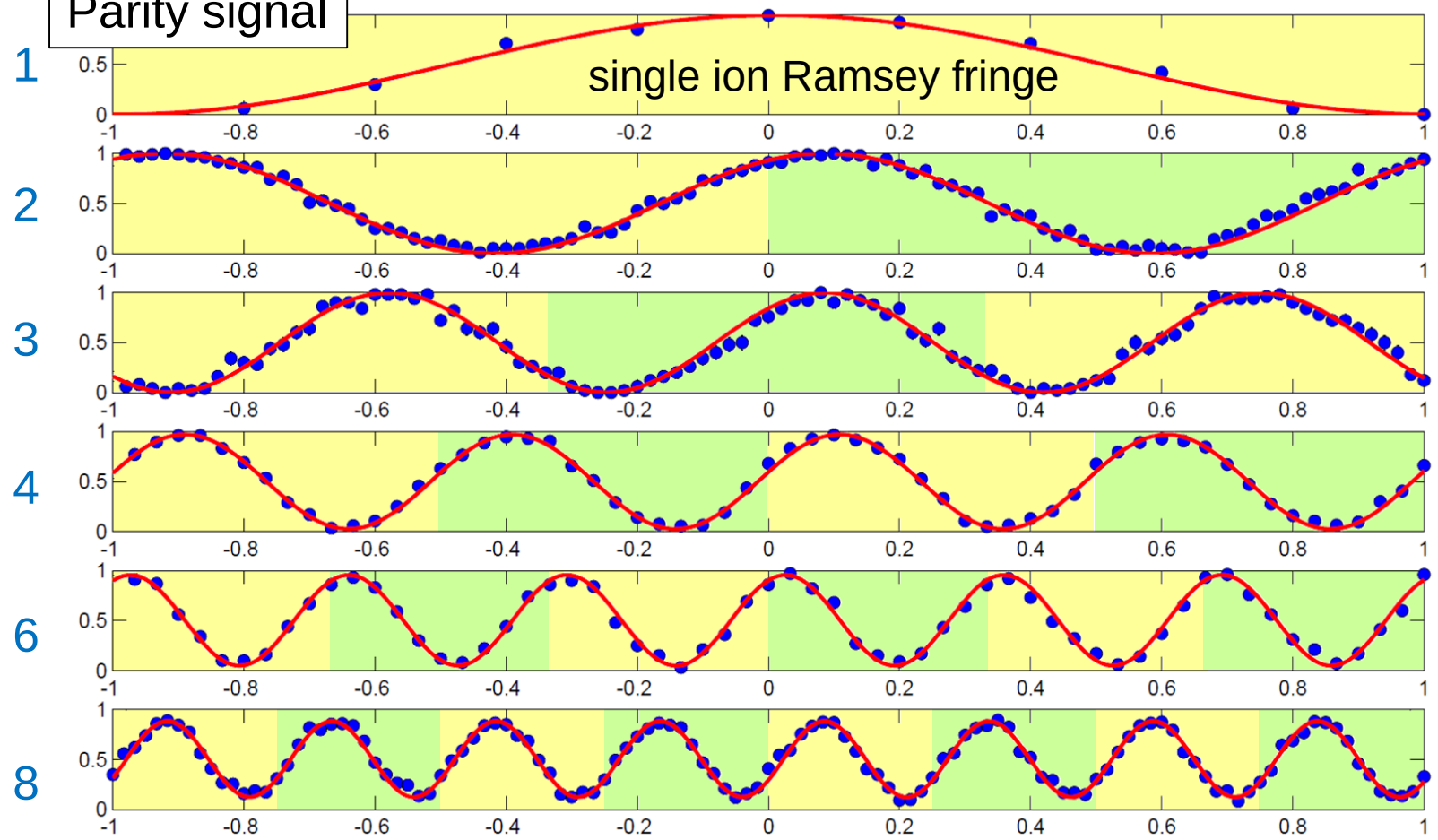
Multi path interferometer – 8 ions



GHZ state fidelity

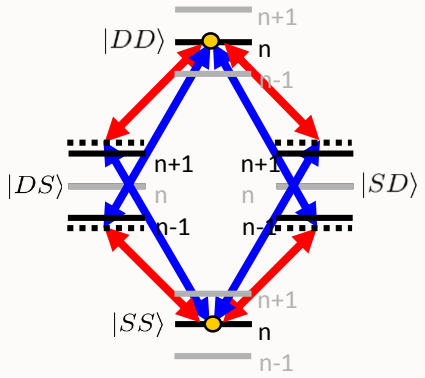
$N =$ $\Psi = \frac{1}{\sqrt{2}}(|SS\ldots S\rangle + |DD\ldots D\rangle)$

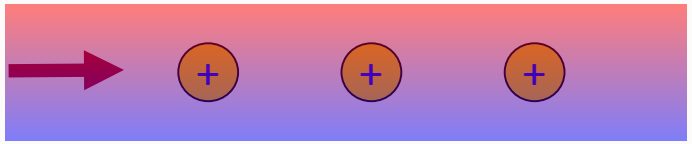
Fidelity (%)



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

Set of operations





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

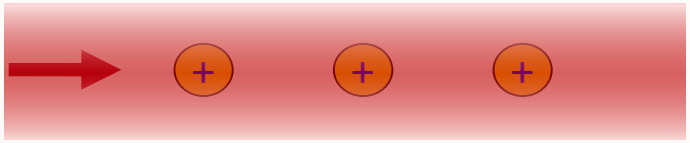
Bichromatic excitation: entangling operations

$^{40}Ca^+$

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

resonant manipulation

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



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

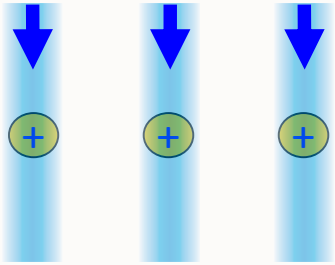
Resonant excitation: collective local operations

$^{40}Ca^+$

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

off-resonant manipulation

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



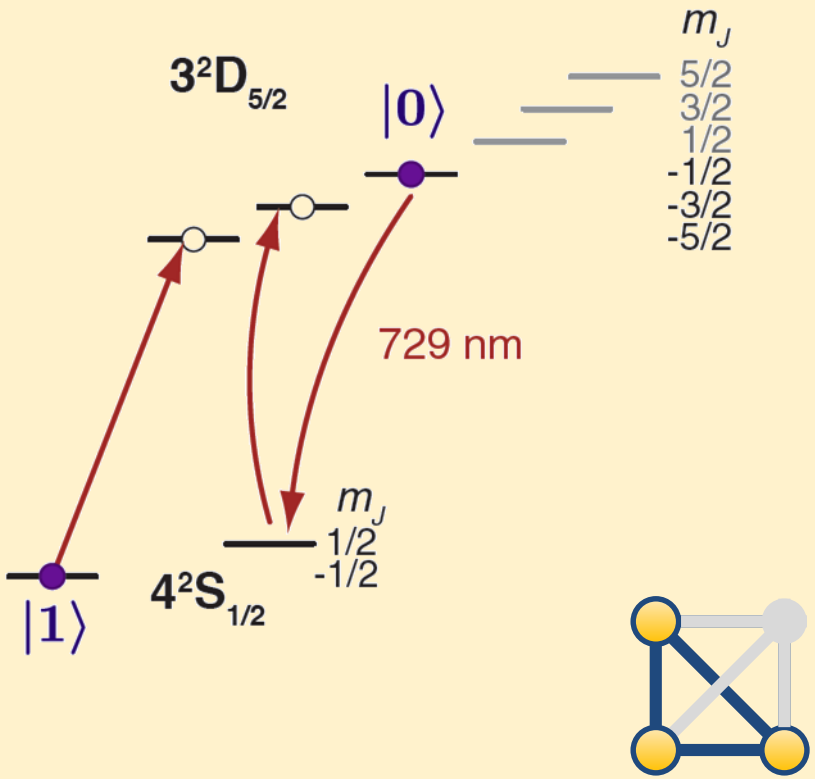
off-resonant excitation: individual local operations (AC Stark shifts)

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

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

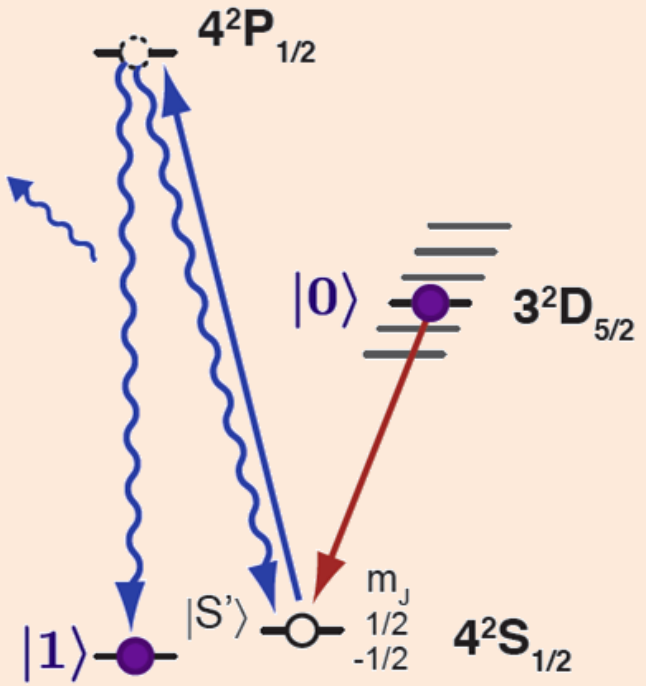
Additional operations

Spectroscopic decoupling



Alters connectivity

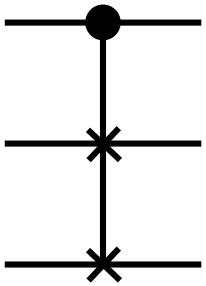
Resetting



initializes the qubit

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

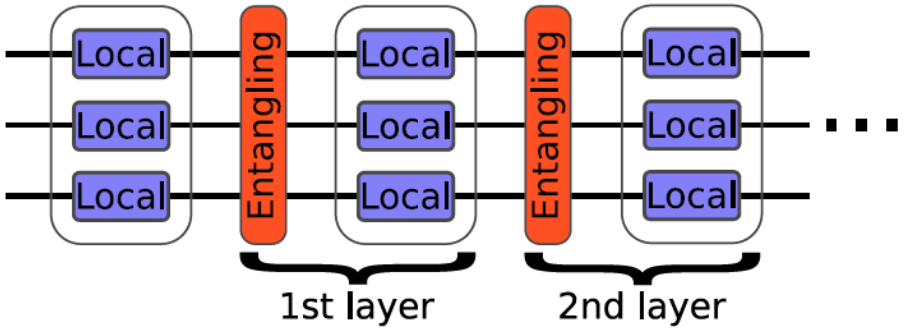
Quantum compiling: Fredkin gate



=

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	$S_z(3/2, 2)$

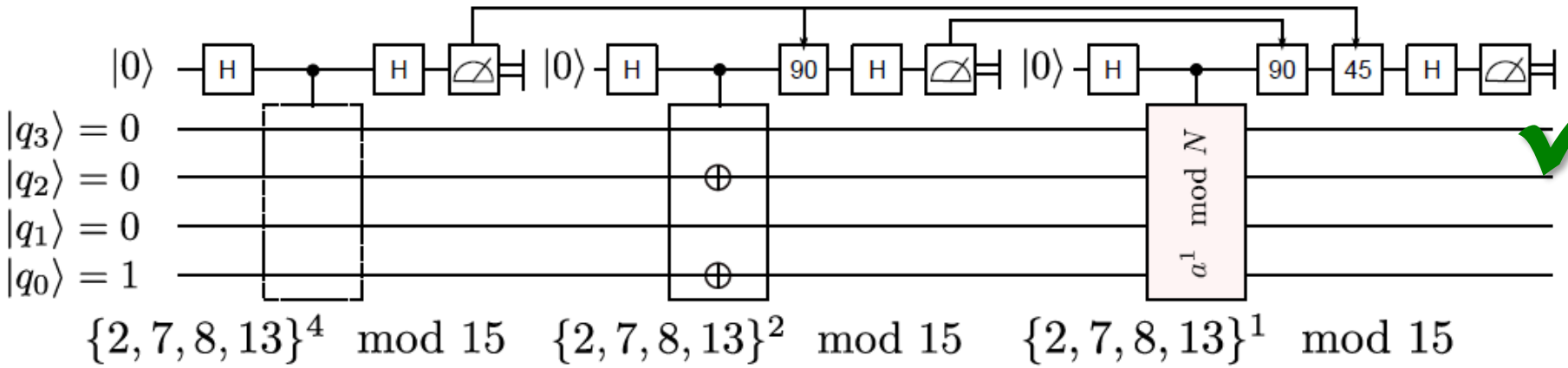
Find optimal pulse sequence with a quantum “compiler”

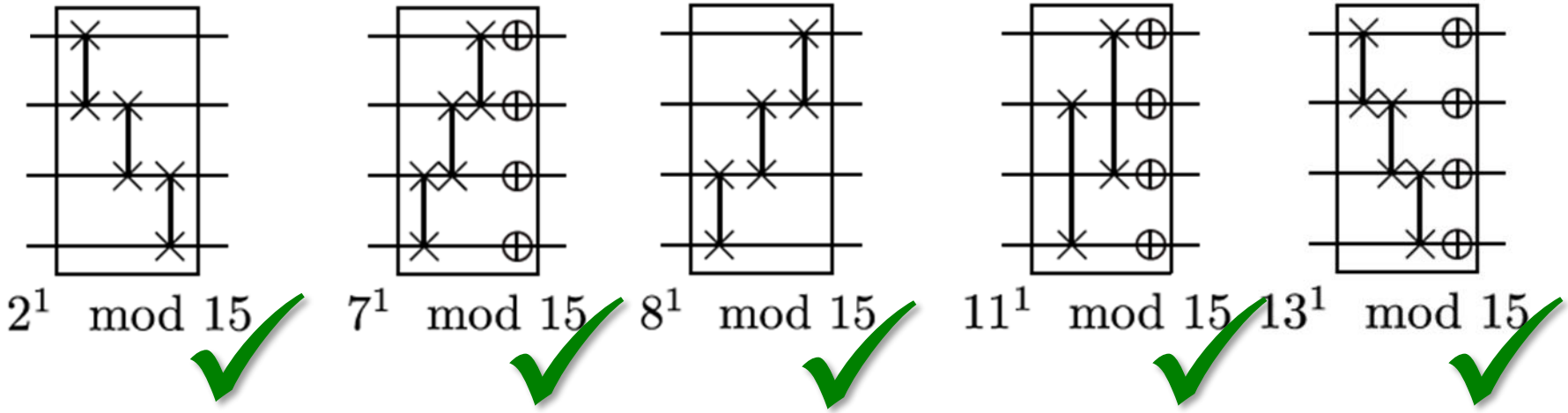


Find sequence with the fewest layers

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

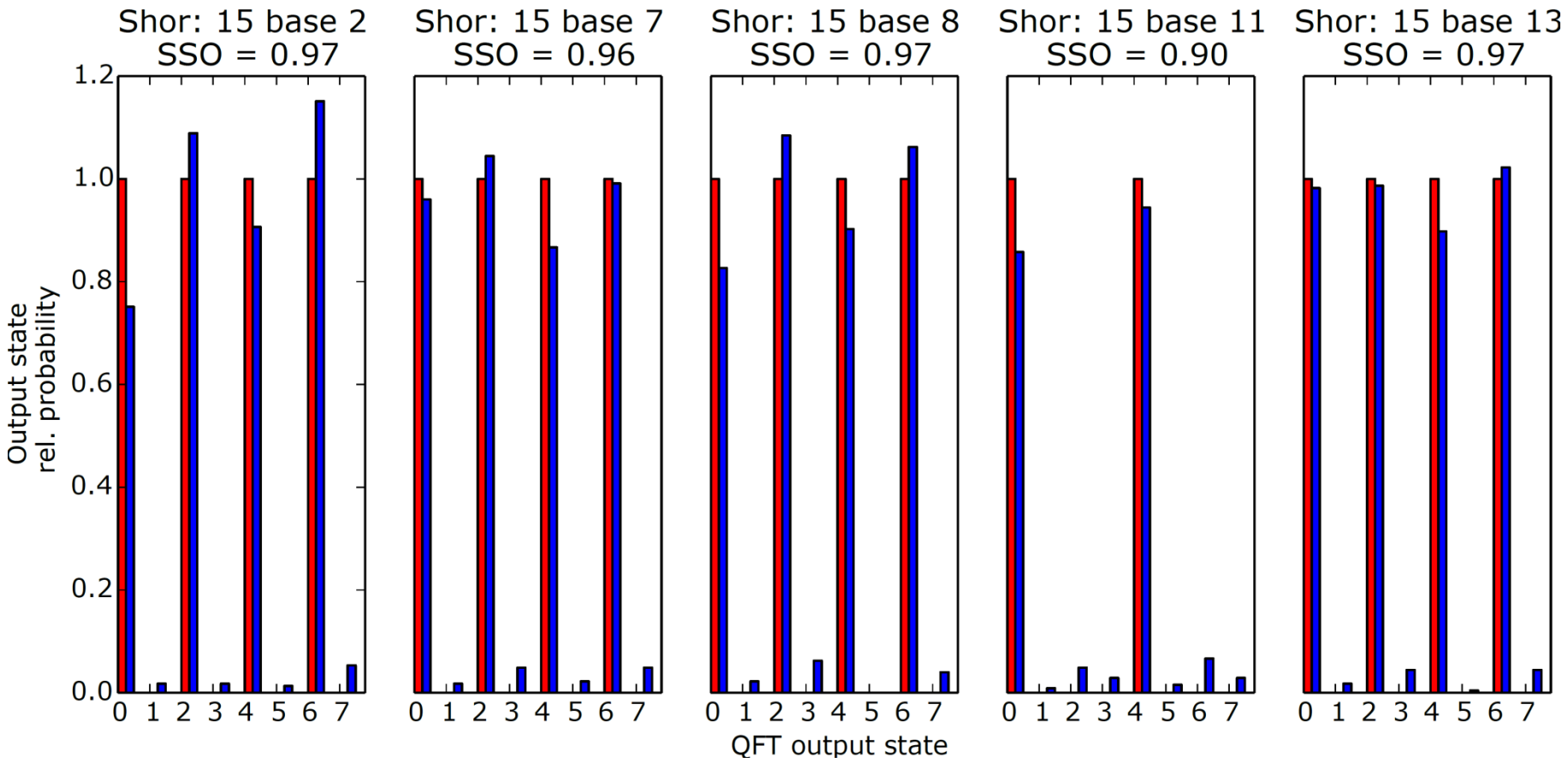
Shor's algorithm – 15 = 3*5





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

Cycle benchmarking, using only local randomizing gates.

A. Erhard, J. Wallman, arXiv:1902.08543

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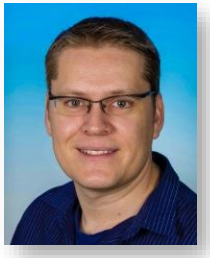
Swansea University
Prifysgol Abertawe



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IQC Institute for Quantum Computing

Cycle Benchmarking

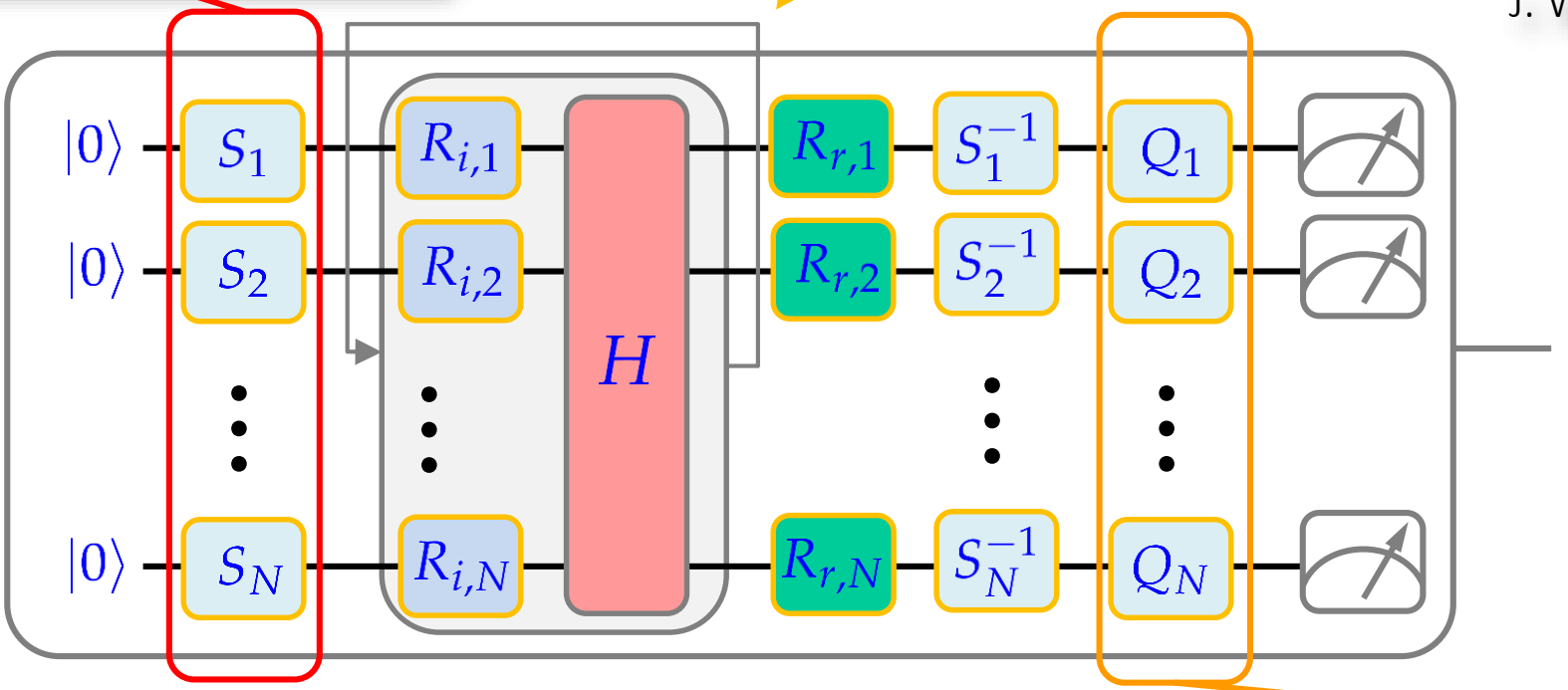
J. Wallman

Experimental protocol:

Random state generation

m times

Operation to be estimated



- Study several independent measurement bases
- Estimated performance of a **cycle**

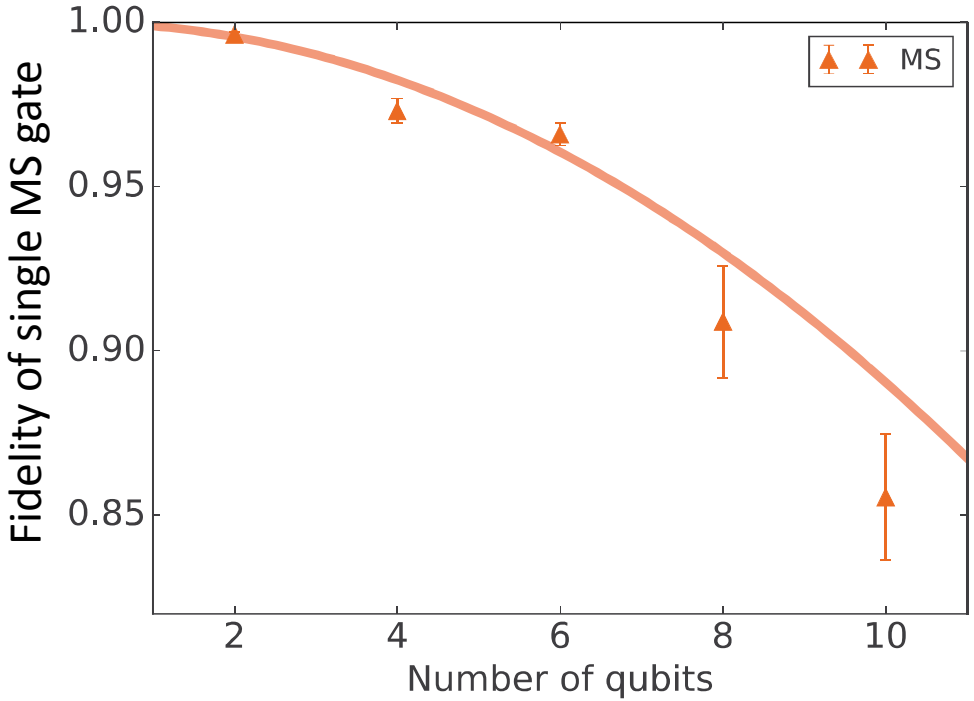
Random measurement.

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

Benchmarking a 10 qubit register

J. Wallman

Perform rigorous cycles benchmarking
with local randomizing operations



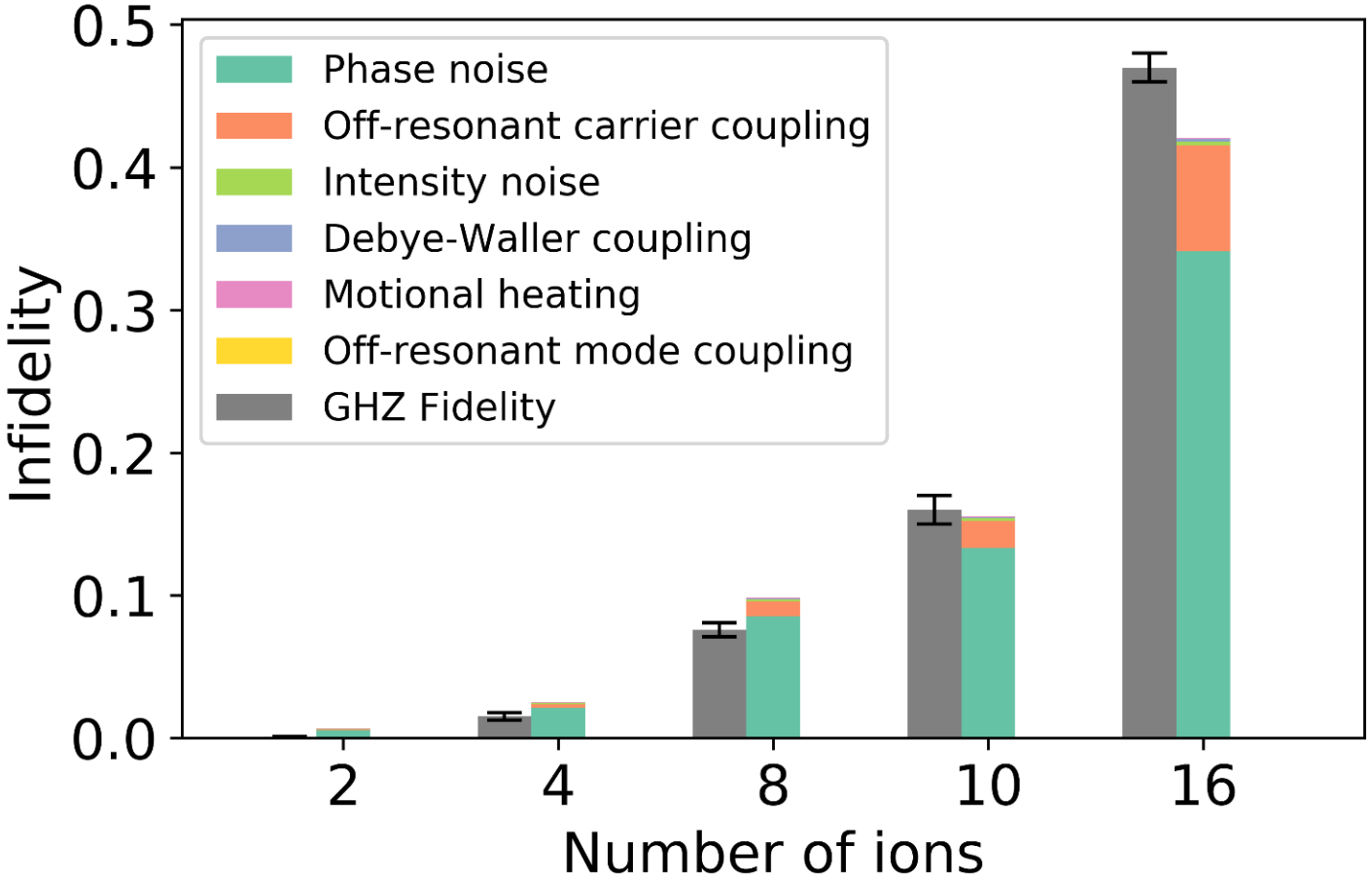
Qubits	MS estimate
2	99.64(6)
4	97.3(4)
6	96.6(3)
8	90.9(1.7)
10	85.6(1.9)

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

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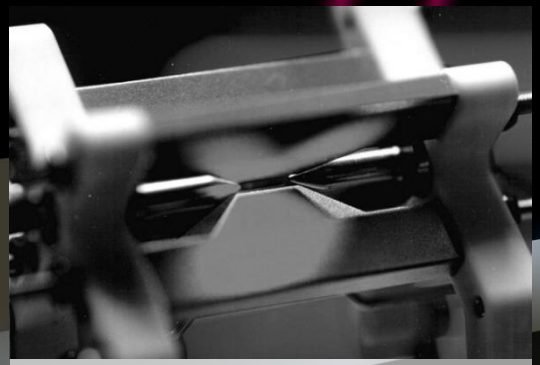
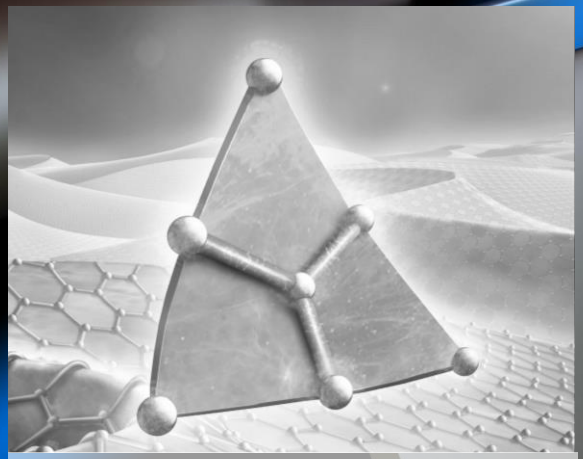
Swansea University
Prifysgol Abertawe

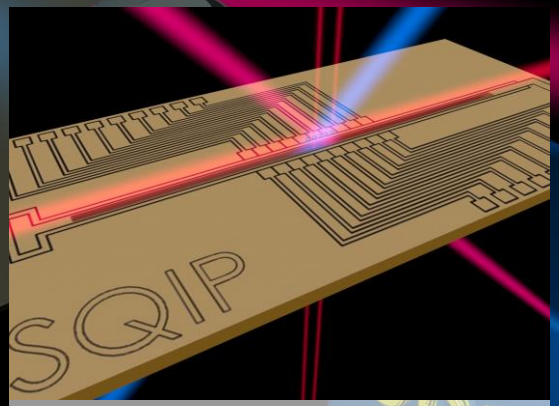
eQual



Ion trapping basics

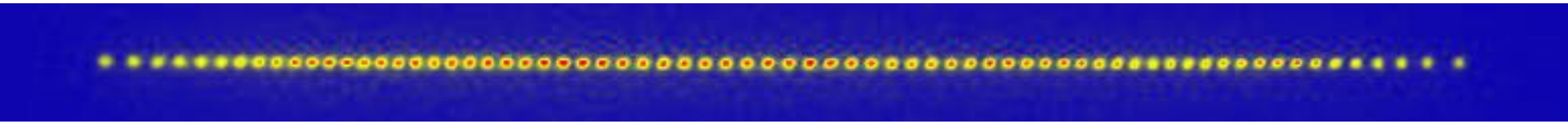


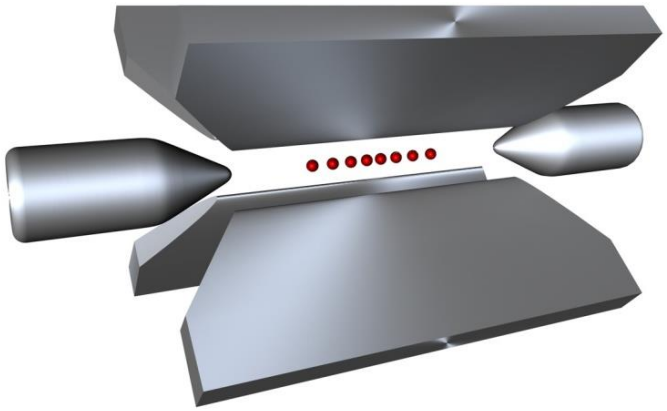
Gates and Algorithms



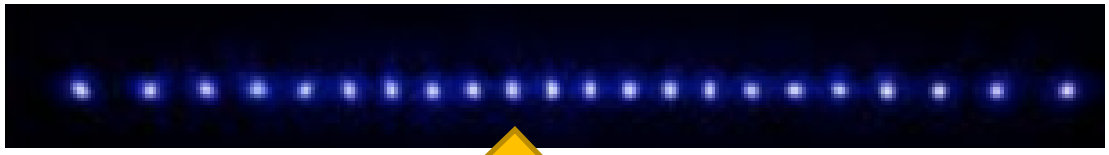
Scalable devices &
Engineering challenges

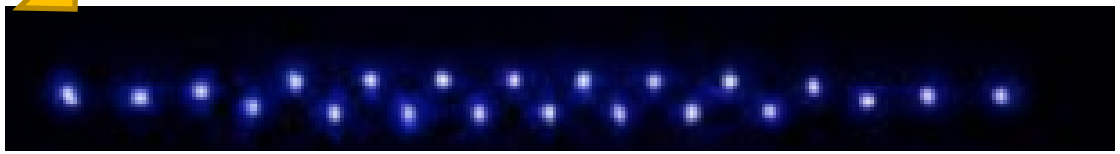
Are ion traps scalable?

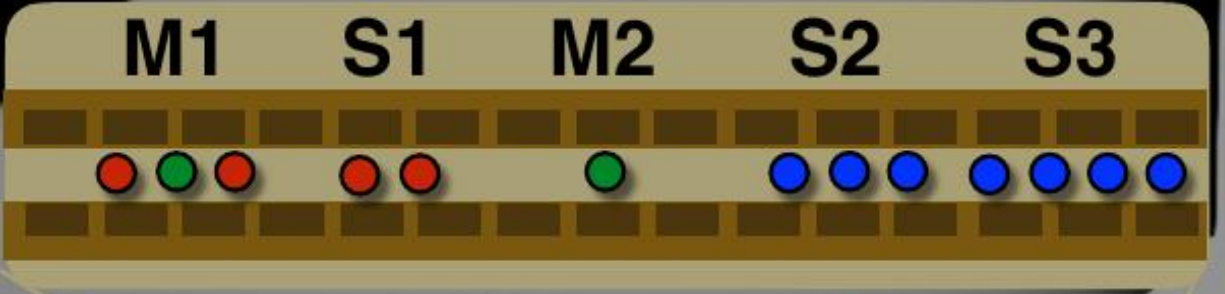




Ion strings for QIP cannot be created for >100 ions.







data ions
ancilla ions
cooling ions

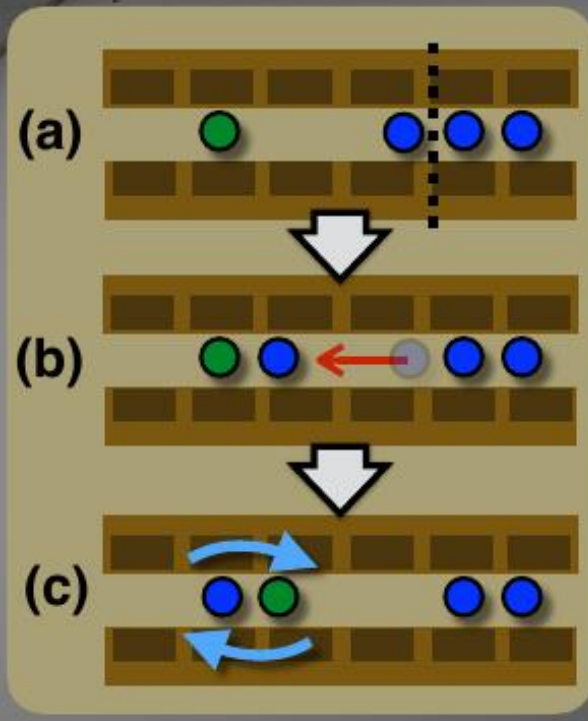
WH, Wed

Idea: split trap into multiple smaller trapping regions.

Requires trap geometry with 100µm features

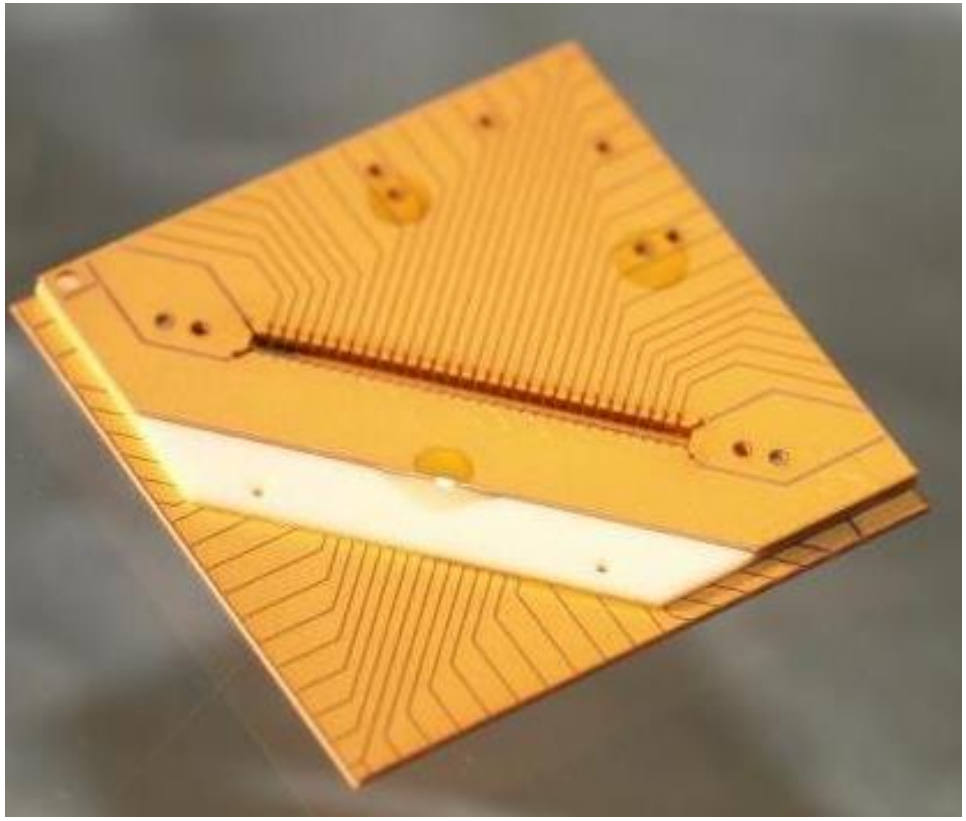
-

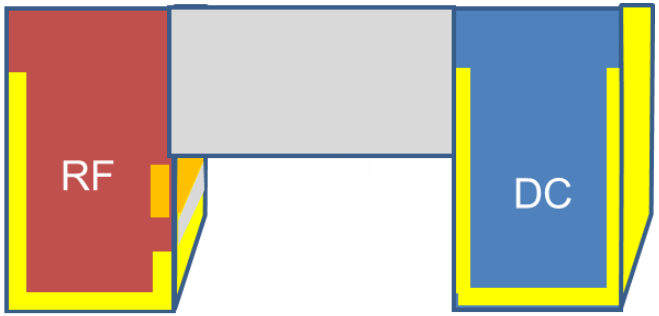
Reduced motional coherence (heating rates)

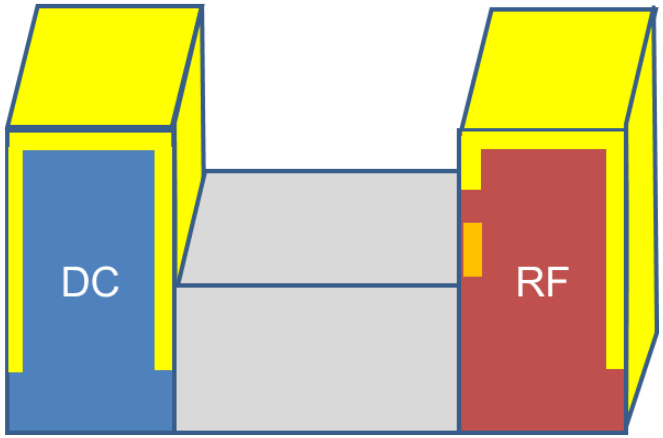


S3400 10.0kV 30.1mm x19 SE 3/30/2015 3.00mm

3D micro-traps



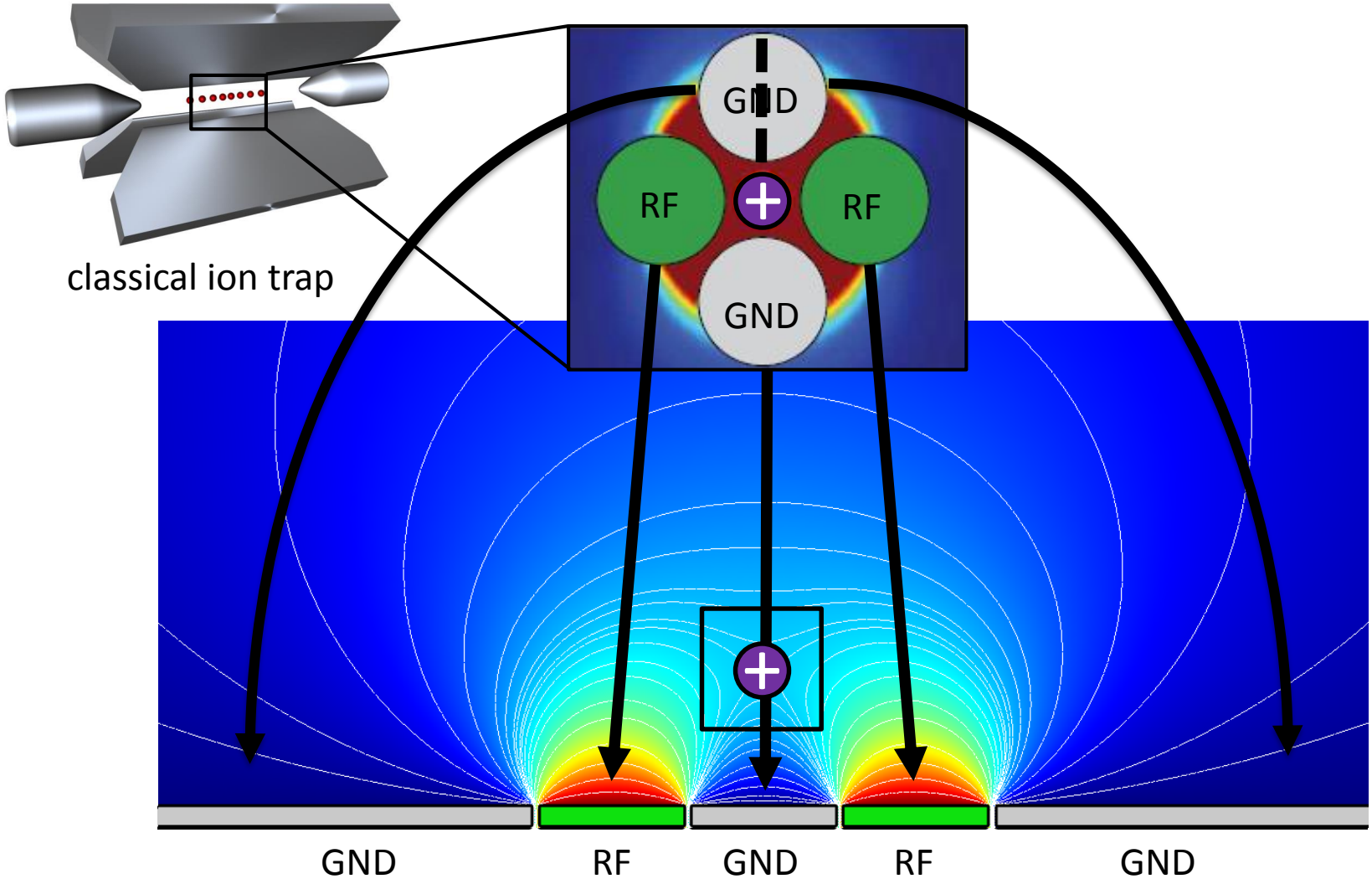




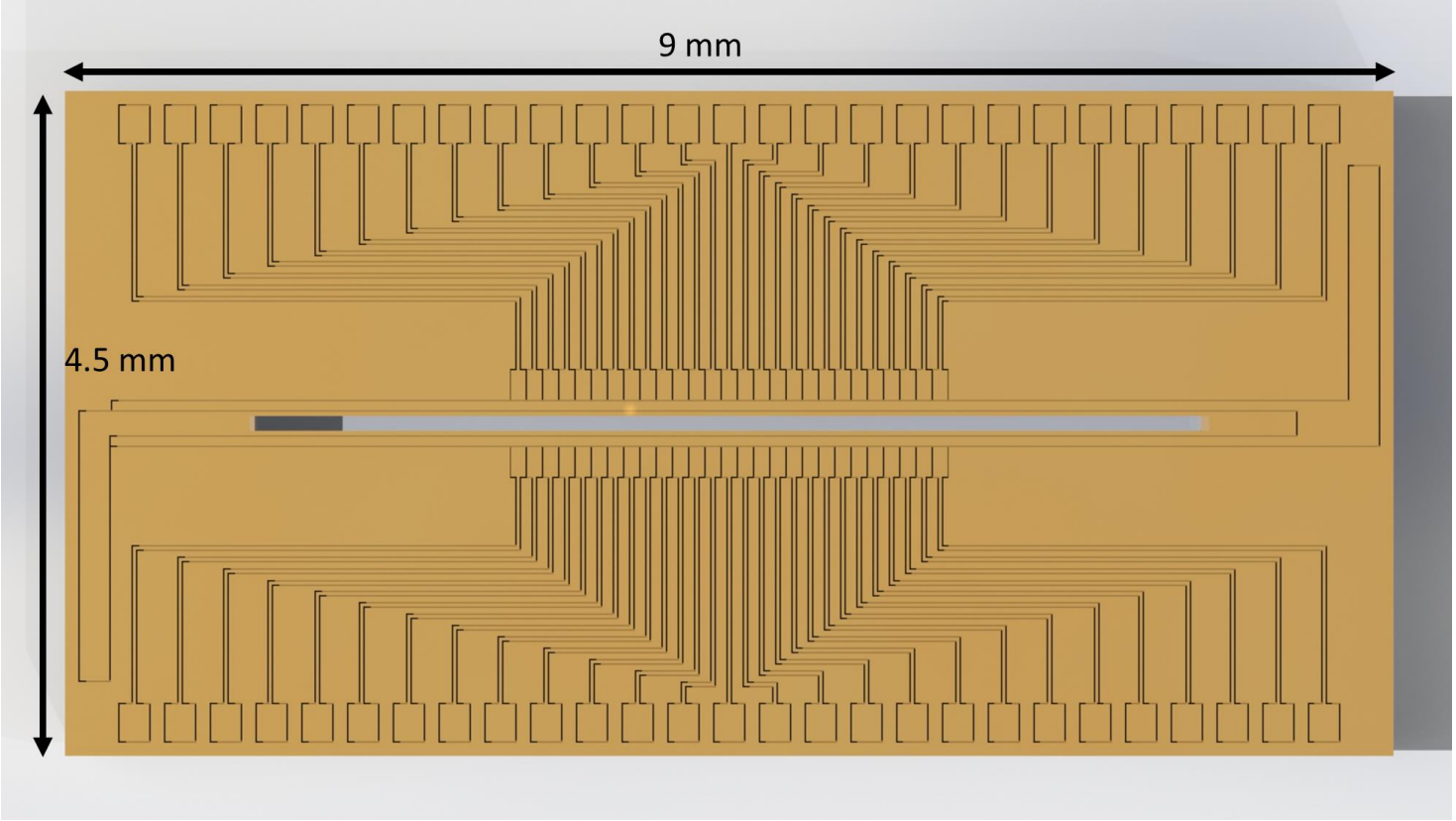
Sandwiched design
Challenges:
- Waver alignment
- Fabrication

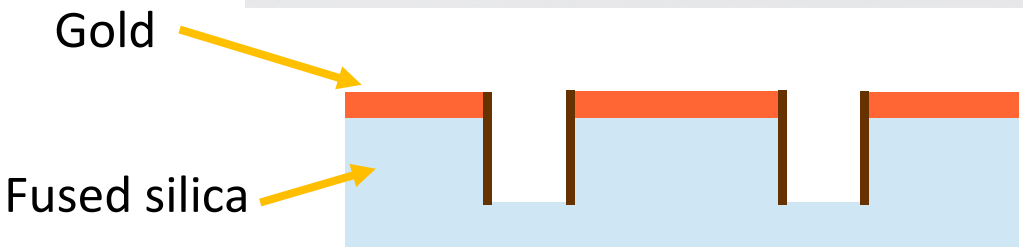
FSK, Thu

Planar ion traps



Single-layer fused-silica traps

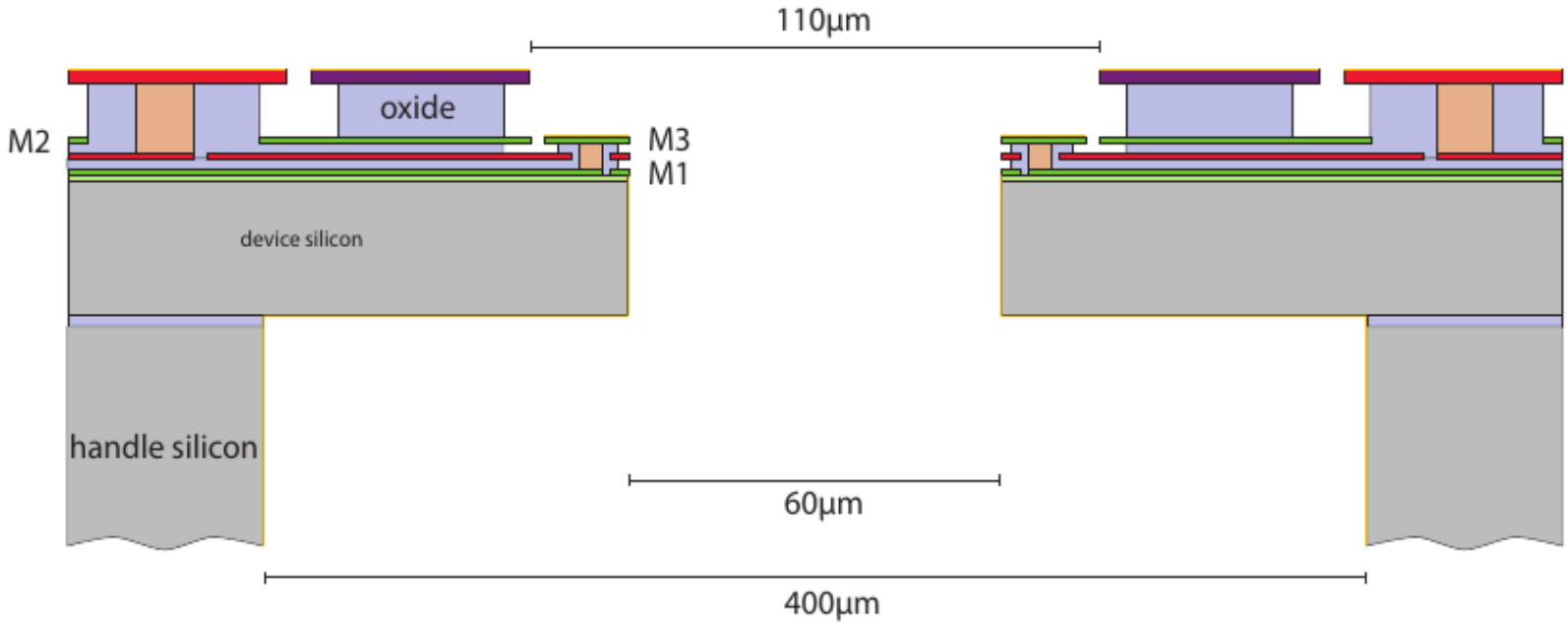




- Simple and clean procedure
- Only single layer routing possible

Commercially available: Translume (USA), Femtoprint (CH)

Multi-layer silicon traps – HOA 2

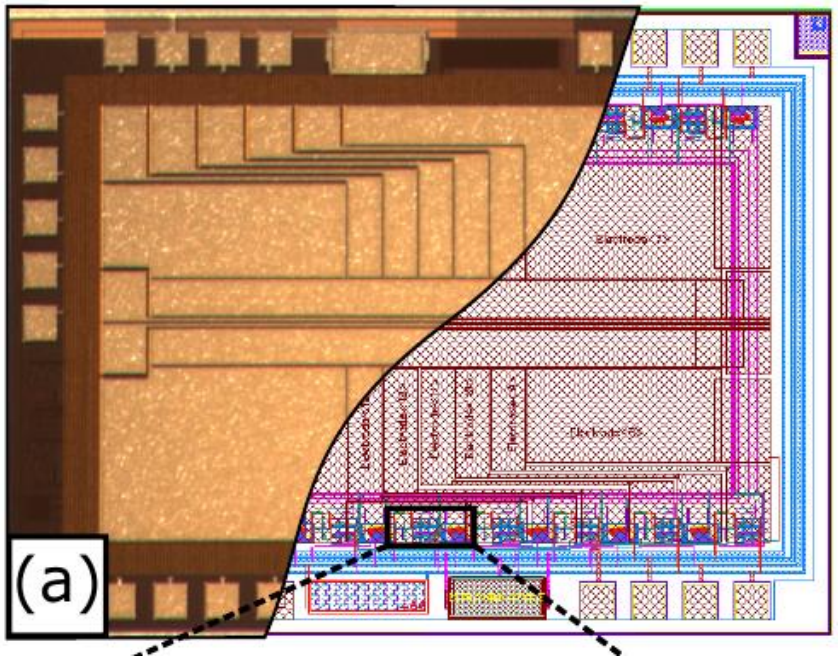


PM, Thu

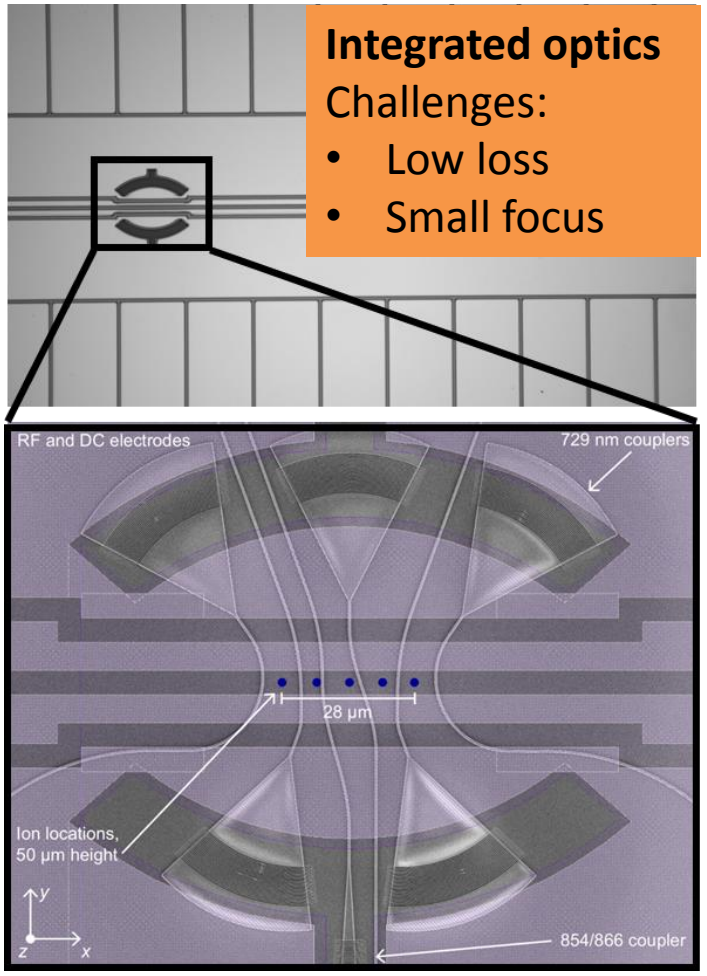
CO, Thu

Sandia National Laboratories

Integrated components



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

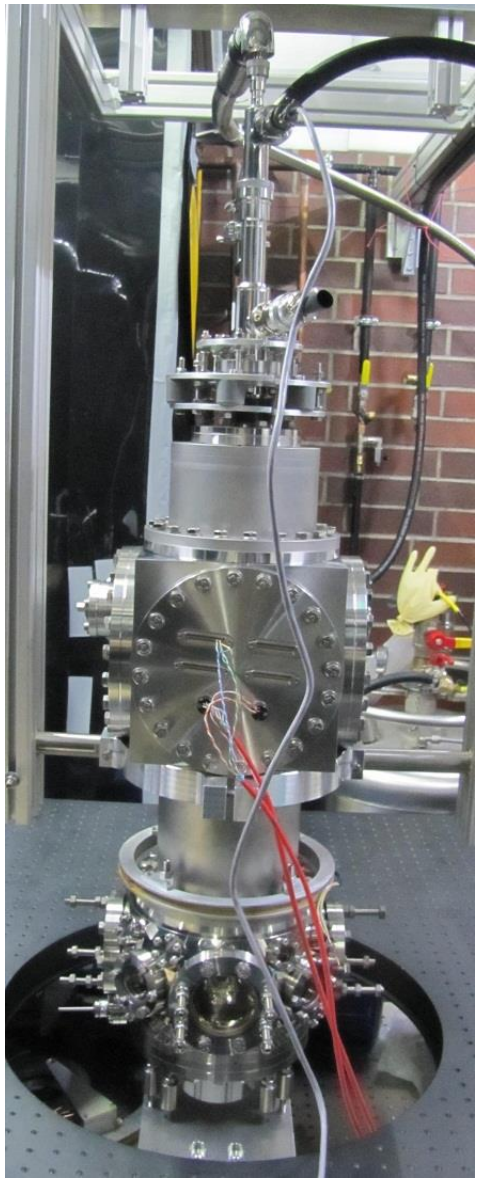


Integrated optics
Challenges:
- Low loss
- Small focus

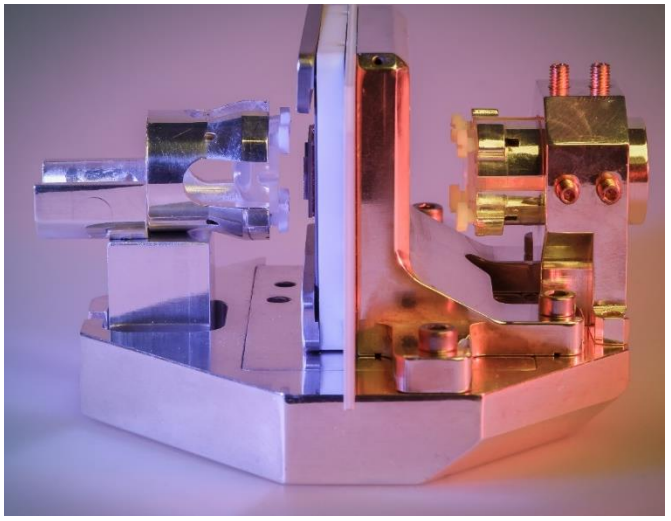
J. Stuart et al, PR Applied 11, 024010 (2019)
Also: ETH, UIBK, Infineon

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

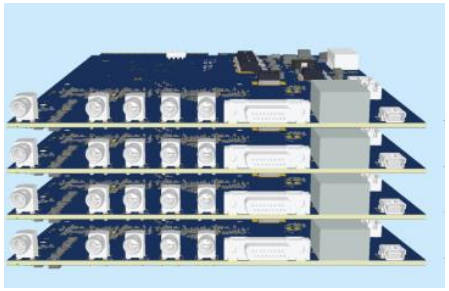
Local oscillator (Laser)

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

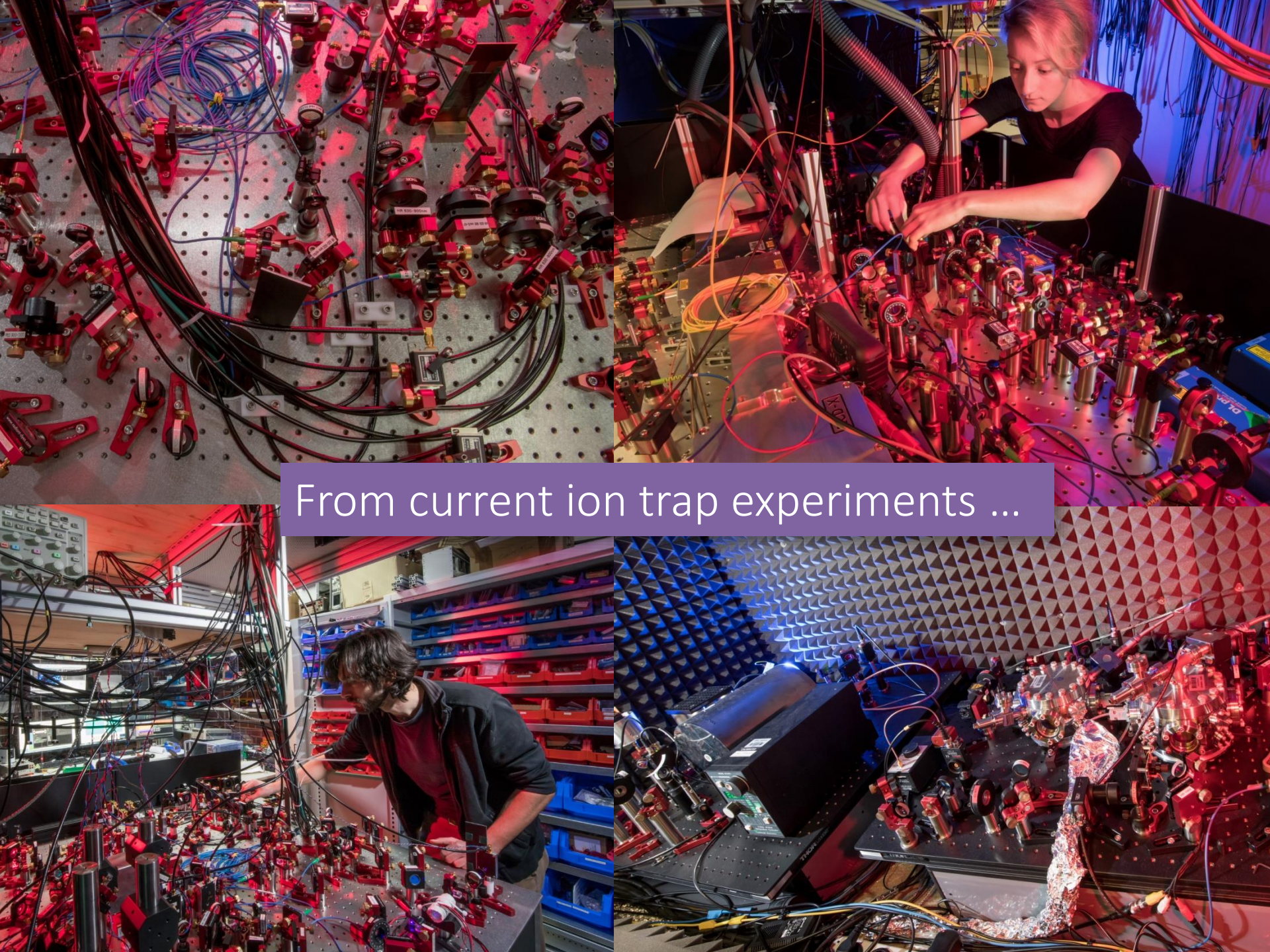
universität innsbruck

TOPTICA PHOTONICS

JG|U

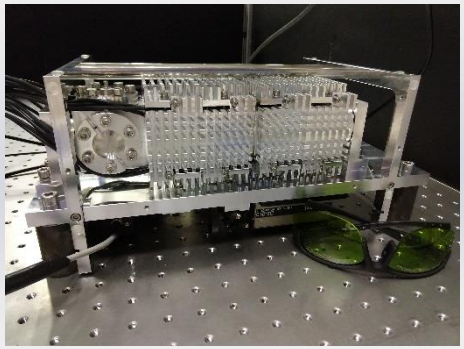
JOHANNES GUTENBERG UNIVERSITÄT MAINZ

AKKA



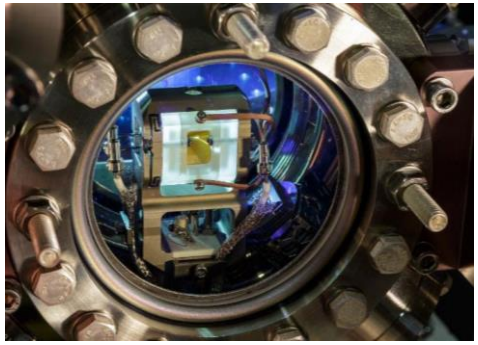
From current ion trap experiments …

… to a compact and robust ion trap QC

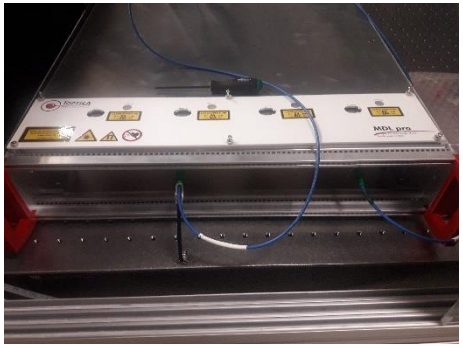


Compact optical reference

Advanced ion traps

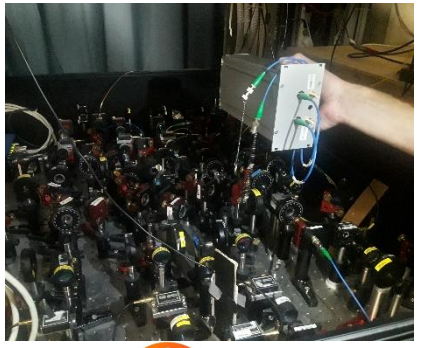


Compact lasers



Control electronics

Optics



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AQT

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AG Quantenoptik und Spektroskopie

The international Team 2018

universität innsbruck

Slides: https://github.com/pschindler/bad_honnef

philipp.schindler@uibk.ac.at

€ erc

IQI GmbH

eQual

FWF

SFB FoQuS

FWF SFB

A TION

IQI

$

IARPA

AG Quantenoptik und Spektroskopie

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Slides: https://github.com/pschindler/bad_honnef

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