Quantum optics and information with trapped ions

- Introduction to ion trapping and cooling
- Trapped ions as qubits for quantum computing and simulation
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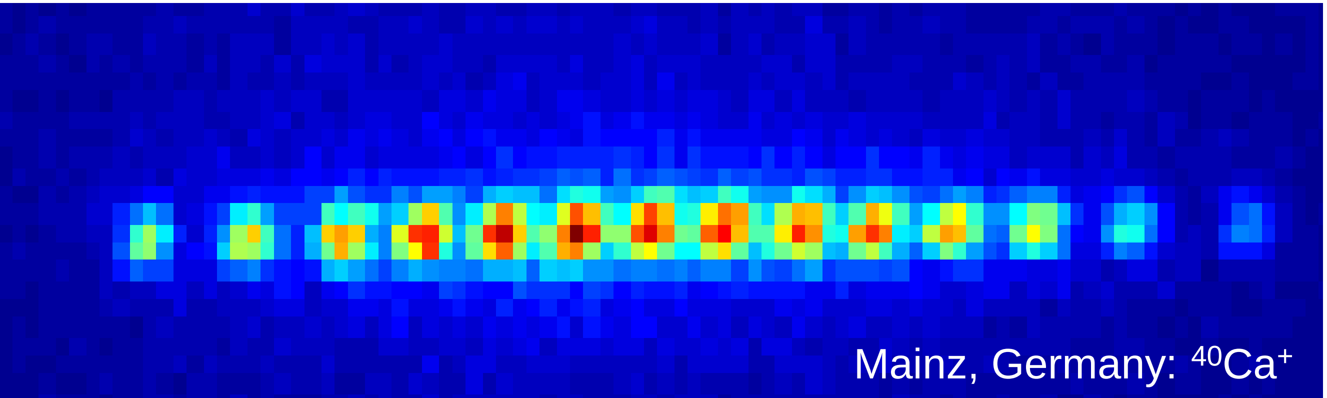
- Quantum thermodynamics, heat engines, phase transitions
- Implanting single ions for a solid state quantum device



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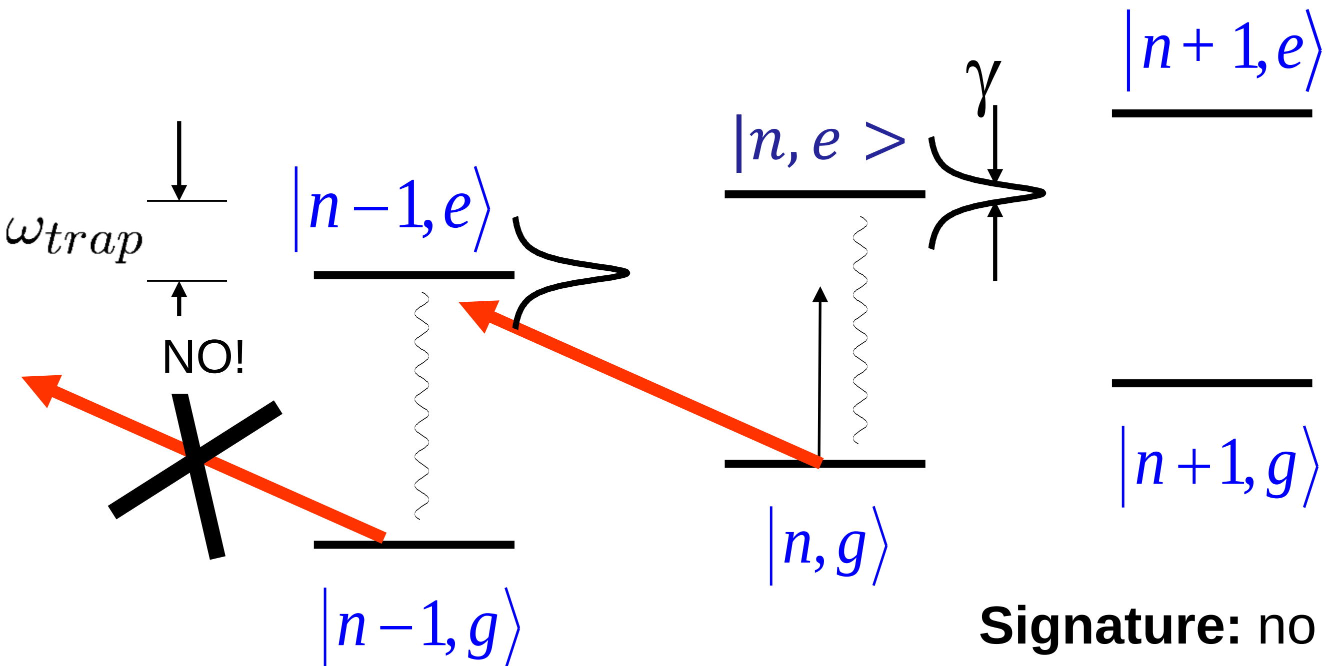
F. Schmidt-Kaler

JOHANNES GUTENBERG UNIVERSITÄT MAINZ

„Strong confinement“

$$\omega_{trap} >> \gamma$$



Signature: no further excitation possible, dark state“ |0>

strong confinement – well resolved sidebands:
detuning for optimum cooling

$$\Delta = -\omega_{trap} \Rightarrow \langle n \rangle_{ss} \approx \left(\frac{\gamma/2}{\omega_{trap}}\right)^2 << 1$$

Temperature measurements

different methods

- observe Rabi oscillations on the blue SB
- compare the excitation on the blue SB and the red SB
- compare the excitation on the red SB and the carrier

Experimental: test excitation $P_e(t)$ for $\Delta=-\omega$ and $\Delta=+\omega$
Analysis: $P_{red}/P_{blue} = m / (m+1)$

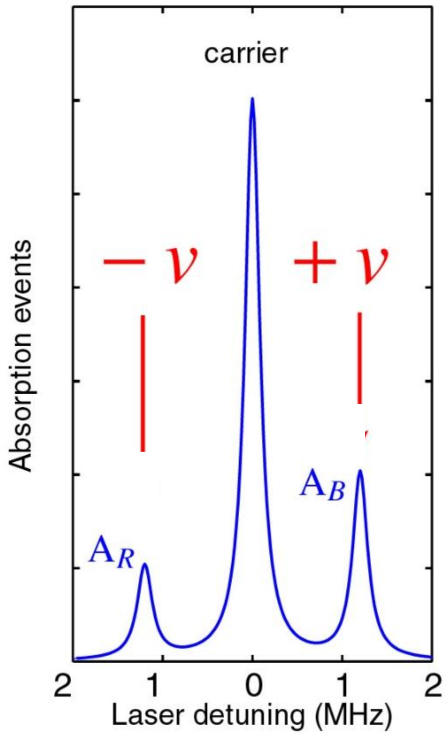
$$P_e^{red}(t) = \sum_{n=1} \frac{m^n}{(m+1)^{n+1}} sin^2(2\pi\Omega_{n,n-1}t)$$

$$= \frac{m}{m+1} \sum_{n=0} \frac{m^n}{(m+1)^{n+1}} sin^2(2\pi\Omega_{n+1,n}t)$$

using: $\Omega_{n+1,n} = \Omega_{n,n+1}$

$$\Rightarrow P_e^{red}(t) = \frac{m}{m+1} P_e^{blue}(t)$$

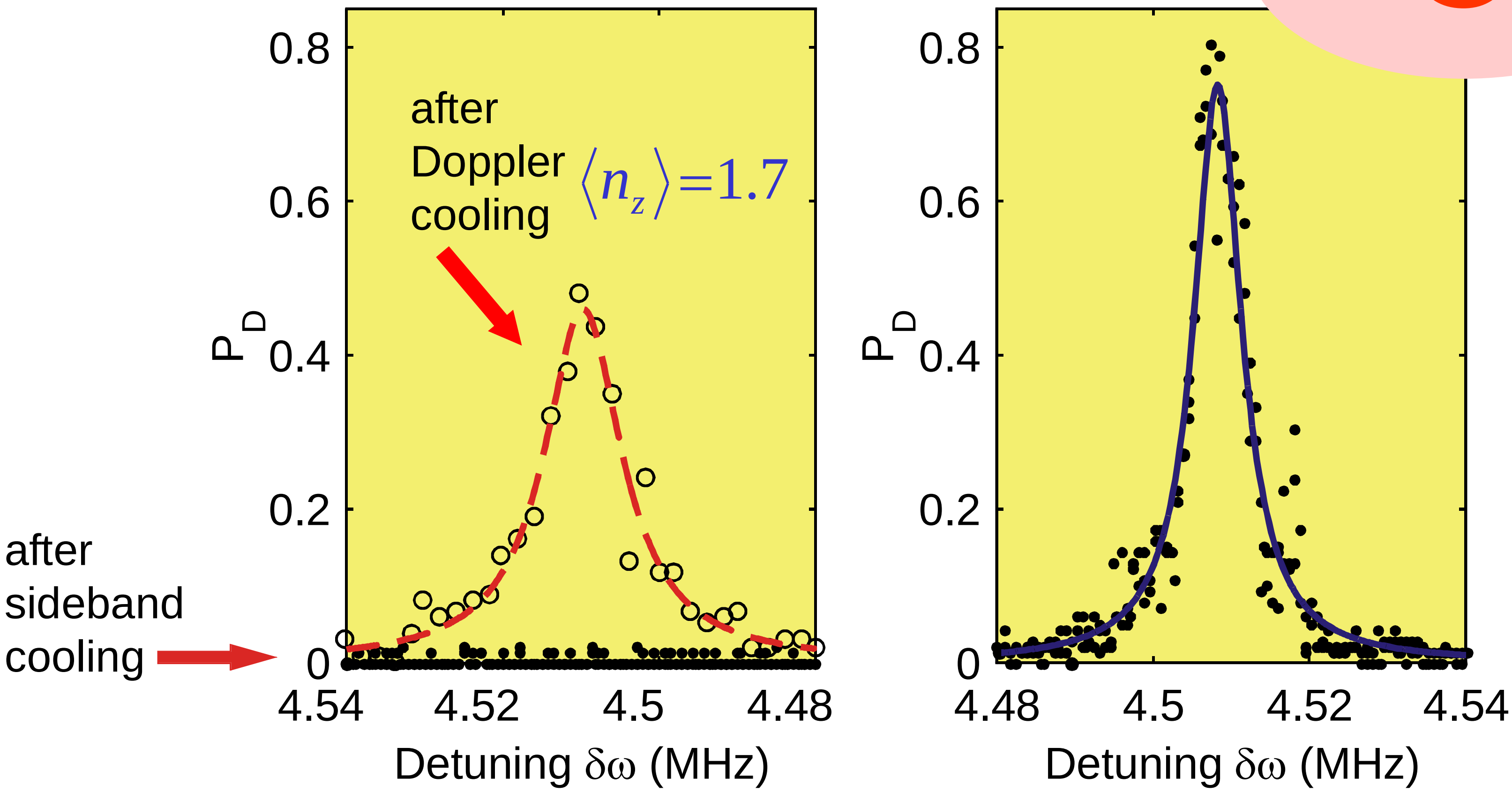
$$m = \frac{R}{1-R}, \quad R = P_e^{red}/P_e^{blue}$$



Example: ground state cooling

99.9% ground state population

$^{40}Ca^{+}$



Ch. Roos et al., Phys. Rev. Lett. 83, 4713 (1999)

Reminder to Doppler cooling

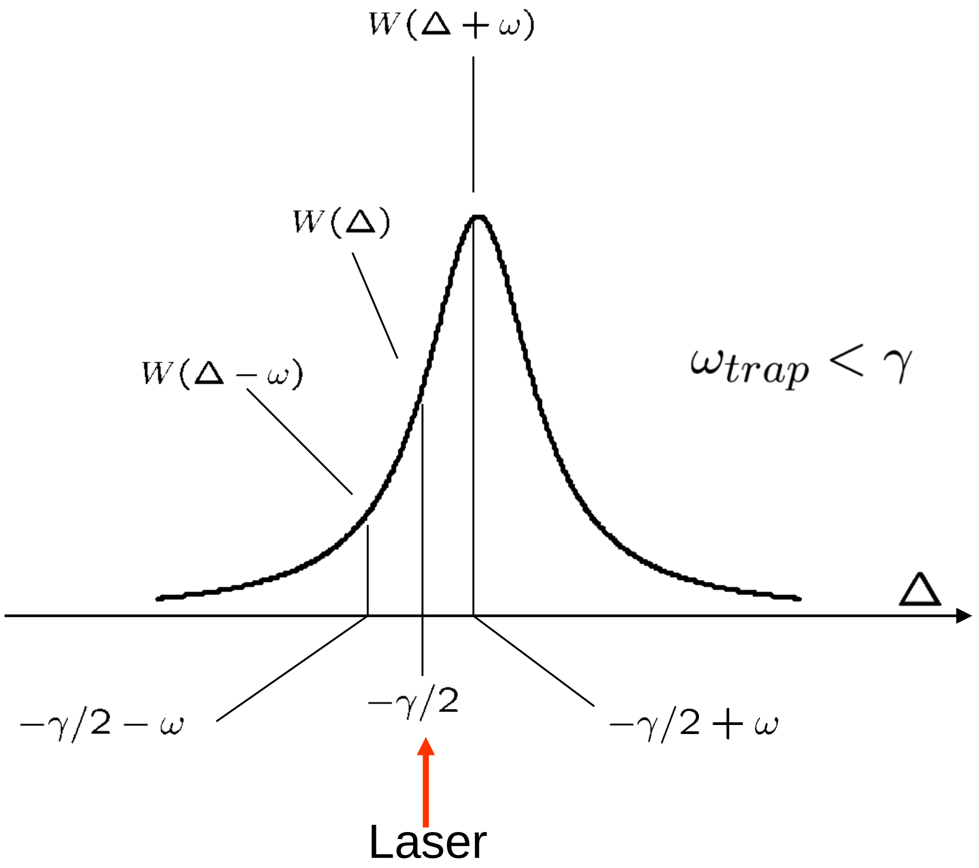
Advantage:
Cools all modes simultaneously

Problems:
But **not** into ground state
a) Sidebands are not resolved on the transition,
⇨ small differences in

$$W(\Delta \pm \omega)$$

b) Carrier excitation leads to diffusion, ⇨ heating:

$$W(\Delta = 0) > 0$$

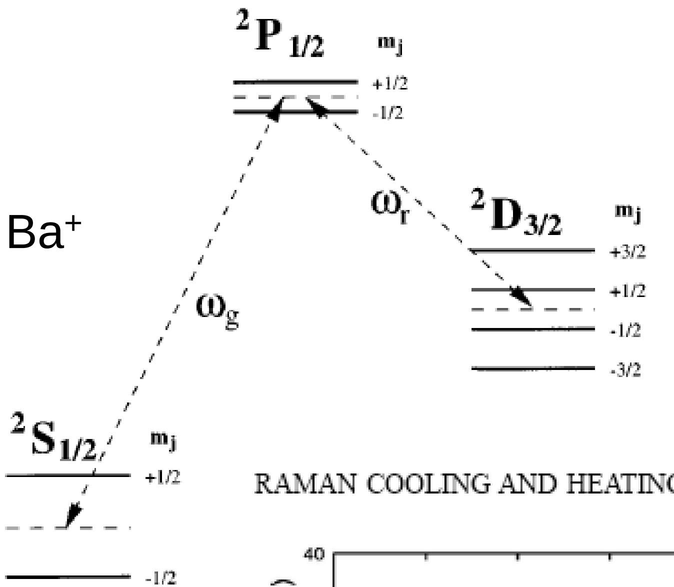


How to shape the atomic resonance line? ⇨ **Quantum-Interference**

Dark states and resonances

Reiß et al., Phys Rev A 65, 053401 (2002)
Reiß et al., Phys Rev A 54, 5133 (1996)

Ba$^+$



Dark resonances: $|\Psi\rangle = \frac{1}{\sqrt{2}}\left(|S_{1/2}\rangle - |D_{5/2}\rangle\right)$

⇨ spectrally much sharper than Dopper profile

RAMAN COOLING AND HEATING OF TWO TRAPPED Ba$^+$ IONS

PHYSICAL REVIEW A **65** 053401

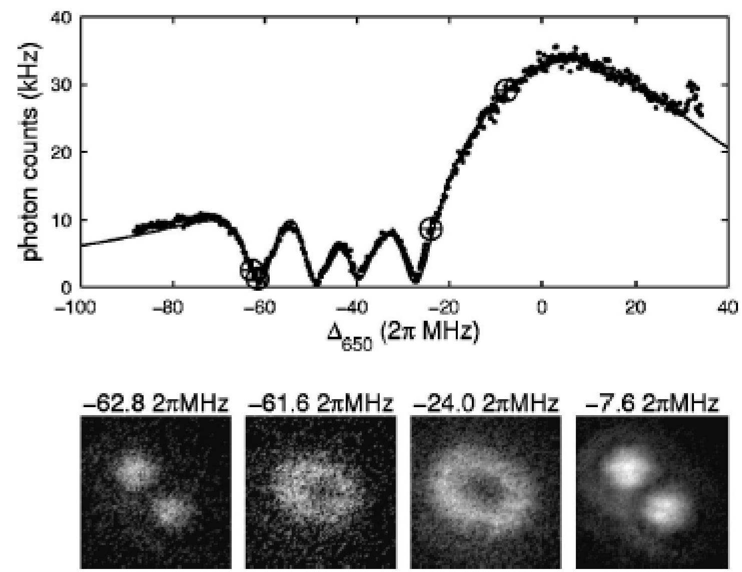


FIG. 2. Two trapped Ba$^+$ ions show different motional states depending on laser parameters. Top: fluorescence of two trapped ions as a function of laser detuning, collected in 0.1 s. Bottom: spatial distribution of the two ions at the detunings indicated above.

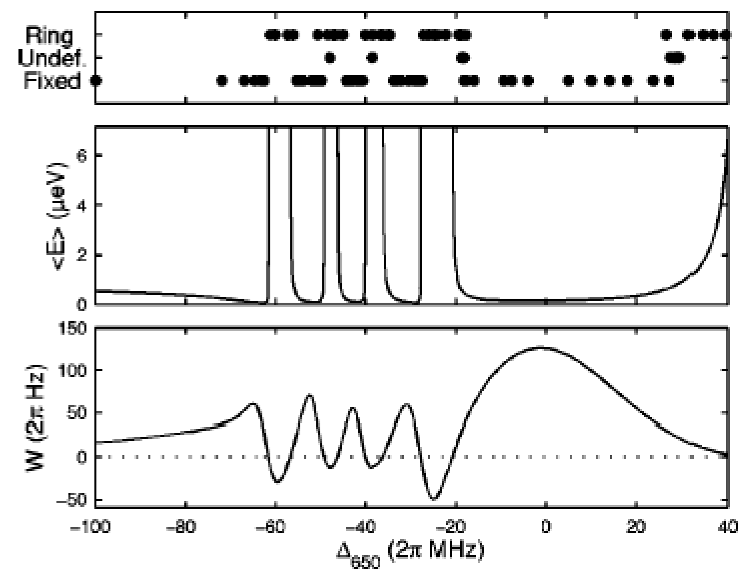
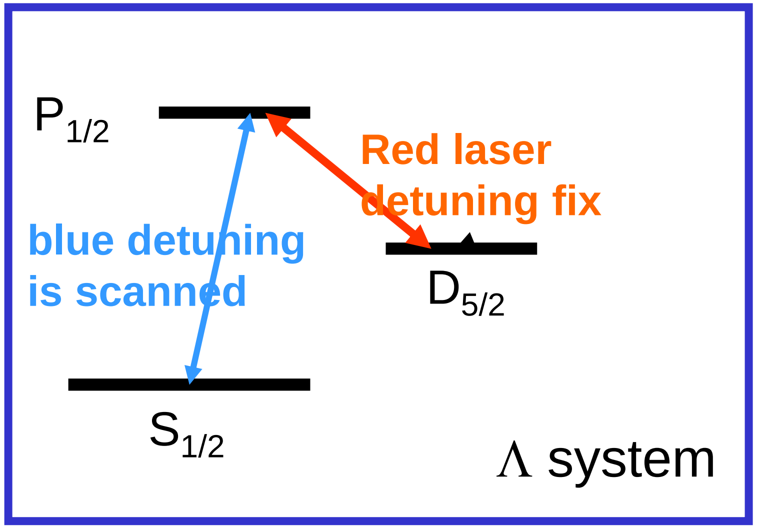


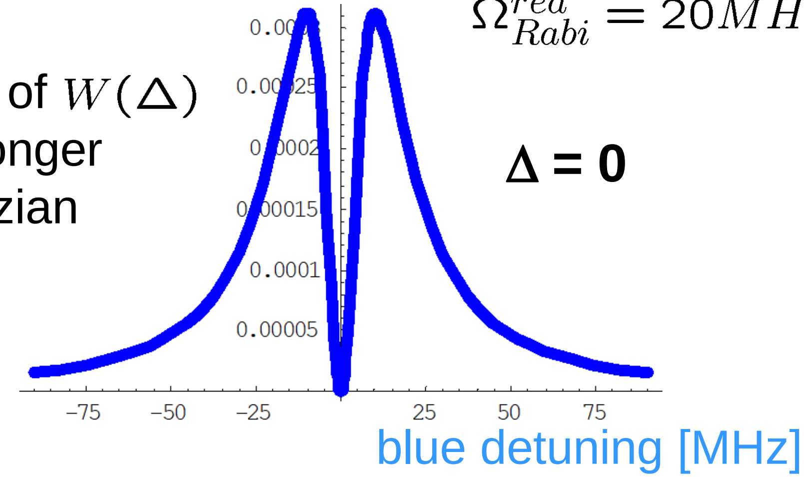
FIG. 3. Top: observed motional states for different detunings of the 650-nm light. The dots correspond to individual observations. Middle: mean motional energy in the $\tilde{y}$ mode calculated from theory. Bottom: cooling rate for the $\tilde{y}$ mode calculated from theory.

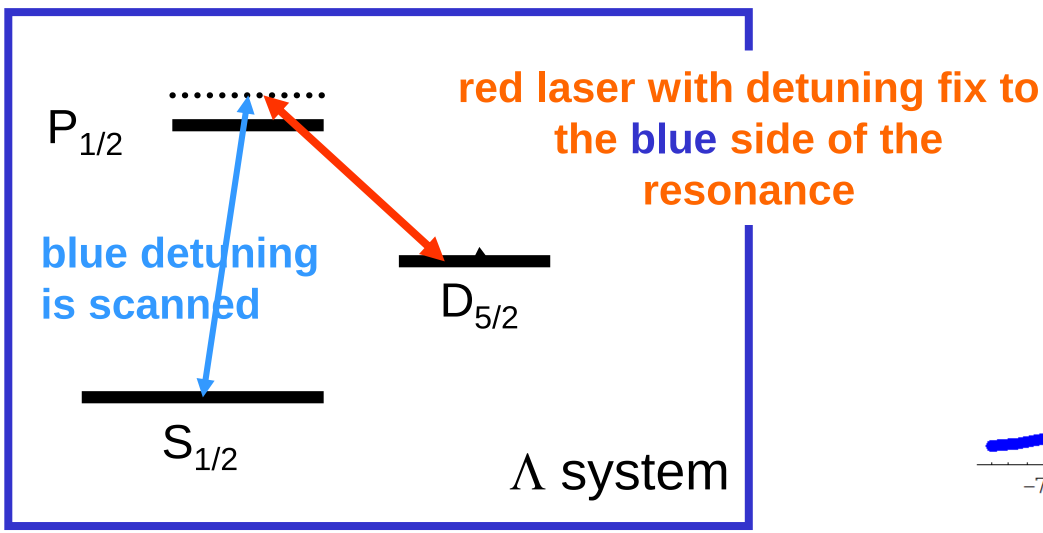
Quantum interference and EIT

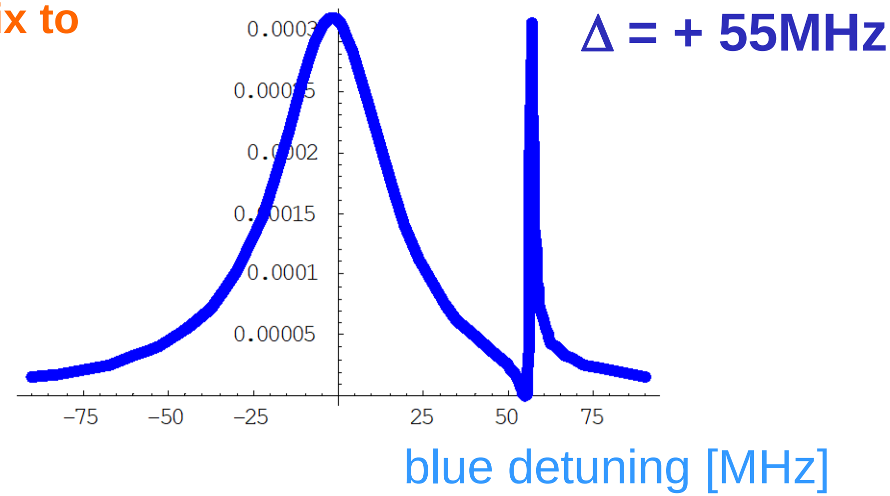


Shape of $W(\Delta)$ is no longer Lorentzian

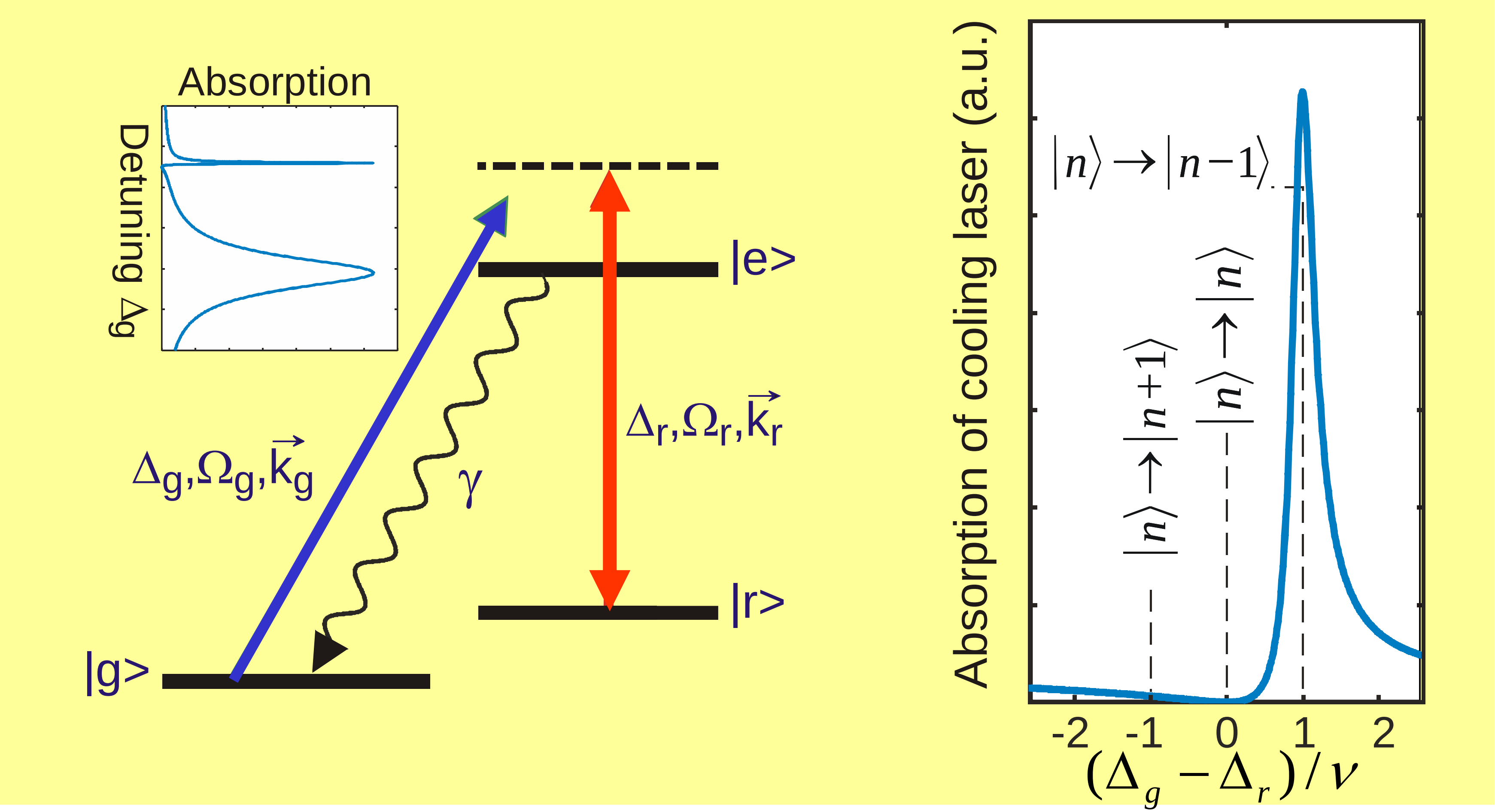
$$\Omega_{Rabi}^{blue} = 0.5MHz$$
$$\Omega_{Rabi}^{red} = 20MHz$$







Ground state cooling with quantum interference

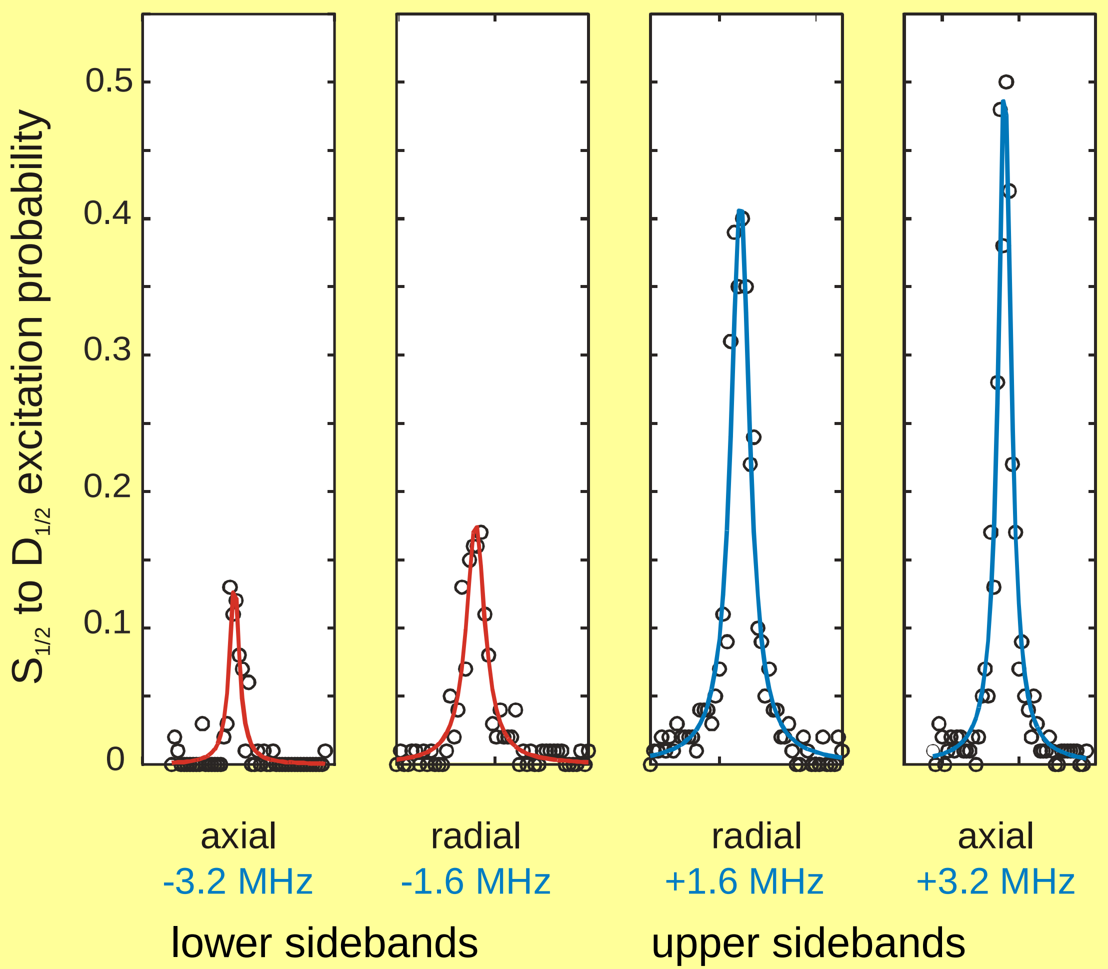


$|n\rangle \to |n-1\rangle$ transitions are enhanced by bright resonance

$|n\rangle \to |n\rangle$ transitions are suppressed by quantum interference – no „carrier“ diffusion contribution !

Morigi, Eschner, Keitel, Phys. Rev. Lett. 85, 4458 (2000)

Simultaneous two-mode ground state cooling



Simultaneous ground state cooling of **axial and radial** motion

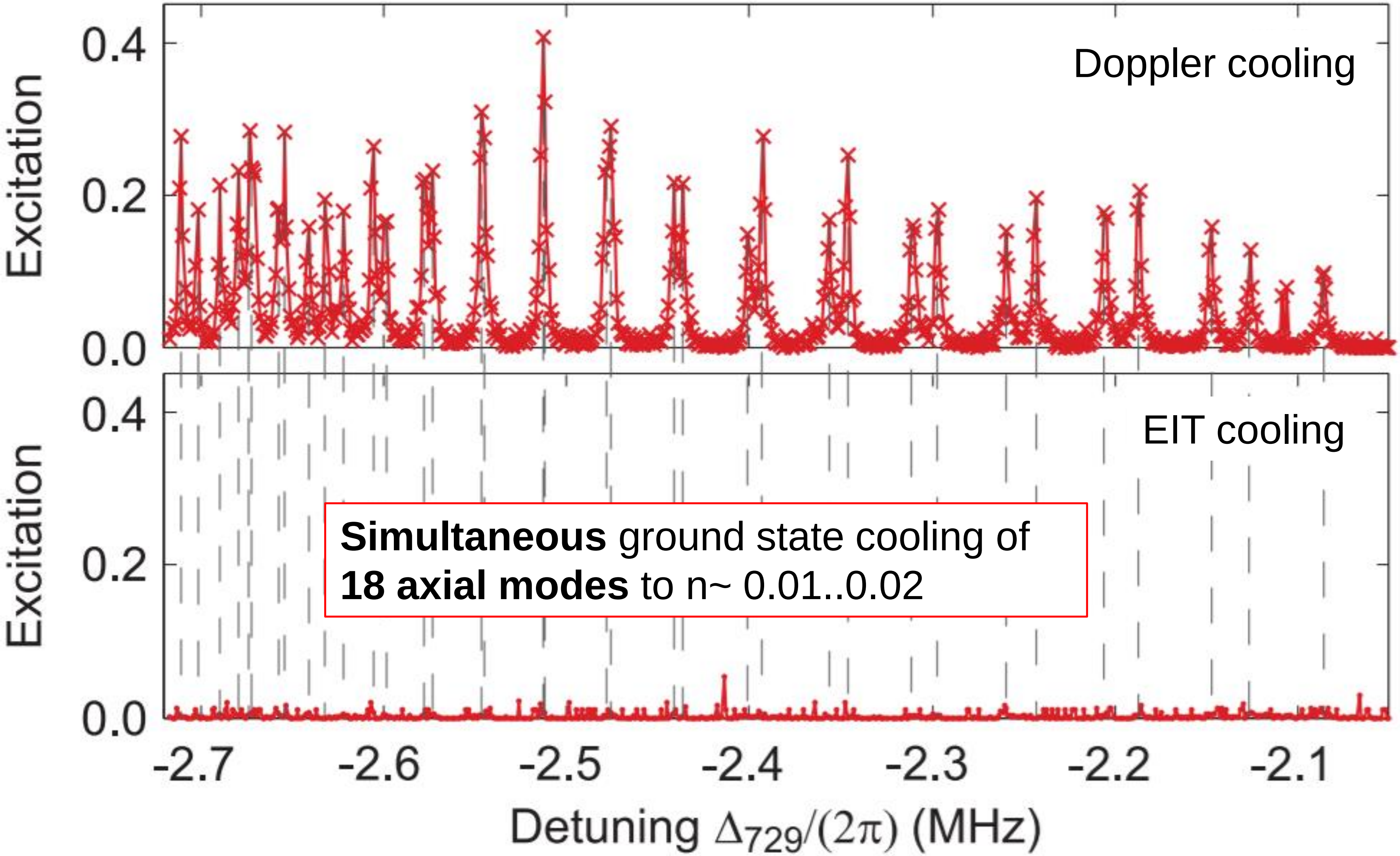
axial:
P(0)=73%

radial:
P(0)=58%

Roos et al., Phys. Rev. Lett. 85, 5547 (2000)

Multi-mode ground state cooling

Lechner et al, PRA 93, 053401 (2016)



Simultaneous ground state cooling of **18 axial modes** to n~ 0.01..0.02

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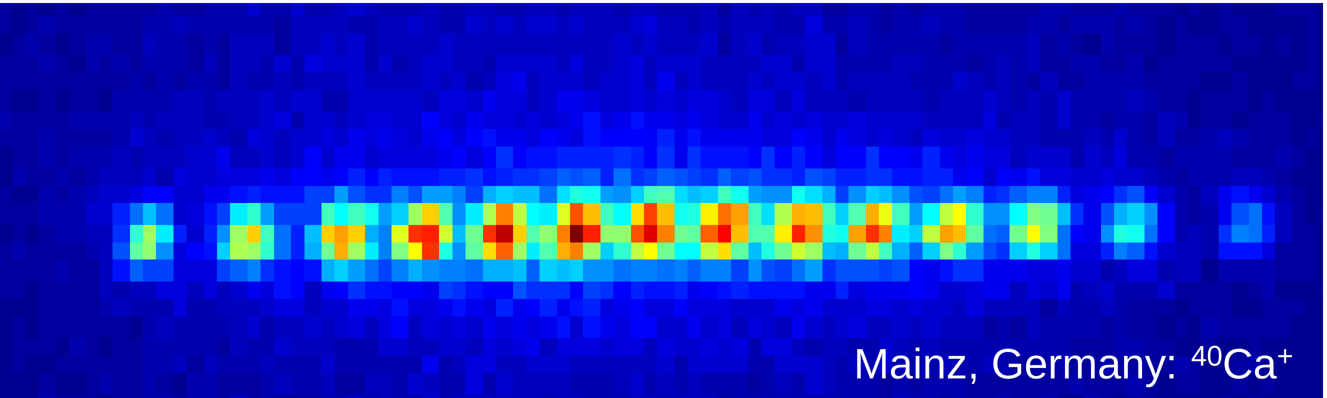

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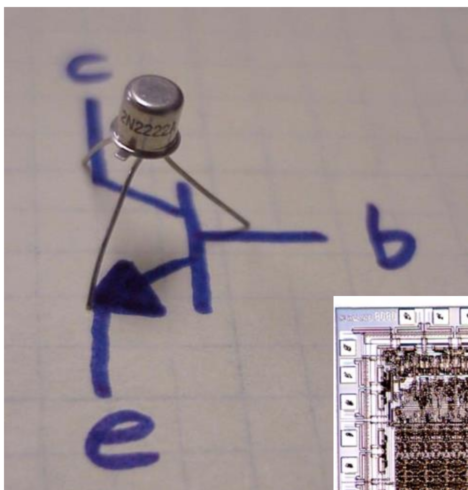
History of classical information processing

Relais: Konrad Zuse Z1
1937 Berlin

Wheels: 1671
Gottfried Leibnitz

Transistor:
Lilienfeld / 1925
Mataré, Welker / 1942
Shockley, Brattain / 1945

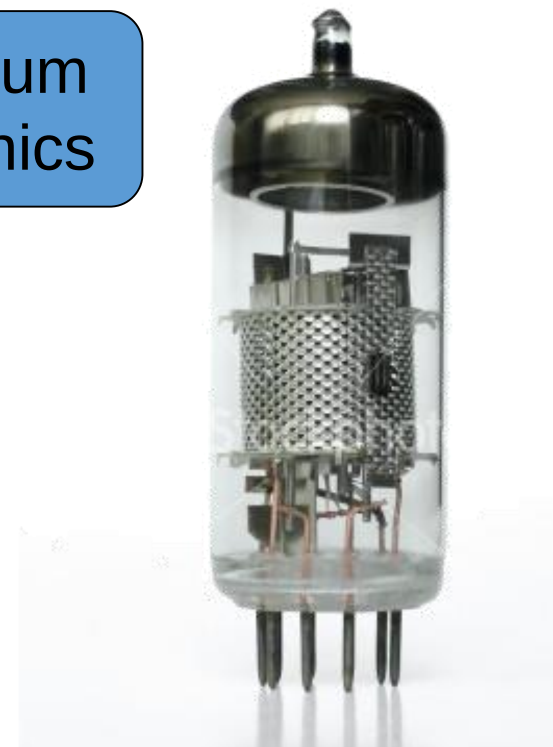


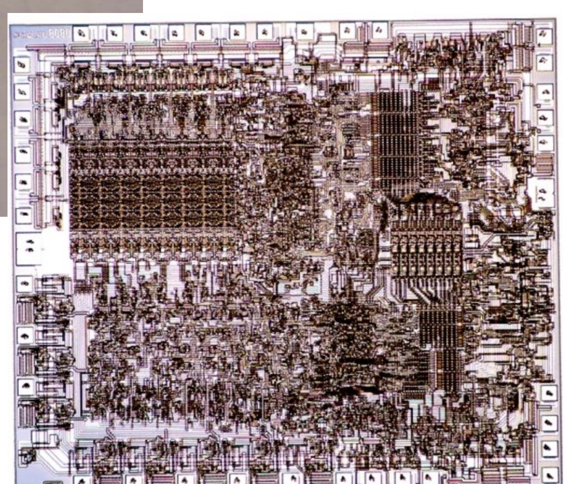
Mechanical computing

semiconductor electronics

in vacuum electronics

Electron tube:
Femming / 1904

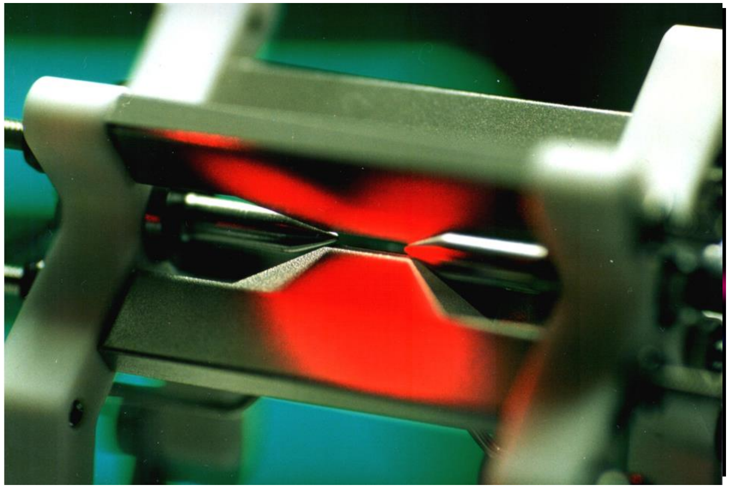


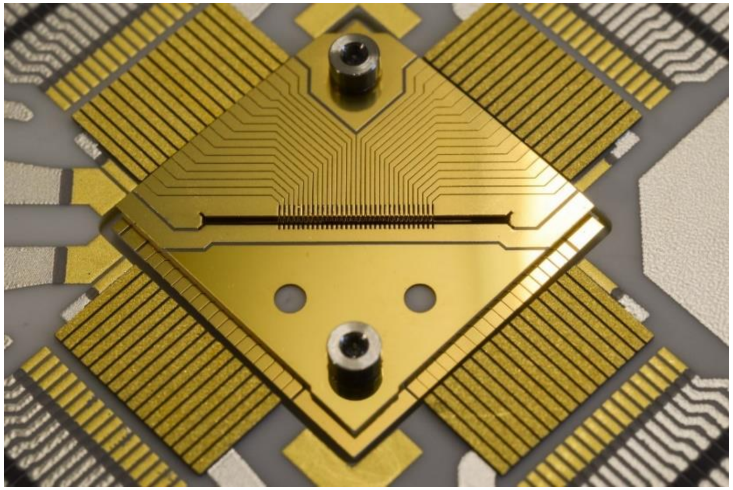


Processor:
Intel 8080
/ 1974

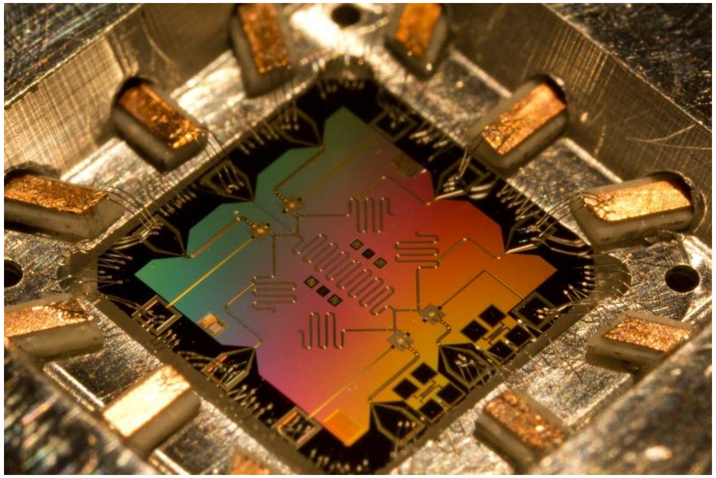
Quantum computing platforms

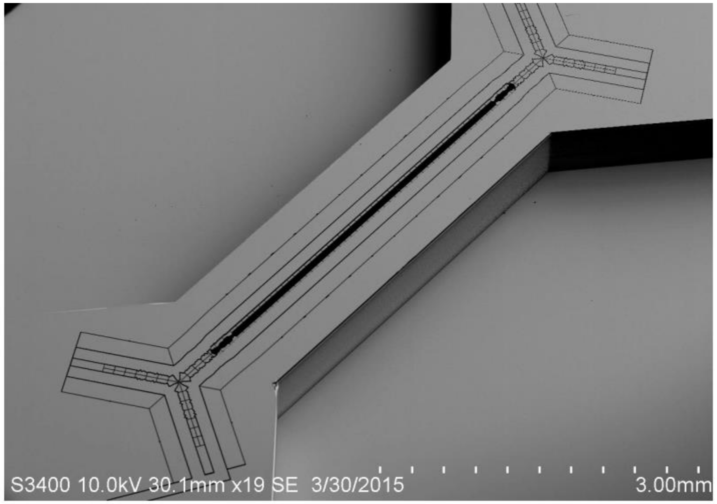
Trapped Ions in Paul traps





Solid state technology: SC qubit circuits & ….

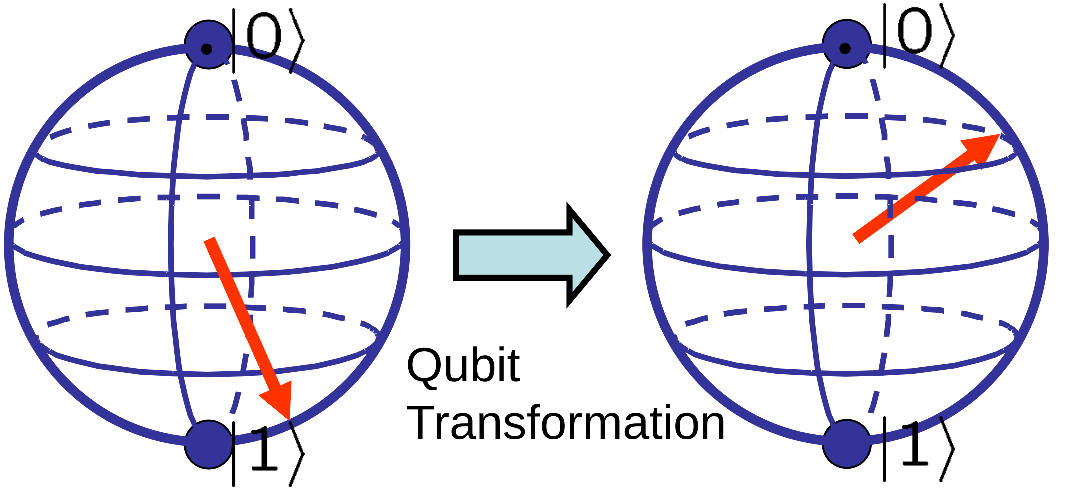


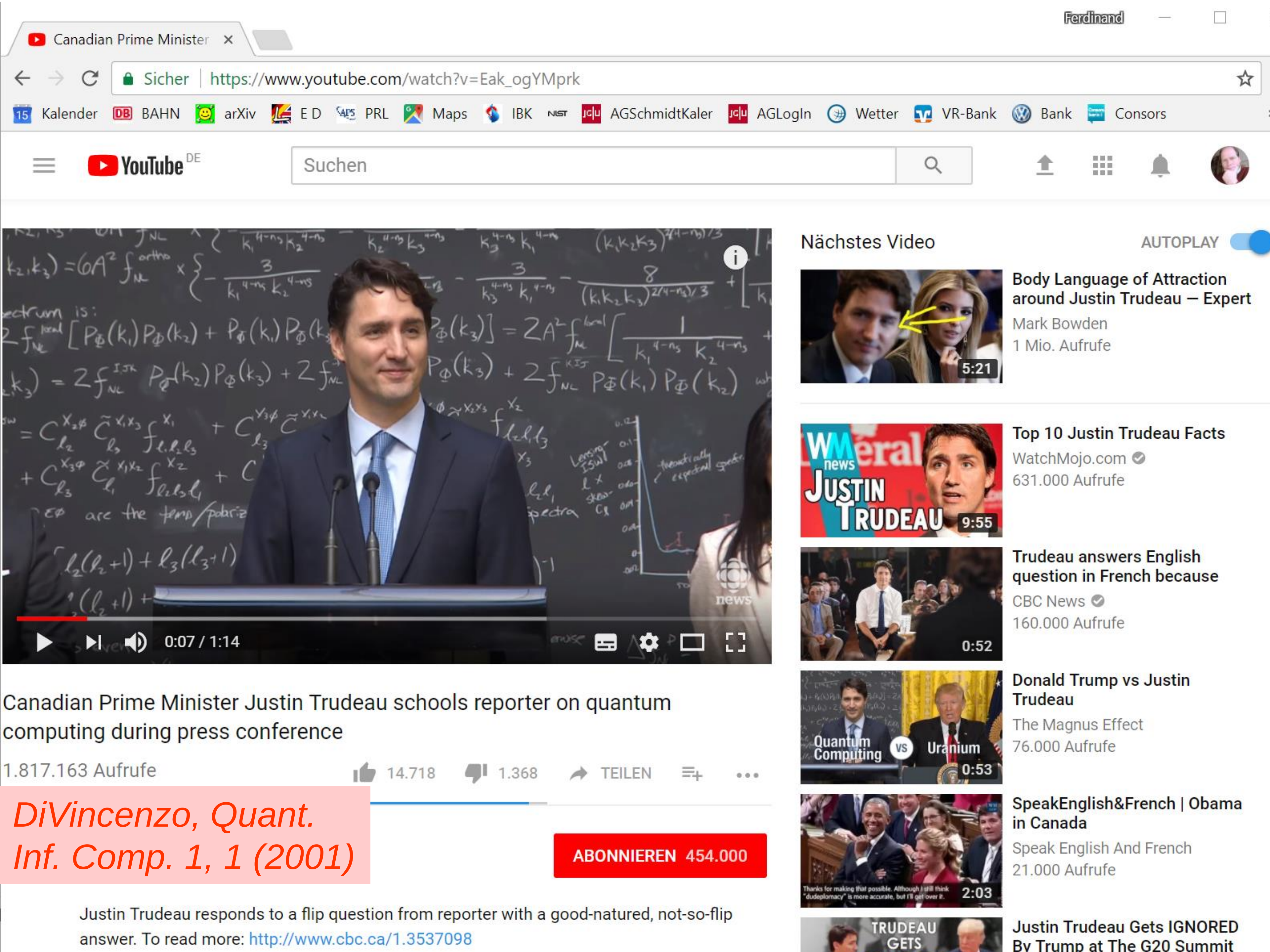


The experimental requirements for quantum computing

DiVincenzo, Quant. Inf. Comp. 1, 1 (2001)

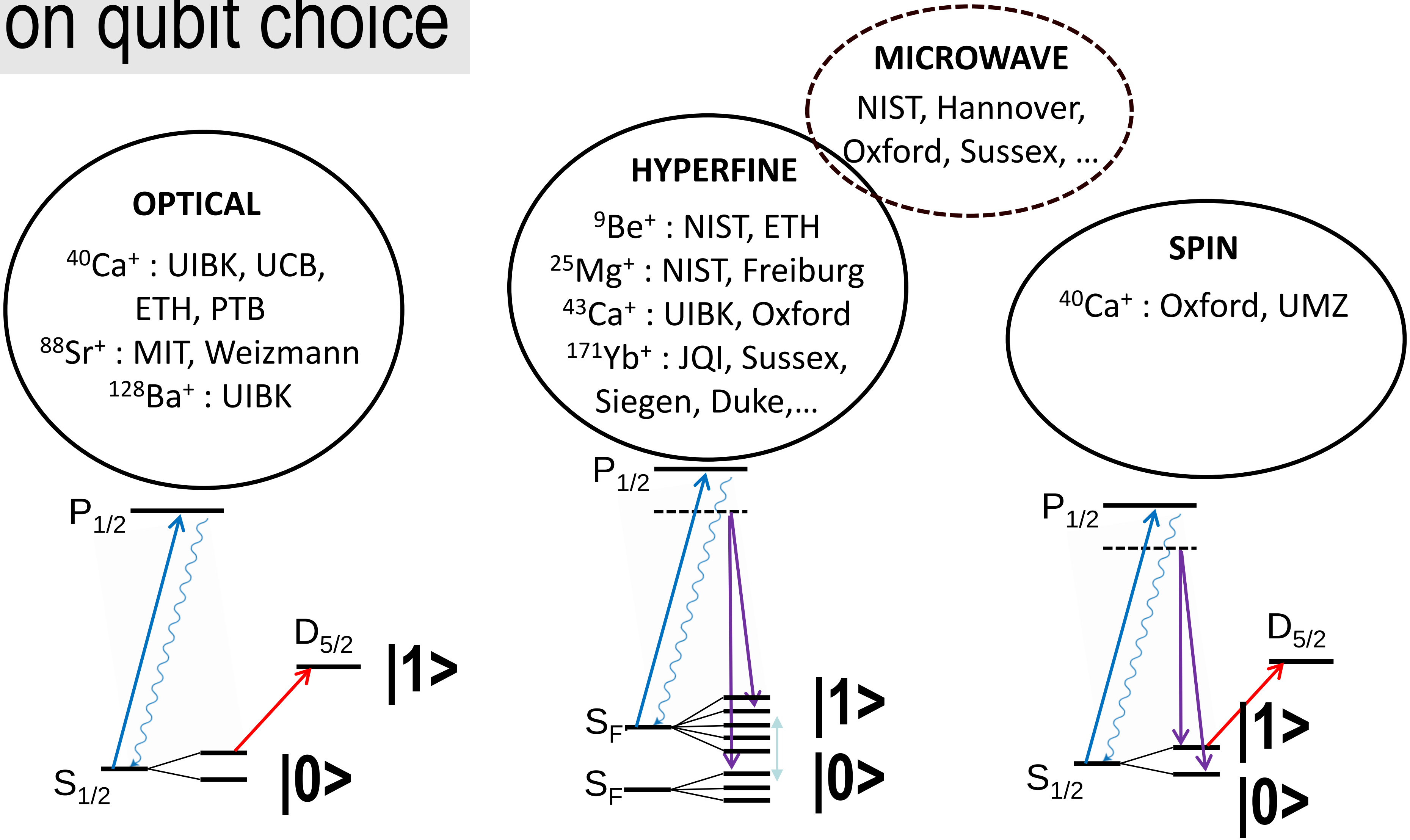
1. Qubits store superposition information, scalable physical system
2. Ability to initialize the state of the qubits $|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$
3. Universal set of quantum gates: Single bit and two bit gates
4. Long coherence times, much longer than gate operation time
5. Qubit-specific measurement capability
6. Qubit connectivity
7. Large distance transmission





DiVincenzo, Quant. Inf. Comp. 1, 1 (2001)

Ion qubit choice



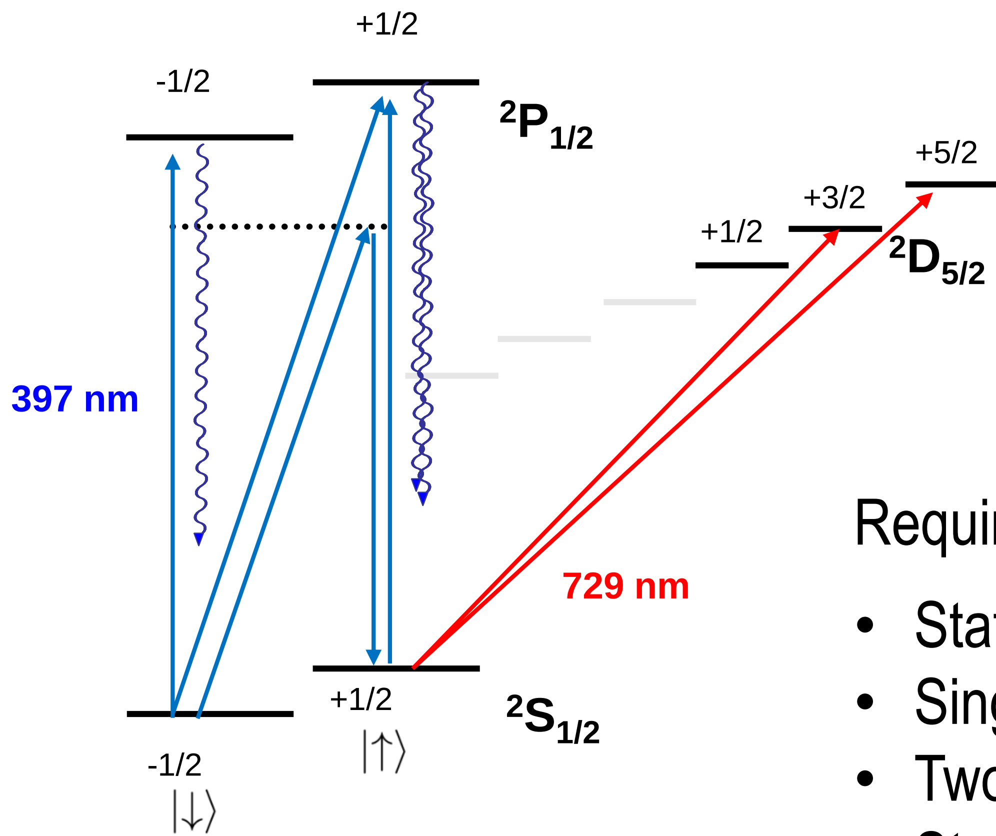
- Best overall performance so far
- Easy readout
- Requires optical phase stability
- Limited by metastable lifetime

- Infinite T_1
  only scattering errors
- complicated level scheme

- Infinite T_1
  only scattering errors
- readout overhead

$^{40}Ca^{+}$ spin qubit

[illegible]

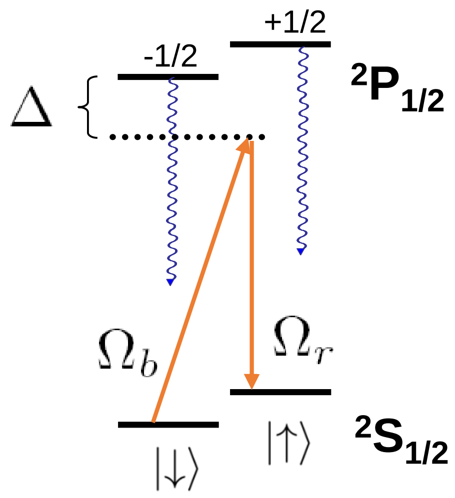


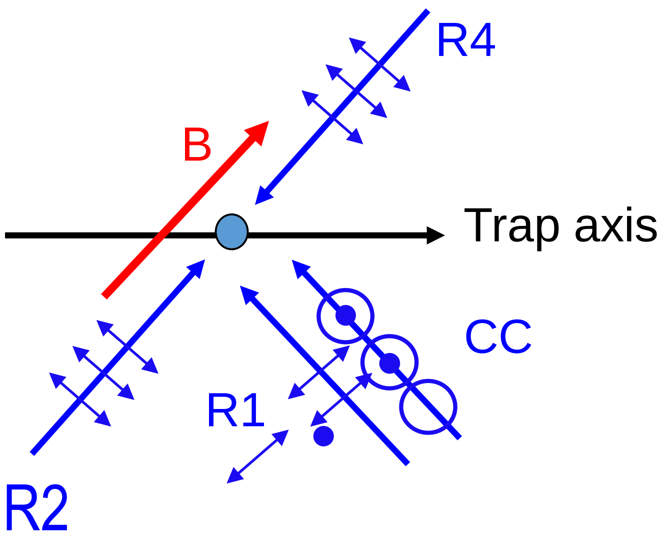
Requirements:

- State preparation
- Single-qubit gates
- Two-qubit gates
- State readout
- Flourescence detection
- Reset

Poschinger et al., J. Phys. B 42 154013 (2009)

Stimulated Raman transitions

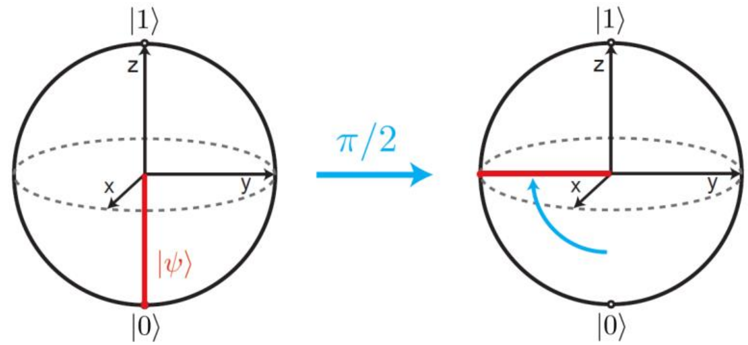


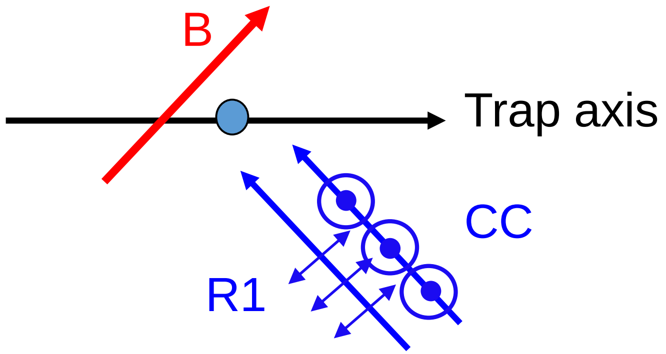


- Single photon detuning Δ much larger than natural linewidth
- Very small spont. scattering rate
- Effective two-level system

Four beams near 397nm used pairwise in different configurations

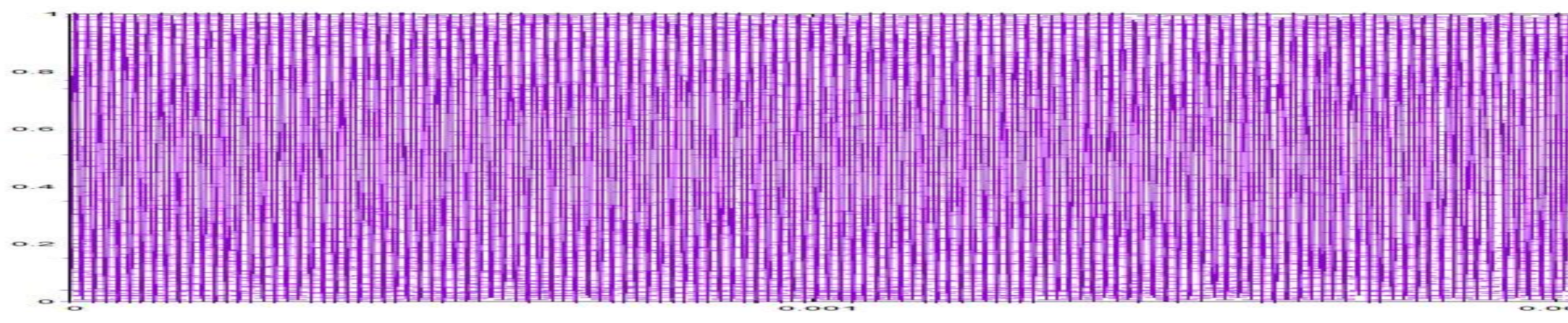
Single qubit rotation





- Copropgating beams
- No effective k-vector
- No coupling to ion motion
- 99,9949(2) % fidelity gates

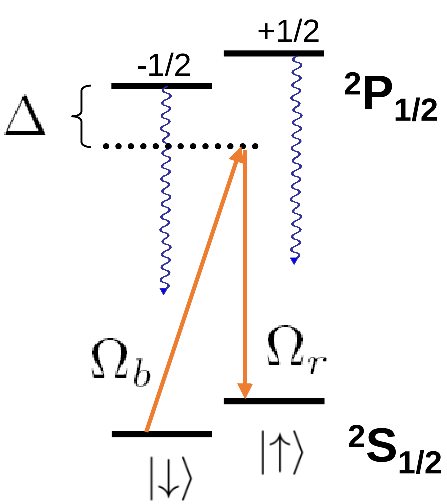
$$\Omega_{Raman} \propto \frac{\Omega_r \Omega_b}{\Delta}$$

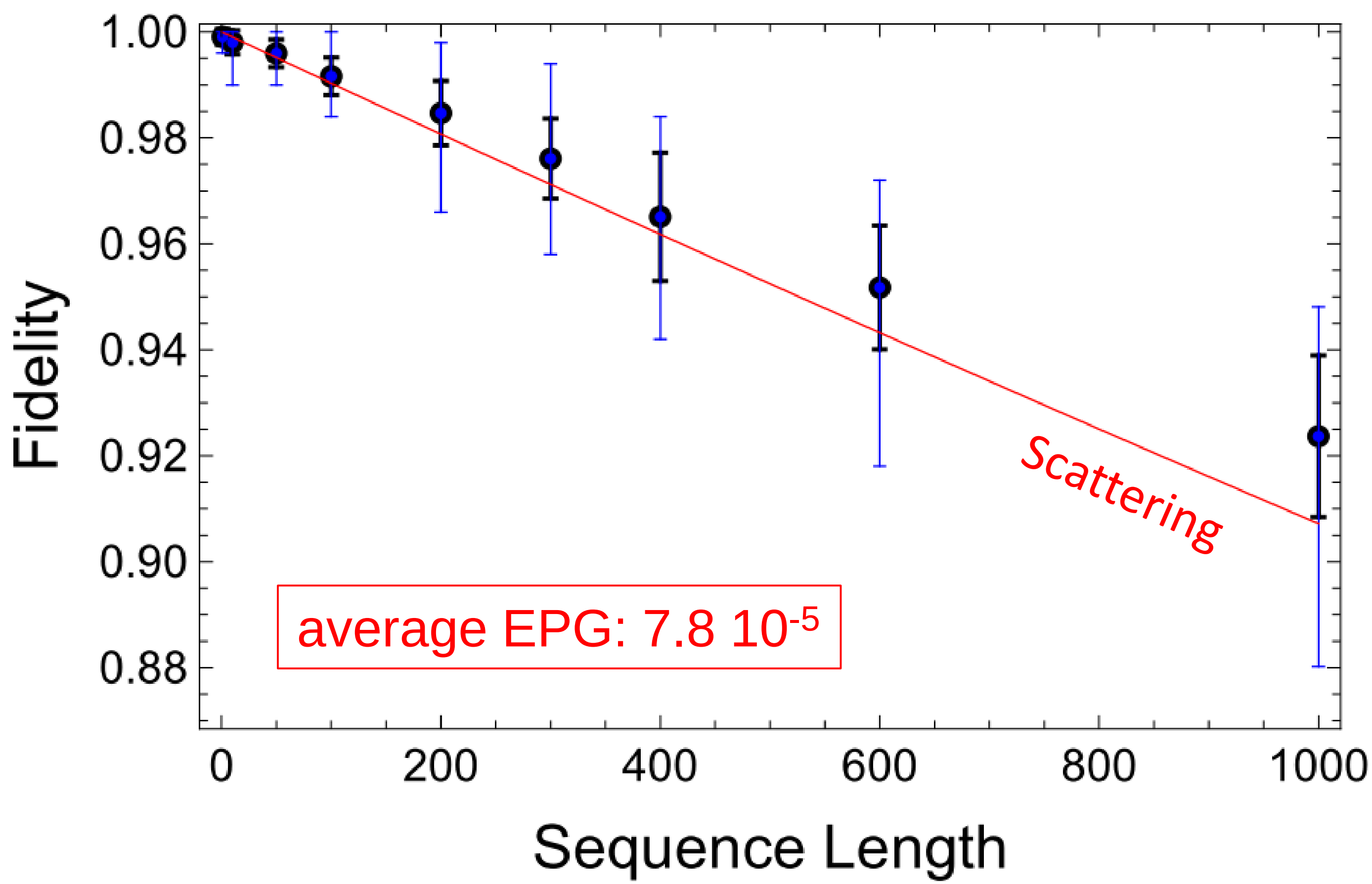


Spin qubit gate operation: Randomized benchmarking

Kaufmann, PhD

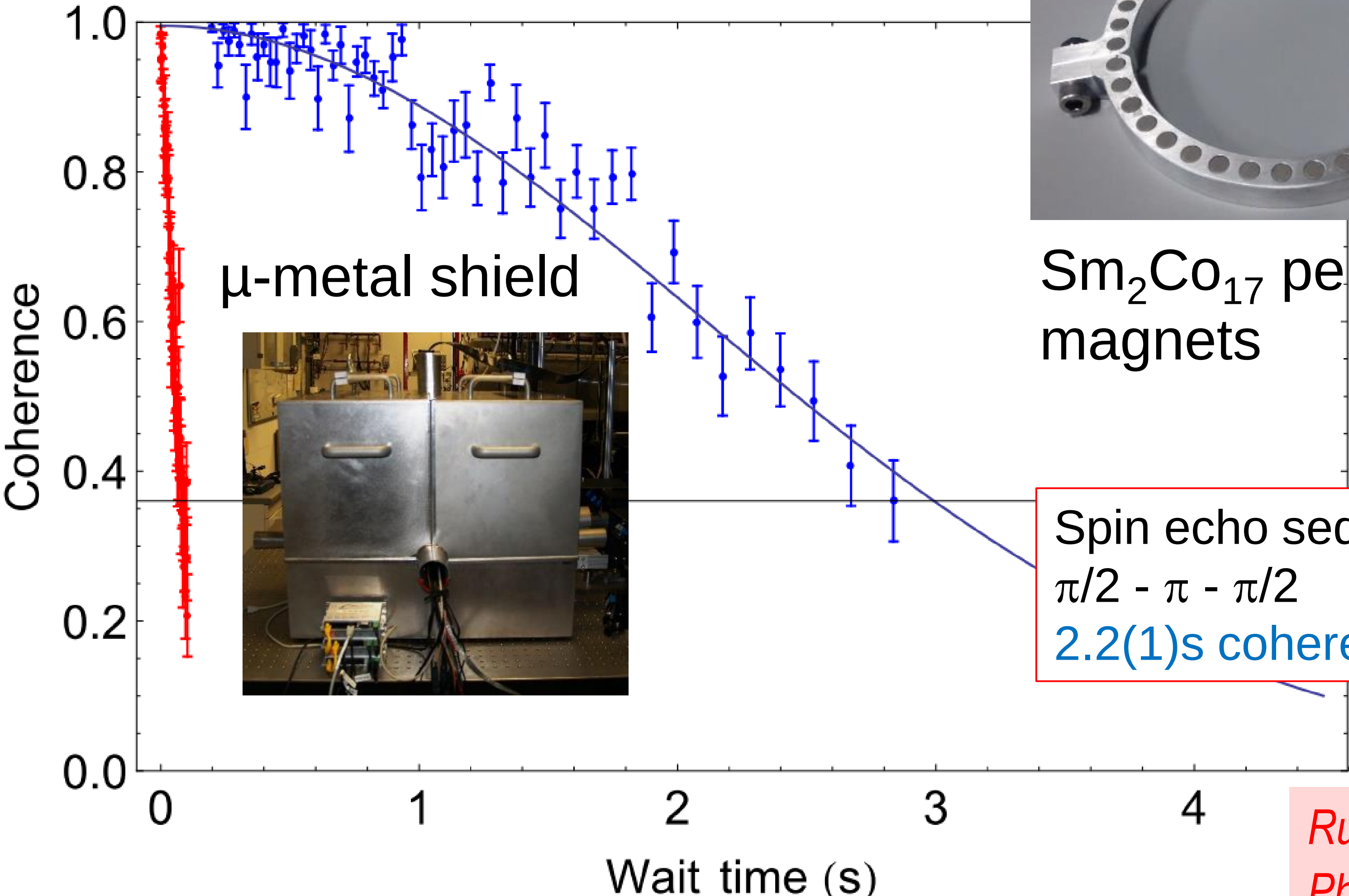
- Blocks of 40 gate sequences
- Gates chosen from $\{I, R_X(\pi/2), R_Y(\pi/2), R_Z(\pi/2), R_X(\pi), R_Y(\pi), R_Z(\pi)\}$, with π-time: 6.2 µs
- 500 repetition per sequence
- Raman detuning: here 300 GHz





Spin qubit coherence

Decoherence only by phase shifts,
magnetic field fluctuations dominate



μ-metal shield

Sm_2Co_{17} permanent magnets

Spin echo sequence:
π/2 - π - π/2
2.2(1)s coherence time

Ruster et al, Appl. Phys. B, 122(10), 1

Two-qubit gate operations

Cirac, Zoller, PRL 74, 4091 (1995)

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

- Cirac Zoller gate

*Sörensen, Mölmer, PRL **82**, 1971 (1999), PRA **62**, 022311 (2000)*

- Mölmer Sörensen gate

Leibfried et al., Nature 412, 422 (2003)

- Spin-dependent light forces
- Spin-dependent magnetic gradient forces

Khromova et al, PRL 108, 220502 (2012), Warring et al, Phys. Rev. A 87, 013437 (2013)

- Cavity-induced interactions

Li, Lesanowsky, Appl. Phys. B 114, 37 (2014)

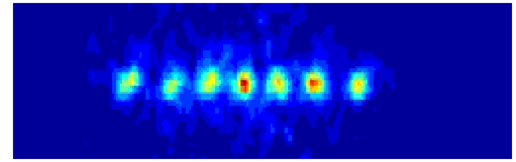
- Rydberg excitation & blockade interaction

Vogel, et al, arXiv:1905.05111

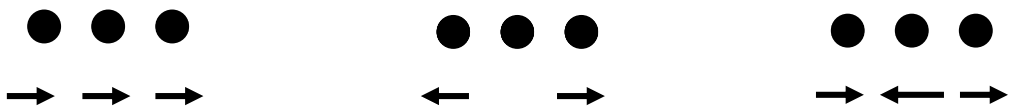
- Rydberg ultra-fast electric kick
- Atom-Ion interactions

Designed qubit interactions

Interactions due to coupling to common modes of vibration

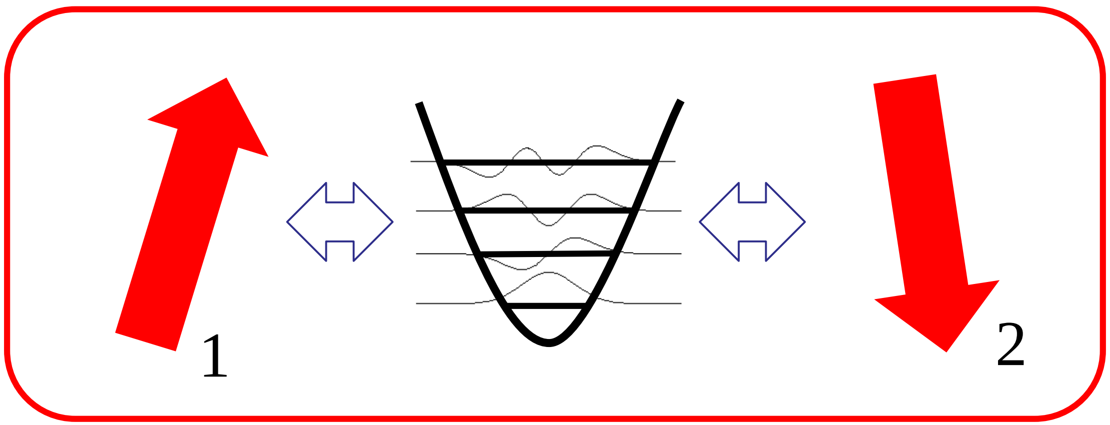


An N-ion crystal has N common modes in axial, radial-x, and radial-y direction



$1\ \omega_{ax}$ $\sqrt{3}\ \omega_{ax}$ $\sqrt{29/5}\ \omega_{ax}$

axial modes for N=3



Spin coupling is mediated by laser light interactions to one or many modes

Advantage: designing

*Monroe, et al, Science **272**, 1131 (1996)*
Leibfried et al., Nature 412, 422 (2003)
*McDonnell et al. PRL **98**, 063603 (2007)*

*Poschinger et al, PRL**105**, 263602 (2010)*

First gate proposal

74, NUMBER 20 4091 PHYSICAL REVIEW LETTERS 15 MAY 1995

Quantum Computations with Cold Trapped Ions

J. I. Cirac and P. Zoller*

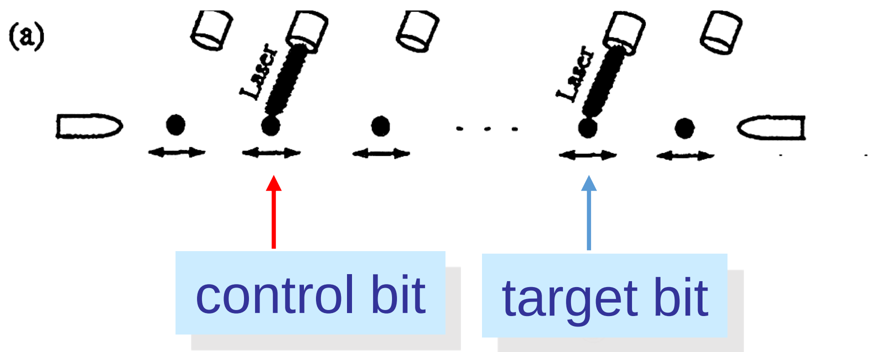
Institut für Theoretische Physik, Universiät Innsbruck, Technikerstrasse 25, A-6020 Innsbruck, Austria

(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.

J. I. Cirac P. Zoller

- single bit rotations and quantum gates
- small decoherence
- unity detection efficiency
- scalable



$$Controlled-NOT : |\varepsilon_1\rangle|\varepsilon_2\rangle \rightarrow |\varepsilon_1\rangle|\varepsilon_1 \oplus \varepsilon_2\rangle$$

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

*F. Schmidt-Kaler et al., Nature **422**, 408 (2003)*
Fidelity : 73%

*M. Riebe et al., PRL **97**, 220407 (2006)*
Fidelity : 92,6%

Controlled-NOT operation

$|\varepsilon_1\rangle \; |\varepsilon_2\rangle$

$|S\rangle|S\rangle \rightarrow |S\rangle|S\rangle$

$|S\rangle|D\rangle \rightarrow |S\rangle|D\rangle$

$|D\rangle|S\rangle \rightarrow |D\rangle|D\rangle$

$|D\rangle|D\rangle \rightarrow |D\rangle|S\rangle$

control target

ion 1 $|S\rangle,|D\rangle$ — SWAP — control qubit

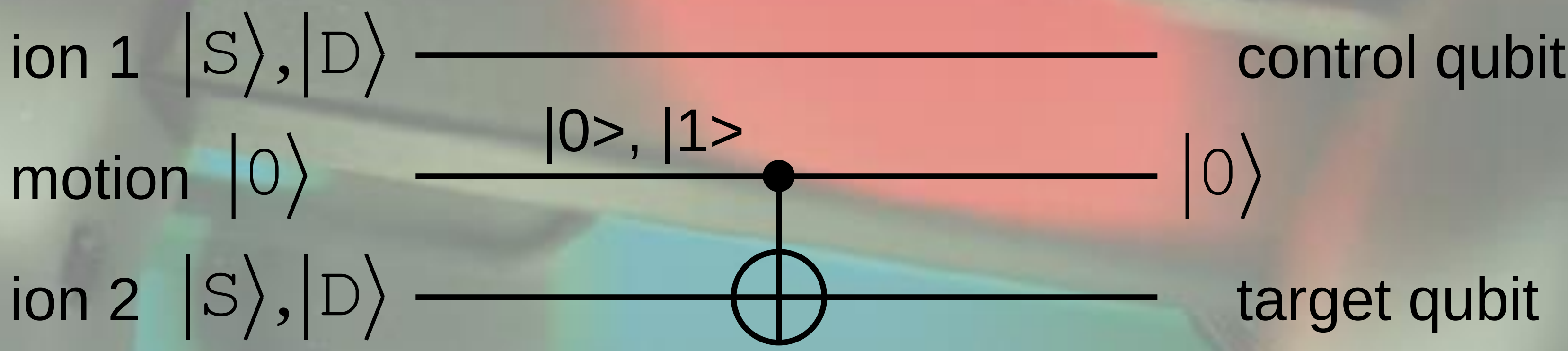
motion $|0\rangle$ — SWAP — $|0\rangle$

ion 2 $|S\rangle,|D\rangle$ — target qubit

Controlled-NOT operation

$|\varepsilon_1\rangle \; |\varepsilon_2\rangle$

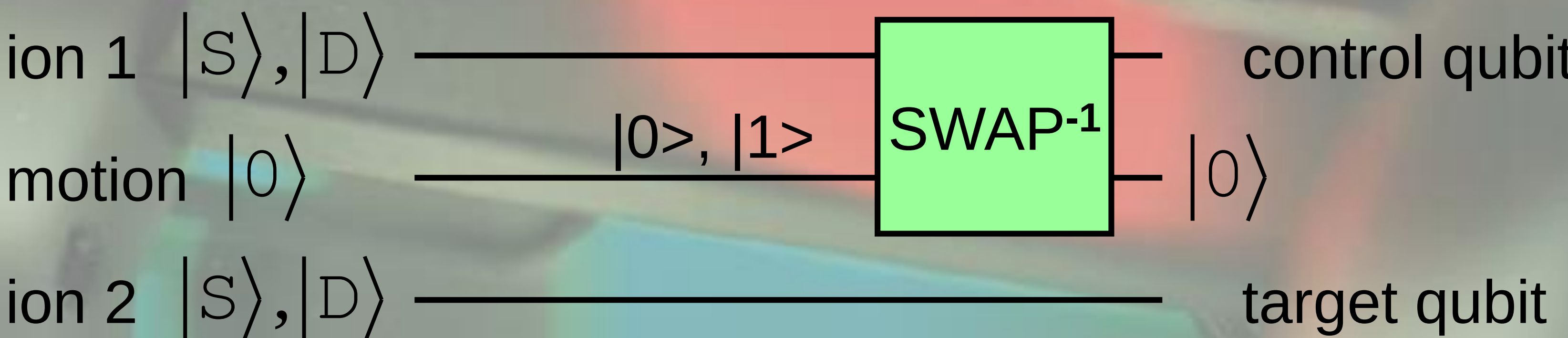
$$|S\rangle|S\rangle \rightarrow |S\rangle|S\rangle$$
$$|S\rangle|D\rangle \rightarrow |S\rangle|D\rangle$$
$$|D\rangle|S\rangle \rightarrow |D\rangle|D\rangle$$
$$|D\rangle|D\rangle \rightarrow |D\rangle|S\rangle$$



Controlled-NOT operation

$|\varepsilon_1\rangle \; |\varepsilon_2\rangle$

$$|S\rangle|S\rangle \rightarrow |S\rangle|S\rangle$$
$$|S\rangle|D\rangle \rightarrow |S\rangle|D\rangle$$
$$|D\rangle|S\rangle \rightarrow |D\rangle|D\rangle$$
$$|D\rangle|D\rangle \rightarrow |D\rangle|S\rangle$$



Controlled-NOT operation

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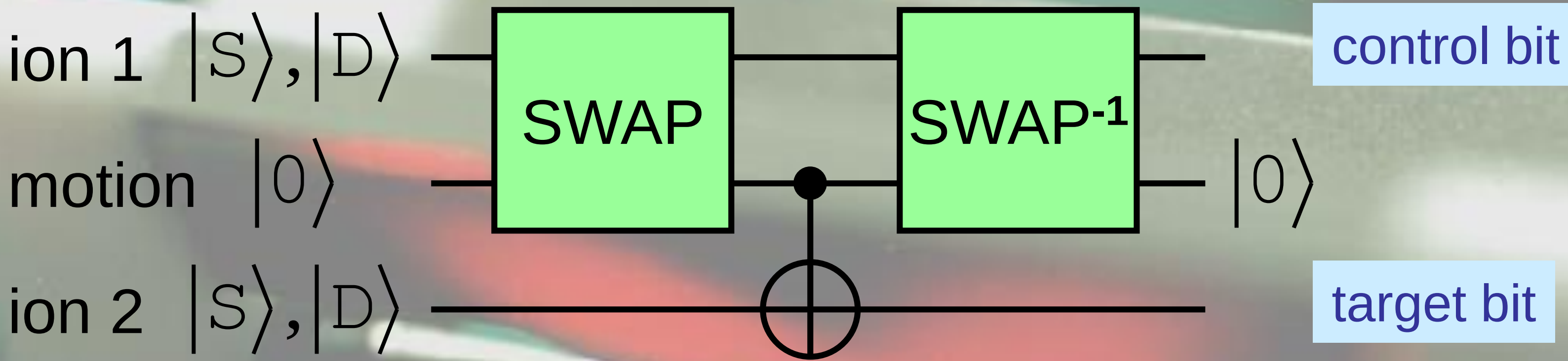
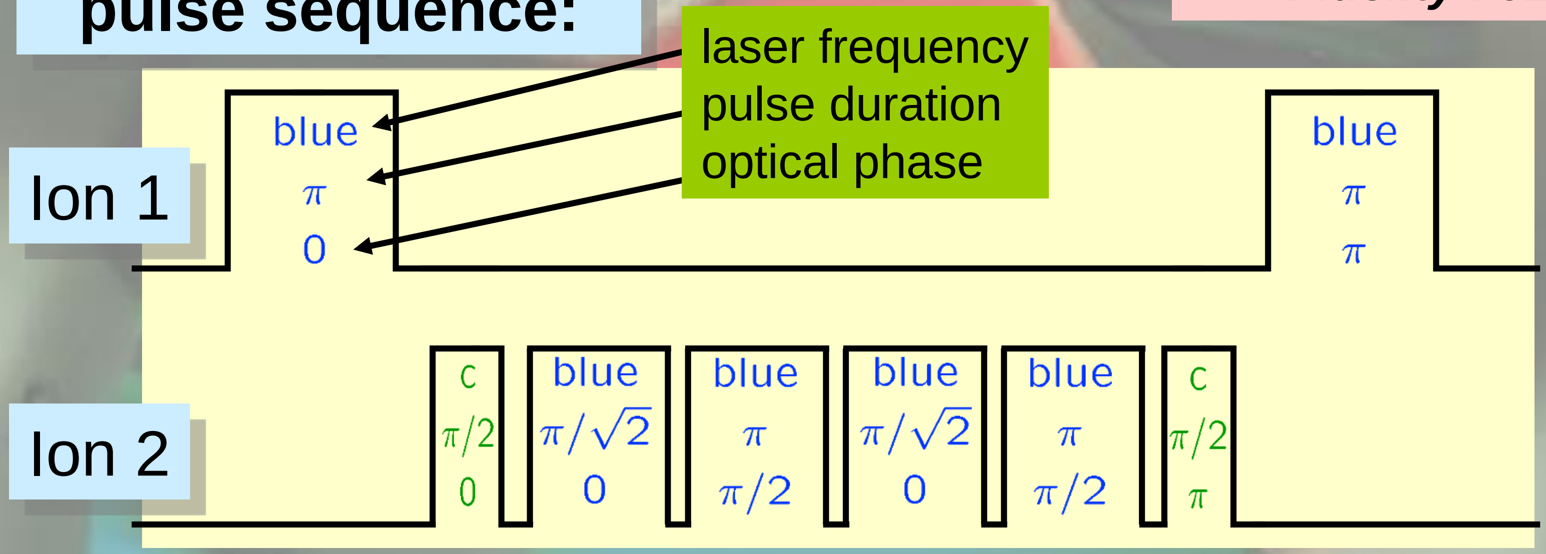


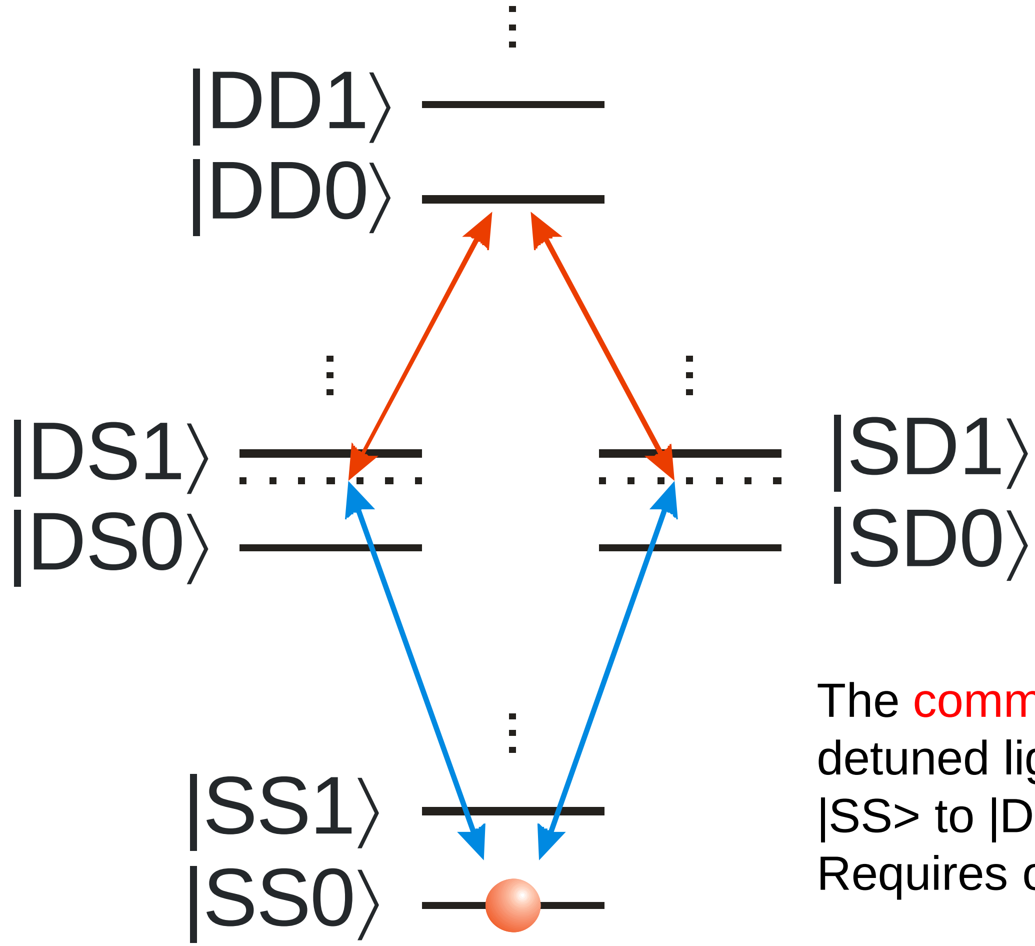
*M. Riebe et al., PRL **97**, 220407 (2006)*
Fidelity : 92,6%

pulse sequence:



Mølmer-Sørensen gate

Milburn, arXiv:quant-ph/9908037.
*Milburn, Schneider, and James, Fortschr. Phys. **48**, 801 (2000).*
*Sörensen and Mölmer, PRL **82**, 1971 (1999).*
*Sörensen and Mölmer, PRA **62**, 022311 (2000).*

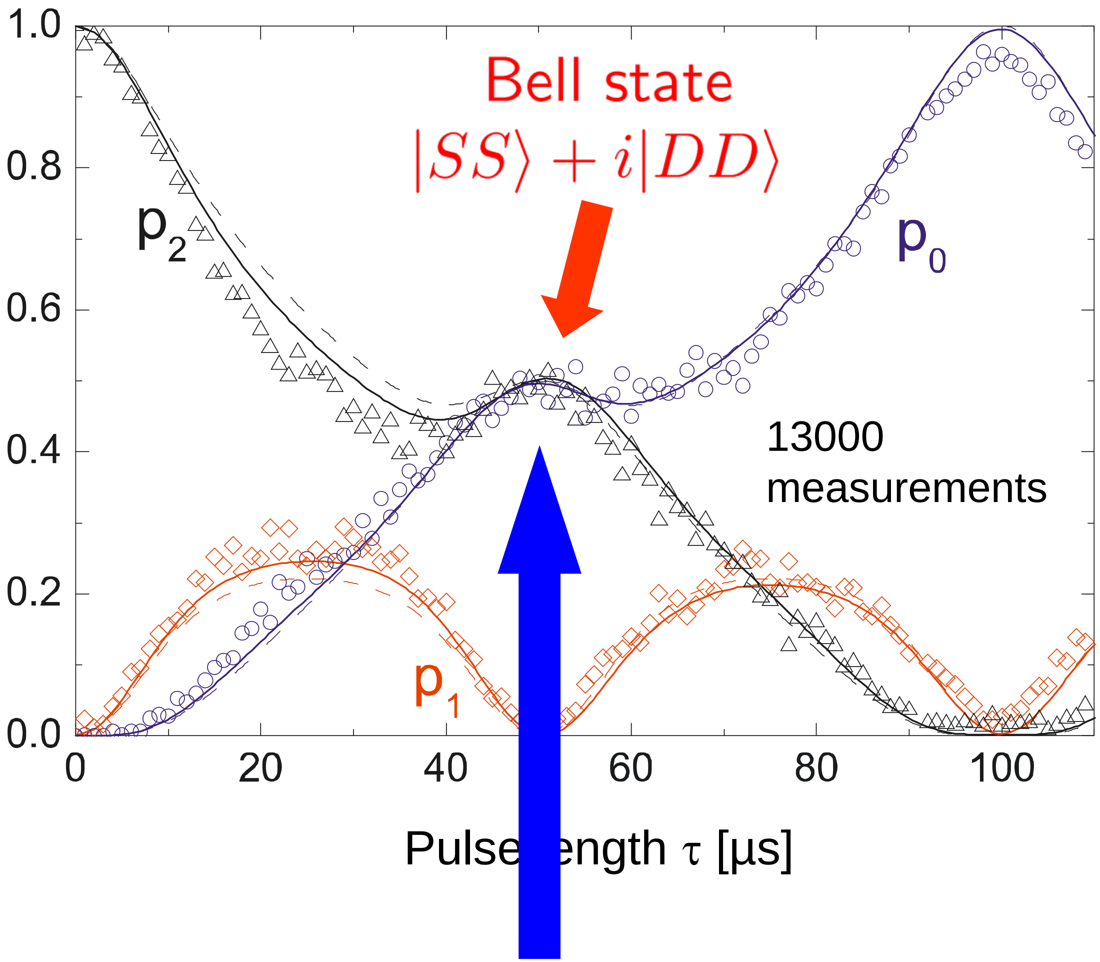


The common absorption of red and blue detuned light leads to a coherent evolution |SS> to |DD>. No excitation of |DS> states.
Requires only Lamb Dicke limit $\eta\sqrt{n_{ther.}} << 1$

Bell state with F=83%
*Sackett et al., Nature **406**, 256 (2000)*

Bell state with F=99.3%
Benhelm et al, Nature Phys. 4, 463 (2008)

Mølmer-Sørensen evolution



p_0+p_2 = 0.9965(4)

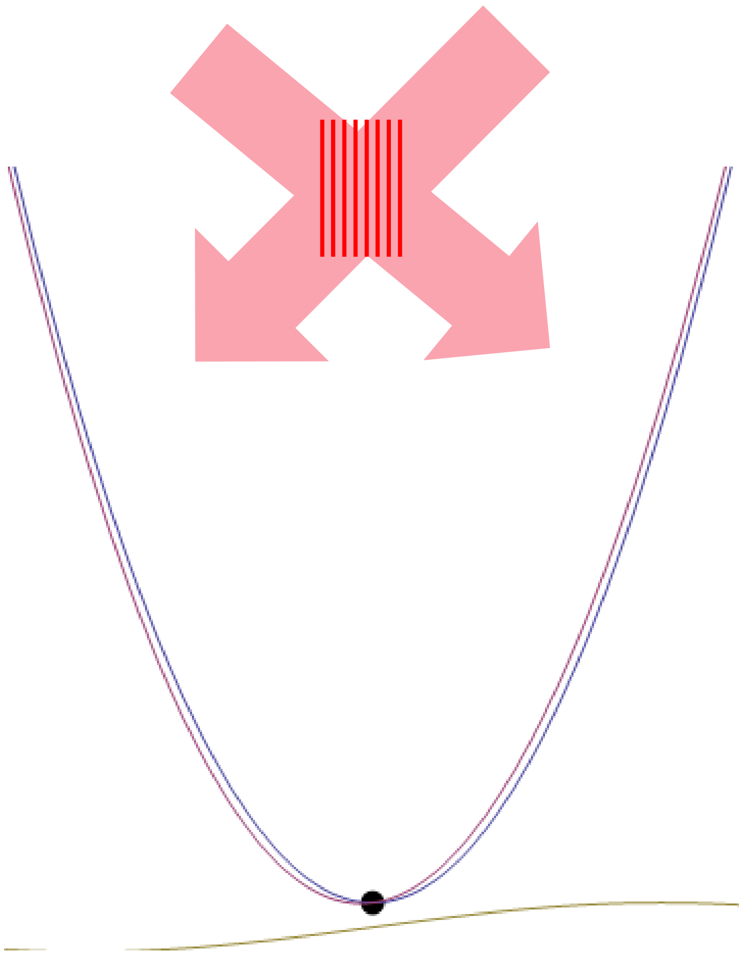
Probabilities

- $p_0 \equiv p(|DD\rangle)$
- $p_1 \equiv p(|SD\rangle) + p(|DS\rangle)$
- $p_2 \equiv p(|SS\rangle)$

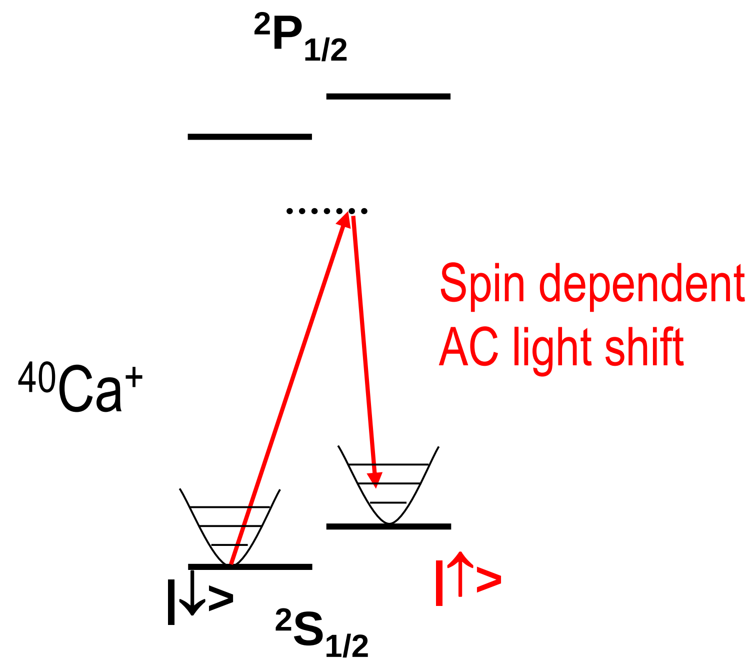
Detuning δ = 20 kHz
→ gate time 50 µs

Benhelm, Kirchmair, Roos, Blatt
Nat. Phys. 4, 463 (2008)

Spin-dependent Light force: single ion case



Excitation of the common motion in a running standing wave



Monroe, et al, Science 272, 1131 (1996)

*McDonnell et al. Phys. Rev. Lett. **98**, 063603 (2007)*

*Poschinger et al, PRL**105**, 263602 (2010)*

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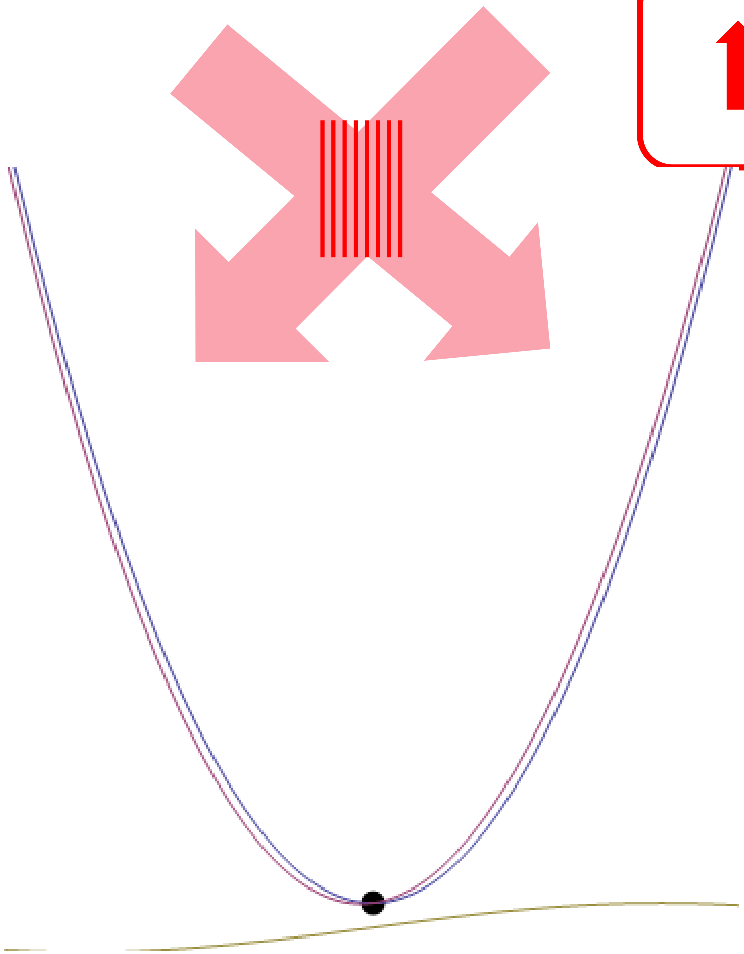
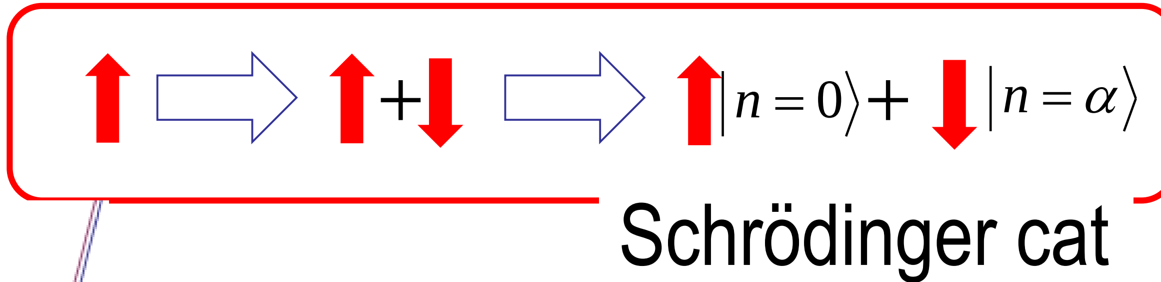
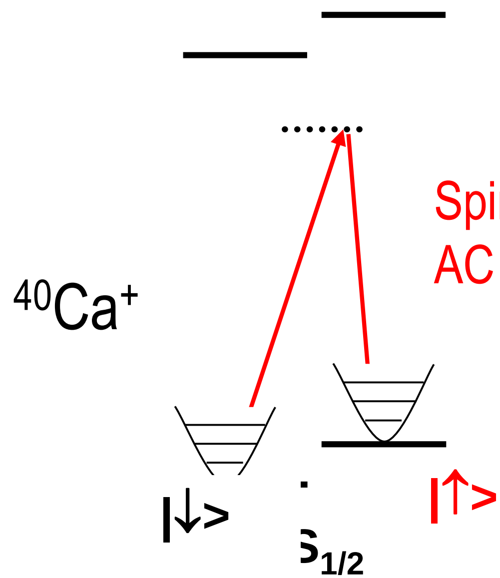






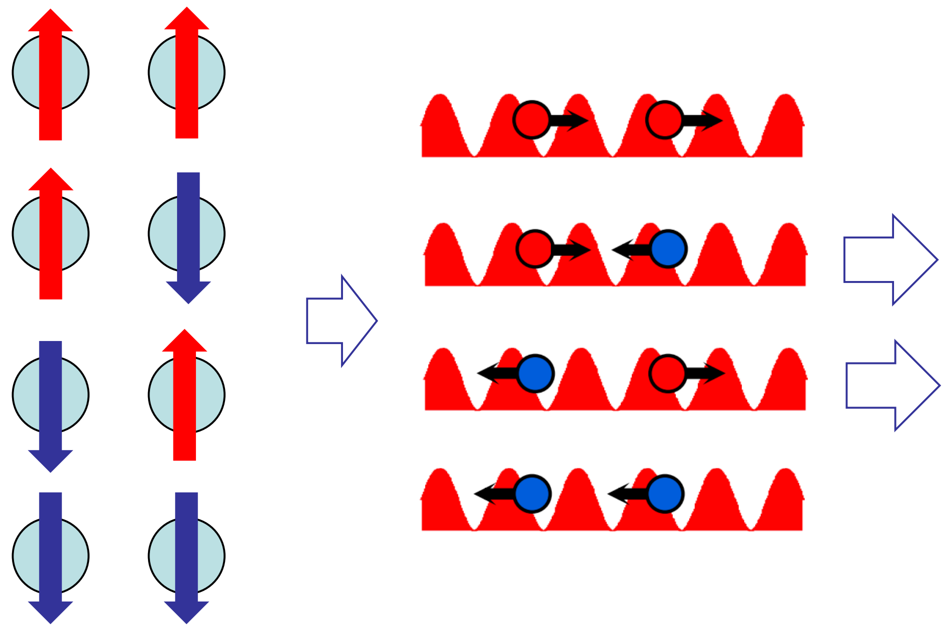
Excitation of the common motion in a running standing wave

Monroe, et al, Science 272, 1131 (1996)

McDonnell et al. Phys. Rev. Lett. ***98****, 063603 (2007)*

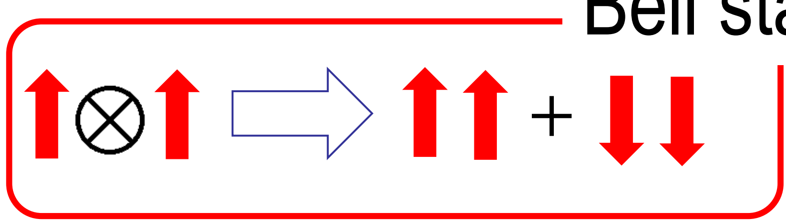
*Poschinger et al, PRL****105****, 263602 (2010)*

Spin-dependent Light force: two ion case



Only this spin configuration couples to the breathing mode → Spin-spin interaction

Bell state



Geometric gate

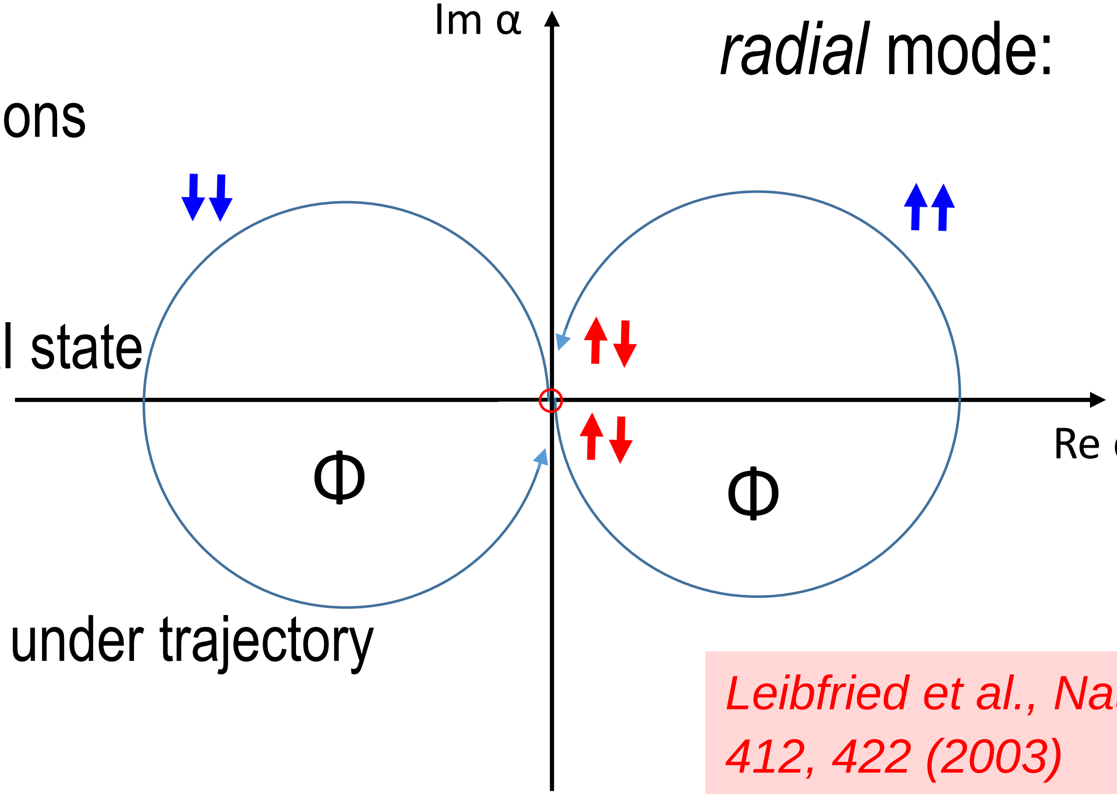
- Only even spin configurations are displaced

- Vibr. mode returns to initial state after time $t_{gate}=2\pi/\delta$

- Only even states pick up geometric phase of Φ : area under trajectory

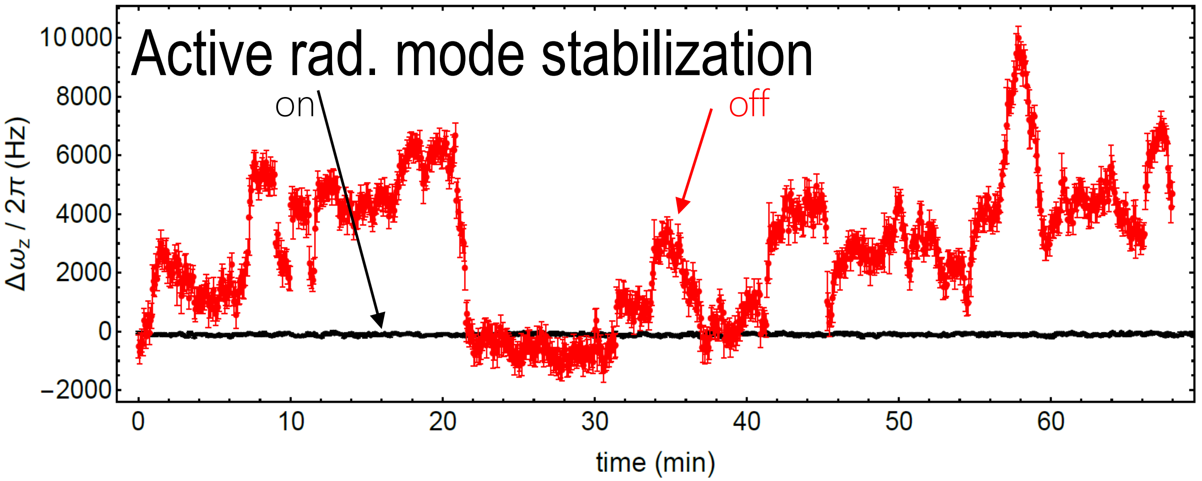
- Bell state generated
- 99.5(1)% fidelity

Phase space of *radial* mode:

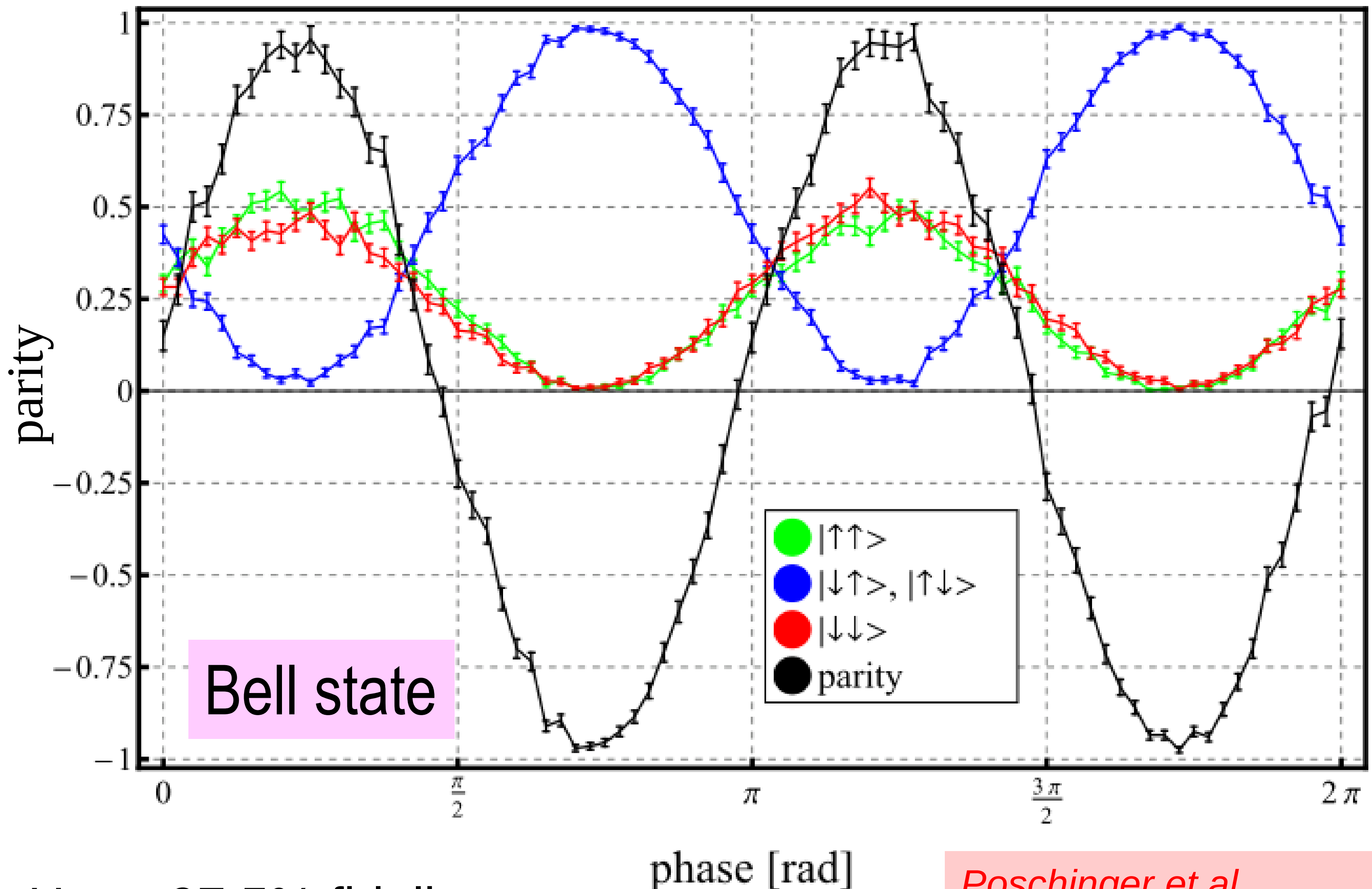


Leibfried et al., Nat. 412, 422 (2003)

rad. mode:
$\Delta n=2.7(9)$/sec
$\Delta\omega=20$ Hz @ 4.4 MHz



Two ion entanglement – parity oscillations



Here: 97.5% fidelity

*Poschinger et al., PRL**105**, 263602 (2010)*

Gate error budget

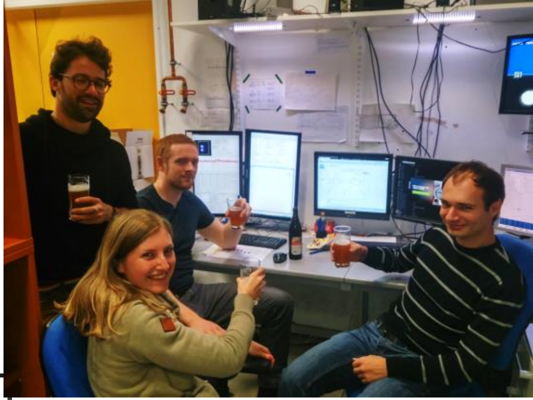
Error type	Current (%)	Countermeasure	Prospective (%)
Gate detuning	0.3	composite pulses	<0.01
Mis-set laser power	0.04	improved calibration	<0.01
Unequal illumination	0.002	-	-
Thermal occupation	0.01	improved cooling	<0.01
Heating	0.01	cryogenic trap, noise supp.	<0.01
Motional dephasing	0.1 .. 1.0	tech. noise suppression	N/A
Anharmonic coupling	0.1	spectator mode cooling	N/A
Scattering	>1.0	20 x laser power	<0.05
Osc. light shift	<0.7	pulse shaping	<0.01
Spectator excitation	<0.3	pulse shaping	<0.01
Laser intensity noise	<0.01	-	-

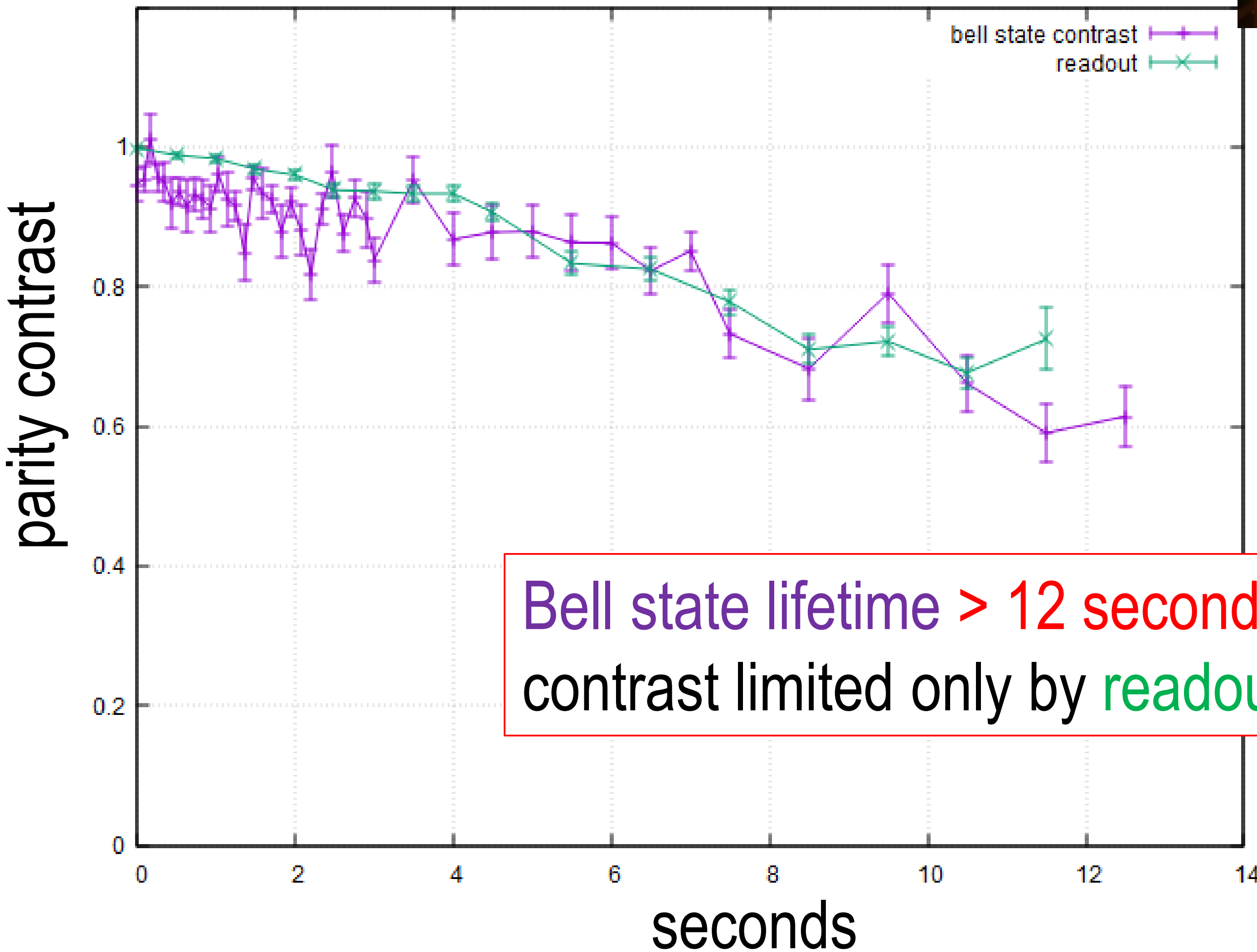
Best two-qubit fidelity: 99.9%
Gate times: 20μs…100μs

Benhelm et al., Nature Physics 4, 463 (2008)
Ballance et al., PRL 117, 060504 (2016)
Gaebler et al., PRL 117, 060505 (2016)

Bell state coherence

$$\psi = |\downarrow\rangle|\uparrow\rangle + e^{i\phi}|\uparrow\rangle|\downarrow\rangle$$



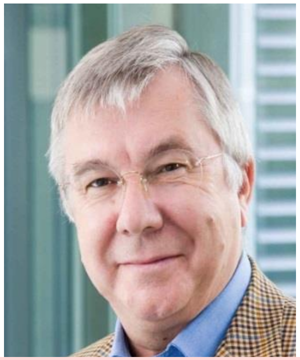


Fidelity 99.6%

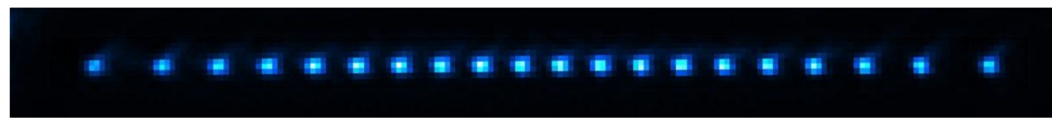
Bell state lifetime > 12 seconds,
contrast limited only by readout infidelity

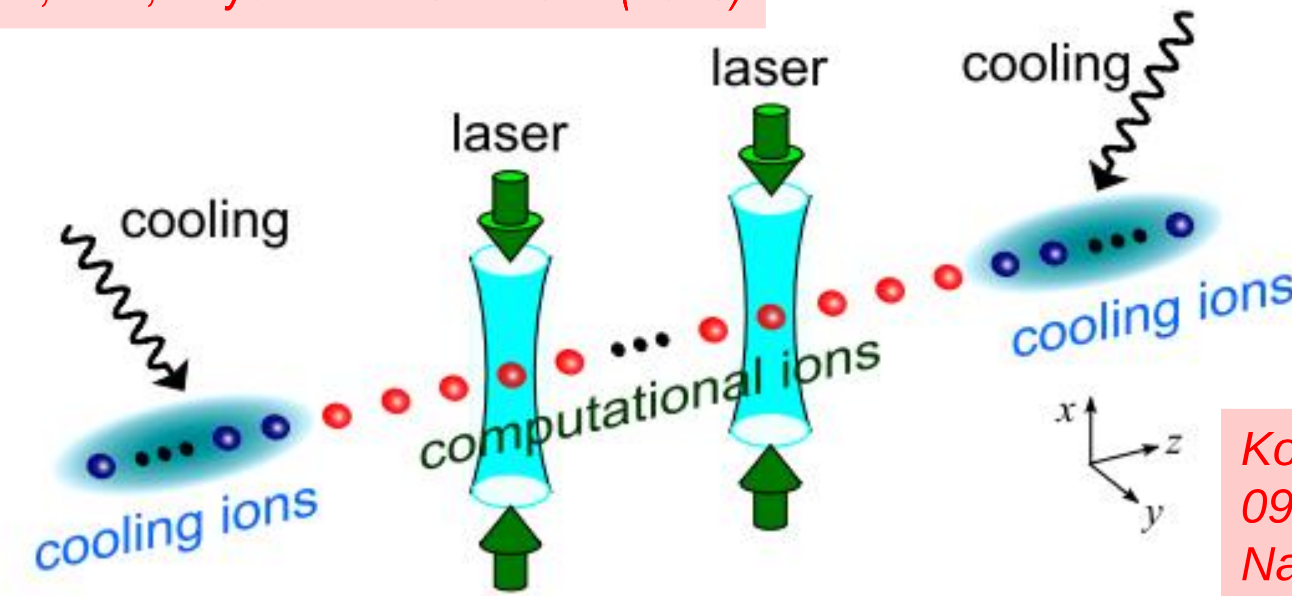
Scalable trapped –ion qubit architectures

Long linear crystals & Individual single ion addressing



Nägerl, et al, PRA 60, 145 (1999)
Schindler et al, NJP 15 123012 (2013)
Friis, et al, Phys Rev X. 8 021012 (2018)

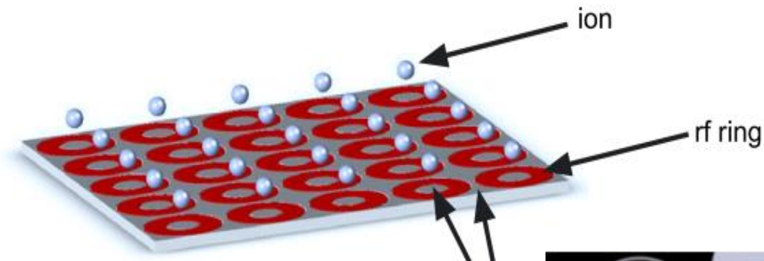


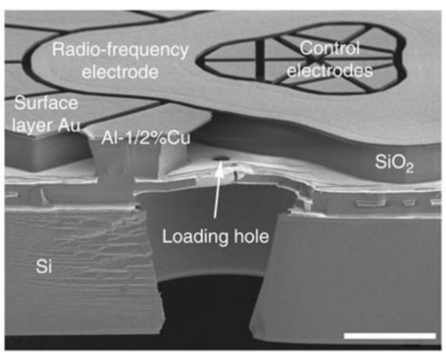


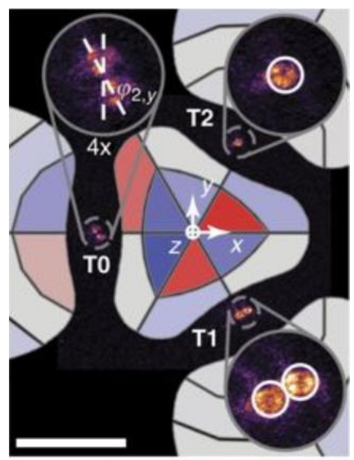
Korenblit et al, NJP 14, 095024, Debenath et al, Nature 536, 63 (2016)

Scaling up trapped ion quantum simulation in 2D

Planar trap arrays

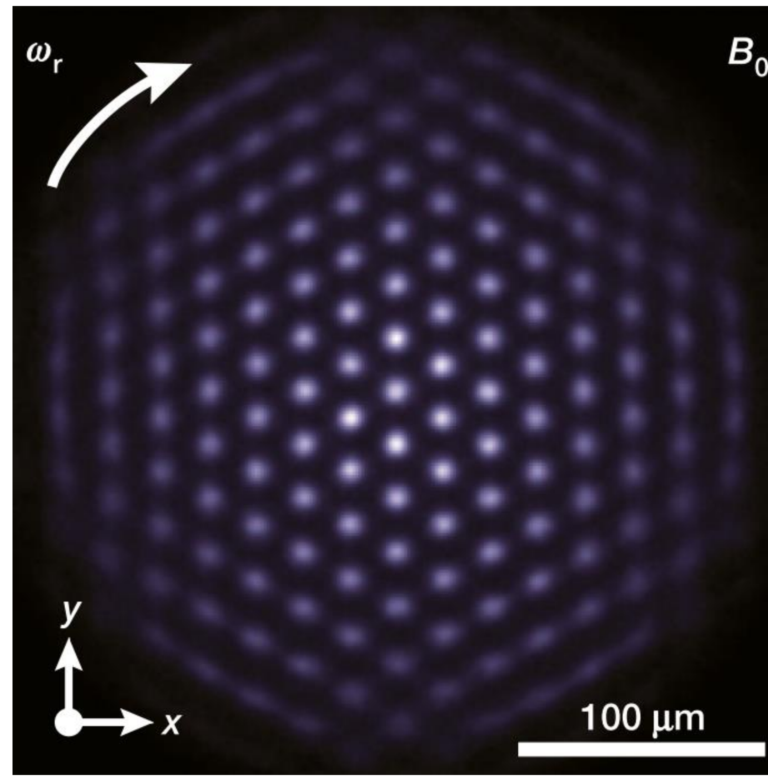






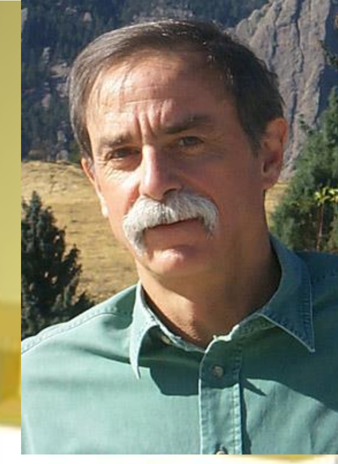
Brownutt et al, NJP 13 073043,
Schmid et al, NJP 13, 115011
Mielnz et al., Nat. Com. 7, 11839

Self assembled two-dim. ion crystals in a Penning trap



Britton et al, Nature 484, 489 (2012)

Dave Wineland – vision of scalabe QC using shuttles in segmented ion traps



Laser pulses generate entangled states

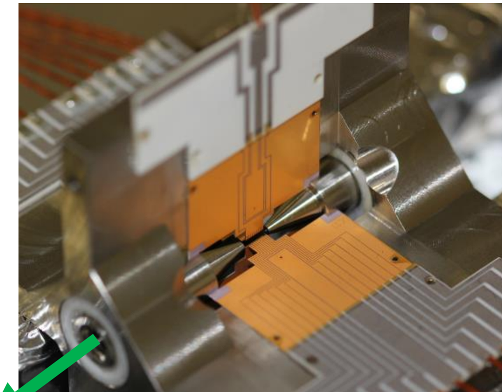
Segmented Micro trap allows controlling the ion positions

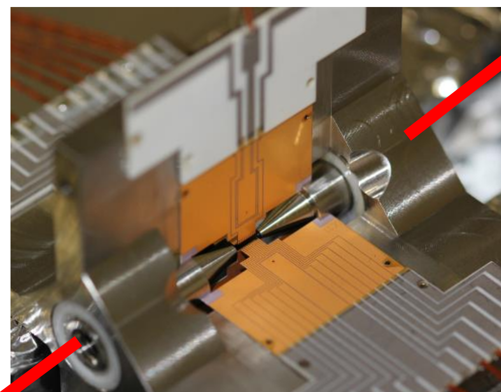
DIVIDE ET IMPERA

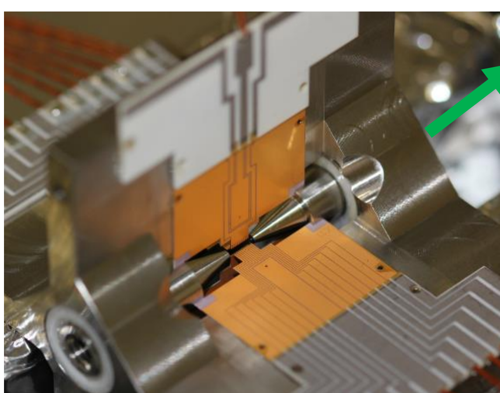
Kielpinski et al., Nature 417, 709 (2002)

Dynamically interfaced ion crystals

Segmented modules, # ≤ 30 qubits with multiple laser interaction zone, optical addressing







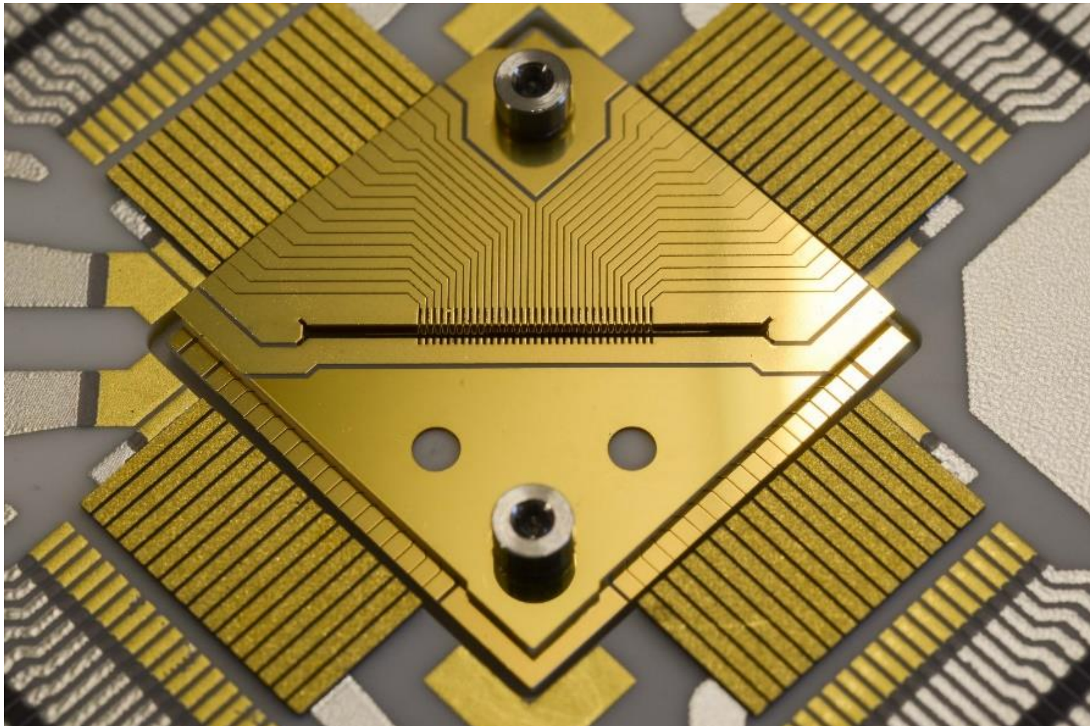
qubit distribution between traps by ion transports, teleportation

EU flagship: Advanced QC with trapped ions

AQTION

Our goal: A scalable 50-qubit QC based on scalable industry standards ...

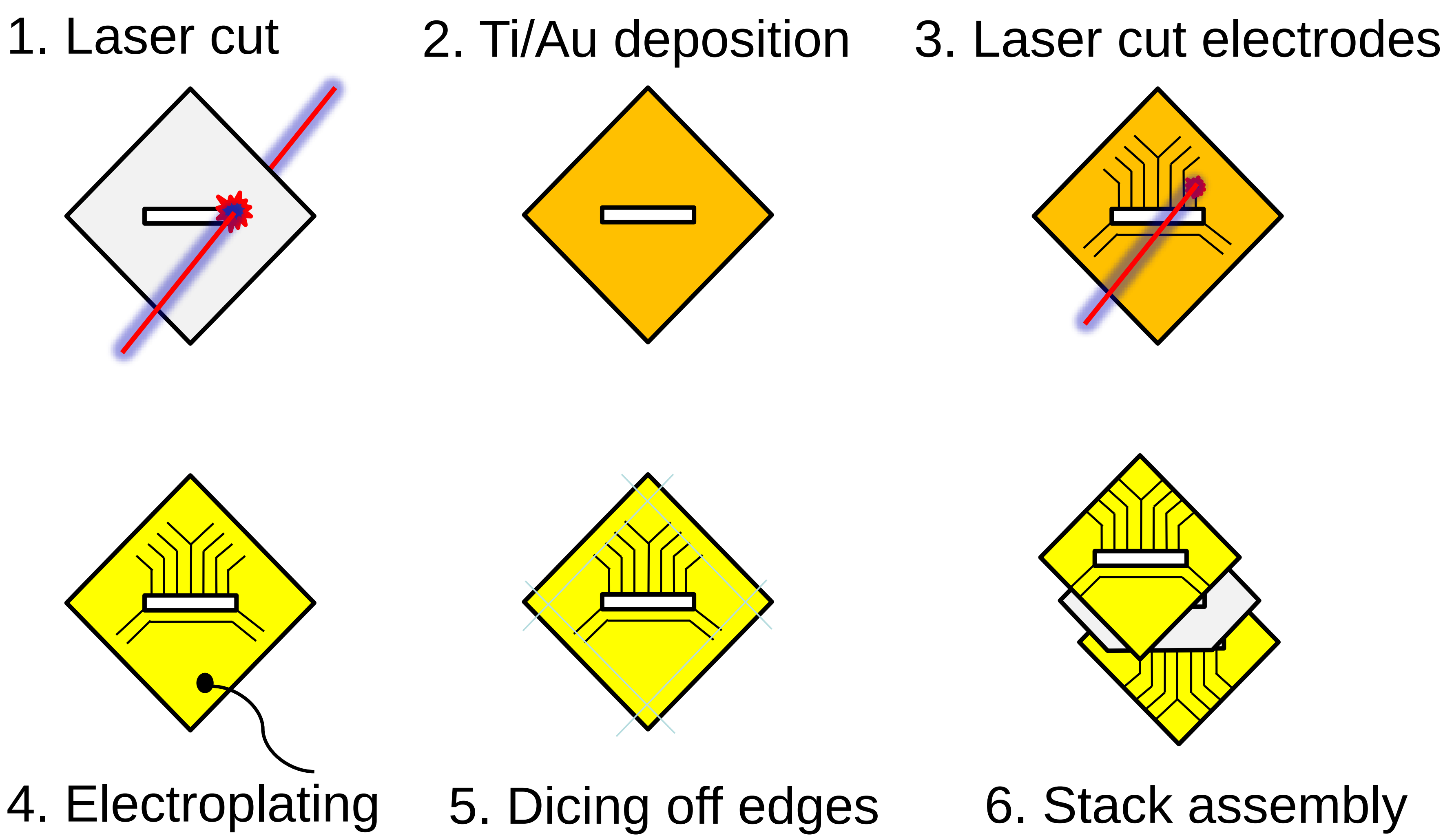
High performance multi-layer ion trap



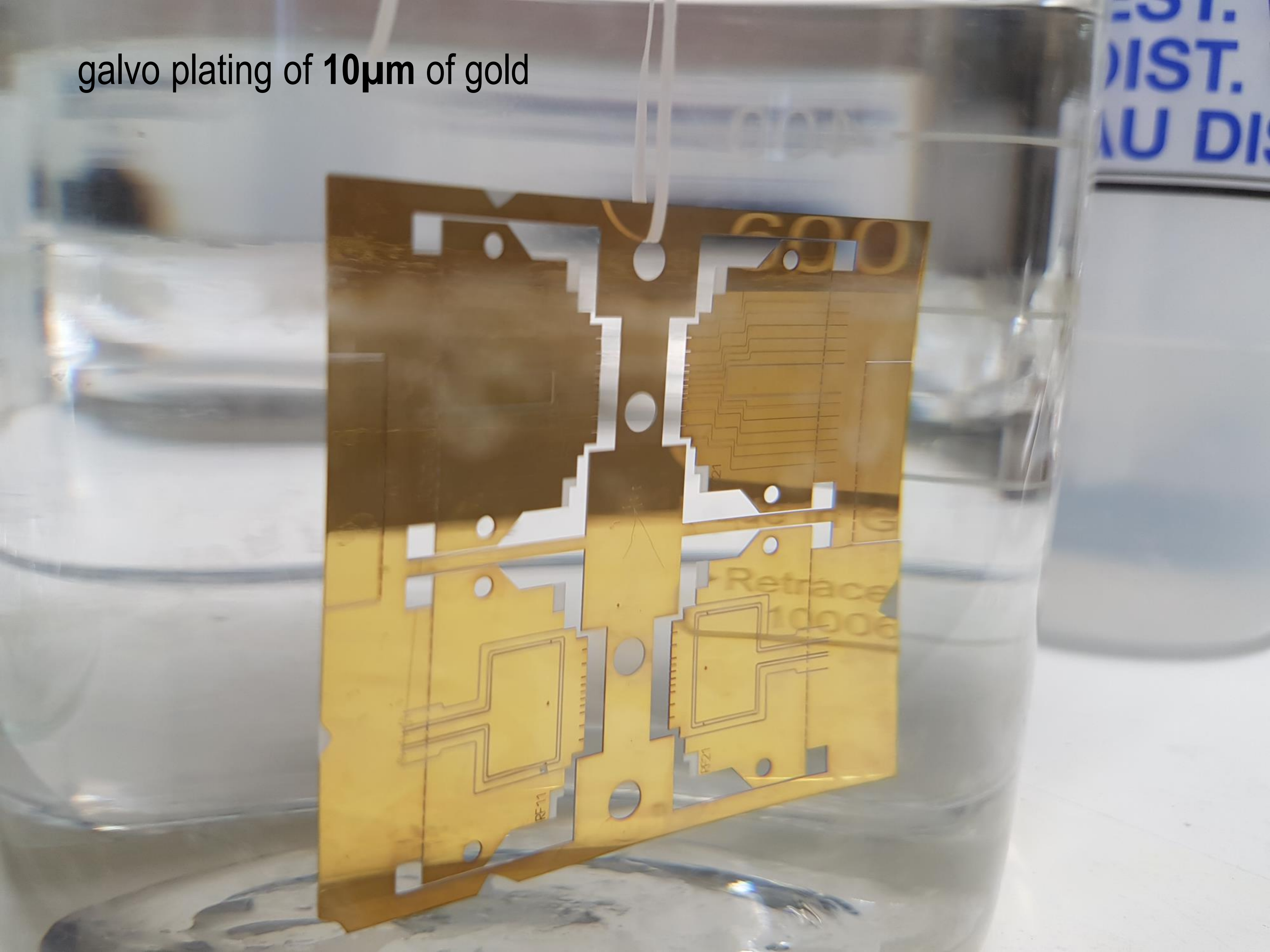
Fabrication
- Laser-cutting of Alumina
- Gold evap./galvoplating
- 32 segment pairs of uniform geometry
- Bonding to capacitor arrays

Performance
- 1.5 MHz axial trap frequency @-6V segment voltage
- Lowest heating rate: 3 phonon/s @ 4 MHz radial trap frequency
- 1 day trapping times

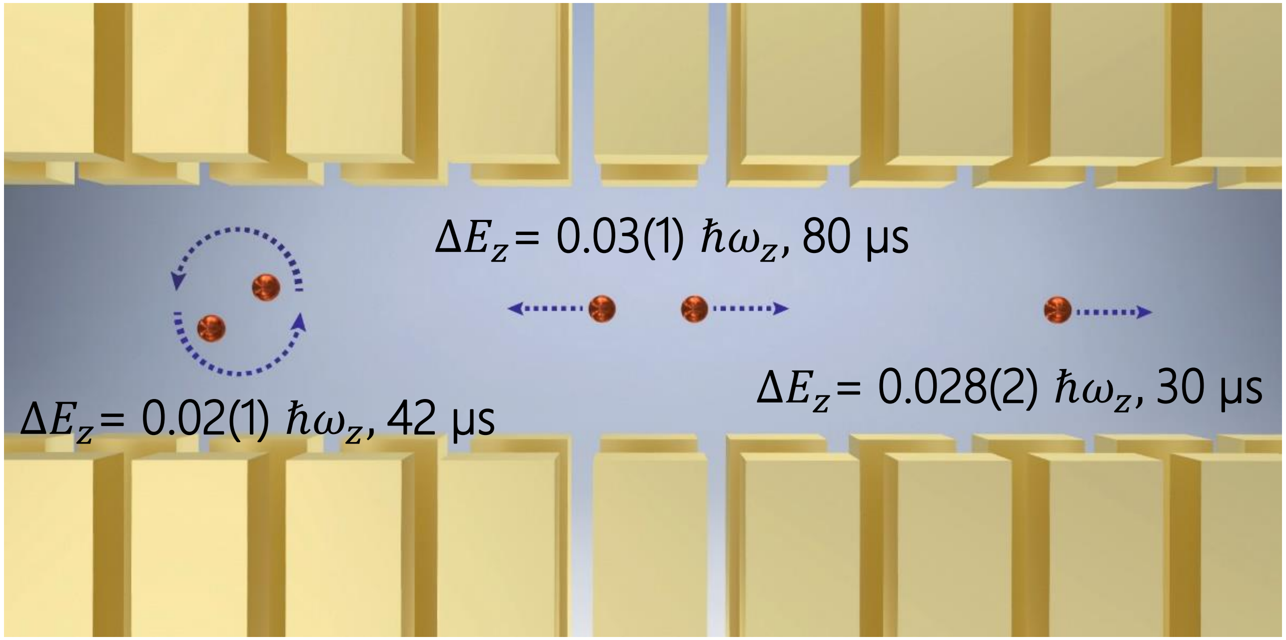
Fabrication of micro traps



galvo plating of **10µm** of gold



Ion movement – qubit register reconfigration

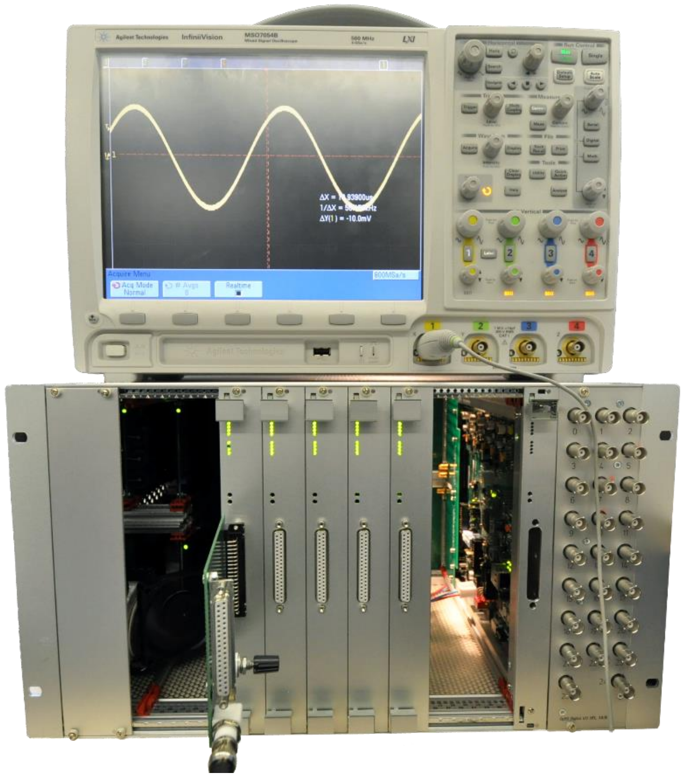


- Shuttle ion crystal
- Separate two-ion crystal
- Merge into two-ion crystal
- Swap ion positions
- Shuttle single ion

Geometric phase gate
99.5(1)% fidelity on *radial* mode

Walter et al., PRL109, 080501 (2012)
Kaufmann et al, NJP 16, 073012 (2014)
Kaufmann et al, RPA 95, 052319 (2017)

Multichannel arbitray waveform generator



DIGITAL

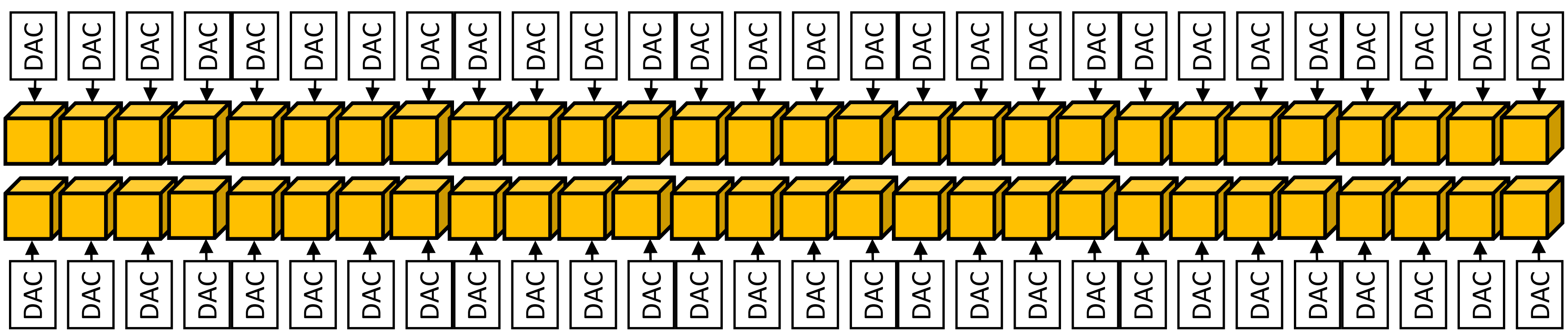
Xilinx ZedBoard

- 128 digital channels
- 10ns update time
- Up to 1 GB memory depth

ANALOG

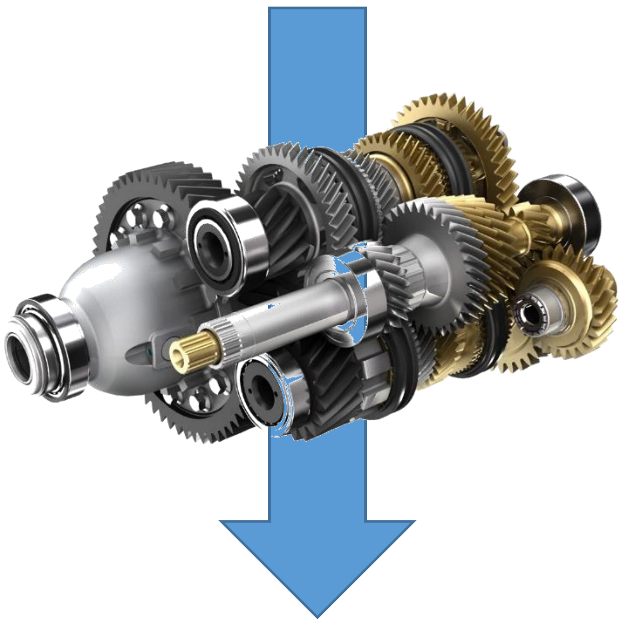
AD5541A single DACs

- 400ns uniform update
- Output range -40V..+40V
- Slew rate ~12V/µs
- Glitch impulse 13 nV ·s



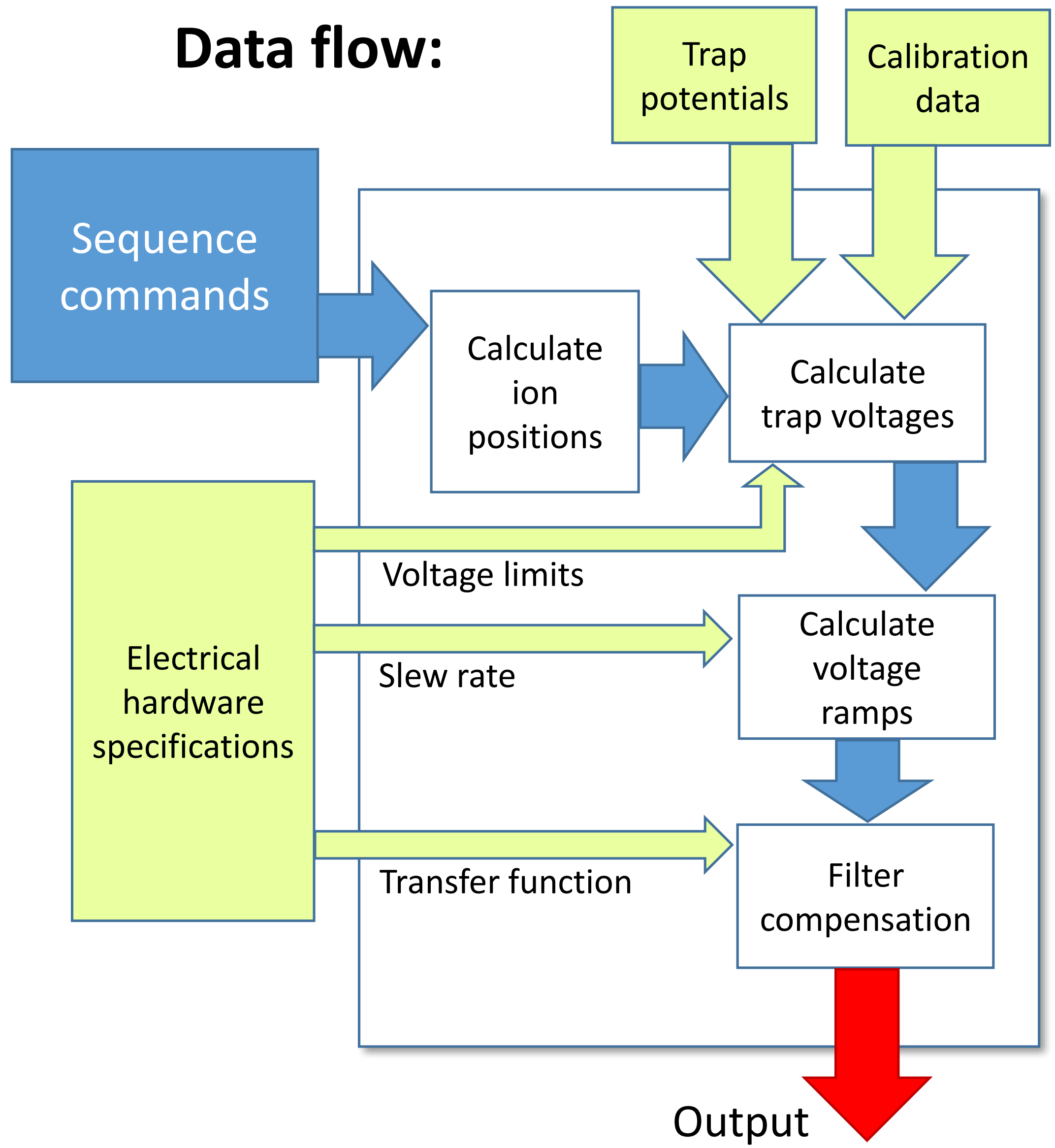
Qubit register reconfiguration control

High level QIP command

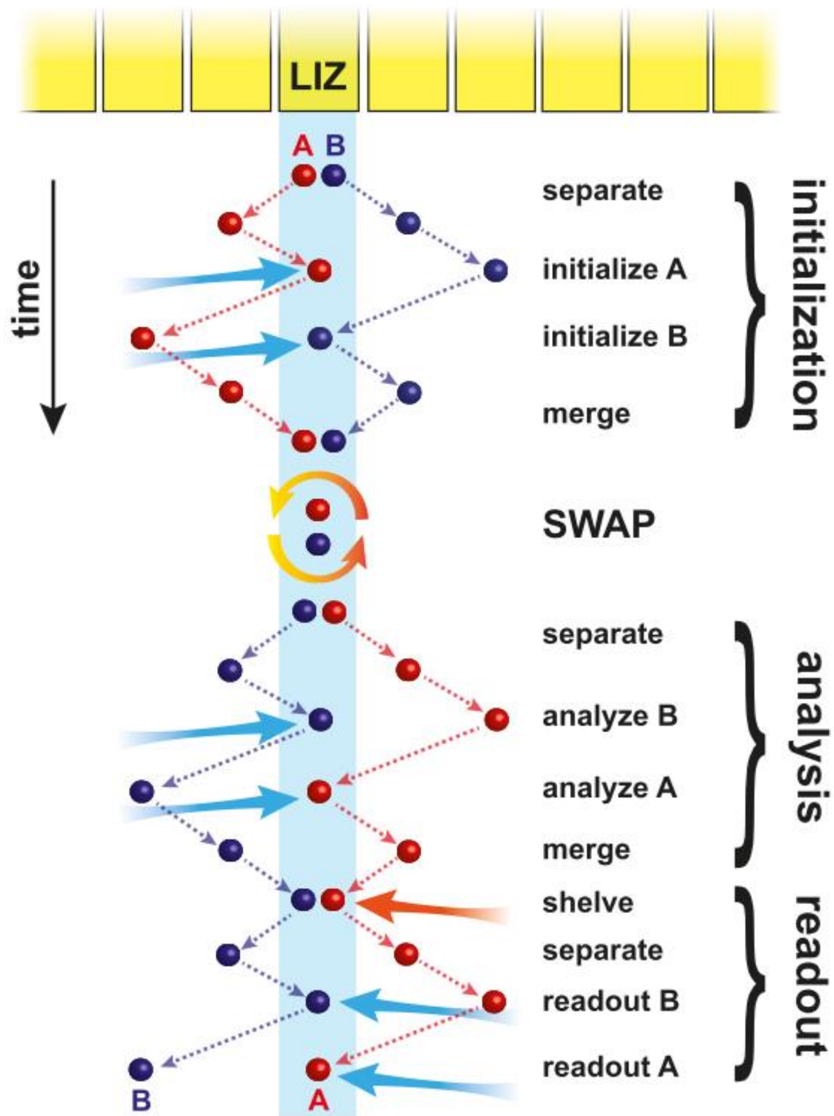


Shuttling voltage ramps
- Technical constraints
- Low motion excitation
- Optimum speed

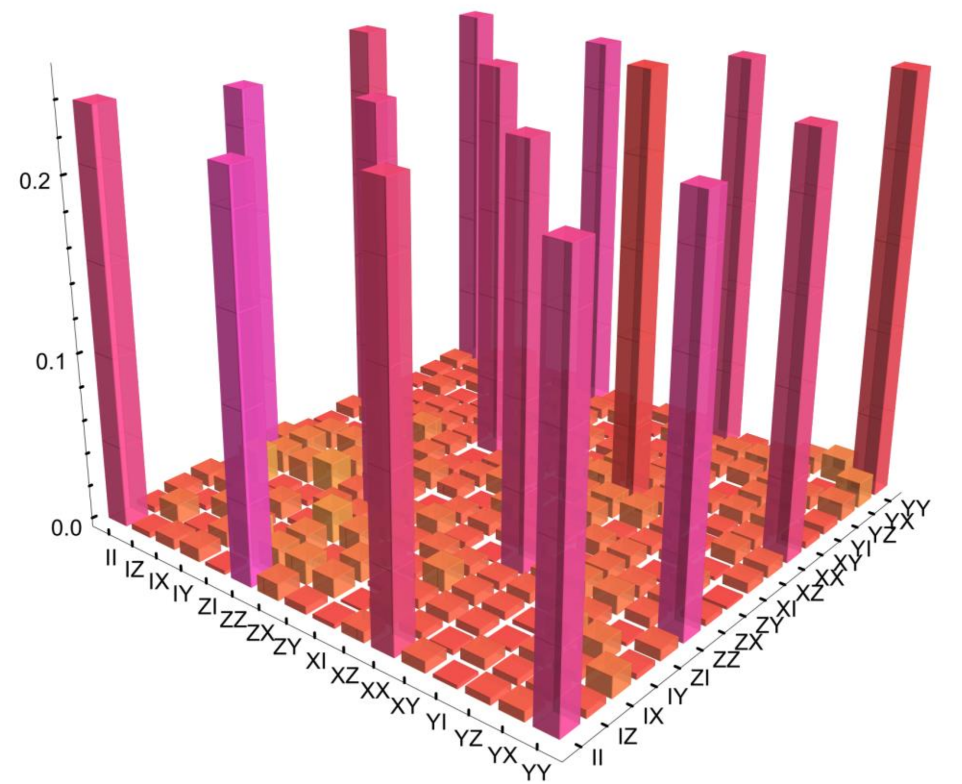
Data flow:



2- and 3-qubit shuttle and swapping



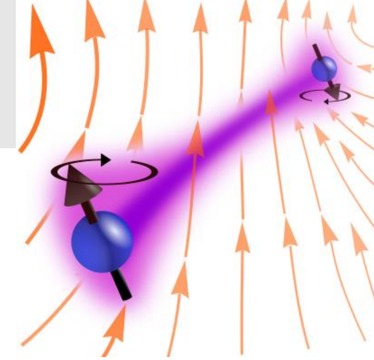
Process tomography data



mean process fidelity 99.96(13)%

Kaufmann et al., PRA 95, 052319 (2017)

B-Field Sensing with entangled ions



1. Prepare entangled sensor state

$$|\Psi\rangle = |\uparrow\downarrow\rangle + |\downarrow\uparrow\rangle$$

2. Accumulate phase

$$|\Psi\rangle = |\uparrow\downarrow\rangle + e^{i\varphi}|\downarrow\uparrow\rangle$$

Linear Zeeman effect:

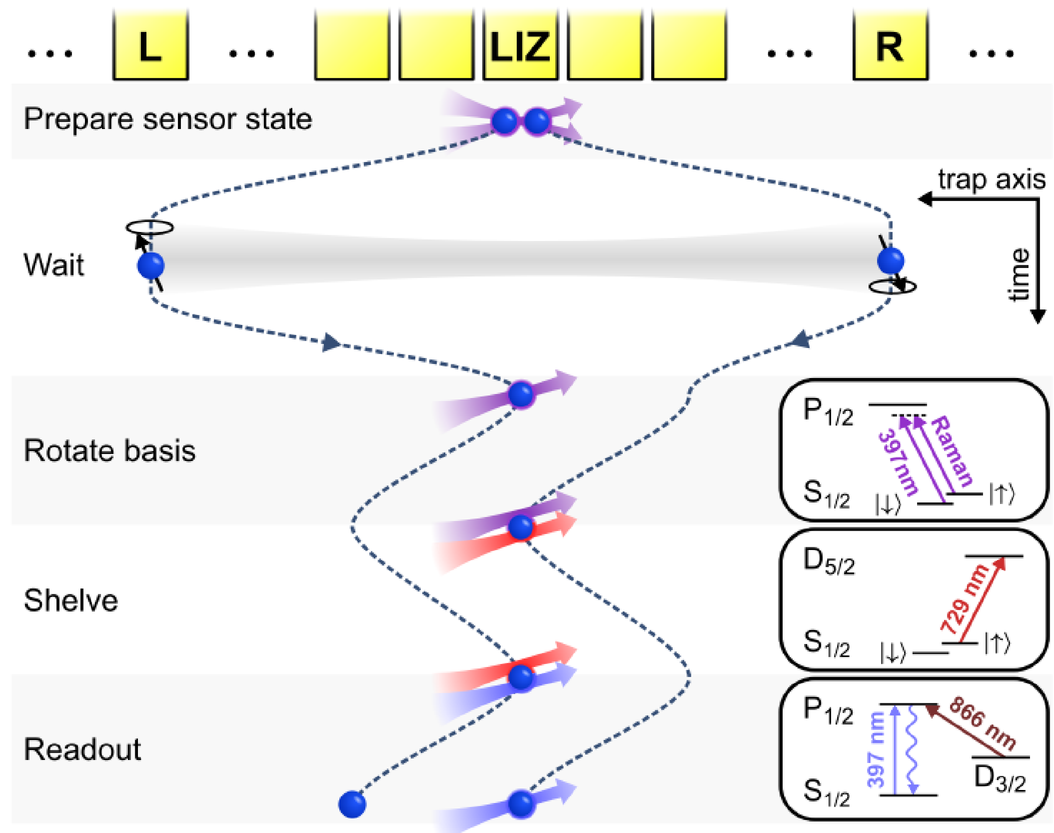
$\Delta B(x_1, x_2) = \frac{\hbar}{g\mu_B}\dot{\varphi}$ caused by inhomogeneous B-field

Interrog. time T = 0 – 3.1 s

3. Individual state readout

Estimate relative phase φ

Use Bayes experimental design for optimum information gain



Ruster et al, PRX 7, 031050 (2017)

Mapping the magnetic field

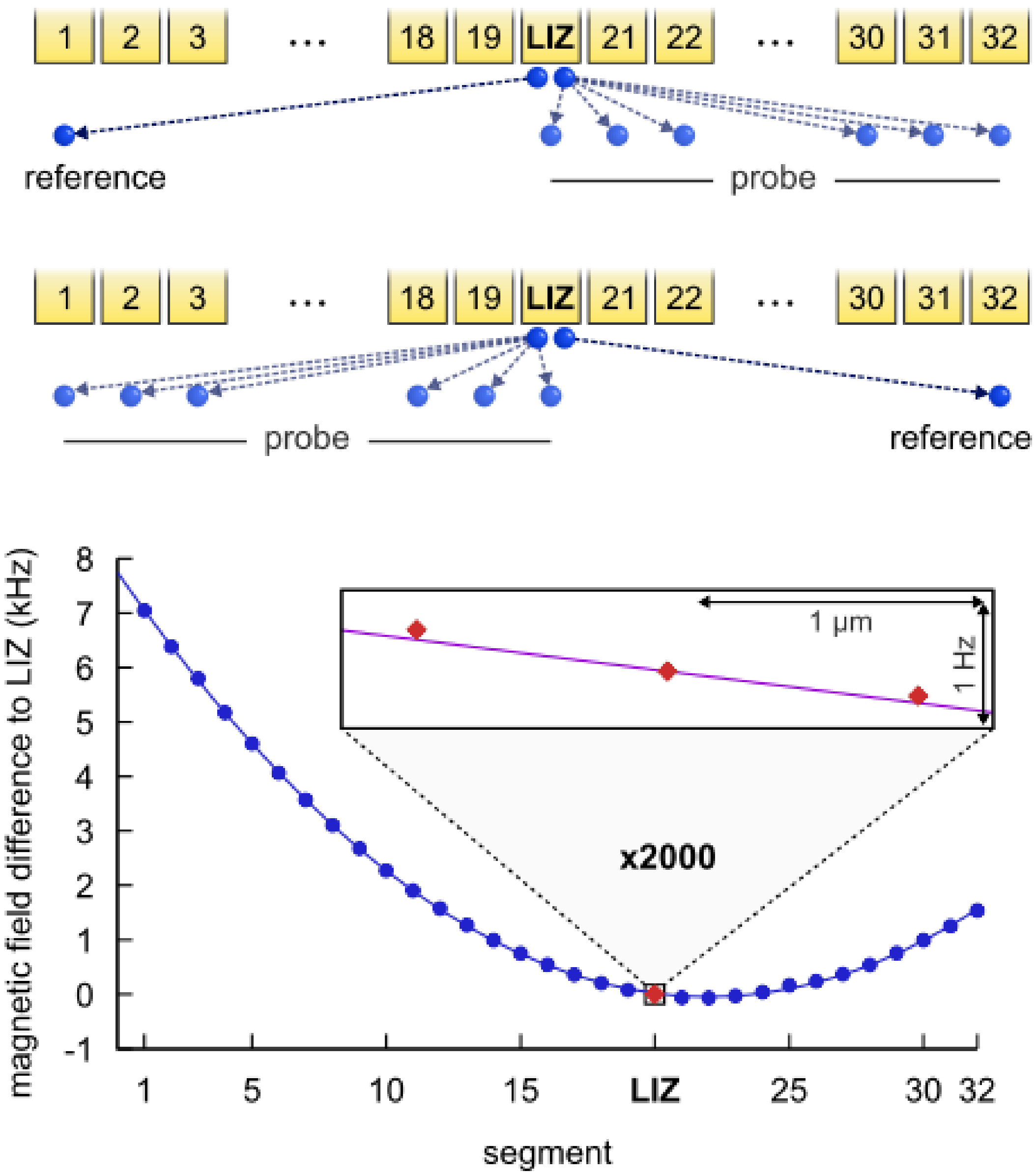
Seconds of coherence time

Sensitivity: 12pT / √ Hz

Separated entanglement, nano-positioning within µs

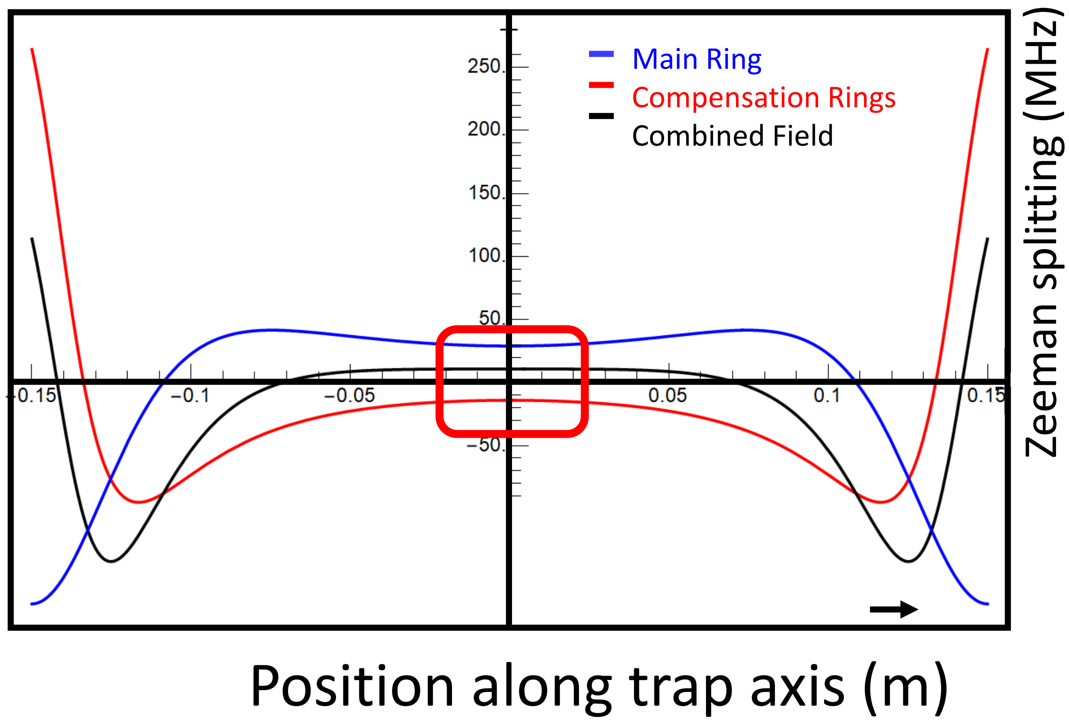
Range: 6mm

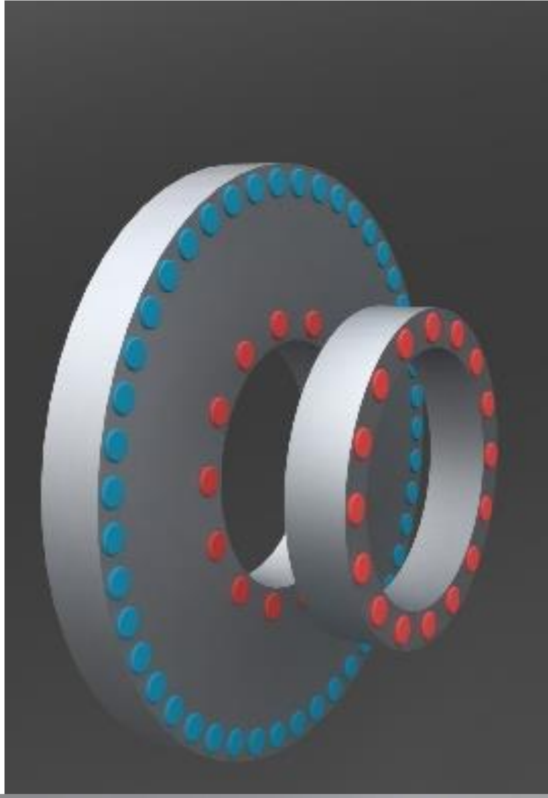
Wavepaket Δx ~10nm
High spatial resolution

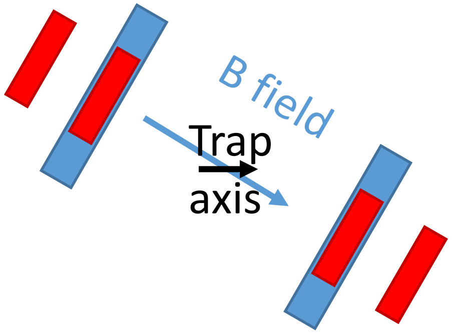


Ruster et al, PRX 7, 031050 (2017)

Inhomogeneity cancellation







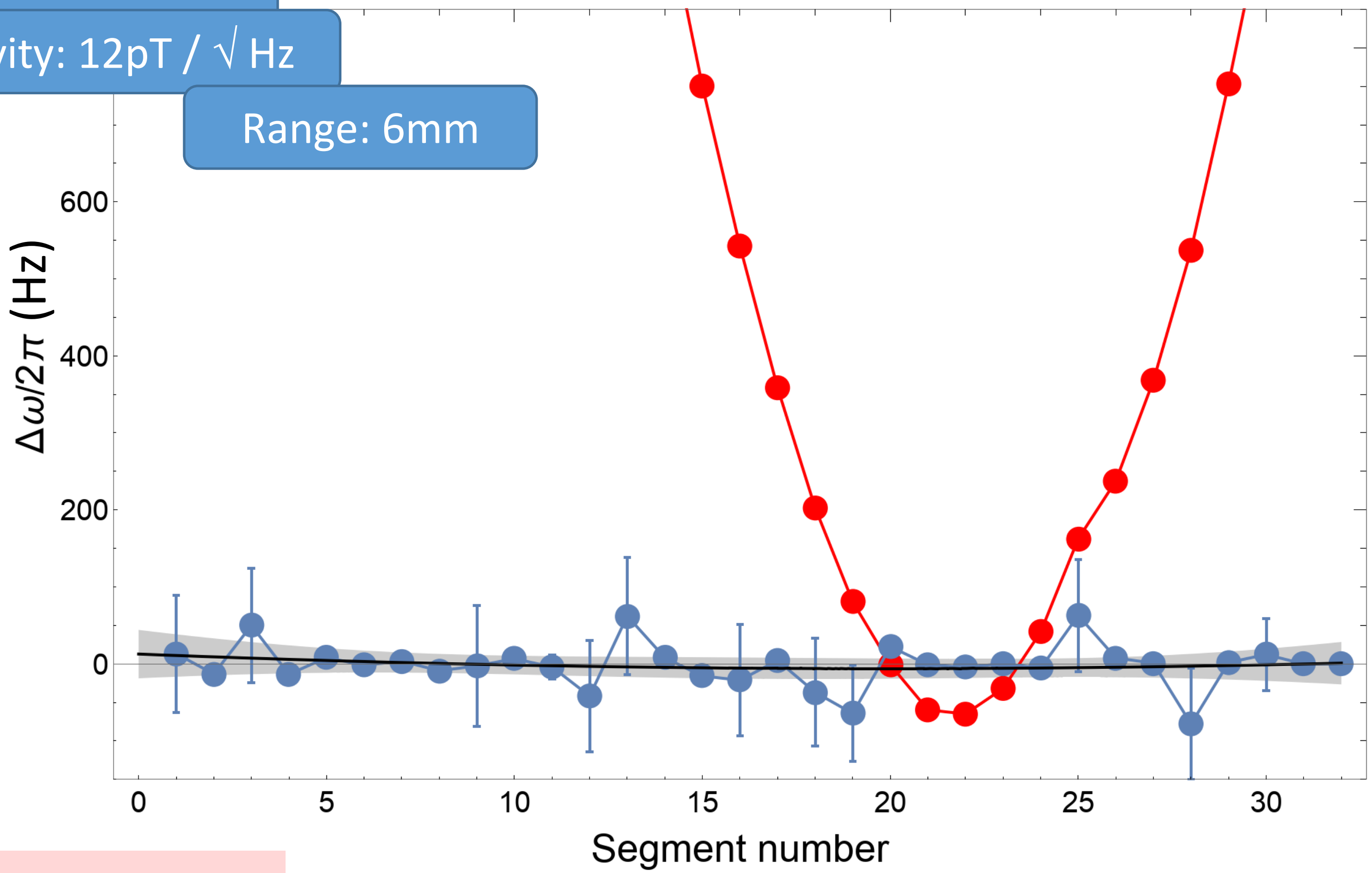
Inhomogeneity cancellation

- Inhomogeneity consistent with zero!
- $\Delta\omega < (2\pi)40$ Hz for outermost segments (1σ)
- No shuttling-induced phase compensation required
- Automatic tracking of frequency drifts, B-field, ….

Seconds of coherence time

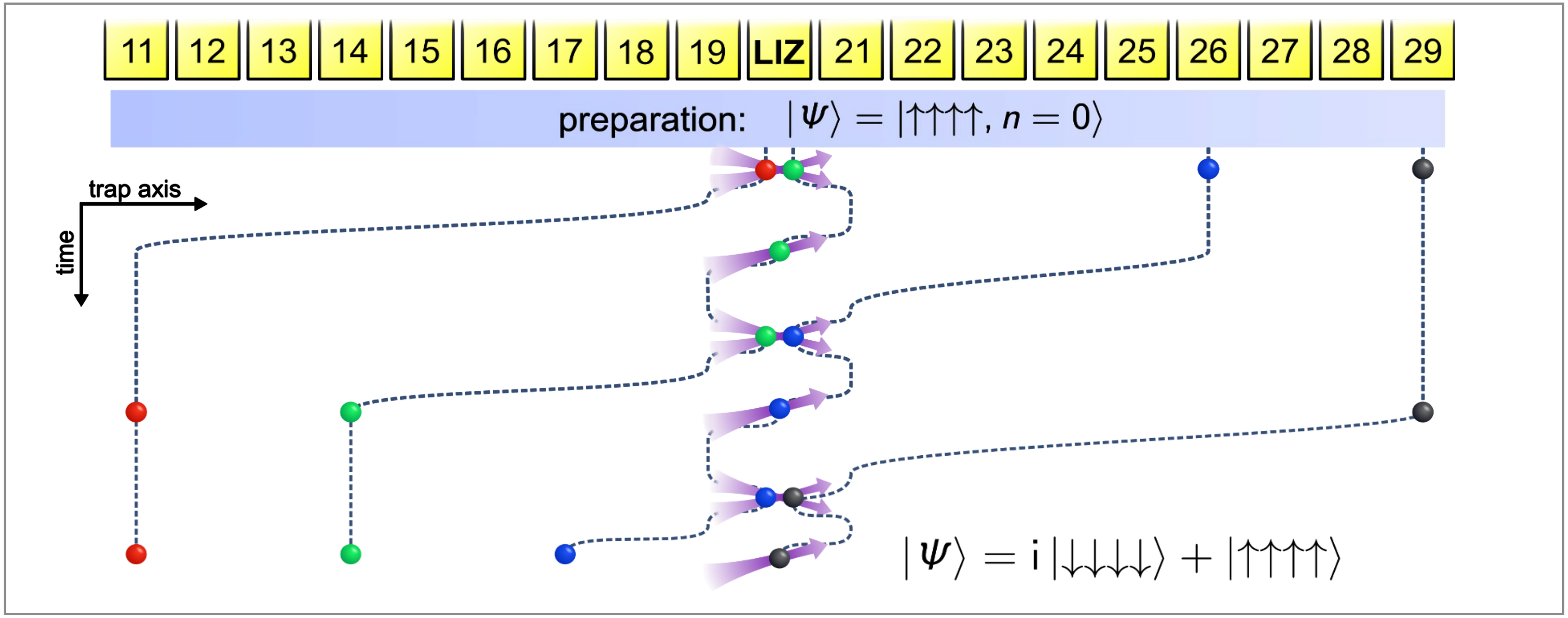
Sensitivity: 12pT / √ Hz

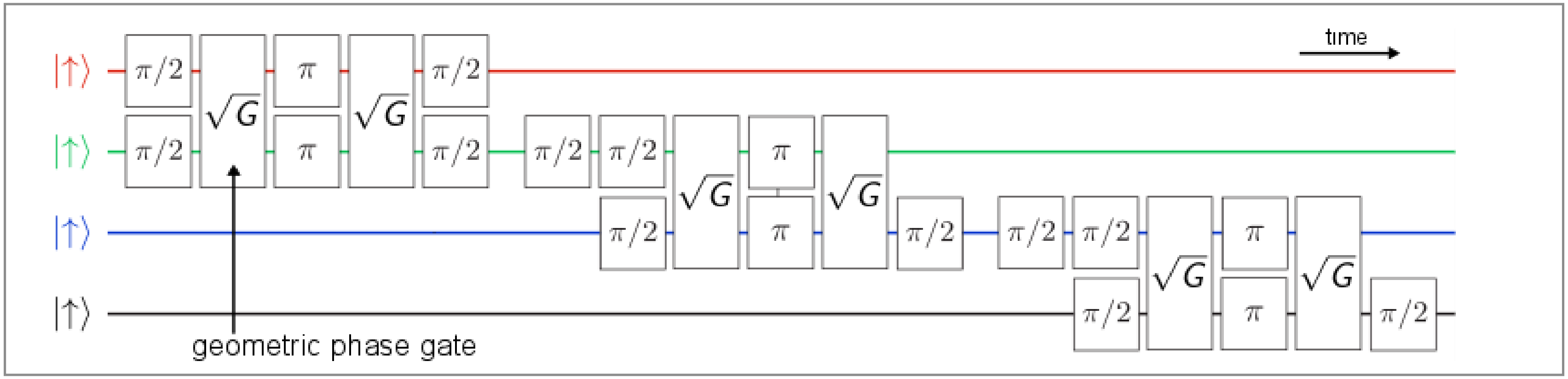
Range: 6mm



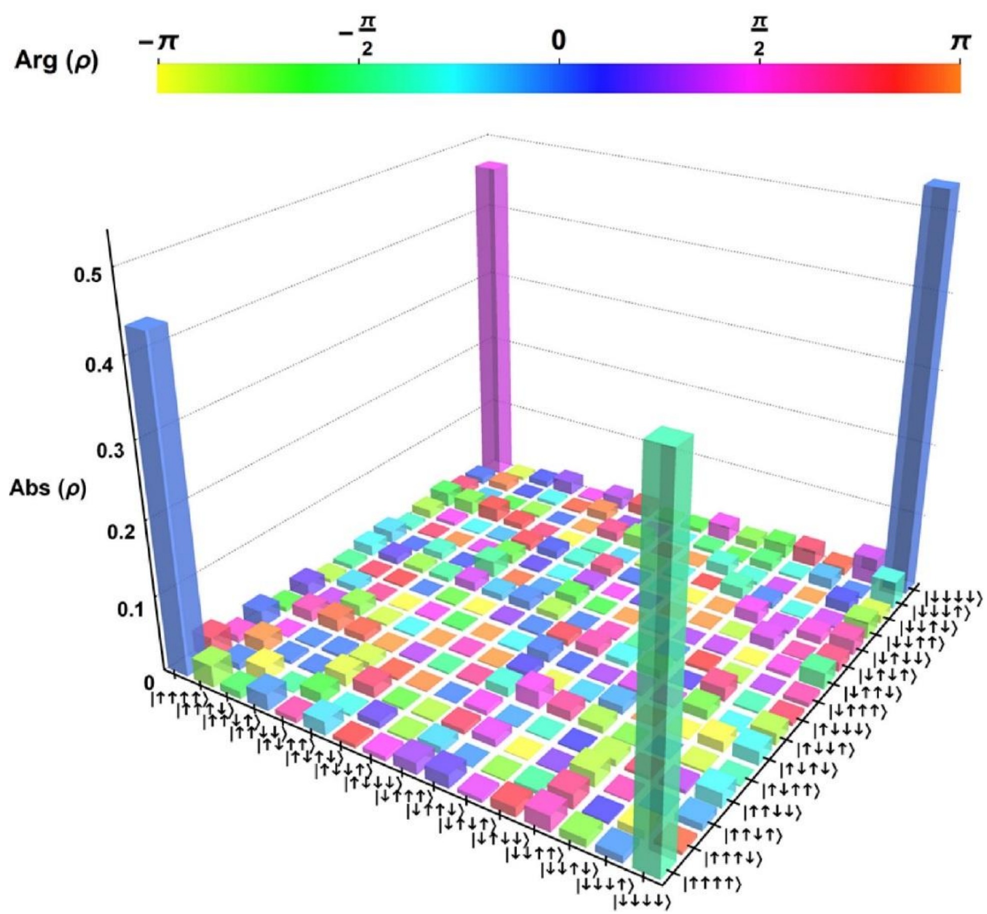
Ruster et al, PRX 7, 031050 (2017)

“Knitting together” a 4-ion GHZ state

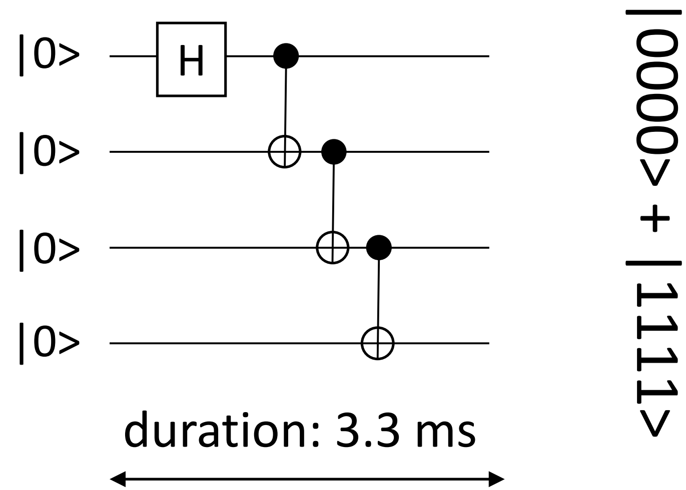




“Knitting together” a 4-ion GHZ state



equivalent circuit:



Full state tomography yields **94.7 % fidelity** from about 50k measurements.

Experimental sequence uses **> 300 shuttling operations** for SB cooling, state preparation, quantum circuit, state analysis.

Kaufmann et al, PRL 119, 150503 (2017)

Experimental sequence for a 4-ion GHZ state

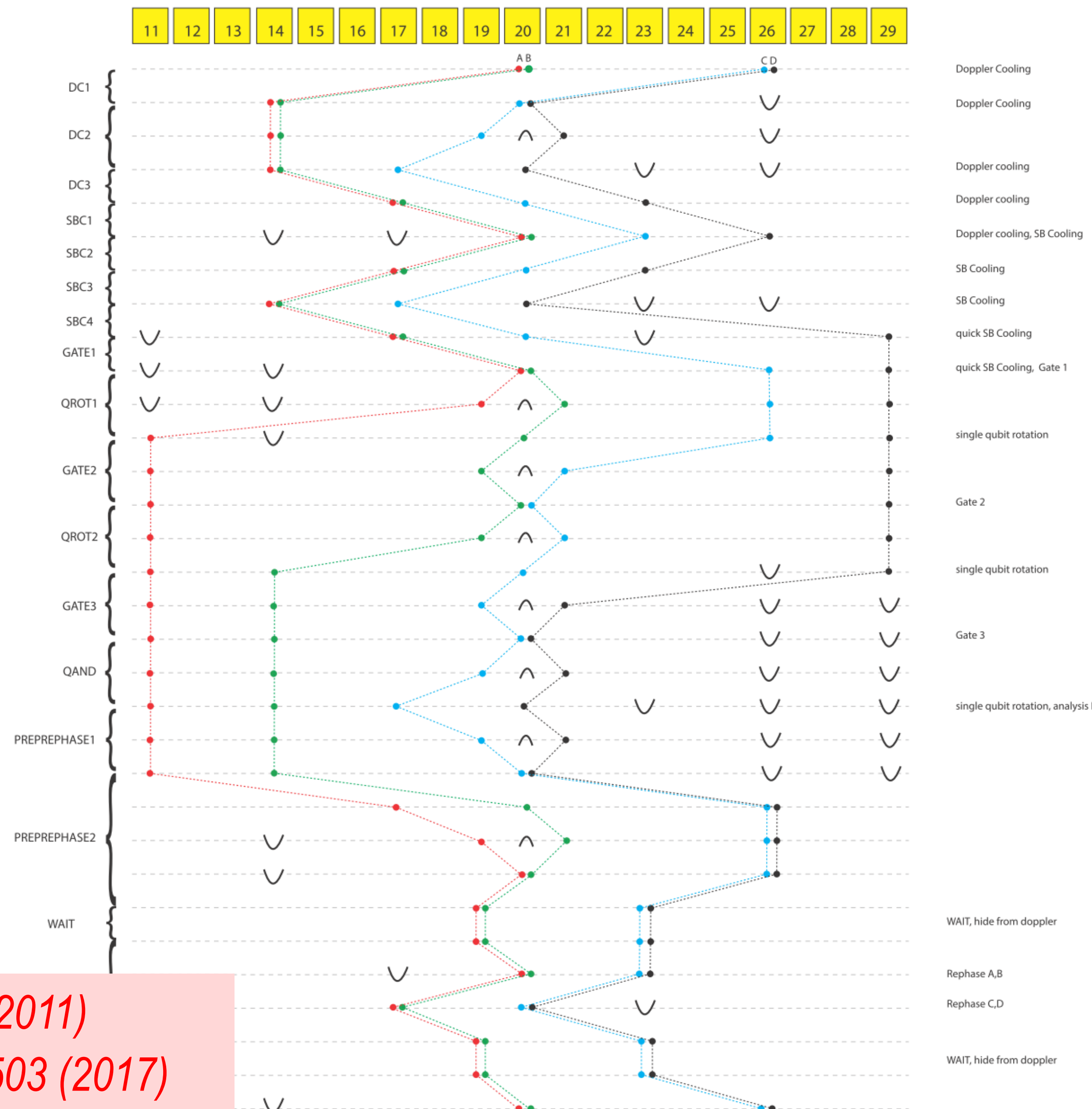
many shuttling op.

- 324 segment to segment transports
- 8 separation/merge operations

+ many gates:

- 12 single qubit gates
- 3 two-qubit gates
- multiple spin echos

0.5 seconds cohernence for |0000> + |1111>



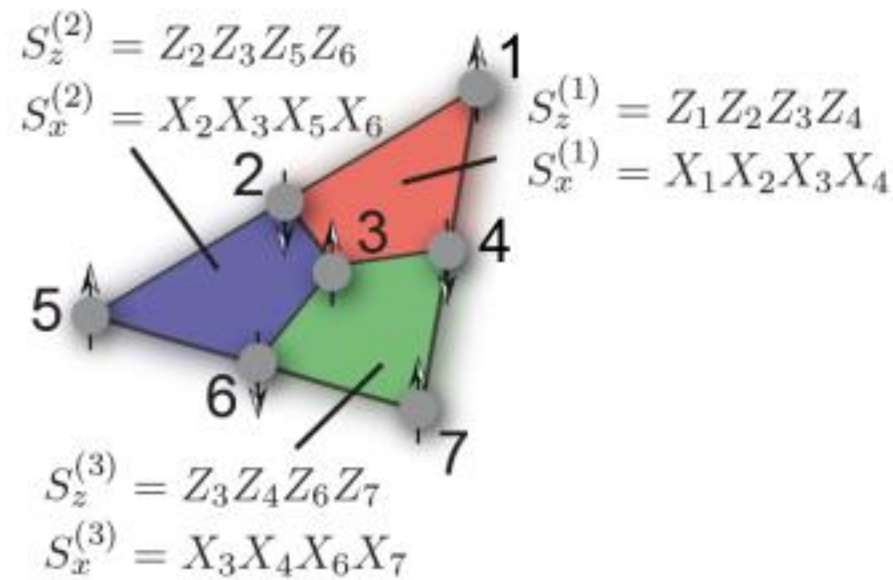
Monz et al, PRL 106, 130506 (2011)

Kaufmann et al, PRL 119, 150503 (2017)

Break-even point for useful QEC ?

Topological quantum error correction, using the reconfigured ion quantum register

- Logical qubit using a 7-qubit color code
- Improve and adapt hardware and software
- Develop strategies to overcome current limitations



Bermudez et al, Phys. Rev. X 7, 041061, Nigg et al., Sci. 234, 302 (2014)

Break-even point for useful QEC ?

$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$

Alice perfectly encodes

$|\psi\rangle = \alpha|0\rangle_L + \beta|1\rangle_L$

Channel, incl. correlated & coherent noise, and

one round of imperfect QEC by Igor

Bob is asked:

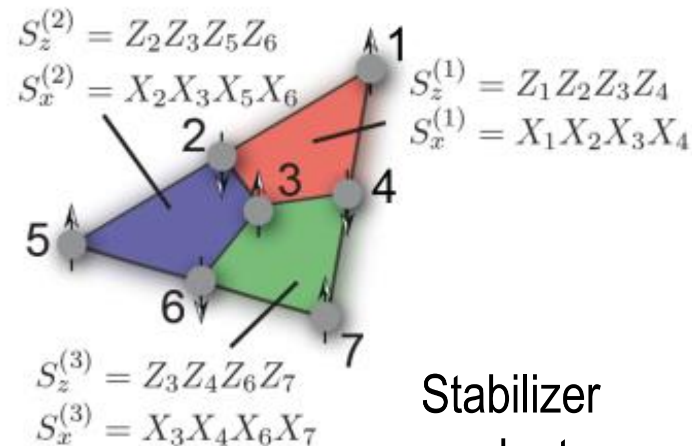
Is it $|\psi\rangle$ or $|\psi\rangle_\perp$?

Or, was Igor really a help?

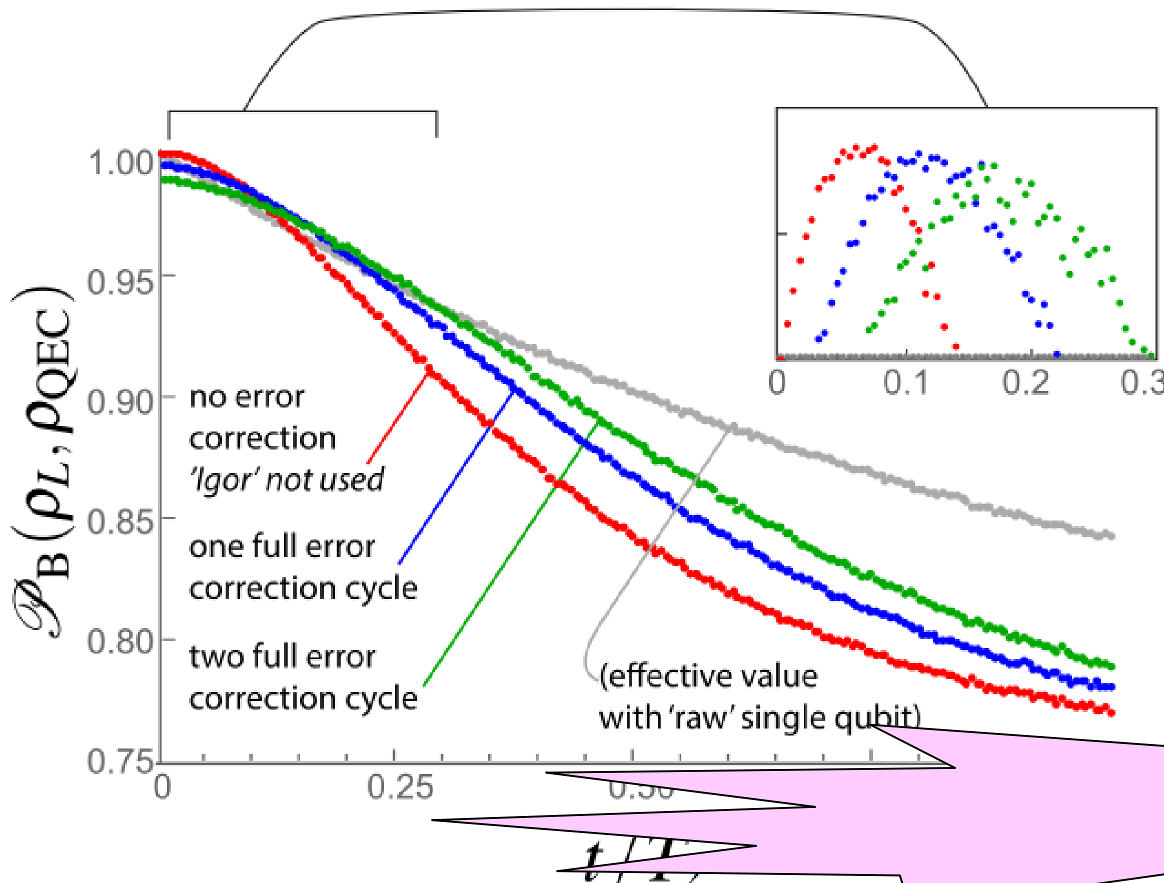
Bermudez et al, Phys. Rev. X 7, 041061

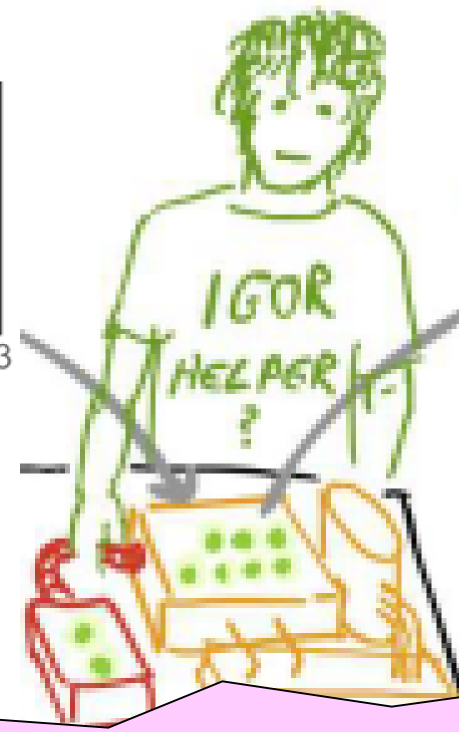
Shuttle based color code QEC

Real-space representation of shuttling-based one-species QEC cycle with multi-qubit MS gates



Stabilizer readout



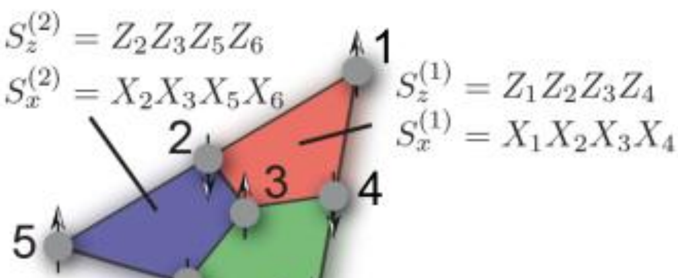


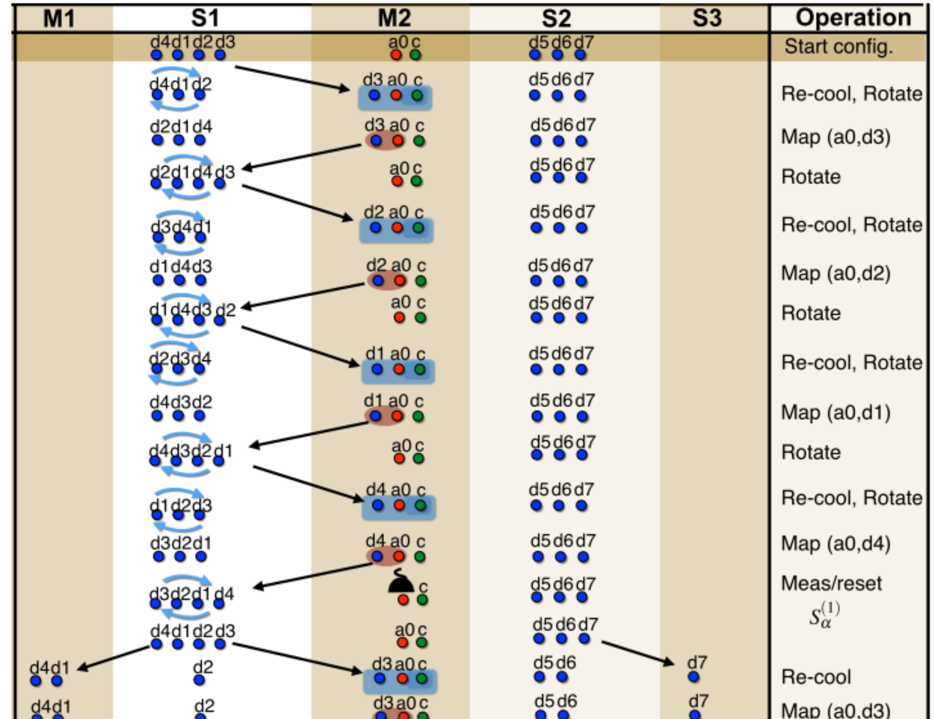
Helpful Igor!

Shuttle based color code QEC

PRX 7, 041061

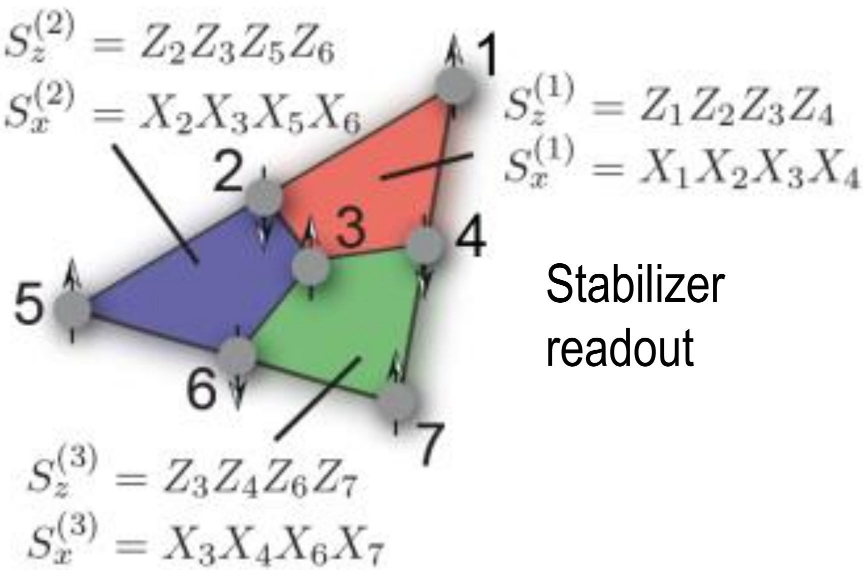
Real-space representation of shuttling-based one-species QEC cycle with 2-qubit gates





	2-ion MS gate	5-ion MS gate	Single-qubit gate	Meas.	Re-cooling	Split, shuttle and merge	Rotation	Total time (current) (ms)	Total time (anticipated) (ms)
Non-fault-tolerant trapped-ion QEC protocols									
Shuttling-based, single-species multi-qubit gate (A.1.)	-	12	42	6	-	20	2	6.7	1.7
Shuttling-based, two-species multi-qubit gate (A.2.)	-	12	42	6	6	6	2	6.8	1.4
Shuttling-based, two-species two-qubit gate (A.3.)	24	-	48	6	24	54	36	23.6	7.2
Hiding-based, two-species multi-qubit gate (A.4.)	-	12	150	6	6	-	-	6.3	1.1
Fault-tolerant trapped-ion QEC protocols									
Shuttling-based, two-species DiVincenzo-Shor (B.1.)	54	-	84	24	54	190	150	71.2	22.4
Shuttling-based, two-species DiVincenzo-Aliferis (B.2.)	54	-	78	24	54	190	144	71.0	22.2

Topological quantum error correction

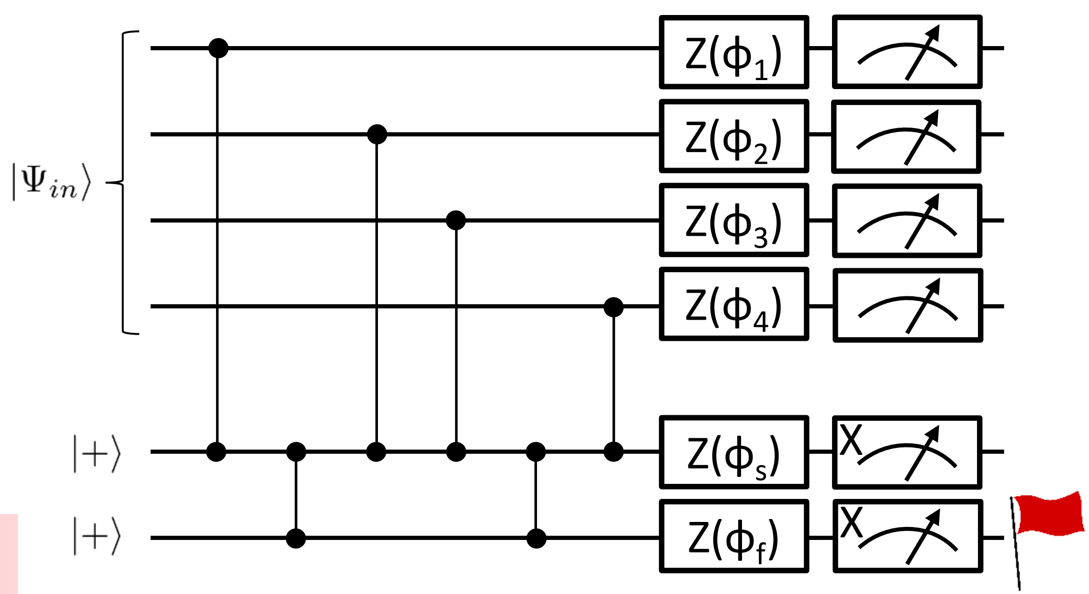


Bermudez et al, Phys. Rev. X 7, 041061
Nigg et al., Sci. 234, 302 (2014)

Stabilizer readout

Logical qubit using
7-data qubit color code

Fault tolerant
Syndrome readout

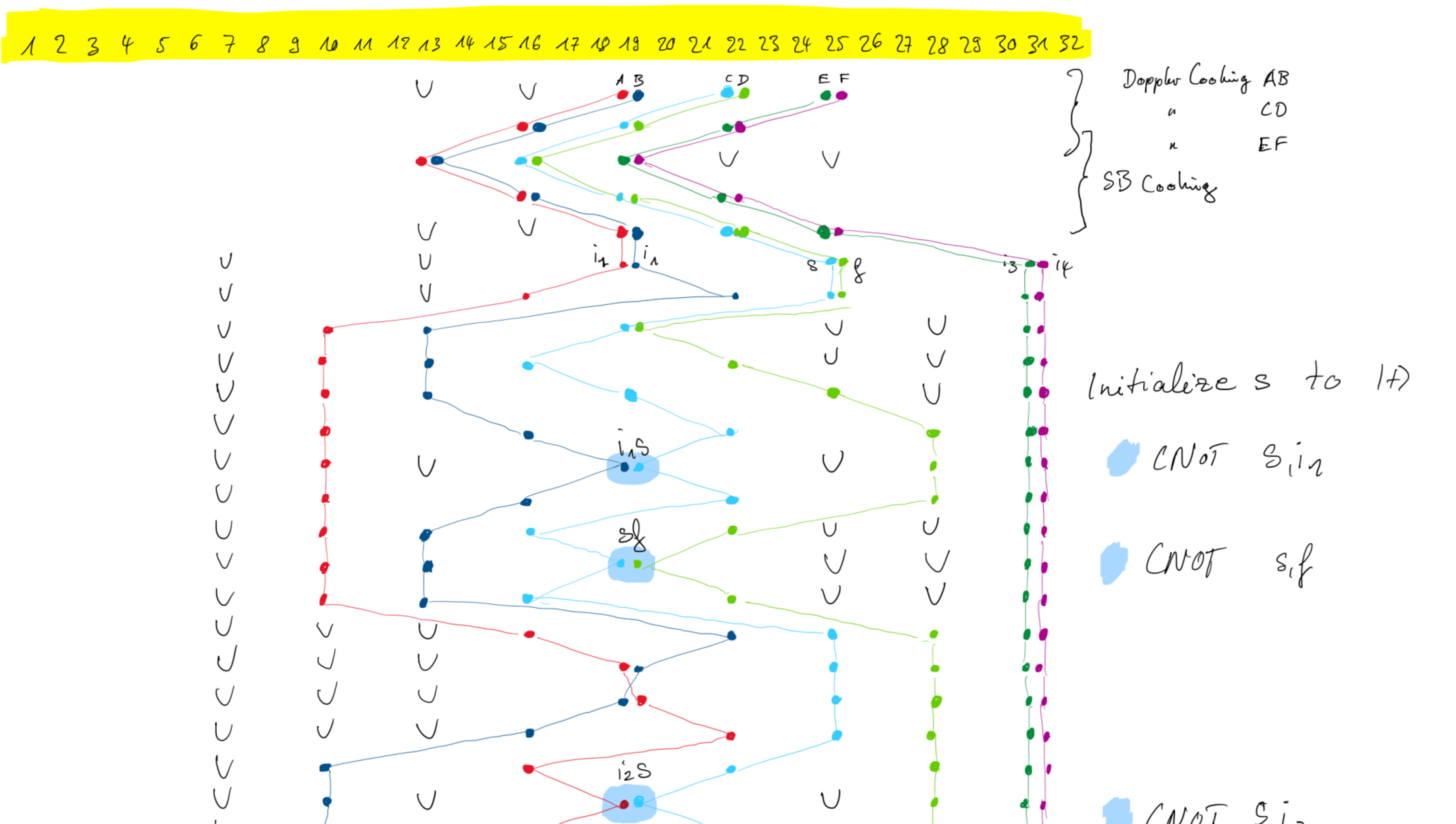


Chao, Reichardt, arXiv:1705.02329
Yoder, Kim, Quantum 1, 2 (2017)

Sequence - Fault tolerant syndrome readout

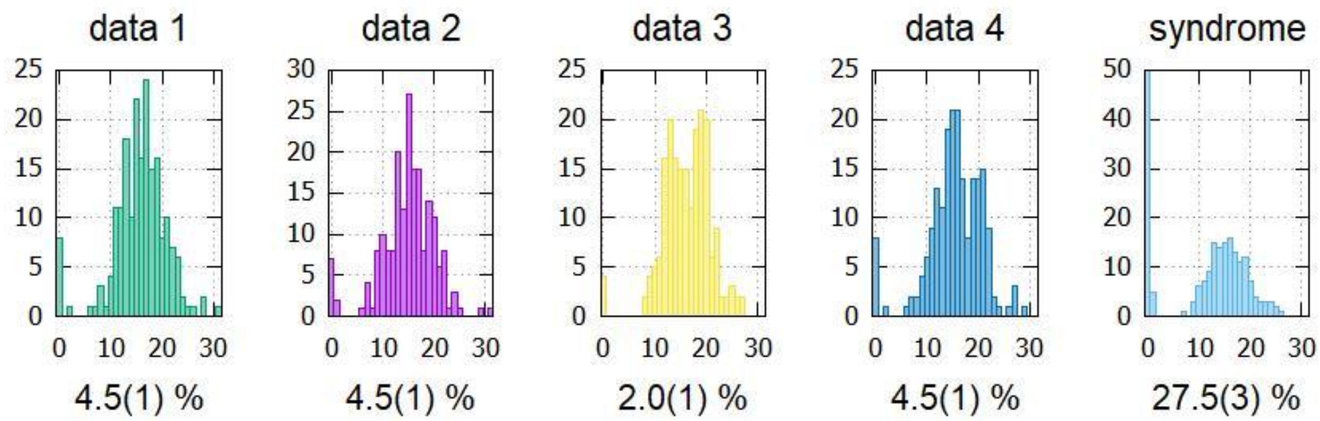
6 ion FT readout

Montag, 19. Februar 2018 12:30



Fault tolerant syndrome – partity readout

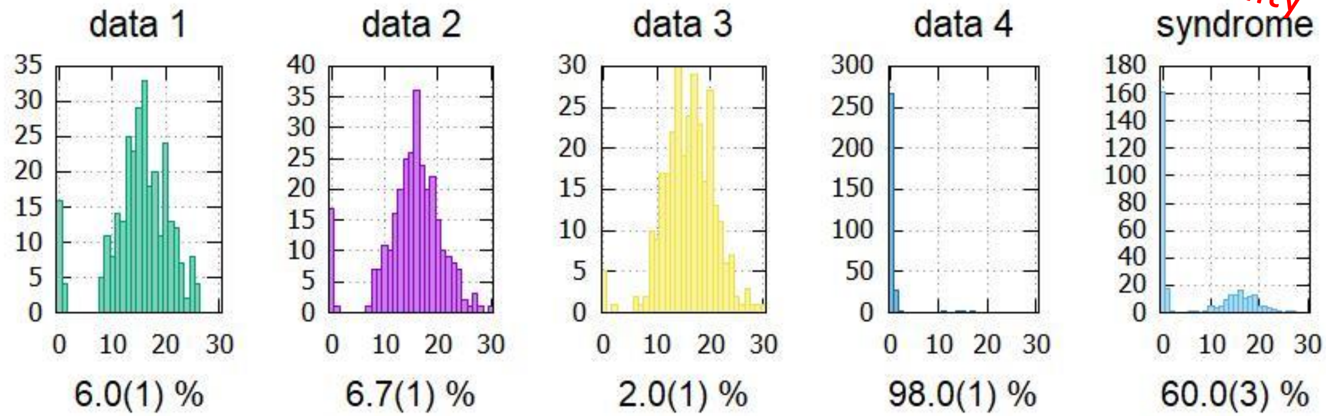
Even parity



72.5(3)% fidelity

Odd parity

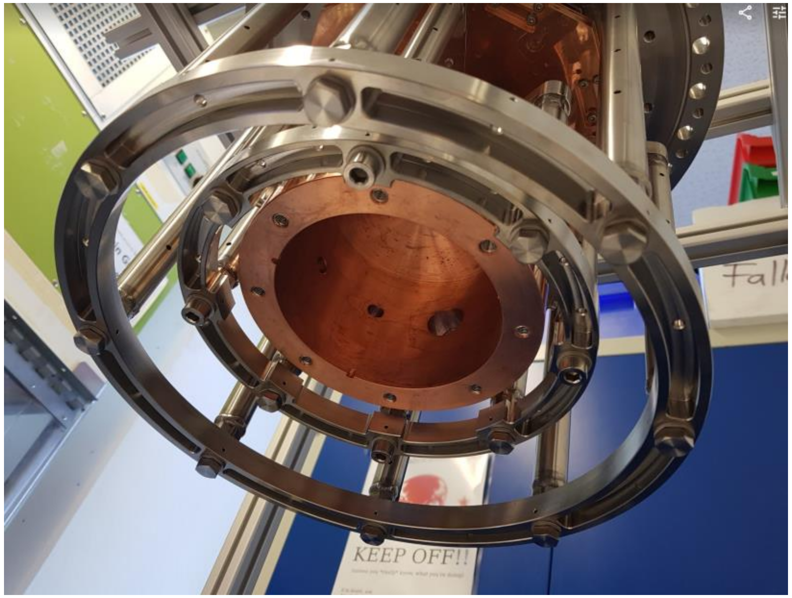
60.0(3)% fidelity

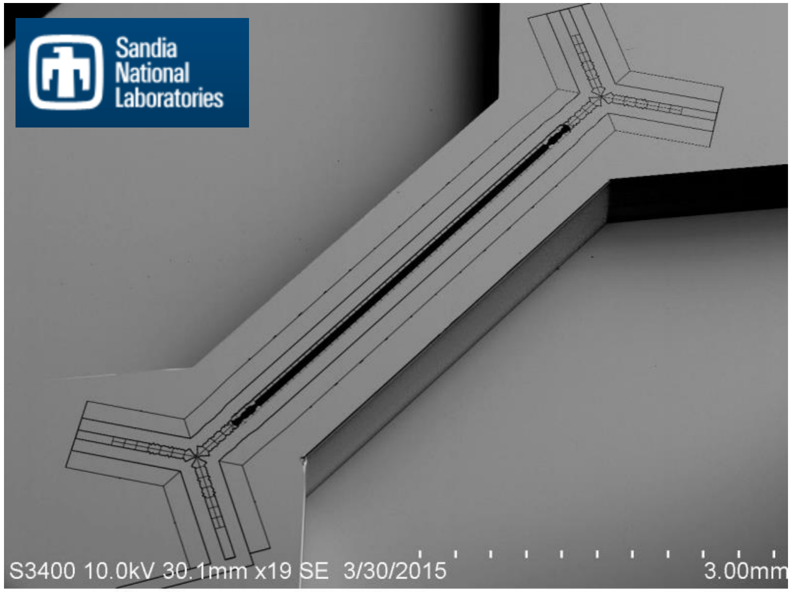


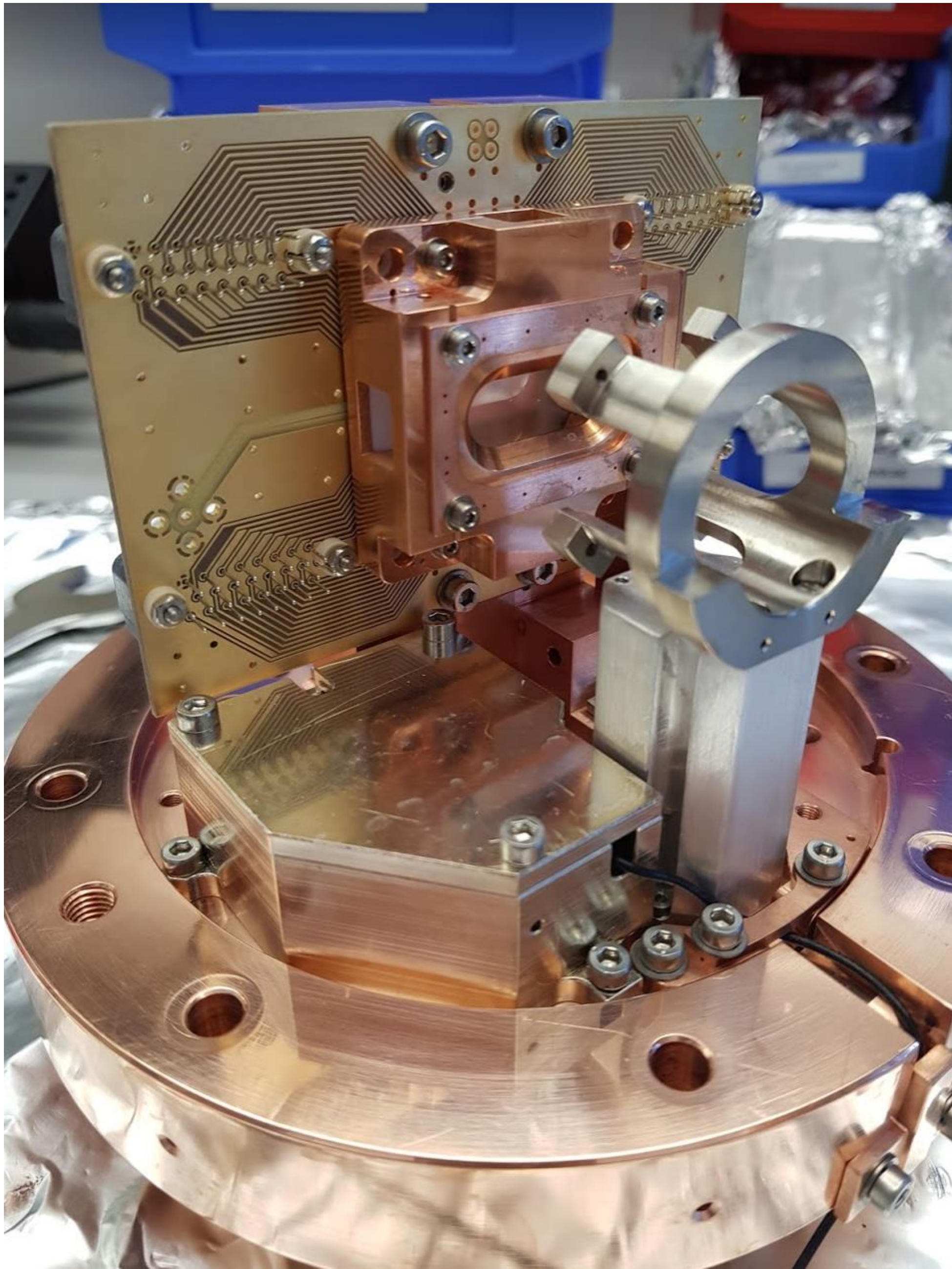
Key figures, now and future, for trapped ion-QC

- Single shot read-out of spin state better $1 - 10^{-4}$
- Single gate fidelity better than $1 - 10^{-4}$….$10^{-5..6}$ mitigating intensity noise, off-resonant excitation, AC Stark shifts
- Two qubit gate fidelity $1 – 10^{-3}$….$10^{-4..5}$ mitigating intensity noise, off-resonant excitation, AC Stark shifts
- Gate operation time ~ 30µs …. ≤10µs using shaped light fields
- Qubit register reconfiguration operations, few µs to 80µs …. ≤1µs optimized electric wave forms
- Long coherence times, up to a few seconds …. ≥ seconds with dynamical decoupling pulse sequences
- Decoherence-free substates, >10s …minutes coherence
- Micro-segmented traps, 30 segments … >100 … 1000 segments
- Cryogenic ion traps, trapping times of days

Cryogenic setup

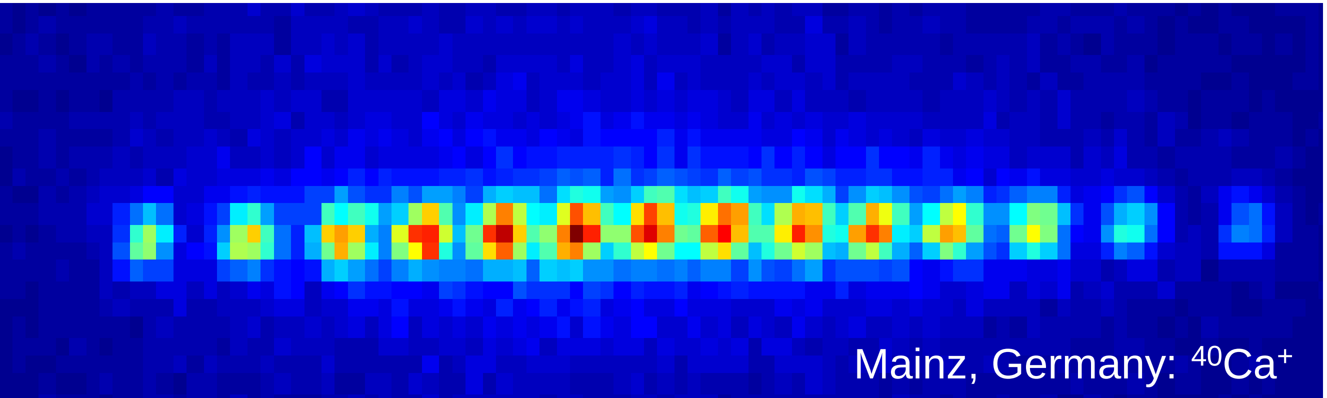






Quantum optics and information with trapped ions

- Introduction to ion trapping and cooling
- Trapped ions as qubits for quantum computing and simulation
- Rydberg excitations for fast entangling operations
- Quantum thermodynamics, heat engines, phase transitions
- Implanting single ions for a solid state quantum device



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F. Schmidt-Kaler

JOHANNES GUTENBERG UNIVERSITÄT MAINZ

History of classical information processing

Wheels: 1671
Gottfried Leibniz

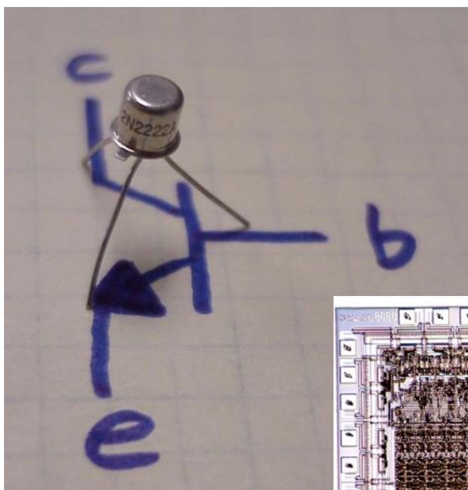
Relais: Konrad Zuse Z1
1937 Berlin

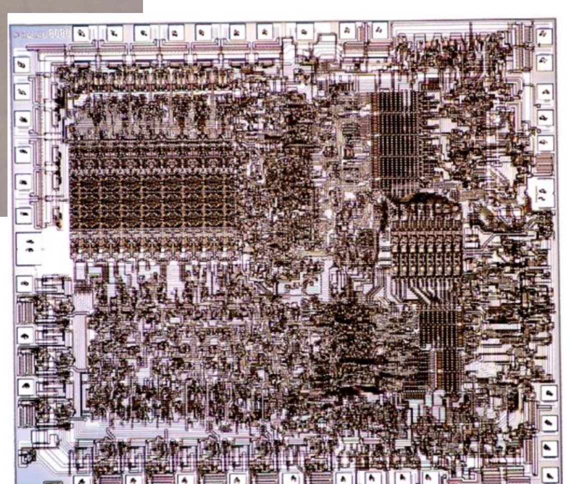
Mechanical computing

semiconductor electronics

in vacuum electronics

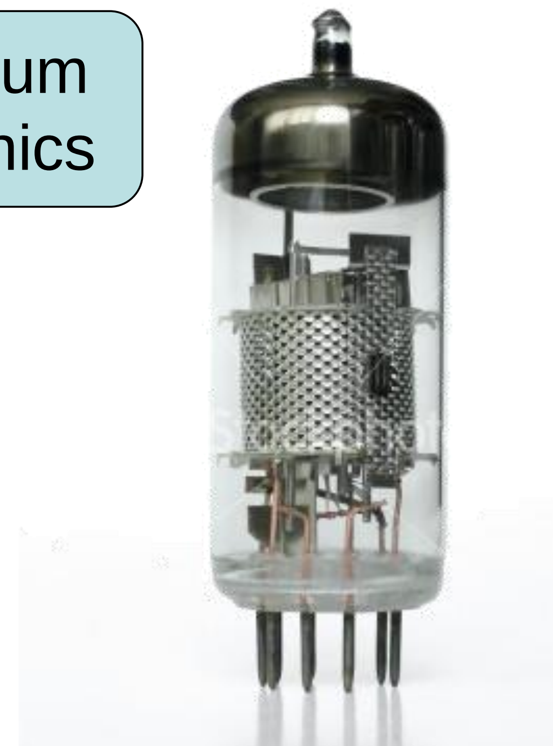
Transistor:
Lilienfeld / 1925
Mataré, Welker / 1942
Shockley, Brattain / 1945



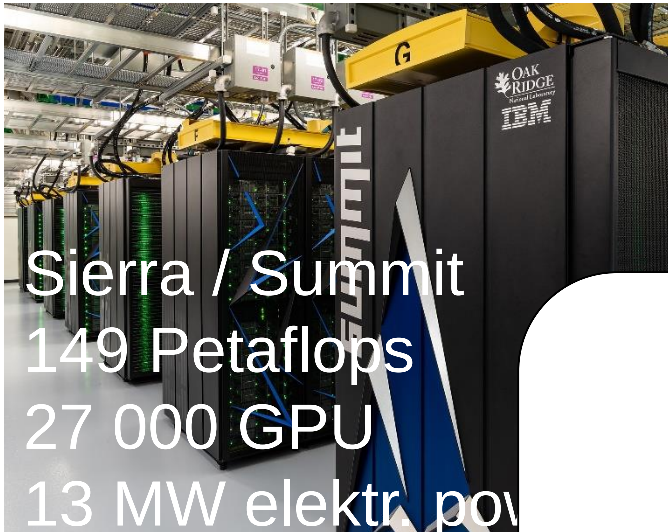


Processor:
Intel 8080
/ 1974

Electron tube:
Femming / 1904



Digital Information processing

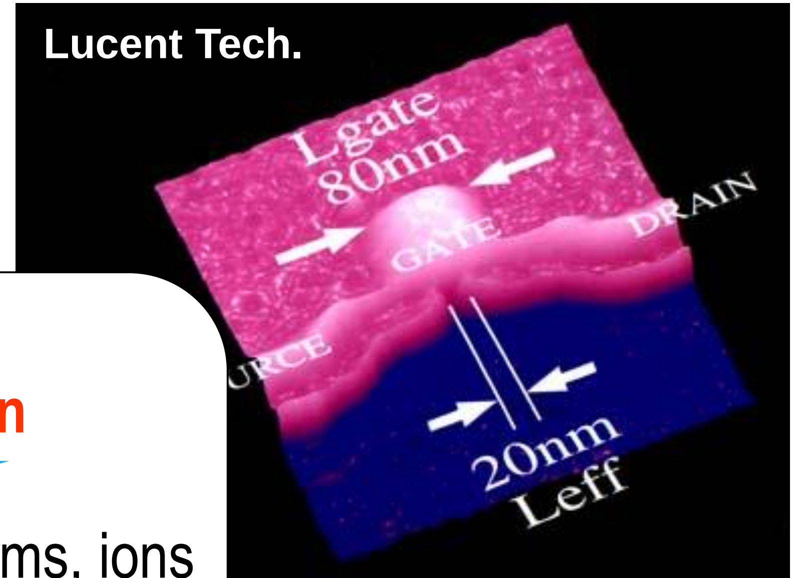


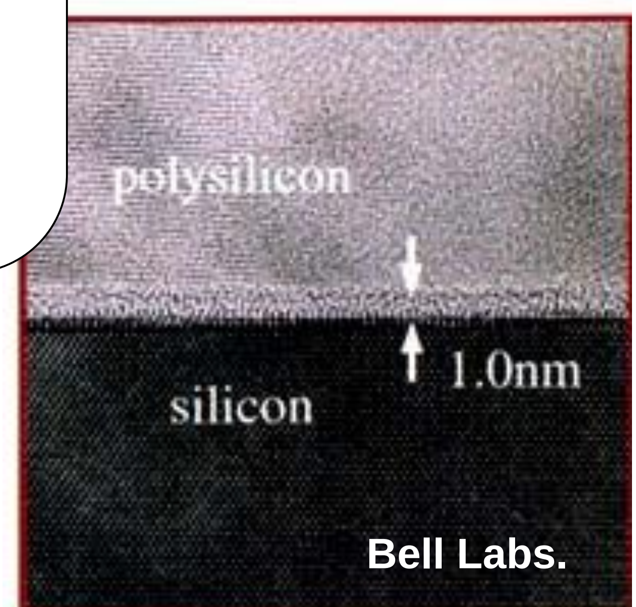
Miniaturization

single electrons, atoms, ions

Quantum effecs

quantum advantage



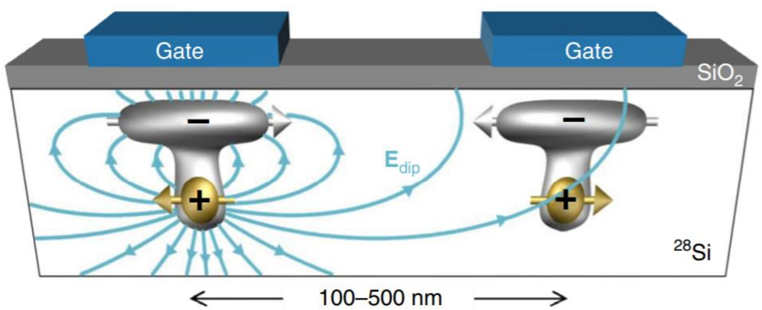


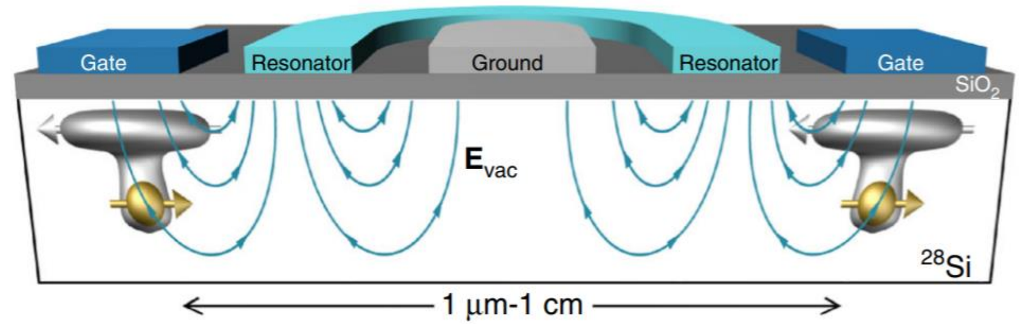
Single donor-based architecture

Silicon quantum processor with robust short & long-distance qubit couplings, P-ions in Si,

Kane, Nature 393, 133 (1998)

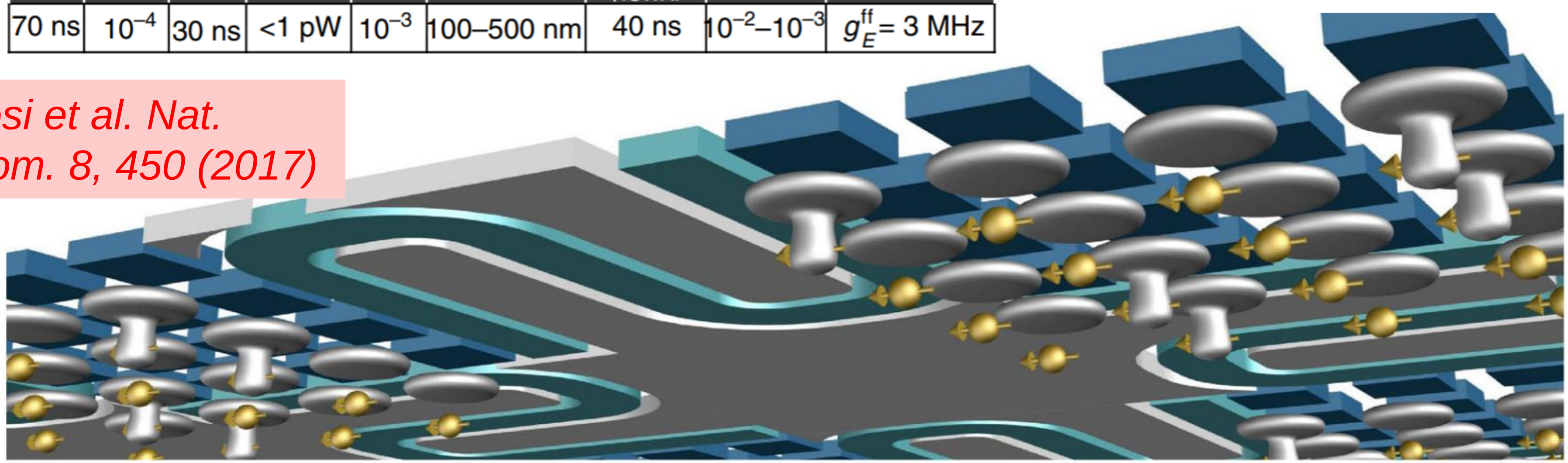
Pla et al. Nature 496, 334 (2013)





z-gates		*x*(*y*)-gates			2-qubit $\sqrt{iSWAP}$ gates			Photonic link
τ_π	Error	$\tau_{\pi/2}$	Power	Error	Distance	$\tau_{\sqrt{iSWAP}}$	Error	Coupling
70 ns	10^{-4}	30 ns	<1 pW	10^{-3}	100–500 nm	40 ns	10^{-2}–10^{-3}	g_E^{ff} = 3 MHz

Tosi et al. Nat. Com. 8, 450 (2017)



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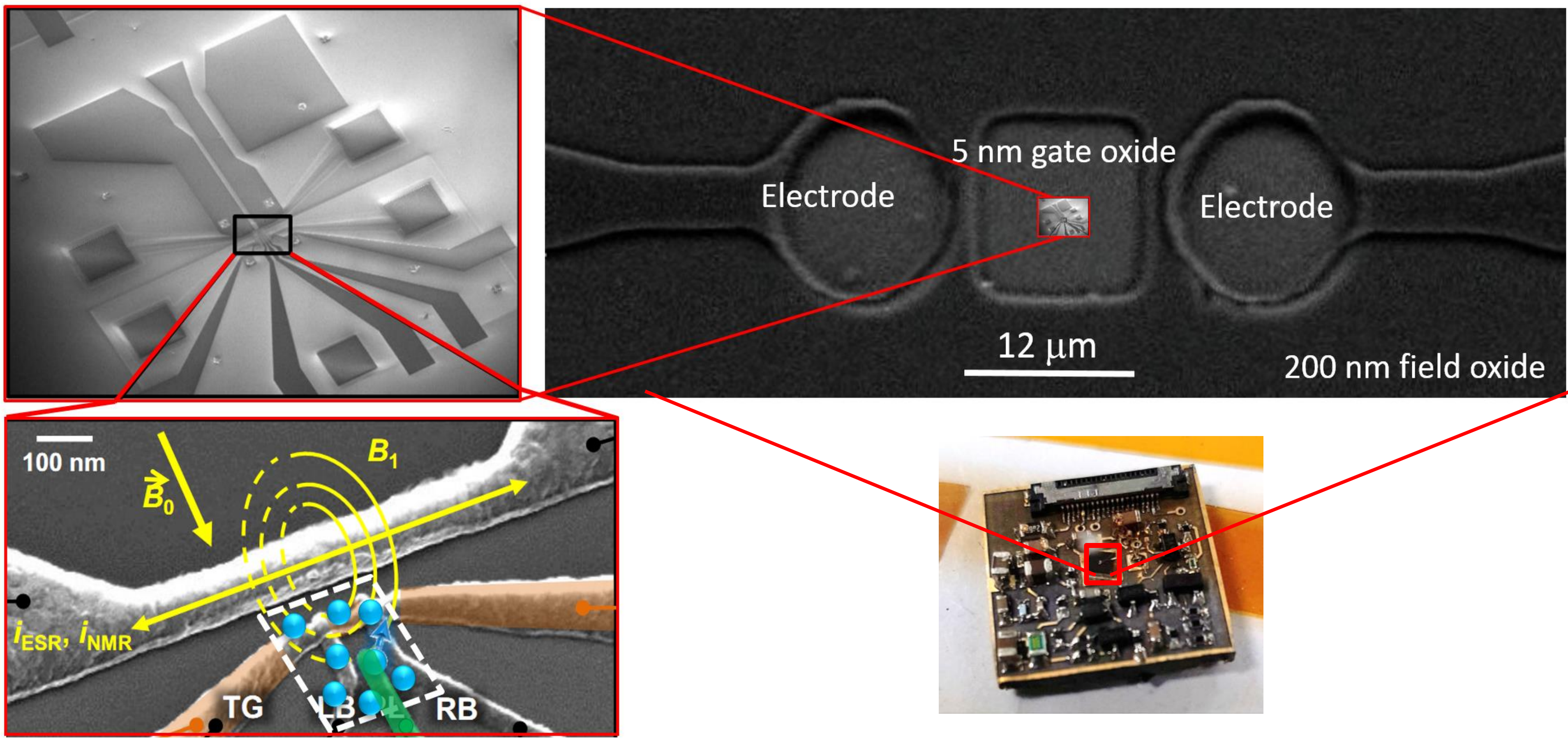
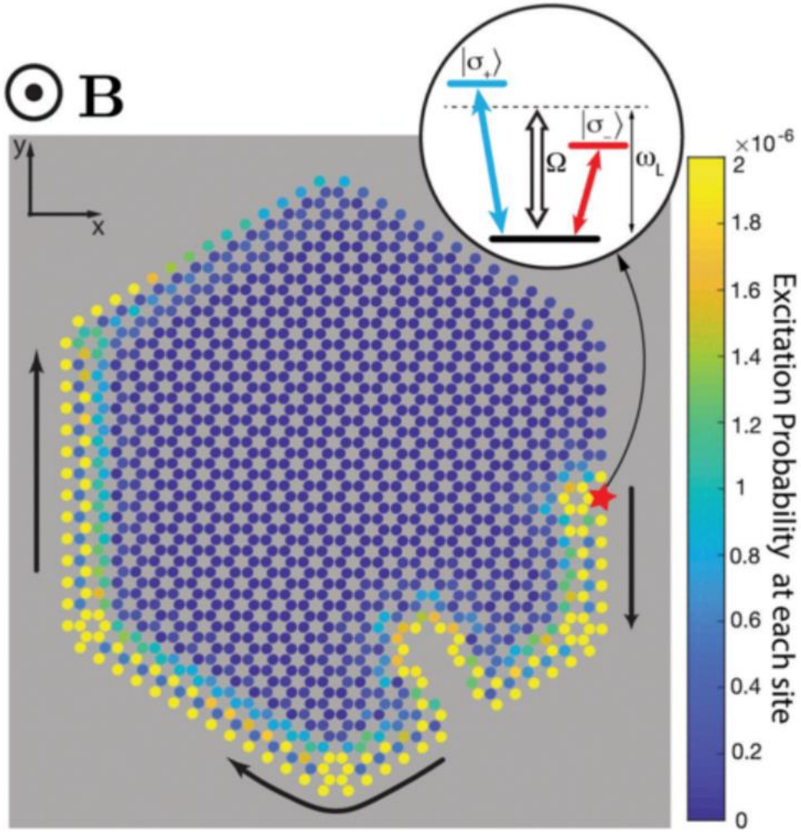
CENTRE FOR QUANTUM COMPUTATION & COMMUNICATION TECHNOLOGY
AUSTRALIAN RESEARCH COUNCIL CENTRE OF EXCELLENCE

Pla et al. Nature 496, 334 (2013)

...... zoom in further .....

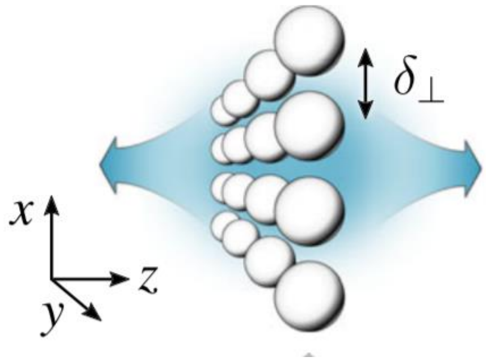


Proposal: Quantum simulation with atomic emitters



Perczel et al. PRL 119, 023603 (2017)

- Rare earth emitters in honey comb structure
- subwavelength spacing
- Protection againts imperfections and noise
- Topological edge states
- Propagating in unidirectional mode

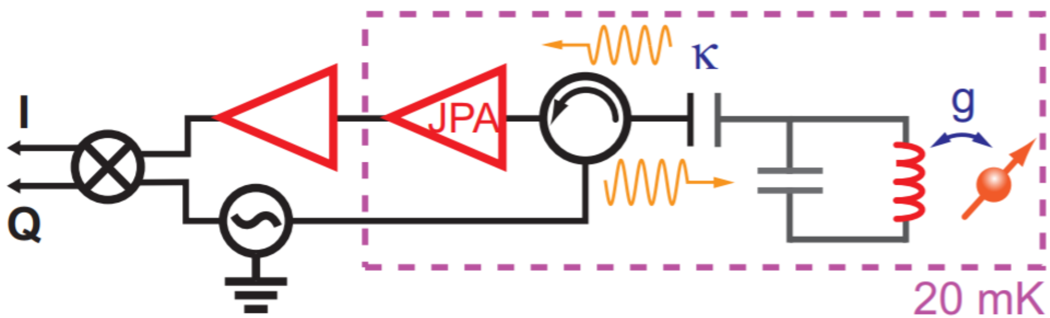


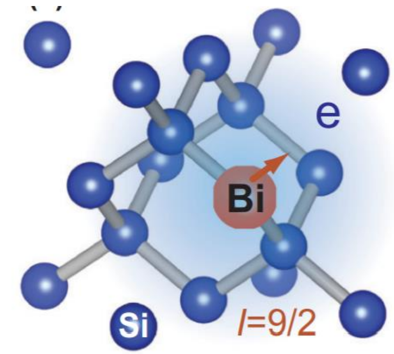
Guimond, et al, PRL 122, 093601 (2019)

- Super/sub radiant states from array

Proposal: Hybrid single donor-based architecture

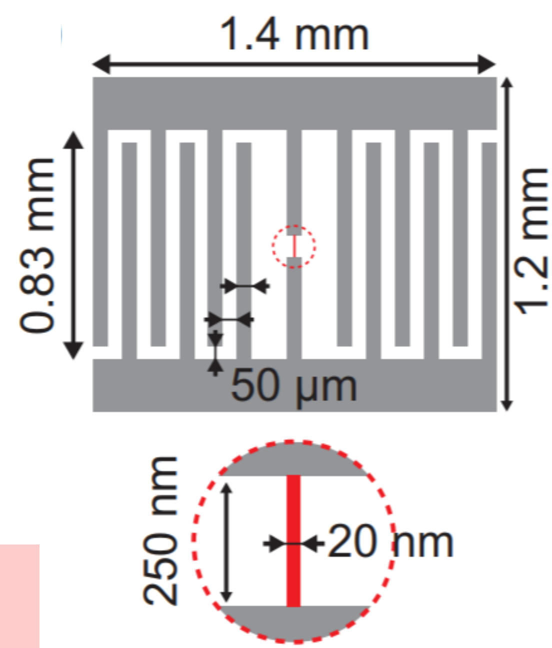
Interfacing single donors, e.g. Bi, to superconducting circuits





Join:

- Scalable architecture of superconducting qubits
- Long coherence times of single donors



Kurizki et al.
PNAS 112, 3866 (2015)

Haika et al. PRA
95, 022306 (2017)

Single donor-based architectures

- Silicon quantum processor with robust short & long-distance qubit couplings, P-ions in Si
- large single photon emitter structures for quantum simulation with e.g. REI, NV's, SiV's …
- Interfacing single donors, e.g. Bi, Er, NV … to superconducting circuits

Pla et al. Nature 496, 334 (2013)

Haika et al. PRA 95, 022306 (2017)

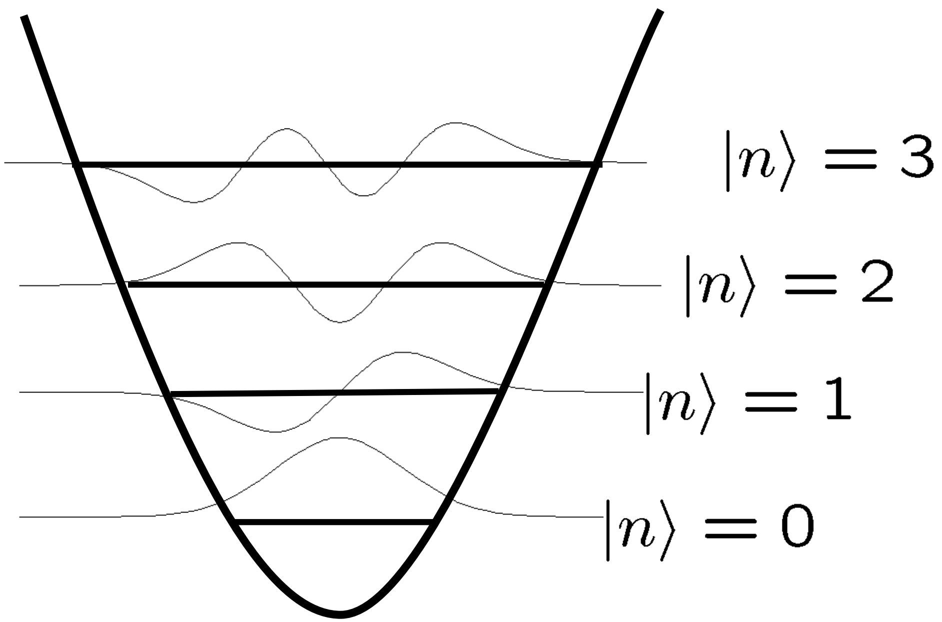
Perczel et al. PRL 119, 023603 (2017)

Challenges:

- implant arrays of single donor atoms
- with technological interesting ions, e.g. P, REI, .. pure
- in 5…15nm depth with <10nm accuracy
- with respect to gate electrodes

Cold ions source for microscopy and impantation

- Load and cool, eventually extract, single ions directly
- Trapping of all charged particles, with large range of *m/q*
- Doppler cooling, eventually cooling to quantum mechanical ground state, Heisenberg uncertainty relation $\Delta p_x \, \Delta x \geq \hbar/2$

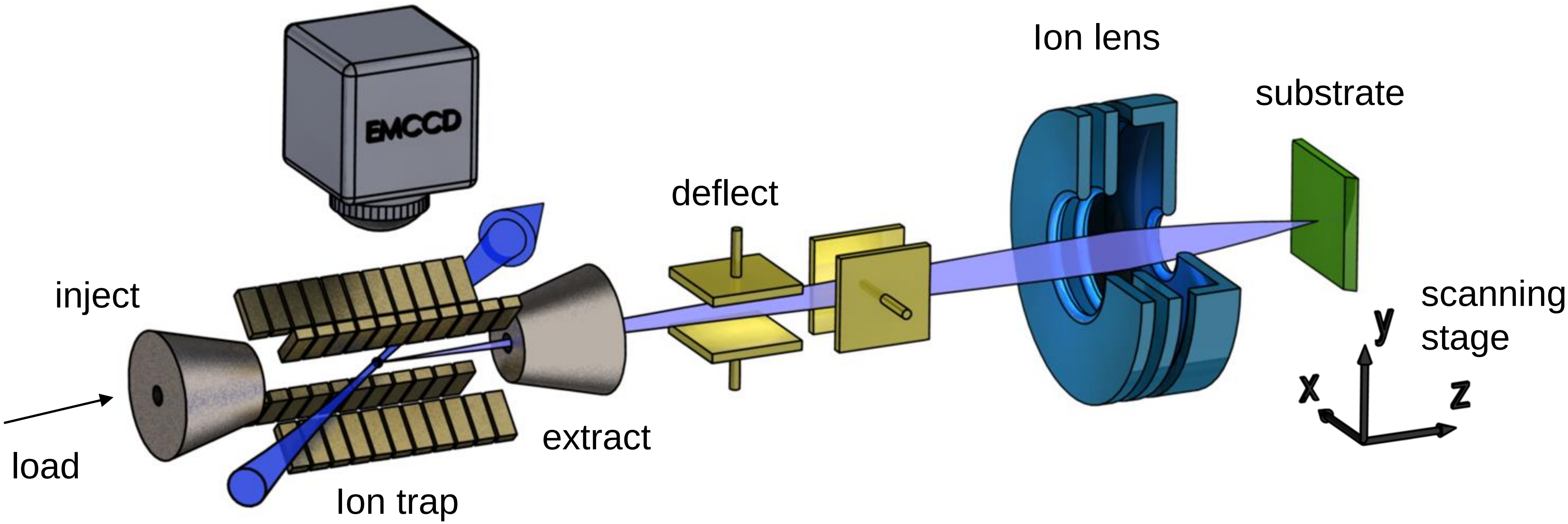


$\Delta x_{n=0} \sim 5\ldots10\text{nm}$

Paul trap as deterministic source - features

- top-down method
- deterministically single ion
- various doping ion species

- low energies (0eV… 6keV… 20keV)
- nm resolution
- low throughput

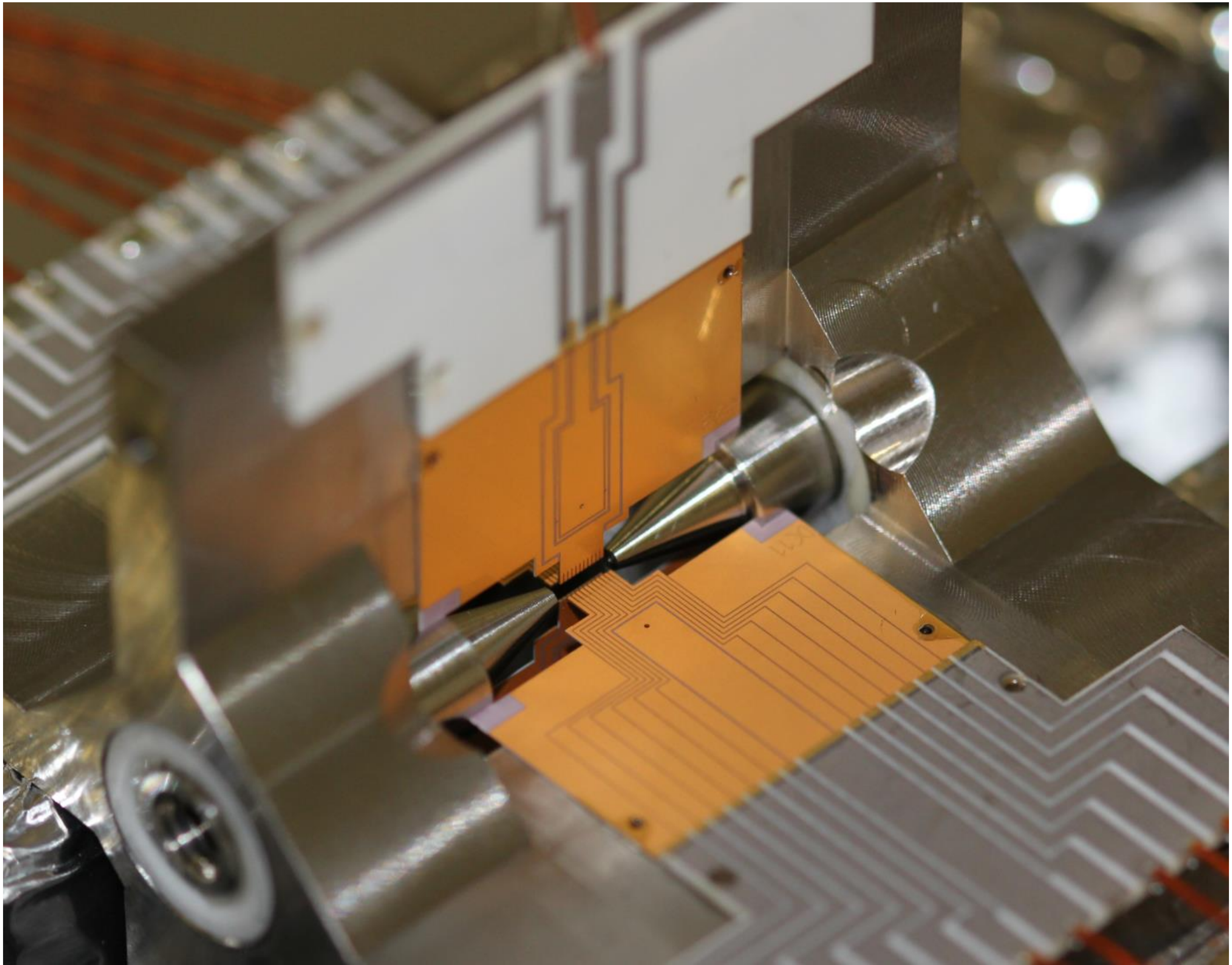


Jakob et al, PRL 117, 043001 (2016)

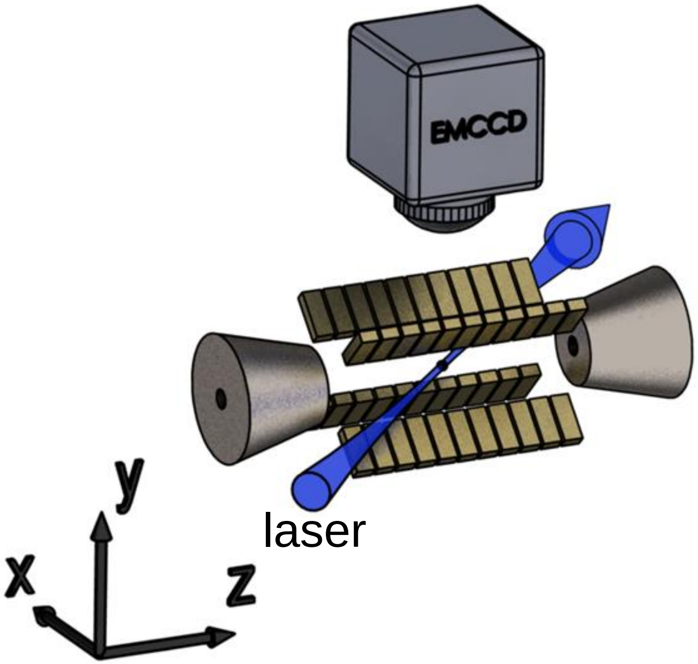
Schnitzler, et al., PRL 102, 070501 (2009)

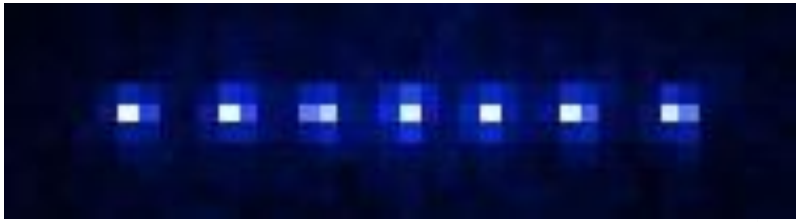
Meijer et al, Appl. Phys. A (2006) 83: 321

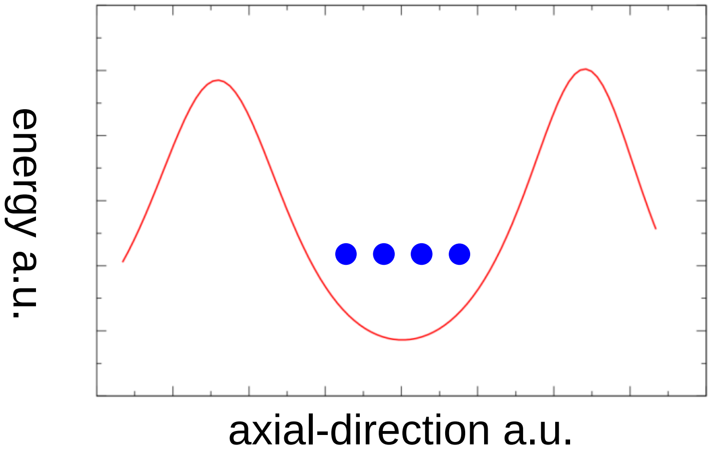
Segmented linear Paul trap



Loading and Cooling of Ca^+ Ions

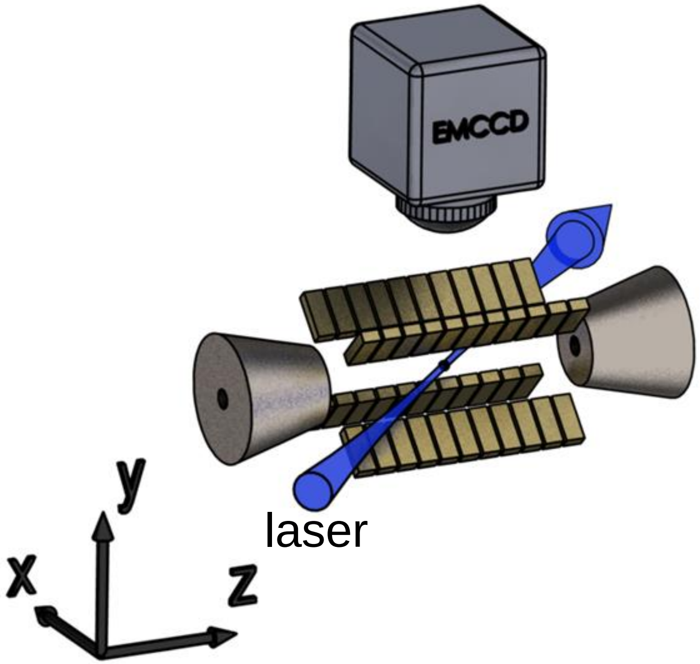




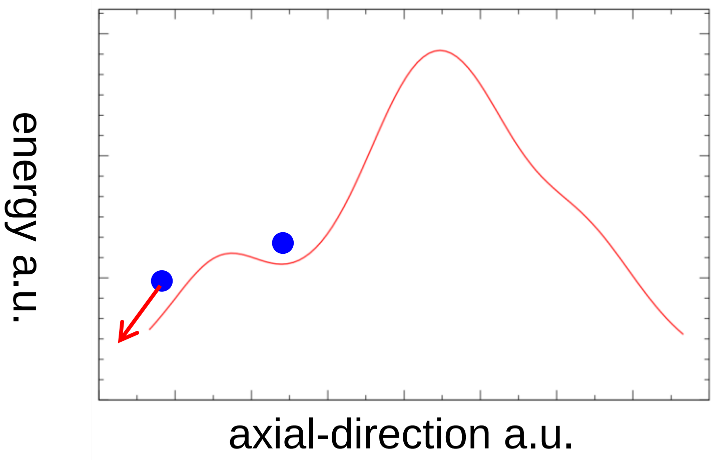


string of ions

Loading and Cooling of Ca^+ Ions

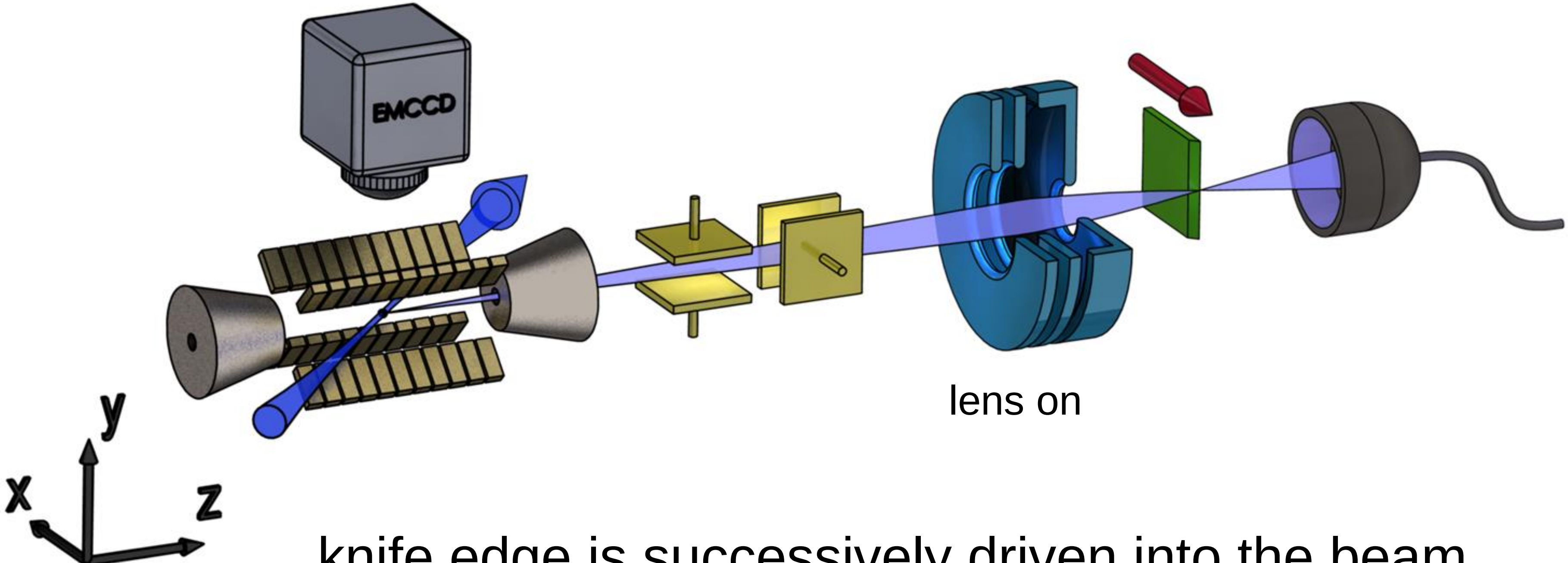


potential is shaped to force excess ions to leave the trap



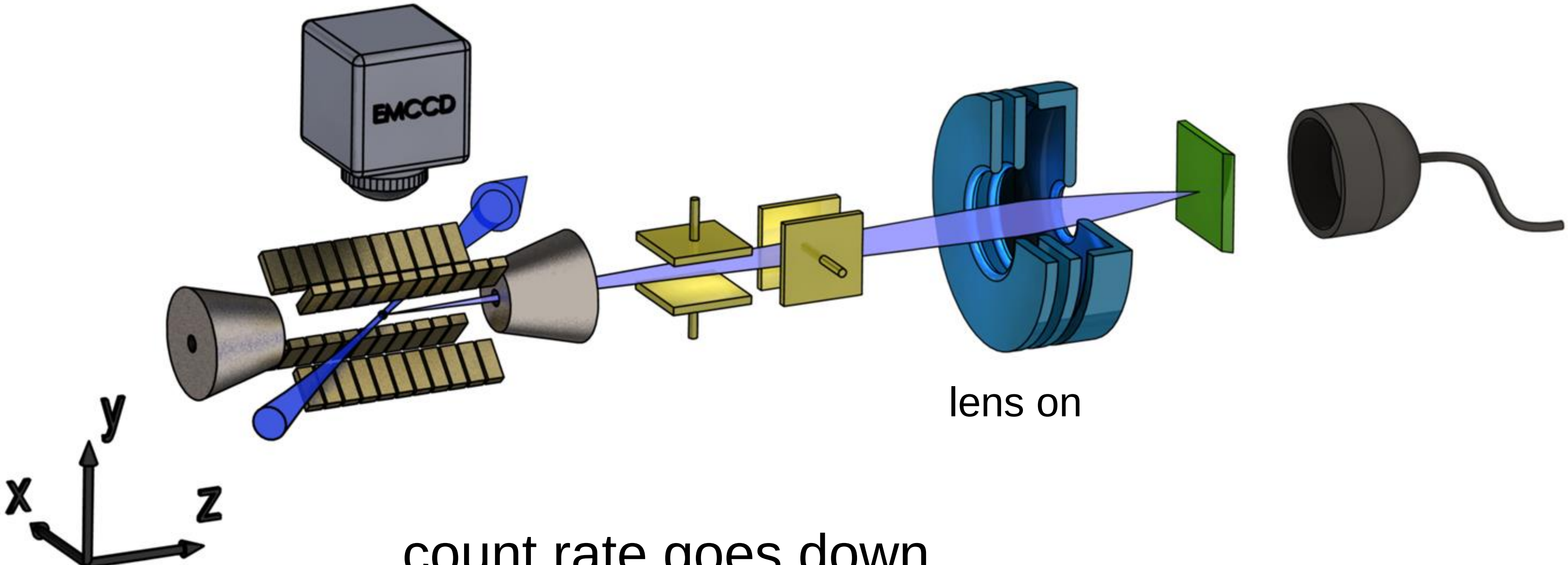
exacly one ion is trapped

Beam profiling



knife edge is successively driven into the beam

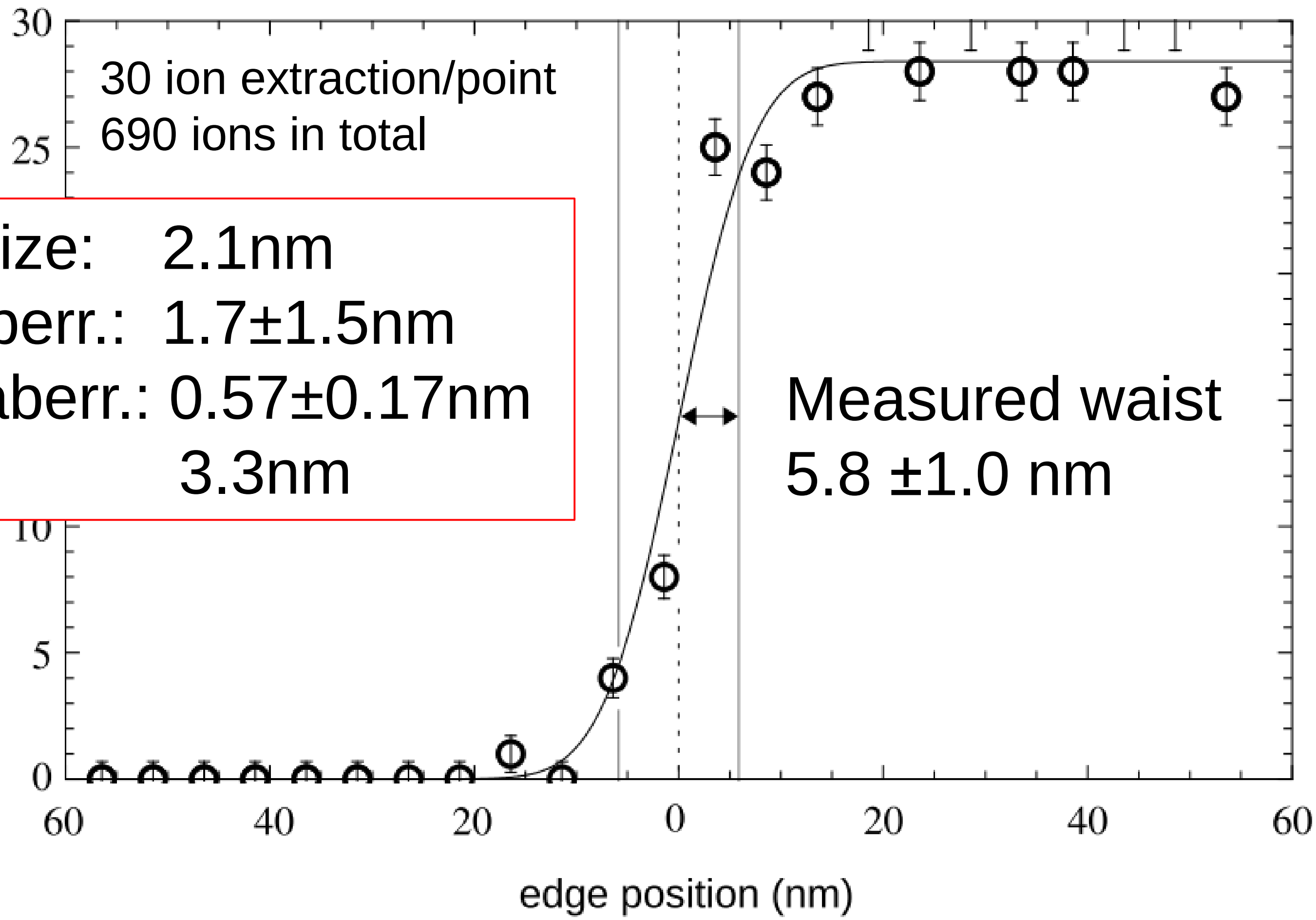
Beam profiling



lens on

count rate goes down
revealing the beam cross section

Beam profiling - result



Source size: 2.1nm
Spher. aberr.: 1.7±1.5nm
Chrom. aberr.: 0.57±0.17nm
Total: 3.3nm

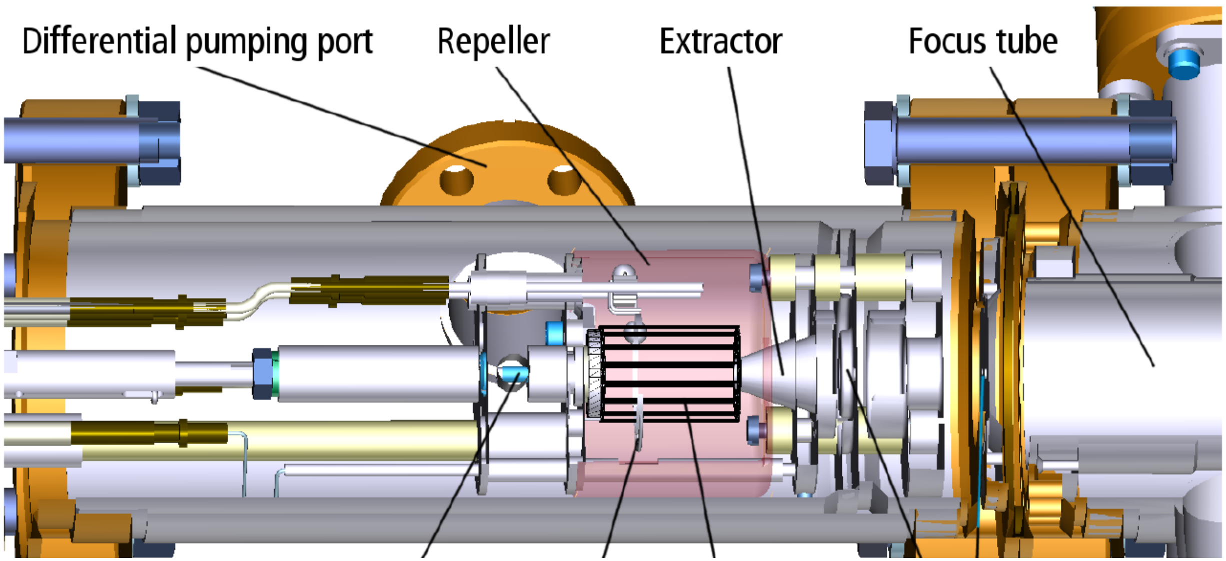
Jakob et al, PRL 117, 043001 (2016)

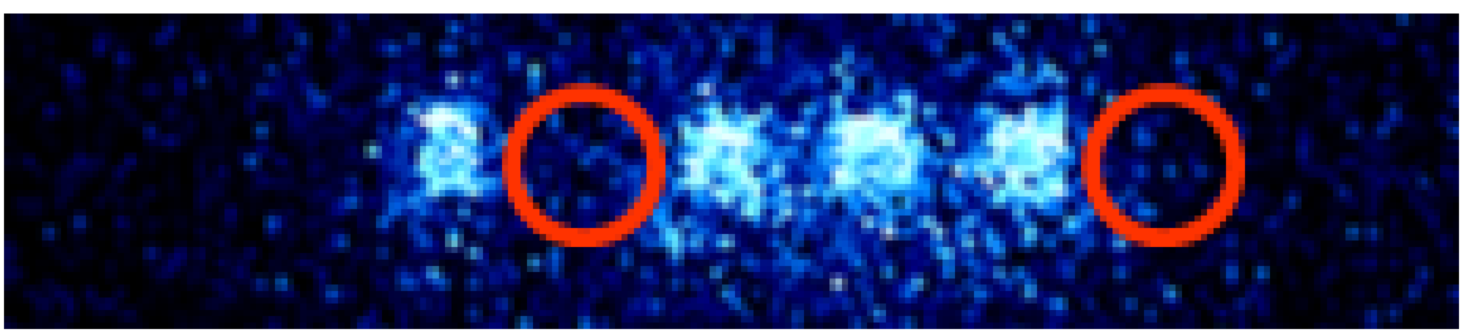
Universal deterministic ion source

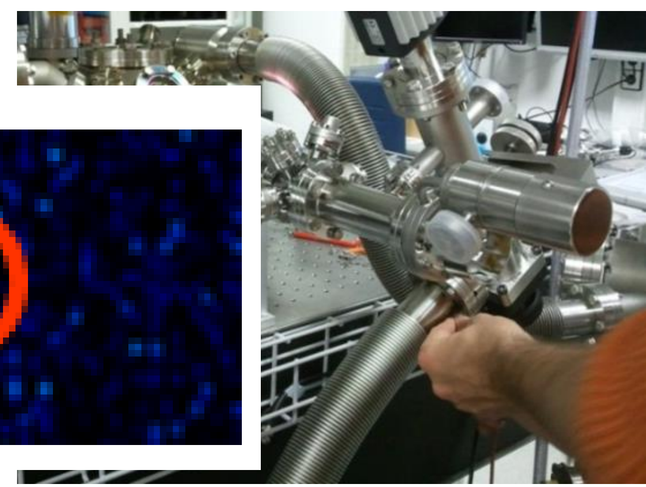
- Extending to more ion species
- Combinations of ion species

- Gas targets
- Laser ablation of solid targets
- Wien filter and ToF identification

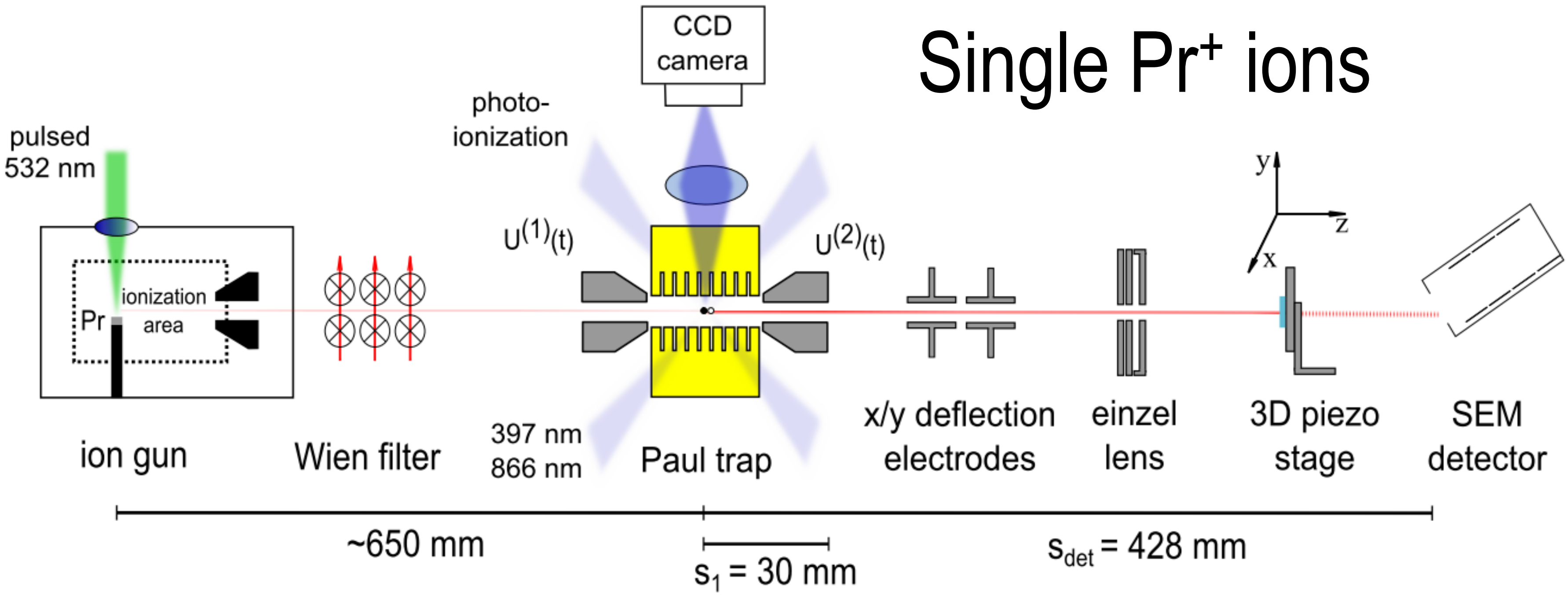
Nitrogen N_2^+,
Praseodymium,
Argon,
Xenon,
Cerium,
Phosphorous,
Bismut

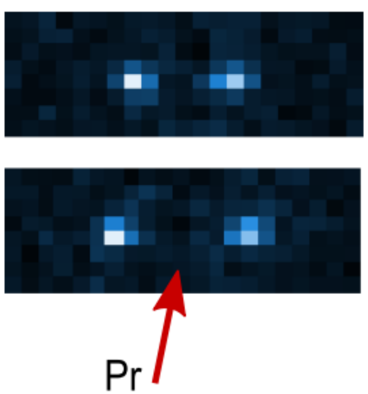


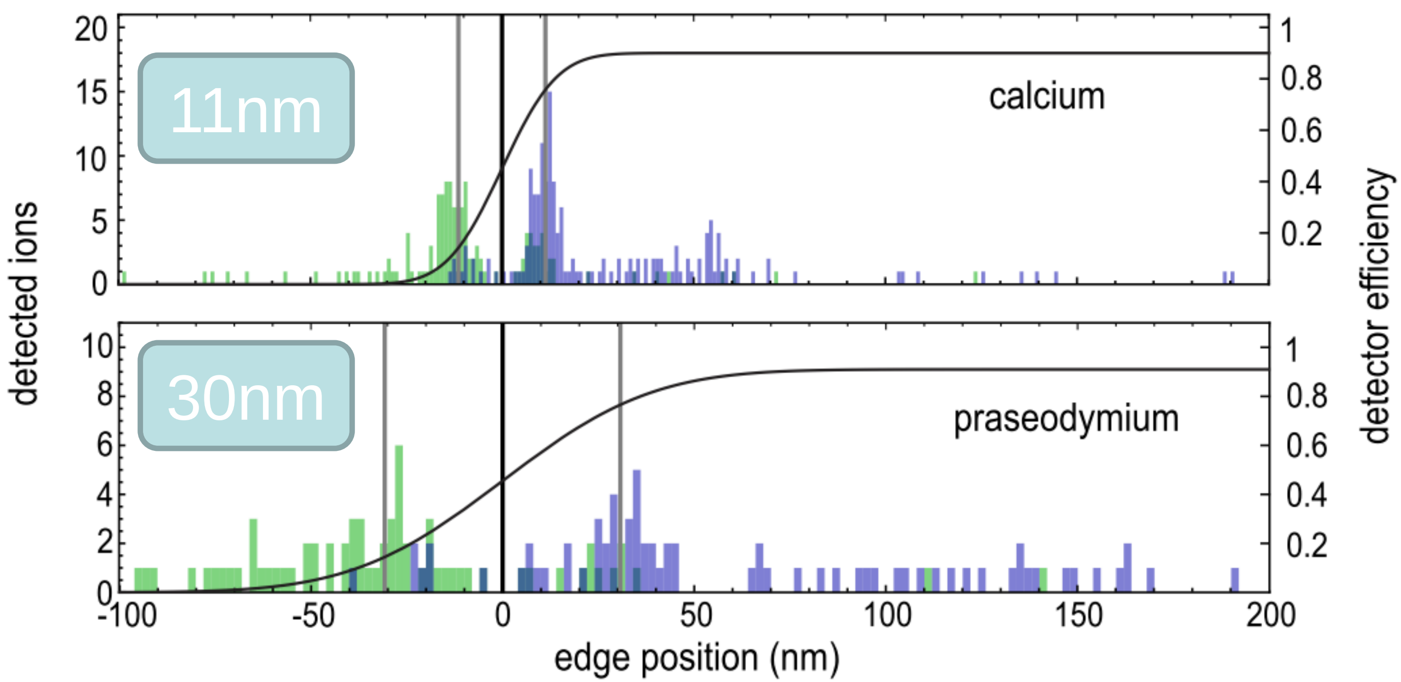




Single Pr^+ ions

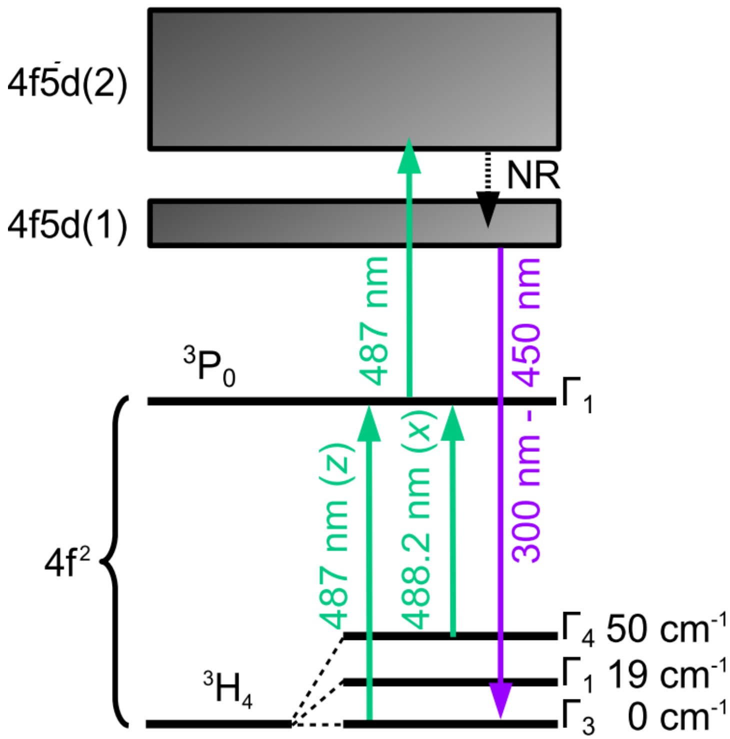


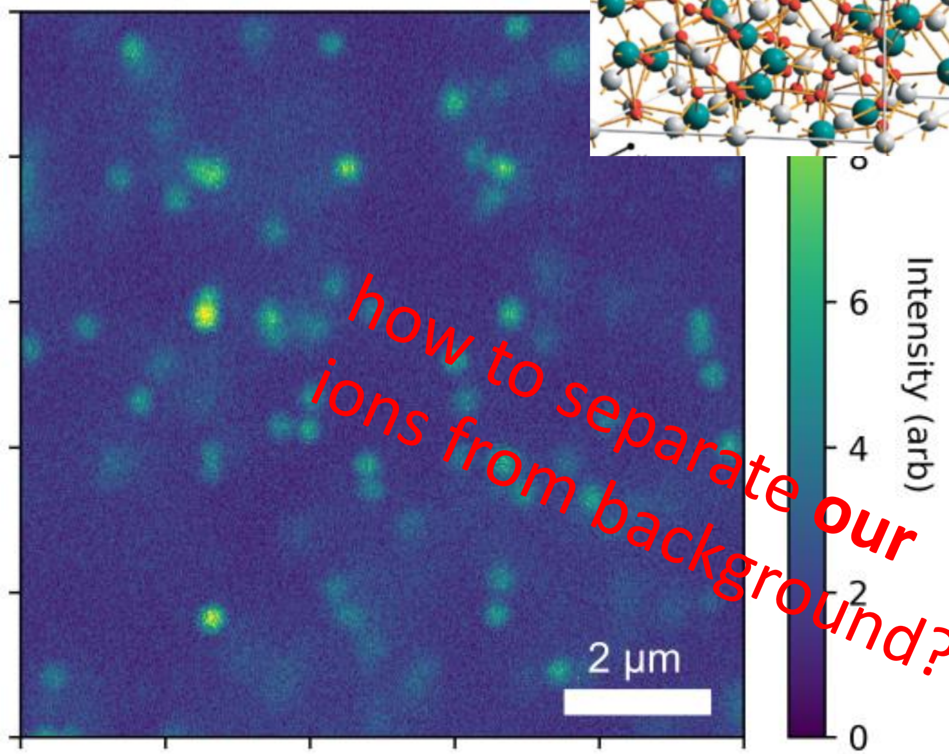


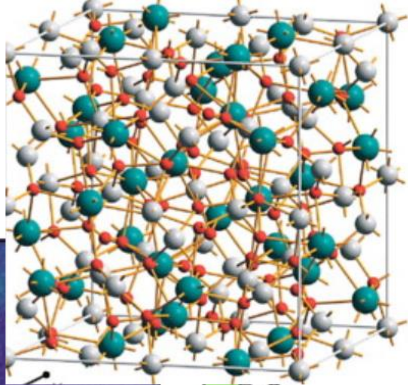


Confocal 2-photon microscope for Pr^{3+}

- shooting pattern into YAG
- anneal 1min @ 1200°C







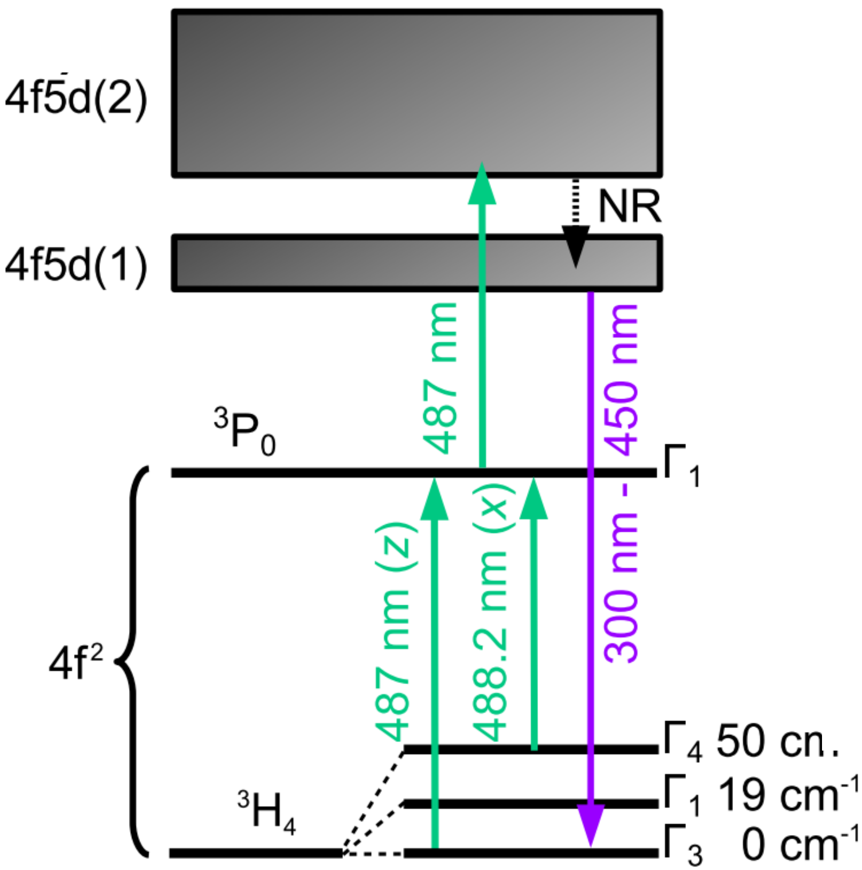
with R. Kolesov, J. Wrachtrup @ Stuttgart

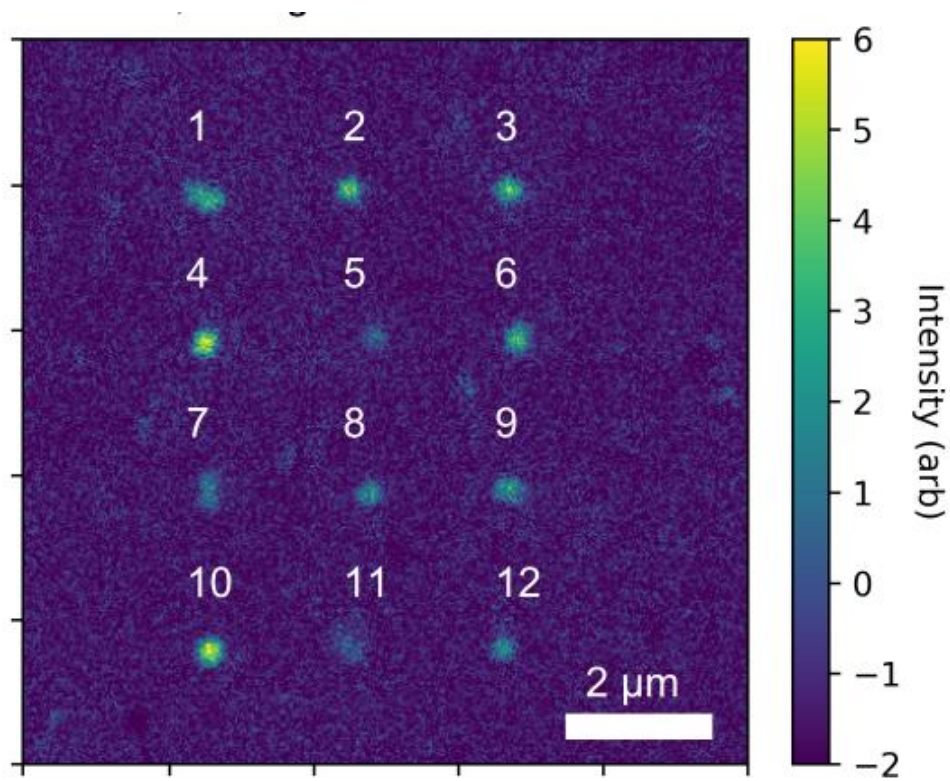
Kornher et al, Appl. Phys. Lett. 108, 053108 (2016)

Groot-Berning et al, arXiv:1902.05308

Confocal 2-photon microscope for Pr^{3+} ions in YAG

University of Stuttgart
3. Physikalisches Institut



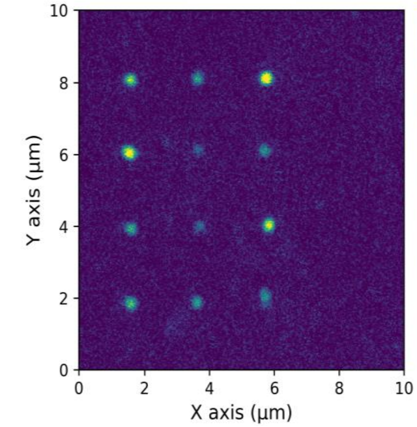


Kornher et al, Appl. Phys. Lett. 108, 053108 (2016)

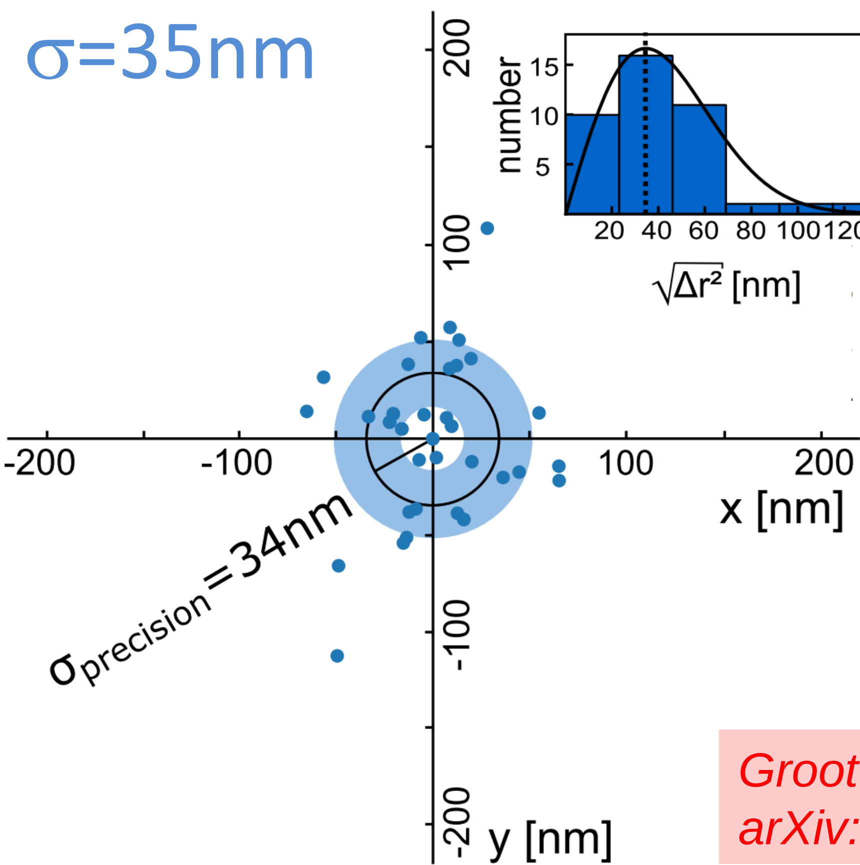
Groot-Berning et al, arXiv:1902.05308

Determination of impantation spot size

- Optical confocal image resolution
- Fit observed fluorescence spots
- precision



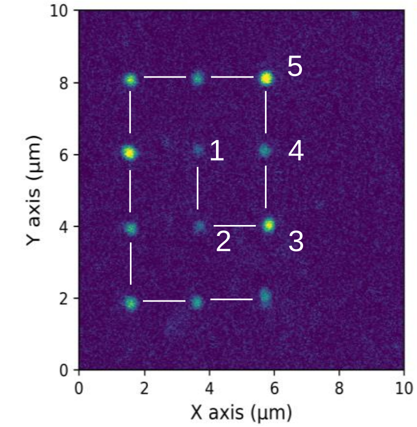
σ=35nm

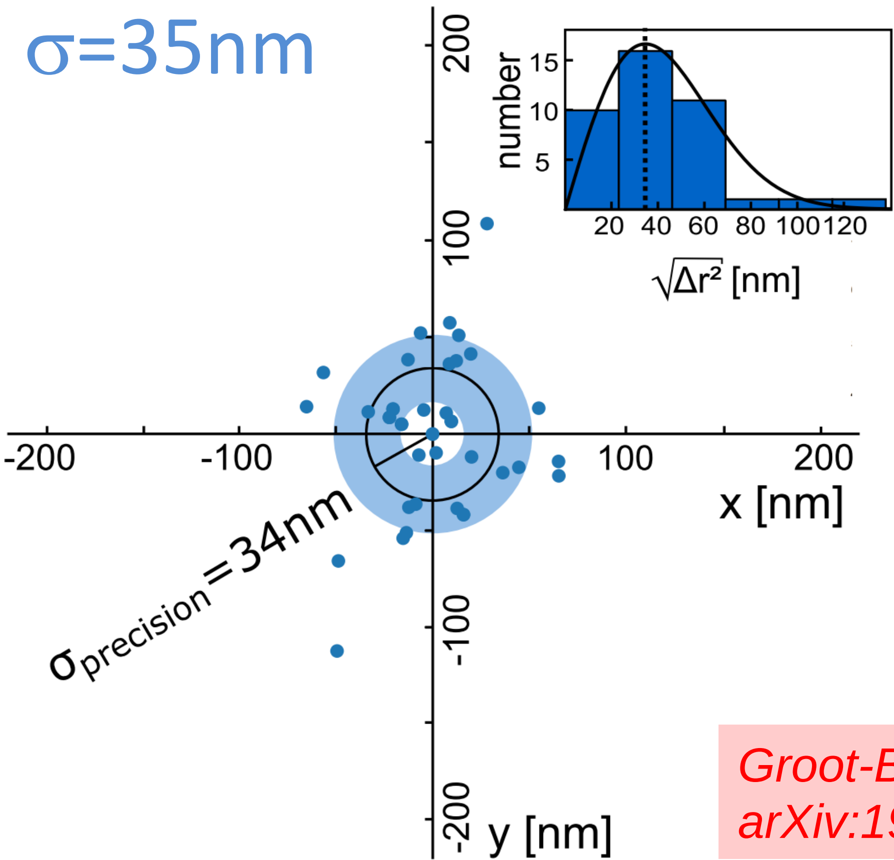


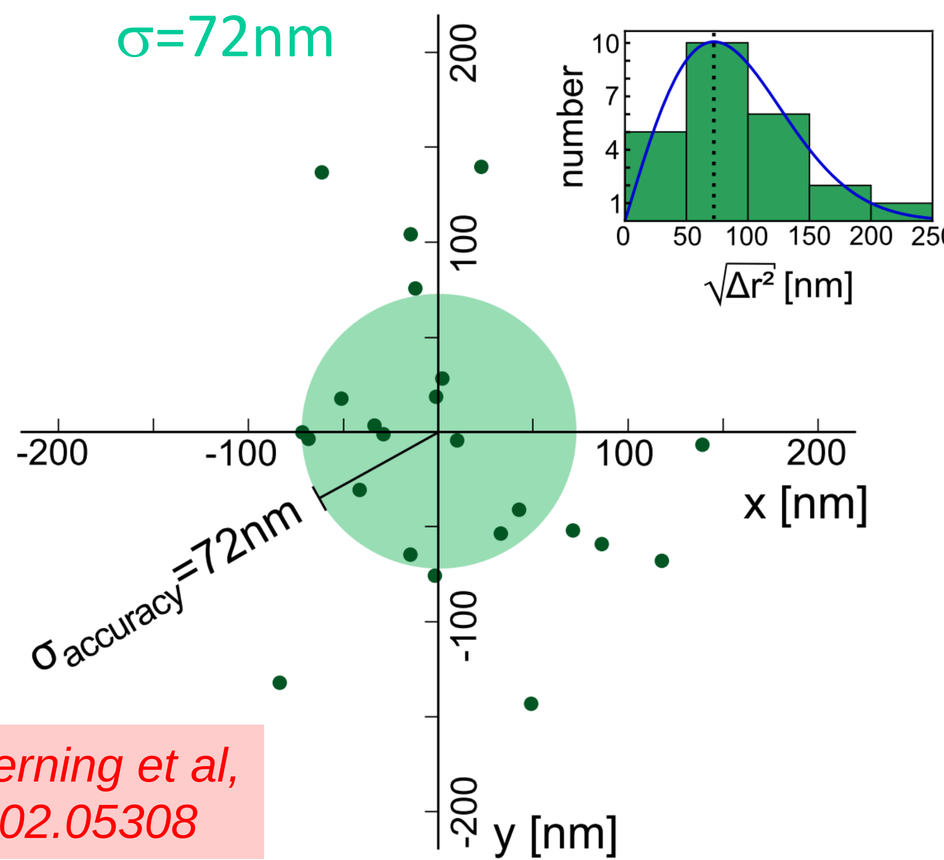
Groot-Berning et al, arXiv:1902.05308

Determination of impantation spot size

- Optical confocal image resolution
- Fit observed fluorescence spots
- precision / accuracy



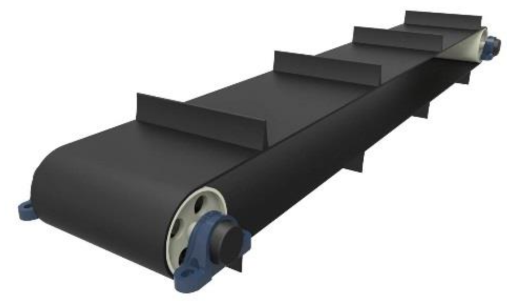


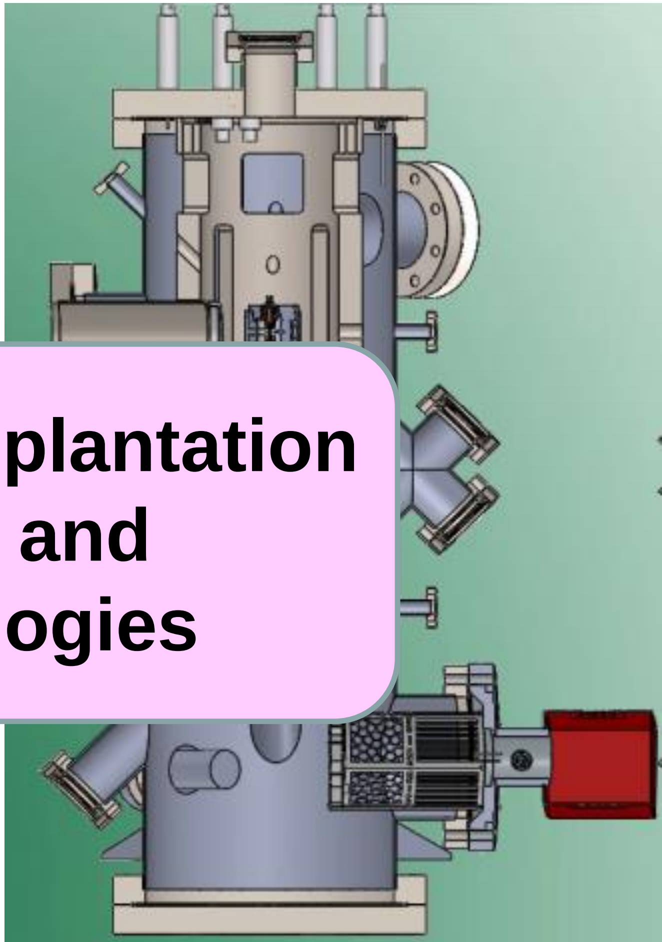


Groot-Berning et al, arXiv:1902.05308

Second generation setup

- Compact & high mech. stability
- Aiming for < 2 nm
- Modular design
- kHz-rate reloading from „reservoir“ trap segment
- Species: Phosphor, Cerium, Bismuth...
- Fast changing probes with lock





Applications of single ion implantation in quantum computing and nanostructuring technologies

The team

Coll.: Folman, Retzker, Wrachtrup, Meijer, Lesanowski, Hennrich, Zanthier, Lutz, Budker, Walz, Plenio, Jelezko, Calarco, Jamieson, Blatt

BMBF QLinkX

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RySQ iRyd

DFG Deutsche Forschungsgemeinschaft

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VolkswagenStiftung

QUANTUM FLAGSHIP

FUNDING OPPORTUNITIES from the FUTURE & EMERGING TECHNOLOGIES scheme

Quantum optics and information with trapped ions

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- Trapped ions as qubits for quantum computing and simulation
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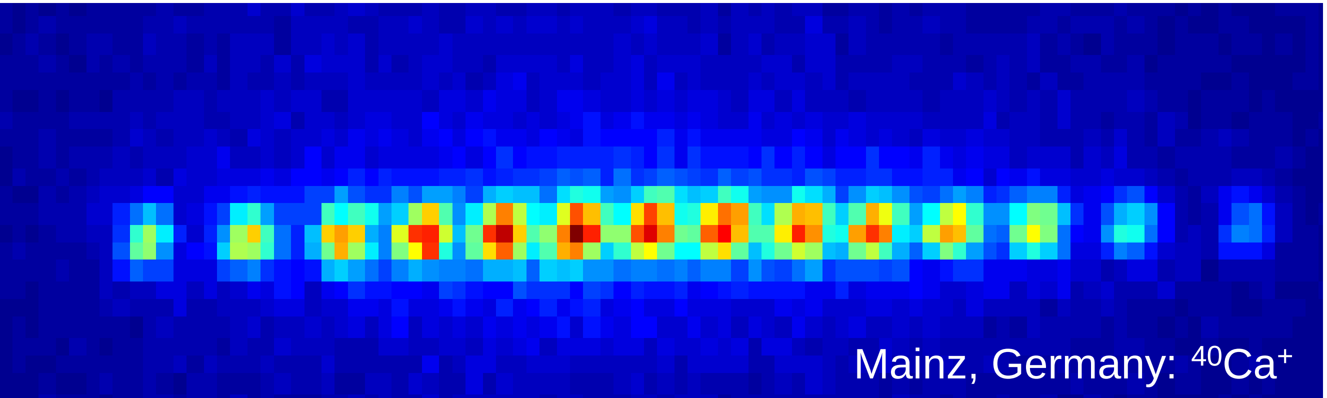

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F. Schmidt-Kaler
JOHANNES GUTENBERG UNIVERSITÄT MAINZ