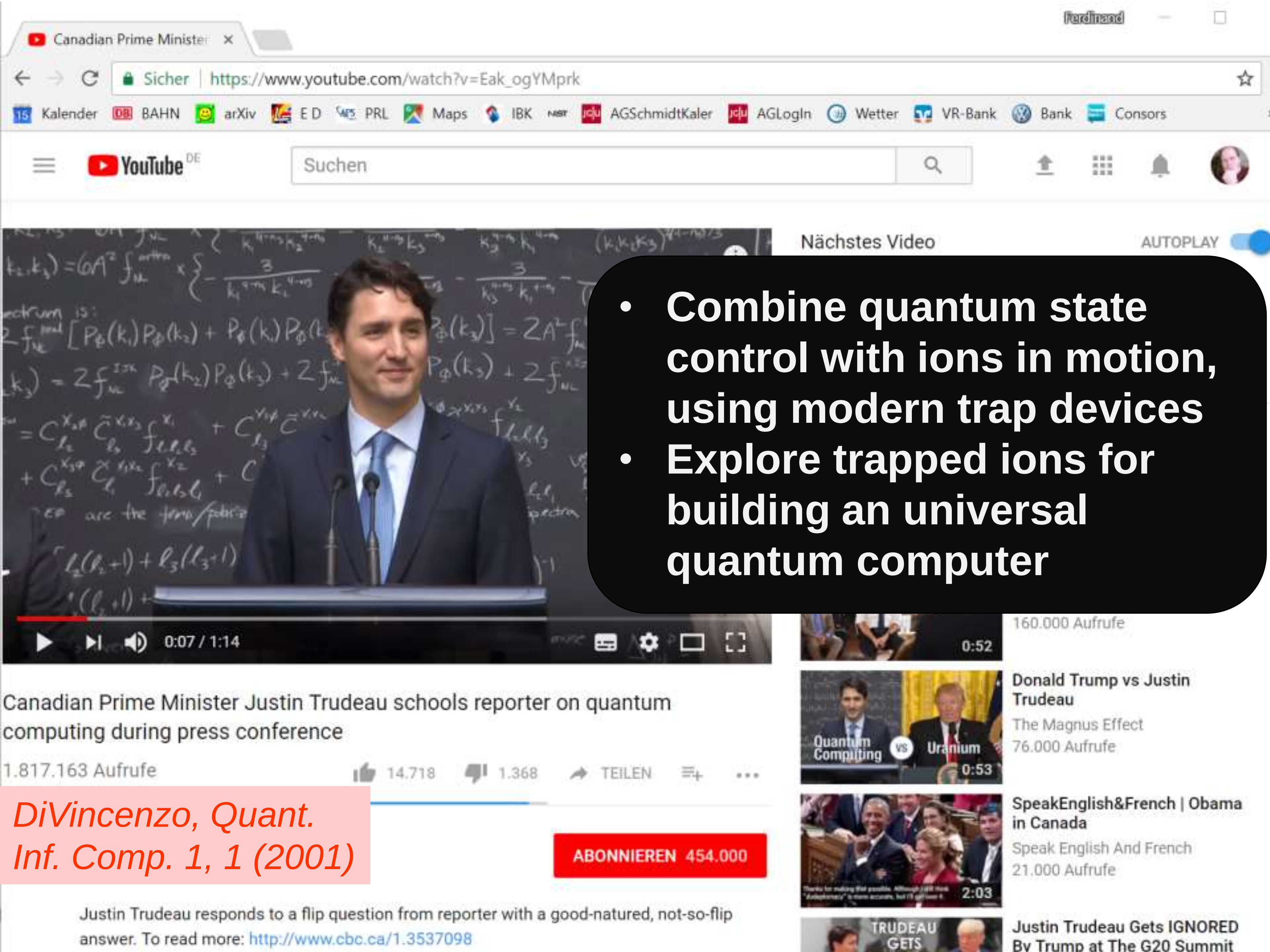
Scalable creation of multi-particle entanglement

- Status – quantum processor
- Spin-qubits in single ions, and
- Quantum register reconfigurations
- Quantum-enhanced magnetometry
- Creation of GHZ states
- Outlook, perspective of scalable QC with trapped ions

F. Schmidt-Kaler

www.quantenbit.de

JOHANNES GUTENBERG UNIVERSITÄT MAINZ



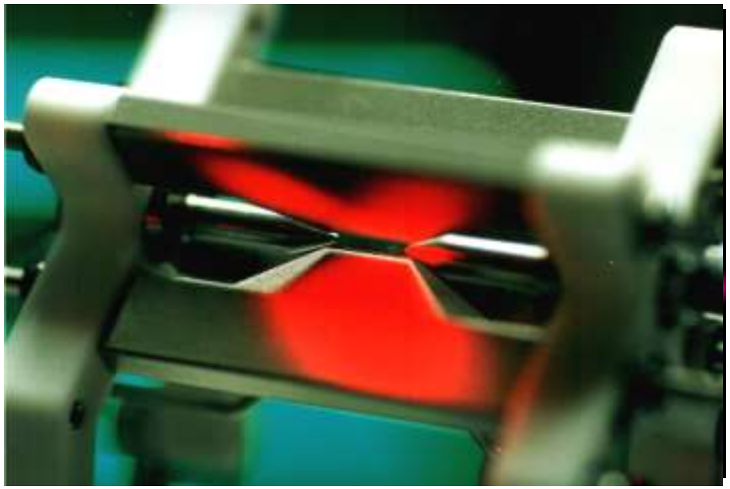
- **Combine quantum state control with ions in motion, using modern trap devices**
- **Explore trapped ions for building an universal quantum computer**

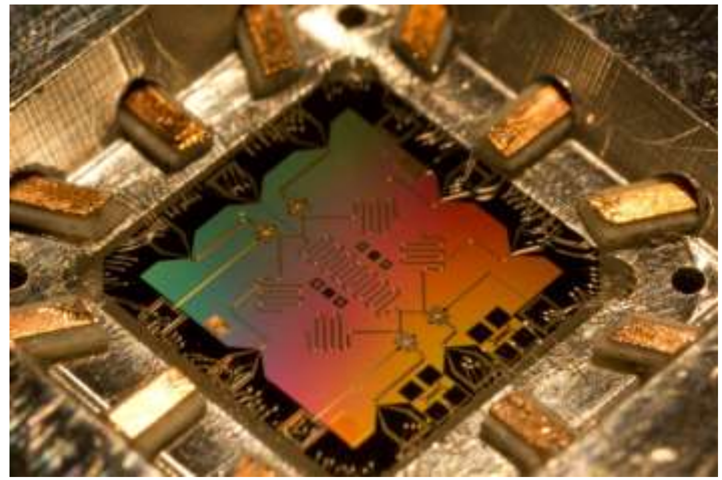
DiVincenzo, Quant. Inf. Comp. 1, 1 (2001)

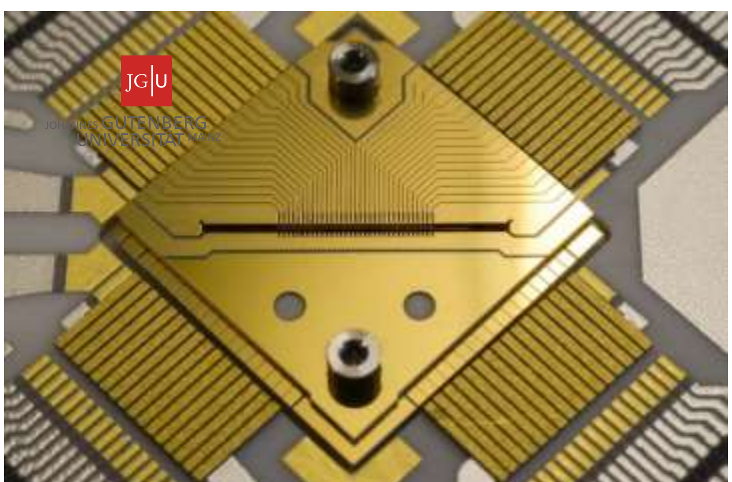
Quantum computing platforms

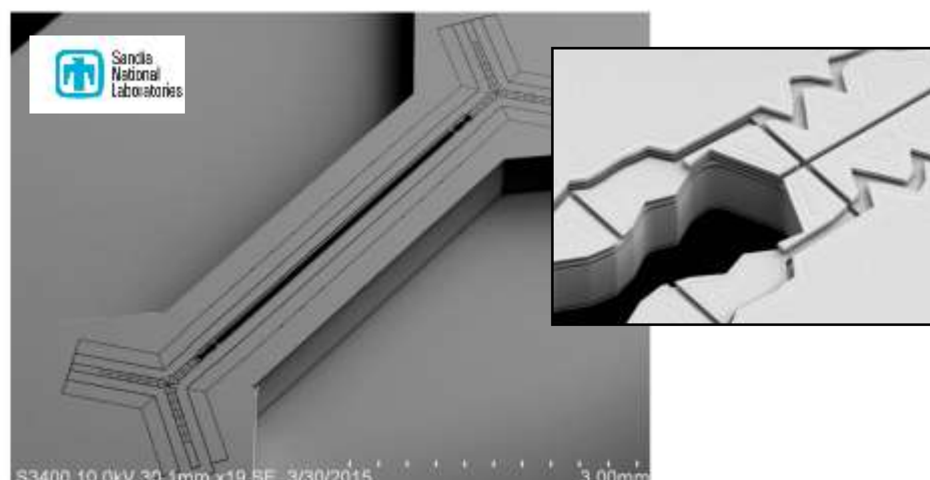
Trapped Ions in Paul traps

SC qubit circuits









Ion qubit choice

MICROWAVE

NIST, Hannover, Oxford, Sussex, …

OPTICAL

$^{40}Ca^{+}$: UIBK, UCB, ETH, PTB

$^{88}Sr^{+}$: MIT, Weizmann

$^{128}Ba^{+}$: UIBK

HYPERFINE

$^{9}Be^{+}$: NIST, ETH

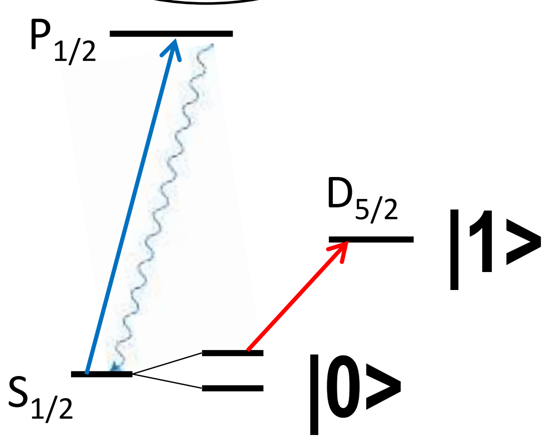
$^{25}Mg^{+}$: NIST, Freiburg

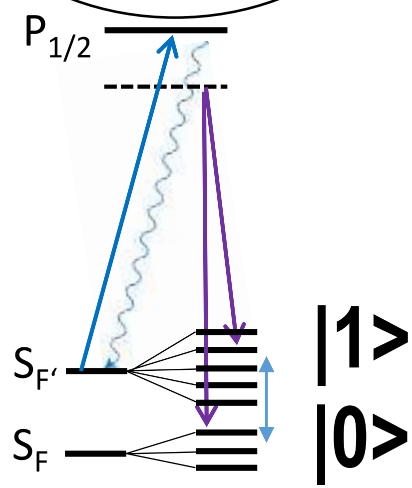
$^{43}Ca^{+}$: UIBK, Oxford

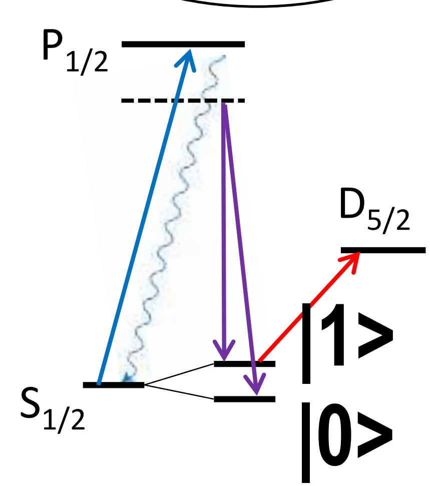
$^{171}Yb^{+}$: JQI, Sussex, Siegen, Duke,…

SPIN

$^{40}Ca^{+}$: Oxford, UMZ







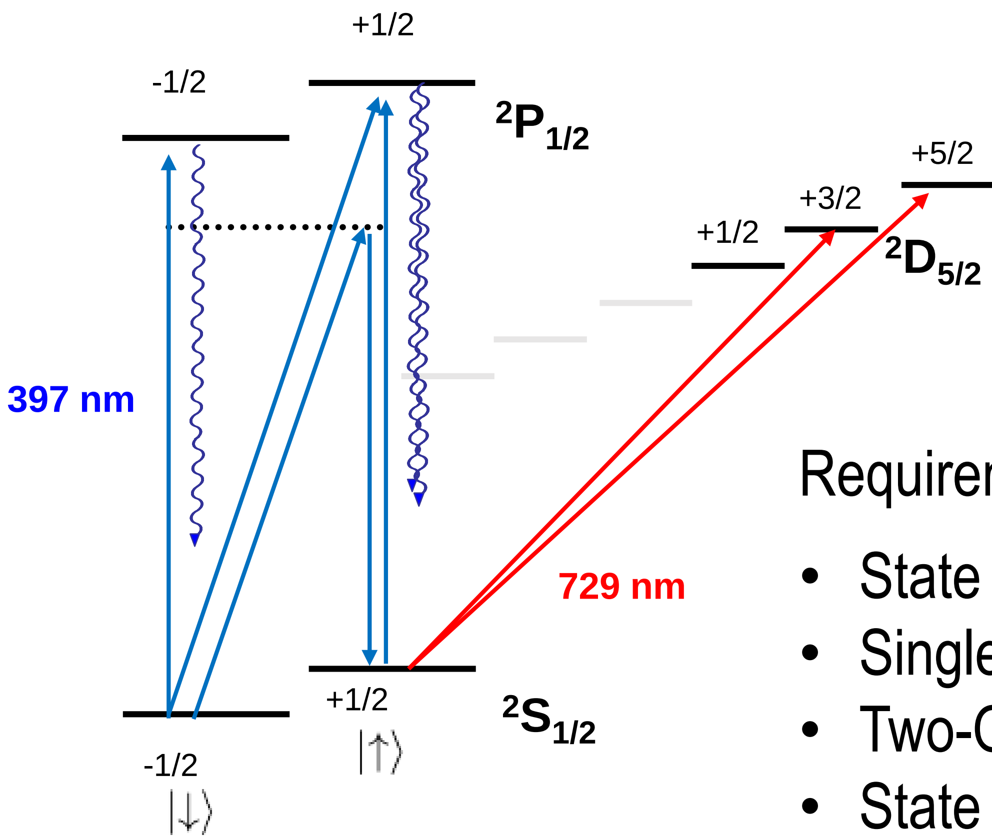
- Best overall performance so far
- Easy readout
- Requires optical phase stability
- Limited by metastable lifetime

- Infinite T_1
  only scattering errors
- complicated level scheme

- Infinite T_1
  only scattering errors
- readout overhead

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

[illegible]

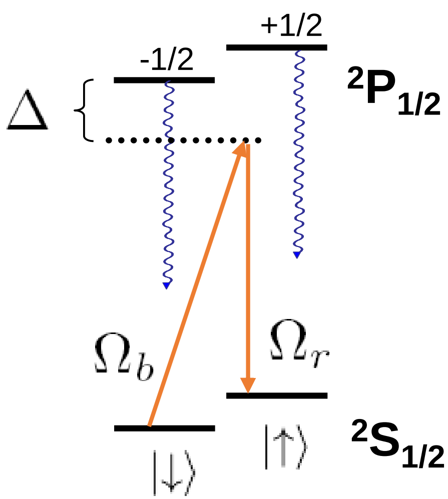


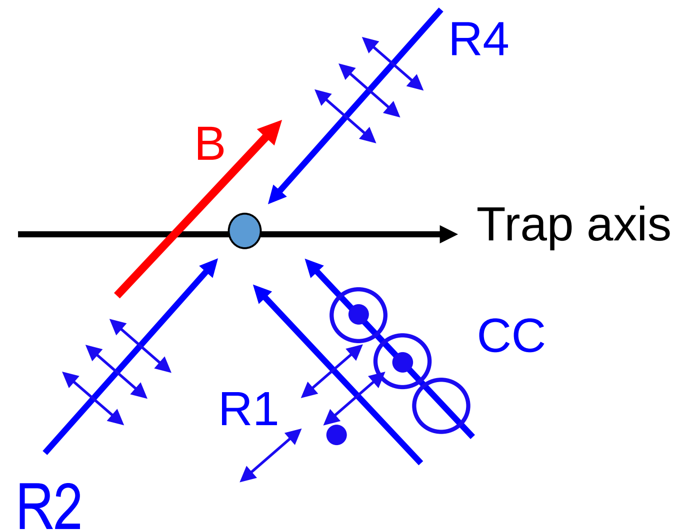
Requirements:

- 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

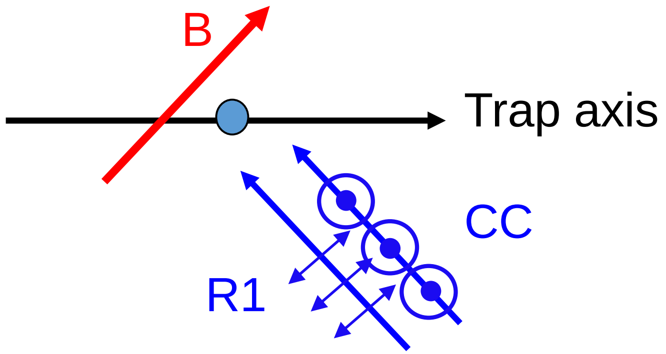




- Single photon detuning Δ much larger than natural linewidth
- Very small spont. scattering rate
- Effective two-level system

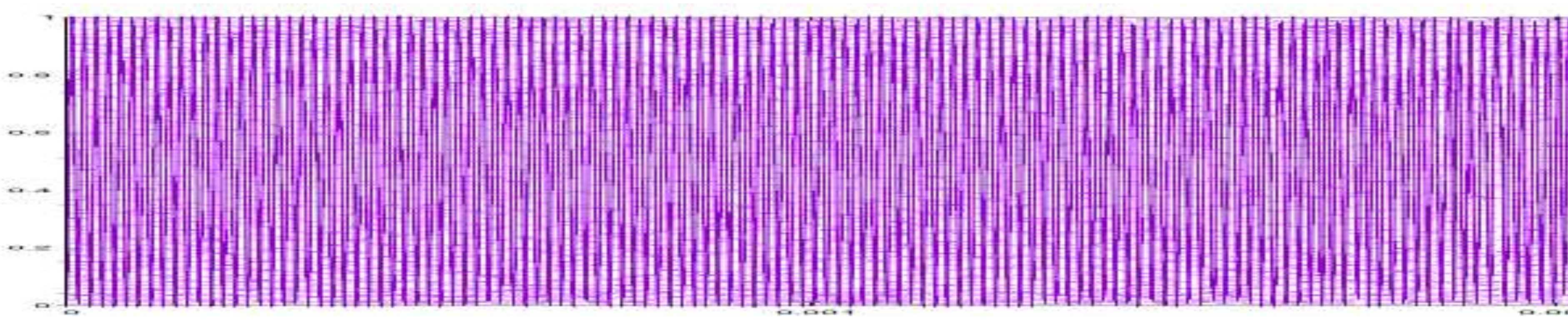
Four beams near 397nm used pairwise in different configurations

Single qubit rotation



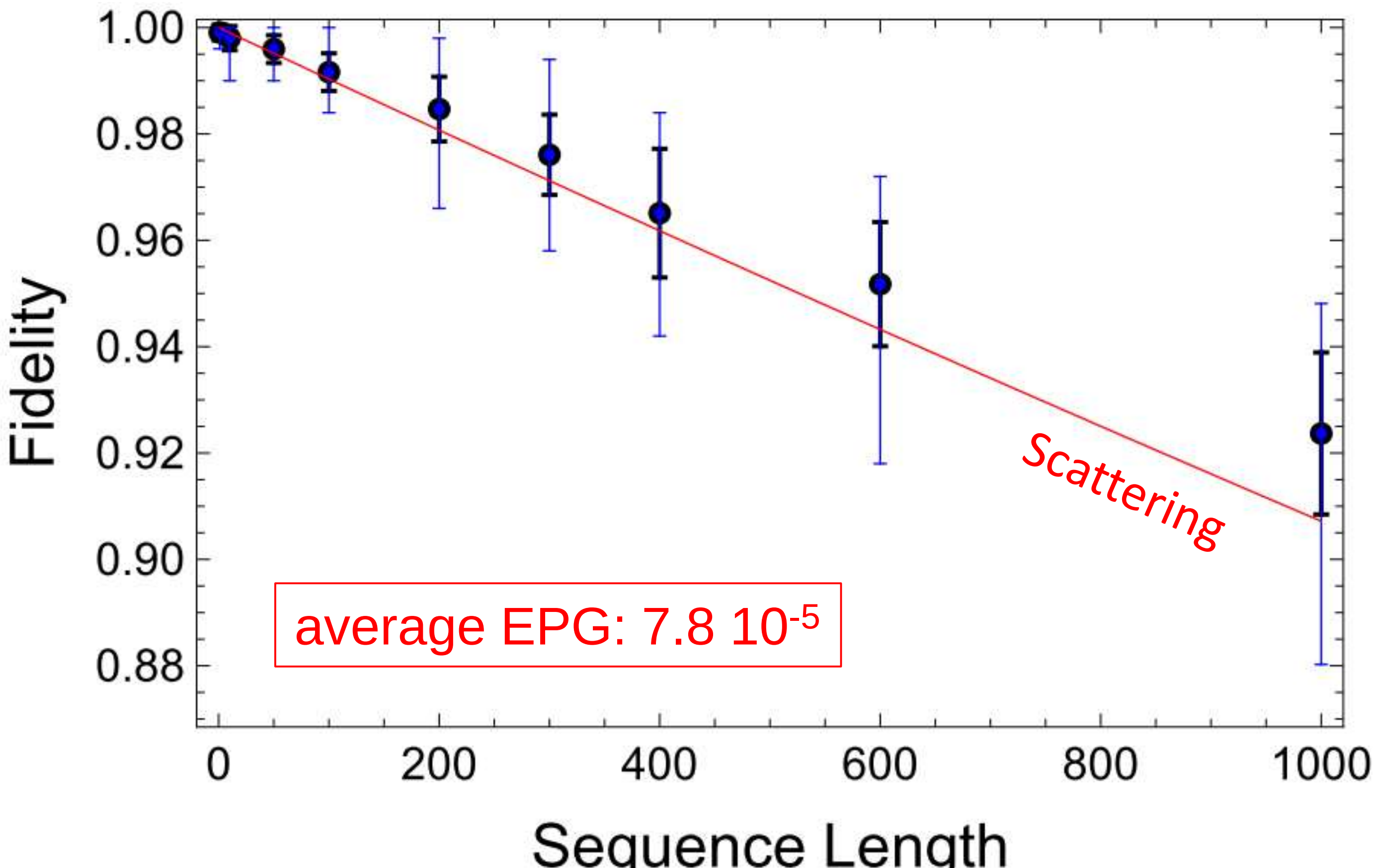
- Copropgating beams
- No effective k-vector
- No coupling to ion motion
- High fidelity single-qubit gates
- No ultrastable laser required

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



Spin qubit gate operation: Randomized benchmarking

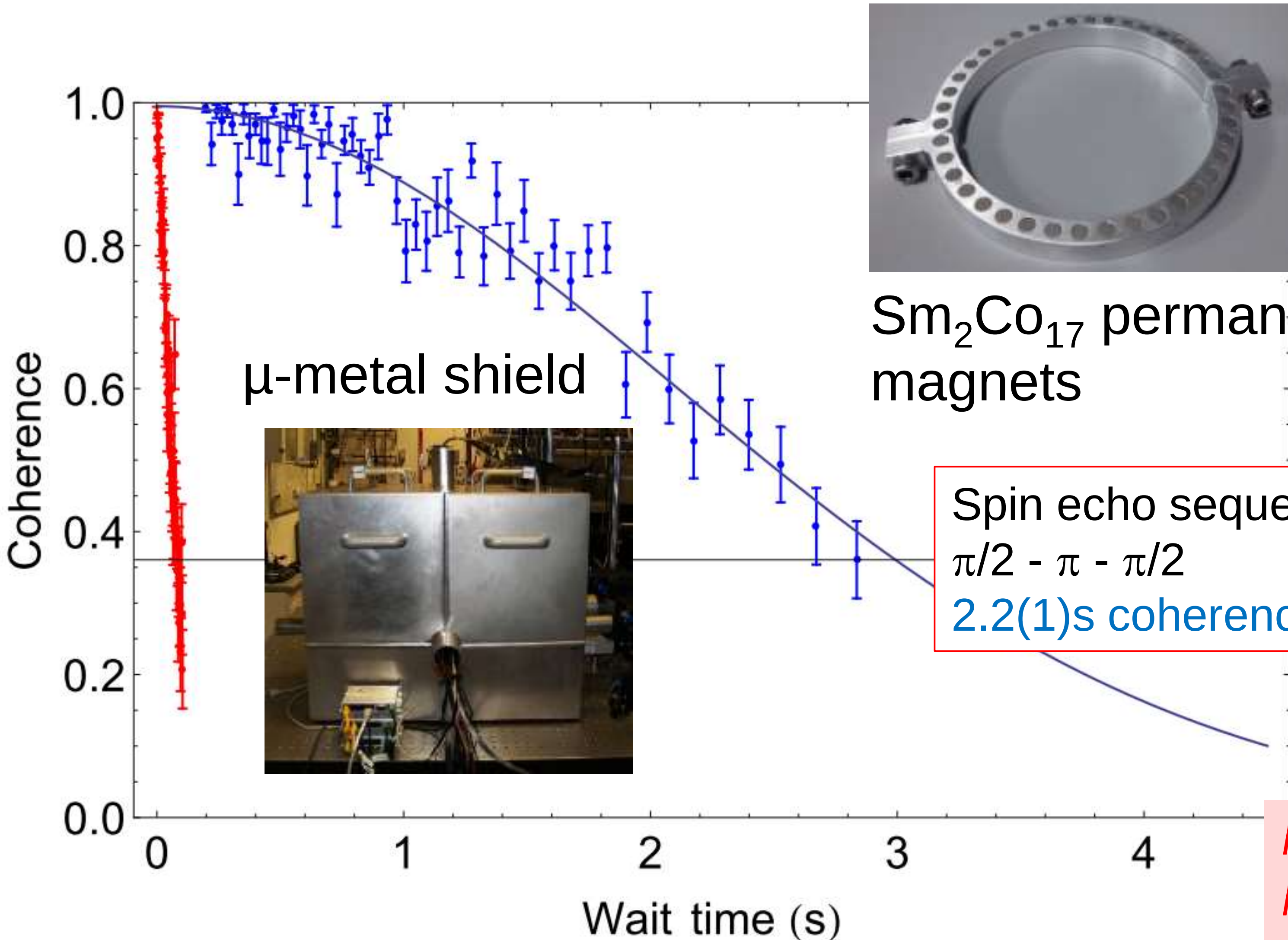
- Blocks of 40 gate sequences
- Gates chosen from $\{I, R_X(\pi/2), R_Y(\pi/2), R_Z(\pi/2), R_X(\pi), R_Y(\pi), R_Z(\pi)\}$, with π-time: 6.2 µs
- 500 repetition per sequence
- Raman detuning: here 300 GHz
- Laser power required: > 2W installed



Kaufmann, PhD

Spin qubit coherence

Decoherence only by phase shifts, magnetic field fluctuations dominate

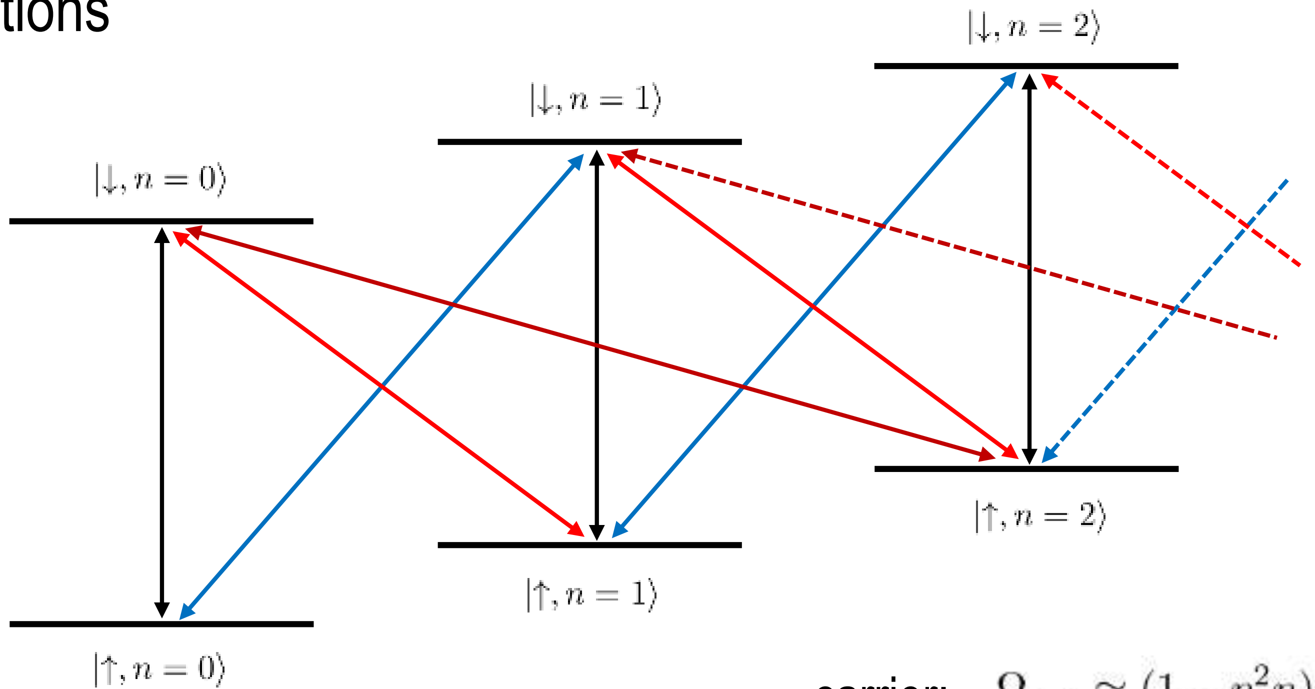


Spin echo sequence:
$\pi/2$ - π - $\pi/2$
2.2(1)s coherence time

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

Coupling of Spin and motion –
Jaynes Cummings Hamilton

Driving spin flips via stimulated Raman transitions:
Rabi oscillations



carrier: $\Omega_{n,n} \approx (1-\eta^2 n)\Omega_0$

red sideband: $\Omega_{n,n-1} \approx \eta\sqrt{n}\Omega_0$

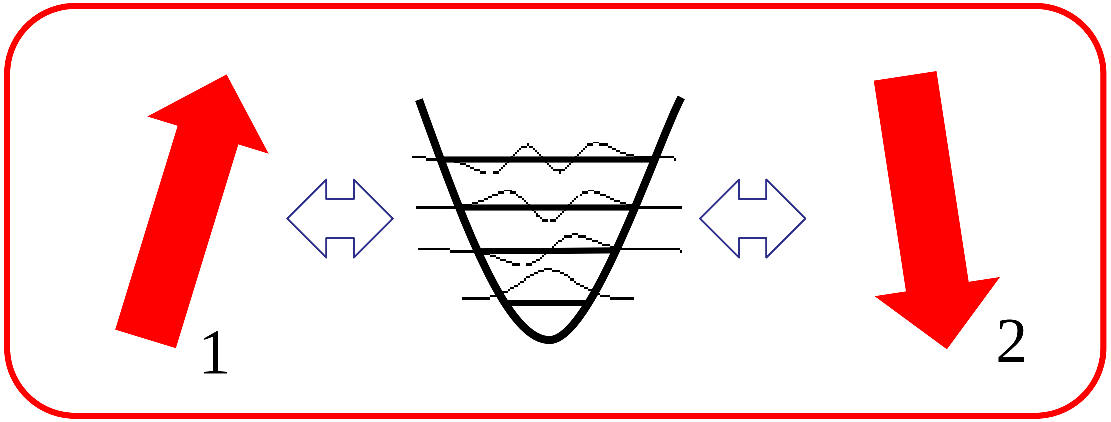
blue sideband: $\Omega_{n,n+1} \approx \eta\sqrt{n+1}\Omega_0$

2nd red sideband: $\Omega_{n\ n+2} \approx \frac{1}{2}\eta^2\sqrt{n(n-1)}\Omega_0$

Brune, et al., PRL76, 1800 (1996)

Designed qubit interactions

Interaction of spin 1 and 2
due to coupling to common mode of vibration



Spin-dependent
light forces

*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)*

Designed qubit interactions

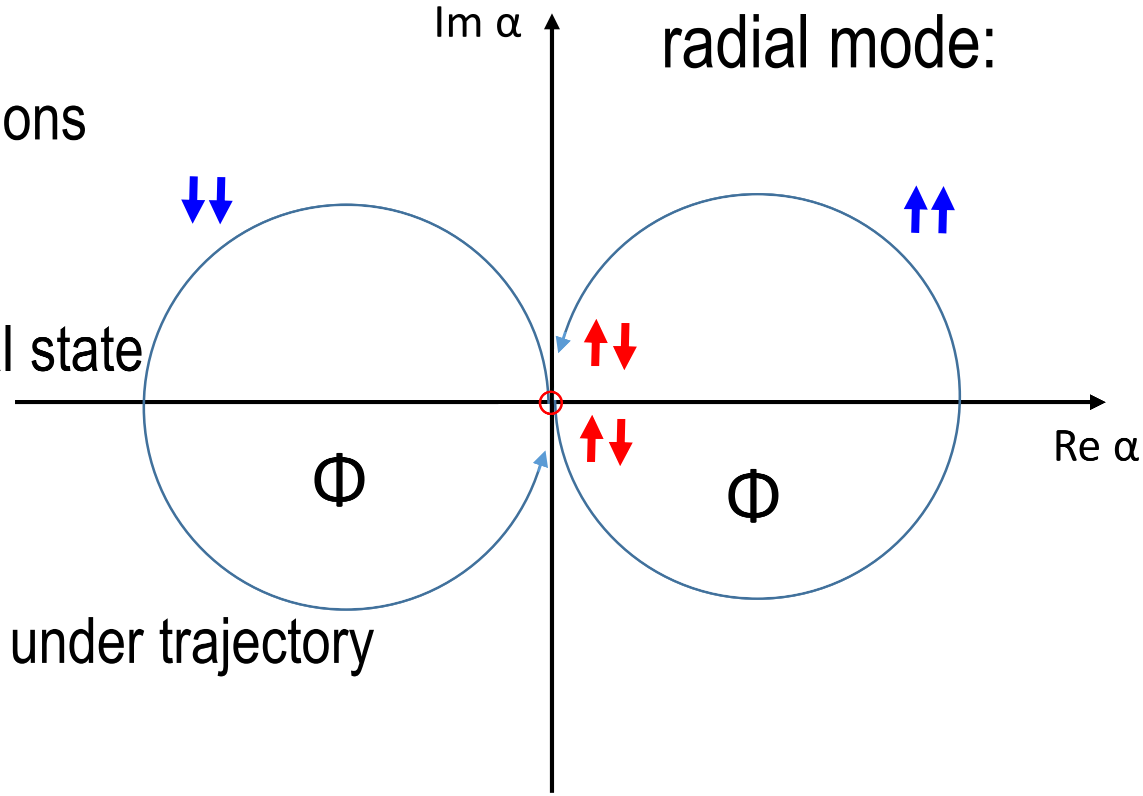
- Only even spin configurations are displaced

- 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

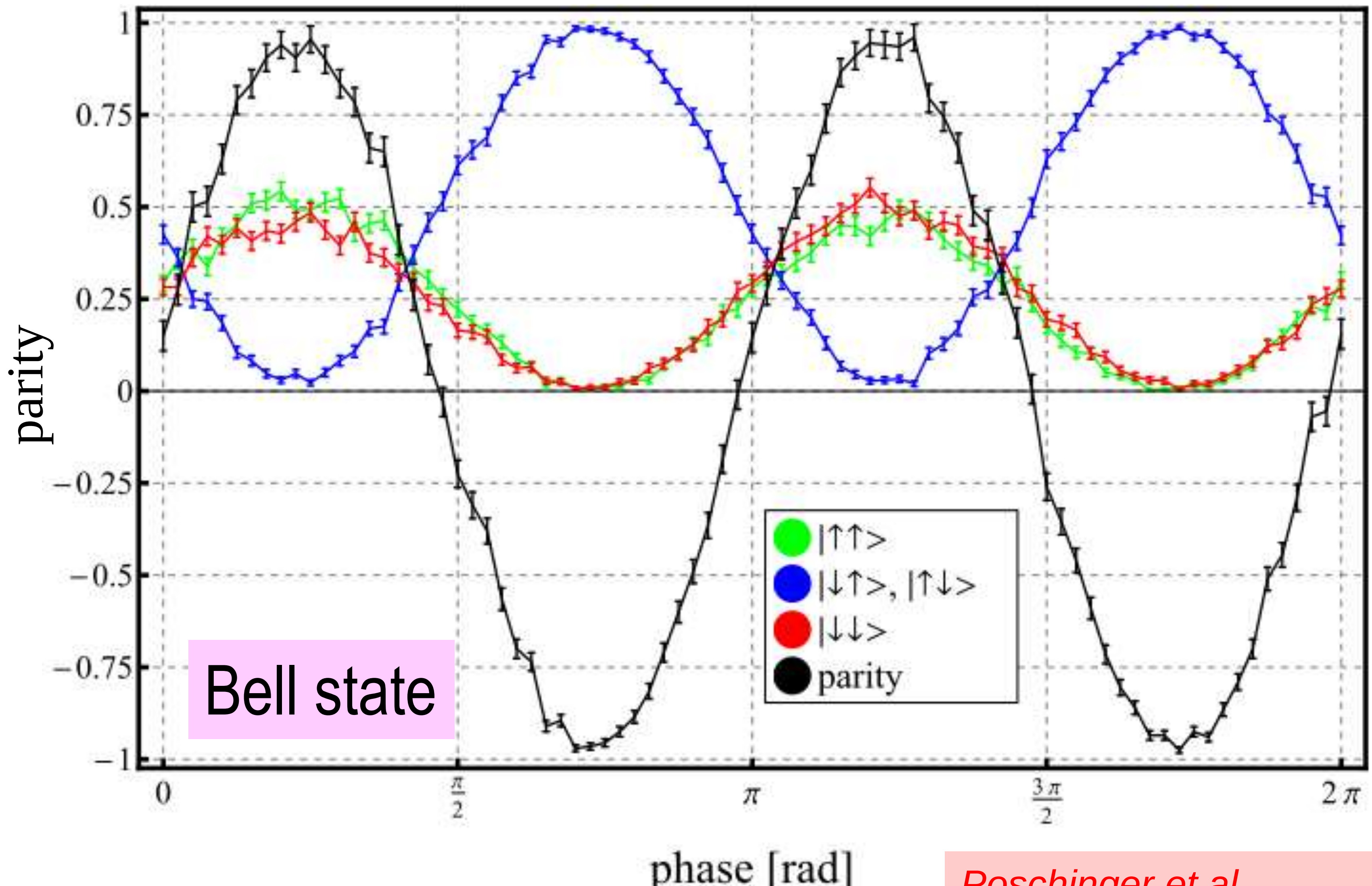
- Bell state generated

Phase space of radial mode:



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

Two ion entanglement – parity oscillations

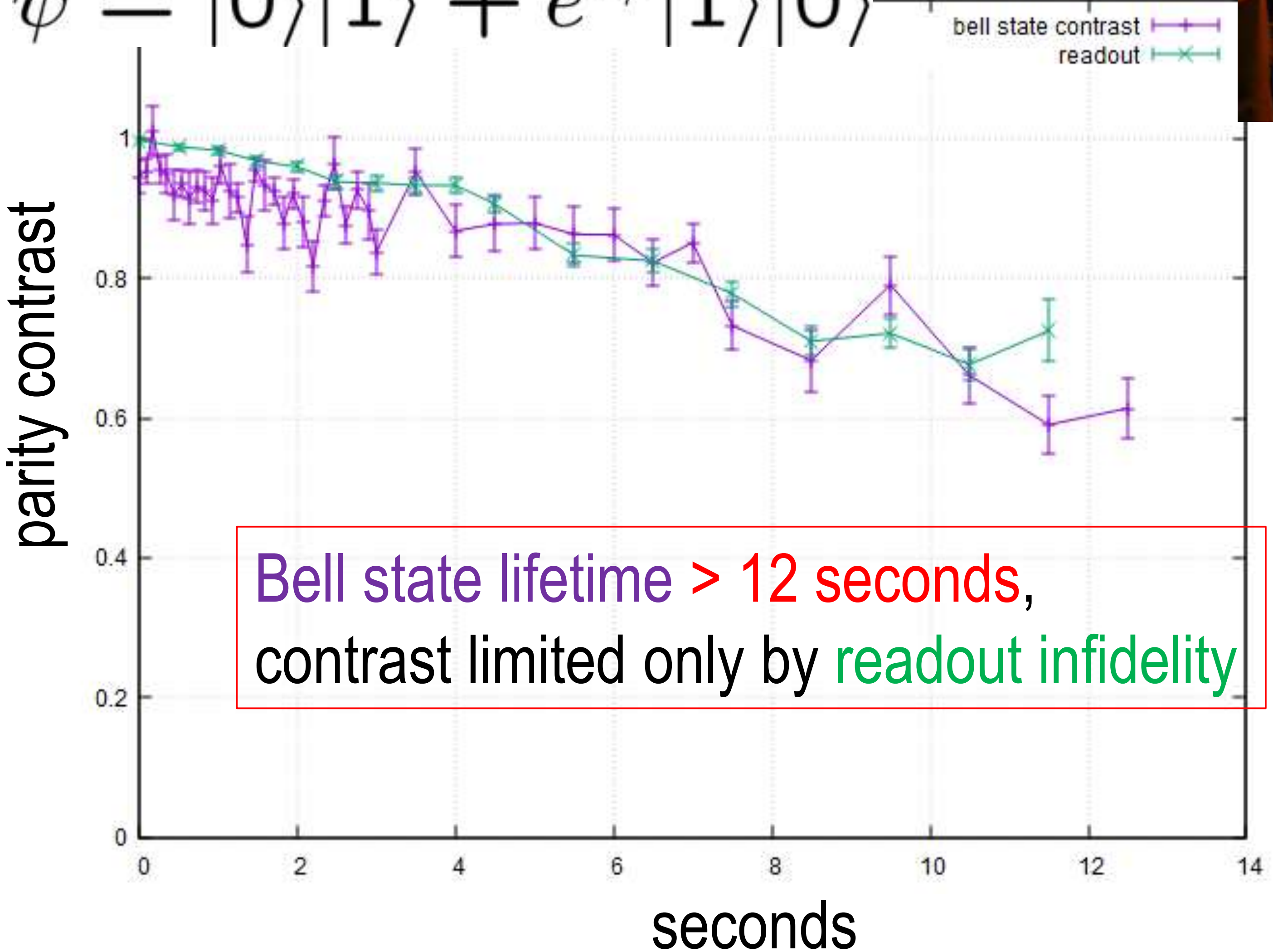


Here: 97.5% fidelity

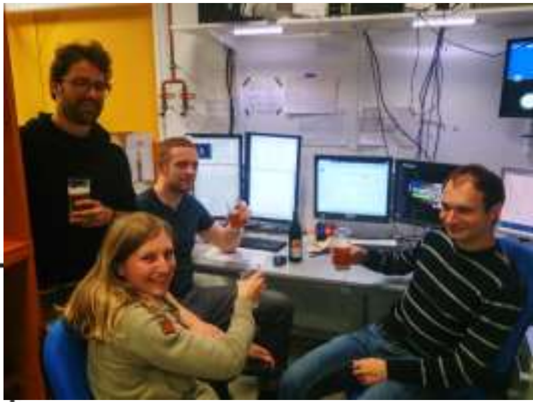
*Poschinger et al., PRL **105**, 263602 (2010)*

Bell state coherence

$$\psi = |0\rangle|1\rangle + e^{i\phi}|1\rangle|0\rangle$$



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

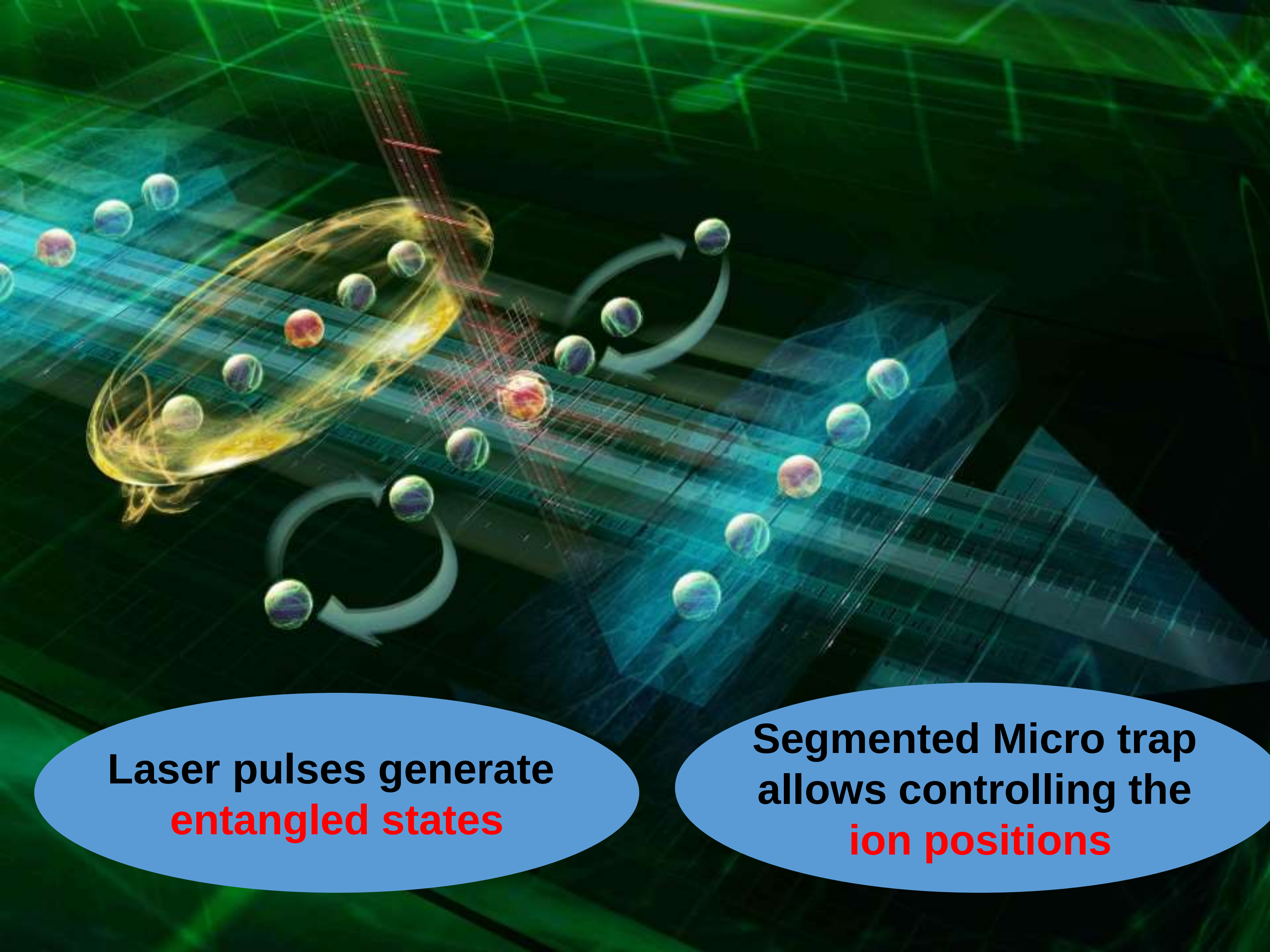


Gate error budget

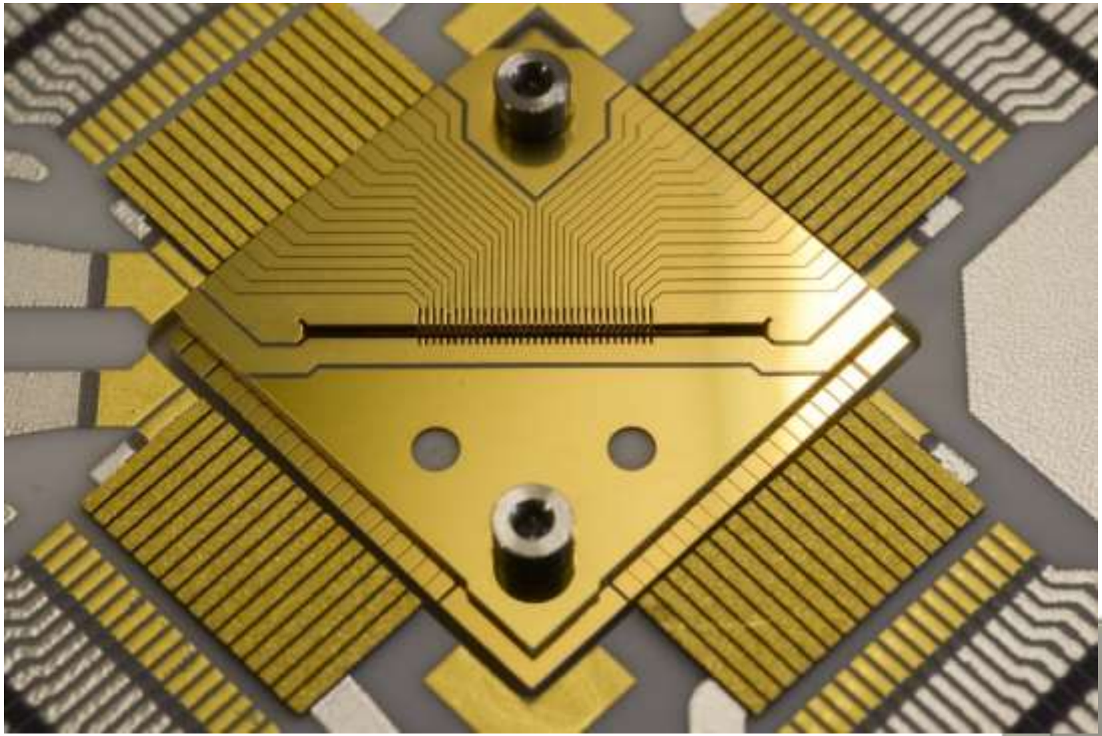
Error type	Current (%)	Countermeasure	Prospective (%)
Gate detuning	0.3	composite pulses	<0.01
Mis-set laser power	0.04	improved calibration	<0.01
Unequal illumination	0.002	-	-
Thermal occupation	0.01	improved cooling	<0.01
Heating	0.01	cryogenic trap, noise supp.	<0.01
Motional dephasing	0.1 .. 1.0	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)


Laser pulses generate entangled states
Segmented Micro trap allows controlling the ion positions

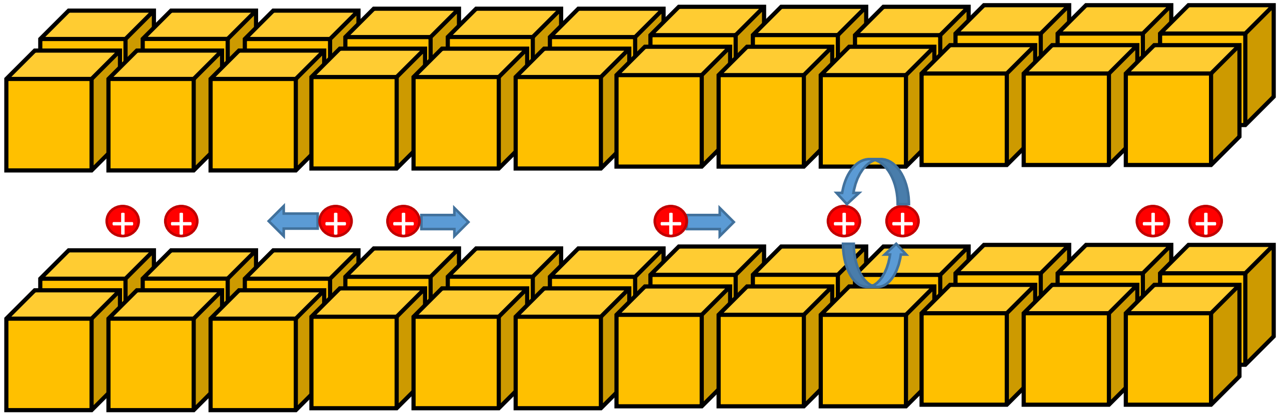
High performance multi-layer ion trap



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

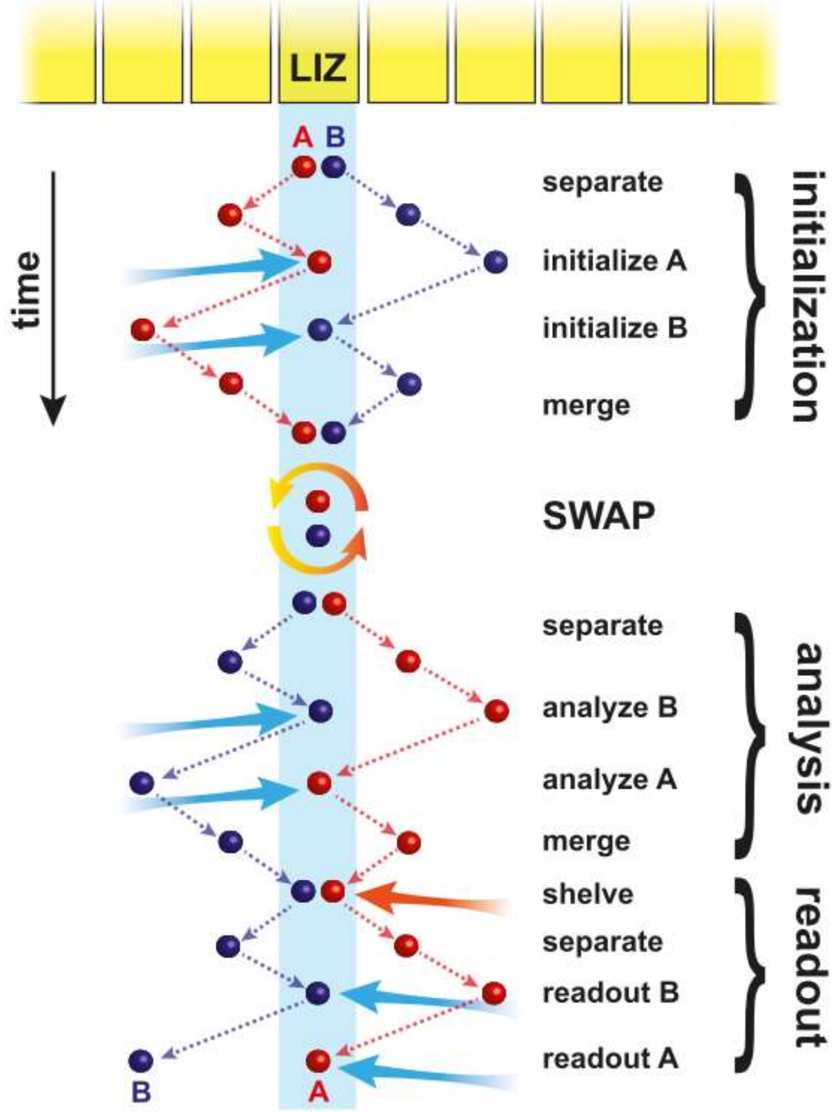
Performance
- 1.5 MHz axial trap frequency @-6V segment voltage
- Lowest heating rate: 3 phonon/s @ 4 MHz radial trap frequency
- 1 day trapping times

Ion movement – qubit register reconfigration

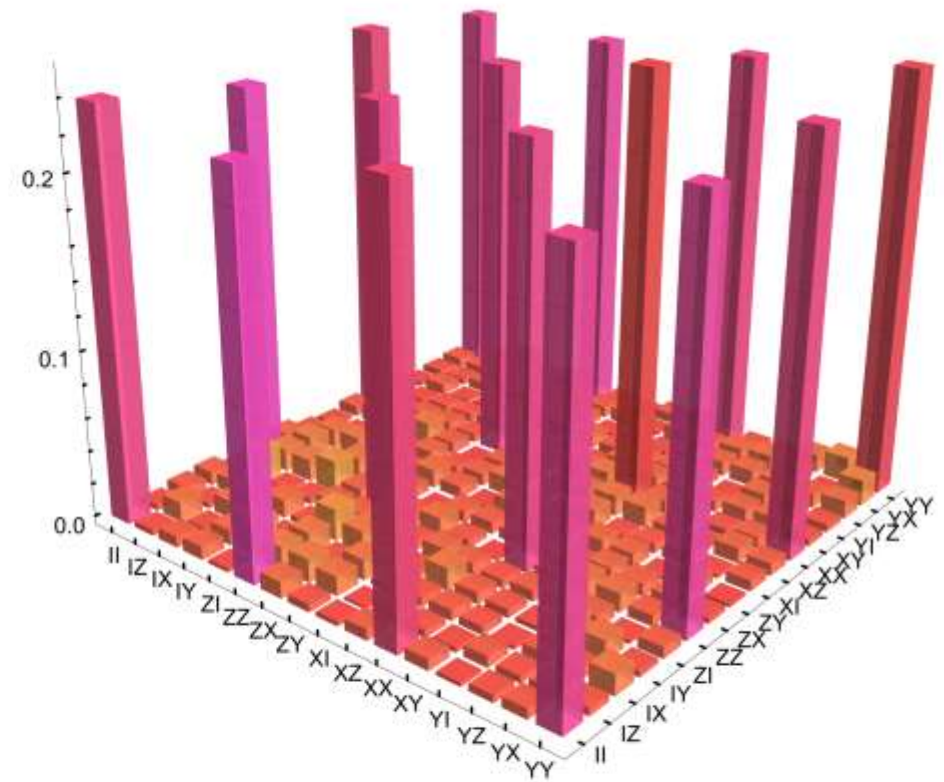


- Shuttle single ion
- Shuttle ion crystal
- Separate two-ion crystal
- Merge into two-ion crystal
- Swap ion positions

Qubit control & two qubit register reconfigration



Process tomography data



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

B-Field Sensing with entangled ions

1. Prepare entangled sensor state

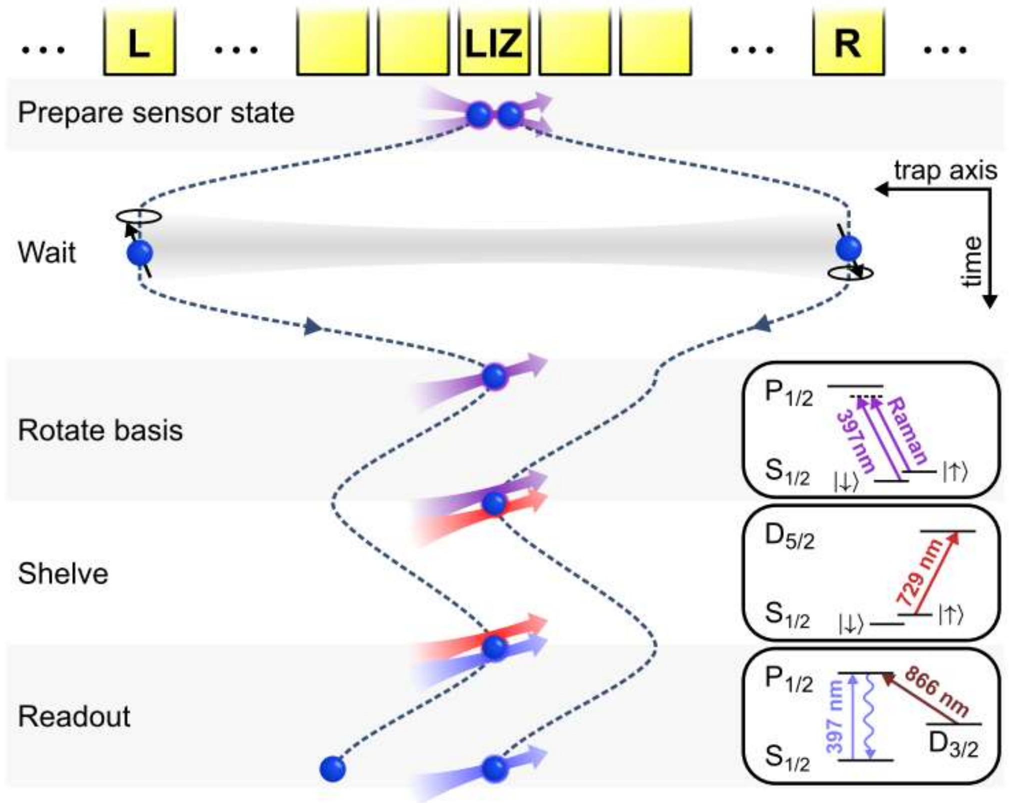
- $|\Psi\rangle = |\uparrow\downarrow\rangle + |\downarrow\uparrow\rangle$

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

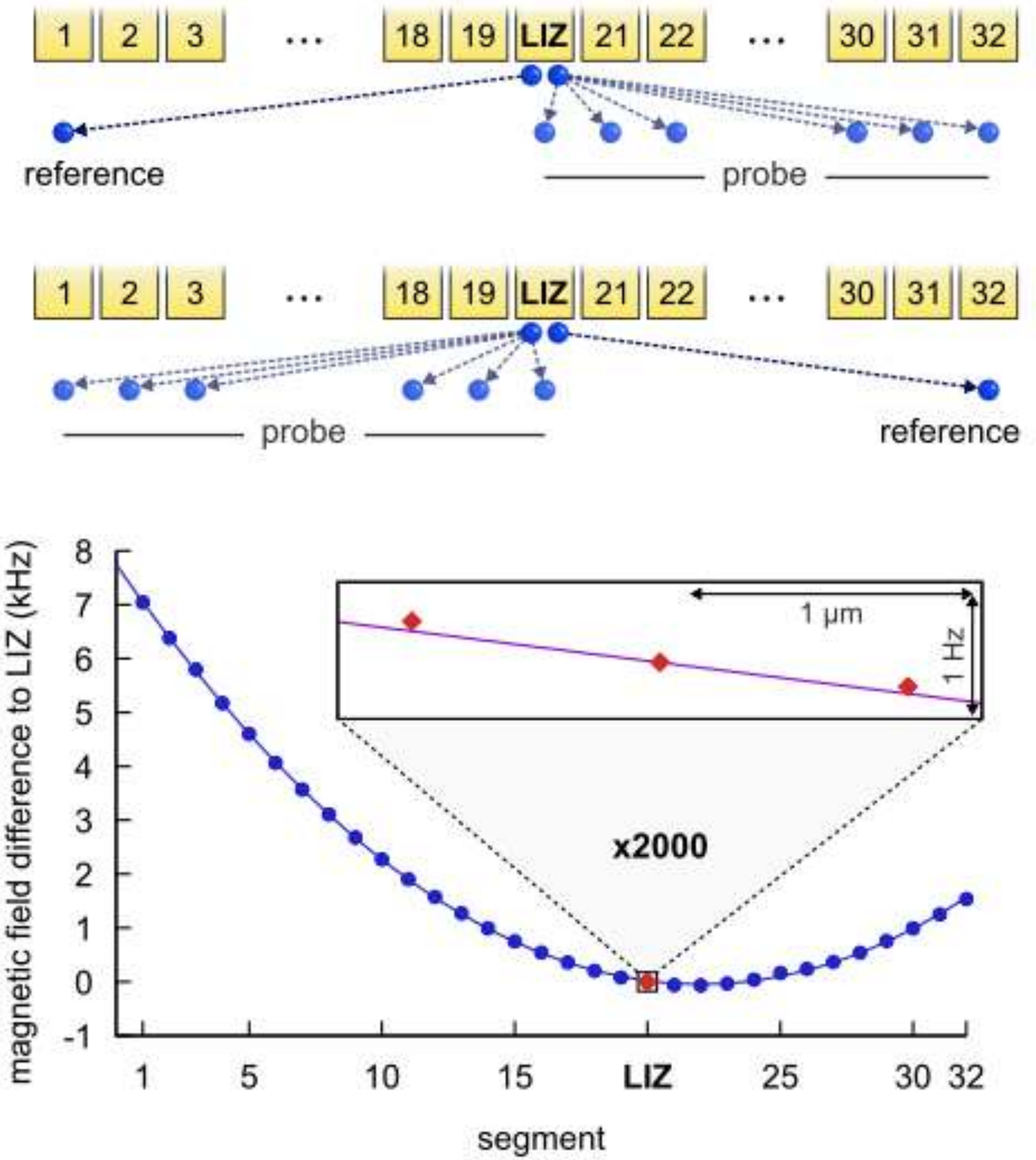
Seconds of coherence time

Sensitivity: 12pT / √ Hz

Separated entanglement,
nano-positioning within µs

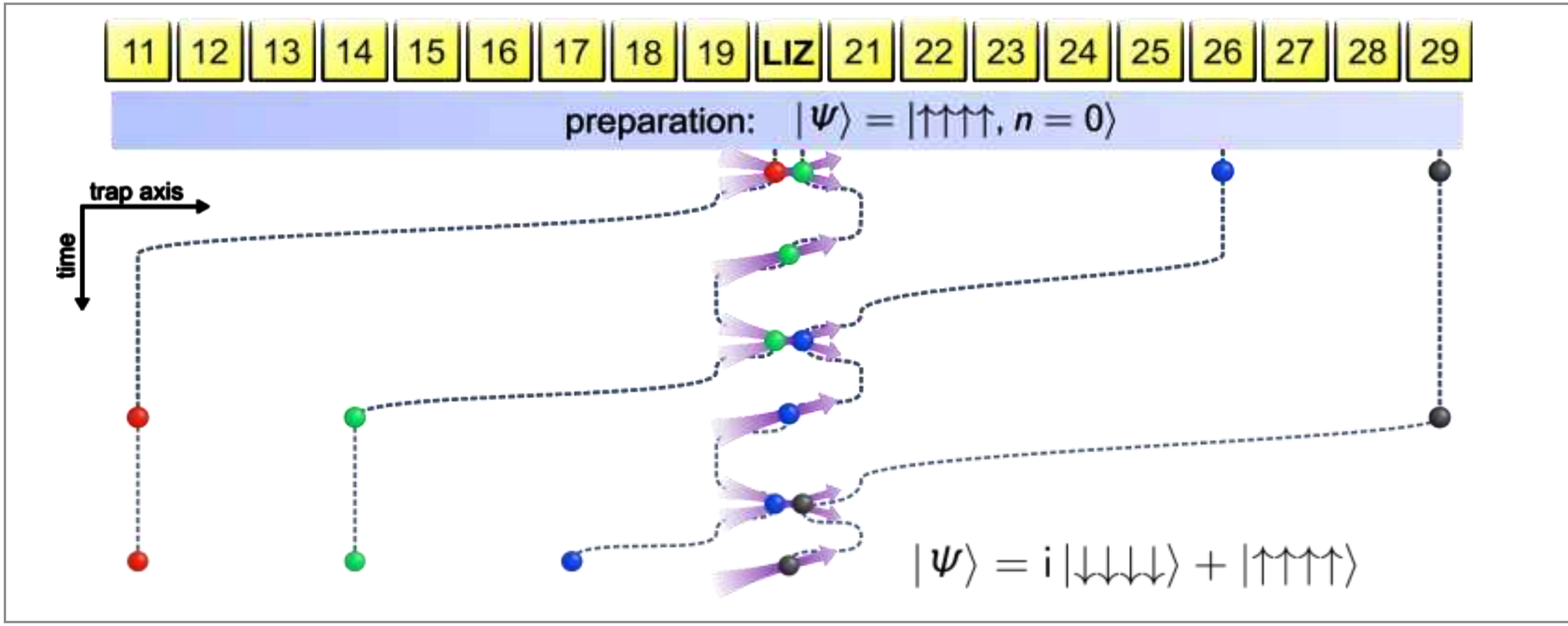
Range: 6mm

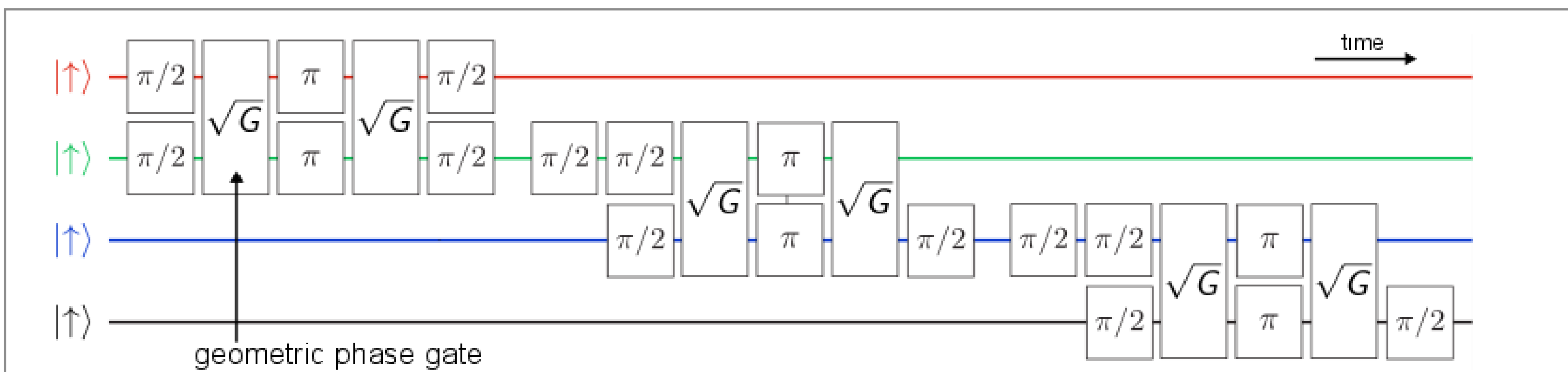
Wavepaket Δx ~10nm
High spatial resolution



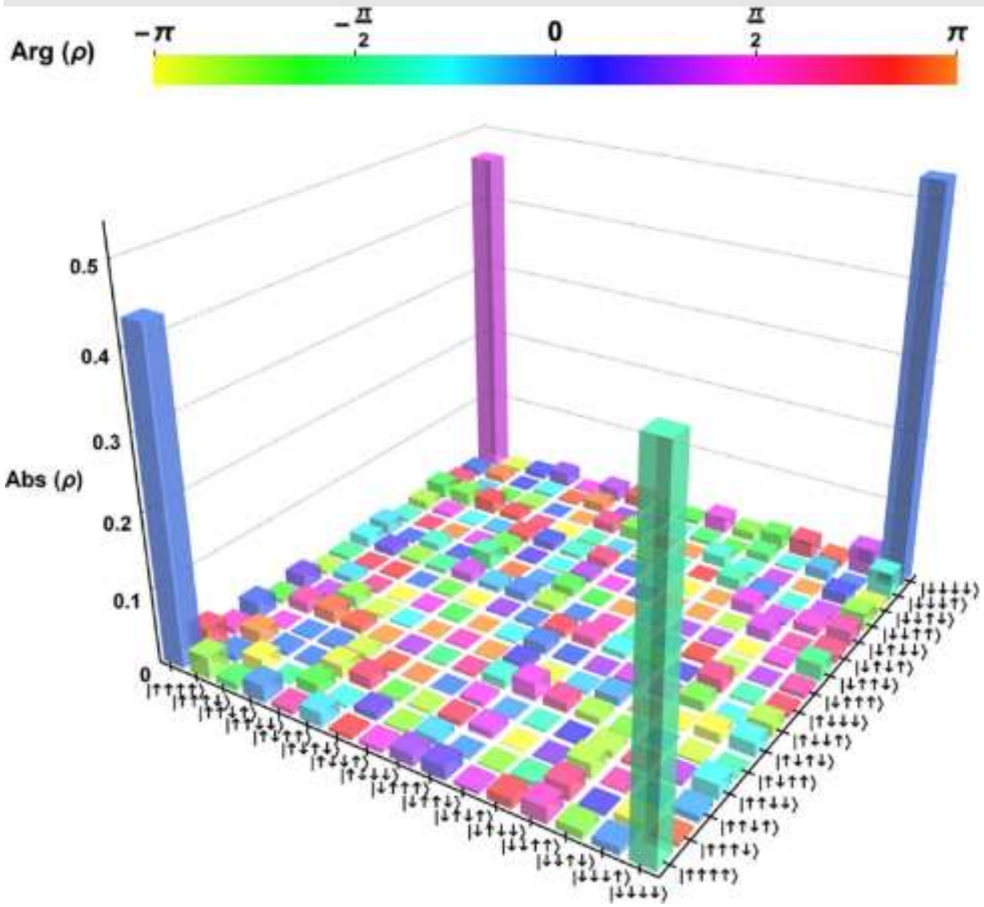
Ruster et al, PRX 7, 031050 (2017)

"Knitting together" a 4-ion GHZ state

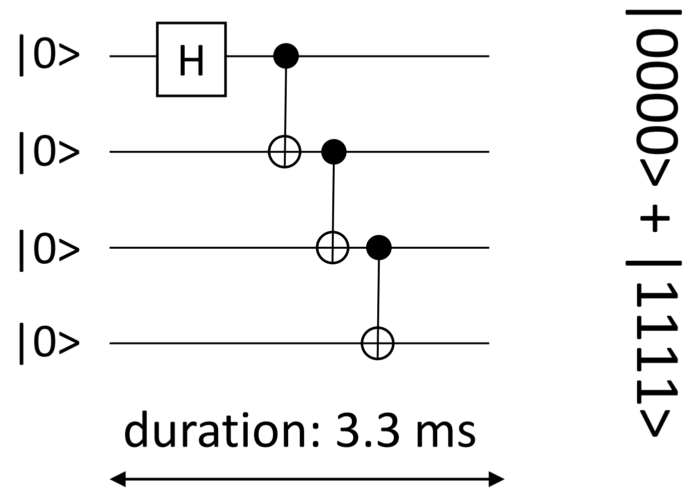




“Knitting together” a 4-ion GHZ state



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

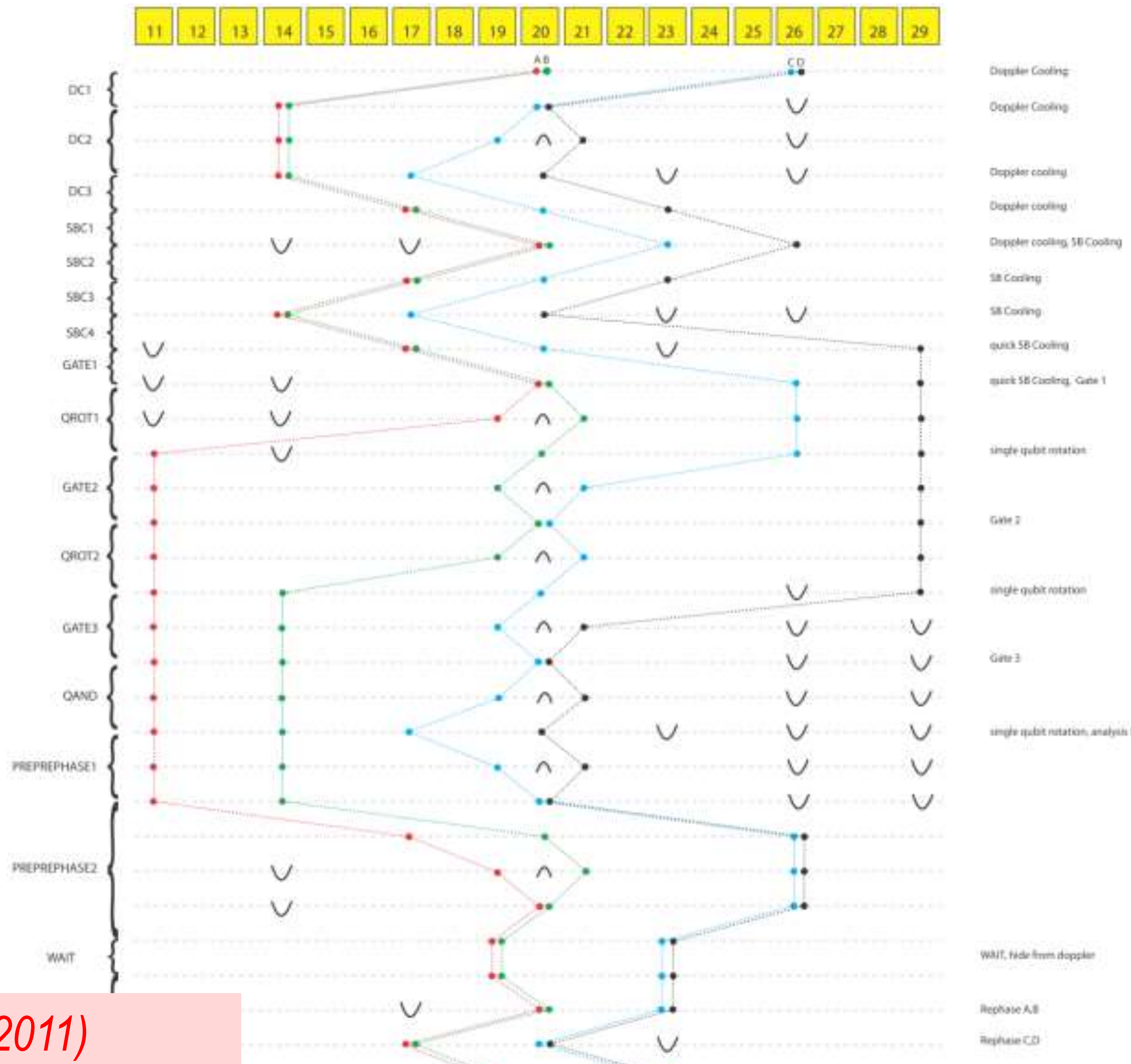
many shuttling op.

- 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)

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

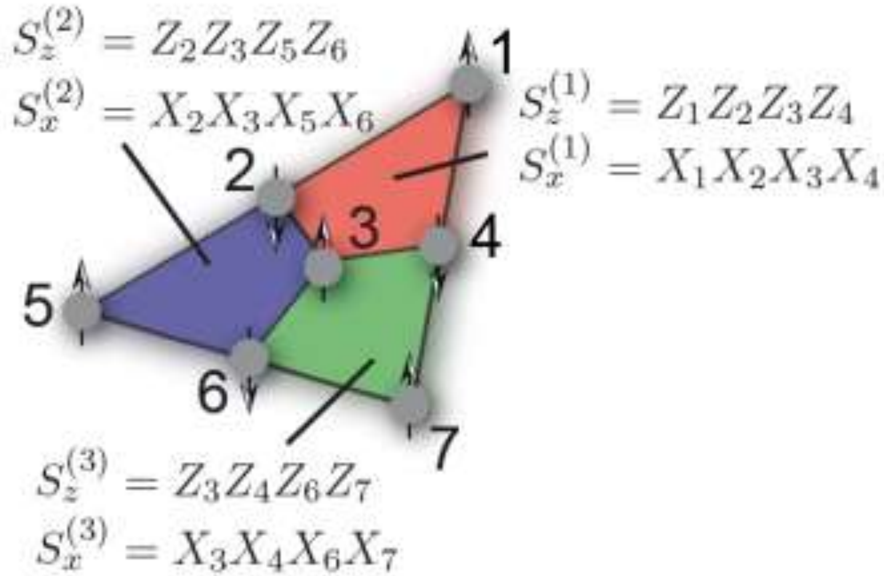
- Single shot read-out of spin state better $1 - 10^{-4}$
- Single gate fidelity better than $1 - 10^{-4}$….$10^{-5..6}$ possible mitigating intensity noise, off-resonant excitation, AC Stark shifts
- Two qubit gate fidelity $1 – 10^{-3}$….$10^{-5..6}$ possible mitigating intensity noise, off-resonant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

Optimization of speed and fidelity required

Future Goal: encoded Qubit alive

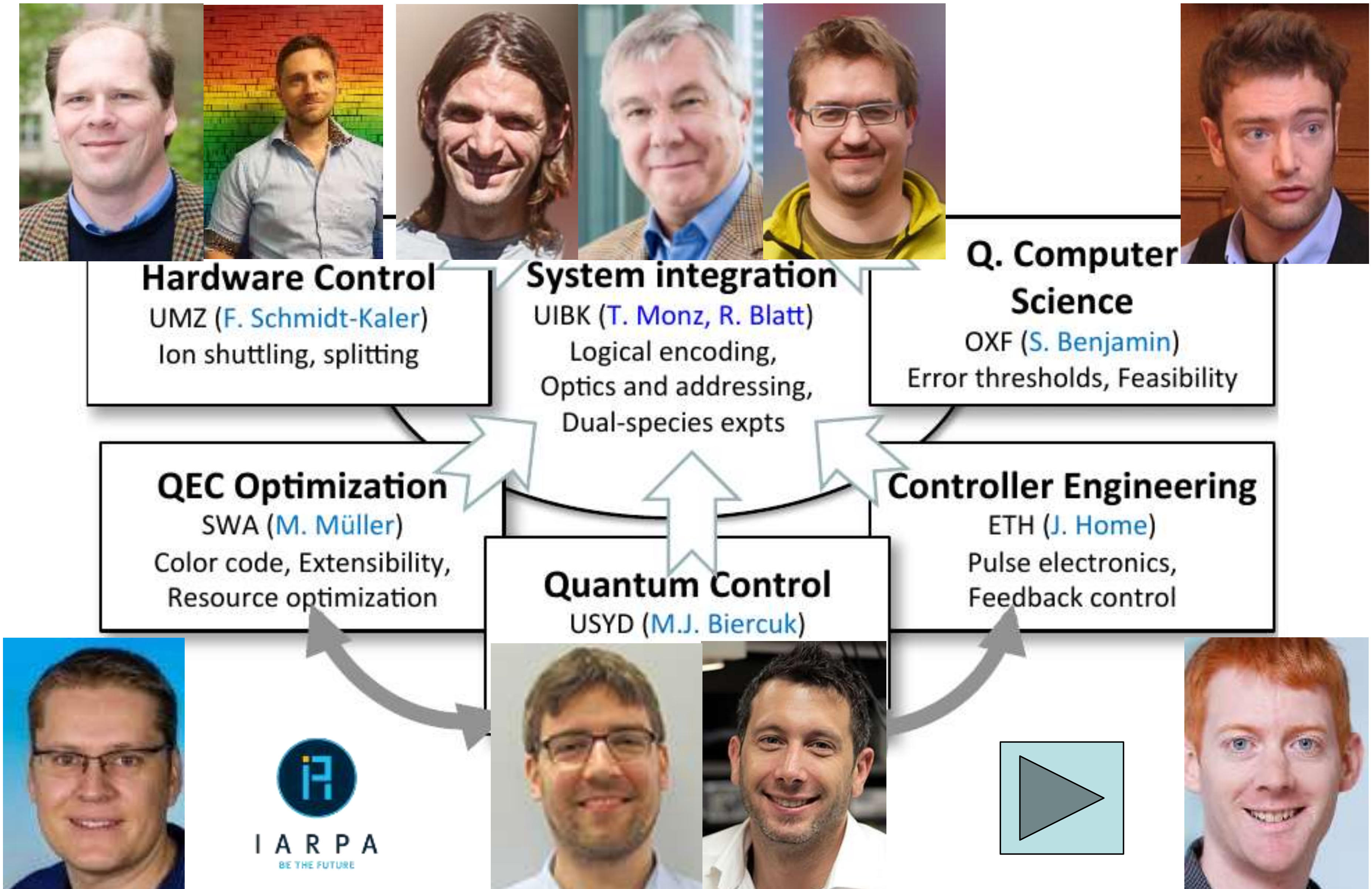
Topological quantum error correction, using the reconfigured ion quantum register

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



Nigg et al., Sci. 234, 302 (2014)

Future Goal: encoded Qubit alive



? Break-even point for useful QEC ?

With current limited gate and readout fidelities
you better keep the physical qubit alone, as it is!

Bermudez et al, PRX (2018), arxiv 1705.02771

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

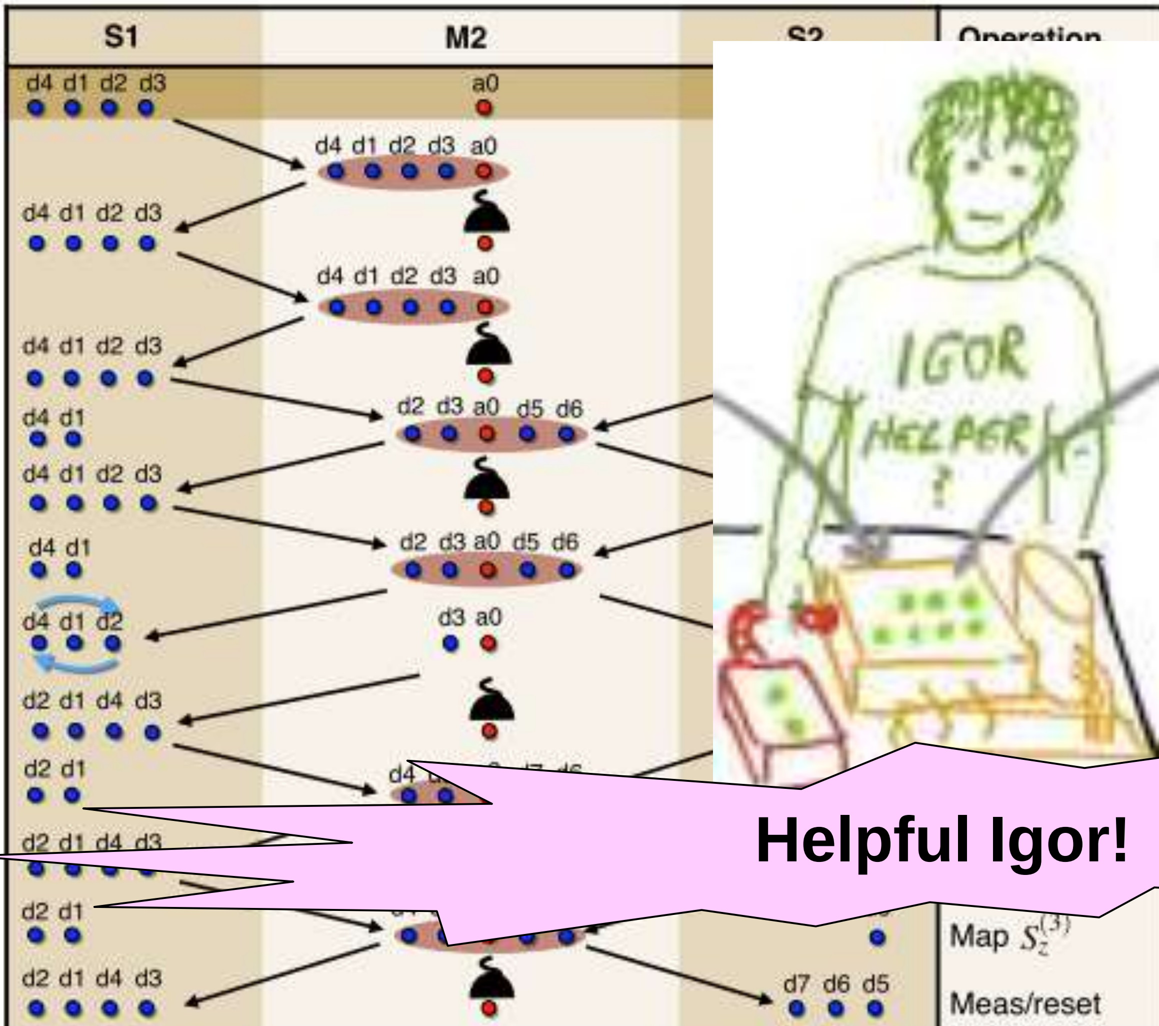
Bob is asked:

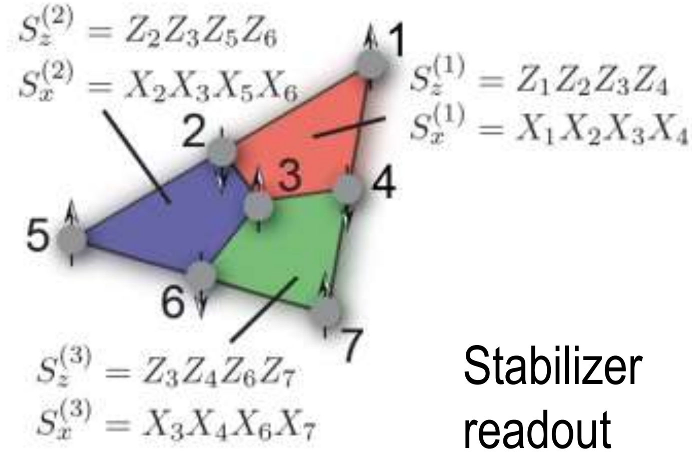
Is it $|\psi\rangle$ or $|\psi\rangle_\perp$?

Or, was Igor really a help?

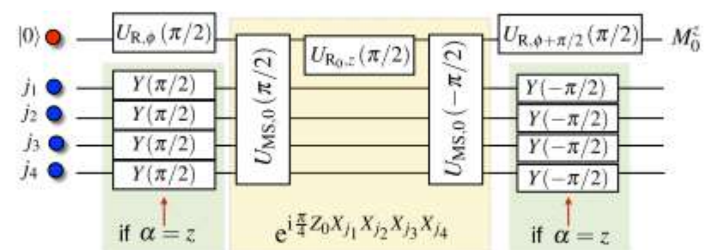
Shuttle based color code QEC

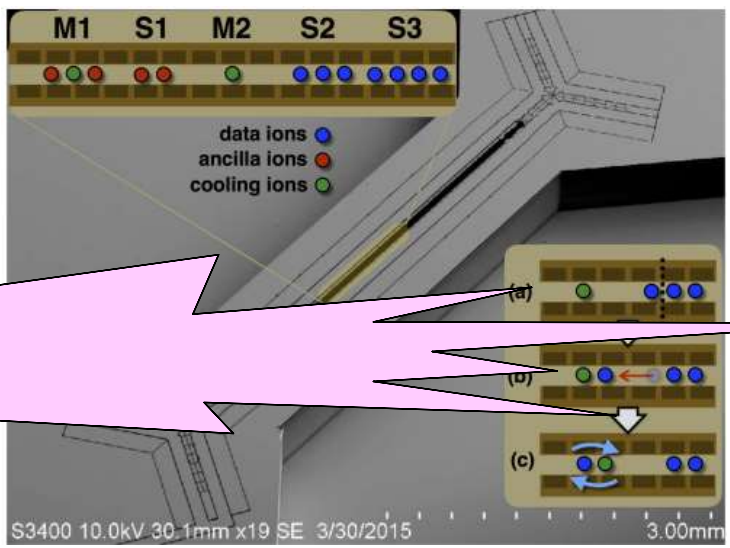
Real-space representation of shuttling-based one-species QEC cycle with multi-qubit MS gates





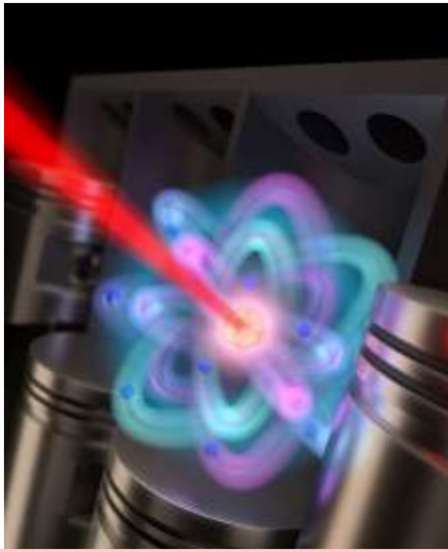
Stabilizer readout





- **combine quantum state control with ions in motion, modern trap devices**
- **scalable QC**
- **future applications of quantum technology**

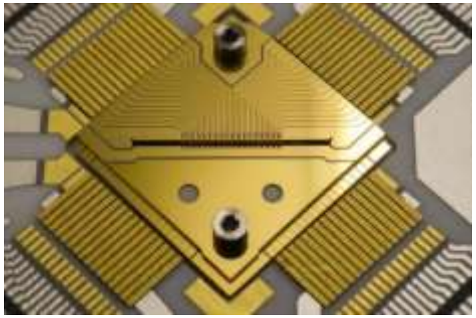
Single ion heat engine

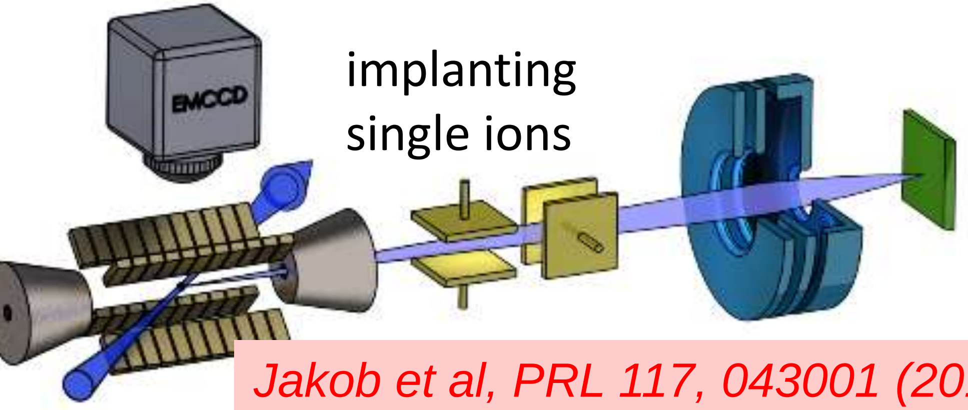


Rossnagel et al, Sci. 352, 325 (2016)

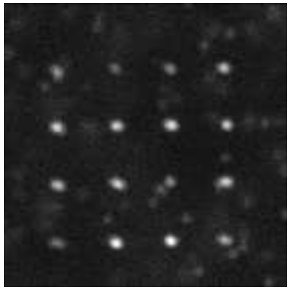
Universal trapped-ion Quantum Computer

Kaufmann et al, PRL 119, 150503,
Ruster et al, PRX 7, 031050,
Bermuez et al, arXive 1705.02771



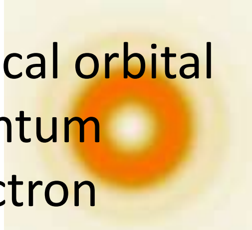


implanting single ions



Jakob et al, PRL 117, 043001 (2016)

Transfer of optical orbital angular momentum to a bound electron



Schmiegelow et al, Nat. comm. 7, 12998 (2016),
arXiv 1709.05571

The team

Do you like to join?

Budker, Walz @Mainz
Zoller, Blatt @Innsbruck
Lesanowski @Nottingham
Wrachtrup @Stuttgart

Zanthier, Lutz @Erlangen
Plenio, Jelezko, Calacro @Ulm
Jamieson @Melburne

Folman @Ber Sheva
Retzker @Jerusalem

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BMBF Q.ComQ

DFG Deutsche Forschungsgemeinschaft

VolkswagenStiftung

RySQ iRyd

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