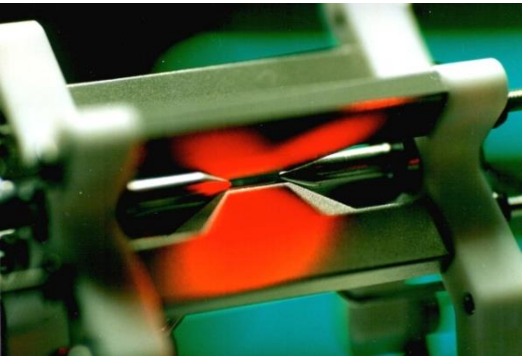
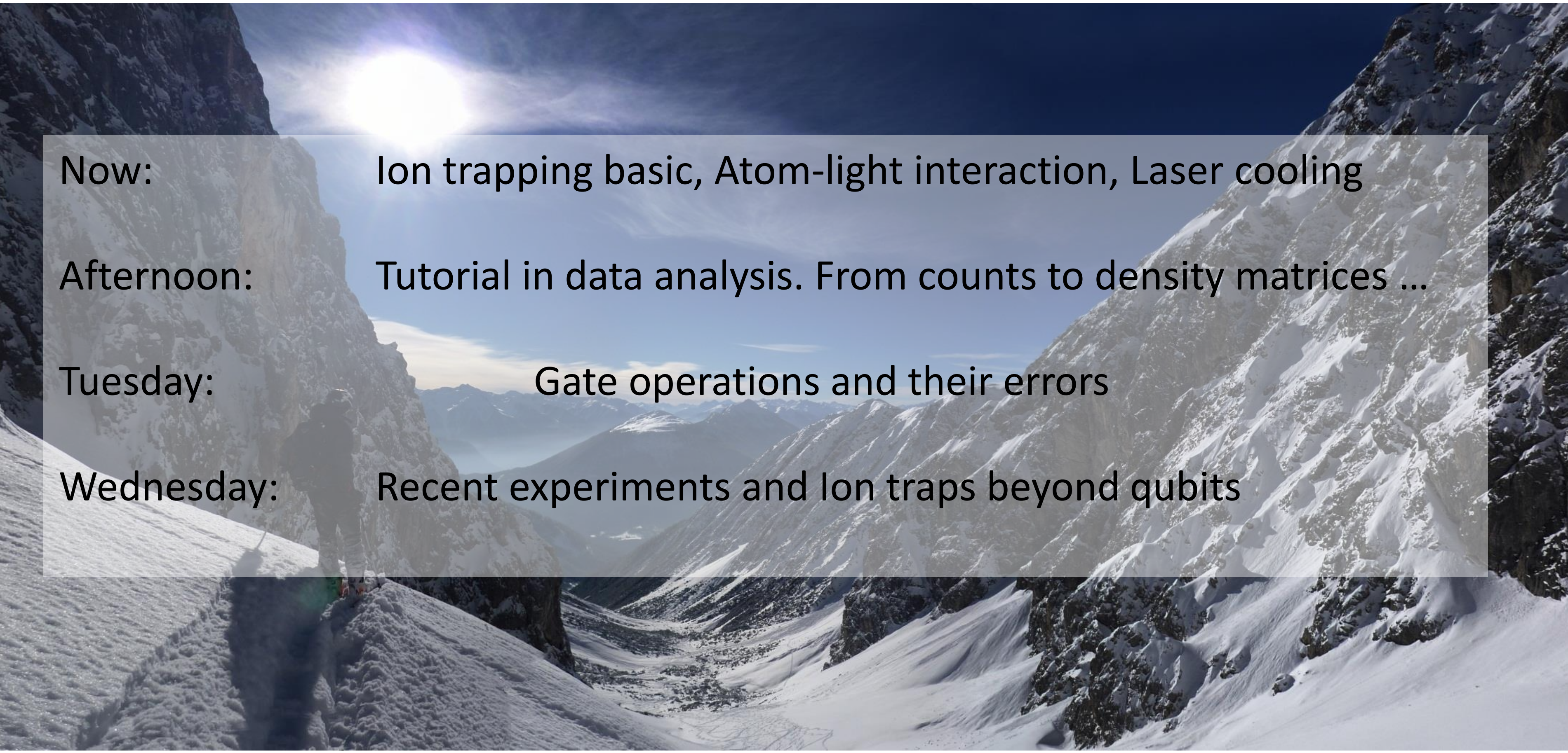
Quantum science with trapped ions



Philipp Schindler

Outline



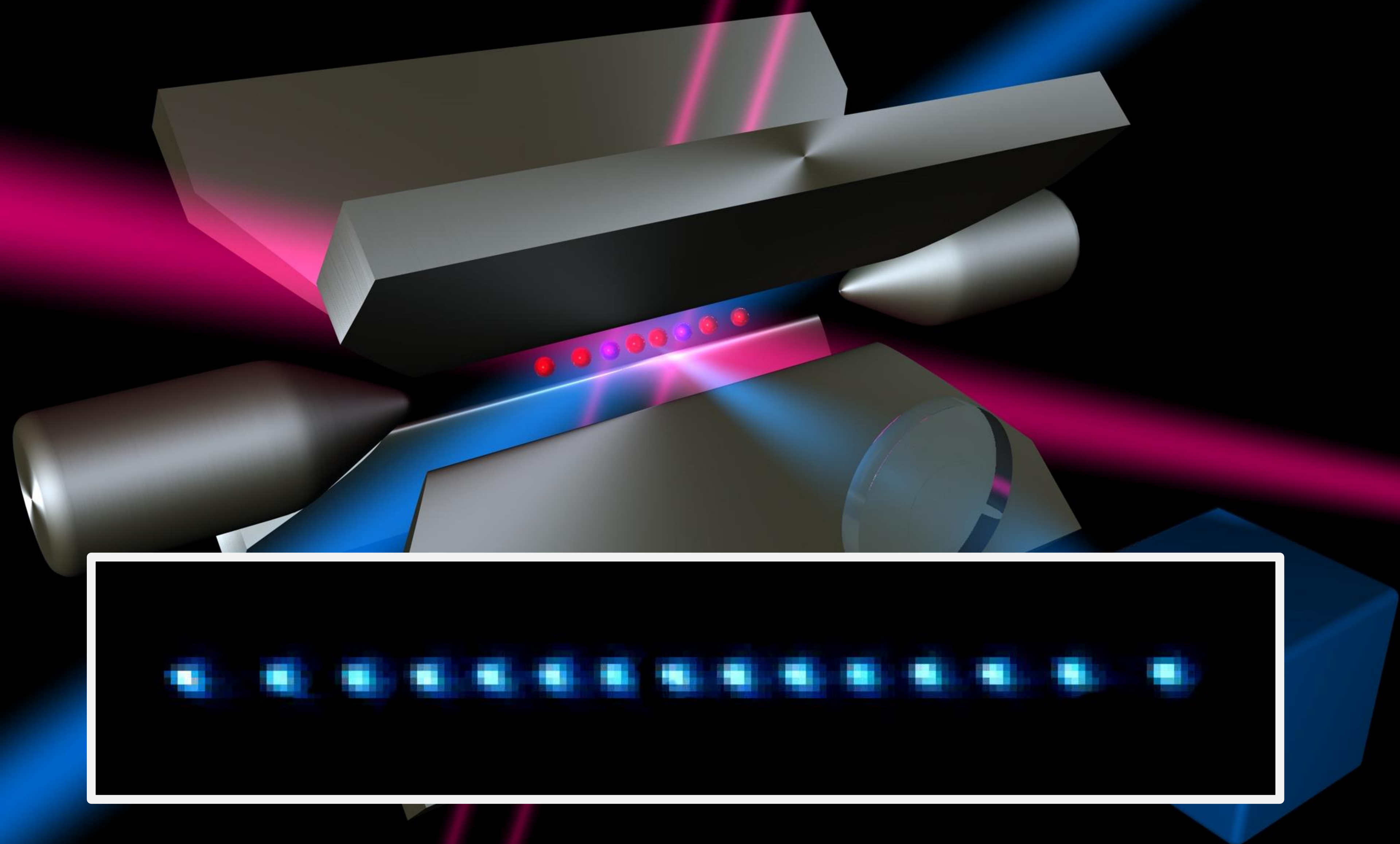
Now: Ion trapping basic, Atom-light interaction, Laser cooling

Afternoon: Tutorial in data analysis. From counts to density matrices …

Tuesday: Gate operations and their errors

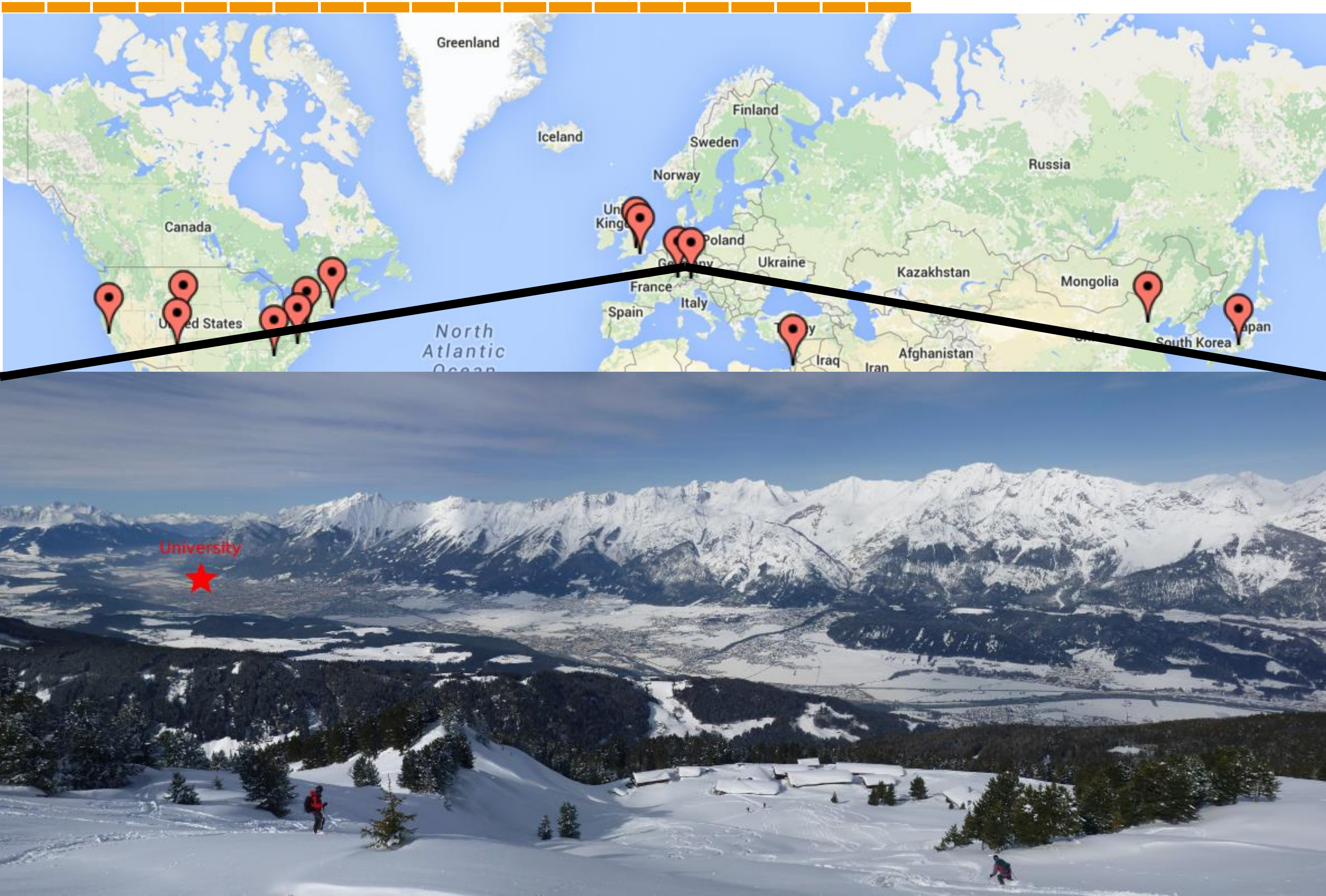
Wednesday: Recent experiments and Ion traps beyond qubits

The Quantum Information Processor with Trapped Ca^+ Ions



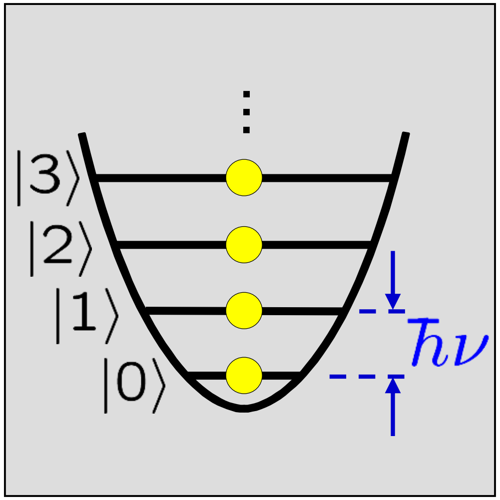
P. Schindler et al., New. J. Phys. 15, 123012 (2013)

Ion trap QC around the globe



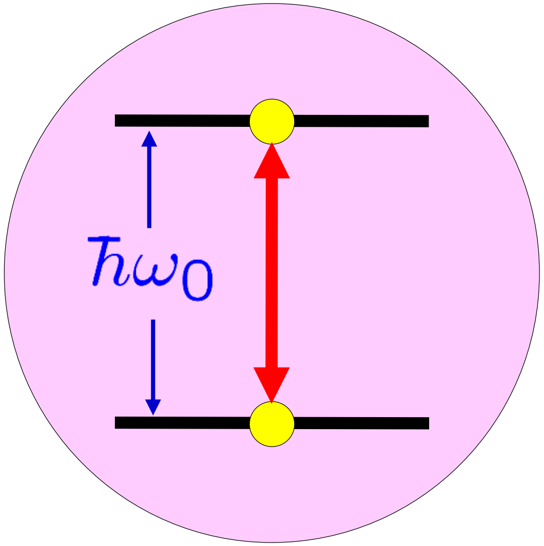
The ideal world

Harmonic oscillator



$\otimes$

Quantum bit



$|D_{5/2}\rangle \equiv |\uparrow\rangle$
$\equiv |\mathbf{0}\rangle$

$|S_{1/2}\rangle \equiv |\downarrow\rangle$
$\equiv |\mathbf{1}\rangle$

motional states

$|0\rangle, |1\rangle, |2\rangle, |3\rangle, \ldots$

internal states

$|\uparrow\rangle, |\downarrow\rangle$

Ion traps – How do they work

- Blackboard: How to trap a charged particle.

„Quantum dynamics of single trapped ions"

D. Leibfried, R. Blatt, C. Monroe, D. Wineland

Rev. Mod. Phys. **75**, 281-324 (2003)

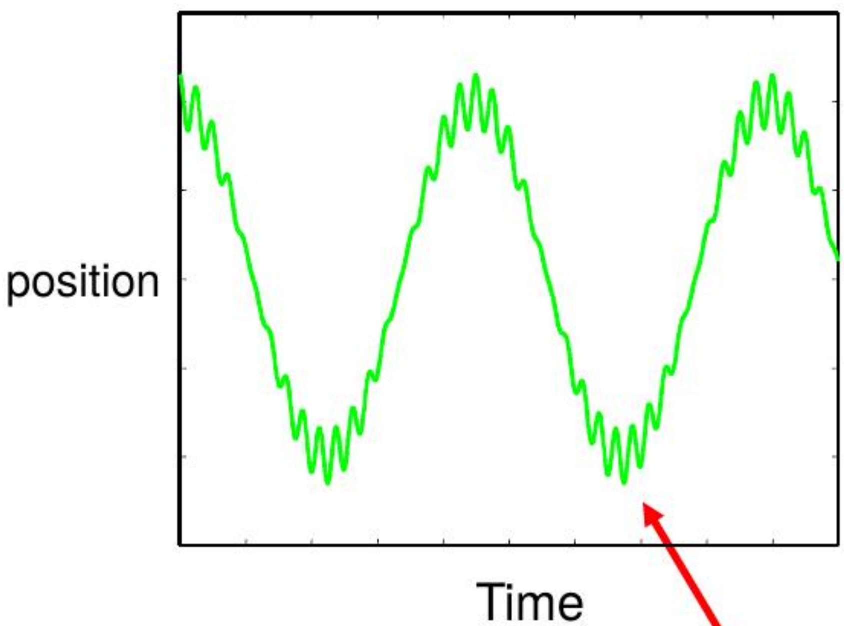
„Experimental Issues in Coherent Quantum-State Manipulation of Trapped Atomic Ions"

D. Wineland et al.

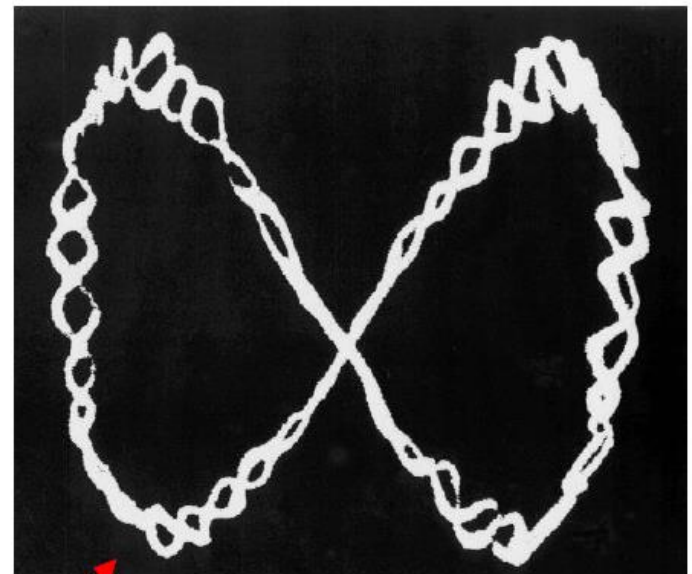
J. Res. Natl. Inst. Stand. Technol. **103**, 259-328 (1998)

Micromotion

1d-solution of Mathieu equation



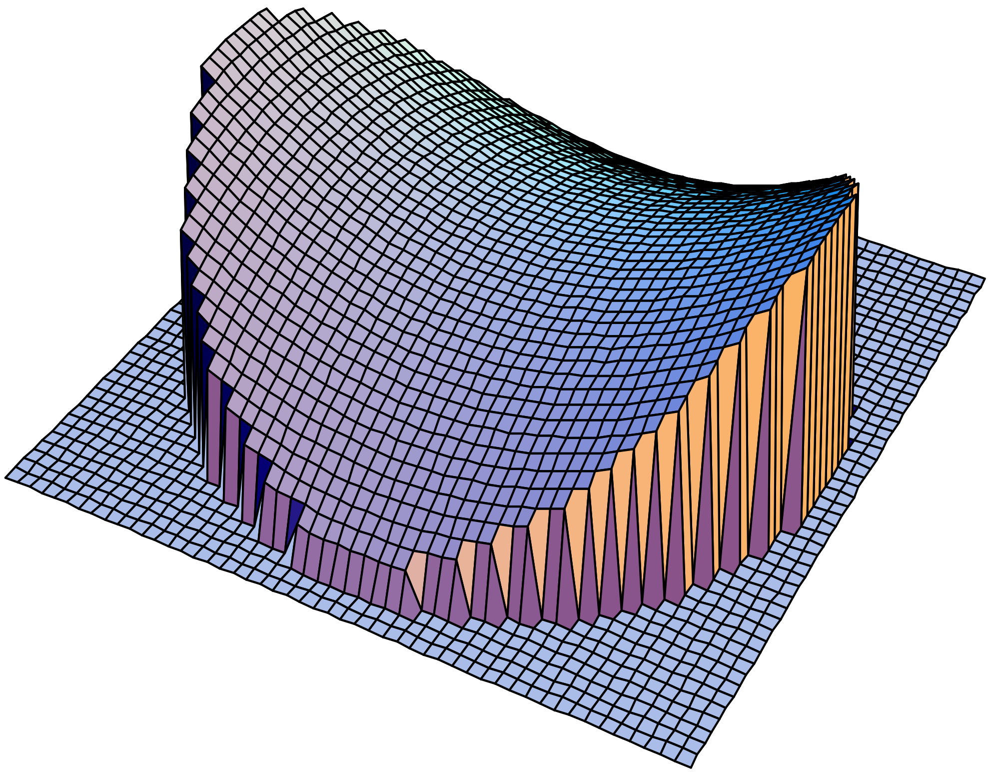
Aluminium particle in trap

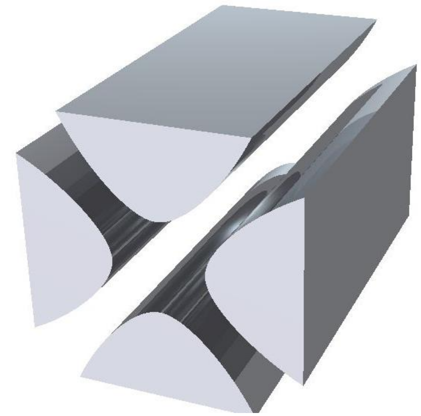


Wuerker, Shelton, Langmuir,
J. Appl. Phys. **30**, 342 (1959)

micromotion

2D linear Paul trap





Exact: Mathieu equation

$$\frac{d^2x}{d\tau^2} + (a - 2q\cos(2\tau))x = 0$$

$$\frac{d^2y}{d\tau^2} - (a - 2q\cos(2\tau))y = 0$$

$$q = \frac{2eU_{rf}}{mr_0^2\Omega^2} \qquad a = \frac{4eU}{mr_0^2\Omega^2}$$

$$\tau = \frac{\Omega t}{2}$$

q - and a - parameter

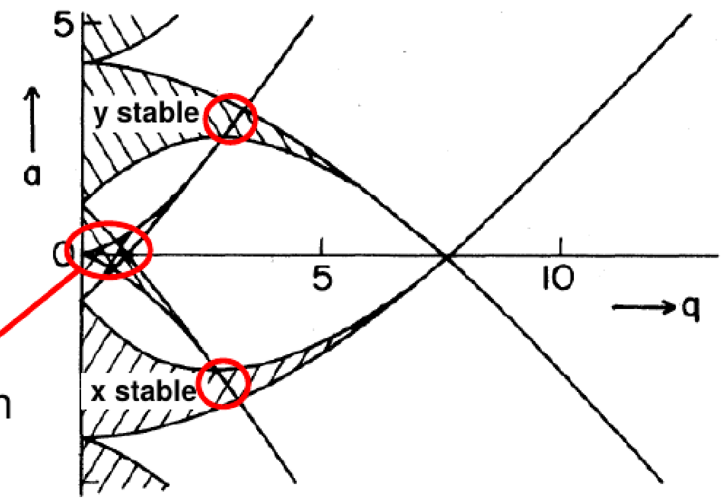
Stable trajectories for certain parameters:

$$x(\tau) = Ae^{i\beta_x\tau} \sum_{n=-\infty}^{\infty} C_{2n} e^{i2n\tau} + Be^{-i\beta_x\tau} \sum_{n=-\infty}^{\infty} C_{2n} e^{-i2n\tau}$$

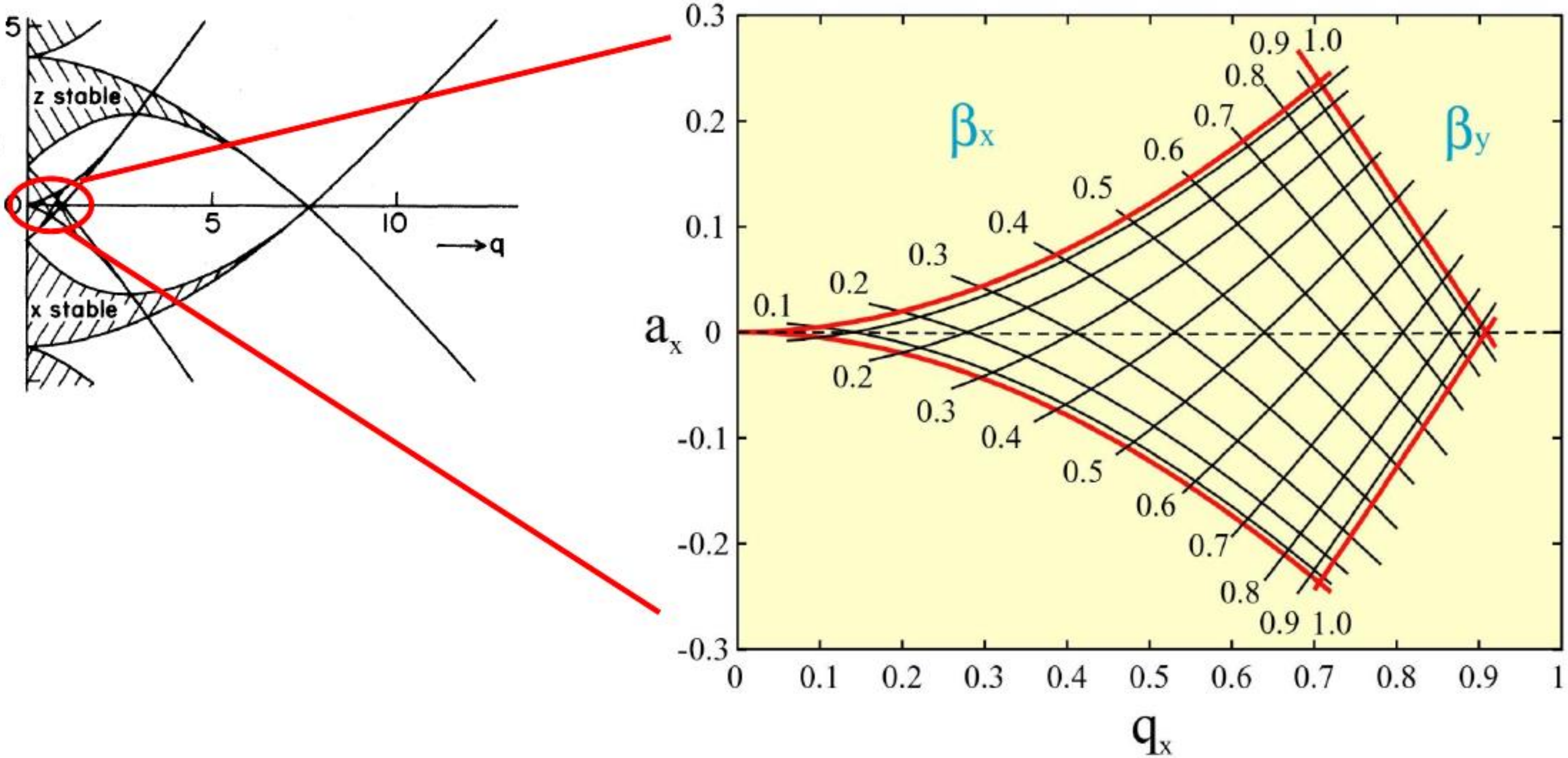
$$\beta = \beta(a,q)$$
$$C_{2n} = C_{2n}(a,q)$$

Stability diagram

first stability region



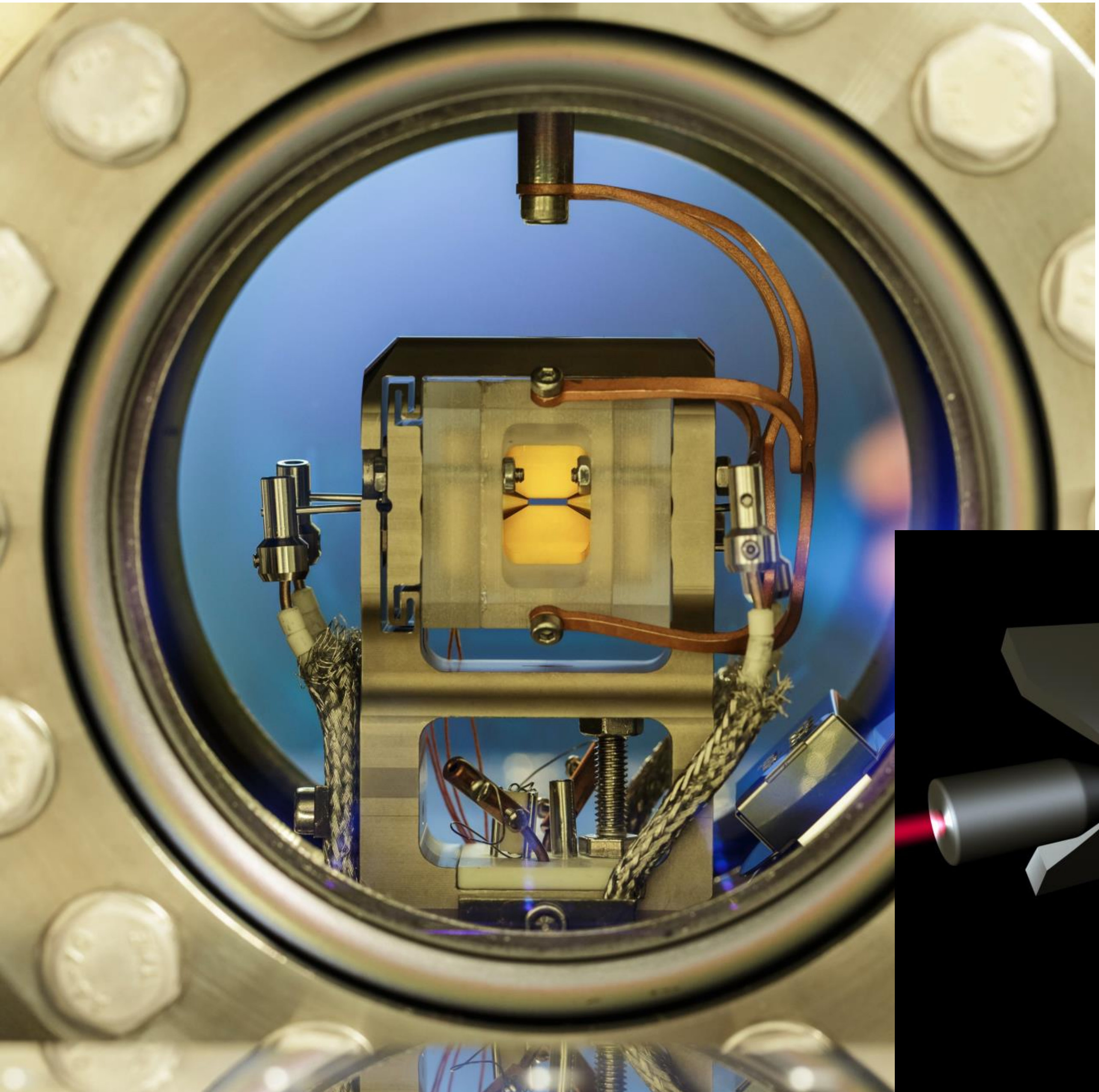
Stability region

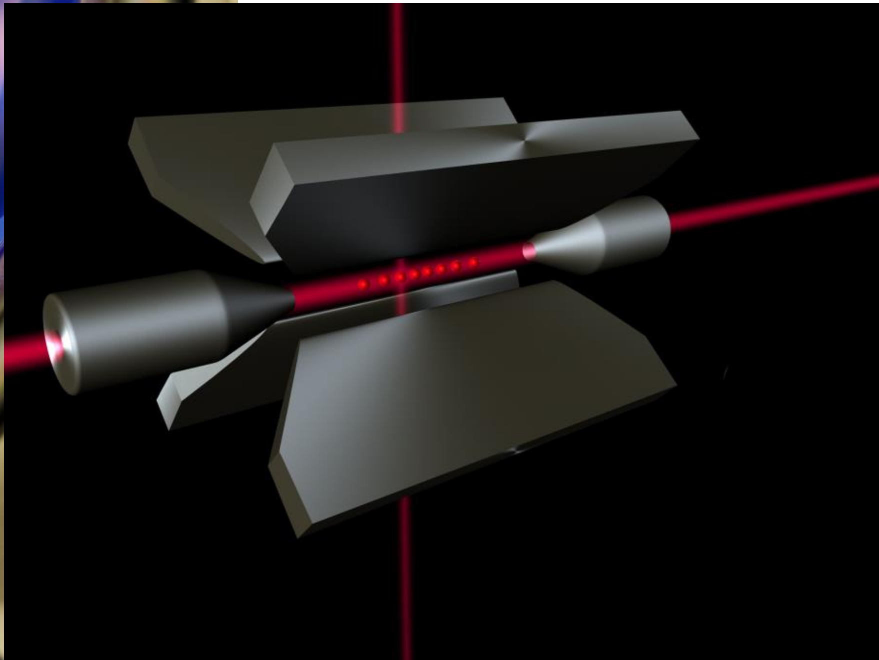


If $q_x^2, |a_x| \ll 1$: Pseudopotential approximation:

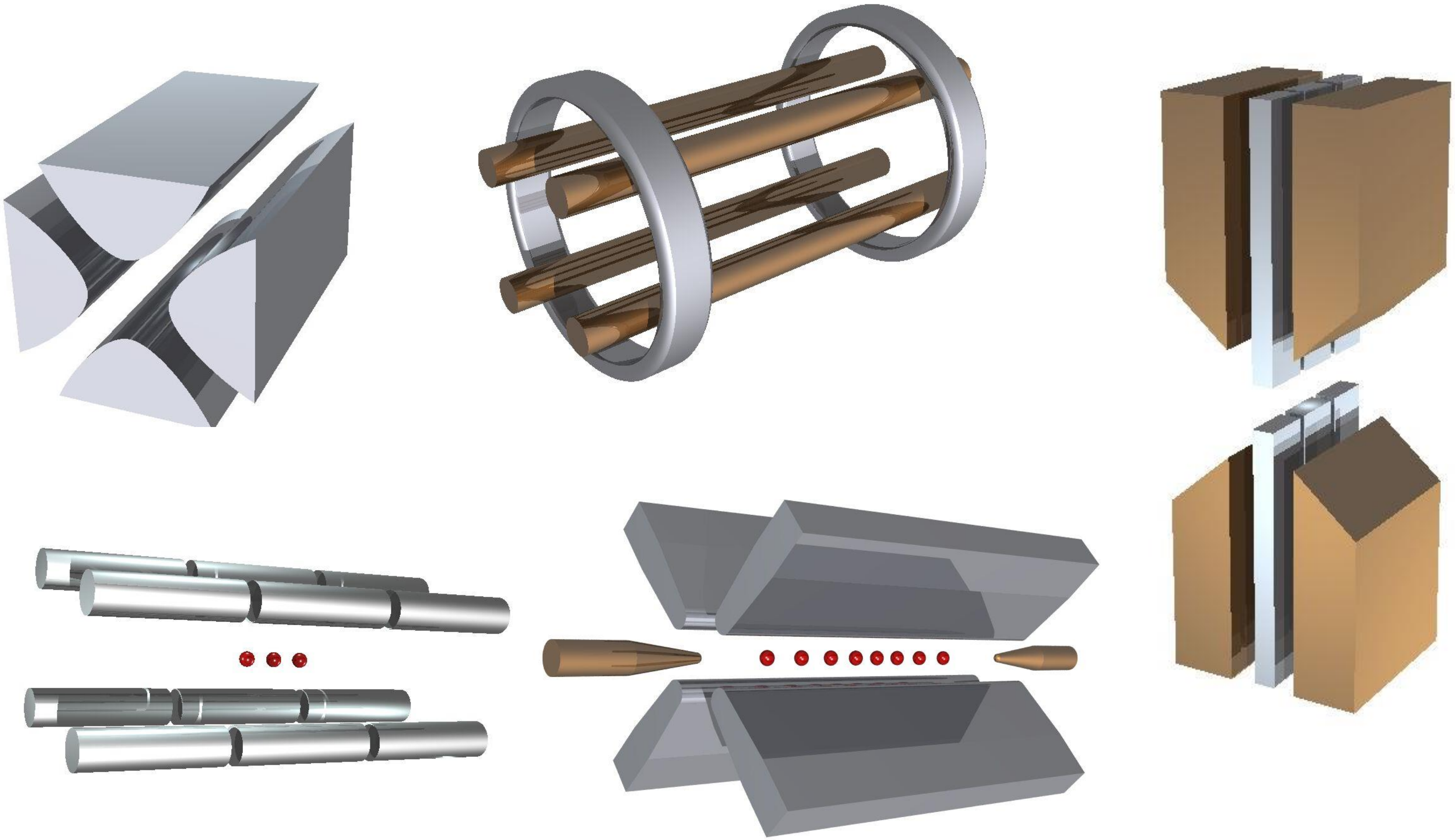
Time-averaged electrical forces create a harmonic potential.

How does it look like?



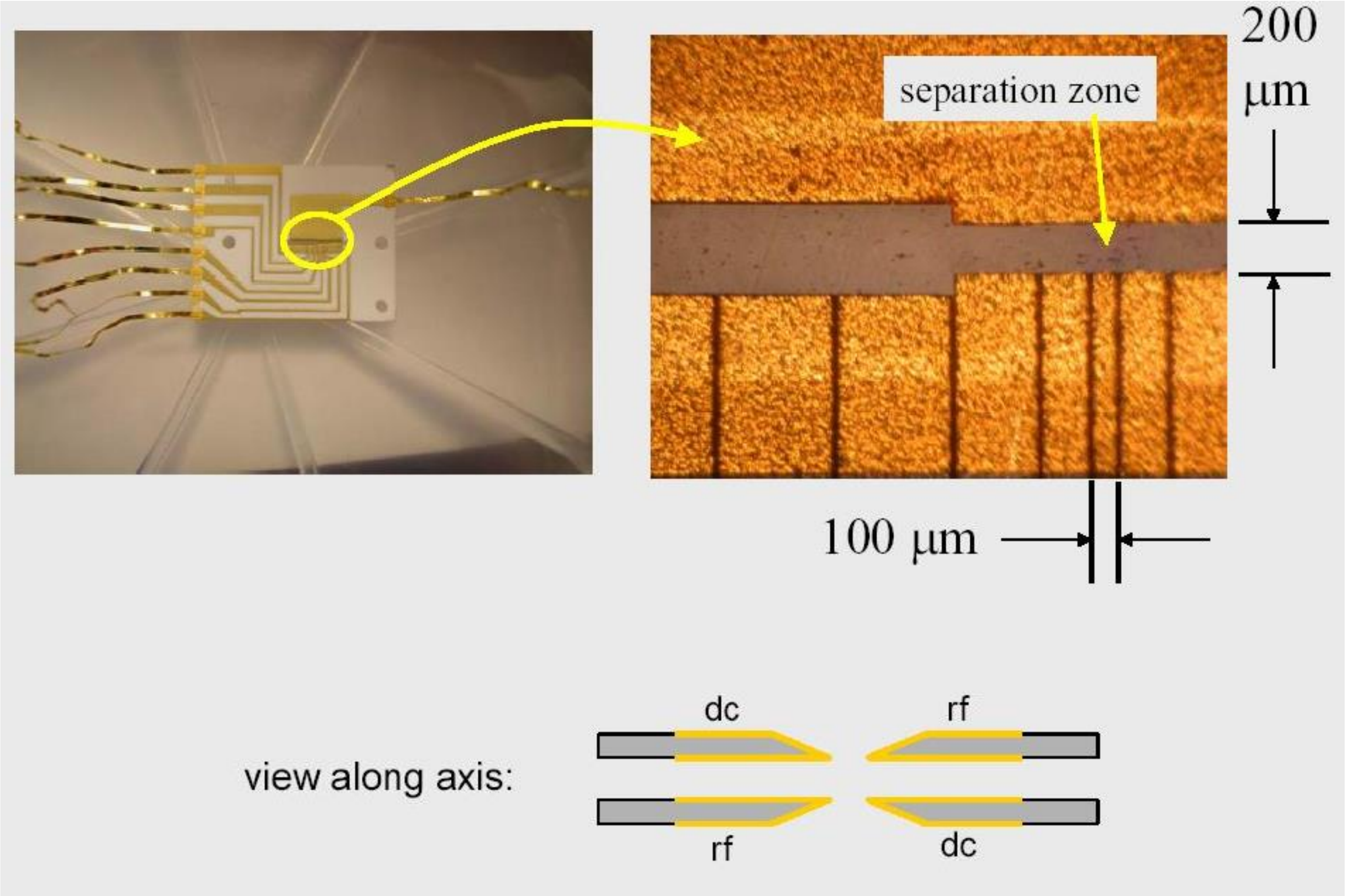


Different linear ion traps



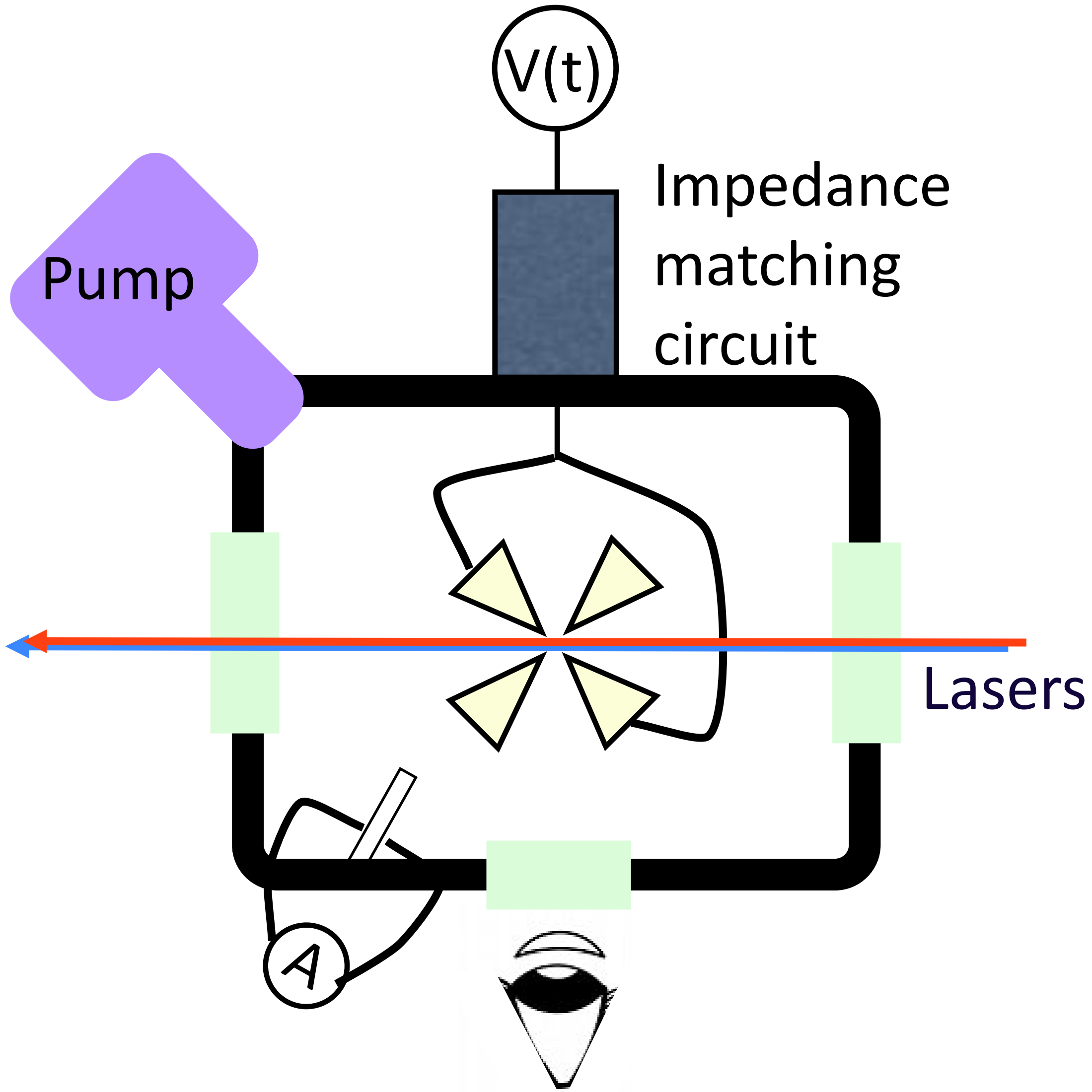
Trap designs differ almost solely in effective distance

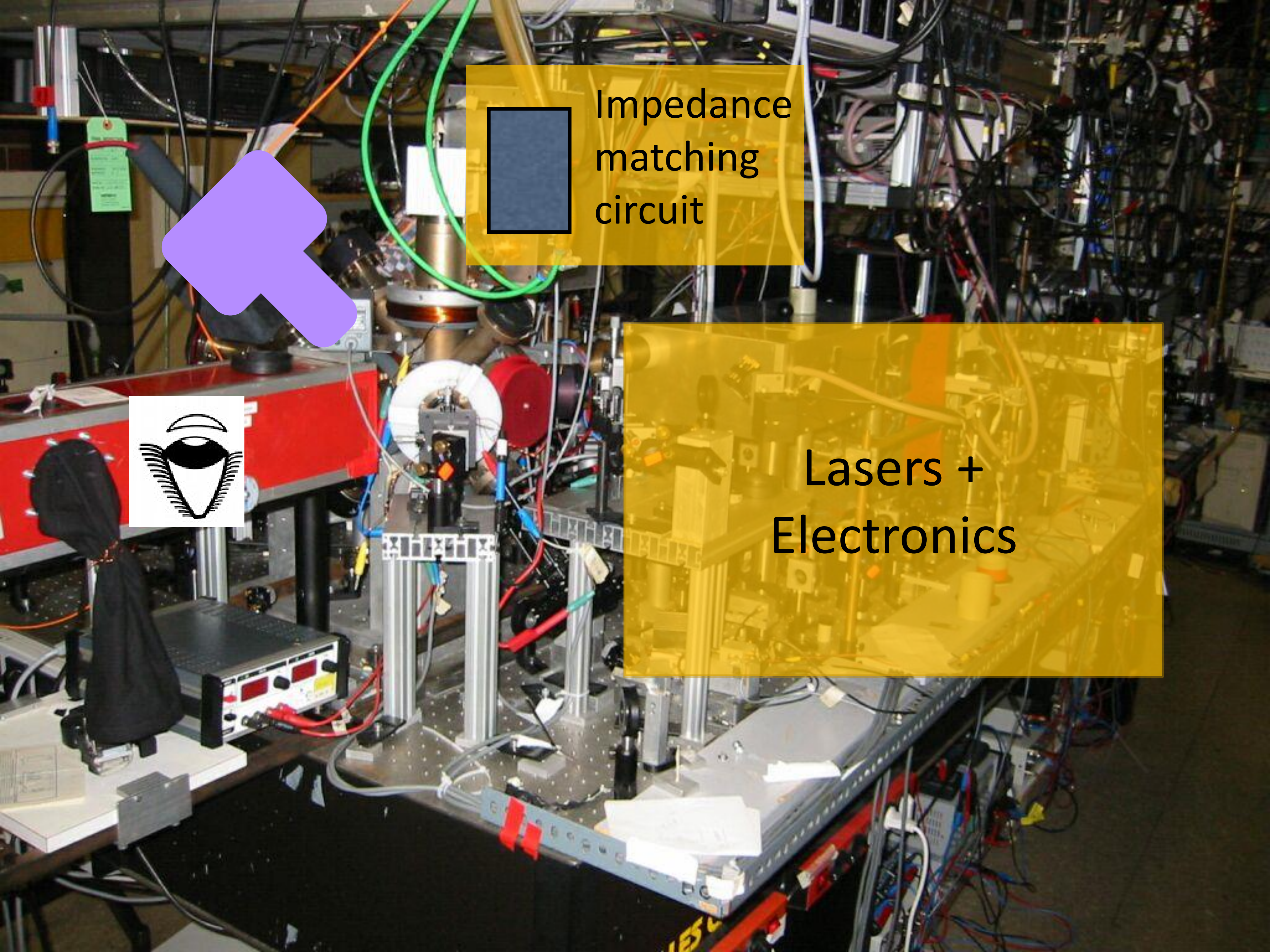
Microtraps



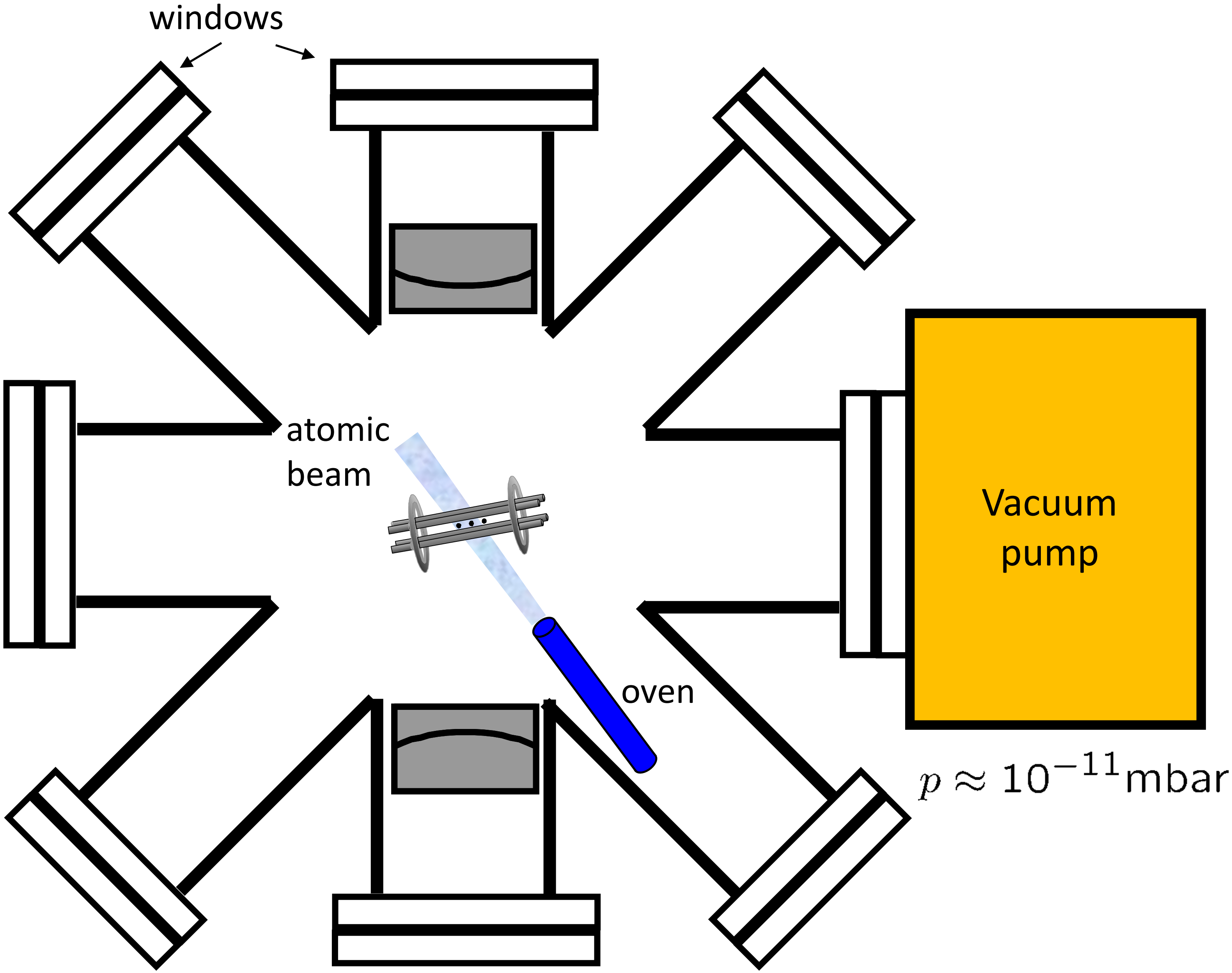
Wineland, NIST

What equipment do I need?




Impedance matching circuit
Lasers + Electronics

Ion loading



Ion loading

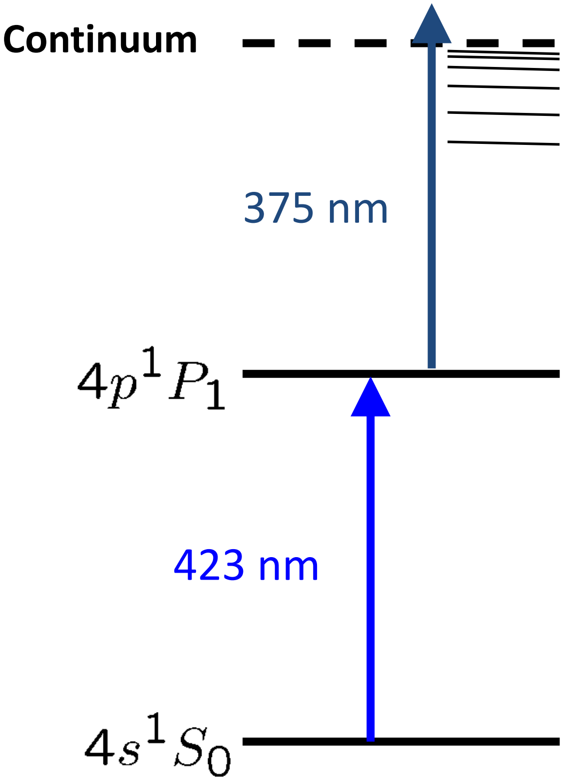
An oven produces a weak atomic beam of neutral calcium crossing the trap

Loading of ions into the trap by

- electron bombardement
- photoionization

(experimentally demonstrated for Mg^+,Ca^+, Cd^+)

2-step photoionization of neutral calcium



Advantages of photoionization:

- higher cross-section
- isotope-selective loading

Summary

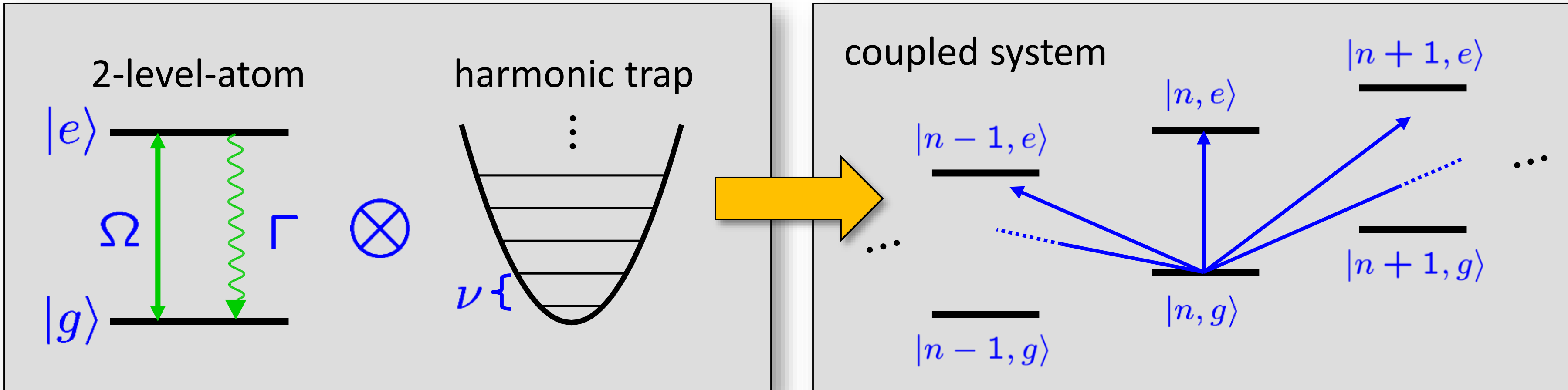
- Charge particles cannot be trapped in 3D by static fields
- Radio-frequency Paul traps are 3D harmonic oscillators
- Motion of particle: Mathieu equation have stability region

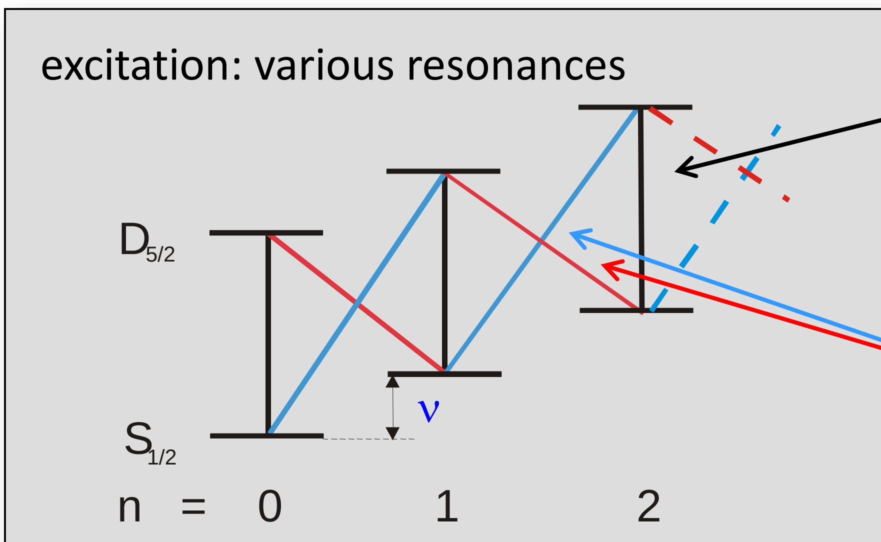
Laser ion interaction

- Blackboard: How can we manipulate a single trapped ion with laser light?

PhD thesis, Christian Roos
www.quantumoptics.at

Qubit manipulation





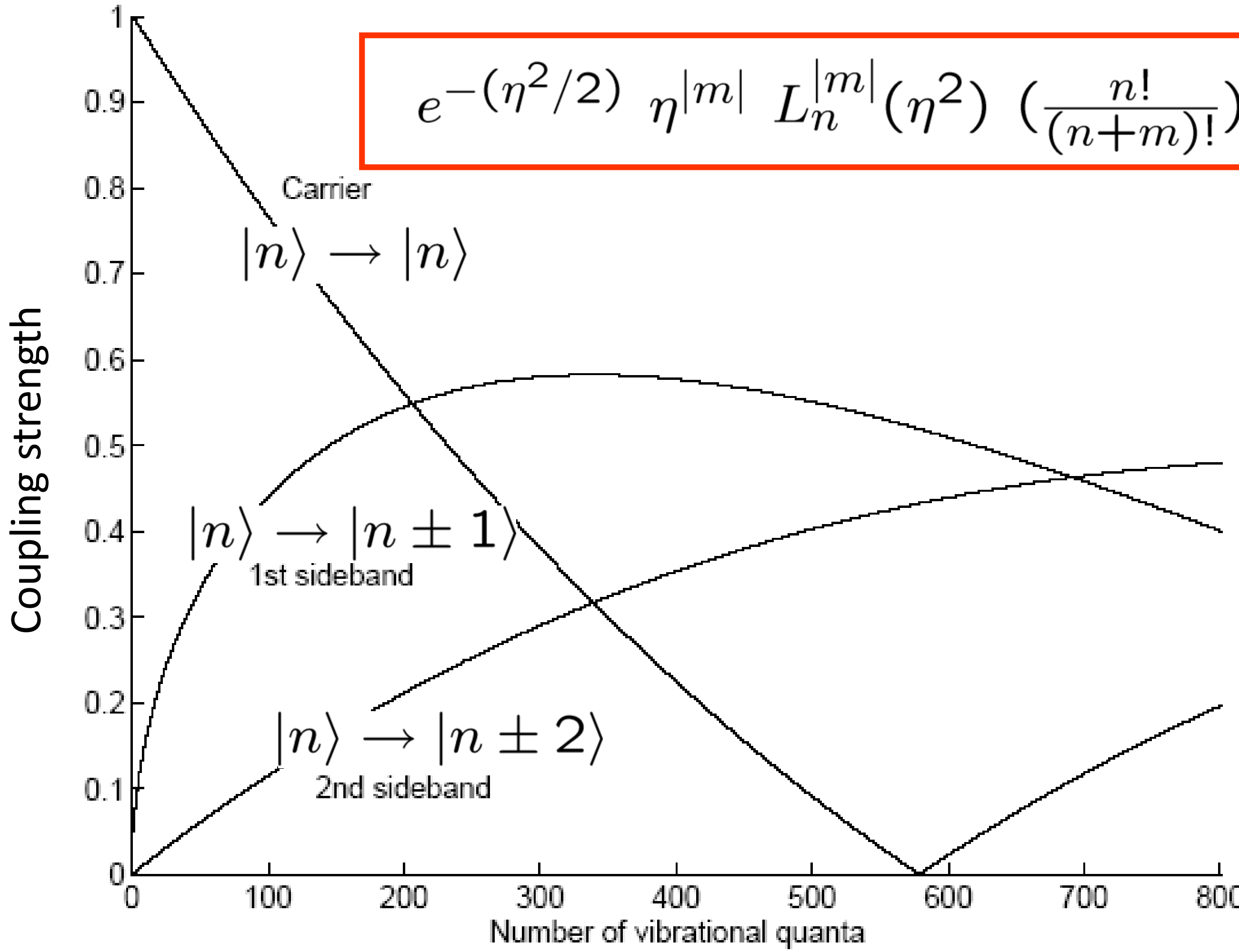
Carrier:
manipulate qubit
→ internal superpositions

Sidebands:
manipulate motion and qubit
→ create entanglement

Beyond the Lamb Dicke regime

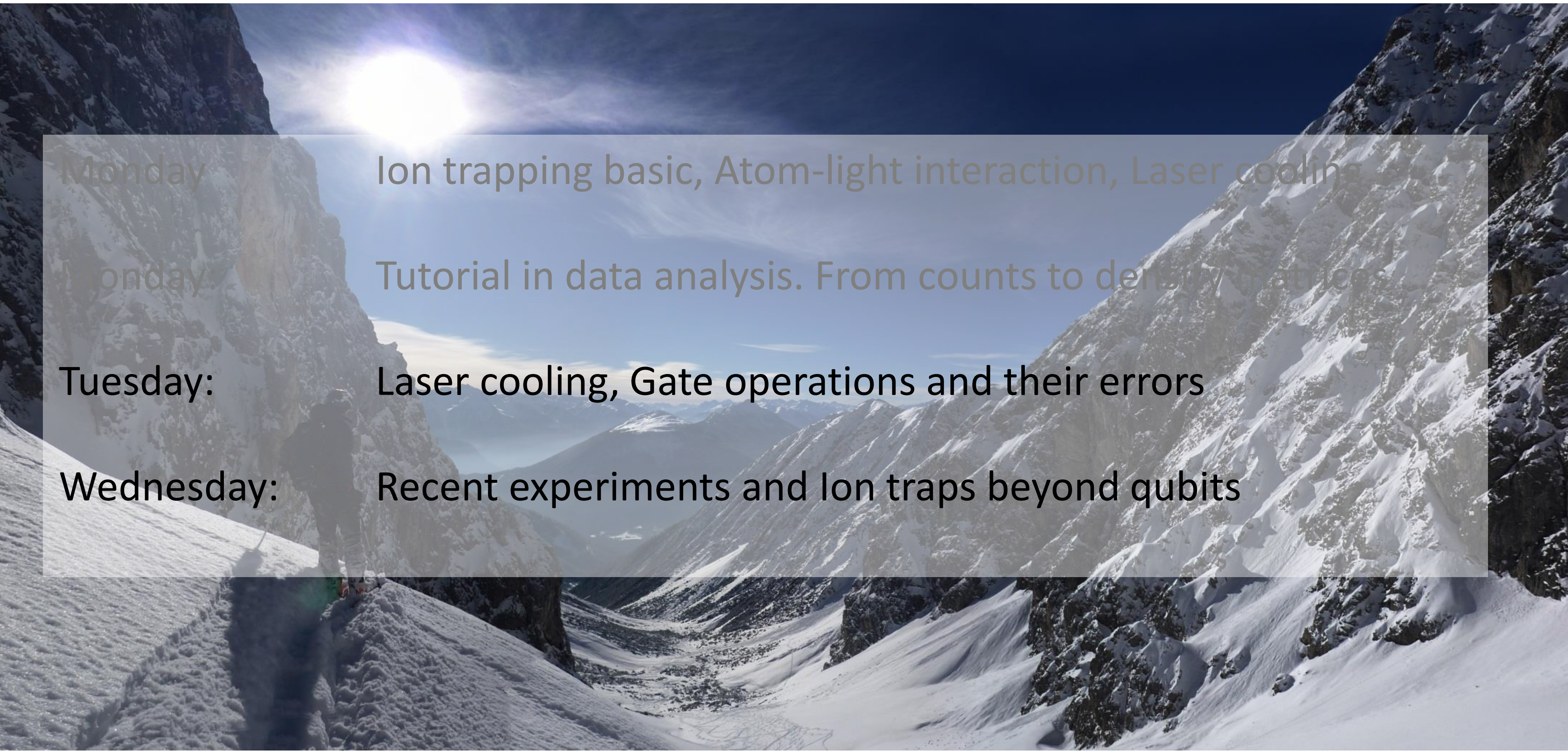
$$\hbar \frac{\Omega_{Rabi}}{2} \langle n | e^{i\eta(a+a^\dagger)} | m \rangle =$$

$$\boxed{e^{-(\eta^2/2)}\ \eta^{|m|}\ L_n^{|m|}(\eta^2)\ \left(\frac{n!}{(n+m)!}\right)^{sign(m)/2}}$$

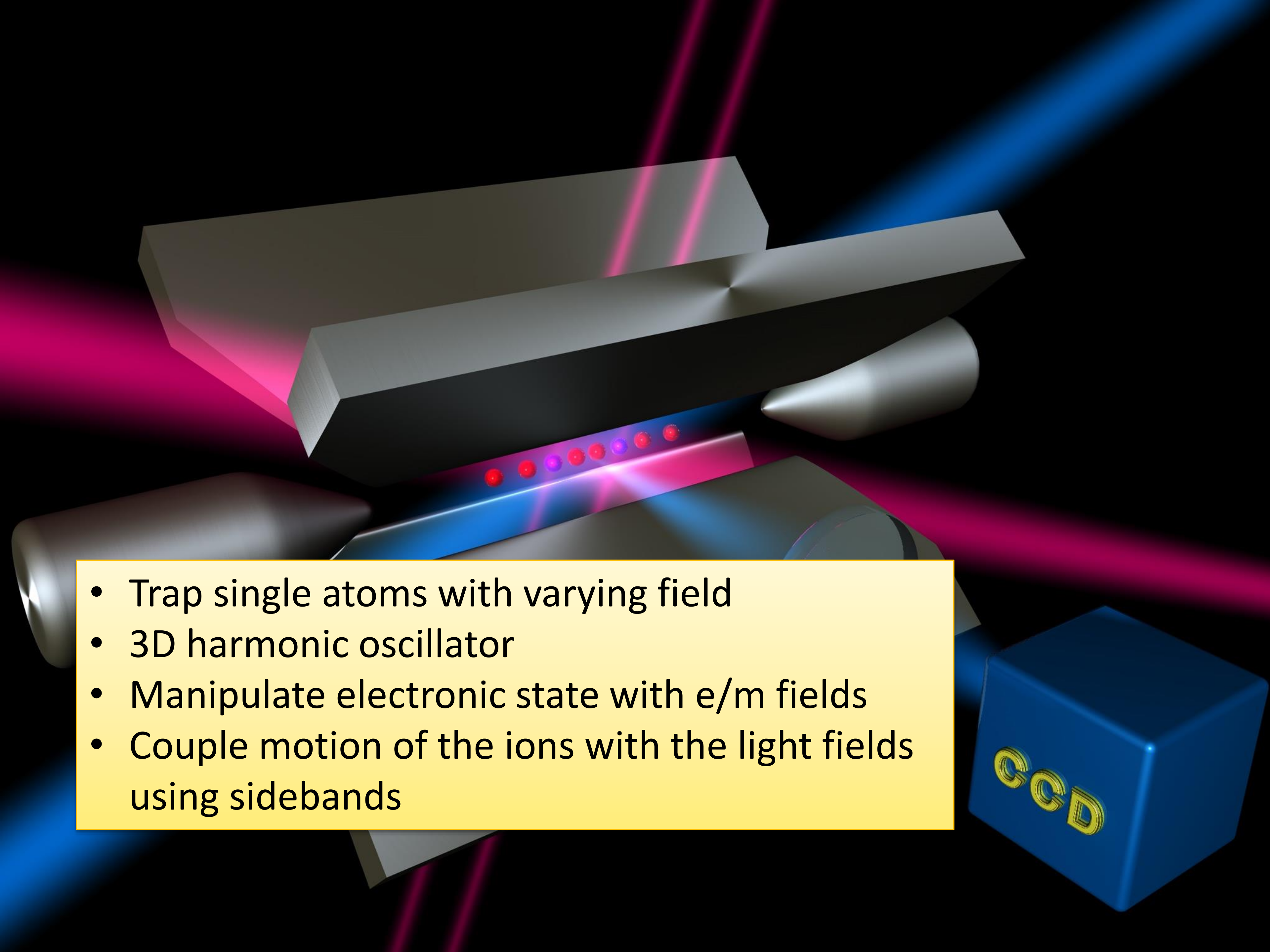


D. Leibfried et al, Rev. Mod. Phys. **75**, 281-324 (2003)

Outline



Monday:	Ion trapping basic, Atom-light interaction, Laser cooling
Monday:	Tutorial in data analysis. From counts to density matrices
Tuesday:	Laser cooling, Gate operations and their errors
Wednesday:	Recent experiments and Ion traps beyond qubits



- Trap single atoms with varying field
- 3D harmonic oscillator
- Manipulate electronic state with e/m fields
- Couple motion of the ions with the light fields using sidebands

Repetition from yesterday

Lamb-Dicke regime:

Extension of the ion's wave function Ψ much smaller than optical wavelength

$$\eta\sqrt{\langle\Psi|(a+a^\dagger)^2|\Psi\rangle} \ll 1$$

For $\Psi = |n\rangle \;:\; \eta\sqrt{2n+1} \ll 1$

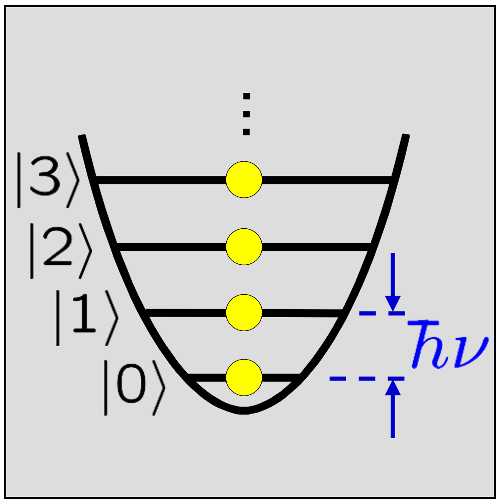
Taylor expansion of the exponentiel up to first order:

$$H_{int} = \frac{\hbar\Omega}{2}\sigma_+\{\mathbb{1}+i\eta(e^{-i\nu t}a+e^{i\nu t}a^\dagger)\}e^{-i\delta t+i\phi} + h.c.$$

Laser cooling

Harmonic oscillator

Quantum bit



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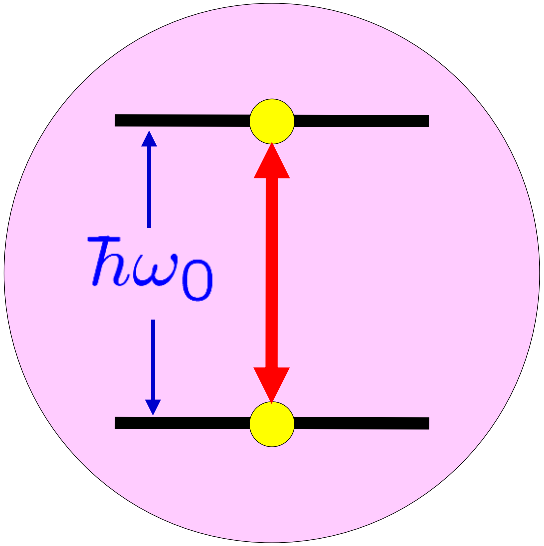


Including spontaneous decay

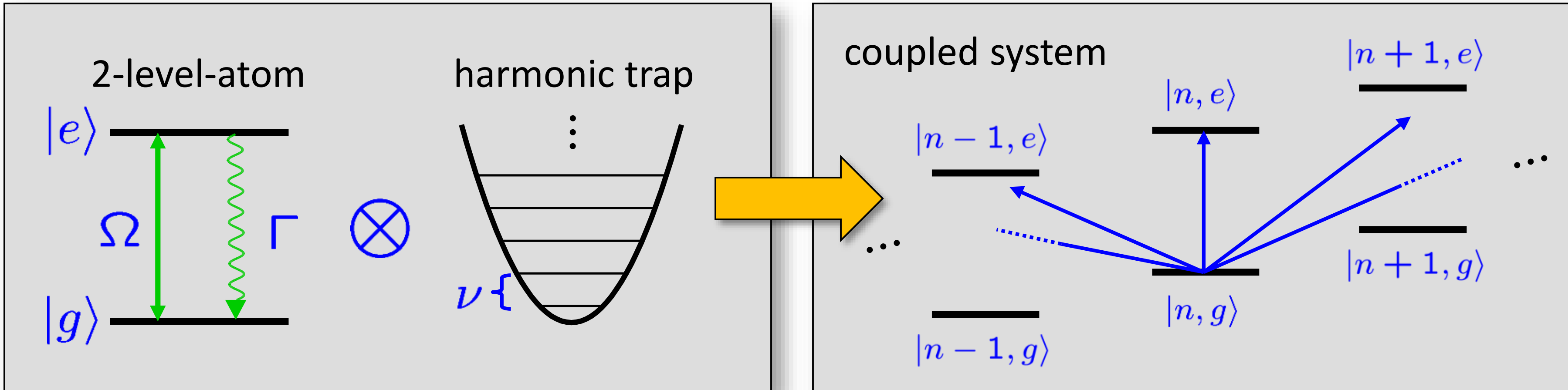
motional states

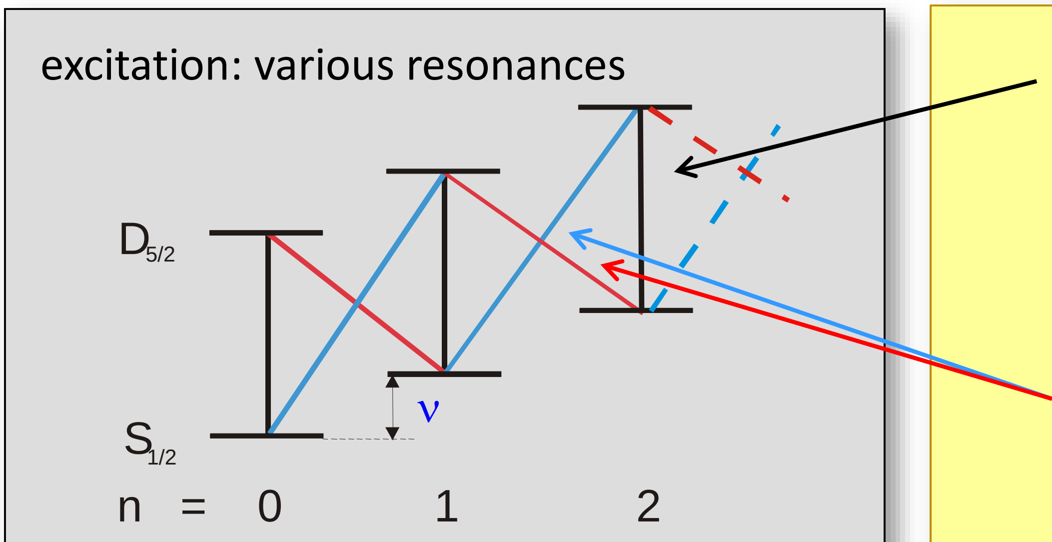
$$|0\rangle, |1\rangle, |2\rangle, |3\rangle, \ldots$$

internal states

$$|\uparrow\rangle, |\downarrow\rangle$$

Qubit manipulation





Carier:
manipulate qubit
→ internal superpositions

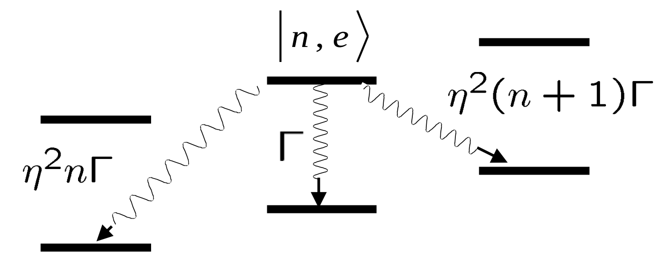
Sidebands:
manipulate motion and qubit
→ create entanglement

Outline

- Laser cooling and ion species
- Local operations
- Entangling operations
- Decoherence
- Implementing algorithms

Laser cooling

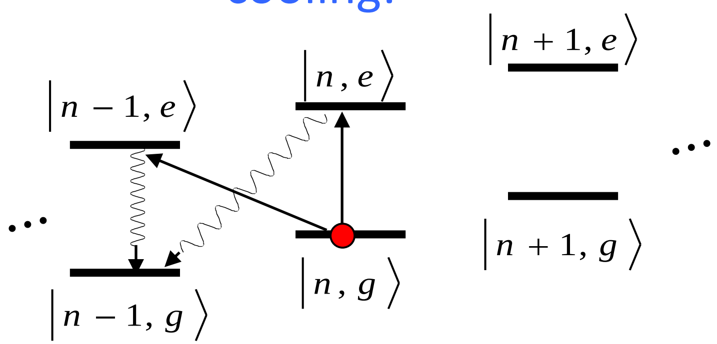
emission



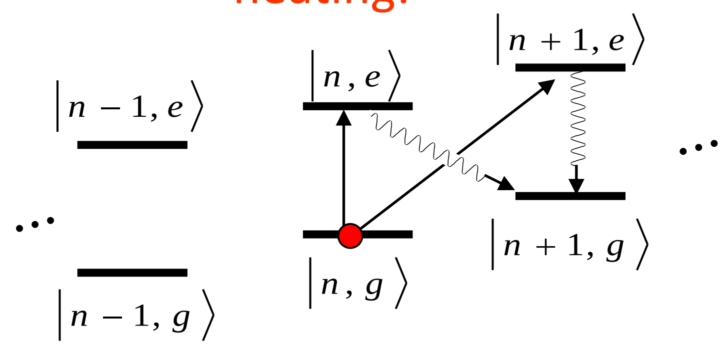
In the Lamb-Dicke regime,
spontaneous photons
rarely change the motional state |n>:

Physical processes that change *n*, in lowest order of *eta*

cooling:



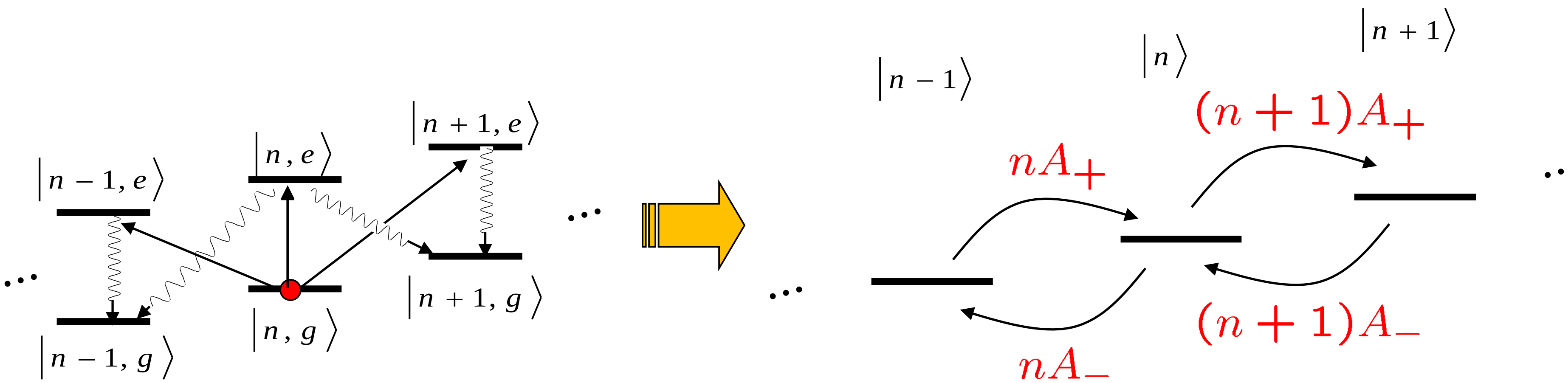
heating:



Laser cooling

Adiabatically eliminate the excited state populations, consider only transitions between motional states |n> and calculate rate equations for motional state populations p_n:

S. Stenholm, Rev. Mod. Phys. ***58****, 699 (1986)*



Detailed balance in steady state:

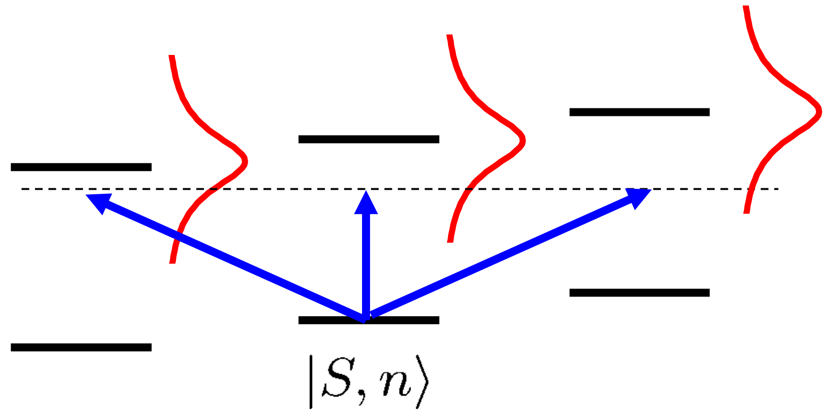
$$p_n A_+ = p_{n+1} A_-$$

$$E_{final} = \hbar\nu\left(\frac{A_+}{A_- - A_+} + \frac{1}{2}\right)$$

$$\langle n\rangle = \frac{A_+}{A_- - A_+}$$

Laser cooling regimes

Doppler cooling

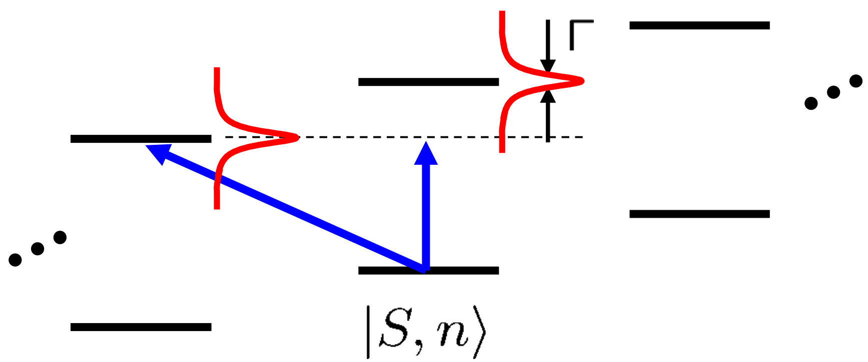


$\nu \ll \Gamma$ **weak** confinement, Doppler cooling

$$\langle n \rangle = \frac{\Gamma}{2\nu} > 1$$

if laser detuned by $\Delta = -\Gamma/2$

Sideband cooling

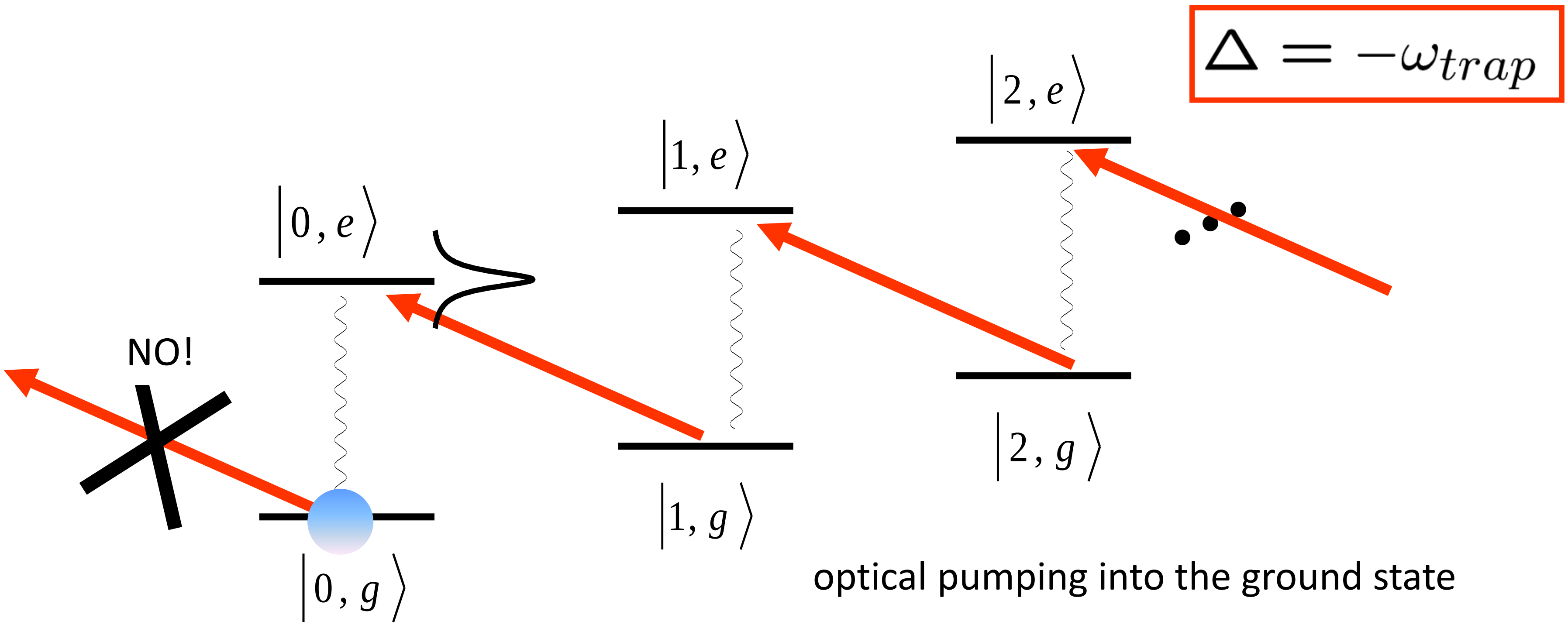


$\nu \gg \Gamma$ **strong** confinement, sideband cooling

$$\langle n \rangle = \frac{\Gamma^2}{4\nu^2} \ll 1$$

if laser detuned by $\Delta = -\nu$

Sideband cooling

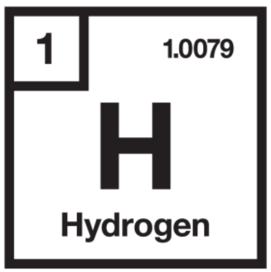


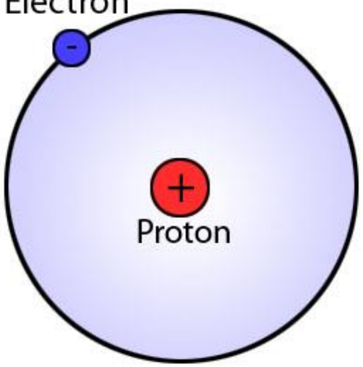
optical pumping into the ground state

Signature: no further excitation possible

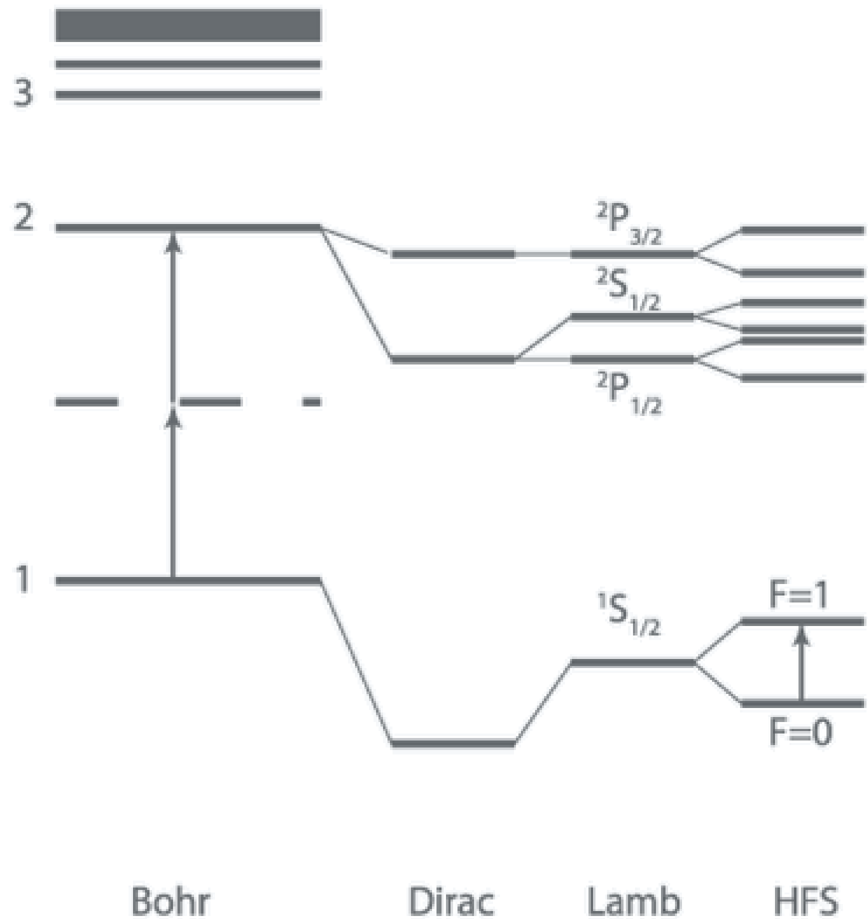
„dark state" |0>

Physicists like it simple





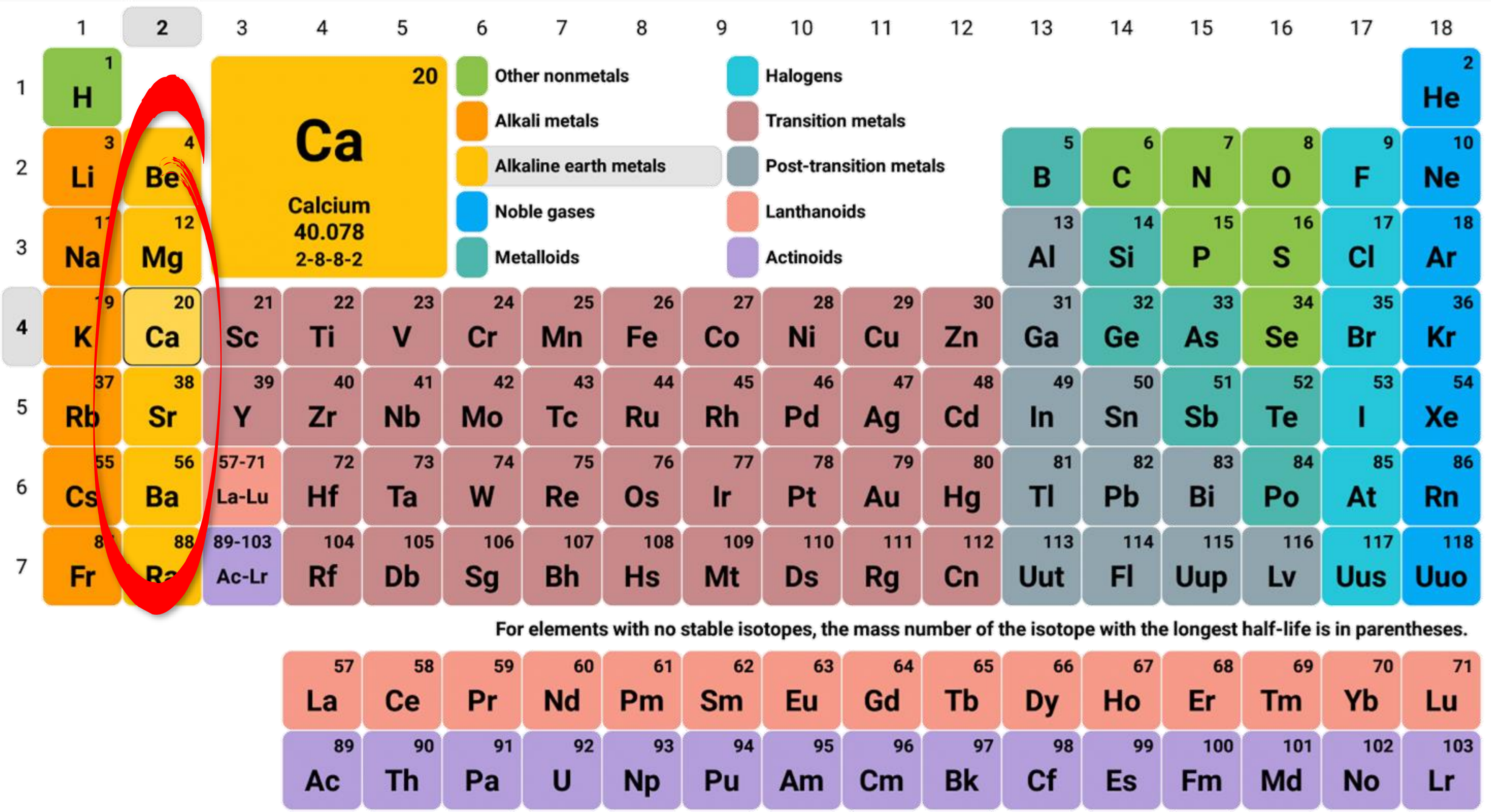
Energy levels



As simple as it gets:

- Only one electron
- No rotations
- No vibrations

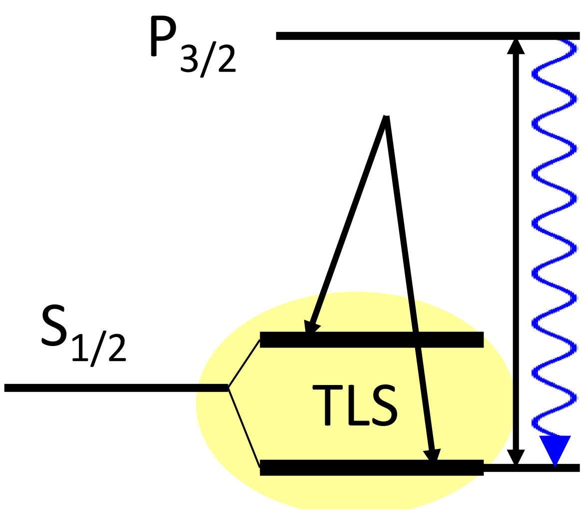
Ion trappers favorites



Possible qubits

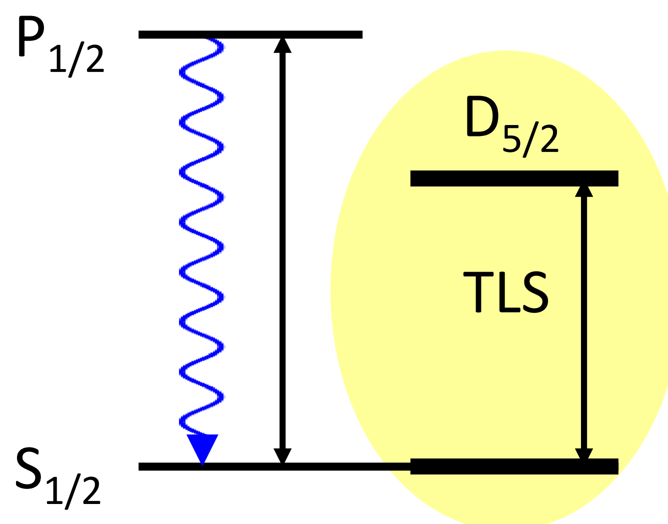
Storing and keeping quantum information requires long-lived atomic states:

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



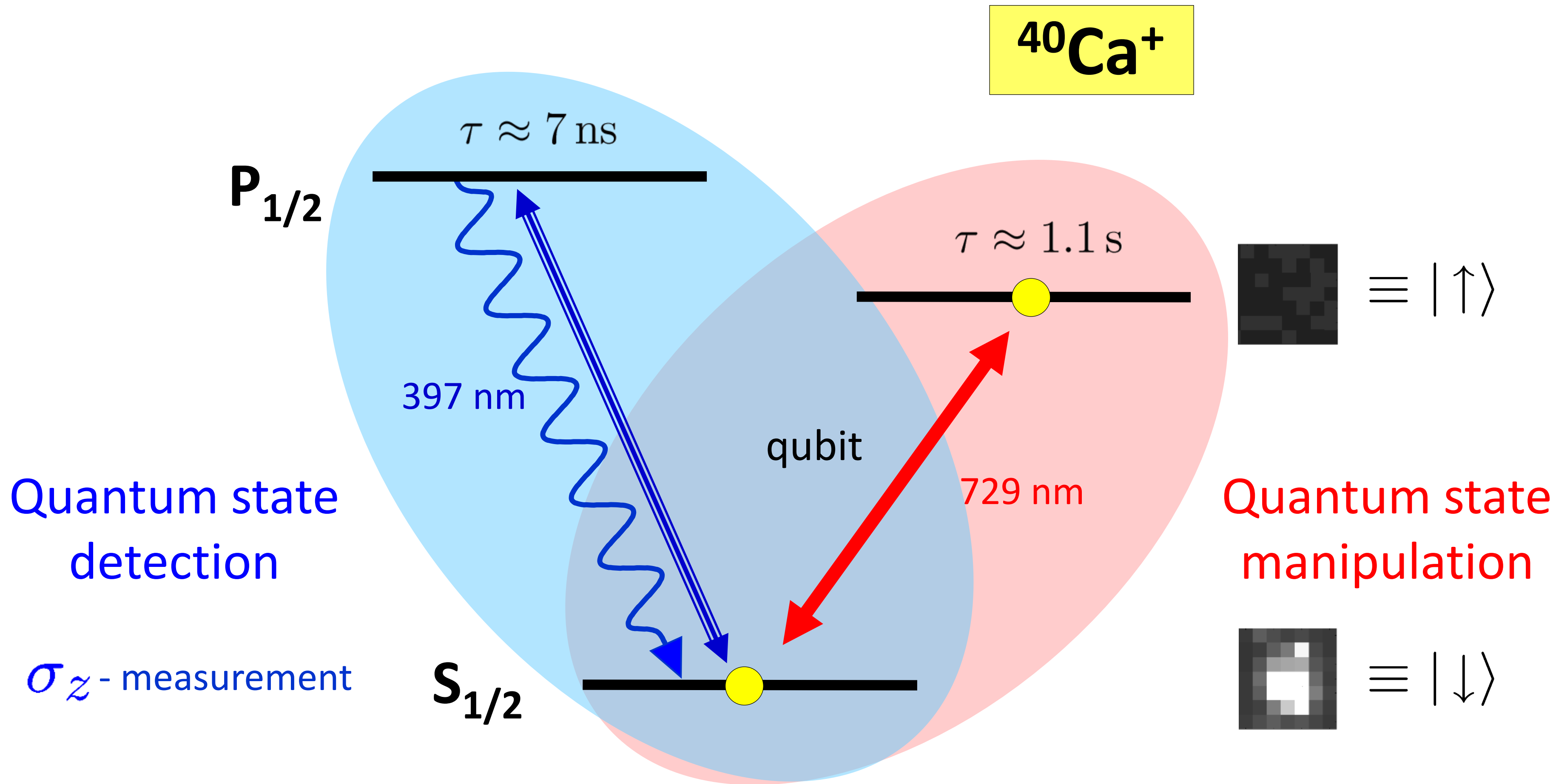
Boulder $^{9}Be^{+}$; Michigan $^{111}Cd^{+}$;
Innsbruck $^{43}Ca^{+}$, Oxford $^{43}Ca^{+}$;
Maryland $^{171}Yb^{+}$;

- optical transition frequencies
(forbidden transitions,
intercombination lines)
S – D transitions in alkaline earths:
Ca^{+}, Sr^{+}, Ba^{+}, Ra^{+}, (Yb^{+}, Hg^{+}) etc.



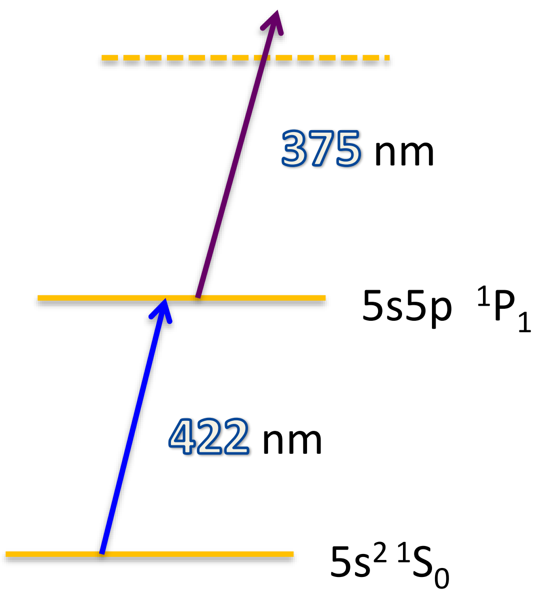
Innsbruck $^{40}Ca^{+}$

Our ion of choice

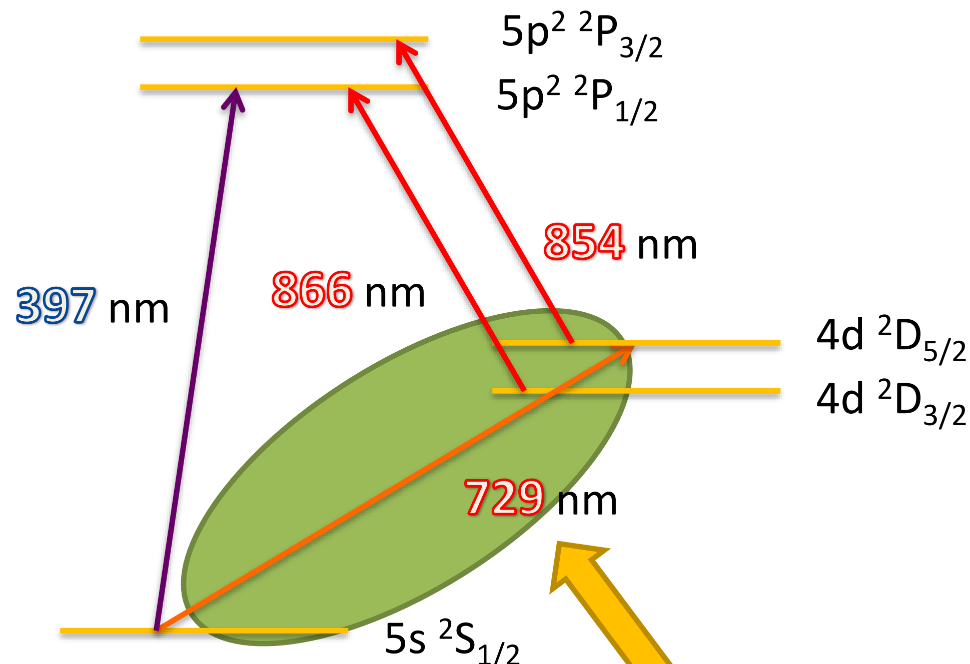


Required lasers

Ca energy levels



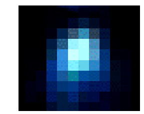
Ca$^+$ energy levels



6 laser systems required

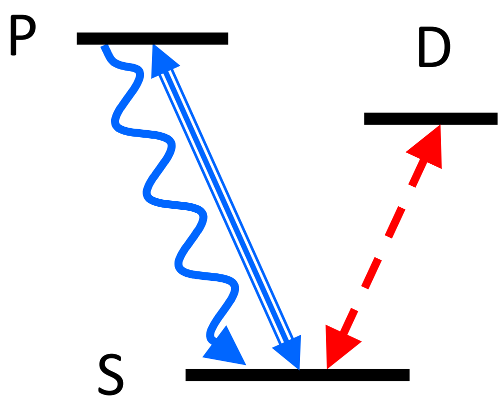
Lasers and electronics

Local oscillator (Laser) → Light modulation (Acousto Optic Modulators) → Focusing optics →



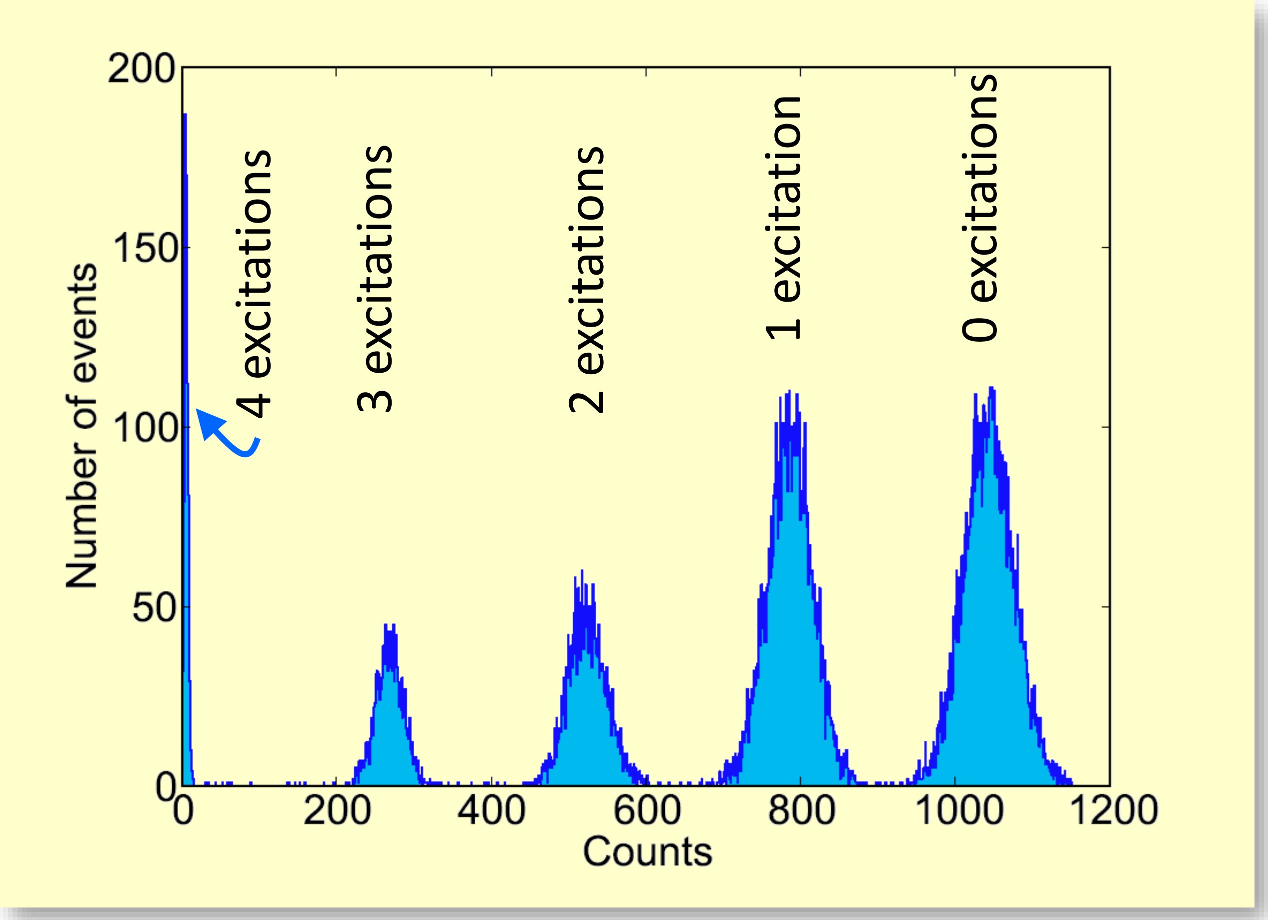
Digital signal (FPGA) → RF-signal (DDS) → Light modulation (Acousto Optic Modulators)

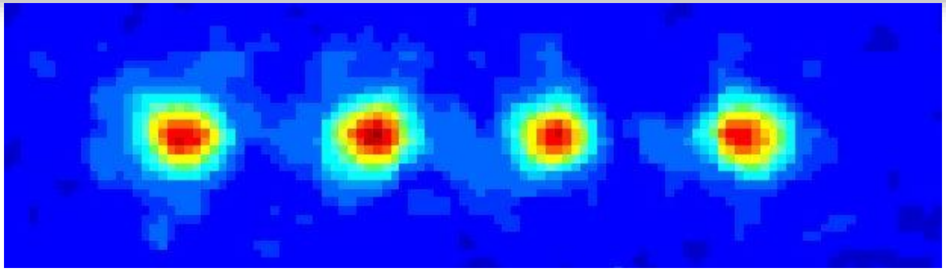
Qubit measurement



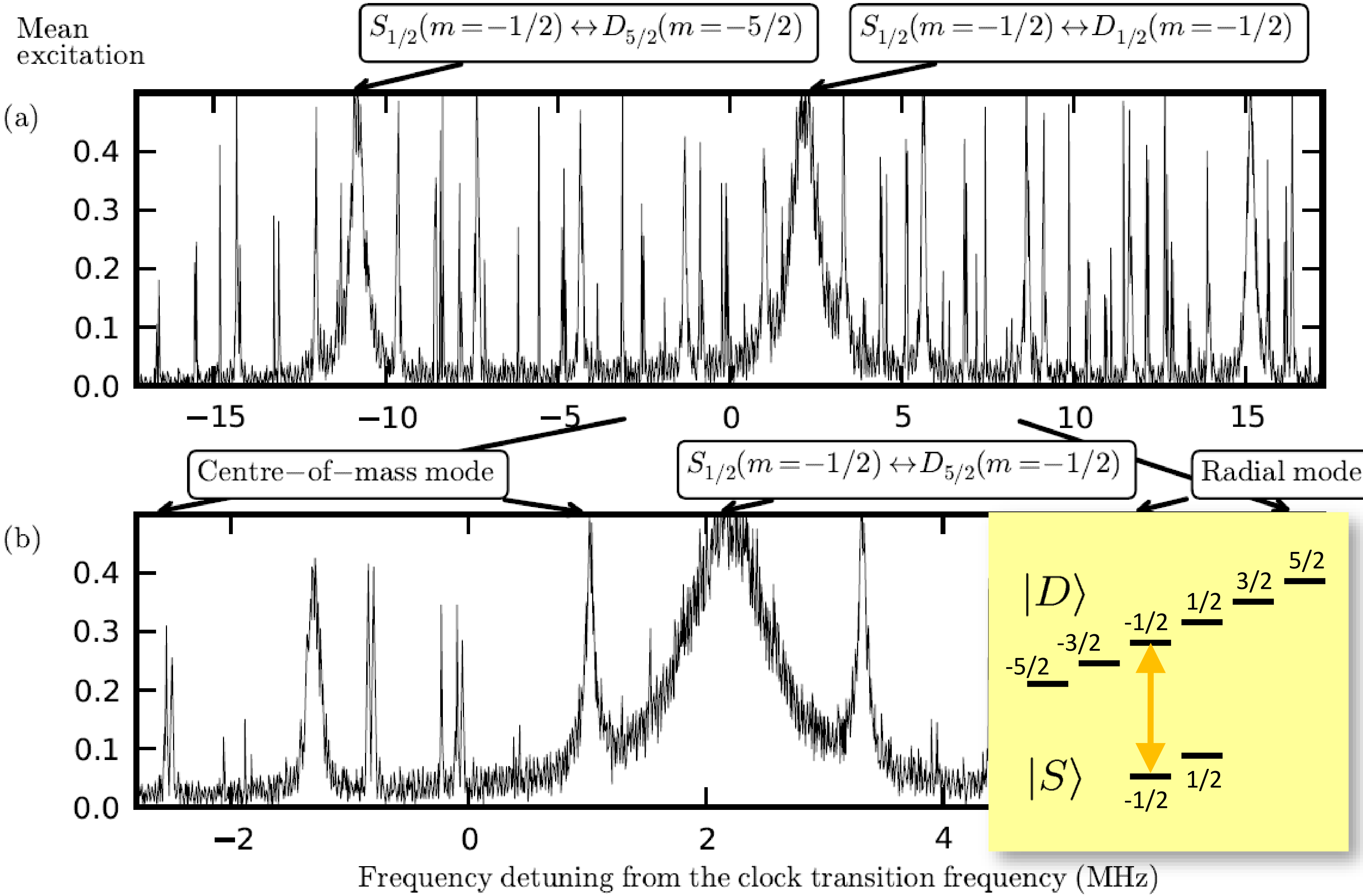
Detection:
Quantum Jumps

- Projection of ions to either S or D states,





It's a two-level system?



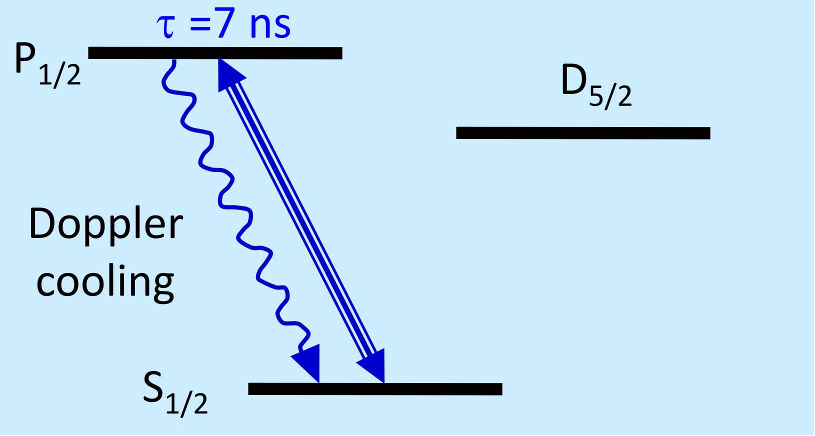
Laser cooling in Ca

1. Doppler cooling on $S_{1/2}$-$P_{1/2}$ transition:

Fast cooling rate

$$\langle n \rangle = \frac{\Gamma}{2\nu} \approx 2 - 10$$

(2 ms Doppler cooling)

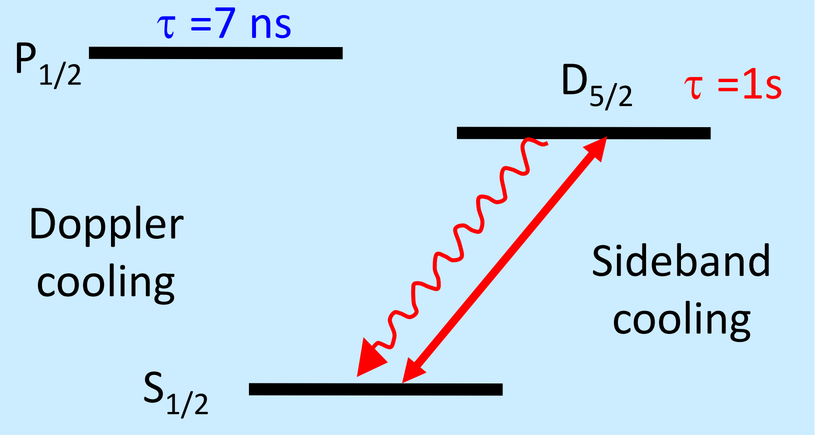


2. Sideband cooling on $S_{1/2}$-$D_{5/2}$ transition:

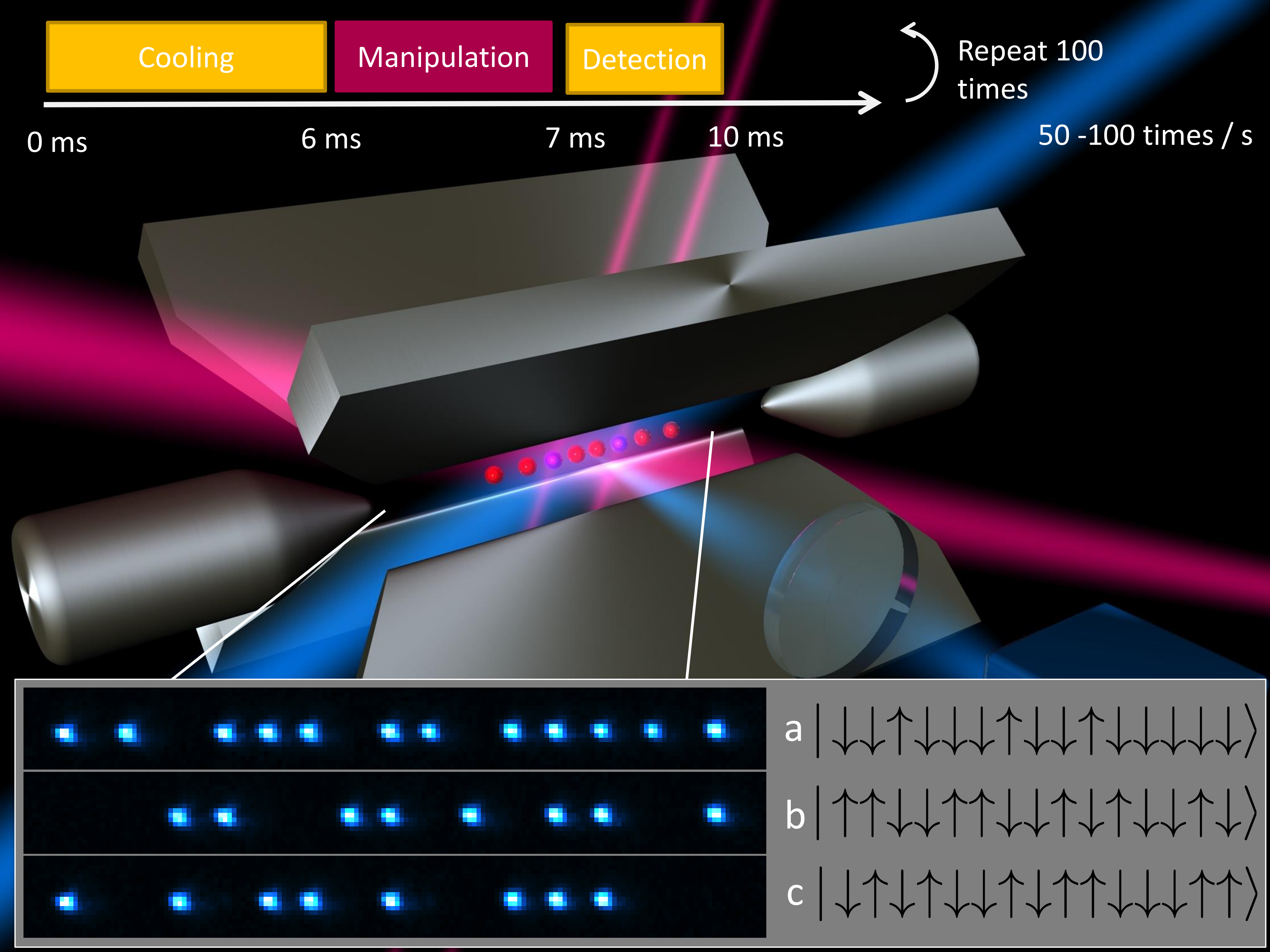
Slower cooling rate, but better cooling results

$$\langle n \rangle_{exp} \approx 0.001 - 0.01$$

(5-10 ms sideband cooling)



(For sideband cooling, the lifetime of the D5/2 state is artificially shortened by coupling it to the P3/2 state -> higher cooling rate)



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

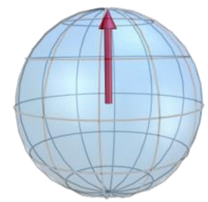
Outline

- Laser cooling and ion species
- Local operations
- Entangling operations
- Decoherence
- Implementing algorithms

The required operations

- **algorithms:**
  sequence of single qubit and two-qubit gate operations

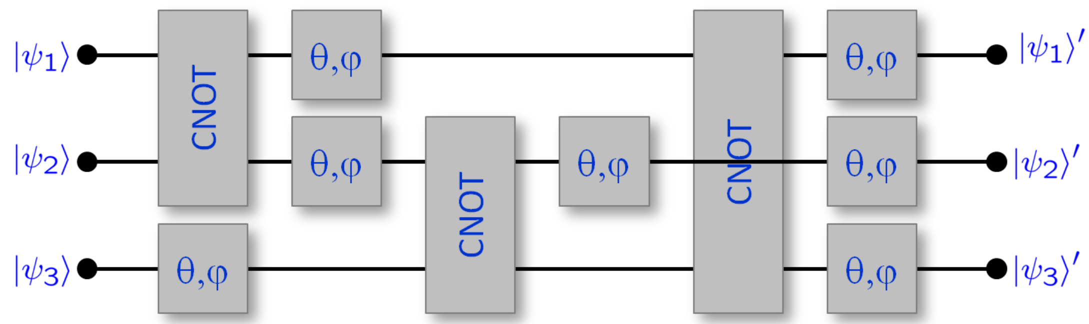
single qubit operation



$$\text{CNOT}\begin{cases}|0\rangle|0\rangle \rightarrow |0\rangle|0\rangle\\ |0\rangle|1\rangle \rightarrow |0\rangle|1\rangle\\ |1\rangle|0\rangle \rightarrow |1\rangle|1\rangle\\ |1\rangle|1\rangle \rightarrow |1\rangle|0\rangle\end{cases}$$

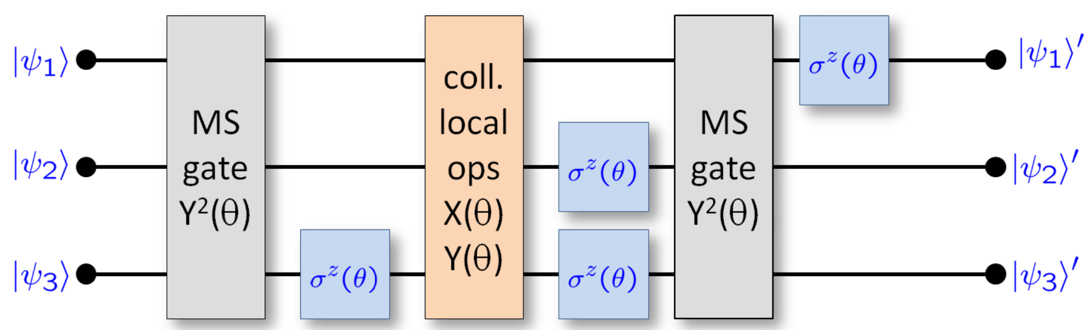
single-qubit (local) operations
two-qubit CNOT gate operations

➔ **universal set**

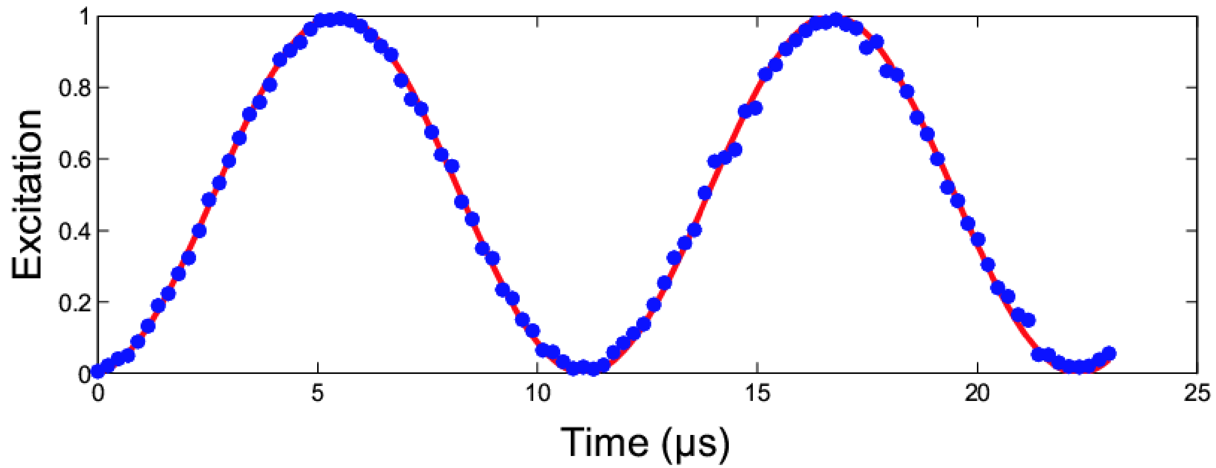


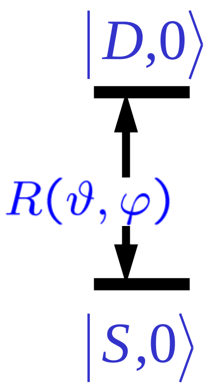
single-qubit (local) operations
two-qubit entangling operations

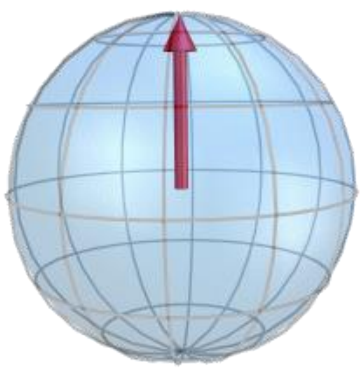
➔ **universal (over-complete) set**



Rabi flopping – Single qubit operations



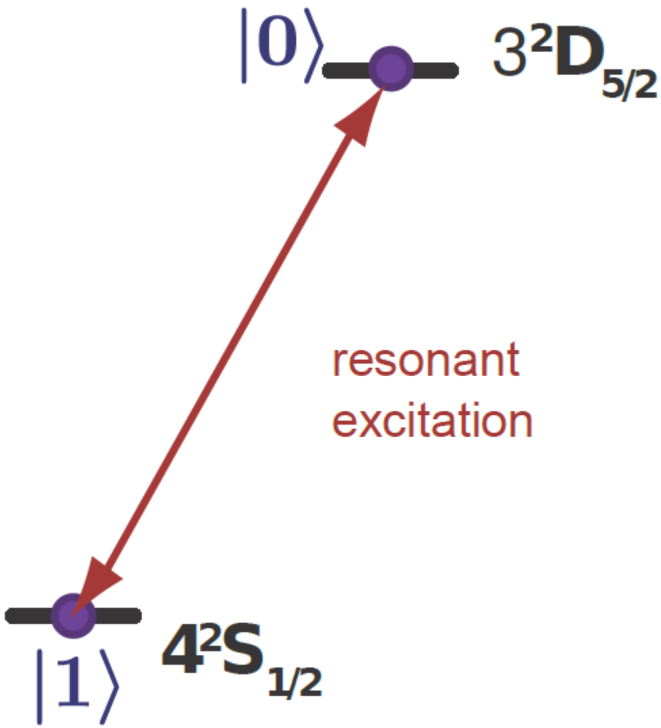


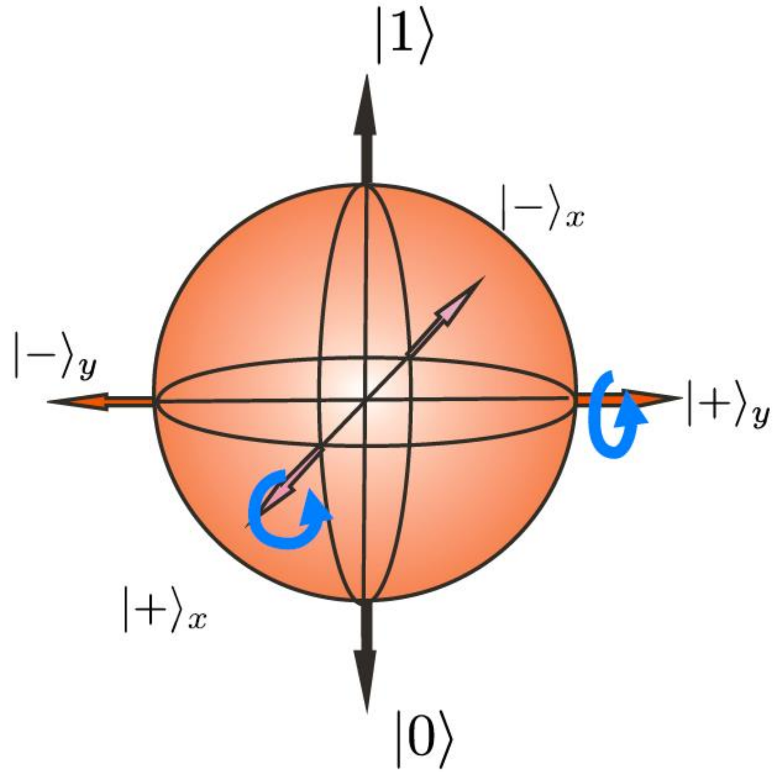


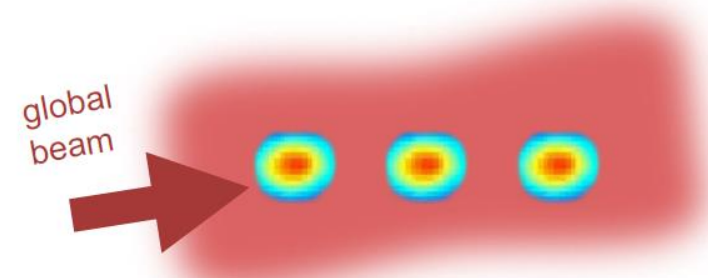
Carrier Rabi oscillations
with Rabi frequencies

Rotations on the Bloch sphere

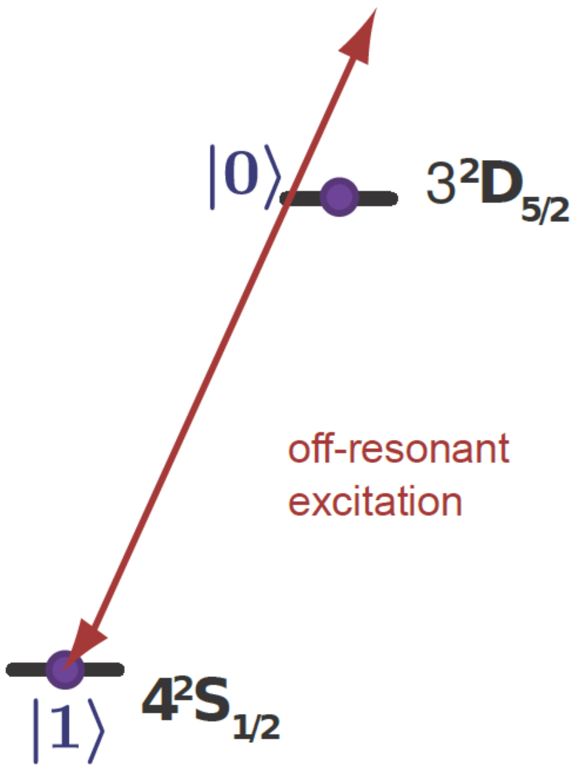
Collective local operations

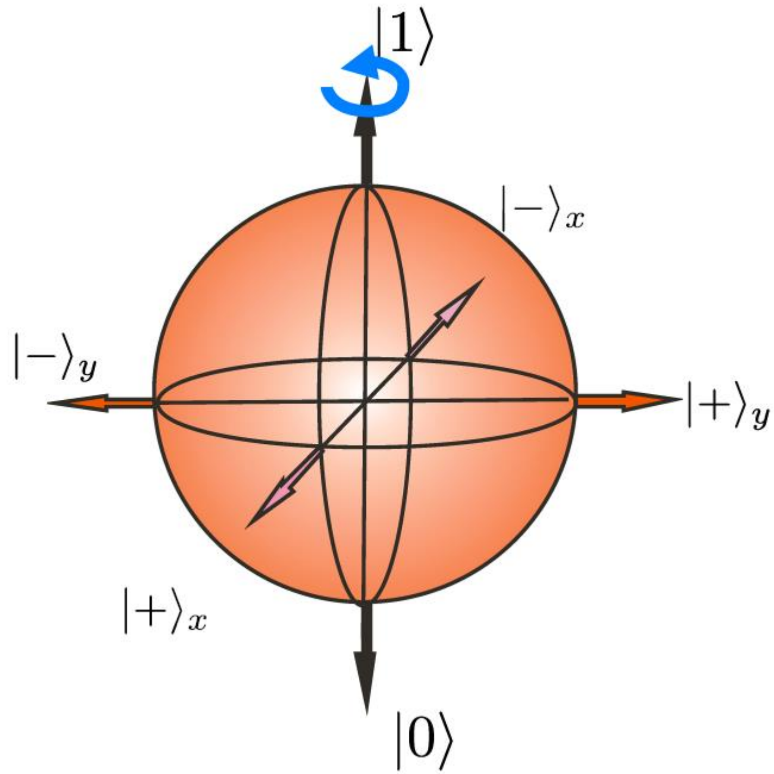


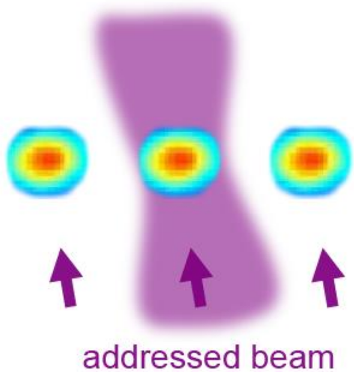




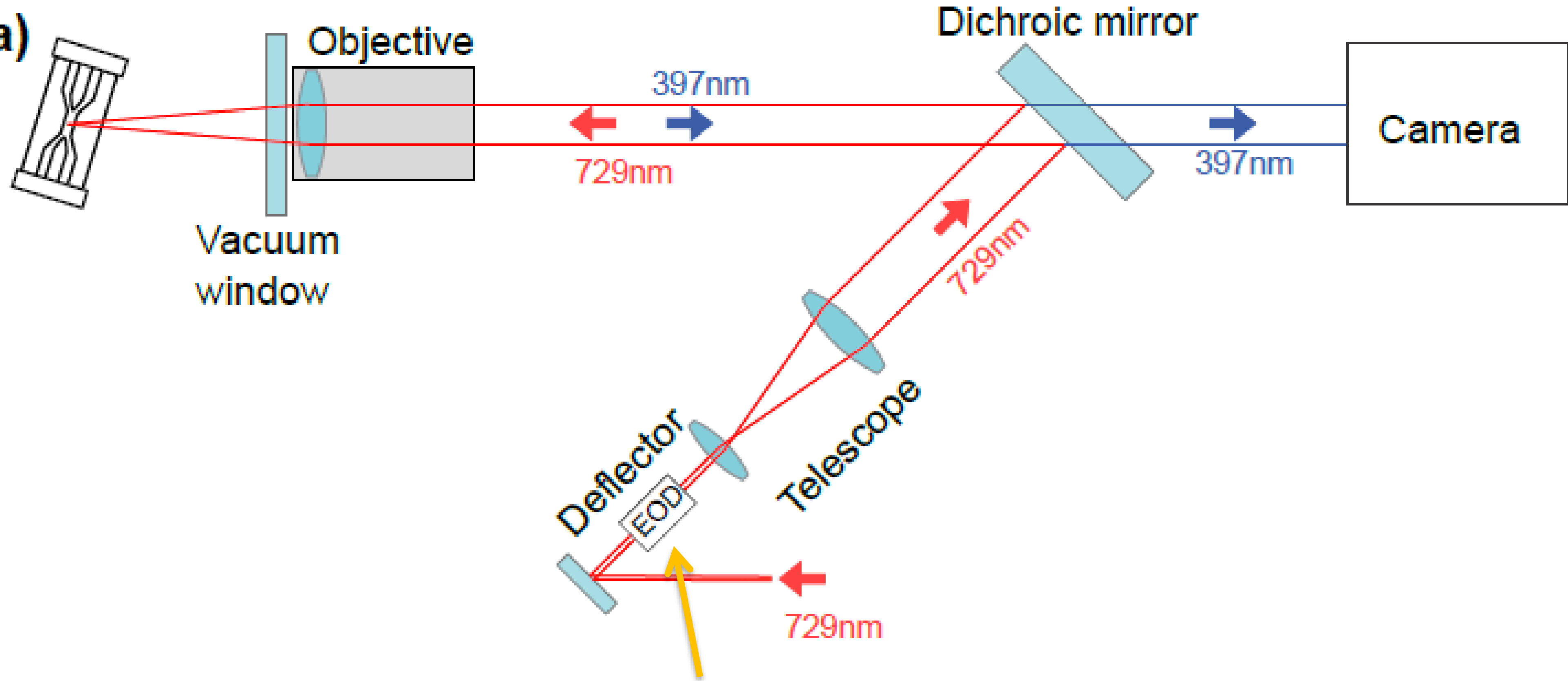
Single qubit operations







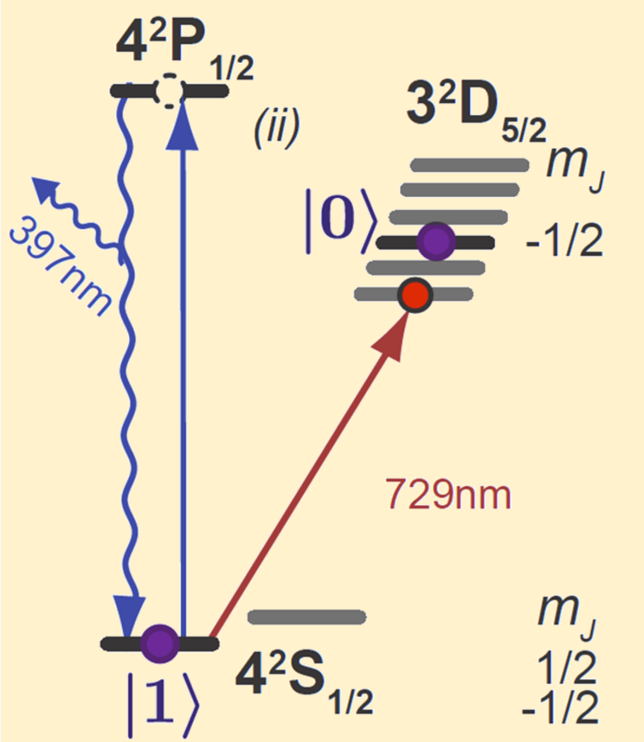
Single ion addressing



Electro optical deflector

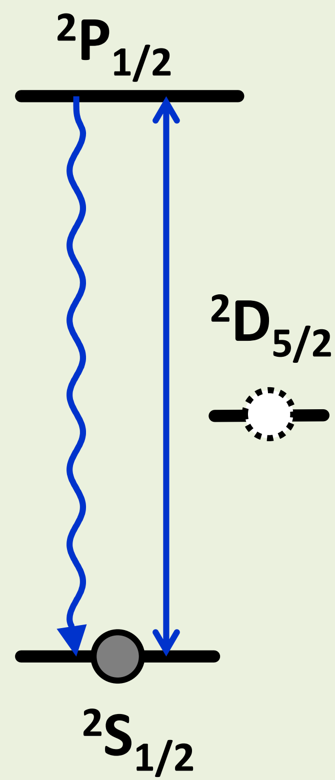
Additional operations

Hiding



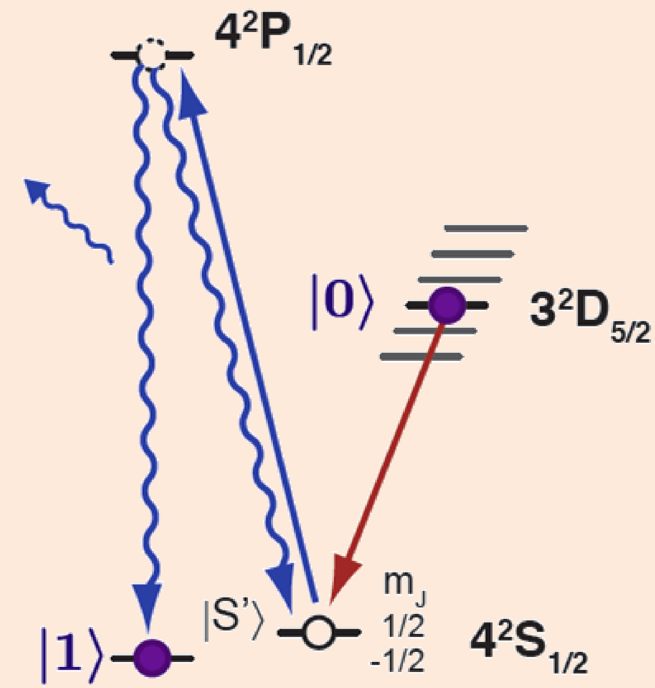
reduces, enlarges the computational subspace

Dephasing



controlled dissipation

Resetting



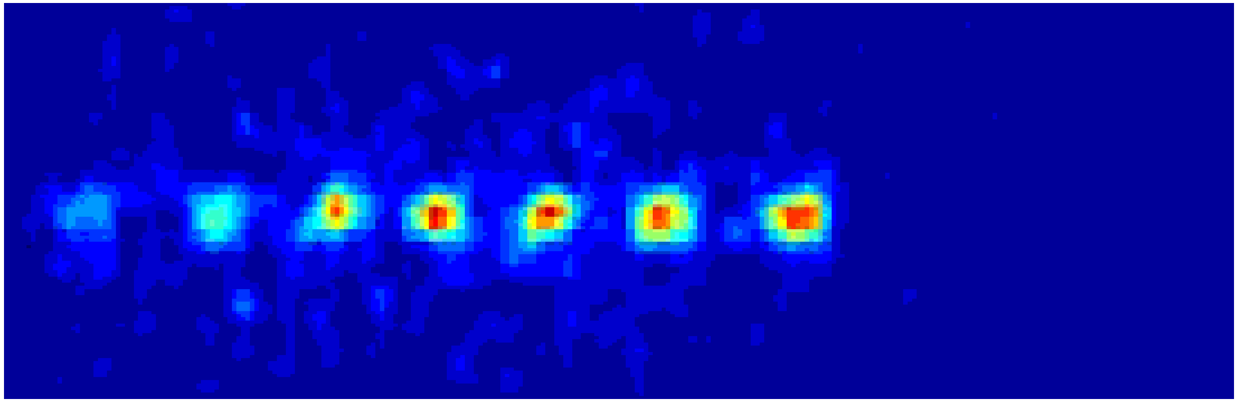
initializes the qubit

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

Outline

- Laser cooling and ion species
- Local operations
- Entangling operations
- Decoherence
- Implementing algorithms

More ions



Normal modes of ion crystals

At low temperatures, ions oscillate around their equilibrium positions

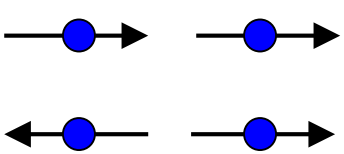
Coulomb interaction: coupling of ion motion

$\longrightarrow$ small excitations : collective normal modes

For the calculation of the normal mode frequencies:

Taylor expansion of Coulomb force and trapping force around the equil. positions

2 ions:



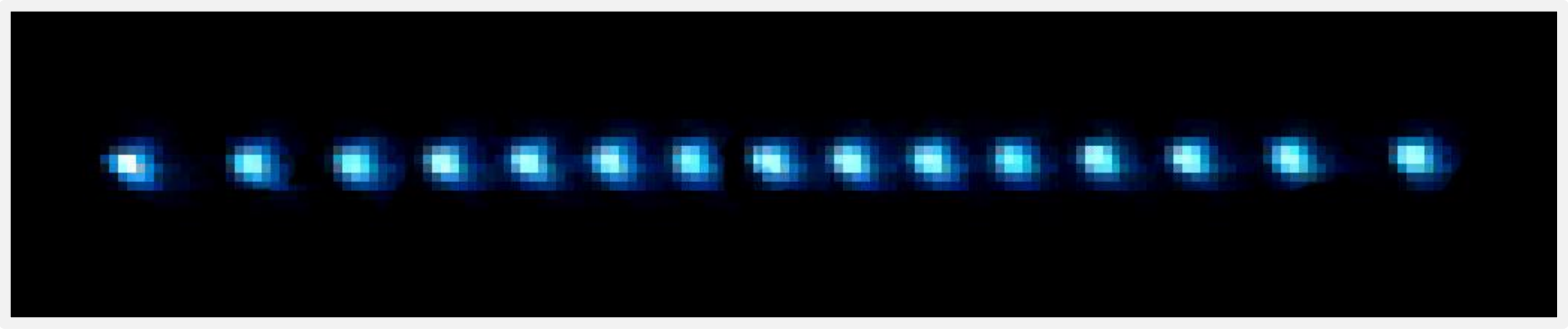
center of mass mode $\nu_1 = \nu_z$

breathing mode $\nu_2 = \sqrt{3}\nu_z$

Ion crystals

Equilibrium positions:
Minimize potential energy of ions in a linear chain:

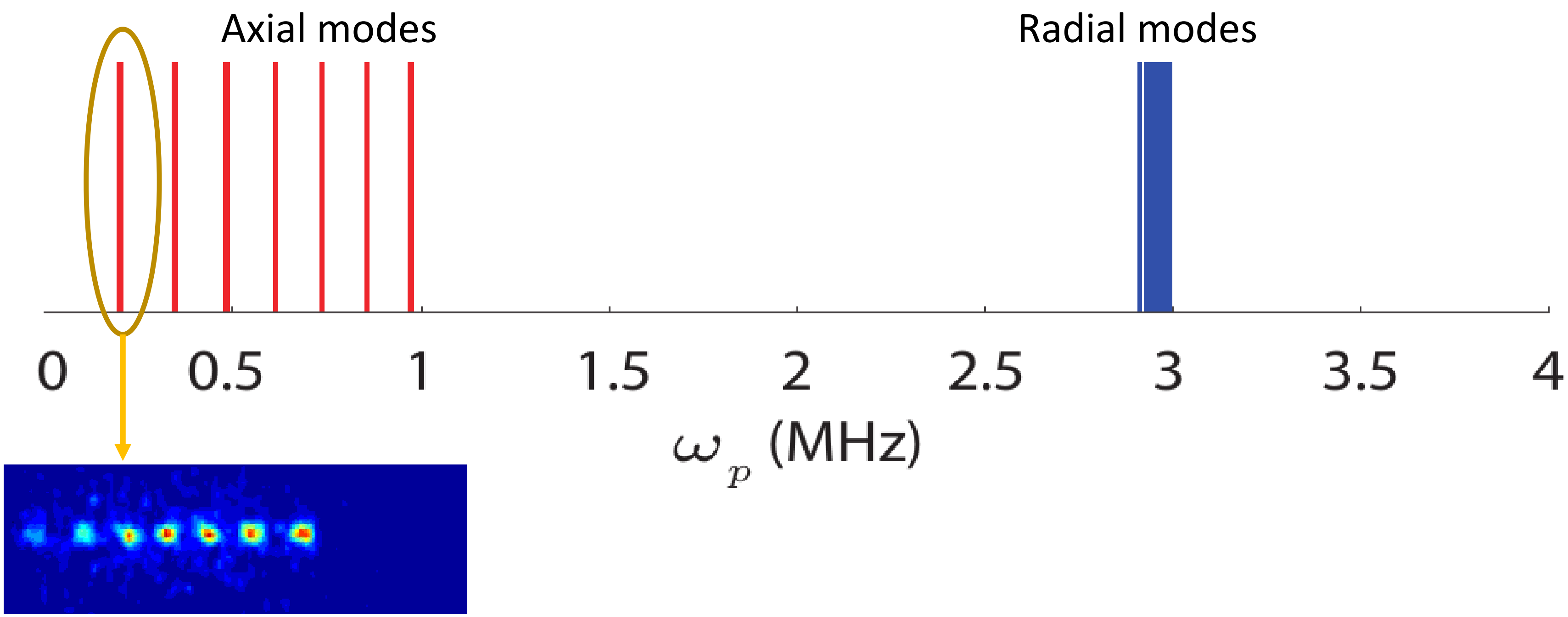
$$V = \frac{m\omega_z^2}{2}\sum_{i=1}^{N} z_i(t)^2 + \frac{(Ze)^2}{8\pi\varepsilon_0}\sum_{\substack{j,i=1\\ n\neq i}}^{N} \frac{1}{|z_j(t) - z_i(t)|}$$



Normal modes

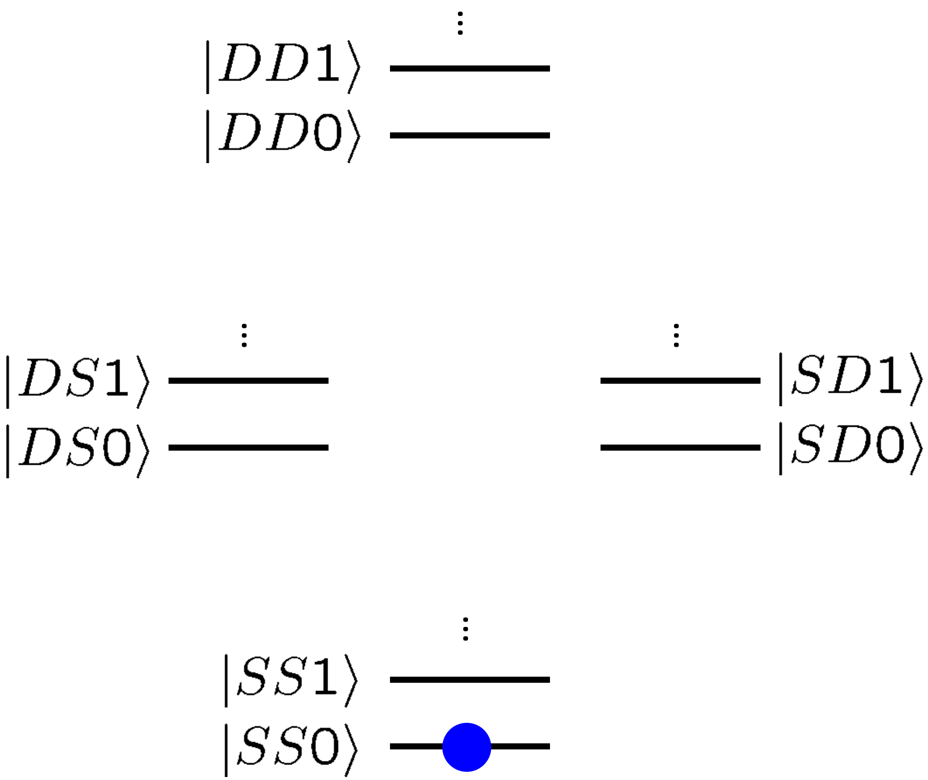
Perform Taylor expansion around equilibrium positions to find normal modes.

Analogous to 3D classical coupled harmonic oscillator: 3N modes.



C. Marquet, F. Schmidt-Kaler, and D. F. V. James, Applied Physics B 76, 199 (2003)

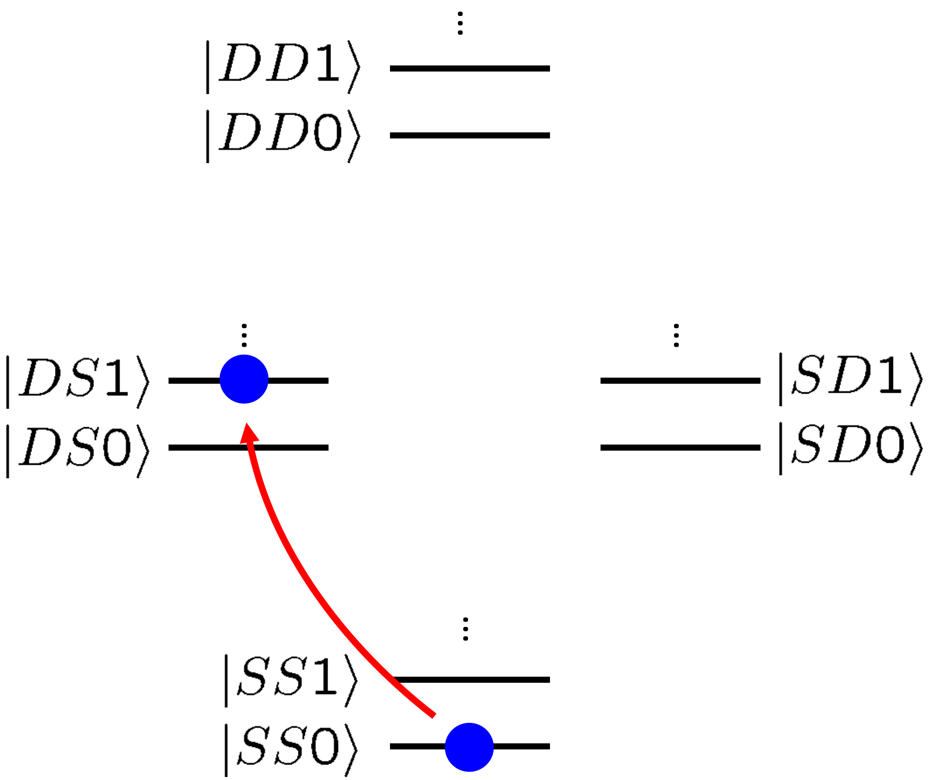
Generating an entangled state



Pulse sequence:

$|SS0\rangle$

Generating an entangled state

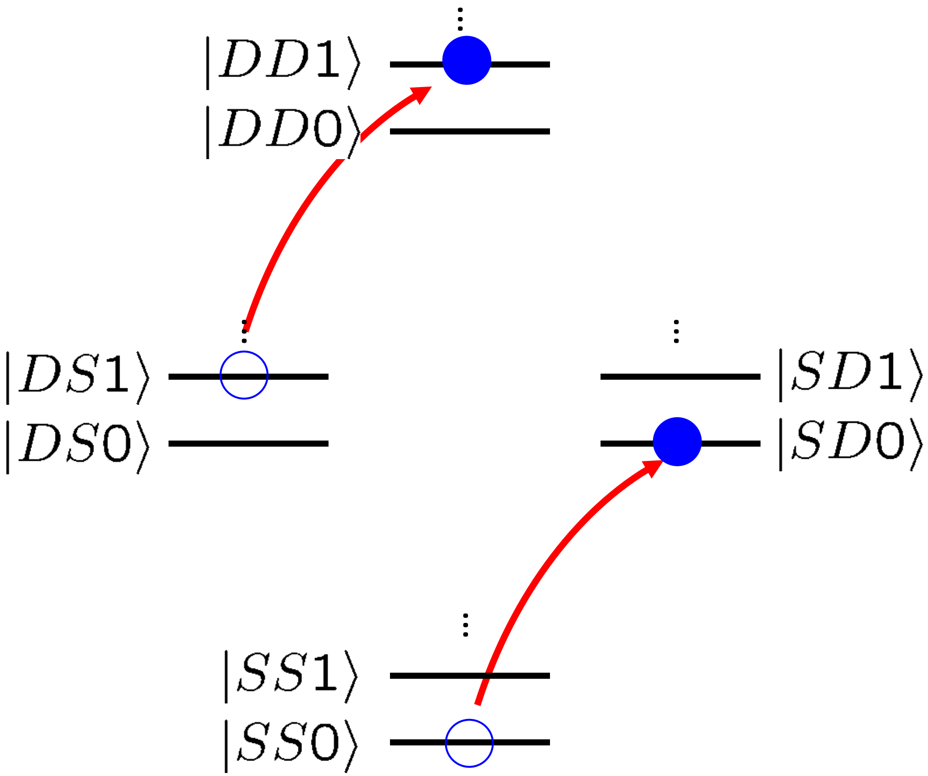


Pulse sequence:

Ion 1: $\pi/2$, blue sideband

$$|SS0\rangle + |DS1\rangle$$

Generating an entangled state



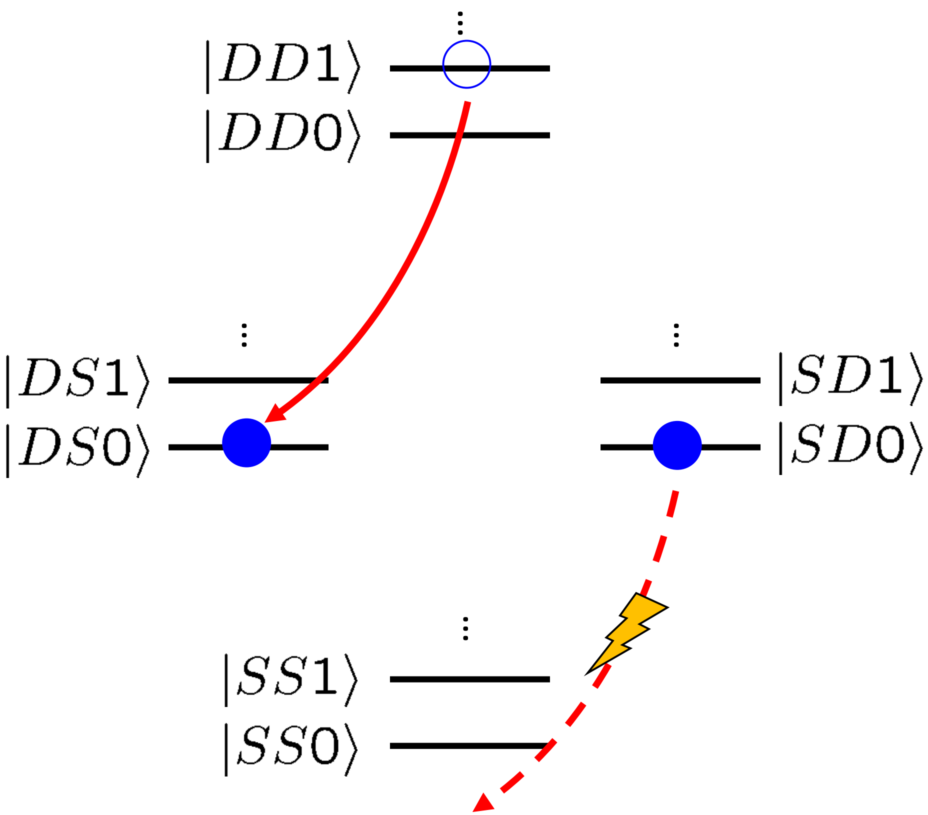
Pulse sequence:

Ion 1: π/2 , blue sideband

Ion 2: π , carrier

$$\boxed{|SD0\rangle + |DD1\rangle}$$

Generating an entangled state



Pulse sequence:

Ion 1: π/2 , blue sideband

Ion 2: π , carrier

Ion 2: π , blue sideband

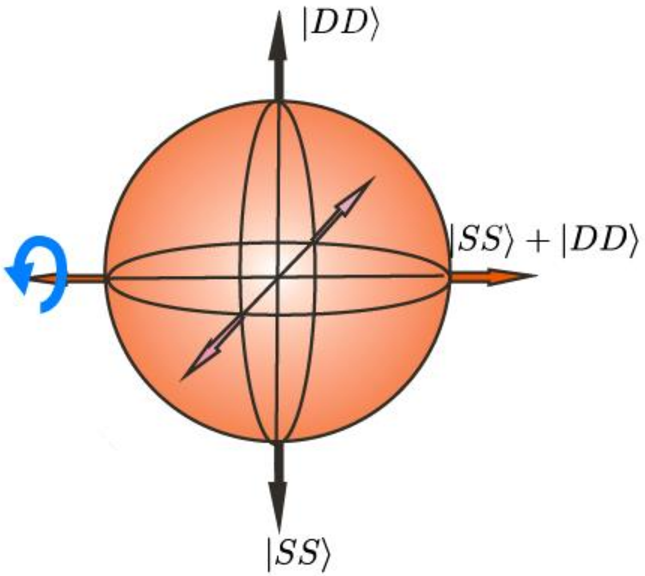
$$(|SD\rangle + |DS\rangle)|0\rangle$$

Mølmer-Sørensen entangling operation

Based on state-dependent light forces.

Works for any number of qubits

Effective infinite range 2-body interaction.



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

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

Mølmer-Sørensen entangling operation

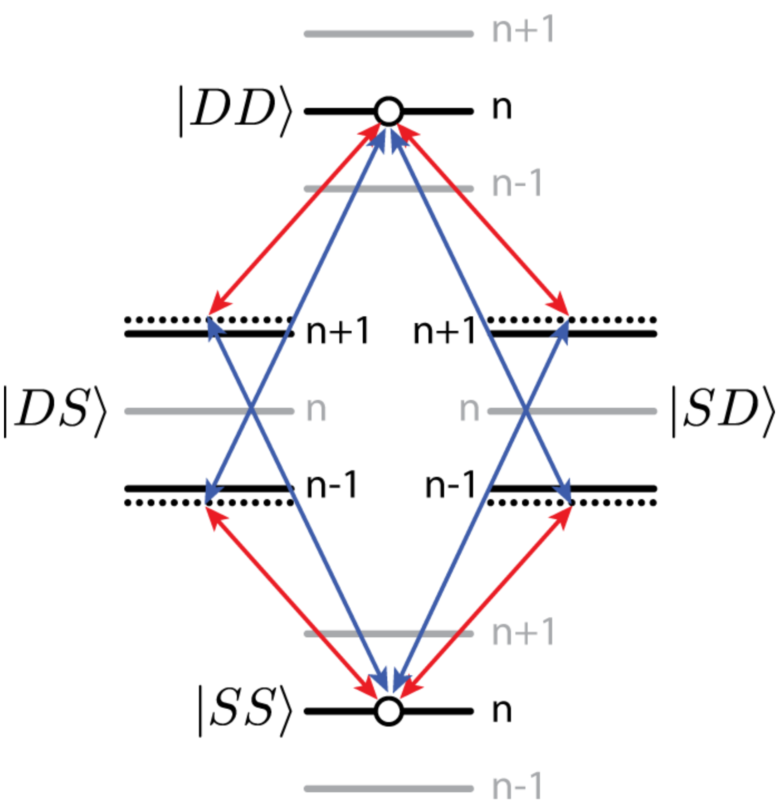
Lamb Dicke approximation interaction Hamiltonian for a single light field:

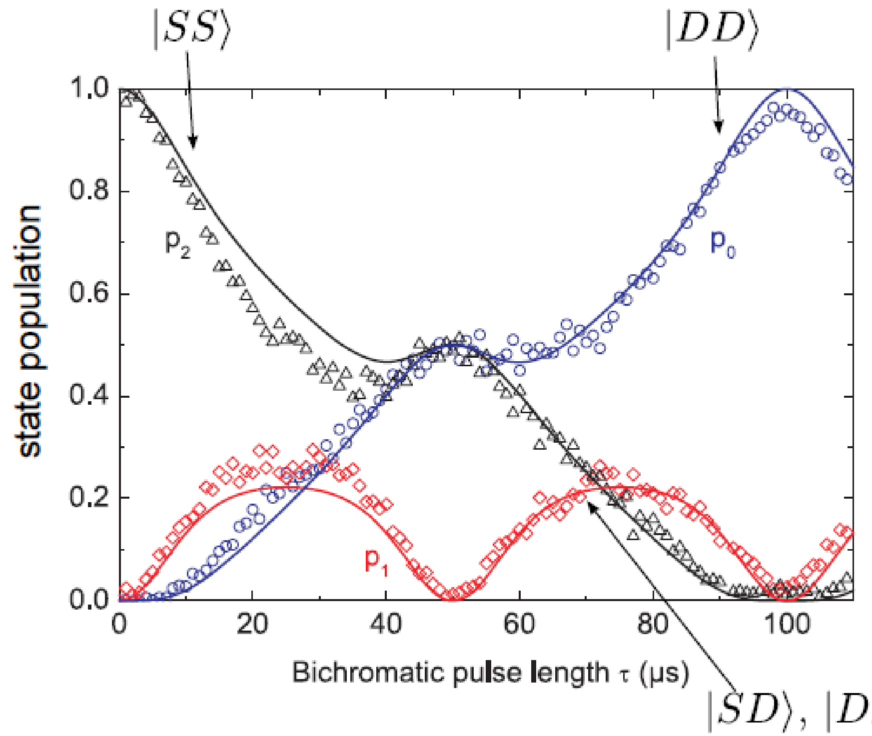
$$\hbar\frac{\Omega}{2}\left\{(e^{-i(\Delta t-\phi_L)}\sigma_+\left[1+i\eta\left(ae^{-i\omega_t t}+a^\dagger e^{i\omega_t t}\right)\right]+h.c.\right\}.$$

Further derivation on the blackboard.

C. F. Roos, New Journal of Physics 10, 013002 (2008)

Mølmer-Sørensen entangling operation





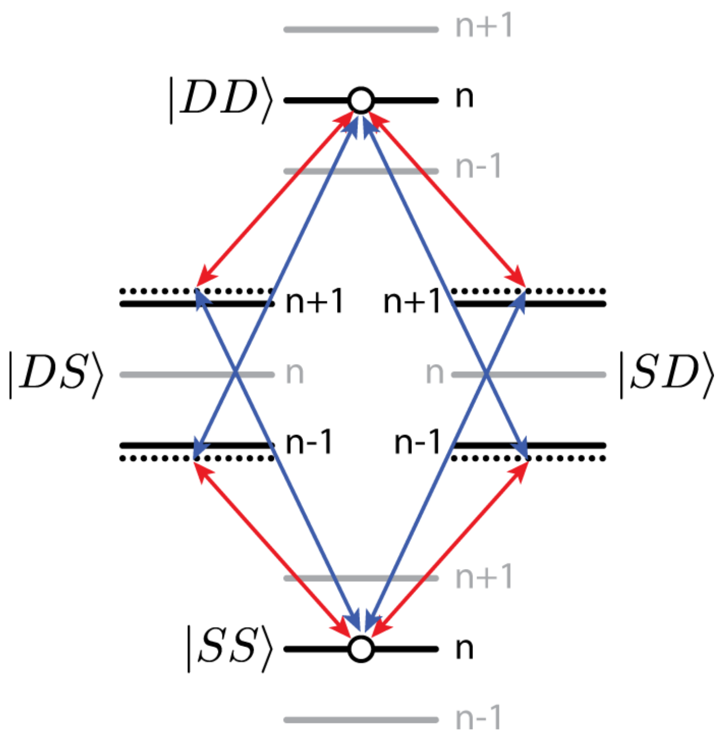
Off-resonant coupling to the sidebands

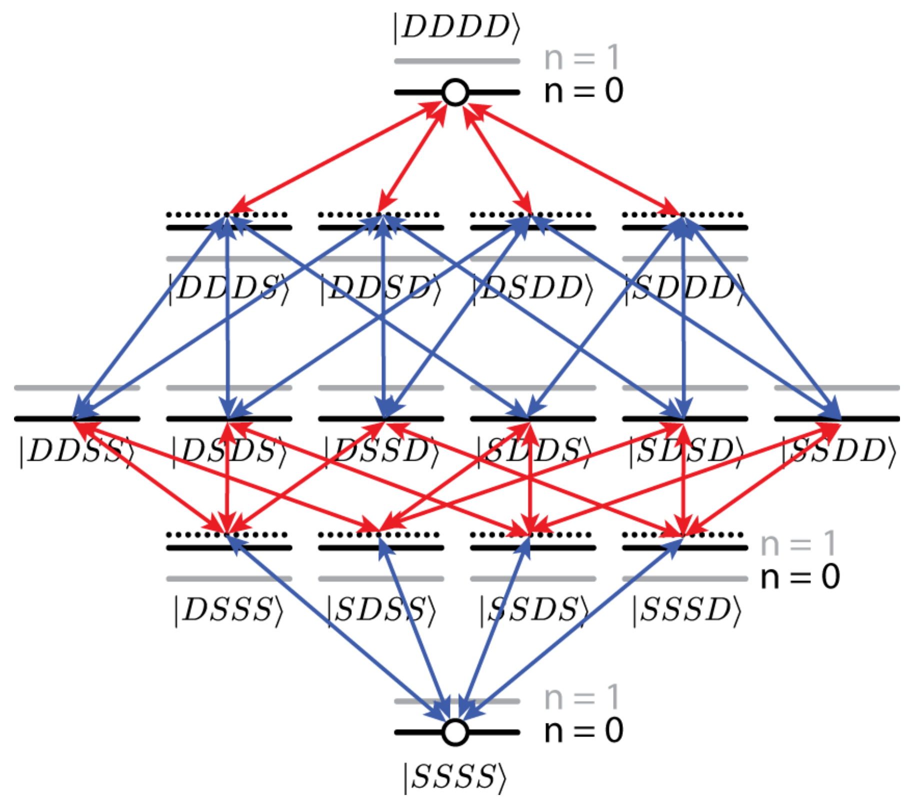
Unwanted populations interfere destructively

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

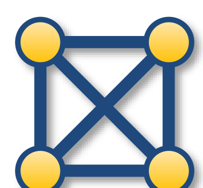
K. Mølmer and A. Sørensen, PRL 82, 1835 (1999).

Multi path interferometer



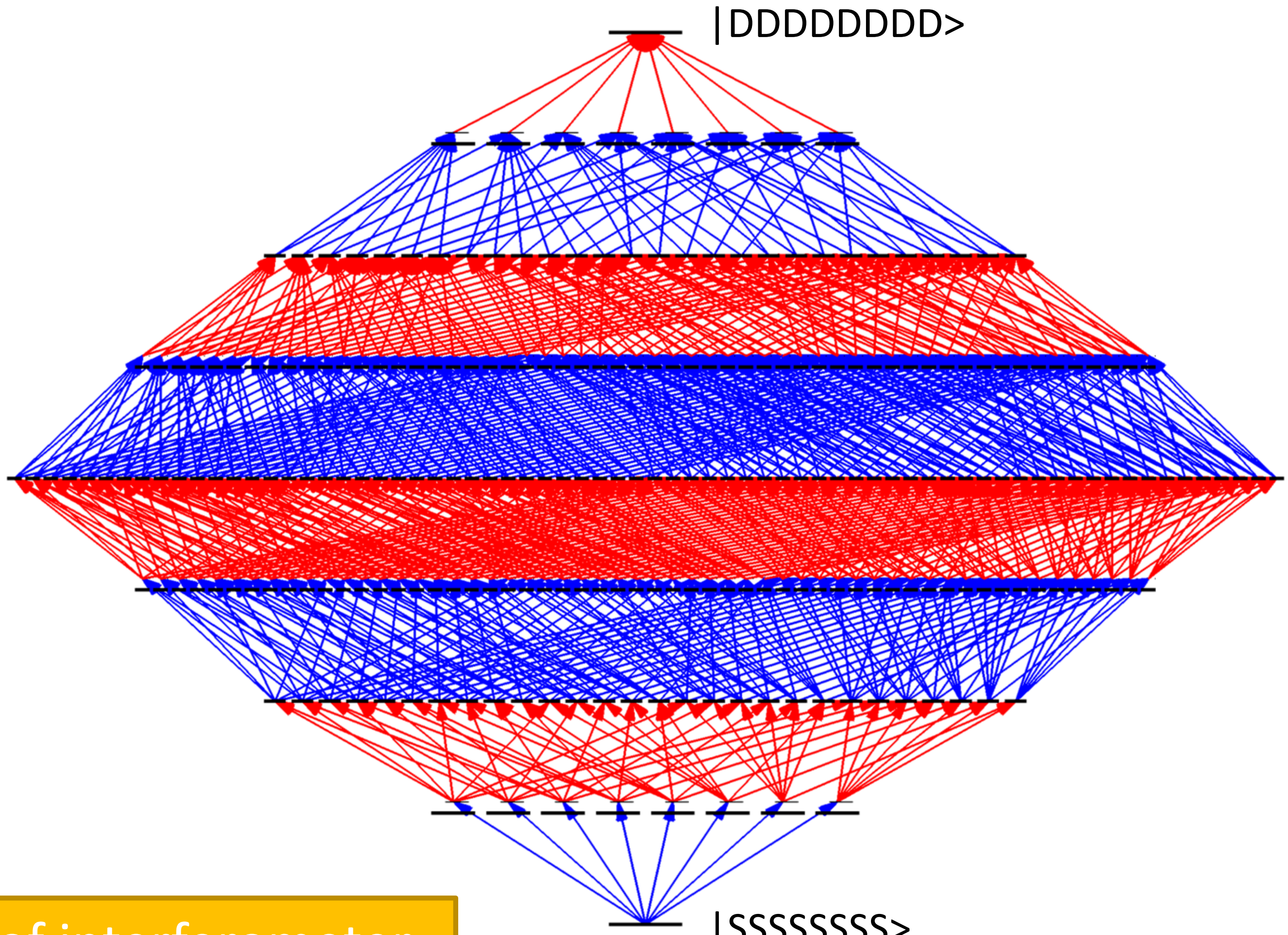


2 qubits



4 qubits

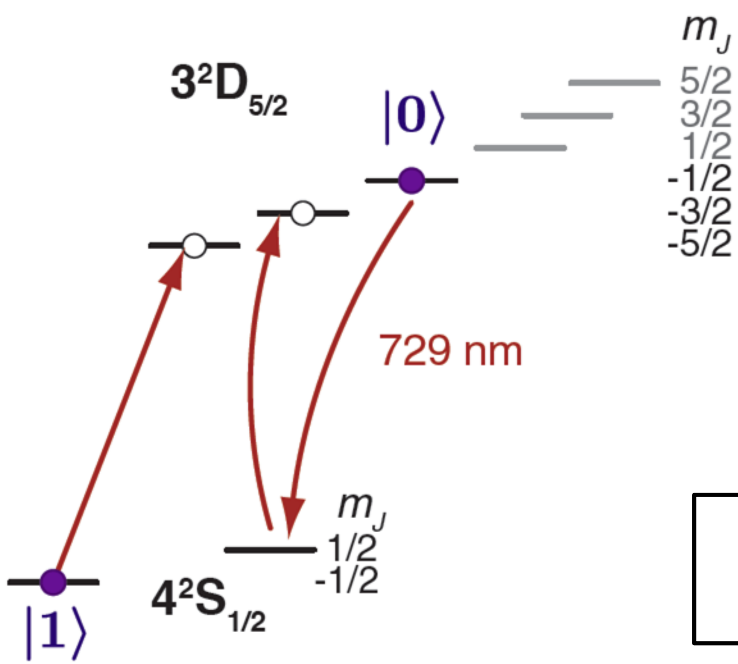
Multi path interferometer – 8 ions

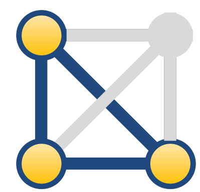


Number of interferometer paths grows exponentially.

Changing connectivity

Spectroscopic decoupling





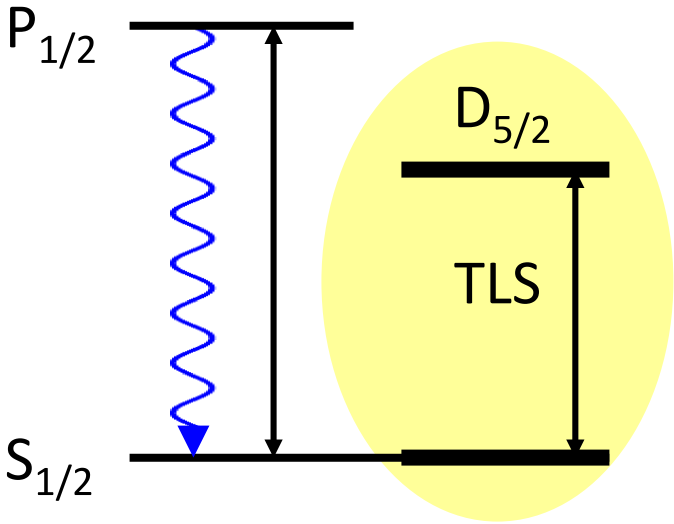
Removes ions from interaction with lasers

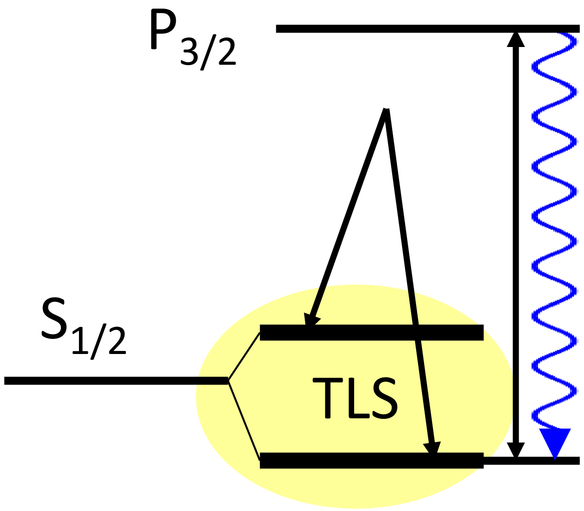
P. Schindler et al., New. J. Phys. 15, 123012 (2013)

Outline

- Laser cooling and ion species
- Local operations
- Entangling operations
- Decoherence
- Implementing algorithms

Decoherence and errors

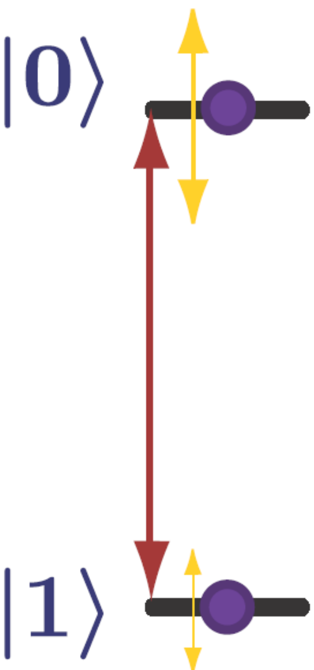




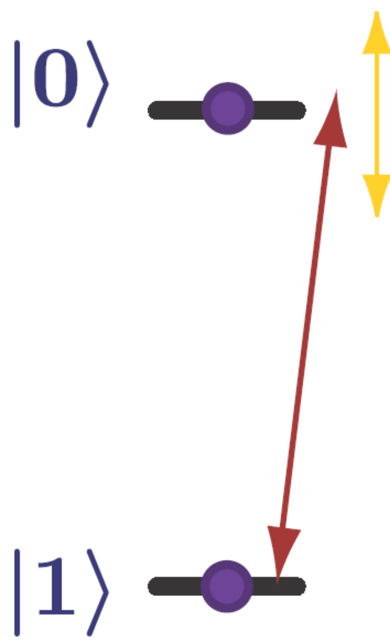
Parameter	Optical qubit	Ground state qubit
T1	1s	infinity
T2	100ms	> 30s
Main limitation	Laser phase noise	Spontaneous decay
Required laser power	Medium	High
Optics complexity	Medium	High

Decoherence – phase damping (T2)

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

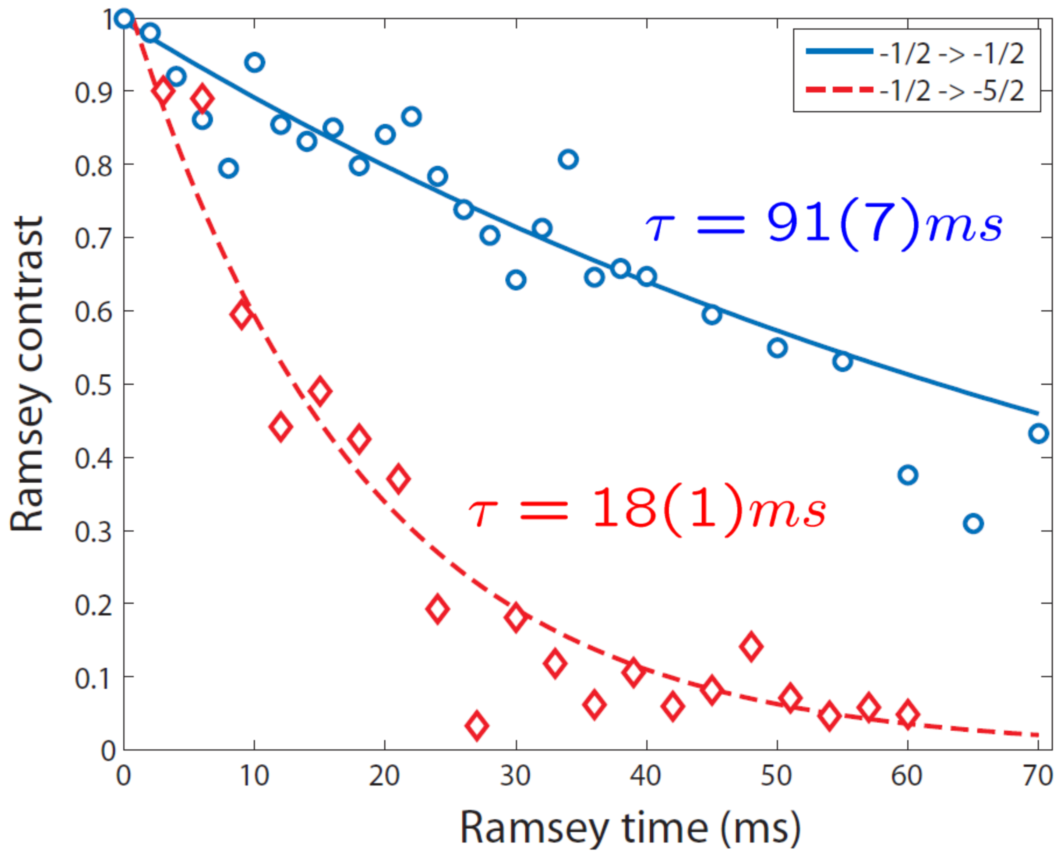


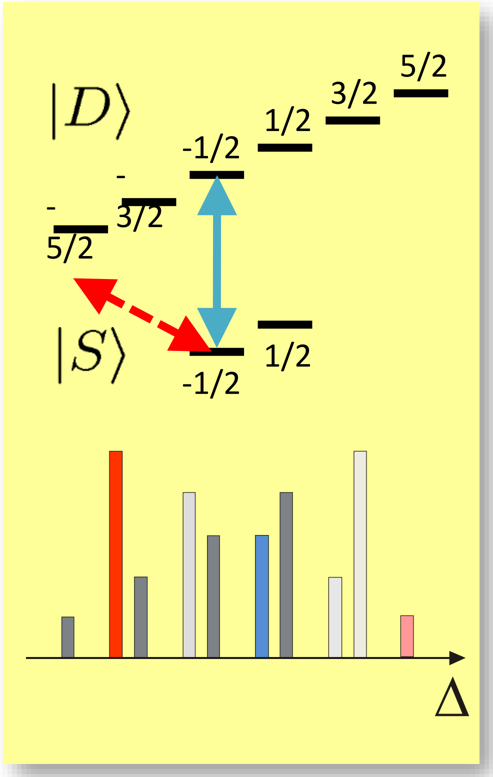
Level spacing fluctuations
(B-field)



Local oscillator fluctuations
(Laser, RF source)

Qubit coherence

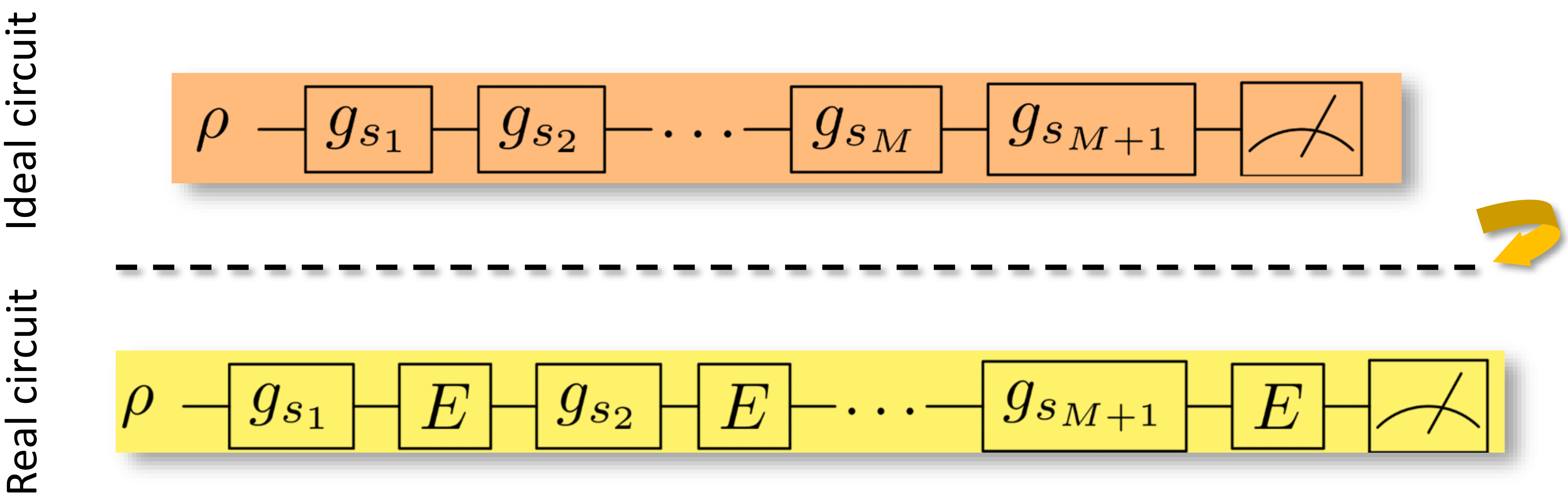




Important limit: $T_2 \leq 2\ T_1$

Tells you when to work on lifetime of the qubit

Benchmarking the quantum computer



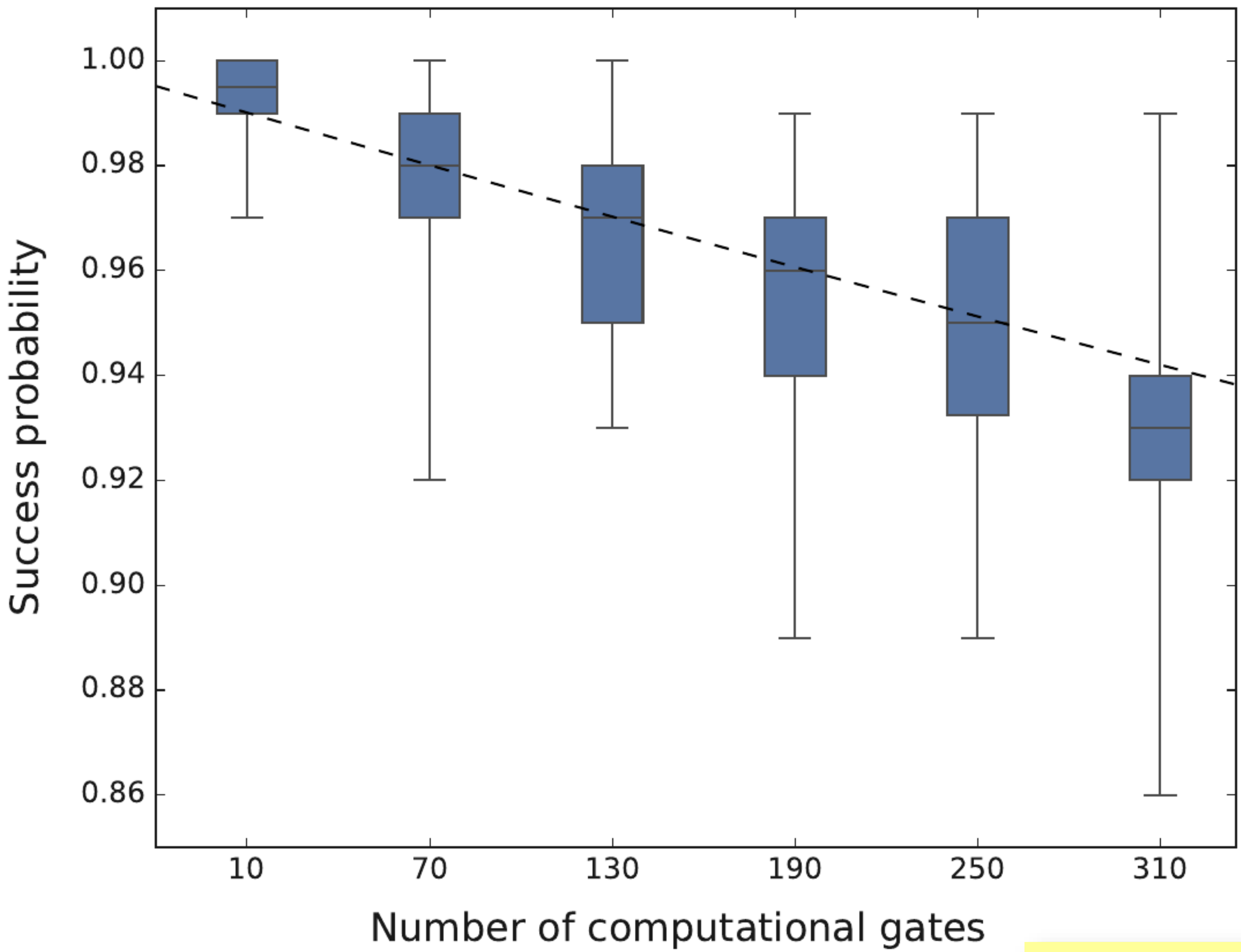
- Average over all sequences of length *M*, ideal circuit does nothing
- Average probability of obtaining a fixed outcome is

$$F_M = Ap^M + B$$

scalable estimate of p is directly related to the average gate infidelity r due to average error E under robust conditions

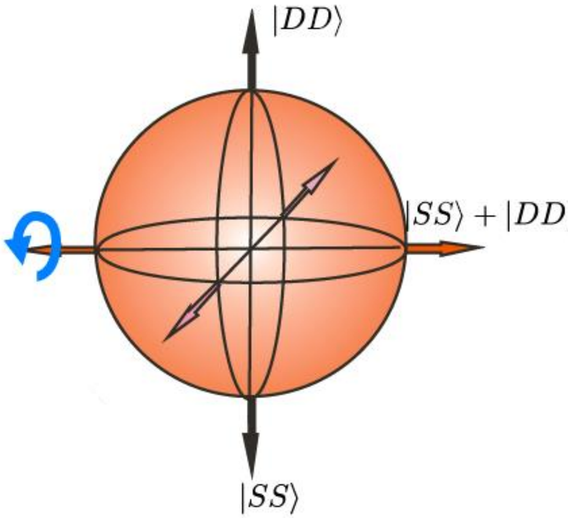
Emerson et al, J. Opt. **B 7**, S347 (2005); Knill et al. Phys. Rev. A **77**, 012307 (2008); Magesan et al. Phys. Rev. Lett. **106**, 180504 (2011).

Single qubit operations

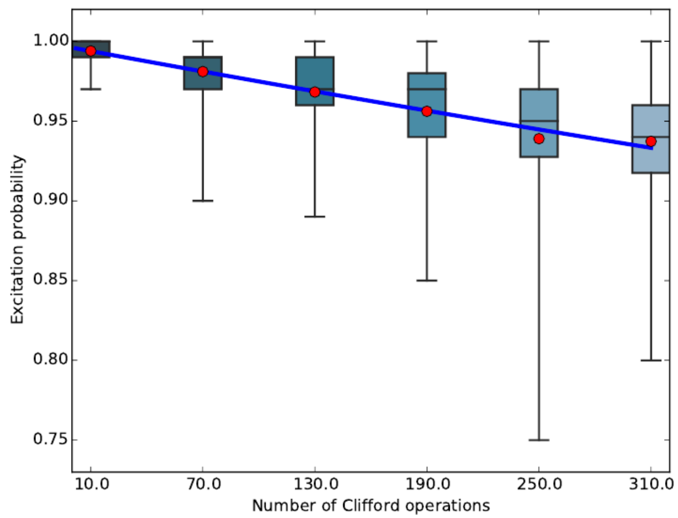


$F_{cliff} = 21(2) \cdot 10^{-5}$

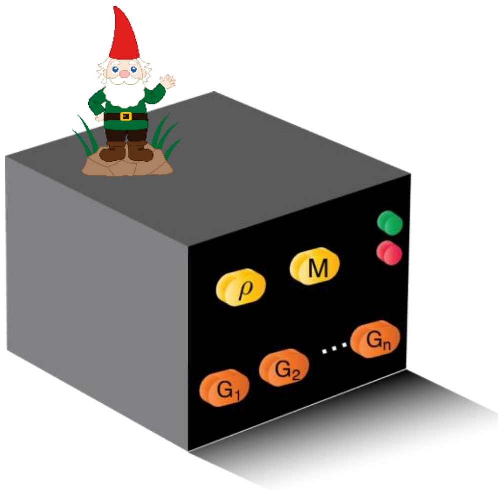
Benchmarking entangling operations



GHZ state fidelity



Randomized benchmarking



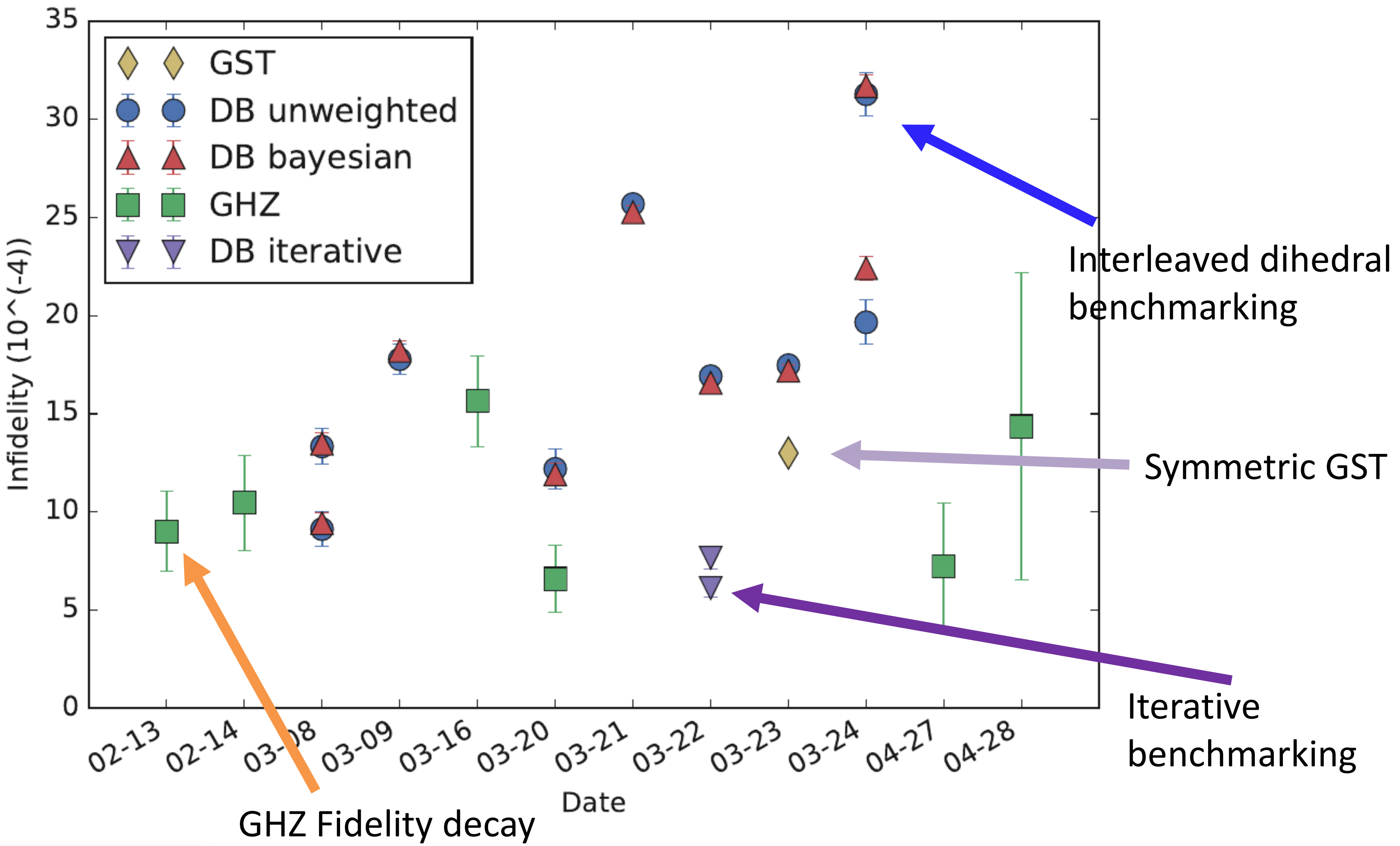
Gate set tomography

Fast

Tedious

Do I want to do this?

Entangling operations



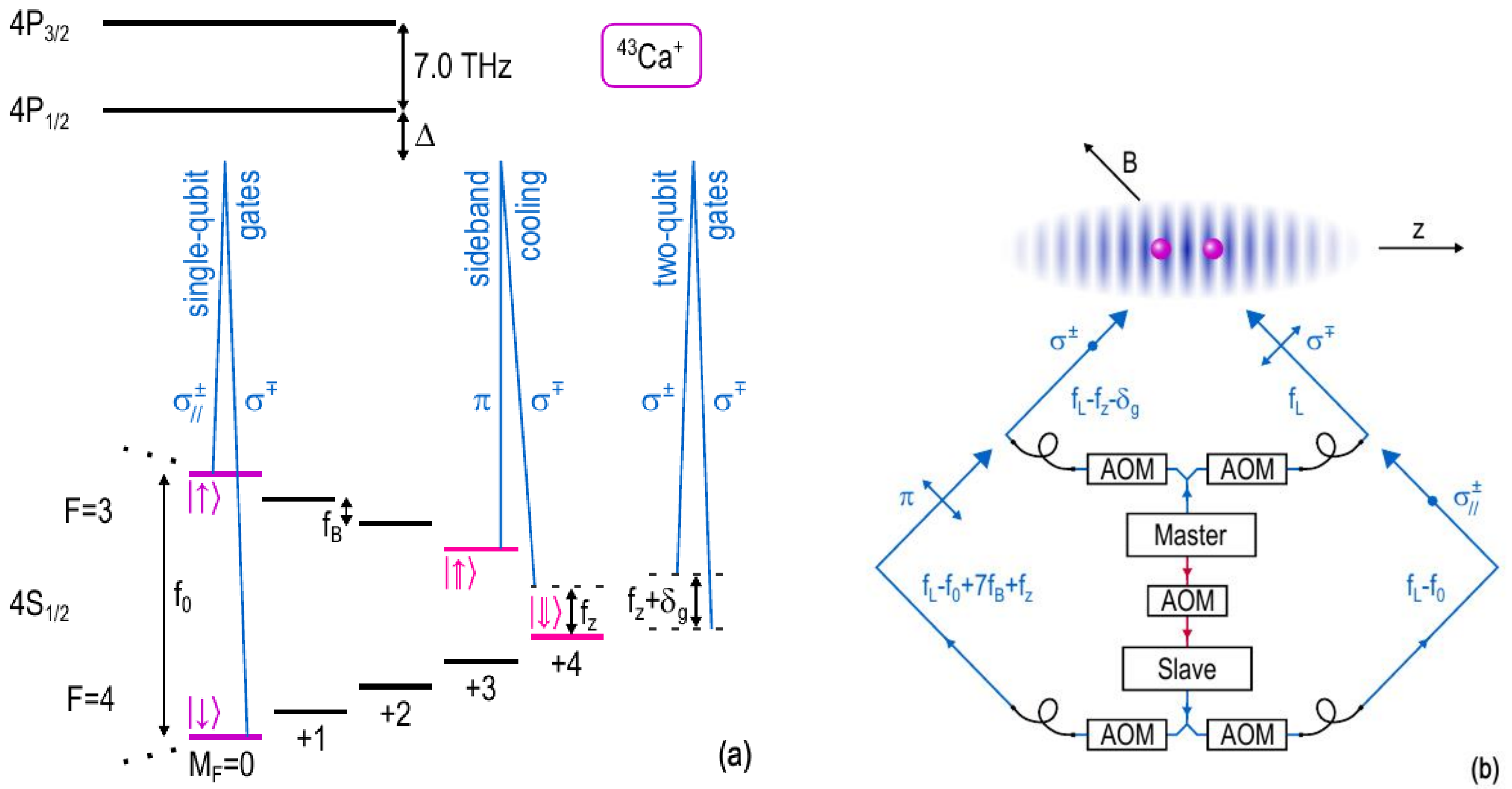
Preliminary

Error budget for entangling operation

Two-loop Mølmer Sørensen gate in Ca ions

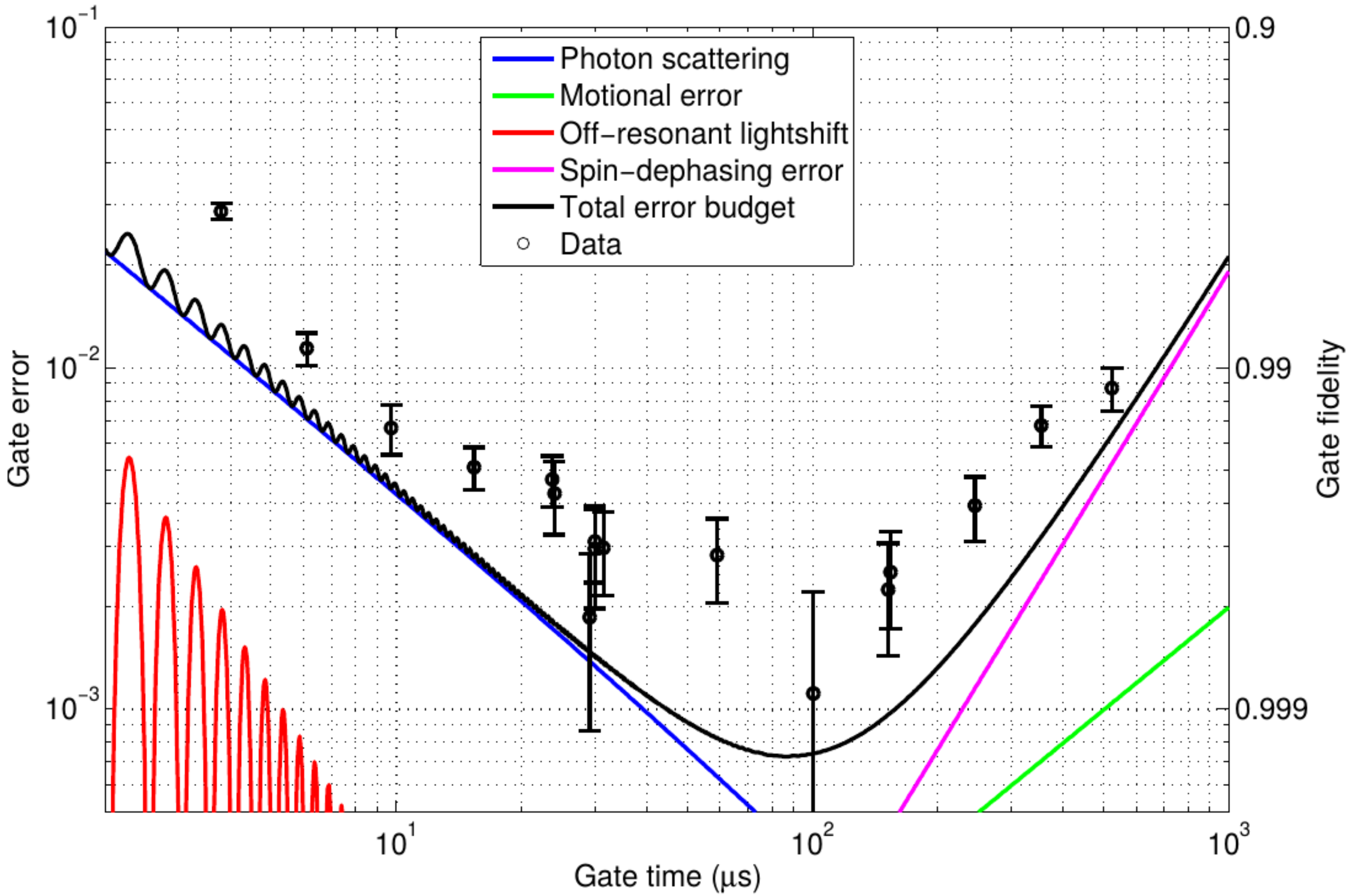
Error type	Current (10^{-4})
Unequal illumination	< 1
Thermal occupation	< 1
Heating	< 1
Motional dephasing	1.5
Spontaneous decay	1.1
Spin dephasing	3.1
Laser intensity noise	1.9
Total	**< 8.5**
Measured (mean over dihedral benchmarking)	**15(6)**

Entangling operations in hyperfine qubit



C. Balance PhD thesis (Oxford)

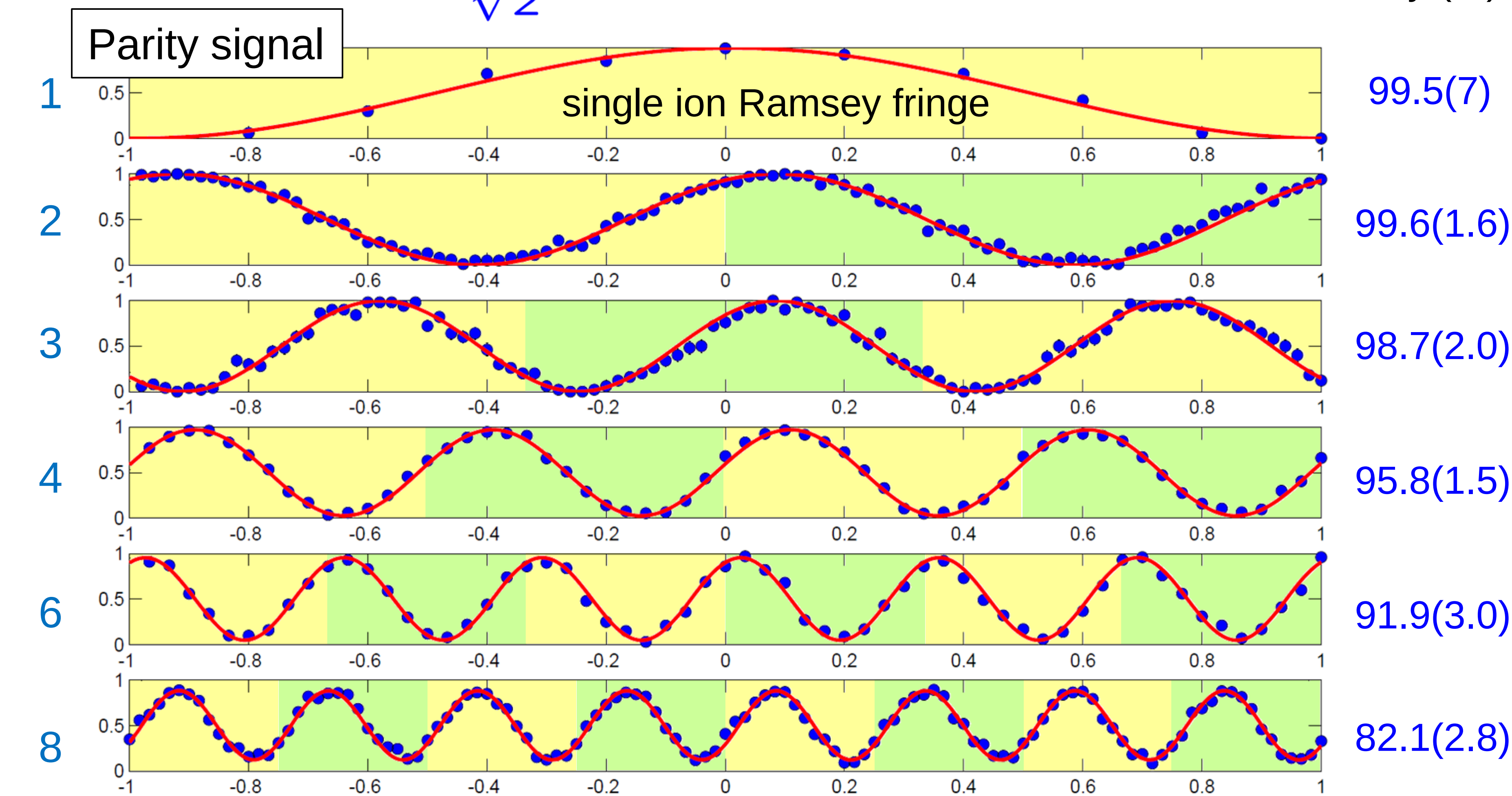
Entangling operations in hyperfine qubit



D. Lucas, C. Balance (Oxforfd)

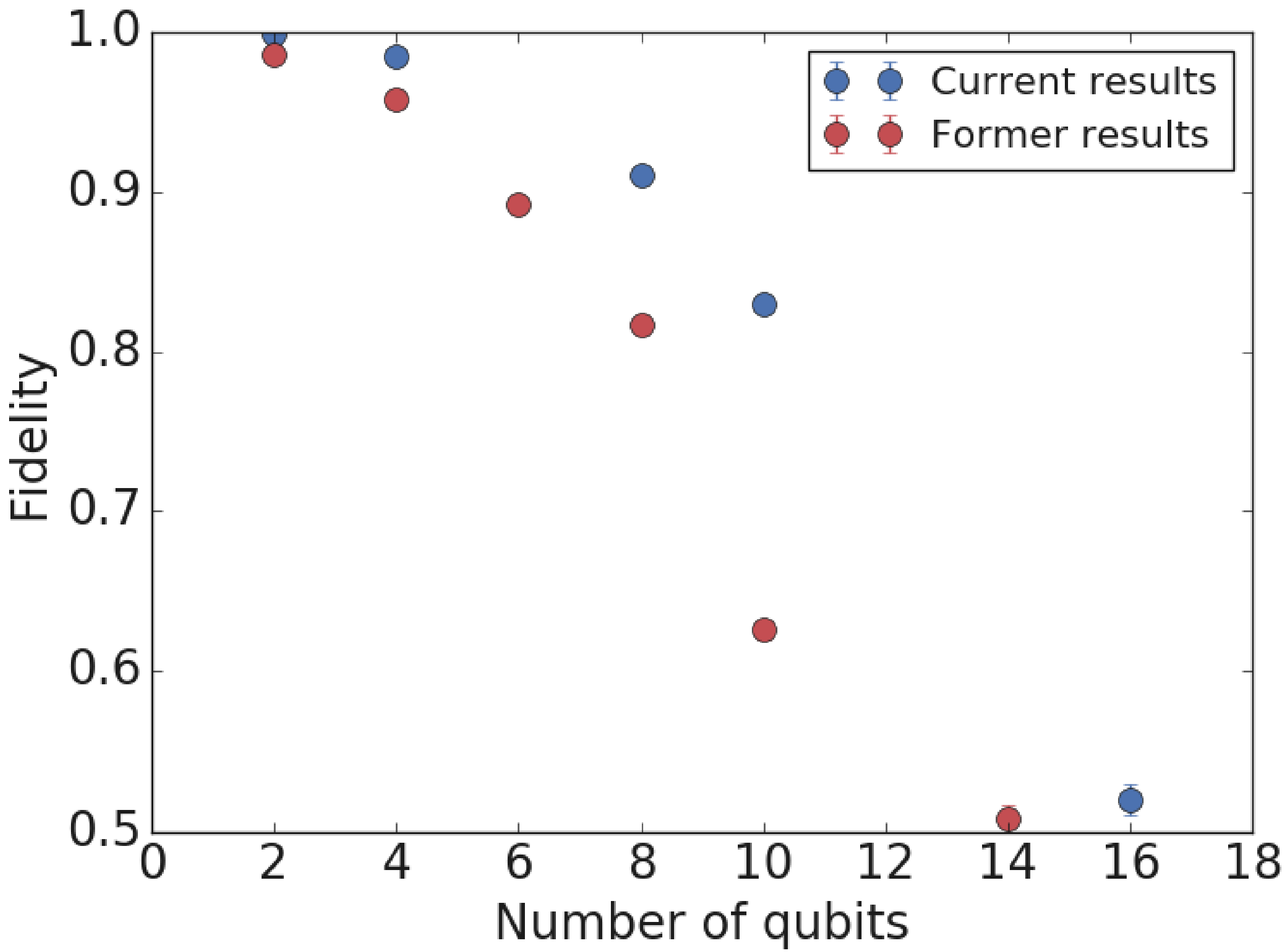
GHZ state fidelity vs register size

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

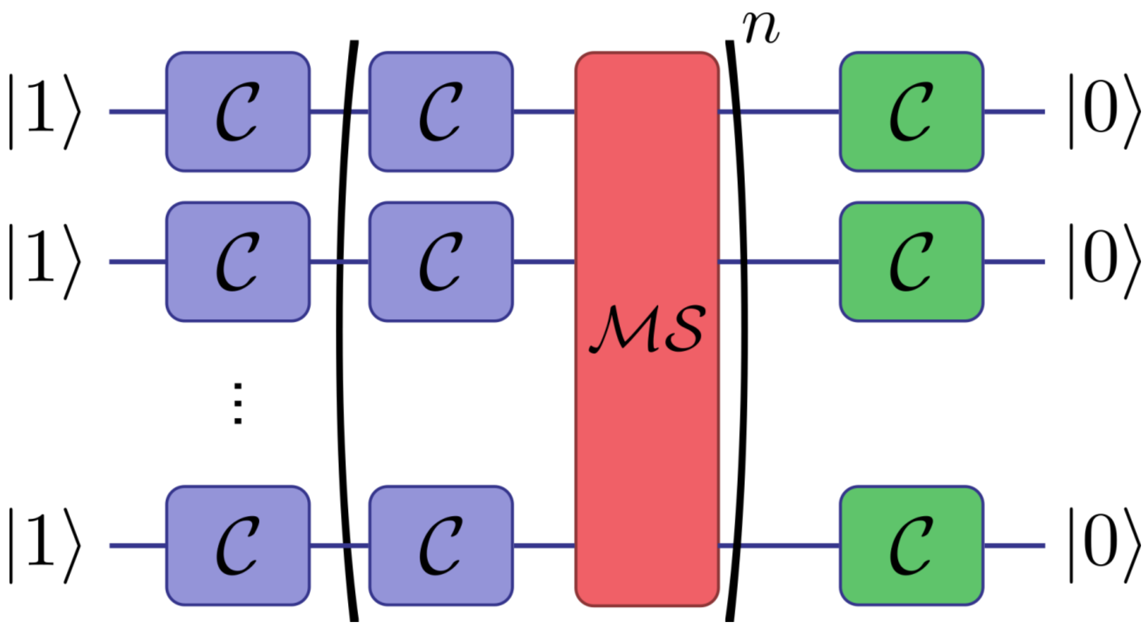


T. Monz et al., *PRL.* **106**, 130506 (2011).

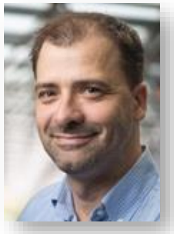
GHZ state fidelity



Multi-qubit benchmarking



J. Wallman



J. Emerson

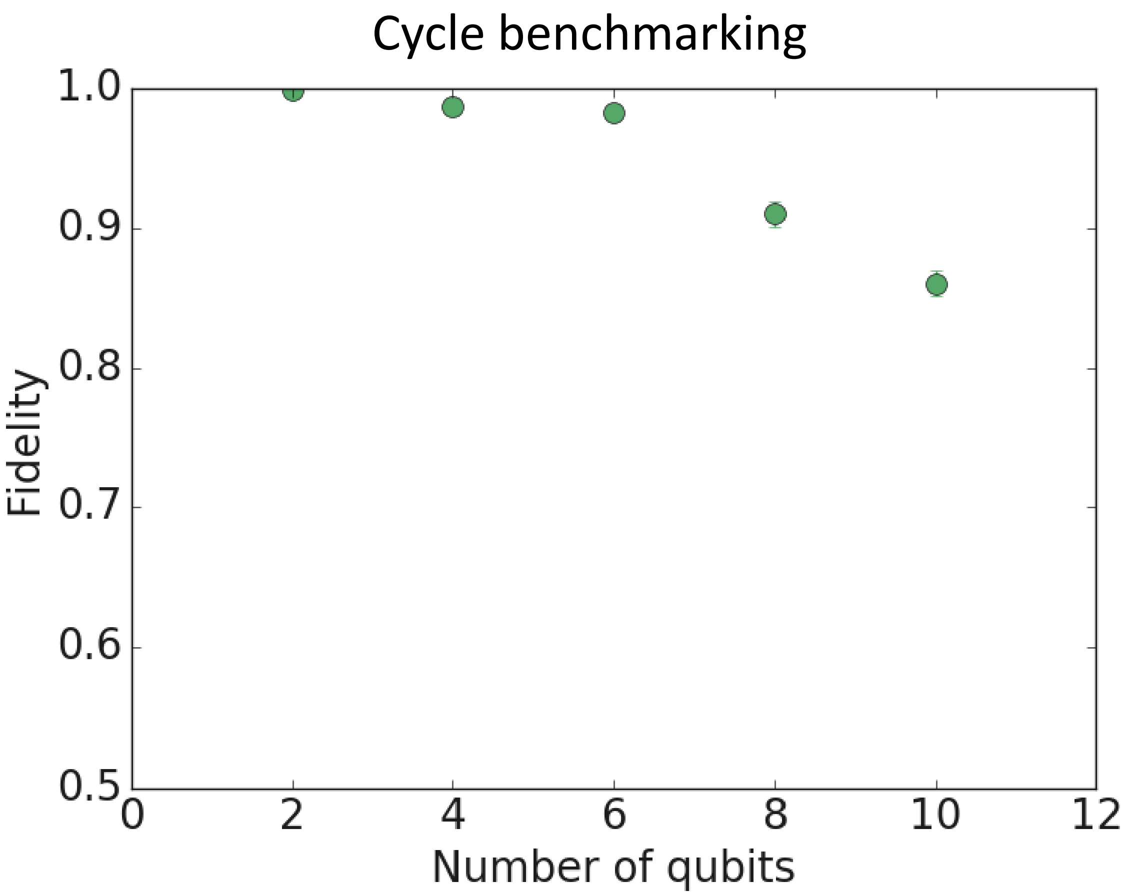
S. Flammia

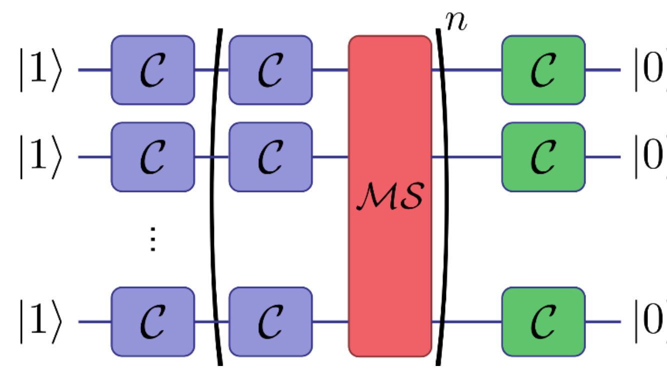
Combine ideas from

- Randomized benchmarking
- Compressed sensing
- Model testing

A scalable and robust benchmarking technique with **local twirling**.

Multi-qubit benchmarking





# of qubits	Fidelity
2	0.9982(7)
4	0.987(2)
6	0.982(4)
8	0.91(2)
10	0.86(2)

Estimated entangling gate fidelity from interleaved benchmarking experiments.

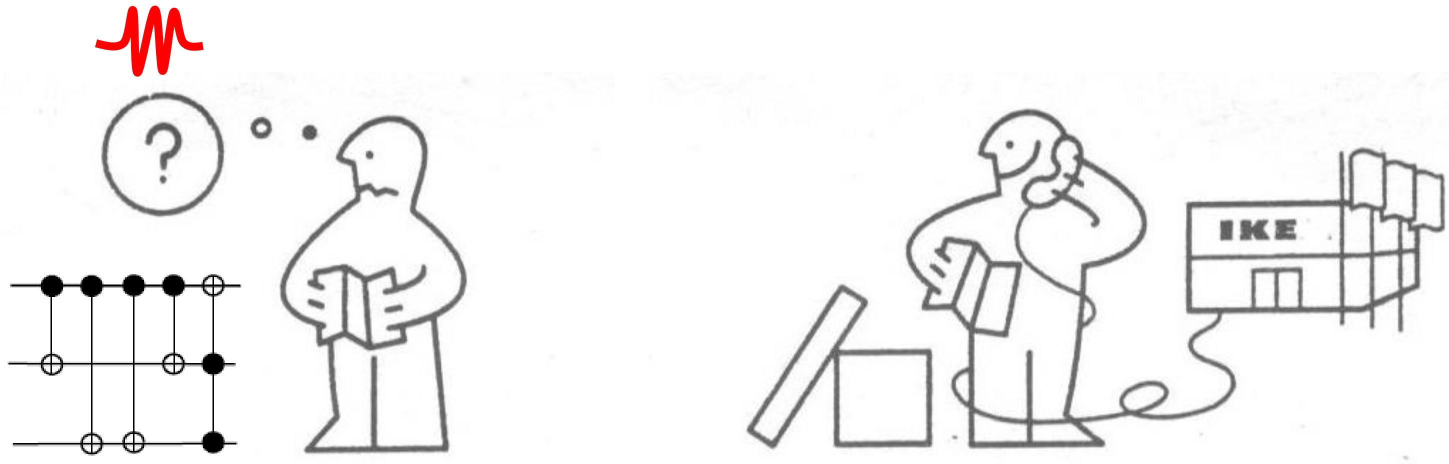
Preliminary data

Outline

- Implementing algorithms
- Scalable techniques and traps
- Quantum communication in ion traps
- Quantum logic for metrology
- Quantum tomography

Implementing algorithms

We have a universal set of operations



But how should we implement a certain algorithm?

Previously used gradient ascent search algorithm is not well suited for our set of operations

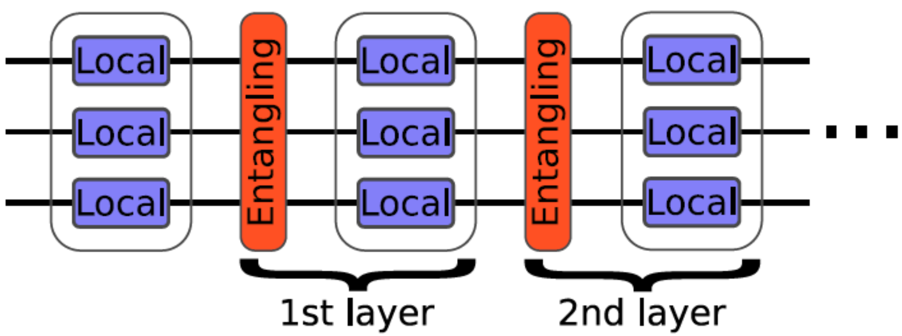
V. Nebendahl et al., Phys. Rev. **A 79**, 012312 (2009)

Quantum “compiling”

Set of operations:

$$\{Z_n, Z_C, C_x, C_y, C(\theta,\phi), MS_x, MS_y, MS(\theta,\phi)\}$$

procedure:



(1) Propose sequence with n=0 entangling gates
(2) Search numerically for sequence parameters that maximize the fidelity with the target unitary
(3) if converging -> STOP ELSE n-> n+1

write arbitrary unitaries as:

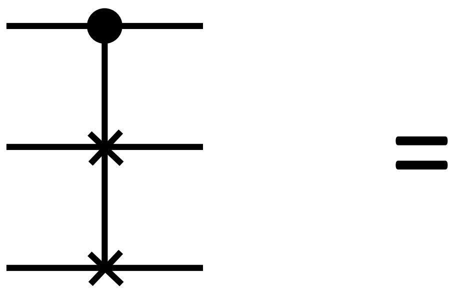
$$U = L_n MS_{\phi_n}(\alpha_n)\ldots L_2 MS_{\phi_2}(\alpha_2) Z_1 MS_{\phi_1}(\alpha_1) L_0$$

with local operations L_i

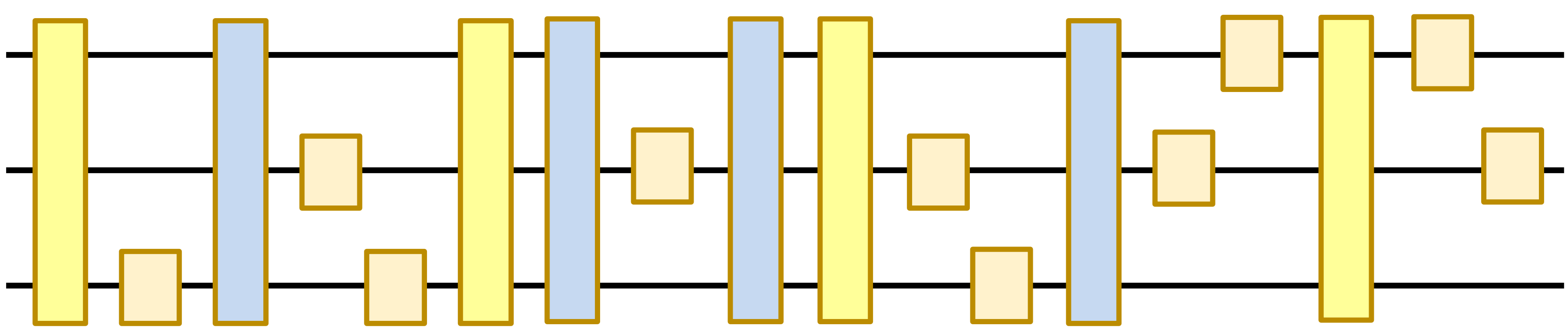
$$U$$

E. Martinez et al., arXiv:1601.06819

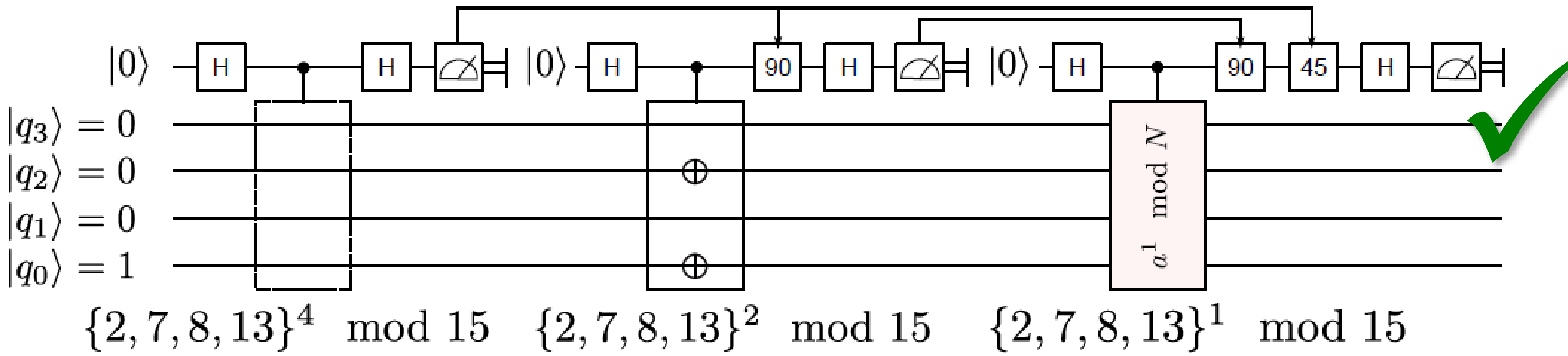
A compiled Fredkin gate

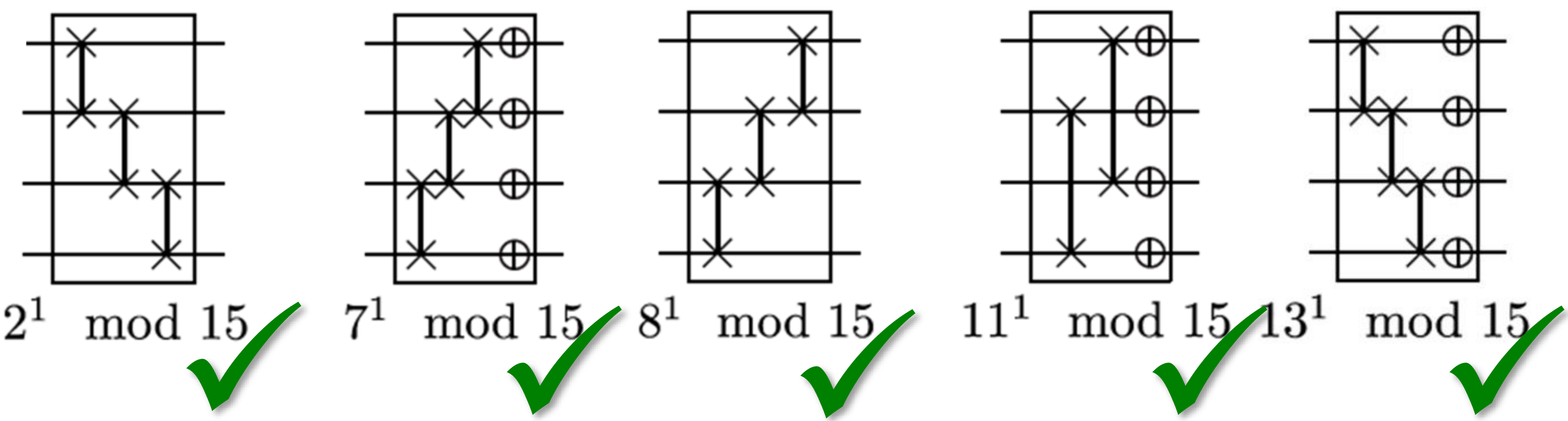


Pulse Nr.	Pulse	Pulse Nr.	Pulse
1	$R(1/2, 1/2)$	10	$R(1/2, 1)$
2	$S_z(3/2, 3)$	11	$S_z(1/4, 2)$
3	$MS(4/8)$	12	$S_z(3/2, 3)$
4	$S_z(3/2, 2)$	13	$MS(4/8)$
5	$S_z(1/2, 3)$	14	$S_z(3/2, 2)$
6	$R(3/4, 0)$	15	$S_z(3/2, 1)$
7	$MS(6/8)$	16	$R(1/2, 1)$
8	$S_z(3/2, 2)$	17	$S_z(3/2, 1)$
9	$MS(4/8)$	18	$S_z(3/2,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



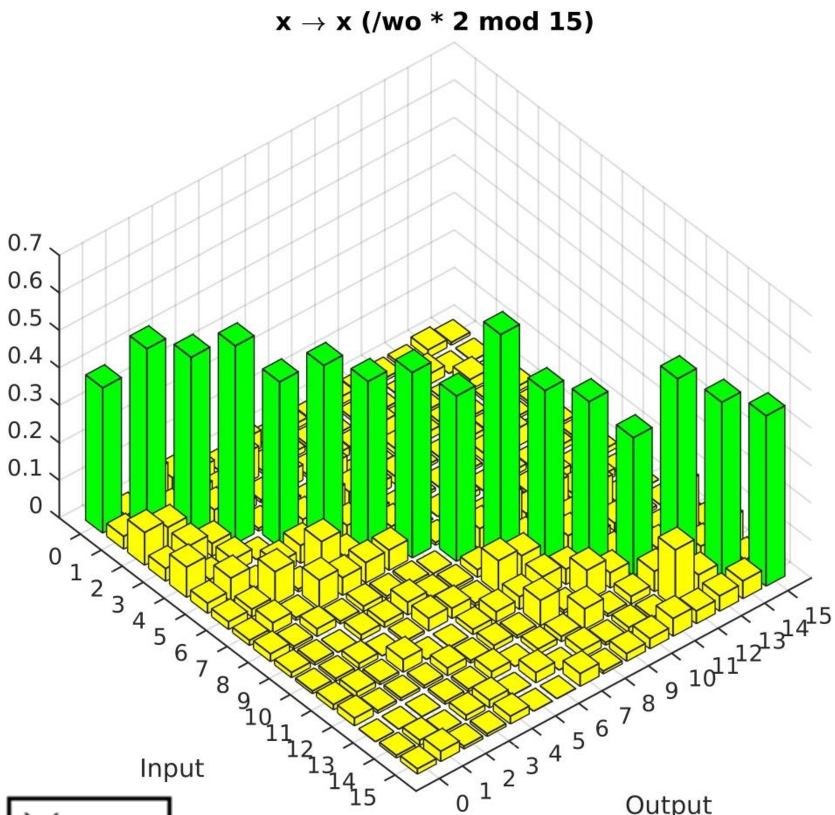
Modular exponentiation

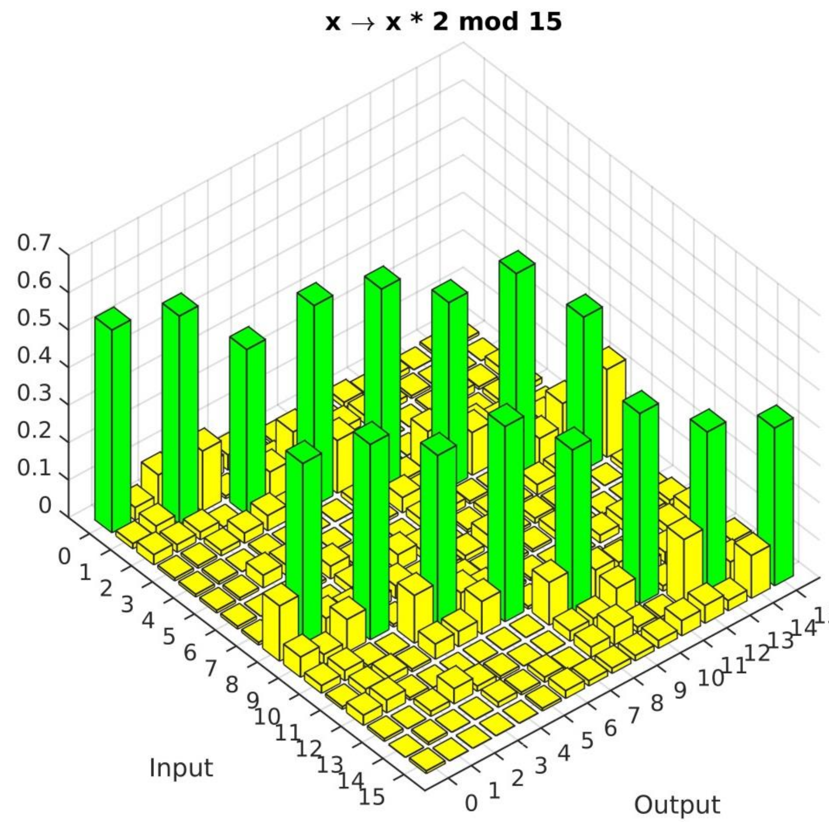


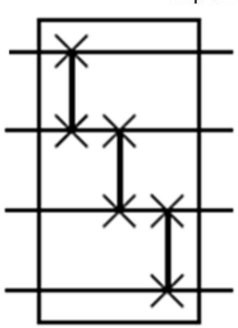


T. Monz et al, Science 351, 1068 (2016)

Modular exponentiation





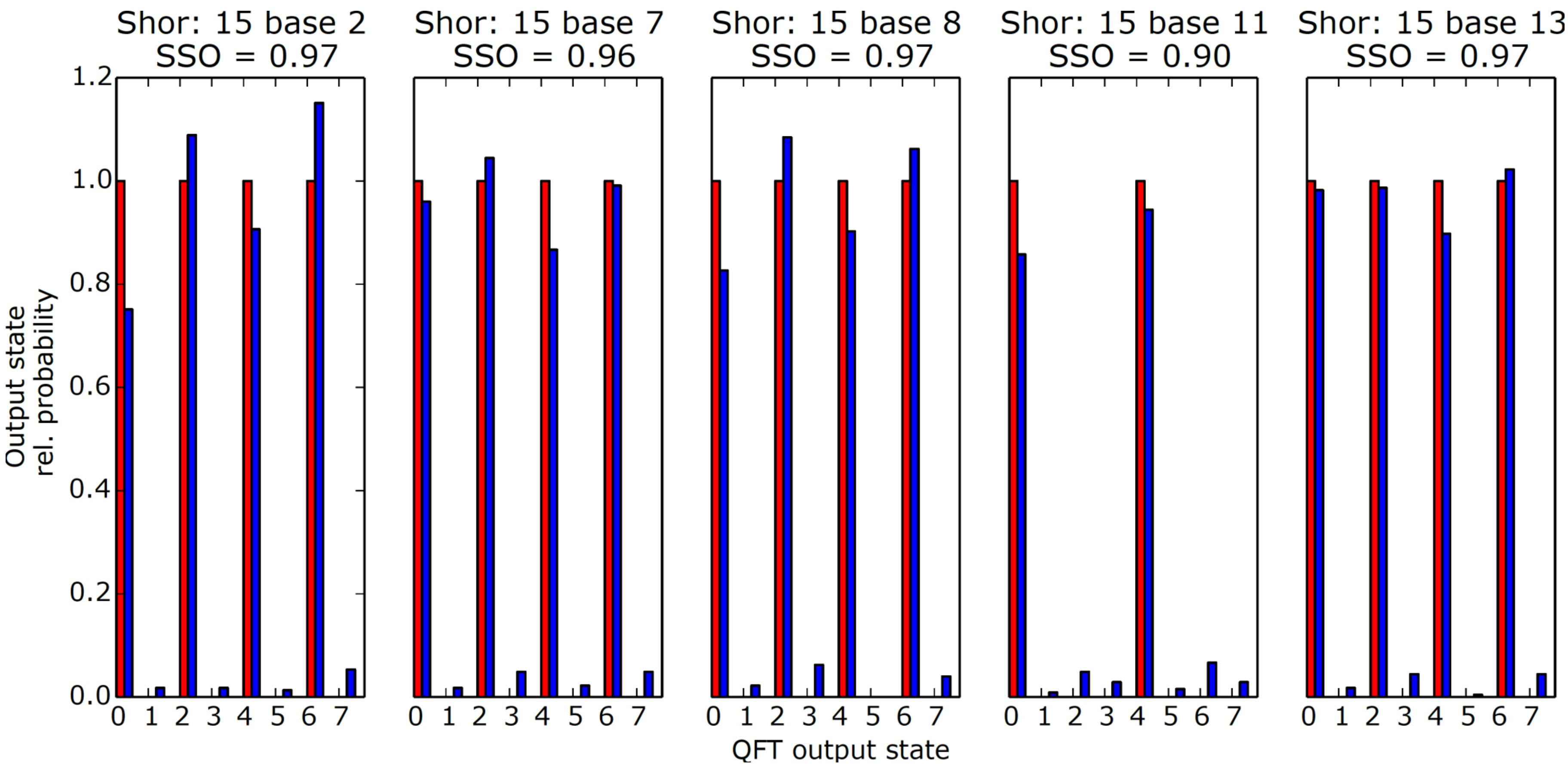


$2^1 \mod 15$

Fidelity: x*2 mod 15 @ 48(5) %
3x Fredkin (23,34,45) @ 37(6) %

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)}

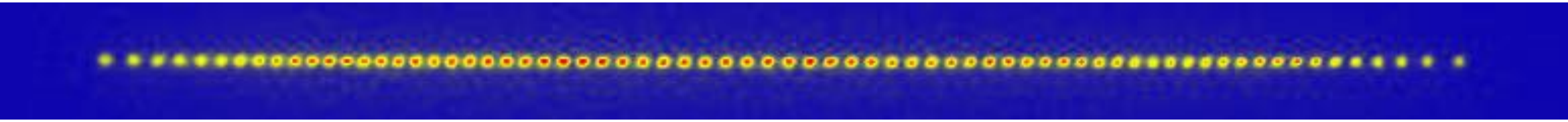
Confidence @ 99% to obtain correct factors after 8 single-shots.

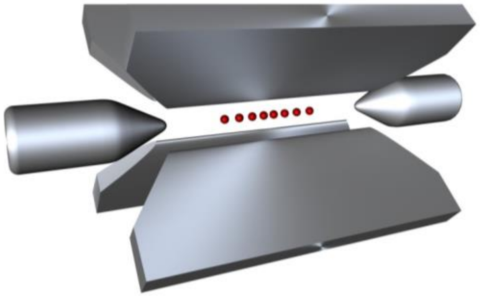
T. Monz et al, Science 351, 1068 (2016)

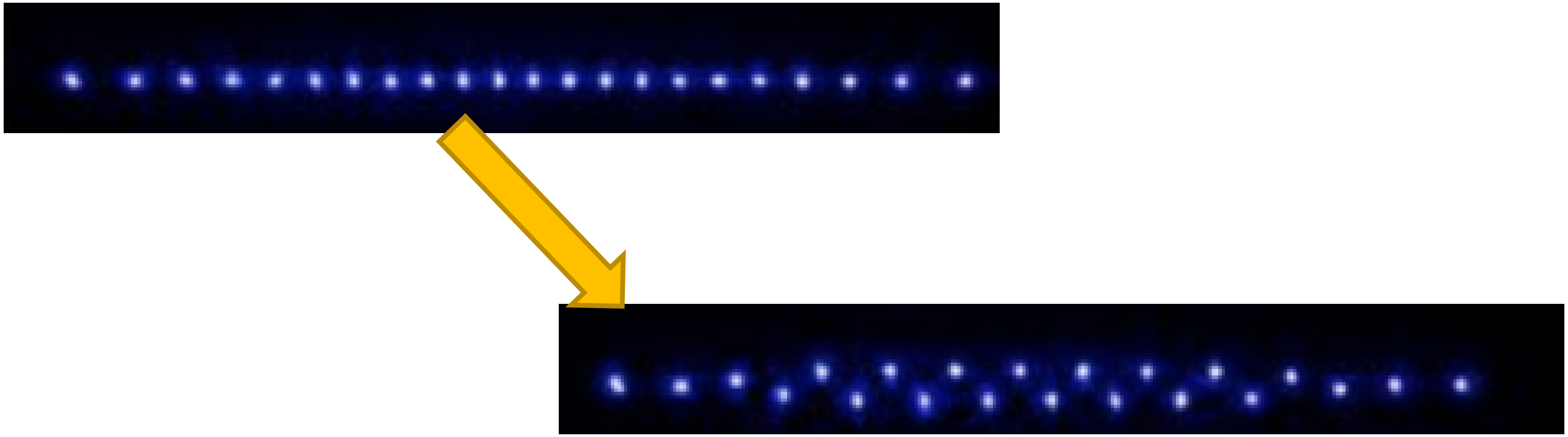
Outline

- Implementing algorithms
- Scalable techniques and traps
- Quantum communication in ion traps
- Quantum logic for metrology
- Quantum tomography

Are ion traps scalable?

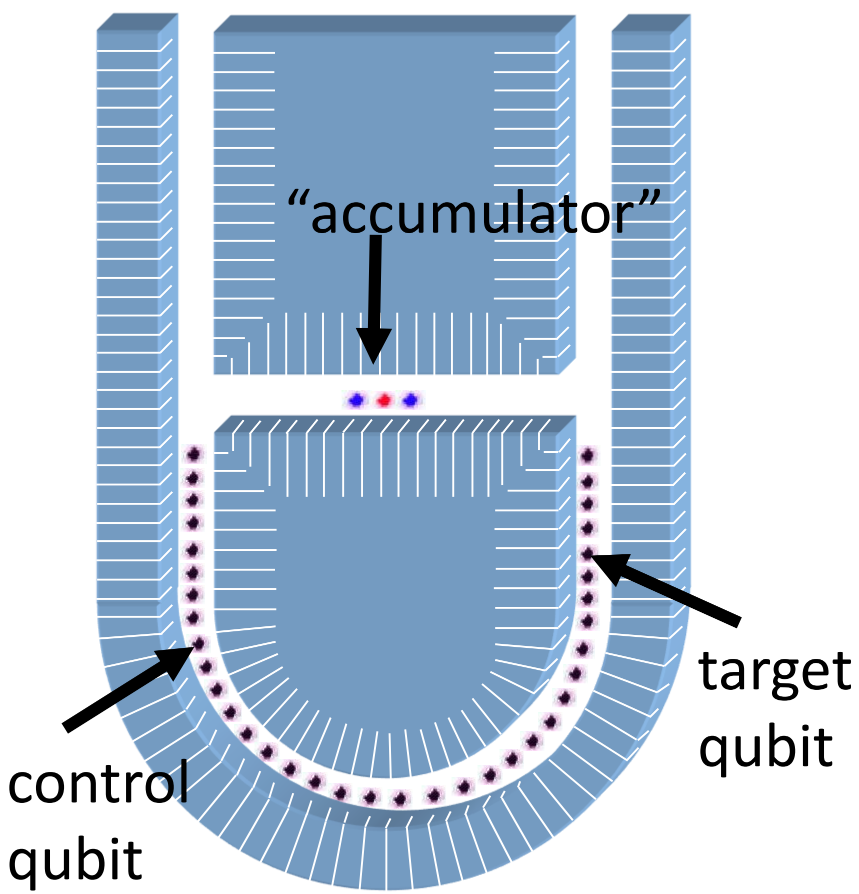


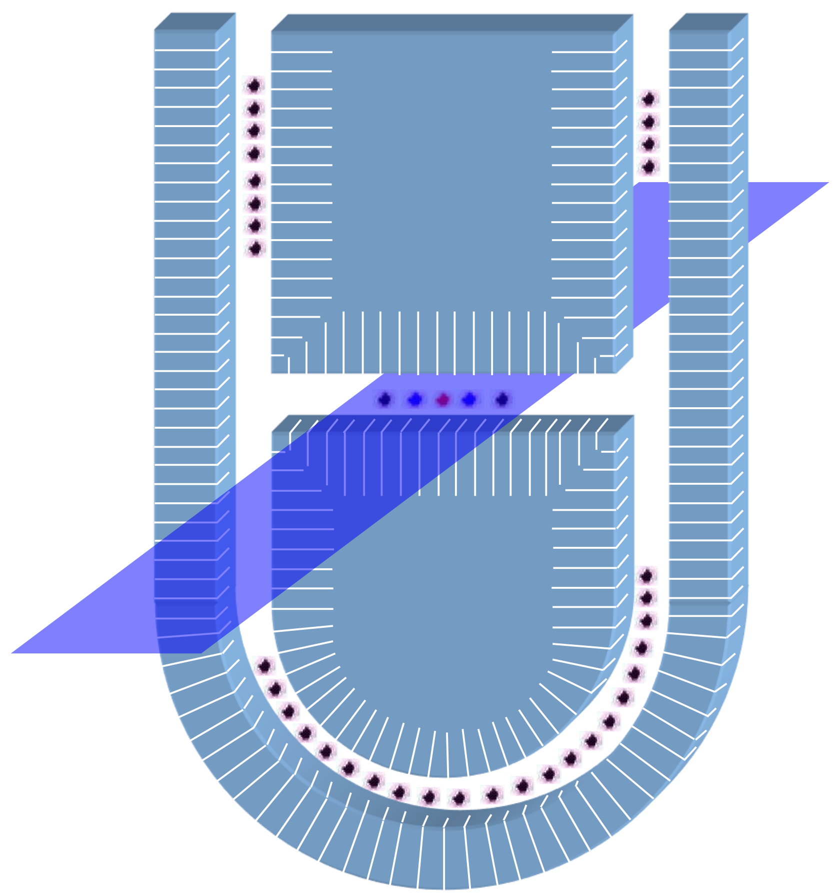




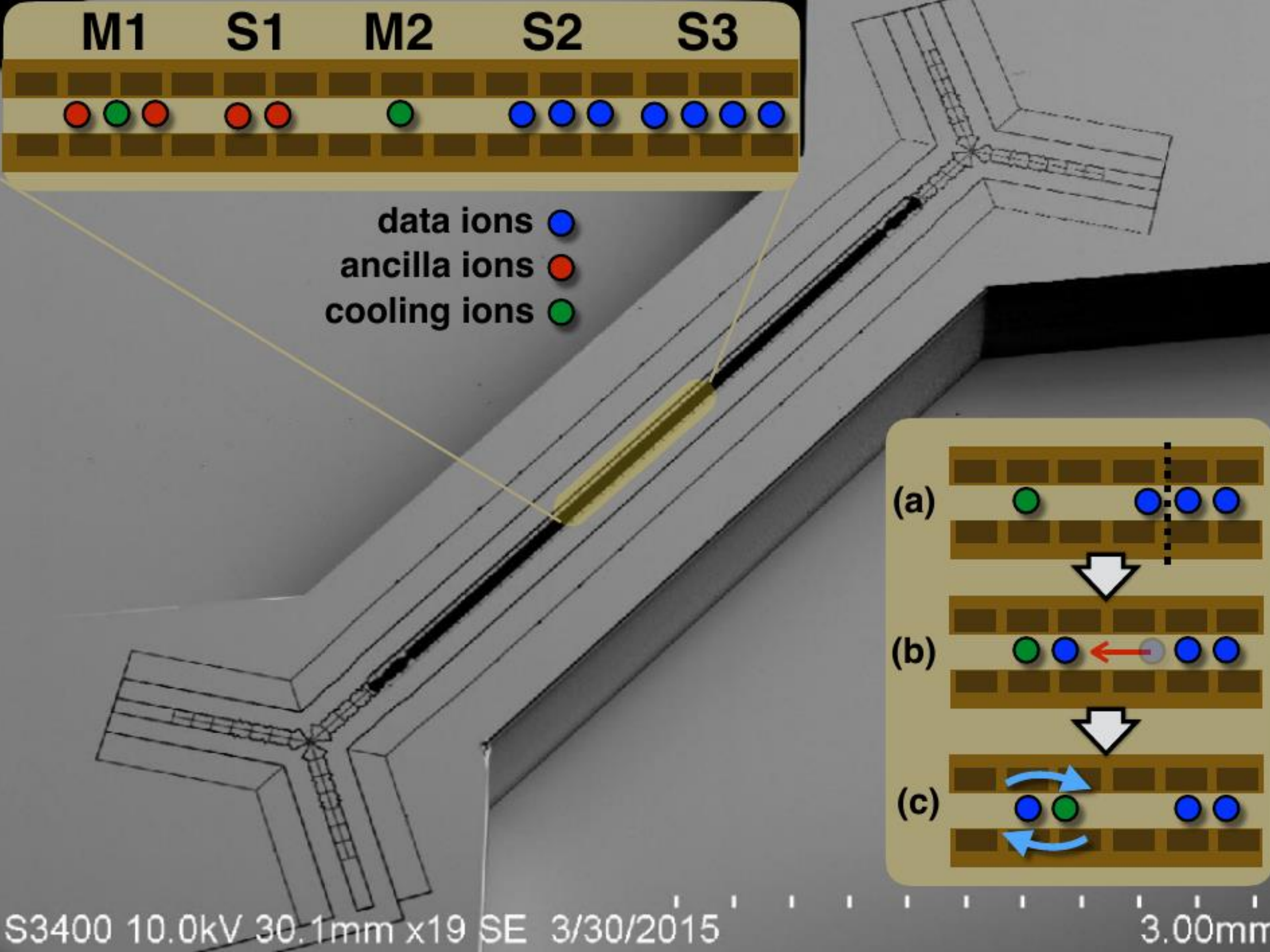
Ion shift register (CCD)

D. Wineland, Boulder, USA
Kieplinski et al, Nature 417, 709 (2002)

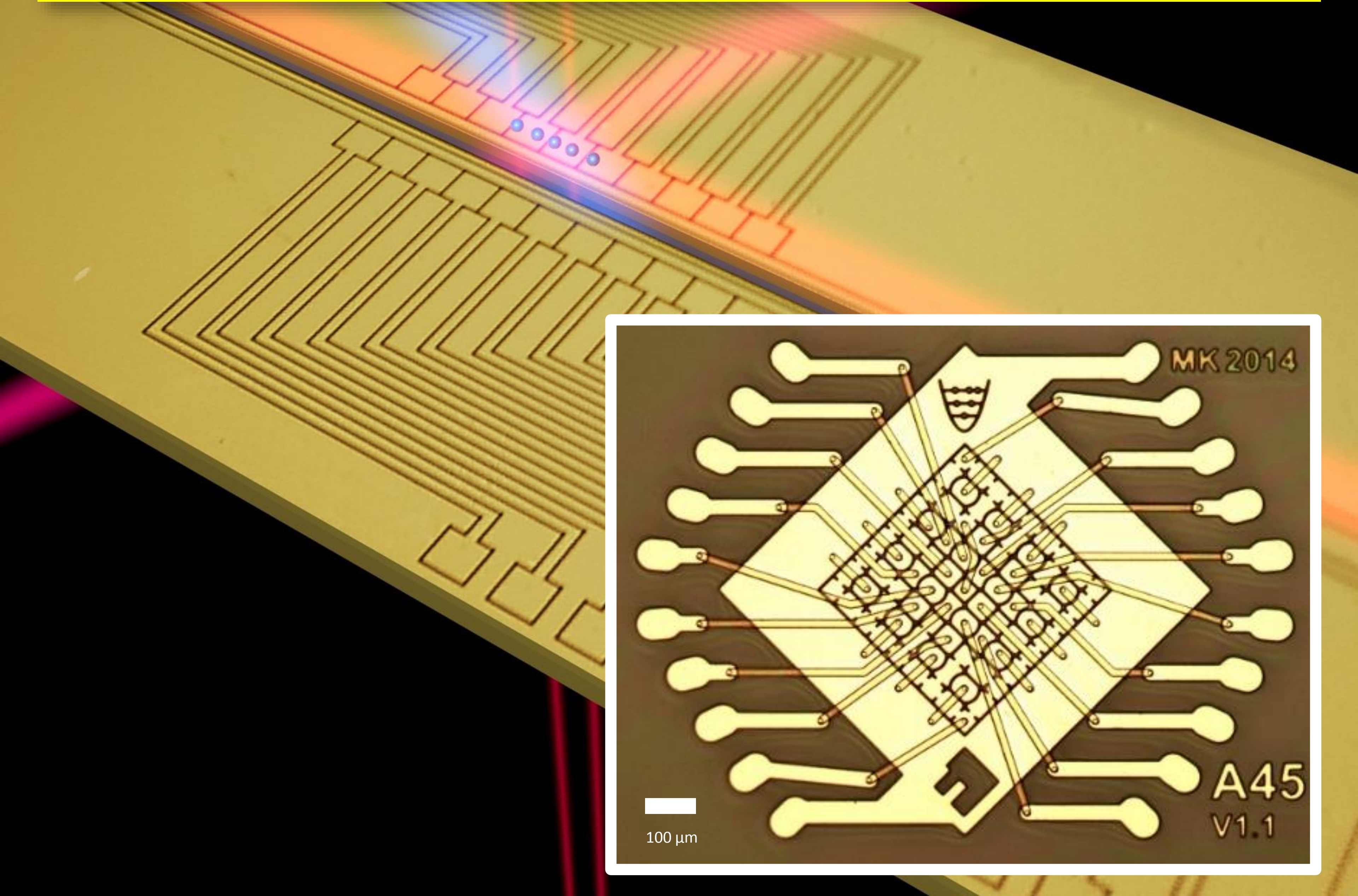




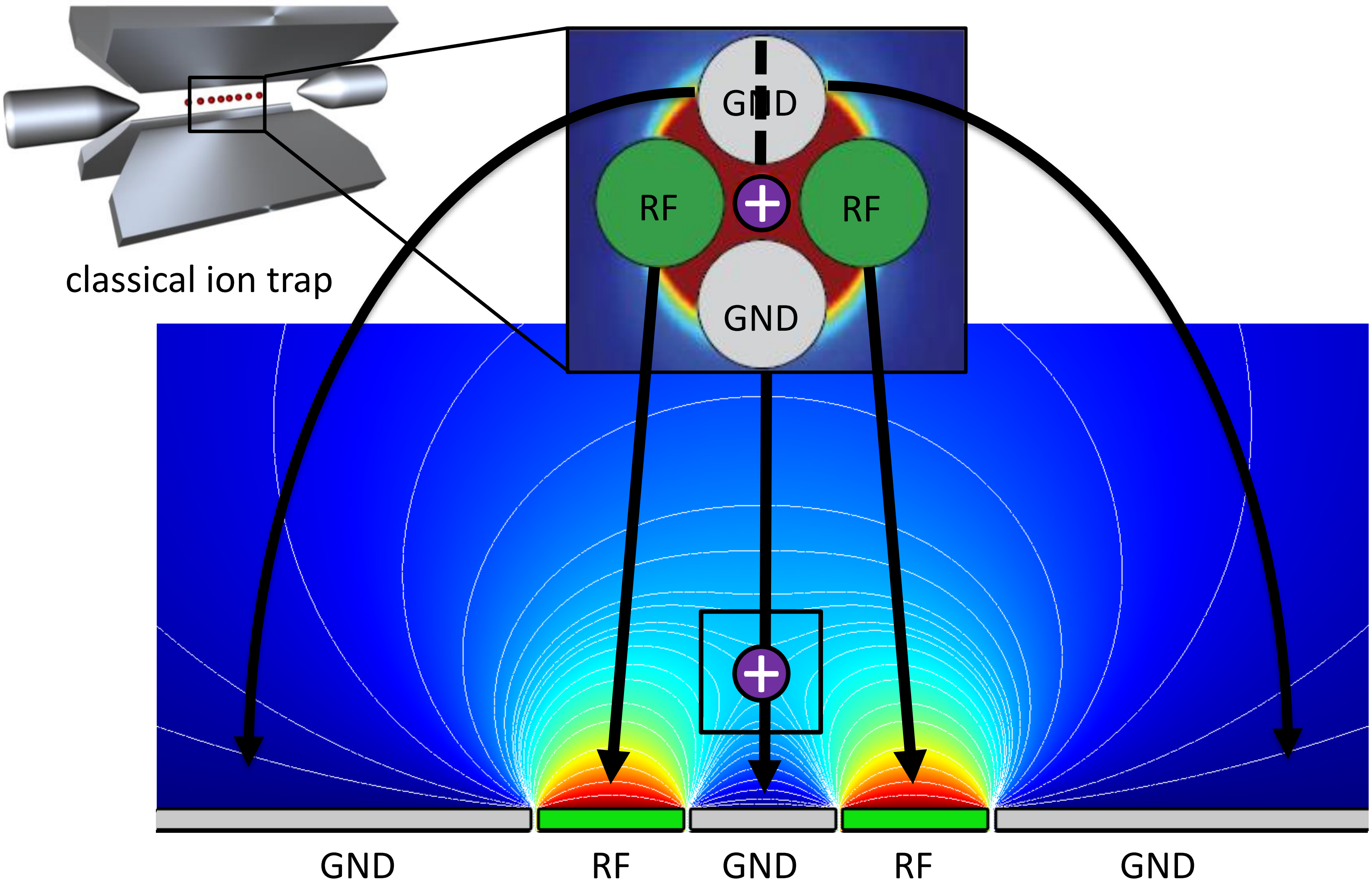
Requires electrode-ion distance in the order of 100µm


M1
S1
M2
S2
S3
data ions
ancilla ions
cooling ions
(a)
(b)
(c)
S3400 10.0kV 30.1mm x19 SE 3/30/2015
3.00mm

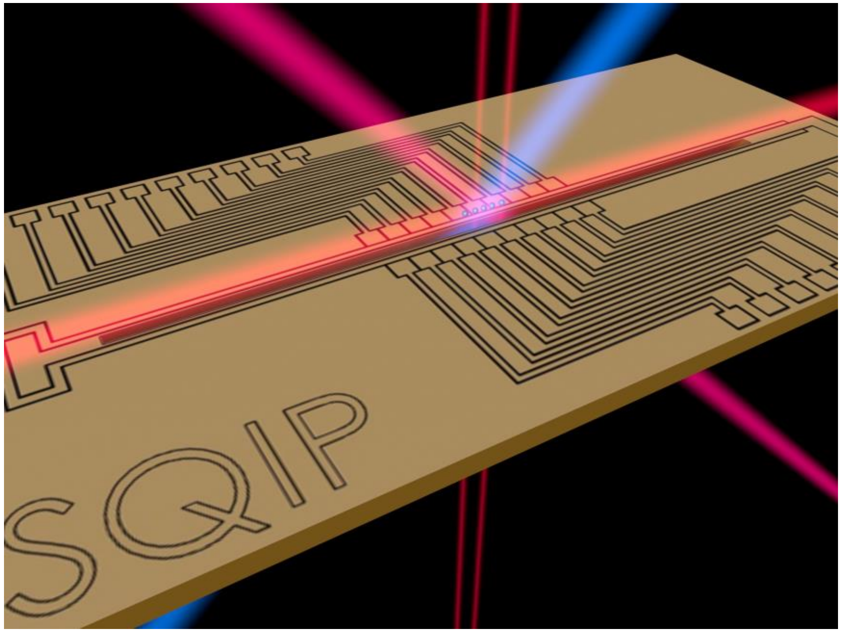
Scalable trap architectures



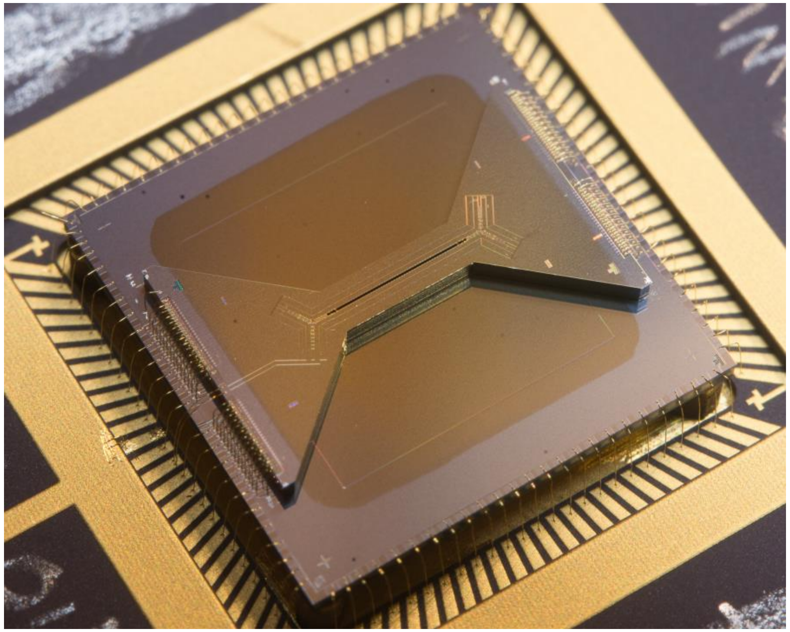
Planar ion traps



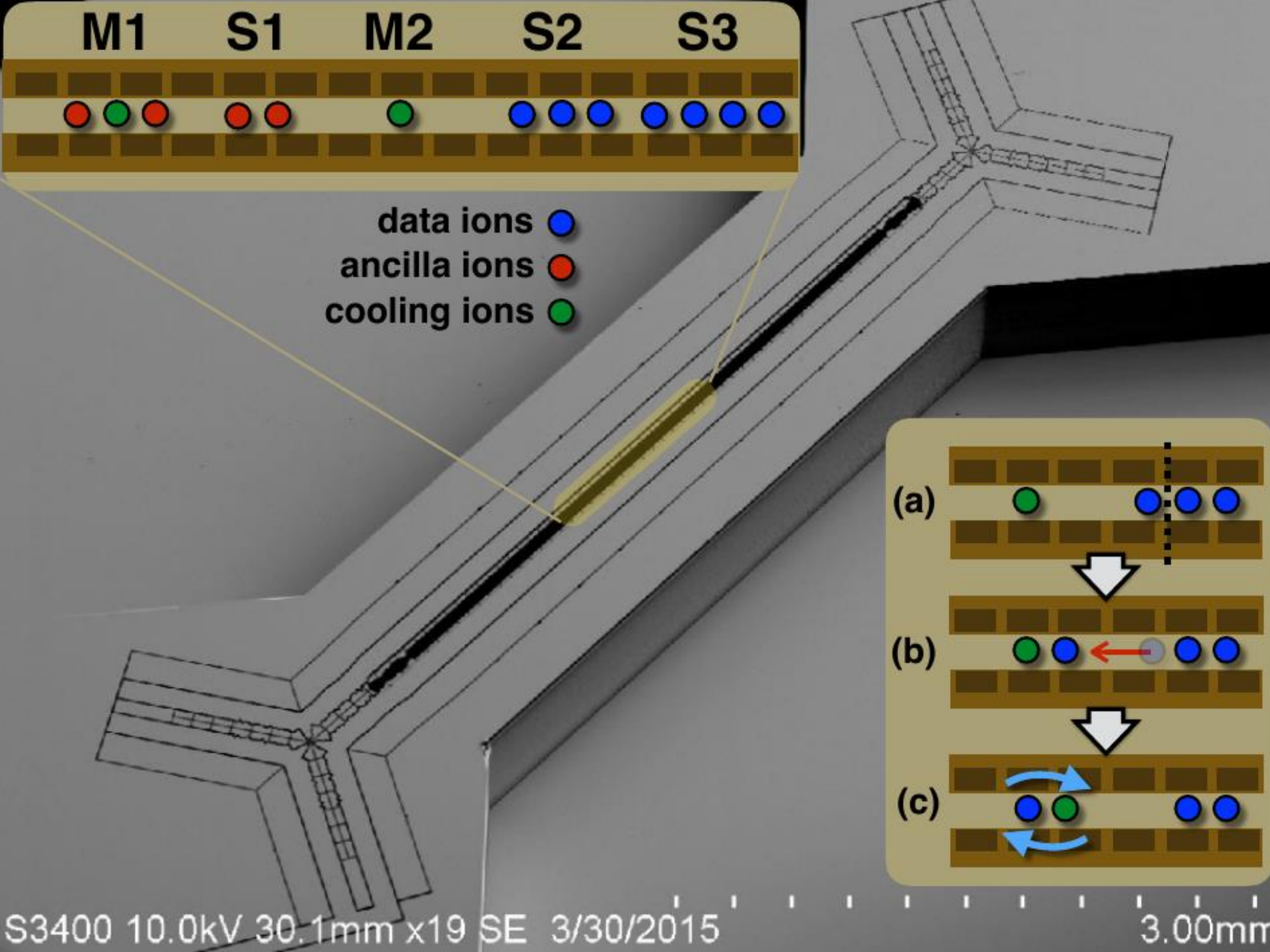
Planar ion traps

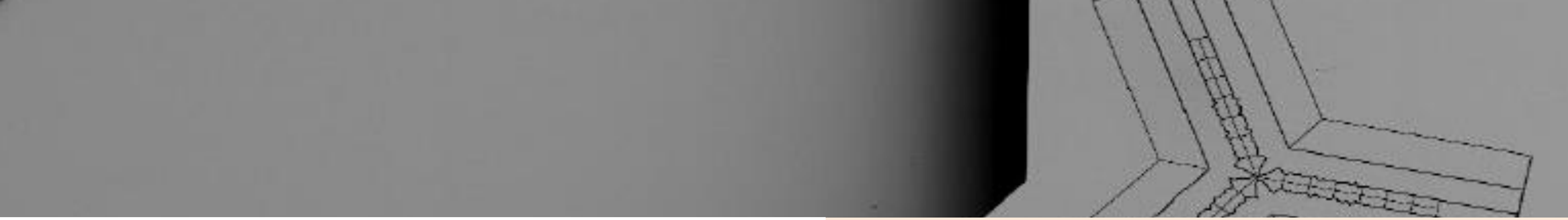


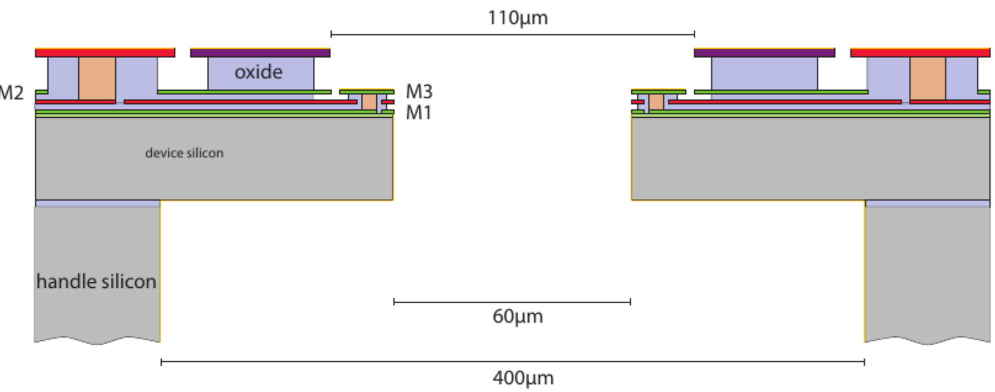
Innsbruck, Berkeley



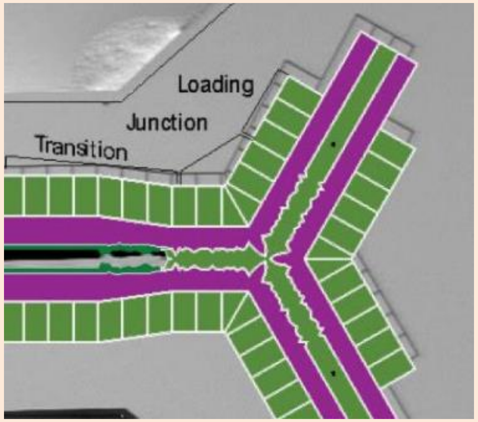
Sandia National Labs


M1
S1
M2
S2
S3
data ions
ancilla ions
cooling ions
(a)
(b)
(c)
S3400 10.0kV 30.1mm x19 SE 3/30/2015
3.00mm





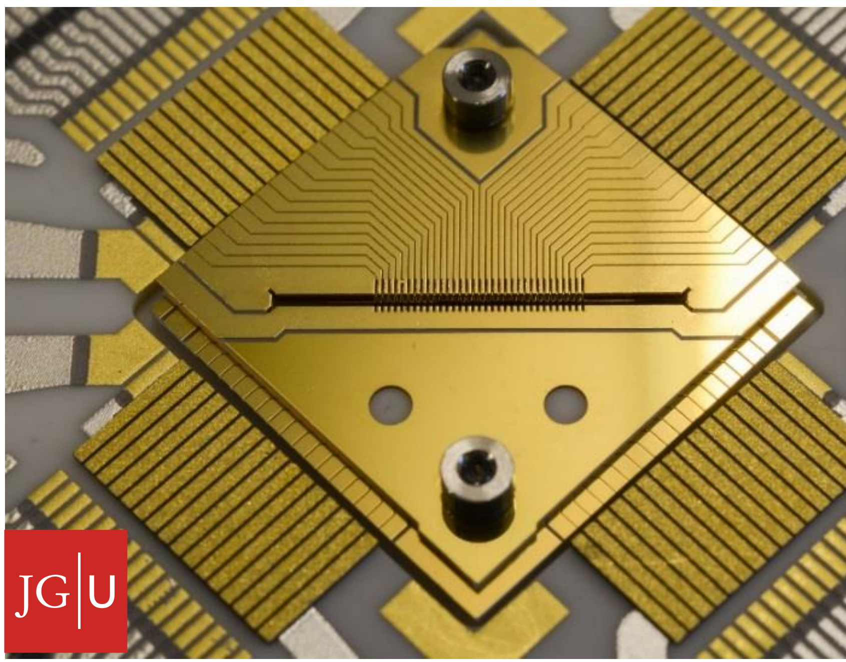
High optical access from 3 sides



Optimized electrode shape for shuttling through Y junctions

Sandia National Laboratories

Sandwich traps

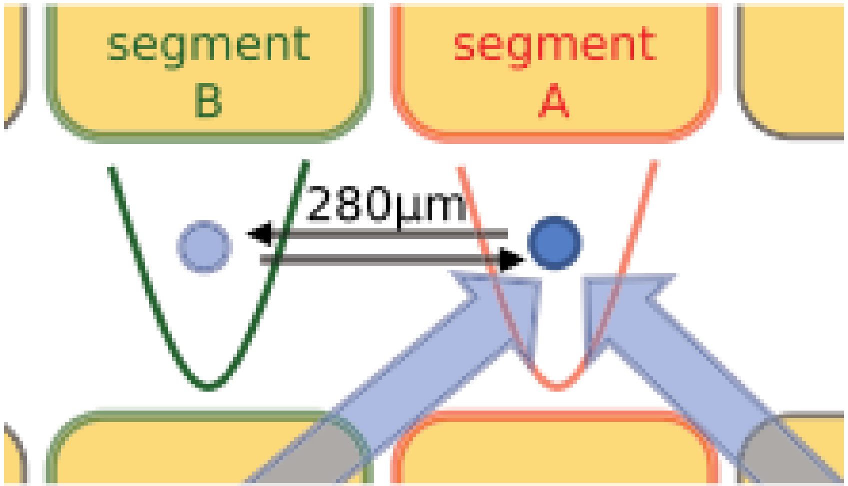


Fabrication
- Laser-cutting of alumina
- Gold evap./electro-plating
- 32 segment pairs of uniform geometry

Performance
- Harder to fabricate
- Alignment of layers critical
- Better cofinement
- Fabrication not scalable

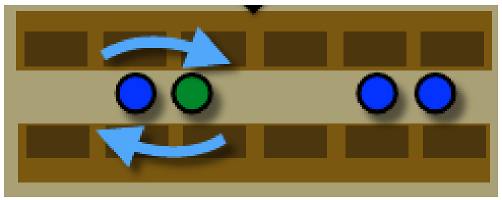
Group of F. Schmidt-Kaler, Mainz
Also: NIST, ETH, NPL

Ion transport

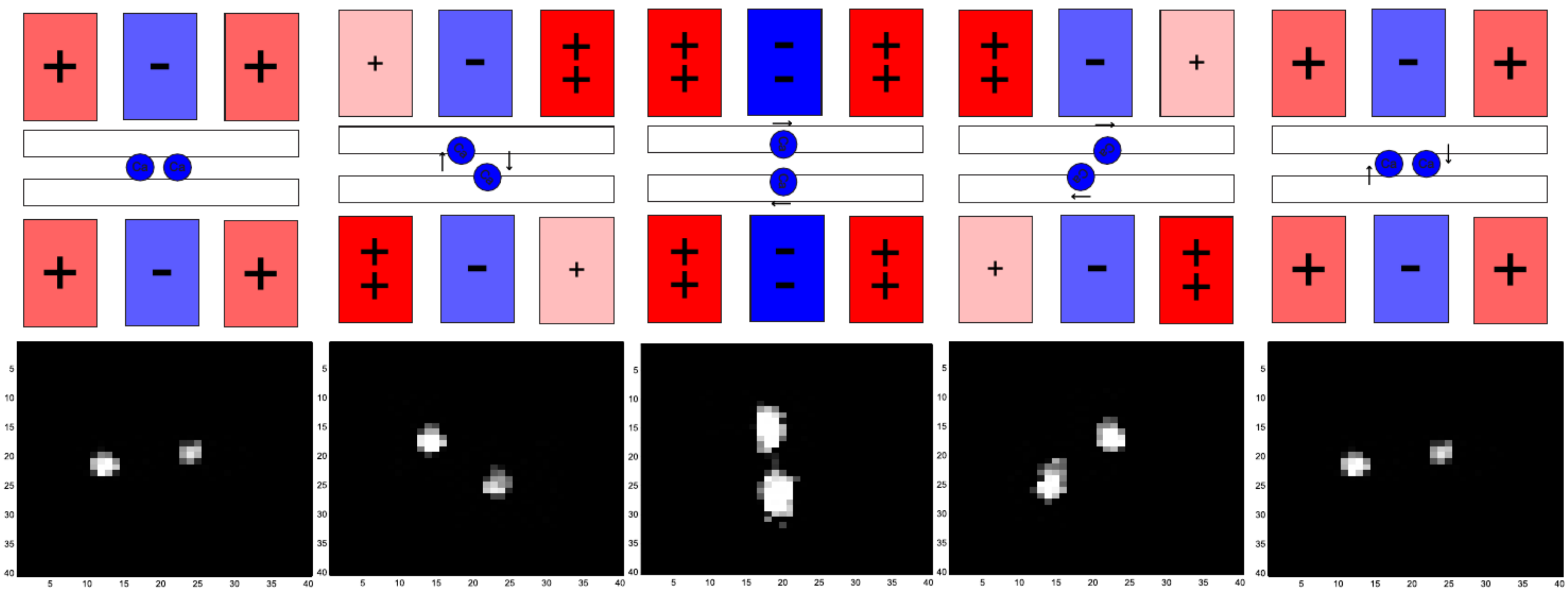


Walter et al, PRL109, 080501 (2012)
Bowler et al, PRL109, 080502 (2012)
Xiao et al, PRA 89, 063414 (2014)

Ion crystal rotation

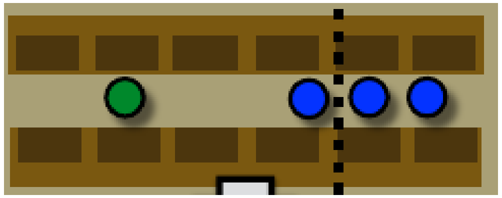


Crystal rotation enables reordering in a linear topology – **Less junctions required.**



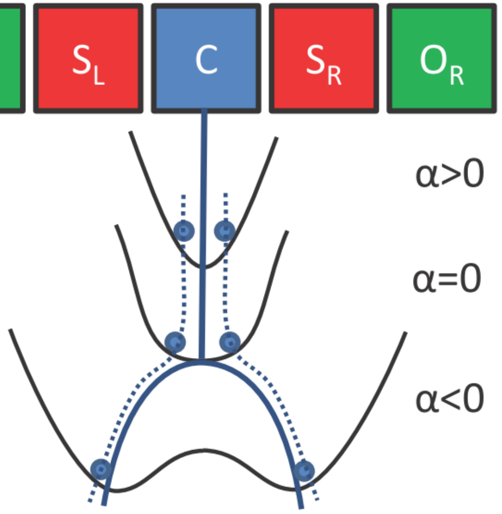
H. Kaufmann et al, PRA 95, 052319 (2017).

Ion crystal splitting



Transition from a single to a double well potential!

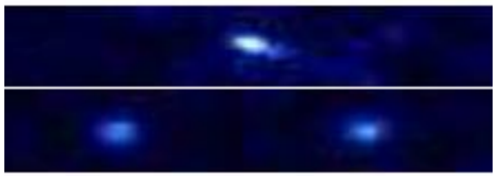
Requires a “critical point” with no harmonic confinement.



T. Ruster et al, PRA 90, 033410

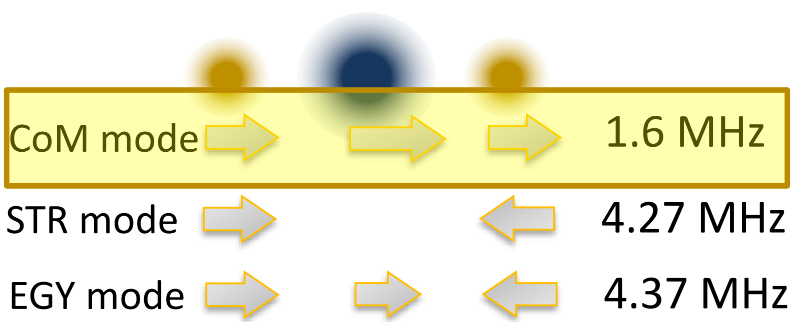
Multi-species operation (J. Home)

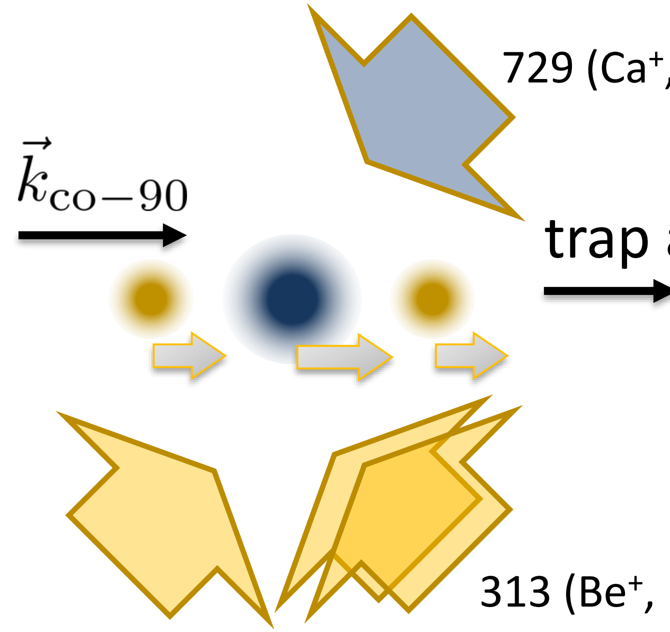
Ca⁺
Be⁺



Be radial freq: 14 MHz
Ca radial freq: 3.5 MHz

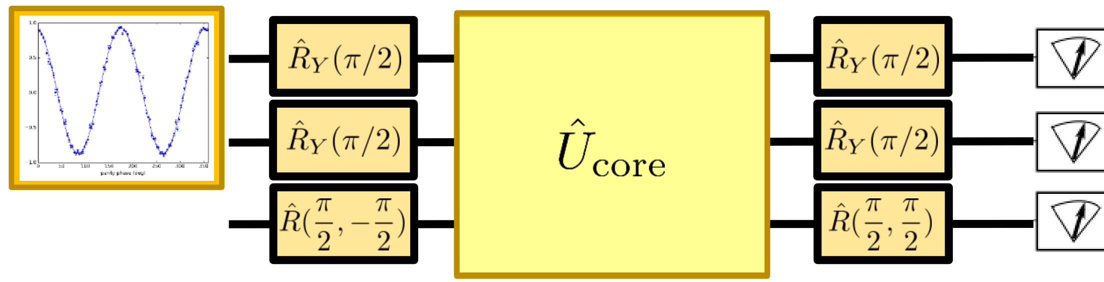
Axial modes





J. Home, ETH Zürich

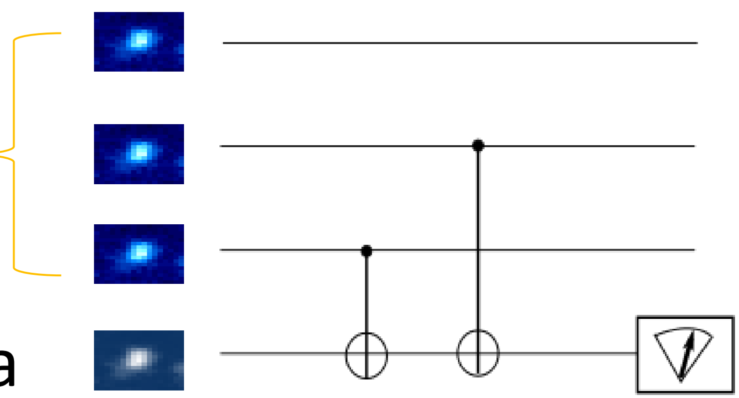
Multi species operation



Logical qubit

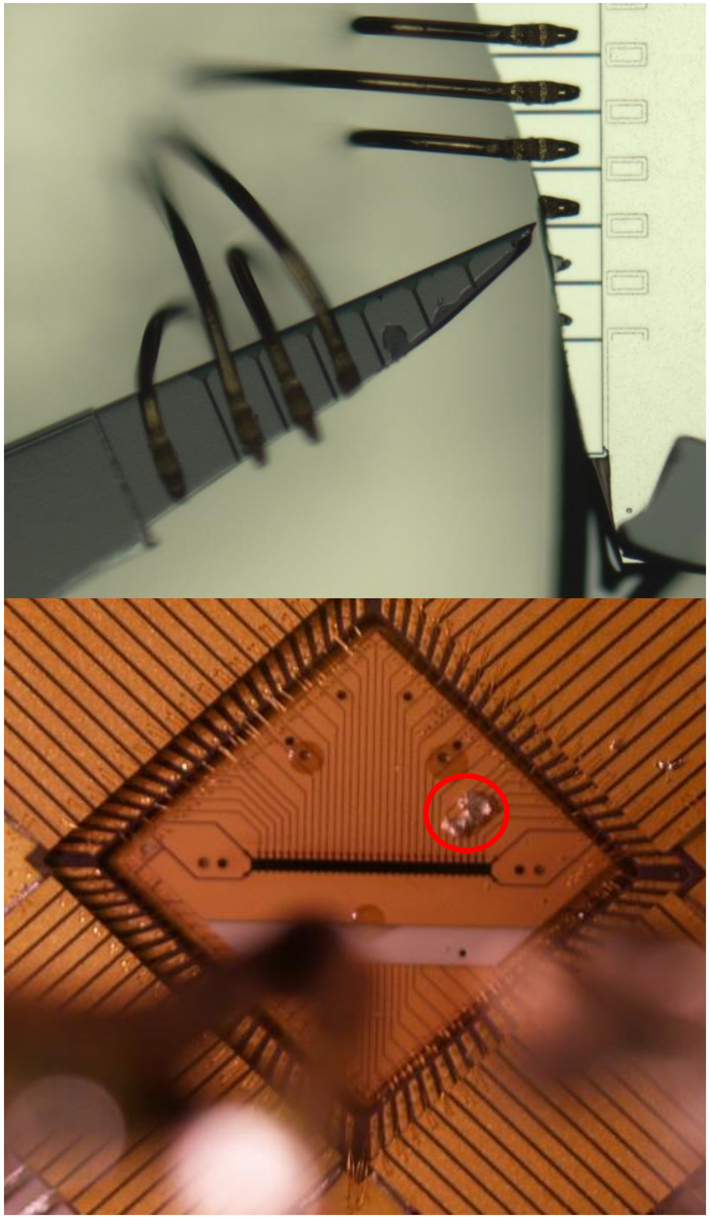
$a\,|111\rangle + be^{i\phi}\,|000\rangle$

Ancilla



J. Home, ETH Zürich

Operating microtraps



Traps can be destroyed
(even without user error)
Fabrication techniques not mature

Ion lifetimes comparable short
Bad vacuum (more materials colder bake)
Trap depth smaller than macroscopic traps

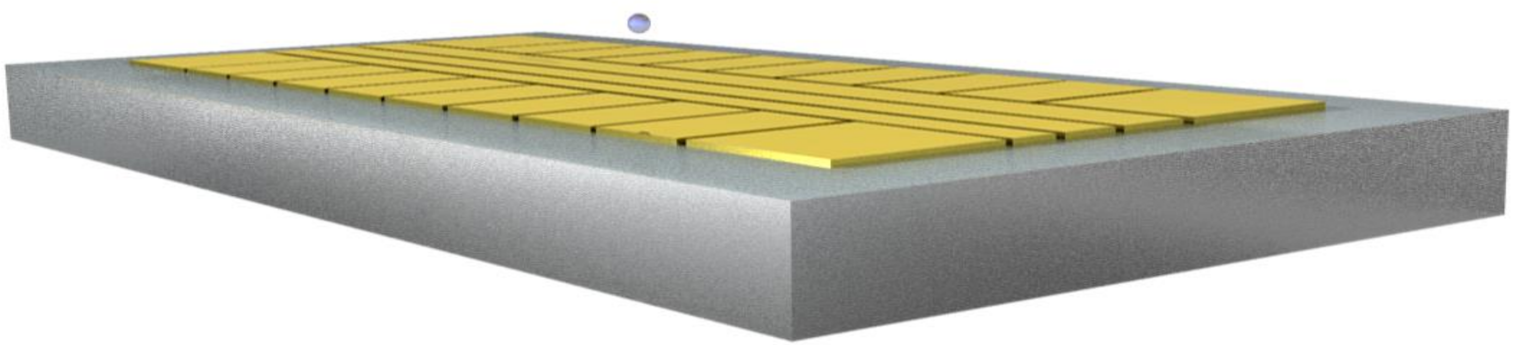
Reproducibility of trap fabrication
Contamination matters
No dedicated cleanrooms

The heating rate problem

Heating rates

Electric field noise on electrodes excerpts stochastic force onto the ion:

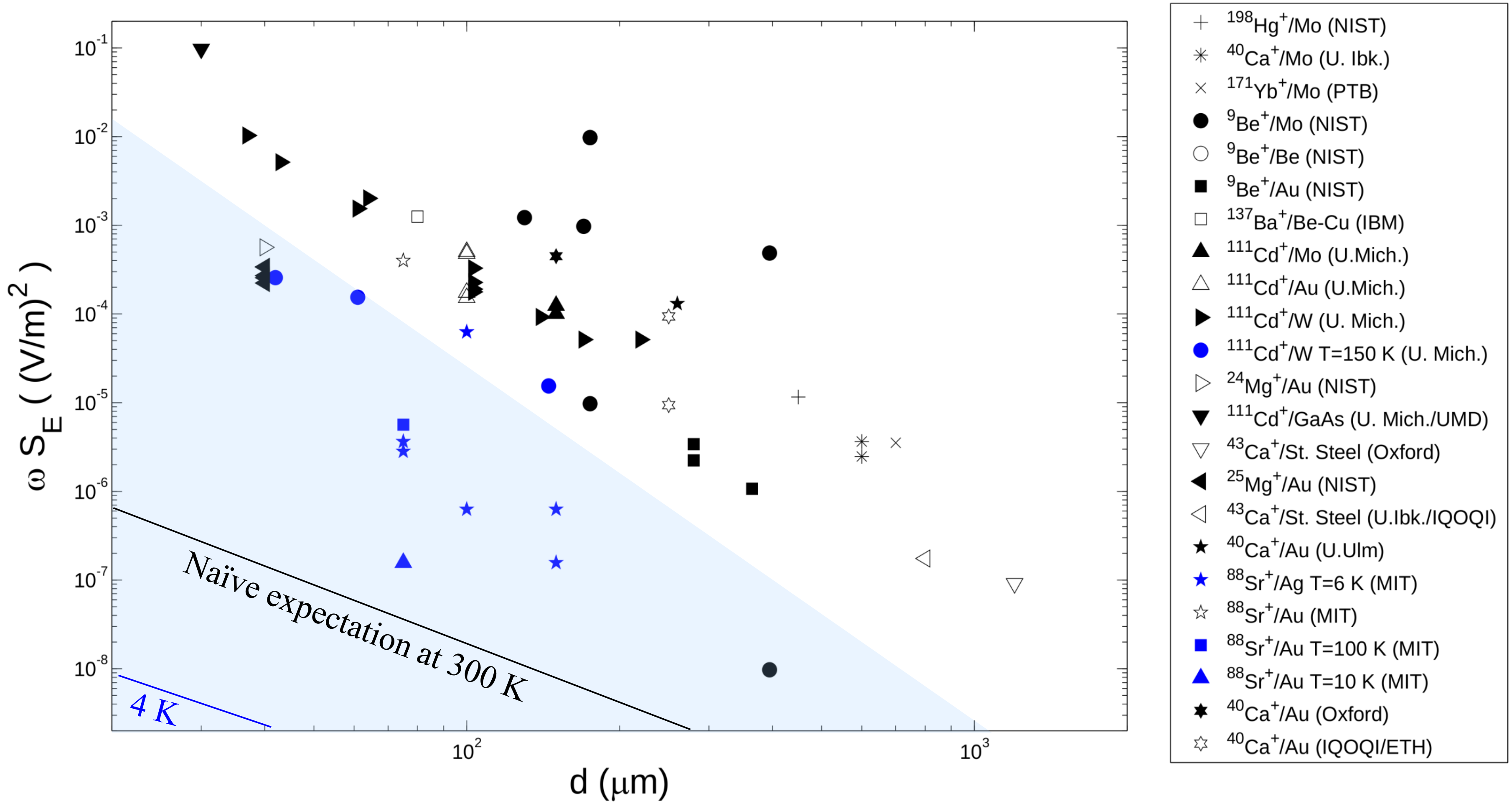
Energy deposition (heating, decoherence of motion)



Differences of planar to traps to 3-D traps:

- ions are much closer to the electrodes
- lower voltages, more electrodes contribute
- avoid filtering for transport

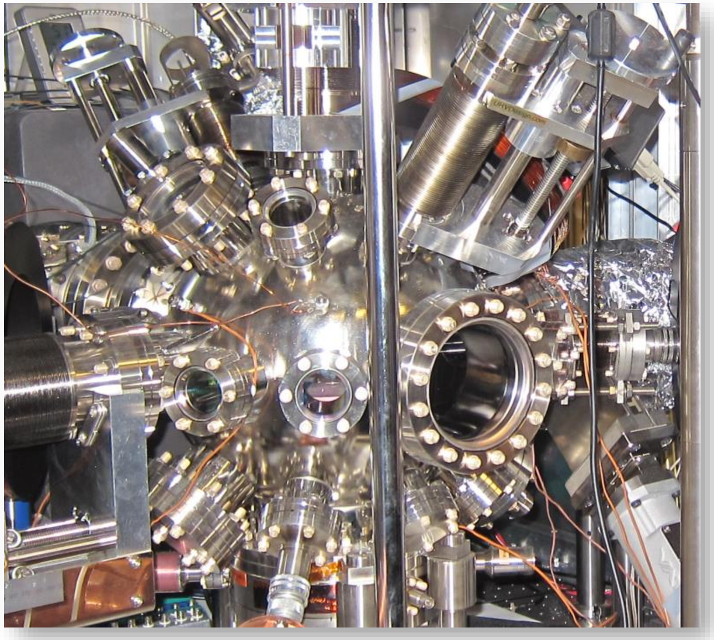
How bad is it?



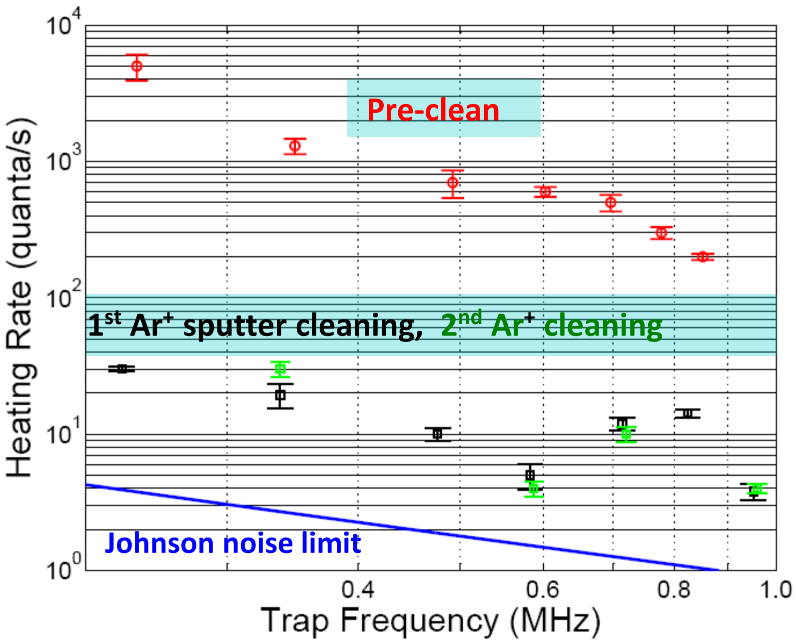
Two-qubit gate with infidelity of 10^{-4} requires < 1 quantum / s
Going cryogenic seems to help.

Cleaning helps

Surface science chamber

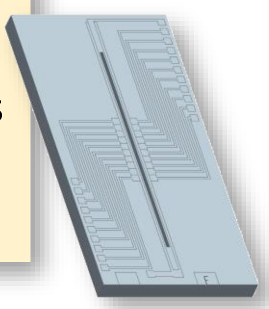


Reduced motional heating



Achievements with this system:

- Reduced motional heating
- Surface compatible w/ bulk traps
- Contamination assessment
- Trap material studies



Achievements with this system:

- Cleaning only required once
- Ultra-clean surface not required
- Hydrocarbon coverage under investigation

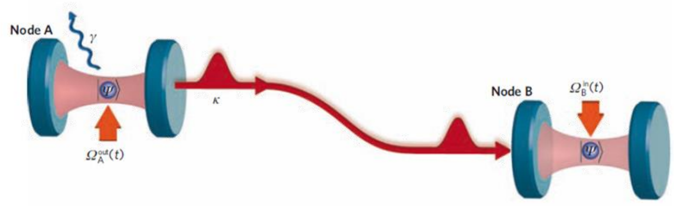
N. Daniilidis et al, PRB 89 245435 (2014)
also D. Pappas, NIST

Other ideas for scaling ion traps

- cavity QED: atom – photon interface, use photons for networking

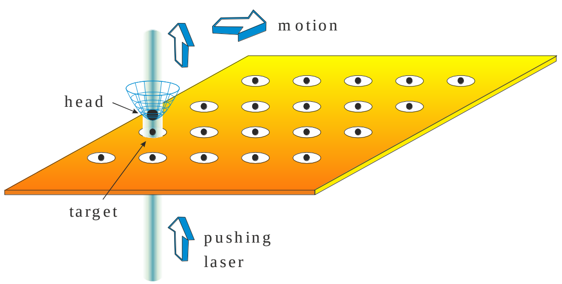
  J. I. Cirac et al., PRL **78**, 3221 (1997)

  T. Northup, M. Keller, C. Monroe



- trap arrays, using single ion as moving head

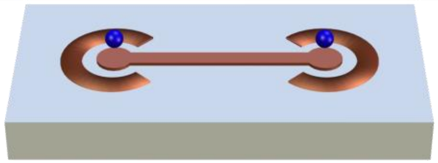
  I. Cirac und P. Zoller, Nature **404**, 579 (2000)



- ion – wire – solid state qubits (e.g. charge qubit)

  L. Tian et al., PRL **92**, 247902 (2004)

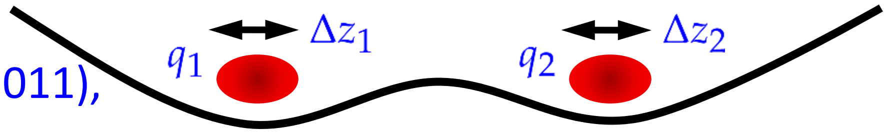
  H. Häffner et al., UC Berkeley



- dipole – dipole coupling

  K. Brown et al., Nature **471**, 196 (2011),

  M. Harlander et al., Nature **471**, 200 (2011)



Outline

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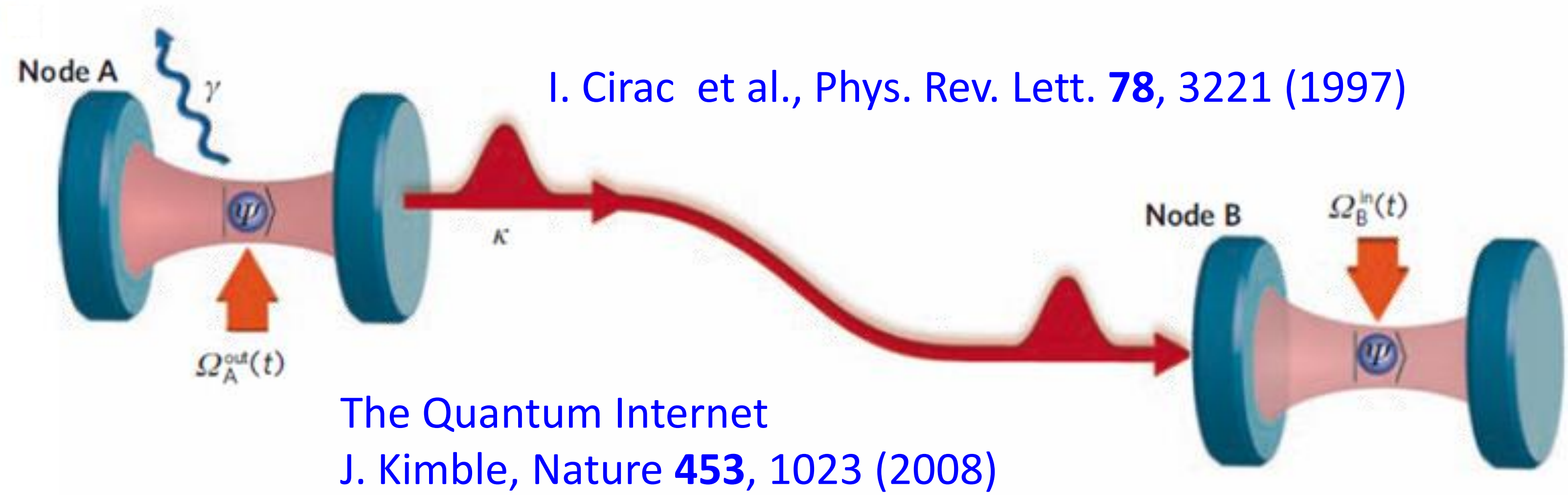
- Quantum tomography

Photonic connection of ion traps



I. Cirac et al., Phys. Rev. Lett. **78**, 3221 (1997)

The Quantum Internet
J. Kimble, Nature **453**, 1023 (2008)

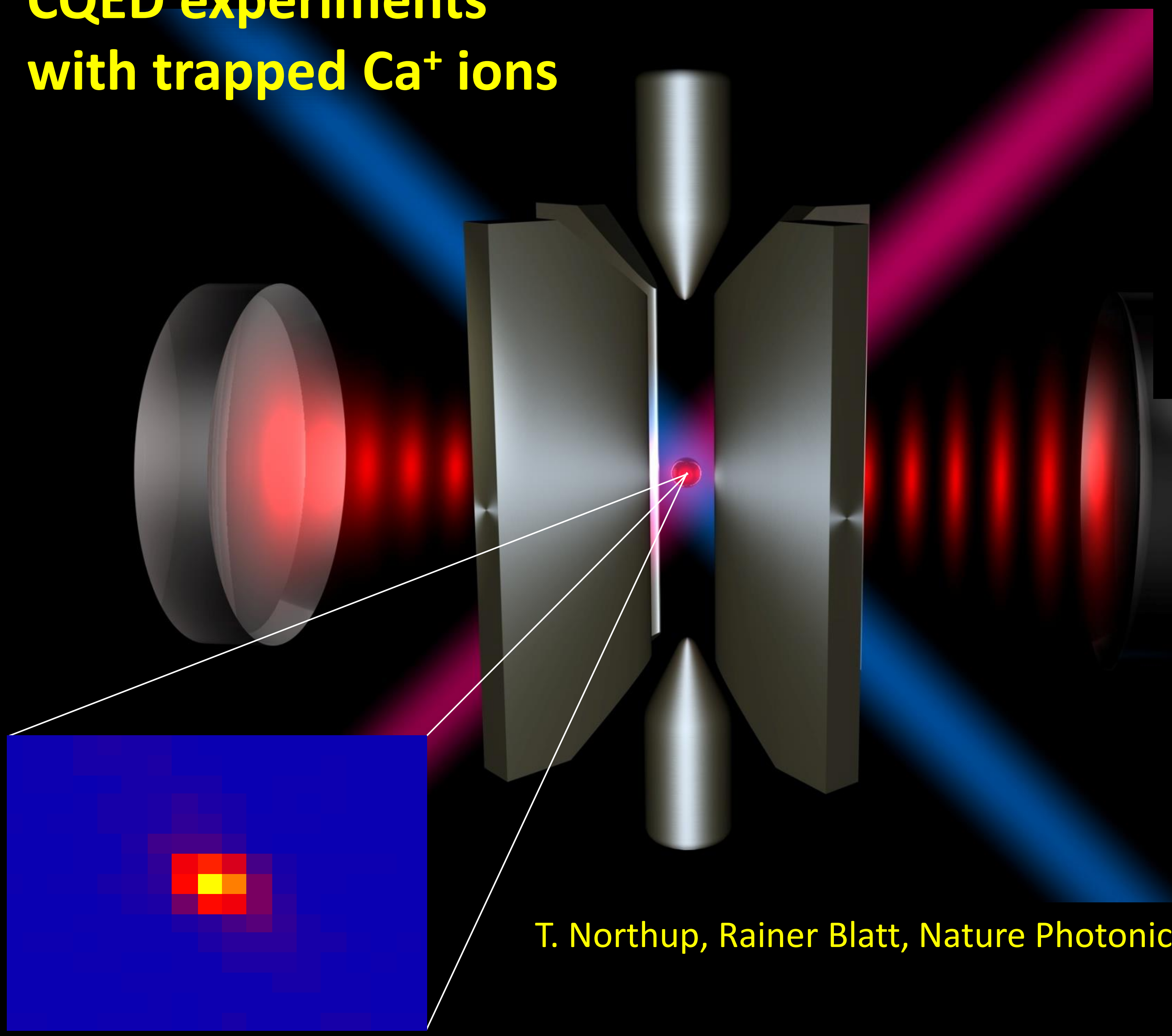
Technology:

- ★ Ions as quantum memory
- ★ Cavities as quantum interface
- ★ Optical fibers as photonic quantum channel

Goals:

- remote ion-ion entanglement — D. Moehring et al., Nature **449**, 68 (2007)
- teleportation between remote atoms — C. Nölleke et al., PRL **110**, 140403 (2013)
- direct state mapping — A. Stute et al., Nat. Photonics **7**, 219 (2013)

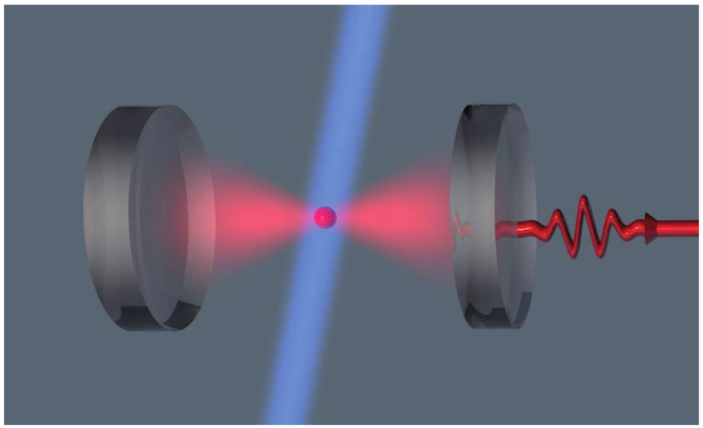
CQED experiments with trapped Ca^+ ions

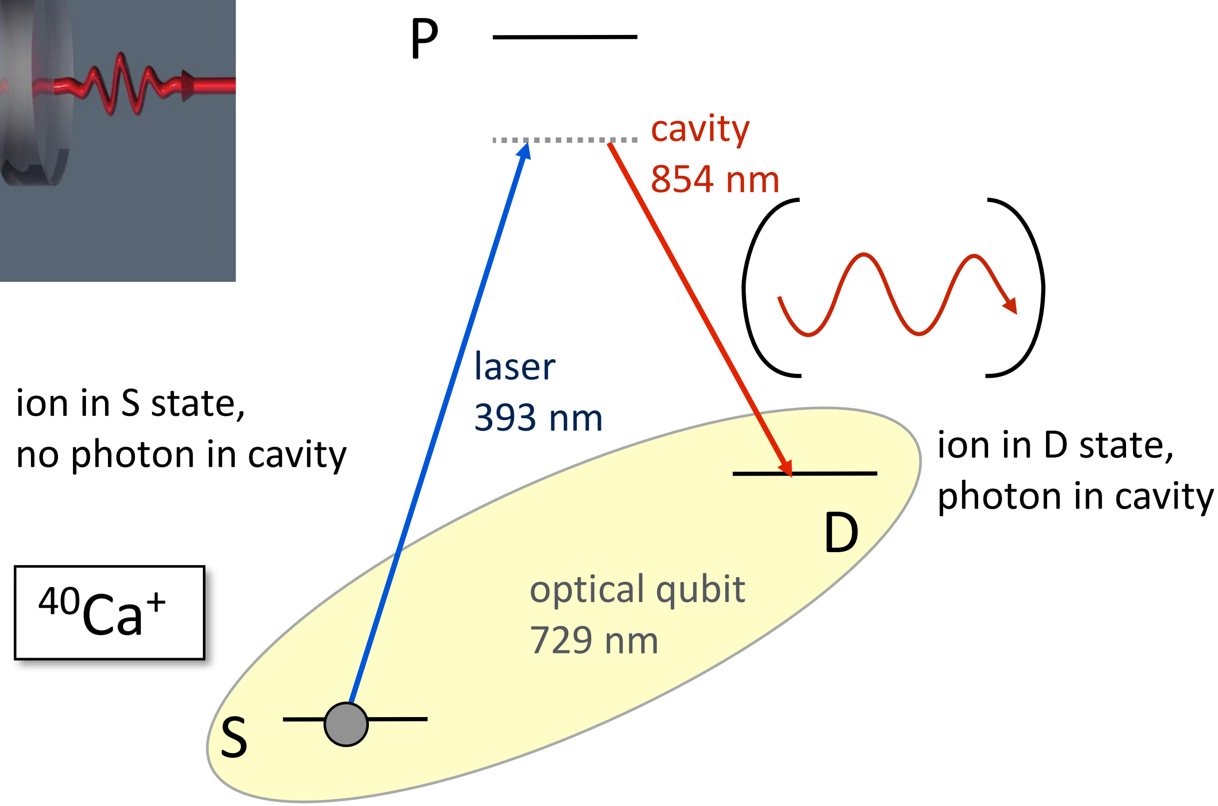


Tracy Northup

T. Northup, Rainer Blatt, Nature Photonics **8**, 356–363 (2014)

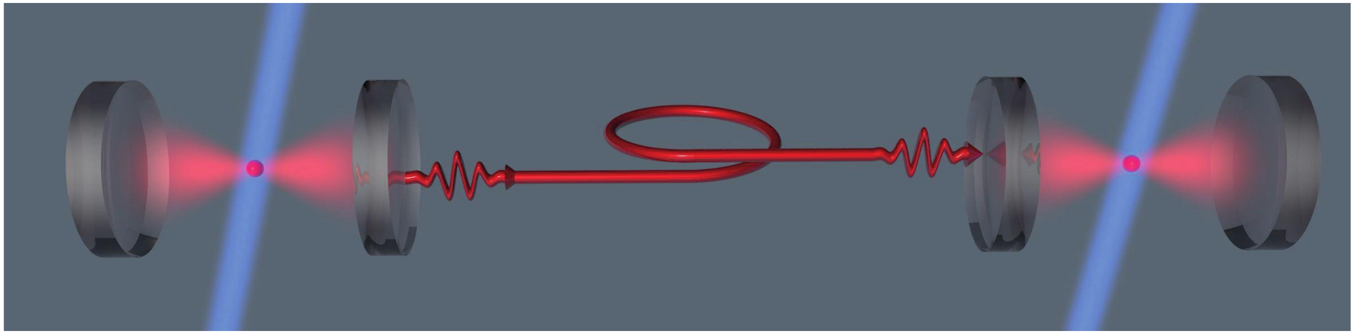
Cavity mediates between two states



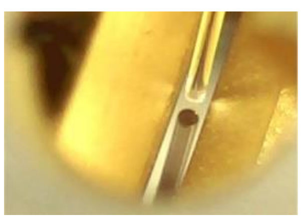


A. Stute et al., Nat. Photonics **7**, 219 (2013)

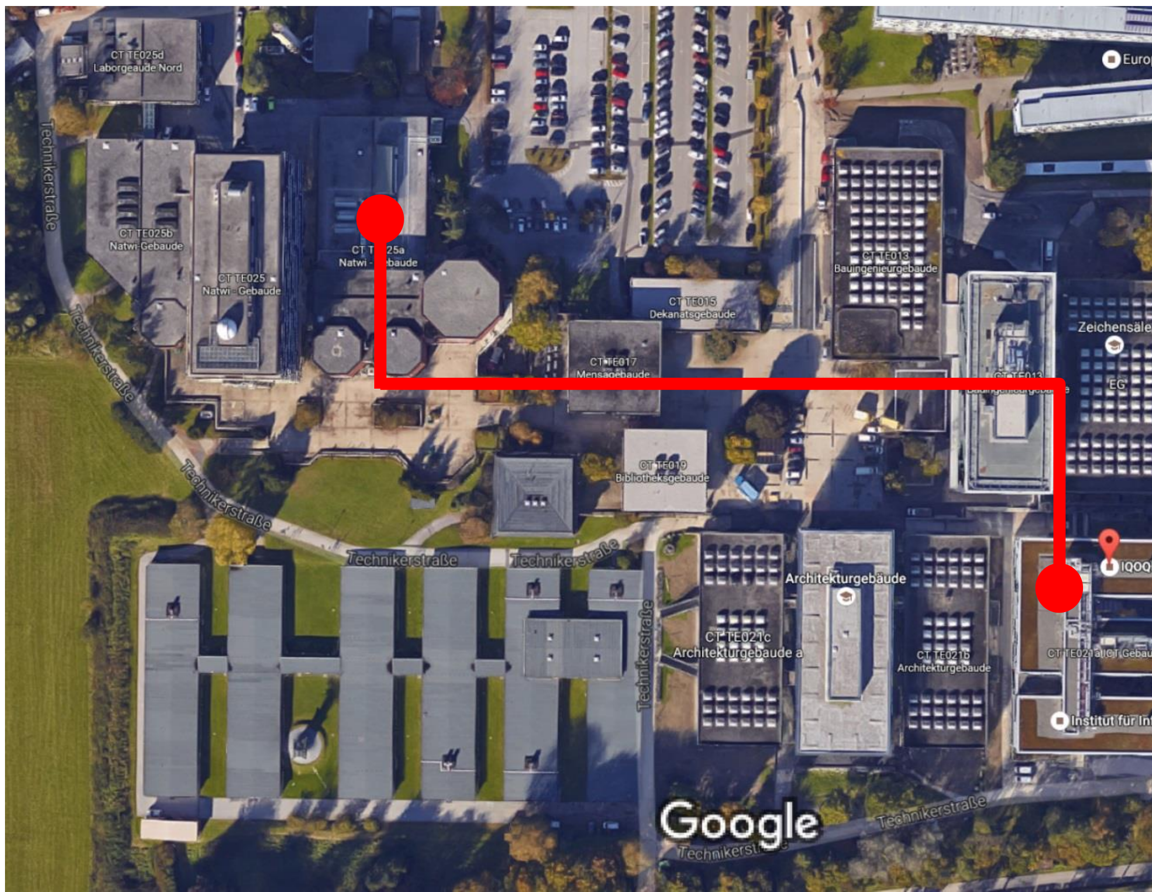
A three node quantum network



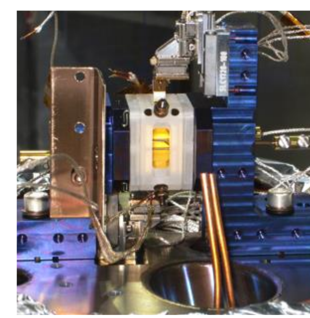
UIBK
bulk-cavity



UIBK
fibre-cavity



IQOQI
node



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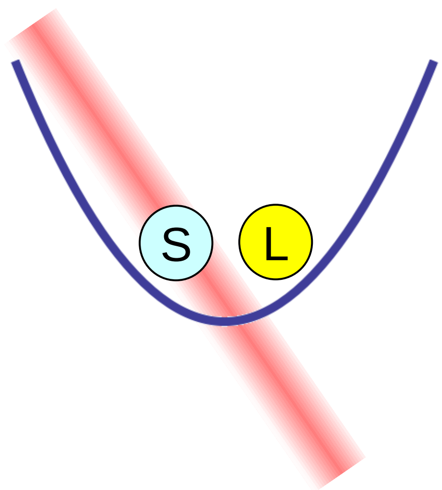
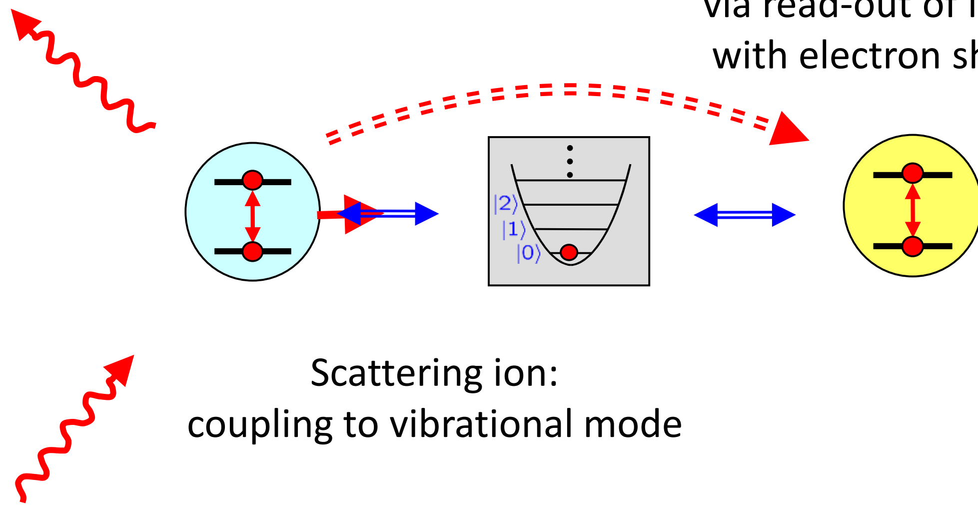
Indirect detection



Photon recoil:
Momentum transfer from the light field to the atom

Photon detection:
via read-out of logic ion with electron shelving



Scattering ion:
coupling to vibrational mode

Quantum Logic Spectroscopy of systems that lack suitable transitions for:

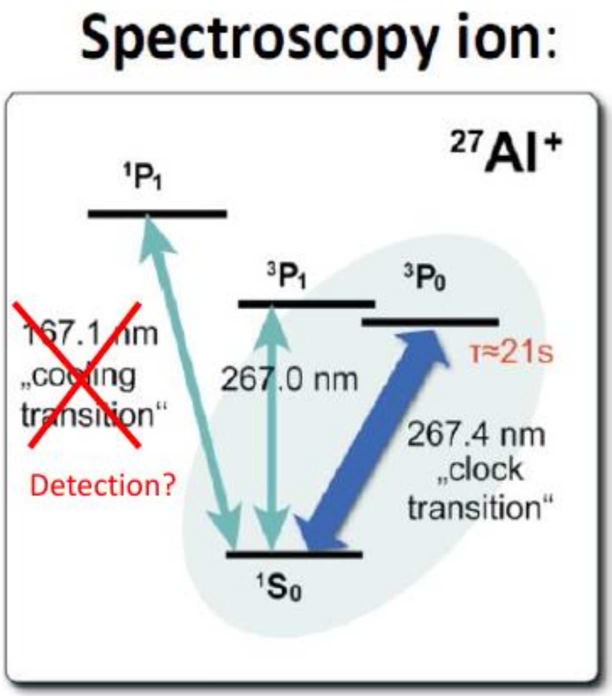
- Efficient laser cooling
- Internal state preparation
- Detection

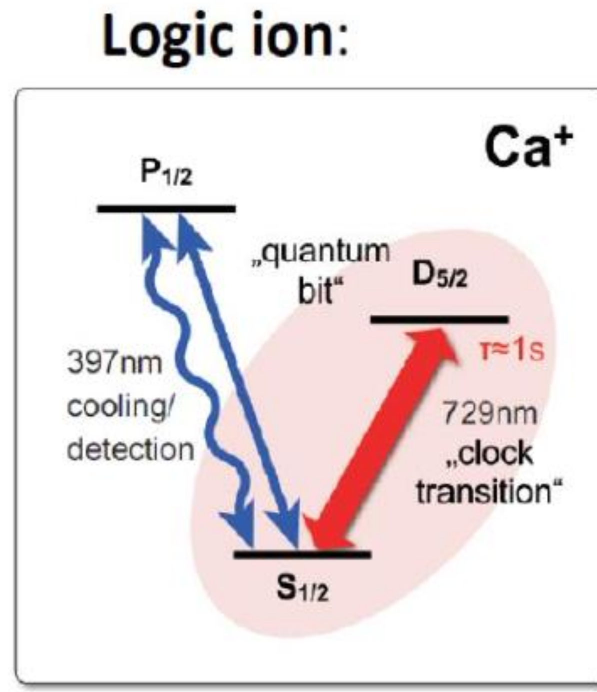
Needs resolved motional sidebands to implement mapping !

☑ Long-lived (=narrow) transitions
☒ Short-lived transitions

P.O. Schmidt et al., Science **309**, 749 (2005)

Optical clocks

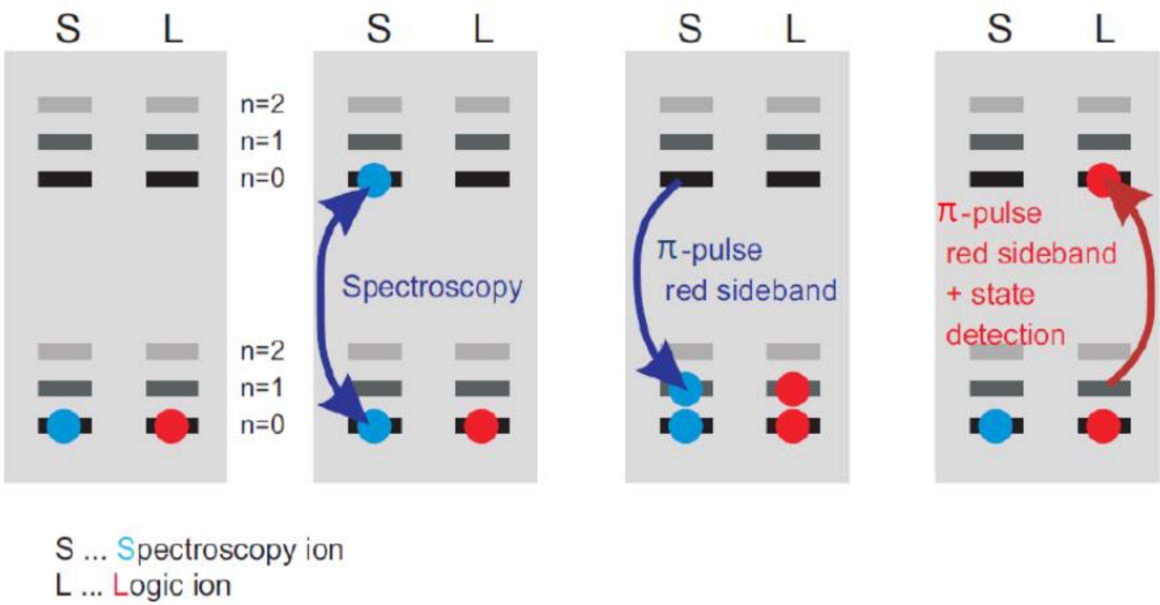




Control and read-out spectroscopy using well controlled logic ion

P.O. Schmidt et al., Science **309**, 749 (2005)

Quantum logic clocks



$|0, g_S, g_L\rangle$

Spectroscopy

$|0, g_L\rangle \otimes \{\alpha|g_S\rangle + \beta|e_S\rangle\}$

Π – pulse red sideband

$\{\alpha|0\rangle + \beta|1\rangle\} \otimes |g_S, g_L\rangle$

Π – pulse red sideband + state detection

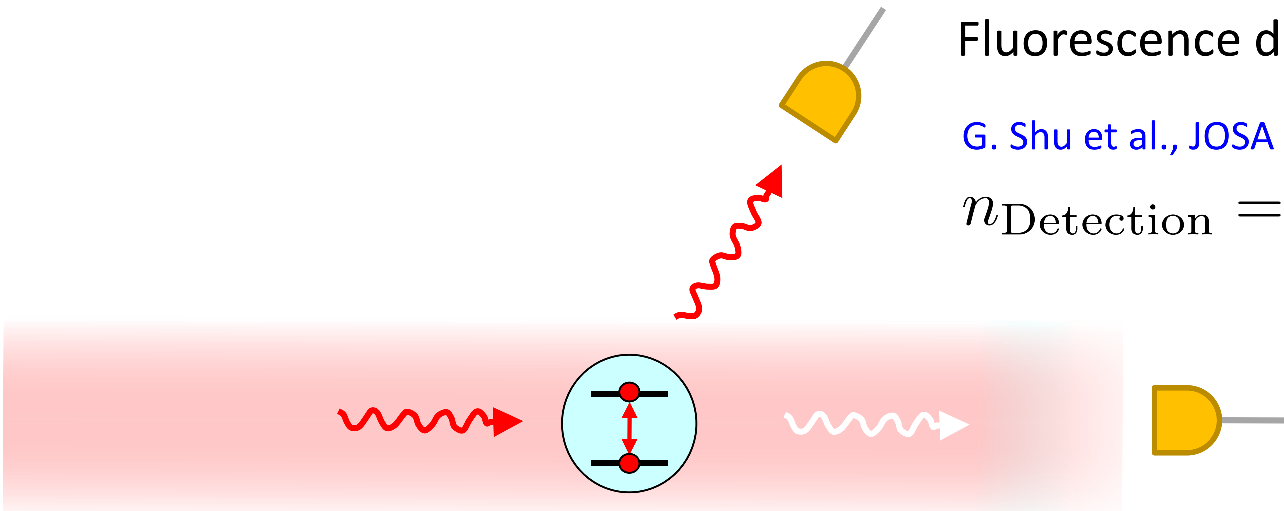
$|0, g_S\rangle \otimes \{\alpha|g_L\rangle + \beta|e_L\rangle\}$

Need to drive sideband transition on spectroscopy ion

P.O. Schmidt et al., Science **309**, 749 (2005)

Detection of photon scattering processes

How efficiently can we detect a photon scattering process
by a trapped atomic or molecular ion?



Fluorescence detection

G. Shu et al., JOSA B **28**, 2865 (2011)

$$n_{\text{Detection}} = 1\%$$

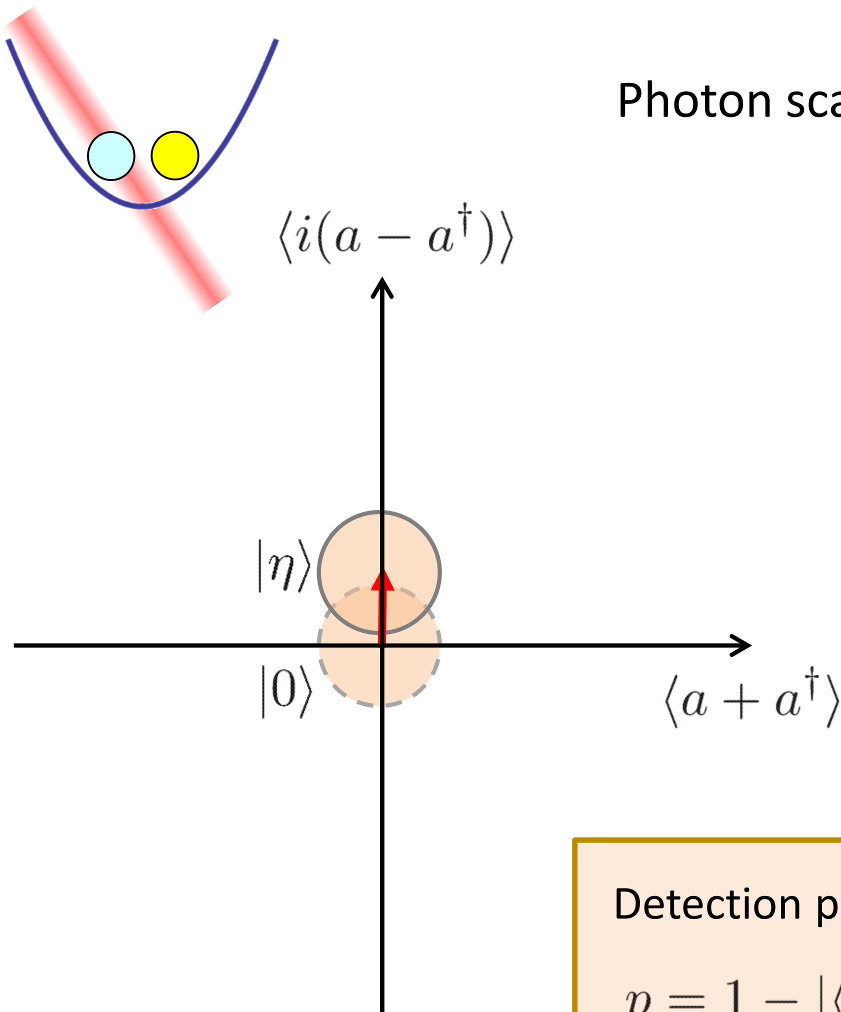
Absorption measurements

E.Streed et al, Nature Comm. **3**, 933 (2012)

$$\eta_{detection} = 3\%$$

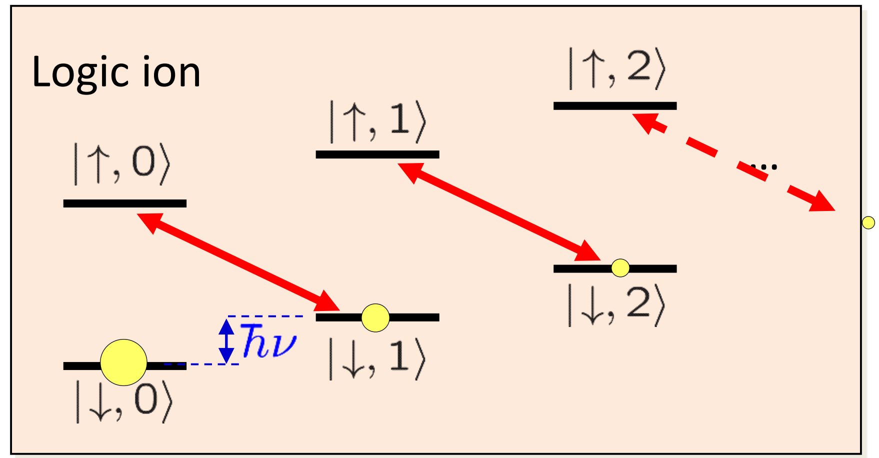
… more efficient methods?

Photon scattering in phase space



Photon scattering displaces the motional state

$$|0\rangle \longrightarrow \hat{D}(\eta)|0\rangle$$

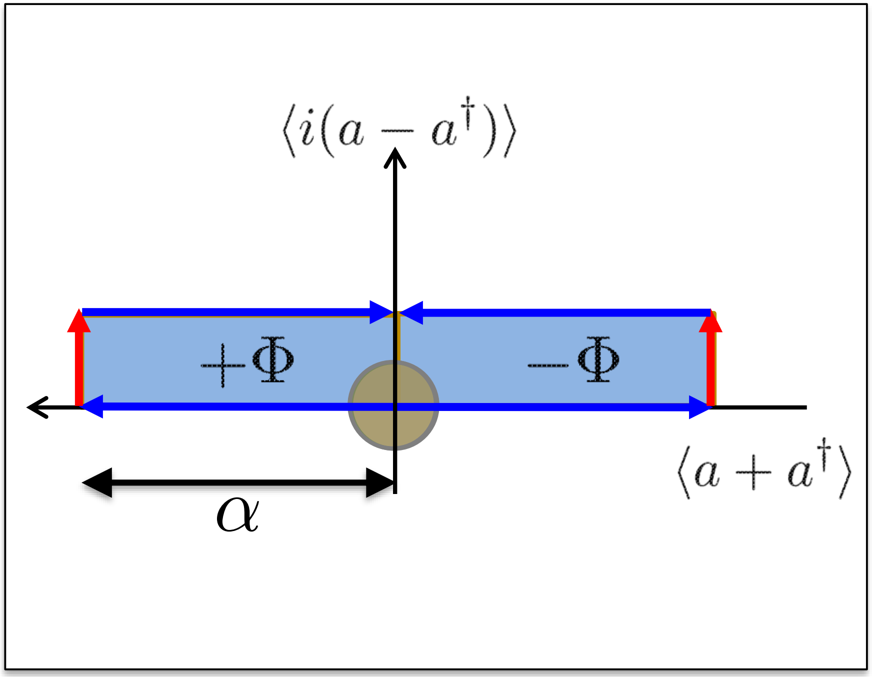


Detection probability for a ground-state cooled ion:

$$p = 1 - |\langle 0|\hat{D}(\eta)|0\rangle|^2 \approx \eta^2 \qquad \eta \ll 1$$

C. Hempel et al., Nat Phot **7**, 630 (2013)

Schrödinger cat state for detection



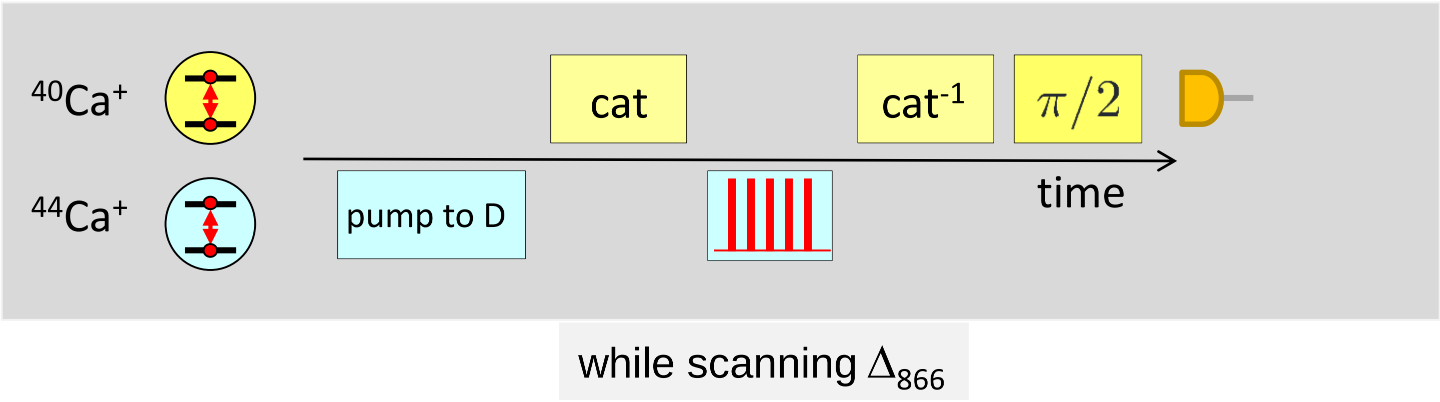
Interferometer sequence

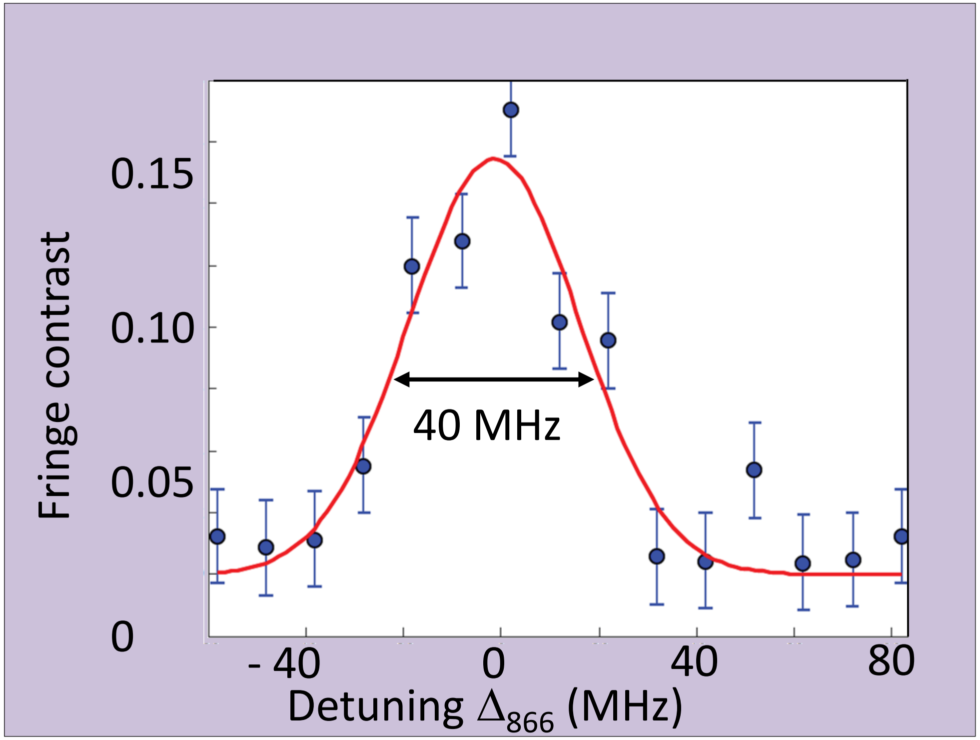
(1) Create cat state	L	S
(2) Scatter photon	L	S
(3) Recombine cat state	L	S
(4) Read out	L	S

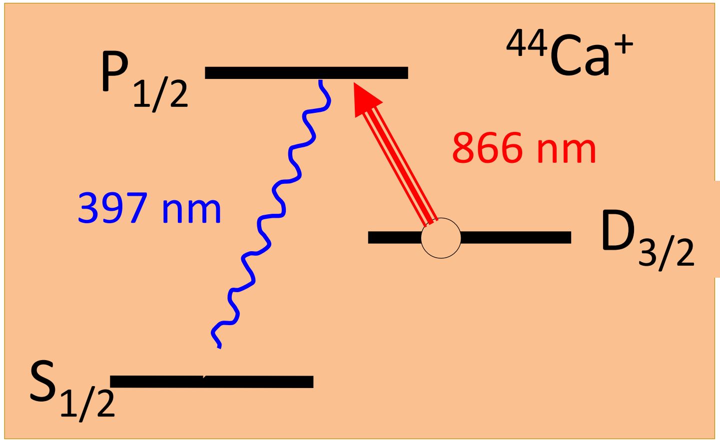
Turchette et al., Phys. Rev. A **62**, 053807 (2000)

C. Hempel et al., Nat Phot **7**, 630 (2013)

Spectroscopy on ^{44}Ca







C. Hempel et al., Nat Phot **7**, 630 (2013)

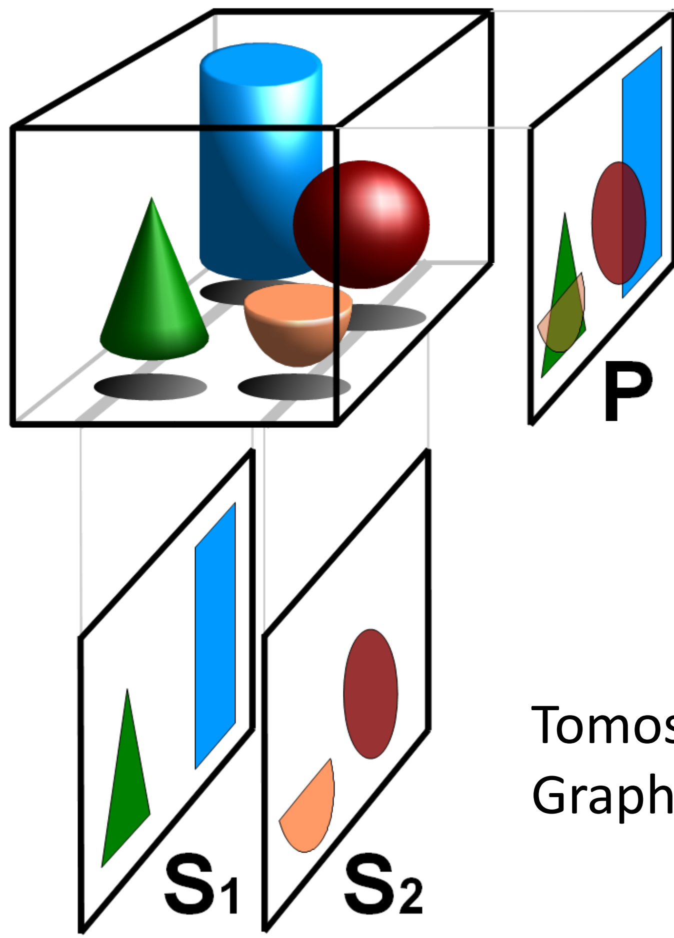
Y. Wan et al., Nat. Com 5, 3069 (2014)

G. Clos, et al. PRL. **112**, 113003 (2014)

Outline

- Implementing algorithms
- Scalable techniques and traps
- Quantum communication in ion traps
- Quantum logic for metrology
- Quantum tomography

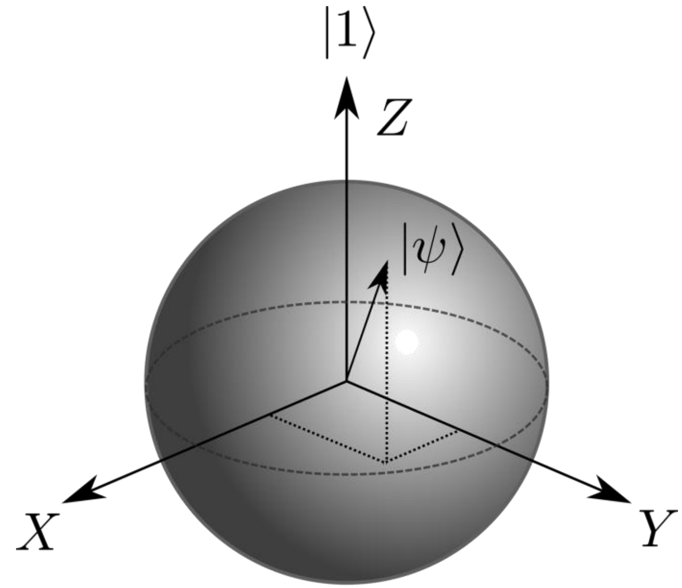
Tomography

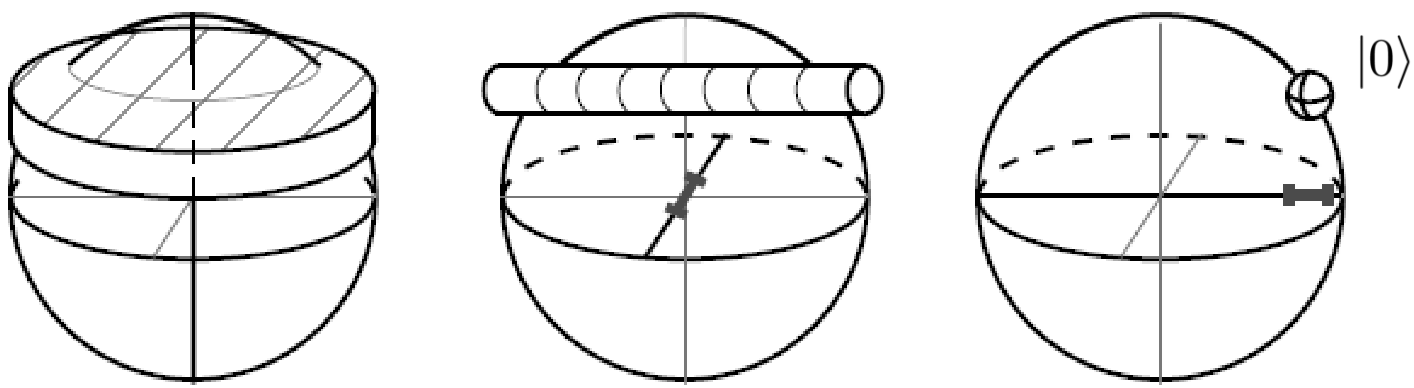


Tomos (greek) = “part, section”
Graphein (greek) = “to write”

Single qubit tomography

$$\rho = \frac{1}{2}(1 + \langle z \rangle \sigma_z + \langle x \rangle \sigma_x + \langle y \rangle \sigma_y)$$





Multi-qubit tomography

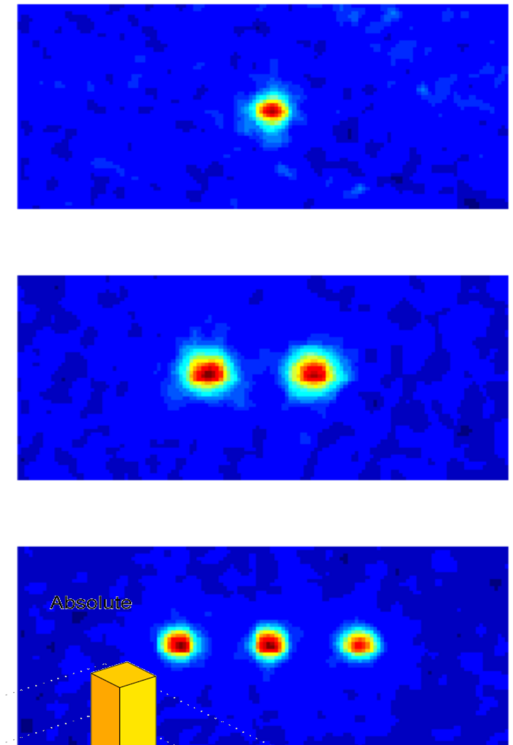
N-qubit density matrix: 4^N-1 parameters

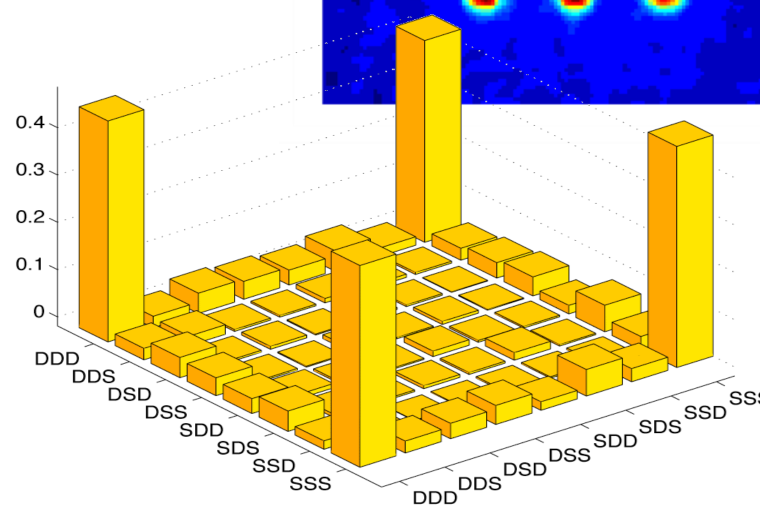
State tomography:

- Pauli basis {X,Y,Z} per qubit
- 3^N measurement settings
- Distinguish 2^N different results (for free)

Over-complete dataset

Reconstruct quantum state:
- positive eigenvalues
- trace ought to be 1





2-qubit state tomography

Representation of ρ as a sum of orthogonal observables A_i :

$$\rho = \sum_i \lambda_i A_i \ \text{ with } \ Tr(A_i A_j) = \delta_{ij}$$

ρ is completely detemined by the expectation values $<A_i>$:

$$\langle A_j \rangle = Tr(\rho A_j) = \sum_i \lambda_i Tr(A_i A_j) = \lambda_j$$

For a two-ion system : $A_i \in \{\sigma_i^{(1)} \otimes \sigma_j^{(2)}, \sigma_i \in \{I, \sigma_x, \sigma_y, \sigma_z\}\}$

$\longrightarrow$ Joint measurements of all spin components $\sigma_i^{(1)} \otimes \sigma_j^{(2)}$

$$\rho_R = \sum_{i=1}^{16} \langle A_i \rangle A_i$$

2-qubit state tomography

Setting #	Transformation applied to ion 1	ion 2	Measured expectation values		
1	-	-	$\sigma_z^{(1)}$	$\sigma_z^{(2)}$	$\sigma_z^{(1)}\sigma_z^{(2)}$
2	$R(\pi/2, 3\pi/2)$	-	$\sigma_x^{(1)}$	$\sigma_z^{(2)}$	$\sigma_x^{(1)}\sigma_z^{(2)}$
3	$R(\pi/2, \pi)$	-	$\sigma_y^{(1)}$	$\sigma_z^{(2)}$	$\sigma_y^{(1)}\sigma_z^{(2)}$
4	-	$R(\pi/2, 3\pi/2)$	$\sigma_z^{(1)}$	$\sigma_x^{(2)}$	$\sigma_z^{(1)}\sigma_x^{(2)}$
5	-	$R(\pi/2, \pi)$	$\sigma_z^{(1)}$	$\sigma_y^{(2)}$	$\sigma_z^{(1)}\sigma_y^{(2)}$
6	$R(\pi/2, 3\pi/2)$	$R(\pi/2, 3\pi/2)$	$\sigma_x^{(1)}$	$\sigma_x^{(2)}$	$\sigma_x^{(1)}\sigma_x^{(2)}$
7	$R(\pi/2, 3\pi/2)$	$R(\pi/2, \pi)$	$\sigma_x^{(1)}$	$\sigma_y^{(2)}$	$\sigma_x^{(1)}\sigma_y^{(2)}$
8	$R(\pi/2, \pi)$	$R(\pi/2, 3\pi/2)$	$\sigma_y^{(1)}$	$\sigma_x^{(2)}$	$\sigma_y^{(1)}\sigma_x^{(2)}$
9	$R(\pi/2, \pi)$	$R(\pi/2, \pi)$	$\sigma_y^{(1)}$	$\sigma_y^{(2)}$	$\sigma_y^{(1)}\sigma_y^{(2)}$

Reconstruction methods

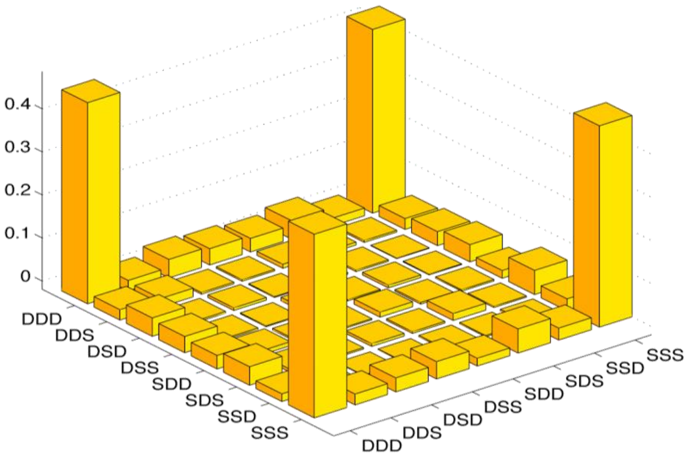
Method	Approach	Reference
Iterative	Iterative method for multinomial measurements	Phys. Rev. A 68, 012305 (2003)
Wizard	Make linear reconstruction, fix eigenvalues	Phys. Rev. Lett. 108, 070502 (2012)
Compressed sensing	If close to a pure/unitary object, get away with less measurements	Phys. Rev. Lett. 105, 150401 (2010)
Max Lik Max Ent	For incomplete data, take the most likely and most mixed state	Phys. Rev. Lett. 107, 020404 (2011)
Hedged tomography	Inferred states should never be rank-deficient	Phys. Rev. Lett. 105, 200504 (2010)

and special cases such as permutationally invariant states, MPS, …

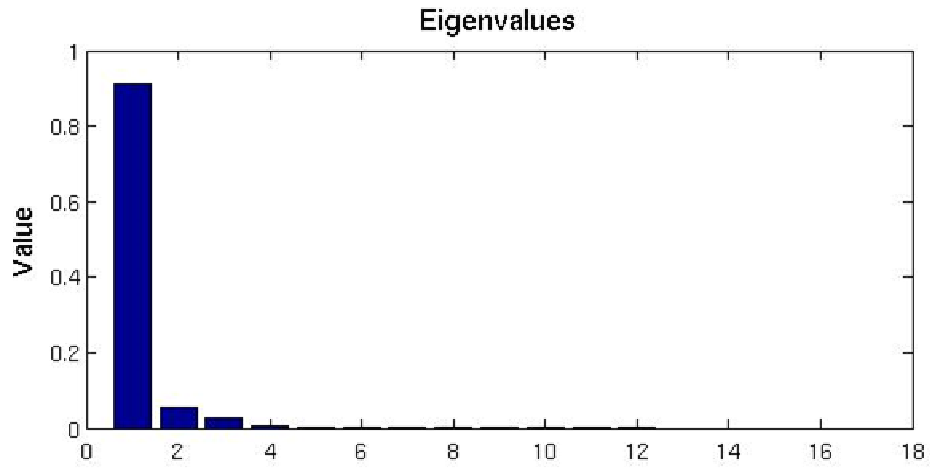
We optimise "like-lihood" (or personal taste) !!!

We try to implement low-rank states

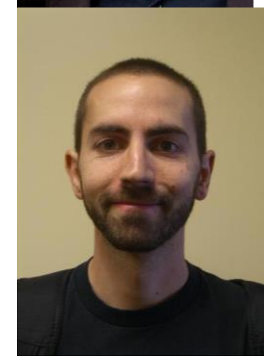
- Why estimate 4^N-1 parameters, if 2^N-1 might to do it?
- Why measure 3^N settings, if notably less ought suffice?



Ideally: rank=1



Compressed sensing



"The purest state compatible
with my (full-rank incomplete) data"

$$\min \|\sigma\|_{\mathrm{tr}}, \qquad \text{subject to } \|\mathcal{R}\sigma - \mathcal{R}\omega\|_2 \leq \varepsilon.$$

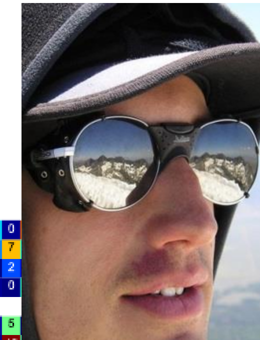
✓ Parameters: r 2^N (compressed sensing) vs 4^N
✓ No need to put rank in in the first place – done automatically
✓ Convex optimisation → tons of (fast) routines

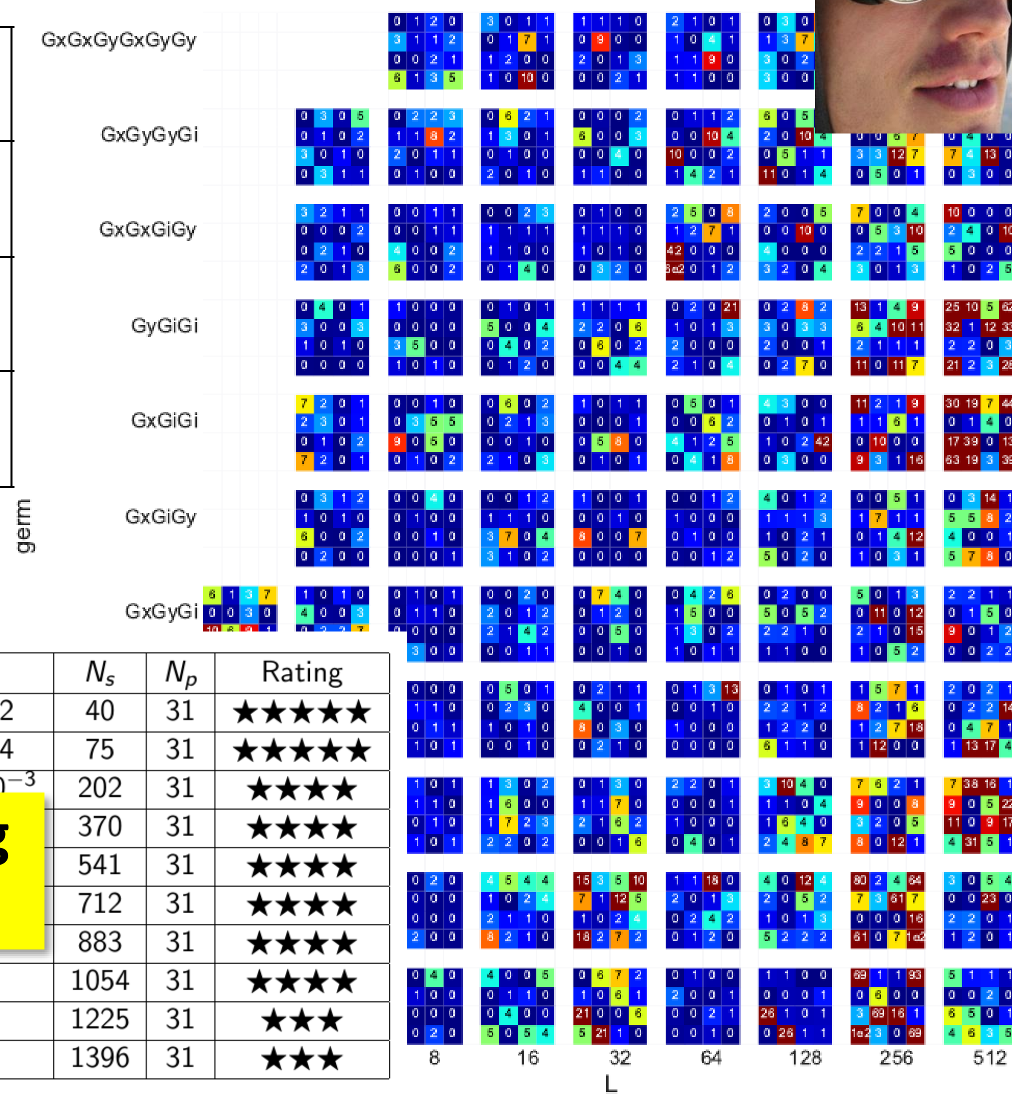
✗ How do you want me to choose ε?
✗ Is low-rank a good assumption?

D. Gross et al., Phys. Rev. Lett. 105, 150401 (2010)

Gate set tomography

Gate	Process Infidelity	1/2 Trace Distance
Gi	0.000067 $\pm$0.000069	0.000762 $\pm$0.000138
Gx	0.000516 $\pm$0.000094	0.005232 $\pm$0.0005
Gy	0.000706 $\pm$0.000102	0.005151 $\pm$0.000549



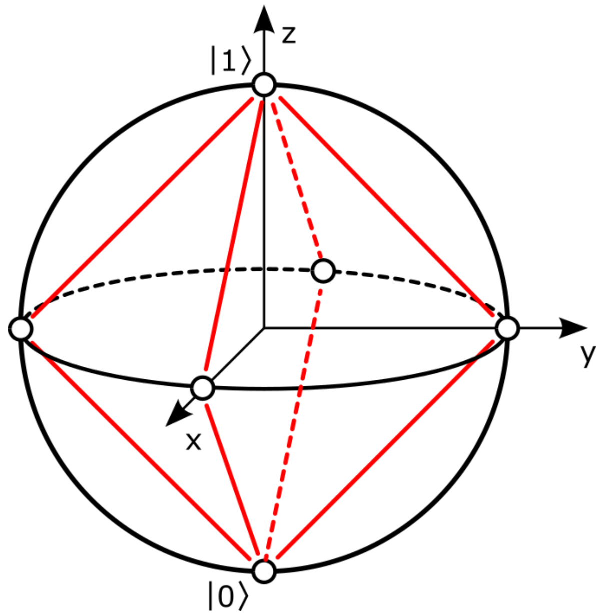


L	$2\Delta\log(\mathcal{L})$	k	$2\Delta\log(\mathcal{L}) - k$	$\sqrt{2k}$	P	N_s	N_p	Rating
0	9.141805	9	0.141805	4.242641	0.42	40	31	★★★★★
2	50.25665	44	6.256655	9.380832	0.24	75	31	★★★★★
4	225.1552	171	54.1552	18.49324	3×10^{-3}	202	31	★★★★
8	458.9723	3[illegible]	[illegible]	[illegible]	[illegible]	370	31	★★★★
16	701.3165	5[illegible]	[illegible]	[illegible]	[illegible]	541	31	★★★★
32	974.6869	6[illegible]	[illegible]	[illegible]	[illegible]	712	31	★★★★
64	2013.528	8[illegible]	[illegible]	[illegible]	[illegible]	883	31	★★★★
128	2523.801	1023	1500.801	45.23273	0	1054	31	★★★★
256	3957.735	1194	2763.735	48.86717	0	1225	31	★★★
512	4800.871	1365	3435.871	52.2494	0	1396	31	★★★

“Good” according to RBK

R. Blume-Kohout, Sandia PyGSTi software

Randomized benchmarking



3 axis

4 rotations

2 reflections

→24 rotational symmetries

$\boxed{\text{= 24 Clifford gates}}$

$$|S\rangle - \mathcal{C}_1 - \mathcal{C}_2 - \cdots - \mathcal{C}_{n-1} - \mathcal{C}_n^{-1} - |D\rangle \Rightarrow P_n(|D\rangle) = Ap^n + B$$

n	Number Clifford-Gates
A, B	Coefficients incl. SPAM-errors (0.5 ideally)
p	Decay-constant (0...1)
$\mathcal{F}_{\text{avg}} = \frac{p+1}{2}$	Average Clifford-Gate fidelity

Phys. Rev. Lett. **106**, 180504 (2011)

AG Quantenoptik und Spektroskopie

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