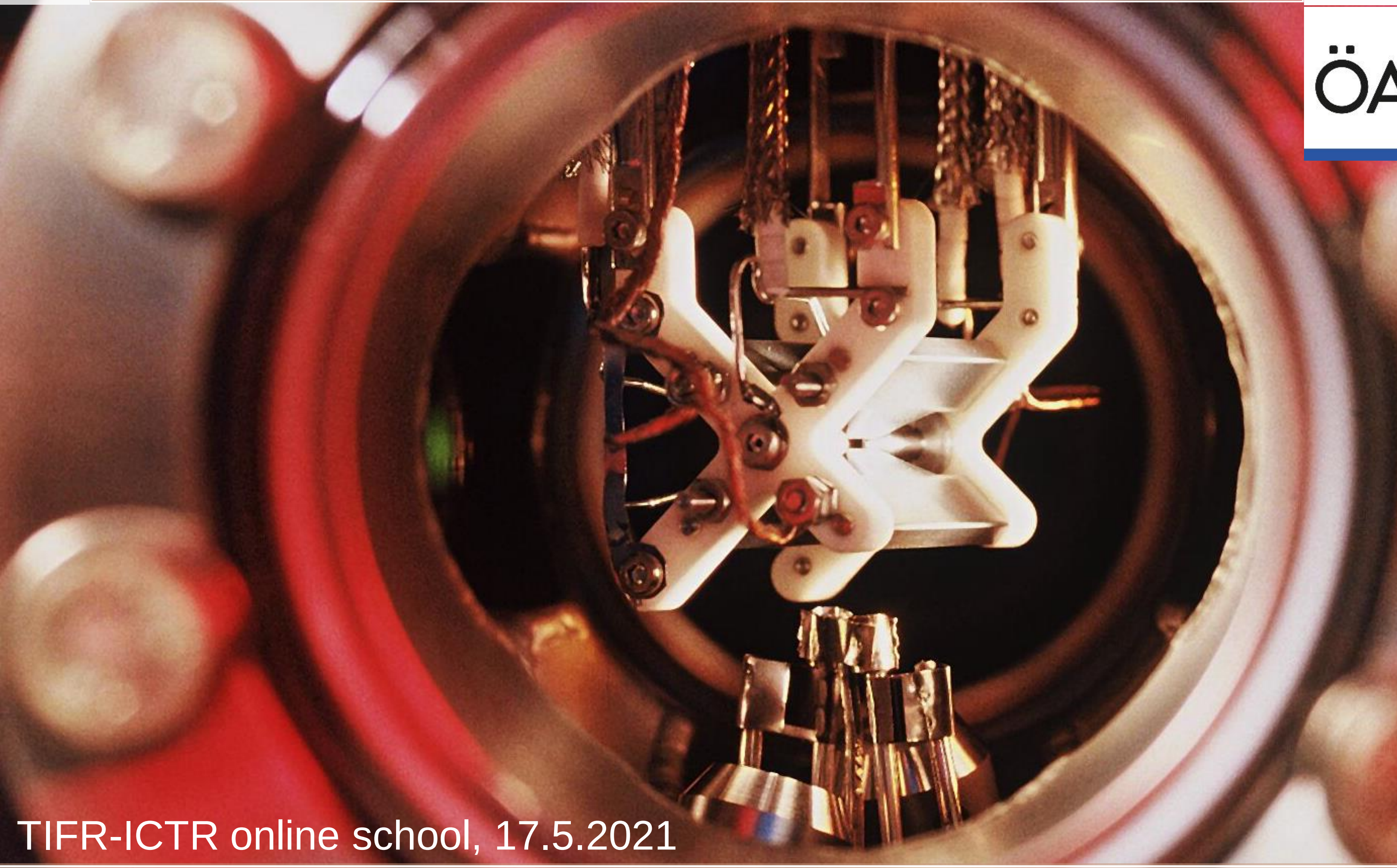
Entanglement in trapped-ion experiments

universität innsbruck
Institut für Experimentalphysik

ÖAW ÖSTERREICHISCHE AKADEMIE DER WISSENSCHAFTEN



TIFR-ICTR online school, 17.5.2021

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Institute for Experimental Physics
University of Innsbruck, Austria

Funding:
PASQuanS
QUANTUM FLAGSHIP
erc

FWF

Quantum physics with trapped ions

Single ions:
an isolated
quantum systen

Frequency standards
Optical clocks

Precision spectroscopy
mass- and g-factor measurements

Quantum optics
Quantum jumps, Antibunching,…

Time

Ion crystals:
an isolated
and complex
quantum systen

Quantum information

Quantum computing

Testing quantum theory

Entanglement for quantum metrology and precision spectroscopy

Quantum simulation

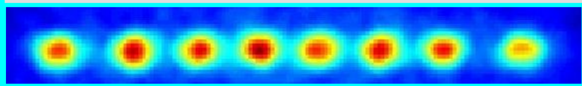
Quantum networks

Outline

- Trapped ions as an interacting quantum system
- Properties of ion crystals
- Advanced laser cooling techniques
- Quantum control of long ion strings
- Entangling interactions
- Gate-based quantum computation

Quantum physics with ion crystals

Ion trap



- Ion loading ~ minutes
- Ion storage ~ day(s)
- Individual experiments ~ 20 ms

(initialization, coherent interaction, + measurement)

→ ~ 10^5 – 10^6 quantum measurements per day

Lasers

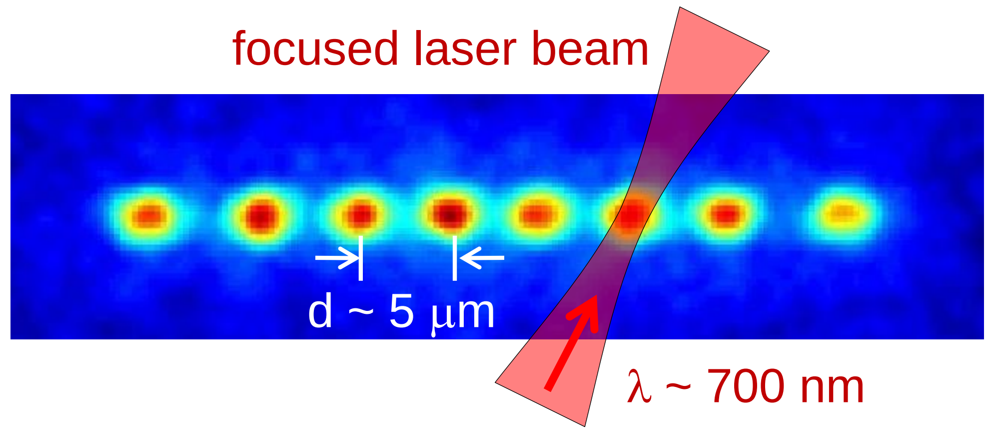
- Ion creation
- Laser cooling

  → quantized ion motion
- Coherent excitation

  → entanglement generation
- Ion detection

  → quantum measurements

Quantum physics with ion crystals



Trap frequencies:

$$\nu_z \quad \propto 1 \text{ MHz}$$
$$\nu_{x,y} \propto 5 \text{ MHz}$$

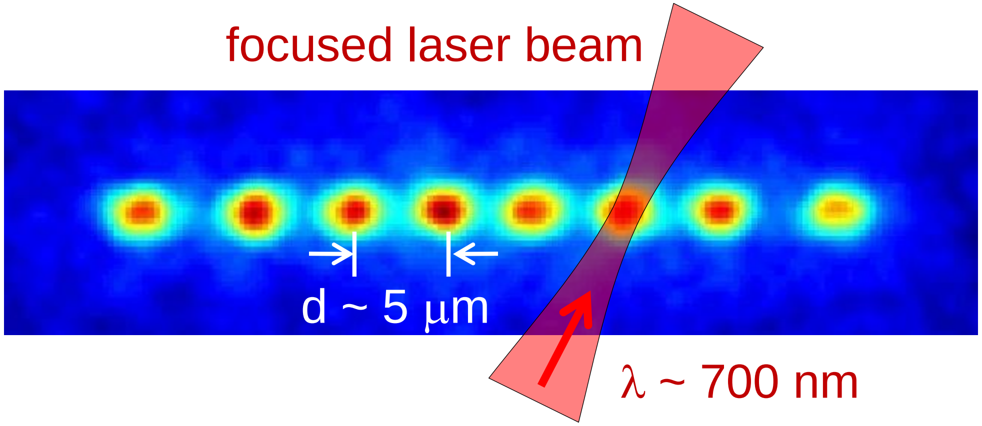
Length scales

ion distance		laser wavelength		ion localisation		Bohr radius
d	$>$	λ	$>>$	z_0	$>>$	a_0
5 μm		700 nm		10 nm		50 pm

- Spatially resolved fluorescence

- Individual addressing

Quantum physics with ion crystals



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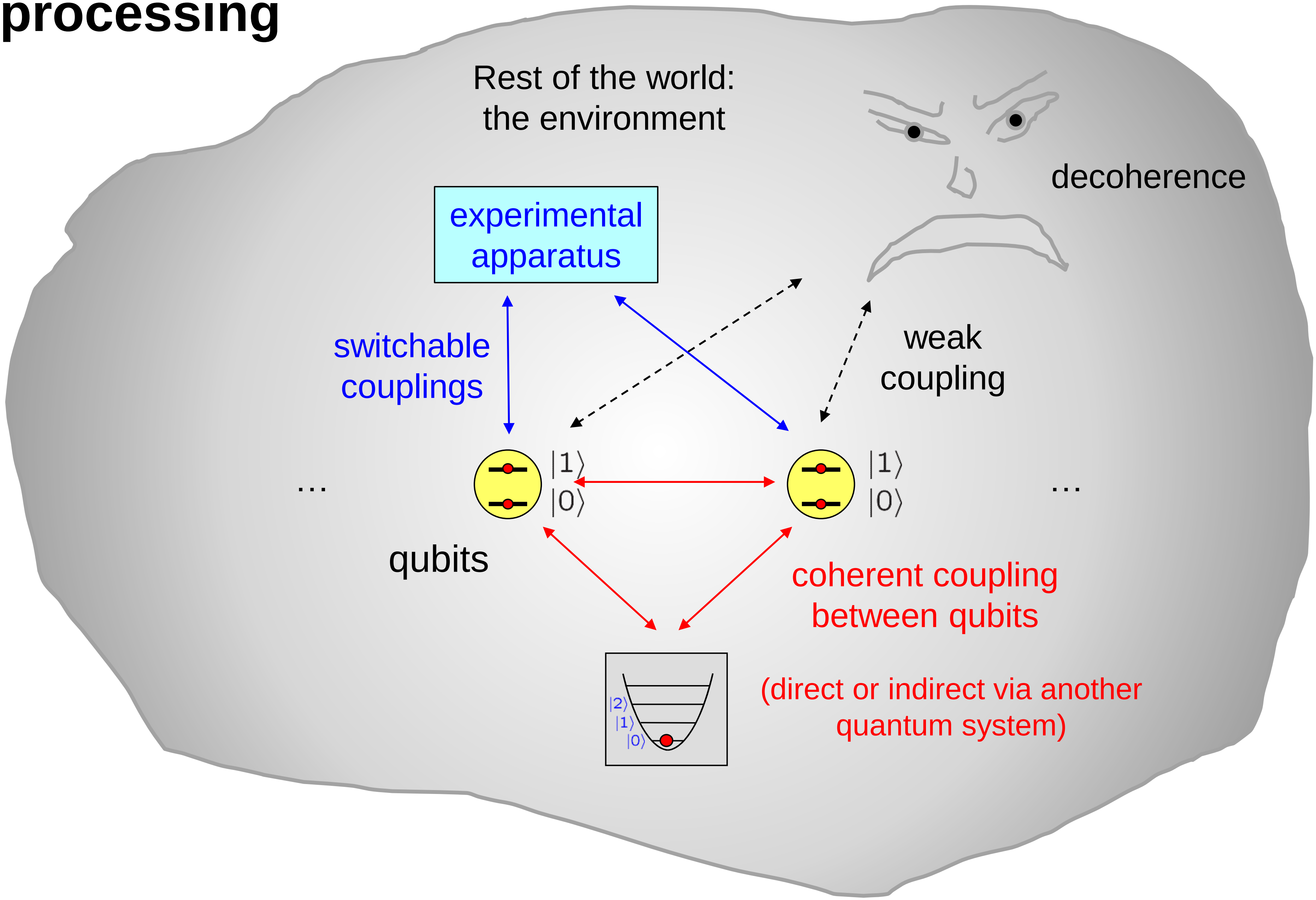
Length scales

ion distance		laser wavelength		ion localisation		Bohr radius
d	$>$	λ	$\gg$	z_0	$\gg$	a_0
5 μm		700 nm		10 nm		50 pm

- Spatially resolved fluorescence
- Individual addressing
- No direct state-dependent interactions between ions

Experimental requirements for quantum information processing



Isolating ions from their environment

In experiments, we want to avoid

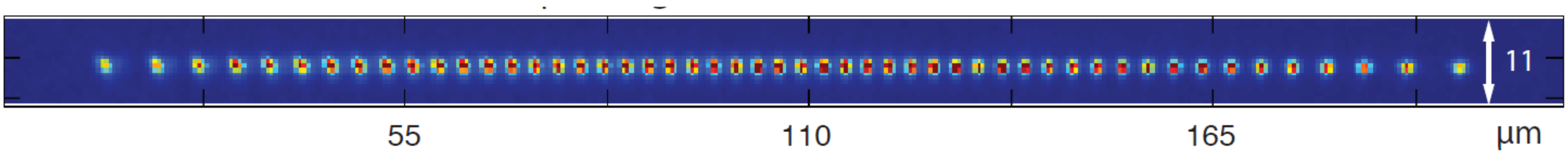
- Ion loss by collisions with the background gas
- Motional heating by fluctuating electric fields and motional dephasing
- Decoherence by spontaneously scattered photons
- Dephasing by fluctuating magnetic fields and laser phase noise
- Decoherence by fluctuating control parameters (laser intensity,…)
- Decoherence induced by the ion motion
- Disturbance by the time-varying fields of a radiofrequency trap
- …

⇒ Ultrahigh vacuum, stable lasers, many feedback systems for keeping parameters stable

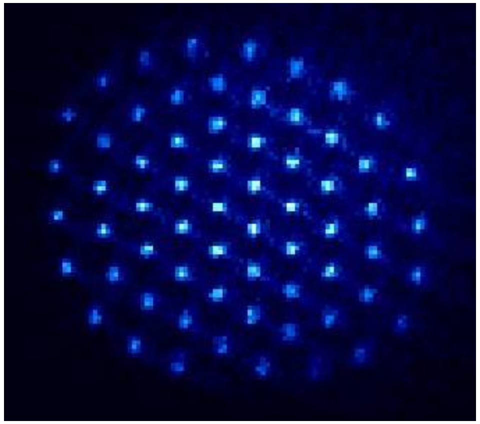
Ion crystals for quantum physics experiments: crystal configurations

Harmonic potential: ratio of trapping frequencies determines the crystal structure

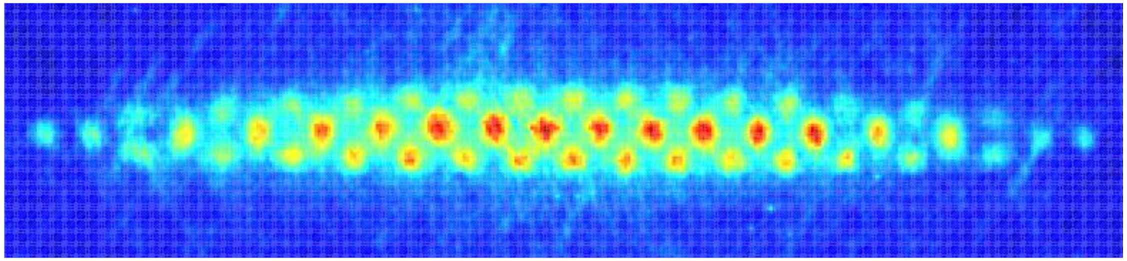
1d: Linear strings



2d: Planar crystals



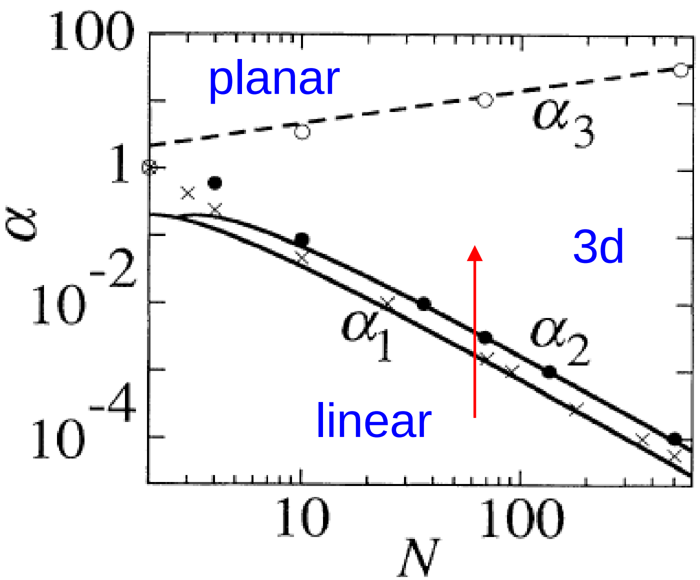
3d: three-dimensional structures



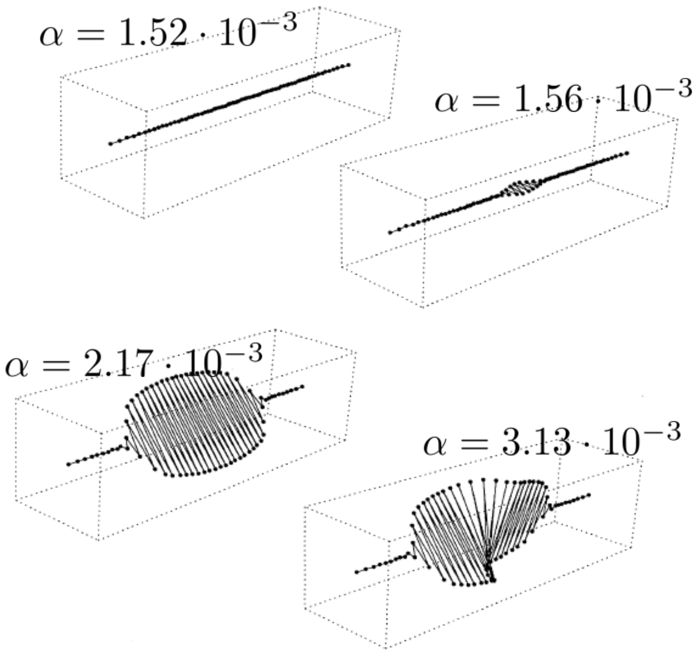
Structural phases of ion crystals

Harmonic potential: ratio of trapping frequencies determines the crystal structure

Anisotropy parameter $\alpha = \omega_z^2/\omega_\perp^2$



D. Dubin, PRL 71, 2753 (1993)



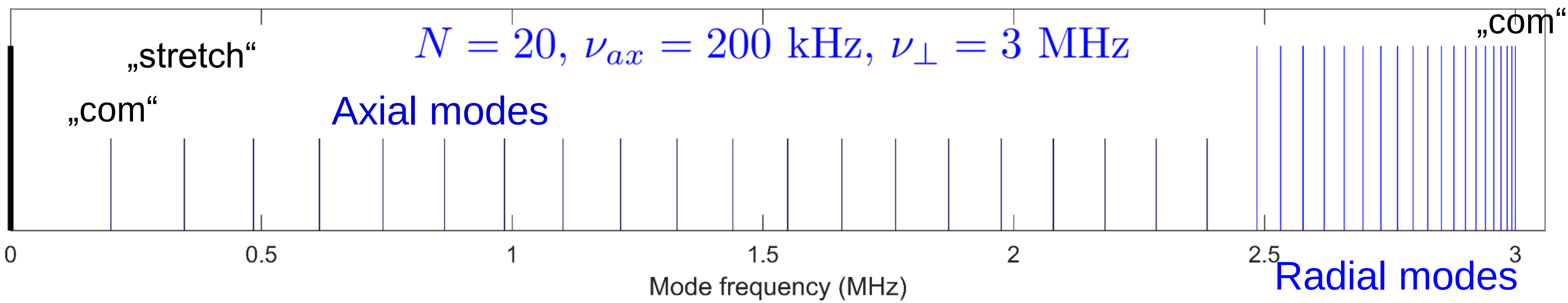
J. Schiffer, PRL 70, 818 (1993)

Ion strings in linear radiofrequency traps
(2d-rf quadrupole + axial confinement by dc electric potential)

All ions are at locations that are micromotion-free

Collective motional modes of ion crystals

Linear strings: collective modes decouple into axial and transverse modes



- Axial center-of-mass mode spectrally well separated

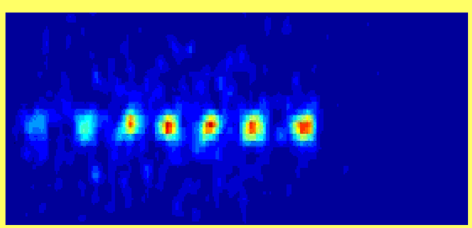
  ⇨ enables coupling to a single oscillator

- Radial modes cluster in frequency space

  ⇨ enables coupling to many oscillators

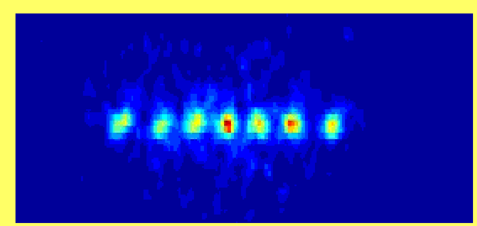
centre-of-mass mode

$\nu = \nu_z$



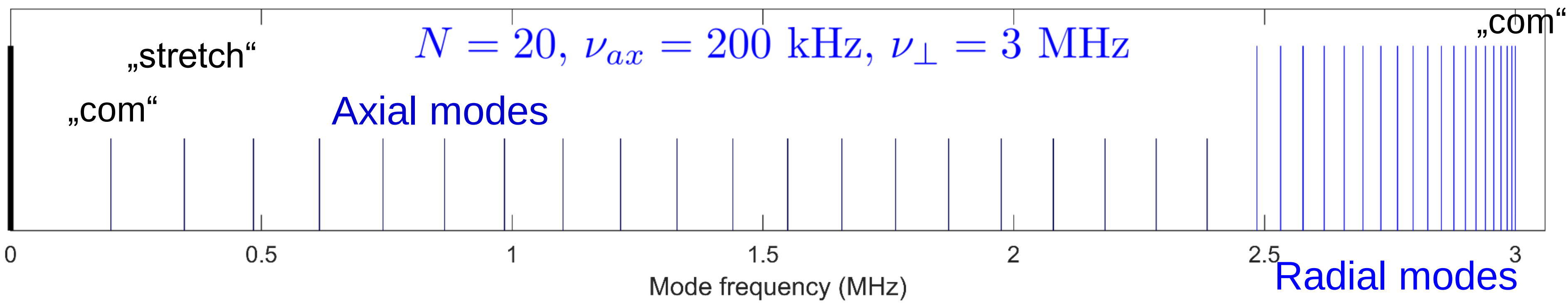
stretch mode

$\nu = \sqrt{3}\,\nu_z$



Collective motional modes of ion crystals

Linear strings: collective modes decouple into axial and transverse modes



- Axial center-of-mass mode spectrally well separated

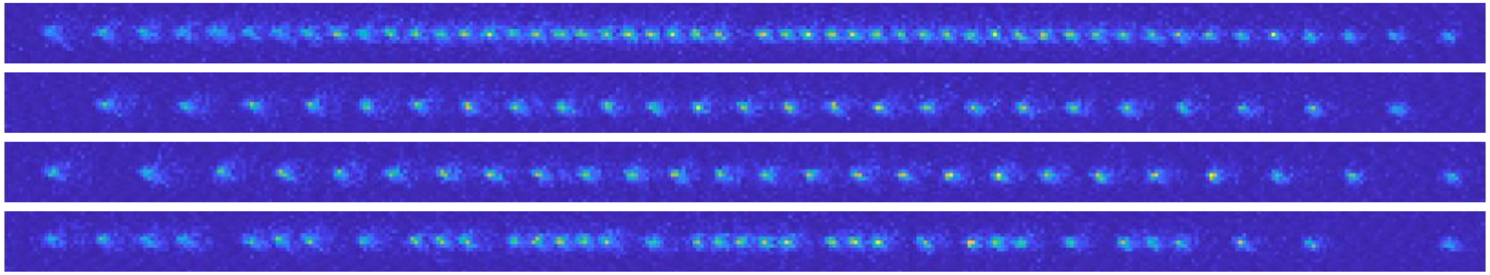
  ⇒ enables coupling to a single oscillator

- Radial modes cluster in frequency space

  ⇒ enables coupling to many oscillators

Planar crystals: collective modes decouple into 2N in-plane and N out-of-plane modes

Quantum control of long ion strings



- Laser cooling techniques

  EIT cooling and polarization gradient cooling

- Controlling individual ion qubits

  Coherent global control and individual addressing

- Quantum measurements of ion qubits

  Measurement in different bases; correlation measurements

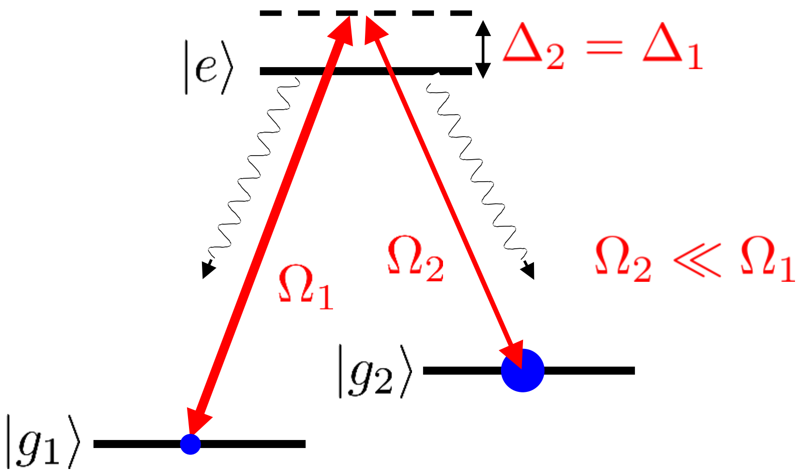
- Entangling interactions by coupling to motional states

  Mølmer-Sørensen interactions and other geometric phase gates

Laser cooling: Schemes and performance metrics

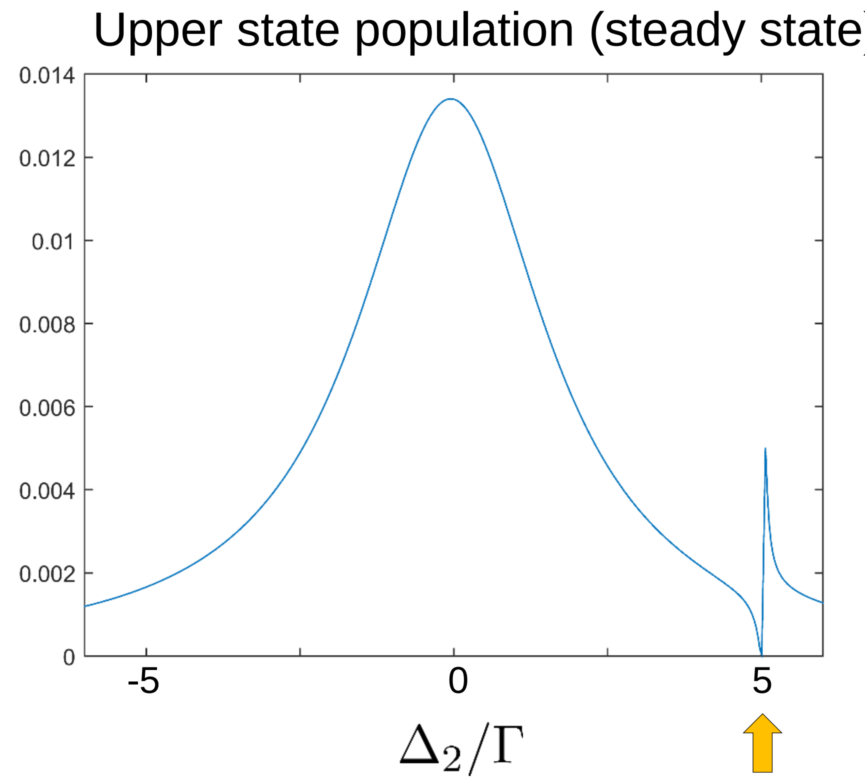
	Final energy	Initial temperature	Cooling speed	Frequency range
Doppler cooling	low	high	high	very high
Resolved Sideband cooling	$\langle n \rangle \approx 0$	low	low	low
EIT cooling	$\langle n \rangle \approx 0$	low	decent	decent
Polarization gradient cooling	sub-Doppler	low	high	high

Cooling by electromagnetically induced transparency (EIT)



Dark state:

$$|g_-\rangle \sim \Omega_2|g_1\rangle + \Omega_1|g_2\rangle$$

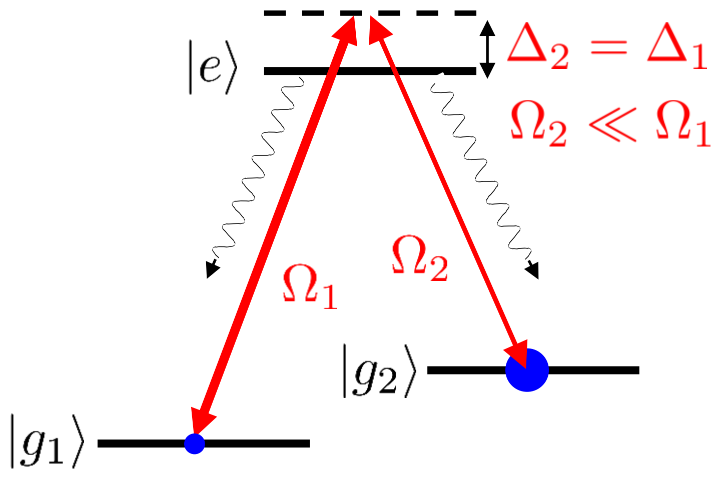


EIT cooling scheme:

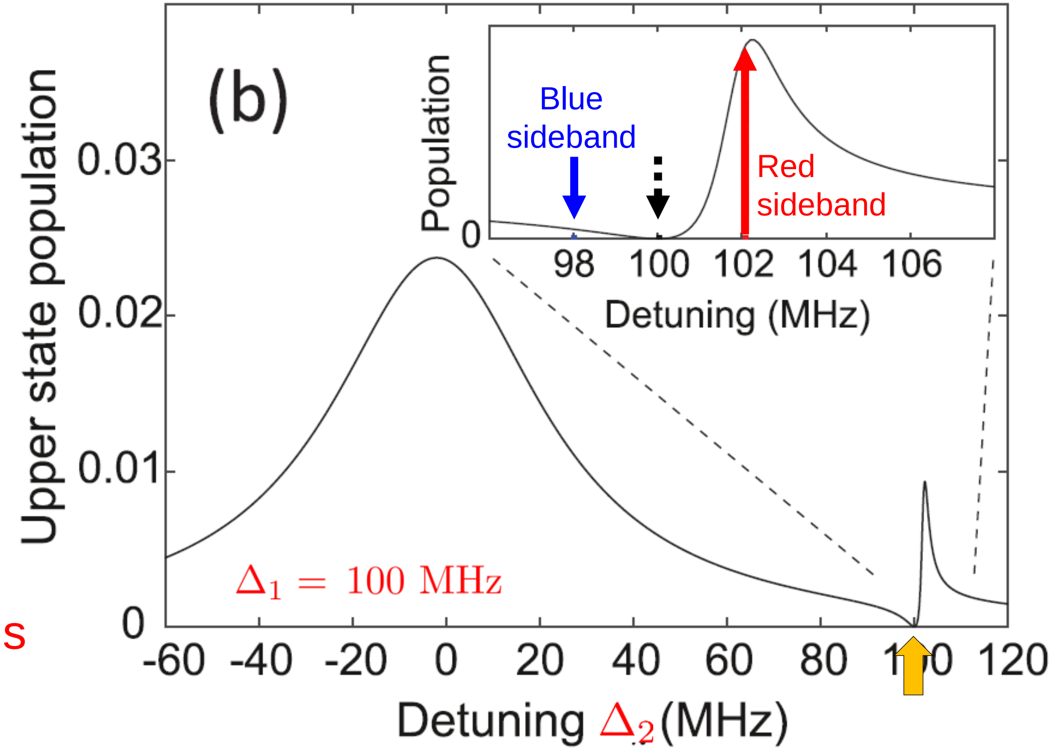
A strong blue-detuned "dressing" beam couples levels $|g_1\rangle$ and $|e\rangle$.
A weak probe beam with detuning $\Delta_2 = \Delta_1$ couples levels $|g_1\rangle$ and $|e\rangle$.
Together, both beams pump the atom into the dark state $|g_-\rangle$, which is has a high overlap with $|g_2\rangle$.

What happens if the atom is free to move in a trap?

EIT cooling scheme: trapped atom



(counter-propagating cooling beams required)

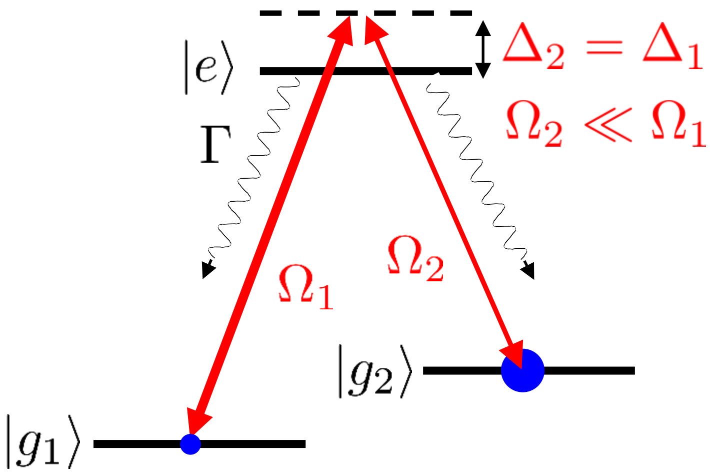


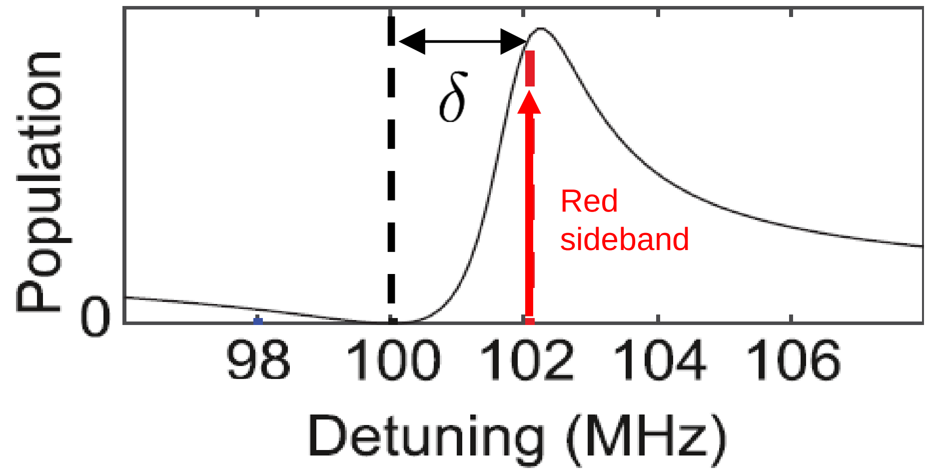
EIT cooling scheme:

An atom in state $|g_-\rangle$ cannot be excited on the carrier transition and very little by a blue sideband process. But it can be excited on the red sideband if the narrow bright resonance is resonant with the sideband.

Ground-state cooling becomes possible!

EIT cooling scheme parameters





The position and width of the bright resonance can be tailored by properly choosing Ω_1 and Δ_1.

- Position controlled by light shift $\delta = \frac{\Omega_1^2}{4\Delta_1}$ (controls for which oscillation frequency the cooling is optimal)
- Width controlled by bright resonance decay rate (admixture of $|e\rangle$)

(control of cooling range)

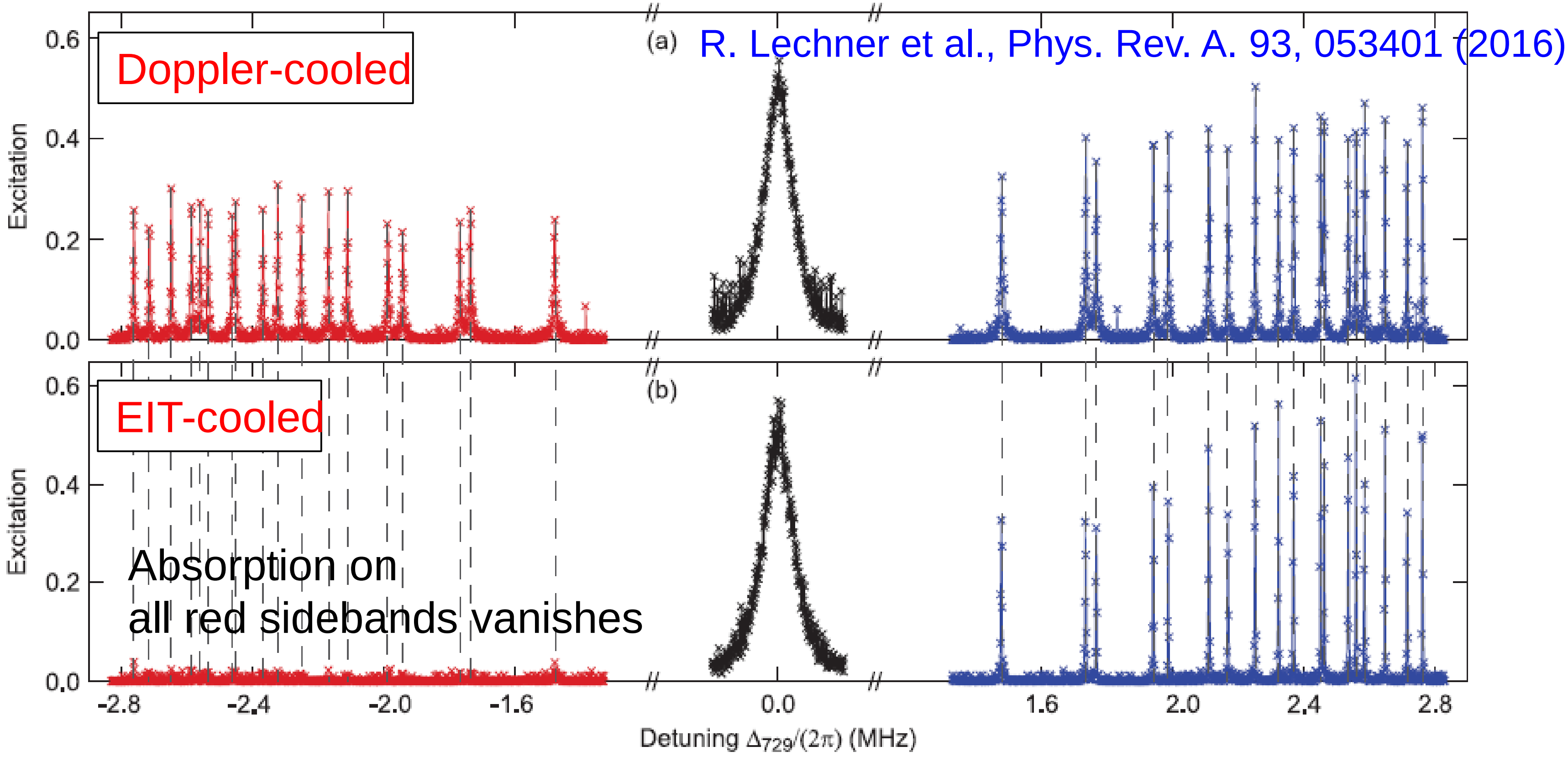
Advantages of the EIT cooling scheme

- There is heating by spontaneous emission from carrier absorption.
  This feature enables ground-state cooling over a wider range of oscillation frequencies
- The absorption profile can be optimally sculpted, resulting in narrow absorption features on a dipole-allowed transition.
- Cooling on a dipole-allowed transition requires less laser power than on a dipole-forbidden transition.
- The frequency stability of the cooling laser is not critical if both beams are derived from the same laser.
- Higher cooling rates can be achieved as compared to sideband cooling.

EIT cooling results

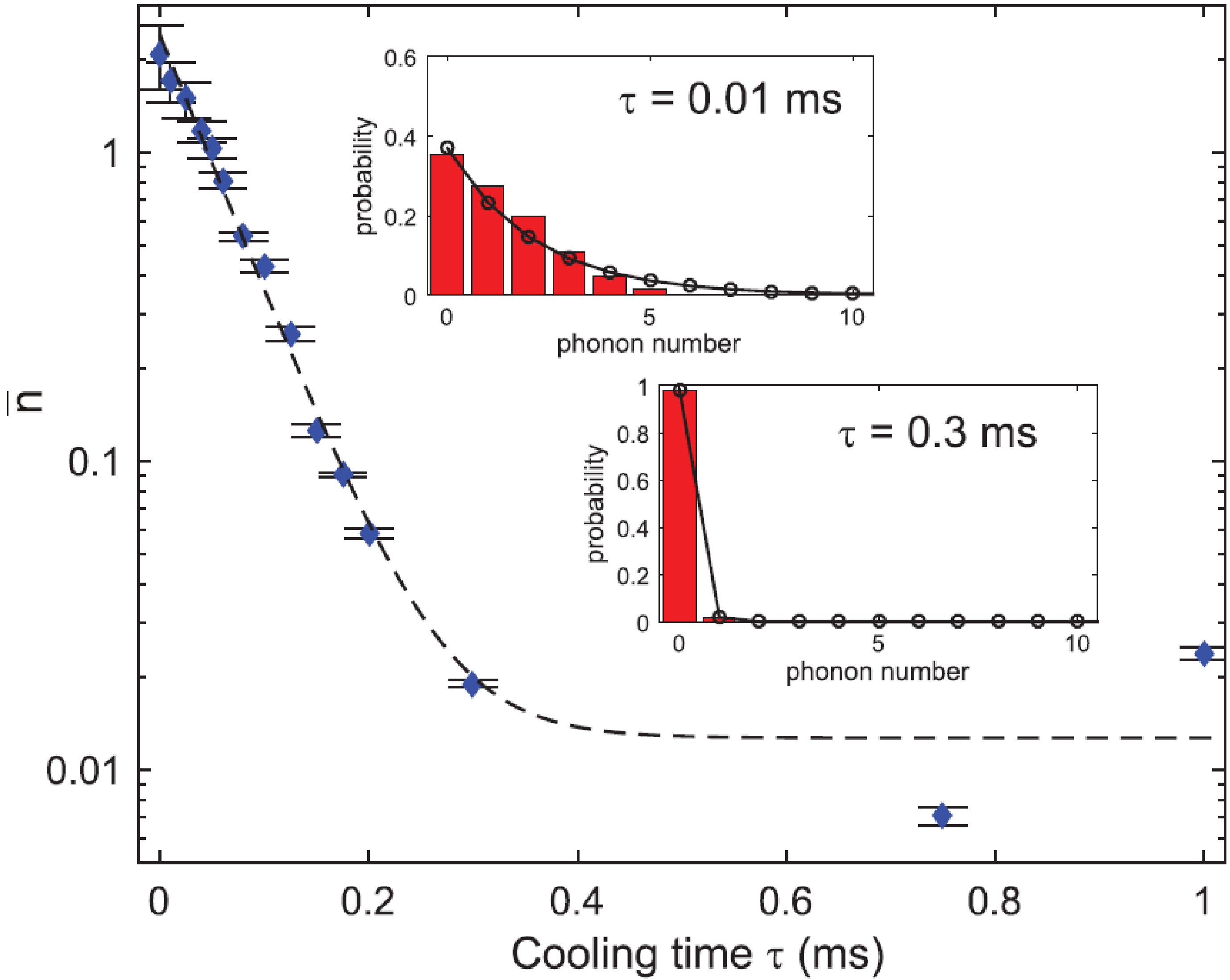
Proposal: Phys. Rev. Lett. 85, 4458 (2000)
First exp: Phys. Rev. Lett. 85, 5547 (2000)

EIT-cooling of all transverse modes of a 9-ion crystal



Here, ground-state cooling is confirmed by sideband spectroscopy on a dipole-forbidden transition.

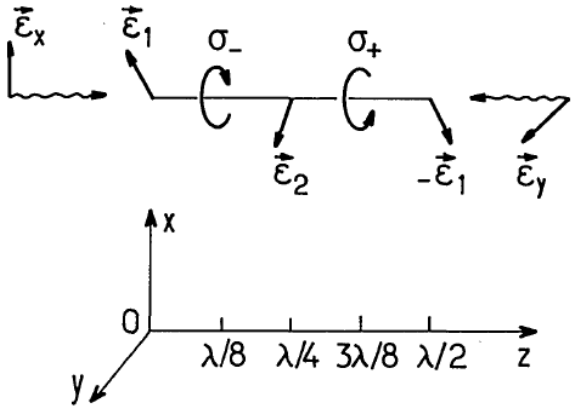
EIT cooling results: 18-ion crystal



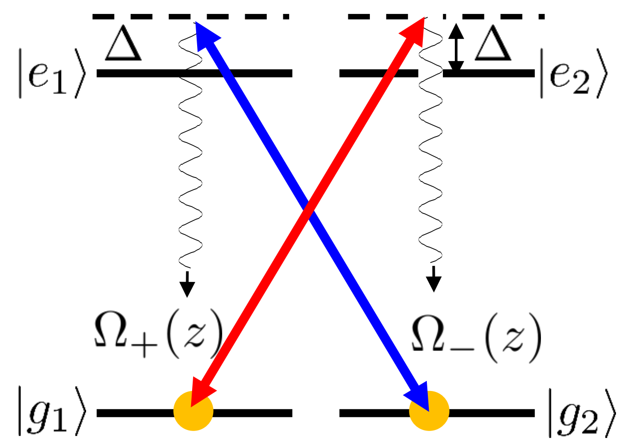
R. Lechner et al., Phys. Rev. A. 93, 053401 (2016)

Polarization gradient cooling of ions

Counterpropagating beams with crossed linear polarizations

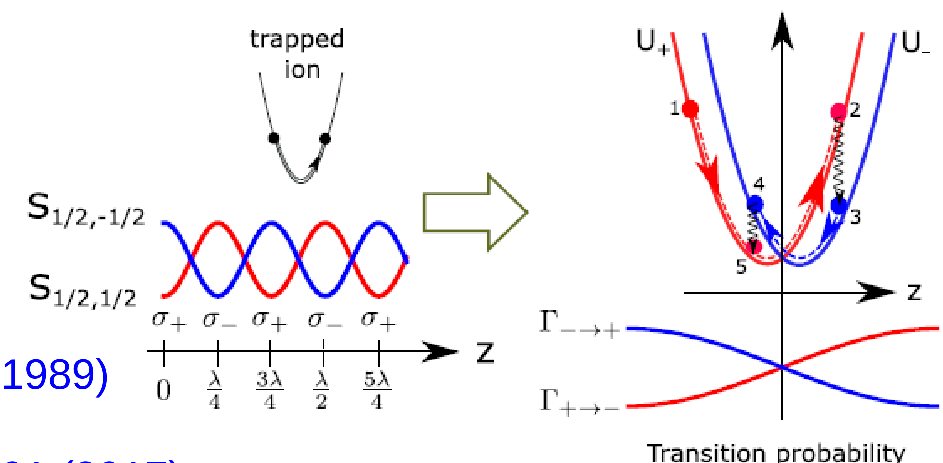


Level scheme and coupled transitions



Cooling principle:

- Position-dependent light shifts
- Position-dependent pumping rates

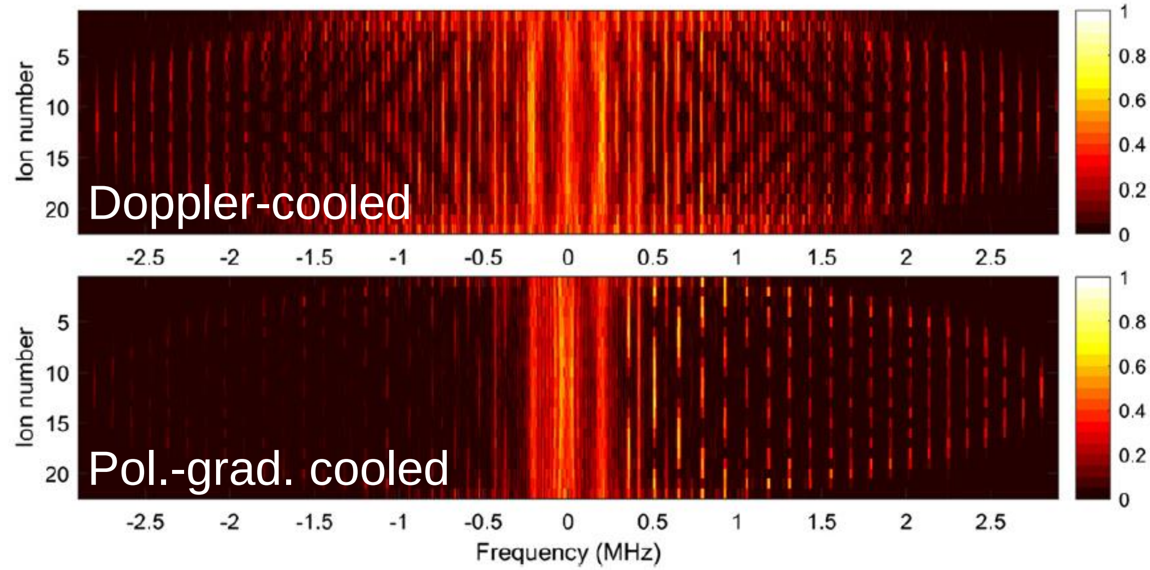


J. Dalibard, C Cohen-Tannoudji, JOSA B **6**, 2023 (1989)
J. I. Cirac et al., Phys. Rev. A **48**, 1434 (1993)
S. Ejtemaee, P. Haljan, Phys. Rev. Lett. **119**, 043001 (2017)
M. K. Joshi et al., NJP **22**, 103013 (2020)

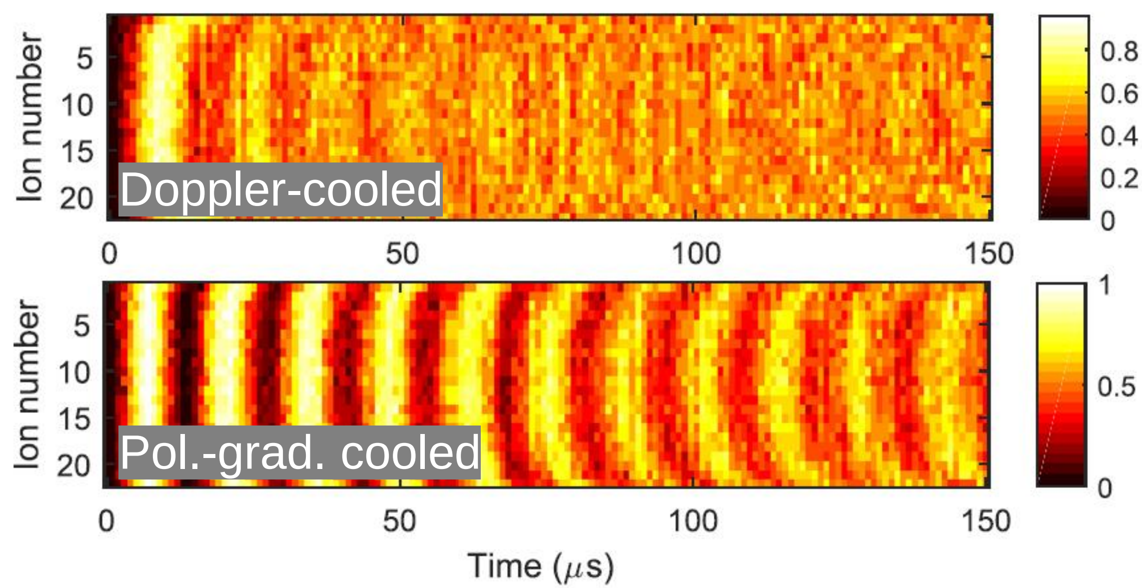
Polarization gradient cooling of ion strings

22-ion string

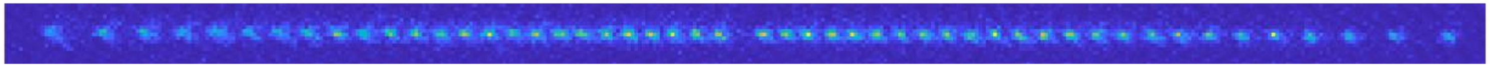
Spatially resolved
Sideband spectrum



Carrier Rabi
oscillations



Experiments with long ion strings



0. Trapping in a very anisotropic potential

$$(\text{for example: } N = 50,\ \nu_{ax} = 130\ \text{kHz},\ \nu_\perp = 3\ \text{MHz})$$

1. Laser cooling:
    1. Doppler cooling into the Lamb-Dicke regime
    2. Sideband cooling of all transverse modes close to their ground state
    3. Polarization gradient cooling of axial modes to sub-Doppler temp.

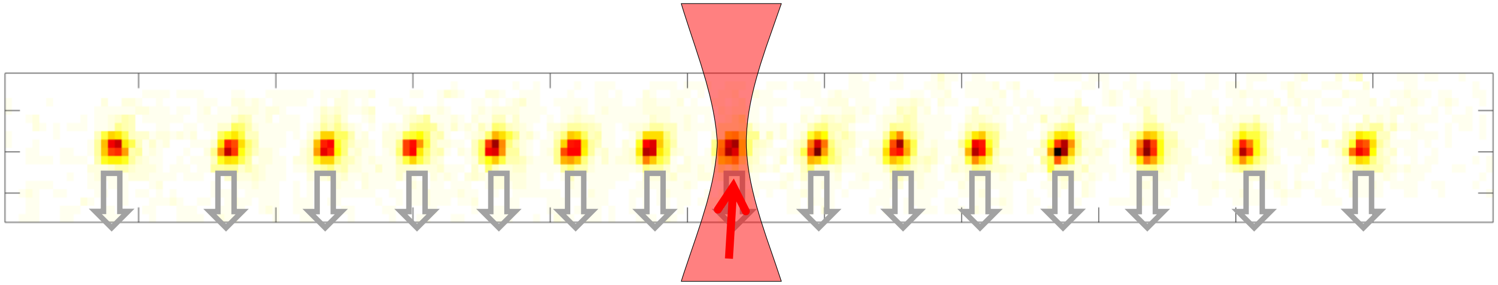
2. Optical pumping

3. Coherent manipulation by laser pulses

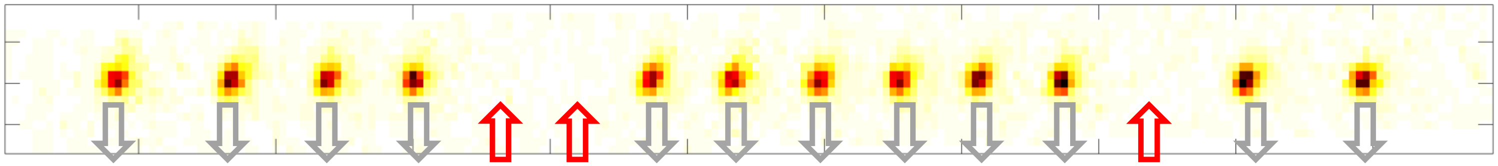
4. Quantum state measurements by spatially resolved fluorescence with CCD camera

Measurement and coherent control of single ions

Spatially resolved fluorescence: detection of individual spin states

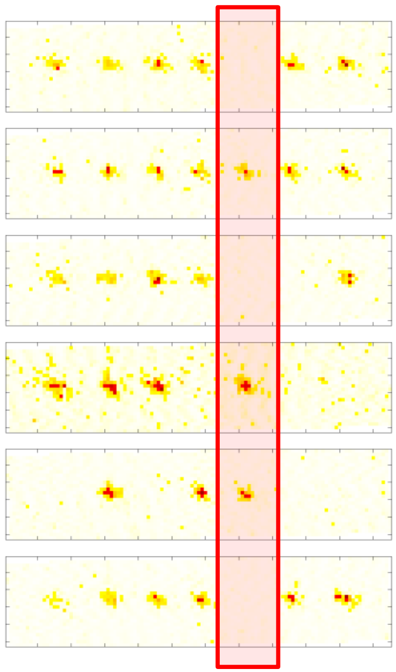


focused steerable laser beam: coherent single-spin manipulation



beam switching time ~ 10 μs

Measuring spins and spin correlations



$\equiv |\downarrow\downarrow\downarrow\downarrow\rightarrow\downarrow\downarrow\rangle$

$\equiv |\downarrow\downarrow\downarrow\downarrow\leftarrow\downarrow\downarrow\rangle$

$\equiv |\downarrow\downarrow\downarrow\downarrow\rightarrow\uparrow\downarrow\rangle$

$\equiv |\downarrow\downarrow\downarrow\uparrow\leftarrow\uparrow\uparrow\rangle$

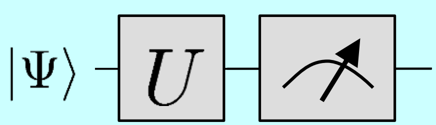
$\equiv |\uparrow\downarrow\uparrow\downarrow\leftarrow\uparrow\uparrow\rangle$

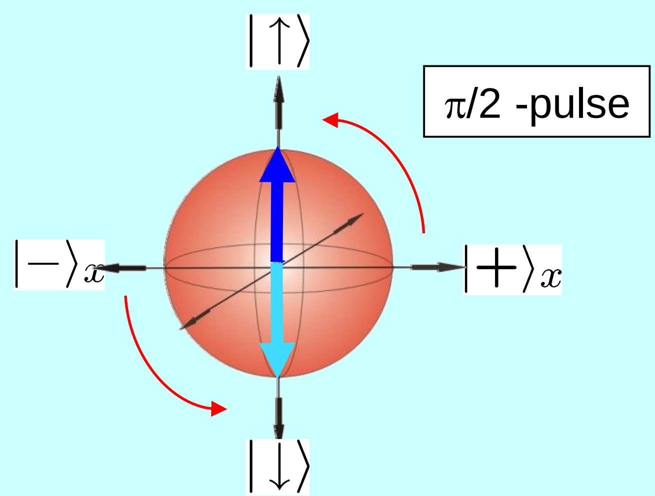
$\equiv |\downarrow\downarrow\downarrow\downarrow\rightarrow\downarrow\downarrow\rangle$

⇨ any correlation $\langle \sigma^{(1)}_{\alpha_1} \sigma^{(2)}_{\alpha_2} \dots \sigma^{(N)}_{\alpha_N} \rangle$ can be measured.

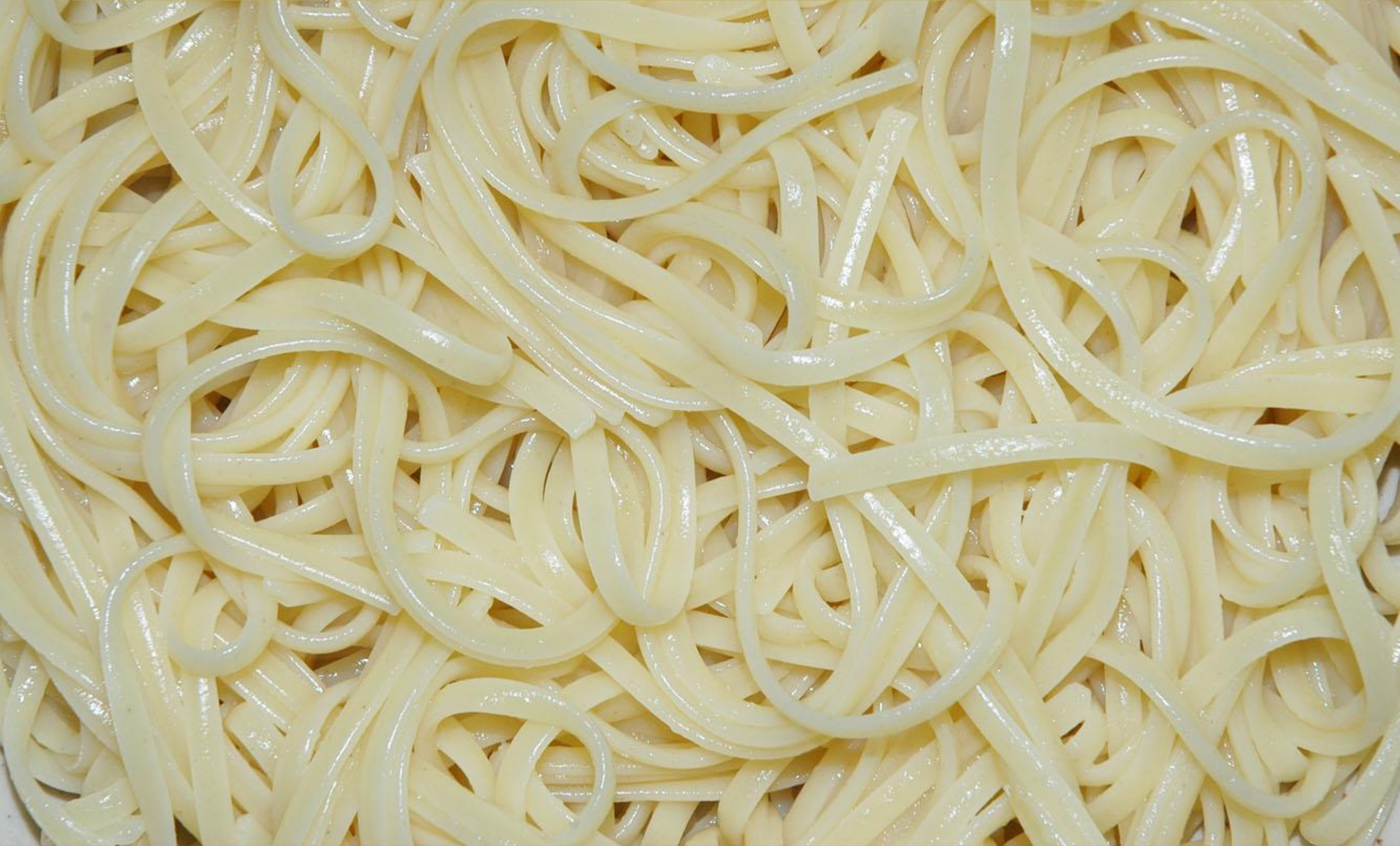
Measurement of σ_x

(single)-spin rotation +
fluorescence measurement

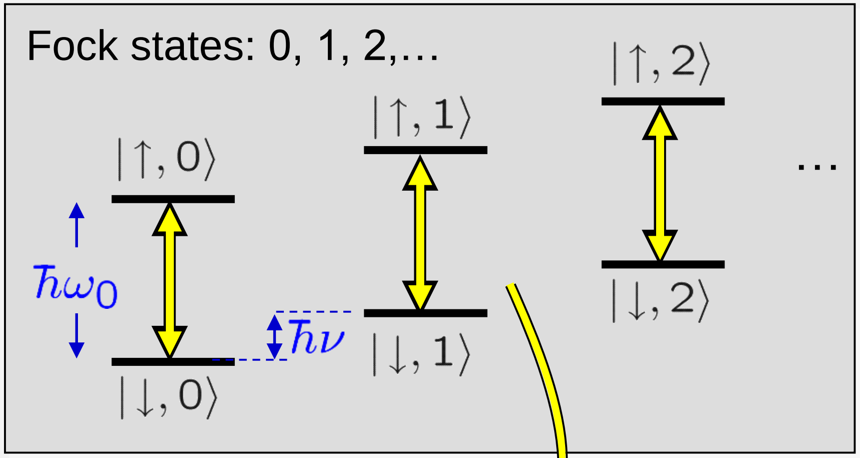




Entangling interactions in trapped-ion experiments



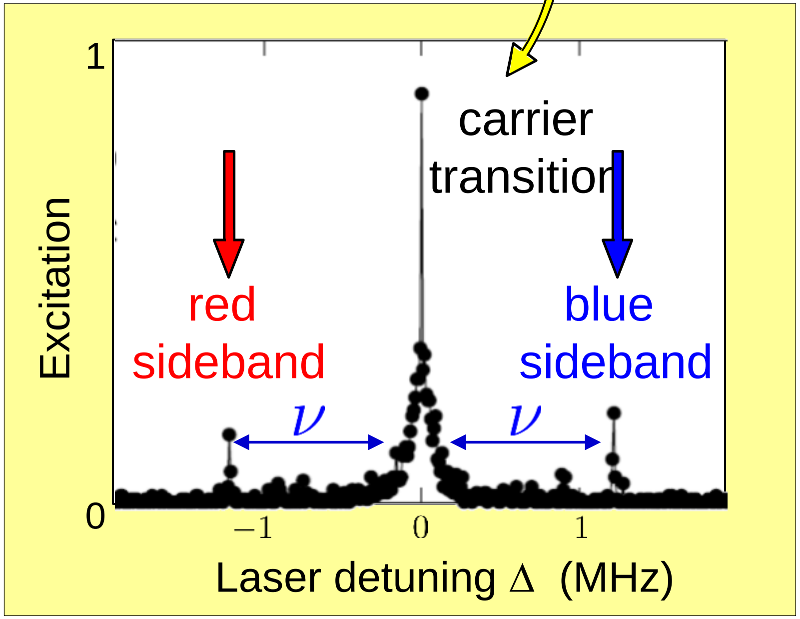
Trapped-ion laser interactions



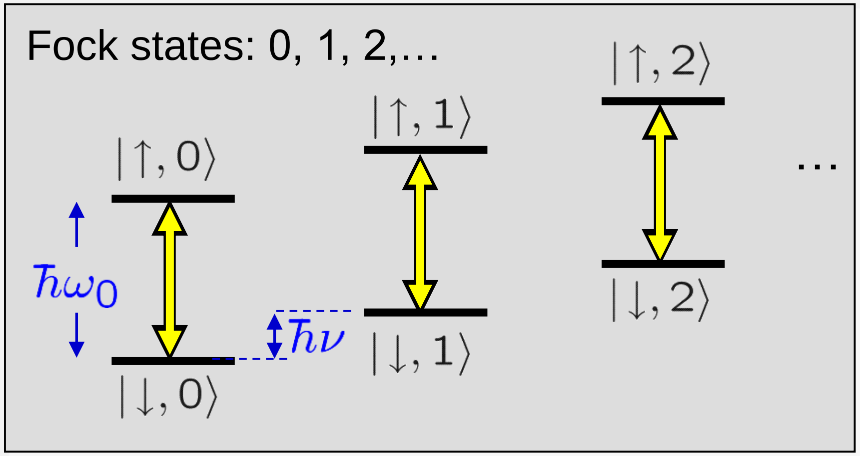
qubit manipulation

$$\omega_{laser} = \omega_0$$

$$H \propto \sigma_x$$



Trapped-ion laser interactions



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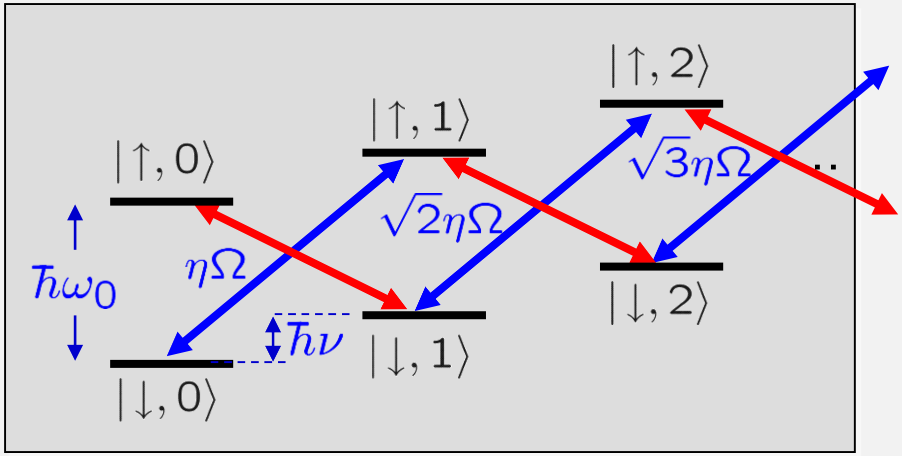


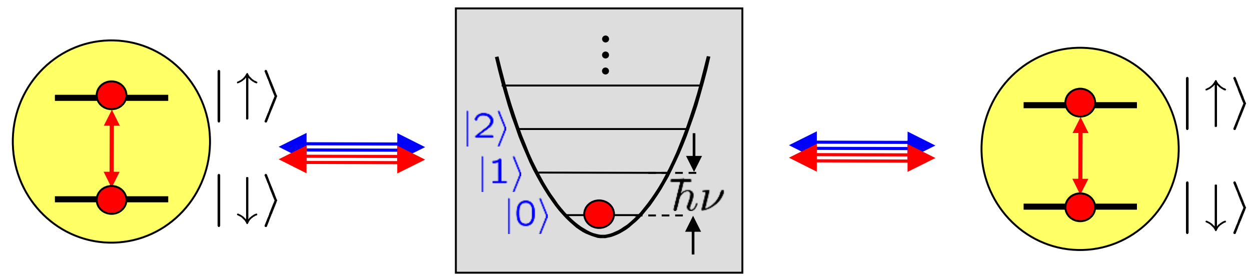
qubit-motion coupling

$$\omega_{laser} = \omega_0 \pm \nu$$

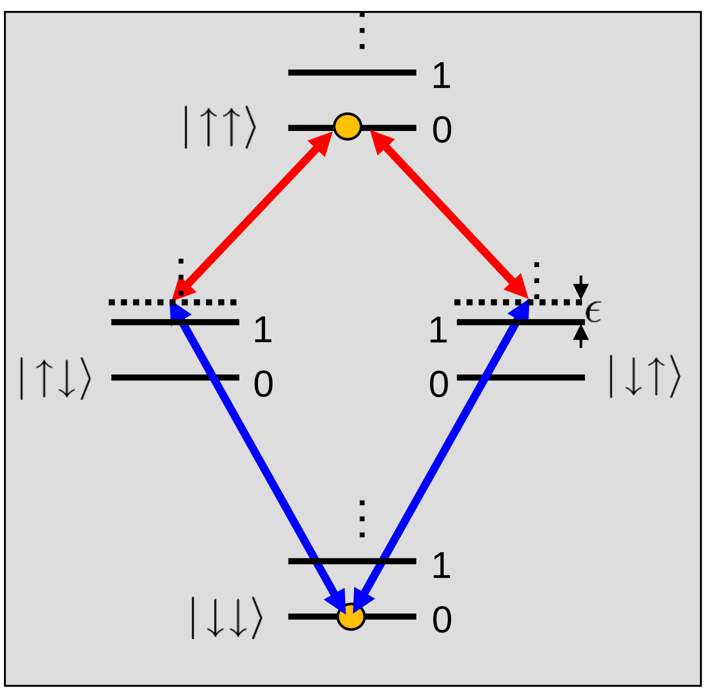
$$H \propto \ (a + a^\dagger)\sigma_x$$

Entangling a pair of ions

Coupling of internal states
via the ion motion



A. Sørensen, K. Mølmer,
Phys. Rev. Lett. **82**, 1971 (1999)



Effective spin-spin interaction

$$|\downarrow\downarrow\rangle \longleftrightarrow |\uparrow\uparrow\rangle$$

$$|\downarrow\uparrow\rangle \longleftrightarrow |\uparrow\downarrow\rangle$$

Creating entanglement:

$$|\downarrow\downarrow\rangle \longrightarrow |\downarrow\downarrow\rangle + |\uparrow\uparrow\rangle$$

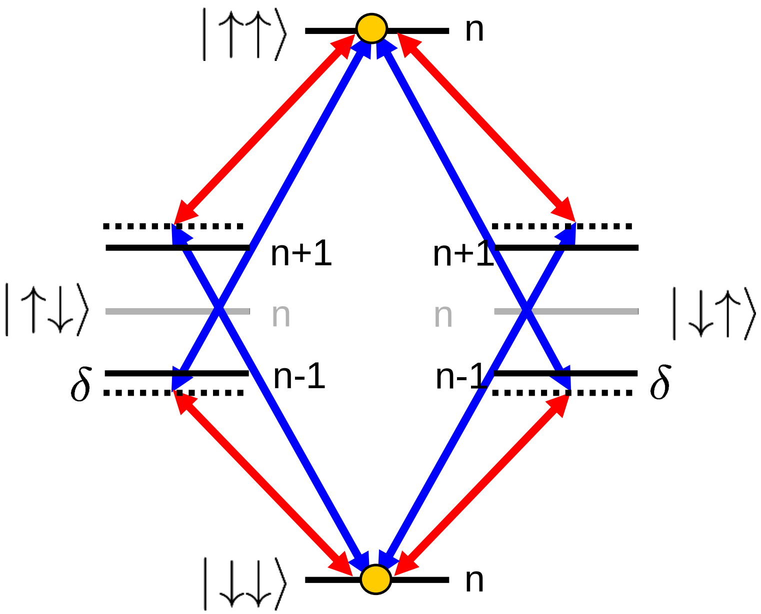
$$H_{eff} = \hbar J \sigma_1^x \sigma_2^x$$

The coupling does not depend on the motional state:

In order to calculate the two-photon coupling strength $\Omega_{\downarrow\downarrow,\uparrow\uparrow}$ between the levels $|\downarrow\downarrow, n\rangle$ and $|\uparrow\uparrow, n\rangle$, we need to sum up four contributions where the coupling is mediated by the intermediate states $|\downarrow\uparrow, n+1\rangle$, $|\uparrow\downarrow, n+1\rangle$, $|\downarrow\uparrow, n-1\rangle$, $|\uparrow\downarrow, n-1\rangle$. We find

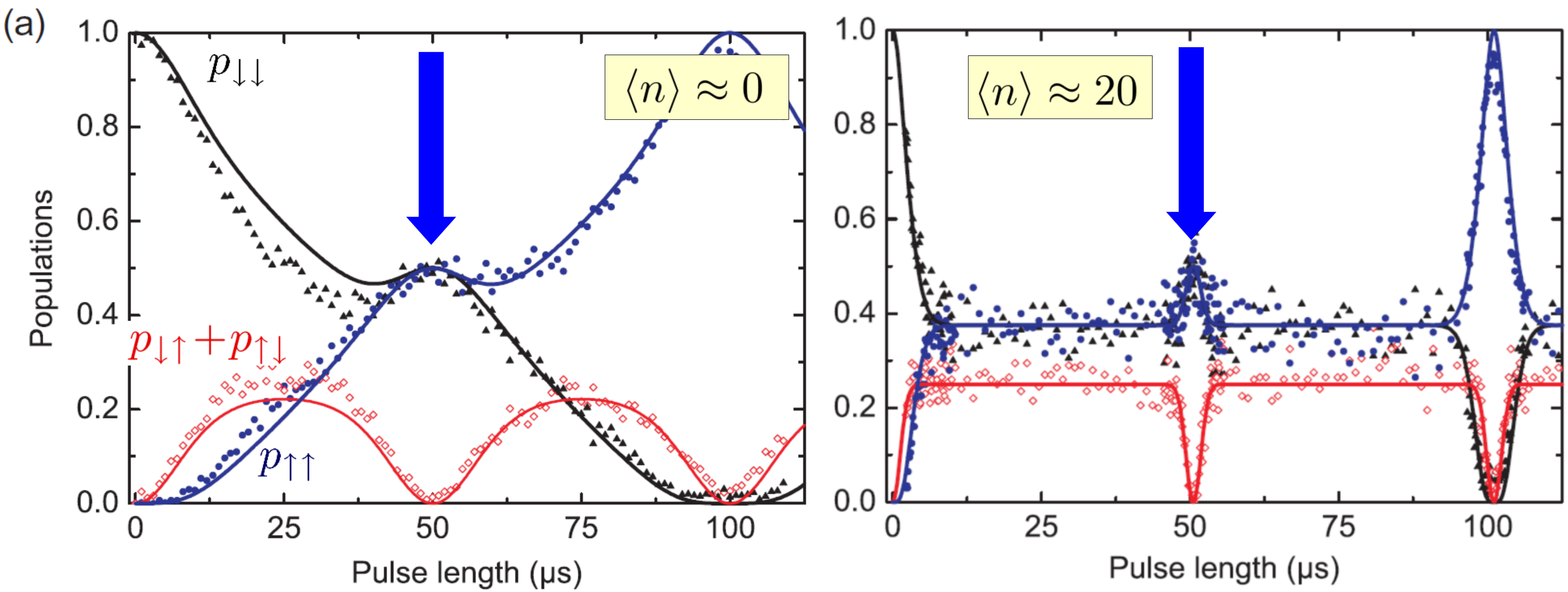
$$\begin{aligned}\Omega_{\downarrow\downarrow,\uparrow\uparrow} &= 2\left[\frac{(\eta\Omega\sqrt{n})(\eta\Omega\sqrt{n})}{\delta} + \frac{(\eta\Omega\sqrt{n+1})(\eta\Omega\sqrt{n+1})}{-\delta}\right] \\ &= -4\frac{\eta^2\Omega^2}{\delta}\end{aligned}$$

where we took into consideration that the detuning of the lasers from the intermediate levels is opposite when coupling to levels with $n+1$ and $n-1$ phonons and that the coupling strength on the second step of the transition needs to be calculated for a vibrational phonon number of $n+1$ and $n-1$ respectively.



Creating Bell states with Mølmer-Sørensen gates

$$|\downarrow\downarrow\rangle \longrightarrow |\downarrow\downarrow\rangle + i|\uparrow\uparrow\rangle$$



$\tau_{gate} = 50\,\mu s$

F=99.3(1) Fidelity F=97.4(1)

$p_{\downarrow\downarrow}+p_{\uparrow\uparrow}$ = 0.9965(4) 13,000 measurements

J. Benhelm *et al.*, Nature Phys. **4**, 463 (2008)

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

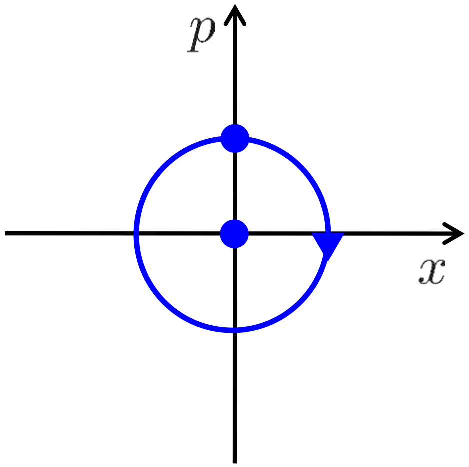
Geometric phases: Another way to understand Mølmer-Sørensen and related gates

1. Driven harmonic oscillator: phase space picture

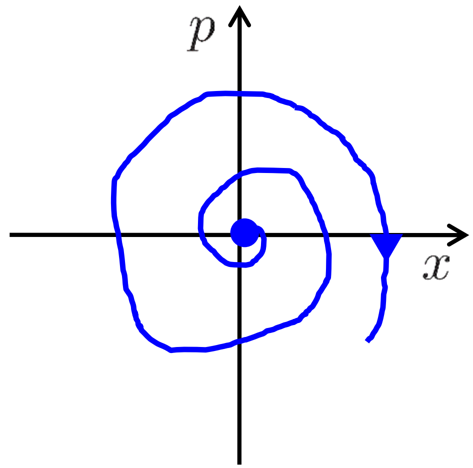
2. Driven harmonic oscillator with qubit state-dependent coupling

Classical harmonic oscillator in phase space

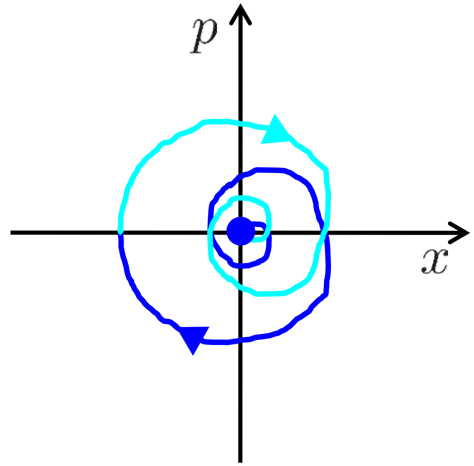
Phase space trajectory
of harmonic oscillator



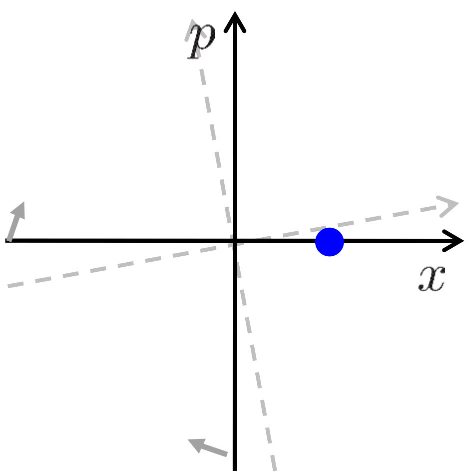
Resonantly driven
harmonic oscillator

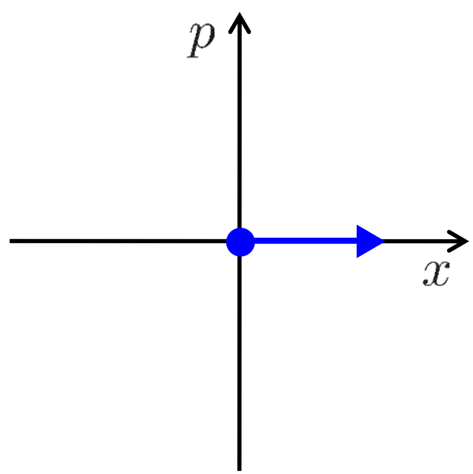


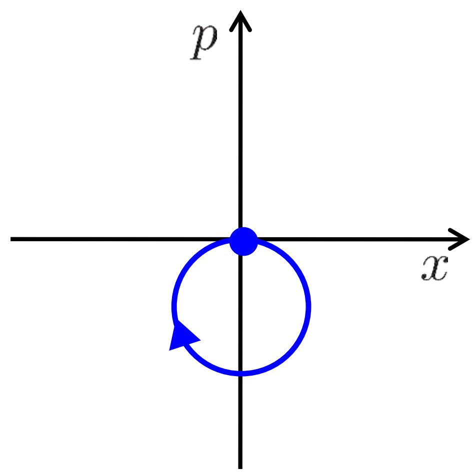
Off-resonantly driven
harmonic oscillator



Rotating frame: get rid of the boring oscillation

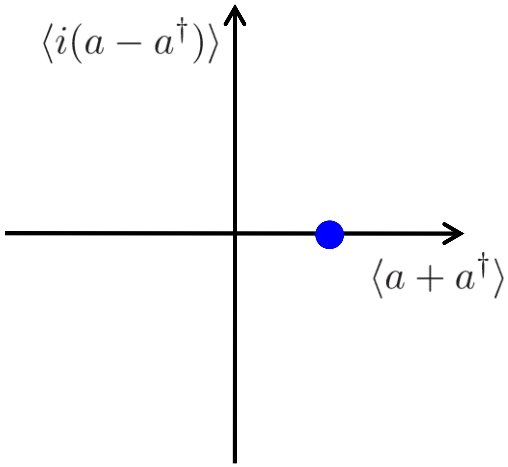




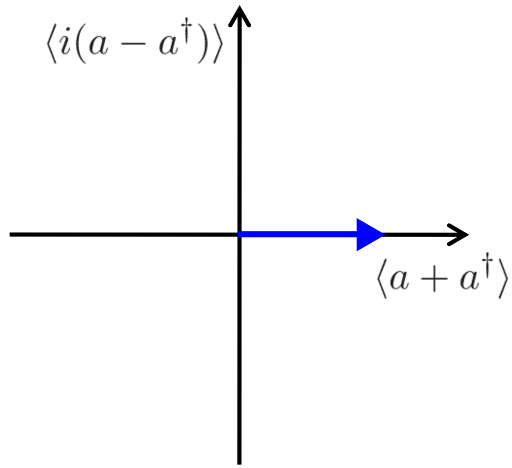


Quantum harmonic oscillator in phase space

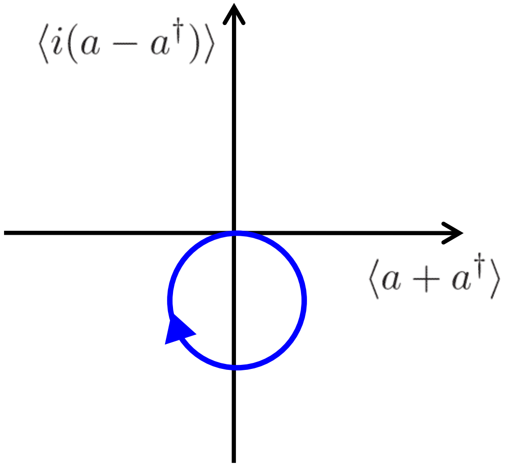
Free harmonic oscillator



Resonantly driven harmonic oscillator



Off-resonantly driven harmonic oscillator

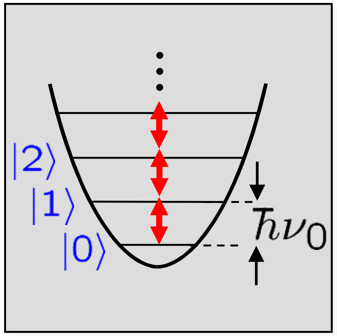


Hamiltonian driving the motion:

$$H = 0 \qquad H = \hbar\Omega i(a - a^\dagger) \qquad H = \hbar\Omega i(a e^{i\delta t} - a^\dagger e^{-i\delta t})$$

Driven quantum harmonic oscillator

Harmonic oscillator



$$H(t) = \hbar\nu_0 a^\dagger a \; + \hbar\Omega i(a^\dagger e^{i\nu t} - a e^{-i\nu t})$$

Drive frequency ν

Interaction picture:

$$H_{int} = \hbar\Omega i(a^\dagger e^{i\delta t} - a e^{-i\delta t})\,, \quad \delta = \nu - \nu_0$$

Time evolution:

$$U(t) = \lim_{n\to\infty} \prod_{k=1}^{n} \exp(-\frac{i}{\hbar} H(t_k)\Delta t) \qquad \Delta t = t/n$$

$$t_k = k\Delta t$$

Displacement operator:

$$\hat{D}(\gamma) = e^{\gamma a^\dagger - \gamma^* a}$$

Baker-Campbell-Hausdorff formula:

$$e^A e^B = e^{A+B} e^{\frac{1}{2}[A,B]} \text{ if } [A,[A,B]] = [B,[A,B]] = 0$$

Driven quantum harmonic oscillator

Time evolution:

$$U(t) = \lim_{n\to\infty} \prod_{k=1}^{n} \exp(-\frac{i}{\hbar} H(t_k)\Delta t) = \lim_{n\to\infty} \prod_{k=1}^{n} \hat{D}(\Omega e^{i\delta t_k}\Delta t)$$

$$= \hat{D}(\alpha(t)) e^{i\Phi(t)} \quad \text{with} \qquad \alpha(t) = i\left(\frac{\Omega}{\delta}\right)(1 - e^{i\delta t})$$

$$\Phi(t) = \left(\frac{\Omega}{\delta}\right)^2 (\delta t - \sin\delta t)$$

Displacement operator:

$$\hat{D}(\gamma) = e^{\gamma a^\dagger - \gamma^* a}$$

$$\boxed{\hat{D}(\alpha)\hat{D}(\beta) = \hat{D}(\alpha+\beta) e^{i\mathrm{Im}(\alpha\beta^*)}}$$

Baker-Campbell-Hausdorff formula:

$$e^A e^B = e^{A+B} e^{\frac{1}{2}[A,B]} \quad \text{if} \quad [A,[A,B]] = [B,[A,B]] = 0$$

Driven quantum harmonic oscillator

Time evolution:

$$U(t) = \lim_{n\to\infty} \prod_{k=1}^{n} \exp\left(-\frac{i}{\hbar} H(t_k)\Delta t\right) = \lim_{n\to\infty} \prod_{k=1}^{n} \hat{D}(\Omega e^{i\delta t_k}\Delta t)$$

$$= \hat{D}(\alpha(t))e^{i\Phi(t)} \quad \text{with} \qquad \alpha(t) = i\left(\frac{\Omega}{\delta}\right)(1 - e^{i\delta t})$$

$$\Phi(t) = \left(\frac{\Omega}{\delta}\right)^2 (\delta t - \sin\delta t)$$

Time evolution for the ground state: $\psi(t=0) = |0\rangle$

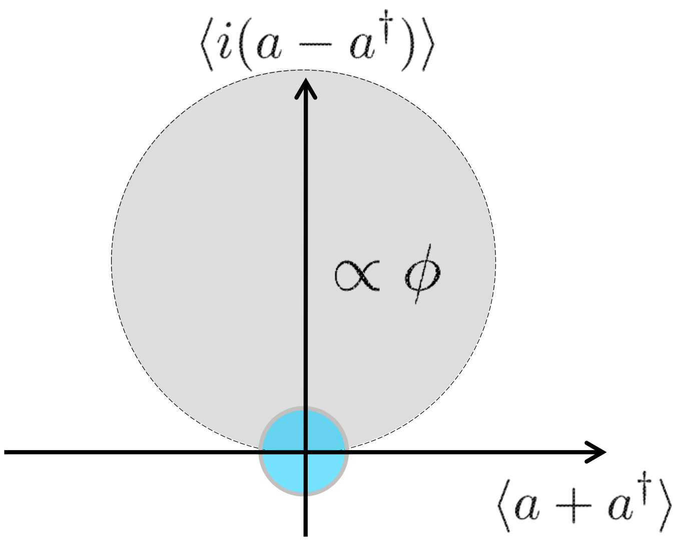
$$U(t)|0\rangle = \hat{D}(\alpha(t))e^{i\Phi(t)}|0\rangle$$

$$= e^{i\Phi(t)}|\alpha(t)\rangle$$

$|\alpha(t)\rangle$: coherent state

Geometric phases in the harmonic oscillator

$$H = \hbar\Omega i(a e^{i\delta t} - a^\dagger e^{-i\delta t})$$



Geometric phase by cyclic quantum evolution:

$$|\psi\rangle \longrightarrow e^{i\phi}\,|\psi\rangle$$

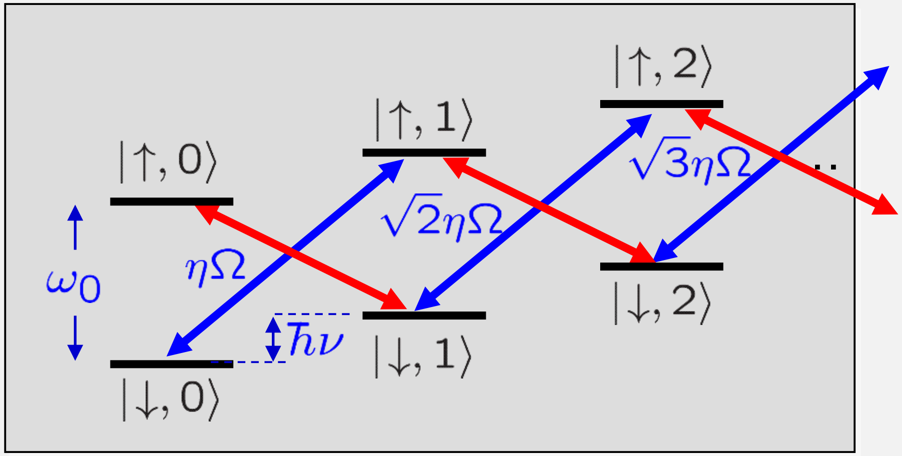
irrelevant global phase

If the phase could be made dependent on the quantum state, the phase would matter:

$$|\psi_1\rangle + |\psi_2\rangle \longrightarrow e^{i\phi_1}\,|\psi_1\rangle + e^{i\phi_2}\,|\psi_1\rangle$$

$\phi \propto$ enclosed area $\propto \Omega^2$ $\longrightarrow$ we need a state-dependent force

State-dependent forces for entangling gates

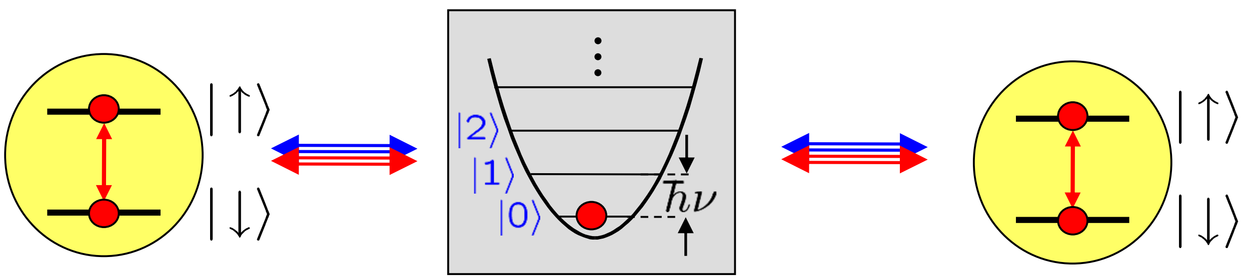


Bichromatic excitation

$$\omega_{laser} = \omega_0 \pm (\nu + \delta)$$

$$H \propto \; (a e^{i\delta t} + a^\dagger e^{-i\delta t})\sigma_x$$

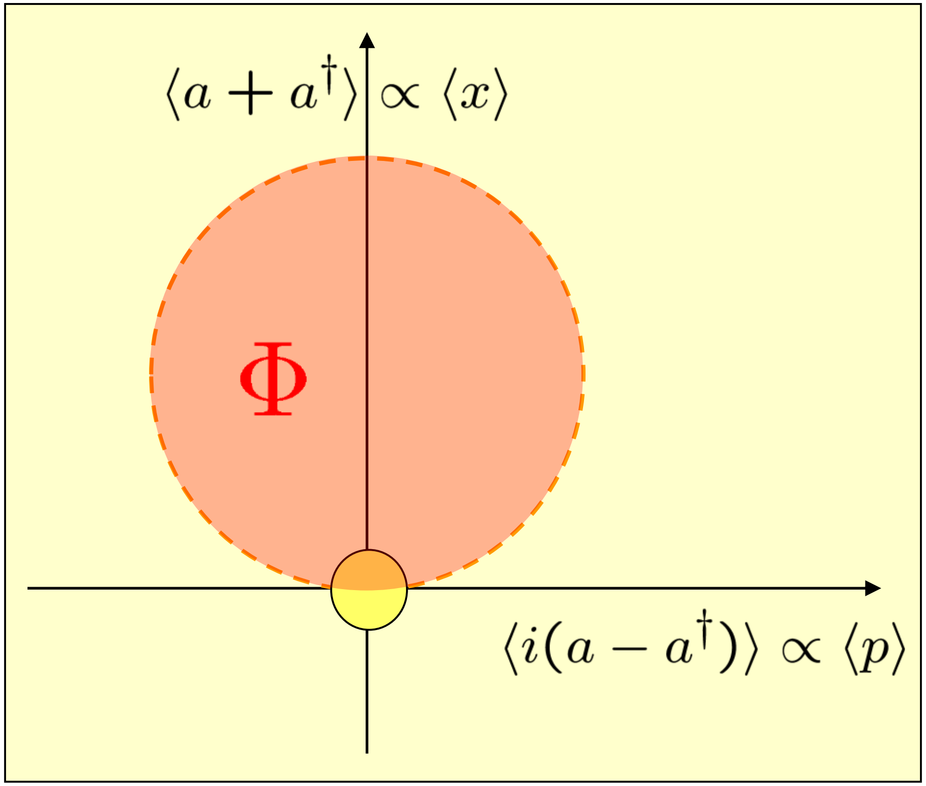
Two ions: $$H \propto \; (a e^{i\delta t} + a^\dagger e^{-i\delta t})(\sigma_x^{(1)} + \sigma_x^{(2)})$$

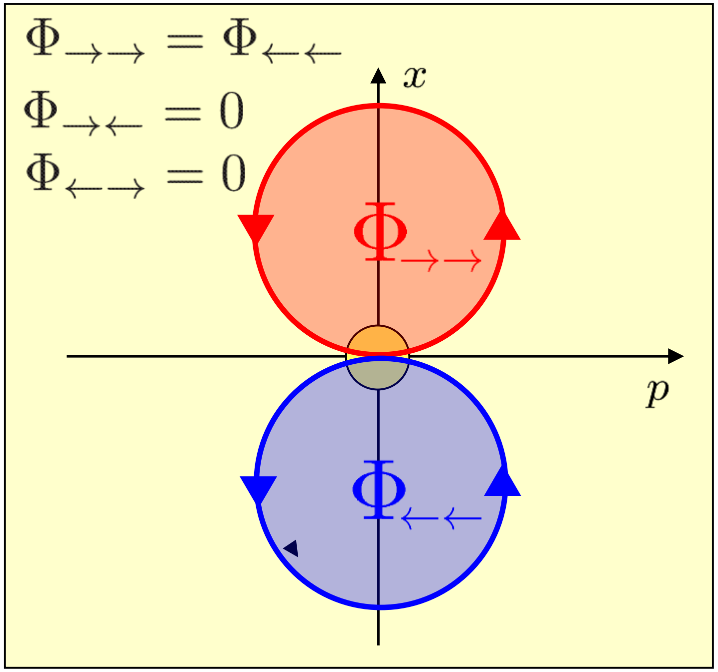


A. Sørensen, K. Mølmer,
Phys. Rev. Lett. **82**, 1971 (1999)

Geometric phase gate

$$H(t) \propto \; (ae^{i\delta t} + a^\dagger e^{-i\delta t})(\sigma_x^{(1)} + \sigma_x^{(2)})$$

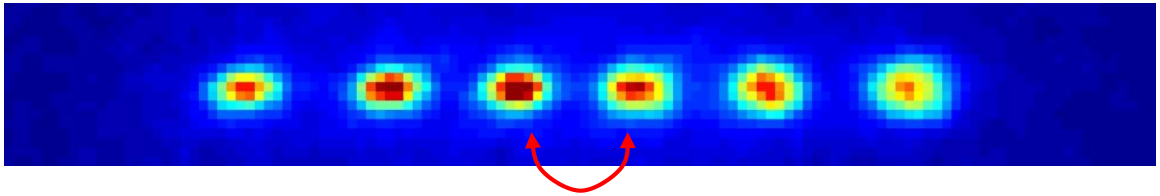




$$H_{eff} = \hbar\Omega\sigma_x^{(1)}\sigma_x^{(2)}$$

$\longrightarrow$ The phase Φ depends nonlinearly on the internal states of the ions

Spin-spin interactions by different approaches



$$\sigma_z \otimes \sigma_z$$

- Direct state-dependent forces between the ions (as in molecules) ?

  Reduce the ion-ion distance to a_0 ? Impossible!

  Make the ions bigger ? Difficult, but possible. <u>Rydberg ions</u> !

- Use external fields for engineering state-dependent forces

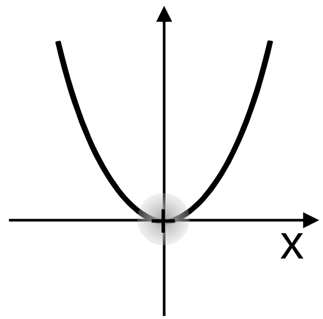
  Spin-spin interactions mediated by Coulomb interaction

  (a) <u>Laser interactions</u>: Absorption and stimulated emission transfer momentum!

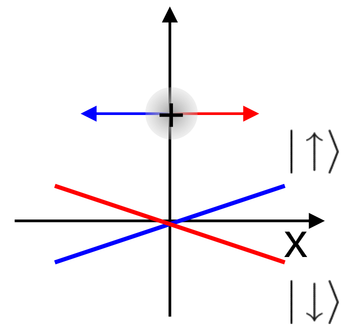
  (b) <u>Magnetic field gradients</u>: Position-dependent Zeeman shifts

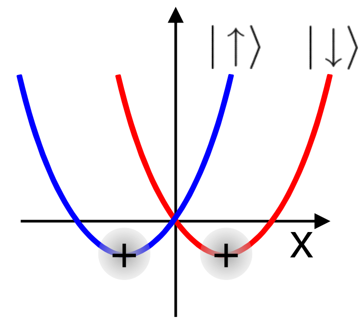
Spin-spin couplings by magnetic field gradients

Trapping potential



Zeeman energy





$$H = \hbar\nu a^\dagger a \;+\; \underbrace{\mu B' \hat{x} \sigma_z / 2}_{\propto\, (a + a^\dagger)\sigma_z}$$

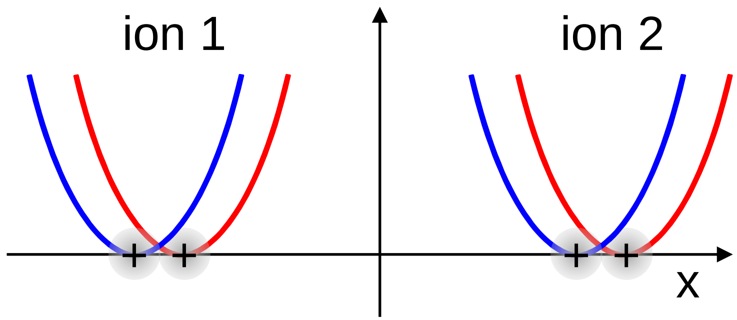
spin-dependent force

In a magnetic field gradient, any microwave-induced spin flip also couples to the vibrational state.

Mintert + Wunderlich, PRL **87**, 257904 (2001)

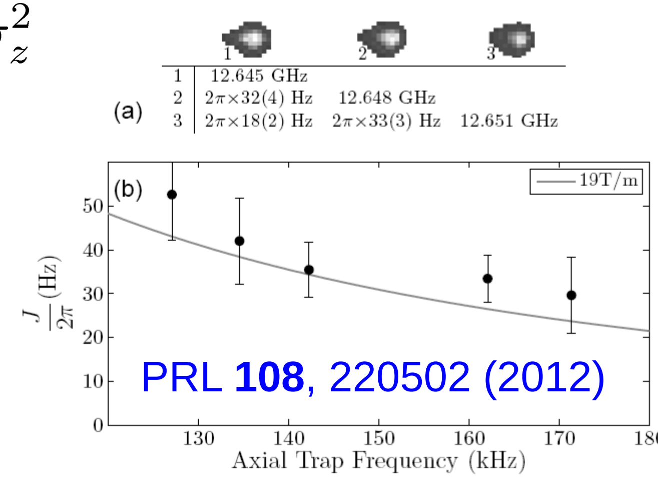
Spin-spin couplings by magnetic field gradients

(a) Ion crystals in a static field gradient



Potential energy (trap + Coulomb energy) depends on both internal states

$$H = J\sigma_z^1\sigma_z^2$$



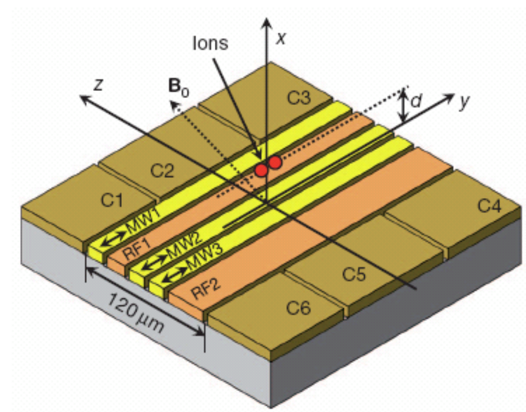
PRL **108**, 220502 (2012)

Wunderlich (Siegen)

(b) Ion crystals in a oscillating field gradient

$$H(t) \propto (ae^{-i\delta t} + a^\dagger e^{i\delta t})\sigma_z \longrightarrow H_{eff} = J\sigma_z^1\sigma_z^2$$

Off-resonant excitation of a vibrational mode with a state-dependent potential



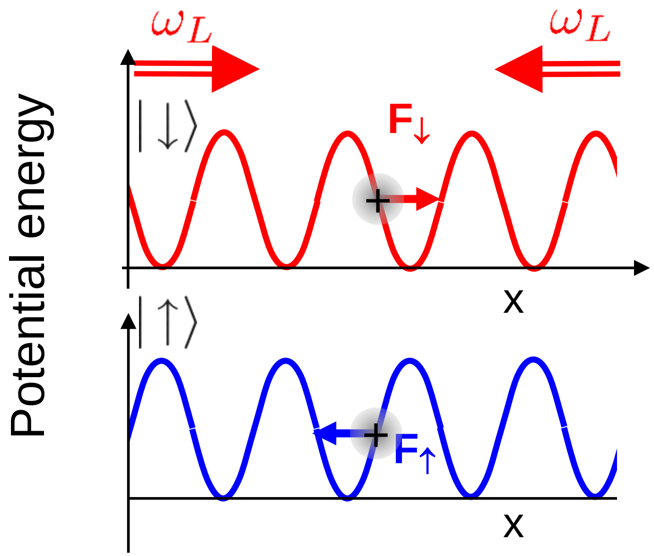
C. Ospelkaus *et al*., Nature **476**, 181 (2011)

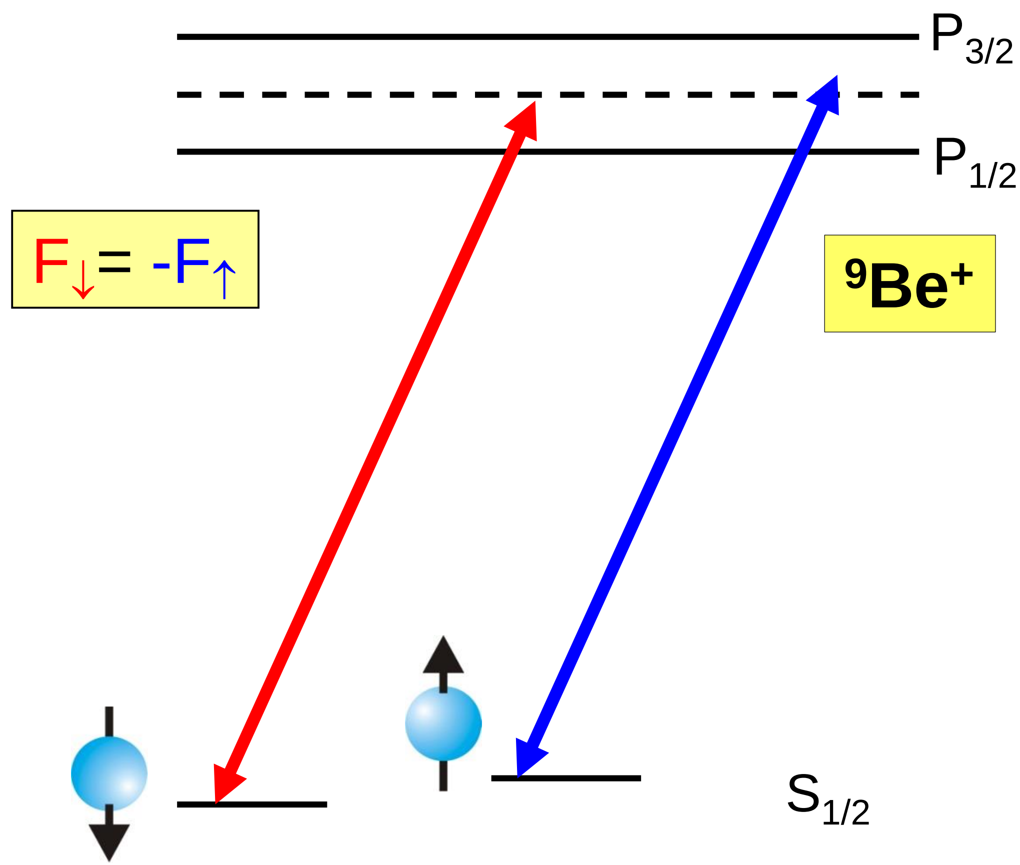
Wineland (NIST Boulder)

Spin-spin couplings by laser-induced potentials

1. Conditional phase shift gate

Spatial light shifts by off-resonant coupling to P-states in a standing wave





Spin-dependent force

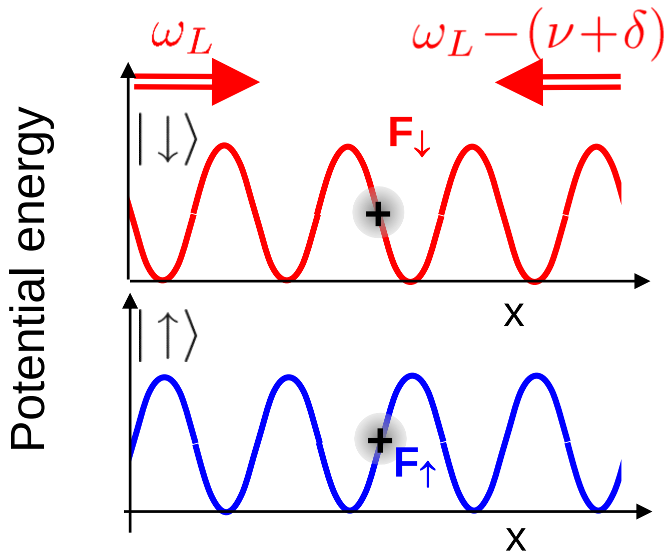
$$H \propto (a + a^\dagger)\sigma_z$$

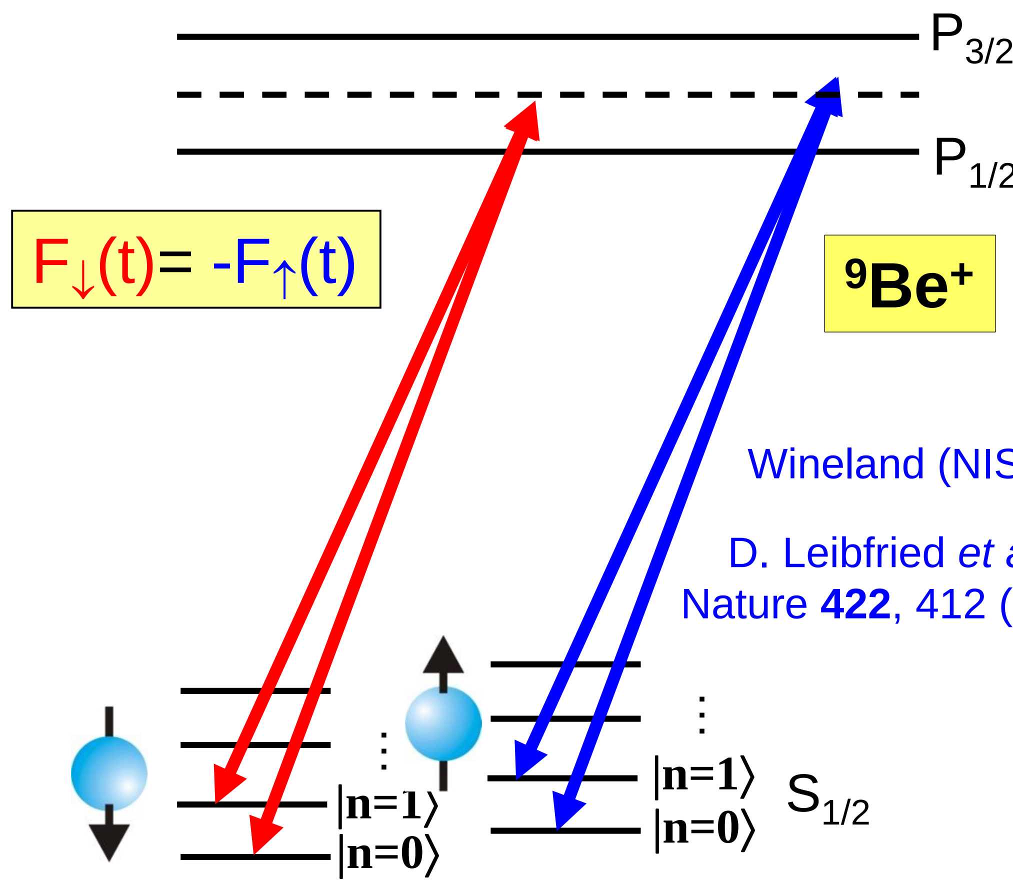
Spin-spin couplings by laser-induced potentials

Conditional phase shift gate

Spatial light shifts by off-resonant coupling to P-states in a standing wave

Frequency shifting one beam creates a moving standing wave.





Wineland (NIST)

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

Spin-dependent force

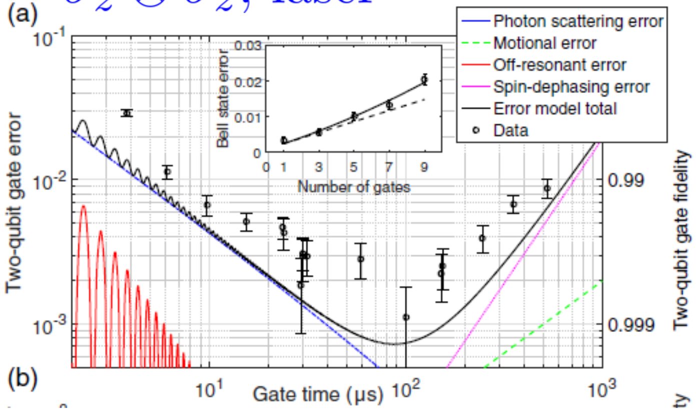
$$H(t) \propto (a e^{-i\delta t} + a^\dagger e^{i\delta t})\sigma_z$$

realizes Ising interaction

$$\xrightarrow{\text{with two ions}} H_{eff} = J\sigma_z^1\sigma_z^2$$

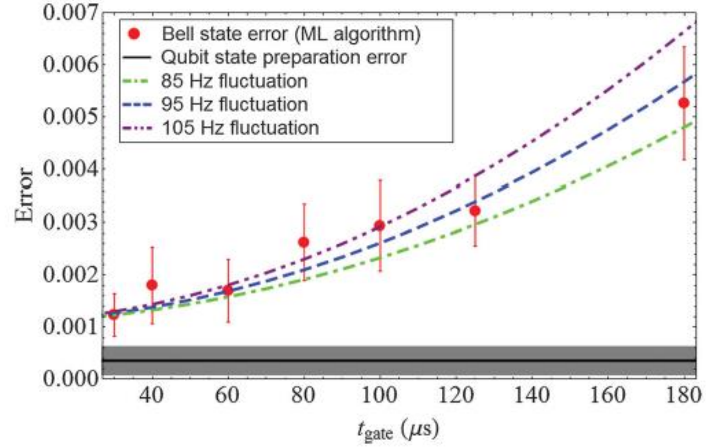
High-fidelity entangling quantum gates

$\sigma_z \otimes \sigma_z$, laser



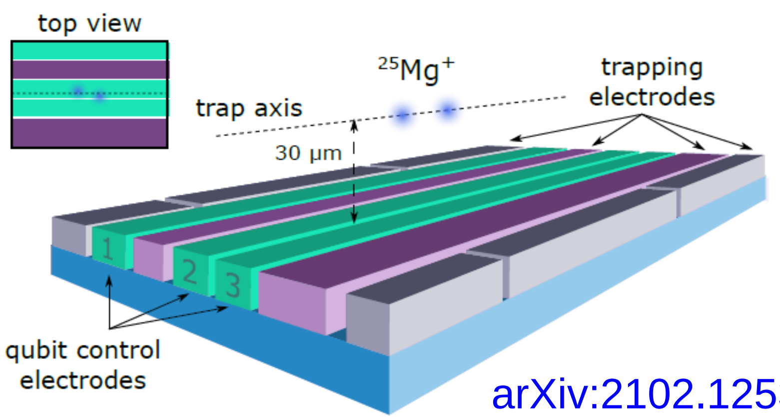
PRL 117, 060504 (2016)

$\sigma_x \otimes \sigma_x$, laser

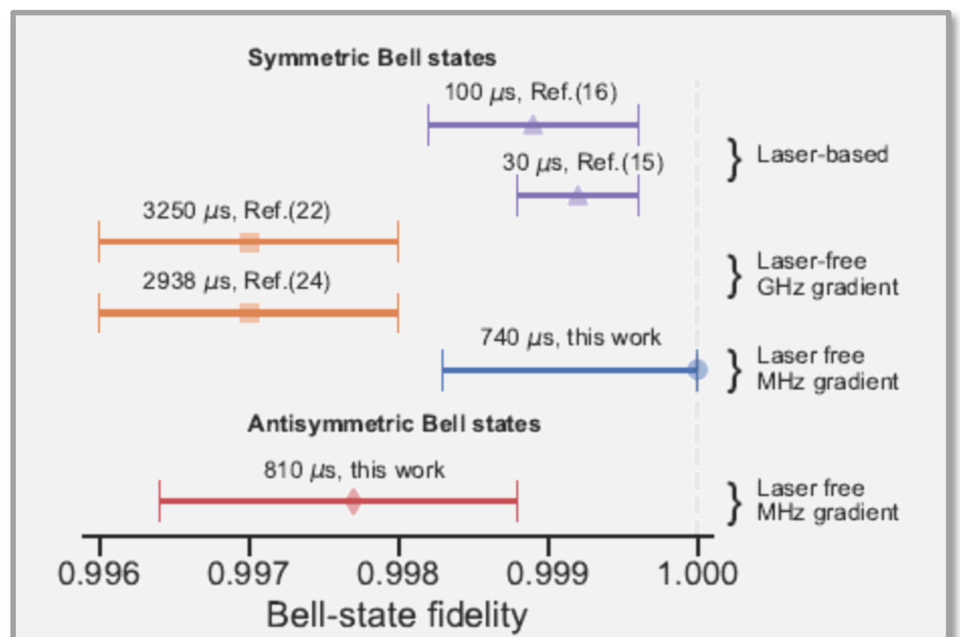


PRL 117, 060505 (2016)

$\sigma_z \otimes \sigma_z$, microwave/rf

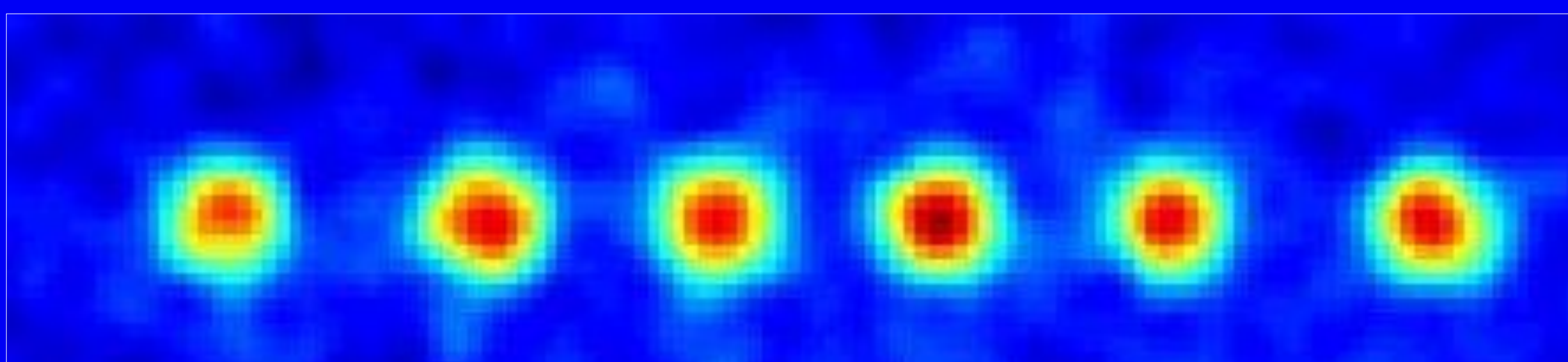


arXiv:2102.12533

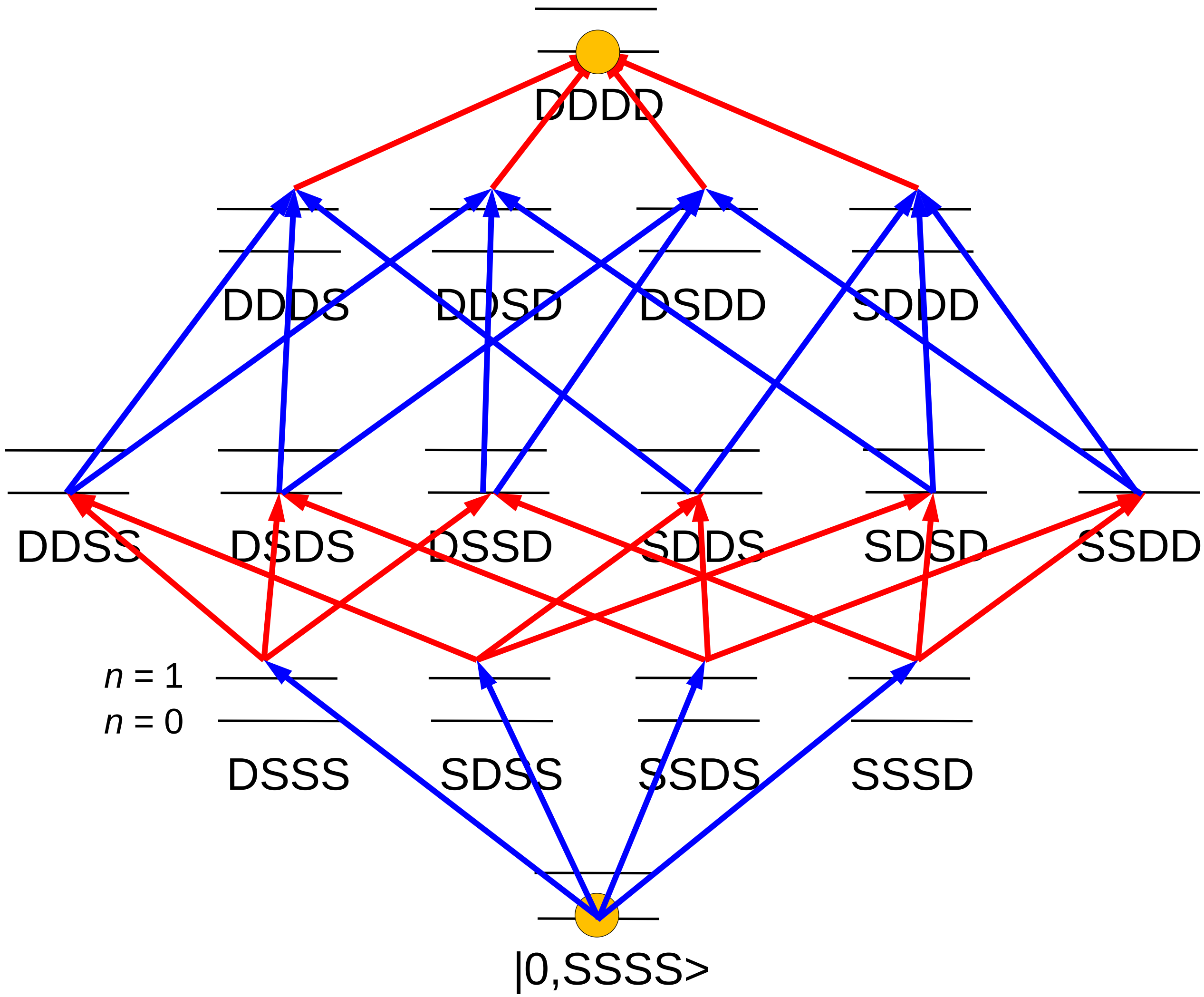


Quantum physics with more than 2 ions

Scaling the system up for gate-based quantum computation

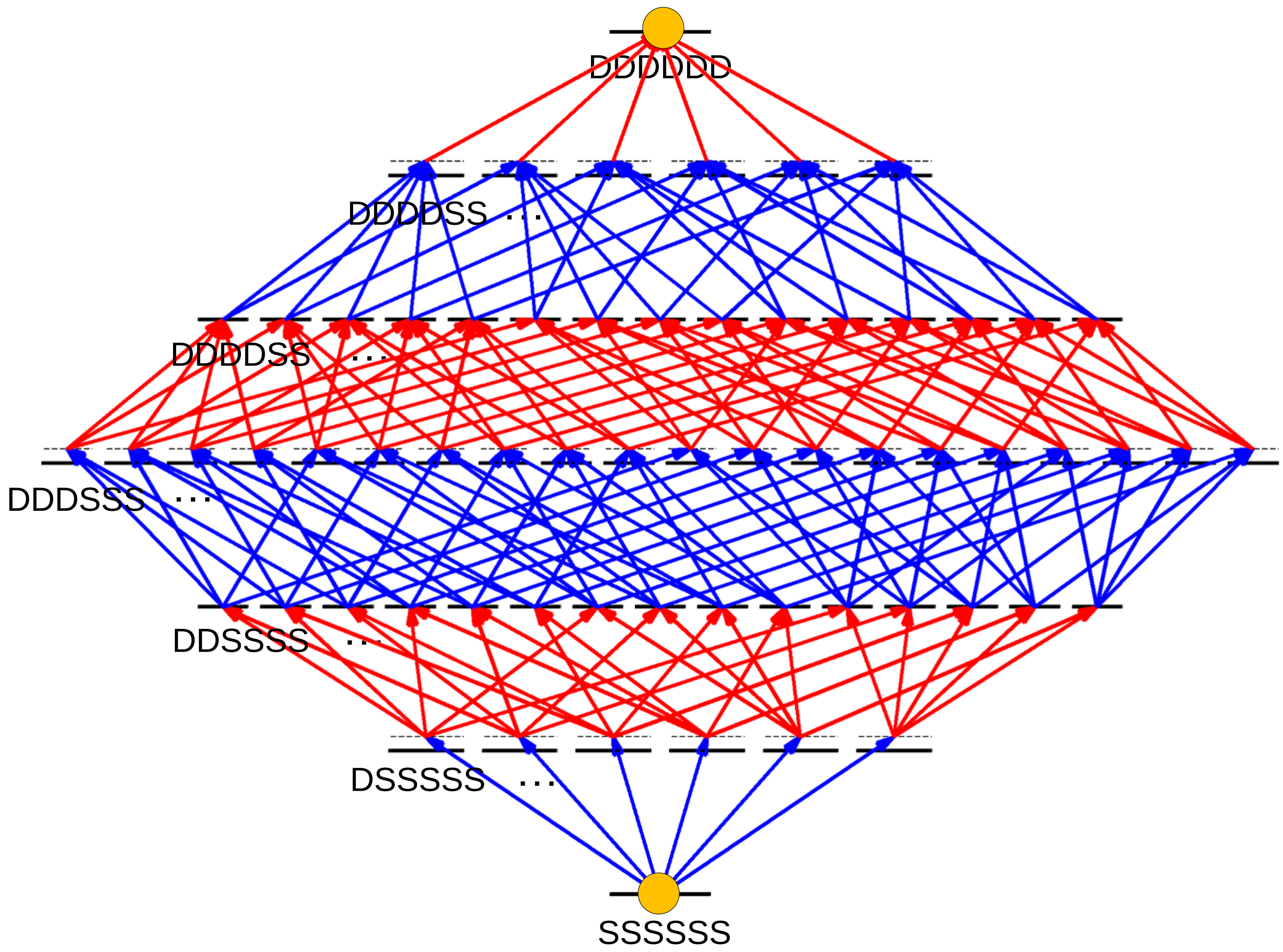


Creating GHZ-states with 4 ions



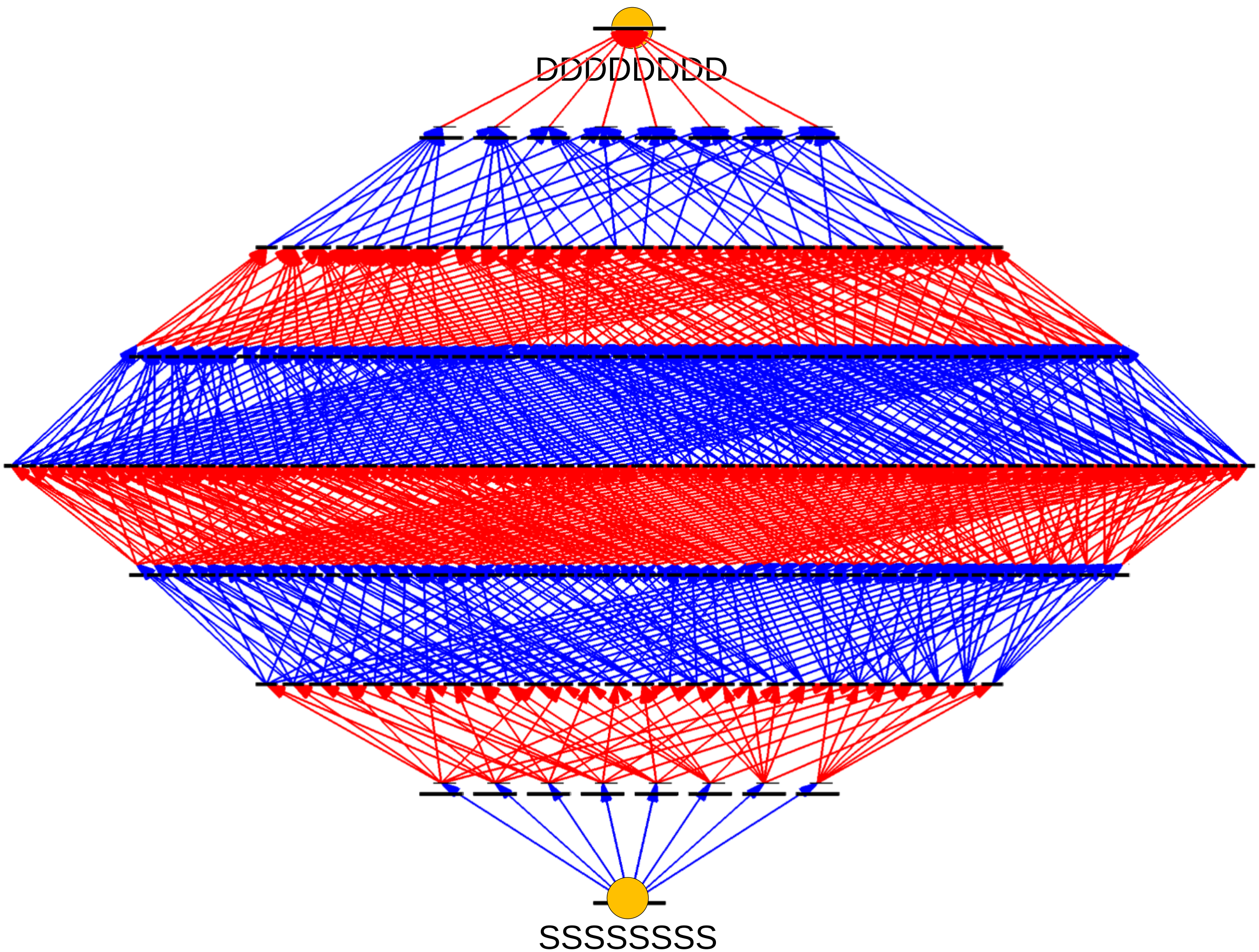
$$|SSSS\rangle \longrightarrow (|SSSS\rangle + |DDDD\rangle)/\sqrt{2}$$

Creating GHZ-states with 6 ions



$$|SSSSSS\rangle \longrightarrow (|SSSSSS\rangle + |DDDDDD\rangle)/\sqrt{2}$$

Creating GHZ-states with 8 ions

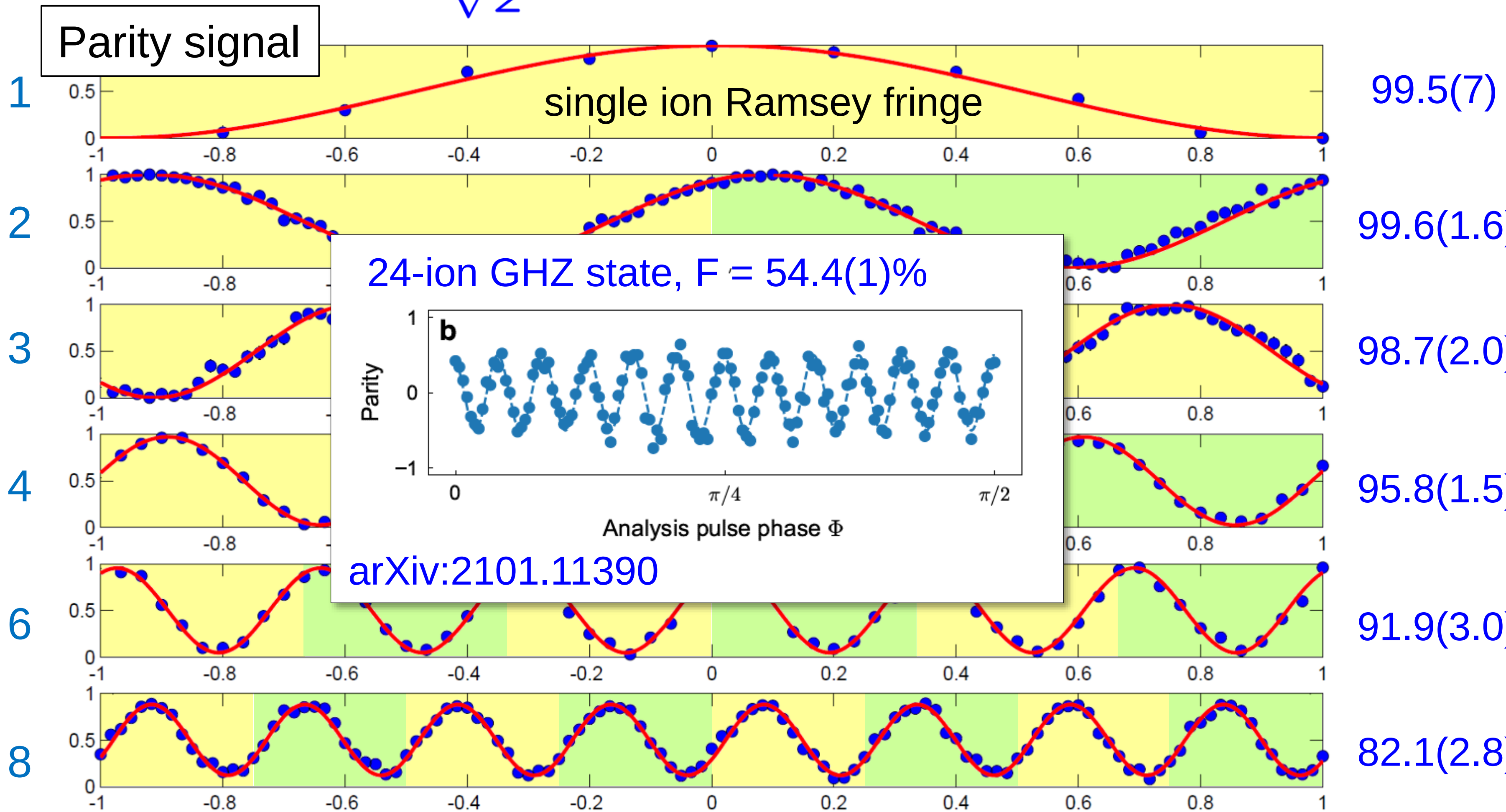


$$|SSSSSSSS\rangle \longrightarrow (|SSSSSSSS\rangle + |DDDDDDDD\rangle)/\sqrt{2}$$

N - qubit GHZ state generation

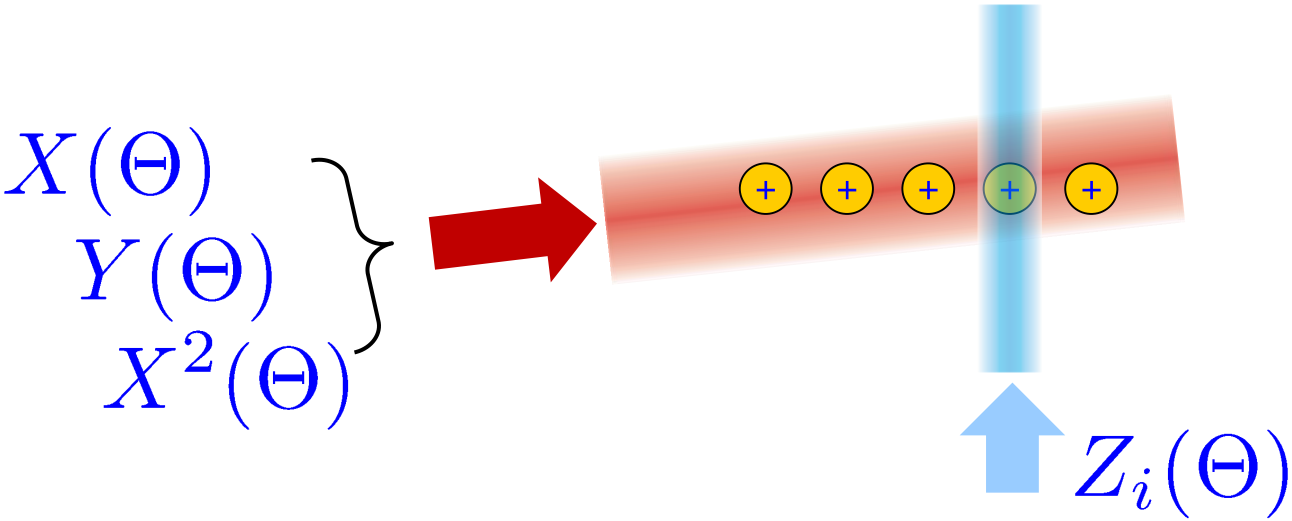
$N =$ $$\Psi = \frac{1}{\sqrt{2}}(|SS\ldots S\rangle + |DD\ldots D\rangle)$$

Fidelity (%)



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

Quantum gate operations: universal toolbox



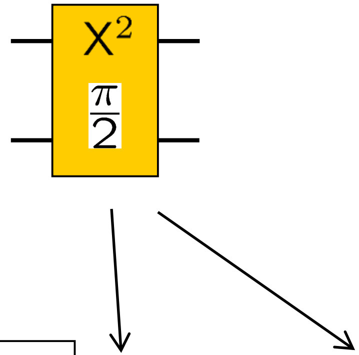
$$\left.\begin{matrix} X(\Theta) \\ Y(\Theta) \end{matrix}\right\}$$ collective local operations

$Z_i(\Theta)$ single-qubit z-rotations

$X^2(\Theta)$ Mølmer-Sørensen entangling operation

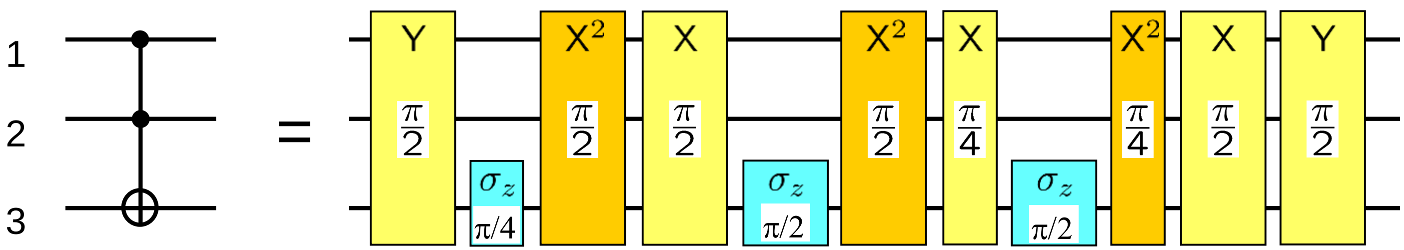
Entangling gates for quantum algorithms

Entangling gate



Building block for realizing quantum algorithms

Example: quantum Toffoli gate



V. Nebendahl *et al*., PRA **79**, 012312 (2009)

Current experiments: 2 to 11 qubits, > 100 gate operations

K. Wright et al., Nat. Commun. 10, 5464 (2019), A. Erhardt et al, Nature 589, 220 (2021)

Scaling the ion trap quantum processor …

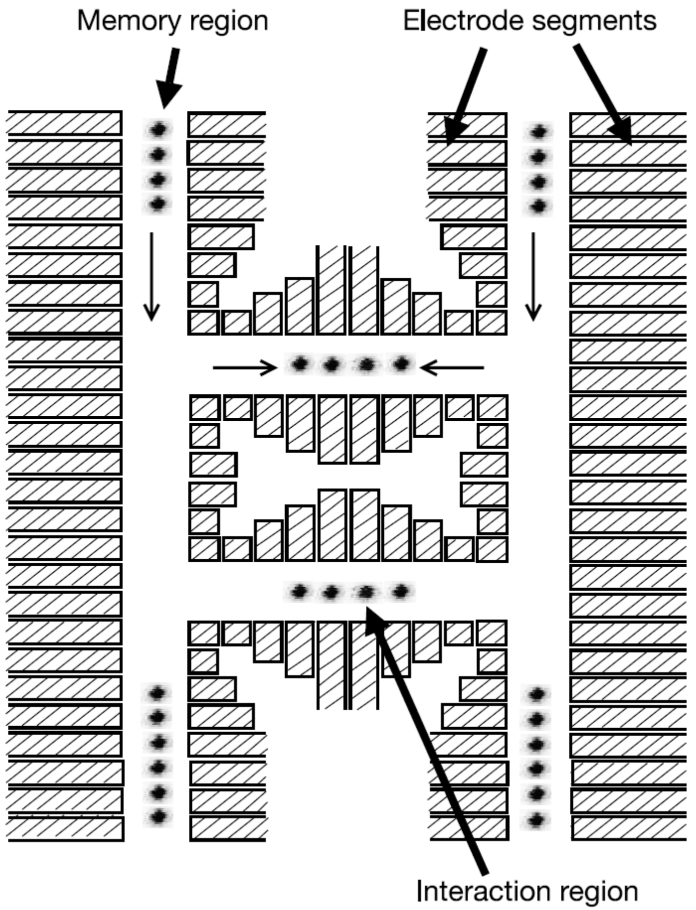
Making ion strings longer and longer is infeasible. Alternatives:

- put ions into arrays of traps, ions couple by exchange of phonons
- move ions, carry quantum information around

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

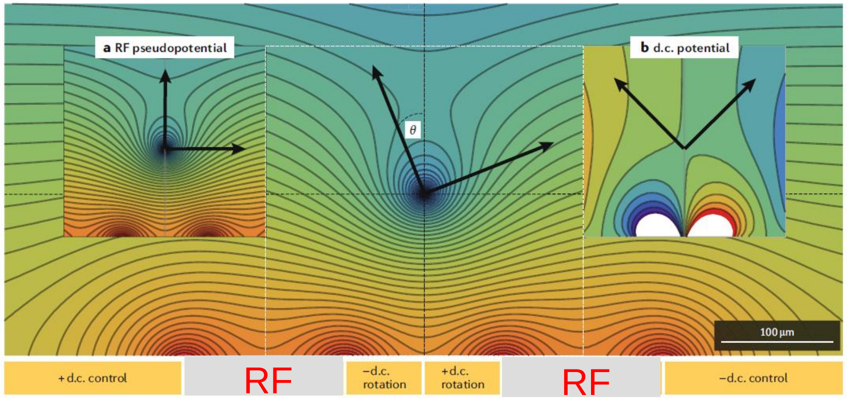
requires small,
integrated trap structures,

miniaturized optics
and electronics



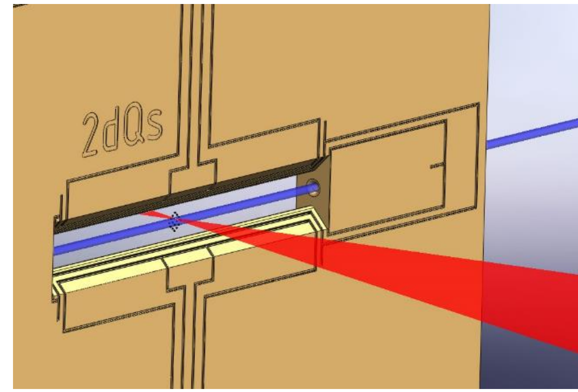
Microfabricated ion traps

Surface ion traps



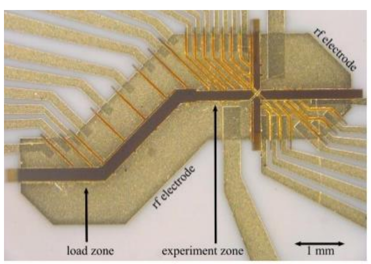
Nature Review Physics 2, 285 (2020)

Monolithic 3d-trap



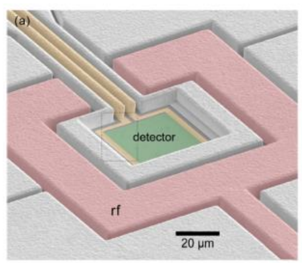
Innsbruck, 2020

Traps with junctions



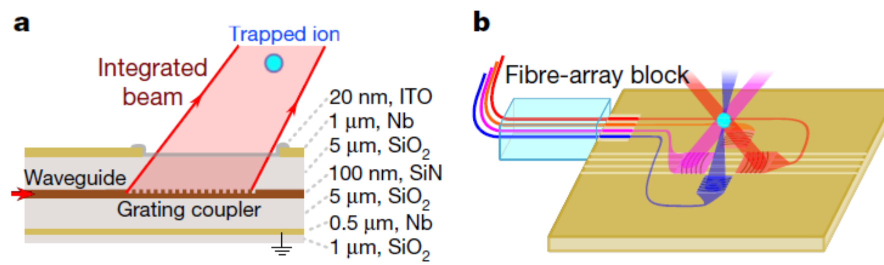
NIST Boulder

Integrated photon detectors



Opt. Express 25, 8705 (2017)

Integrated optics

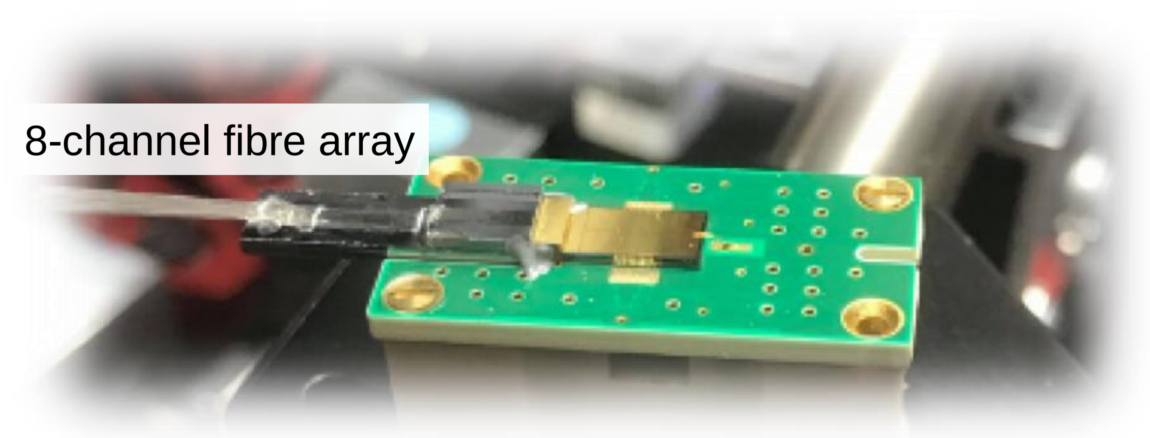


Nature 586, 538 (2020)

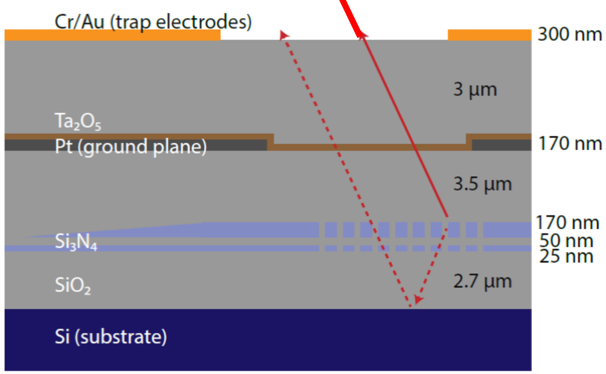
Further features:
High optical access, thick metal layers, CMOS-compatible traps, backside loading,…

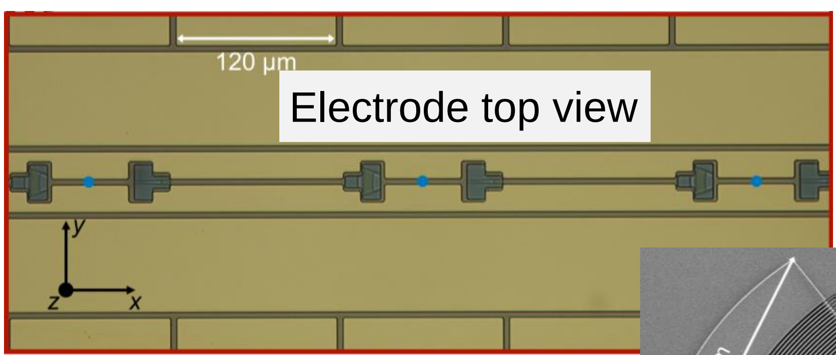
Optical wiring for trapped-ion quantum computers

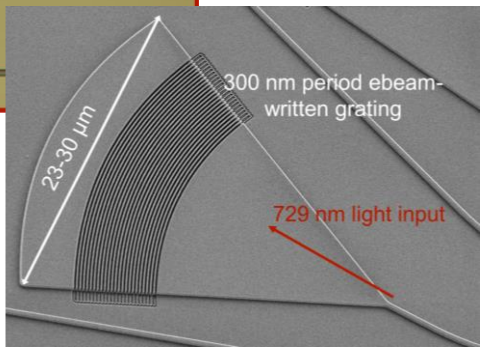
- MIT/Lincoln labs: Single-qubit gates: K. Mehta et al. Nature Nano 11, 1066 (2016)
- ETH Zürich: Two-qubit gates: K. Mehta et al. Nature 586, 533 (2020)



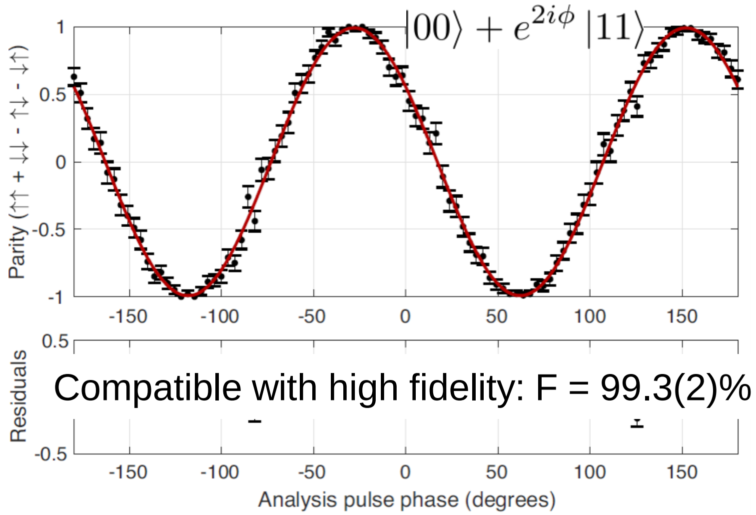
Light to ion
50 micron above
surface







e-beam written gratings
for focussed light



Compatible with high fidelity: F = 99.3(2)%

slide courtesy of Jonathan Home

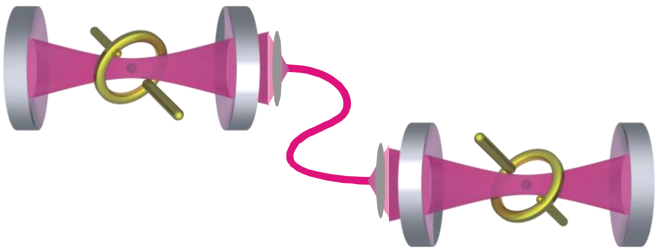
Scaling the ion trap quantum computer: Coupling ions to photons

Cavity QED: atom – photon interface, use photons for networking

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

T. Northup, B. Lanyon, Univ. Innsbruck

More experiments: JQI, Sussex, Bonn, Duke, Sandia, ETH, Saarbrücken,SK telekom…



Idea:

- Spontaneously emitted photons can become entangled in polarization/frequency with internal states of an ion
- Putting an ion into a high-finesse cavity can give rise to highly directional spontaneous emission
- Remote entanglement between ions by (i) joint measurements of emitted photons, or (ii) coupling the photon into a second ion-cavity system

References

Linear ion strings: positions and collective modes

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Ion Coulomb crystals

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R. Thompson, Contemporay Physics 56, 63 (2015)

Laser cooling

S. Stenholm, Rev. Mod. Phys. 56, 699 (1986)
J. Eschner, JOSA B 20, 1003 (2003)

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