Quantum states and quantum gates with trapped ions

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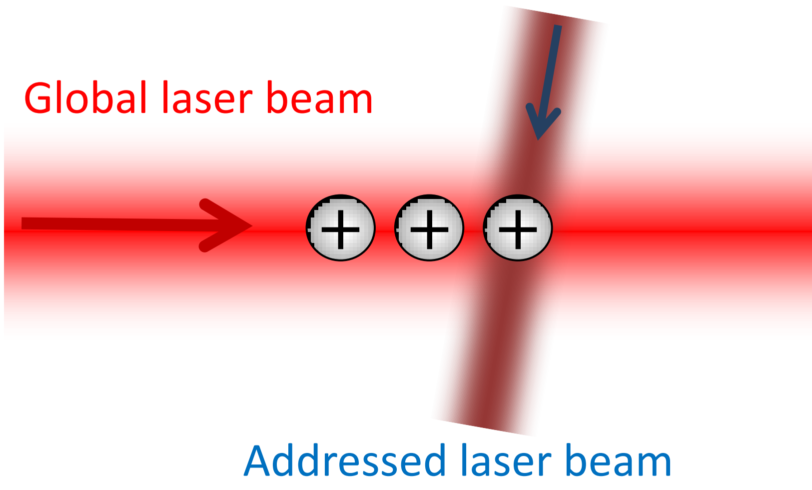
Bad Honnef, 22/23 August 2011

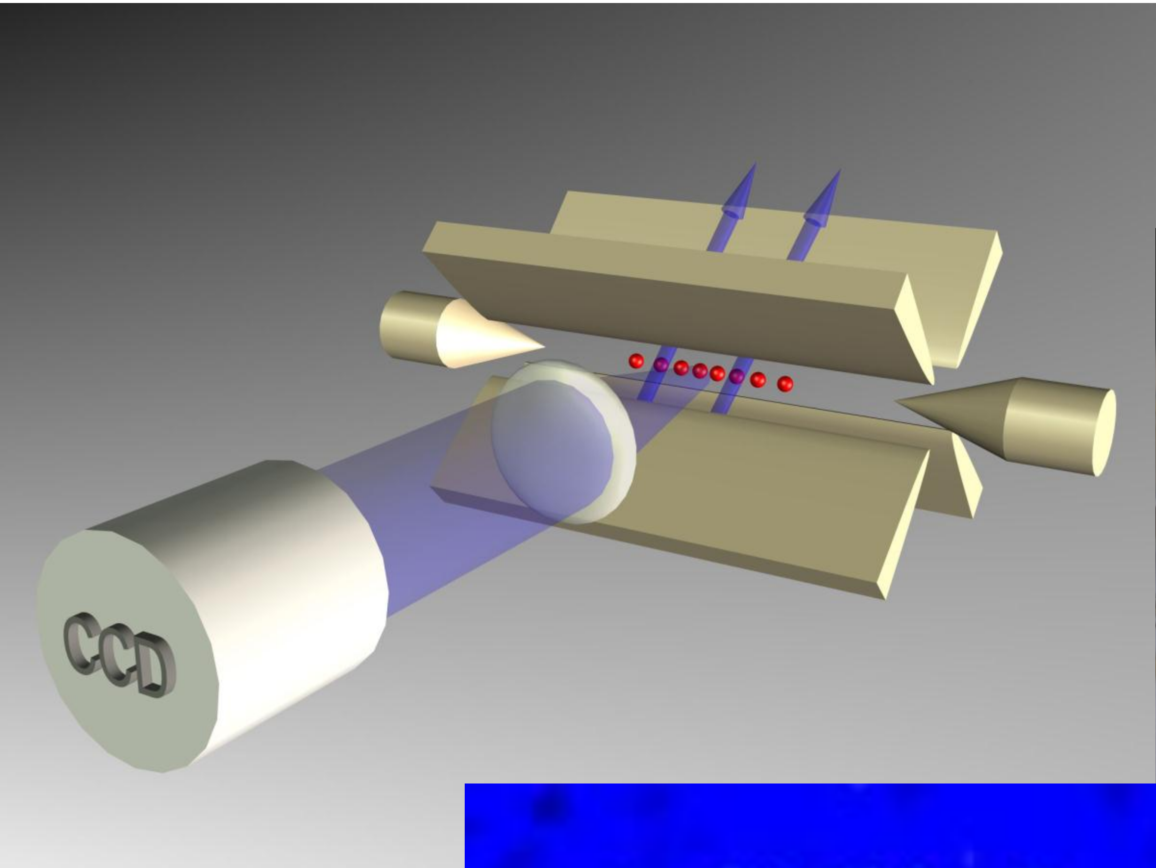
Outline

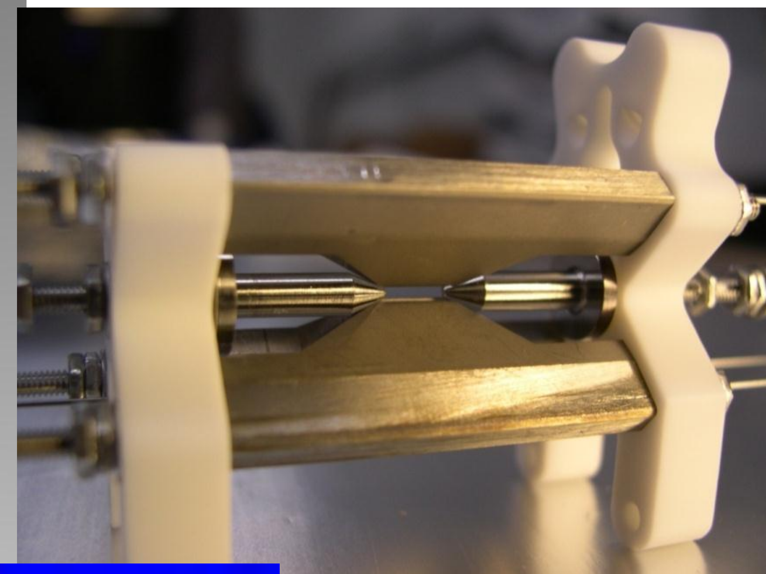
- Quantum information processing with trapped ions
- Generating and detecting entangled quantum states
- Quantum processes with trapped ions
- Non-unitary operations
- Summary and Outlook

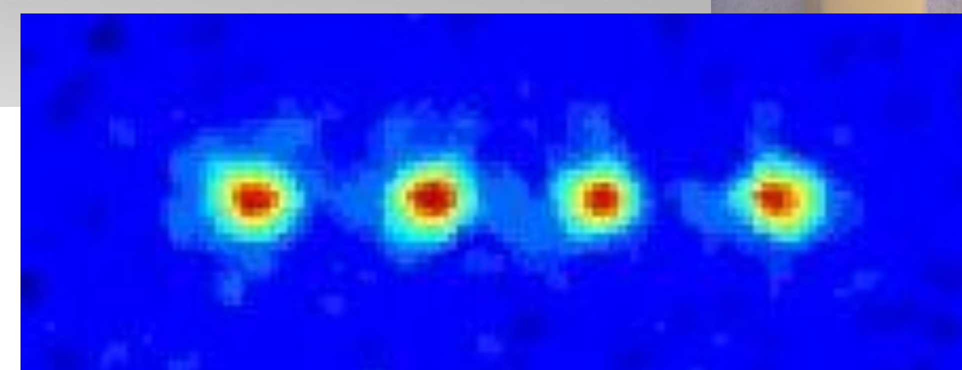


A string of trapped ions

$$\omega_z \approx 0.7 - 2\,\mathrm{MHz}$$
$$\omega_{x,y} \approx 1.5 - 4\,\mathrm{MHz}$$



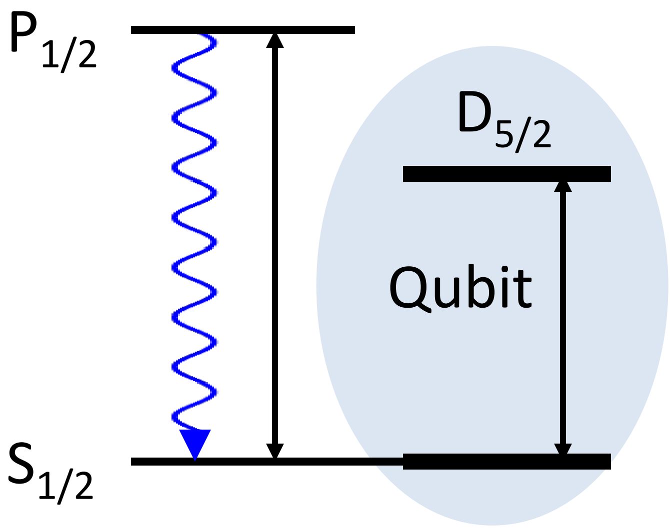




Qubits with trapped ions

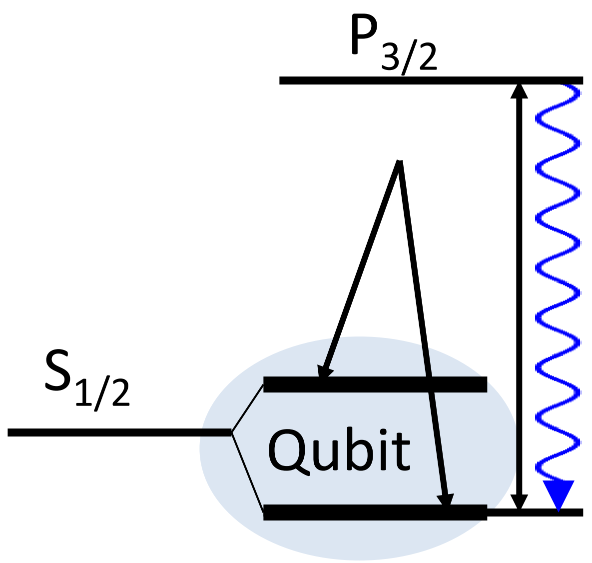
Storing quantum information requires ***long-lived atomic states***:

Optical transitions on metastable states
S ⇔ D transitions in alkaline earths:
Ca^+, Sr^+, Ba^+, (Yb^+, Hg^+)



Innsbruck $^{40}Ca^+$

Microwave transitions on hyperfine or Zeeman states alkaline earths:
$^{9}Be^+$, $^{25}Mg^+$, $^{43}Ca^+$, $^{87}Sr^+$, $^{137}Ba^+$, $^{115}Cd^+$, $^{171}Yb^+$



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

Ion species

Ions in use:

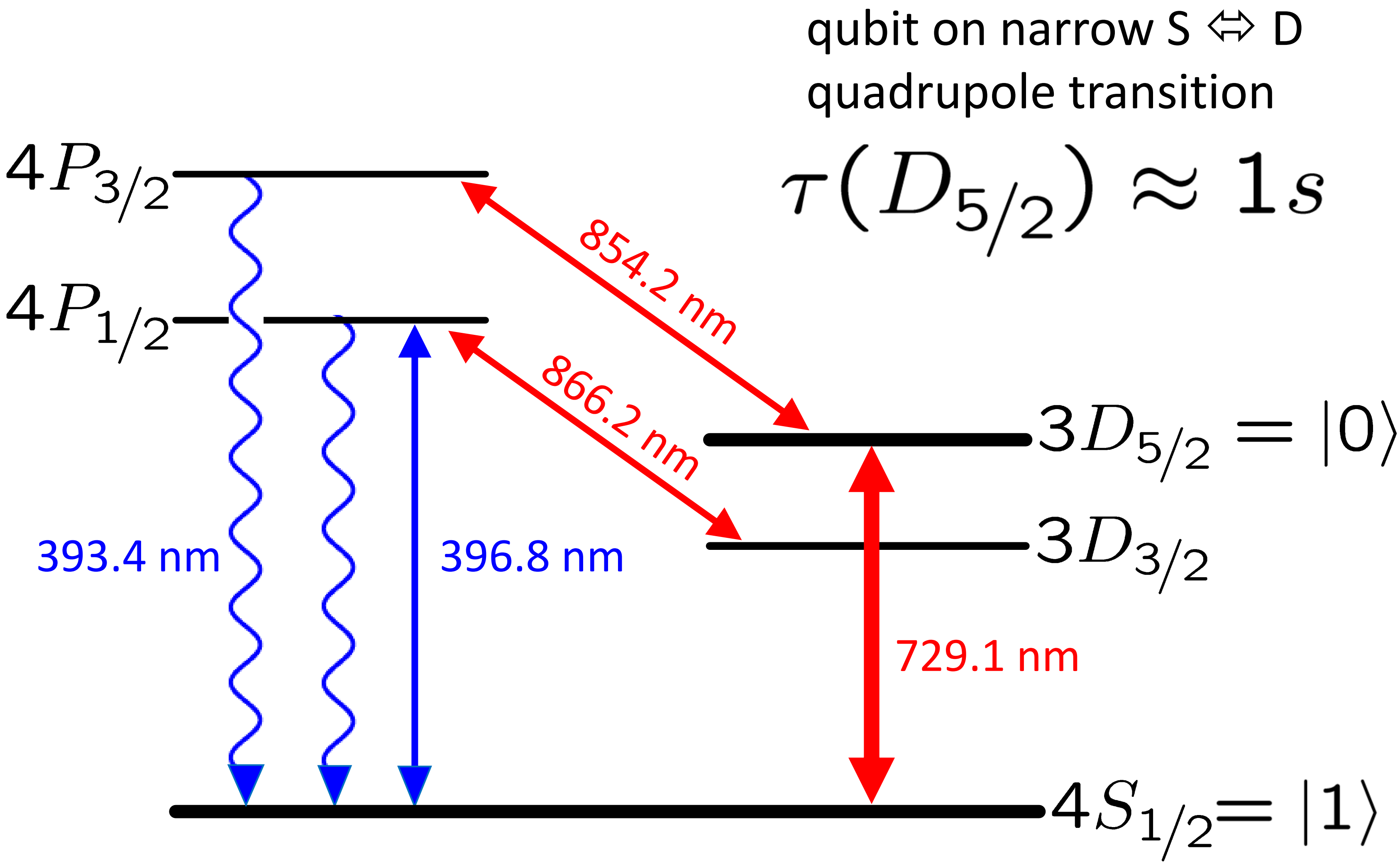
Group	1a	2a		3a	4a	5a	6a	7a	8a	8a'	8a''	1b	2b	3b	4b	5b	6b	7b	8
Period																			
1	1																		2
2	3	4 Be												5 B	6	7	8	9	10
3	11	12 Mg												13 Al	14	15	16	17	18
4	19	20 Ca		21	22	23	24	25	26	27	28	29	30 Zn	31 Ga	32	33	34	35	36
5	37	38 Sr		39	40	41	42	43	44	45	46	47	48 Cd	49 In	50	51	52	53	54
6	55	56 Ba	*	71	72	73	74	75	76	77	78	79	80 Hg	81 Tl	82	83	84	85	86
7	87	88 Ra	**	103	104	105	106	107	108	109	110	111	112						
*Lanthanoids			*	57	58	59	60	61	62	63	64	65	66	67	68	69	70 Yb		
*Actinoids			**	89	90	91	92	93	94	95	96	97	98	99	100	101	102 No		

from QC group C. Monroe, Univ. of Michigan

Choosing the right ion species:

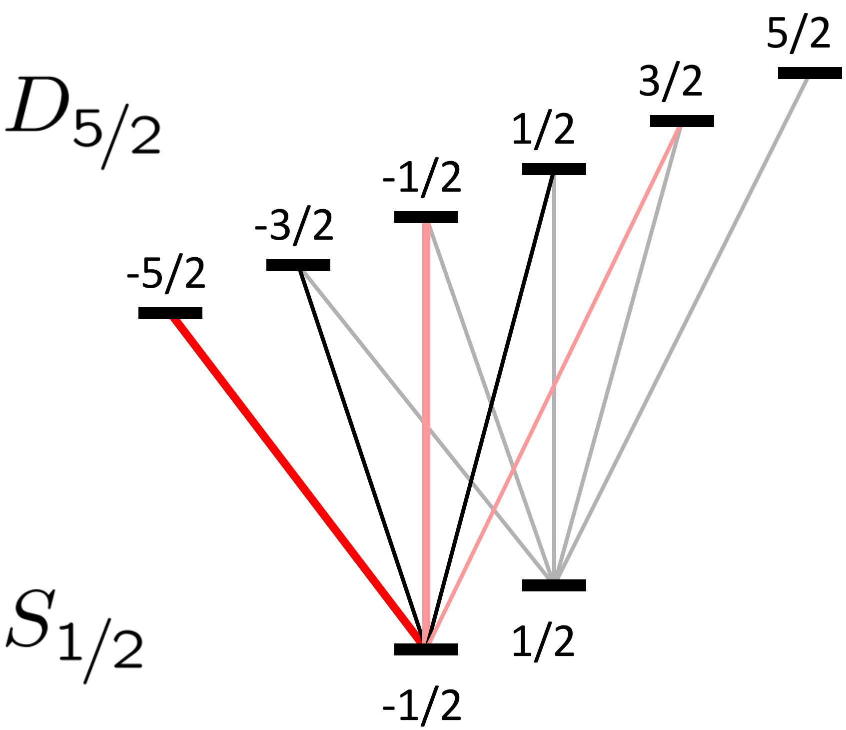
- strong cooling transition
- availability of suitable laser sources
- …

Level scheme of Ca^+



Spectroscopy of the $S_{1/2} \Leftrightarrow D_{5/2}$ transition

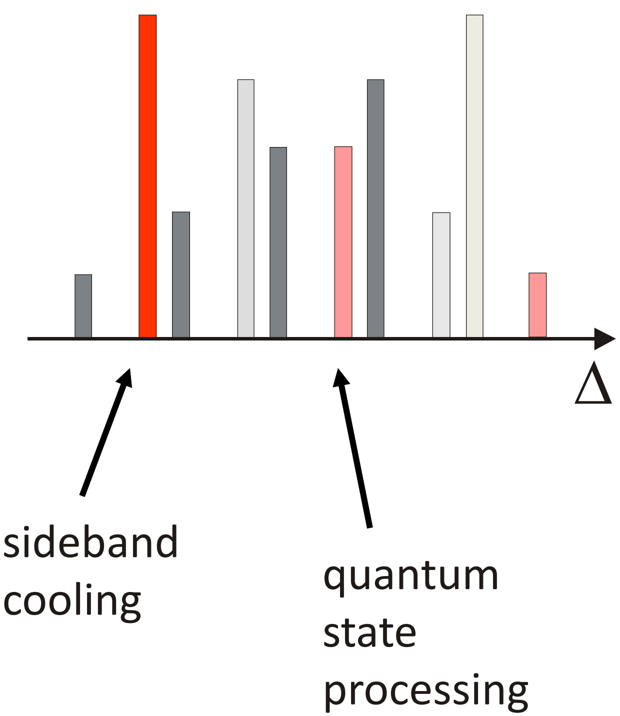
Zeeman structure in non-zero magnetic field:



+ vibrational degrees of freedom

2-level-system:

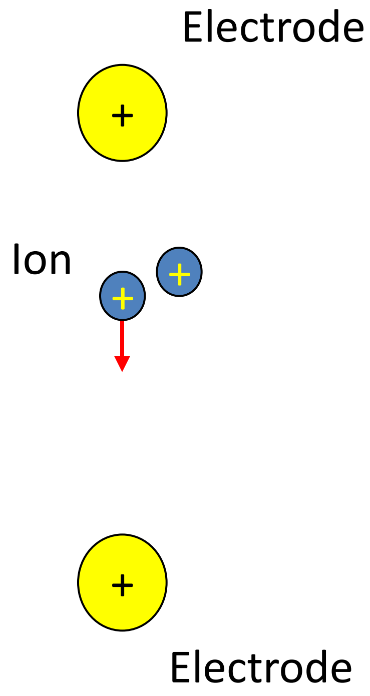
$-1/2 \longrightarrow -5/2(-1/2)$



Ion traps

Goal: To trap a charged particle in 3 dimensions

Force due to electrical fields



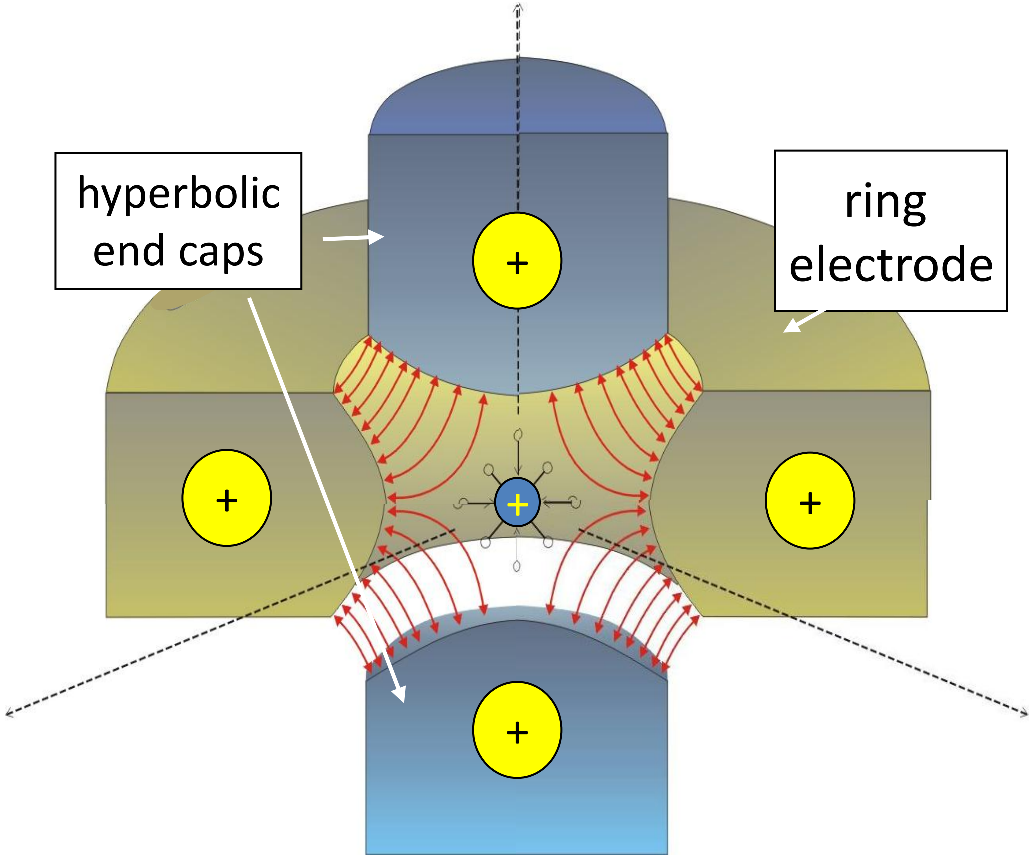
Ion traps

Goal: To trap a charged particle in 3 dimensions

Force due to electrical fields

Is it possible to use positively charged electrodes in all directions???

No potential minimum!



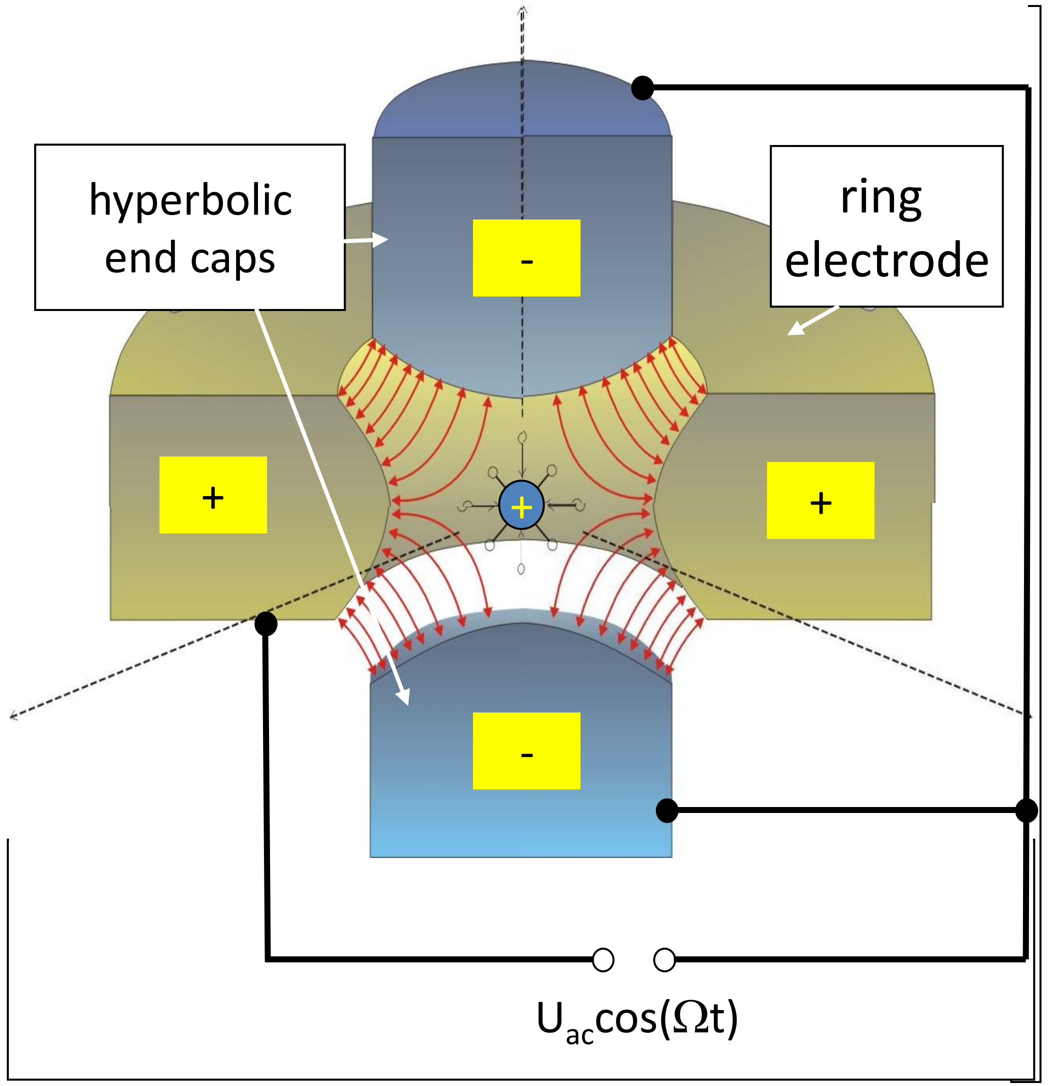
Paul trap: Alternating electric field

Alternating electric field

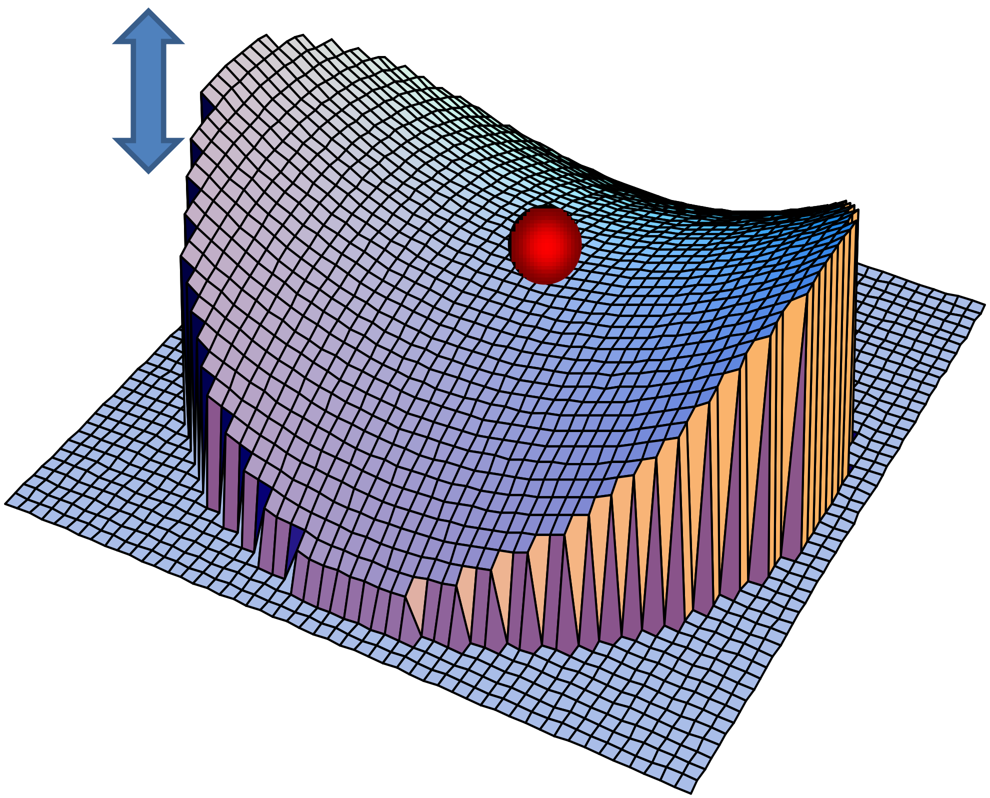
Alternating attractive and repulsive force on the ion,

Effective trapping potential.

Ion stays trapped.

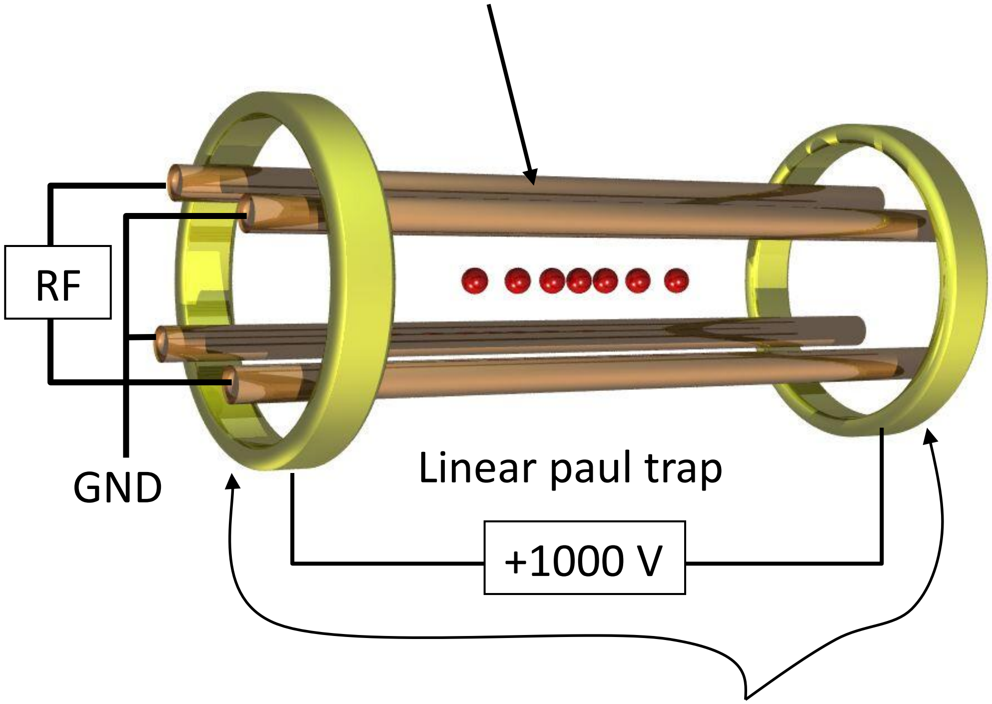


Oscillating saddle potential

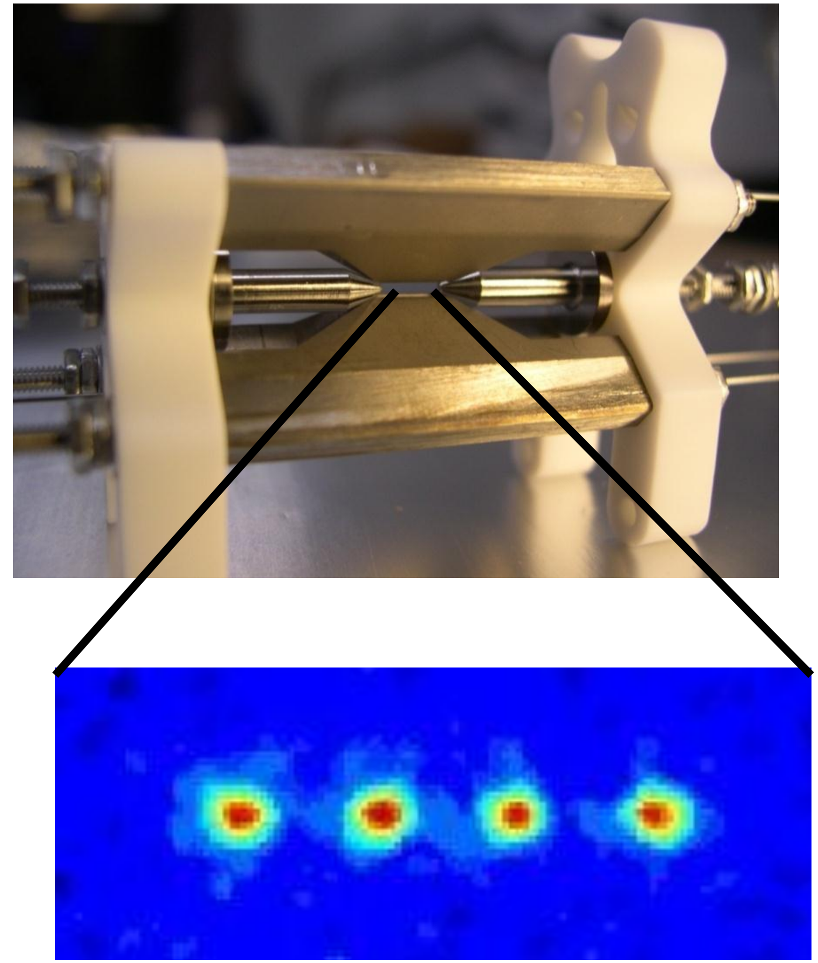


Linear Paul traps

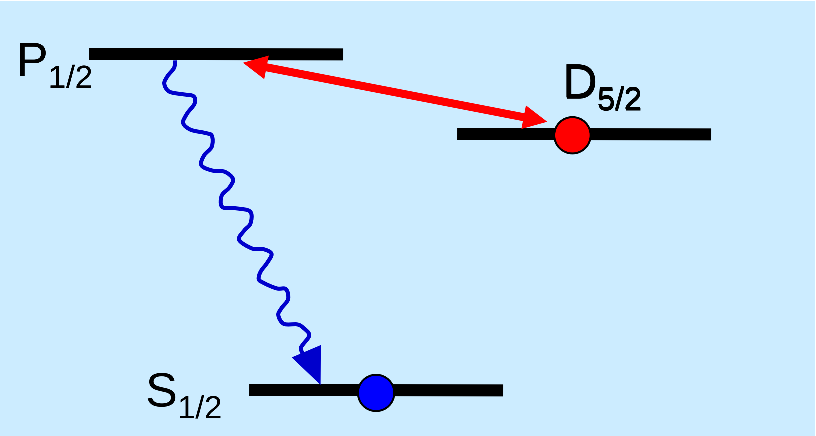
Radial electrodes:
Apply radiofrequency (20 MHz) with few hundred volts amplitude. Generates quadrupole potential.



Axial electrodes:
Apply DC voltage of 500 – 2000 V.
Provides axial confinement.

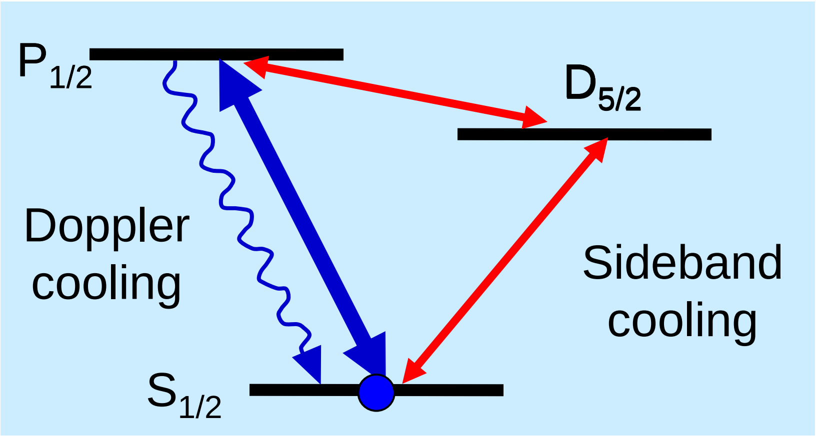


Experimental procedure



1. Initialization in a pure quantum state

Experimental procedure



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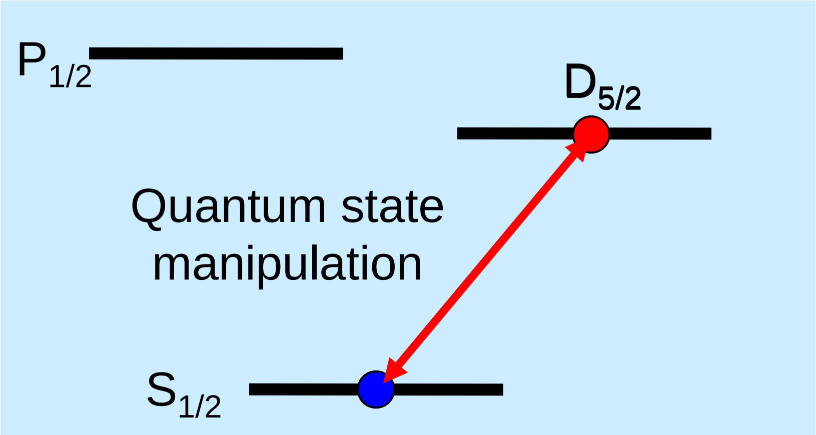
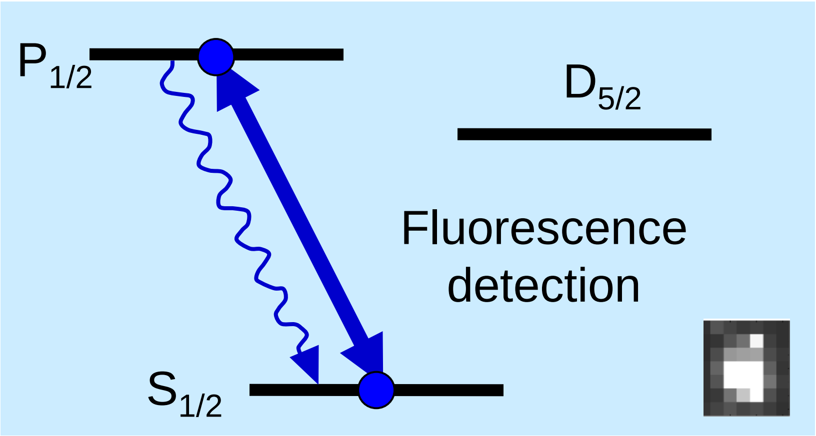


1. Initialization in a pure quantum state

2. Quantum state manipulation on $S_{1/2}$ – $D_{5/2}$ transition

Experimental procedure



1. Initialization in a pure quantum state:

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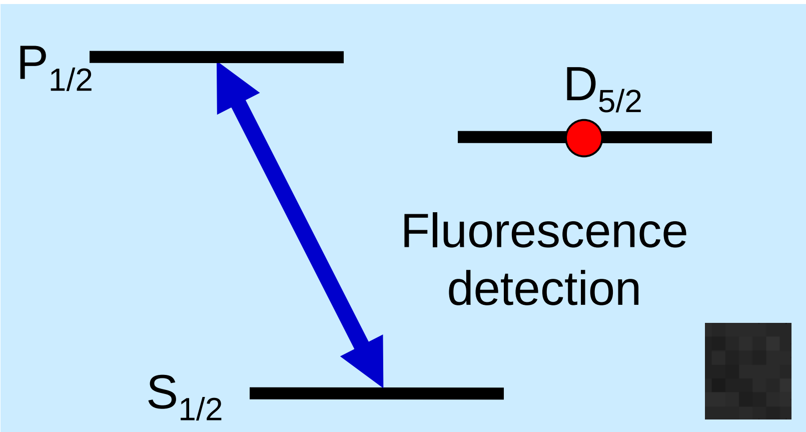
3. Quantum state measurement by fluorescence detection

Experimental procedure



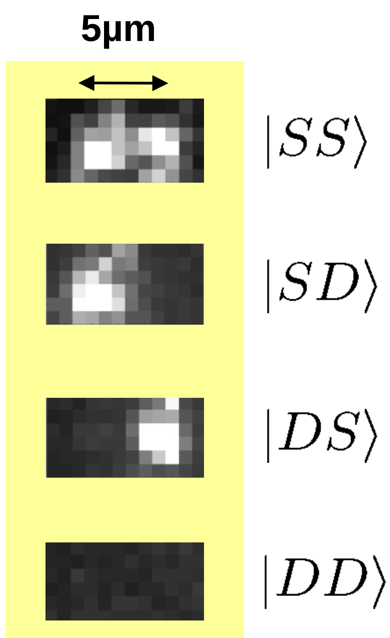
1. Initialization in a pure quantum state:

2. Quantum state manipulation on $S_{1/2} – D_{5/2}$ transition

3. Quantum state measurement by fluorescence detection

<u>Two ions:</u>

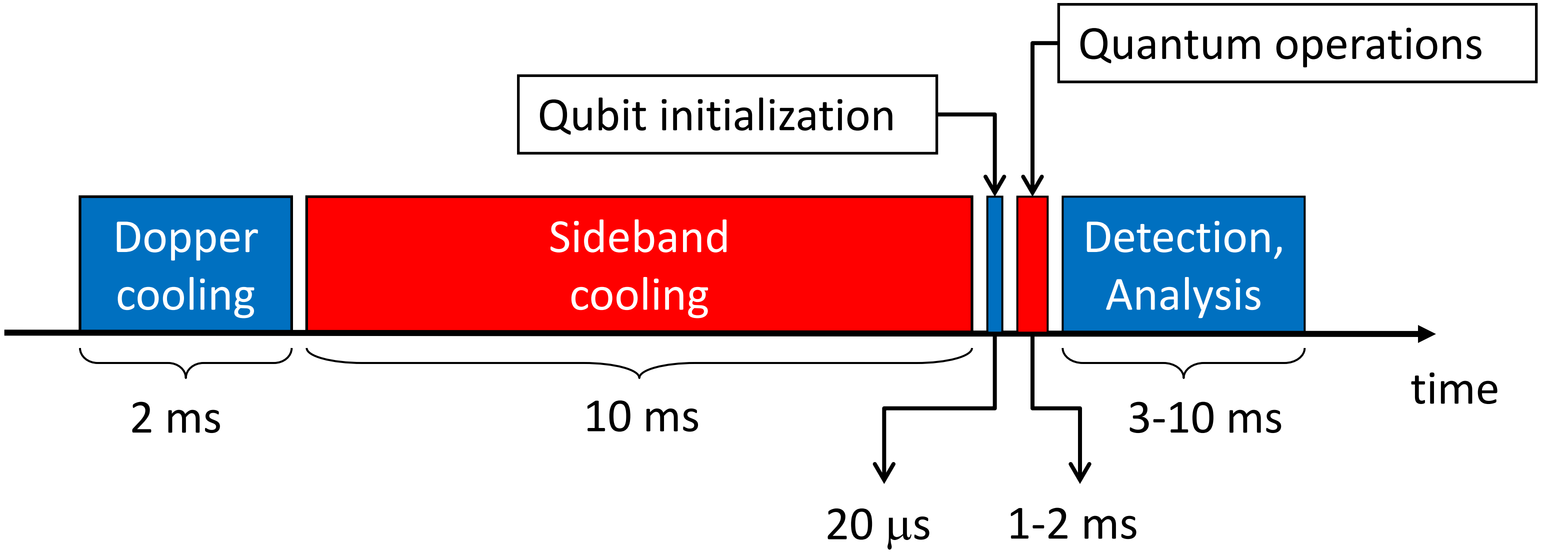
Spatially resolved detection with CCD camera



50 experiments / s

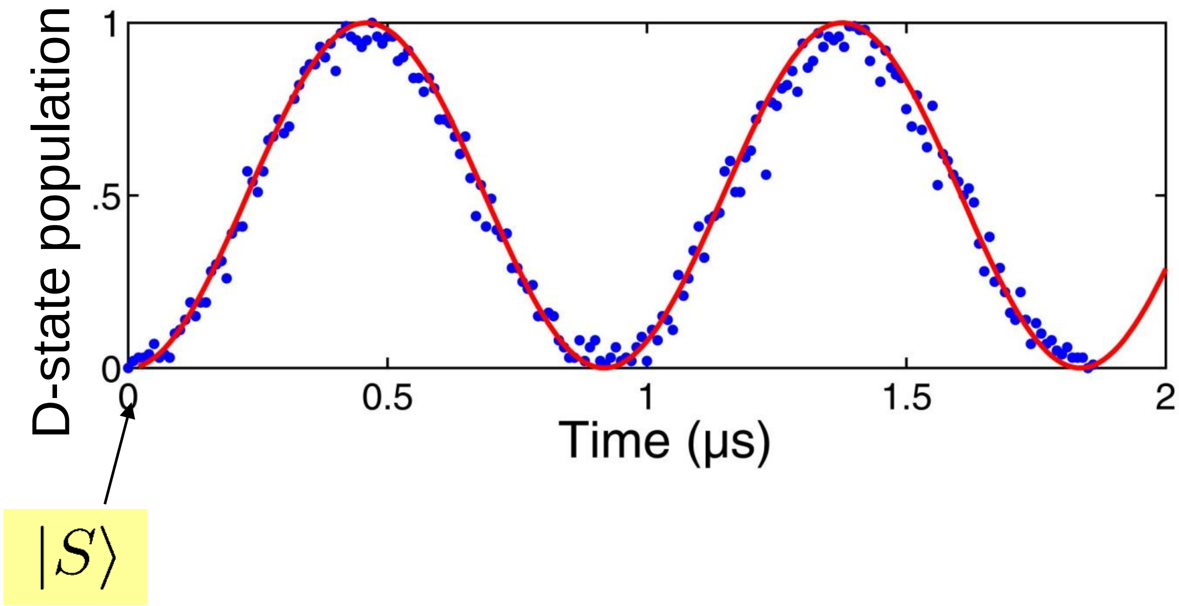
Repeat experiments 100-200 times

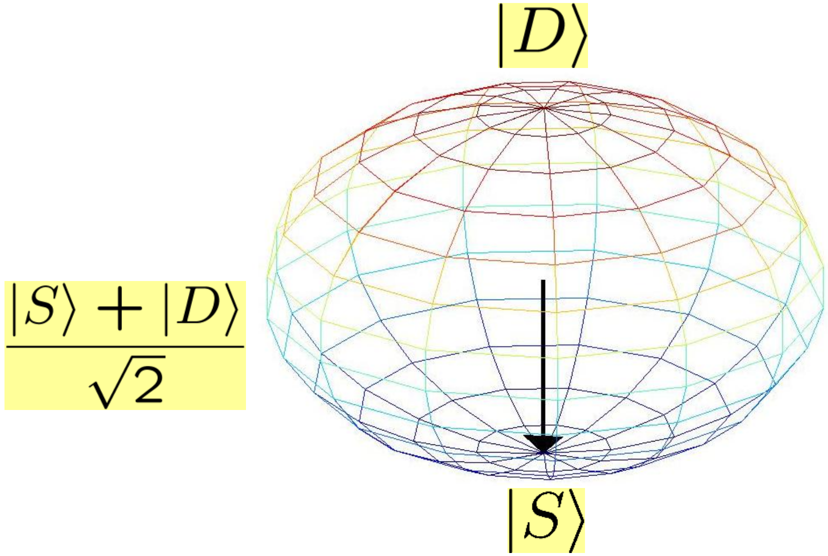
A typical experimental sequence



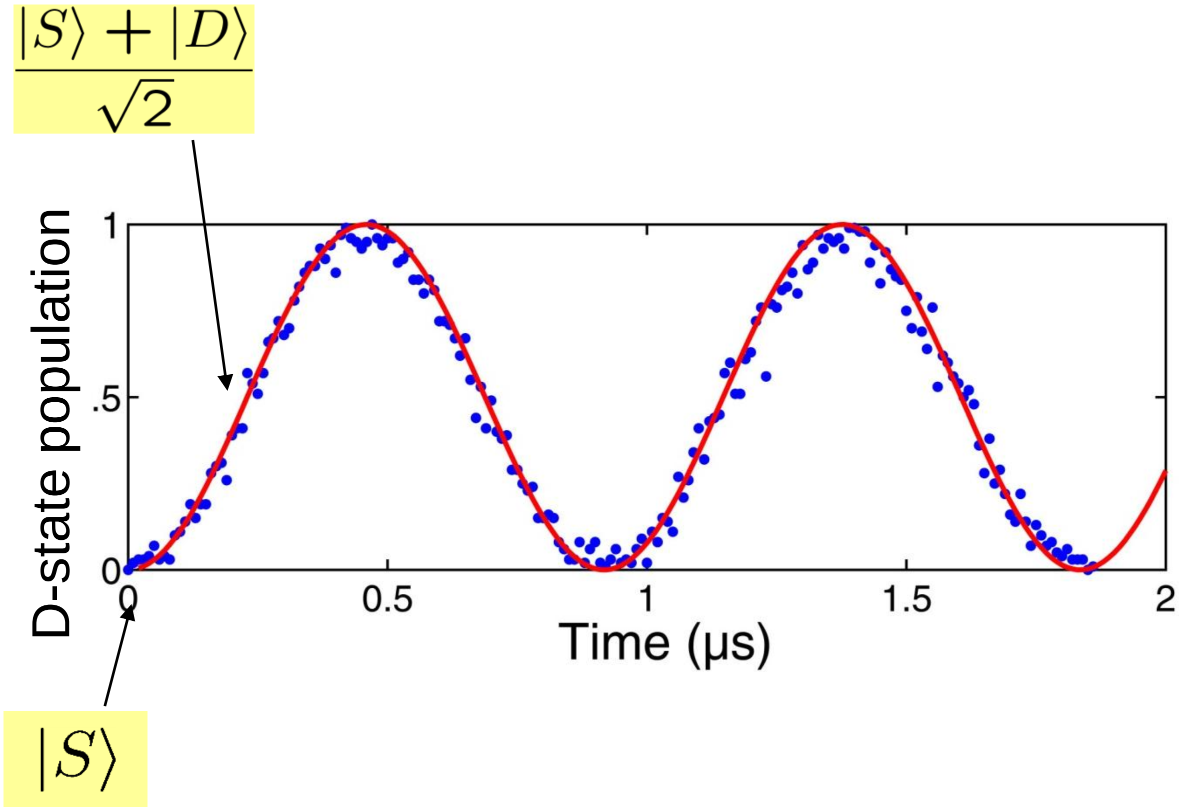
Cycle is repeated for 100 – 200 times in order to determine the final quantum state of the ion string.

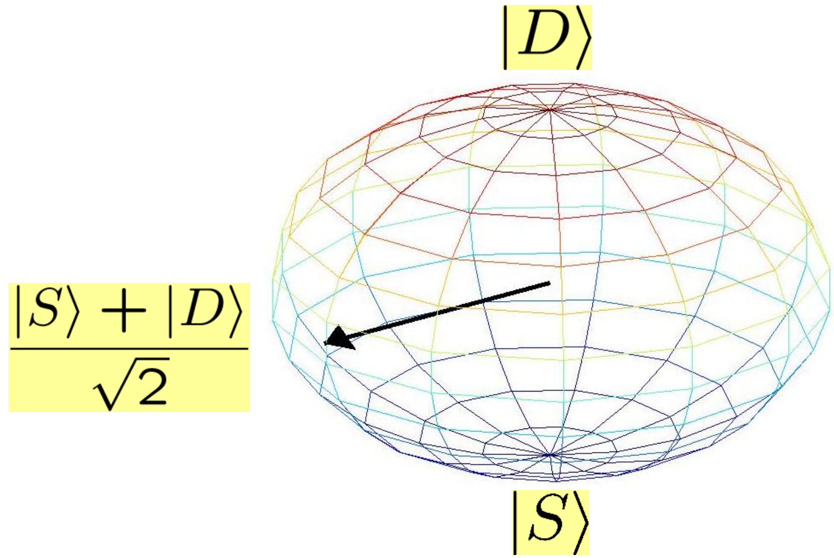
Rabi oscillations



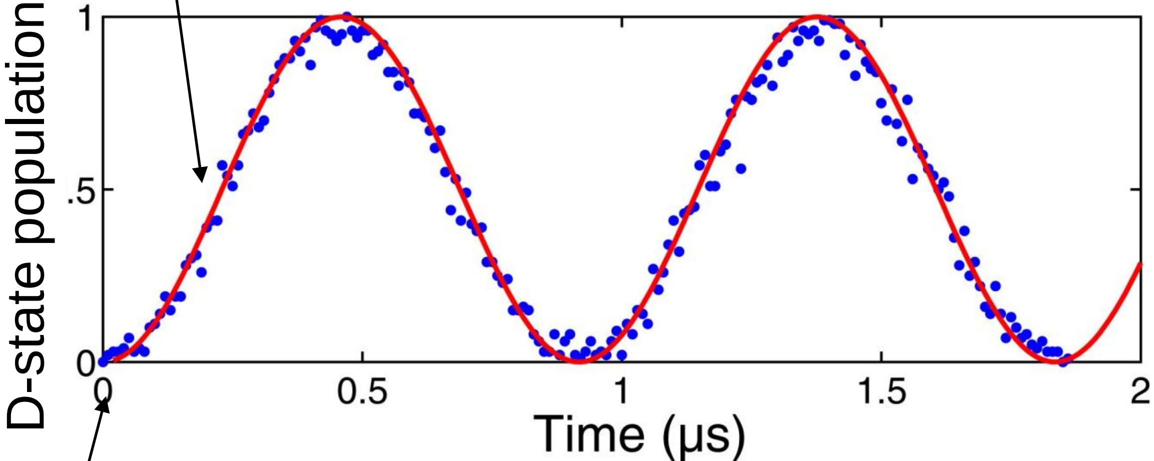


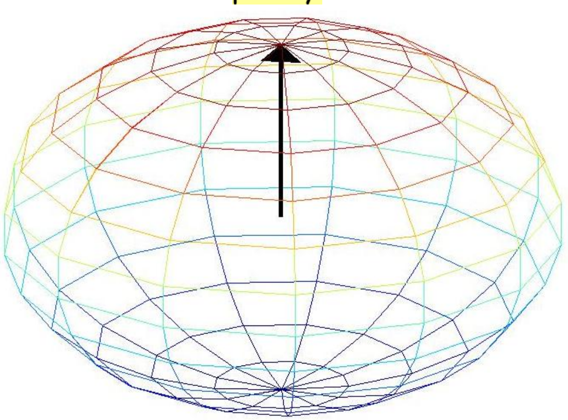
Rabi oscillations



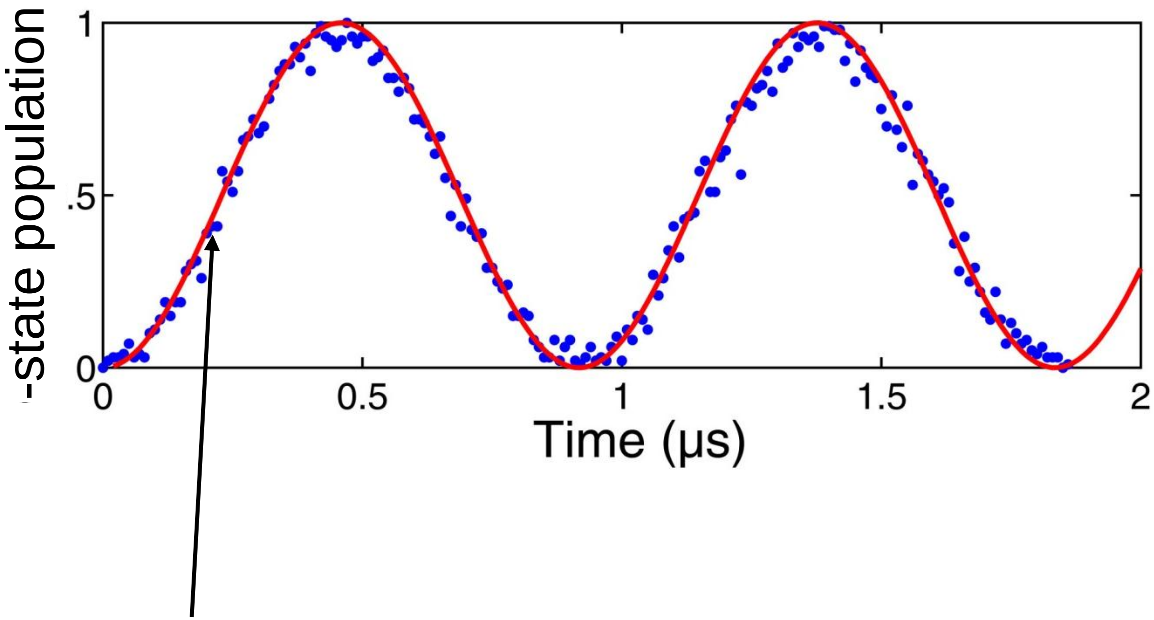


Rabi oscillations

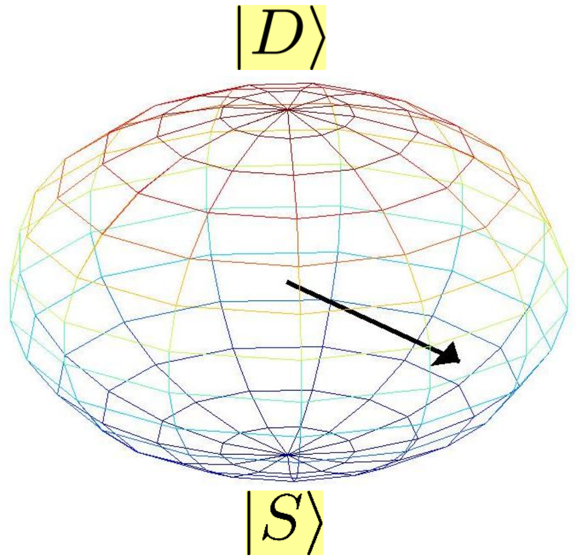




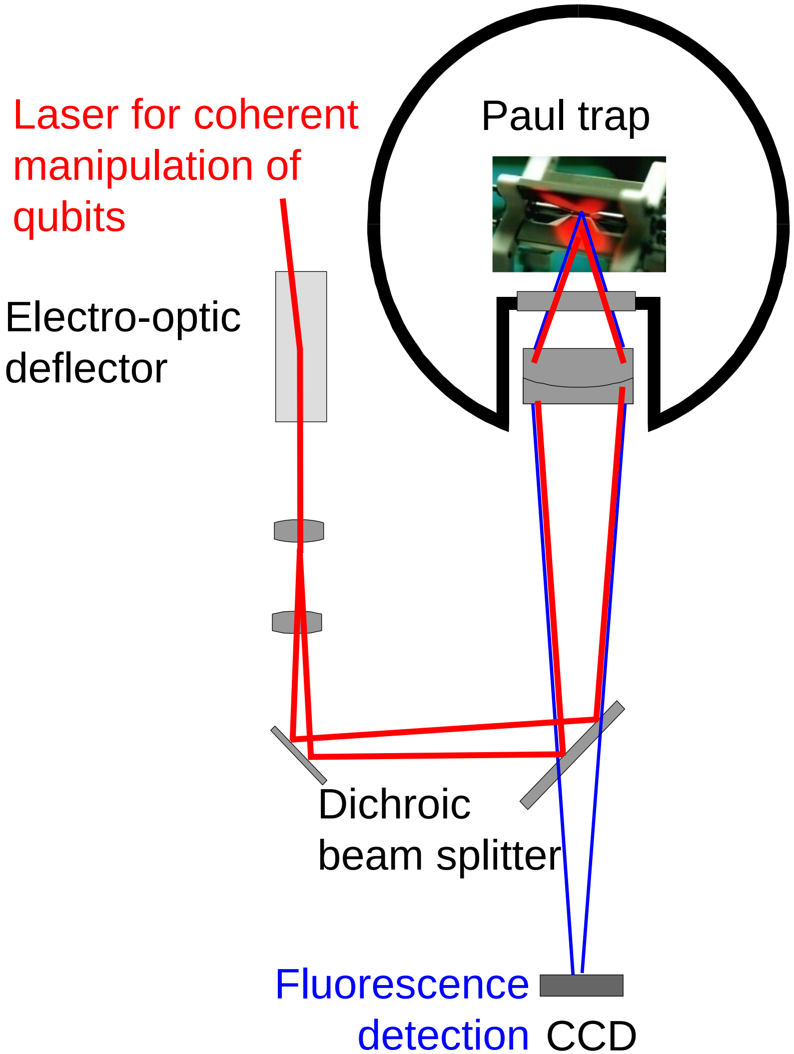
Rabi oscillations

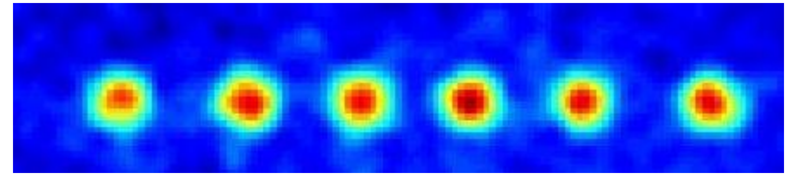


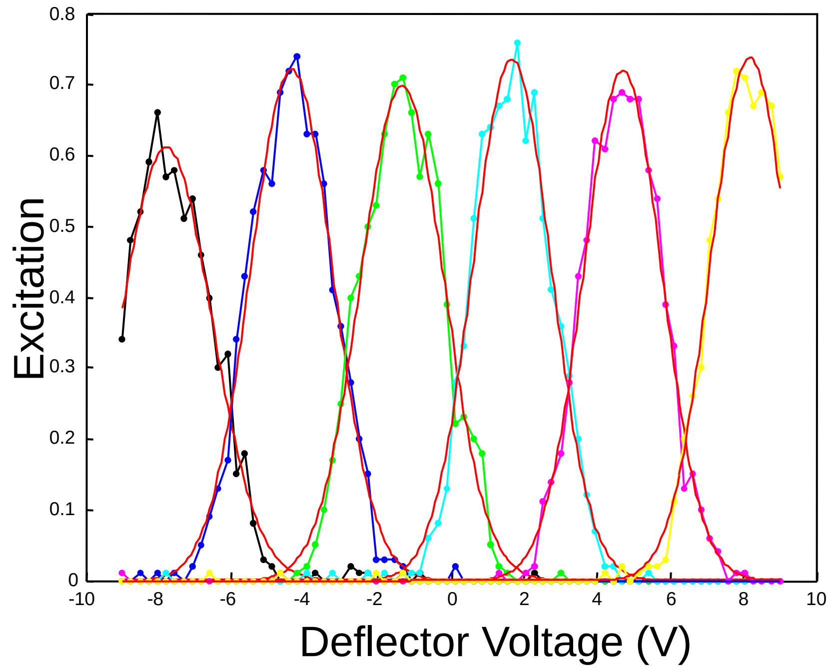
The phase is the phase difference between the atomic polarization and the lasers electric field.



Addressing of individual ions





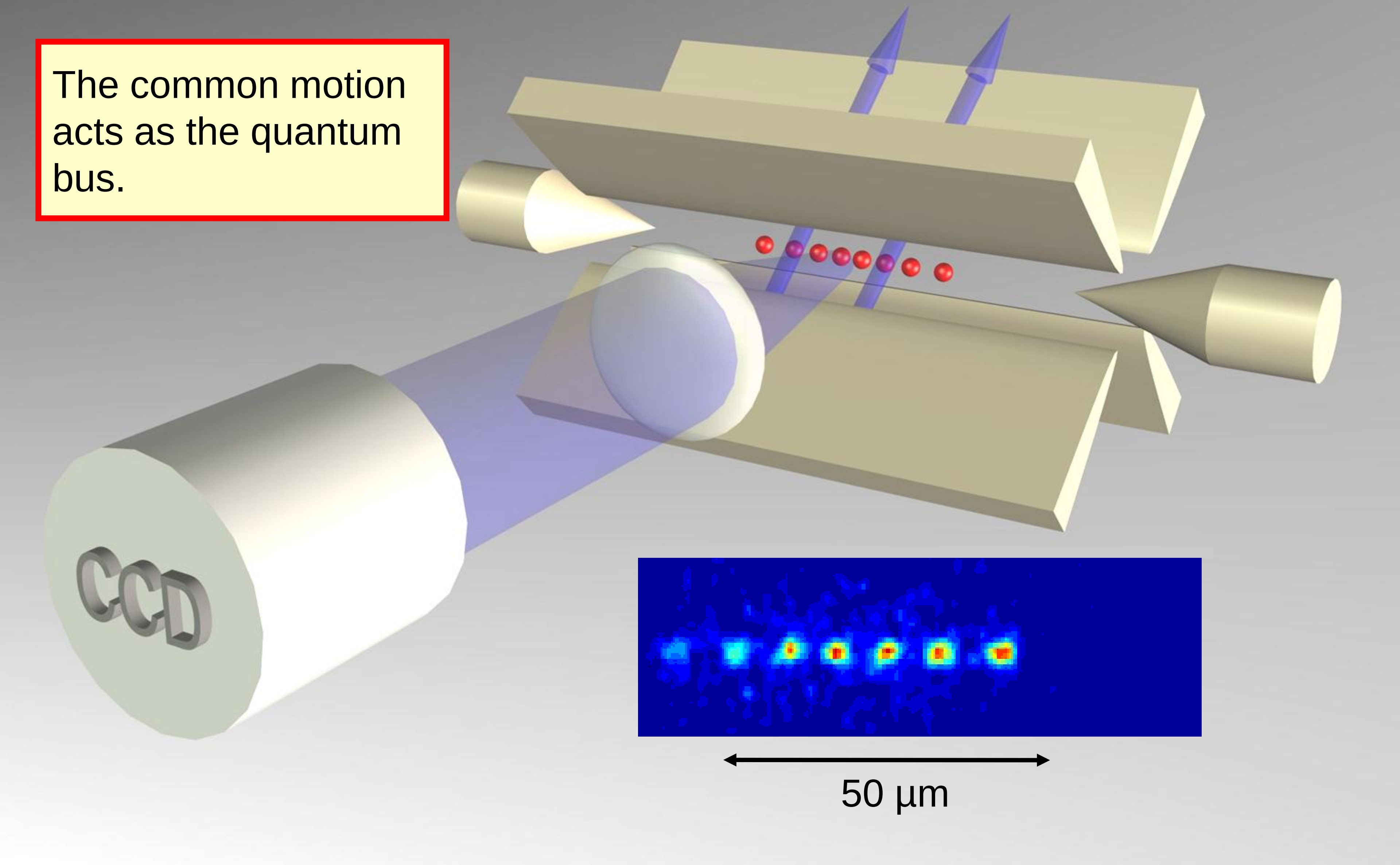


- inter ion distance: ~ 4 µm
- addressing waist: ~ 2 µm

< 0.1% intensity on neighbouring ions

Letting the qubits interact

The common motion acts as the quantum bus.



Letting the qubits interact

VOLUME 74, NUMBER 20 PHYSICAL REVIEW LETTERS 15 MAY 1995

Quantum Computations with Cold Trapped Ions

J. I. Cirac and P. Zoller*
Institut für Theoretische Physik, Universiät Innsbruck, Technikerstrasse 25, A-6020 Innsbruck, Austria
(Received 30 November 1994)

A quantum computer can be implemented with cold ions confined in a linear trap and interacting with laser beams. Quantum gates involving any pair, triplet, or subset of ions can be realized by coupling the ions through the collective quantized motion. In this system decoherence is negligible, and the measurement (readout of the quantum register) can be carried out with a high efficiency.

PACS numbers: 89.80.+h, 03.65.Bz, 12.20.Fv, 32.80.Pj

...allows the realization of a ***universal*** quantum computer !

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

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

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

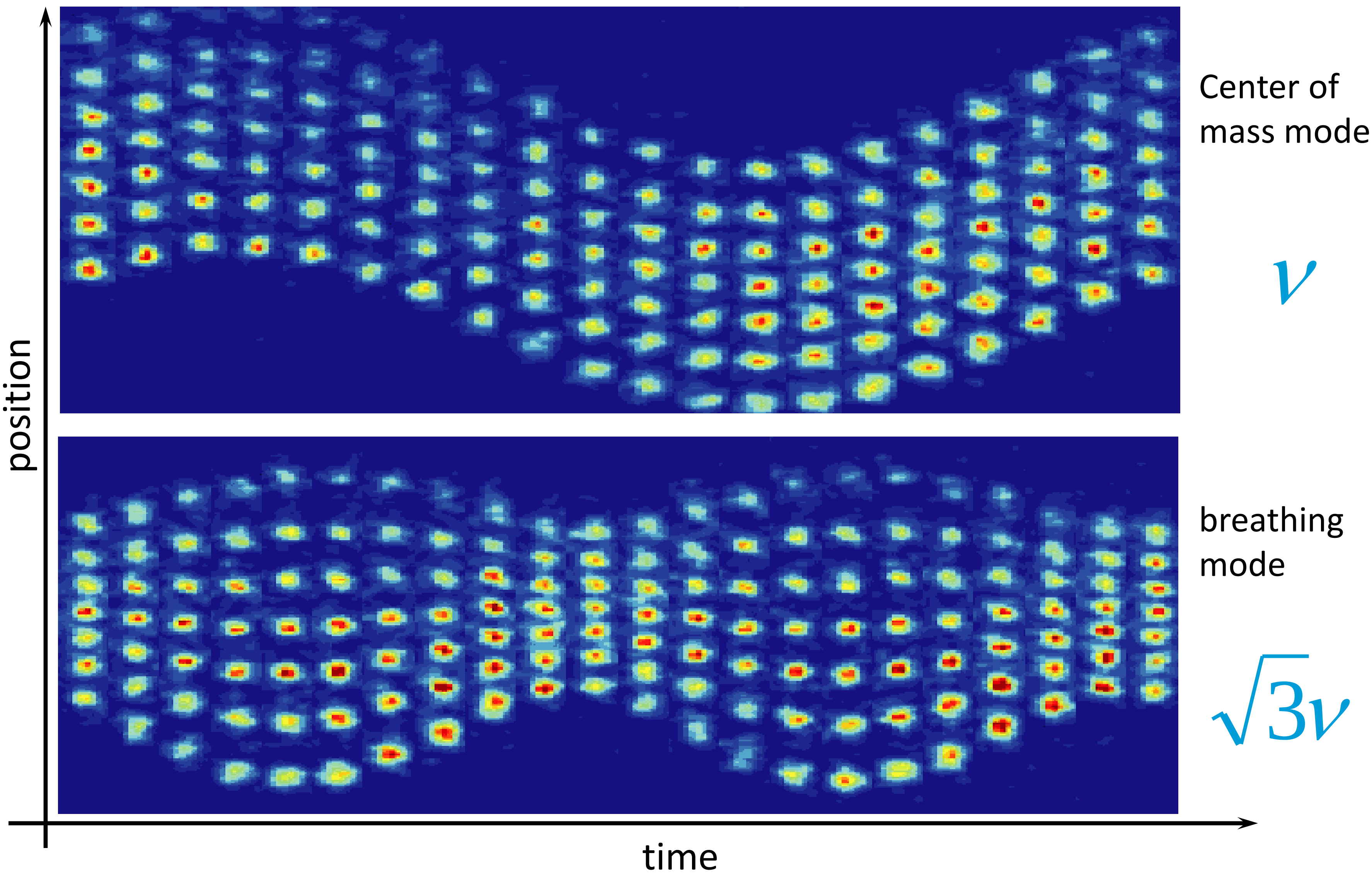
$$|S\rangle|S\rangle \rightarrow |S\rangle|D\rangle$$

control target

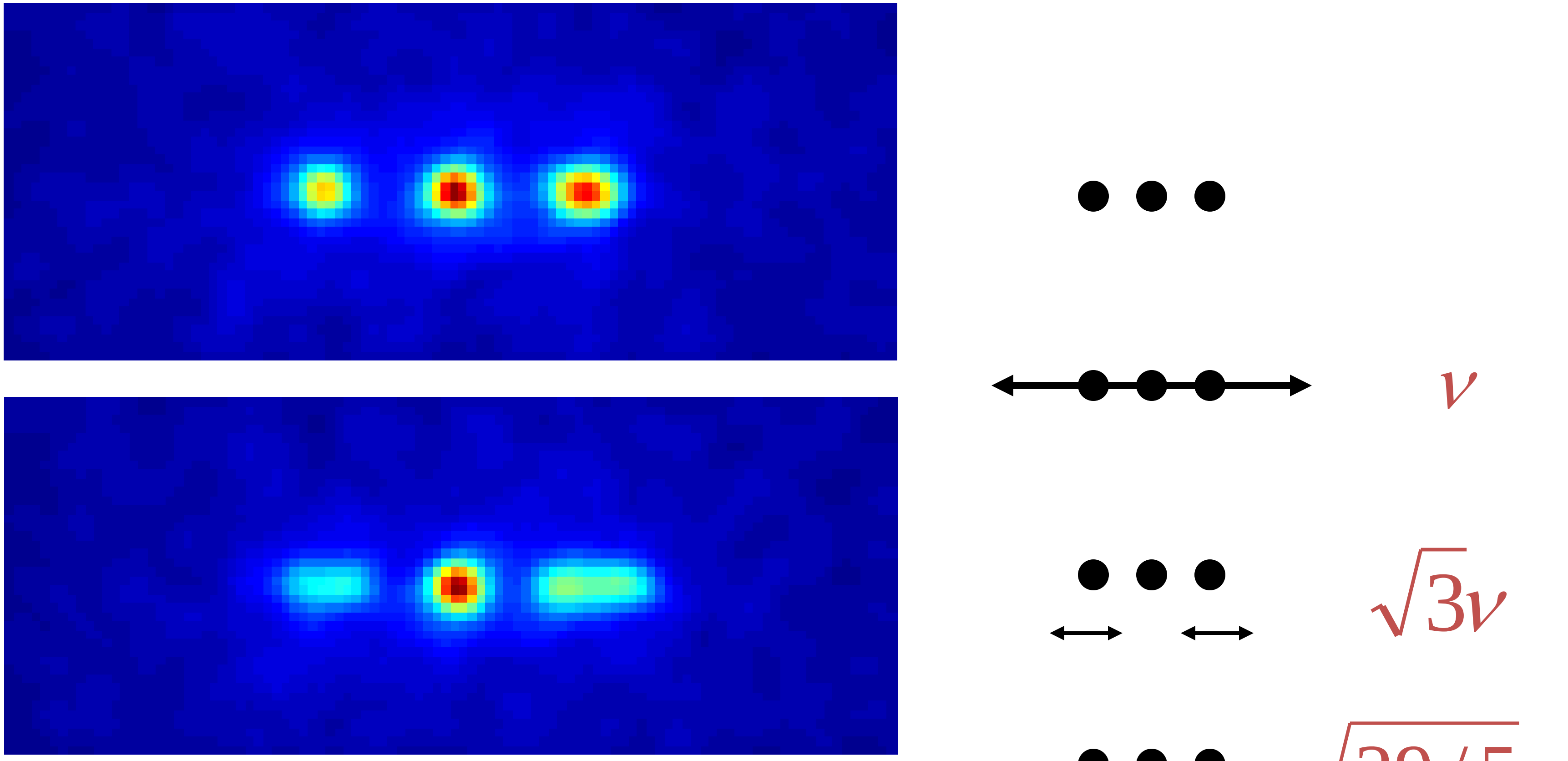
other gate proposals include:

- Cirac & Zoller
- Mølmer & Sørensen, Milburn
- Jonathan & Plenio & Knight
- Geometric phases
- Leibfried & Wineland

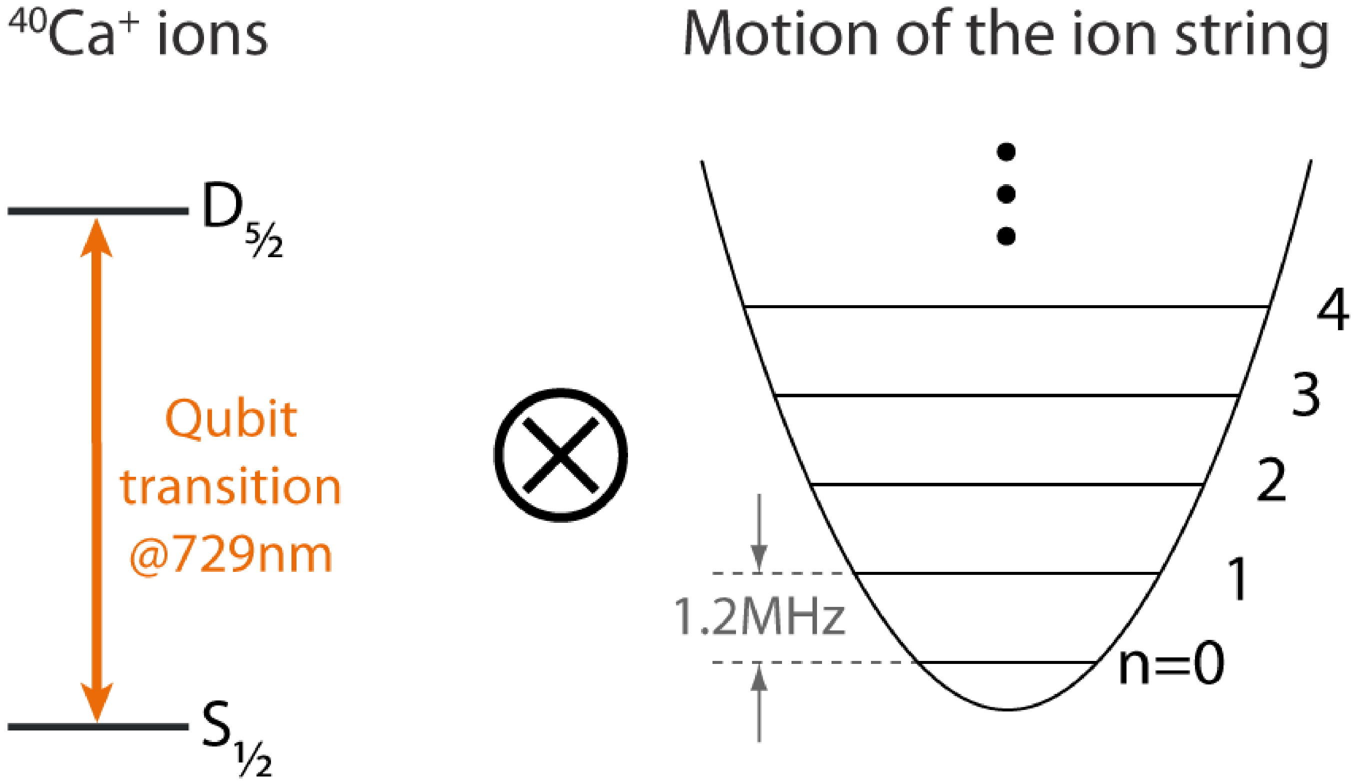
Common mode excitations



Common mode excitations



A string of trapped ions coupled to the motion



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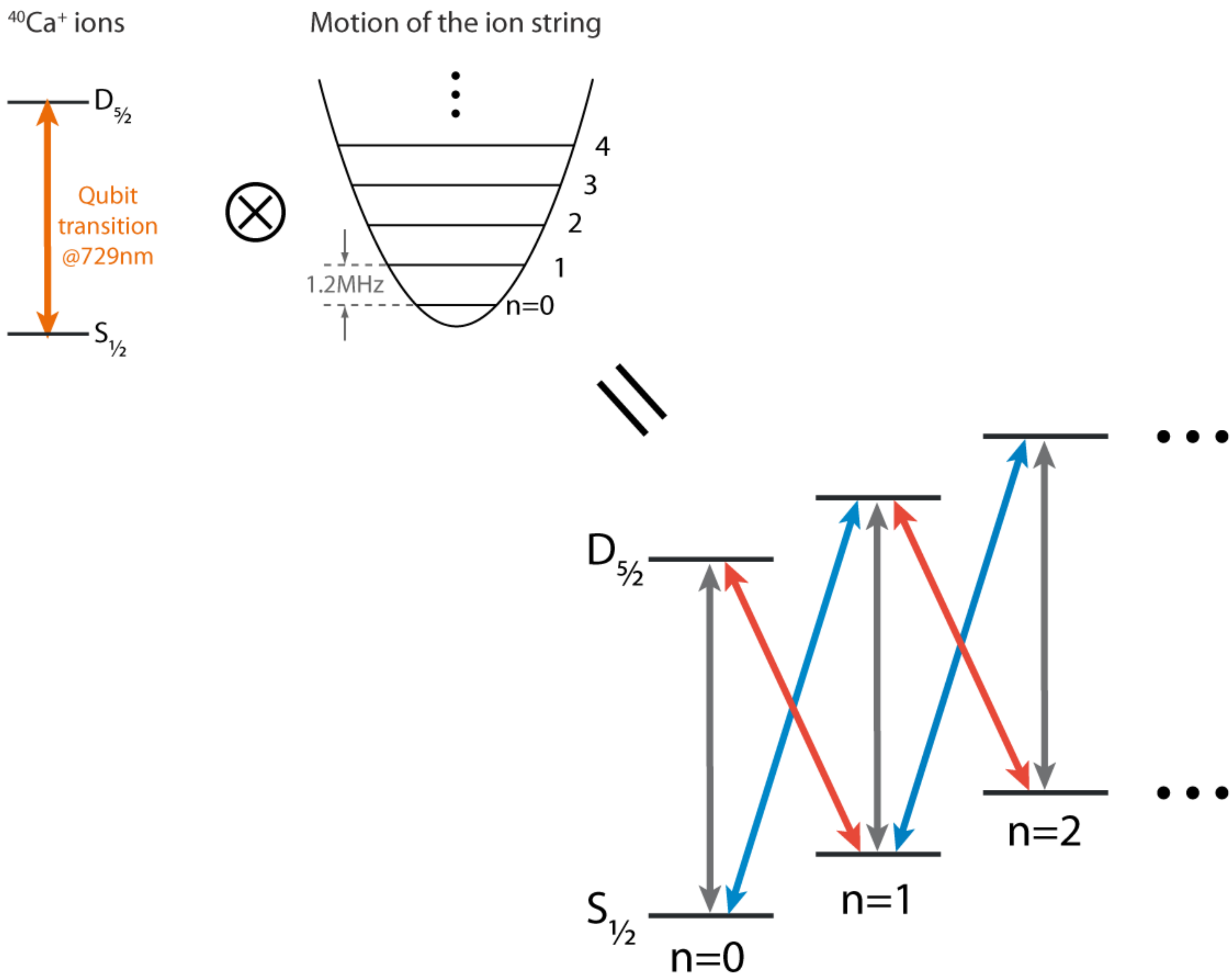
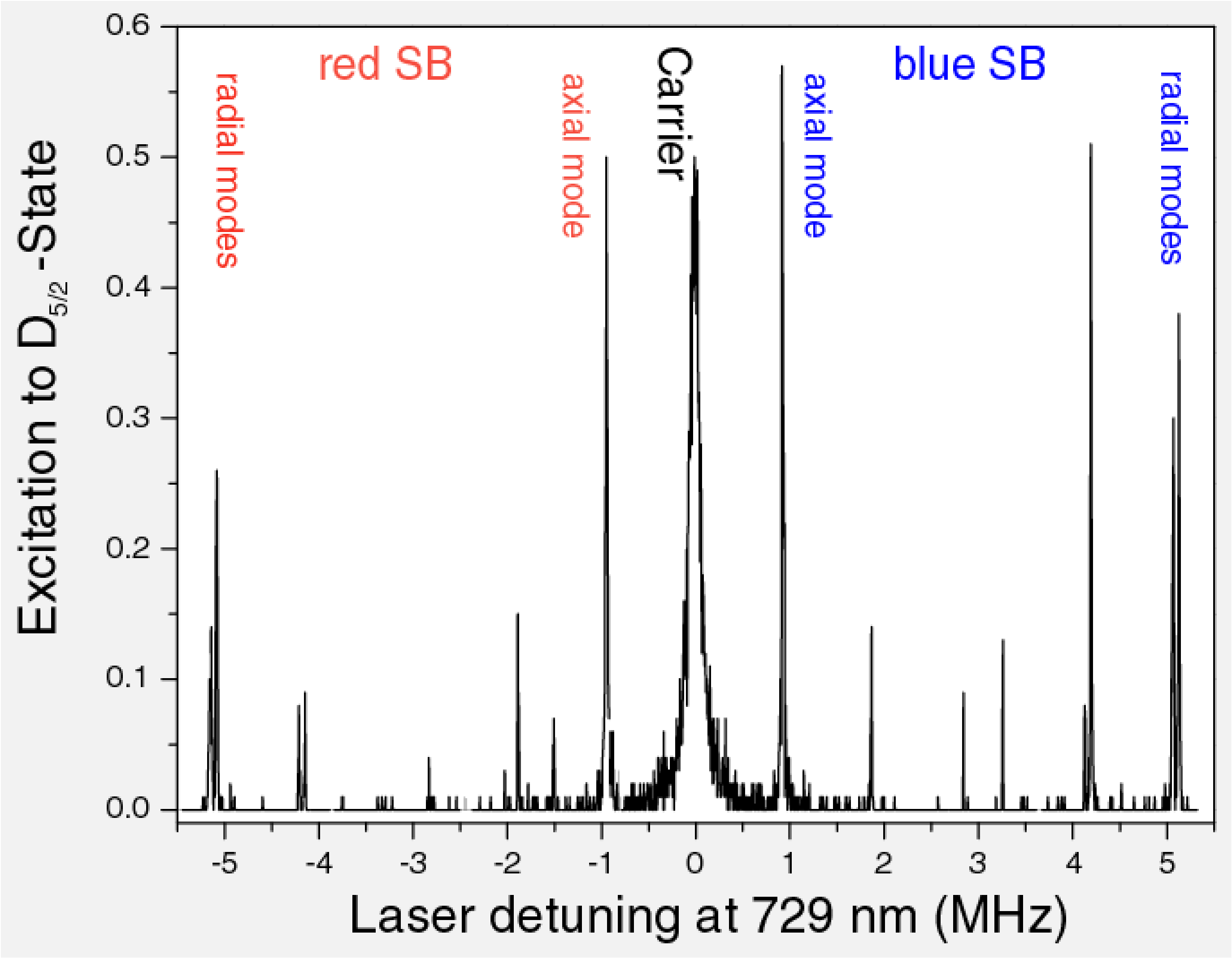


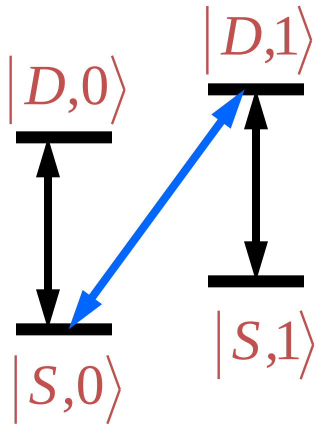
Excitation spectrum of single ion in linear trap

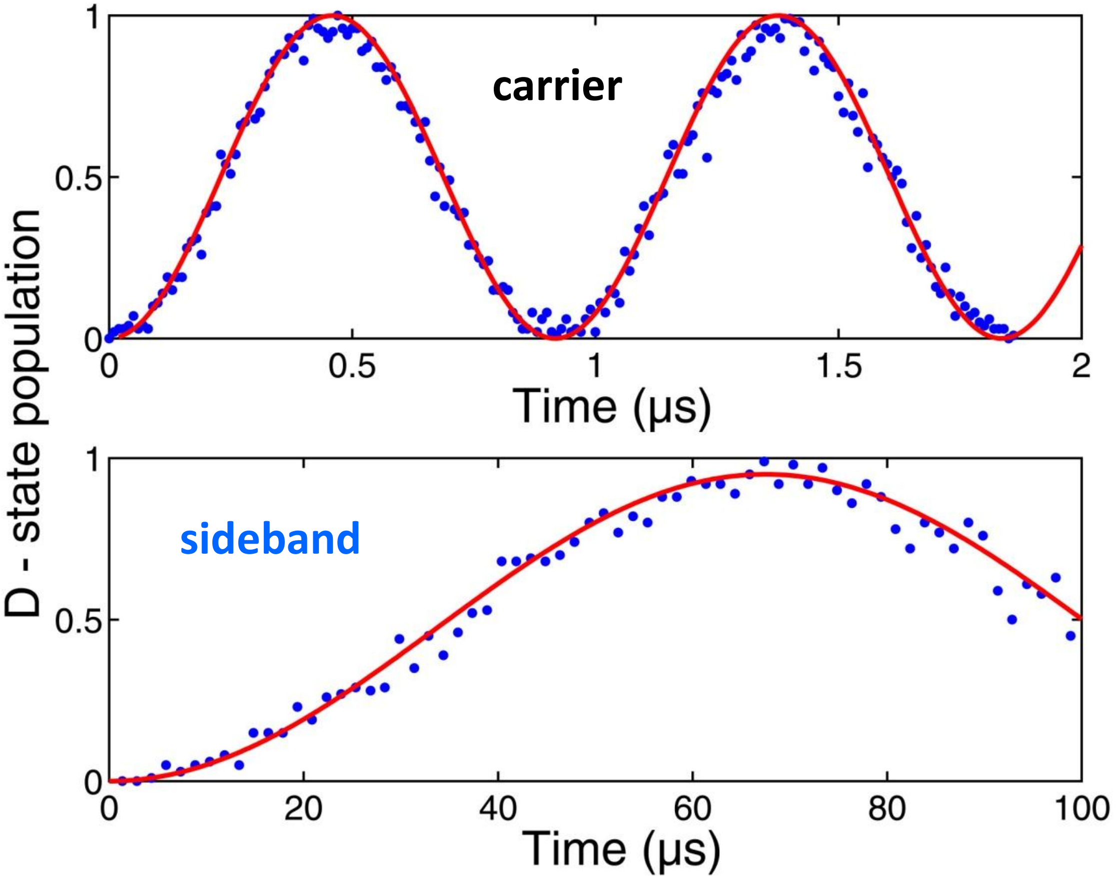


ω_{ax} = 1.0 MHz

ω_{rad} = 5.0 MHz

Coherent state manipulation





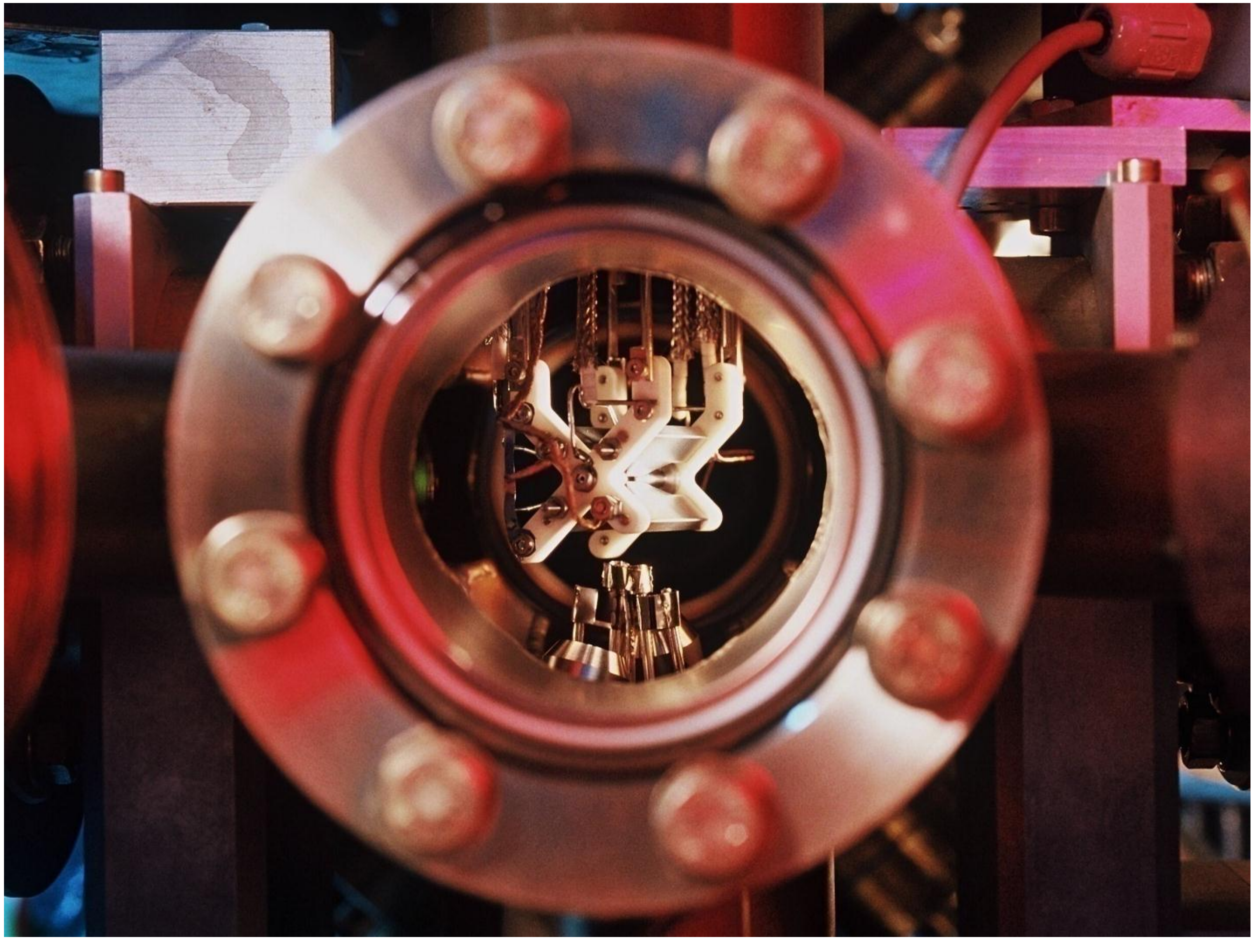
carrier and sideband
Rabi oscillations
with Rabi frequencies

$\Omega, \quad \eta\Omega\sqrt{n+1}$

$\eta = kx_0$ Lamb-Dicke parameter

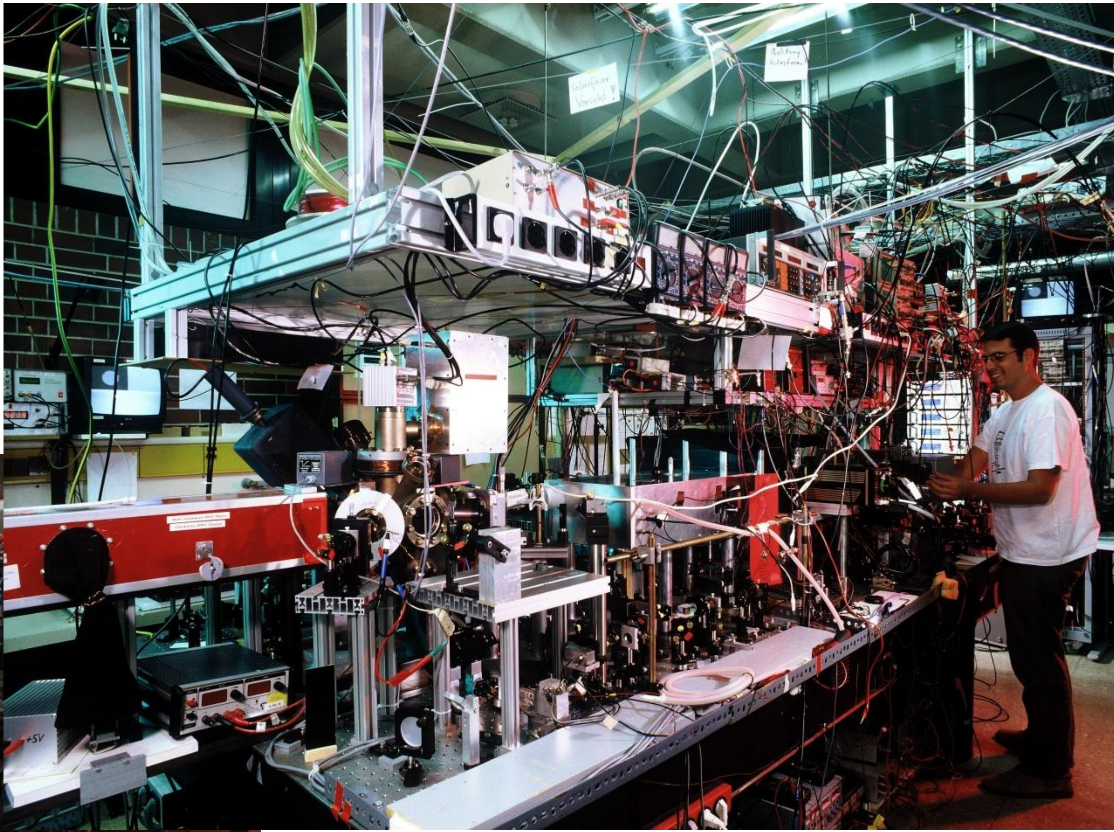
And that is how it looks like in real life....

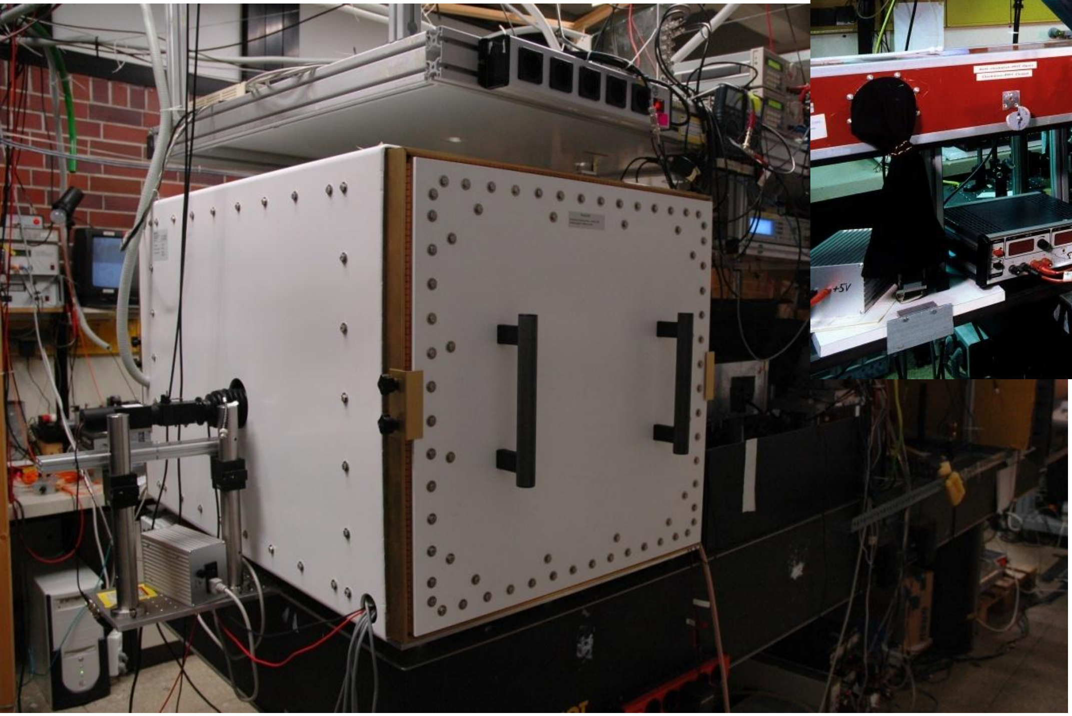
…the ion trap inside the vacuum chamber...



And that is how it looks like in real life….

…and the optical table (2003)...

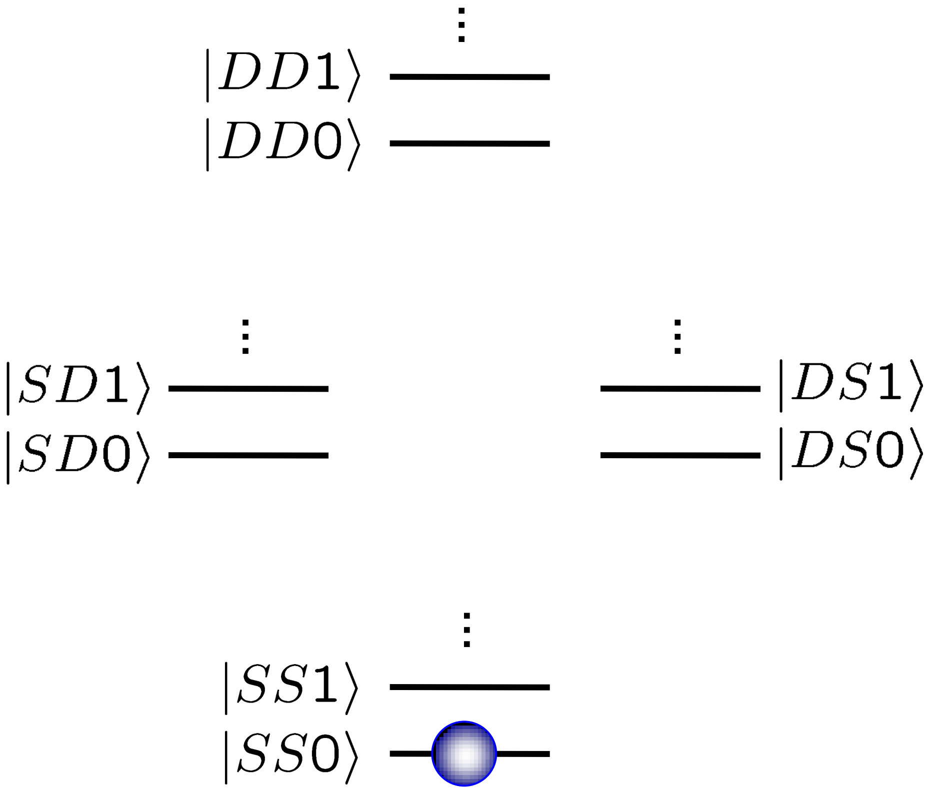


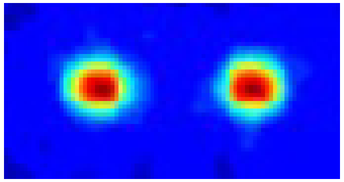


…and now with magnetic shielding.

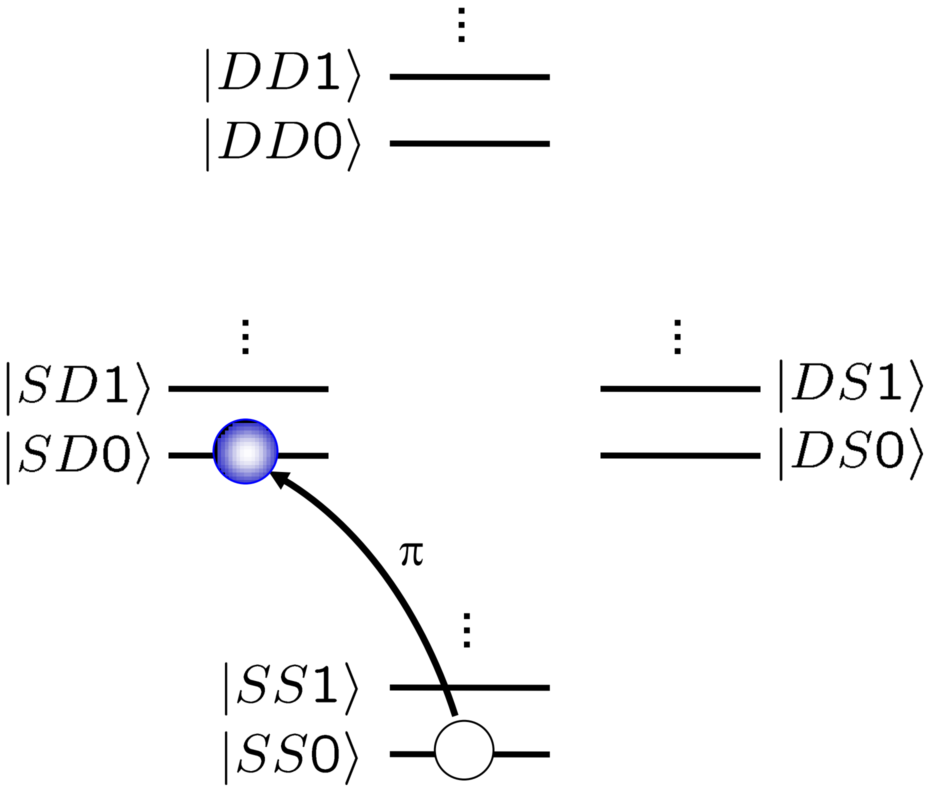
Generation of Bell states

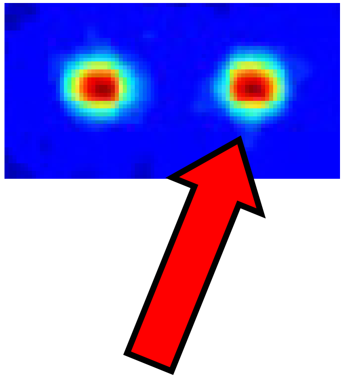
Generation of Bell states



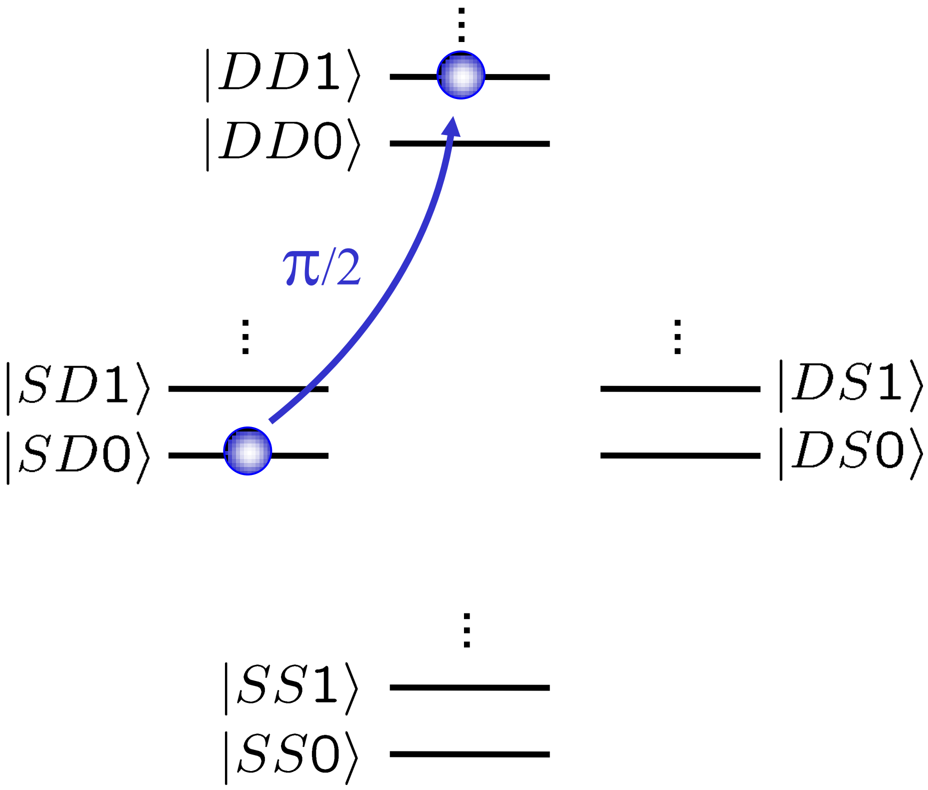


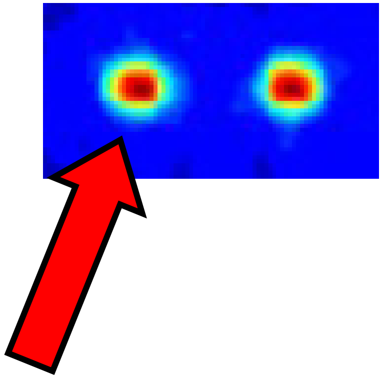
Generation of Bell states



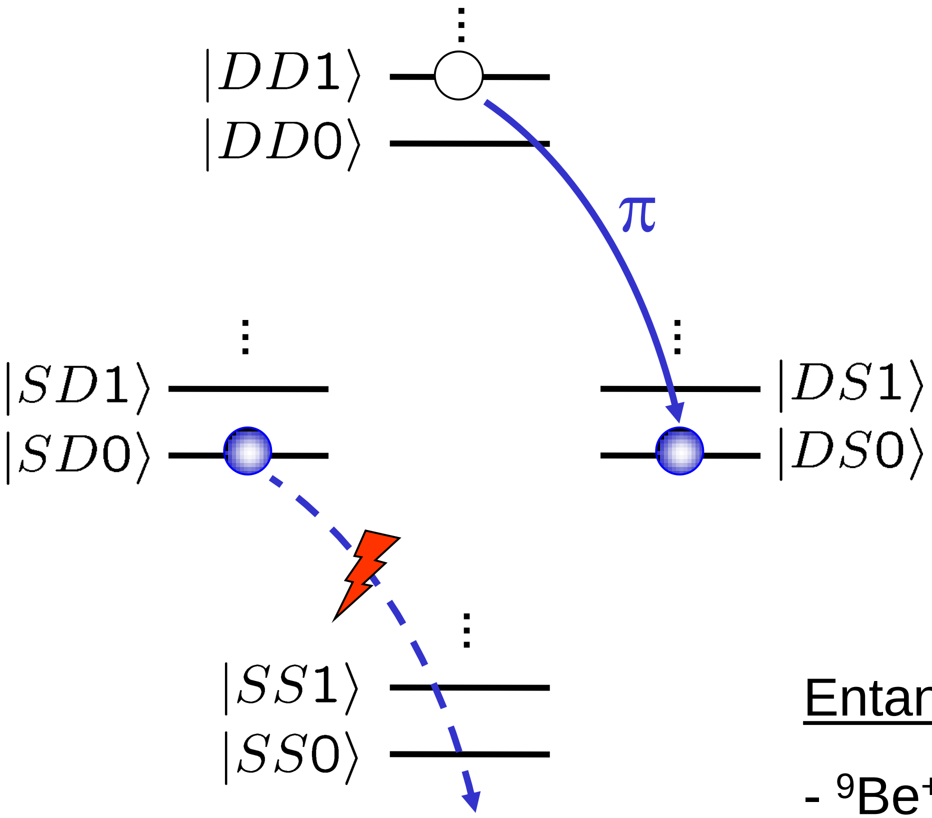


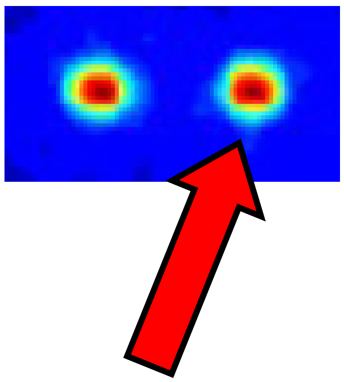
Generation of Bell states





Generation of Bell states





<u>Entangled ions using a geometric gate:</u>

- $^{9}Be^{+}$: Boulder, D. Wineland
- $^{40}Ca^{+}$: Oxford, A. Steane
- $^{111}Cd^{+}$: Ann Arbor, C. Monroe

Analysis of Bell states

$$|SD\rangle + |DS\rangle$$

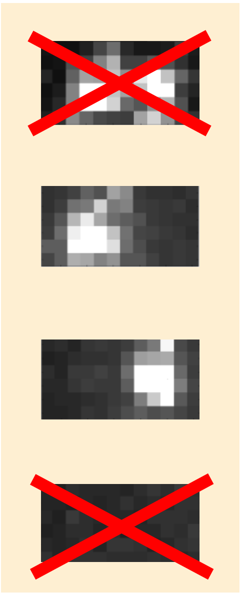
Fluorescence detection with CCD camera:

$|SS\rangle$

$|SD\rangle$

$|DS\rangle$

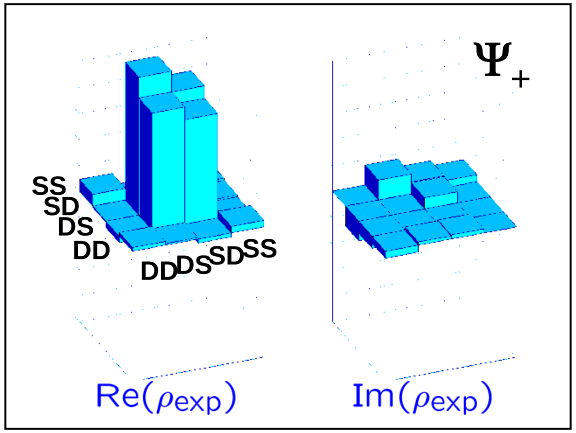
$|DD\rangle$



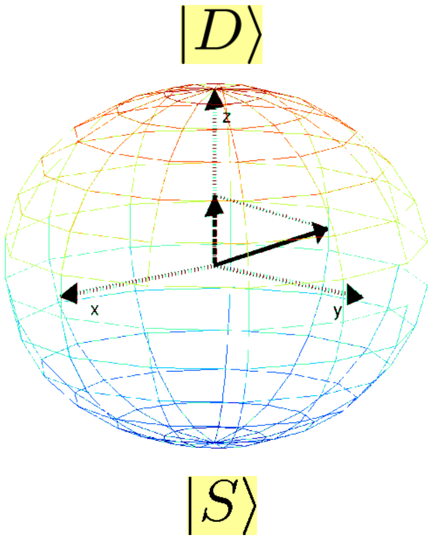
Coherent superposition or incoherent mixture ?

What is the relative phase of the superposition ?

→ **Measurement of the density matrix:**



Measuring a density matrix



A measurement yields the *z*-component of the Bloch vector
→Diagonal of the density matrix

$$\rho = \begin{pmatrix} P_S & C - iD \\ C + iD & P_D \end{pmatrix}$$

Measuring a density matrix

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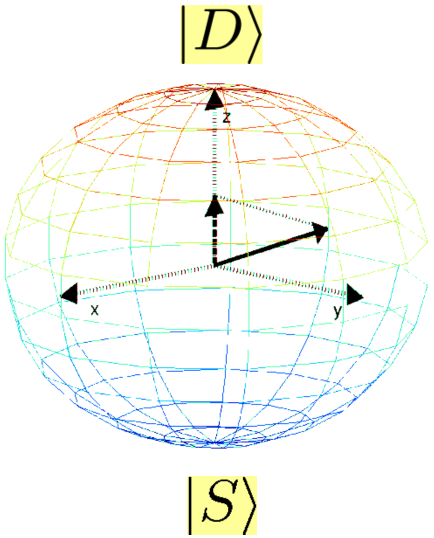
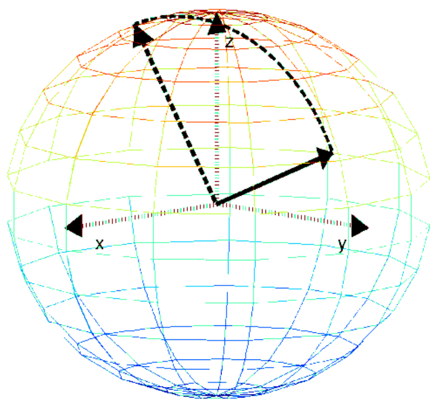
→Diagonal of the density matrix

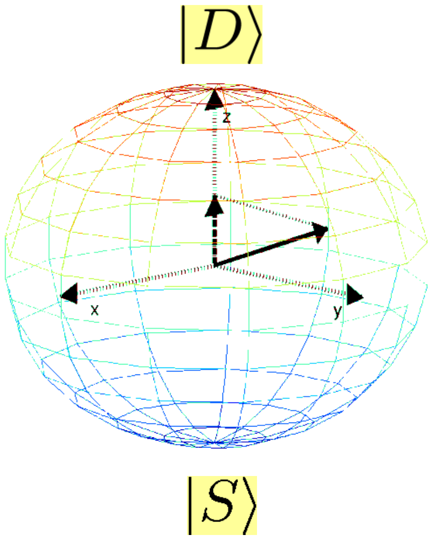
$$\rho = \begin{pmatrix} P_S & C - iD \\ C + iD & P_D \end{pmatrix}$$



Rotation around the *x*- or the *y*-axis prior to the measurement yields the phase information of the qubit.

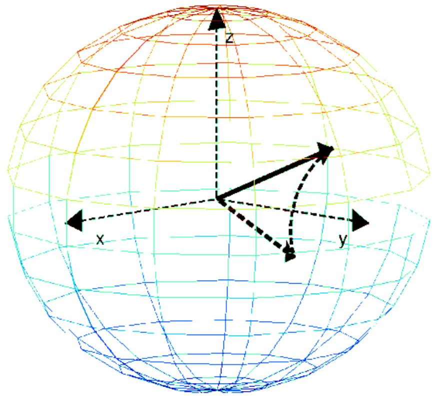


Measuring a density matrix



A measurement yields the *z*-component of the Bloch vector
→Diagonal of the density matrix

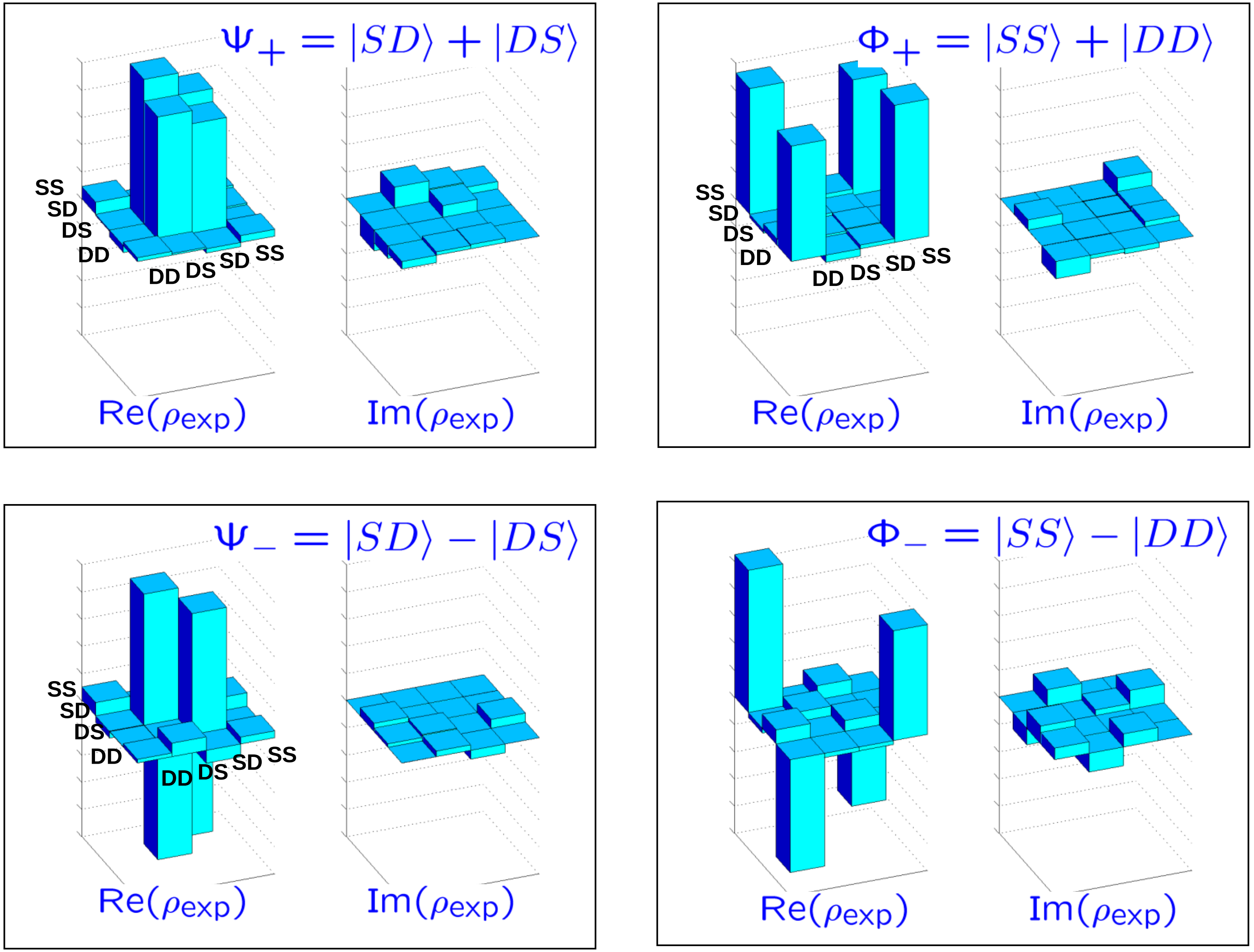
$$\rho = \begin{pmatrix} P_S & C - iD \\ C + iD & P_D \end{pmatrix}$$



Rotation around the *x*- or the *y*-axis prior to the measurement yields the phase information of the qubit.

→ coherences of the density matrix

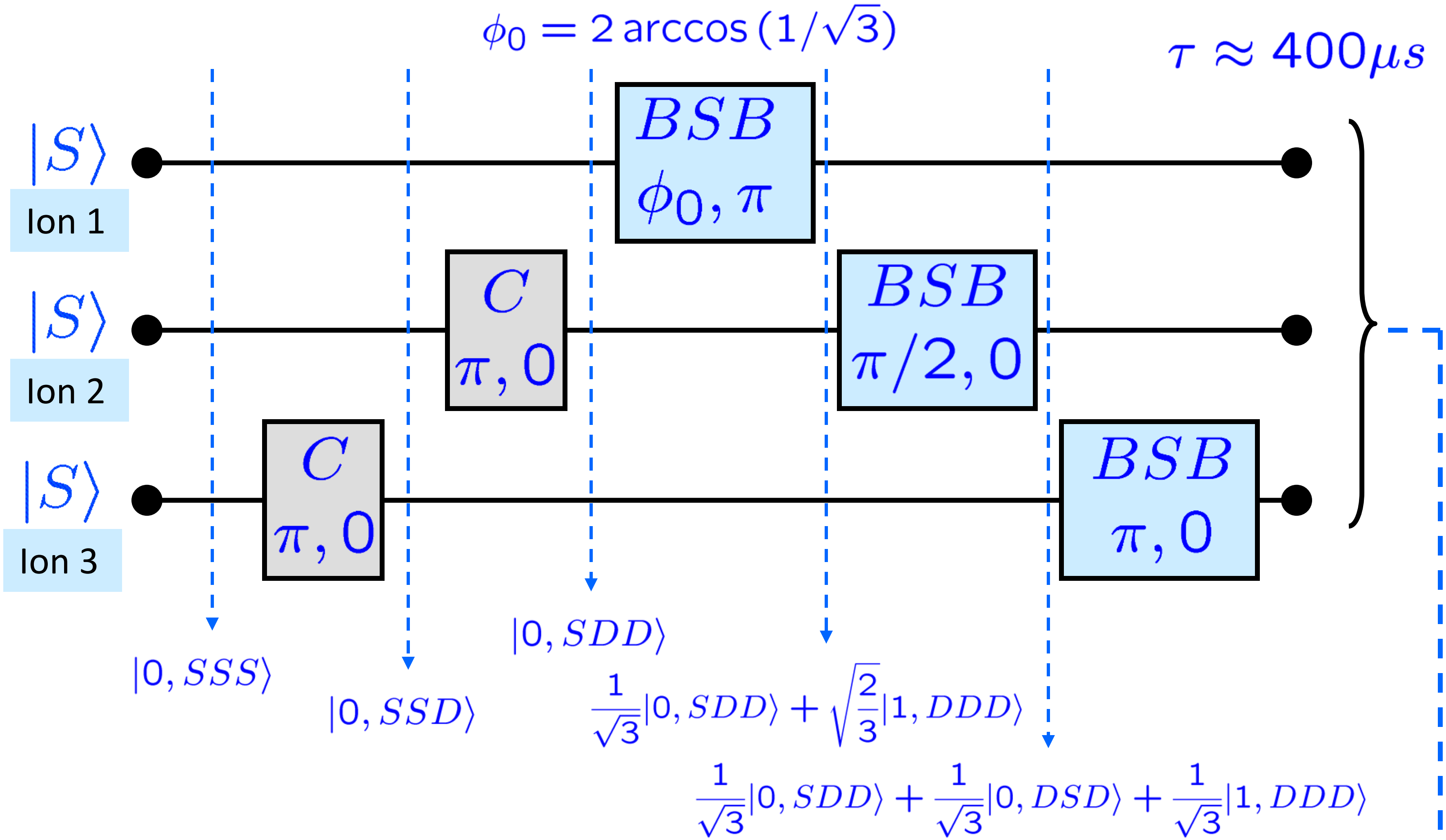
Tomography of Bell states



C. Roos, et al, Phys. Rev. Lett. 92, 220402 (2004).

Generation of W-states

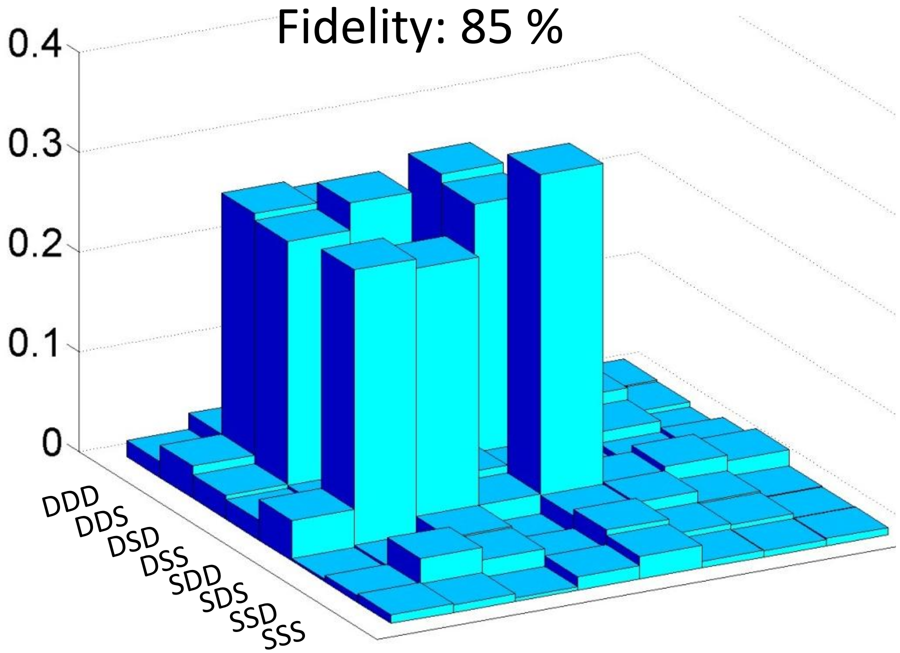
3 Ions: Preparation of W – states



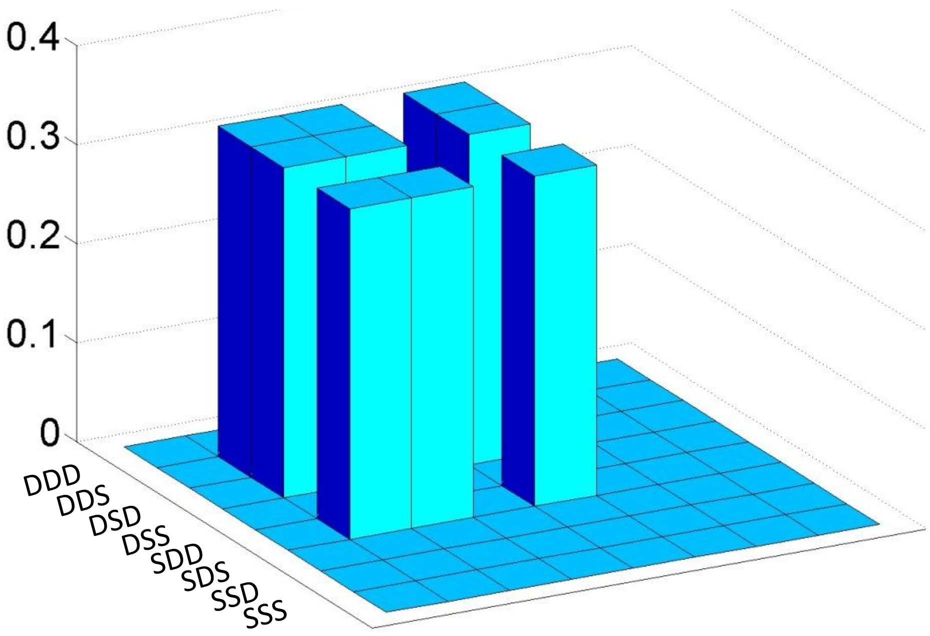
$$|\Psi\rangle_W = \frac{1}{\sqrt{3}}(|0, SDD\rangle + |0, DSD\rangle + |0, DDS\rangle)$$

W – states

$$|\Psi\rangle = \frac{1}{\sqrt{3}}(|SDD\rangle + |DSD\rangle + |DDS\rangle)$$



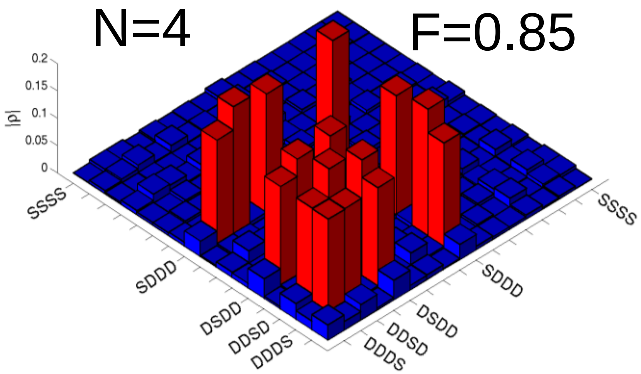
experimental result

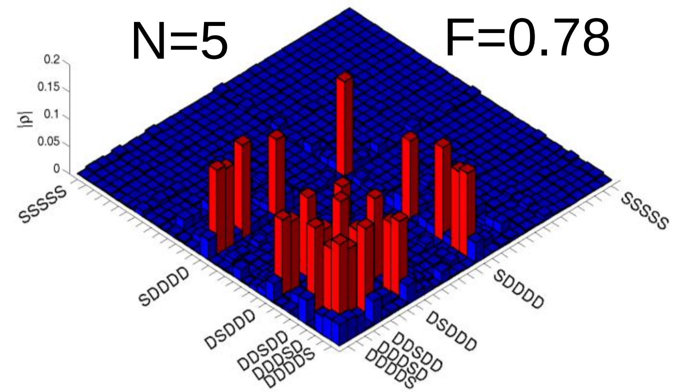


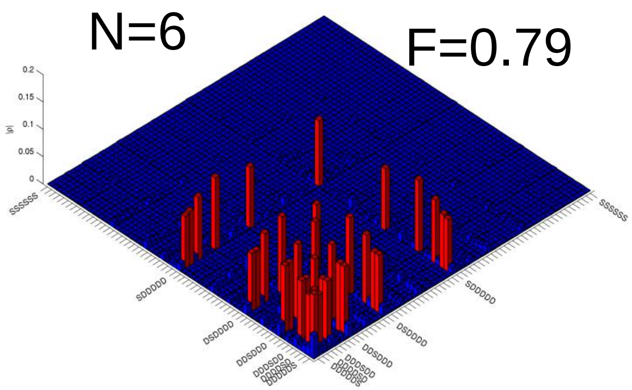
theoretical expectation

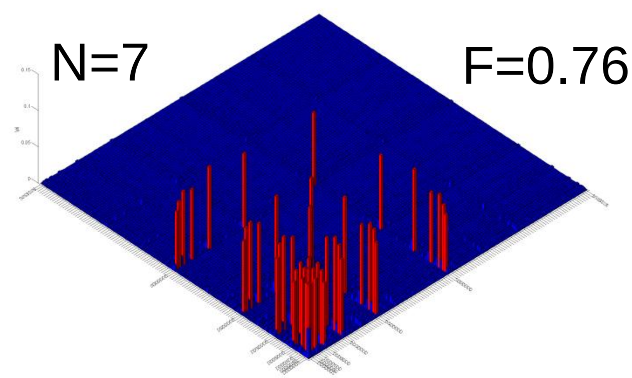
C. Roos et al., Science **304**, 1478 (2004)

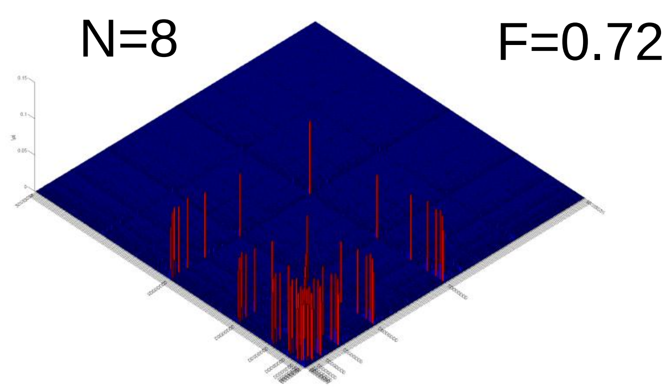
W-states









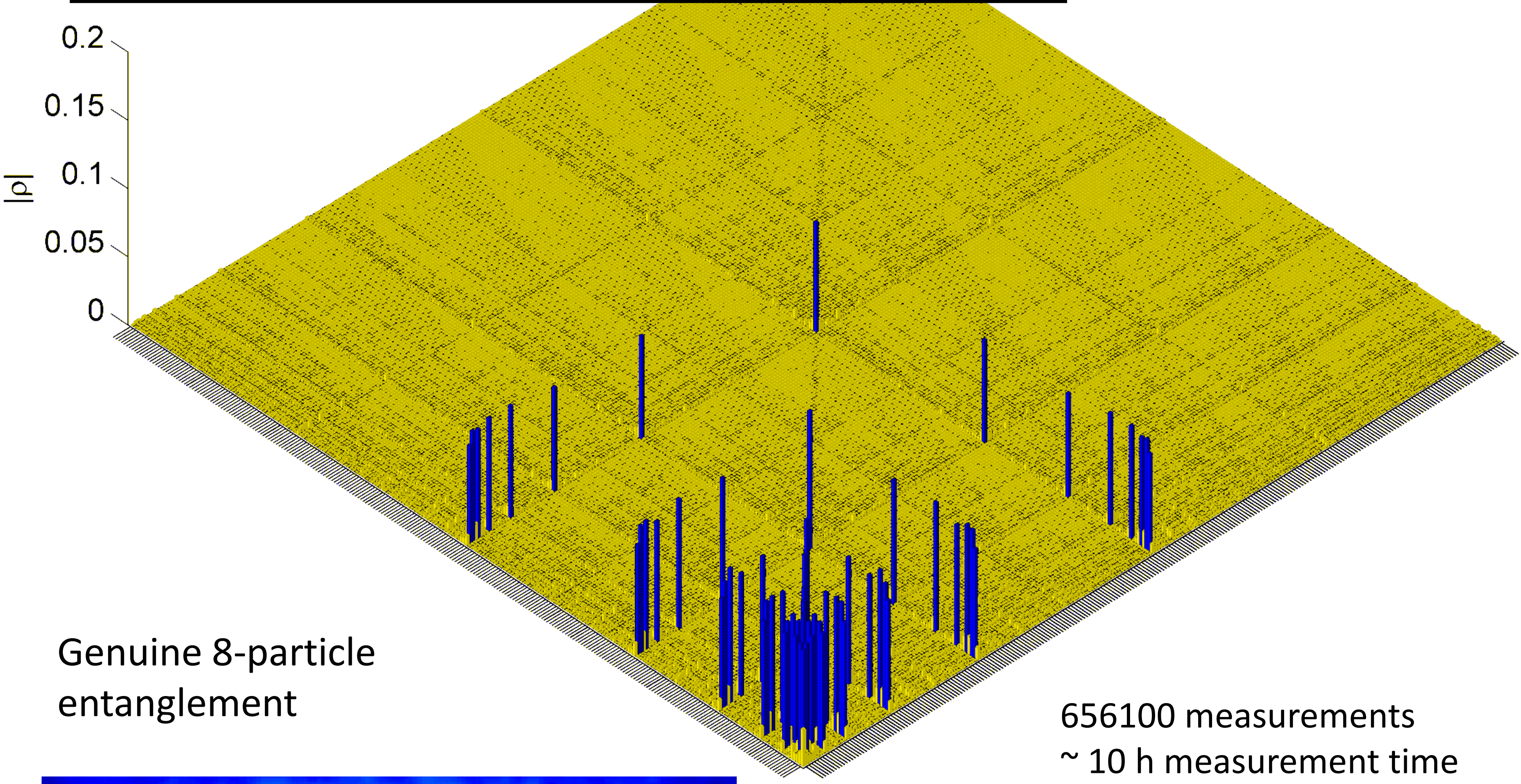


$$\frac{1}{\sqrt{N}}(|SS\dots SD\rangle + |SS\dots SDS\rangle + |DS\dots SS\rangle)$$

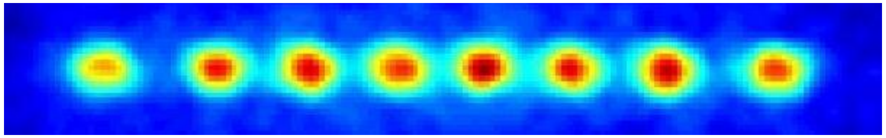
Häffner et al., Nature **438**, 643 (2005)

W-states

$$\frac{1}{\sqrt{8}}(|SSSSSSSD\rangle + |SSSSSSDS\rangle + \ldots + |DSSSSSSS\rangle)$$



Genuine 8-particle entanglement

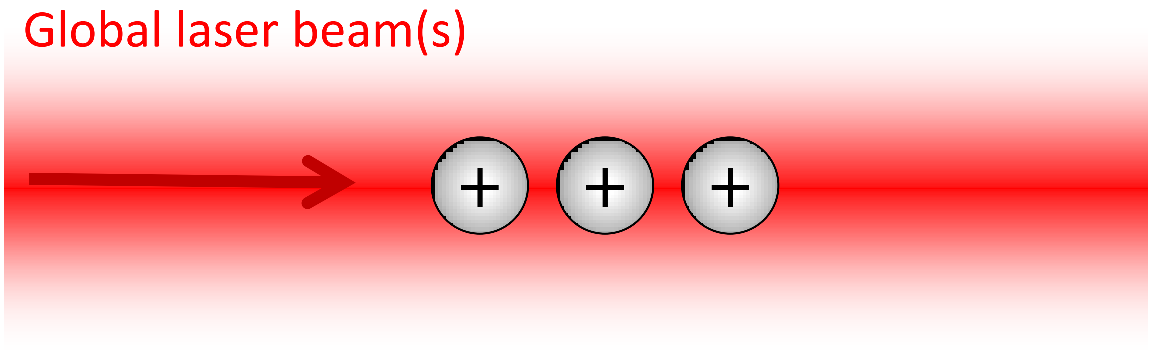


656100 measurements
~ 10 h measurement time

Häffner et al., Nature **438**, 643 (2005)

Generation of high-fidelity GHZ states

Generation of high-fidelity GHZ states



$$|\mathrm{GHZ}_N\rangle = \frac{1}{\sqrt{2}}\left(|00\ldots0\rangle + |11\ldots1\rangle\right)$$

Why interesting?

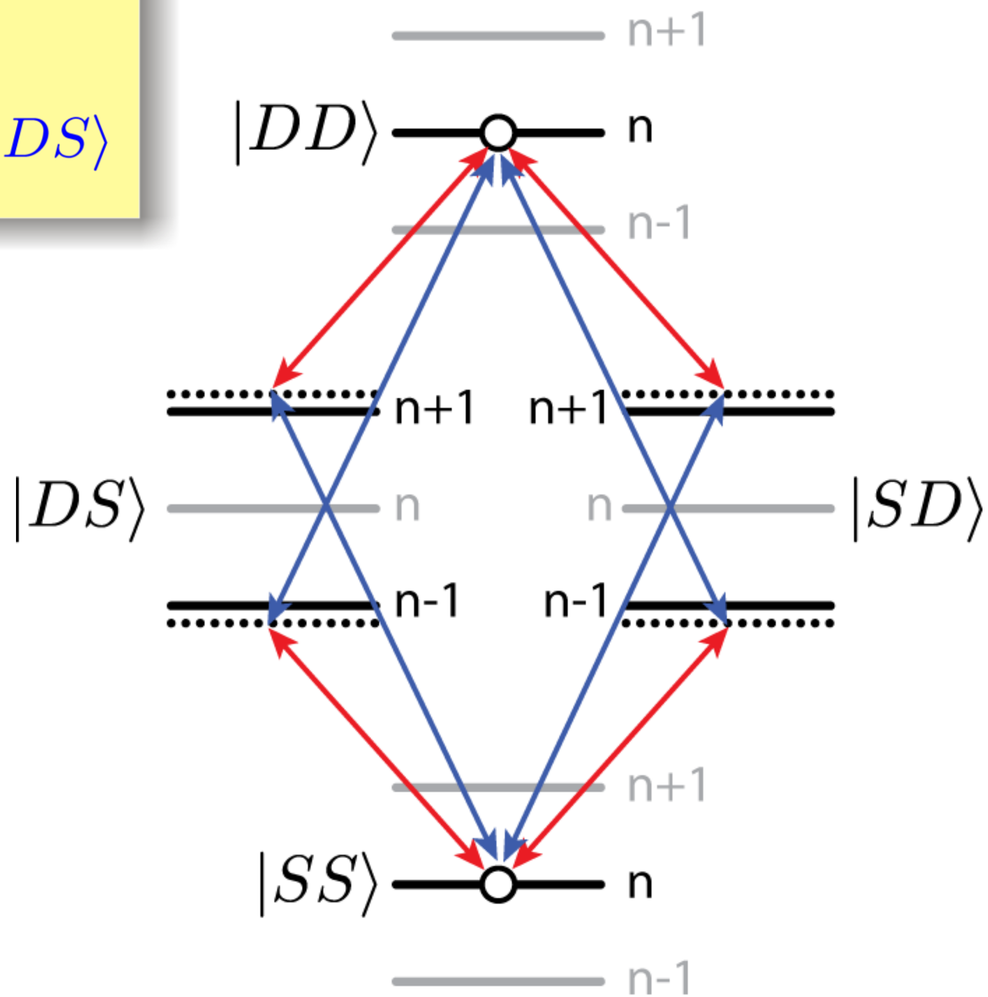
- highly non-classical: test fundamental physics (locality, Bell inequalities)
- applications: quantum key distribution, quantum communication
- quantum metrology (enhanced phase sensitivity)

High-fidelity gate operation

bichromatic laser excitation close to upper and lower sidebands induces collective state changes (spin flips)

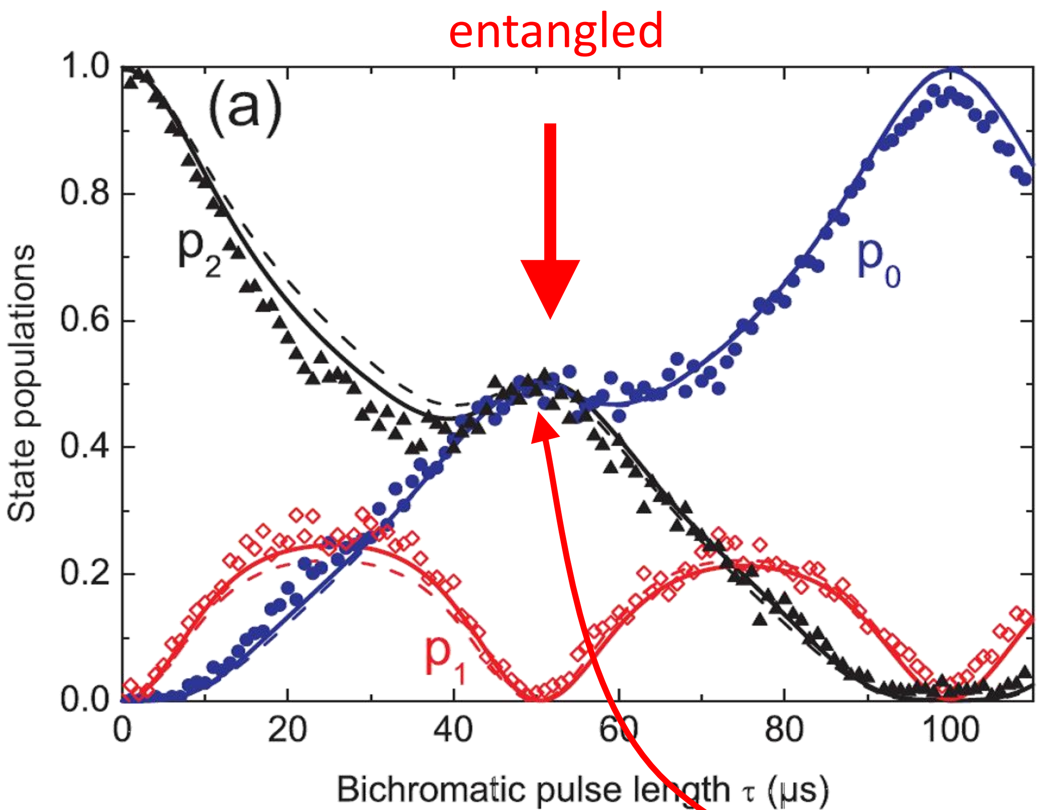
$|SS\rangle \rightarrow |DD\rangle, \ |SD\rangle \rightarrow |DS\rangle$

K. Mølmer, A. Sørensen, Phys. Rev. Lett. **82**, 1971 (1999)
C. A. Sackett et al., Nature **404**, 256 (2000)



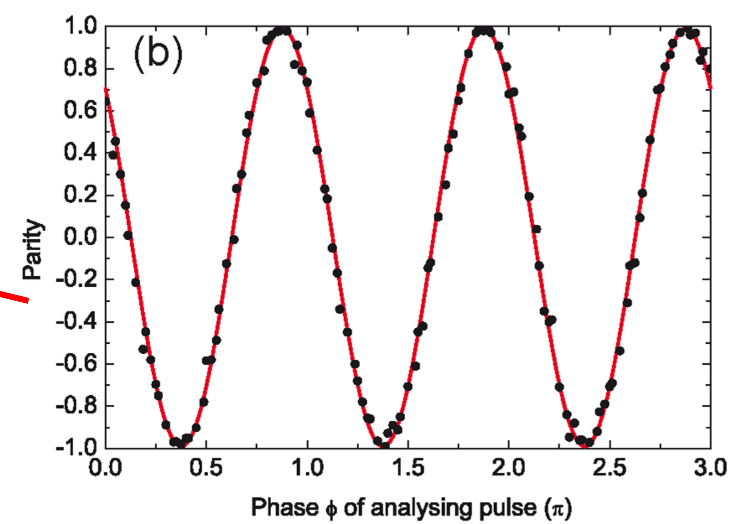
on an optical transition, the gate can be realized by co-propagating beams

Deterministic Bell states with the Mølmer-Sørensen gate



J. Benhelm et al.
*Nature Physics **4**, 463 (2008)*
Theory:
C. Roos, NJP 10 (2008)

measure entanglement
via parity oscillations



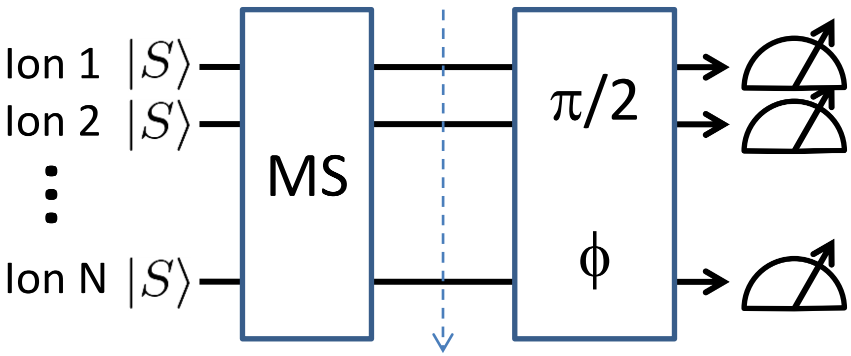
gate duration $51\mu s$

average fidelity

$$F_{\text{Bell}} = 99.3(0.2)\%$$

Measuring the entanglement

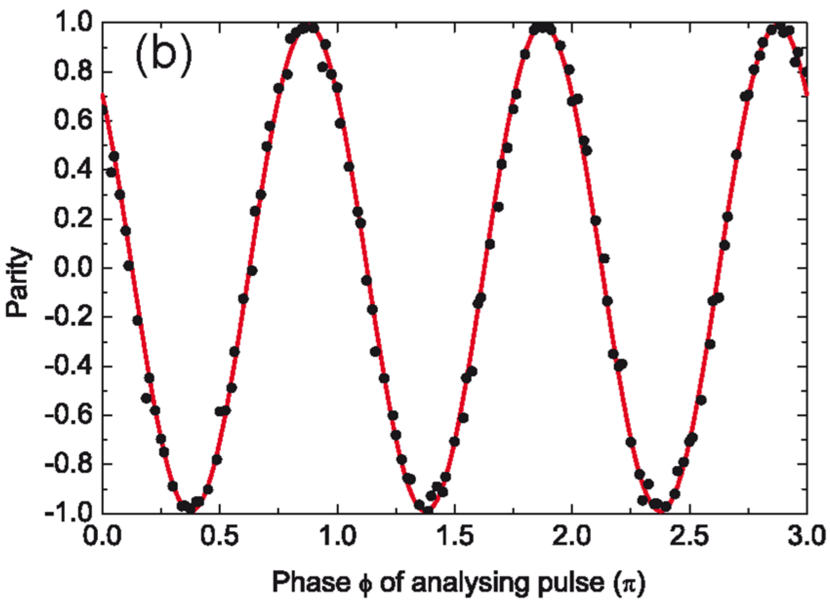
measure the parity [Sackett et al., Nature **404**, 256 (2000)]



$$(|SS\cdots S\rangle + |DD\cdots D\rangle)/\sqrt{2}$$

$$\Pi = \langle \prod_{j=1}^{N} \sigma_j^z \rangle$$

Parity Π oscillates with Nϕ



Bell / GHZ – Fidelity:

$$F = \frac{1}{2}(P_{SS\ldots S} + P_{DD\ldots D} + C)$$

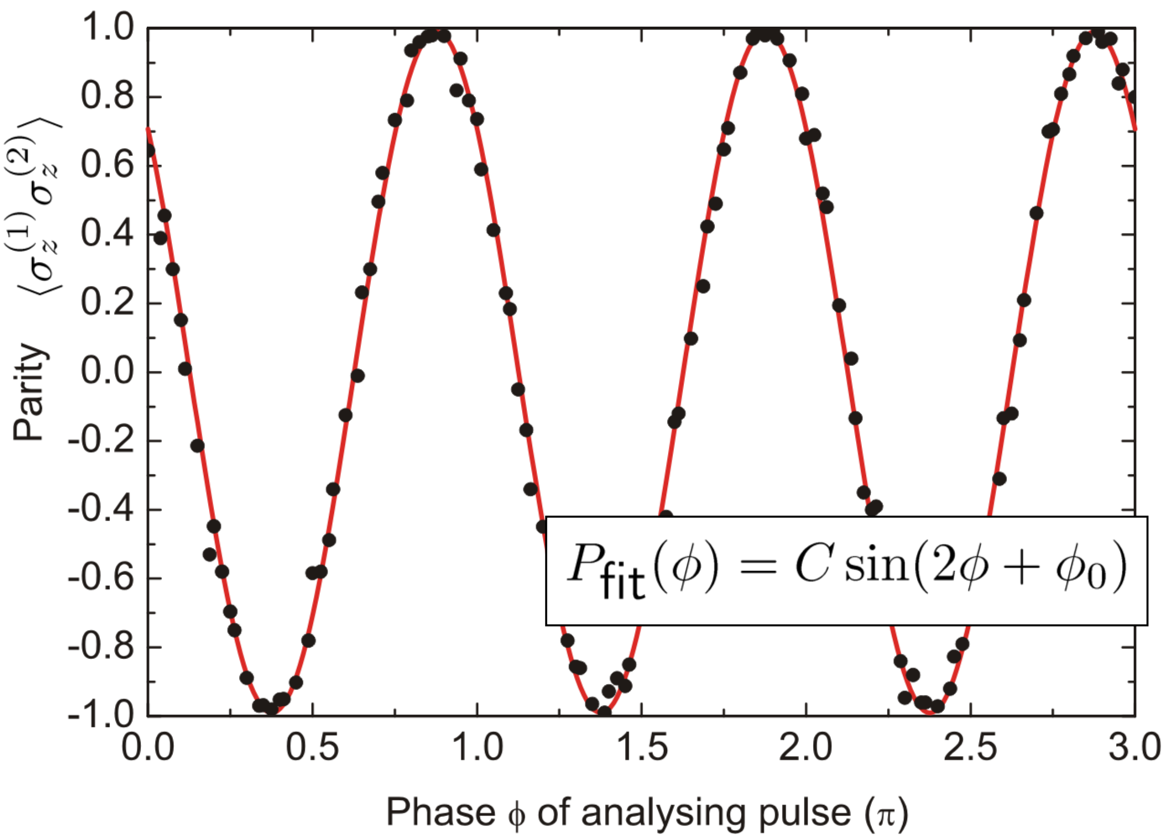
Witness:

$$W = 1 - 2 \cdot C$$

C: amplitude of the parity oscillations

Mølmer-Sørensen gate: parity oscillations

Parity oscillation contrast: $|\langle SS|\rho_\Psi|DD\rangle|$



Bell state:
$\Psi = |SS\rangle + i|DD\rangle$

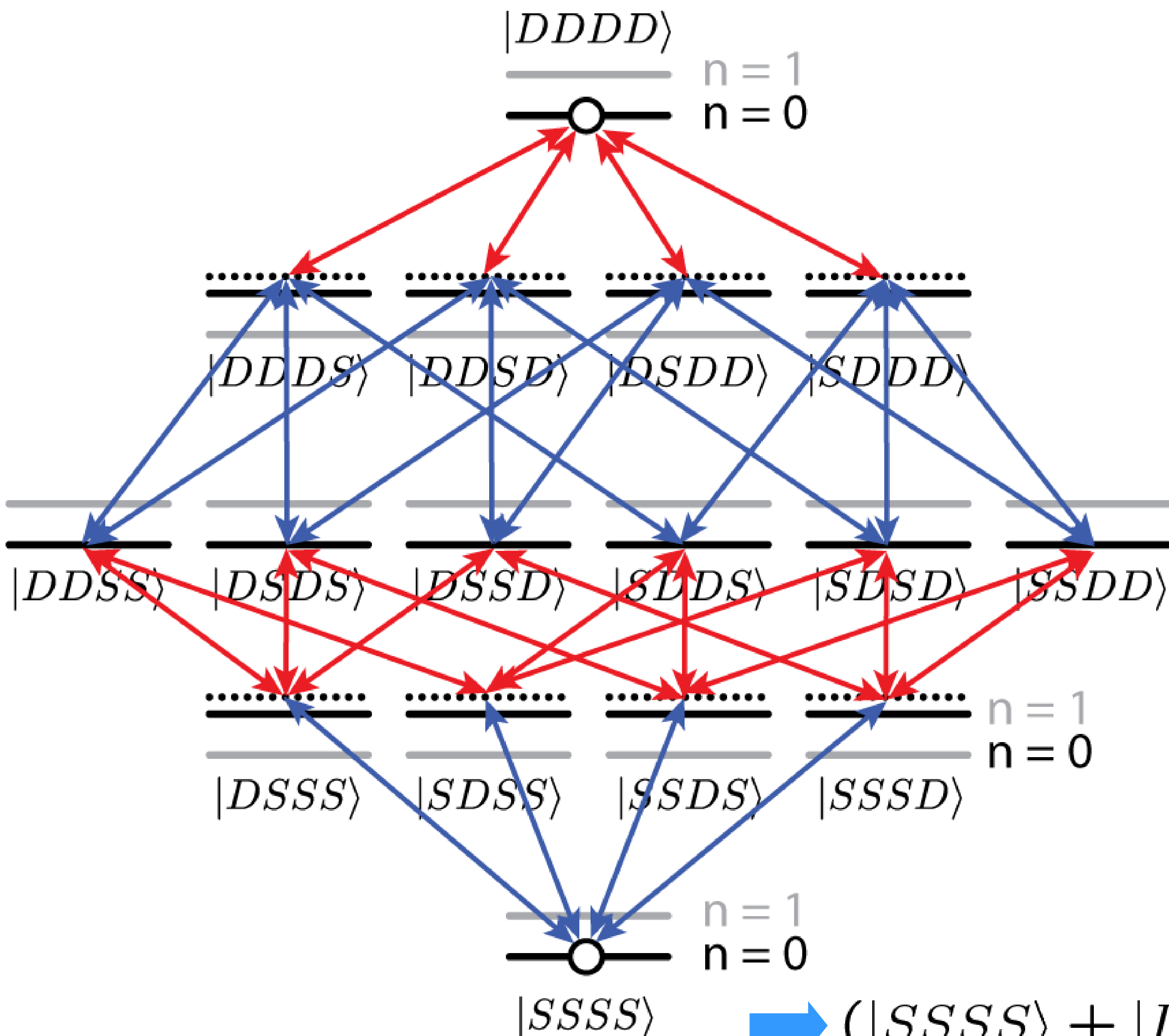
C = 0.990(1) 29,400 measurements

$p_{SS}+p_{DD}$ = 0.9965(4) 13,000 measurements

Bell state fidelity

F=99.3(1)%

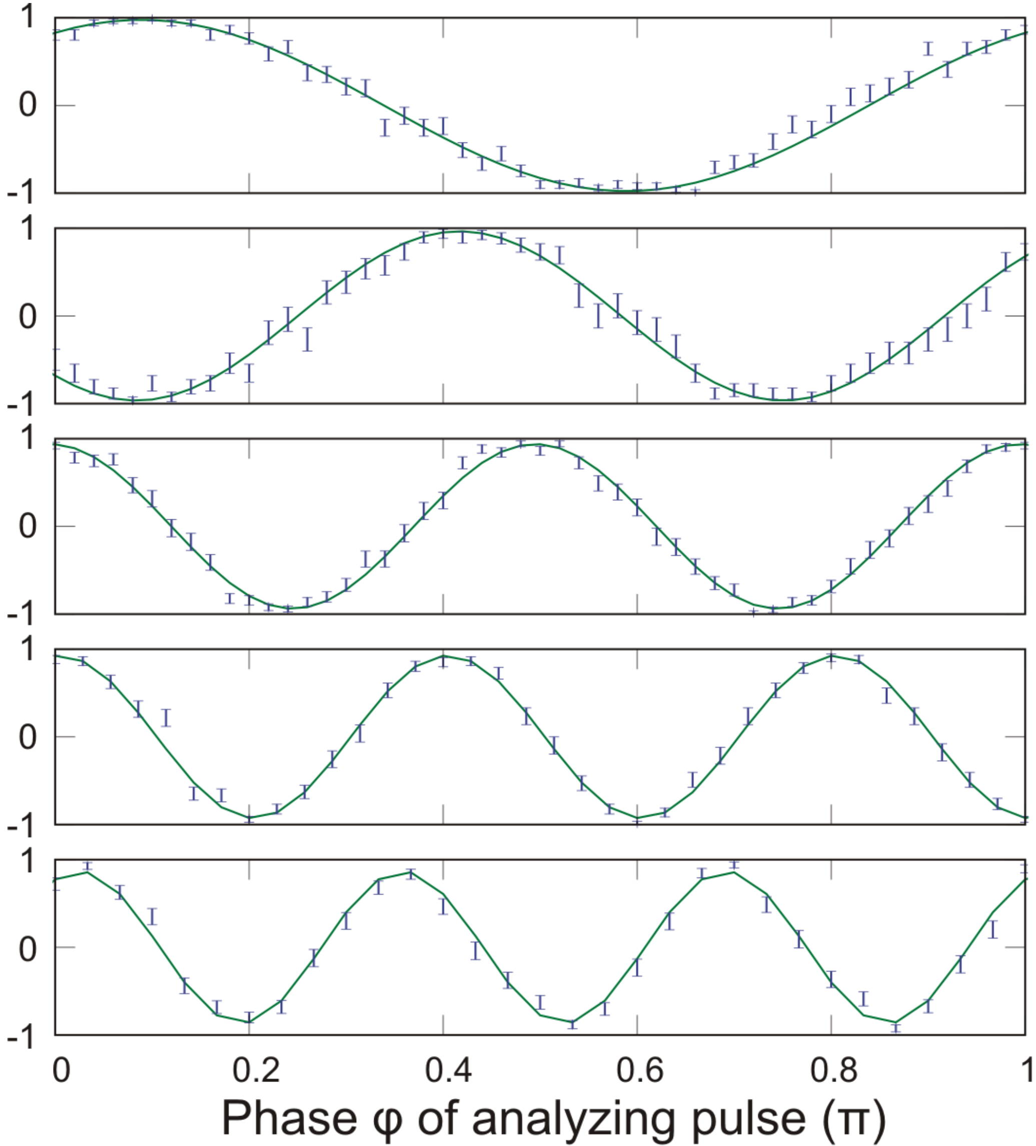
Entangling four ions



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

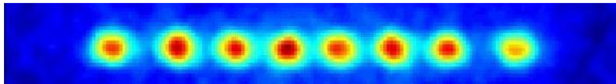
N - qubit GHZ state generation with global MS gates

Parity signal $P \propto 1 + N \cos\phi$



$N =$	Fidelity (%)
2	98.6(2)
3	97.0(3)
4	95.7(3)
5	94.4(5)
6	89.2(4)

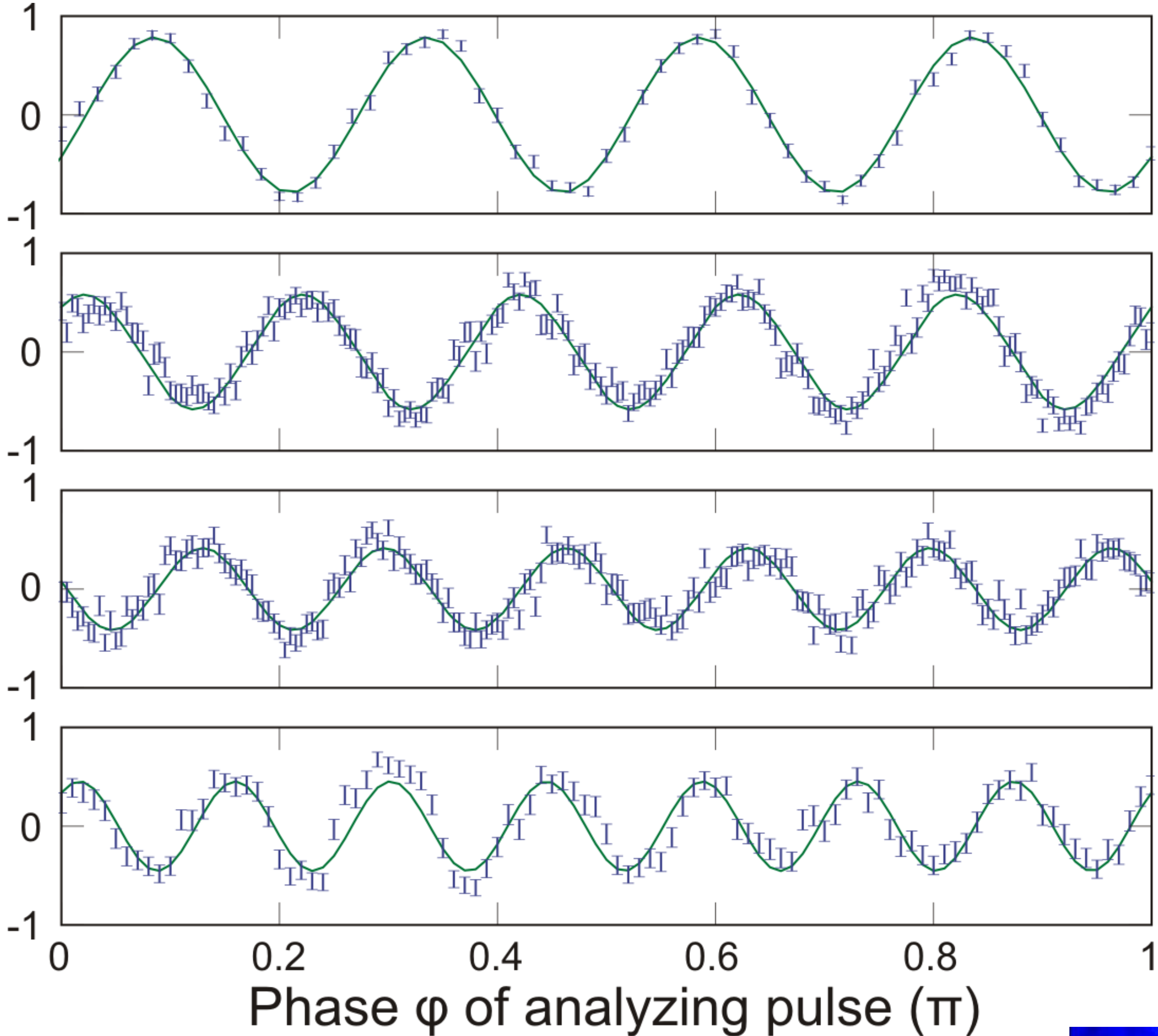
T. Monz et al., PRL **106**, 130506 (2011).



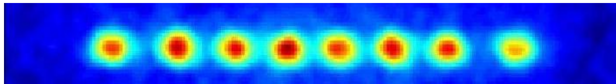
N - qubit GHZ state generation with global MS gates

Parity signal $P \propto 1 + N \cos\phi$

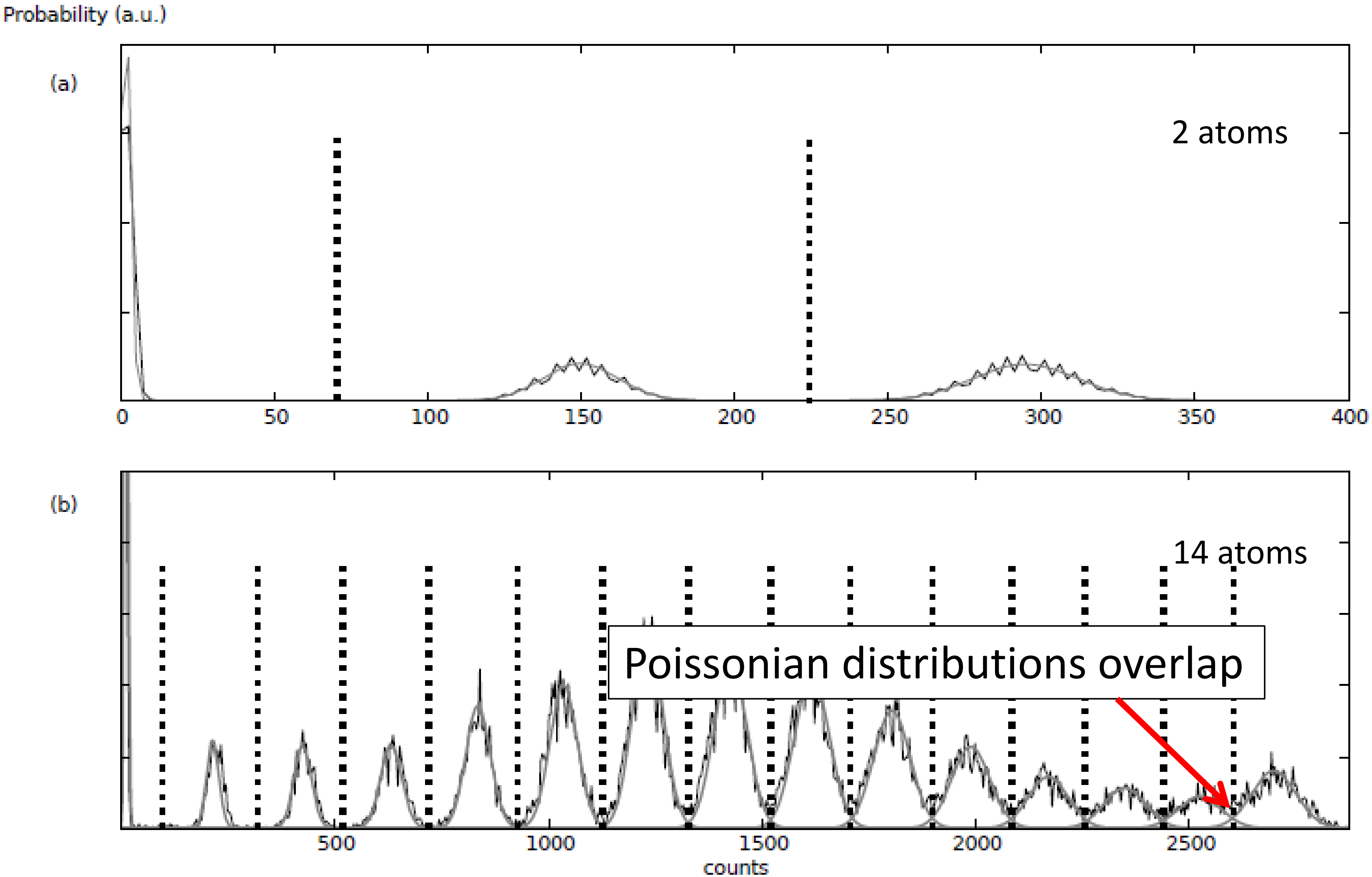
$N =$		Fidelity (%)
8		81.7(4)
10		62.6(6)
12		47.4(7)
14		50.8(9)



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



State detection using a photomultiplier



See: Thomas Monz, PhD thesis (2011).

Remember: We want to know the populations and the coherences.

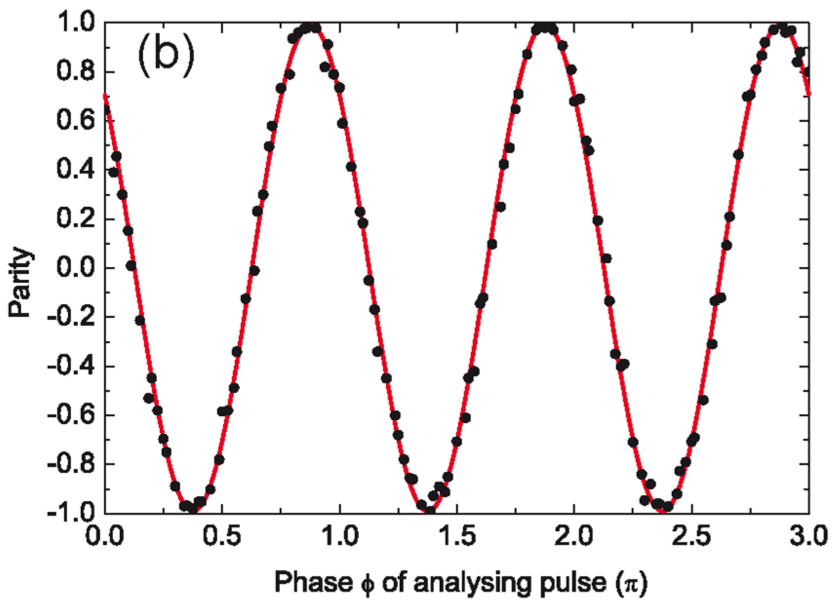
Bell / GHZ – Fidelity:

$$F = \frac{1}{2}(P_{SS\ldots S} + P_{DD\ldots D} + C)$$

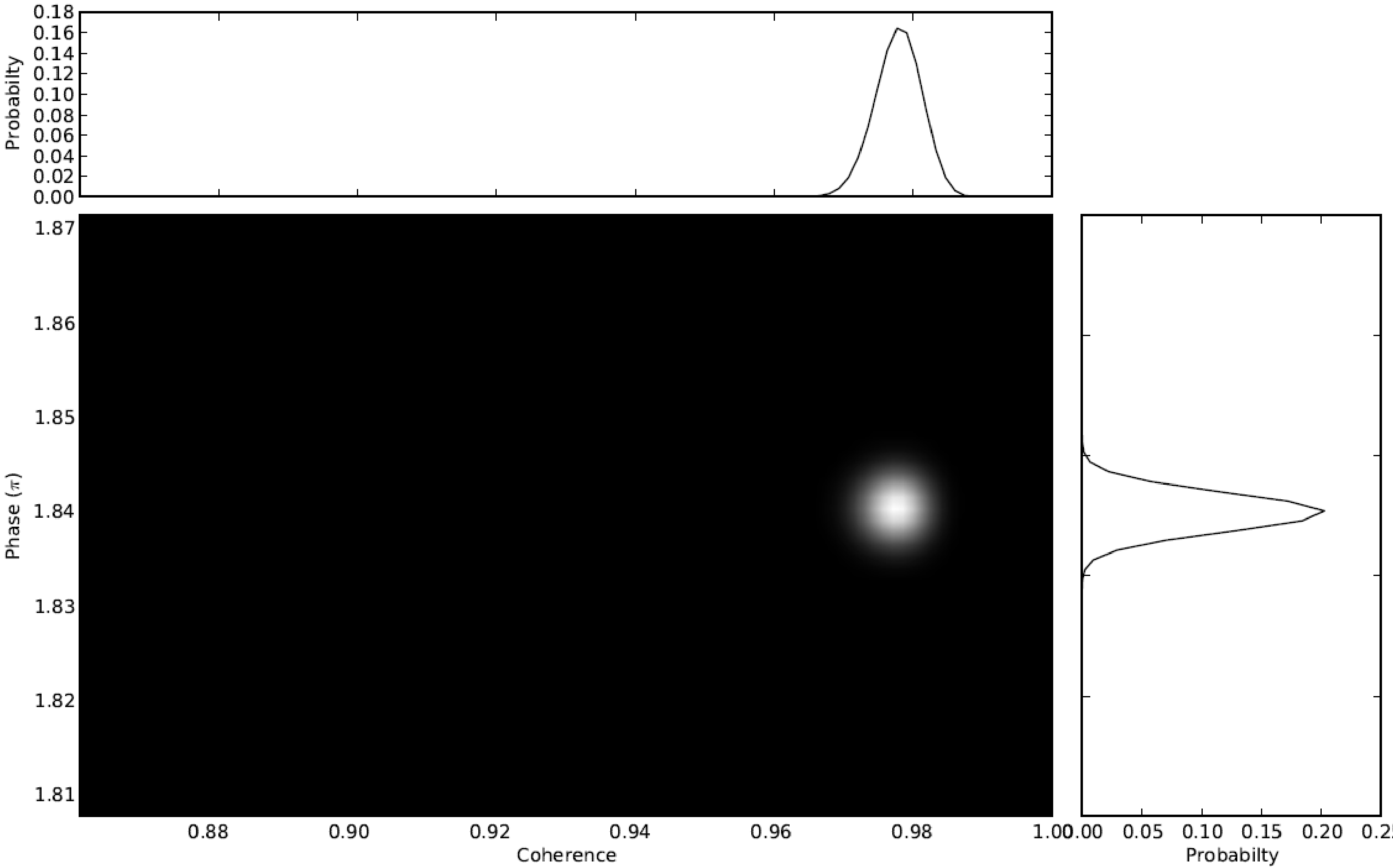
Witness:

$$W = 1 - 2 \cdot C$$

C: amplitude of the parity oscillations

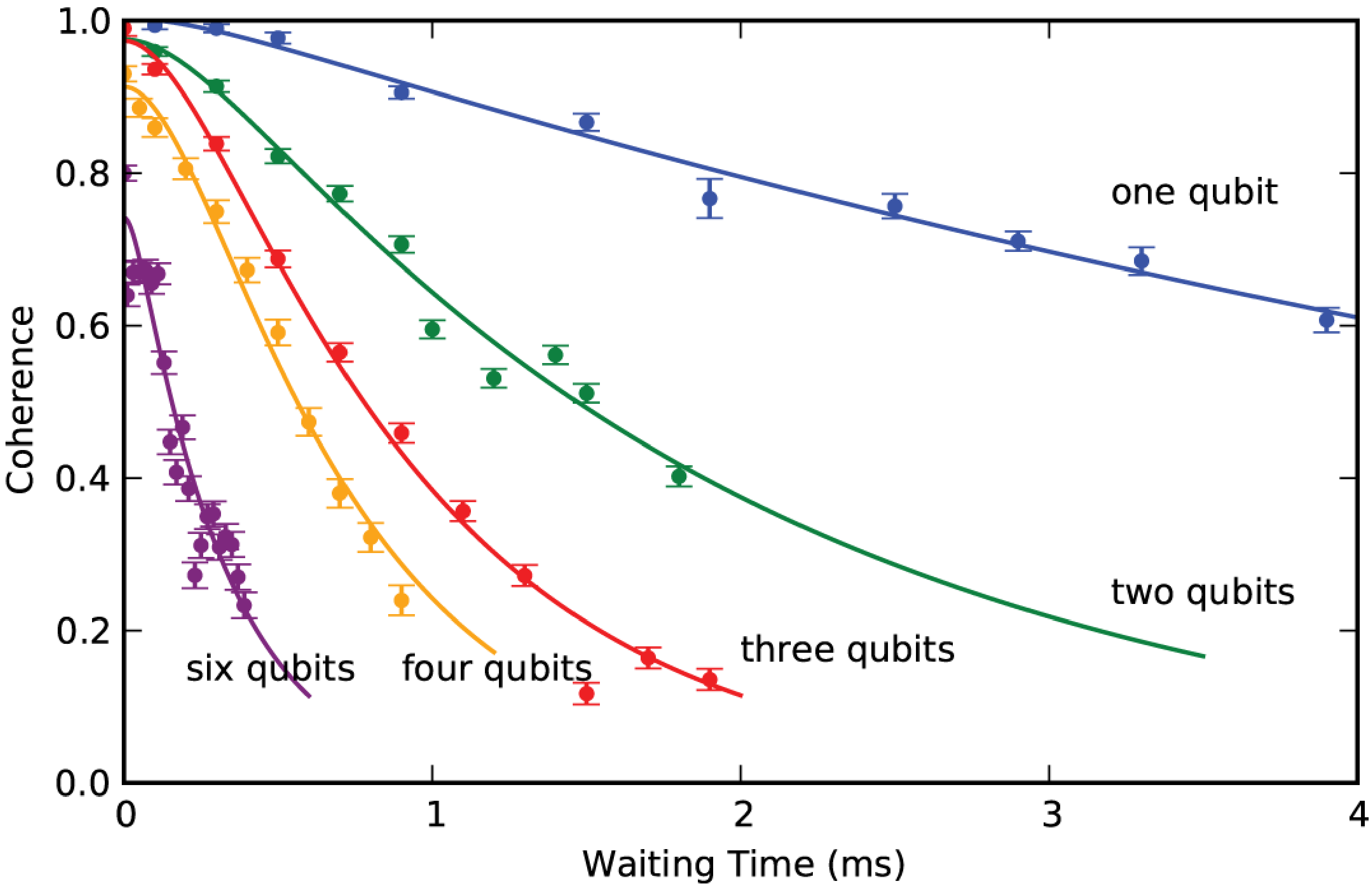


Bayesian analysis of the GHZ coherence



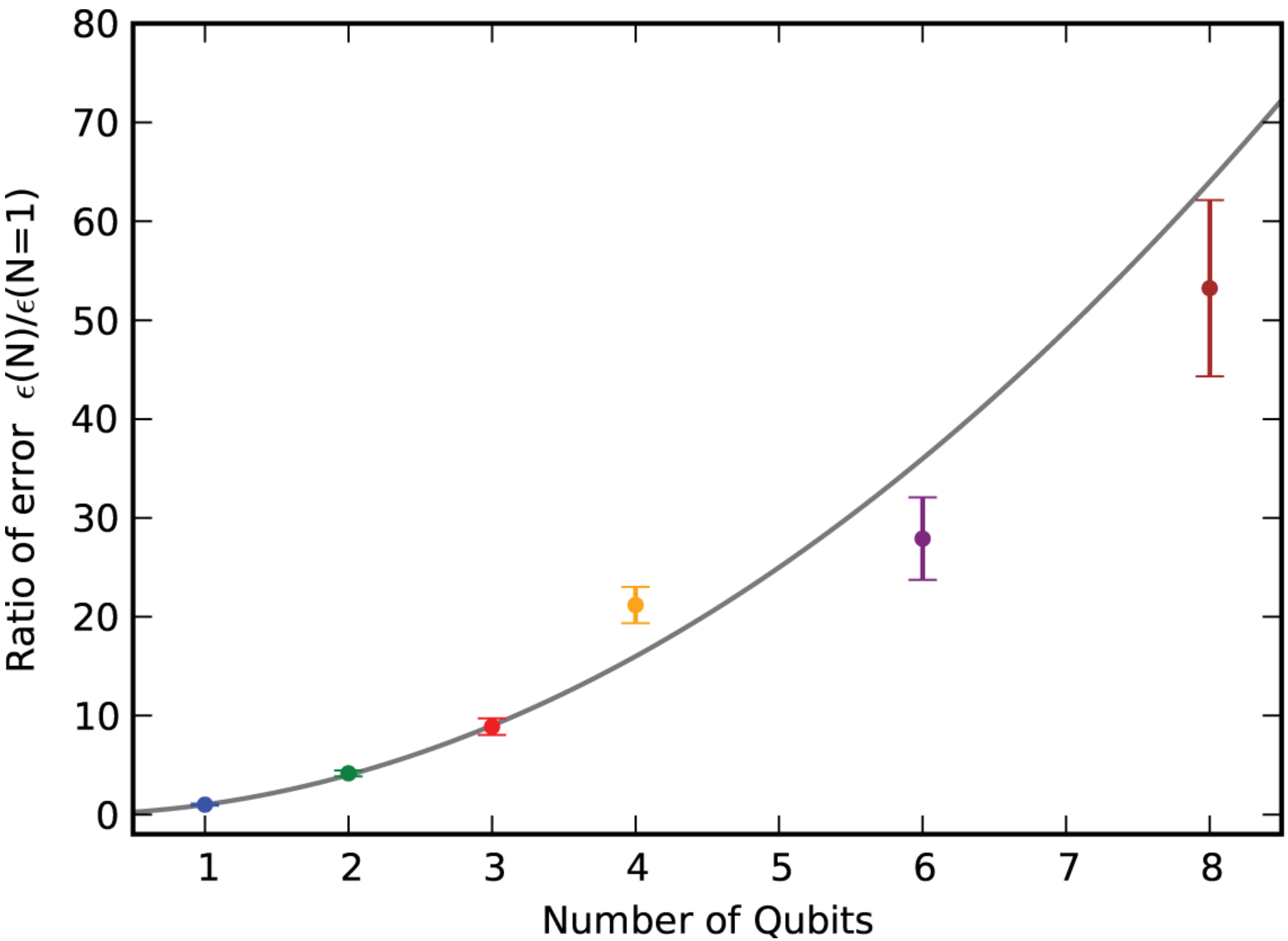
See: Thomas Monz, PhD thesis (2011).

Decay of N-qubit GHZ states



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

Scaling of entanglement decay



Decay scales with N^2 !

Dephasing model

Master equation - dephasing
(e.g. Huelga et al., PRL 79, 3865 (1997)]

Uncorrelated dephasing of qubits

$$Contrast \propto e^{-N\gamma t}$$

But we observe: **correlated dephasing**

$$Contrast \propto e^{-N^2\gamma t}$$

Does that make sense?

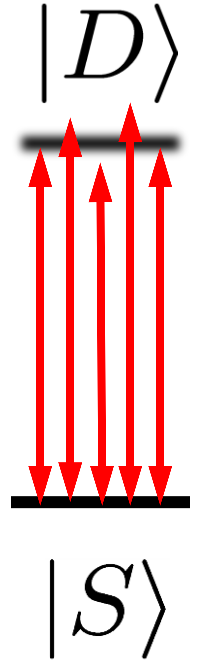
Sources of dephasing

Laser vs. atomic transition frequency fluctuations by

a. Laser noise

b. Magnetic field fluctuations

Effect all ions equally! → Correlated!



Solution: Use decohence free subspace against dephasing.

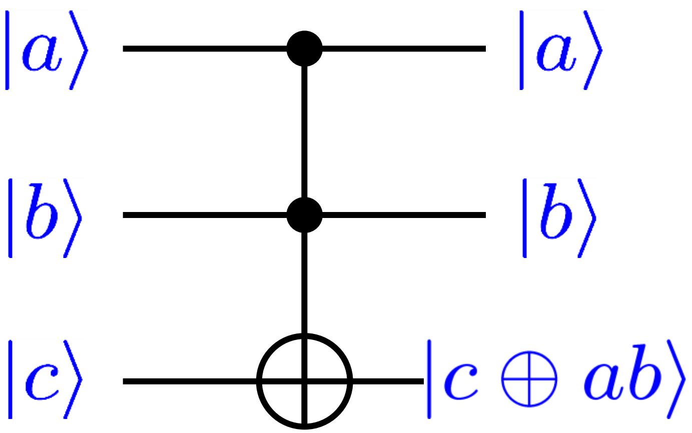
Quantum process tomography of the quantum Toffoli operation

Toffoli gate: controlled-controlled NOT

Toffoli gate (Tommaso Toffoli, 1980):

…… is a universal reversible logic gate, i.e. any reversible circuit can be constructed from Toffoli gates.

also known as the controlled-controlled-NOT or CCNOT-gate operation

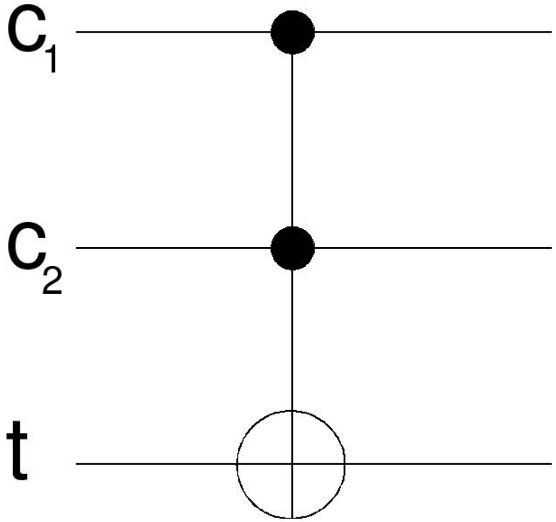


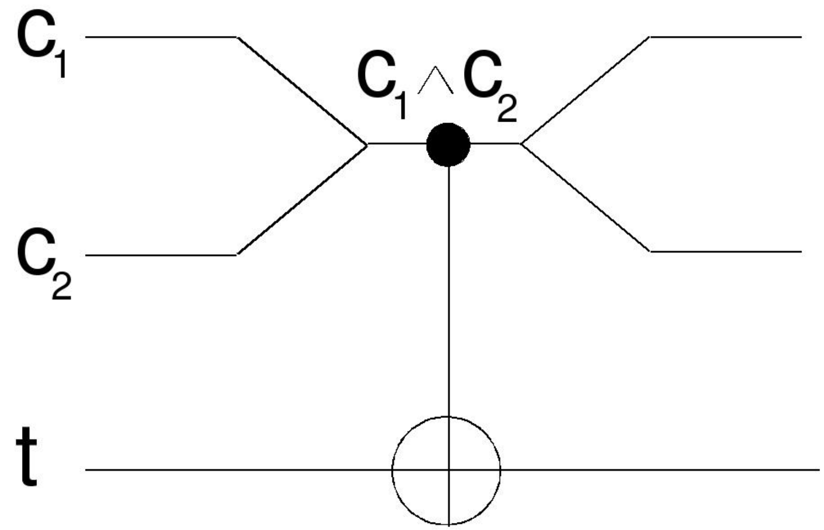
$$= \begin{pmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & i \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & -i & 0 \end{pmatrix}$$

useful, e.g. for error correction

…the basic implementation idea

1. Map the combined logical information onto the motion
2. Perform a standard Cirac-Zoller CNOT gate
3. Unmap the motional information

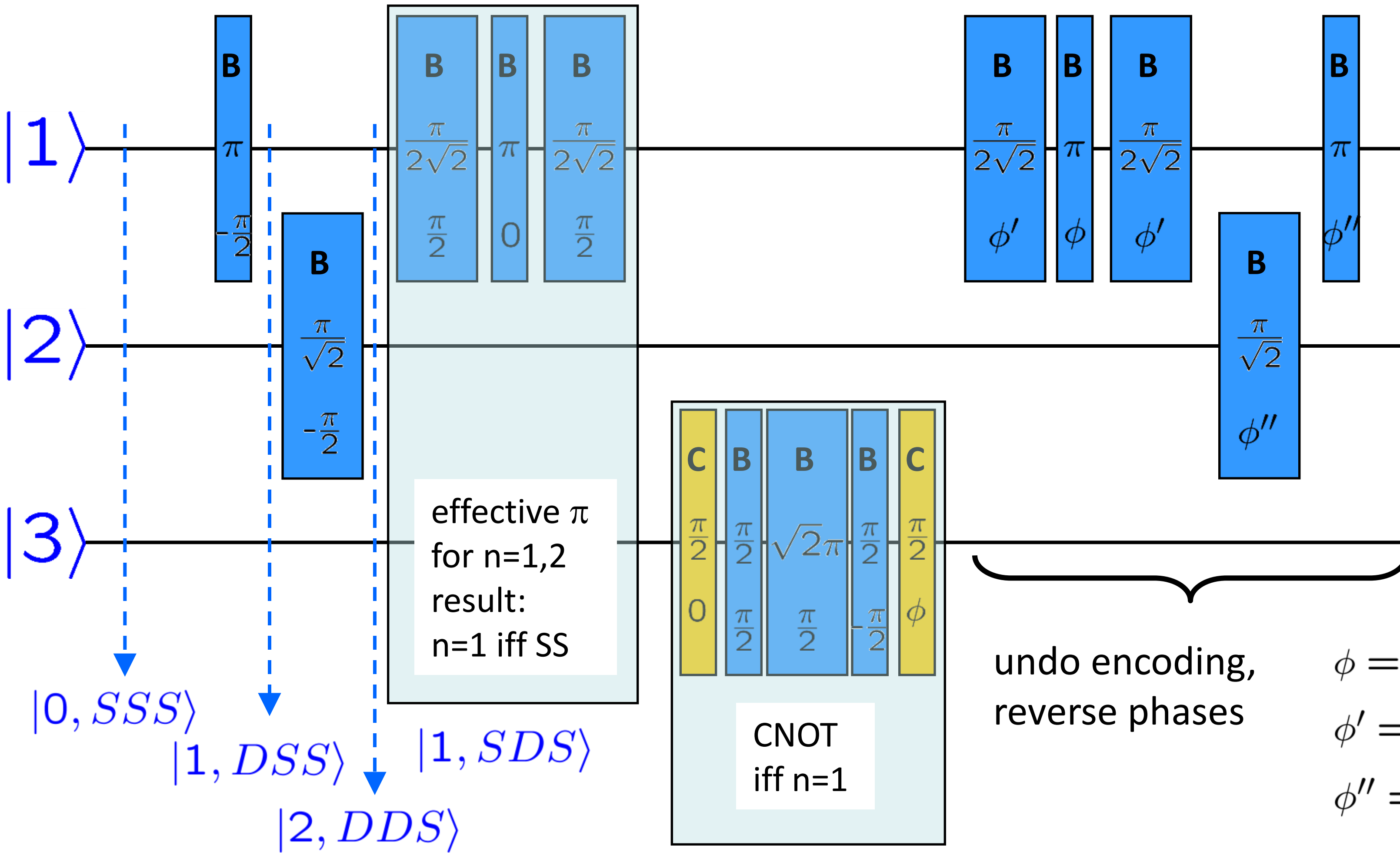




Toffoli gate: pulse sequence

use 2-phonon excitation

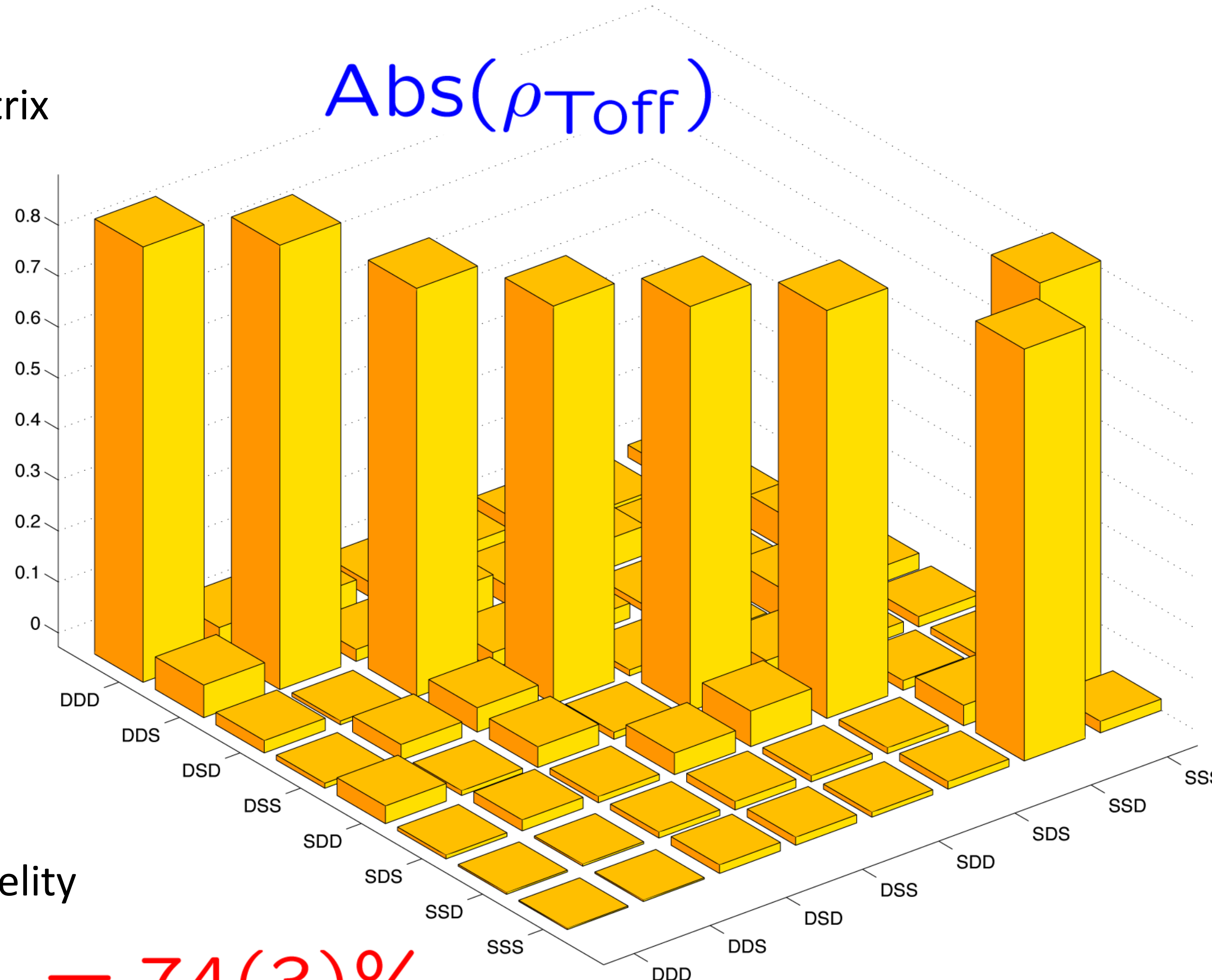
T. Monz, K. Kim et al., PRL 103, 200503 (2009).



$$\phi = (\tfrac{1}{\sqrt{2}} - 1)\pi$$
$$\phi' = (-\tfrac{1}{2} + \tfrac{1}{\sqrt{2}})\pi$$
$$\phi'' = (\tfrac{1}{2} + \tfrac{1}{\sqrt{2}})\pi$$

Toffoli gate: experimental truth table

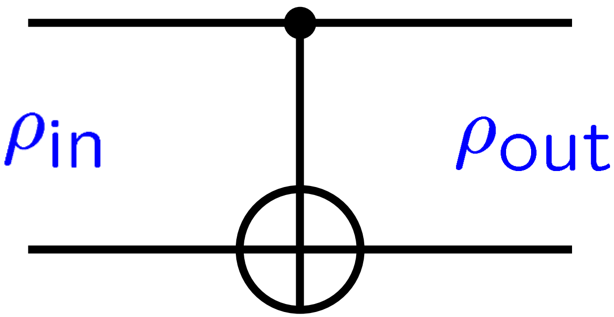
density matrix



State Fidelity

$$F_{\mathrm{Toff}} = 74(3)\%$$

Quantum process tomography



$$\rho_{\text{out}} = \sum \chi_{ij} E_i \rho_{\text{in}} E_j^\dagger$$

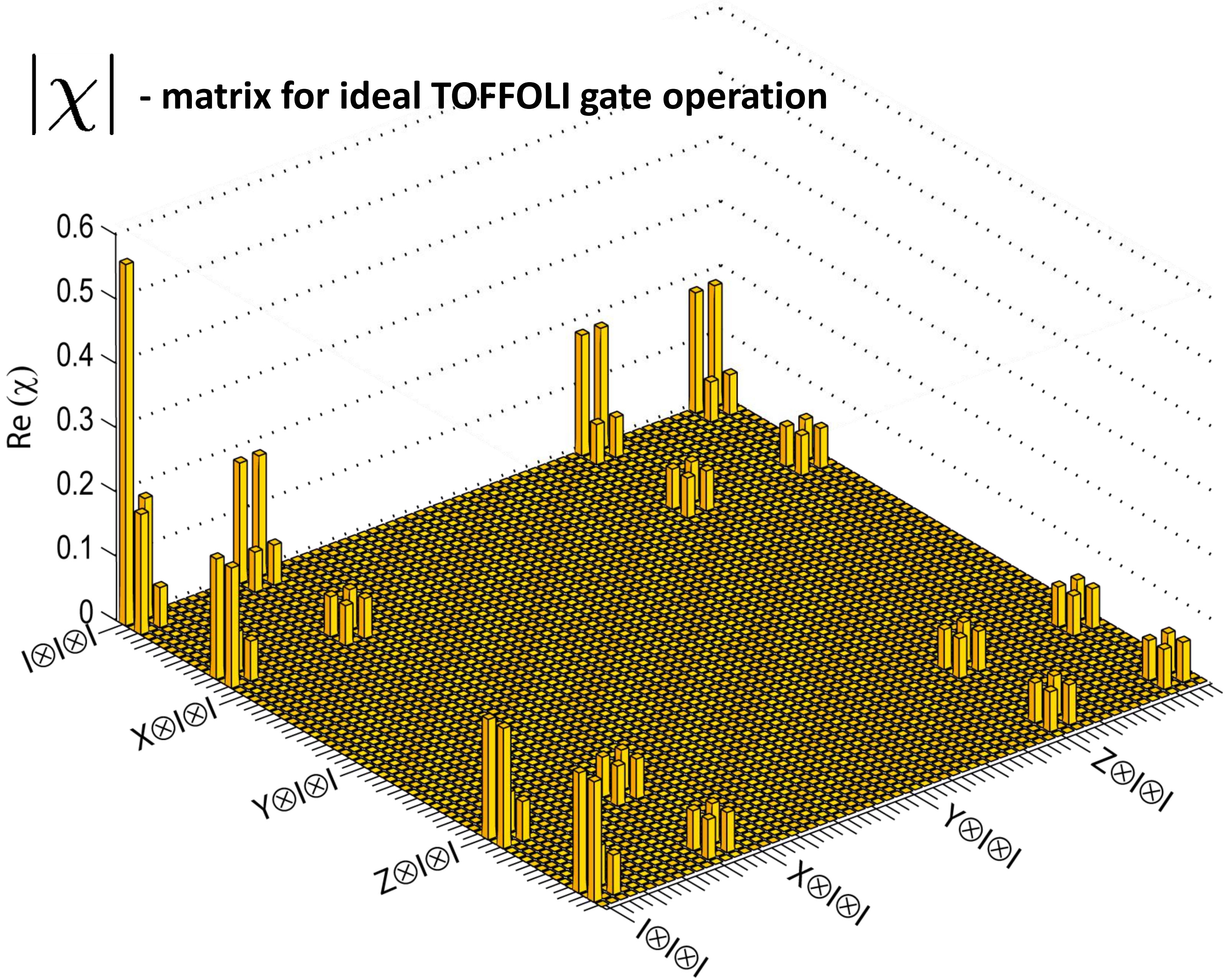
$$E_i = A_i \otimes A_j$$

$$A_i \in \{I, \sigma_x, \sigma_y, \sigma_z\}$$

χ_{ij} characterizes gate operation completely

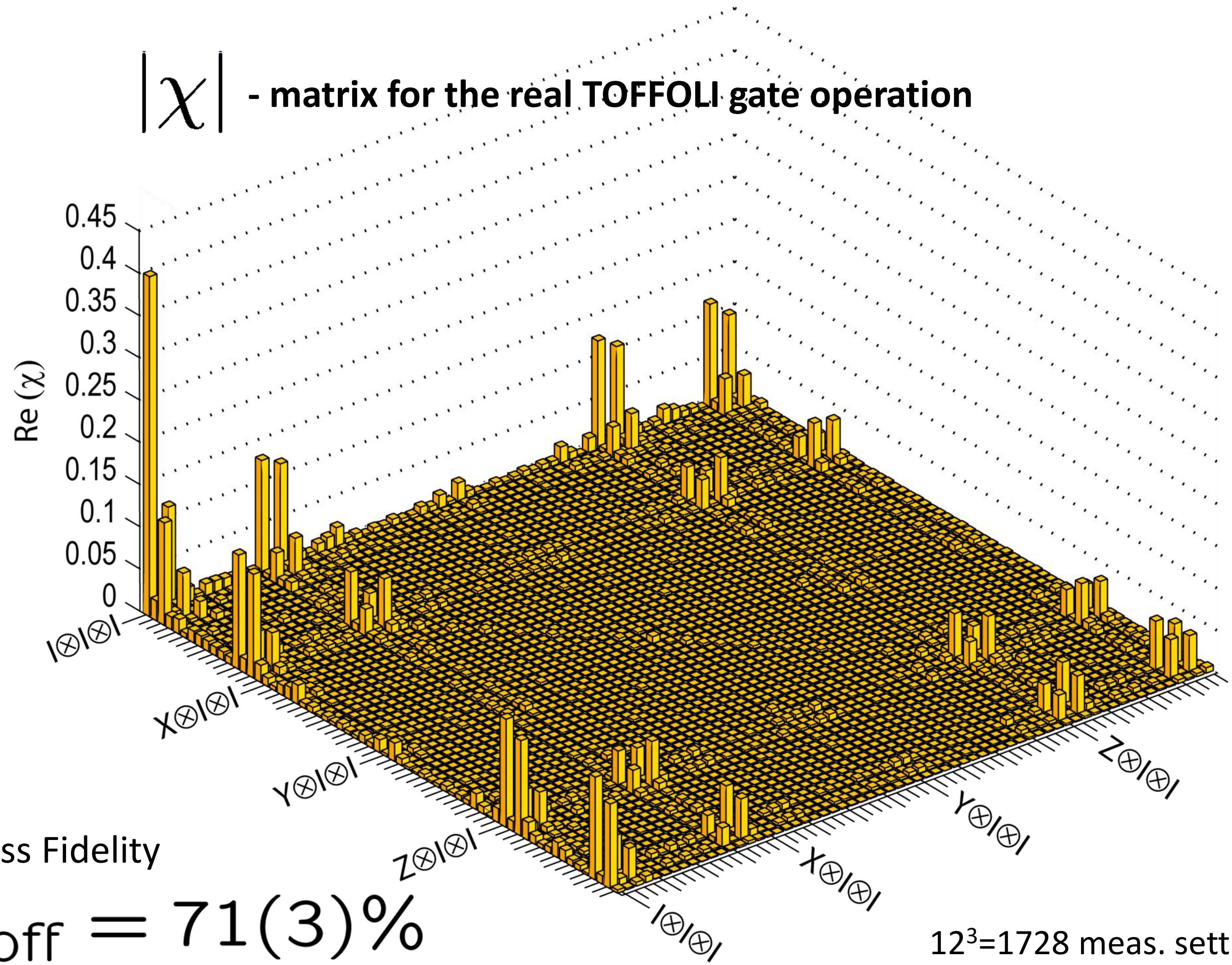
Toffoli gate: process tomography

$\left|\chi\right|$ **- matrix for ideal TOFFOLI gate operation**



Toffoli gate: process tomography

$|\chi|$ **- matrix for the real TOFFOLI gate operation**



Mean
Process Fidelity

$$F_{\text{Toff}} = 71(3)\%$$

12^3=1728 meas. settings

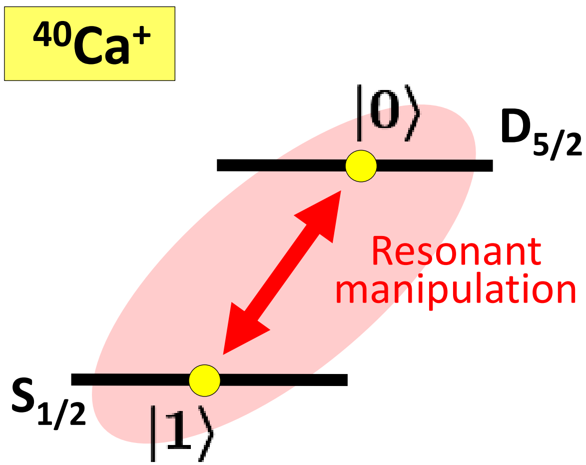
Toolbox for generating

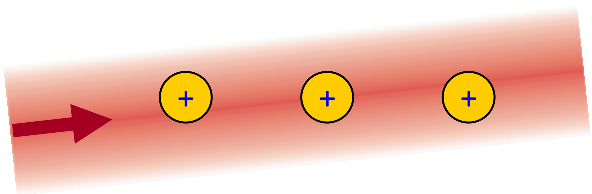
high-fidelity operations

and

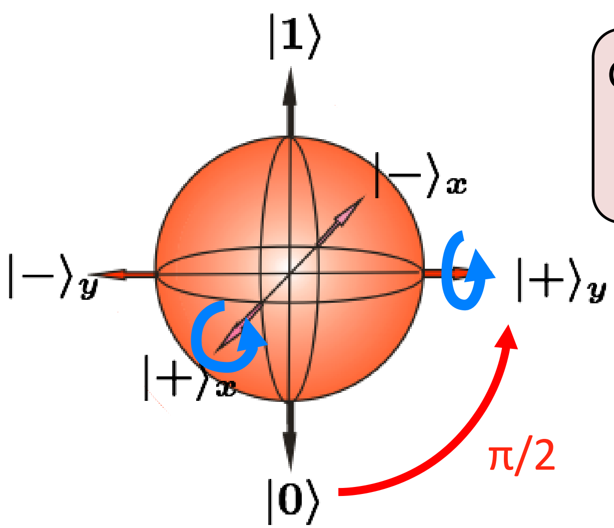
dissipation

Gates: Collective rotations





$$S_x = \sigma_x^{(0)} + \sigma_x^{(1)} + \sigma_x^{(2)}$$
$$S_y = \sigma_y^{(0)} + \sigma_y^{(1)} + \sigma_y^{(2)}$$



$$|\pm\rangle_x = (|0\rangle \pm |1\rangle)/\sqrt{2}$$
$$|\pm\rangle_y = (|0\rangle \pm i|1\rangle)/\sqrt{2}$$

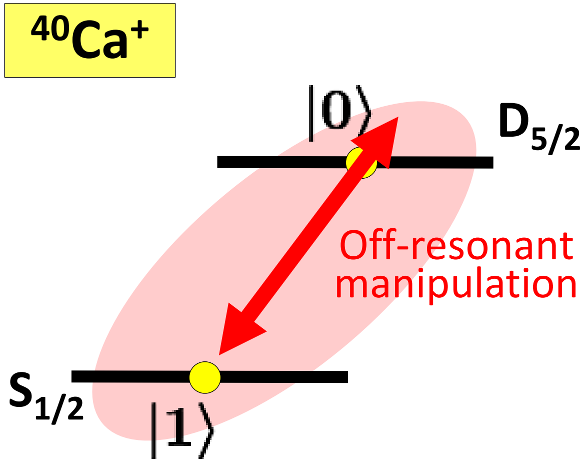
Generate rotations around **x/y** axis

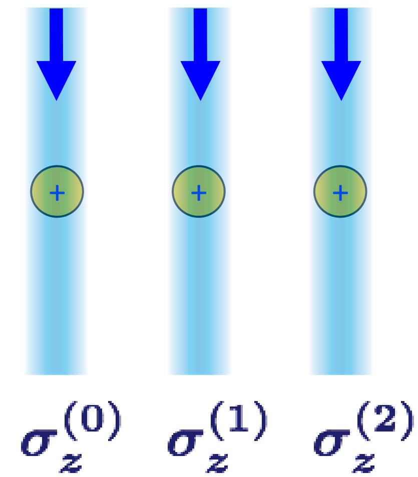
$$U_{S_{x,y}}(\theta) = e^{-i\frac{\theta}{2}S_{x,y}}$$

Examples:

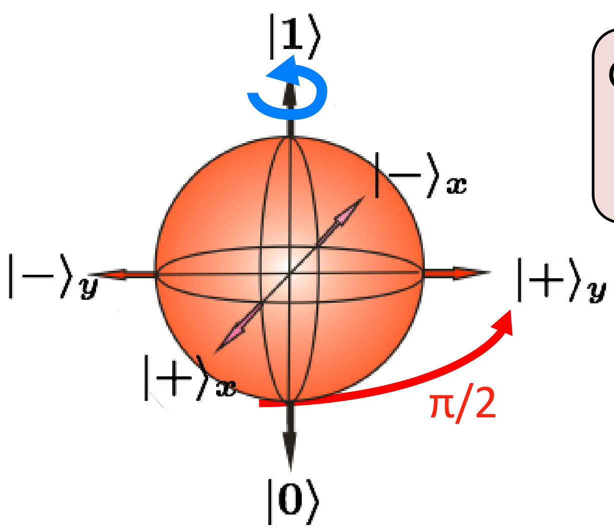
$$U_{S_x}(\pi/2)|000\rangle = |+\rangle_y|+\rangle_y|+\rangle_y$$
$$U_{S_y}(\pi/2)|000\rangle = |+\rangle_x|+\rangle_x|+\rangle_x$$
$$U_{S_x}(\pi)|000\rangle = |111\rangle$$

Gates: Single-qubit rotations





Single-qubit rotations
(far detuned laser, AC-stark shift):



Generate rotations around **z** axis

$$U_{\sigma_z^{(i)}}(\theta) = e^{-i\frac{\theta}{2}\sigma_z^{(i)}}$$

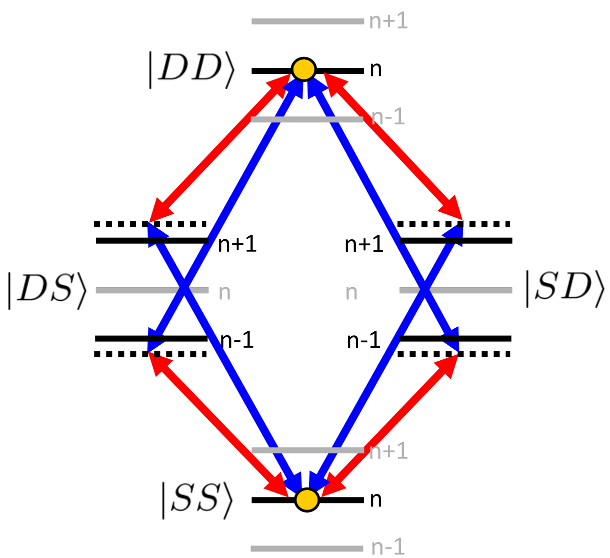
Examples:

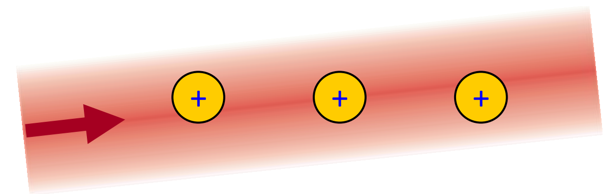
$$U_{\sigma_z^{(0)}}(\pi/2)|+++\rangle_x = |+\rangle_y|++\rangle_x$$

$$U_{\sigma_z^{(1)}}(\pi)|+++\rangle_x = |+-+\rangle_x$$

$$U_{\sigma_z^{(1)}}(2\pi)|000\rangle = -|000\rangle$$

Entangling gate: Mølmer-Sørensen





Bichromatic lasers

$$\omega_r = \omega_0 - (\nu + \epsilon)$$
$$\omega_b = \omega_0 + (\nu + \epsilon)$$
$$\omega_b + \omega_r = 2\omega_0$$

$$|00\rangle \longrightarrow |00\rangle + |11\rangle$$

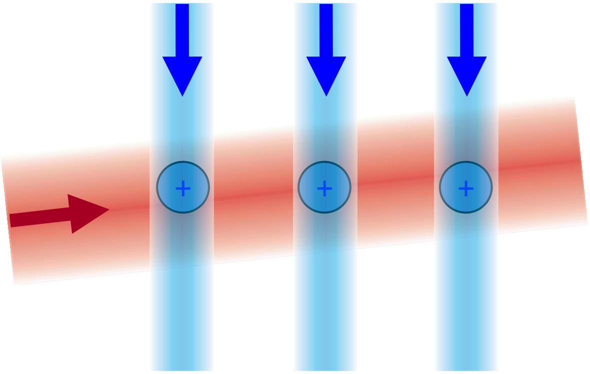
MS-gate generates GHZ states

$$|0\cdots 0\rangle \longrightarrow |0\cdots 0\rangle + |1\cdots 1\rangle$$

Realizes a two-body Hamiltonian where every ion interacts with every other, e.g., for 3 ions

$$S_x^2 = \sigma_x^{(0)}\sigma_x^{(1)} + \sigma_x^{(1)}\sigma_x^{(2)} + \sigma_x^{(0)}\sigma_x^{(2)}$$

Together a toolbox for arbitrary unitary operations!



Basic set of operations:

collective spin flips S_x, S_y

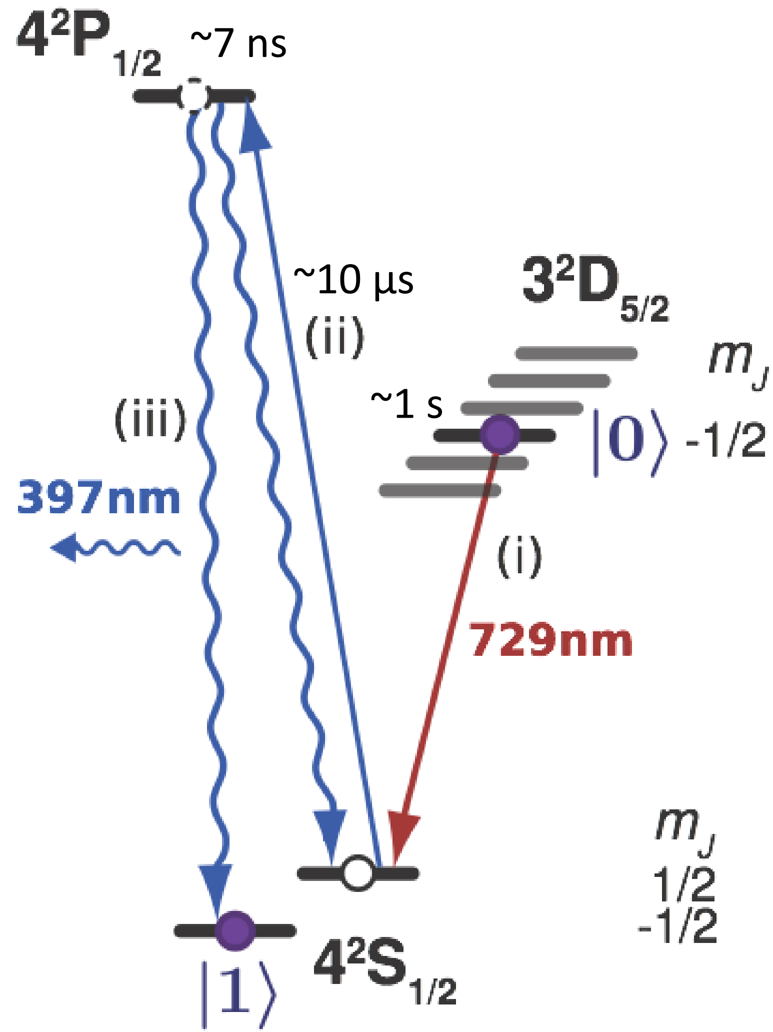
individual light shift gates $\sigma_z^{(0)}, \sigma_z^{(1)}, \sigma_z^{(2)}$

Mølmer-Sørensen gate S_x^2

Arbitrary unitary operations can be achieved !

Qubit reset by optical pumping = dissipation

$^{40}Ca^{+}$-Zeeman level structure:



(i) transfer population to S'

(ii) shine laser tuned to S-P with σ pol.

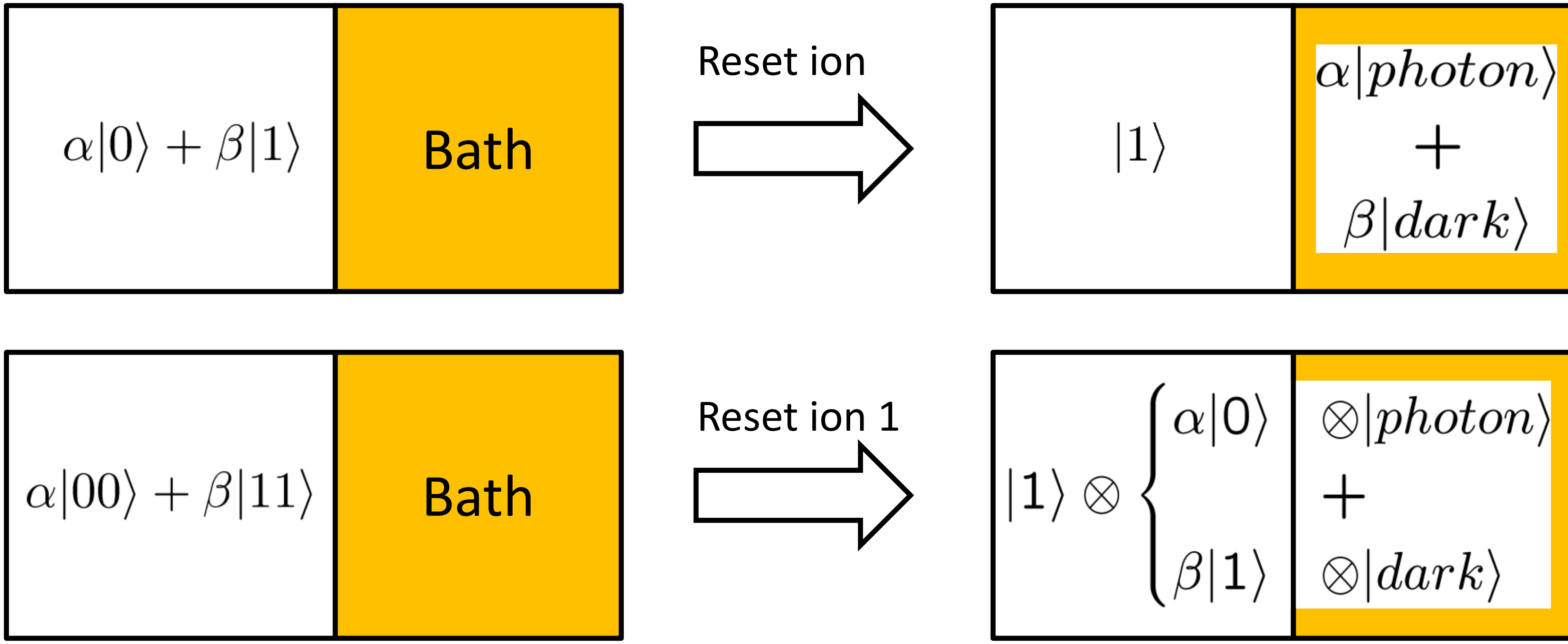
(ii) spontaneous decay

On avg. 2 photons scattered

Heating rate: $\Delta n = 0.015$

Note: Scattered photons carry information about previous ionic quantum state. When entangled, tracing over photonic bath leads to decoherence.

Qubit reset by optical pumping = dissipation



Can be used for:

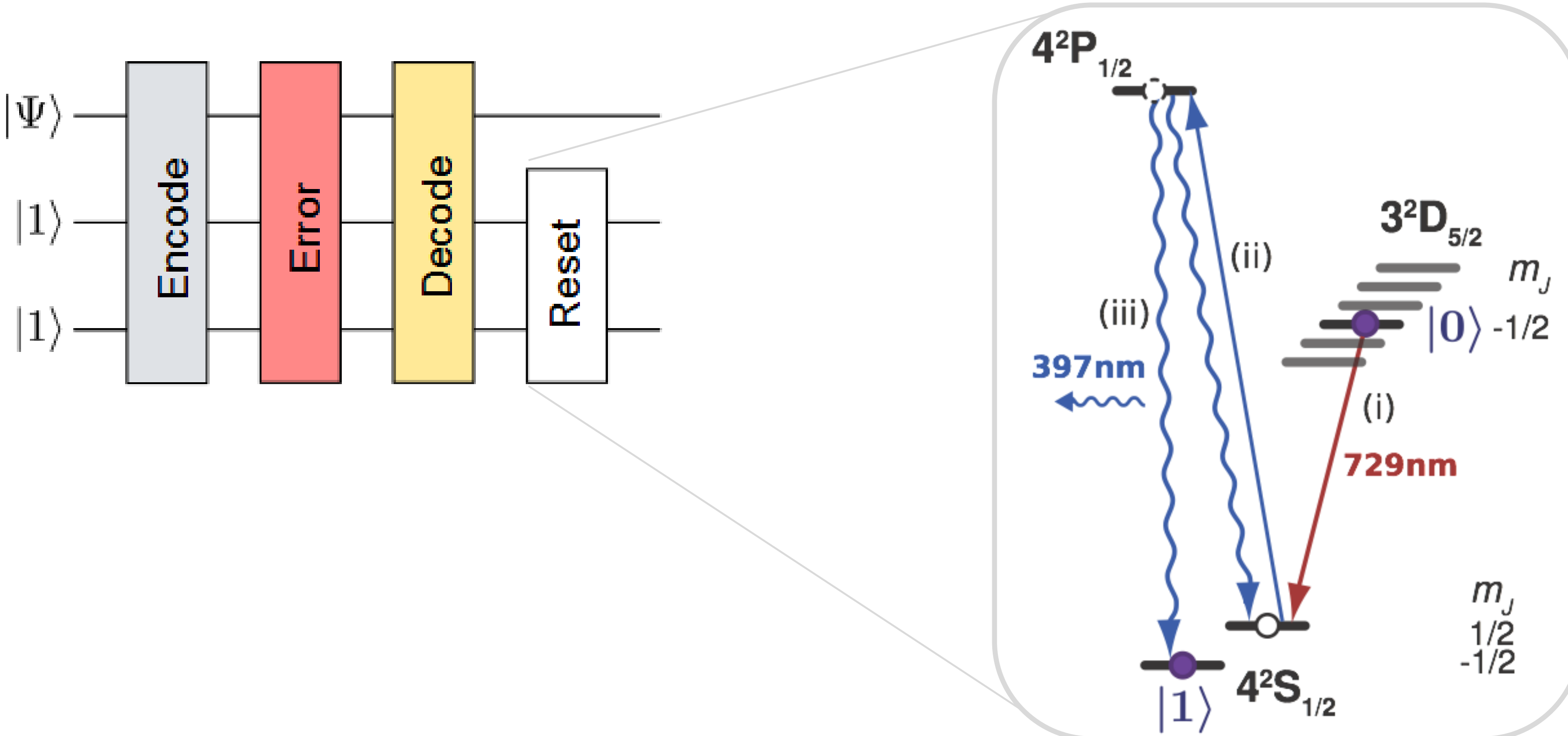
- qubit reset
- controlled decoherence (after tracing over bath)
- removing entropy

- optical pumping into entangled states
- simulating general open-system dynamics

Repeated quantum error correction

Quantum error correction algorithm

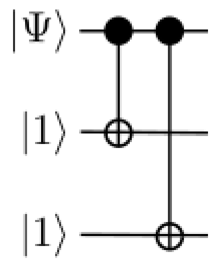
Qubit reset
= removes error syndrome



Repetition code with quantum feedback

Encoding

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

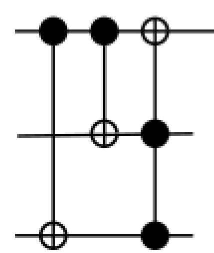


$\alpha|000\rangle + \beta|111\rangle$

Measurement-free decoding

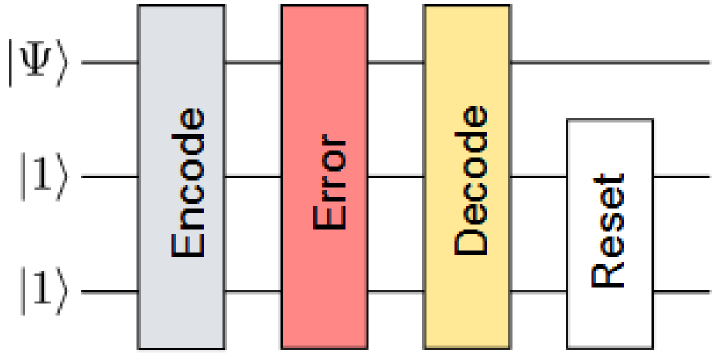
single-qubit error

$$\alpha|000\rangle + \beta|111\rangle$$
$$\alpha|001\rangle + \beta|110\rangle$$
$$\alpha|010\rangle + \beta|101\rangle$$
$$\alpha|100\rangle + \beta|011\rangle$$



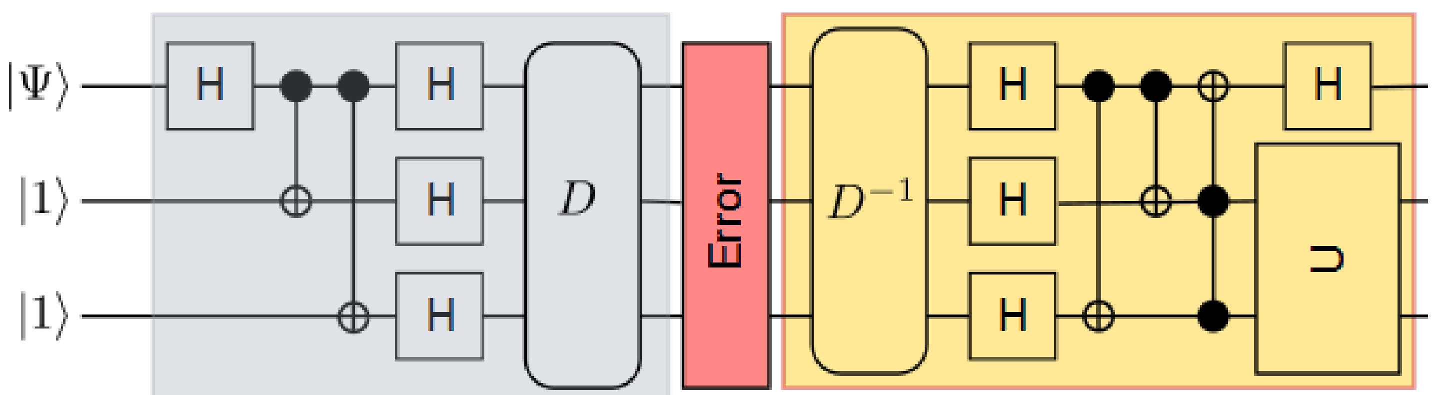
$\alpha|0\rangle + \beta|1\rangle$

Creating the pulse sequence – part I



Adapted quantum repetition code

Algorithm corrects for phase flip errors



Optimizing the algorithm

Modified gradient ascent pulse engineering (GRAPE) algorithm

Pulse sequence: $U = \prod_m e^{-i\,\Theta_m\,H_m}$

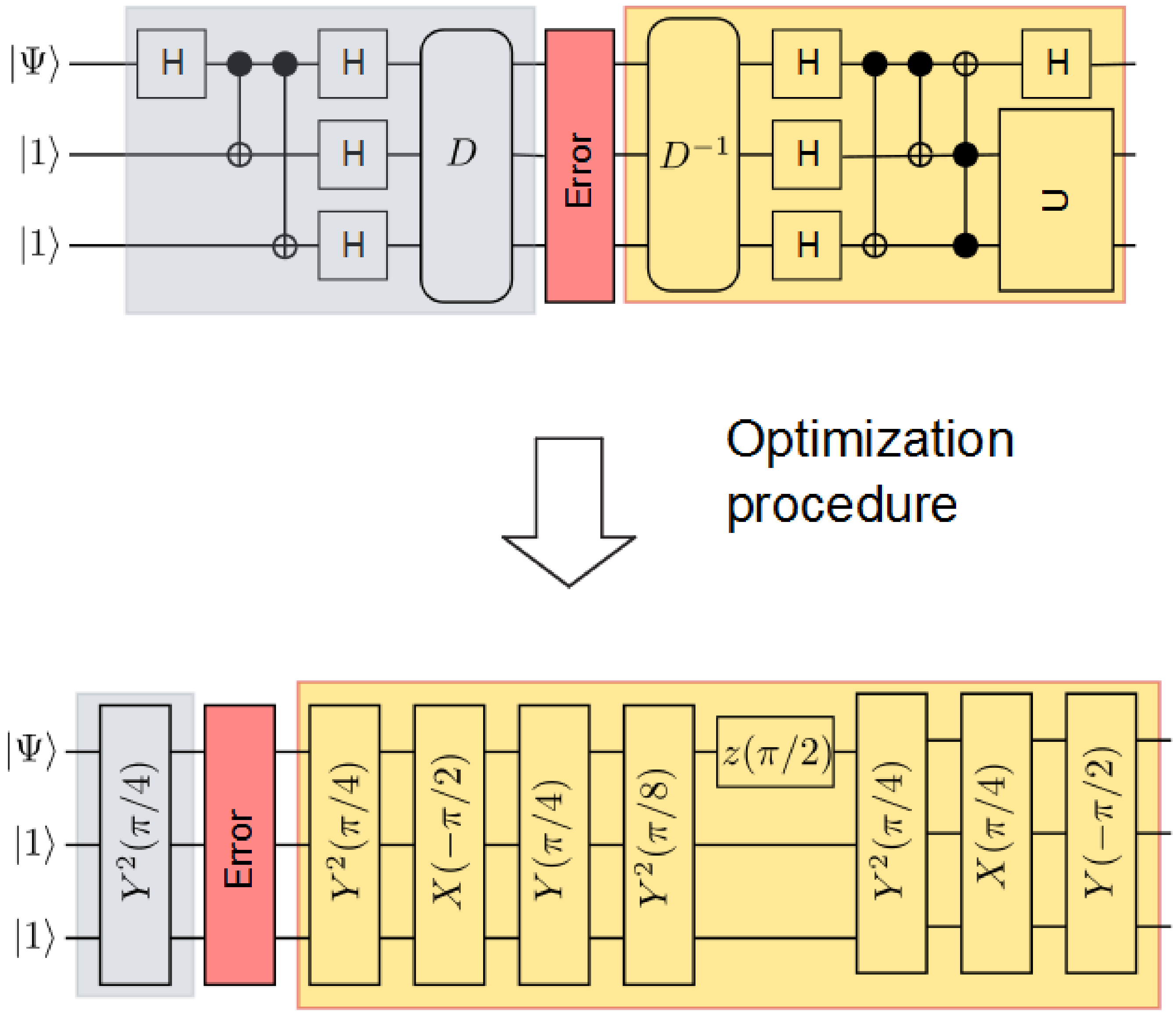
Performance function Φ that has maximum for exact algorithm.

Optimize pulse length along gradient: $\Theta_m = \Theta_m + \frac{\partial \Phi}{\partial \Theta_m}$

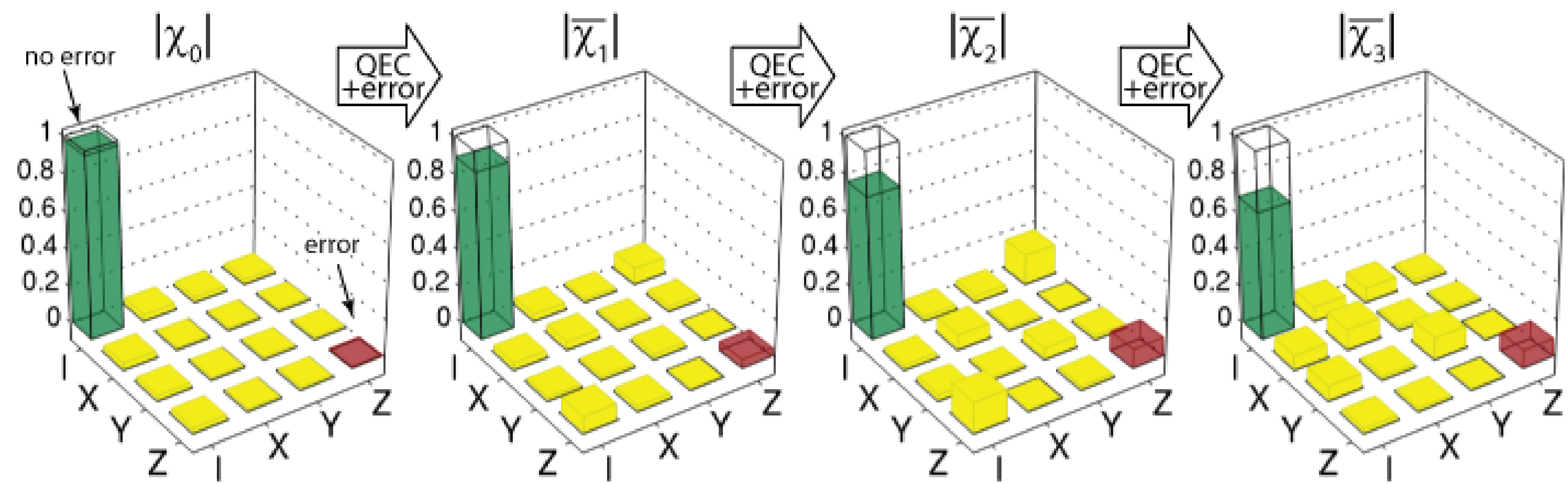
Add random pulses Hm from time to time.

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

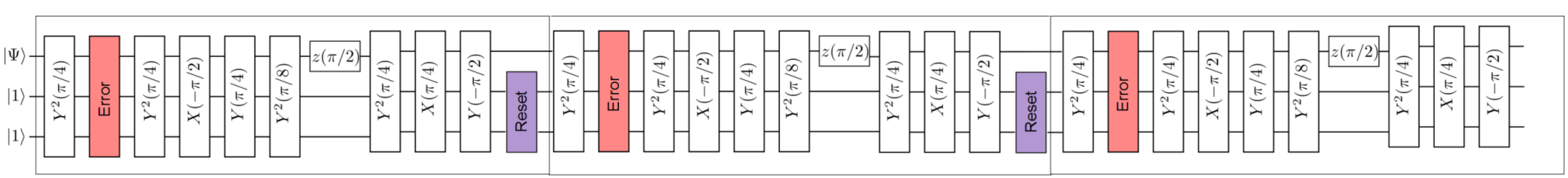
Creating the pulse sequence – part II



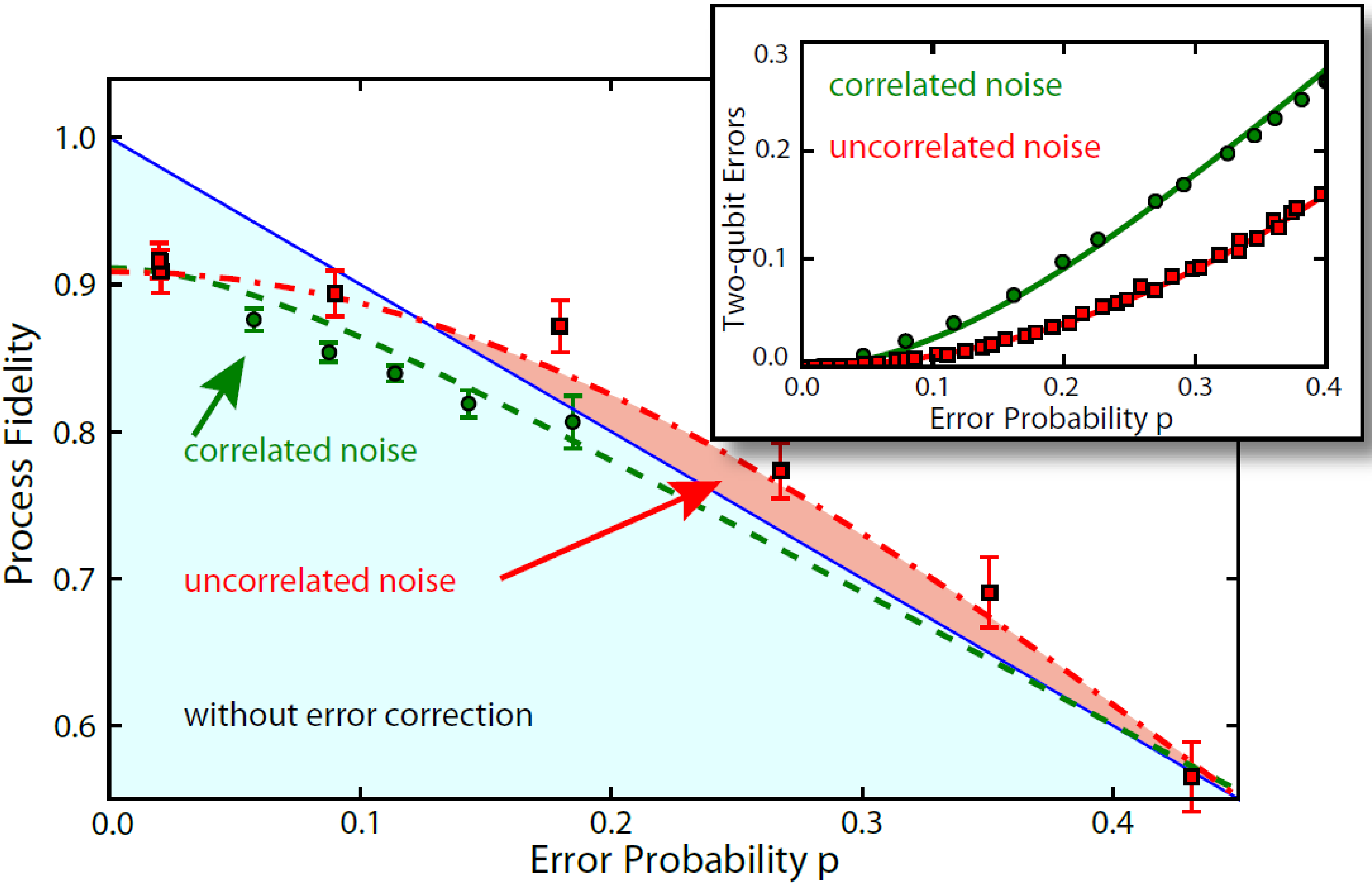
Multiple repetitions of the QEC algorithm



		1 Step	2 Steps	3 Steps
Sequence only:	F=97(2)%	F=90.1(2)%	F=79.8(4)%	F=72.9(5)%
With single qubit error:		F=90.1(2)%	F=80.1(2)%	F=70.2(3)%
Random single qubit error:		F=85(2)%	F=79(3)%	F=70(2)%



Quantum error correction of phase noise



Thanks to…

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