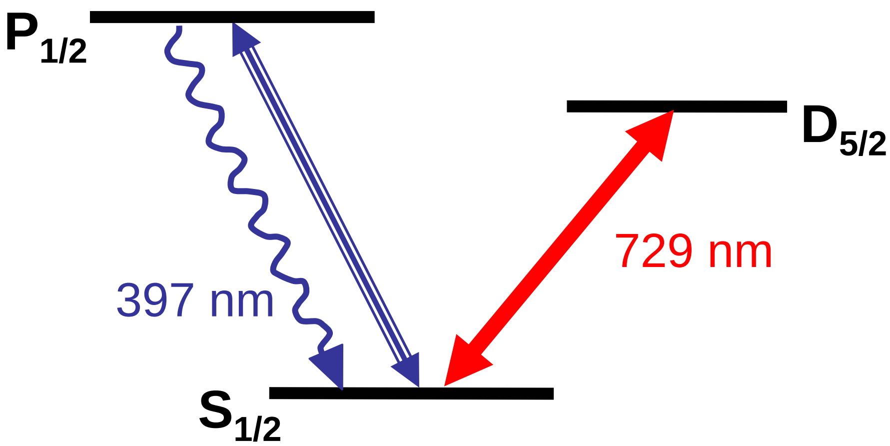
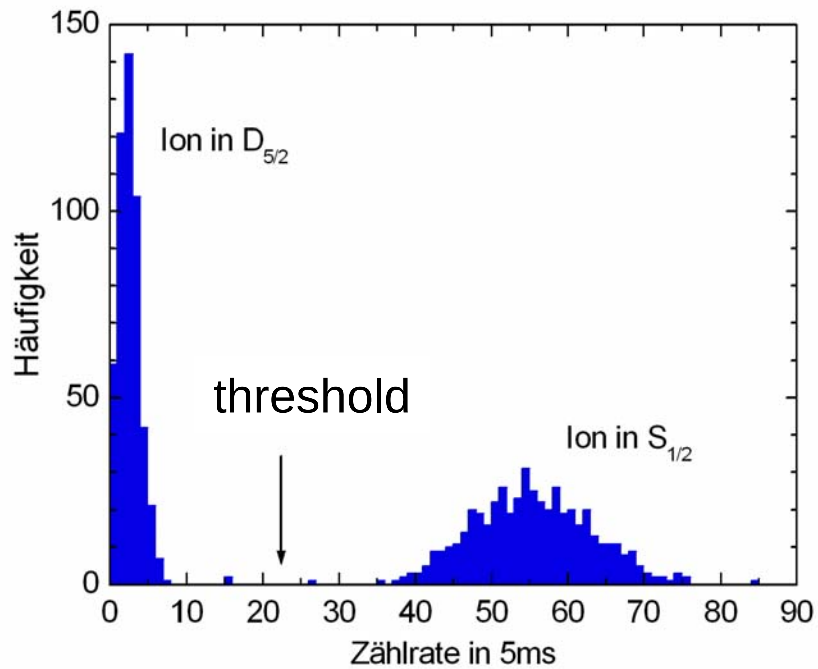
Zustandsnachweis

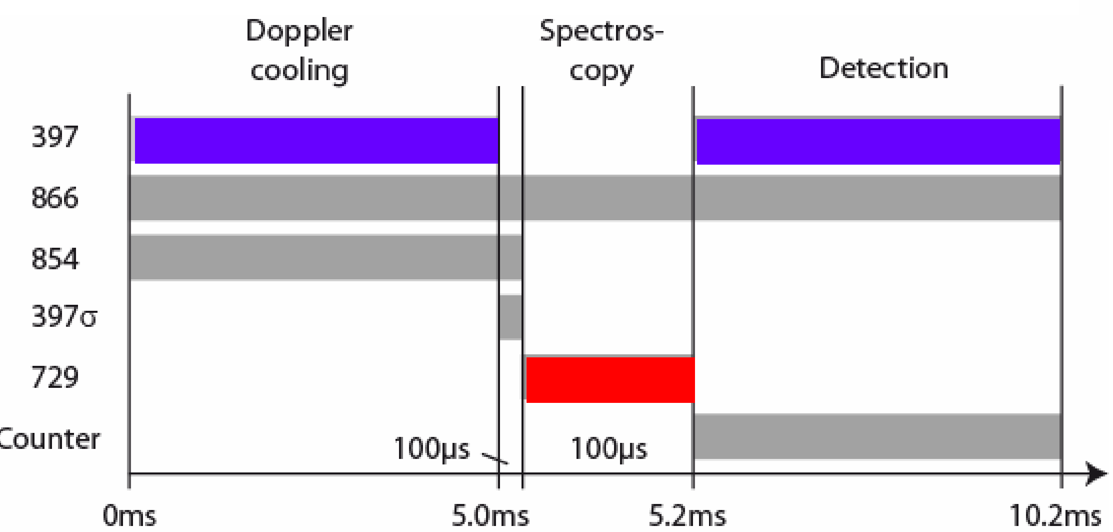
Quantum jump spectroscopy: Sequence

Simplified level scheme





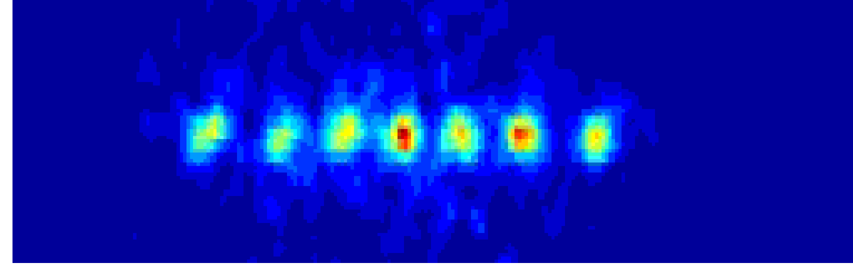
Quantum state detection



Pulse-Sequence

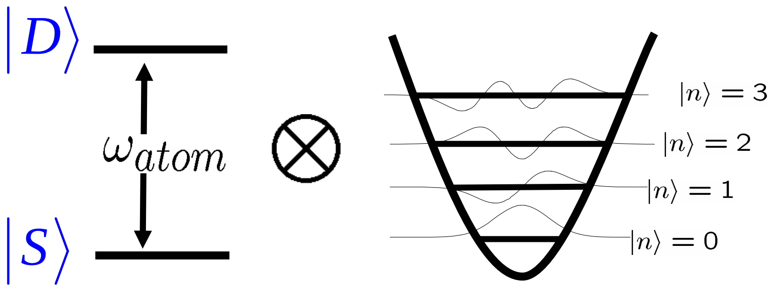
Rabioszillationen

Laser coupling

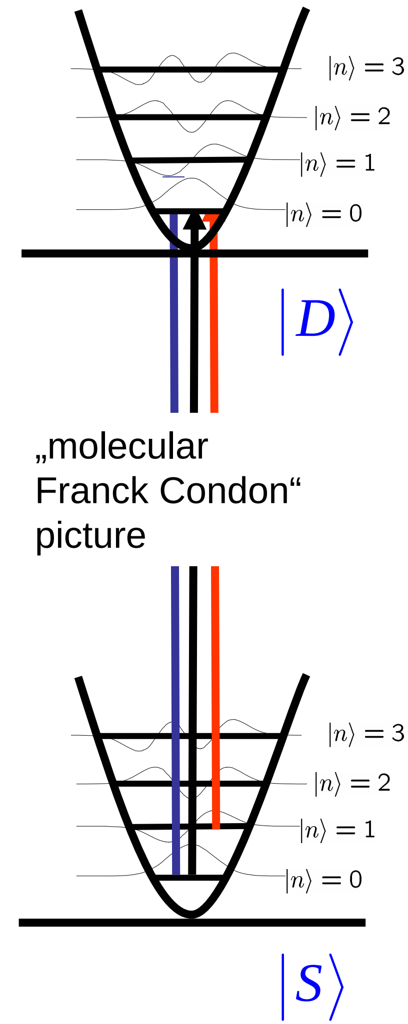


2-level-atom

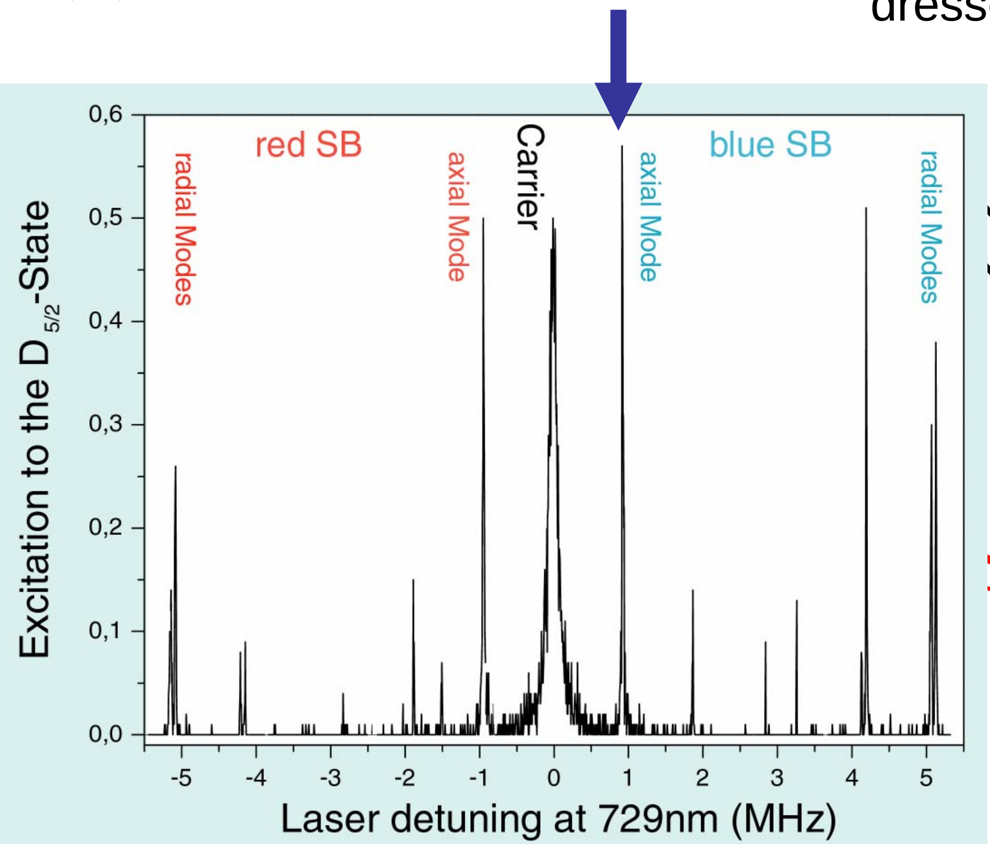
harmonic trap



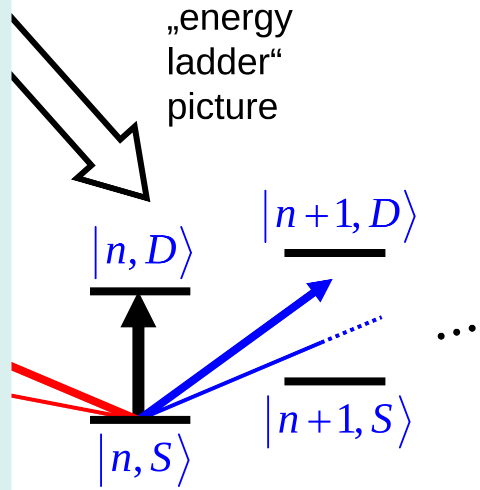
dressed system



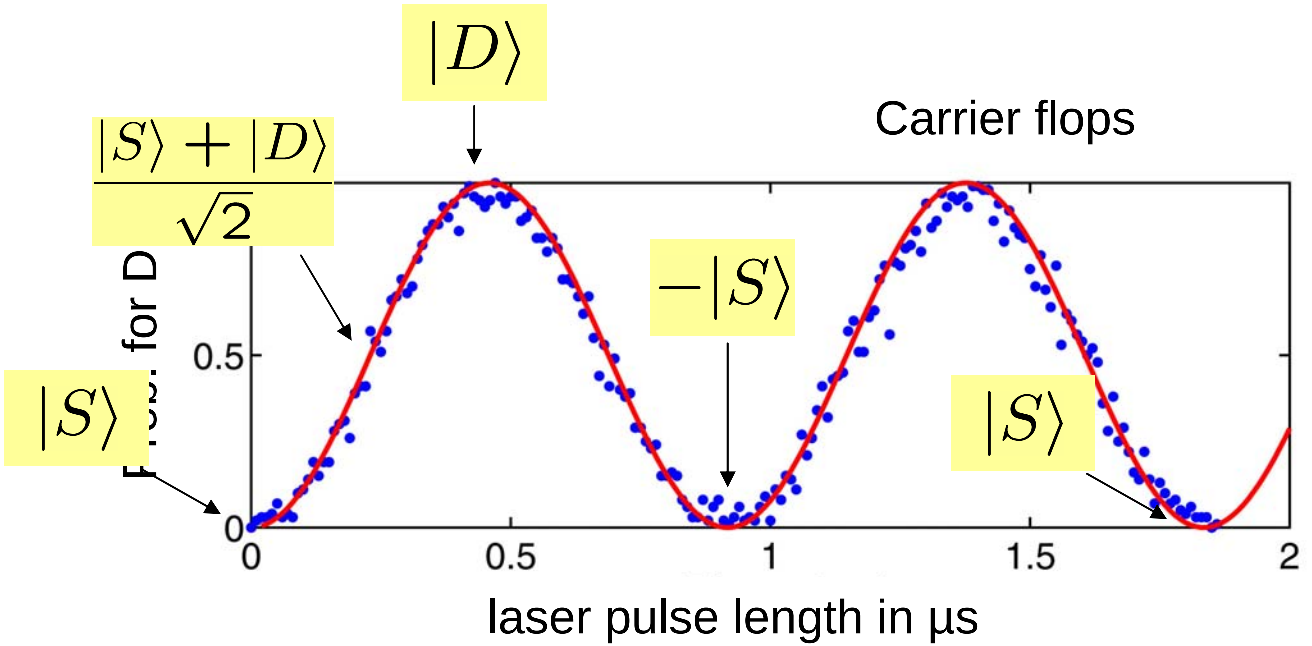
„molecular Franck Condon“ picture

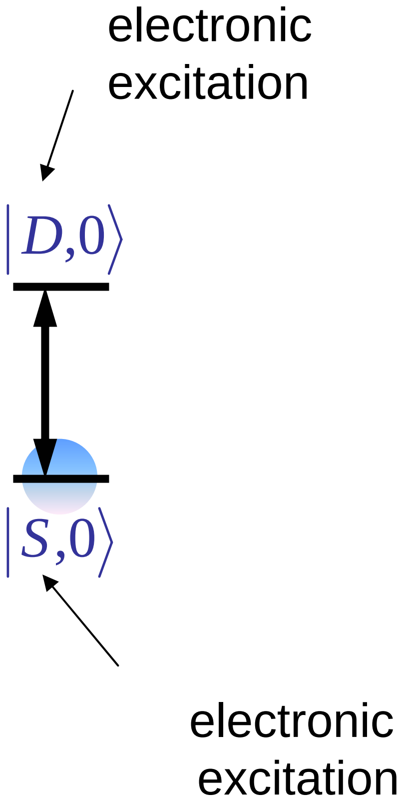


„energy ladder“ picture

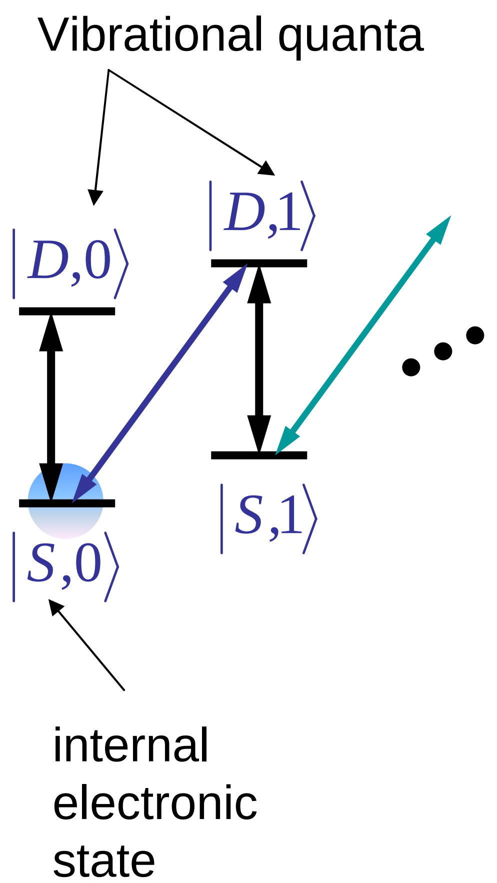


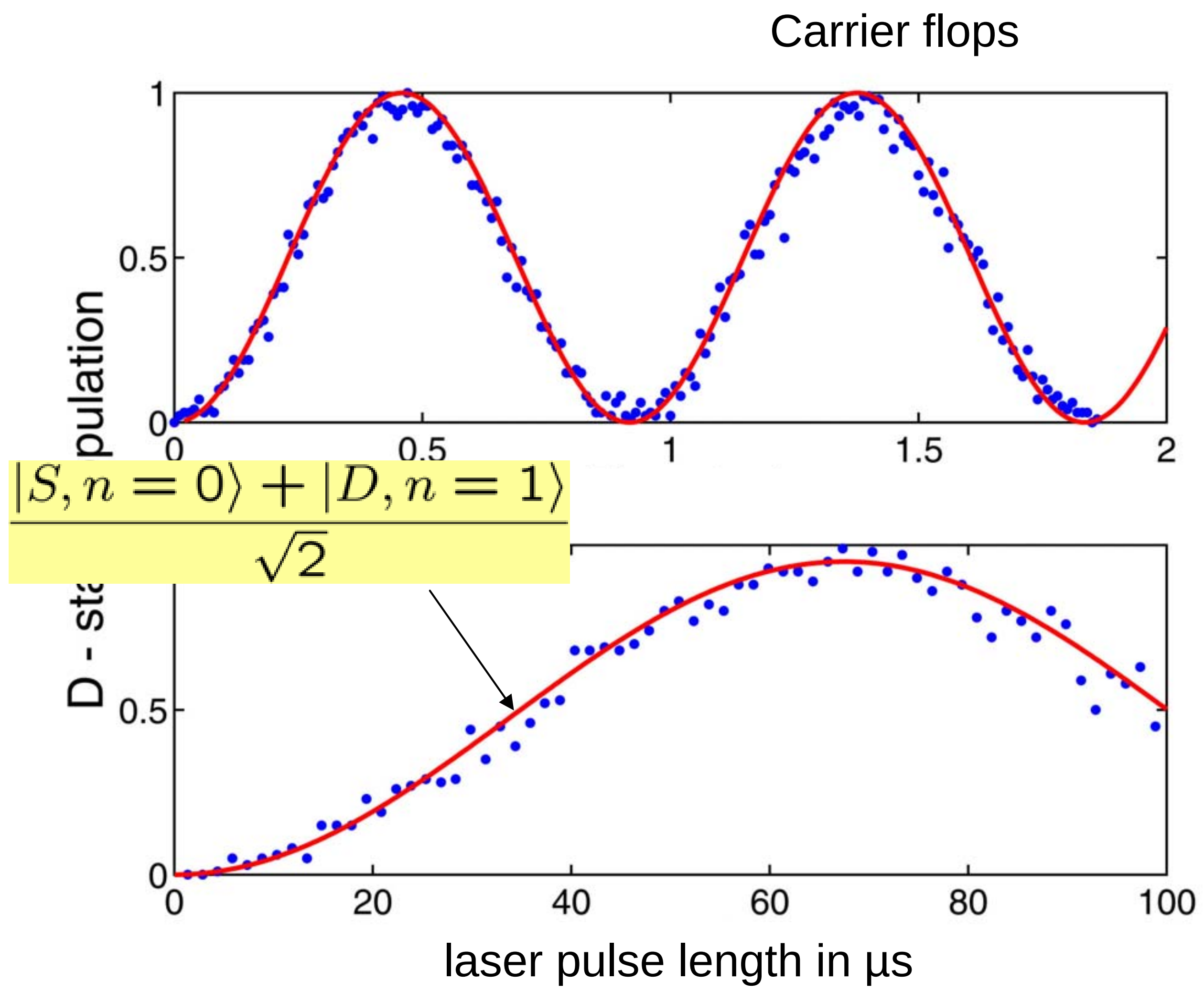
Coherent qubit rotation





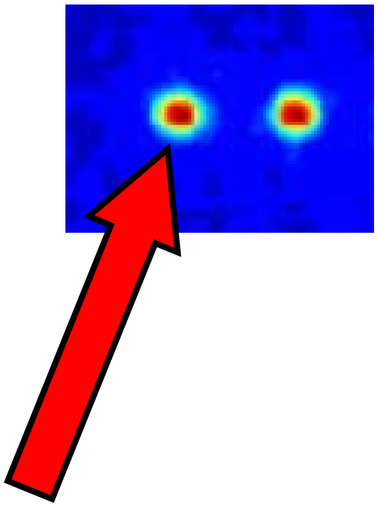
Coherent qubit rotation

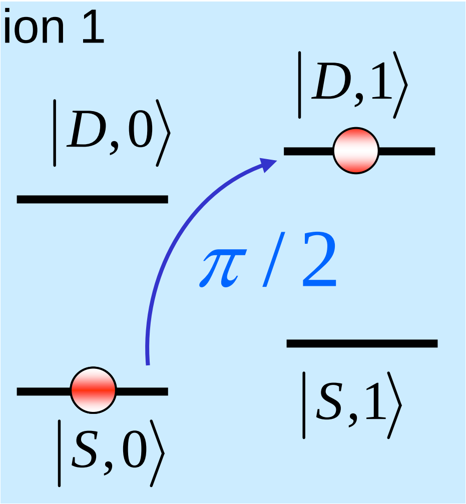




Bellzustände

Deterministic Bell state generation

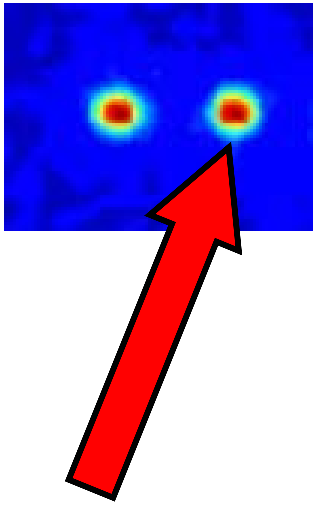


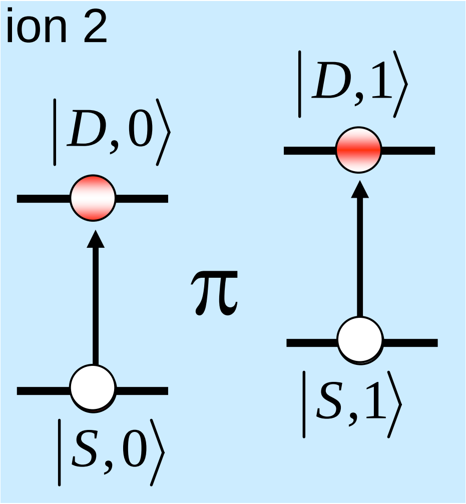


blue $\pi/2$ pulse

$$|SS\rangle|0\rangle \longrightarrow |SS,0\rangle + |DS,1\rangle$$

Deterministic Bell state generation

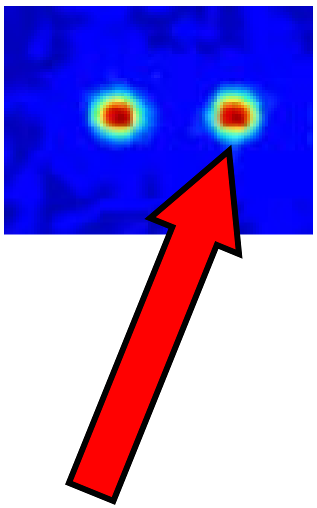


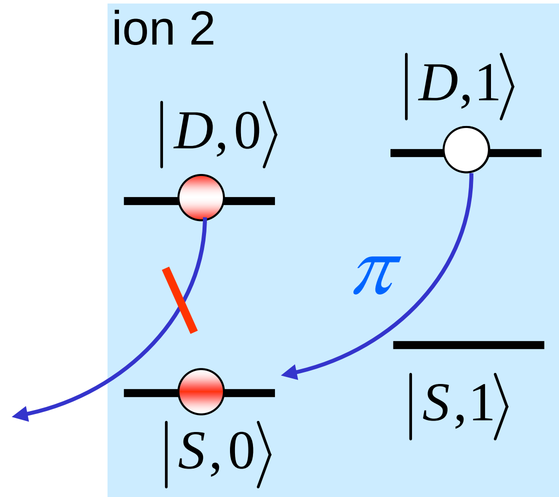


$$|SS\rangle|0\rangle \xrightarrow{\text{blue } \pi/2 \text{ pulse}} |SS,0\rangle + |DS,1\rangle$$

$$\xrightarrow{\text{carrier } \pi \text{ pulse}} |SD,0\rangle + |DD,1\rangle$$

Deterministic Bell state generation





$$|SS\rangle|0\rangle \xrightarrow{\text{blue } \pi/2 \text{ pulse}} |SS,0\rangle + |DS,1\rangle$$

$$\xrightarrow{\text{carrier } \pi \text{ pulse}} |SD,0\rangle + |DD,1\rangle$$

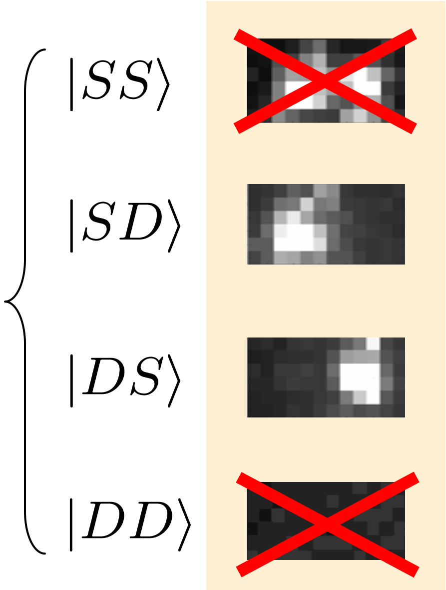
$$\xrightarrow{\text{blue } \pi \text{ pulse}} |SD\rangle|0\rangle + |DS\rangle|0\rangle$$

Bell state analysis

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

- Coherent superposition of SD and DS states?
- Phase relation between both wave function components?

Fluorescence detection with CCD camera:

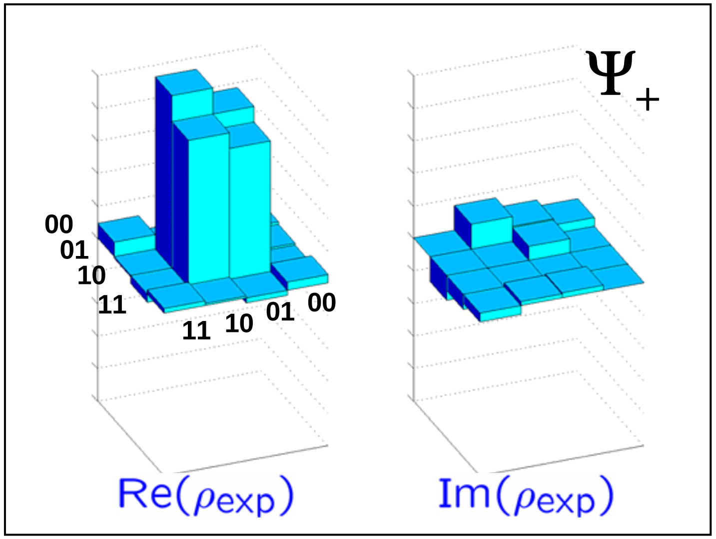


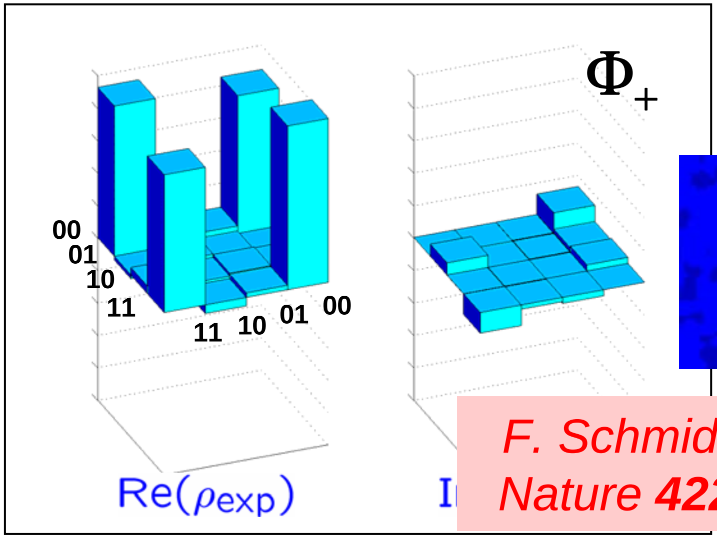
Entire information is contained in the density matrix

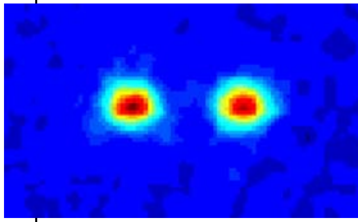
⟶ Measure the density matrix

Density matrix for 2 ion entanglement

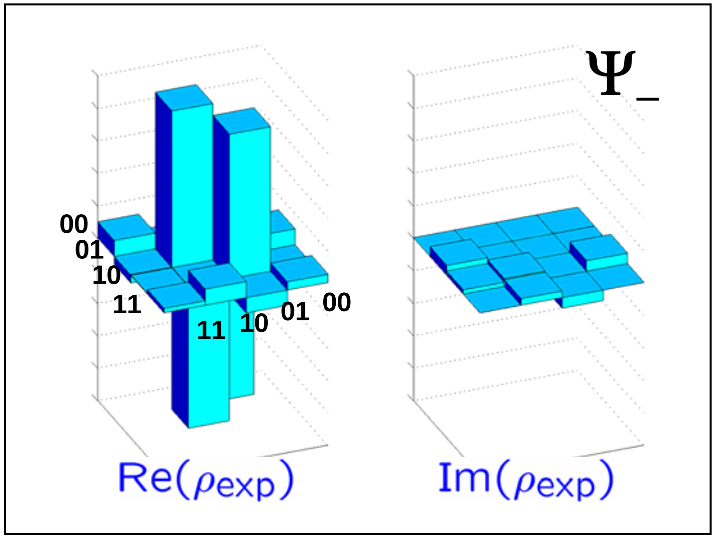
$\psi = |0\rangle|1\rangle + e^{i\phi}|1\rangle|0\rangle$ $\phi = |1\rangle|1\rangle + e^{i\phi}|0\rangle|0\rangle$

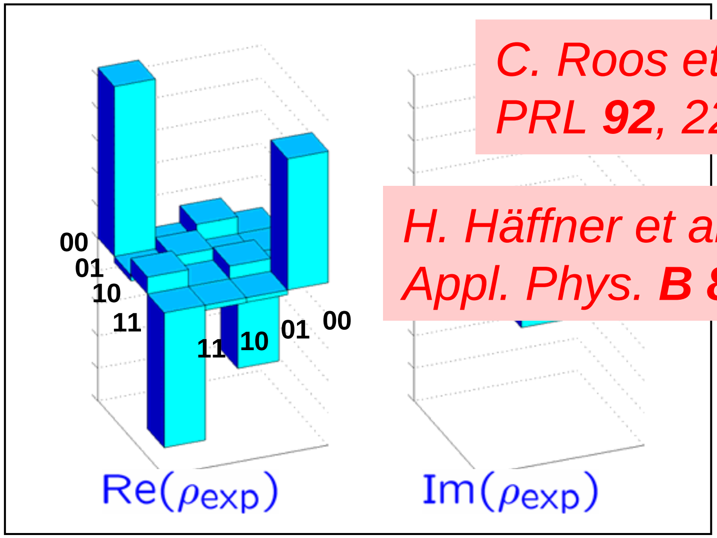






*F. Schmidt-Kaler et al., Nature **422**, 408 (2003)*





*C. Roos et al., PRL **92**, 220402 (2004)*

*H. Häffner et al, Appl. Phys. **B 81**, 151 (2005)*

CNOT Gatter

Quantum gate proposal

W. Paul J. I. Cirac P. Zoller

74, NUMBER 20 4091 PHYSICAL REVIEW LETTERS 15 MAY 1995

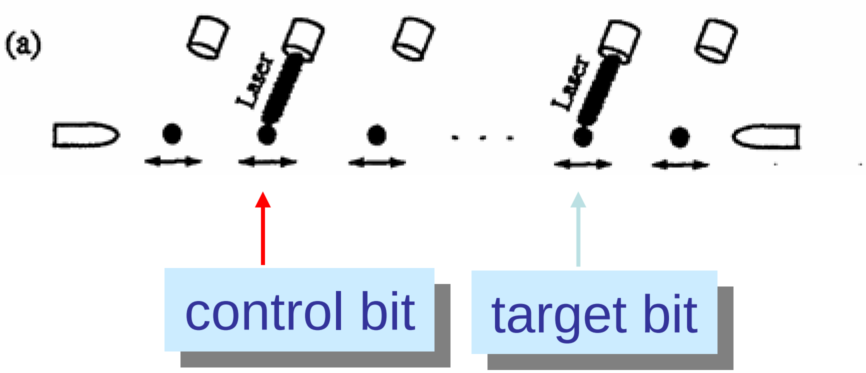
Quantum Computations with Cold Trapped Ions

J. I. Cirac and P. Zoller*

Institut für Theoretische Physik, Universität 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.



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

Quantum gate proposal

J. I. Cirac

P. Zoller

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

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

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

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

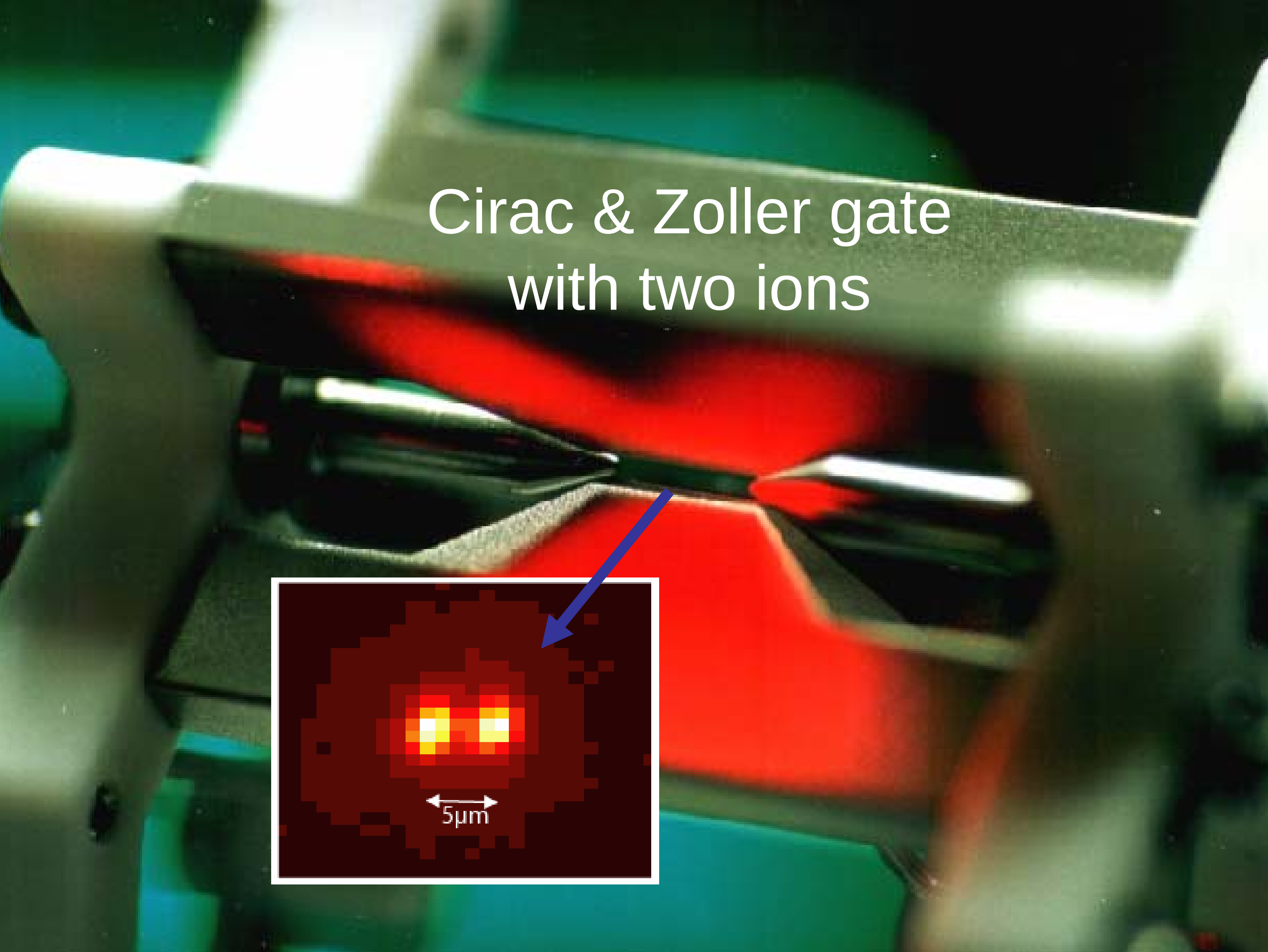
$$|1\rangle|1\rangle \rightarrow |1\rangle|0\rangle$$

control bit

target bit

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

Cirac & Zoller gate with two ions



Controlled-NOT operation

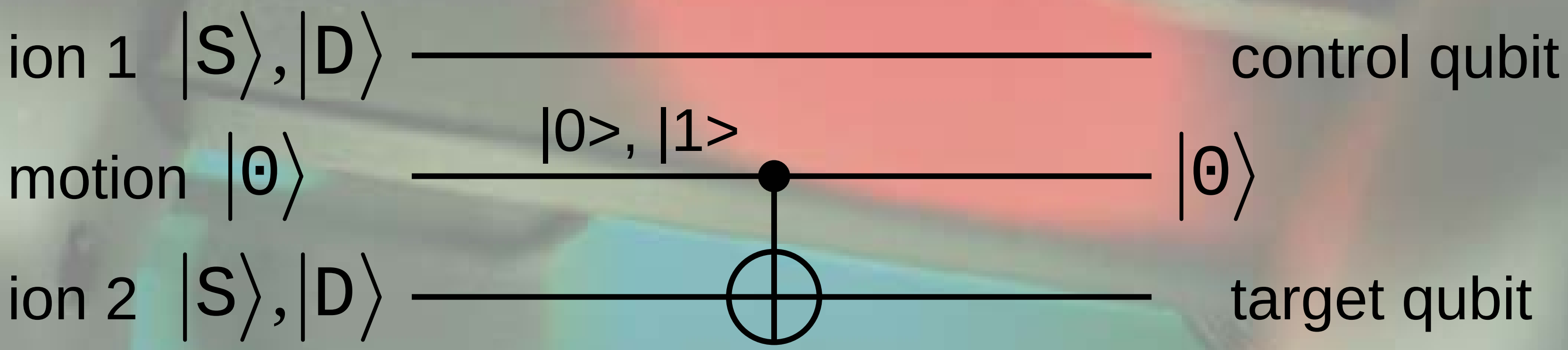
$|\varepsilon_1\rangle$ $|\varepsilon_2\rangle$

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

control target

Controlled-NOT operation

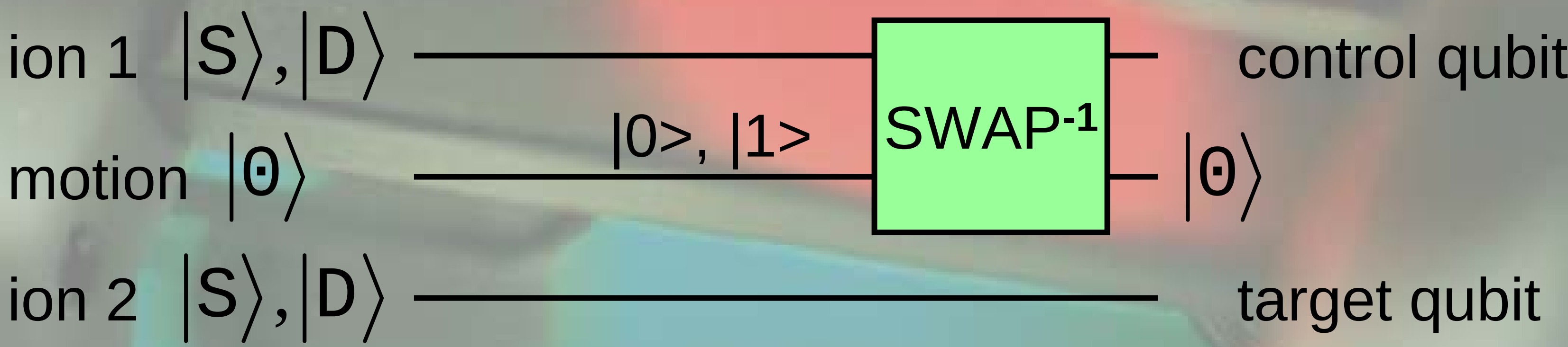
$$|S\rangle|S\rangle \rightarrow |S\rangle|S\rangle$$
$$|S\rangle|D\rangle \rightarrow |S\rangle|D\rangle$$
$$|D\rangle|S\rangle \rightarrow |D\rangle|D\rangle$$
$$|D\rangle|D\rangle \rightarrow |D\rangle|S\rangle$$



Controlled-NOT operation

$|\varepsilon_1\rangle \quad |\varepsilon_2\rangle$

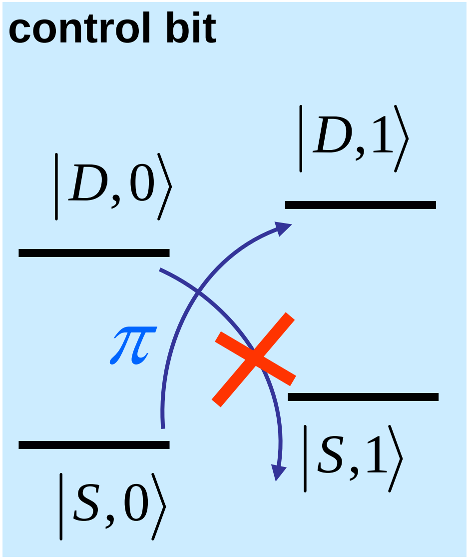
$$|S\rangle|S\rangle \rightarrow |S\rangle|S\rangle$$
$$|S\rangle|D\rangle \rightarrow |S\rangle|D\rangle$$
$$|D\rangle|S\rangle \rightarrow |D\rangle{\color{red}|D\rangle}$$
$$|D\rangle|D\rangle \rightarrow |D\rangle{\color{red}|S\rangle}$$



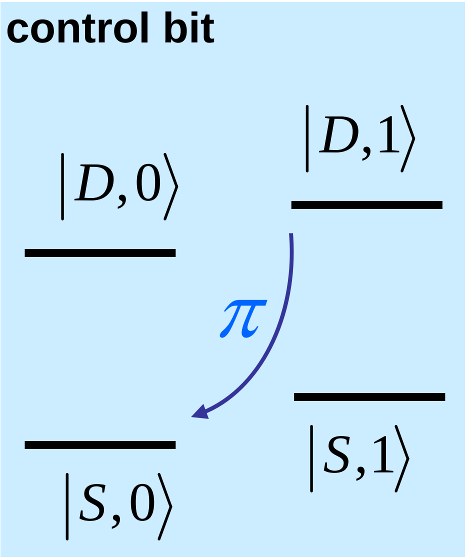
SWAP and SWAP^{-1}

starting with |n=0> phonons,
write into and read from the common vibrational mode

π-pulse on blue SB



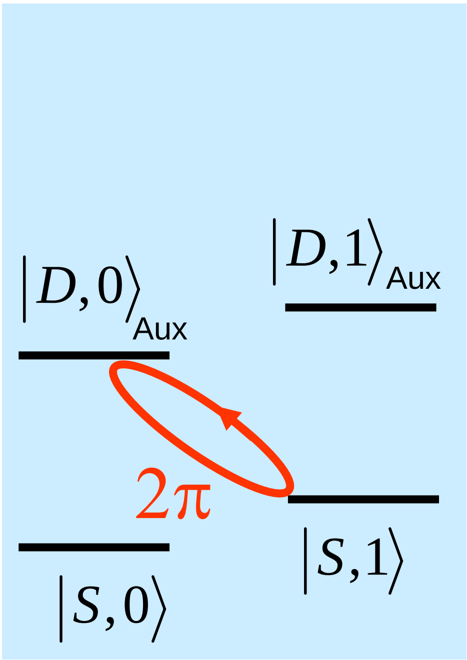
SWAP



SWAP^{-1}

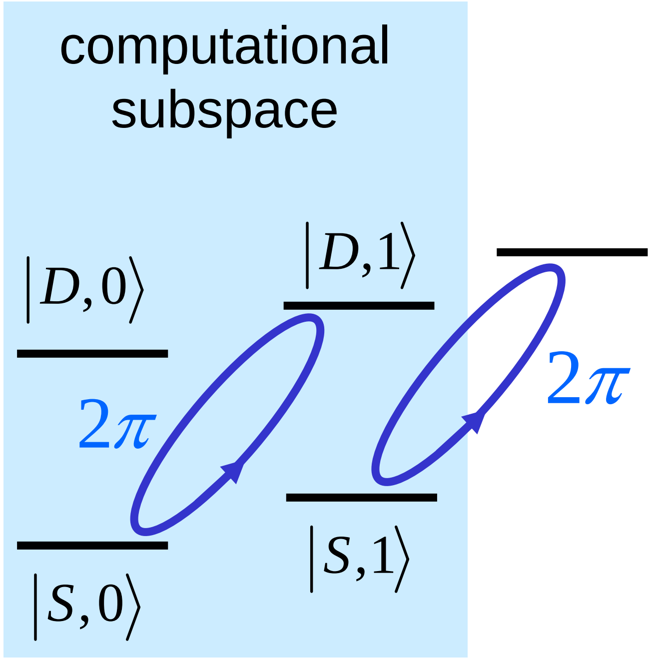
Conditional phase gates

Cirac & Zoller (1995)



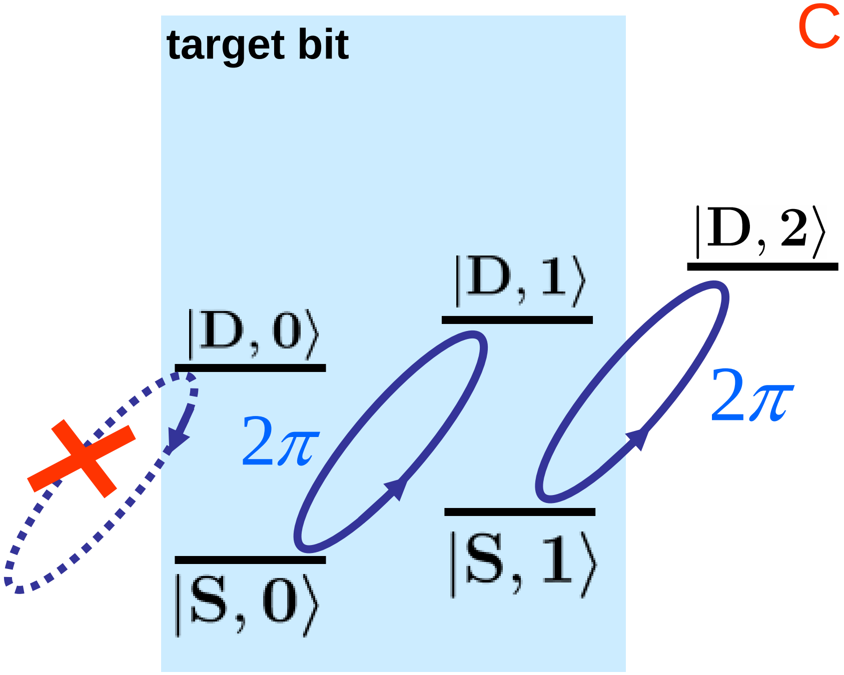
<u>Effect:</u>
phase factor of **-1**
for |S,1 >

Composite phase gate



<u>Effect:</u>
phase factor of **-1**
for all, except |D,0 >

Conditional phase gate



Composite pulse phase gate

I.Chuang,
MIT Boston

Rabi frequency:

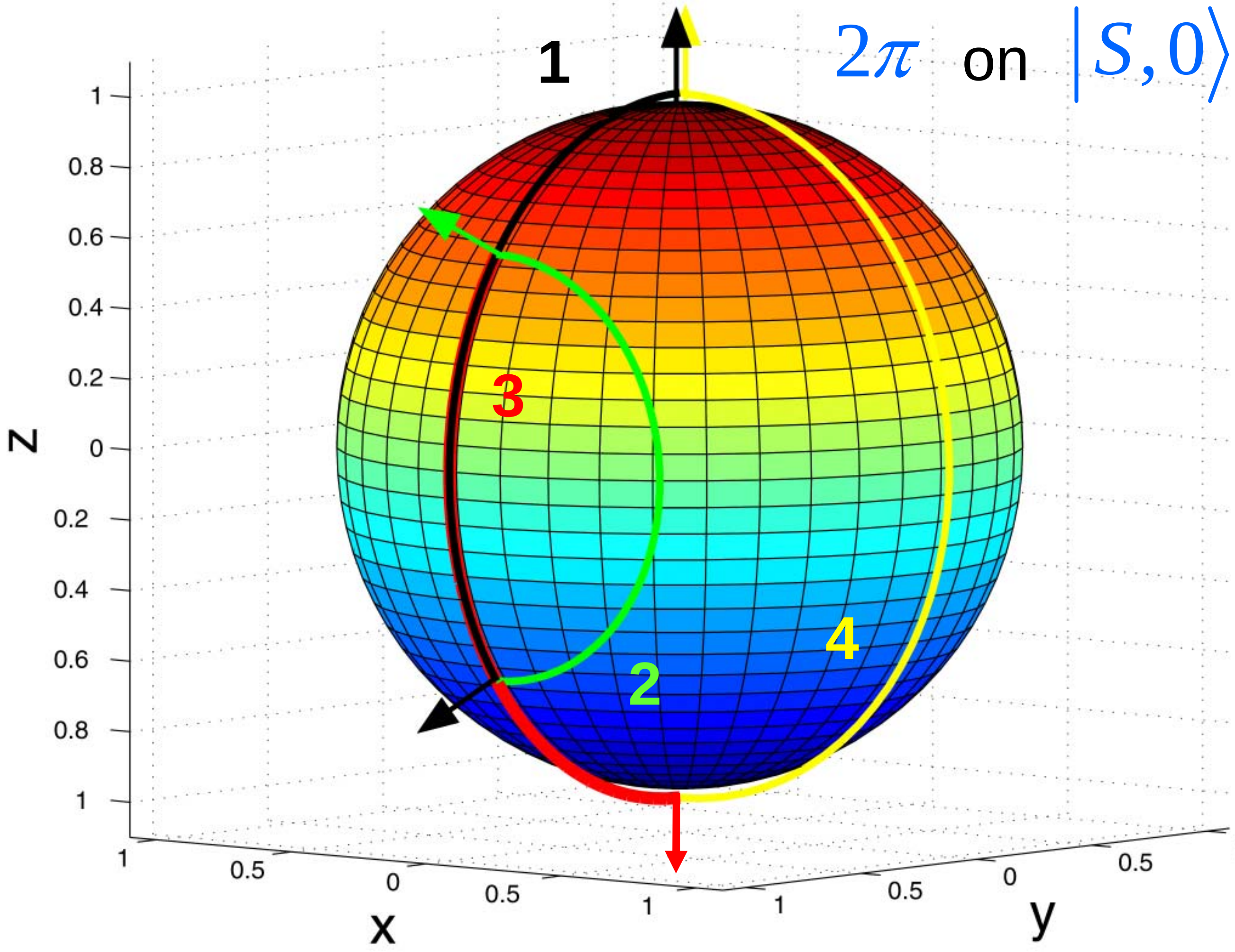
Blue SB: $\Omega \cdot \eta \cdot \sqrt{n+1}$

<u>Effect:</u>
phase factor of **-1**
for all, except |D,0 >

Composite phase gate (2π rotation)

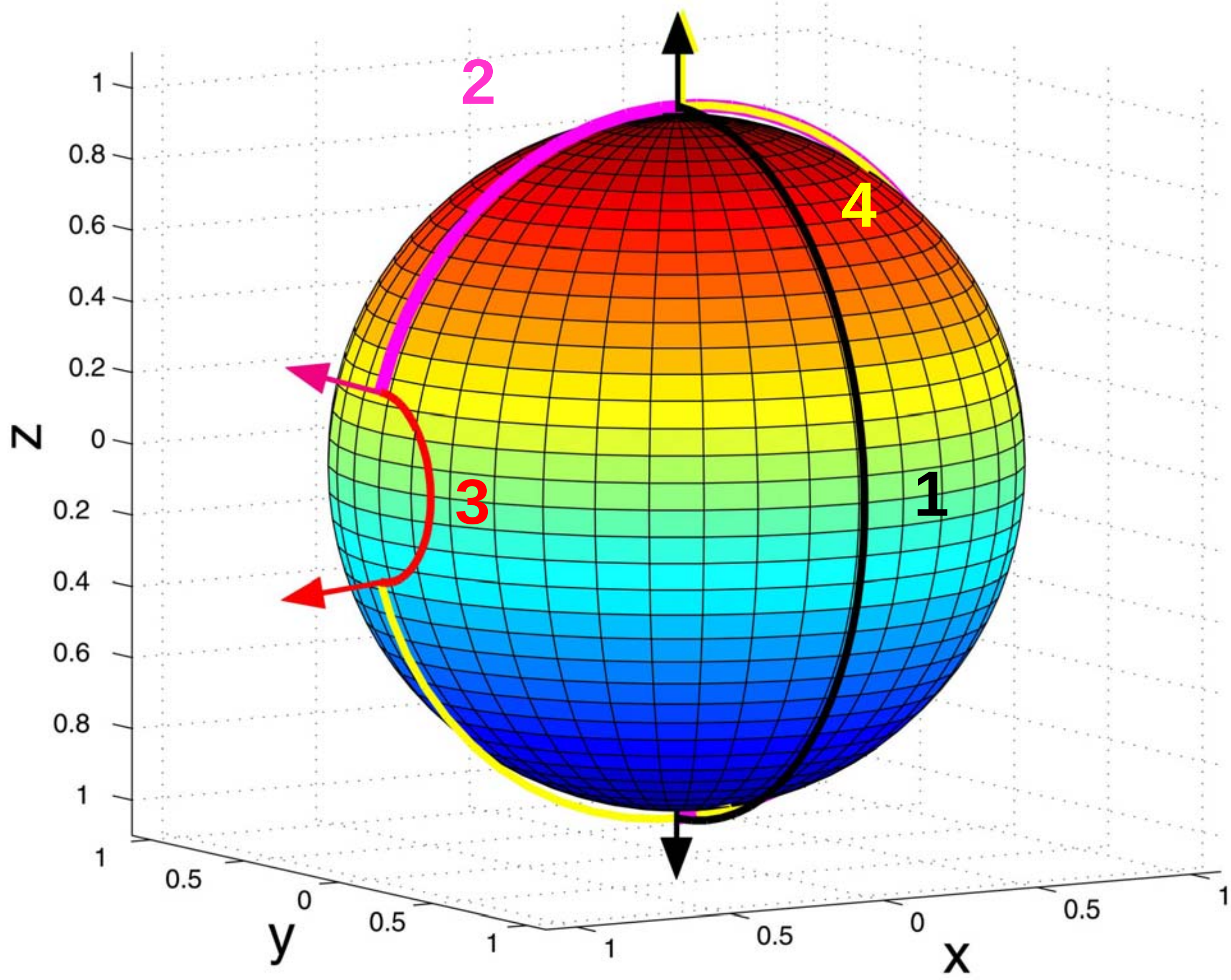
$$R(\theta,\phi) = R_1^+(\pi,\pi/2)\,R_1^+\left(\pi/\sqrt{2},0\right)R_1^+(\pi,\pi/2)\,R_1^+\left(\pi/\sqrt{2},0\right)$$

2π on $|S,0\rangle \leftrightarrow |D,1\rangle$



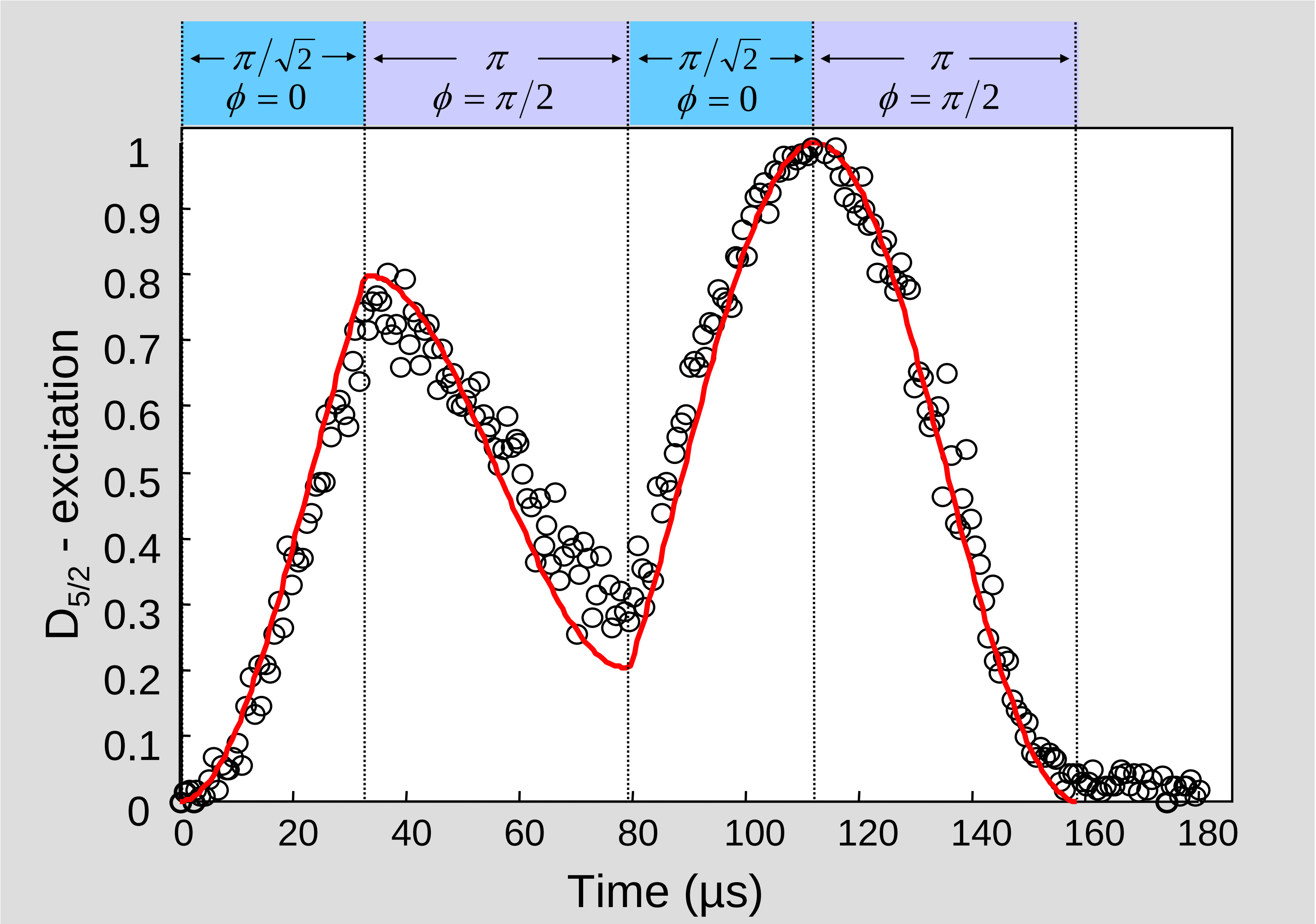
Population of |S,1> - |D,2> remains unaffected

$$R(\theta,\phi) = R_1^+\left(\pi\sqrt{2},\pi/2\right)R_1^+\left(\pi,0\right)R_1^+\left(\pi\sqrt{2},\pi/2\right)R_1^+\left(\pi,0\right)$$



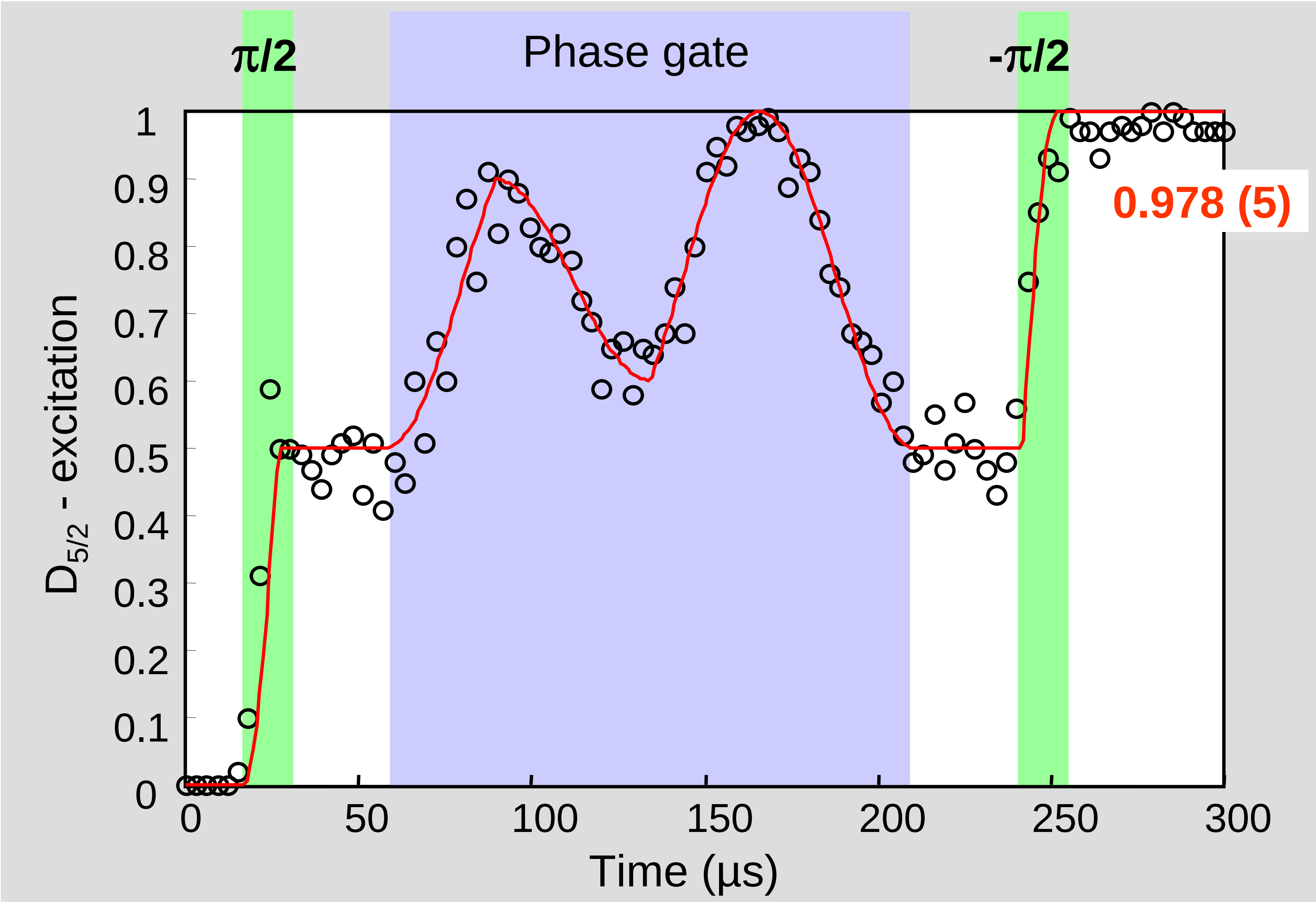
Single ion composite phase gate

state preparation $\left|S,0\right\rangle$, then application of phase gate pulse sequence

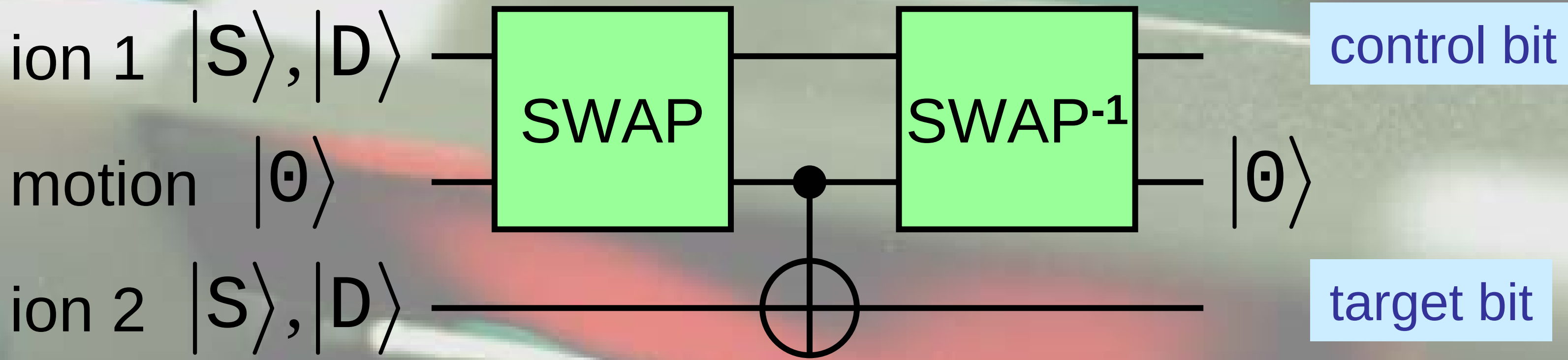


Single ion composite CNOT gate

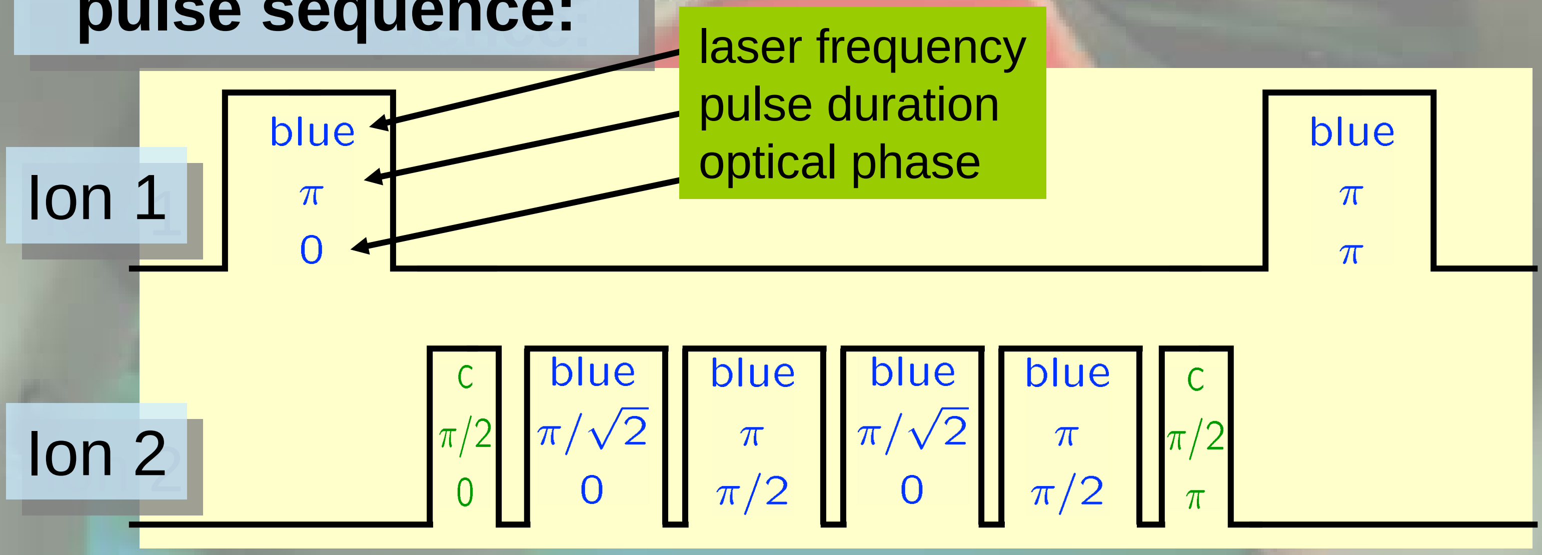
state preparation $\left|S,0\right\rangle$, then application of CNOT gate pulse sequence



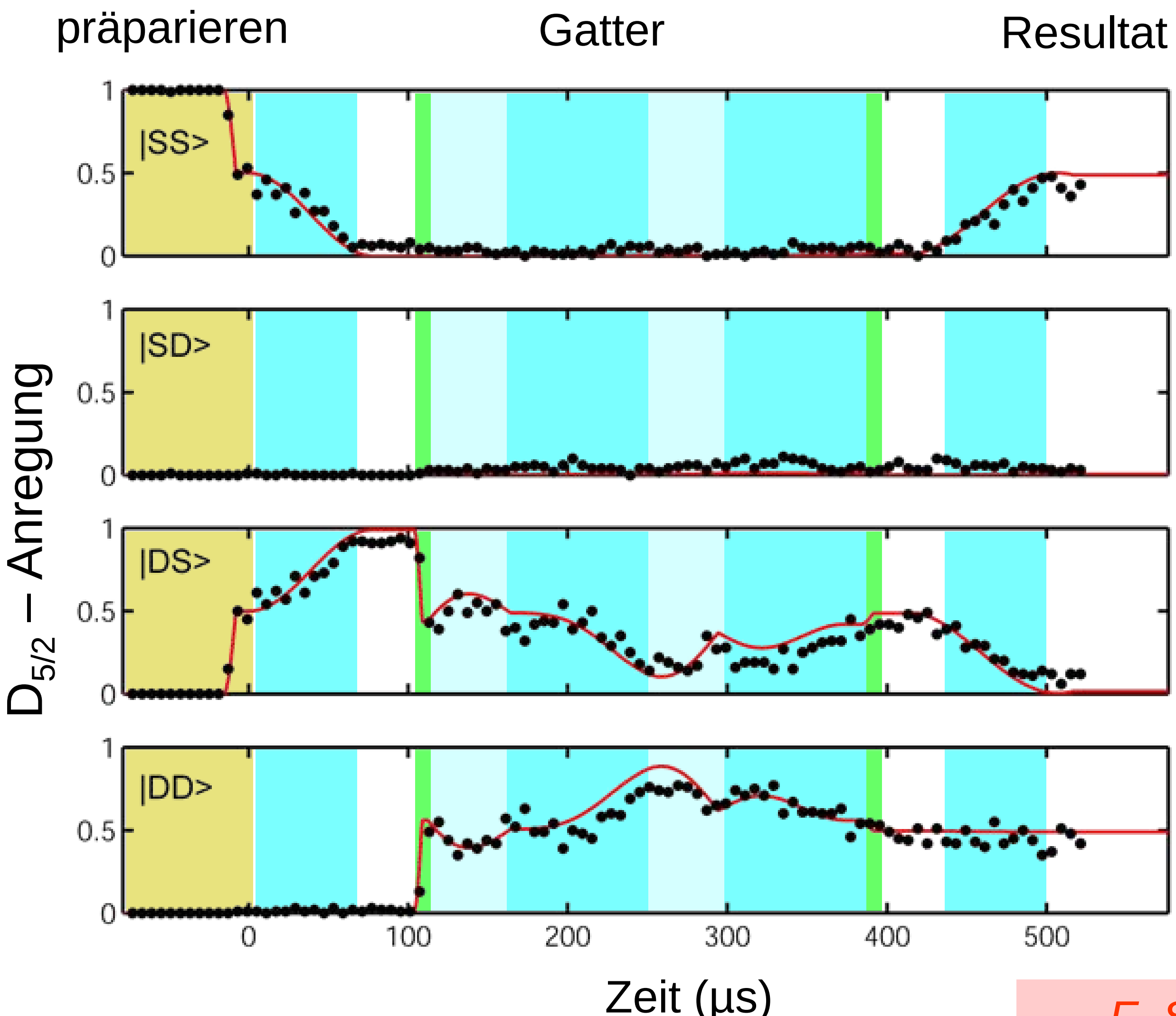
Controlled-NOT operation

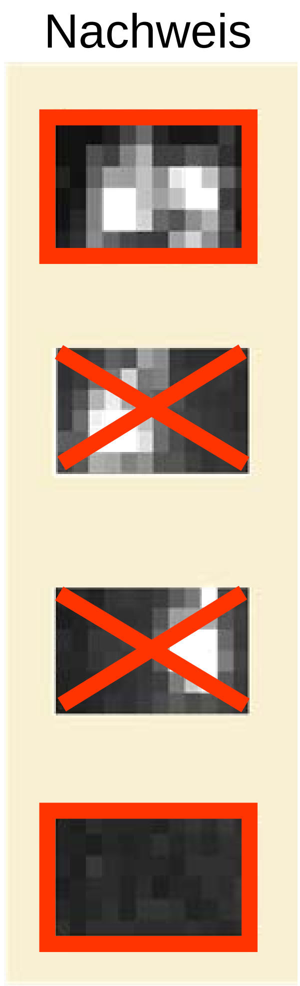


pulse sequence:



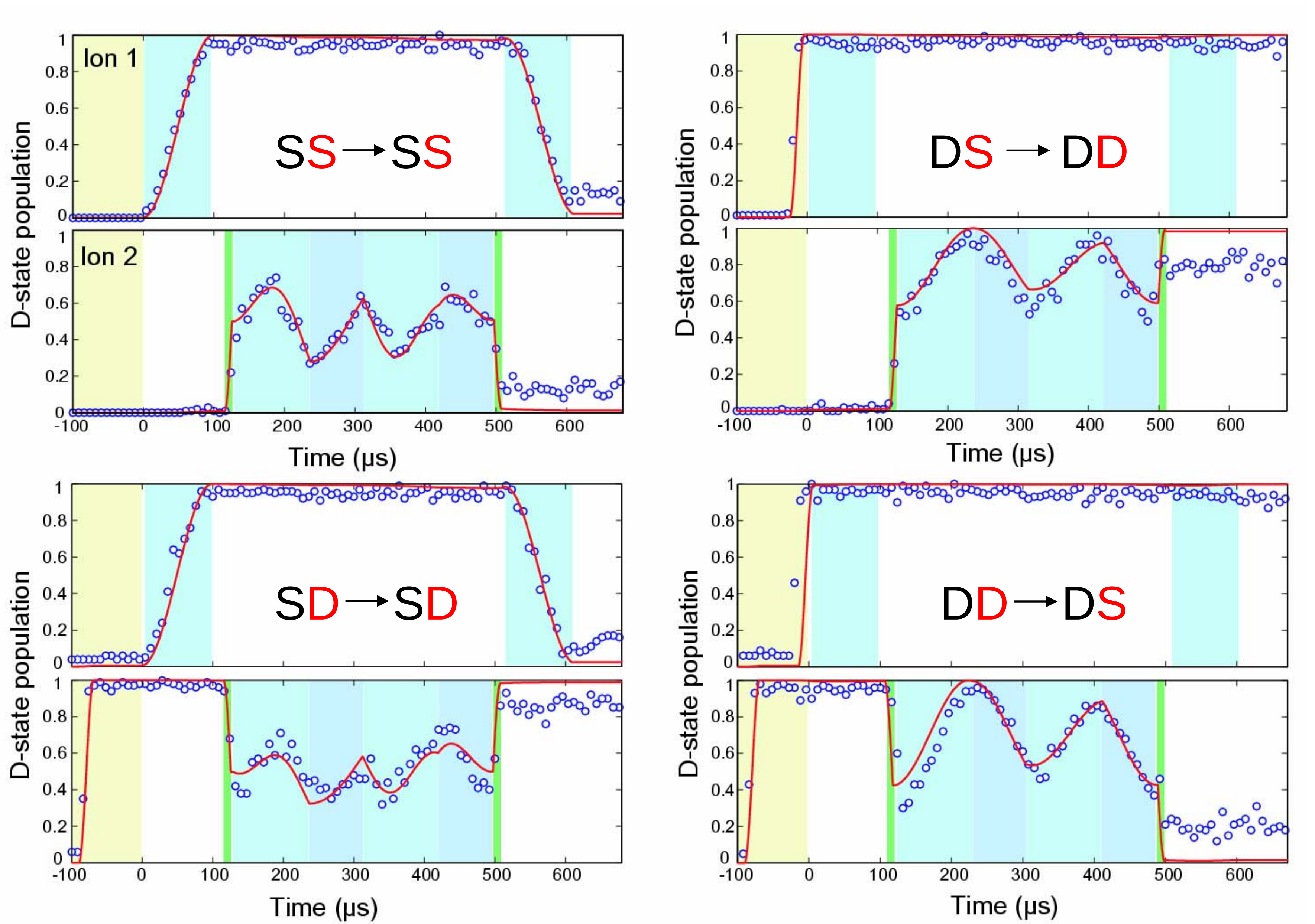
$$|S+D,S\rangle \xrightarrow{\text{CNOT}} |SS\rangle + |DD\rangle$$



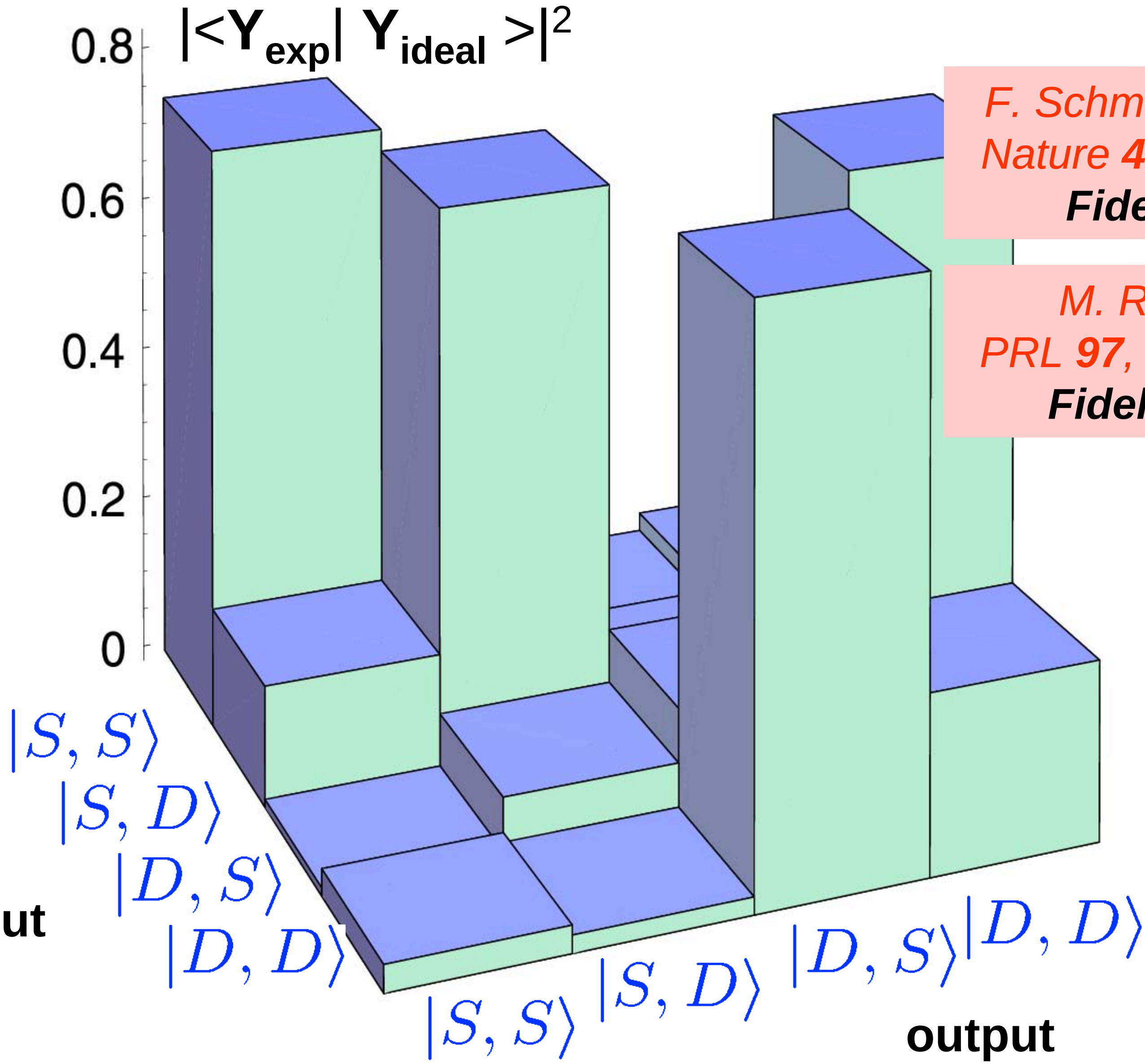


*F. Schmidt-Kaler et al., Appl.Phys.**B77,** 789 (2003)*

Cirac – Zoller CNOT gate operation



Fidelity of Cirac-Zoller CNOT



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

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

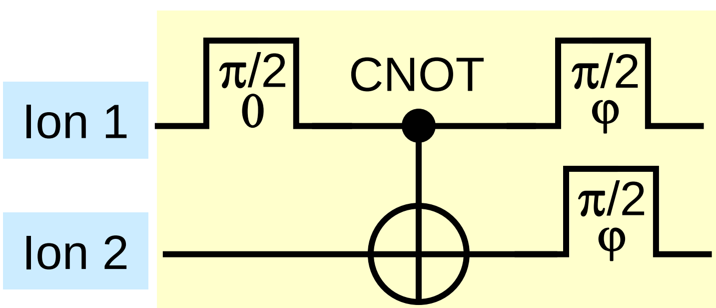
Entanglement

$|S+D\rangle|S\rangle \xrightarrow{\text{CNOT}} |SS + e^{i\phi} DD\rangle \xrightarrow{\text{loc. rotation: } \varphi}$

control bit | target

$\{\, |SS+DD\rangle,\ |SS-DD\rangle,\ |SD+DS\rangle,\ |SD-DS\rangle \,\}$

Sequence:



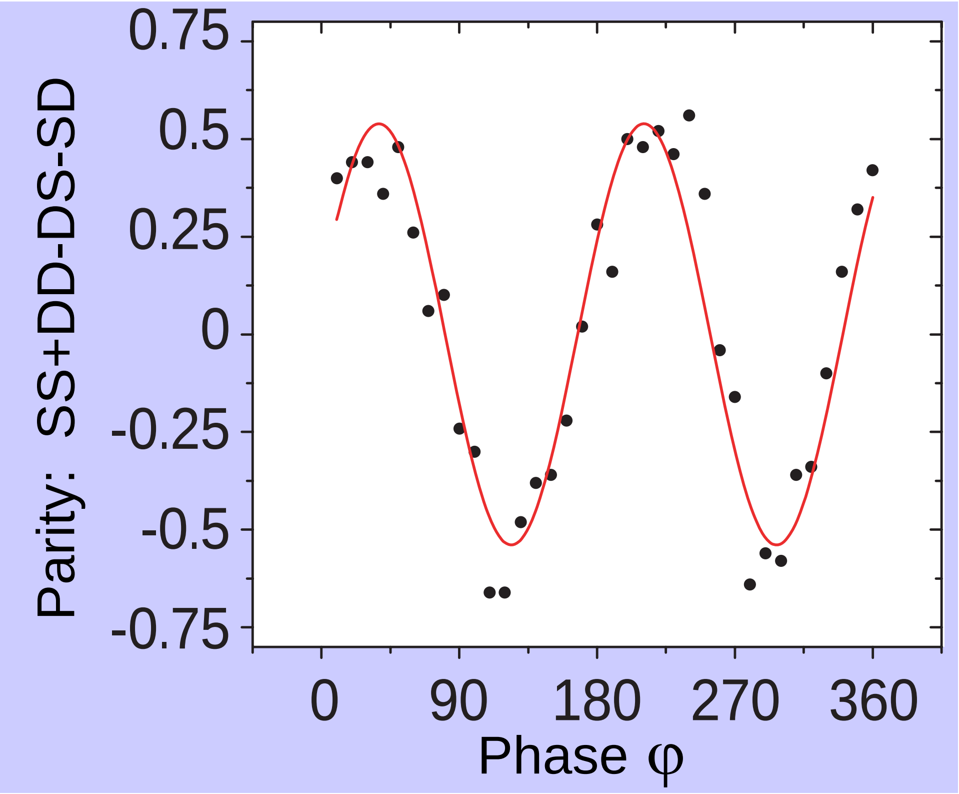
- Super-Ramsey experiment
- Parity check

Entanglement

$|S+D\rangle|S\rangle$ $\xrightarrow{\text{CNOT}}$ $|SS + e^{i\phi} DD\rangle$ $\xrightarrow{\text{loc. rotation: } \varphi}$

control bit   target

{ $|SS+DD\rangle$, $|SS-DD\rangle$, $|SD+DS\rangle$, $|SD-DS\rangle$ }



oscillates with 2φ !
54% contrast

Fidelity = $0.5\,(P_{SS} + P_{DD} + \text{contrast})$ =

71(3)%

Teleportation

Principle of the ion trap quantum processor

Universal two-qubit gate

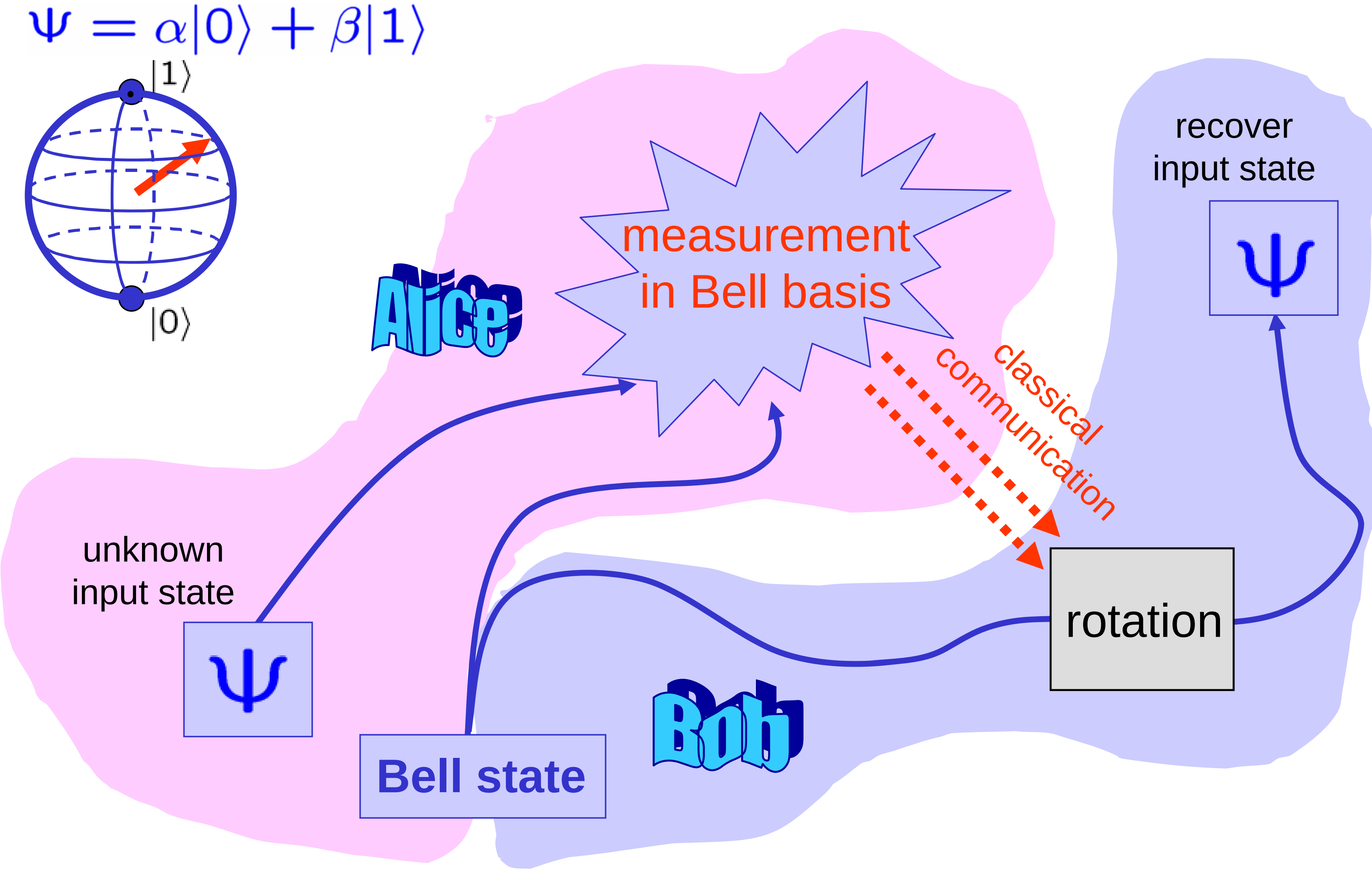
Entangled states of two and three ions

Teleportation

Theorie: D. James, Los Alamos

Teleportation

Bennett et al, Phys. Rev. Lett. 70, 1895 (1993)



Quantum teleportation: No black magic

Source qubit(#1): pure state $|\chi\rangle_1 = \alpha|0\rangle_1 + \beta|1\rangle_1$

Target qubit(#3) and ancilla (#2): maximally entangled state

$$|\Psi^+\rangle_{23} = \frac{1}{\sqrt{2}}\left(|0\rangle_2|0\rangle_3 + |1\rangle_2|1\rangle_3\right)$$

Combined state $|\varphi\rangle = |\chi\rangle_1 \frac{1}{\sqrt{2}}\left(|0\rangle_2|0\rangle_3 + |1\rangle_2|1\rangle_3\right)$

Rearrange terms:

$$|\varphi\rangle = \frac{1}{2}\left(|\Phi^+\rangle_{12}\ \sigma_x|\chi\rangle_3 + |\Phi^-\rangle_{12}\ (-i\sigma_y)|\chi\rangle_3 + |\Psi^+\rangle_{12}\ |\chi\rangle_3 + \boxed{|\Psi^-\rangle_{12}\ \sigma_z|\chi\rangle_3}\right)$$

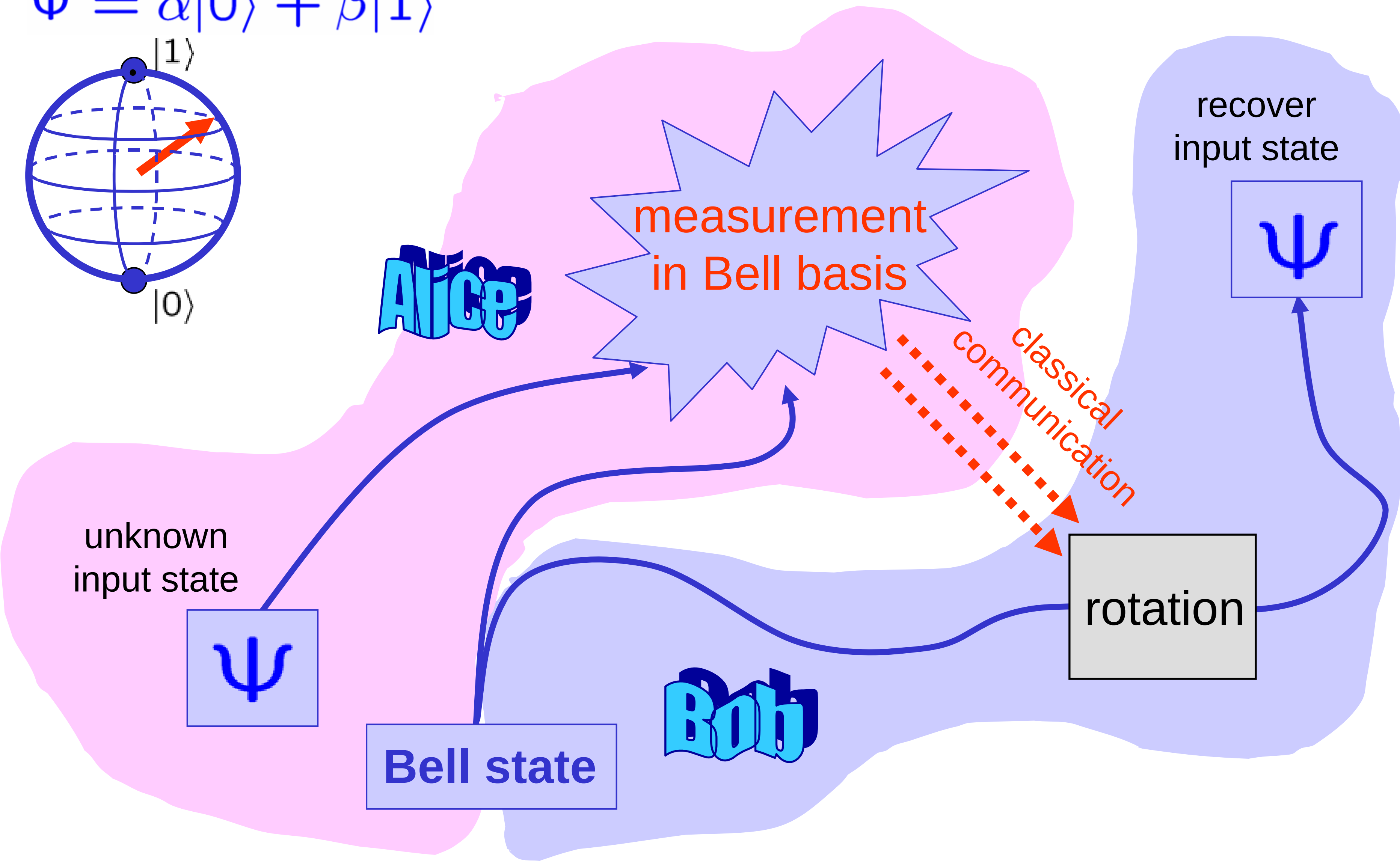
$$|\Psi^\pm\rangle_{12} = \frac{1}{\sqrt{2}}\left(|0\rangle_1|0\rangle_2 \pm |1\rangle_1|1\rangle_2\right)$$
$$|\Phi^\pm\rangle_{12} = \frac{1}{\sqrt{2}}\left(|0\rangle_1|1\rangle_2 \pm |1\rangle_1|0\rangle_2\right)$$

measure #1 and #2 in Bell basis: $|\varphi>$ is projected onto one of 4 pure states
e.g. measure $|\Psi^->_{12}$:perform $-\sigma_z$ operation on qubit #3 to yield input state back

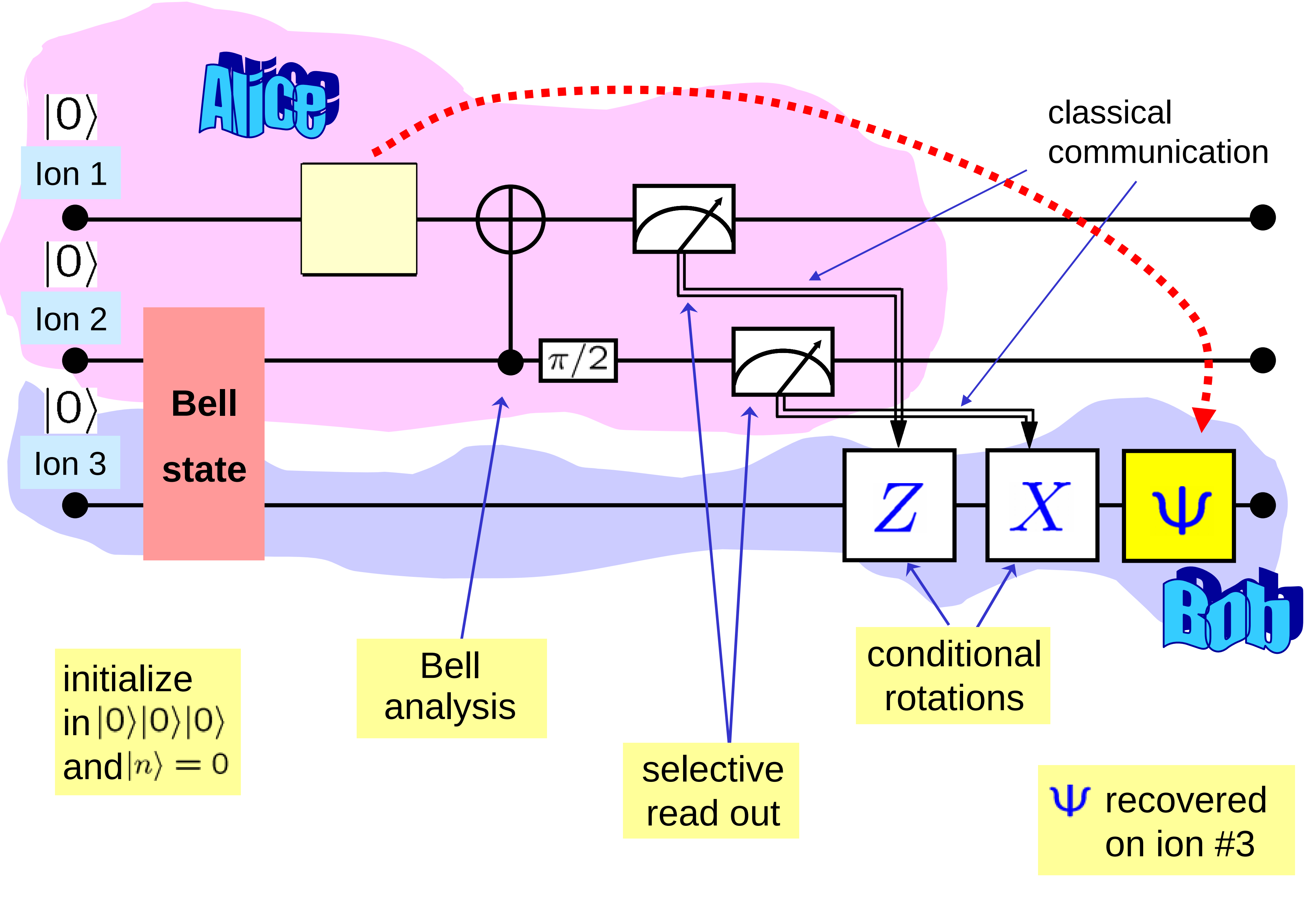
Teleportation

Bennett et al, Phys. Rev. Lett. 70, 1895 (1993)

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

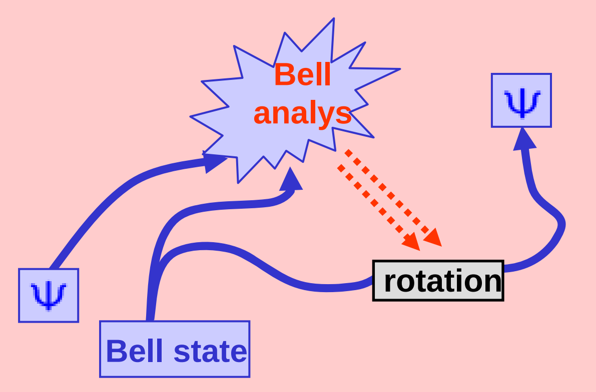


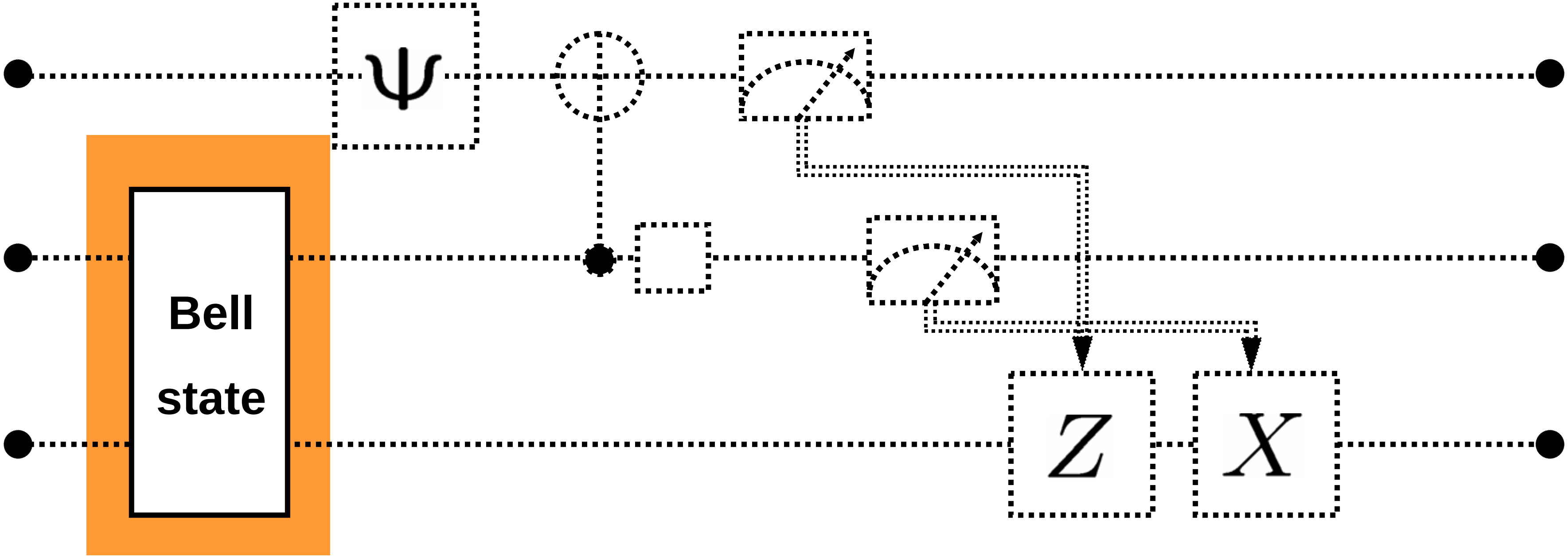
Quantum teleportation protocol



Step by step

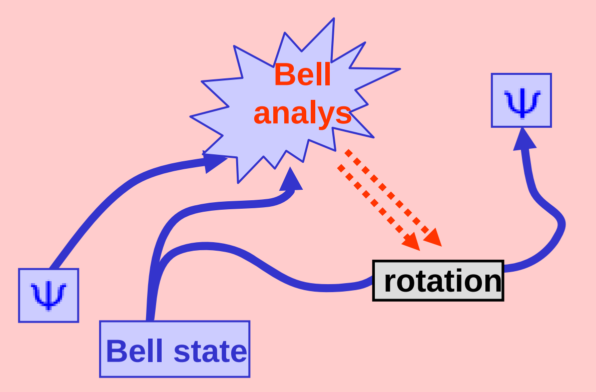
1. *Bell state generation*

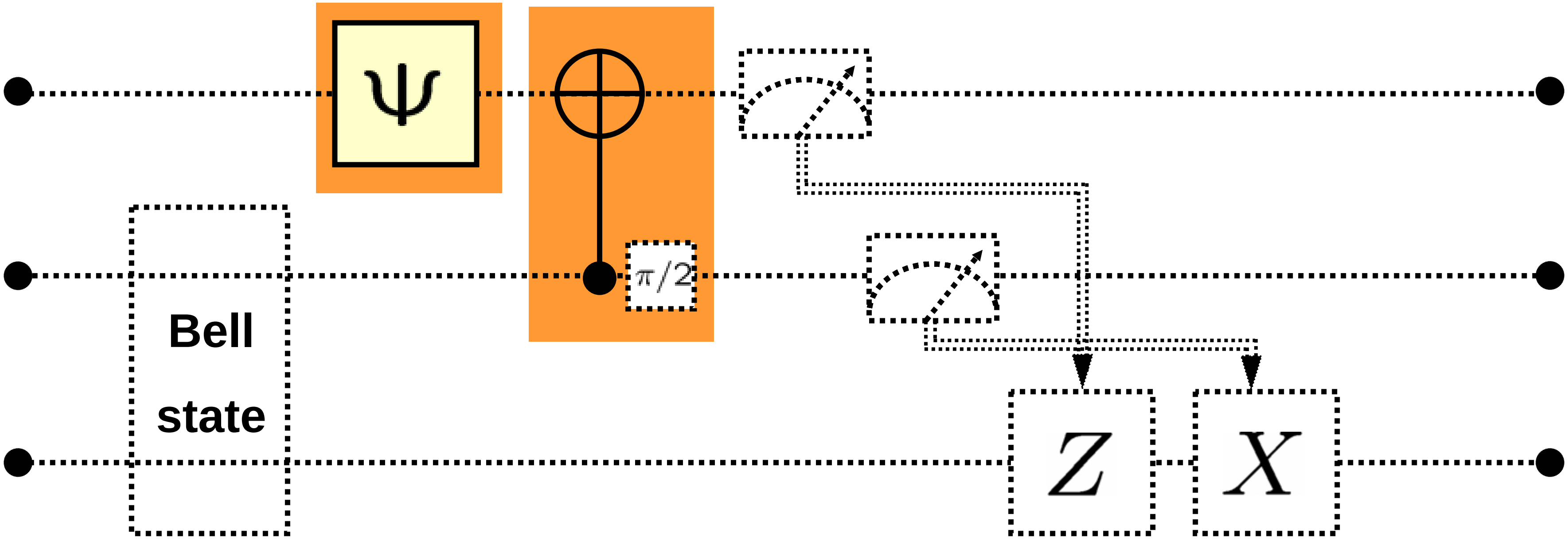




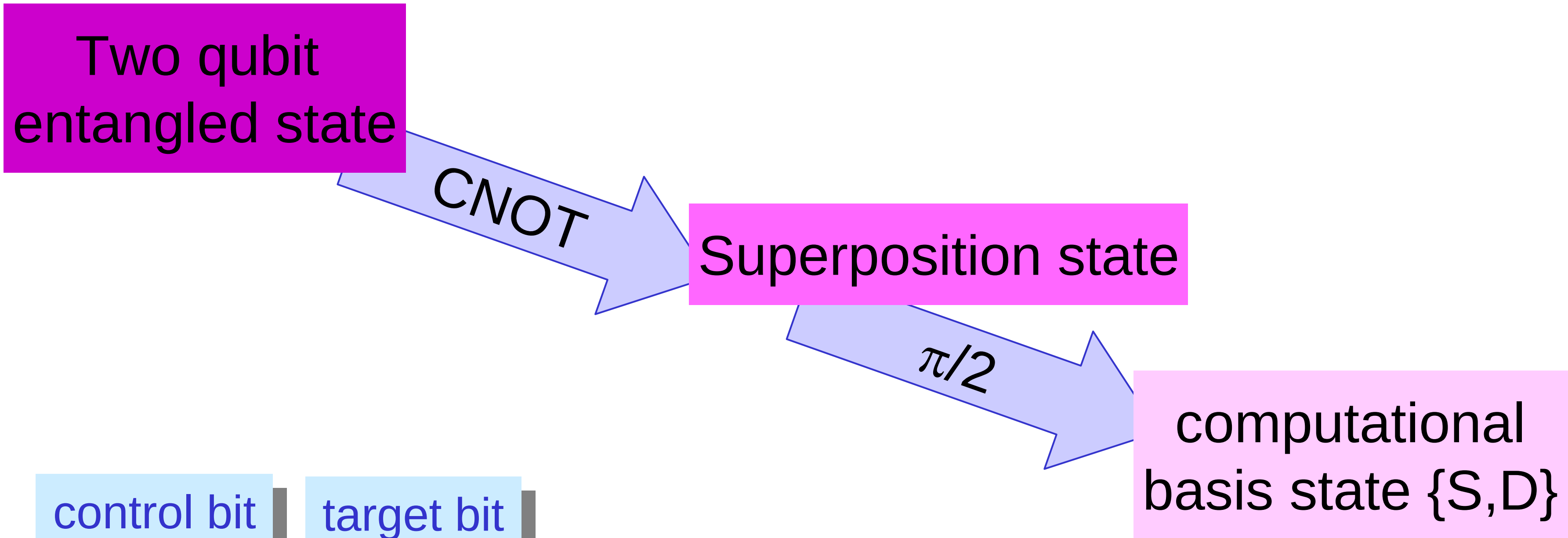
Step by step

1. *Bell state generation*
2. ***Generate ψ***
3. ***Bell analysis***





complete Bell analysis



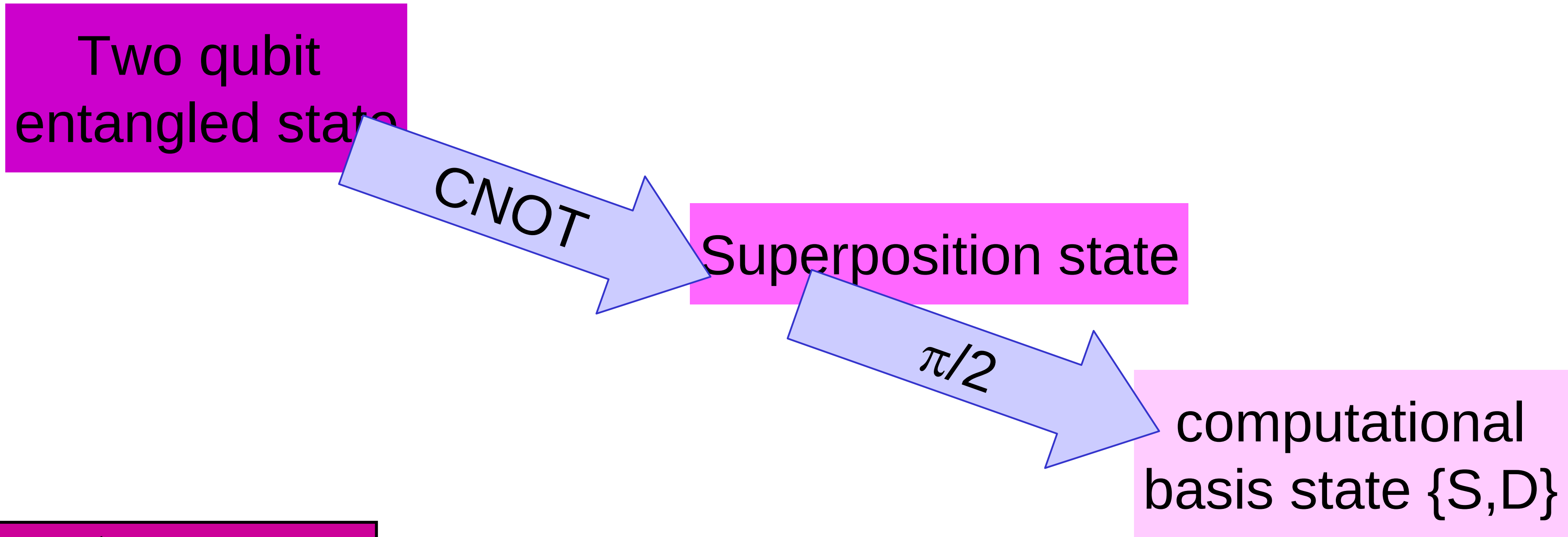
control bit　target bit

$$1/\sqrt{2}\{|S,S\rangle + |D,D\rangle\} \xrightarrow{\text{CNOT}}$$

$$1/\sqrt{2}\{|S+D\rangle|S\rangle\} \xrightarrow{\pi/2}$$

$$|S,S\rangle$$

complete Bell analysis

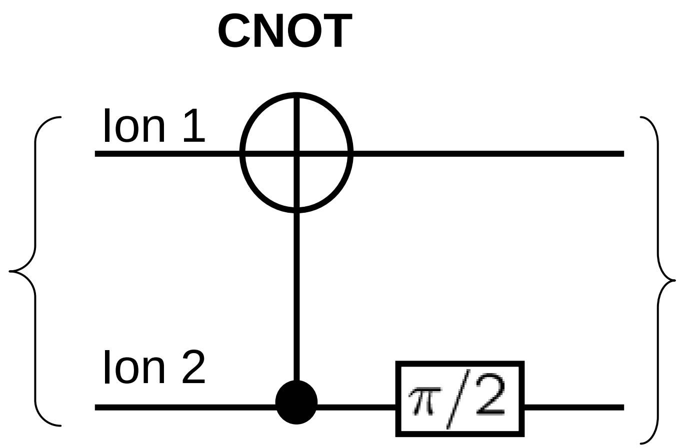


$$\beta_{00} = \frac{1}{\sqrt{2}}\left(|SS\rangle + |DD\rangle\right)$$

$$\beta_{10} = \frac{1}{\sqrt{2}}\left(|SD\rangle + |DS\rangle\right)$$

$$\beta_{01} = \frac{1}{\sqrt{2}}\left(|SS\rangle - |DD\rangle\right)$$

$$\beta_{11} = \frac{1}{\sqrt{2}}\left(|SD\rangle + |DS\rangle\right)$$



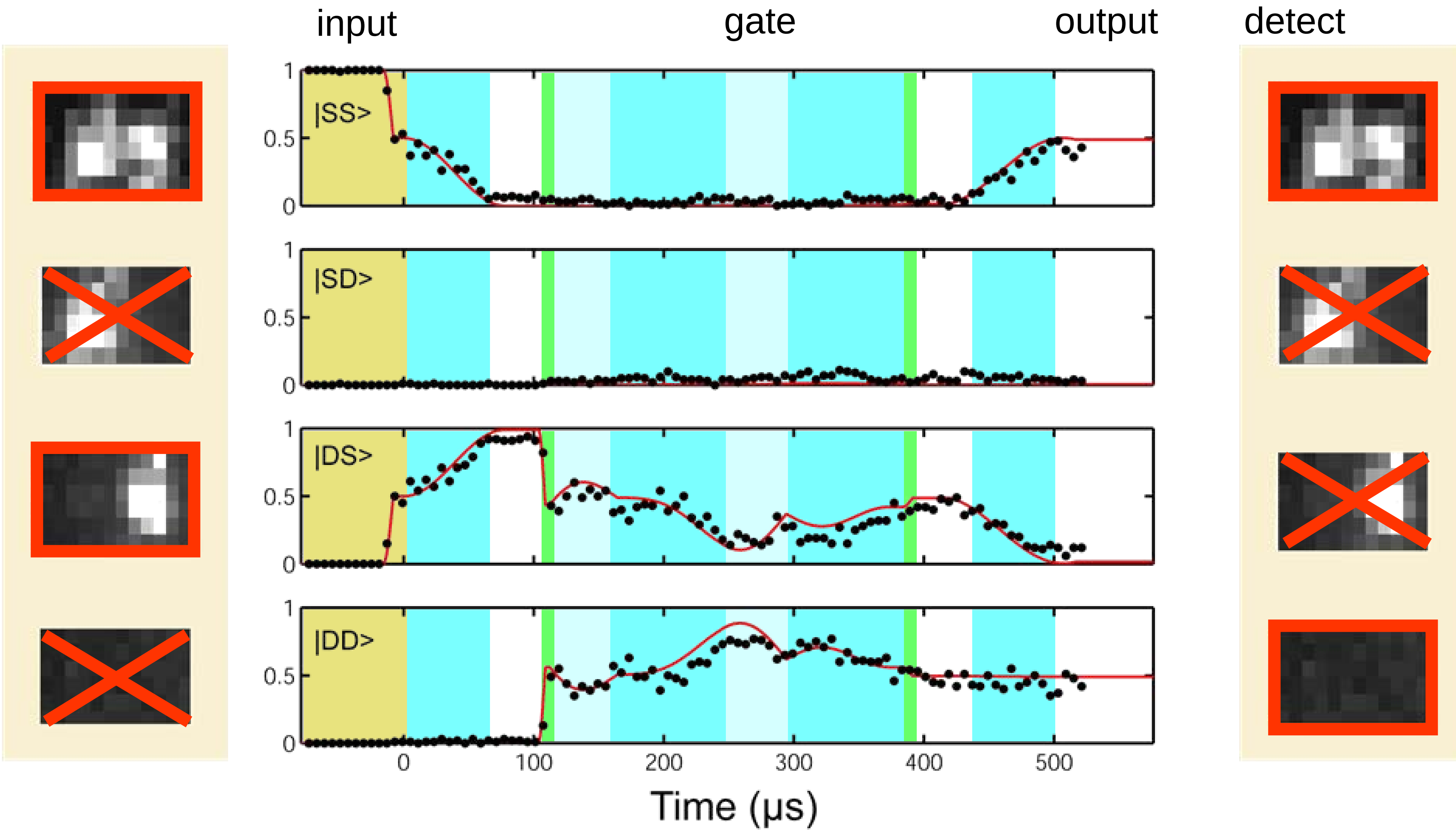
$|SS\rangle$

$|DS\rangle$

$|SD\rangle$

$|DD\rangle$

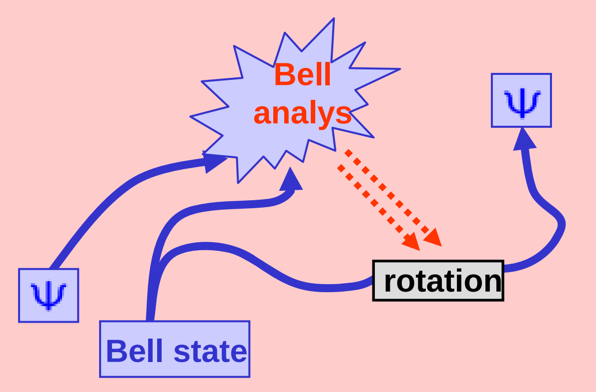
$|S+D,S\rangle \xrightarrow{\text{CNOT}} |SS\rangle + |DD\rangle$

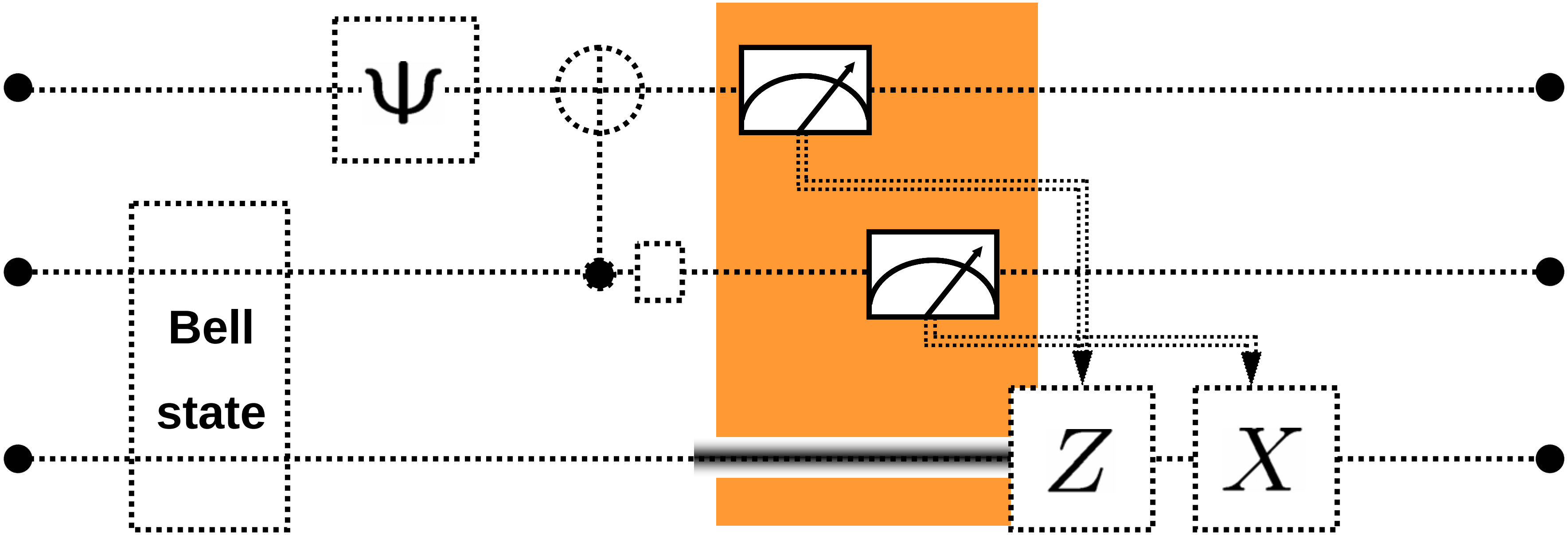


F. Schmidt-Kaler et al., Appl. Phys. B ***77****, 789 (2003)*

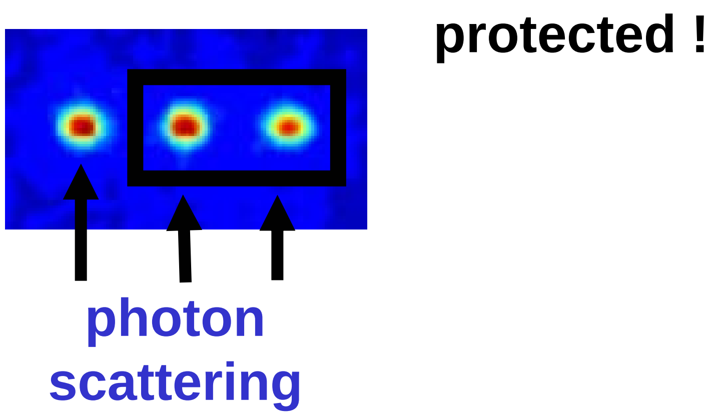
Step by step

1. *Bell state generation*
2. *Generate* Ψ
3. *Bell analysis*
4. ***Selective read-out (and hiding)***

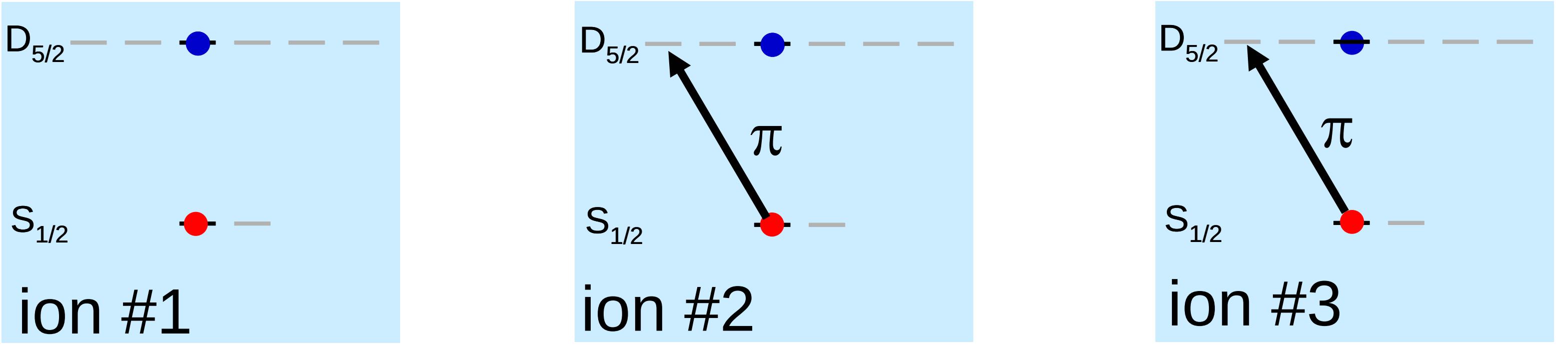




Hiding a qubit

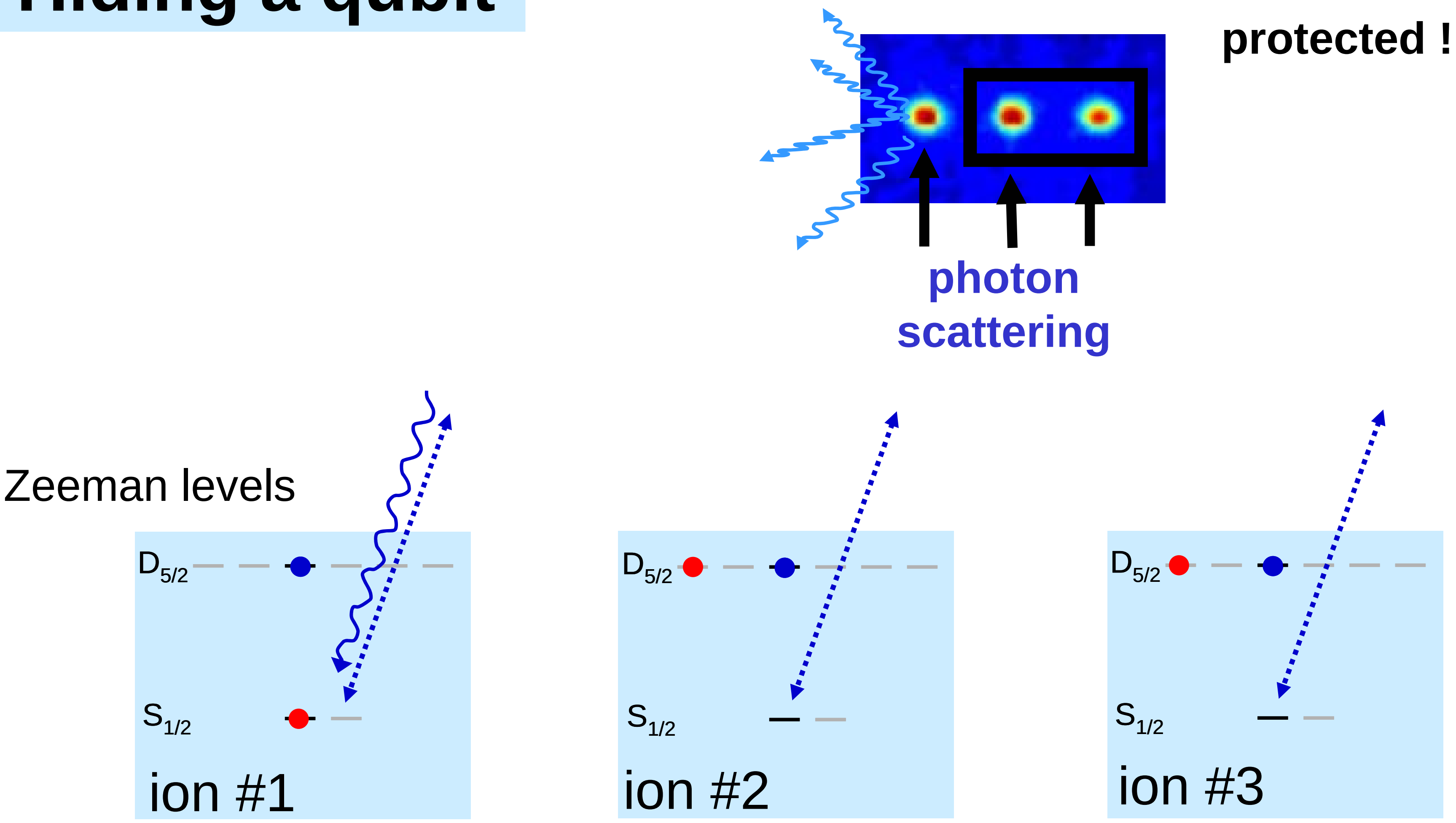


Zeeman levels



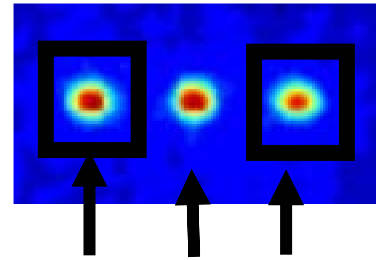
detect quantum state of ion #1 only

Hiding a qubit



detect quantum state of ion #1 only

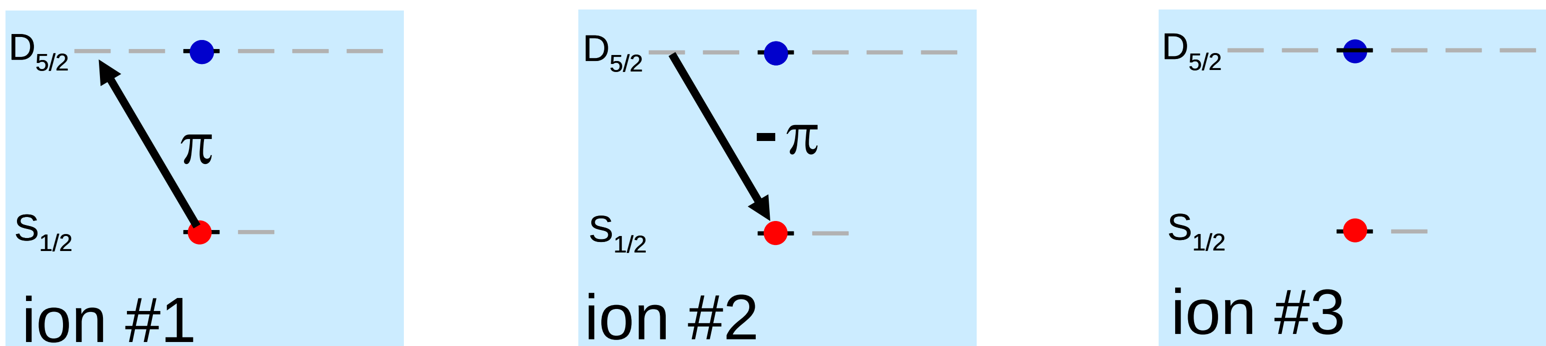
Hiding and unhiding



protected !

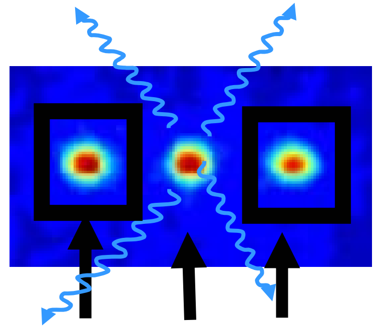
photon scattering

Zeeman levels



detect quantum state of ion #2 only

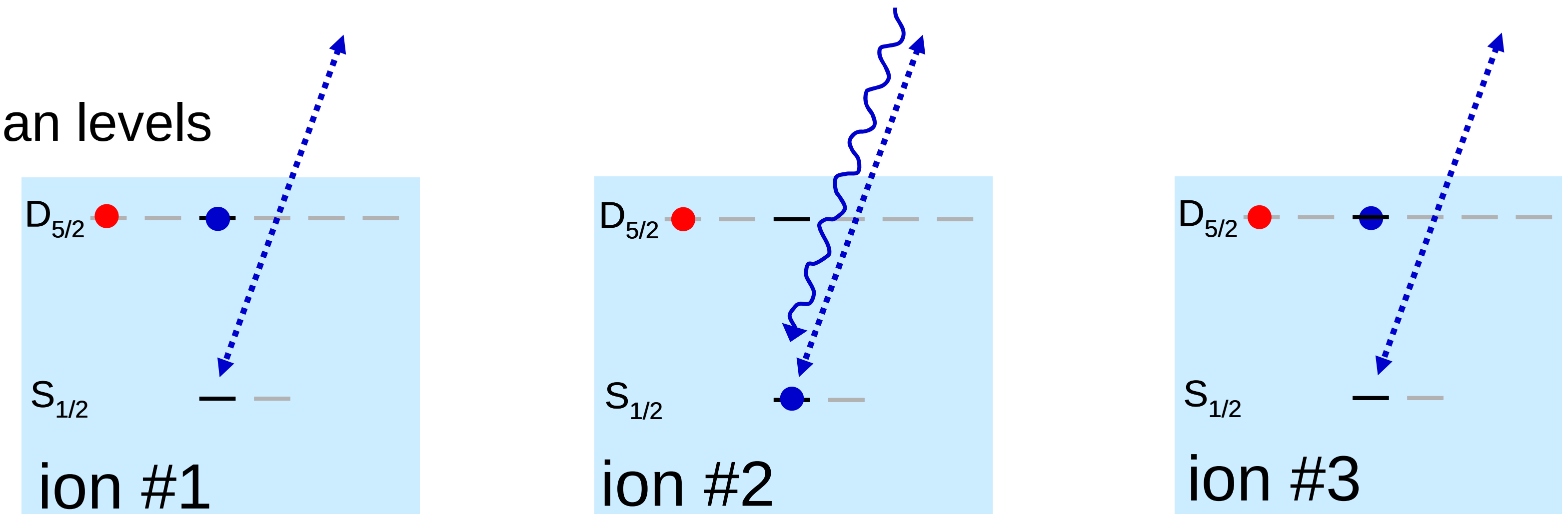
Hiding a qubit



protected !

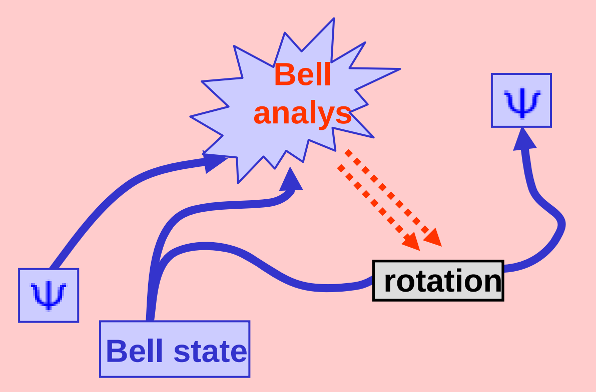
photon scattering

Zeeman levels

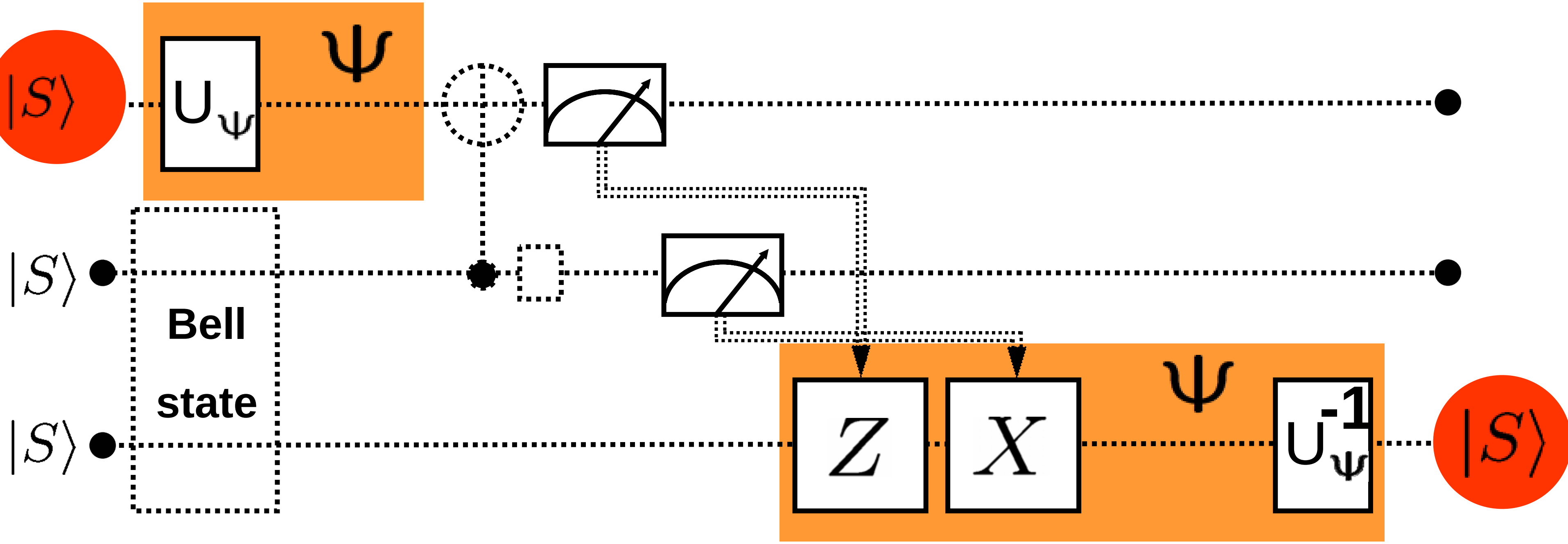


detect quantum state of ion #2 only

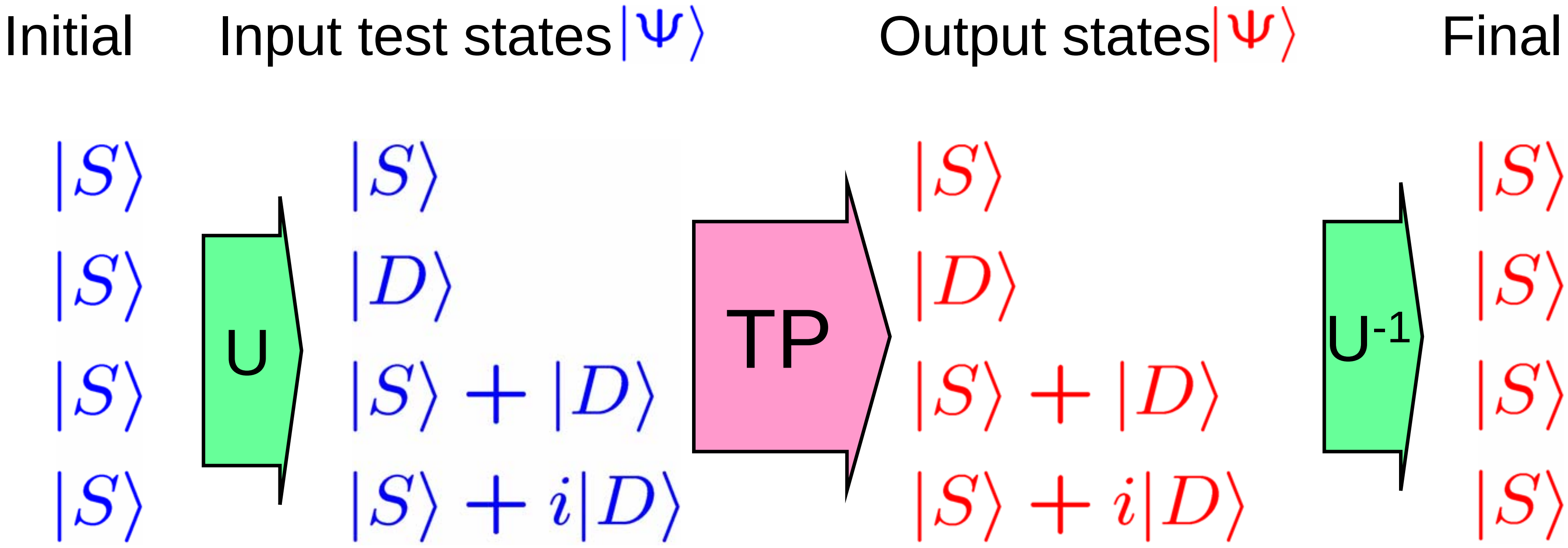
Step by step

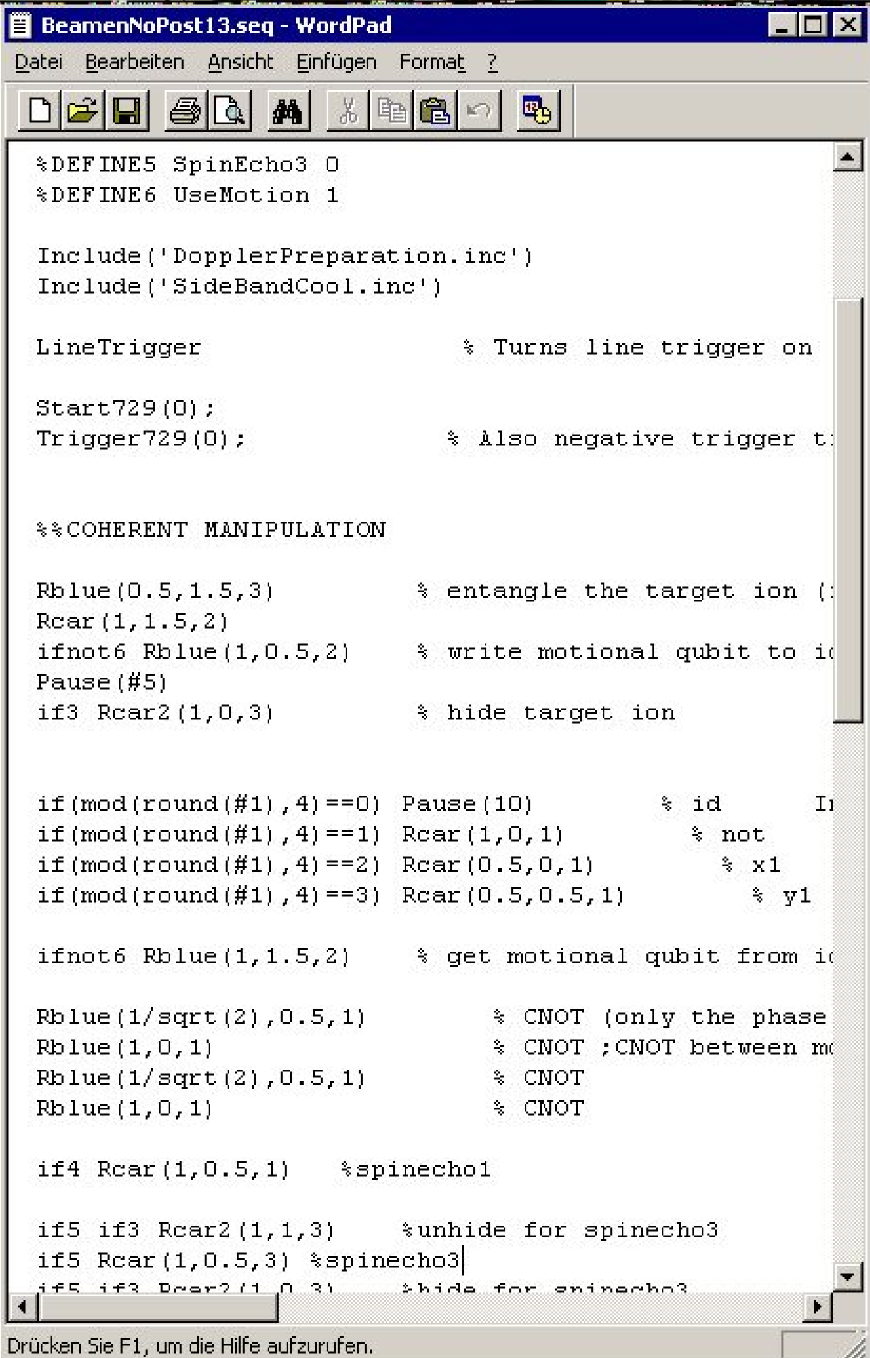
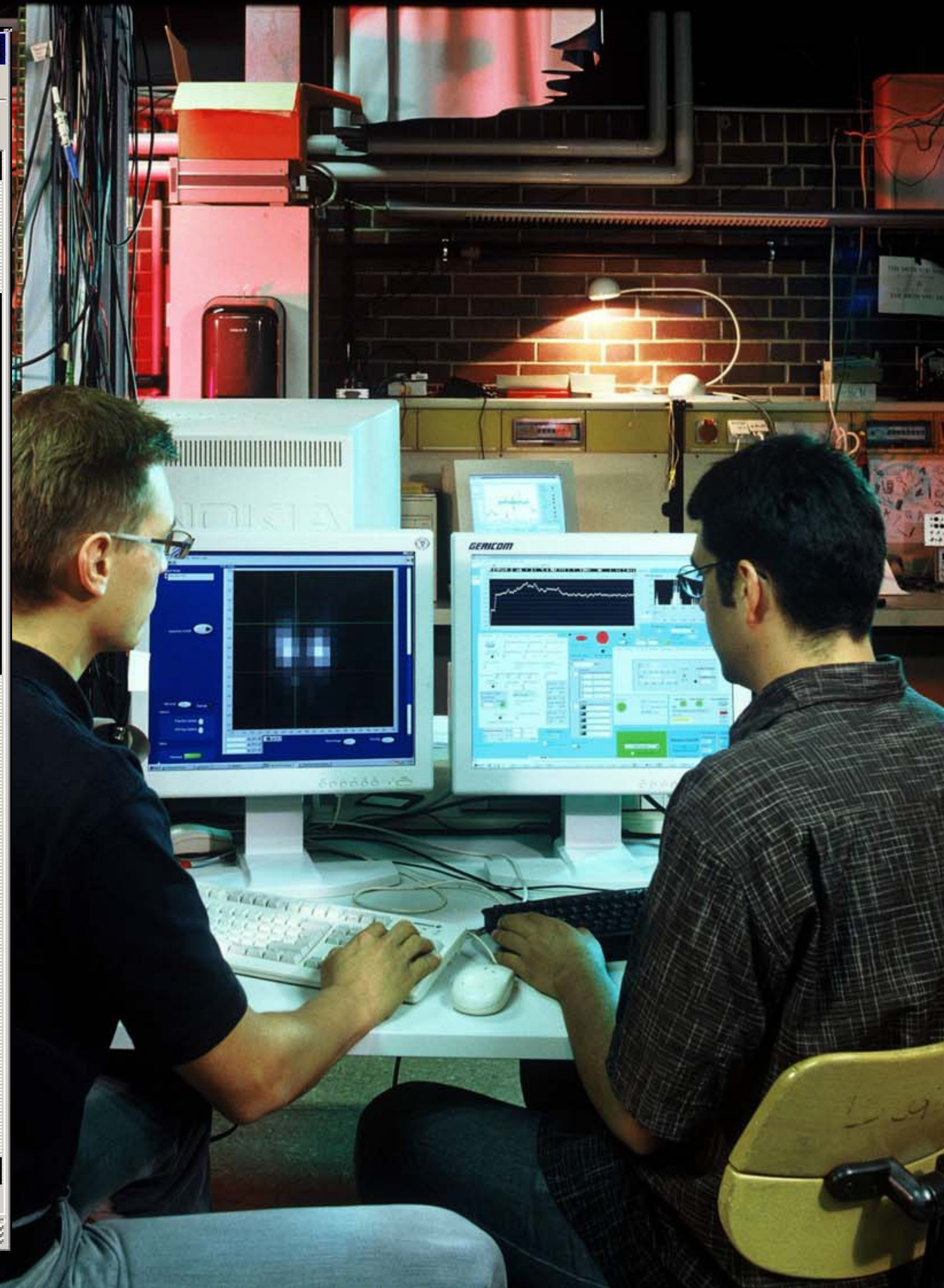


1. *Bell state generation*
2. *Generate* Ψ
3. *Bell analysis*
4. *Selective read-out*
5. ***Conditional rotations***
6. ***Test performance !***

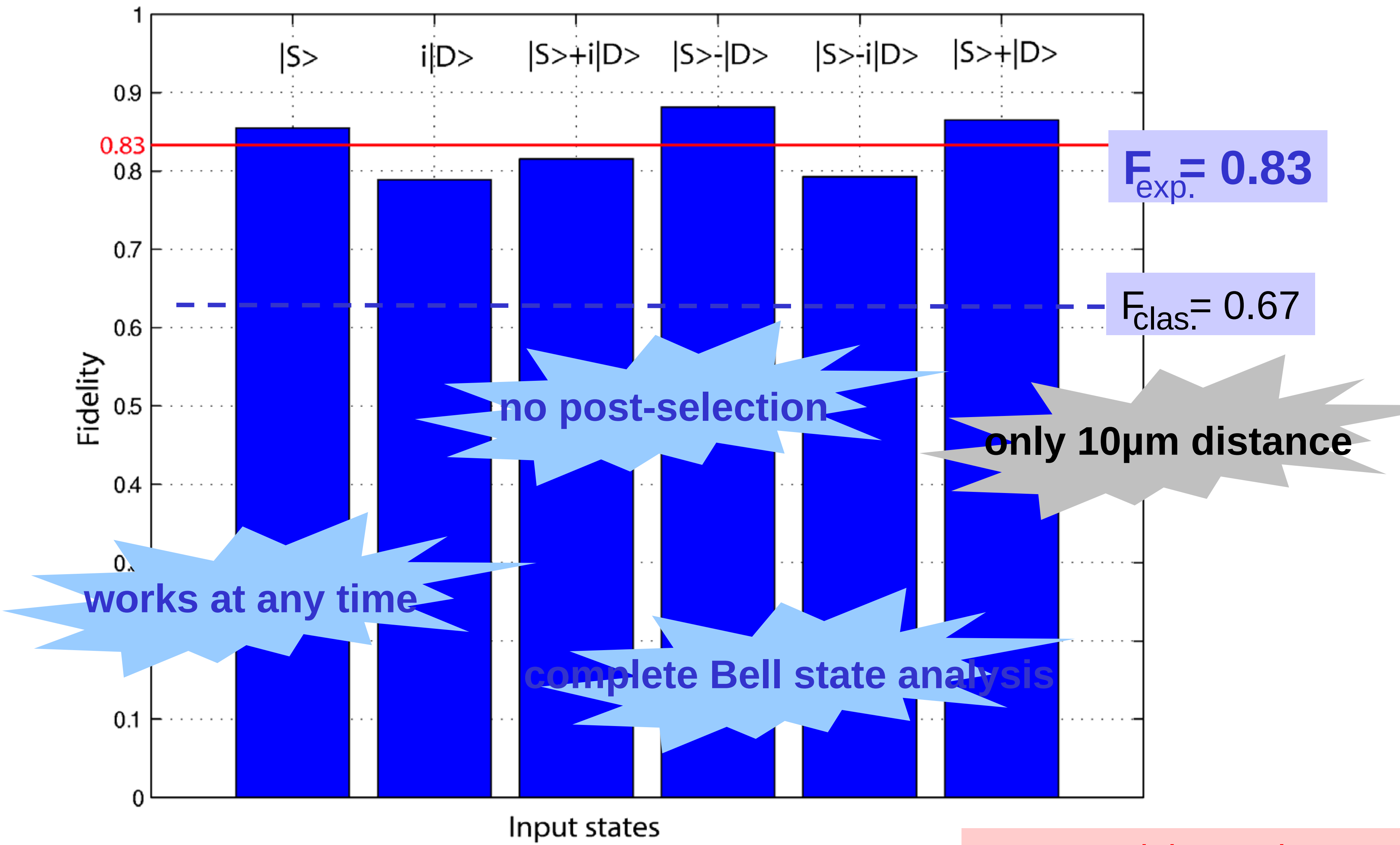


Analysis of teleportation I: Inverse preparation



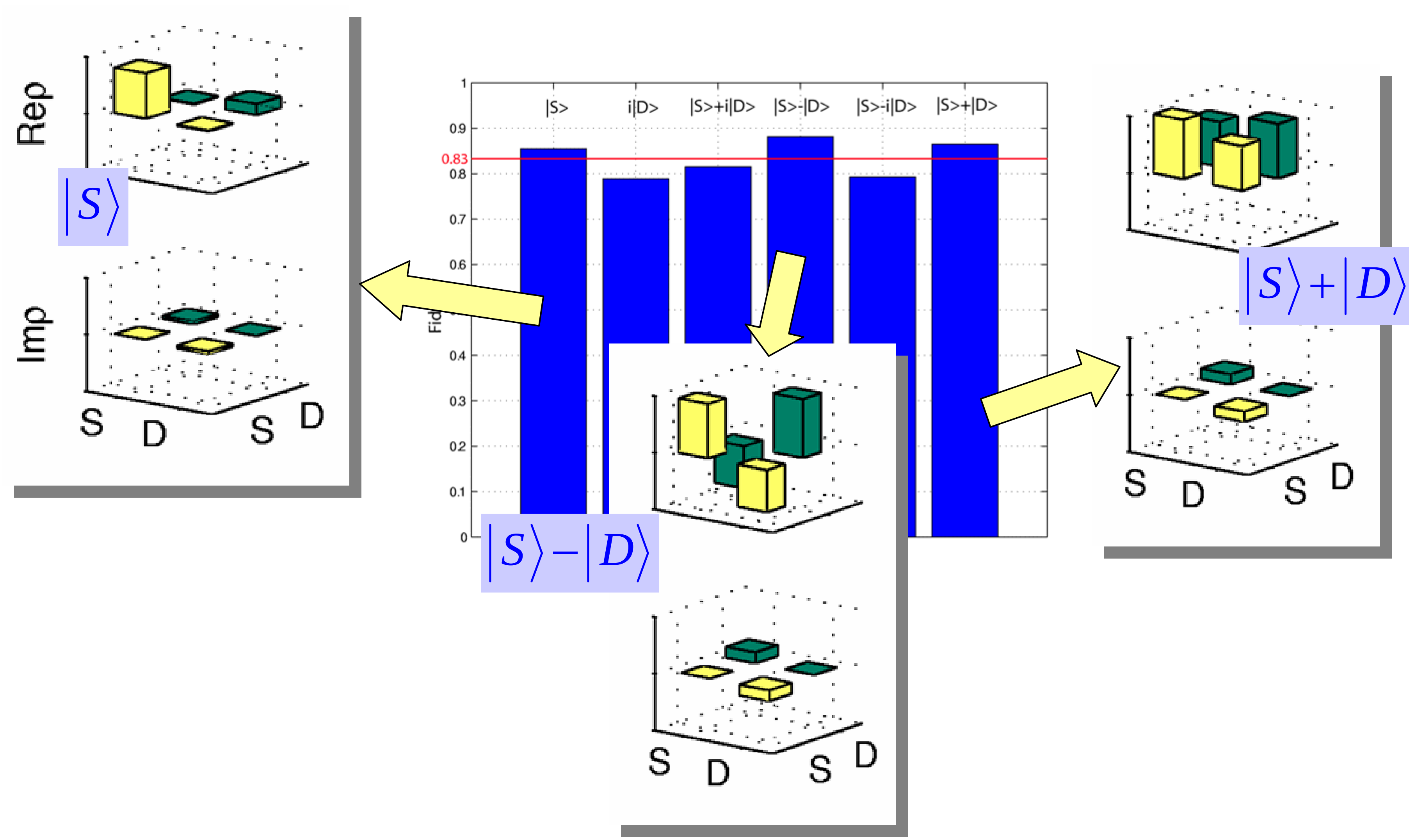

BeamenNoPost13.seq - WordPad
Datei Bearbeiten Ansicht Einfügen Format ?
%DEFINE5 SpinEcho3 0
%DEFINE6 UseMotion 1
Include('DopplerPreparation.inc')
Include('SideBandCool.inc')
LineTrigger % Turns line trigger on
Start729(0);
Trigger729(0); % Also negative trigger t
%%COHERENT MANIPULATION
Rblue(0.5,1.5,3) % entangle the target ion (
Rcar(1,1.5,2)
ifnot6 Rblue(1,0.5,2) % write motional qubit to io
Pause(#5)
if3 Rcar2(1,0,3) % hide target ion
if(mod(round(#1),4)==0) Pause(10) % id I
if(mod(round(#1),4)==1) Rcar(1,0,1) % not
if(mod(round(#1),4)==2) Rcar(0.5,0,1) % x1
if(mod(round(#1),4)==3) Rcar(0.5,0.5,1) % y1
ifnot6 Rblue(1,1.5,2) % get motional qubit from io
Rblue(1/sqrt(2),0.5,1) % CNOT (only the phase
Rblue(1,0,1) % CNOT ;CNOT between mo
Rblue(1/sqrt(2),0.5,1) % CNOT
Rblue(1,0,1) % CNOT
if4 Rcar(1,0.5,1) %spinecho1
if5 if3 Rcar2(1,1,3) %unhide for spinecho3
if5 Rcar(1,0.5,3) %spinecho3
Drücken Sie F1, um die Hilfe aufzurufen.


Teleportation „on demand“ : Results

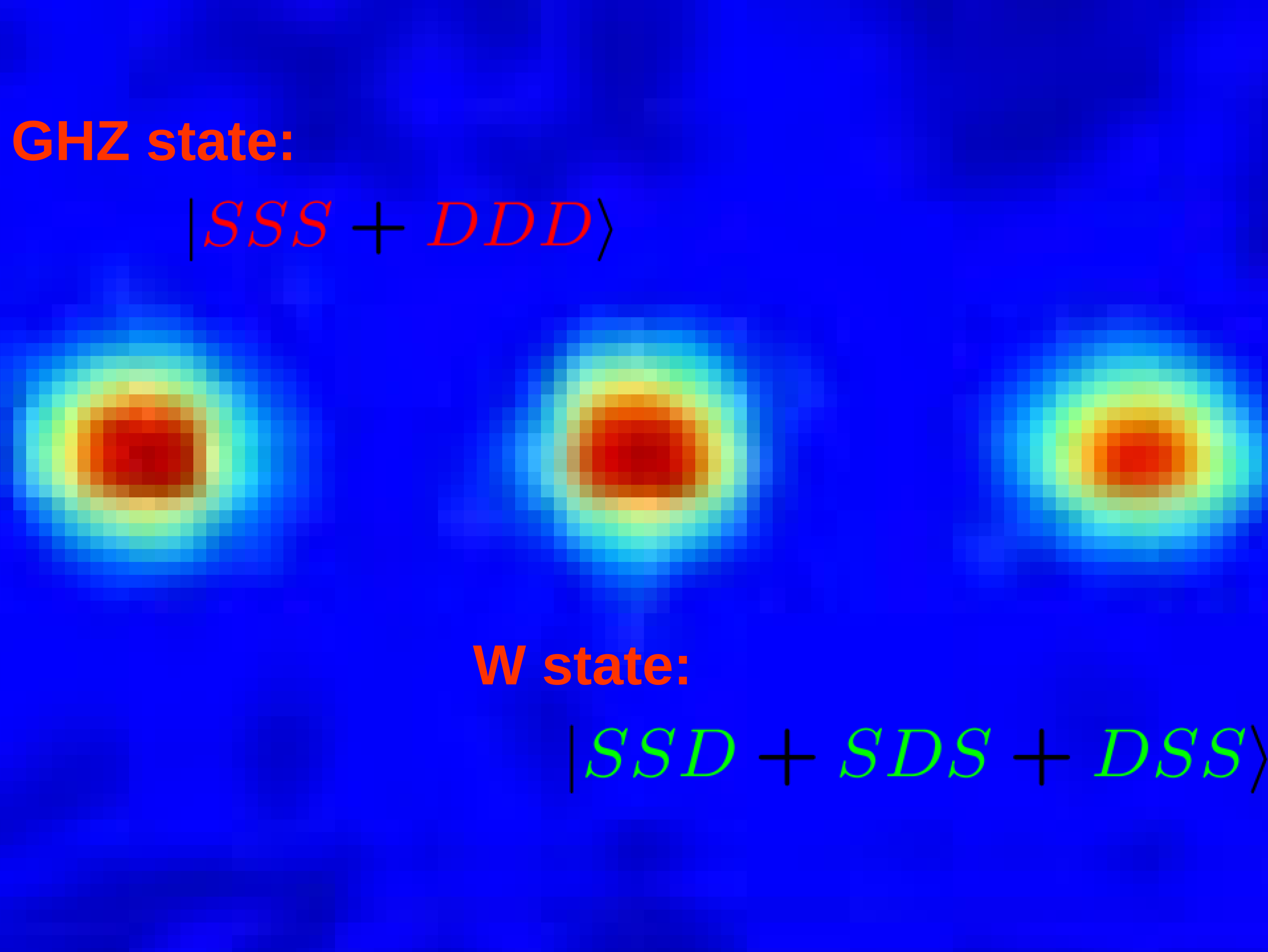


M. Riebe et al., Nature ***429****, 734 (2004)*

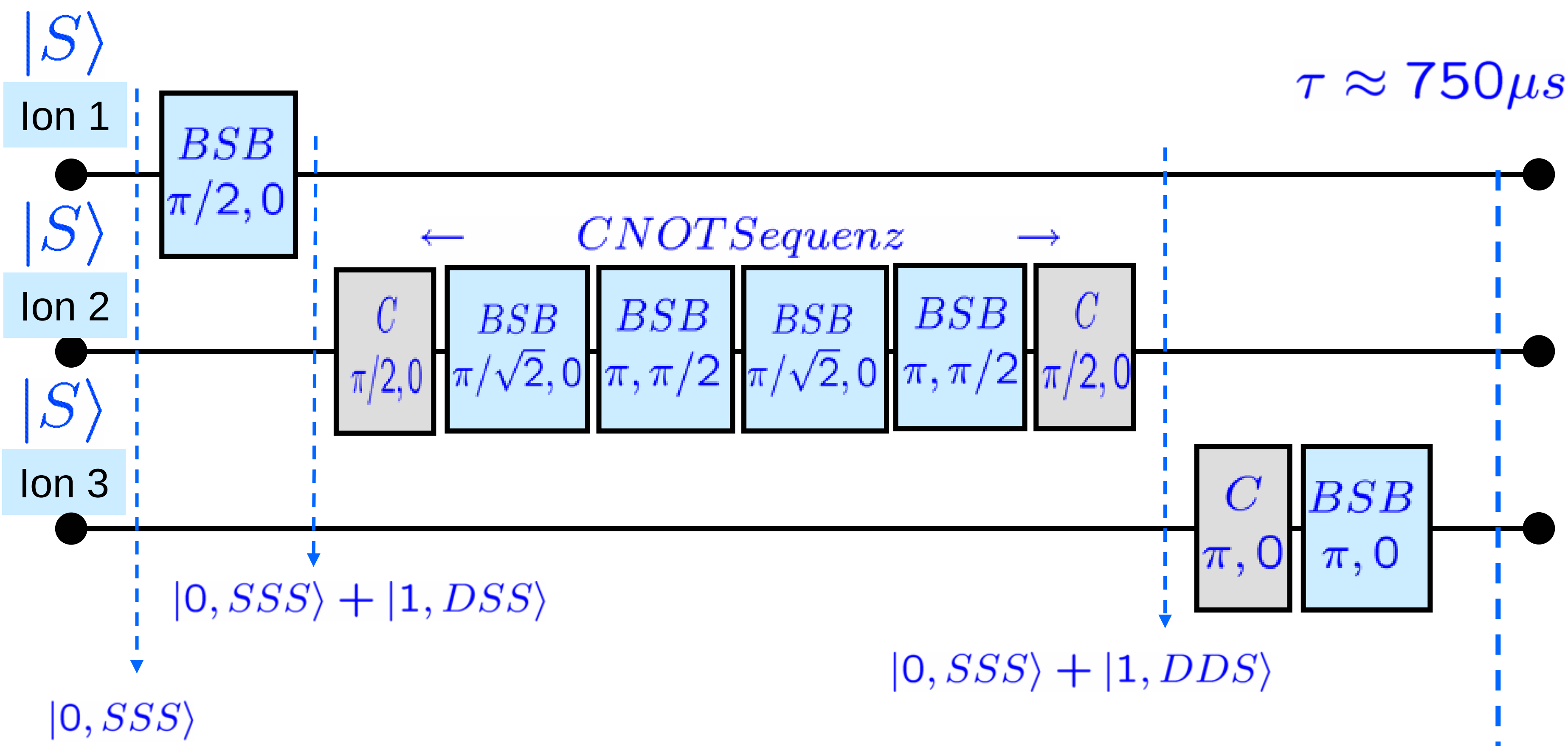
Analysis of teleportation II: Process tomography



GHZ und W Zustände


GHZ state:
$|SSS + DDD\rangle$
W state:
$|SSD + SDS + DSS\rangle$

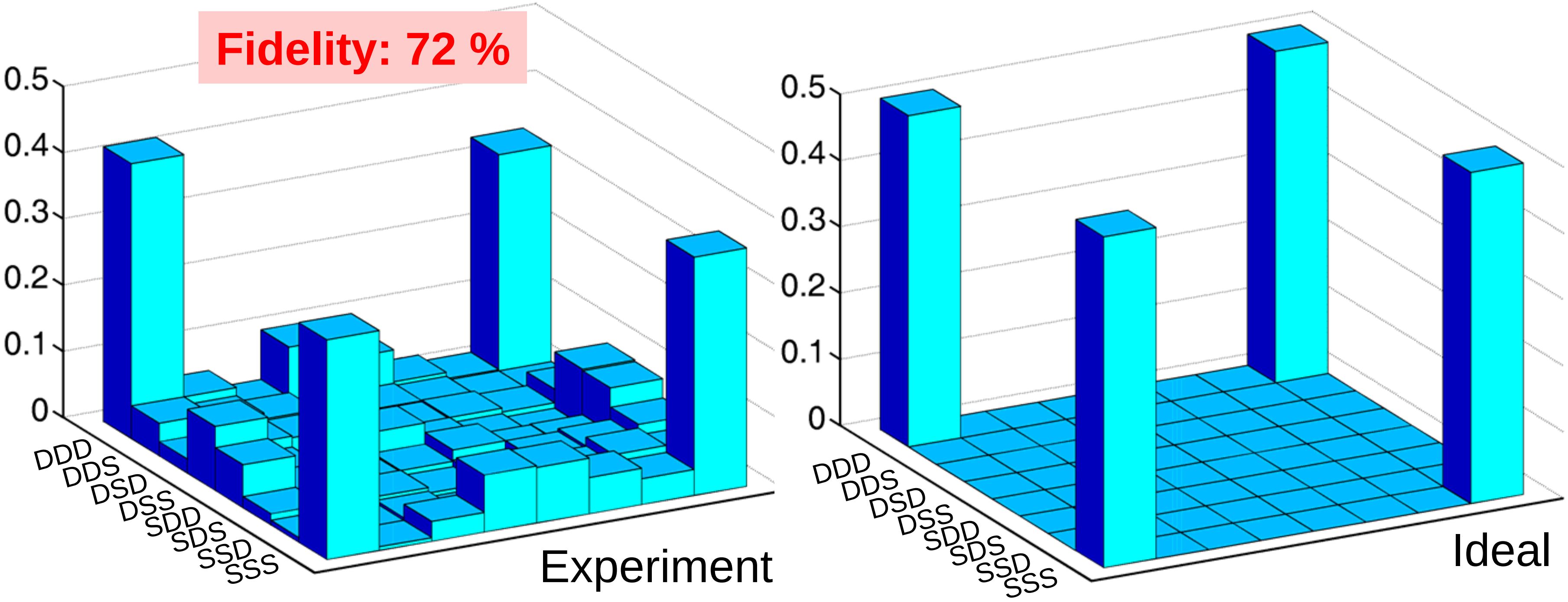
Deterministic generation of GHZ state



$$|\Psi\rangle_{GHZ} = \frac{1}{\sqrt{2}}(|DDD\rangle + |SSS\rangle)|0\rangle$$

Tomography of the GHZ state

$$|\Psi\rangle_{GHZ} = \frac{1}{\sqrt{2}}(|SSS\rangle - |DDD\rangle)$$

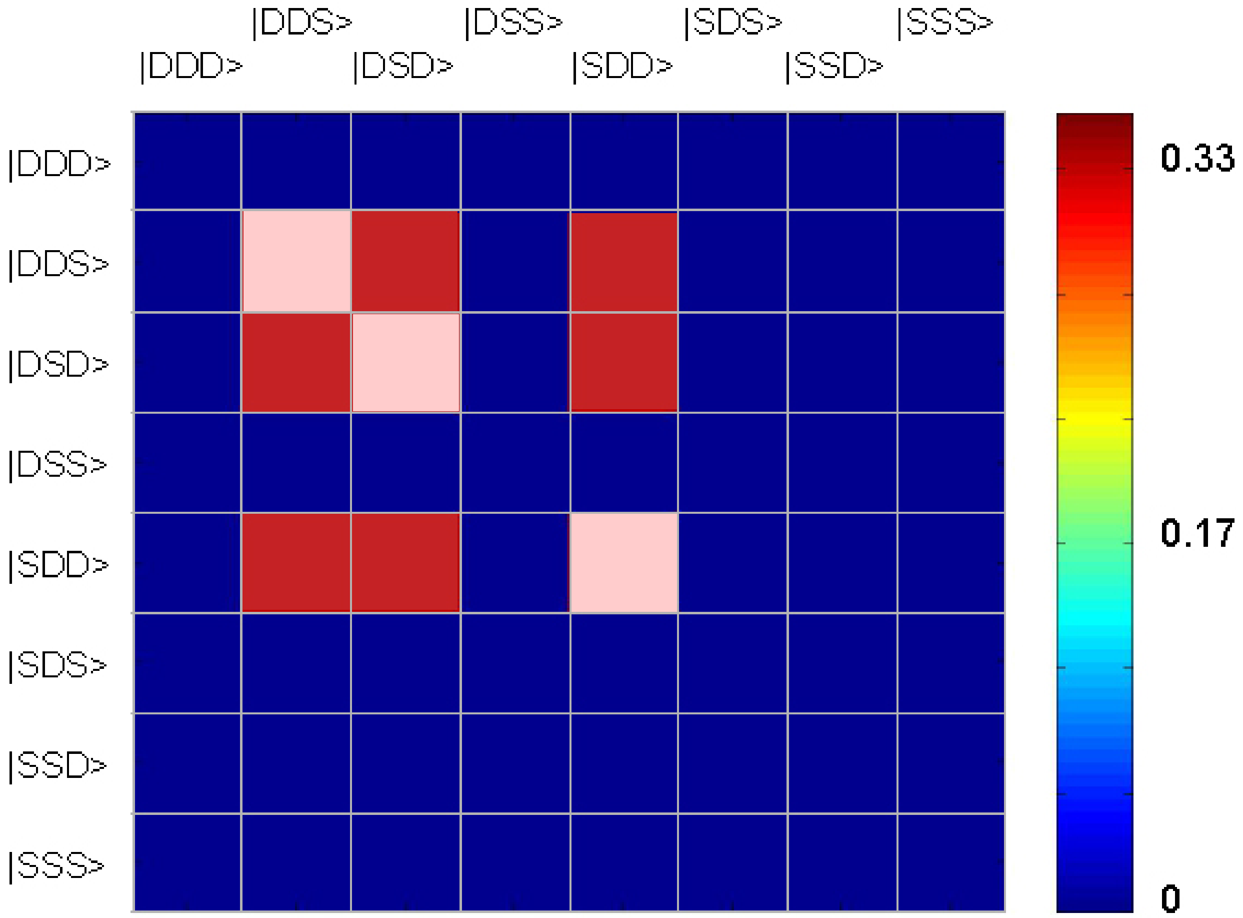


$\mathrm{Abs}(\rho_{\exp})$

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

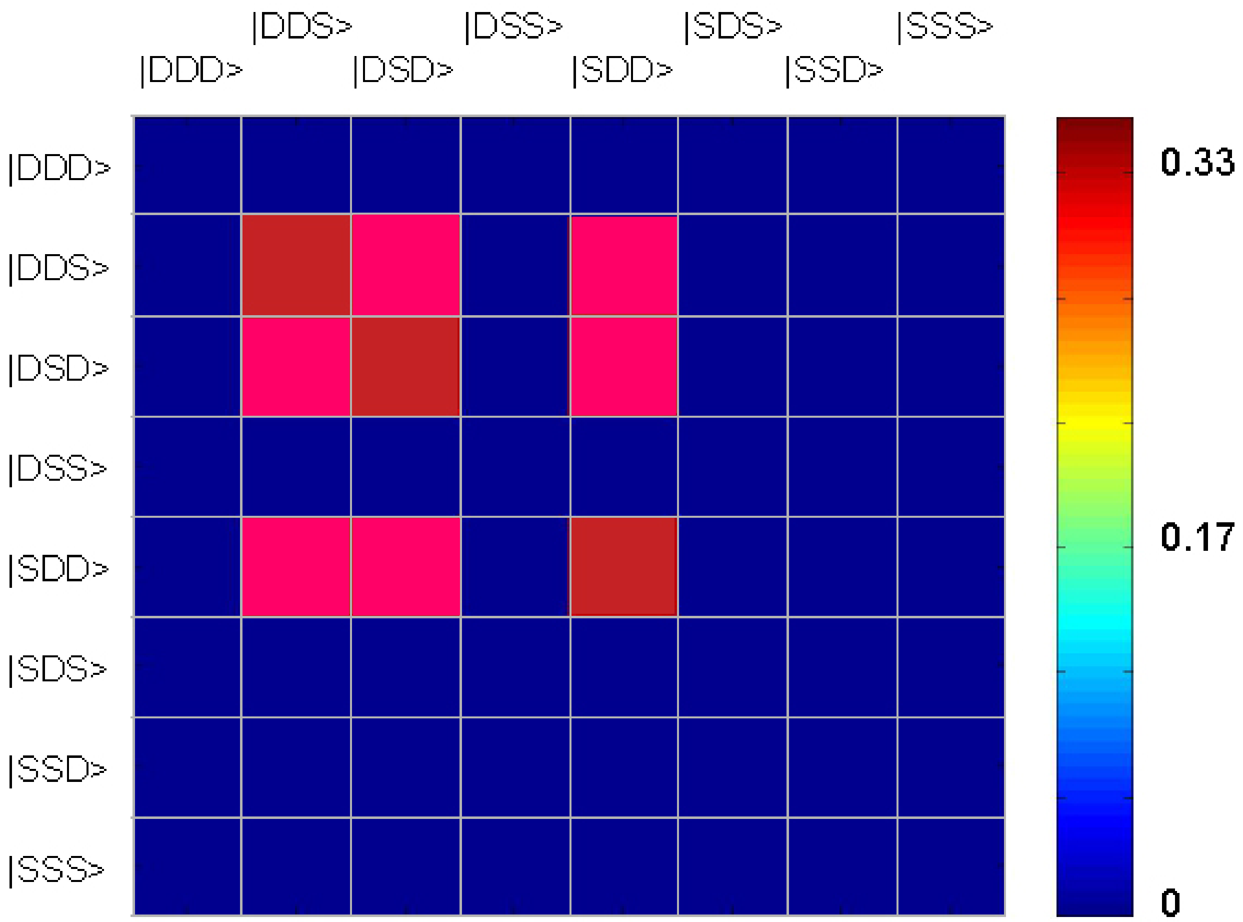
W state: |SDD> + |DSD> + |DDS>

ideal 3-ion density matrix

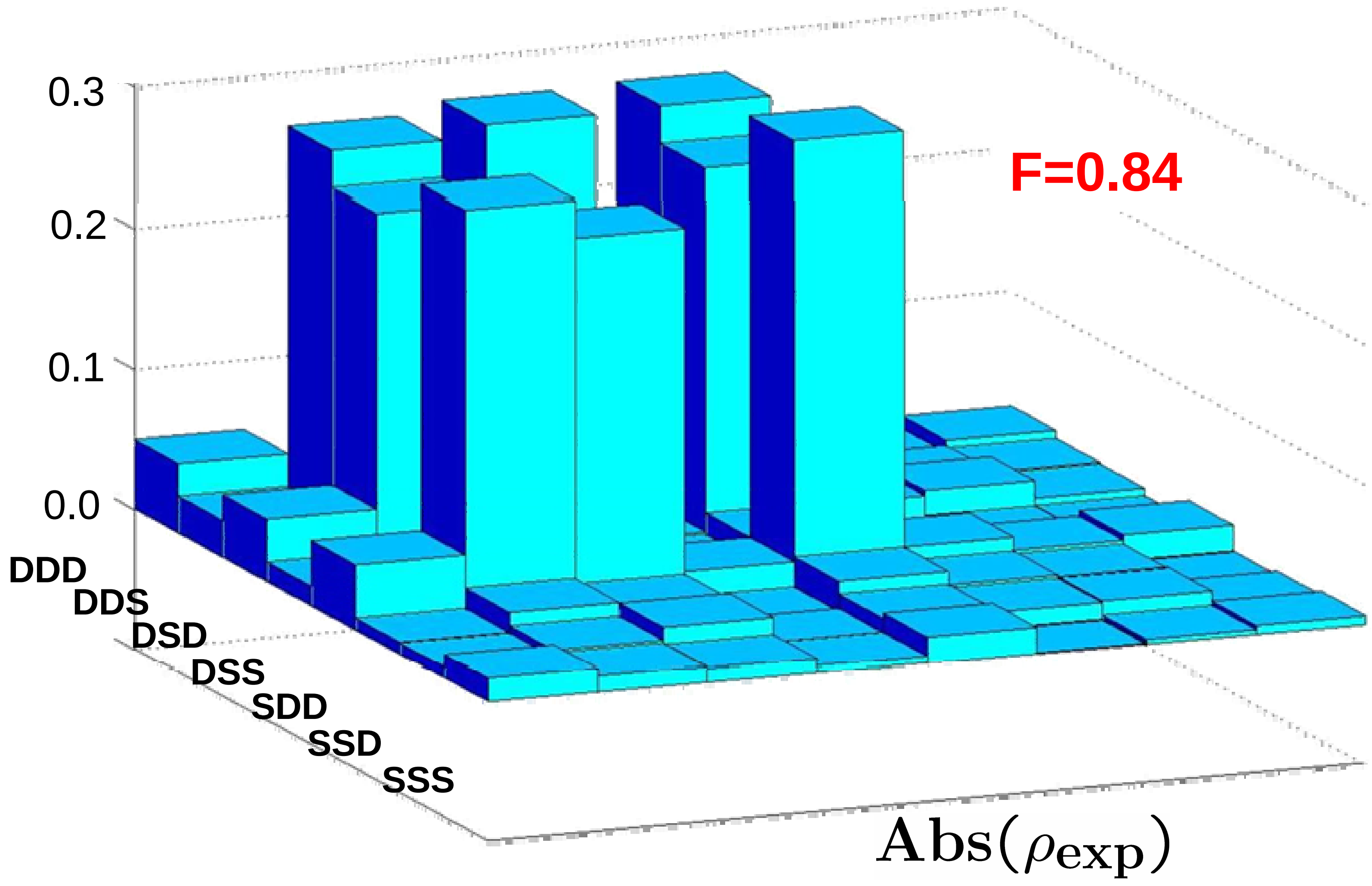


W state: |SDD> + |DSD> + |DDS>

ideal 3-ion density matrix



|SDD> - |DSD> - |DDS>



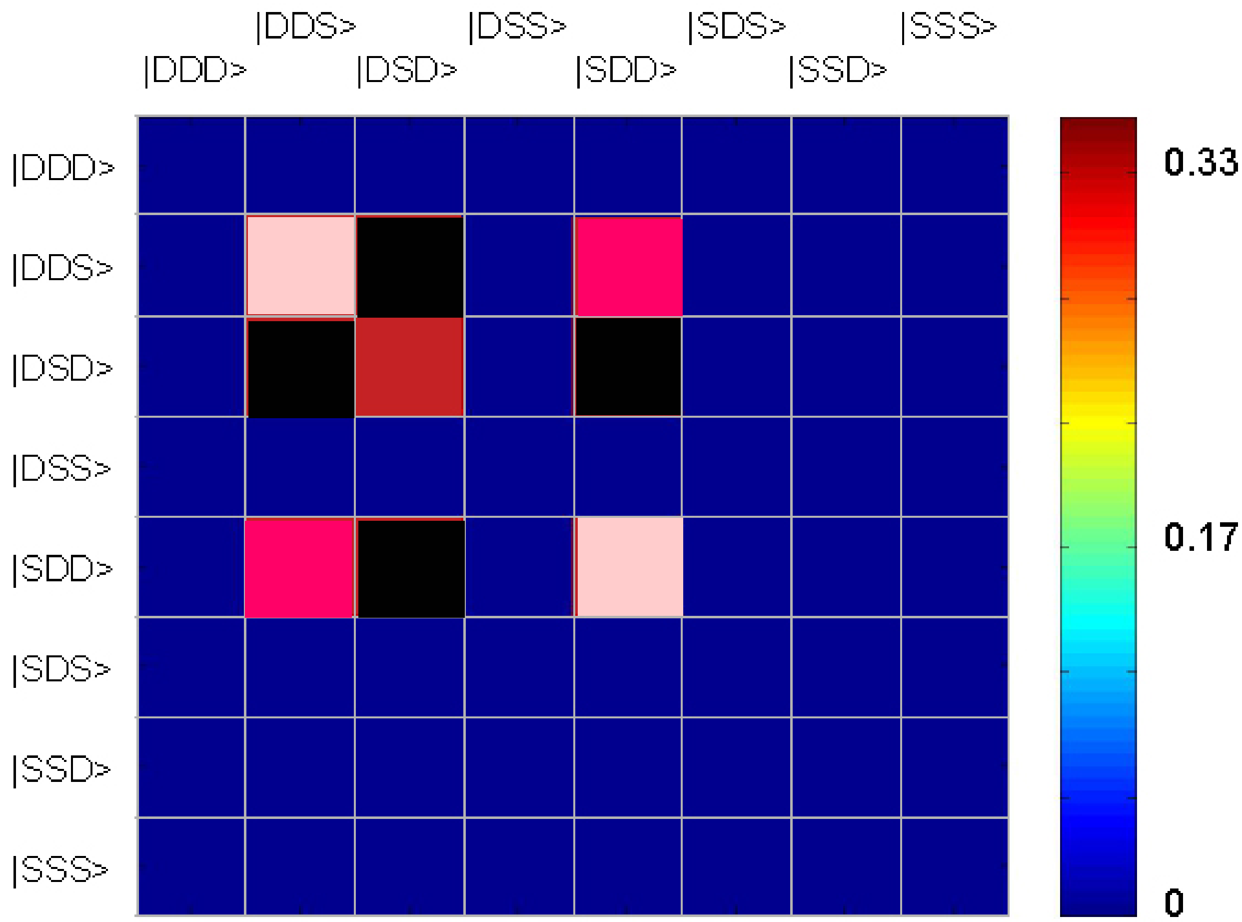
0.3
0.2
0.1
0.0
DDD
DDS
DSD
DSS
SDD
SSD
SSS
F=0.84
$\mathrm{Abs}(\rho_{\mathrm{exp}})$

W state: |SDD> + |DSD> + |DDS>

measure

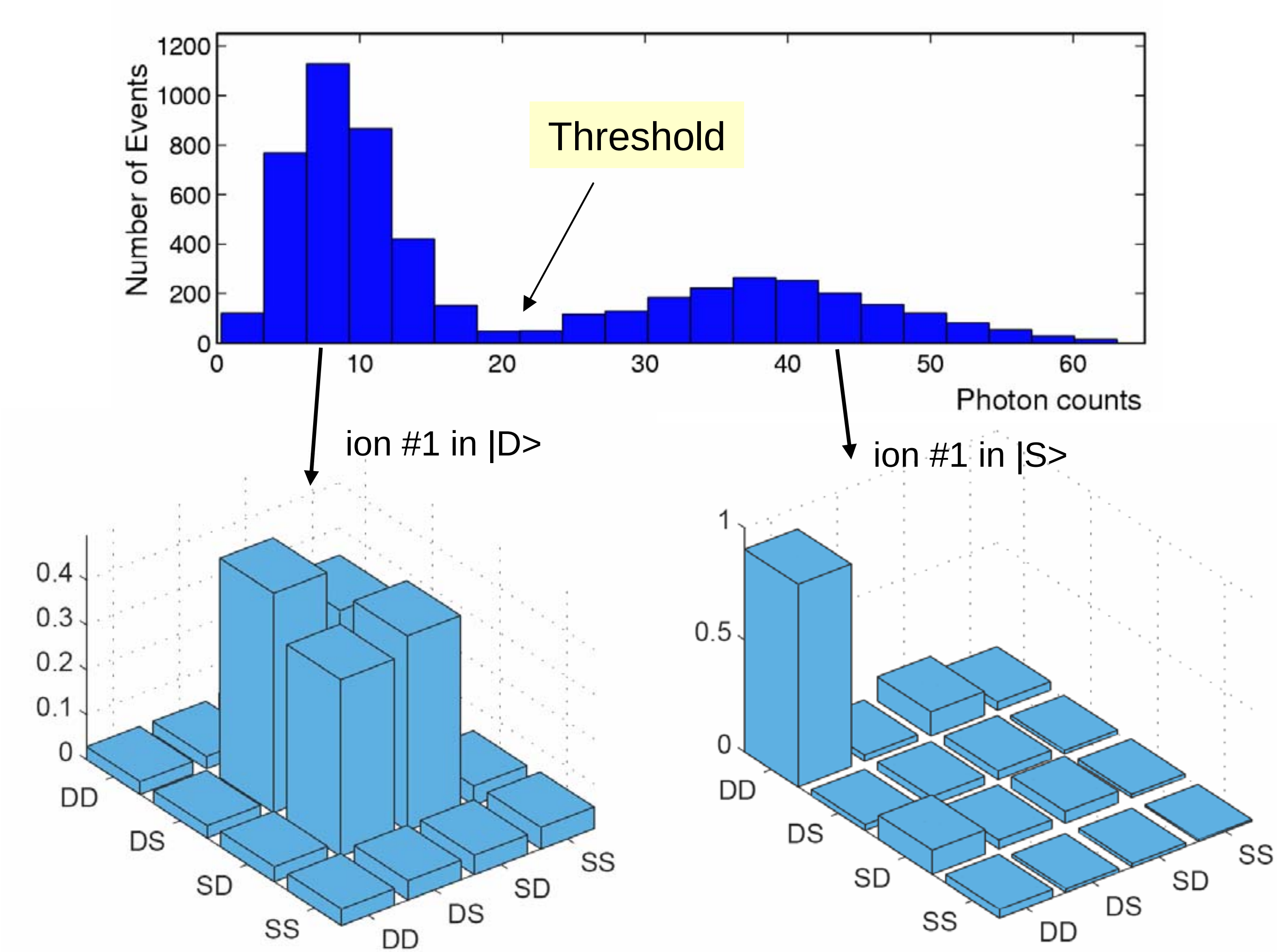
measure only
the middle ion in D

Bell state
SD+DS



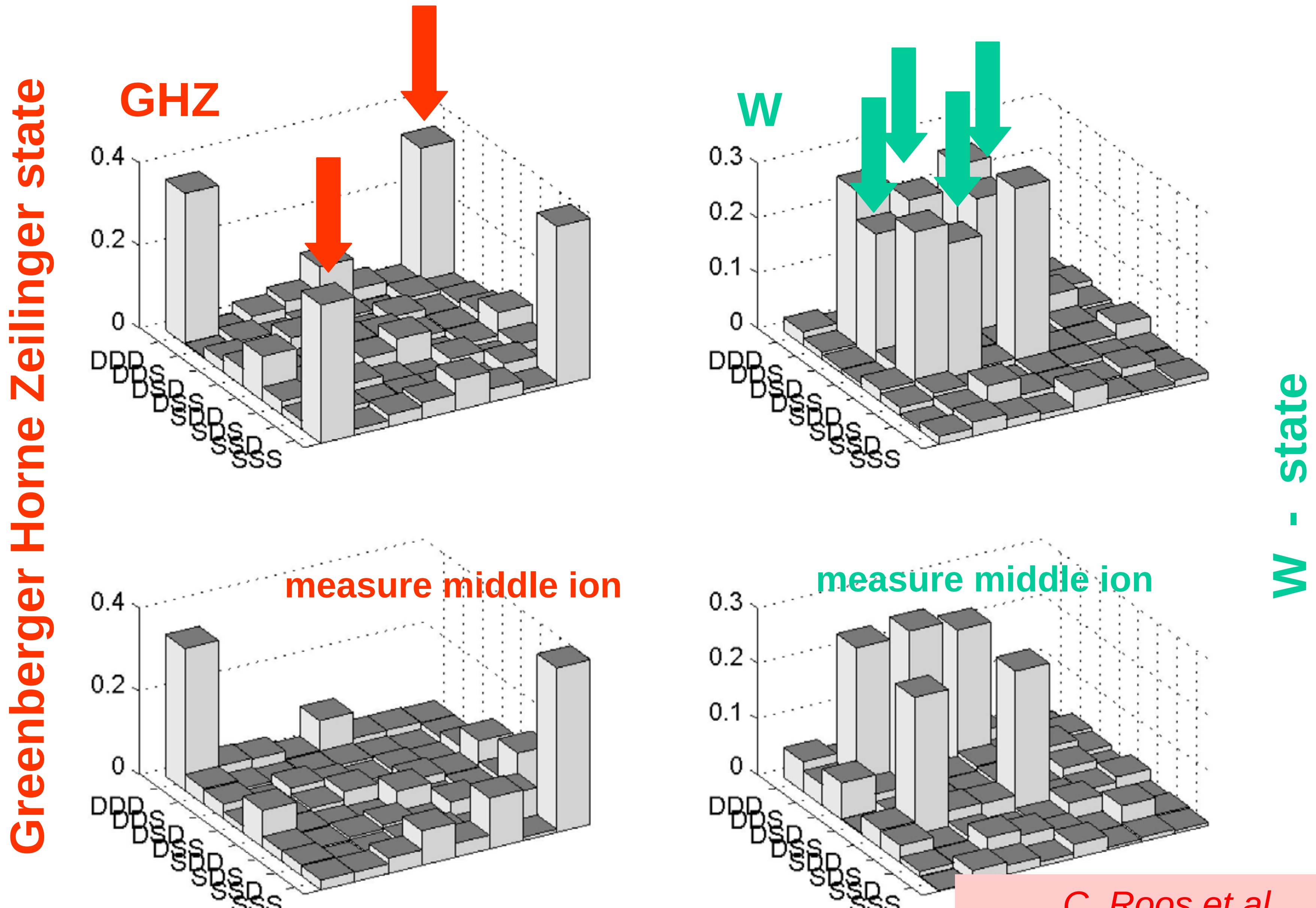
Selective measurment

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



Tomography **after** the measurement result is available!

Selectivly projected 3-ion entanglement



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

selective read-out in rotated basis

$$|\Psi\rangle_{GHZ} = \frac{1}{\sqrt{2}}(|SDS\rangle - |DSD\rangle)$$

rotate qubit #1 by $\pi/2$

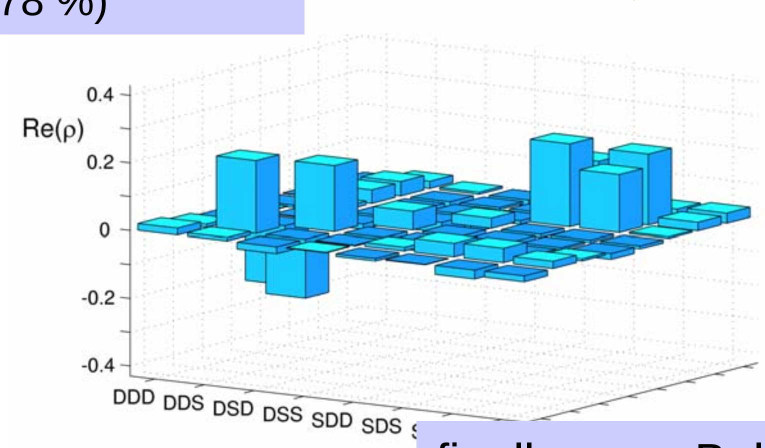
quantum algorithm includes decisions

$$\rightarrow \frac{1}{\sqrt{2}}(|(S+D)DS\rangle - |(D-S)SD\rangle) = \frac{1}{\sqrt{2}}(|SDS\rangle + |DDS\rangle - |DSD\rangle + |SSD\rangle)$$

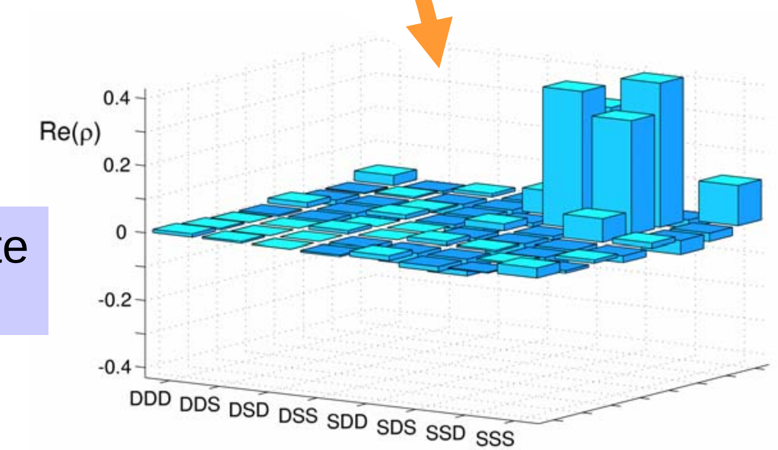
$$\rightarrow \{(|DS\rangle - |SD\rangle), (|DS\rangle + |SD\rangle)\}$$

measure Ion #1

mixture of two Bell states
(Fidelity: 78 %)



depending on the outcome „|D>$_1$“:
π–pulse on ion #1 and Z-rotation on ion #3



finally: pure Bell state
(Fidelity: 77 %)

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