Cold Ions and their Applications for Quantum Computing and Frequency Standards

universität ulm

- Trapping Ions
- Cooling Ions
- Superposition and Entanglement
- Quantum computer: basics, gates, algorithms, future challenges
- Ion clocks: from Ramsey spectroscopy to quantum techniques

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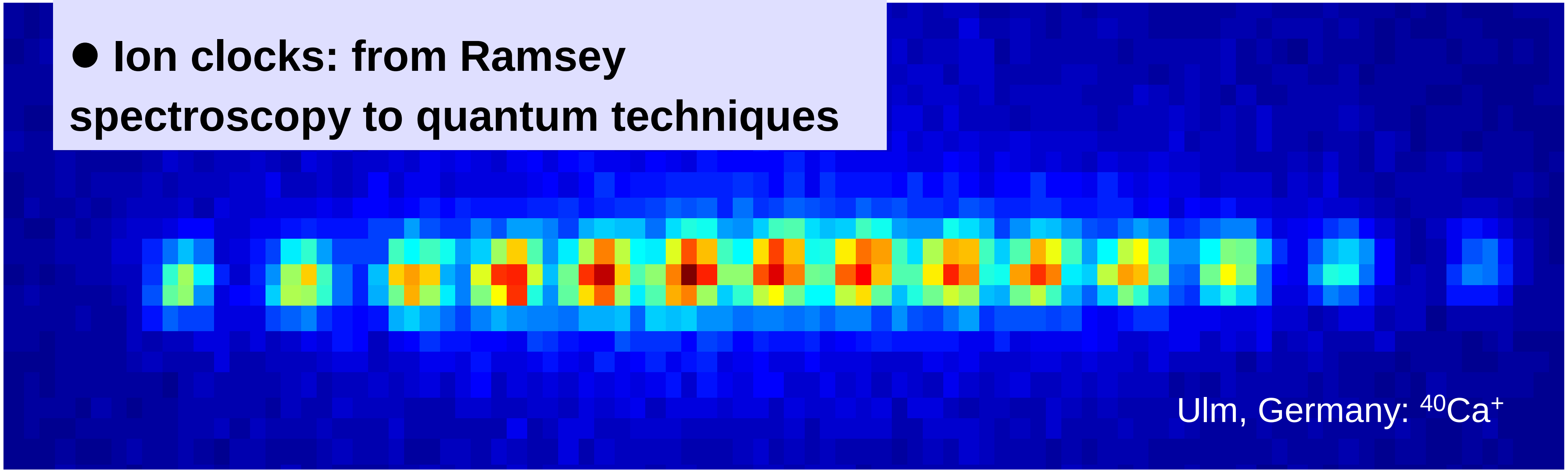
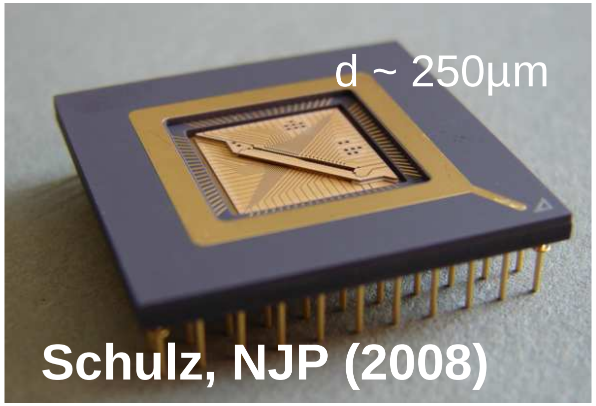
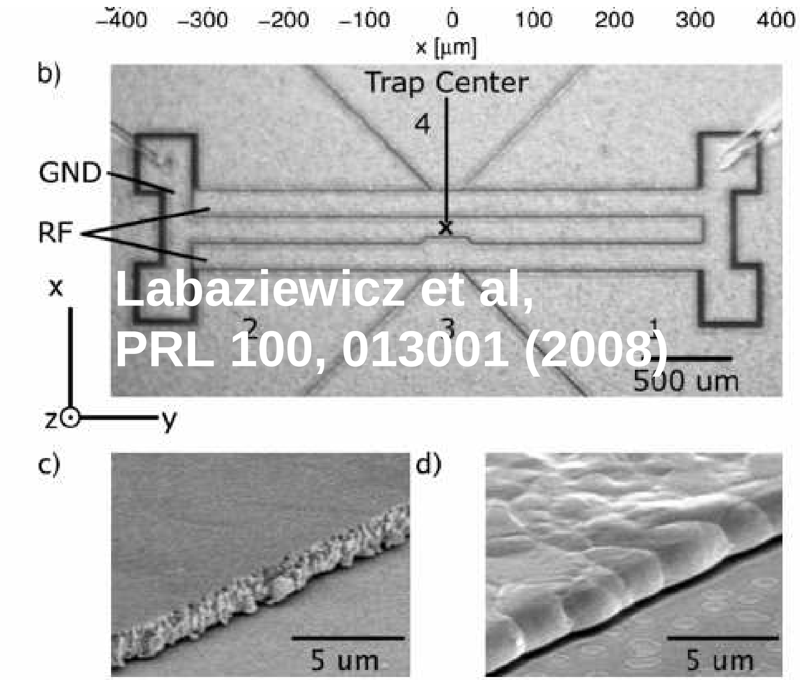
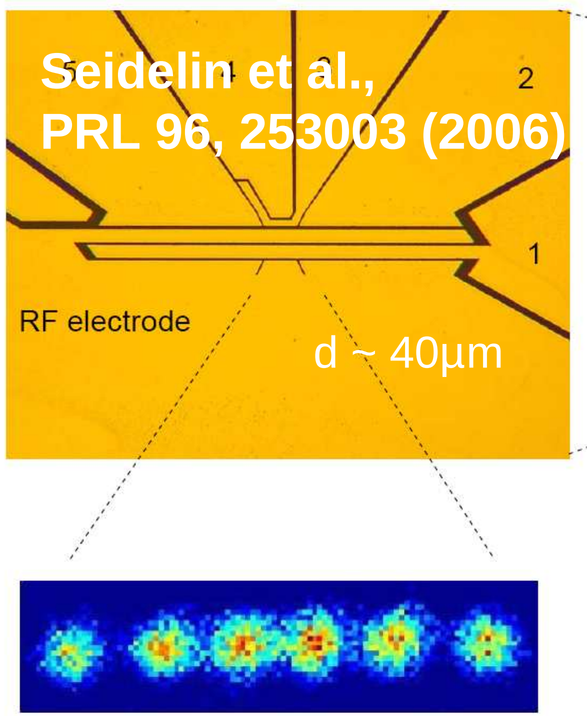


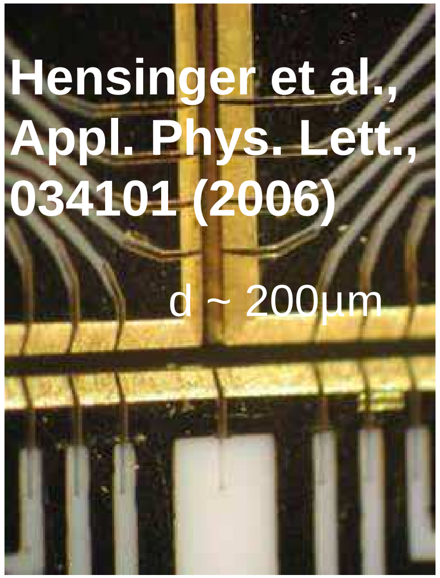
Micro ion traps

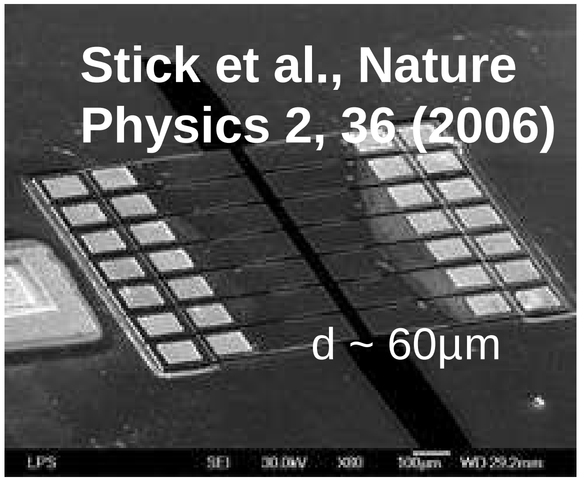
Kielpinski et al, Nature 417, 709 (2002)

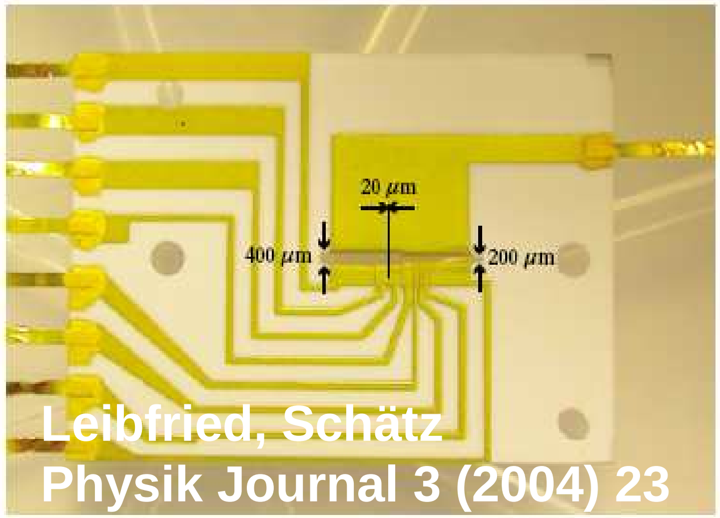




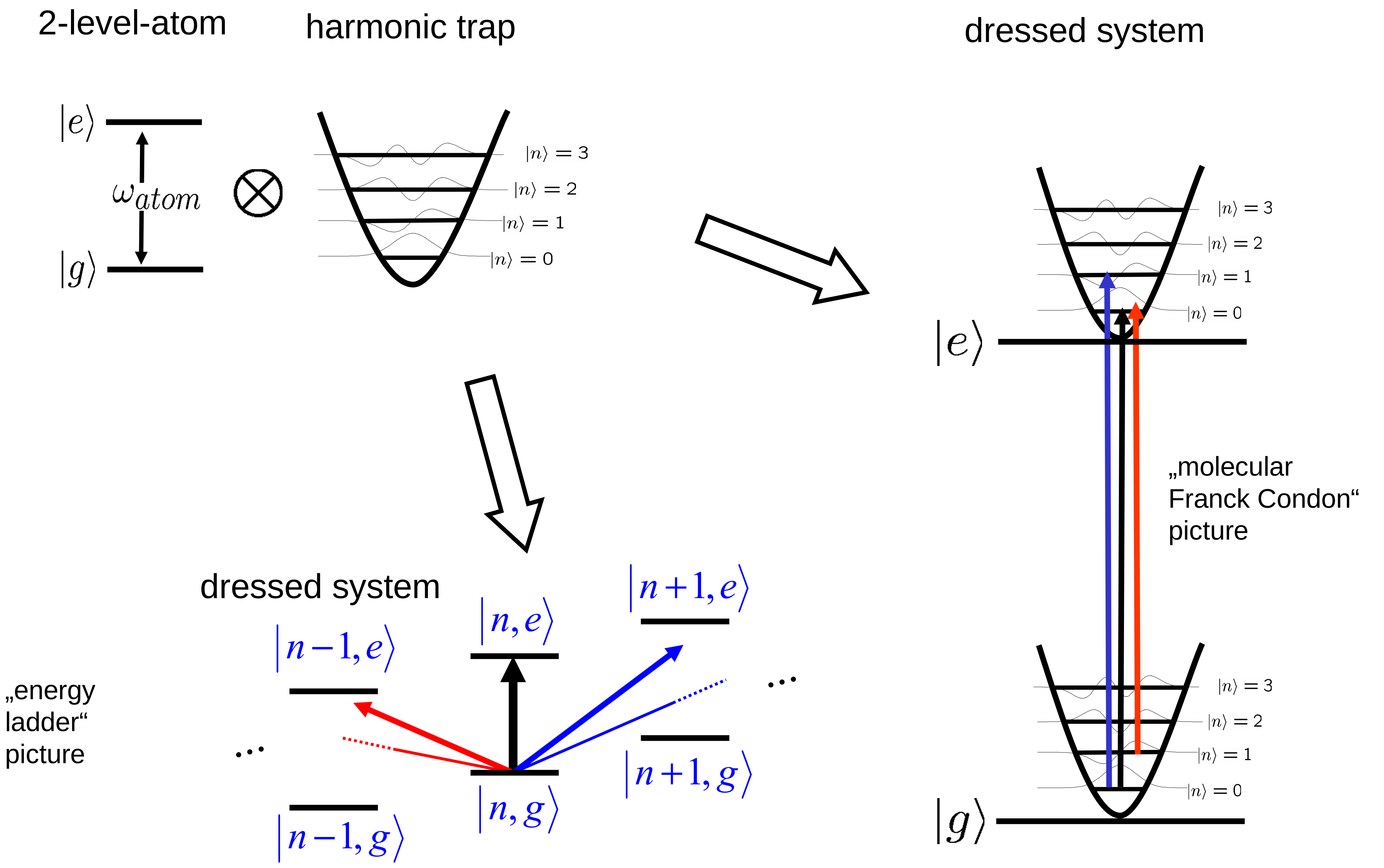








Laser – Ion coupling



Experiments: Resolved sideband spectroscopy

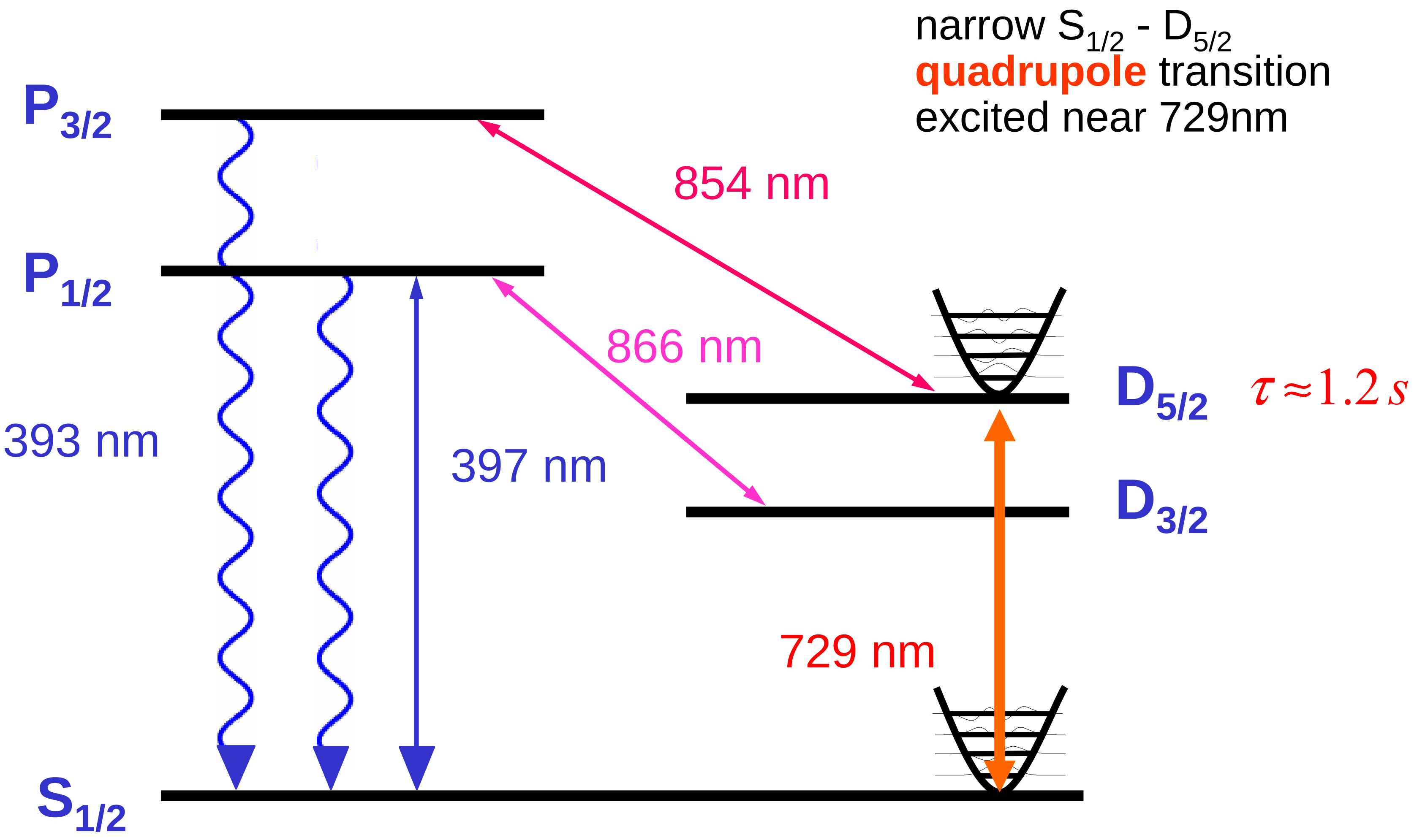
Select narrow optical transition with: $\omega_{trap} >> \gamma$

a) Quadrupole transition
b) Raman transition between Hyperfine ground states
c) Raman transition between Zeeman ground states
d) Octopole transition
e) Intercombination line
f) RF transition

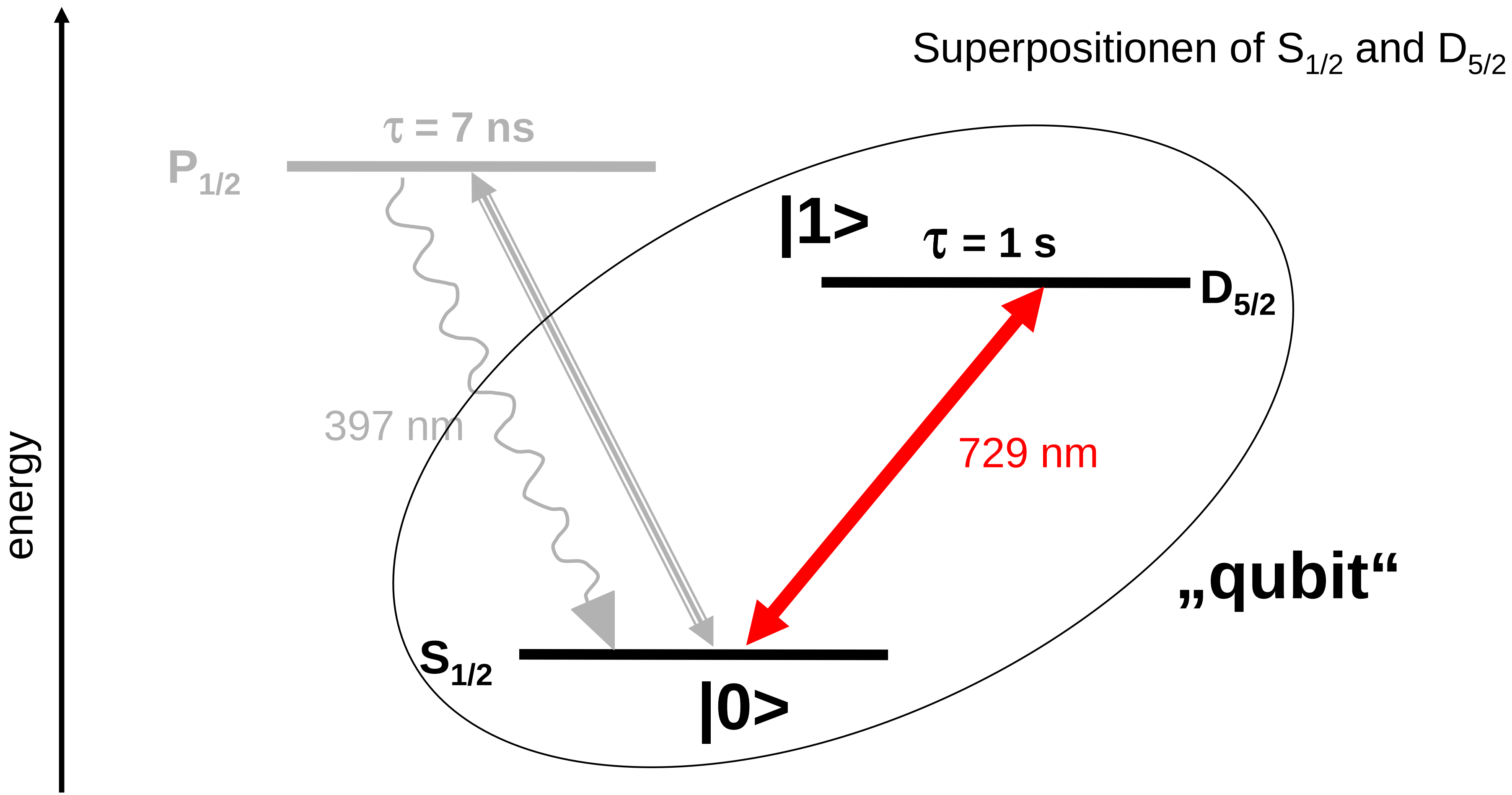
Species and Isotopes:

for (a)	^{40}Ca, ^{43}Ca, ^{138}Ba, ^{199}Hg, ^{88}Sr, ...
for (b)	^{9}Be, ^{43}Ca, ^{111}Cd, ^{25}Mg....
for (c)	^{40}Ca, ^{24}Mg, ...
for (d)	$^{172/172}$Yb, ...
for (e)	^{115}In, ^{27}Al, ...
for (f)	^{171}Yb, ...

Level scheme of $^{40}Ca^+$



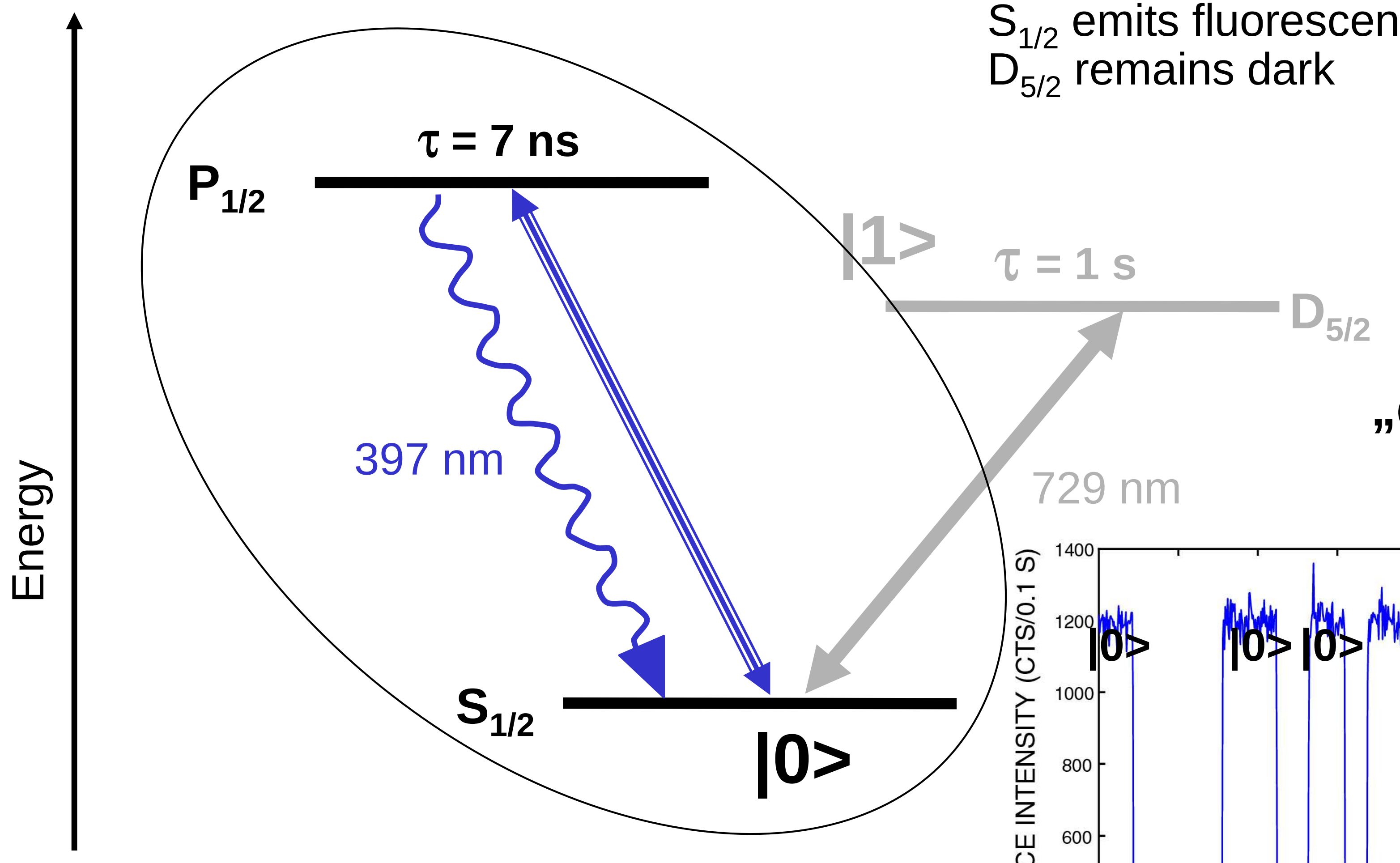
Ion energy levels



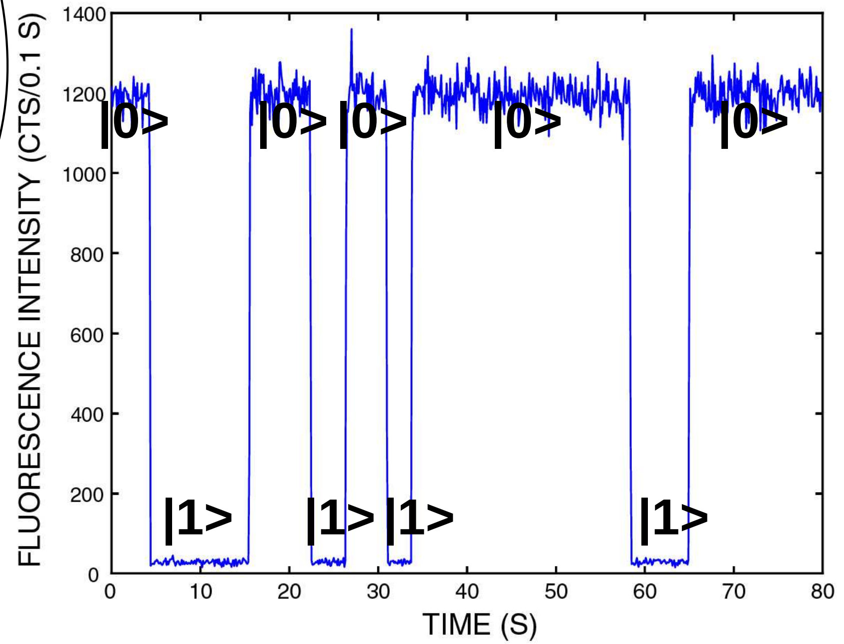
Ion energy levels

Specroscopy pulse followed by detection of qubits:

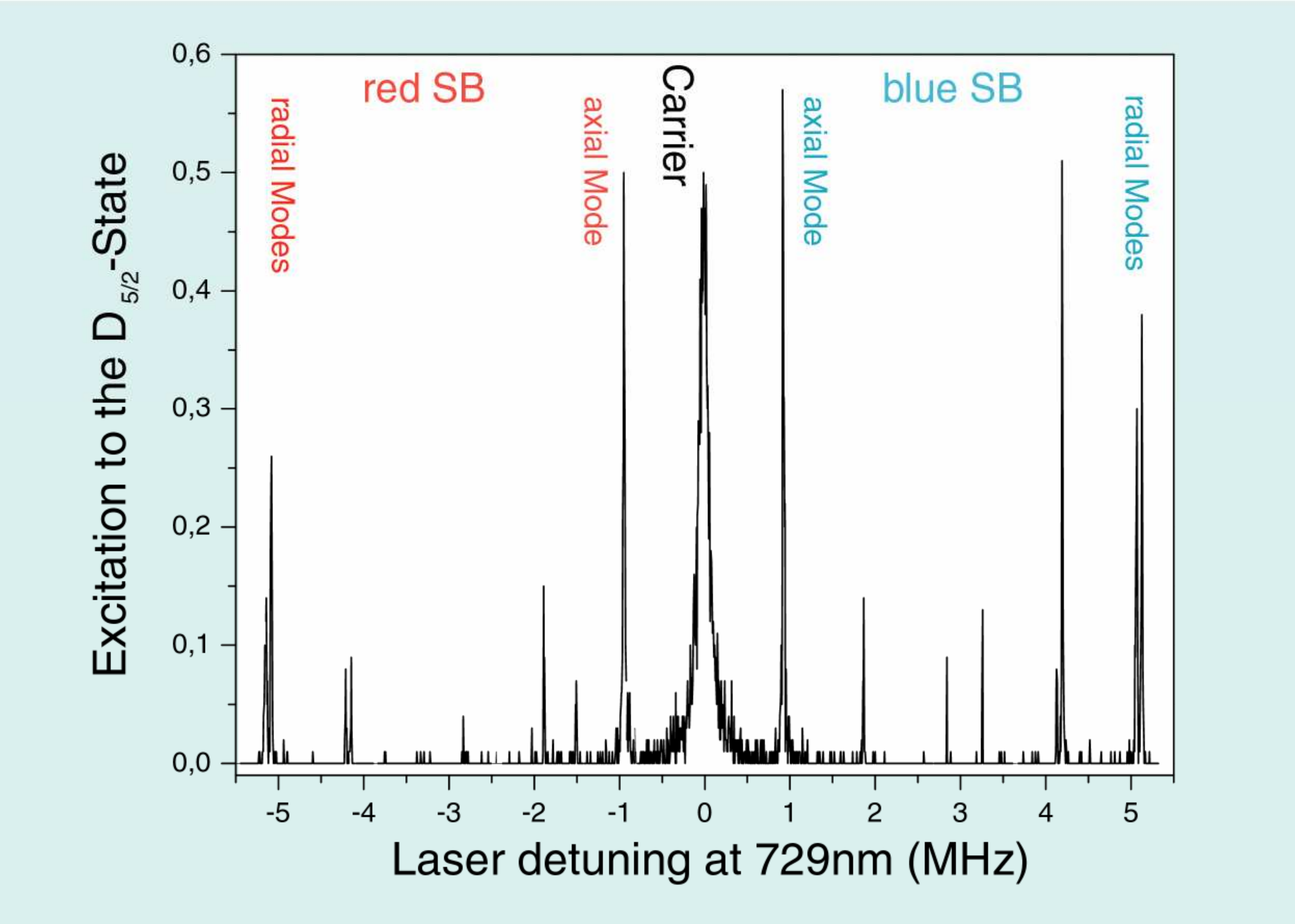
Scatter light near 397nm:
$S_{1/2}$ emits fluorescence
$D_{5/2}$ remains dark



„qubit -measurement“



Excitation spectrum of the $S_{1/2}$ – $D_{5/2}$ transition



$\omega_{ax.}$ = 1.0 MHz,

$\omega_{rad.}$ = 5.0 MHz

Temperature measurements

different methods

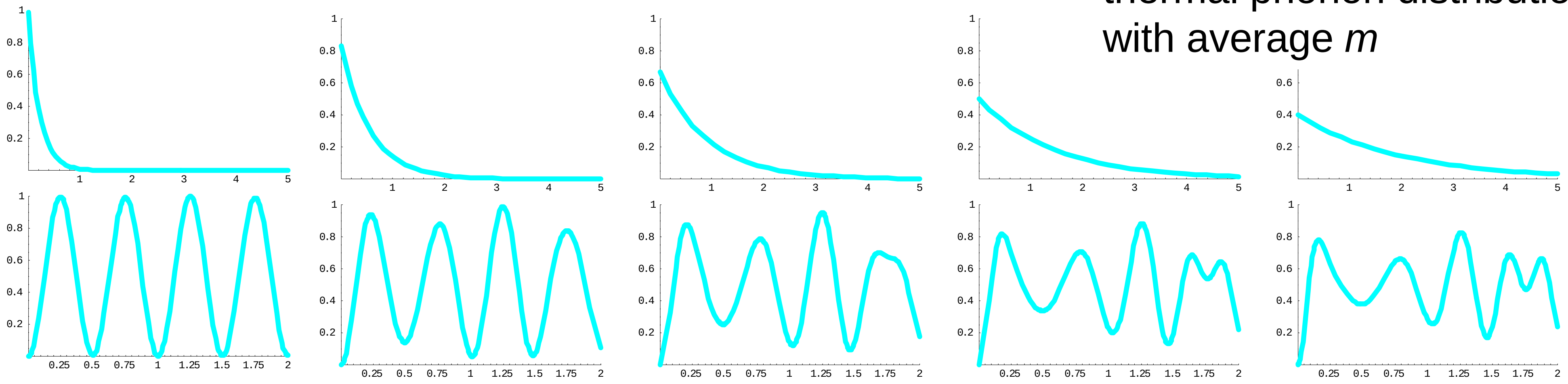
- observe Rabi oscillations on the blue SB
- compare the excitation on the blue SB and the red SB
- compare the excitation on the red SB and the carrier
- observe Rabi oscillations on the carrier
- measure the linewidth of the cooling transition (not recommended)

Experimental: vary the length *t* of the excitation and record $P_e(t)$
Analysis: Fit, or Fourier transformation

$$P_e^{blue}(t) = \sum n_m \, sin^2(2\pi\Omega_{n,n+1} t), \quad n_m = \frac{m^n}{(m+1)^{n+1}}; \quad \langle n \rangle_{ss} = m$$

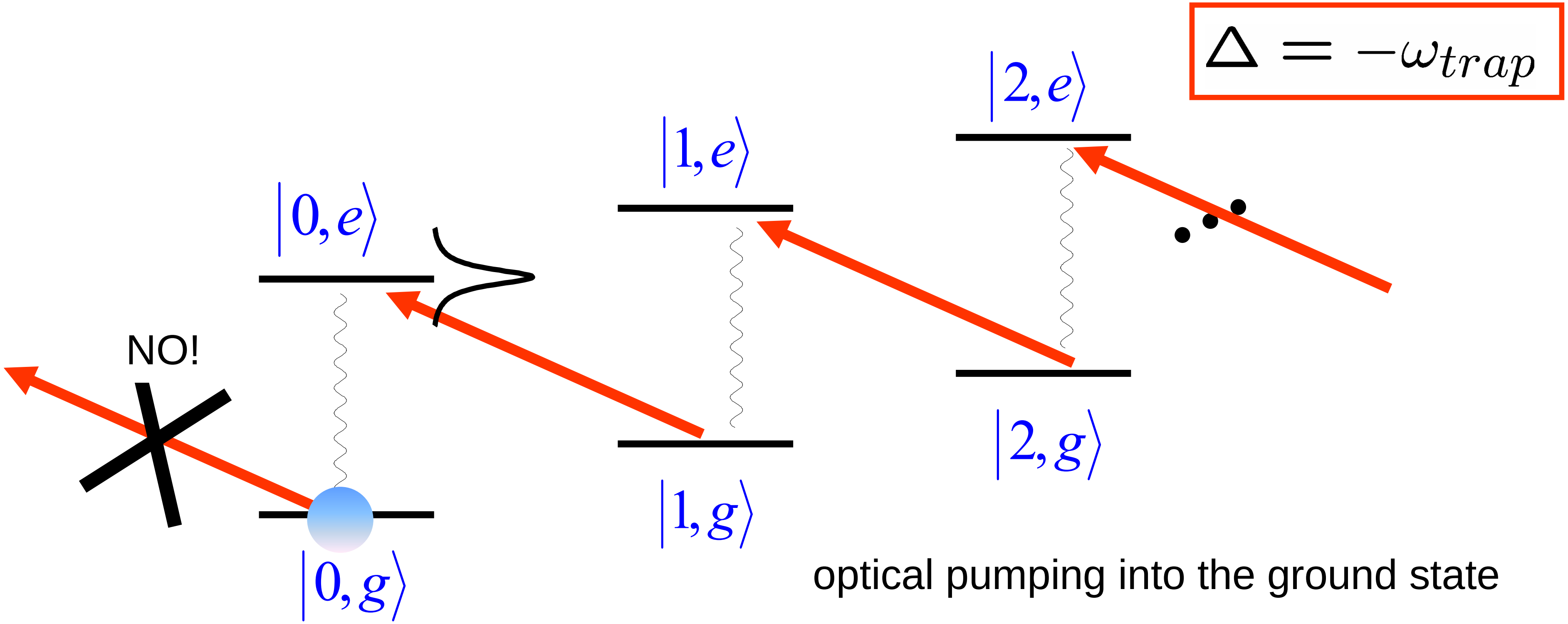
$$= \sum n_m \; sin^2(2\pi\Omega_0 \sqrt{n+1}\, t)$$

thermal phonon distribution with average *m*



m=0.01 m=0.2 m=0.5 m=1.0 m=1.5

„Strong confinement“



Signature: no further excitation possible
„dark state“ |0>

Temperature measurements

different methods

- observe Rabi oscillations on the blue SB
- compare the excitation on the blue SB and the red SB
- compare the excitation on the red SB and the carrier
- observe Rabi oscillations on the carrier
- measure the linewidth of the cooling transition (not recommended)

Experimental: test excitation $P_e(t)$ for $\Delta=-\omega$ and $\Delta=+\omega$
Analysis: $P_{red}/P_{blue} = m/(m+1)$

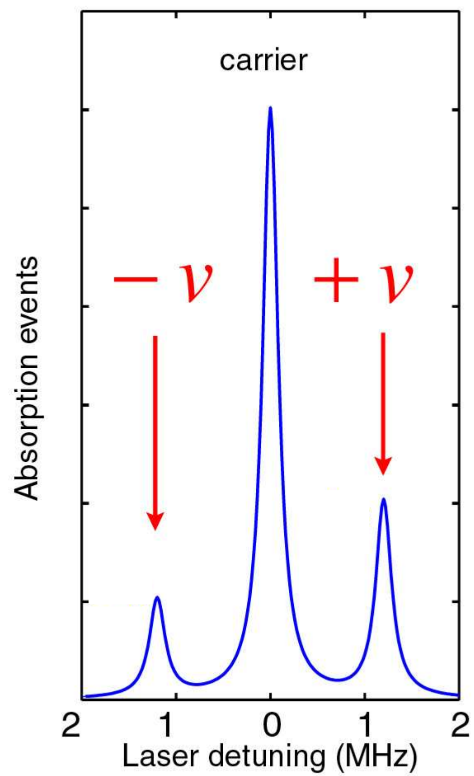
$$P_e^{red}(t) = \sum_{n=1} \frac{m^n}{(m+1)^{n+1}} sin^2(2\pi\Omega_{n,n-1}t)$$

$$= \frac{m}{m+1} \sum_{n=0} \frac{m^n}{(m+1)^{n+1}} sin^2(2\pi\Omega_{n+1,n}t)$$

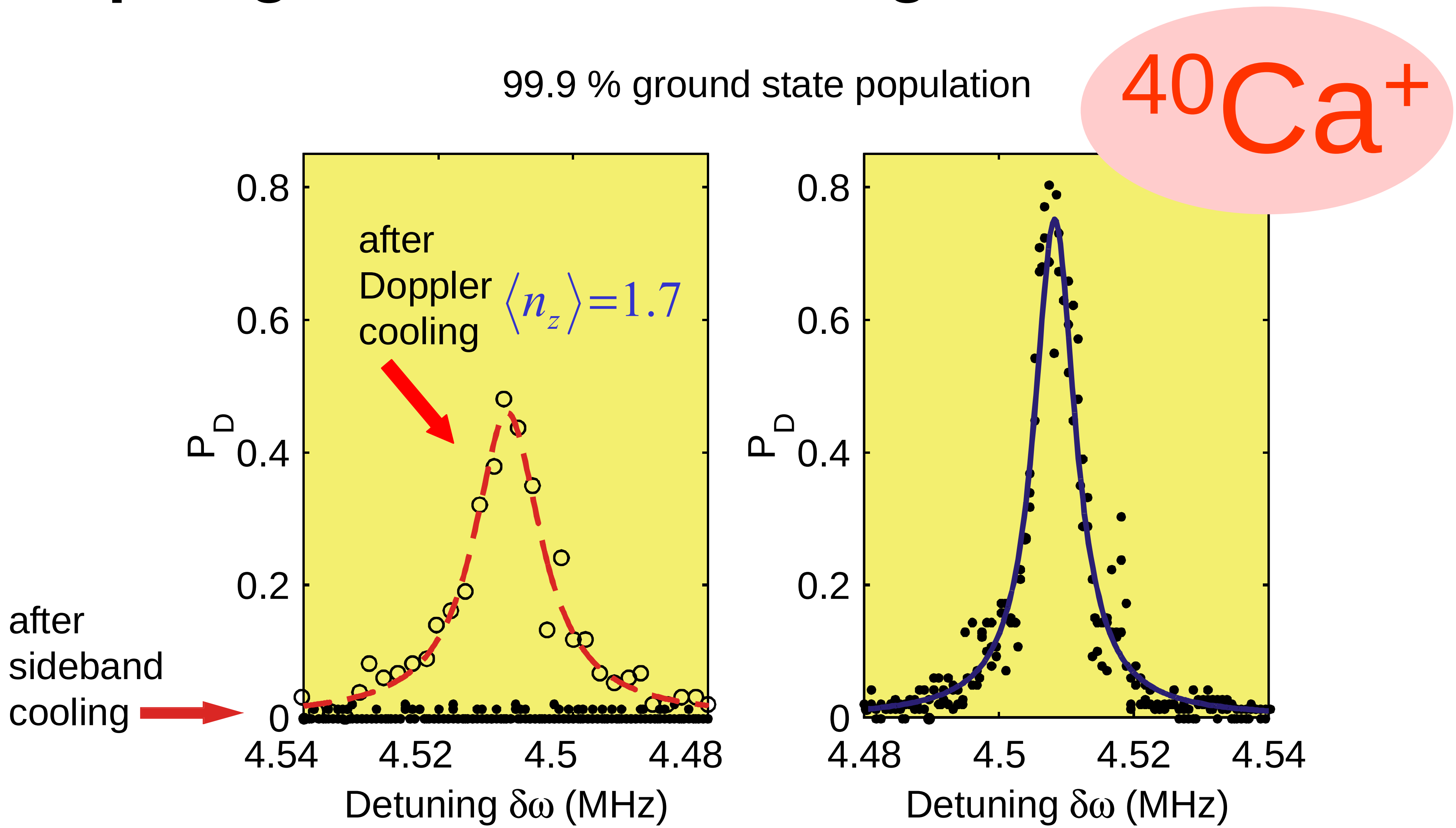
using: $\Omega_{n+1,n} = \Omega_{n,n+1}$

$$\Rightarrow \quad P_e^{red}(t) = \frac{m}{m+1} P_e^{blue}(t)$$

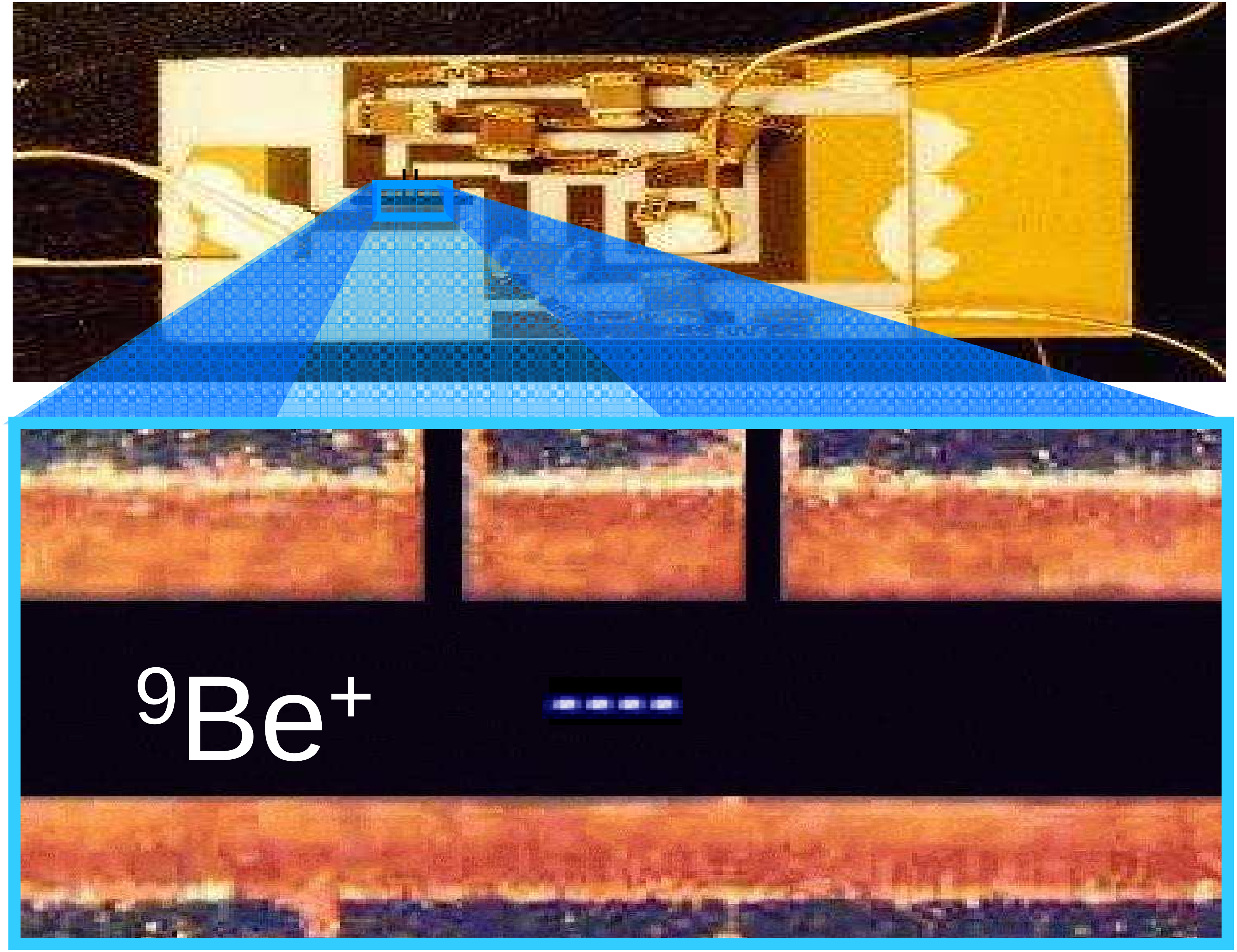
$$m = \frac{R}{1-R}, \quad R = P_e^{red}/P_e^{blue}$$



Example: ground state cooling



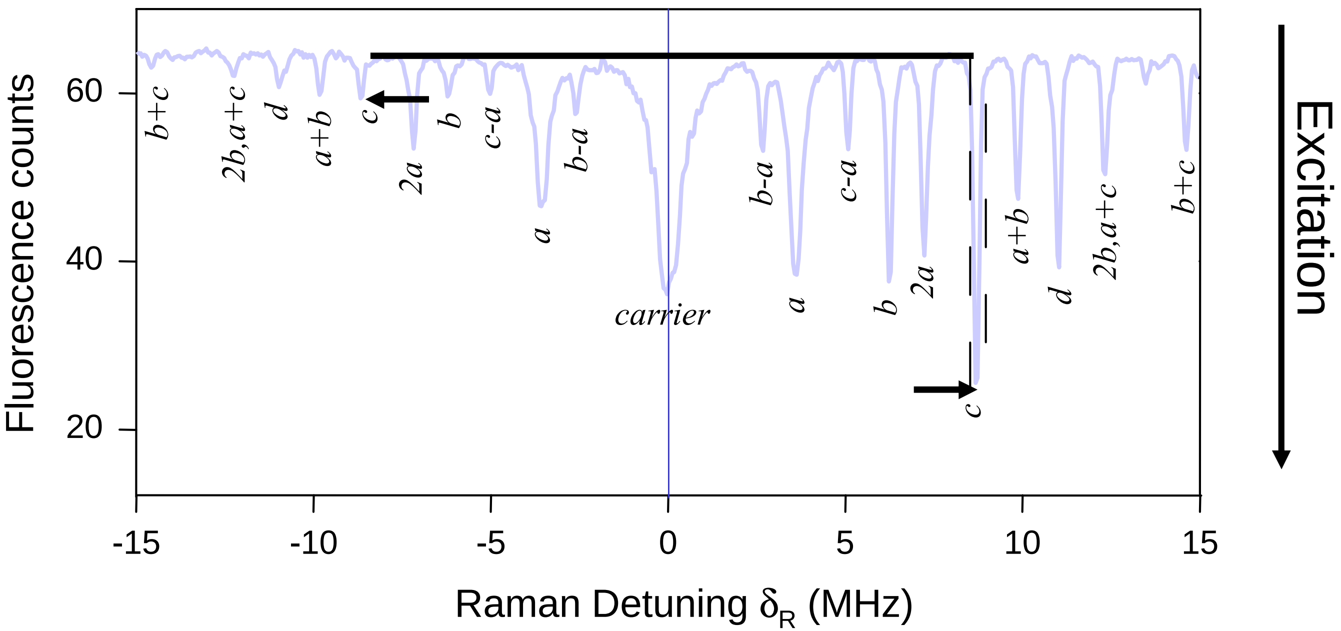
Ch. Roos et al., Phys. Rev. Lett. 83, 4713 (1999)



C.A. Sackett, et al., Nature ***404****, 256 (2000)*

D. Wineland, Boulder, USA (2000)

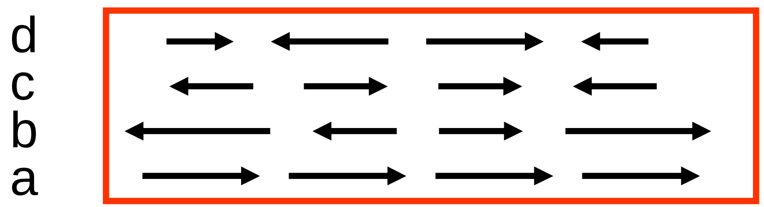
Example: 4-ion axial spectrum



Doppler cooling:

$P_{red}/P_{blue} \sim 1 / 7$
$m_c = 0.16$

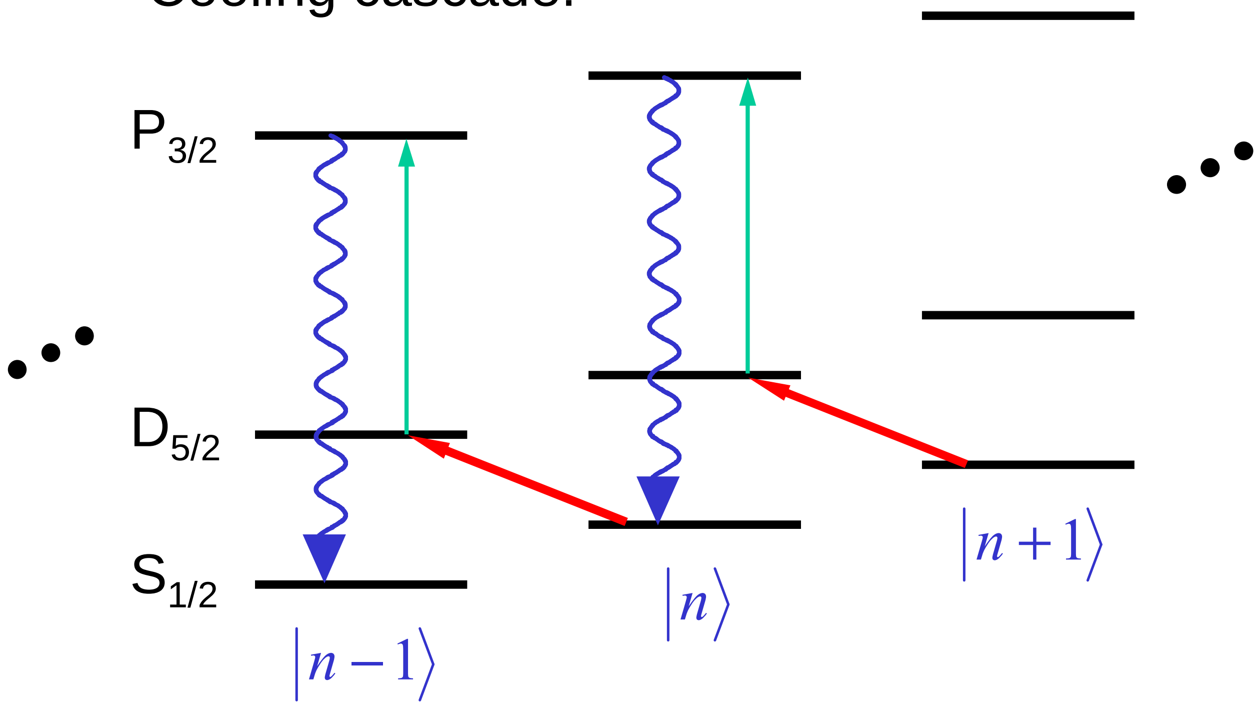
pictorial eigenmodes



C.A. Sackett, et al., Nature ***404****, 256 (2000)*

Quadrupole transition: optimize cooling

Cooling cascade:



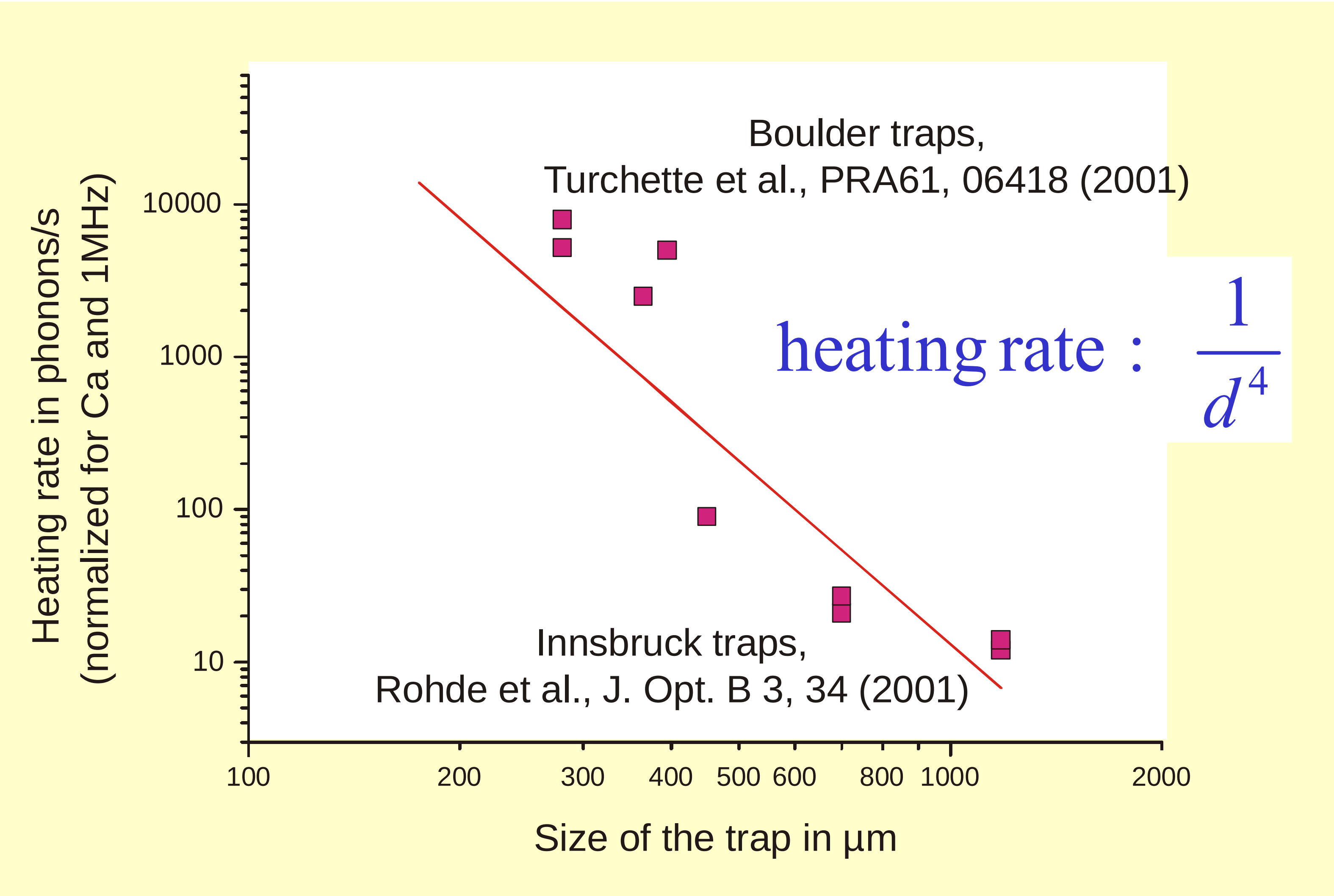
Effective two-level system:

$$\gamma_{eff} \approx \frac{\Omega_{PD}^2}{\gamma_{SP}^2 + 4\Delta_{PD}^2}\gamma_{SP}$$

⇨ optimize γ_{eff} using the 854nm laser power:
large γ_{eff} : large cooling rate
small γ_{eff} : small *m*

I. Marzoli et al.,
Phys. Rev. A 49, 2771 (1994)

Comparing heating rates



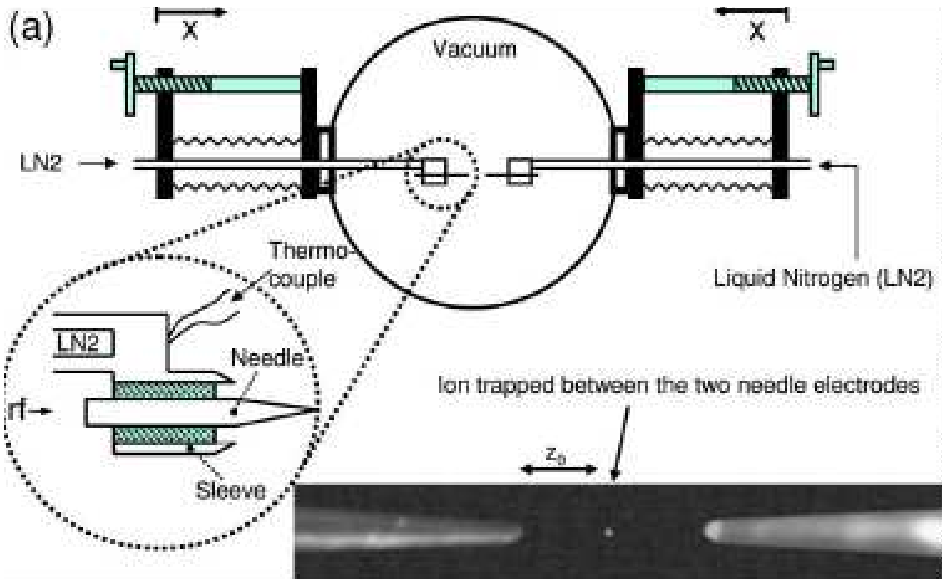
D. J. Wineland et al.,
J. Res. Nat Inst. Stand. Tech. 103 (259)

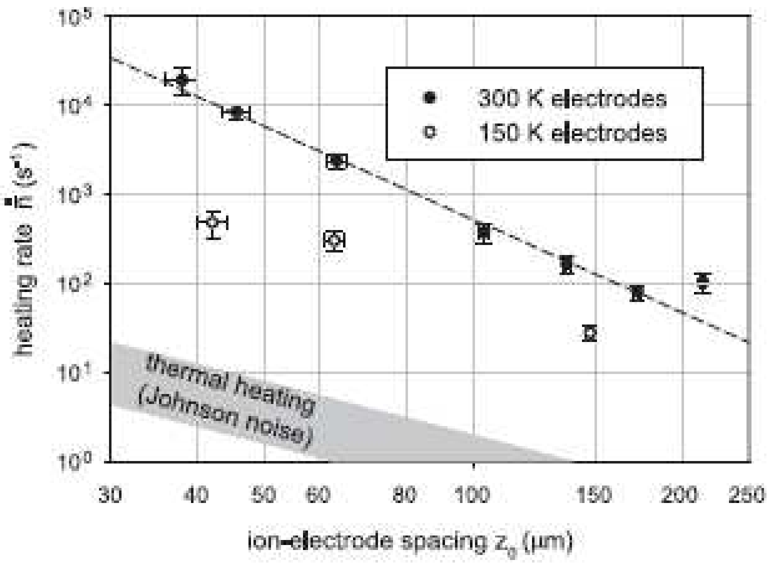
Heating rate …

PRL **97,** 103007 (2006) PHYSICAL REVIEW LETTERS week ending 8 SEPTEMBER 2006

Scaling and Suppression of Anomalous Heating in Ion Traps

L. Deslauriers, S. Olmschenk, D. Stick, W. K. Hensinger, J. Sterk, and C. Monroe*
FOCUS Center and Department of Physics, University of Michigan, Ann Arbor, Michigan 48109, USA
(Received 31 January 2006; published 8 September 2006)





Measured heating scales with d^{-4}

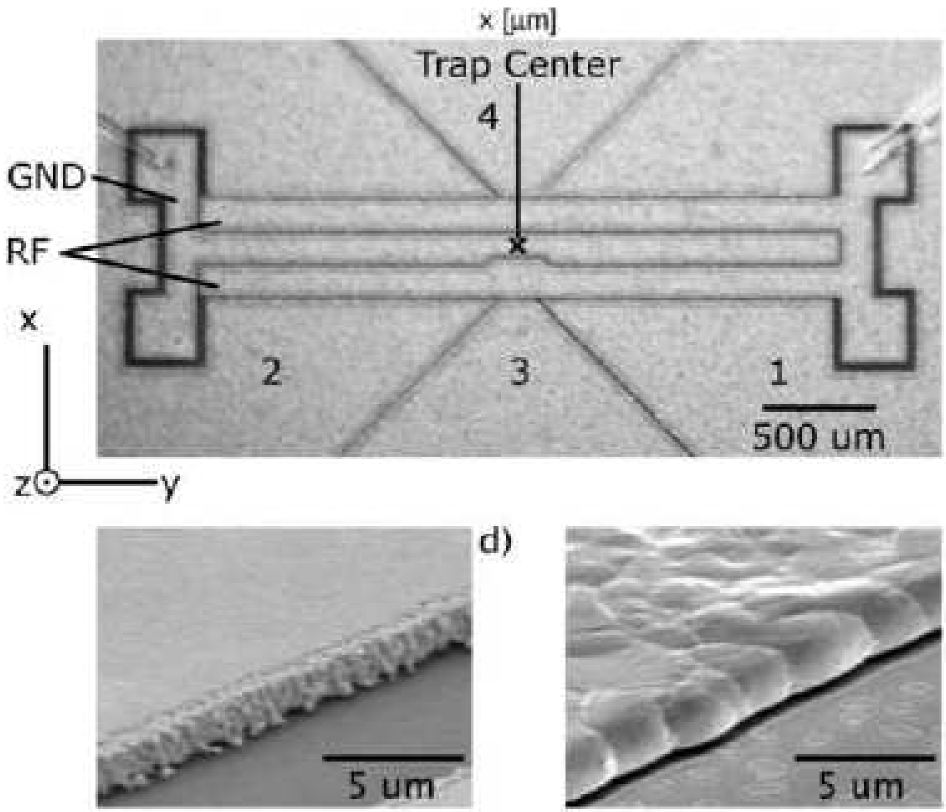
and is reduced at 150K

Heating rate in planar cryogenic trap

Suppression of Heating Rates in Cryogenic Surface-Electrode Ion Traps

Jaroslaw Labaziewicz,* Yufei Ge, Paul Antohi, David Leibrandt, Kenneth R. Brown, and Isaac L. Chuang
Massachusetts Institute of Technology, Center for Ultracold Atoms,
Department of Physics, 77 Massachusetts Avenue, Cambridge, MA, 02139, USA
(Dated: June 26, 2007)

Labaziewicz et al,
PRL 100, 013001 (2008)



…..and even much improved at 6K to ~ two phonons/s which is a 10^7 reduction compared to heating rates at room temperature

Reminder to Doppler cooling

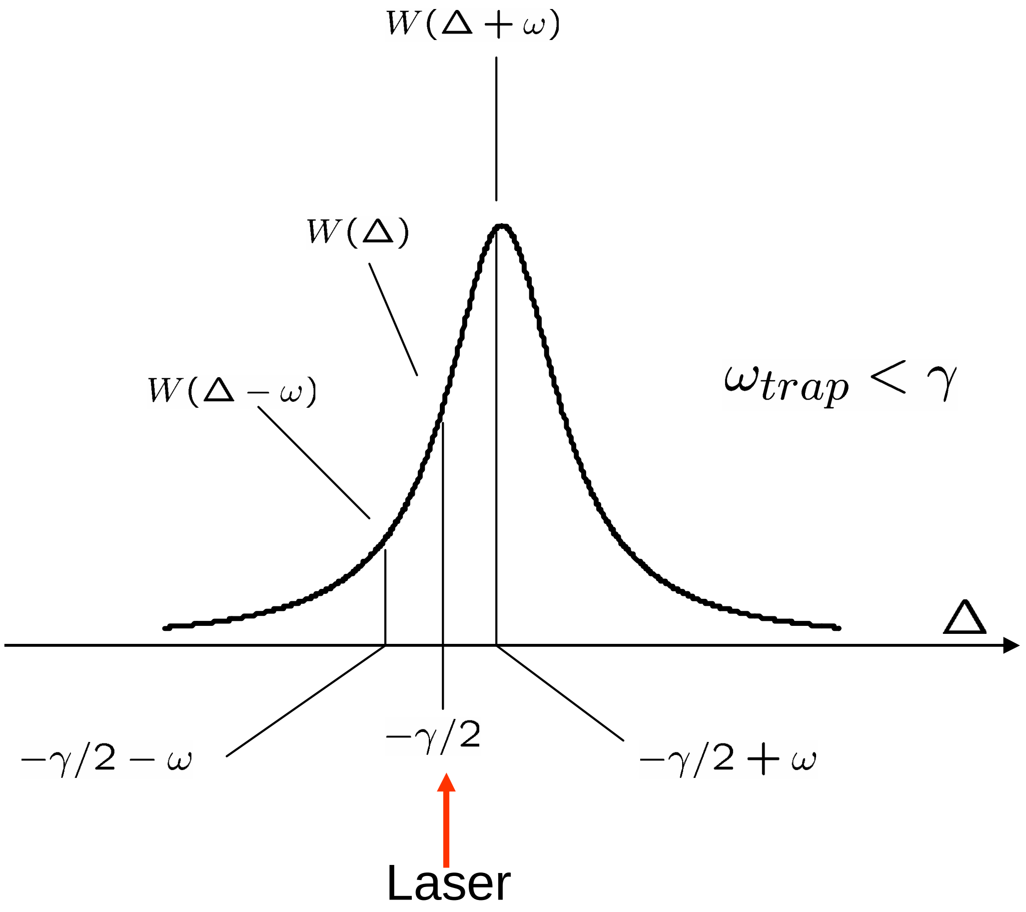
Problems:

a) Sidebands are not resolved on the transition,
⇨ small differences in

$$W(\Delta \pm \omega), W(\Delta - \omega)$$

b) Carrier excitation leads to diffusion, ⇨ heating:

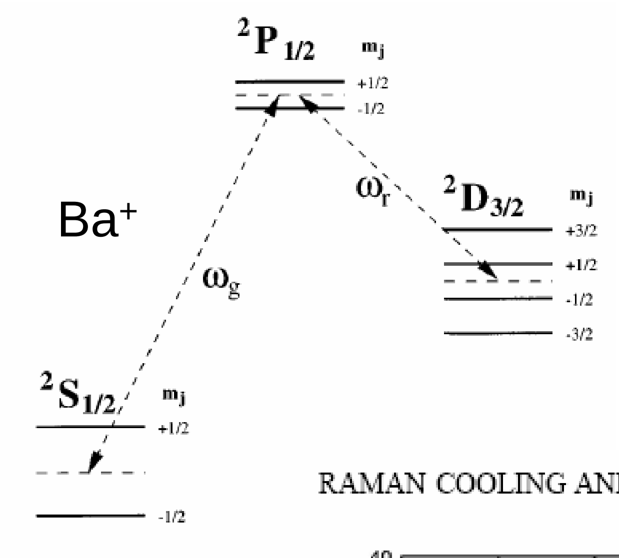
$$W(\Delta = 0) \neq 0$$



How to shape the atomic resonance line? ⇨ **Interference**

Dark states

Reiß et al., Phys Rev A 65, 053401 (2002)
Reiß et al., Phys Rev A 54, 5133 (1996)



Dark resonances: $|\Psi\rangle = \frac{1}{\sqrt{2}}\left(|S_{1/2}\rangle - |D_{5/2}\rangle\right)$

⇨ spectrally much sharper than Dopper profile

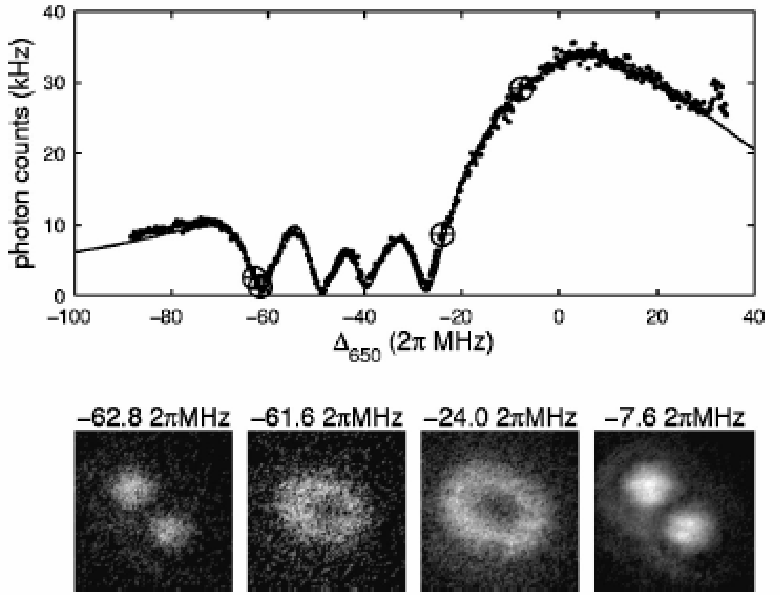


FIG. 2. Two trapped Ba⁺ ions show different motional states depending on laser parameters. Top: fluorescence of two trapped ions as a function of laser detuning, collected in 0.1 s. Bottom: spatial distribution of the two ions at the detunings indicated above.

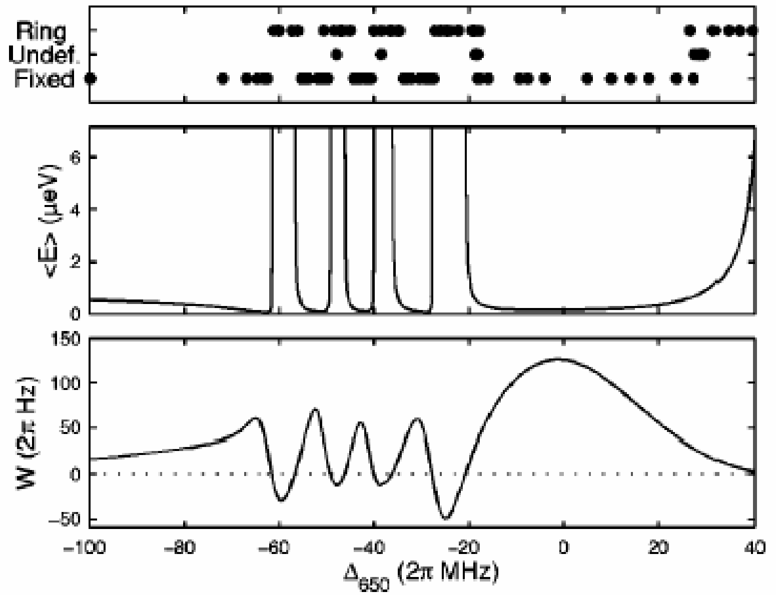
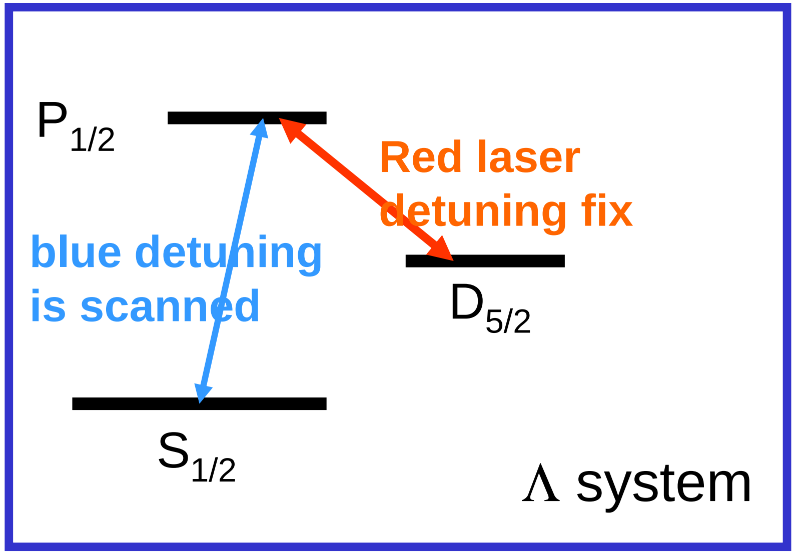


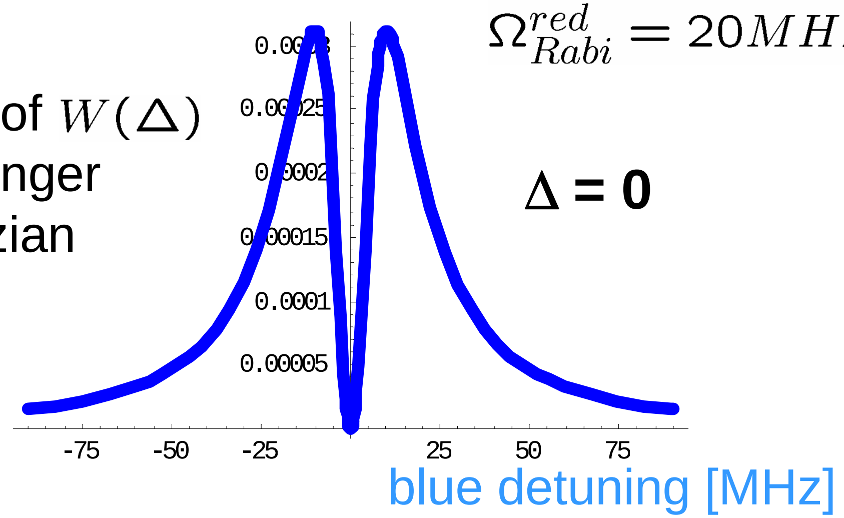
FIG. 3. Top: observed motional states for different detunings of the 650-nm light. The dots correspond to individual observations. Middle: mean motional energy in the $\tilde{y}$ mode calculated from theory. Bottom: cooling rate for the $\tilde{y}$ mode calculated from theory.

Quantum interference and dark states

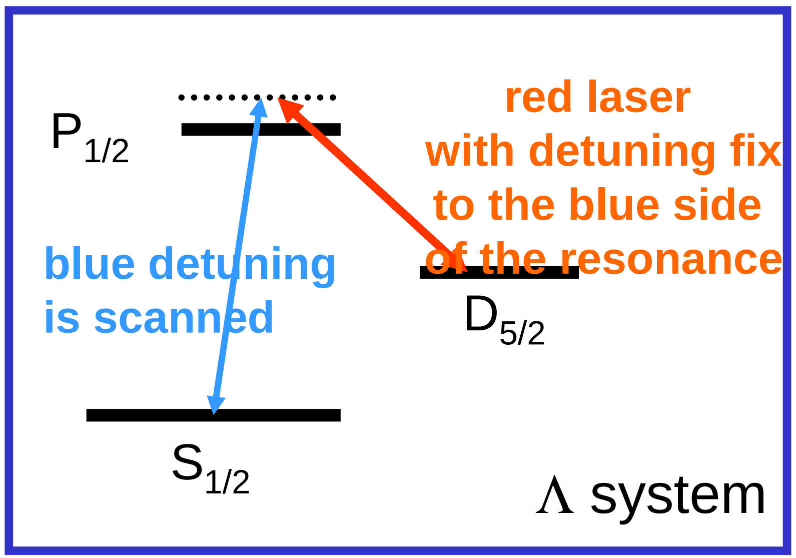
$\Omega^{blue}_{Rabi} = 0.5MHz$
$\Omega^{red}_{Rabi} = 20MHz$

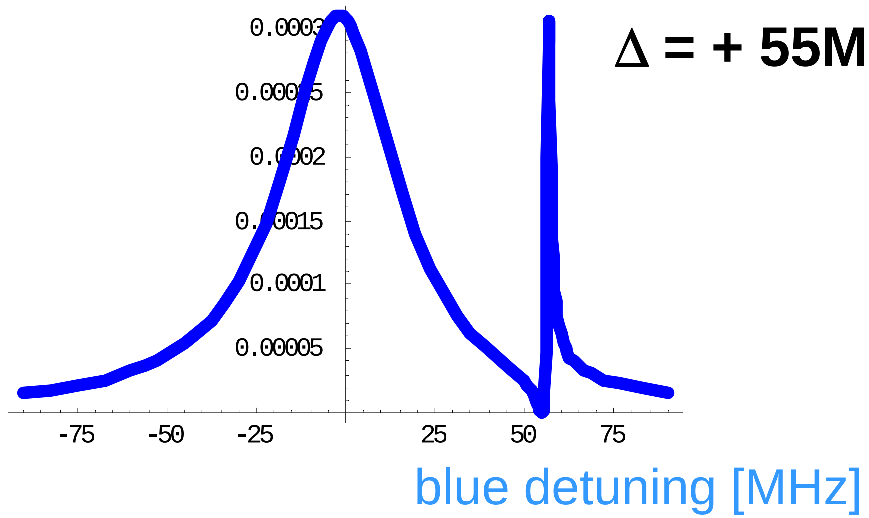


Shape of $W(\Delta)$ is no longer Lorentzian



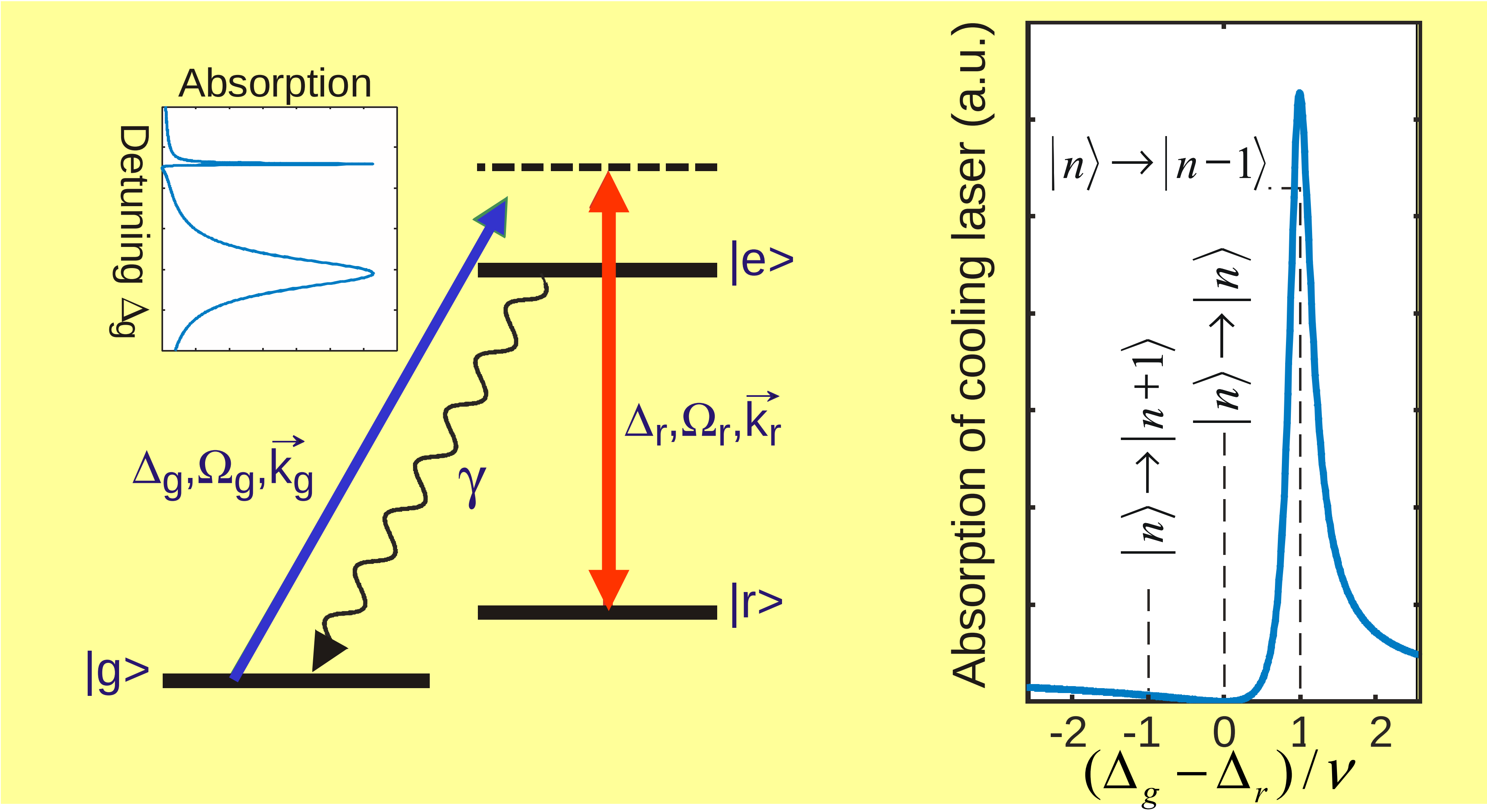
Δ = 0





Δ = + 55MHz

Ground state cooling with quantum interference



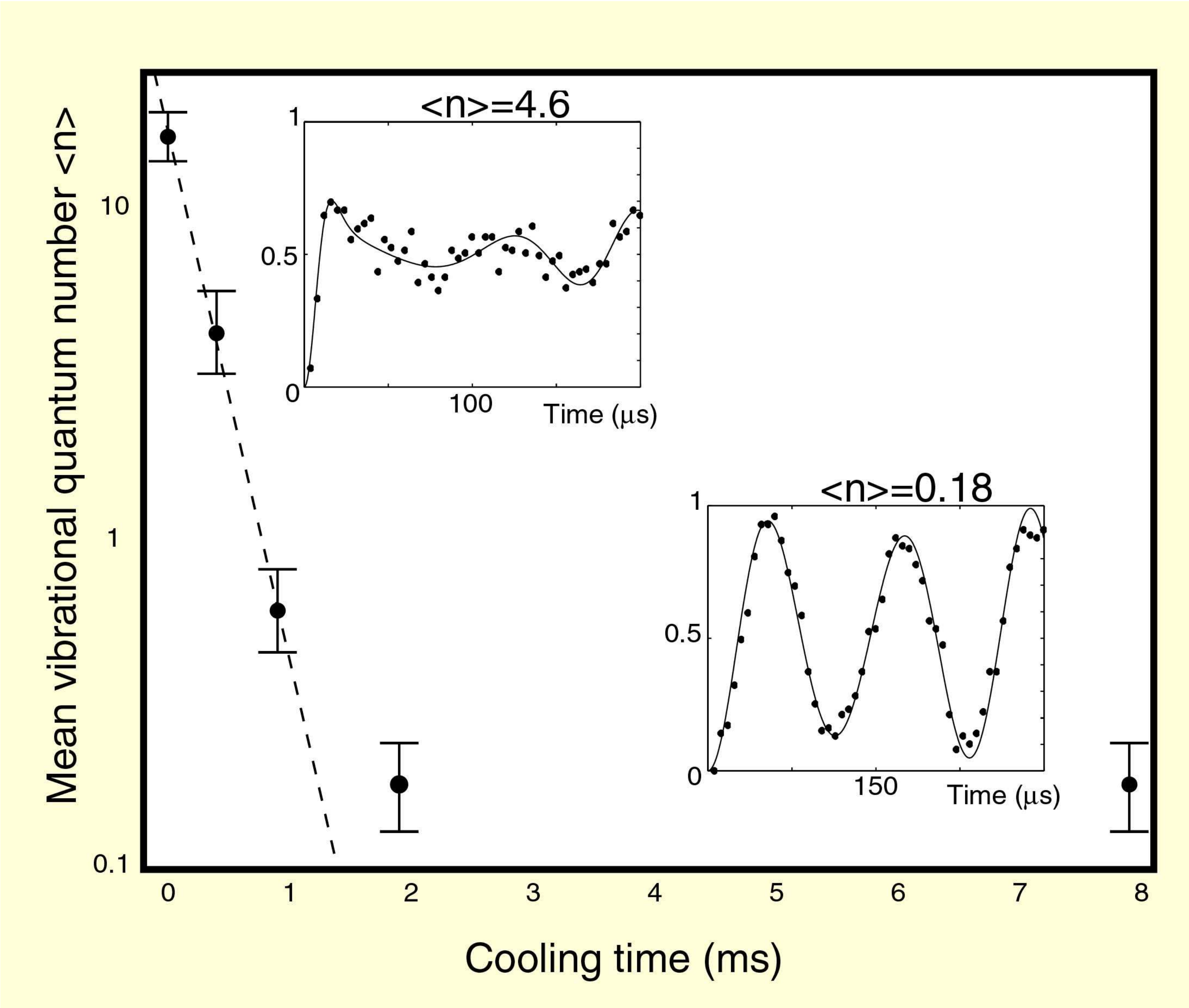
$|n\rangle \rightarrow |n-1\rangle$ transitions are enhanced by bright resonance

$|n\rangle \rightarrow |n\rangle$ transitions are suppressed by quantum interference – no „carrier“ diffusion contribution !

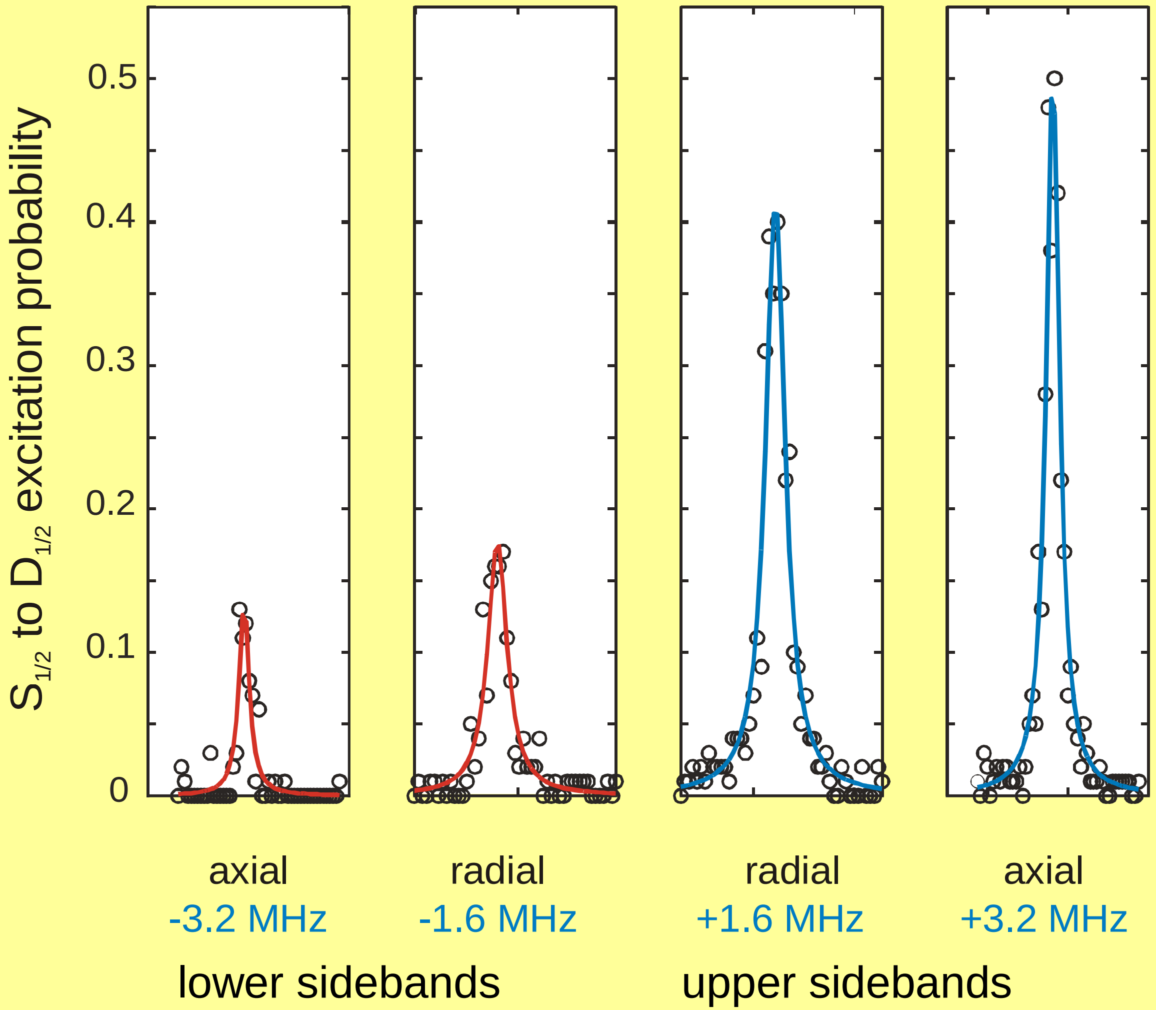
G. Morigi, J. Eschner, C. Keitel, Phys. Rev. Lett. 85, 4458 (2000)

EIT cooling time

C.F. Roos et al., Phys. Rev. Lett. 85, 5547 (2000)



Simultaneous two mode ground state cooling



Simultaneous ground state cooling of axial and radial motion

axial:
P(0)=73%

radial:
P(0)=58%

C.F. Roos et al., Phys. Rev. Lett. 85, 5547 (2000)

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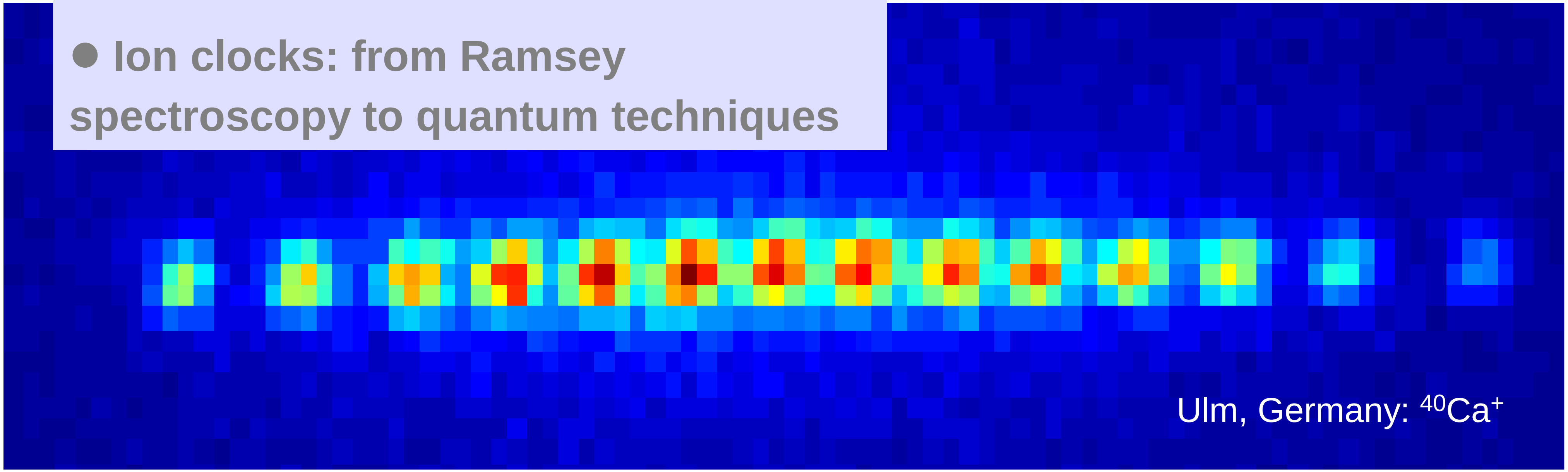
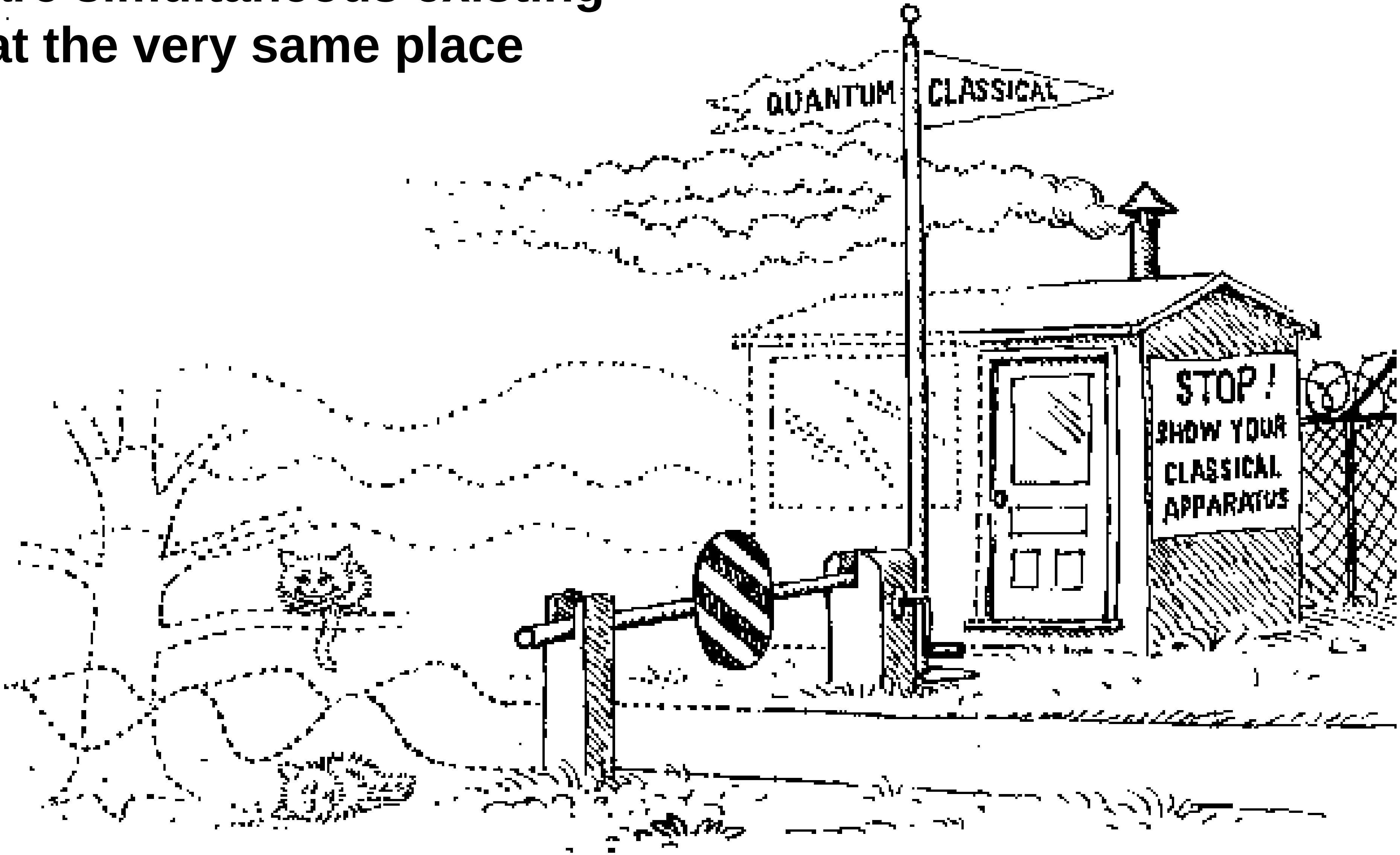


What is a Superposition?

two **different quantum states**
are simultaneous existing
at the very same place



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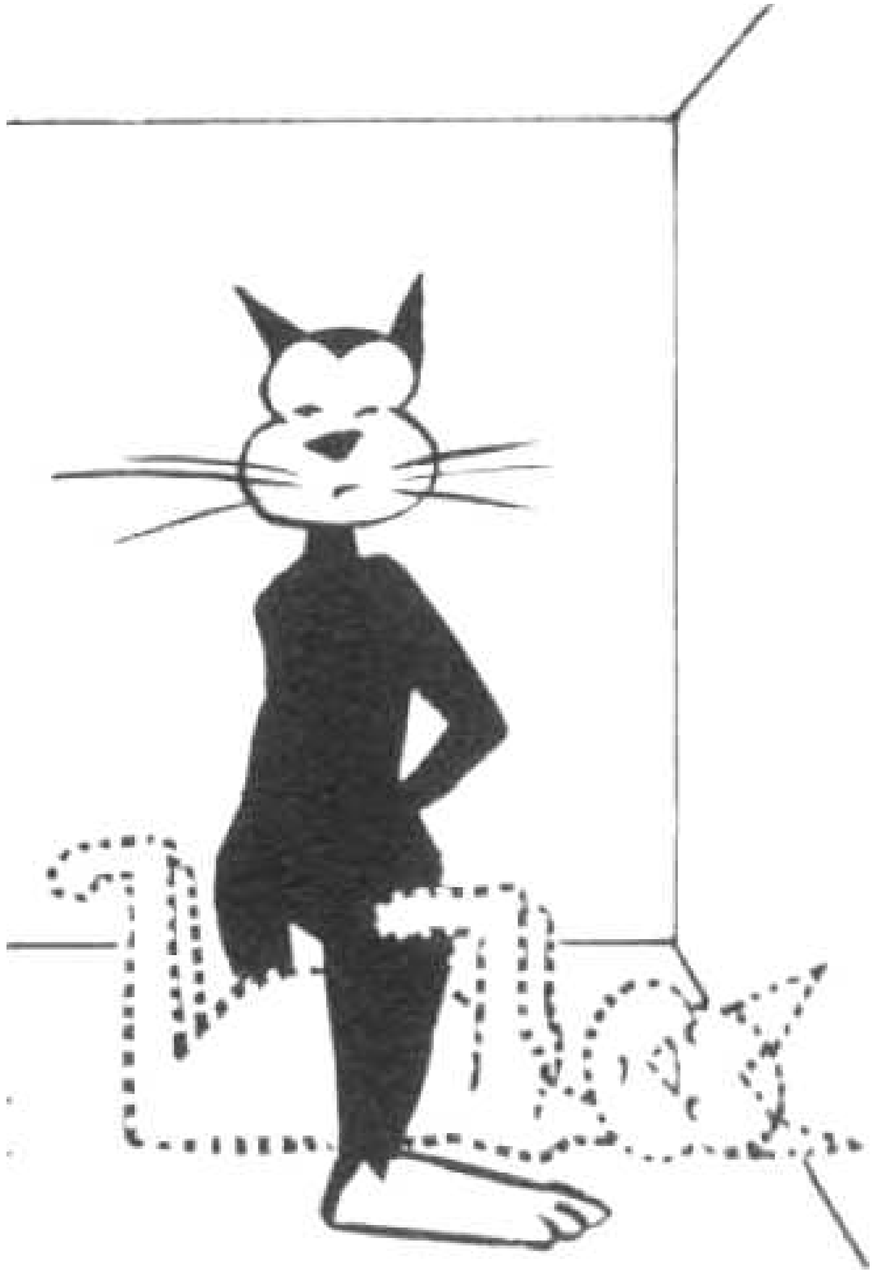

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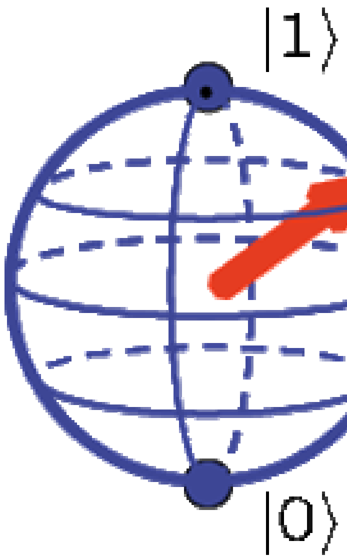
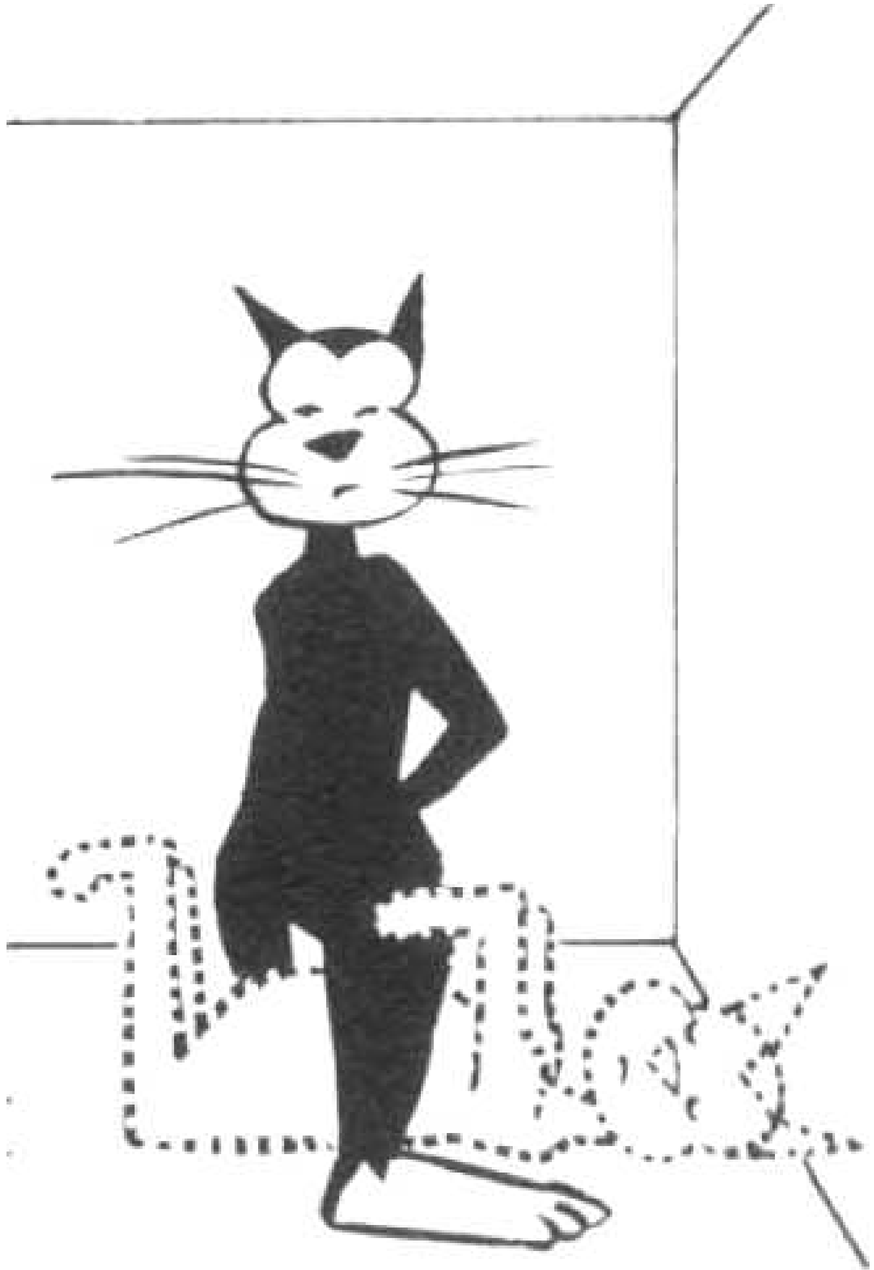


Vector on the Bloch-sphere



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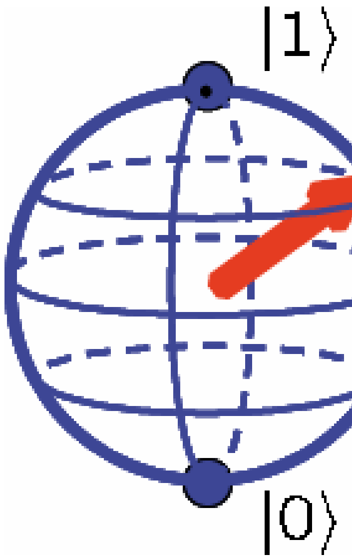


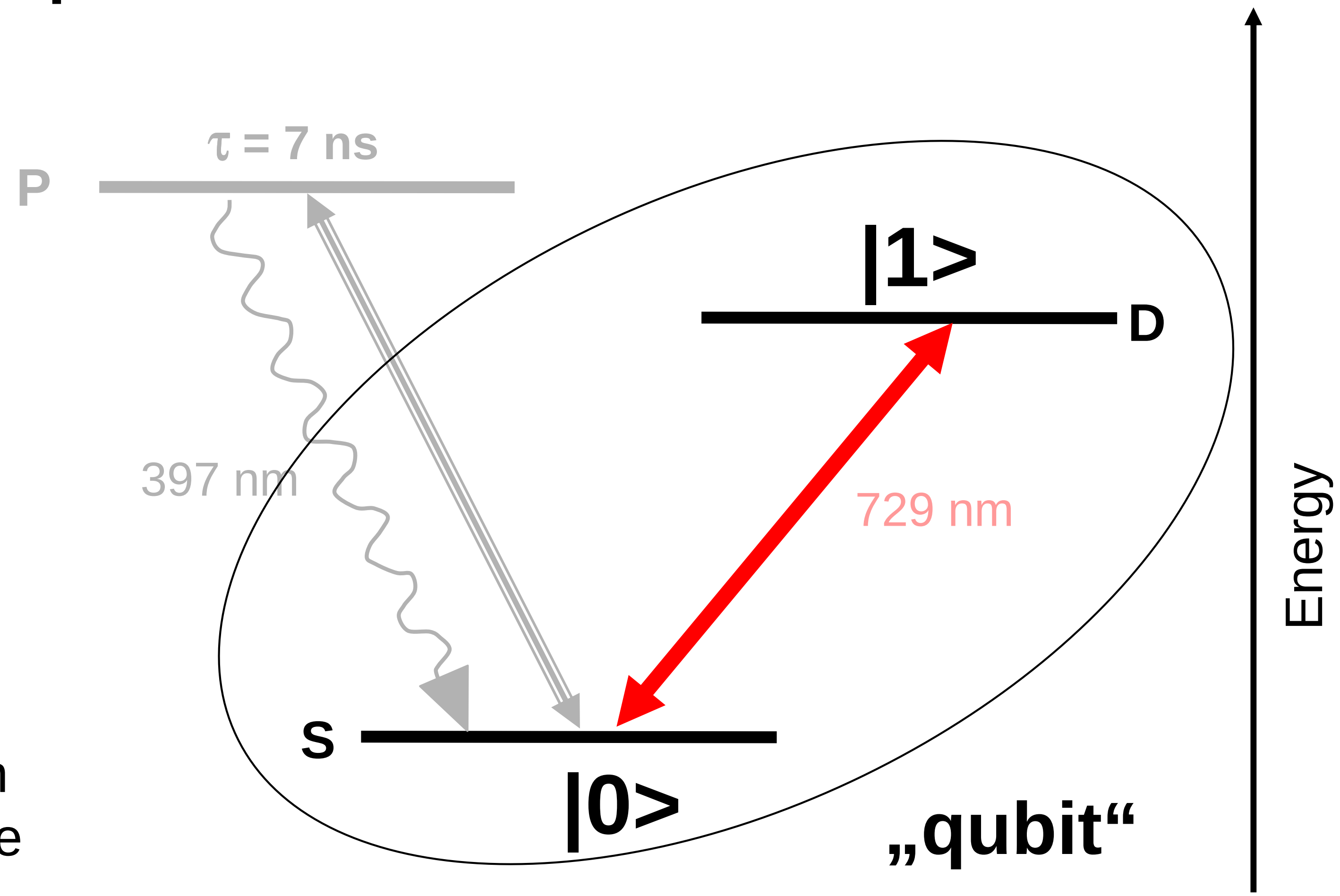
A single quantum-bit

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

in superposition of Zero and One

What is a Superposition?

two **different quantum states**
are simultaneous existing
at the very same place

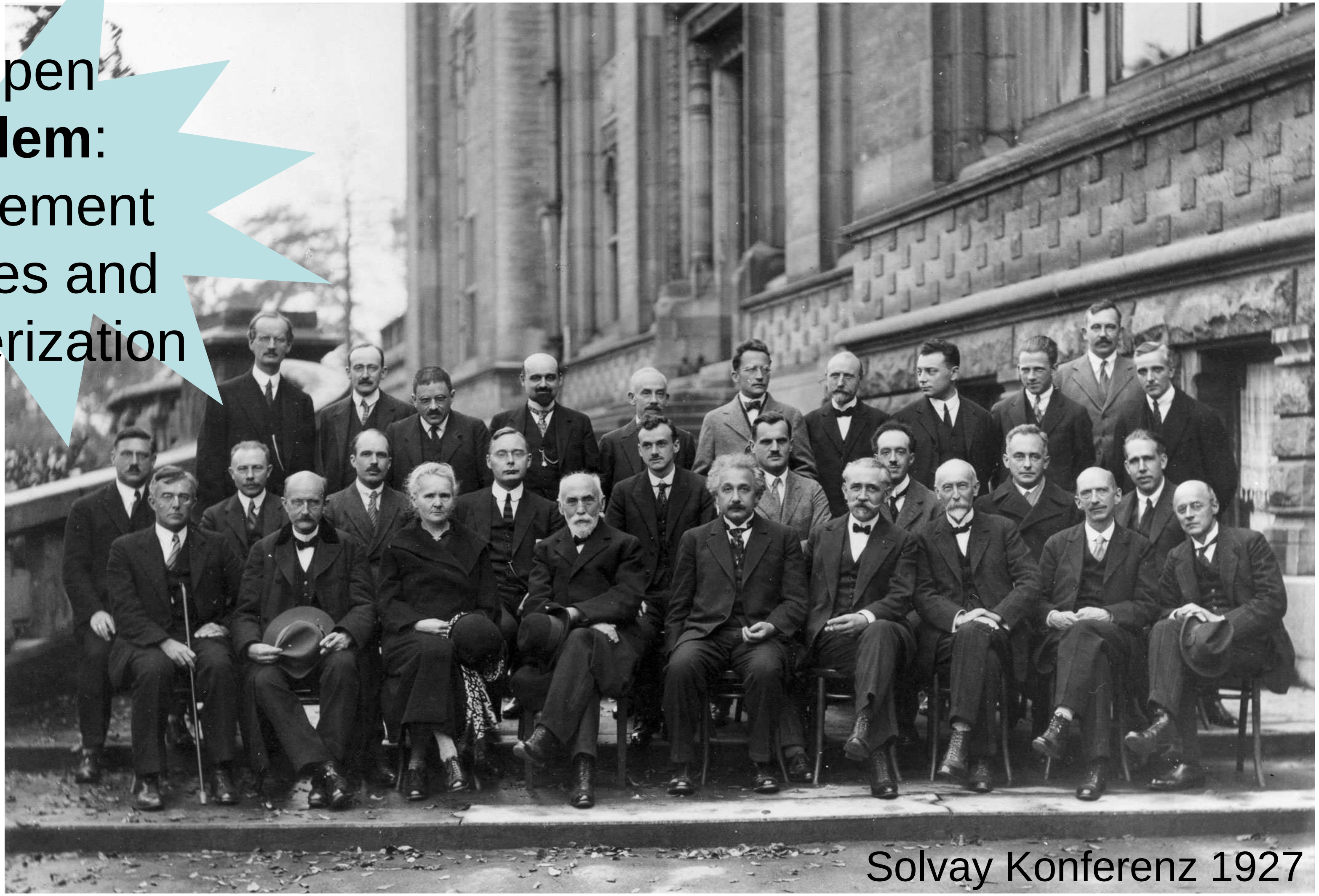


A single **Ion**
in superposition
of Zero and One

What is entanglement?

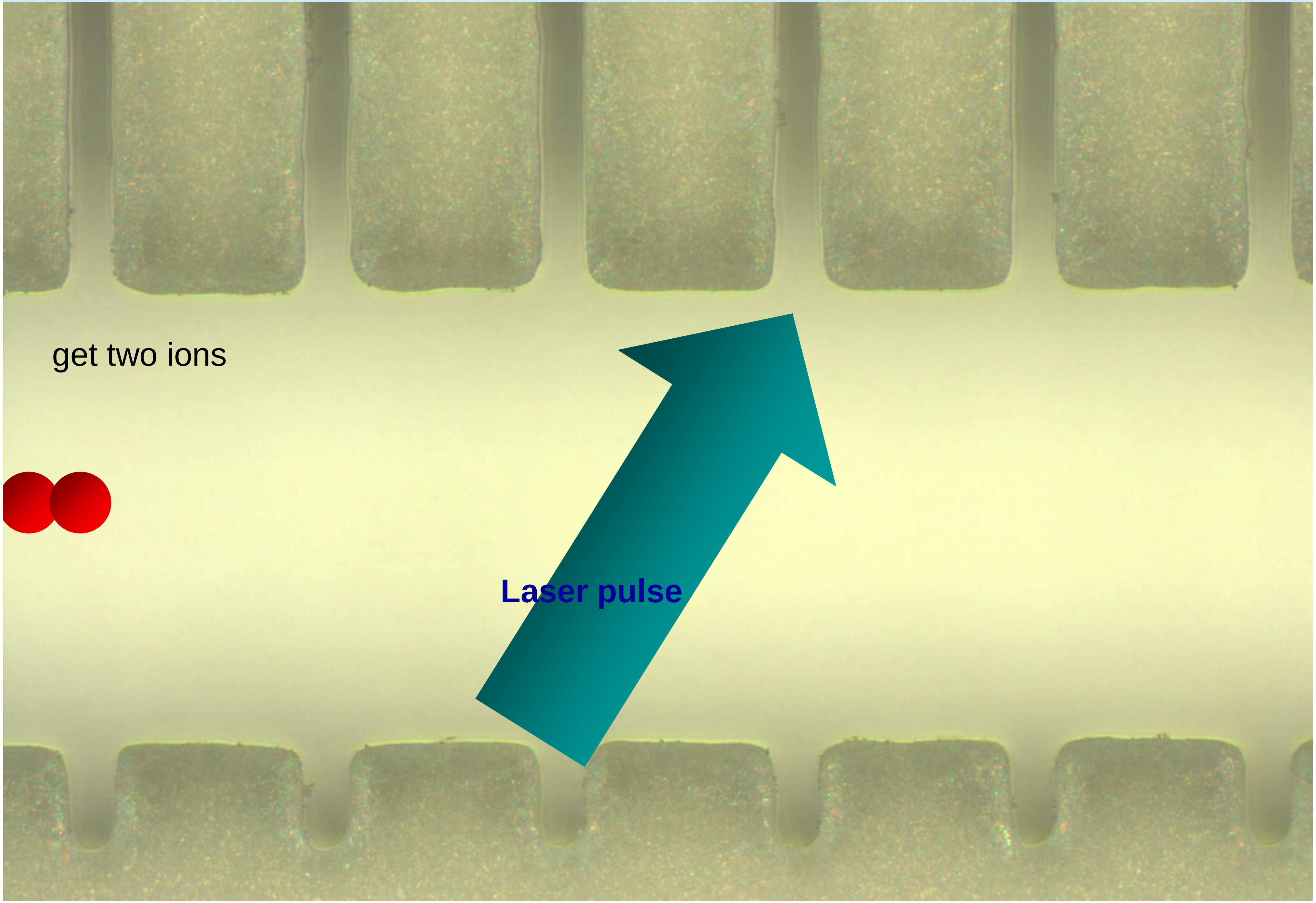
Entangled particles show correlations and can only propery discribed by a common quantum state, regardless how far appart they are.

Still open **Problem**: Entanglement measures and characterization

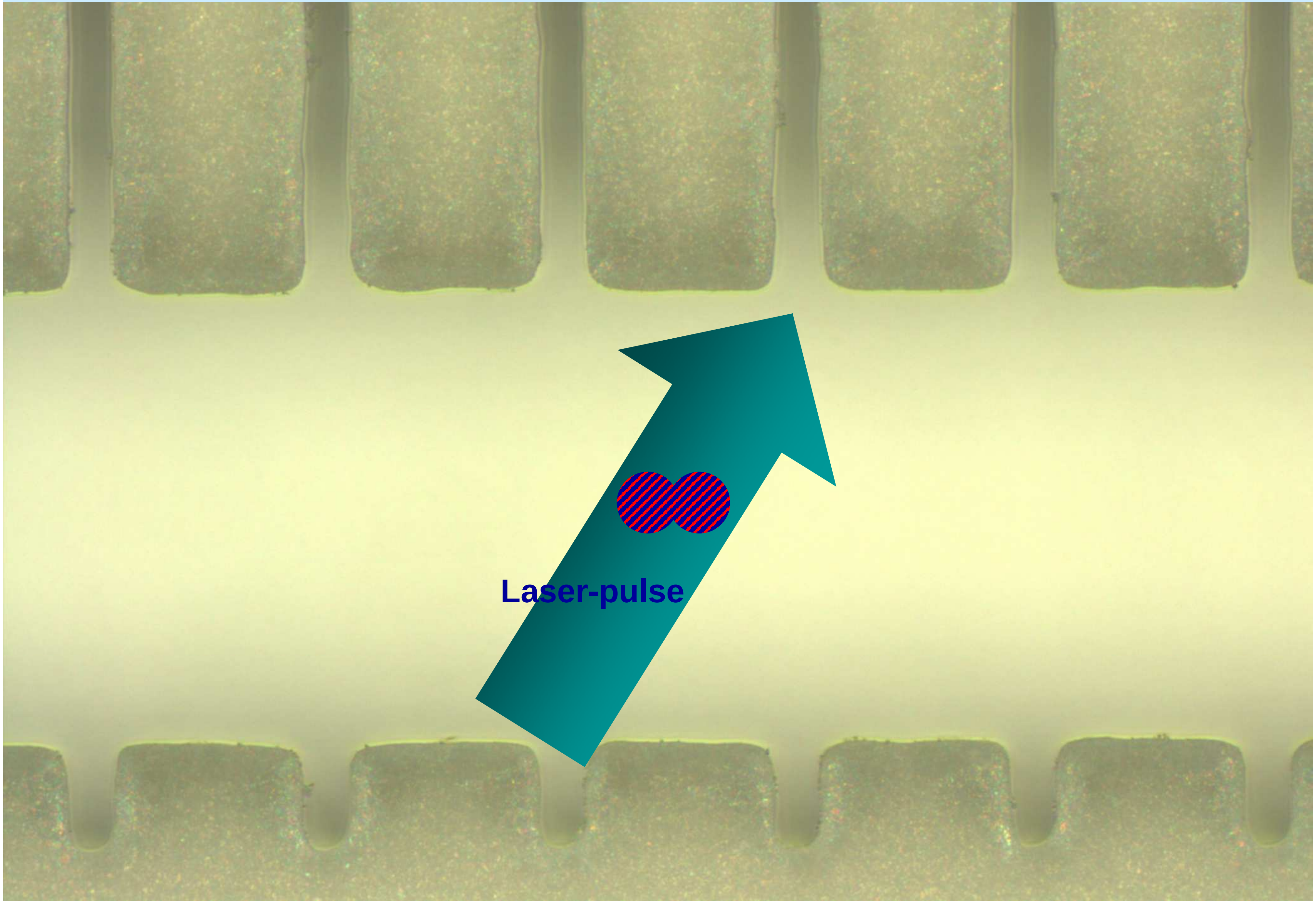


Solvay Konferenz 1927

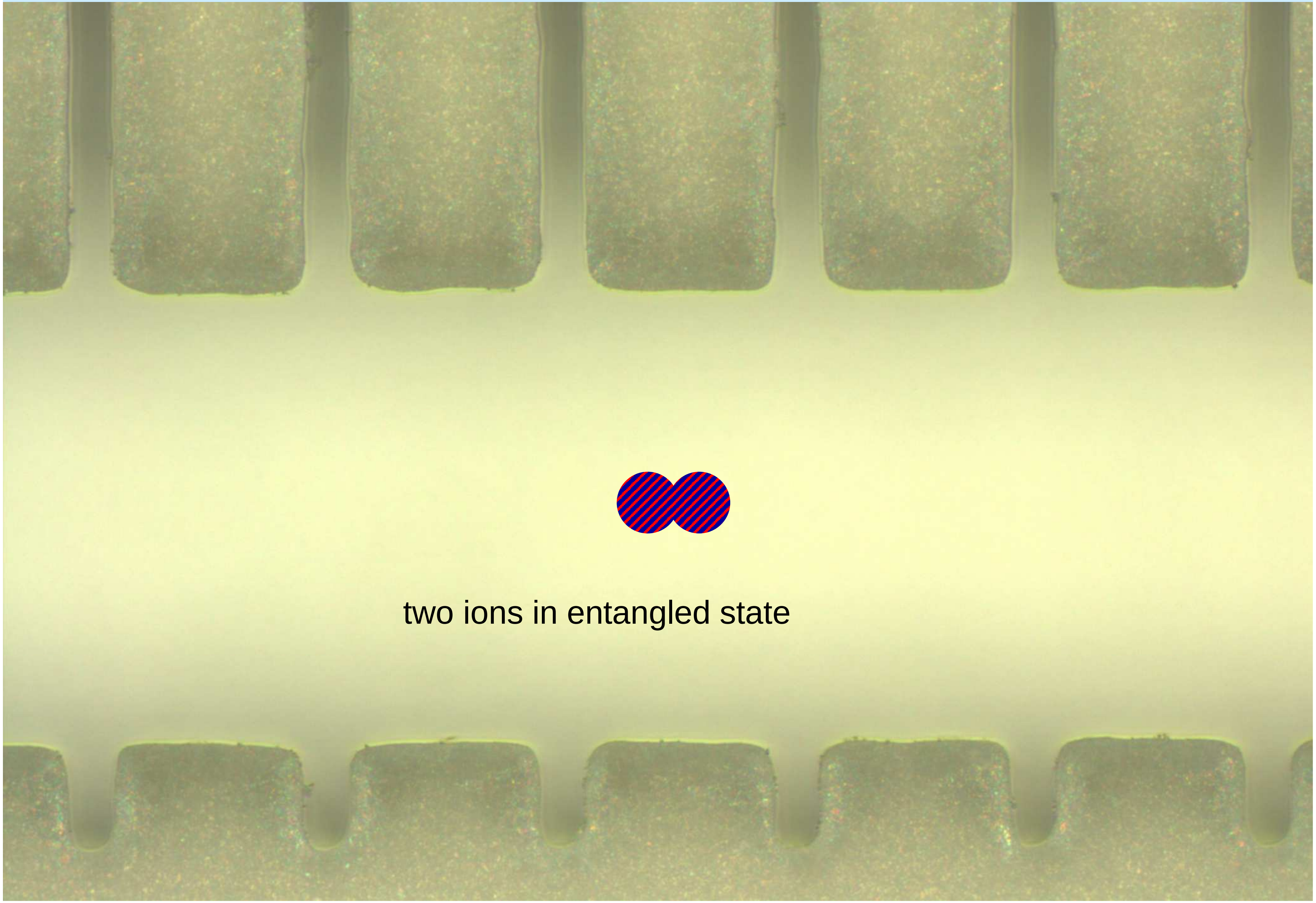
Entanglement by Laser pulses



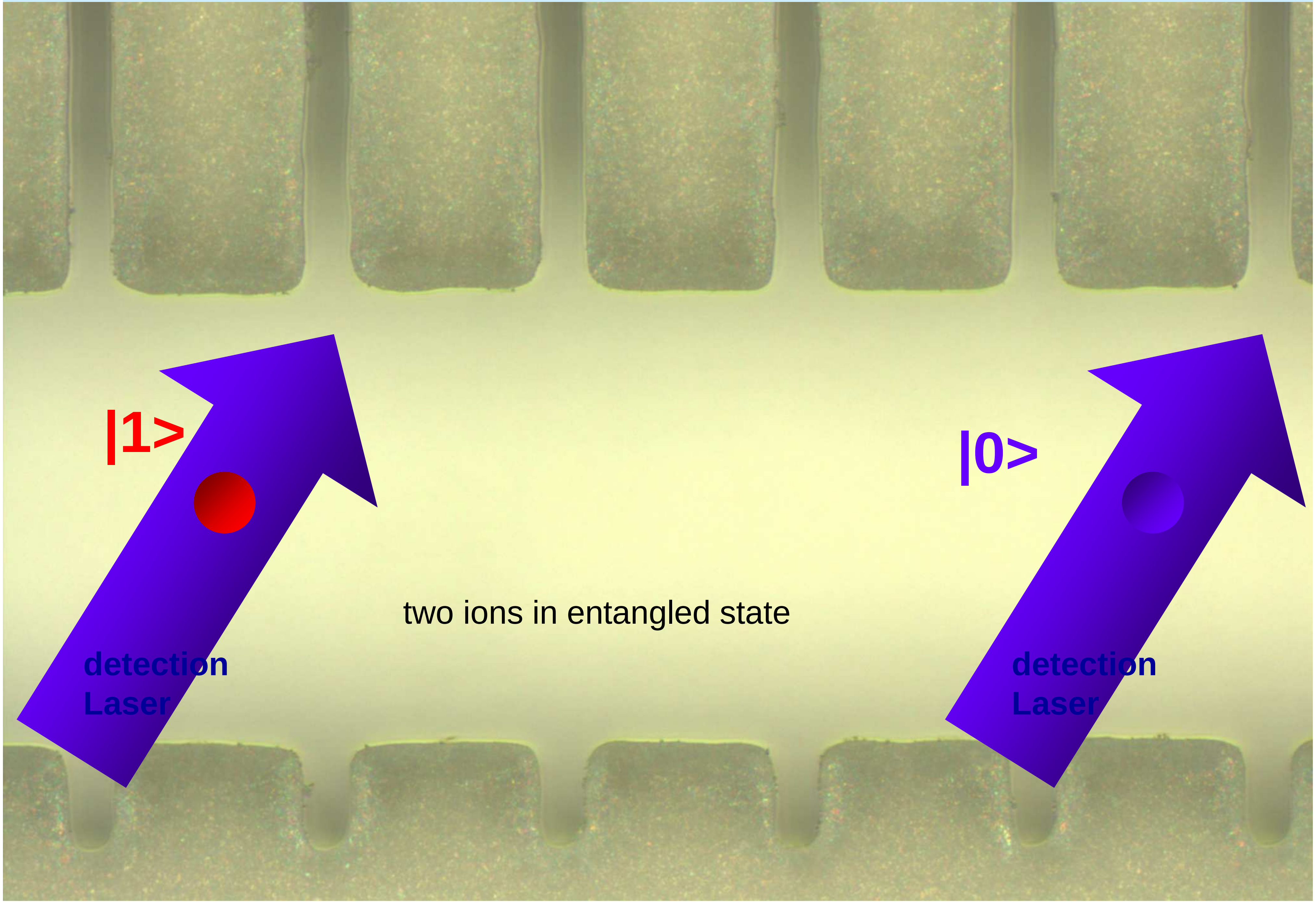
Entanglement by Laser pulses



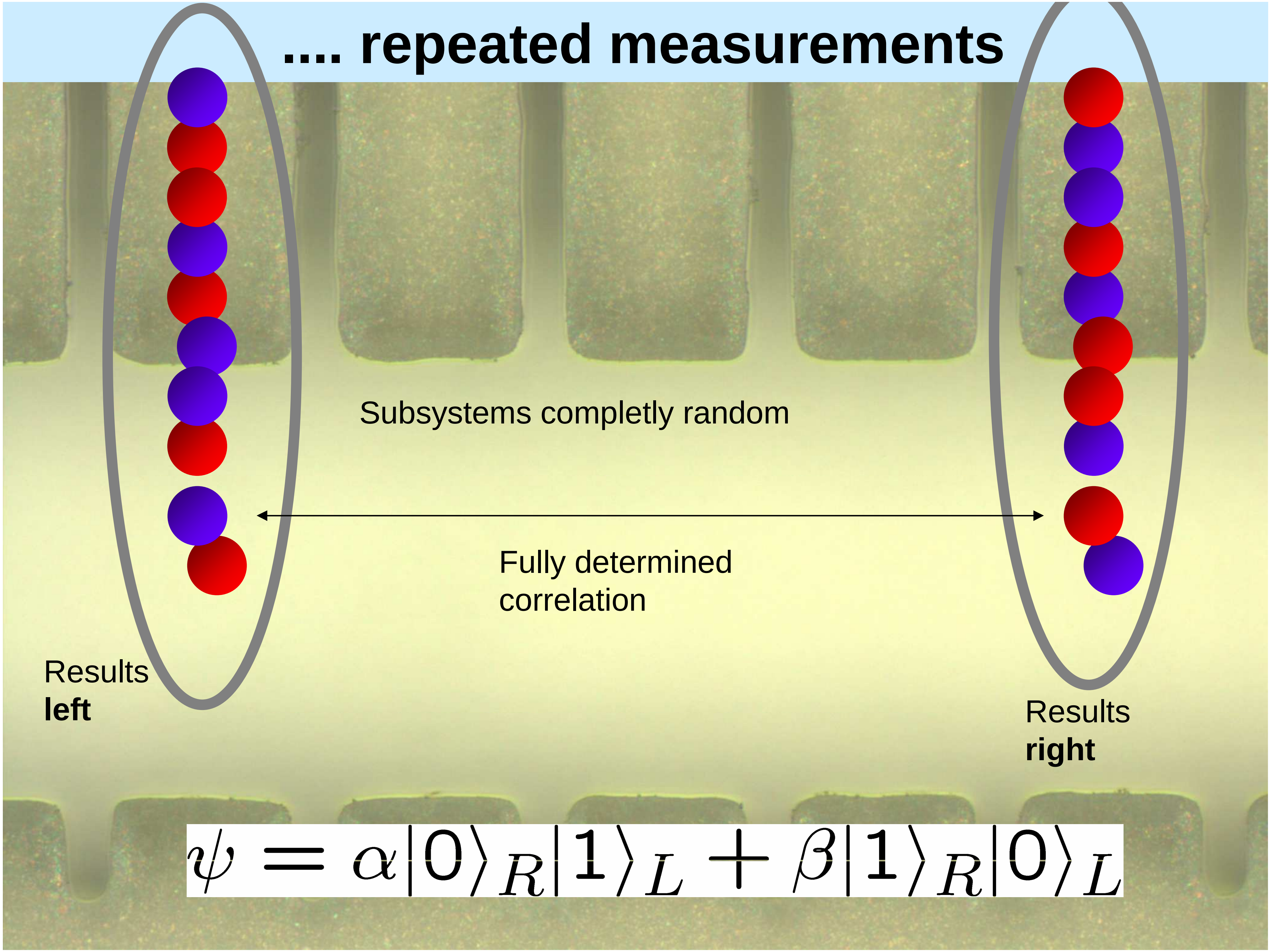
Entanglement by Laser pulses



Measurement

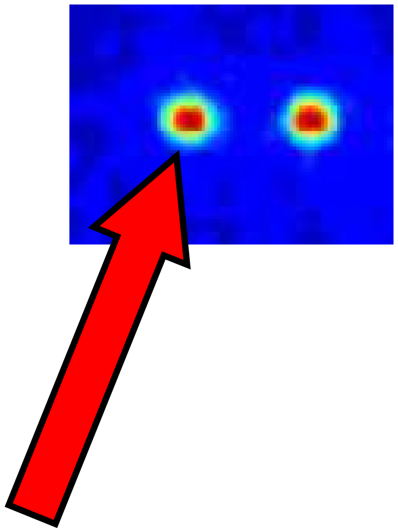


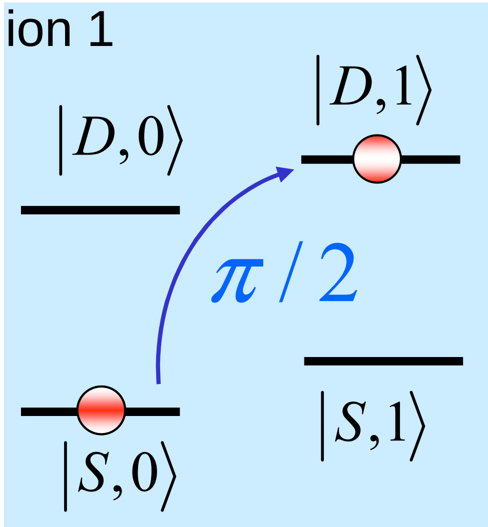
.... repeated measurements



$$\psi = \alpha|0\rangle_R|1\rangle_L + \beta|1\rangle_R|0\rangle_L$$

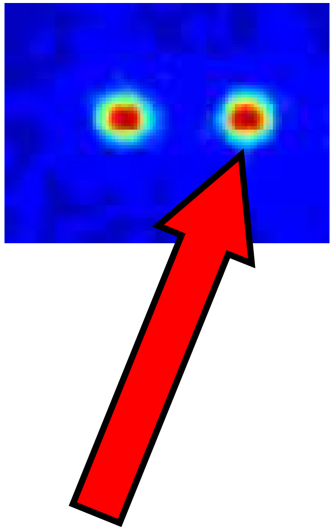
Deterministic Bell state generation

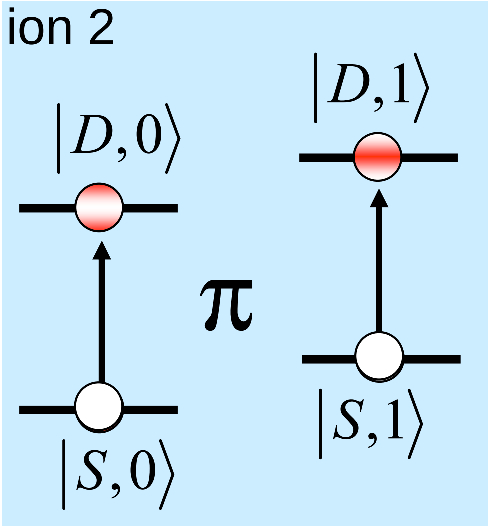




$$|SS\rangle|0\rangle \xrightarrow{\text{blue } \pi/2 \text{ pulse}} |SS,0\rangle + |DS,1\rangle$$

Deterministic Bell state generation

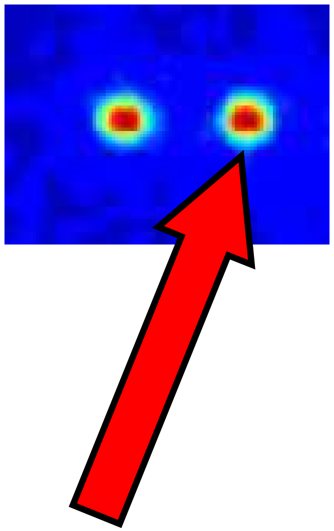


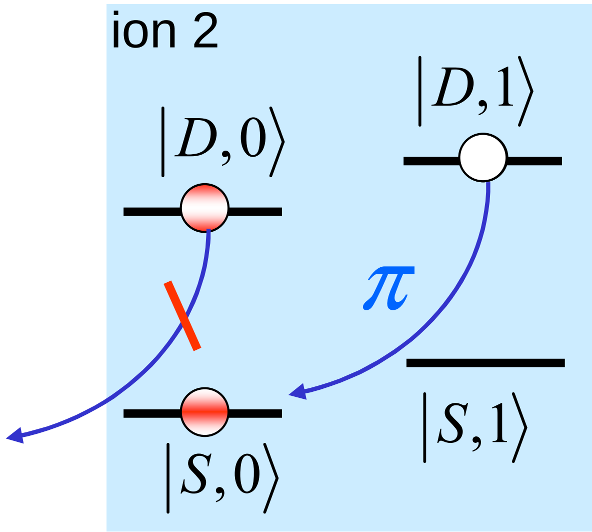


$$|SS\rangle|0\rangle \xrightarrow{\text{blue } \pi/2 \text{ pulse}} |SS,0\rangle + |DS,1\rangle$$

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

Deterministic Bell state generation





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

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

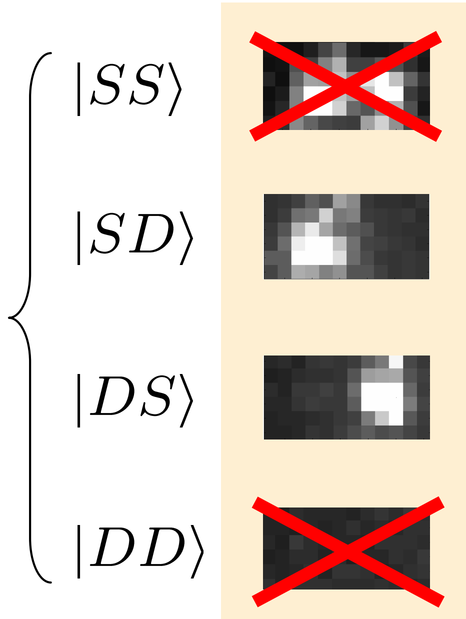
$$\xrightarrow{\text{blue } \pi \text{ pulse}} |SD\rangle|0\rangle + |DS\rangle|0\rangle$$

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:

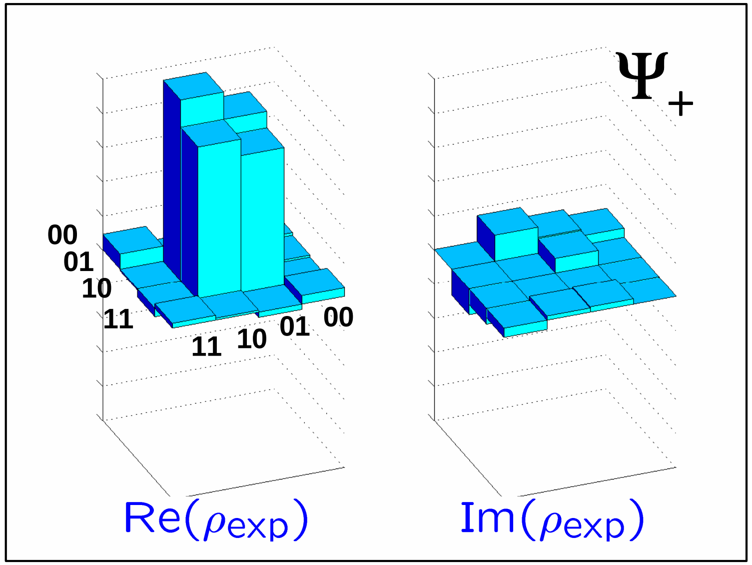


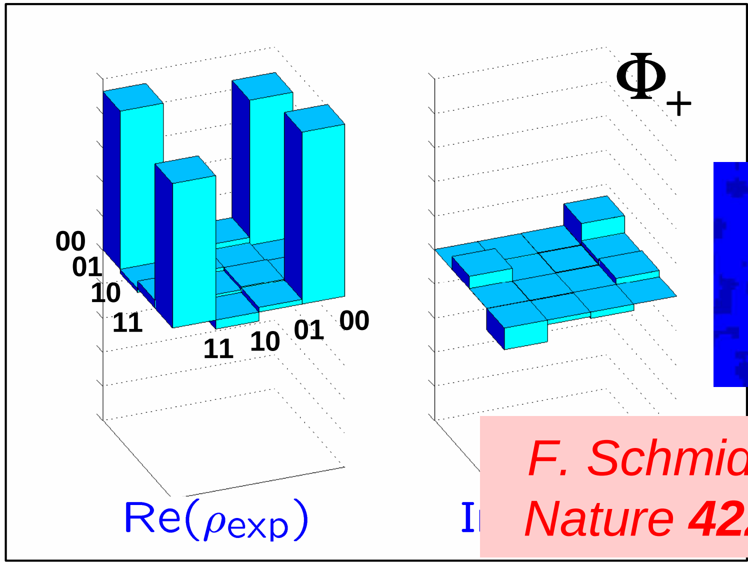
Entire information is contained in the density matrix

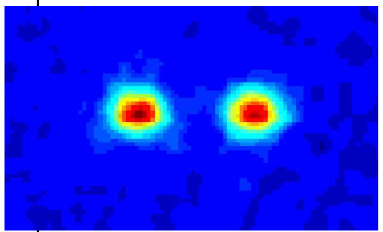
⟶ Measure the density matrix

Density matrix for 2 ion entanglement

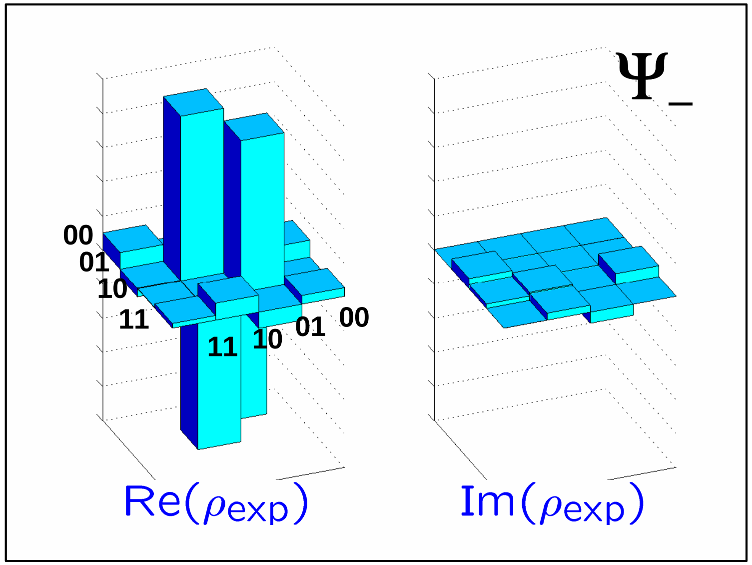
$$\psi = |0\rangle|1\rangle + e^{i\phi}|1\rangle|0\rangle \qquad \phi = |1\rangle|1\rangle + e^{i\phi}|0\rangle|0\rangle$$

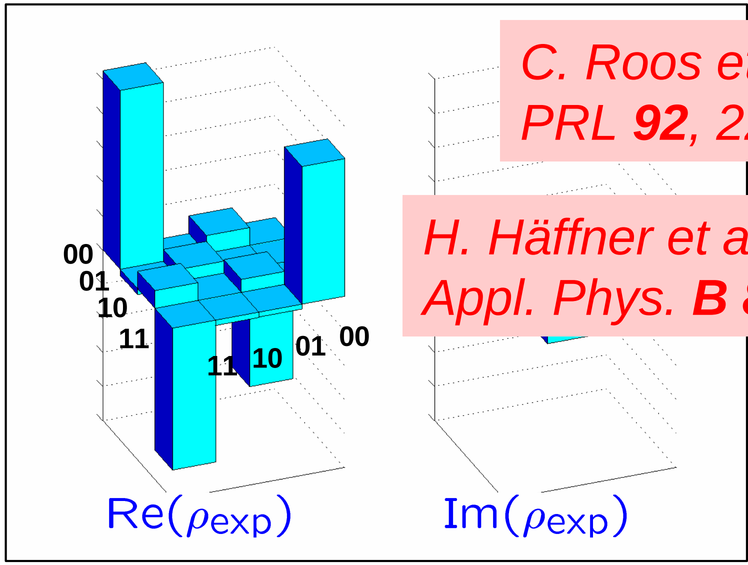






F. Schmidt-Kaler et al.,
*Nature **422**, 408 (2003)*





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

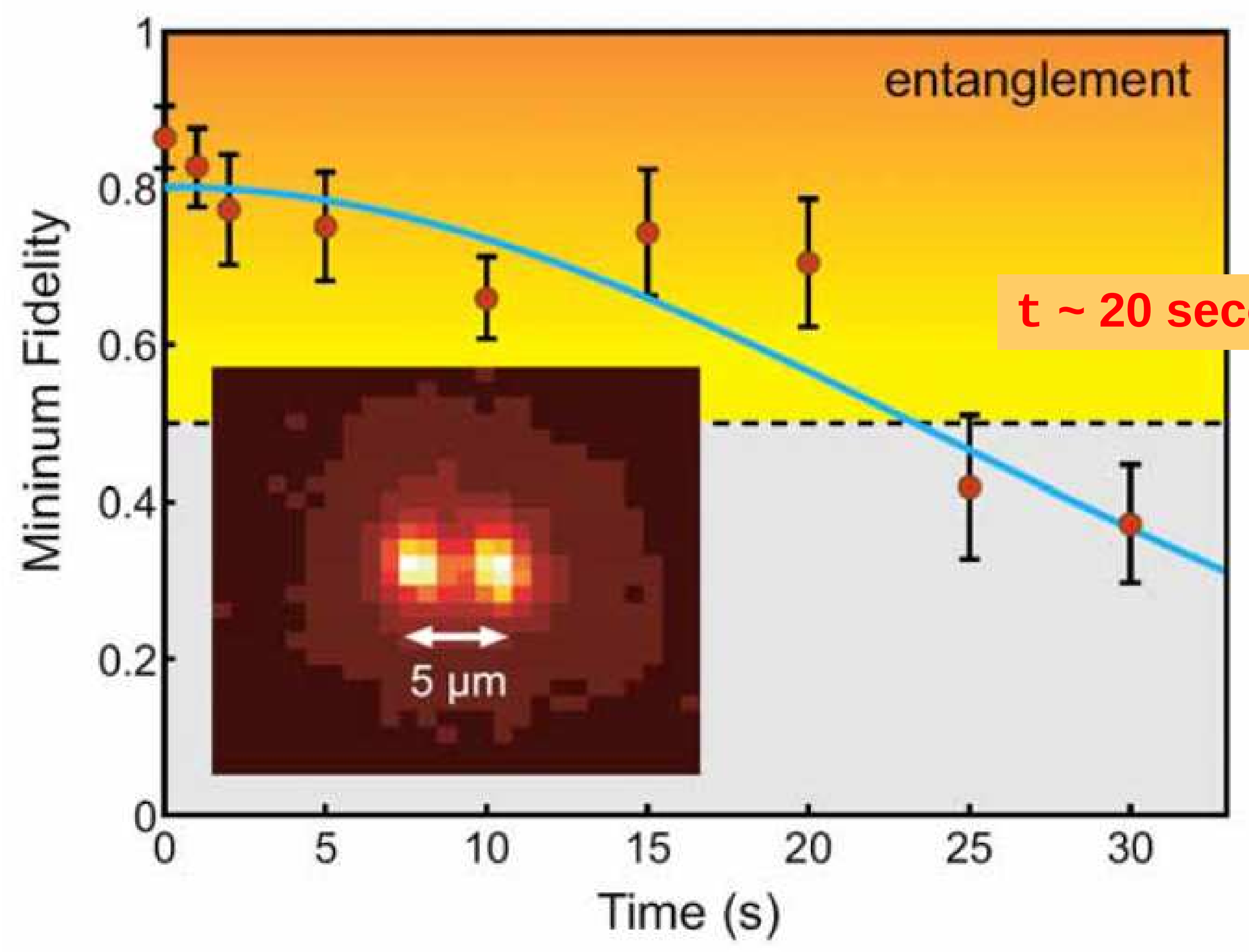
H. Häffner et al,
*Appl. Phys. **B 81**, 151 (2005)*

Decoherence-free Bell states

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

$$\psi = |S_-\rangle|S_+\rangle + e^{i\phi}|S_+\rangle|S_-\rangle$$

entanglement in Zeeman levels m=±1/2



t ~ 20 seconds

John Bell

What is Entanglement?

Properties of the
complete system are fully determined,

but properties of sub-systems
completely undeterined

Erwin Schrödinger 1935:

"I would call entanglement not one but rather *the characteristic trait* of quantum mechanics, the one that enforces its entire departure from classical lines of thought."

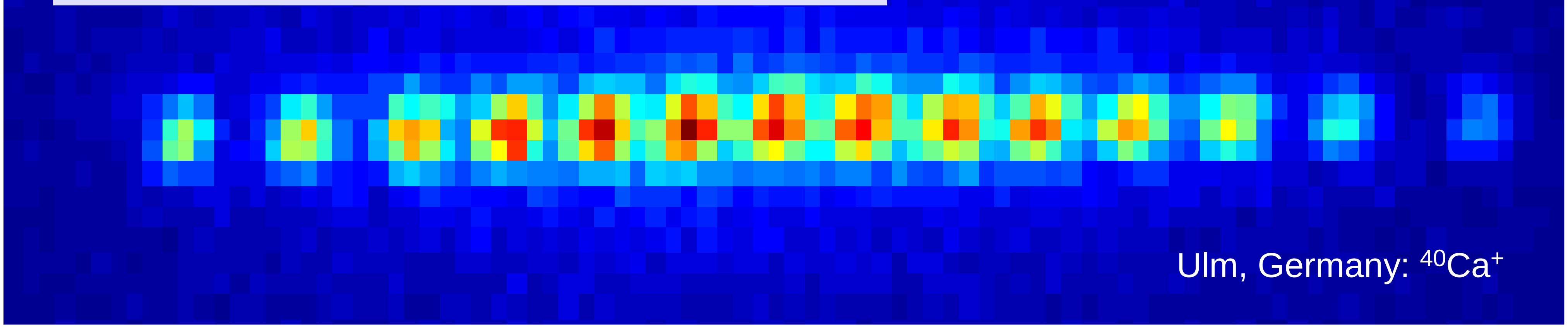
Cold Ions and their Applications for Quantum Computing and Frequency Standards

- Trapping Ions
- Cooling Ions
- Superposition and Entanglement
- **Quantum computer: basics, gates, algorithms, future challenges**
- Ion clocks: from Ramsey spectroscopy to quantum techniques

- single qubit gate
- various two qubit gates

… baby-steps shown so far with ion quantum processors

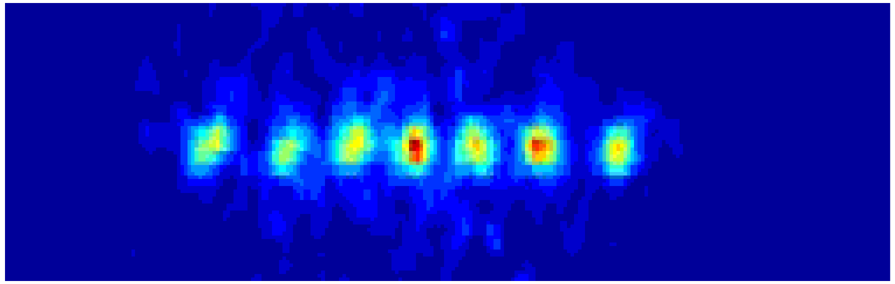
- and how to reach a scalable device in future



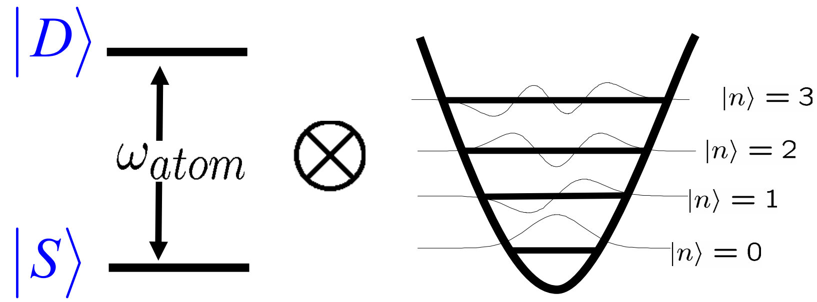
III) Quantum computing with trapped ions

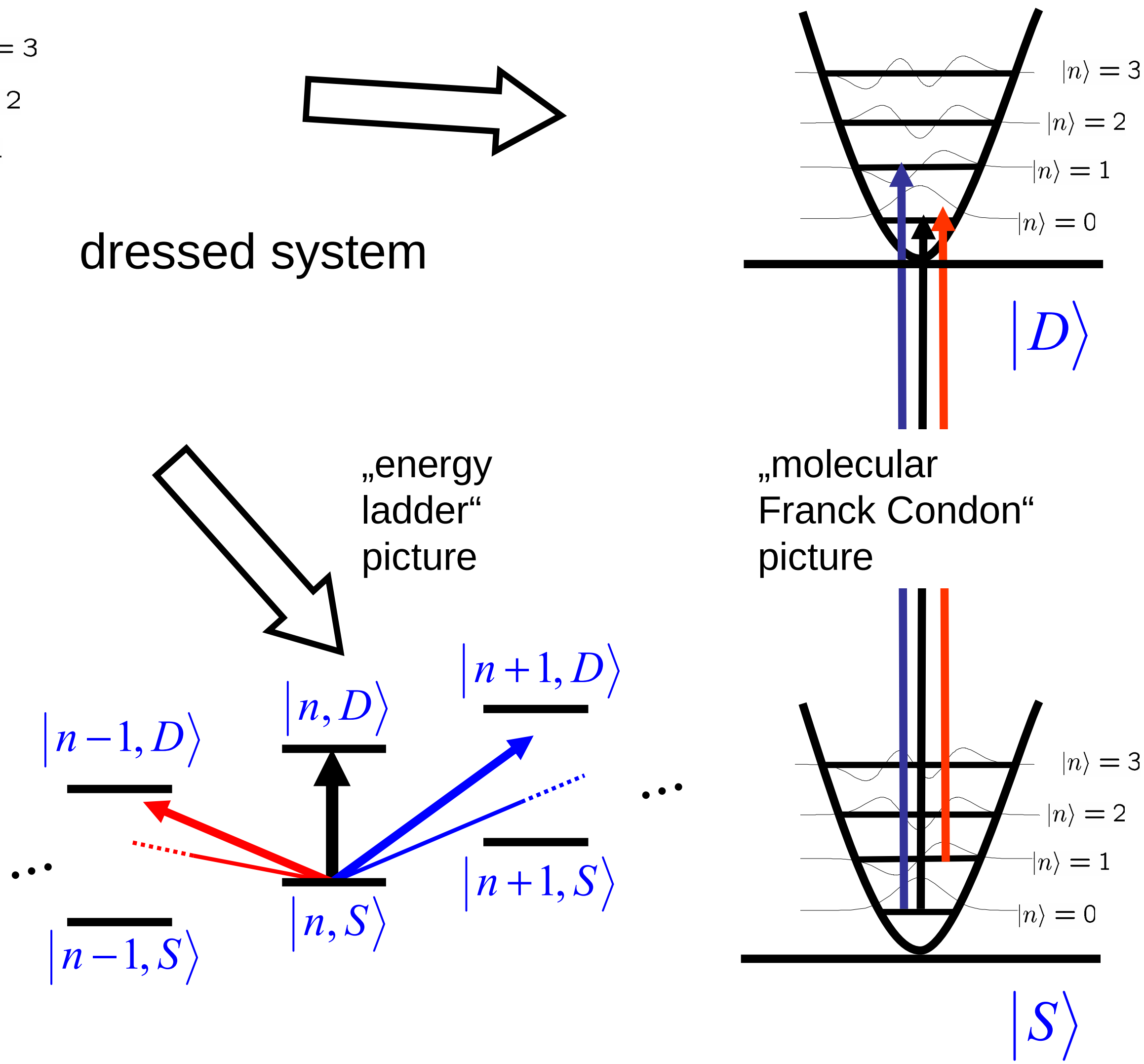
Quantum computation, basic description and single qubit gates,
Cirac-Zoller two qubit gate operation, other two qubit gates
long lived Bell states
GHZ- and W-states
Teleportation with ions

Laser coupling

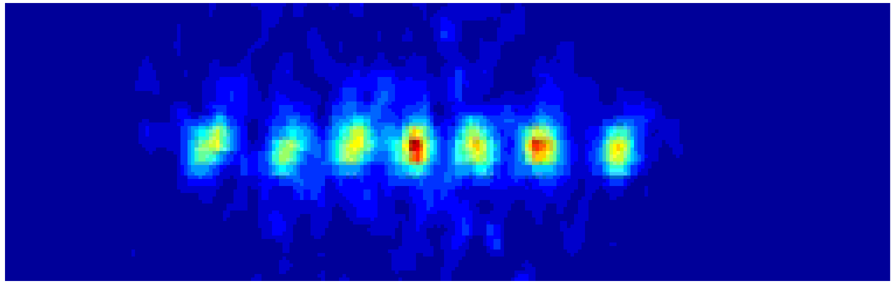


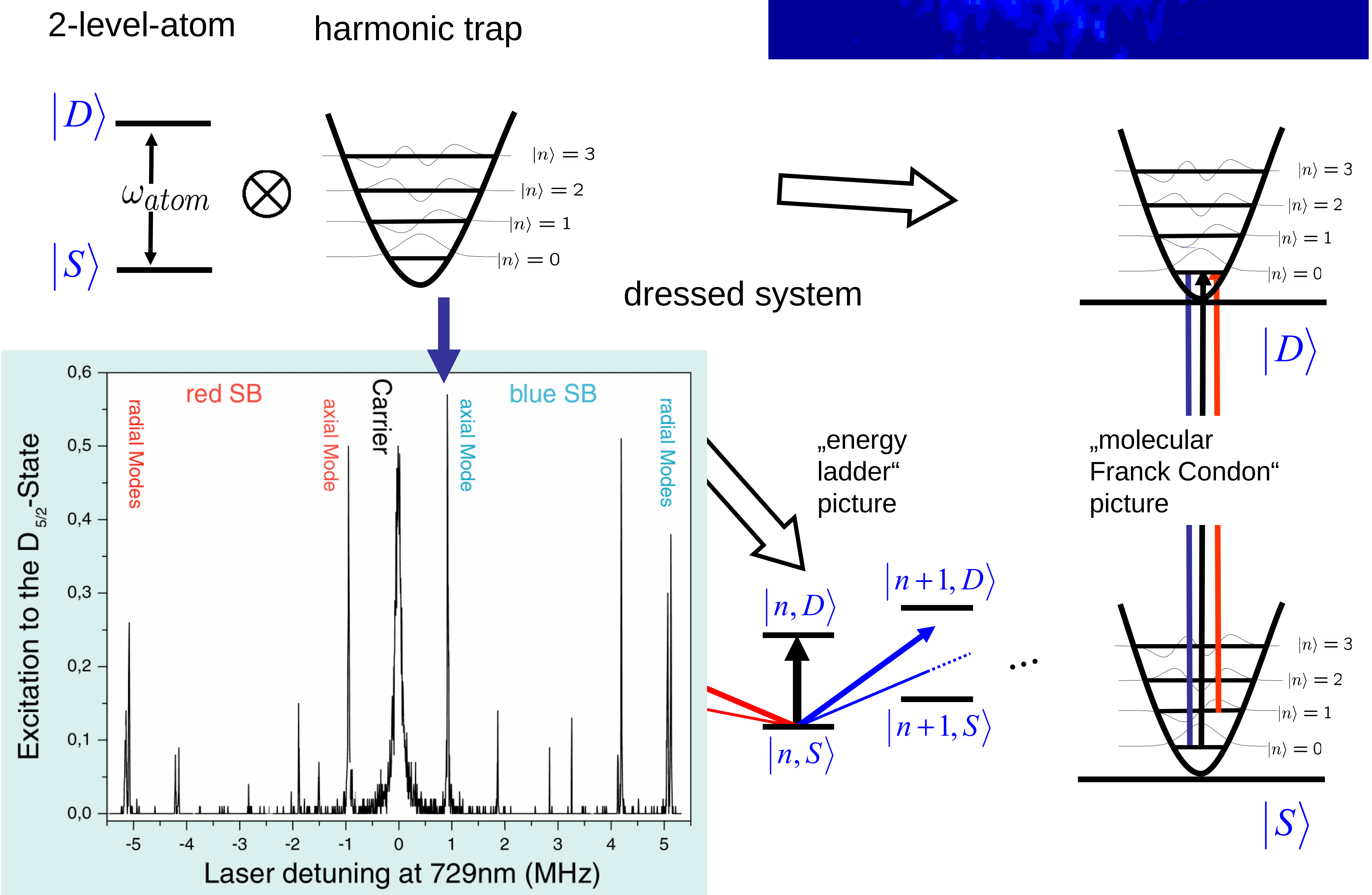
2-level-atom   harmonic trap



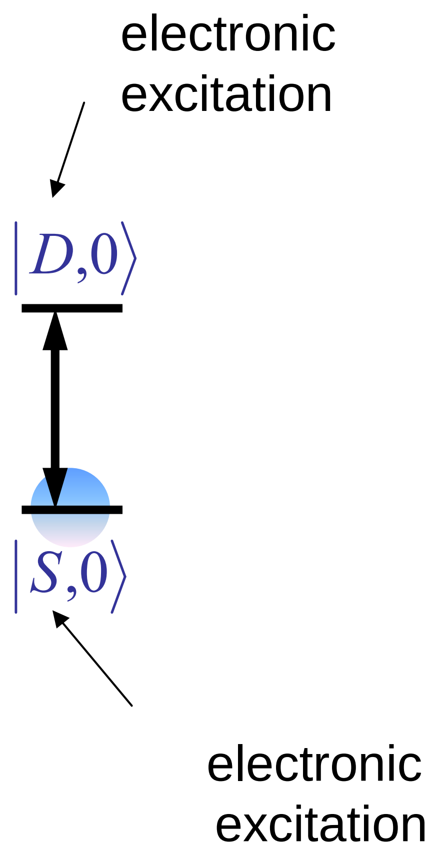


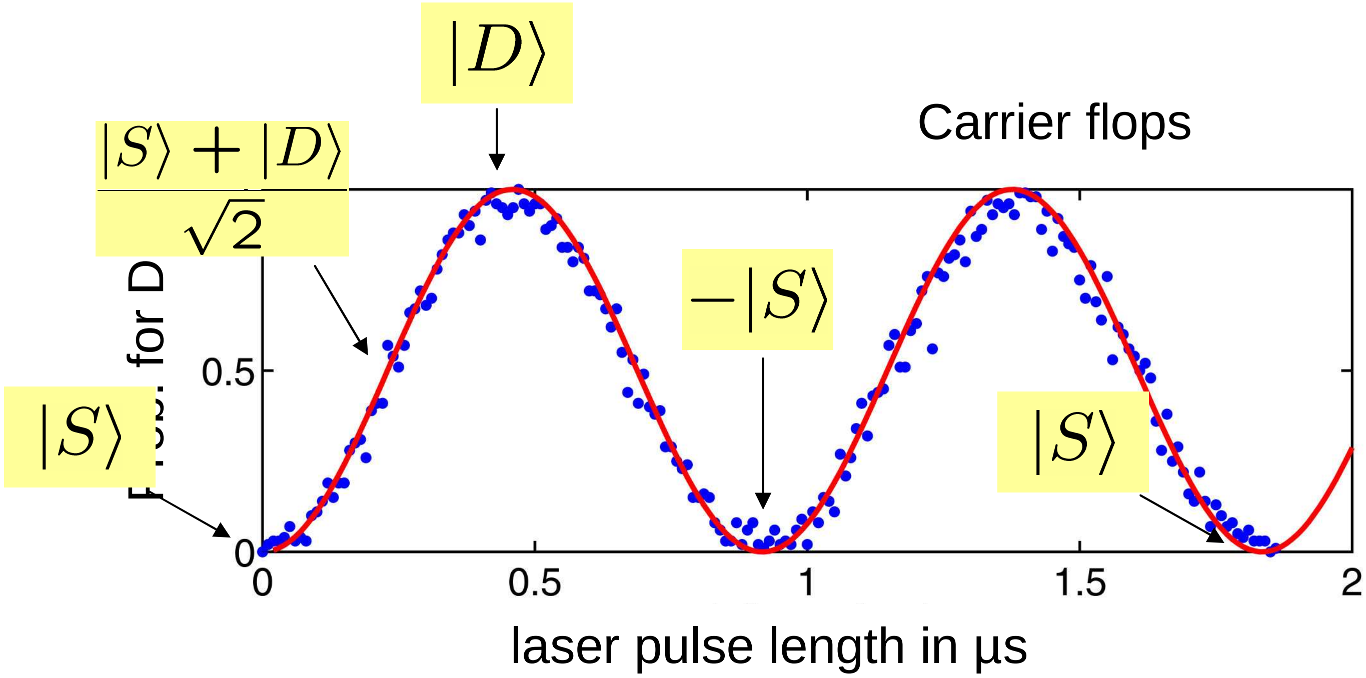
Laser coupling



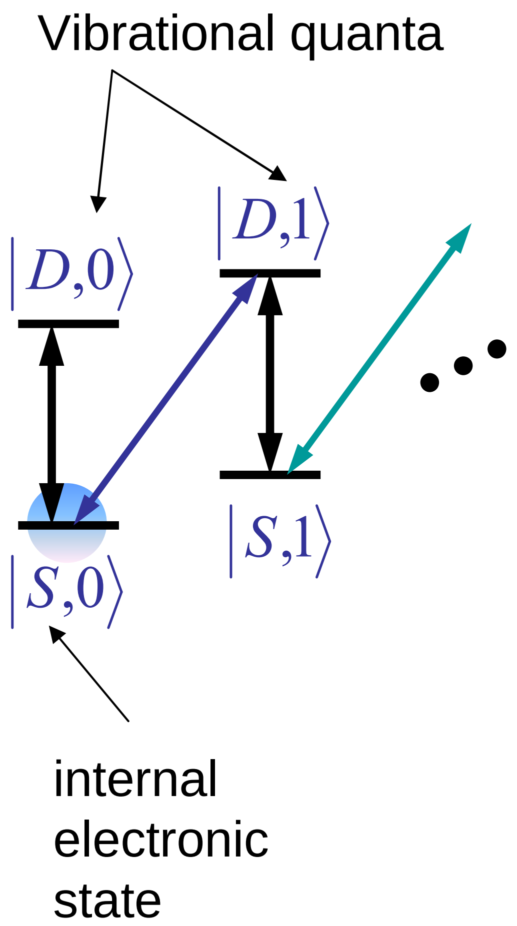


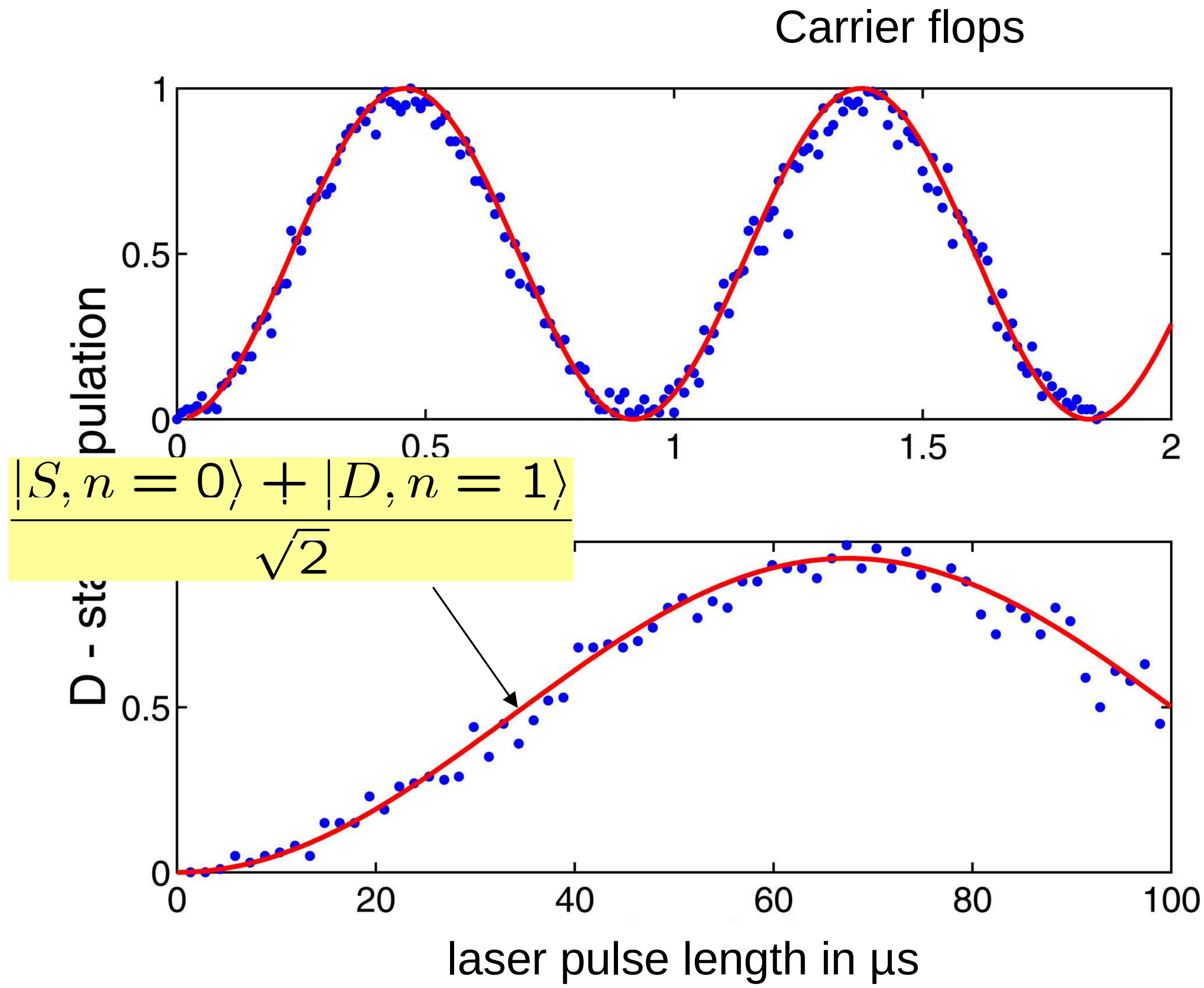
Coherent qubit rotation



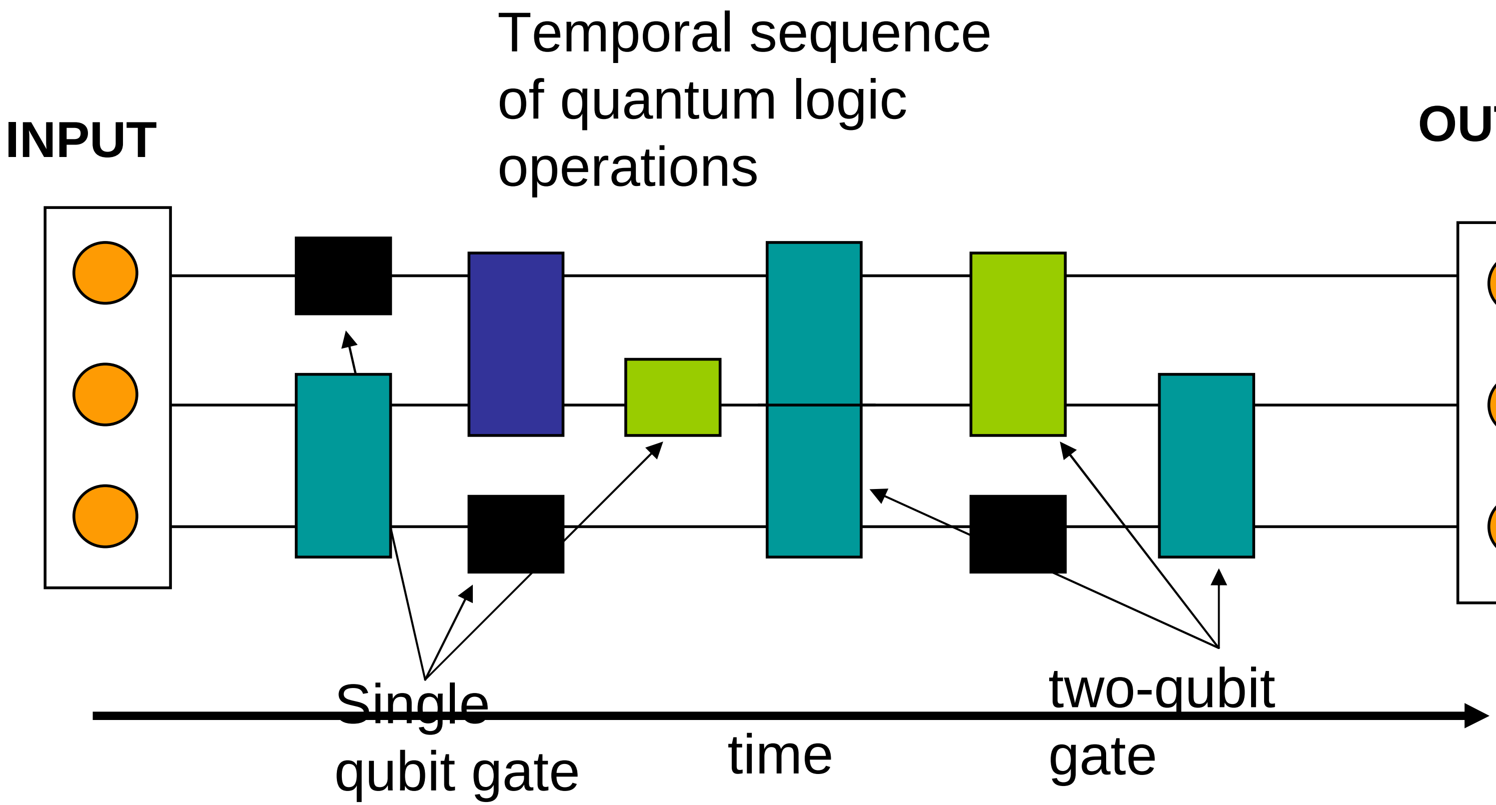


Coherent qubit rotation





Basics of a quantum computer



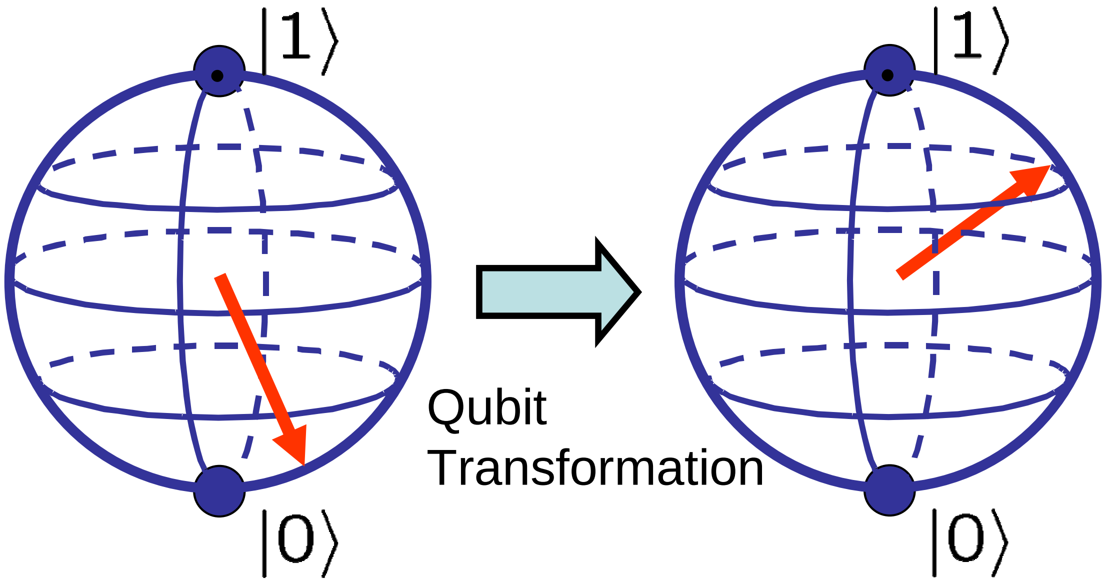
Why?

→ **applications in physics and informatics**

- P. Shor, 1994: factorization of large numbers, L digits, is much more efficient on a quantum computer than with a classical computer:
  classical computer: $\sim\exp(L^{1/3})$, quantum computer: $\sim L^2$
- L. Grover, 1997: search data base - quantum computer: $\sim \sqrt{L}$
- simulation of Schrödinger equations or any unitary evolution
- spin interactions, quantum phase transitions
- quantum cryptography / repeaters / quantum links
- improved atomic clocks
- understanding the fundamentals of quantum mechanics / Gedanken-Experimente
- Experiments with entangled matter

The requirements for experimental qc

- Qubits store superposition information, scalable physical system
- Ability to initialize the state of the qubits $|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$
- Universal set of quantum gates: Single bit and two bit gates
- Long coherence times, much longer than gate operation time
- Qubit-specific measurement capability



D. P. DiVincenzo, Quant. Inf. Comp. 1 (Special), 1 (2001)

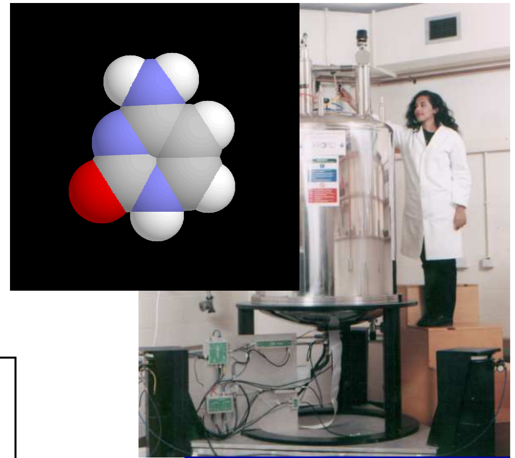
Experimental status

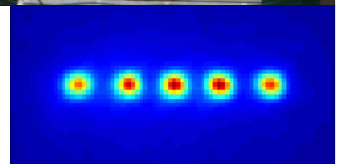
Scalable device?

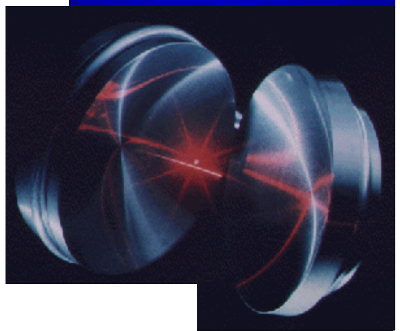
Table 4.0-1

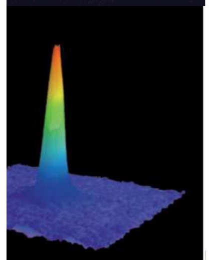
…um Computation Roadmap: Promise Criteria

QC Approach	The DiVincenzo Criteria: Quantum Computation #1	#2	#3	#4	#5		QC Networkability #6	#7
NMR	red	yellow	yellow	green	yellow		red	red
Trapped Ion	yellow	green	yellow	green	green		yellow	yellow
Neutral Atom	yellow	green	yellow	yellow	yellow		yellow	yellow
Optical	green	yellow	green	yellow	yellow		yellow	green
Solid State	yellow	yellow	yellow	red	yellow		red	red
Superconducting	yellow	green	yellow	yellow	yellow		red	red
Unique Qubits								







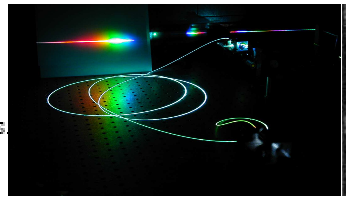


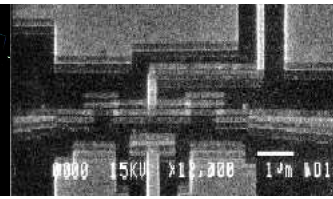
"… it seems that the laws of physics present no barrier to reducing the size of computers until bits are the size of atoms, and quantum behavior holds sway."

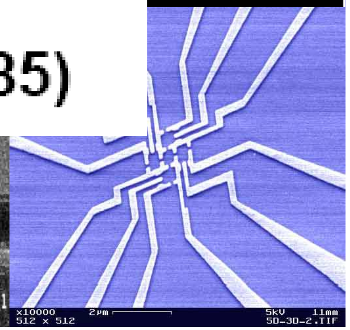
Richard P. Feynman (1985)

Quantum Information Roadmaps
http://qist.ect.it/
http://qist.lanl.gov/

ations







Quantum gate proposal

W. Paul J. I. Cirac P. Zoller

74, NUMBER 20 4091 PHYSICAL REVIEW LETTERS 15 MAY 1995

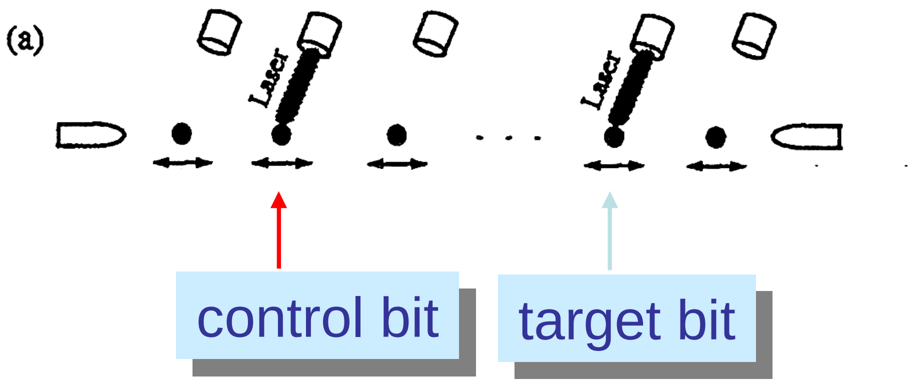
Quantum Computations with Cold Trapped Ions

J. I. Cirac and P. Zoller*

Institut für Theoretische Physik, Universität Innsbruck, Technikerstrasse 25, A-6020 Innsbruck, Austria

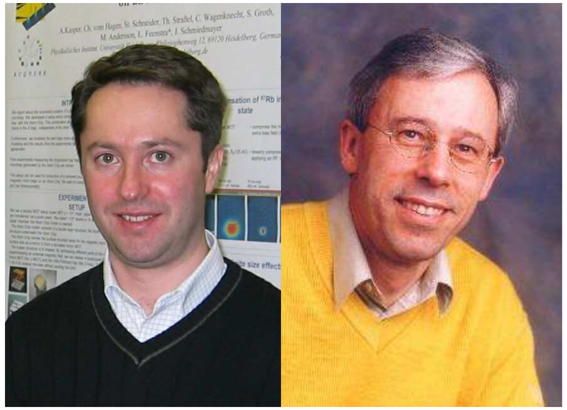
(Received 30 November 1994)

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

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

$$|0\rangle|0\rangle \to |0\rangle|0\rangle$$

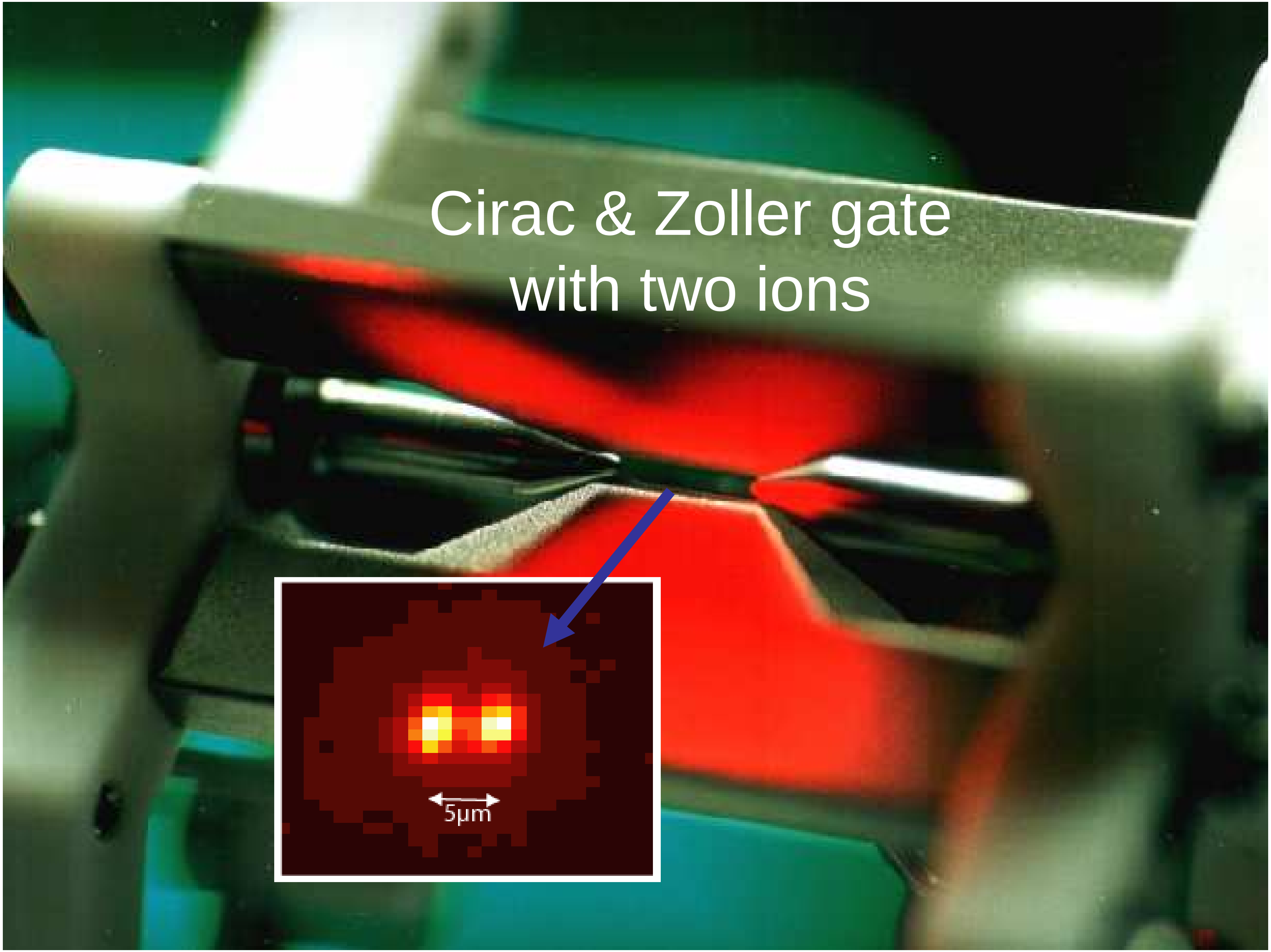
$$|0\rangle|1\rangle \to |0\rangle|1\rangle$$

$$|1\rangle|0\rangle \to |1\rangle|1\rangle$$

$$|1\rangle|1\rangle \to |1\rangle|0\rangle$$

control bit target bit

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


Cirac & Zoller gate
with two ions
5µm

Controlled-NOT operation

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

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

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

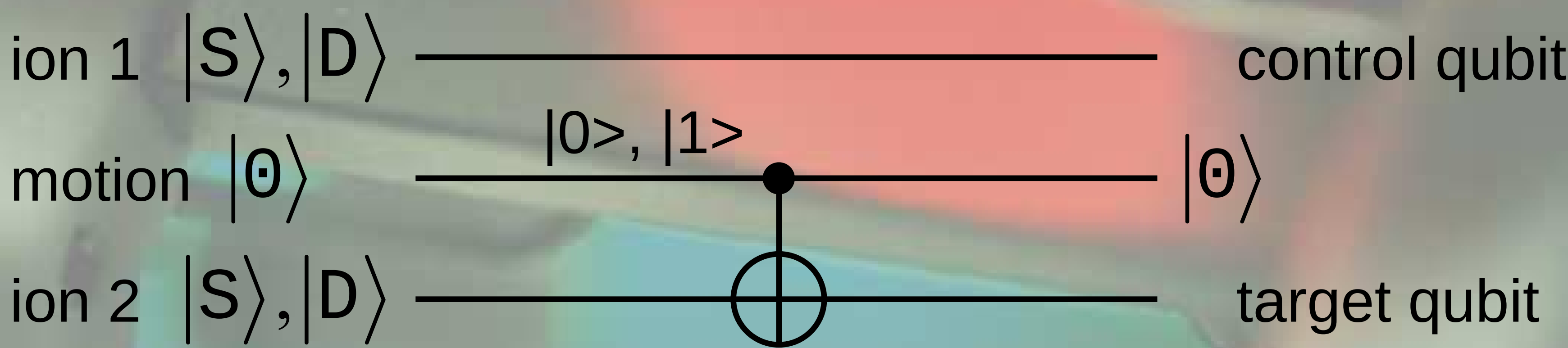
$$|D\rangle|D\rangle \rightarrow |D\rangle|S\rangle$$

control target

Controlled-NOT operation

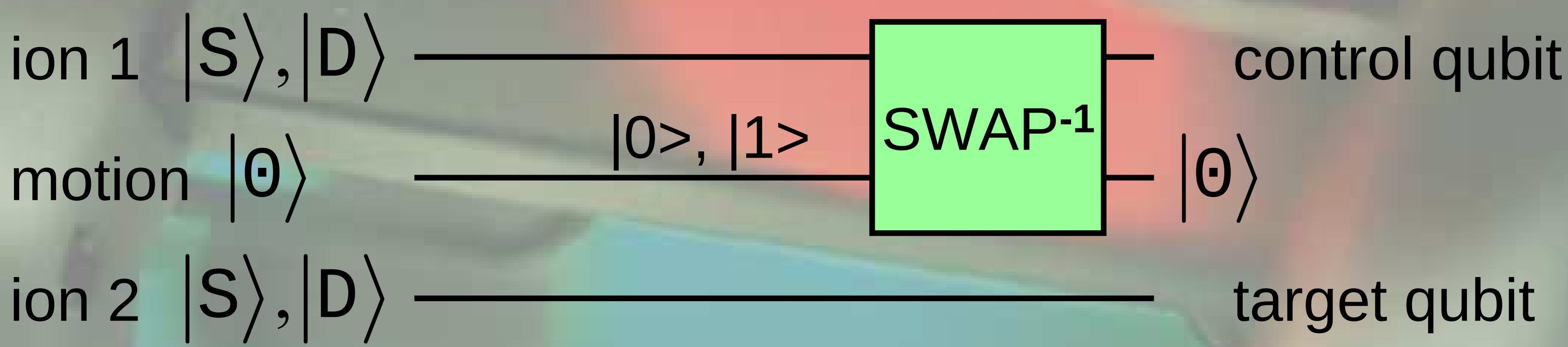
$$|\varepsilon_1\rangle \quad |\varepsilon_2\rangle$$

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



Controlled-NOT operation

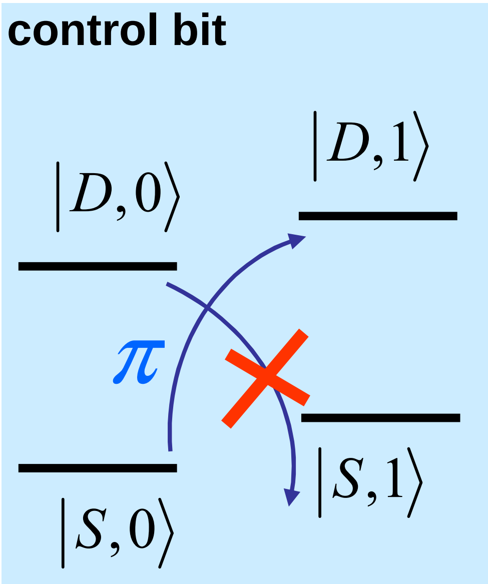
$$|S\rangle|S\rangle \rightarrow |S\rangle|S\rangle$$
$$|S\rangle|D\rangle \rightarrow |S\rangle|D\rangle$$
$$|D\rangle|S\rangle \rightarrow |D\rangle|D\rangle$$
$$|D\rangle|D\rangle \rightarrow |D\rangle|S\rangle$$



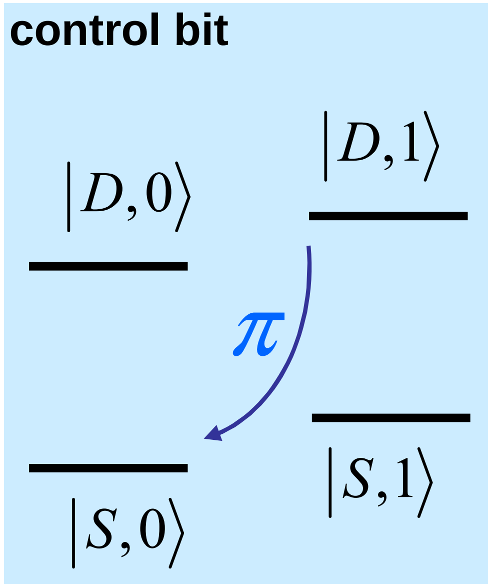
SWAP and SWAP^{-1}

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

π-pulse on blue SB

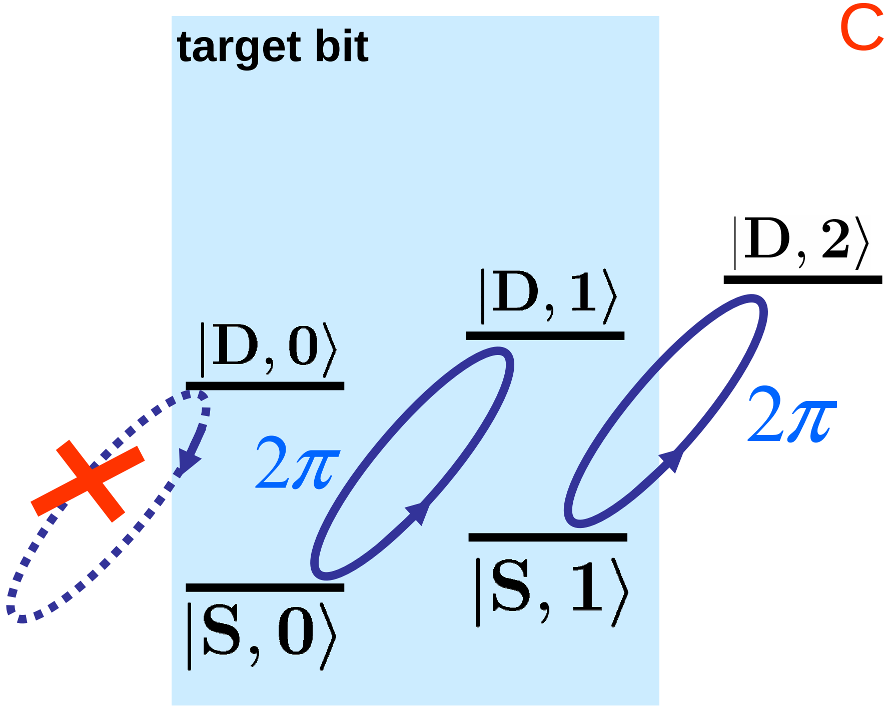


SWAP



SWAP^{-1}

Conditional phase gate



Composite pulse phase gate

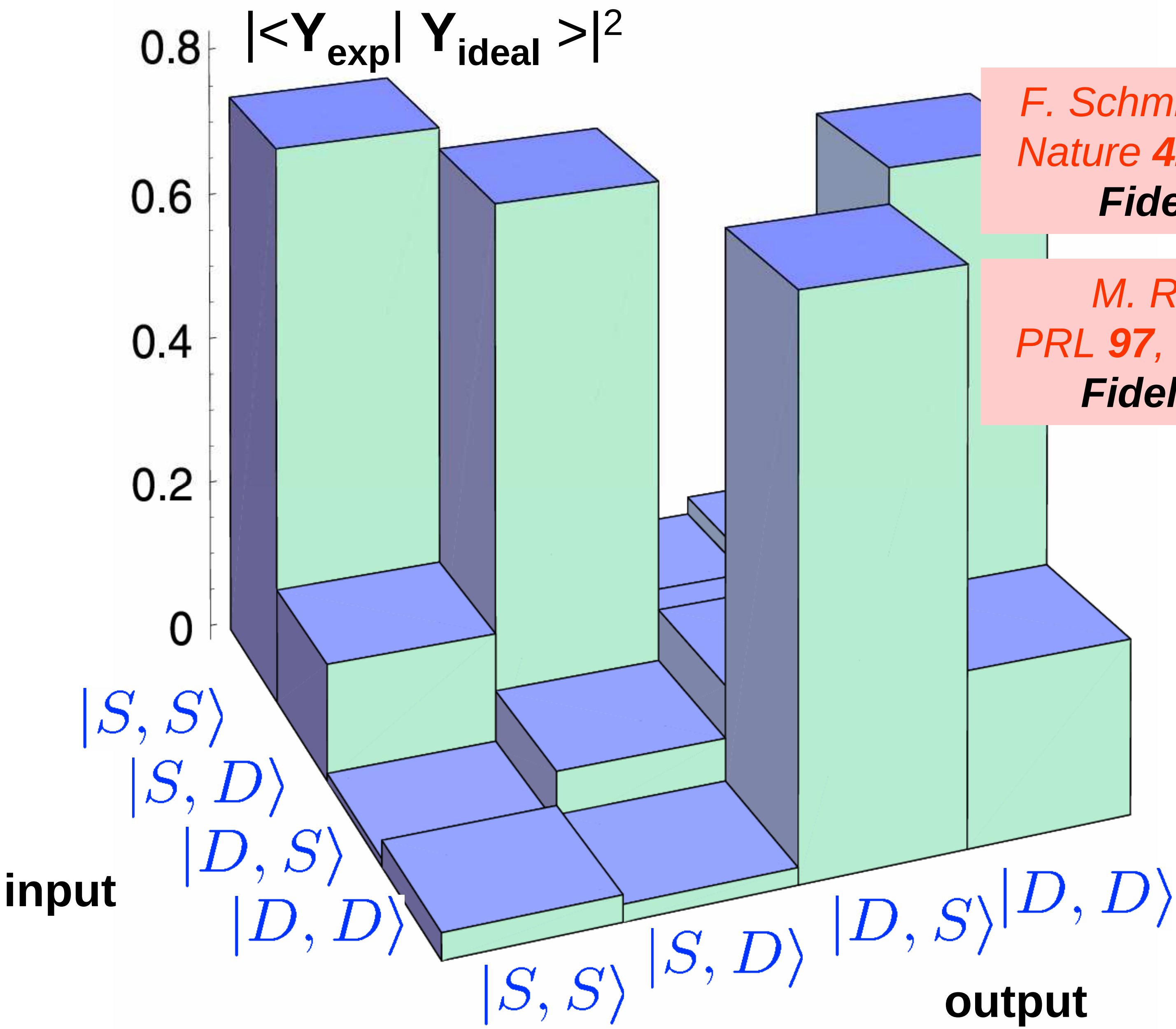
I.Chuang,
MIT Boston

Rabi frequency:

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

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

Fidelity of Cirac-Zoller CNOT

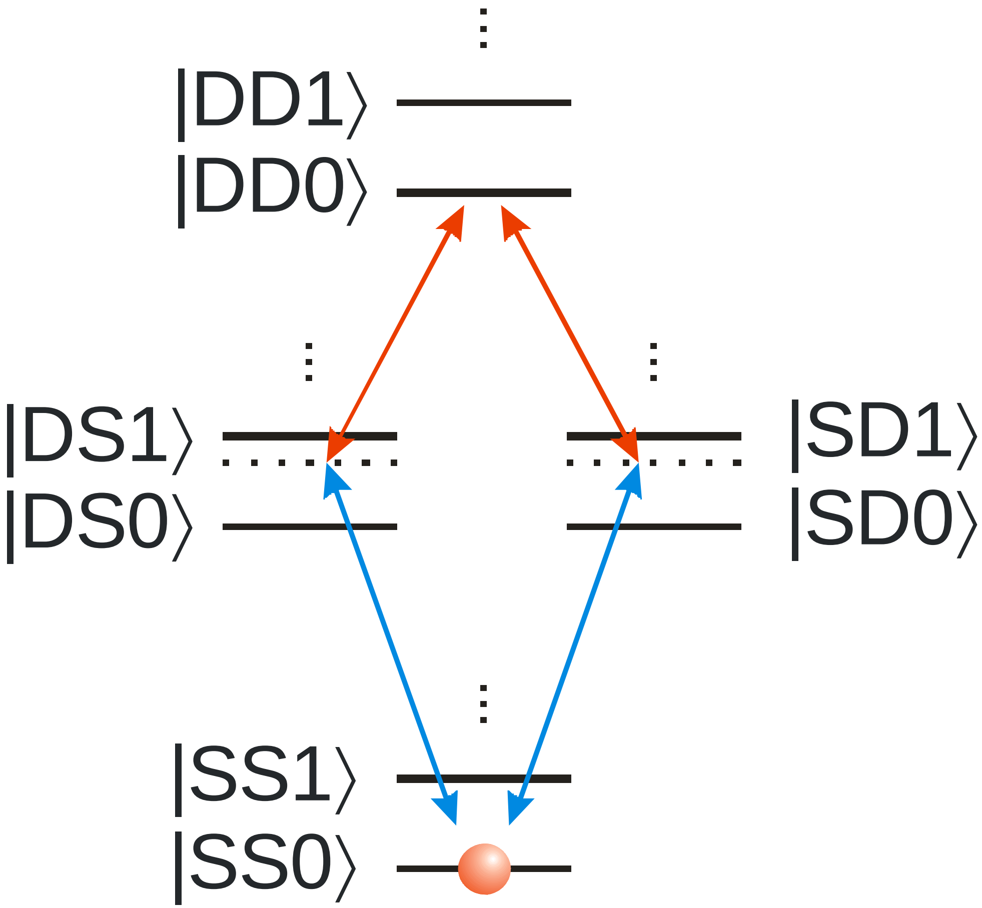


F. Schmidt-Kaler et al.,
*Nature **422**, 408 (2003)*
Fidelity : 73%

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

Bichromatic two-qubit gate

Milburn, arXiv:quant-ph/9908037.
Milburn, Schneider, and James, Fortschr. Phys. ***48****, 801 (2000).*
Sörensen and Mölmer, PRL ***82****, 1971 (1999).*
Sörensen and Mölmer, PRA ***62****, 022311 (2000).*



The common absorption of red and blue detuned light leads to a coherent evolution |SS> to |DD>. No excitation of |DS> states.
Requires only Lamb Dicke limit $\eta\sqrt{n_{ther.}} << 1$

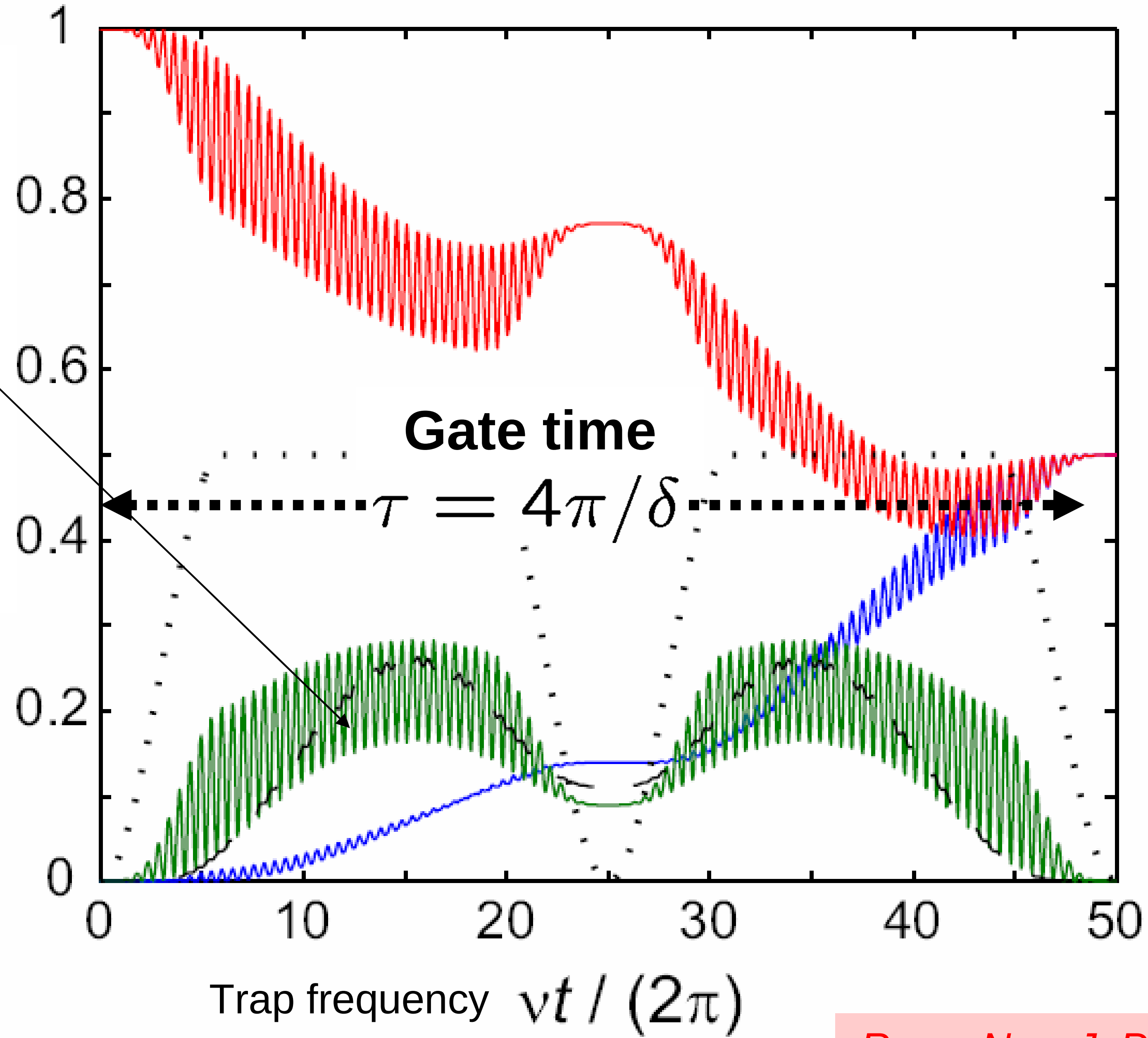
Bell state with F=83%
Sackett et al., Nature ***406****, 256 (2000)*

Bichromatic two-qubit gate

For slow evolution no excitation of the states |SD> and |DS>

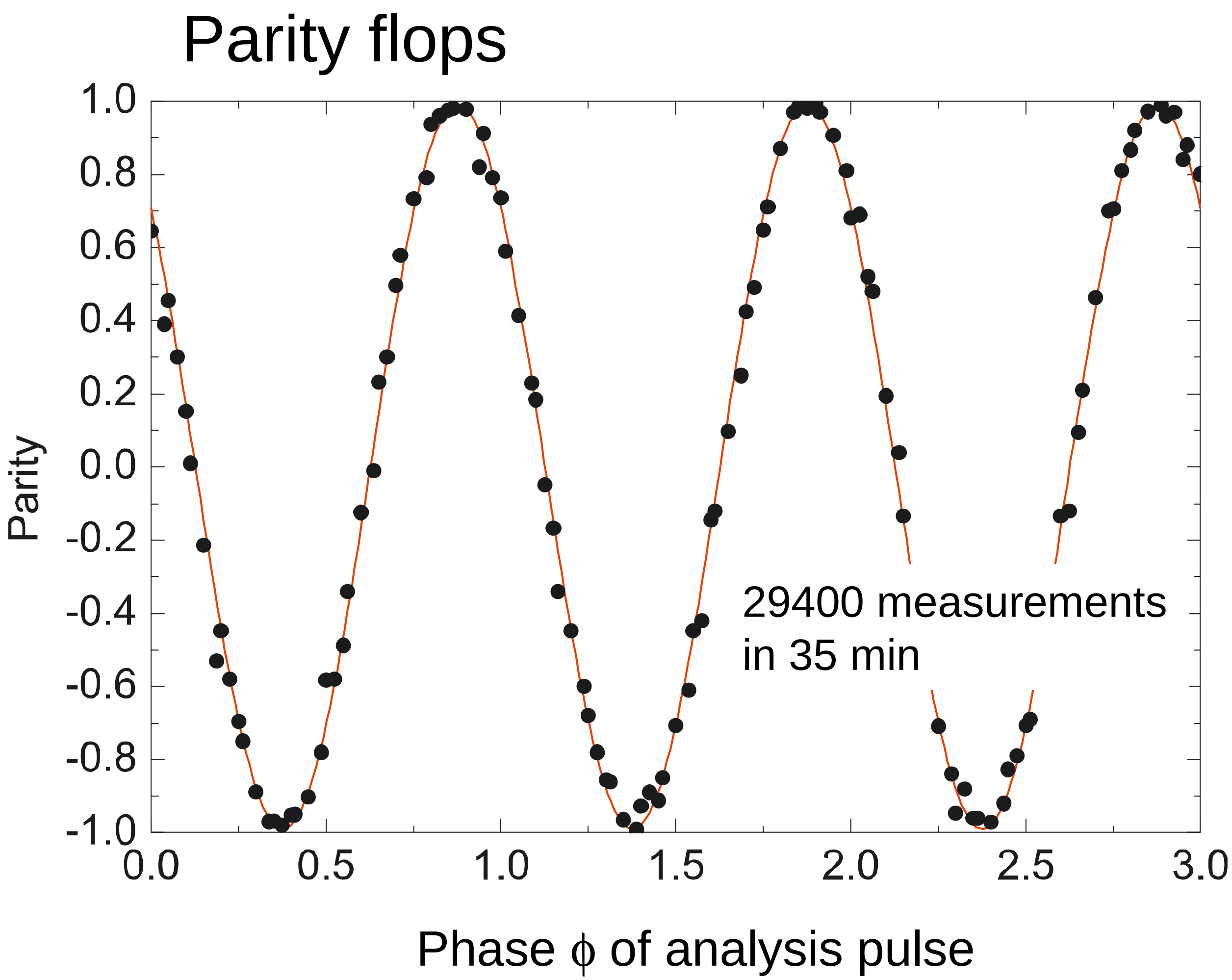
For fast evolution excitation and de-excitation

Amplitude shaped laser pulses help improving F > 99.9%



Roos, New J. Phys. 10, 013002, (2008)

Fidelity of the created Bell state



$$P_{\text{fit}}(\phi) = A\sin(2\phi + \phi_0)$$

A = 0.990(1)

p_0+p_2 = 0.9965(4)

Bell state analysis
$|SS\rangle + i|DD\rangle$
$\rightarrow$ global $\pi/2$ pulse
with variable phase ϕ

Parity:
$\Pi \equiv p_0 + p_2 - p_1$

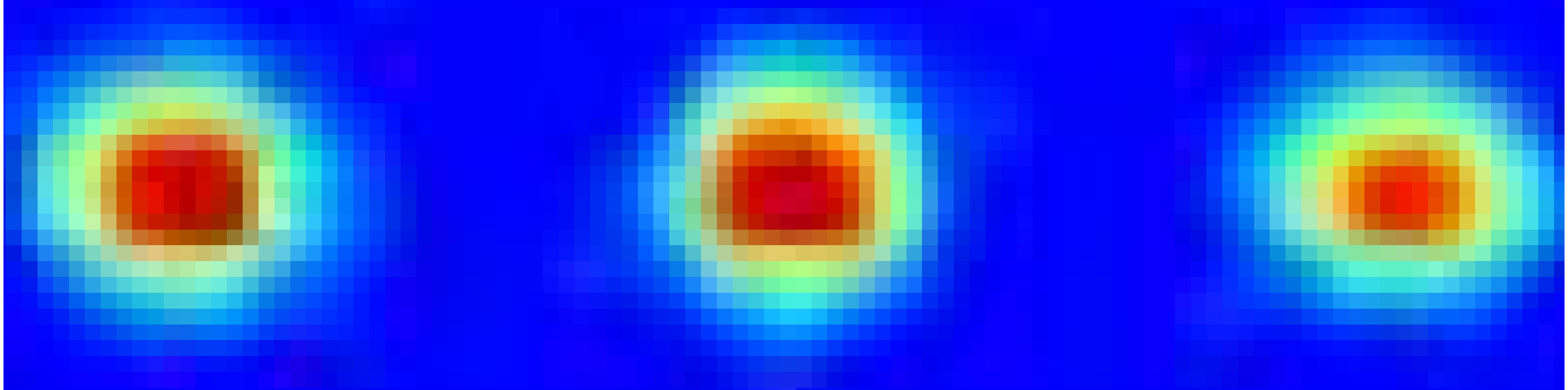
$\rightarrow$ F = 99.3(1)%

F_{21}=80%

Roos et al, unpublished data

GHZ state:

$$|SSS + DDD\rangle$$

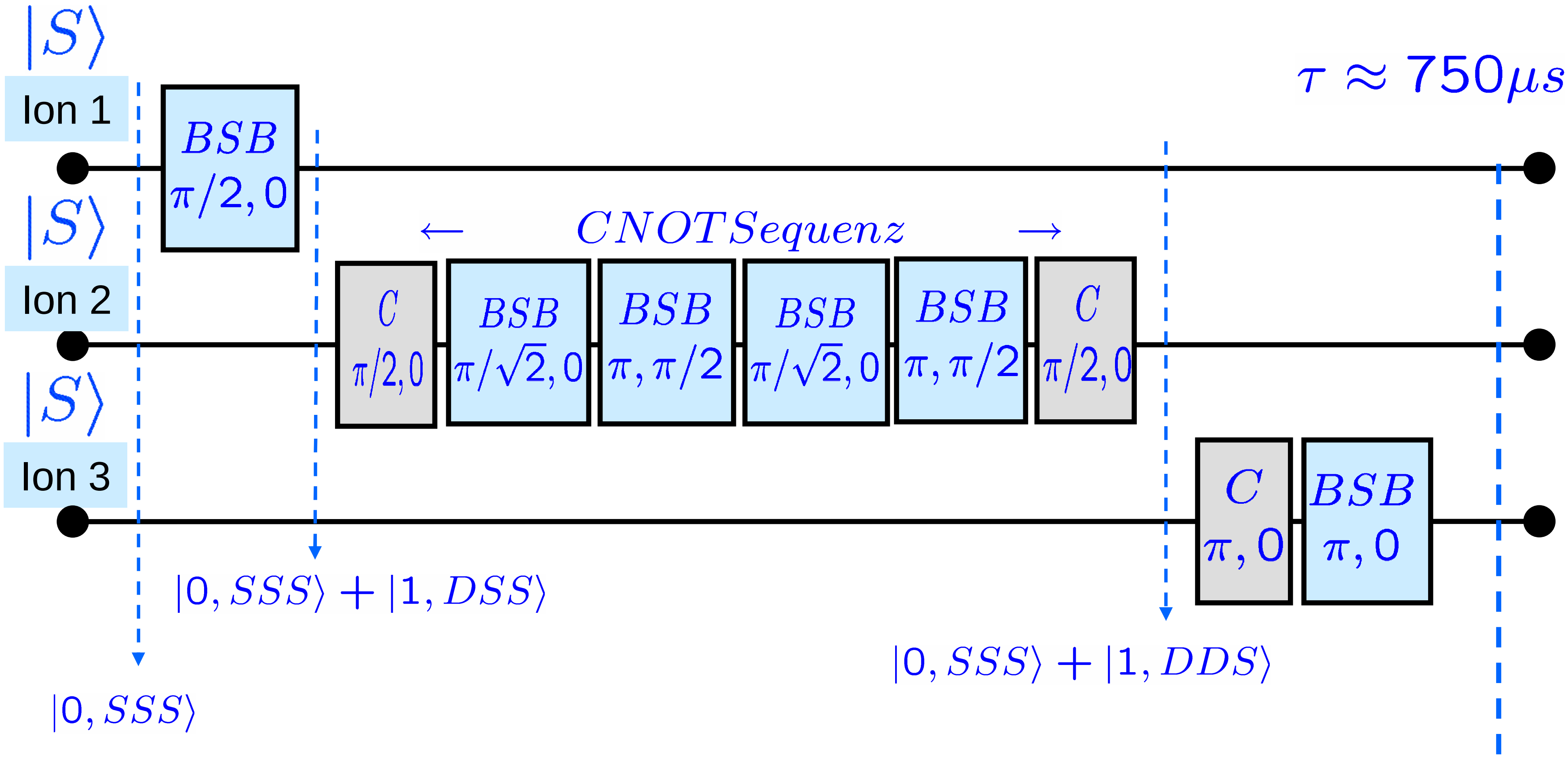


W state:

$$|SSD + SDS + DSS\rangle$$

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

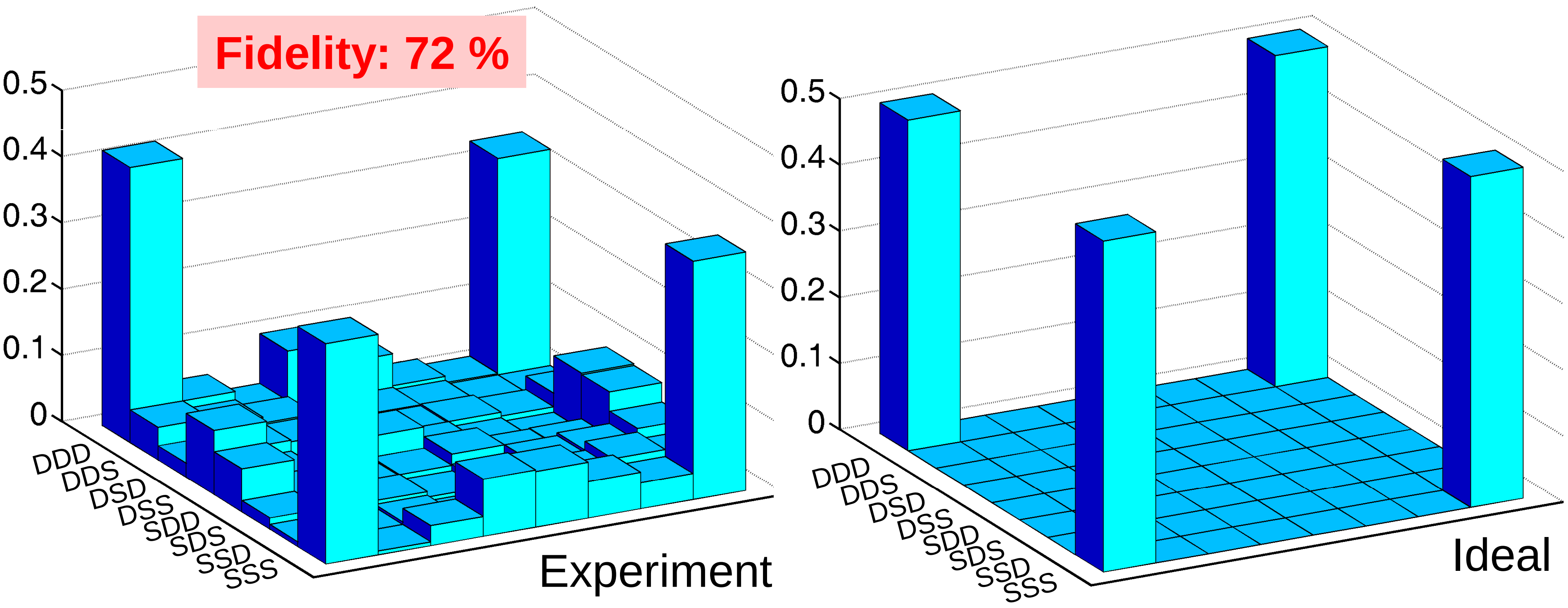
Deterministic generation of GHZ state



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

Tomography of the GHZ state

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

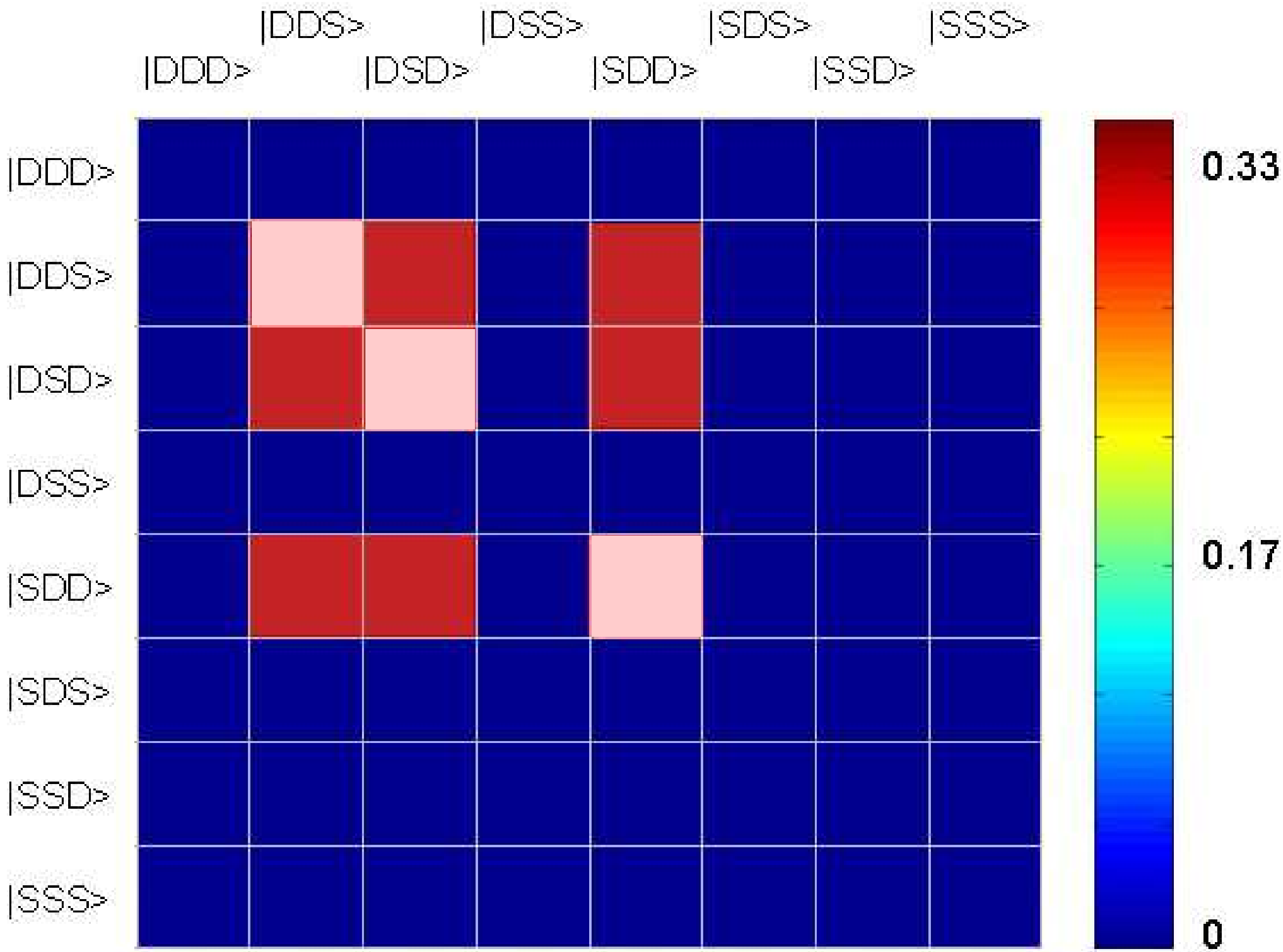


$\mathrm{Abs}(\rho_{\mathrm{exp}})$

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

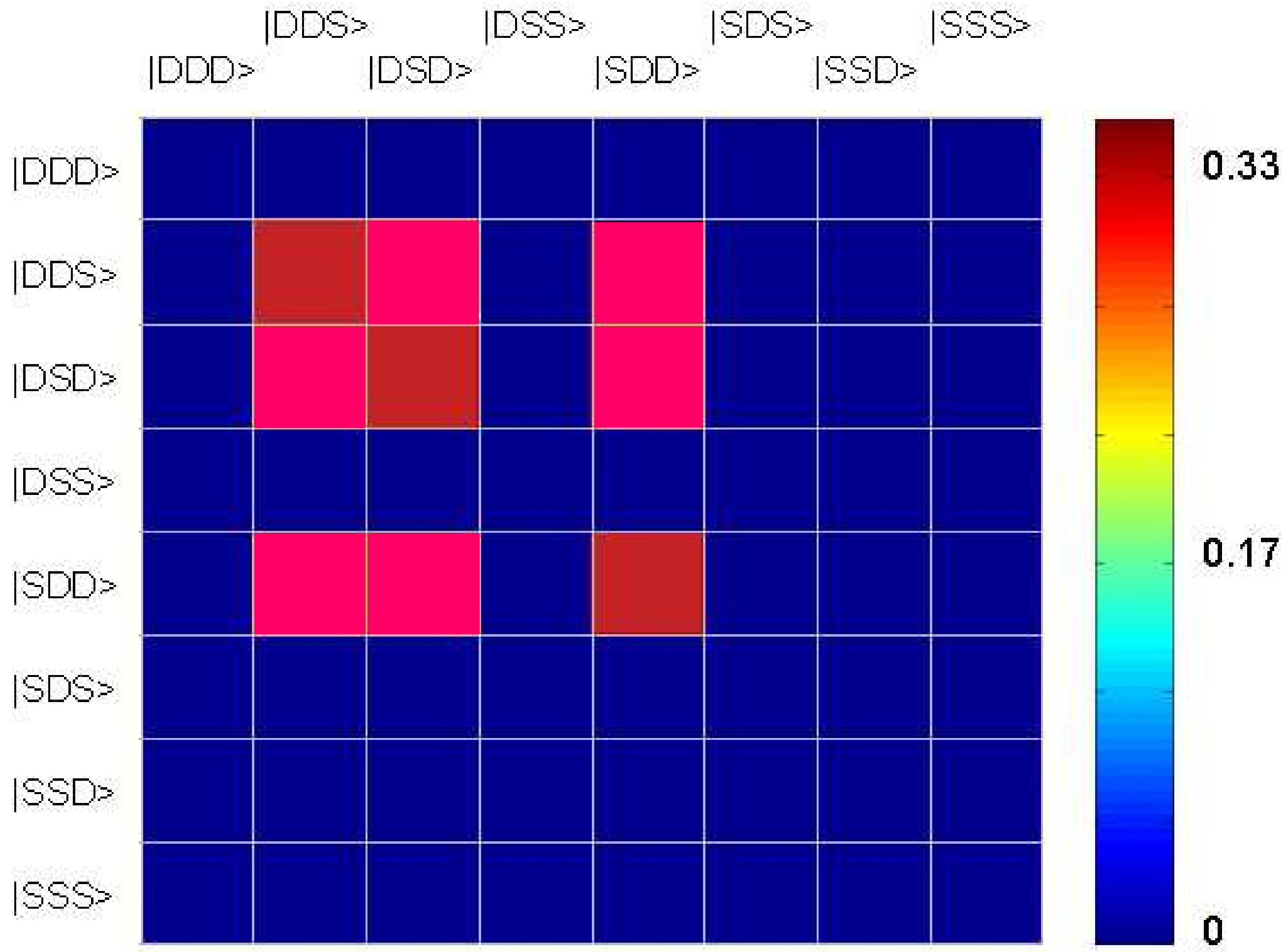
W state: |SDD> + |DSD> + |DDS>

ideal 3-ion
density matrix

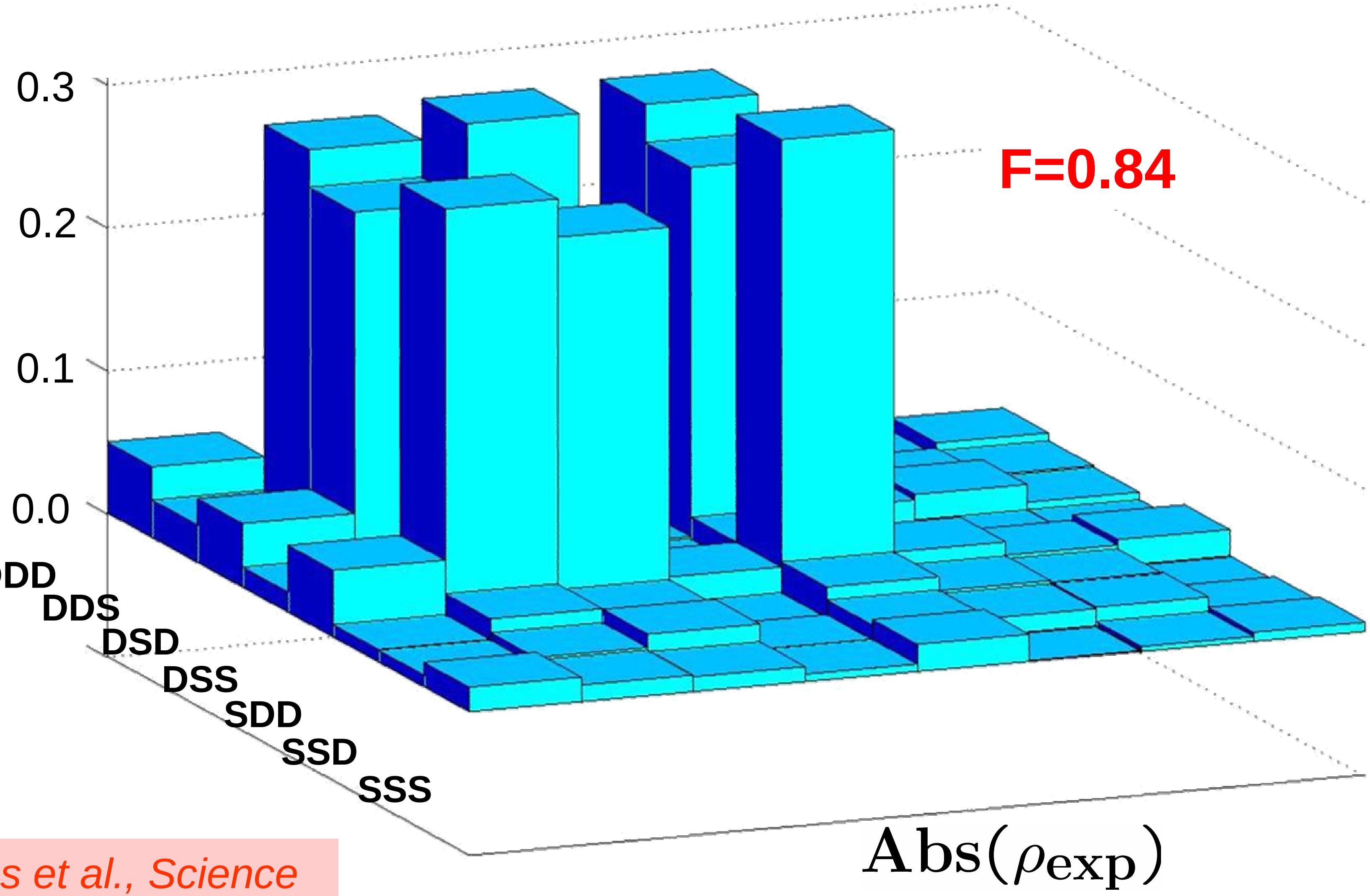


W state: |SDD> + |DSD> + |DDS>

ideal 3-ion
density matrix



|SDD> - |DSD> - |DDS>



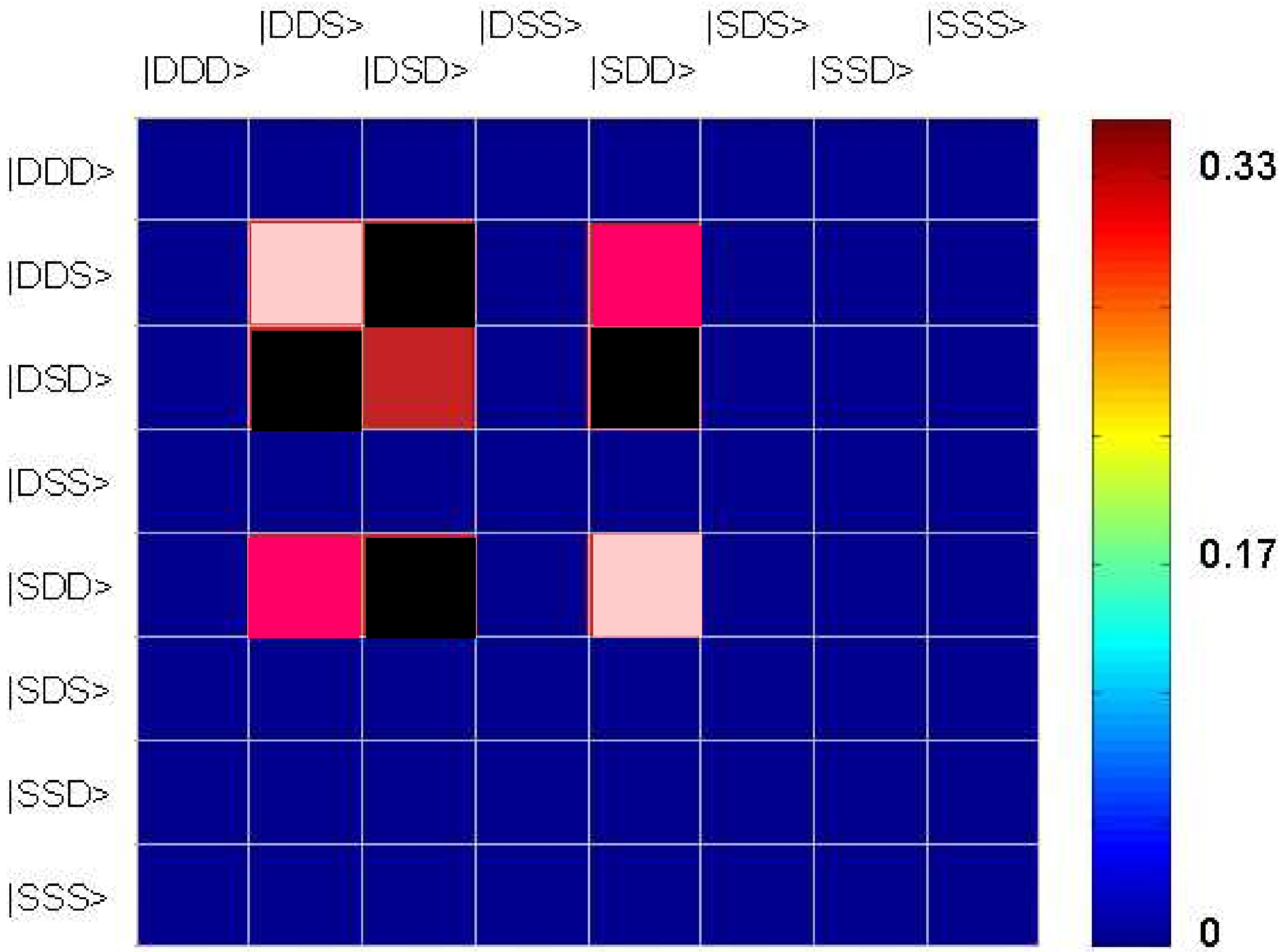
C. Roos et al., Science 304, 1478 (2004)

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

measure

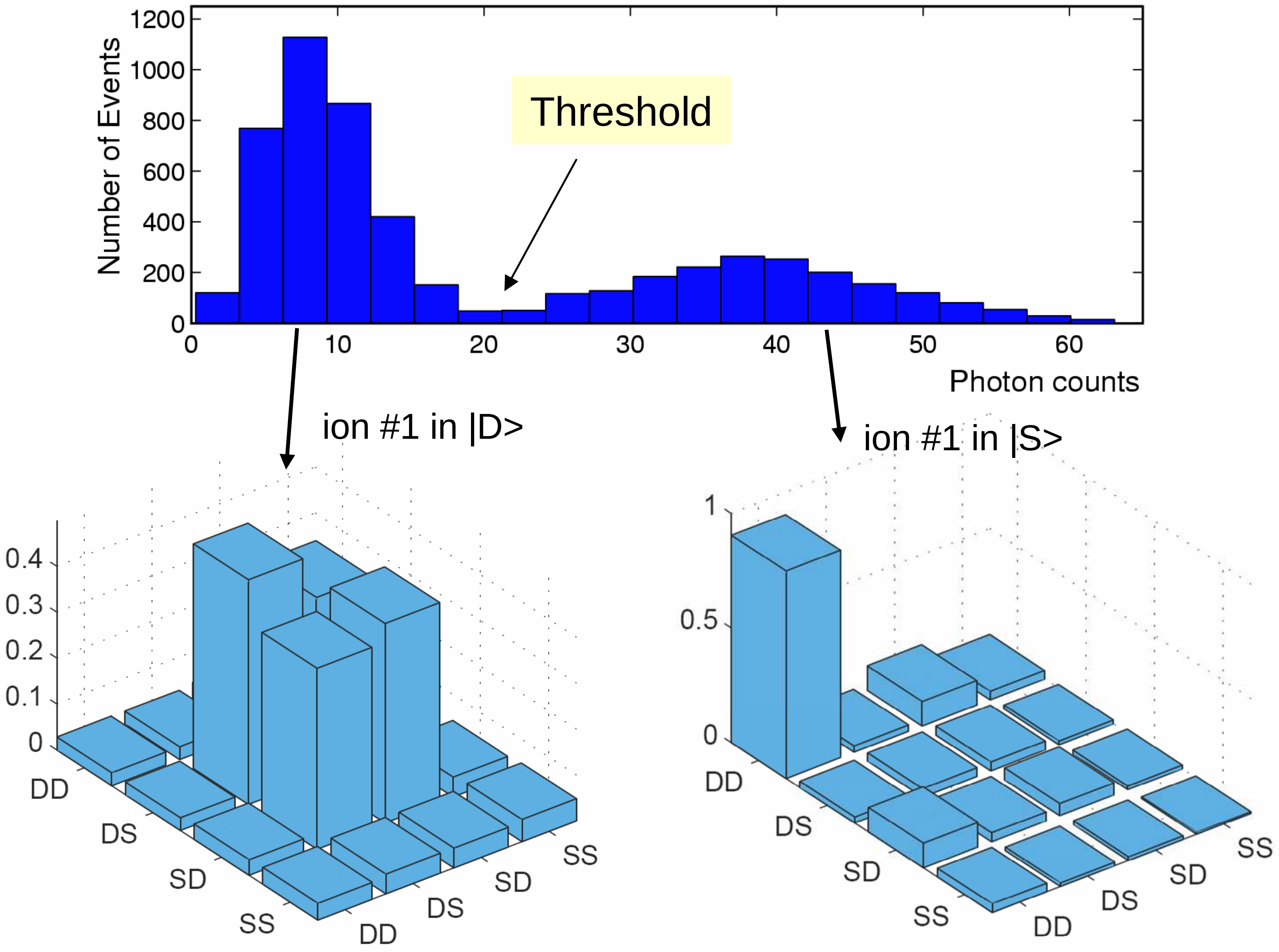
measure only
the middle ion in D

Bell state
SD+DS



Selective measurement

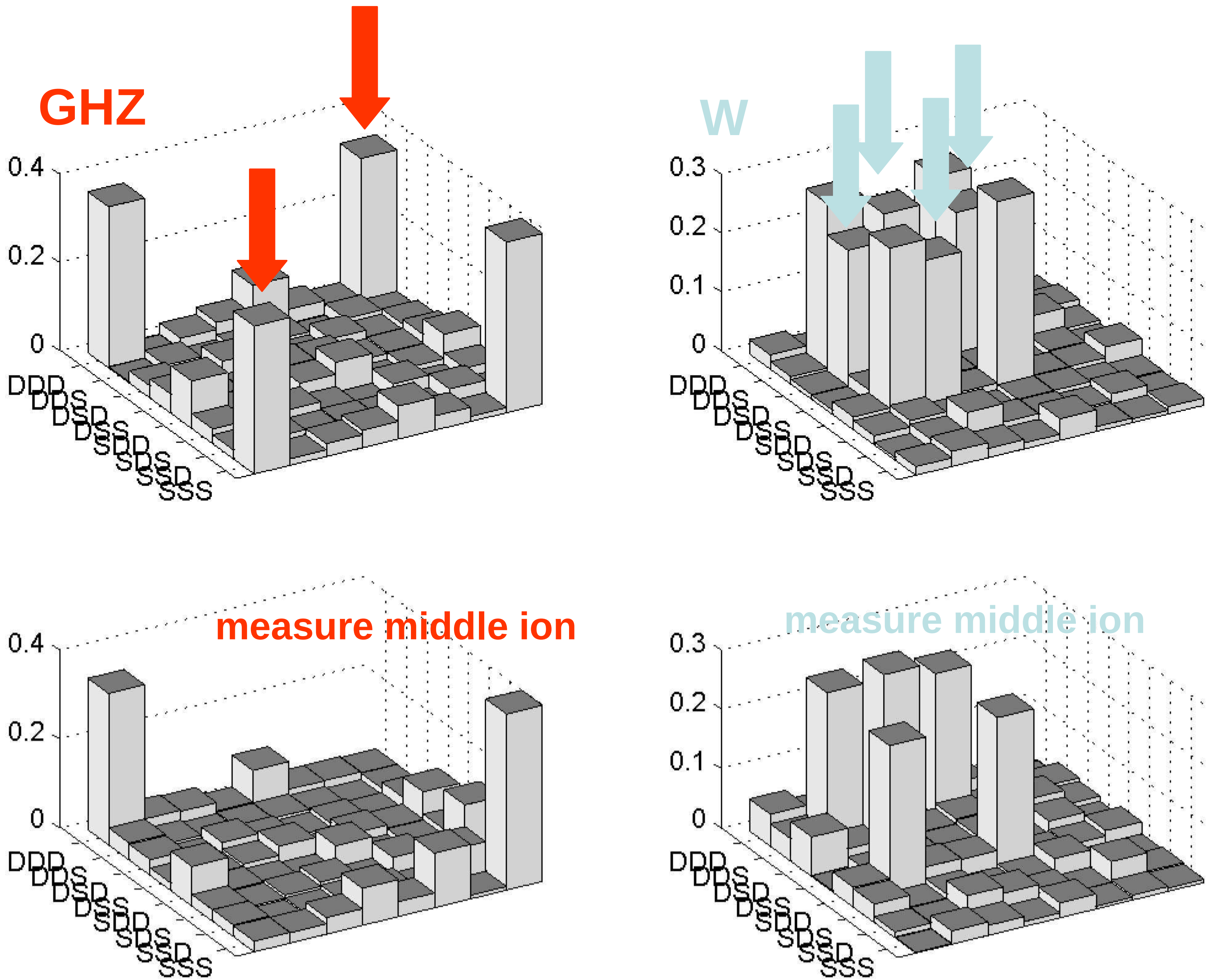
$$|\Psi\rangle_W = \frac{1}{\sqrt{3}}(|SDD\rangle + |DSD\rangle + |DDS\rangle)$$



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

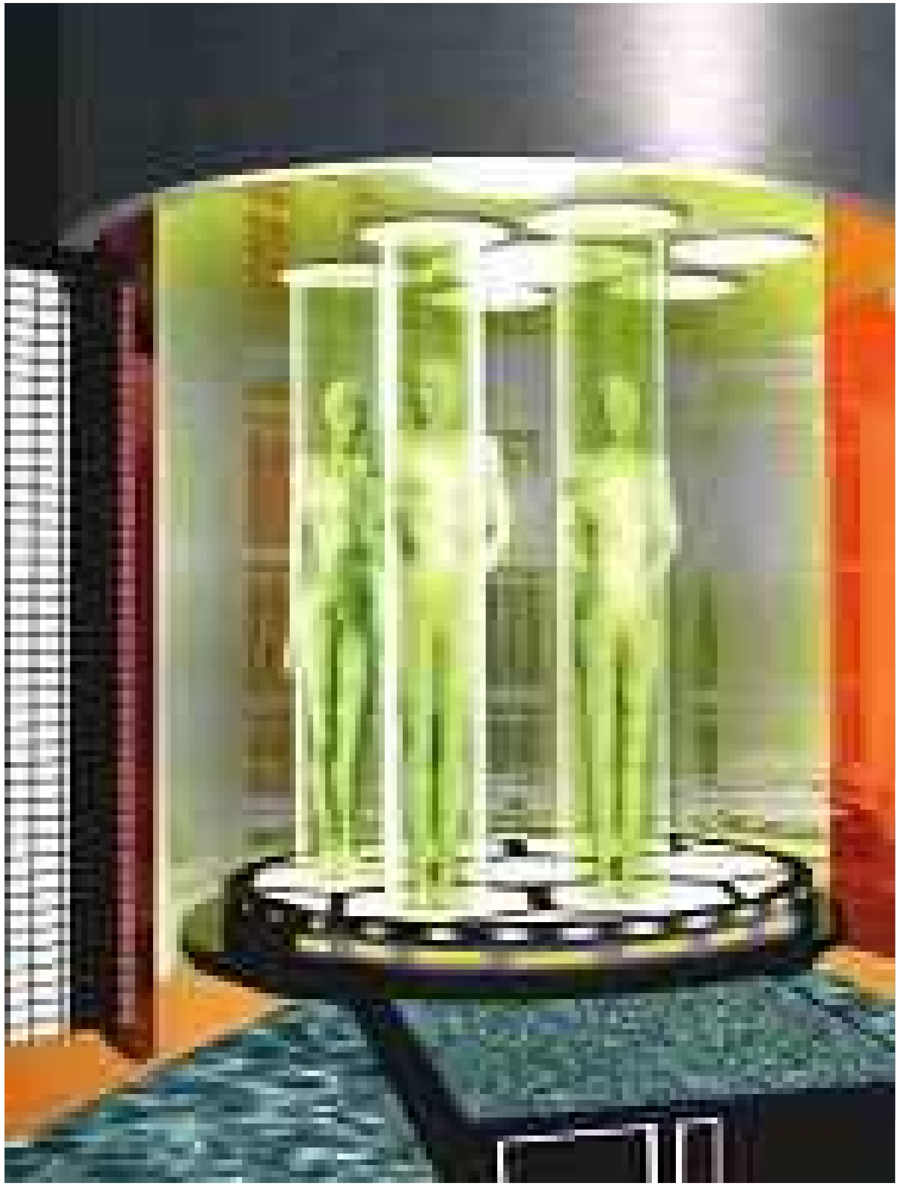
Selectivly projected 3-ion entanglement

Greenberger Horne Zeilinger state



W - state

Teleportation



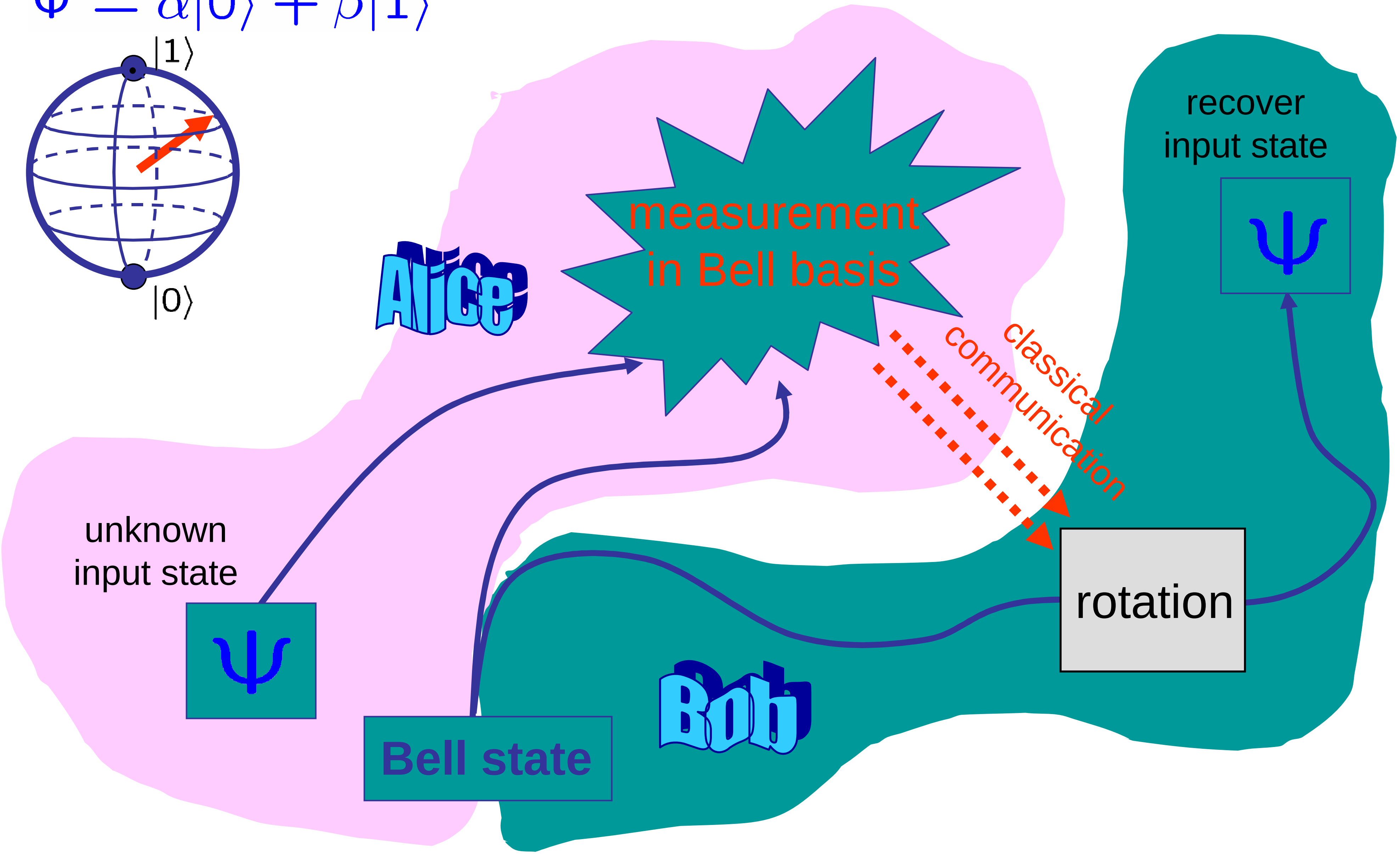
R. Blatt, H. Häffner, C. Becher,
F. Schmidt-Kaler, J. Benhelm, T. Körber,
G. Lancaster, C. Roos, W. Hänsel, M. Riebe

Theorie: D. James, Los Alamos

Teleportation

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

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



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:

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

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

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

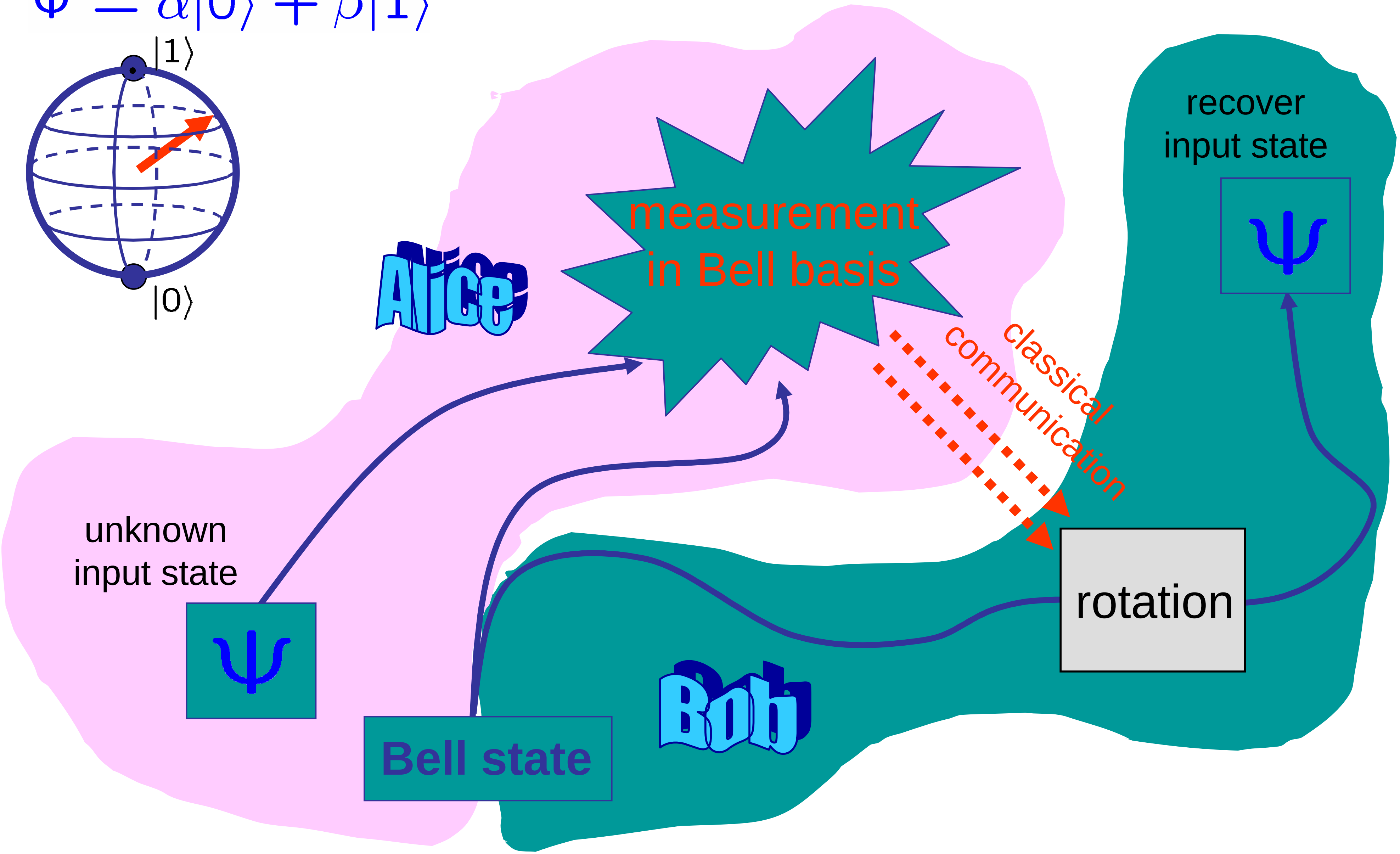
measure #1 and #2 in Bell basis: $|\varphi\rangle$ is projected onto one of 4 pure states

e.g. measure $|\Psi^-\rangle_{12}$:perform $-\sigma_z$ operation on qubit #3 to yield input state back

Teleportation

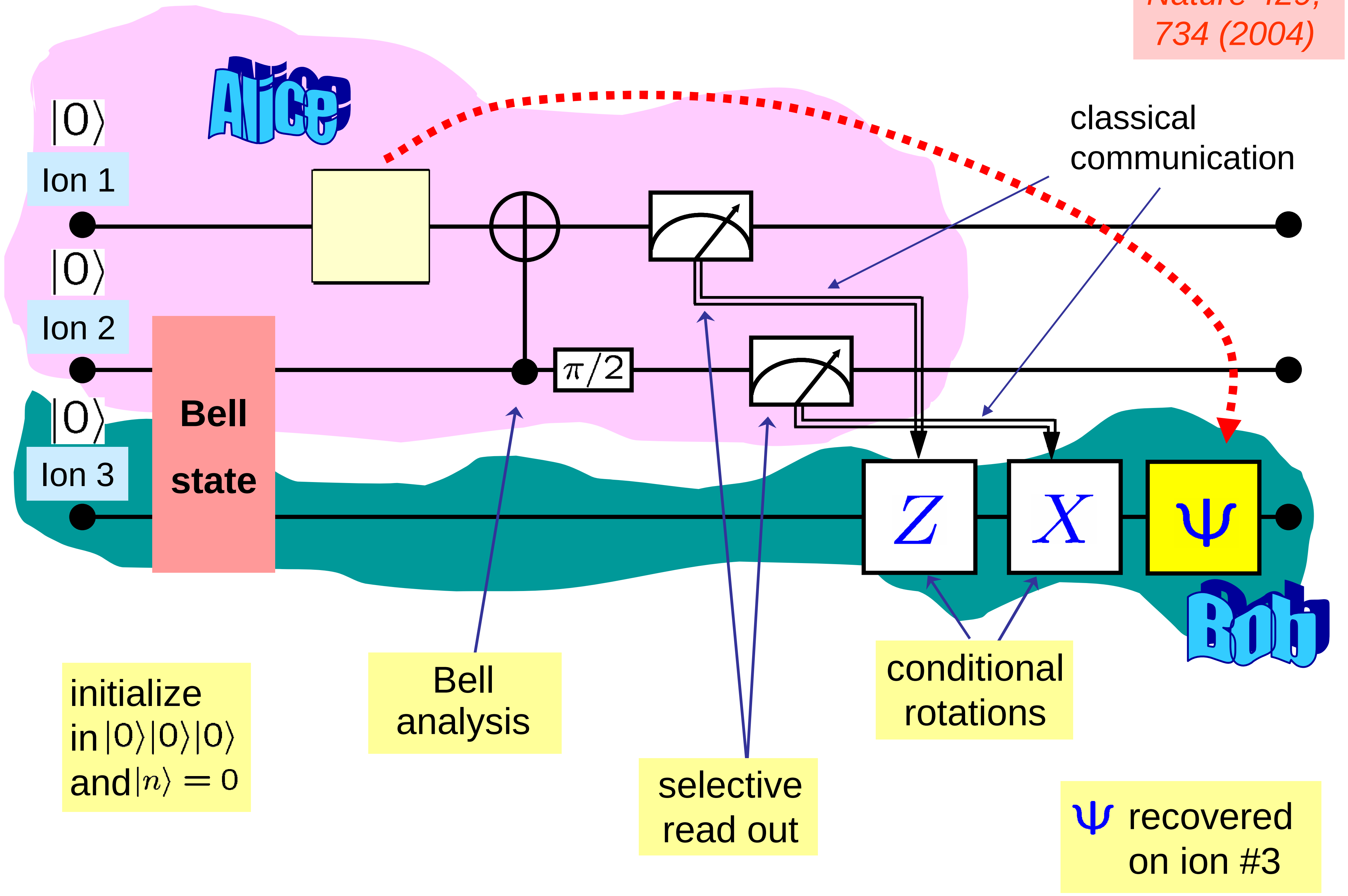
Bennett et al, Phys. Rev. Lett. 70, 1895 (1993)

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

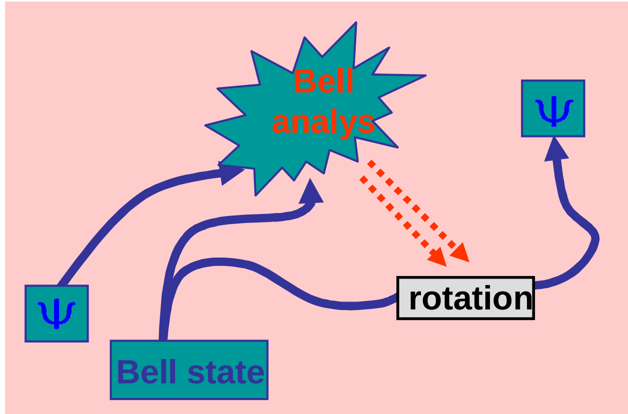


Quantum teleportation protocol

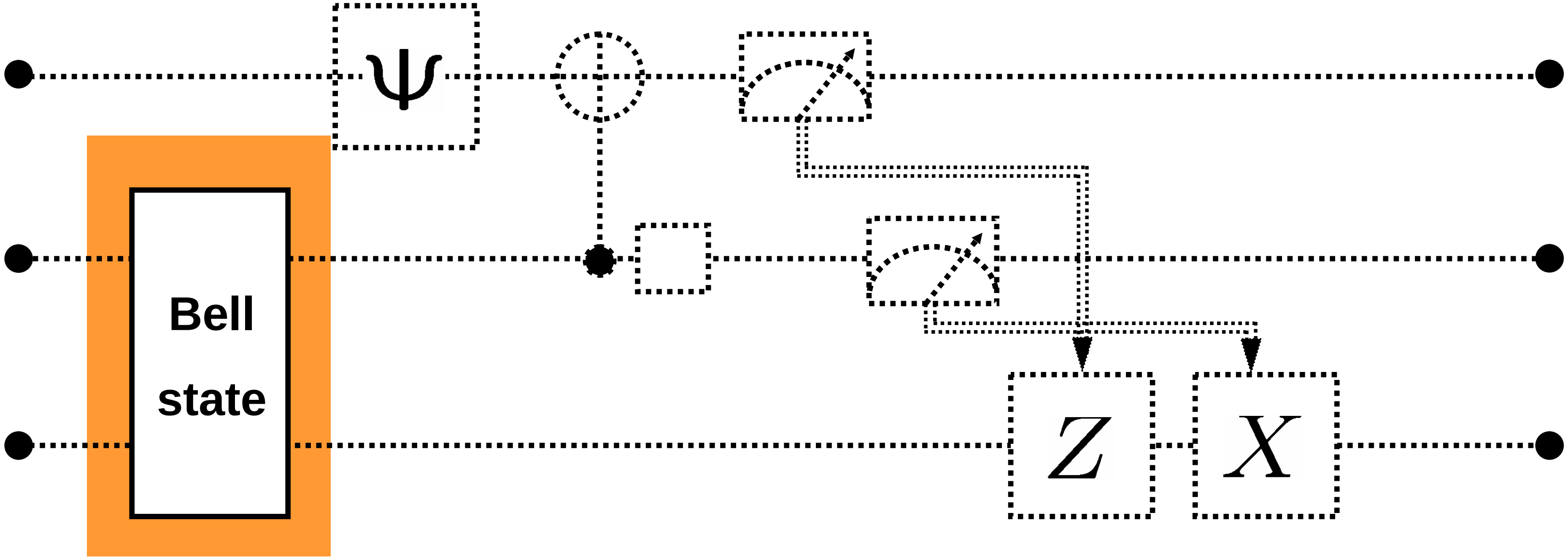
Riebe et al, Nature 429, 734 (2004)



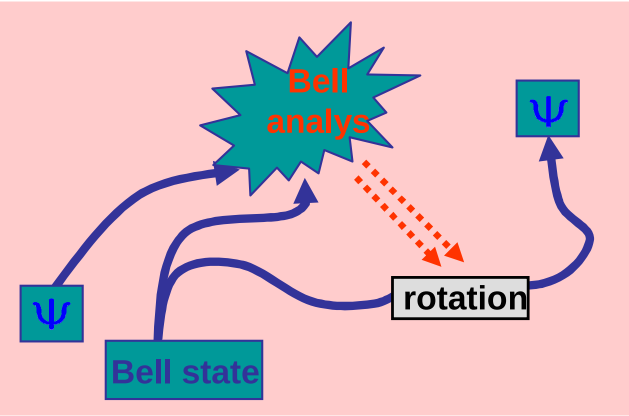
Step by step



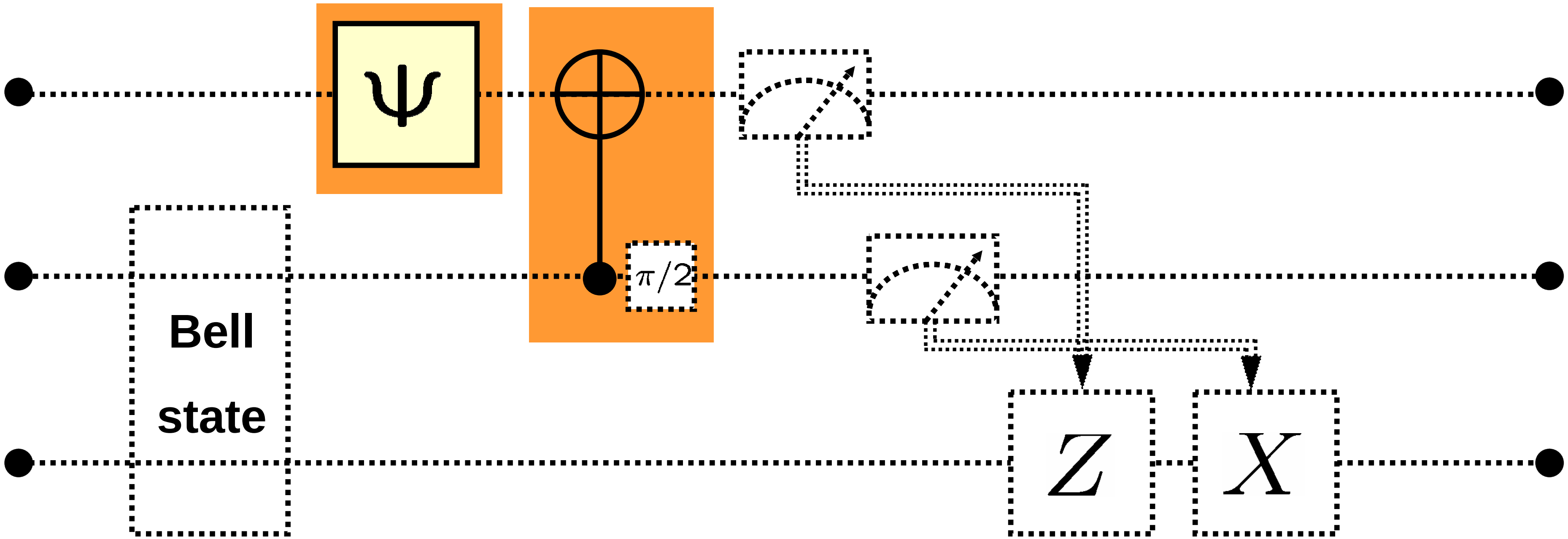
1. *Bell state generation*



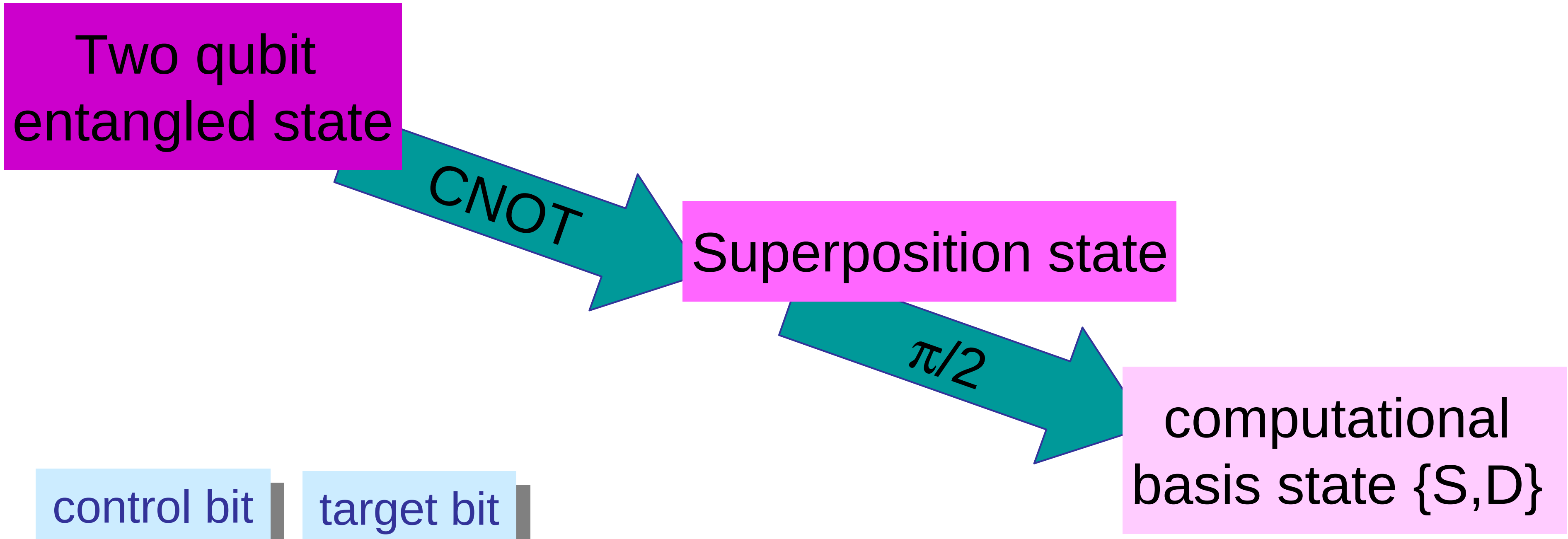
Step by step



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



complete Bell analysis



control bit

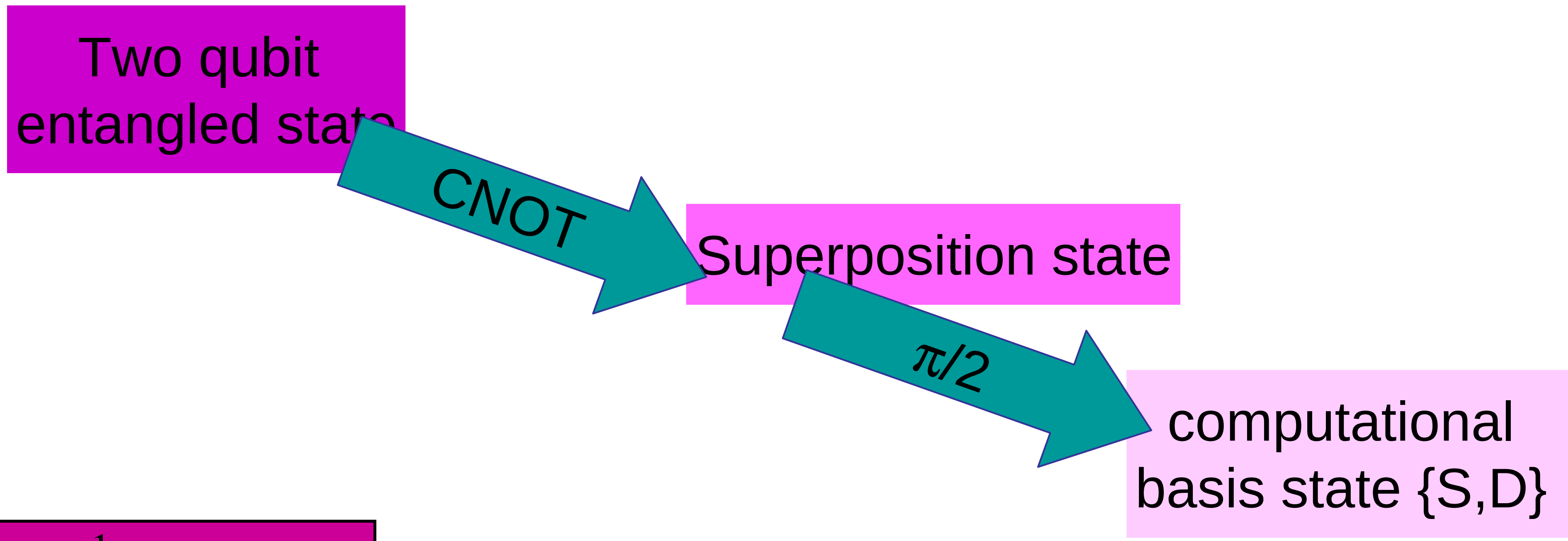
target bit

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

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

$$|S,S\rangle$$

complete Bell analysis

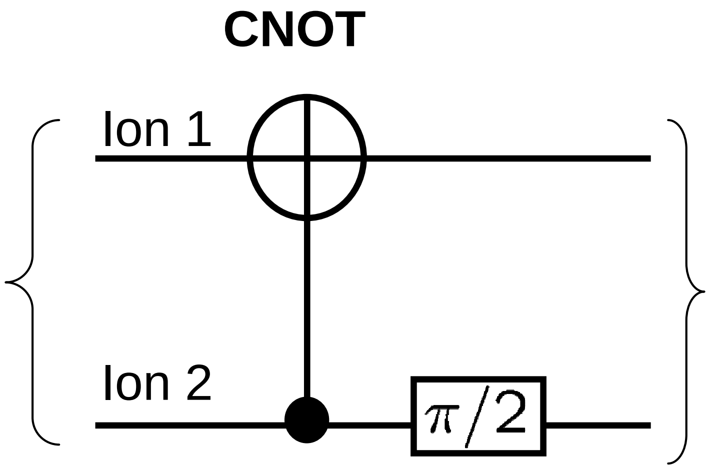


$$\beta_{00} = \frac{1}{\sqrt{2}}\left(|SS\rangle + |DD\rangle\right)$$

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

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

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



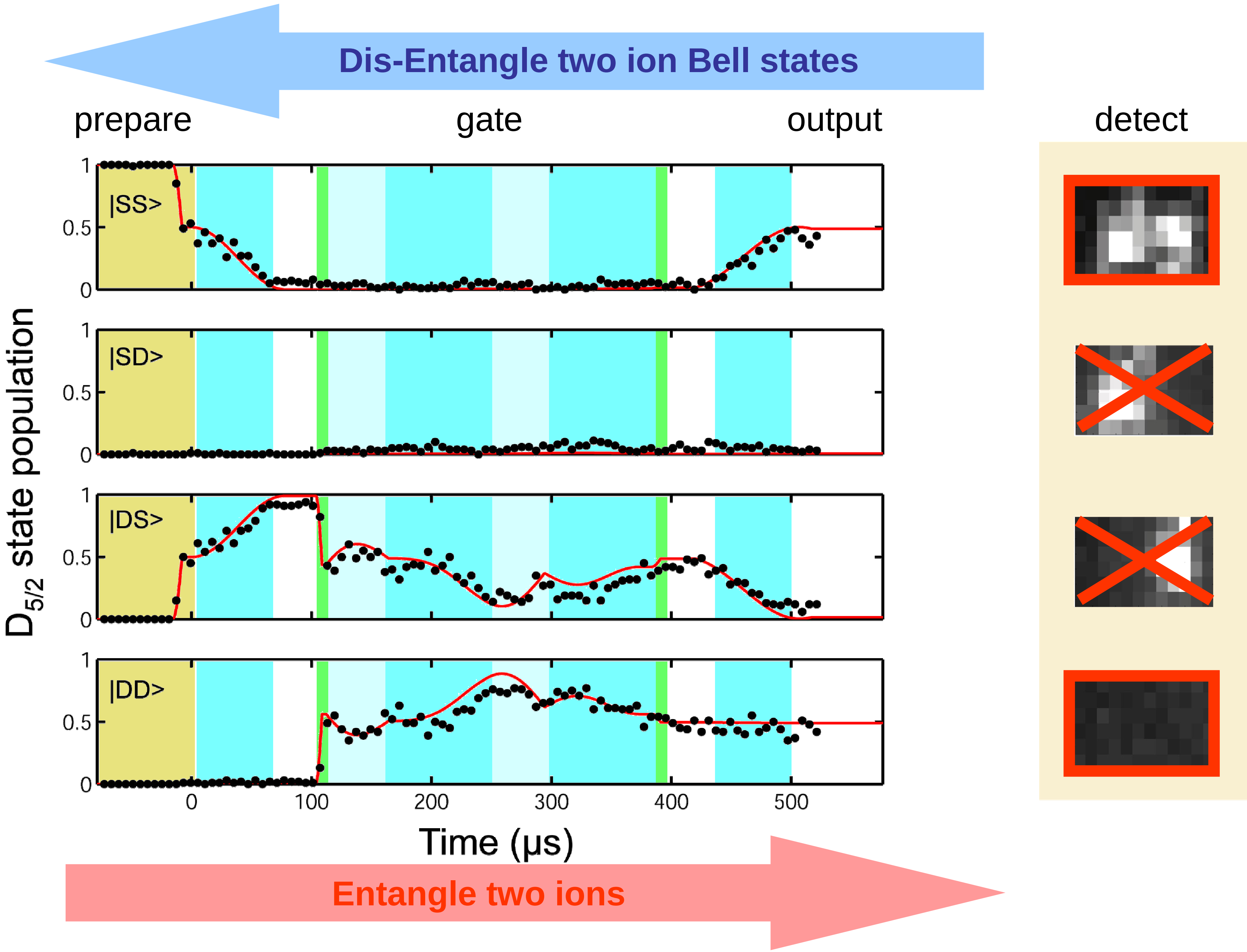
$|SS\rangle$

$|DS\rangle$

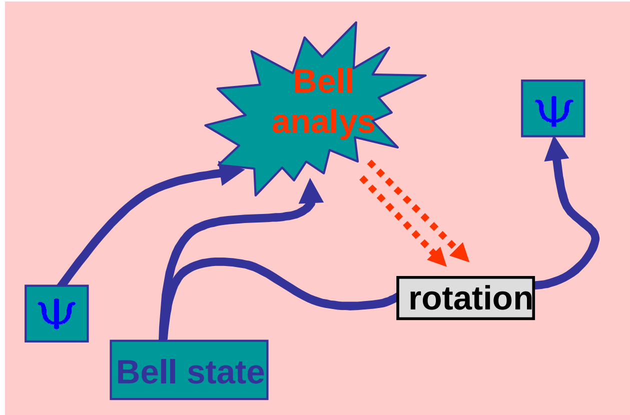
$|SD\rangle$

$|DD\rangle$

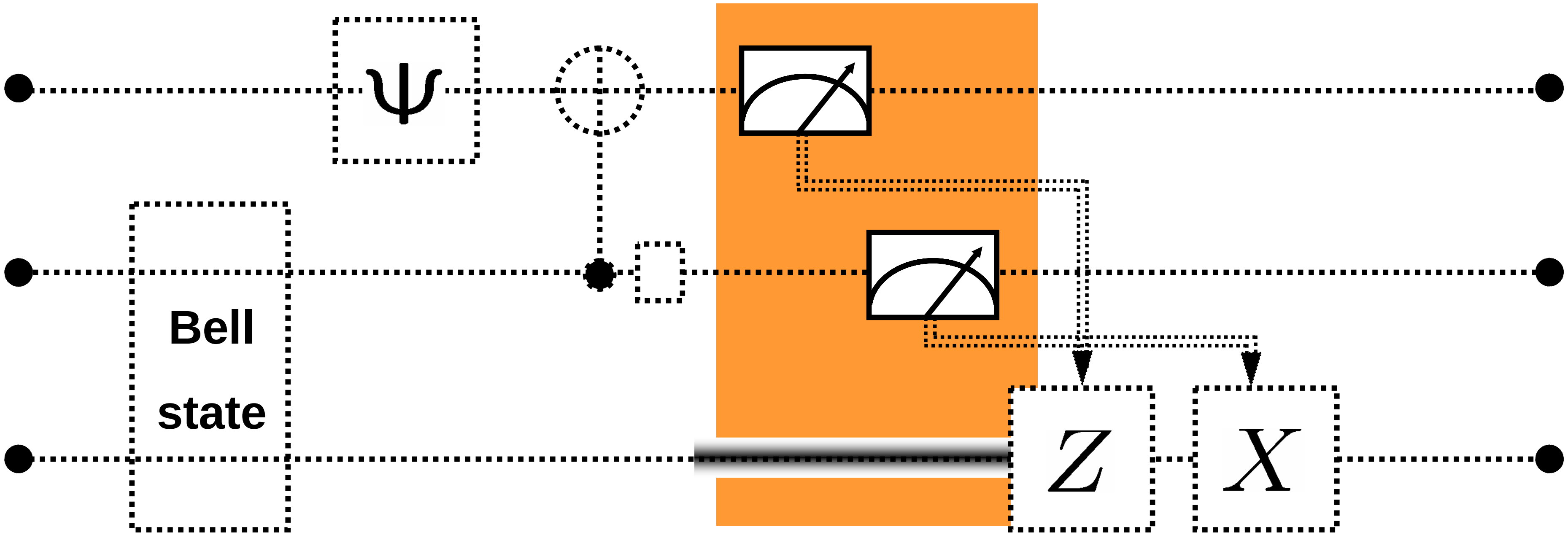
|S+D,S> $\xrightarrow{\text{CNOT}}$ |SS> + |DD>



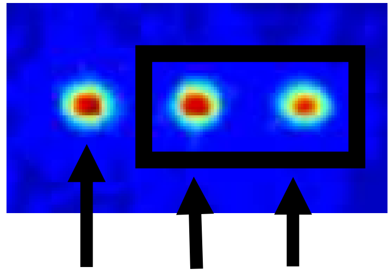
Step by step



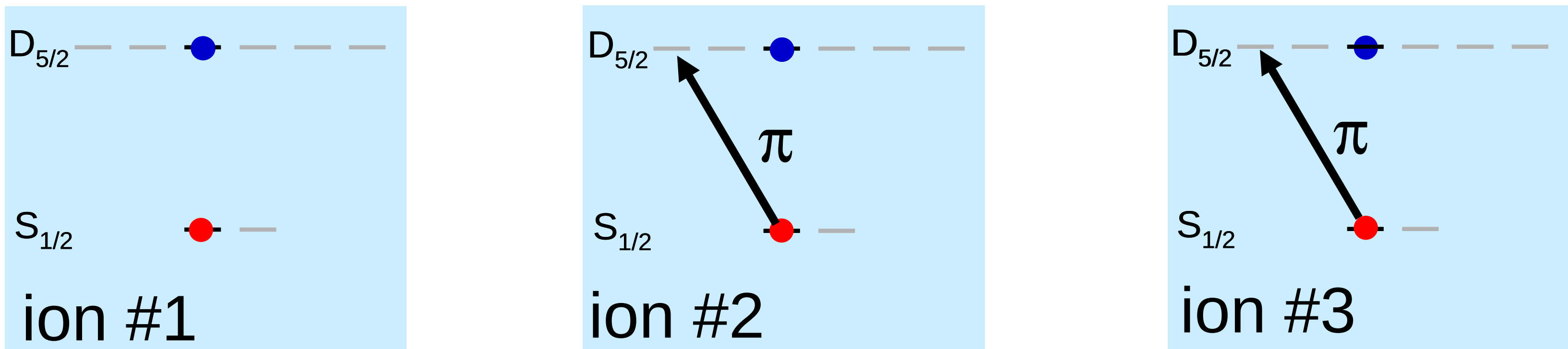
1. *Bell state generation*
2. *Generate Ψ*
3. *Bell analysis*
4. ***Selective read-out (and hiding)***



Hiding a qubit

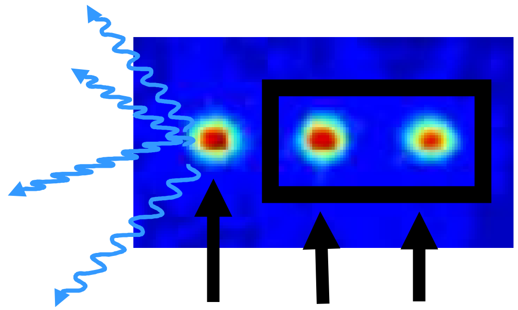


Zeeman levels

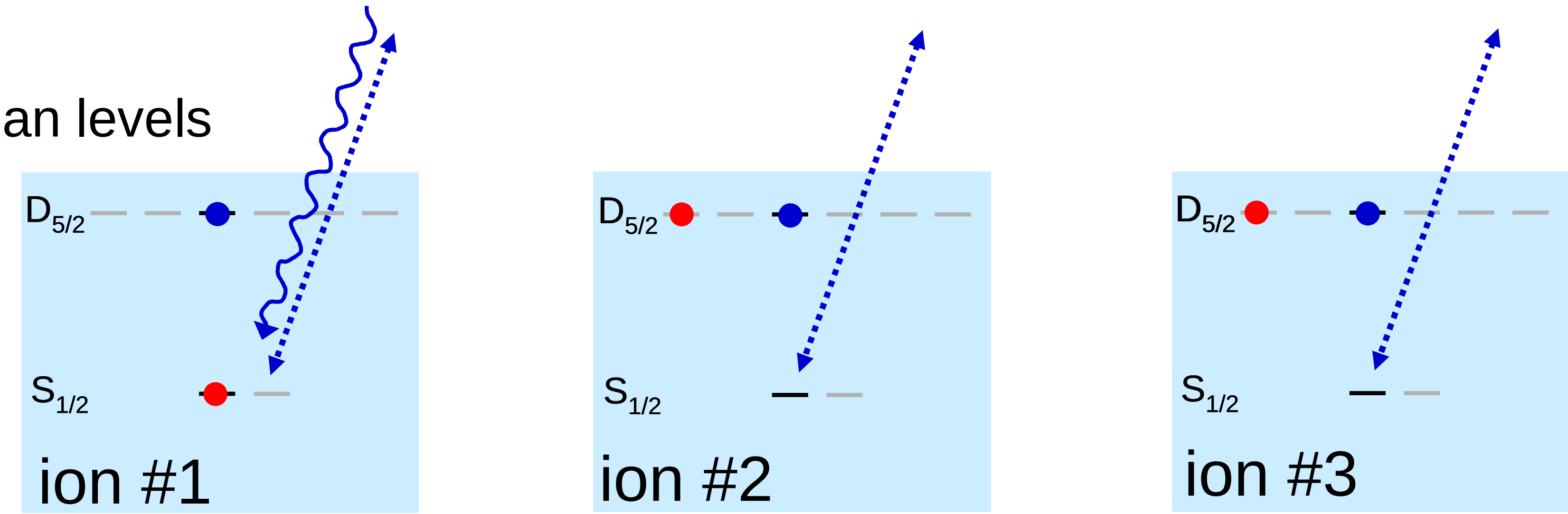


detect quantum state of ion #1 only

Hiding a qubit

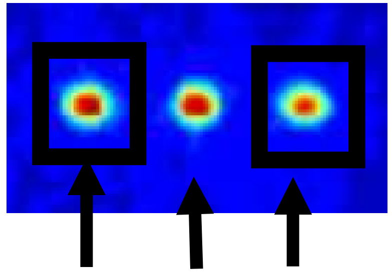


Zeeman levels



detect quantum state of ion #1 only

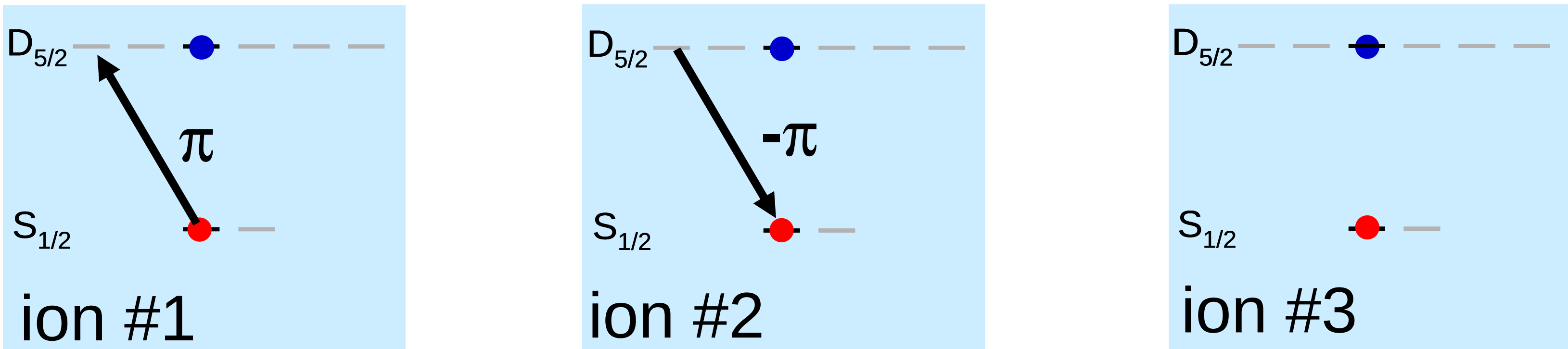
Hiding and unhiding



protected !

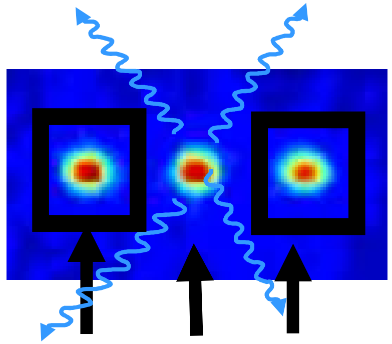
photon scattering

Zeeman levels



detect quantum state of ion #2 only

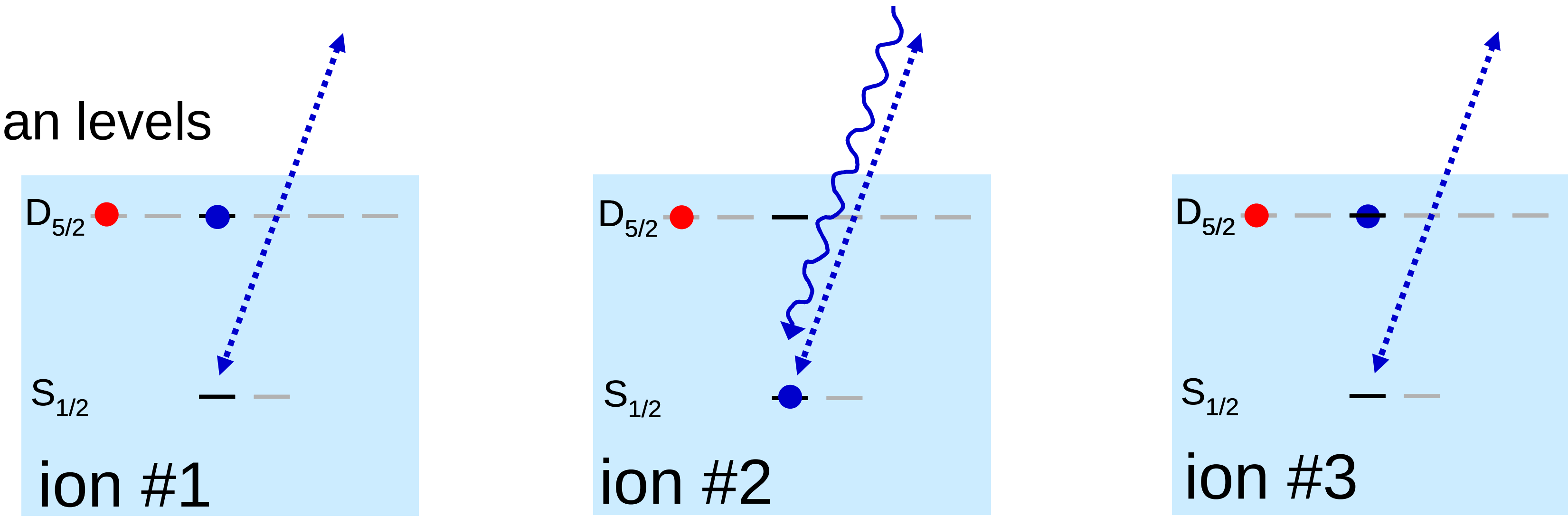
Hiding a qubit



protected !

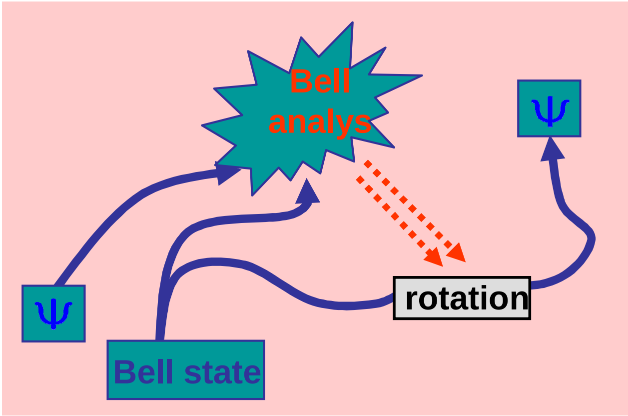
photon scattering

Zeeman levels

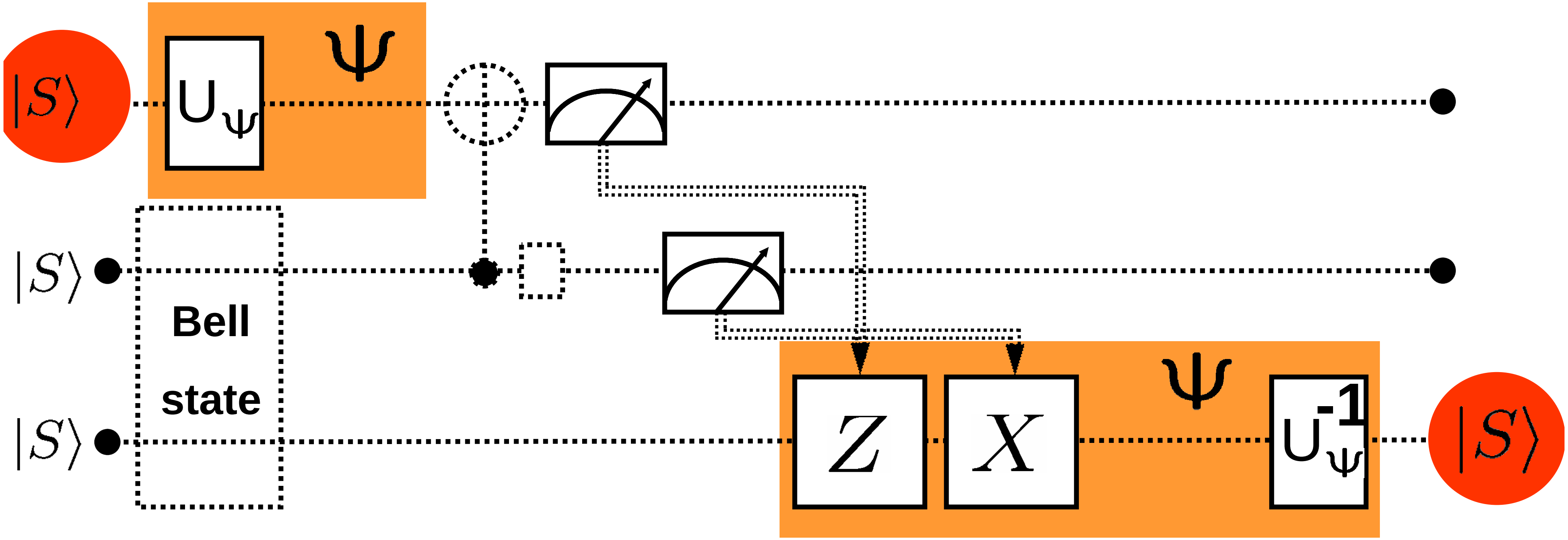


detect quantum state of ion #2 only

Step by step

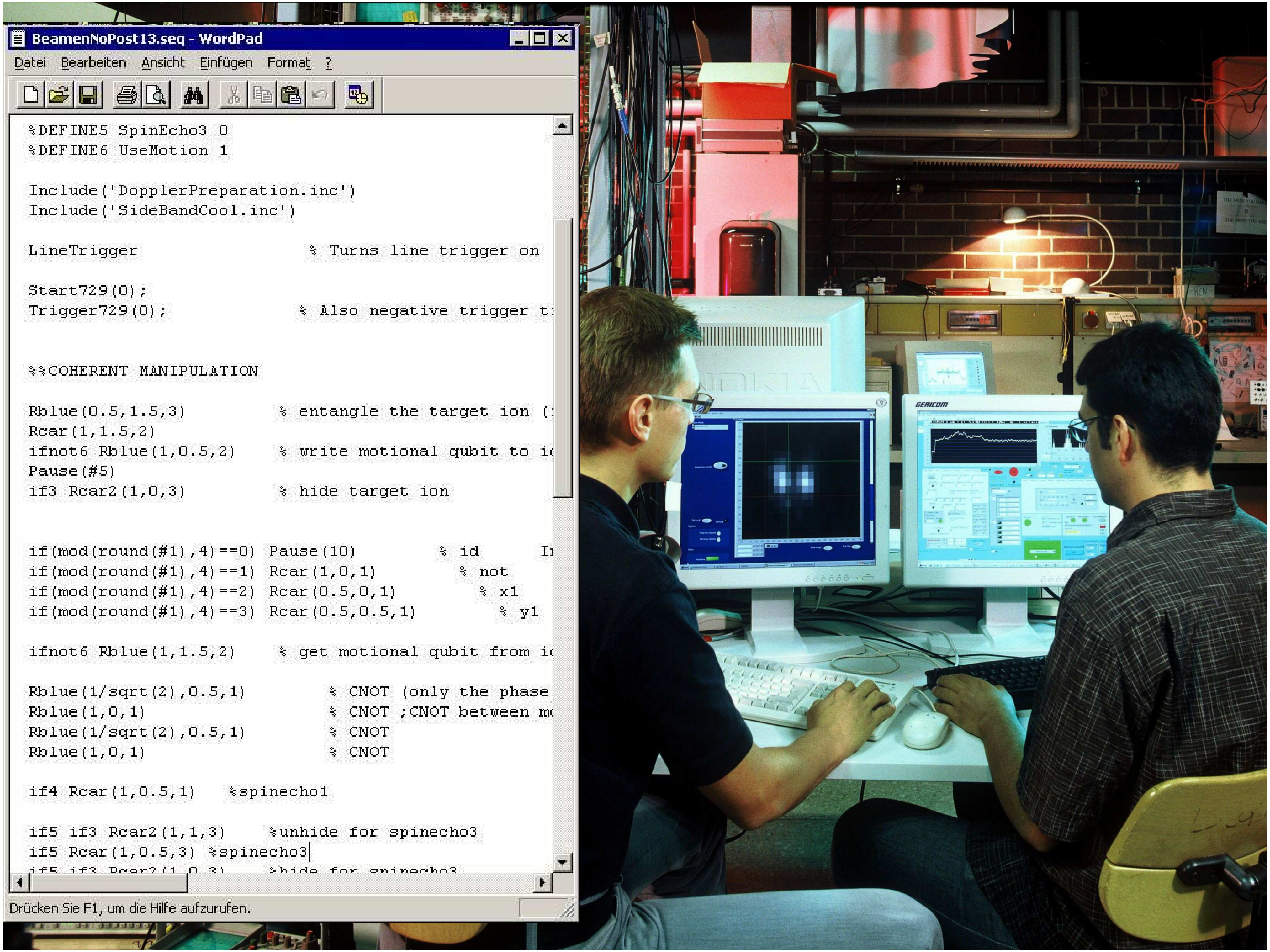


1. *Bell state generation*
2. *Generate Ψ*
3. *Bell analysis*
4. *Selective read-out*
5. ***Conditional rotations***
6. ***Test performance !***



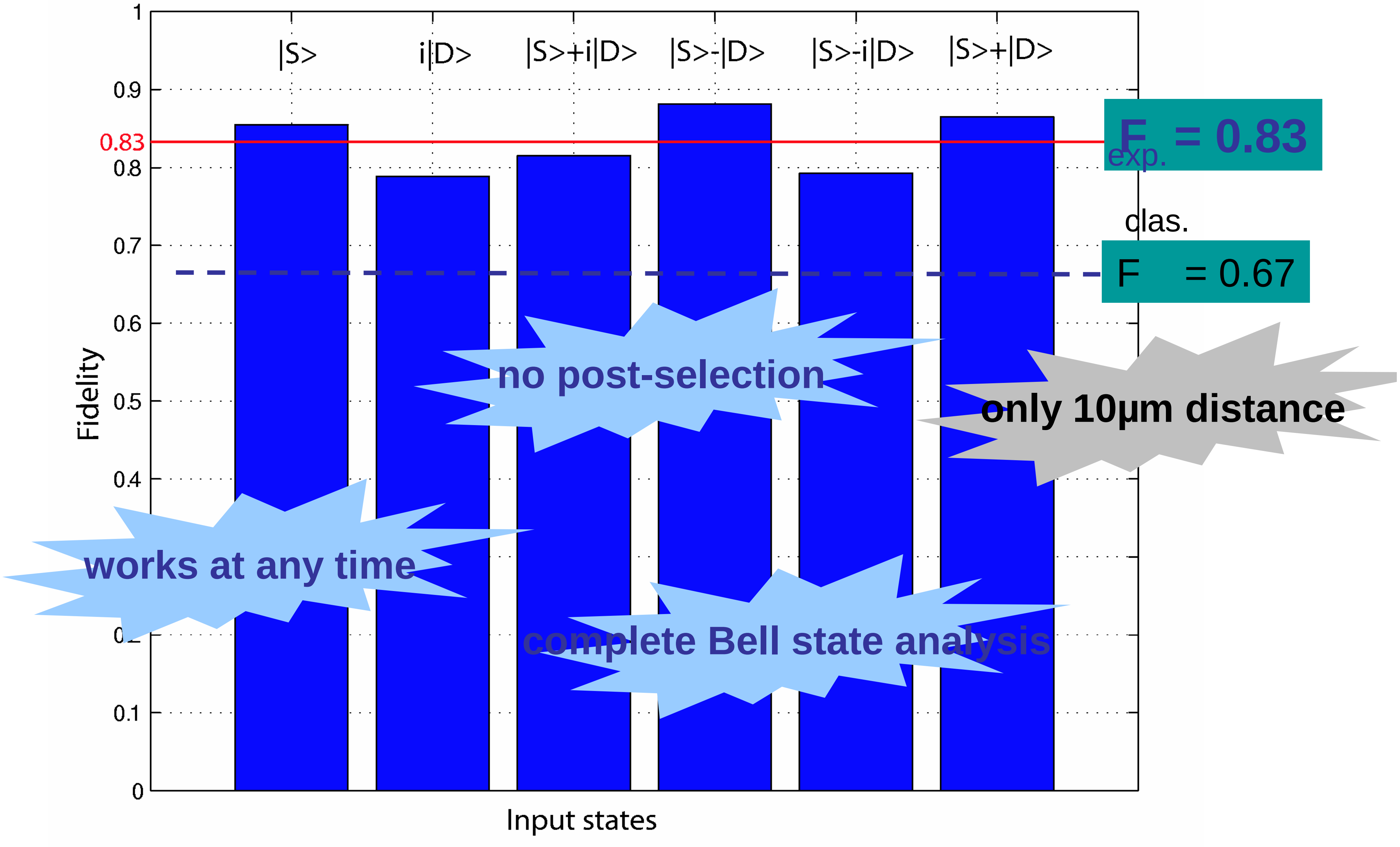
Analysis of teleportation

Initial		Input test states $\vert\Psi\rangle$		Output states $\vert\Psi\rangle$		Final
$\vert S\rangle$		$\vert S\rangle$		$\vert S\rangle$		$\vert S\rangle$
$\vert S\rangle$	U	$\vert D\rangle$	TP	$\vert D\rangle$	U^{-1}	$\vert S\rangle$
$\vert S\rangle$		$\vert S\rangle + \vert D\rangle$		$\vert S\rangle + \vert D\rangle$		$\vert S\rangle$
$\vert S\rangle$		$\vert S\rangle + i\vert D\rangle$		$\vert S\rangle + i\vert D\rangle$		$\vert S\rangle$


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 In
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.
GERICOM

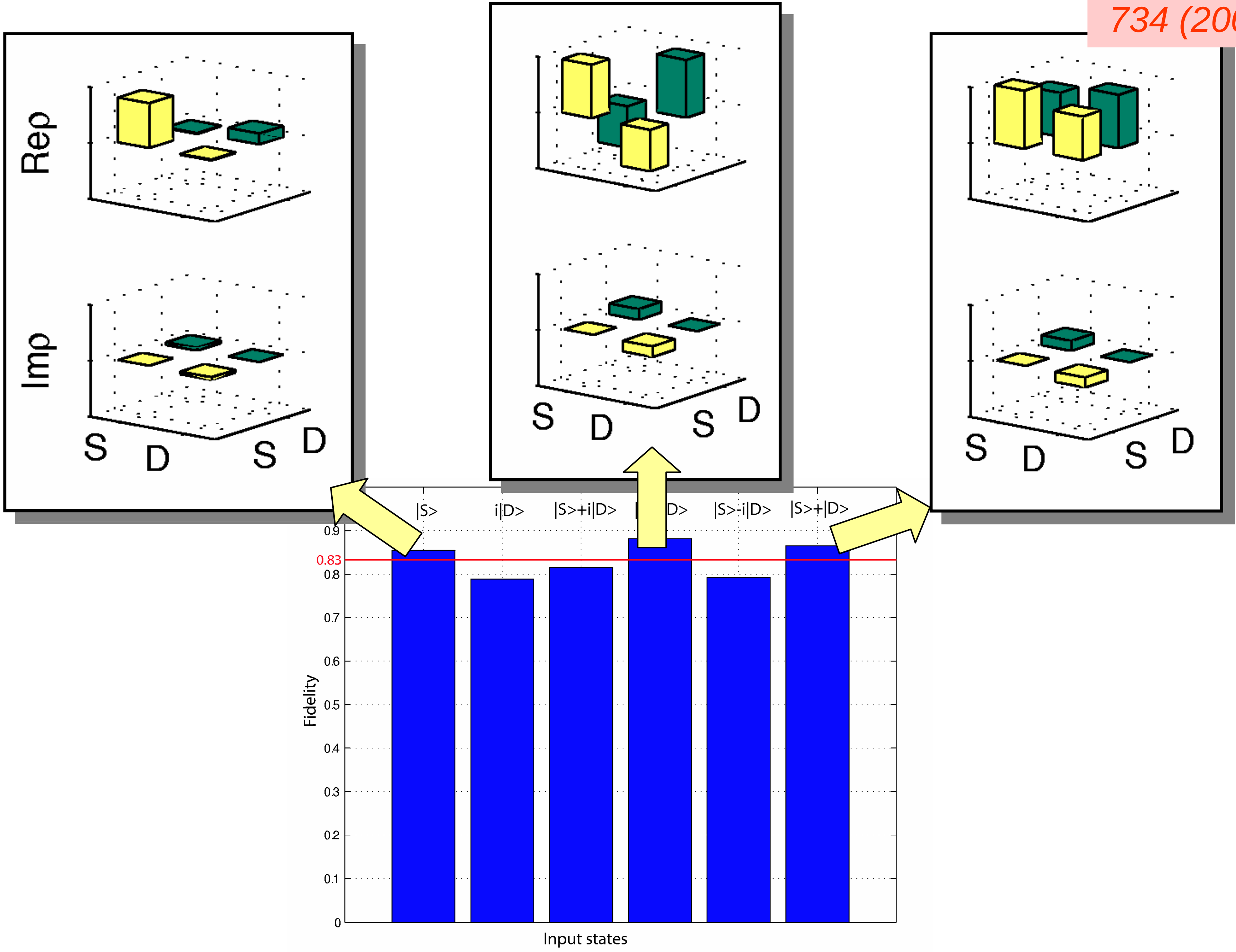
Teleportation „on demand“ : Results

Riebe et al, Nature 429, 734 (2004)



Process tomography of teleportation

Riebe et al, Nature 429, 734 (2004)



„Trapology“ for Boulder Teleportation

Teleportation / Boulder

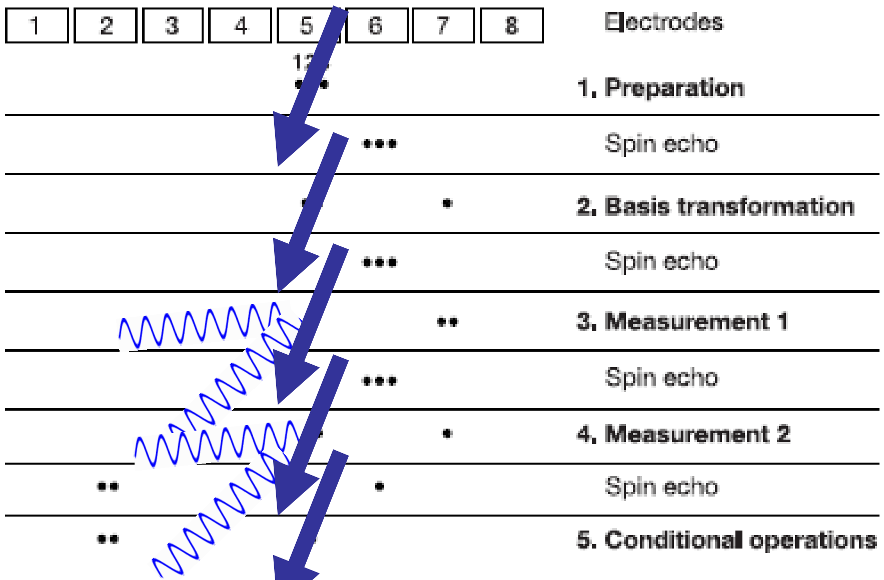
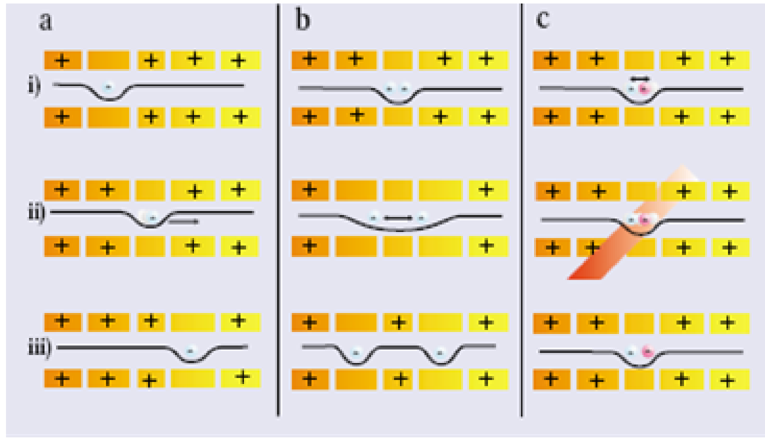
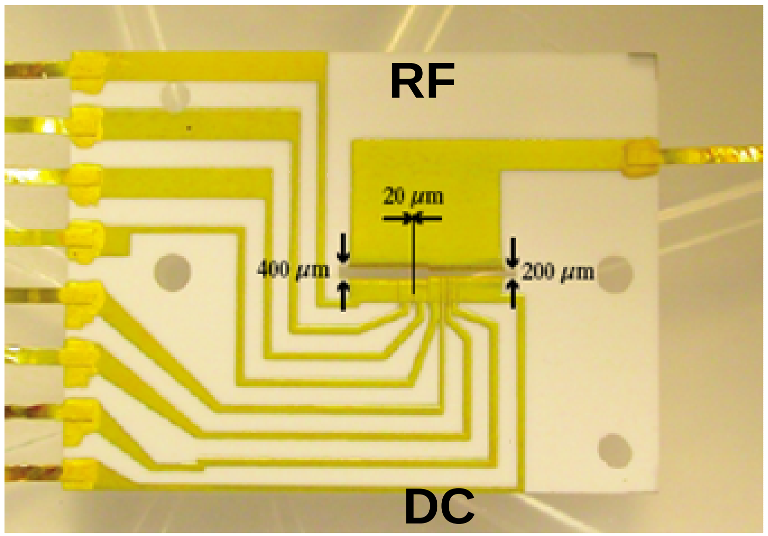


Figure 1 Schematic representation of the teleportation protocol. The ions are numbered left to right, as indicated at the top, and retain their order throughout. Positions, relative to the electrodes, are shown at each step in the protocol. The widths of the electrodes vary, with the width of the separation electrode (6) being the smallest at 100 μm. The spacing between ions in the same trap is about 3 μm, and laser-beam spot sizes (in traps 5 and 6) at the position of the ions are approximately 30 μm. In step 1 we prepare



a) Transport ions from right to left
b) Separate two ions to right and left side

NIST Boulder

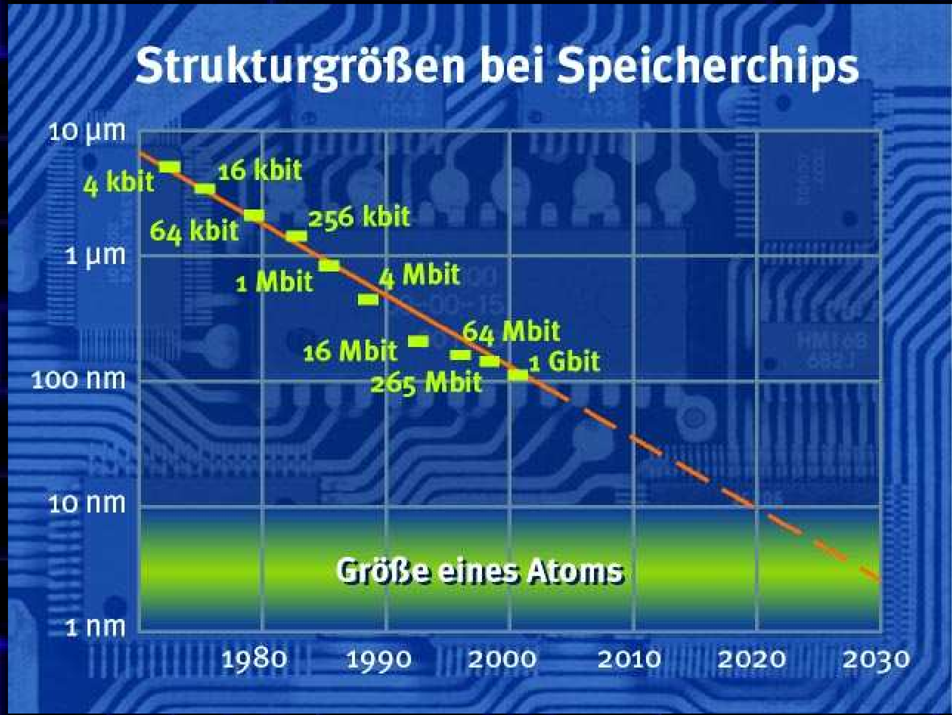


Barrett et al, Nature 429, 727 (2004)

Resultats and Aims for QIP

- Quantum-Gates
- Bell states
- Entangled states

  of 3 .. 8 –qubits
- Deterministic Teleportation
- Scalable QC – Micro traps
- Error correction, improved gates
- Quantum simulation
- Improved frequency standards
- **Atomic Information Processing**



Groups with single ions:
**Arhus, Barcelona,
NIST Boulder,
NPL Teddington,
Innsbruck,
Michigan, MPQ, MIT,
Oxford, Siegen,
Southhampton, Ulm, …….**

Team of QIV-ULM

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M. Murpey
J. Baldrusch
H. Doerk-Bendig

S. Schulz
G. Huber
W. Schnitzler
U. Poschinger
M. Hellwig
J. Eble

N. Linke
F. Ziesel
M. Hettrich
R. Tammer
M. Ferner
M. Bürzle

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atomics, A8

Bundesministerium für Bildung und Forschung

MICROTRAP
EMALI, SCALA

Deutsche Forschungsgemeinschaft DFG
SFB CO.CO.MAT

Koll. with: R. Kleiner, C. Zimmermann (Tüb.), G. Werth, W. Nörthershäuser (Mainz), J. Wrachtrup (Stuttgart), R. Blatt (Innsbruck), C. Wunderlich (Siegen), P. Gill (Teddington)