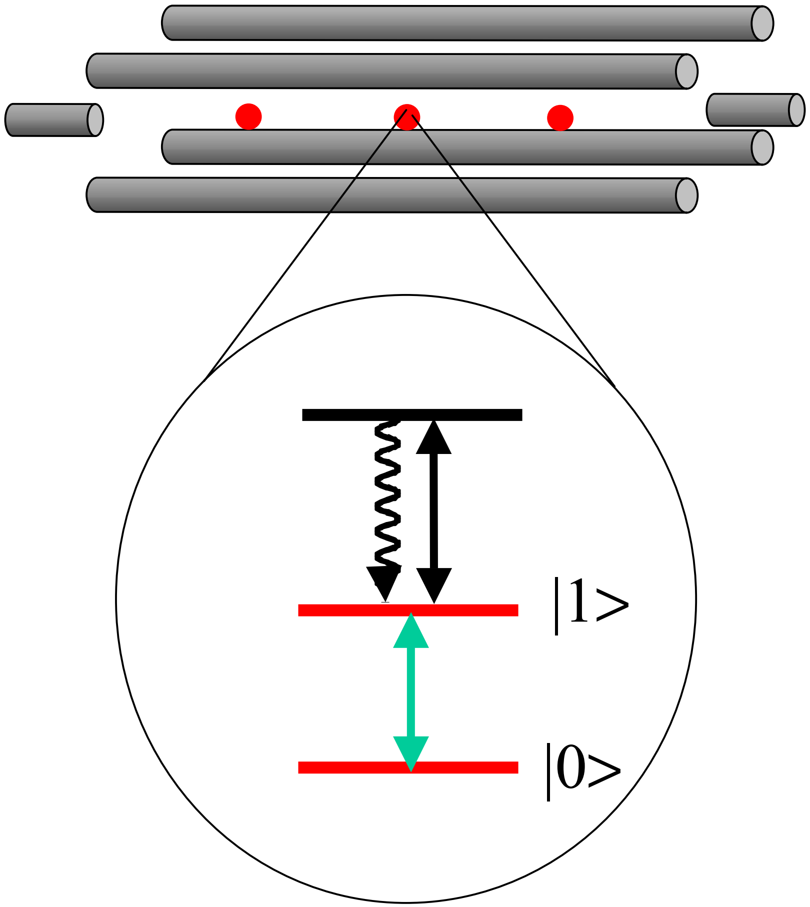
Universität Hamburg, Institut für Laser-Physik

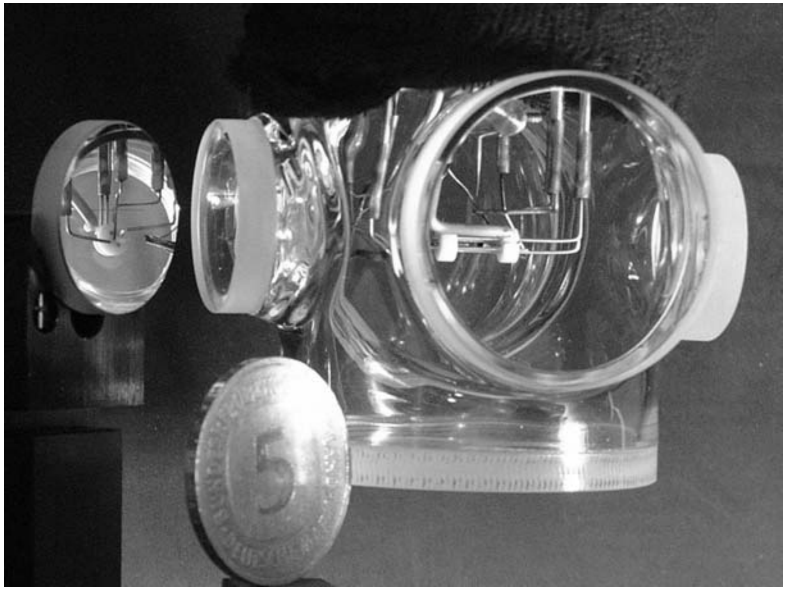
Spin resonance with trapped ions: experiments and new concepts

Christof Wunderlich

Quantum information processing with trapped ions

Qubits





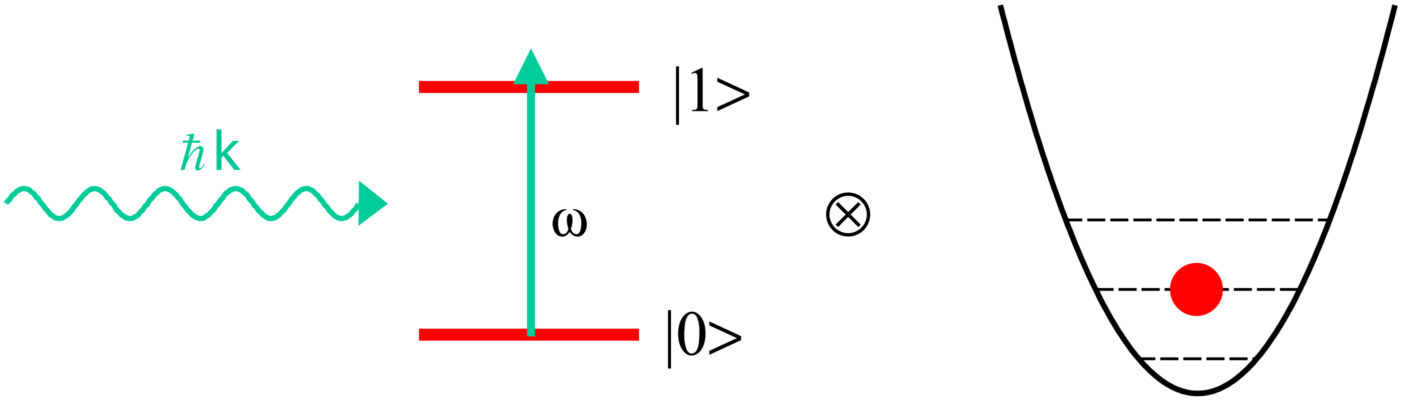
Internal states: qubits

Vibrational motion: bus-qubit

J. I. Cirac, P. Zoller, PRL **74**, 4091 (1995)

QIP with trapped ions
Qubits and bus-qubit

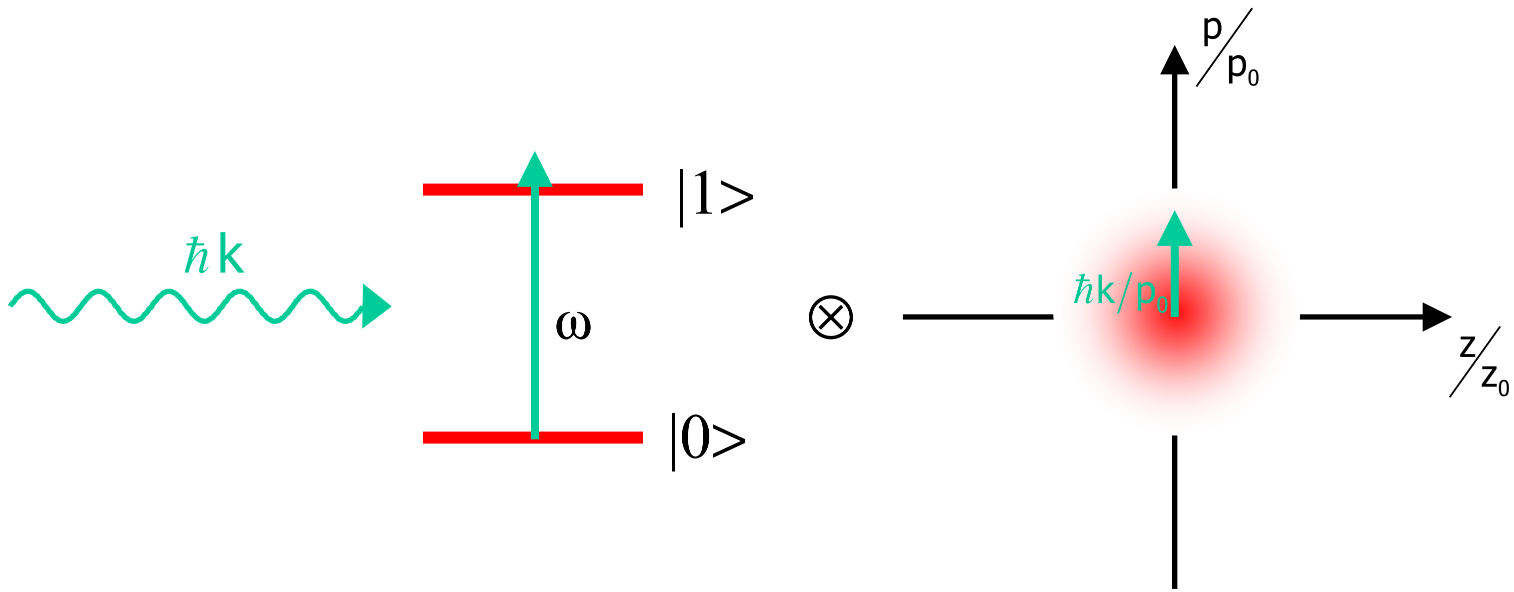
- Coupling internal and external dynamics:



QIP with trapped ions

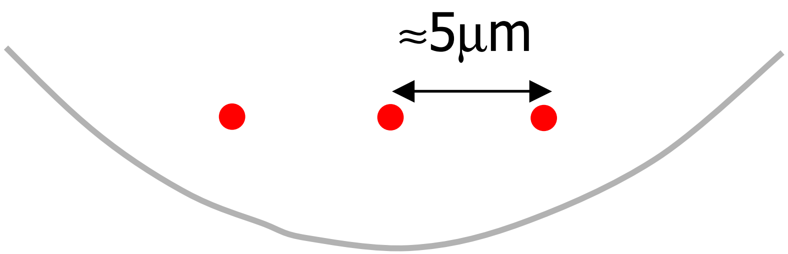
Qubits and bus-qubit

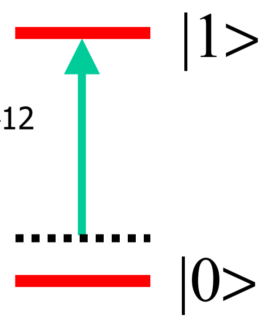
- Coupling internal and external dynamics:



$$H_I \propto \sigma_+ \exp\left[i\eta\left(a + a^+\right)\right] + \text{ h.c. } \quad \text{where} \quad \eta \equiv \frac{\hbar k}{2p_0} = \frac{z_0}{\lambda} 2\pi$$

QIP with trapped ions





$\Delta\nu / \nu \approx 10^{-12}$

Electromagnetic radiation used to

- couple internal and external degrees of freedom

$$\eta = \frac{z_0}{\lambda} 2\pi \qquad z_0 \approx 10\text{nm}$$

$\Rightarrow$ optical wavelengths

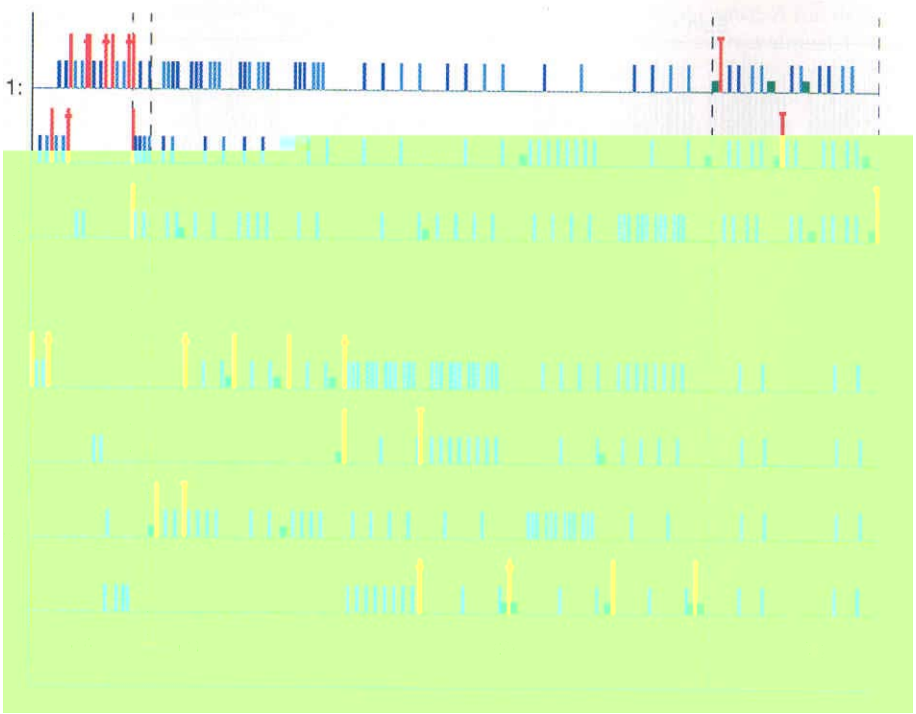
- address individual qubits

$\Rightarrow$ optical wavelengths

$\Rightarrow$ Precise coherent operations demand:
Small emission bandwidth, high absolute stability of frequency and intensity. Beam quality, pointing stability, diffraction.

Spin resonance

- Quantum algorithms demonstrated.
- Sophisticated techniques.
- Technological basis: coherent manipulation using rf and microwave radiation.

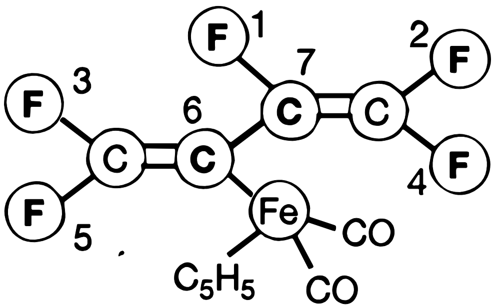


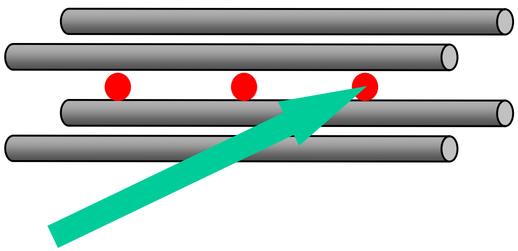
- Macroscopic ensemble
$\Rightarrow$ exponential cost
- Design of molecules nontrivial

Vandersypen et al., Nature **414**, 883 (2001)

Spin resonance with trapped ions?

Ion traps:





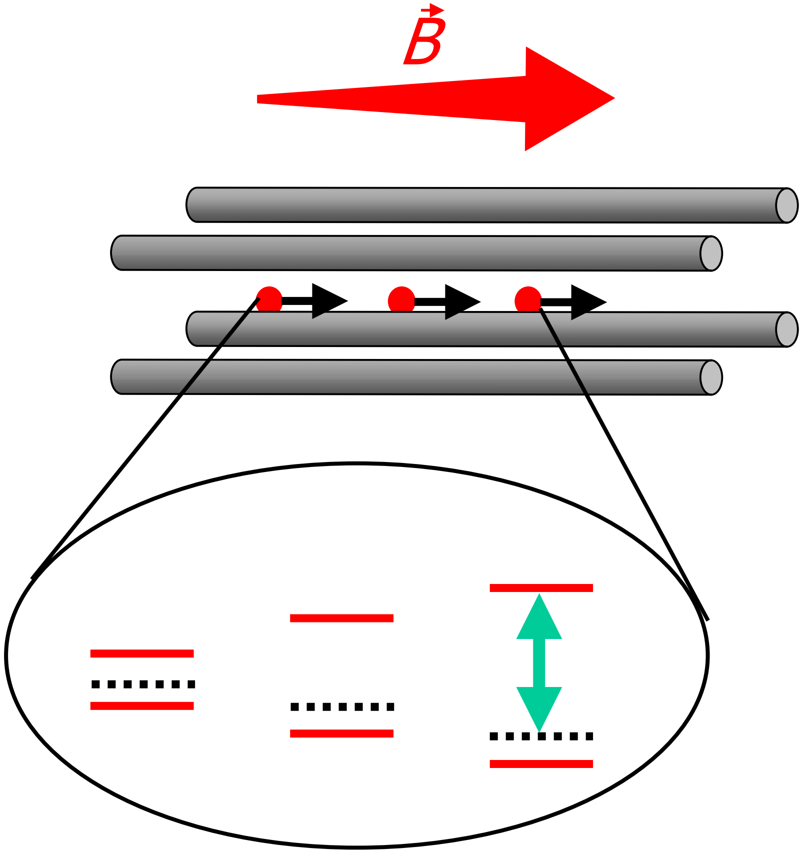
Macroscopic ensemble
⇒ exponential cost.
Design of molecules nontrivial.

Individual qubits.
Efficient readout.
Use microwaves?

Spin resonance with trapped ions

New concept:

- Qubit resonances shifted individually
- Coupling of internal and external dynamics

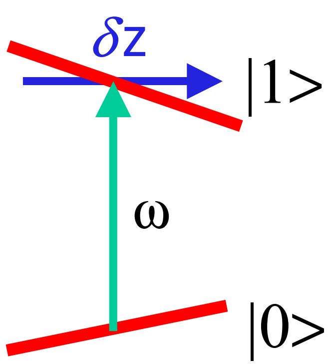


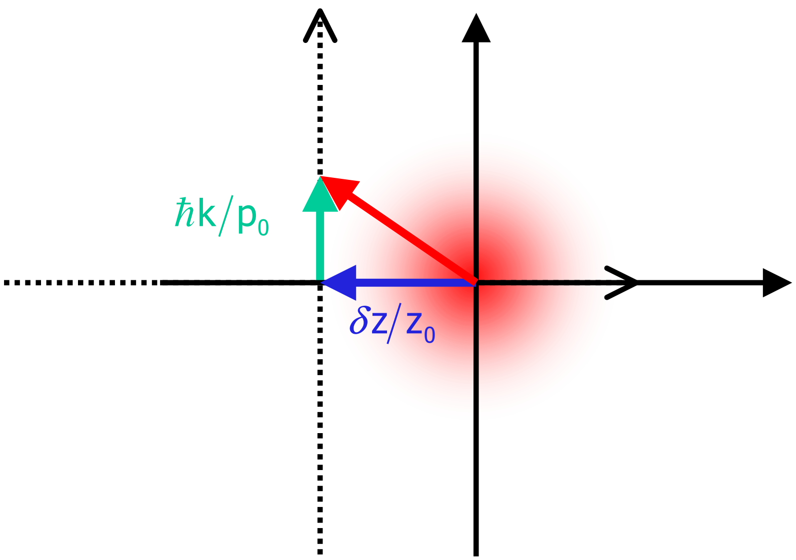
F. Mintert, Ch. Wunderlich,
Phys. Rev. Lett. **87**, 257904 (2001).

Spin resonance with trapped ions

- Coupling internal and external dynamics:

Magnetic field gradient





Equilibrium shifted by $\delta z = -\hbar \frac{\partial_z \omega}{m \nu^2}$

effective Lamb-Dicke parameter:

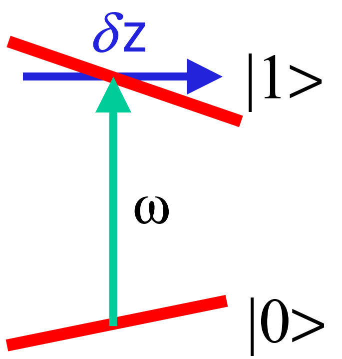
$$\eta' \equiv \eta - i\,\varepsilon$$

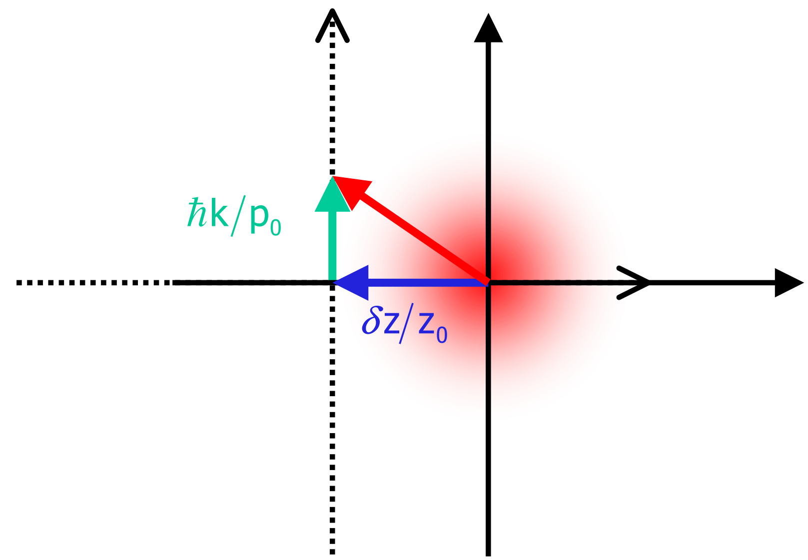
where $\varepsilon \equiv \frac{\delta z}{z_0} = z_0 \frac{\partial_z \omega}{\nu}$

Spin resonance with trapped ions

- Coupling internal and external dynamics:

Magnetic field gradient





Equilibrium shifted by $\delta z = -\hbar \frac{\partial_z \omega}{m \nu^2}$

$H_I \propto \sigma_+ \exp\left[i\eta' \left(a + a^+ \right) \right] + \text{ h.c.}$ where $\eta' \equiv (\eta^2 + \varepsilon^2)^{1/2}$

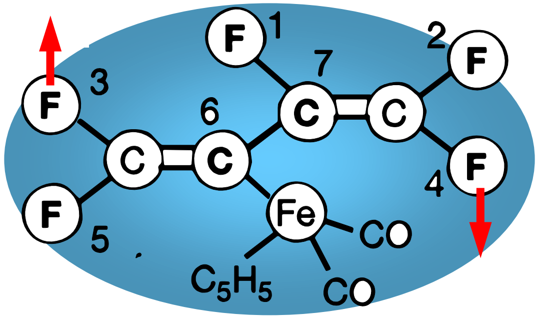
$\Rightarrow$ All optical schemes suitable for spin resonance

F. Mintert, Ch. Wunderlich, Phys. Rev. Lett. **87**, 257904 (2001).

Spin resonance with trapped ions

Analogy with NMR

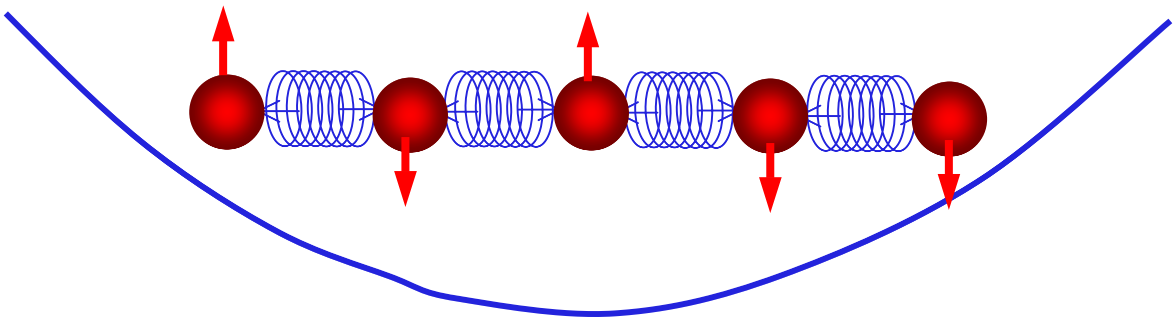
Conditional dynamics: $\hbar \sum_{n<l}^{N} \sigma_{z,n}\sigma_{z,l} \; J_{nl}$



Spin resonance with trapped ions

Analogy with NMR

Conditional dynamics: $\hbar \sum_{n<l}^{N} \sigma_{z,n} \sigma_{z,l} J_{nl}$ with $J_{nl} \propto \left(\frac{\partial_z B}{\nu_1} \right)^2$

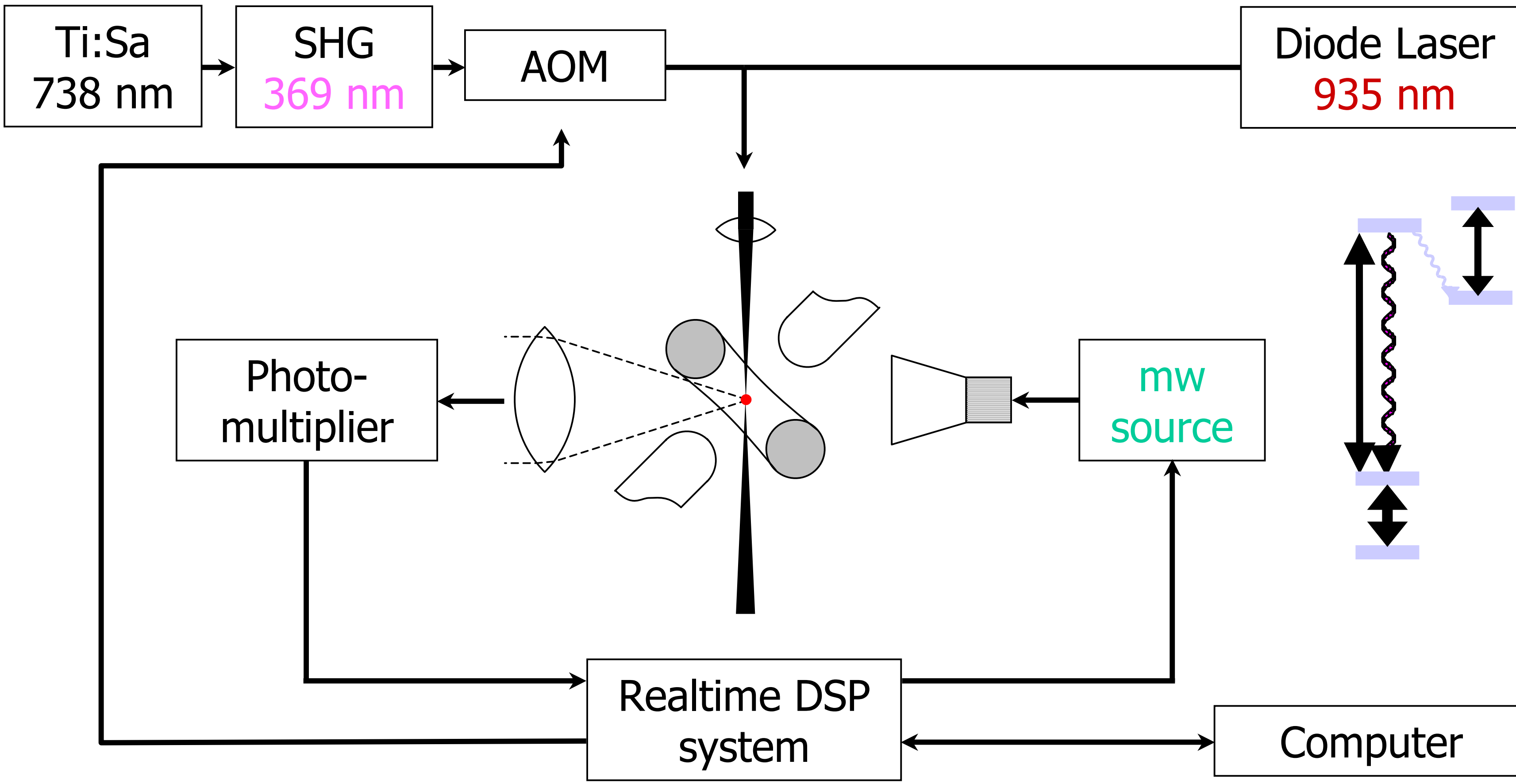


Single N-qubit „designer“ molecule:

- adjustable coupling constants
- Efficient read out of individual qubits

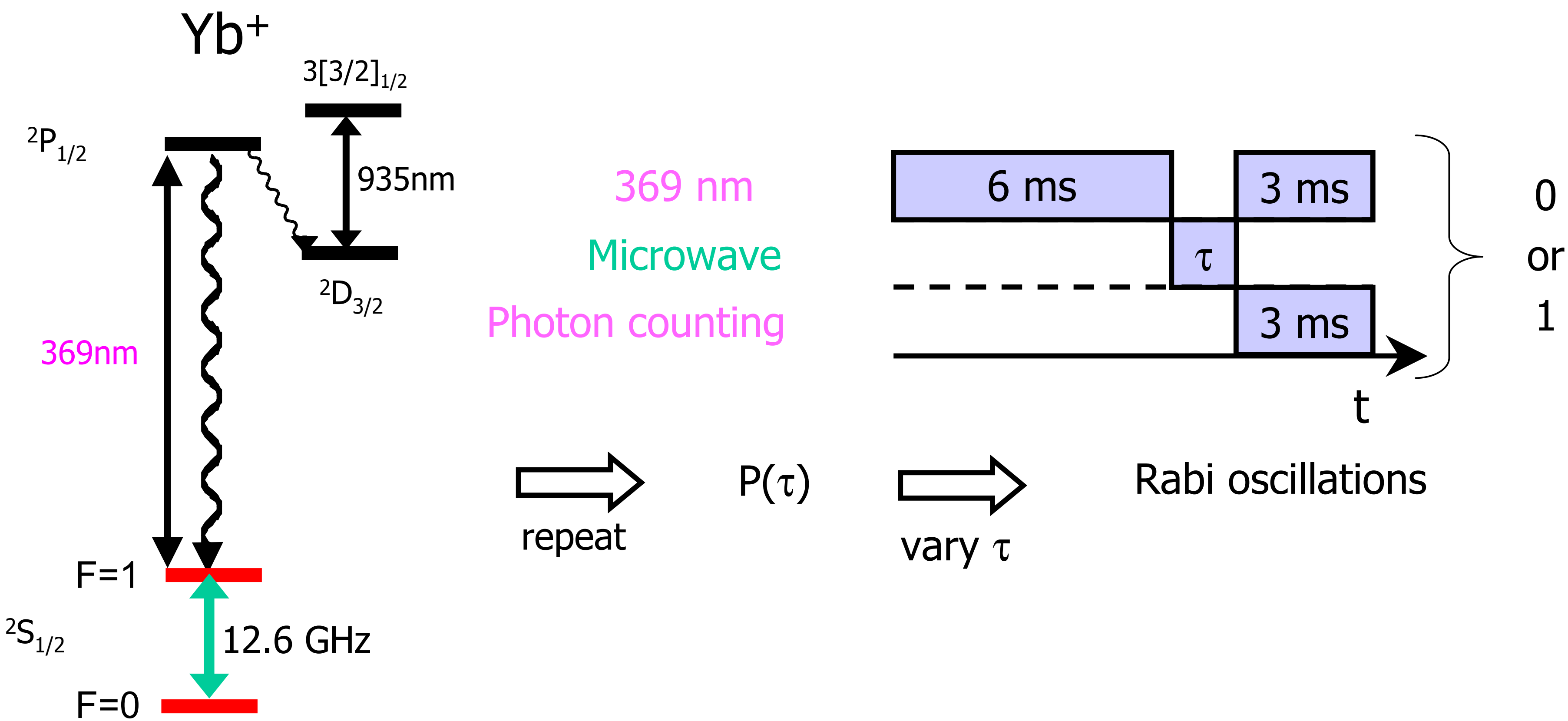
CW in *Laser Physics at the Limit*, Springer, 2002, p. 261.

Experiment
Setup



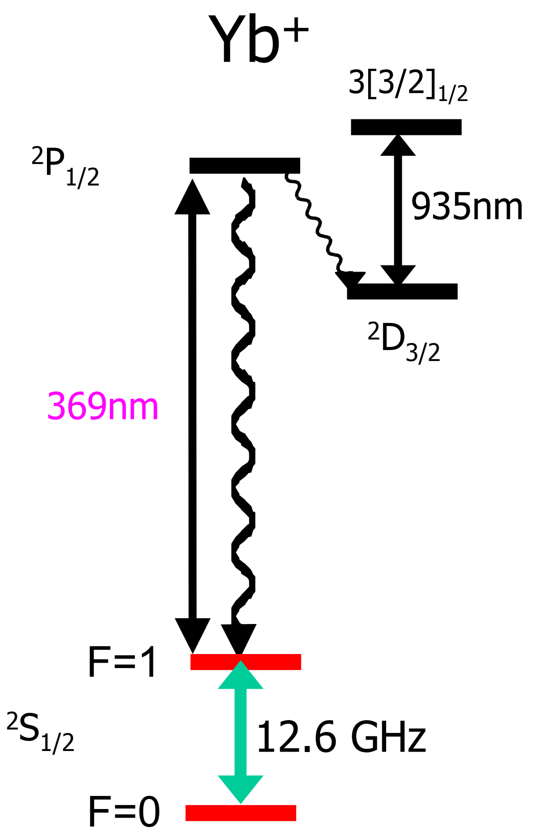
Trapped Yb$^+$ ions

Coherent preparation of individual quantum systems

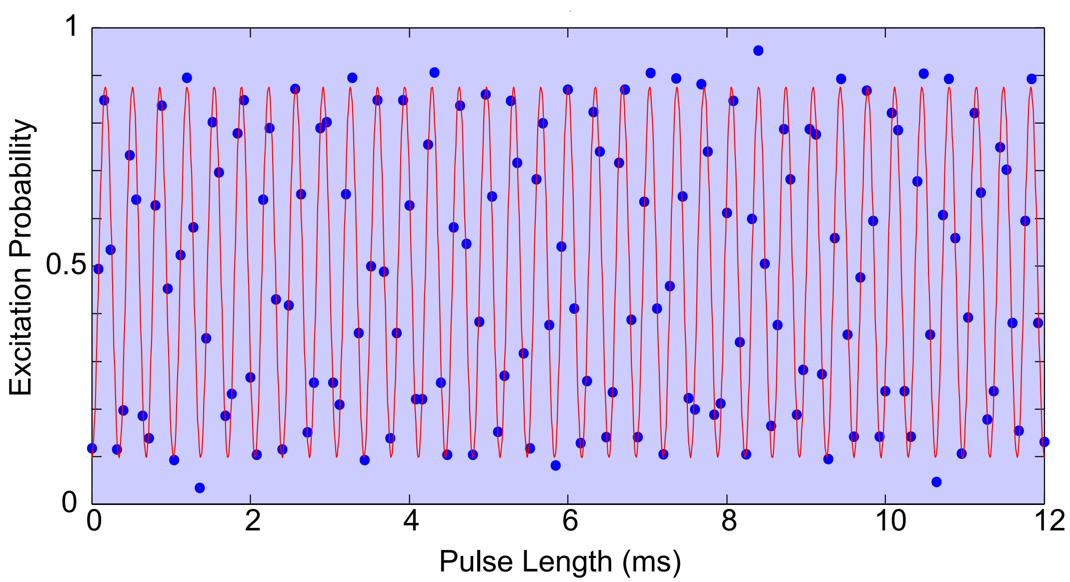


Trapped Yb^+ ions

Coherent preparation of individual quantum systems

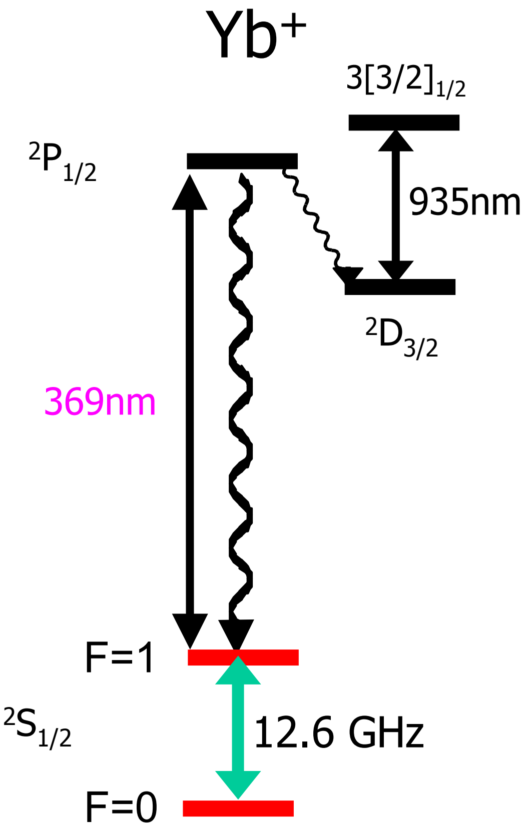


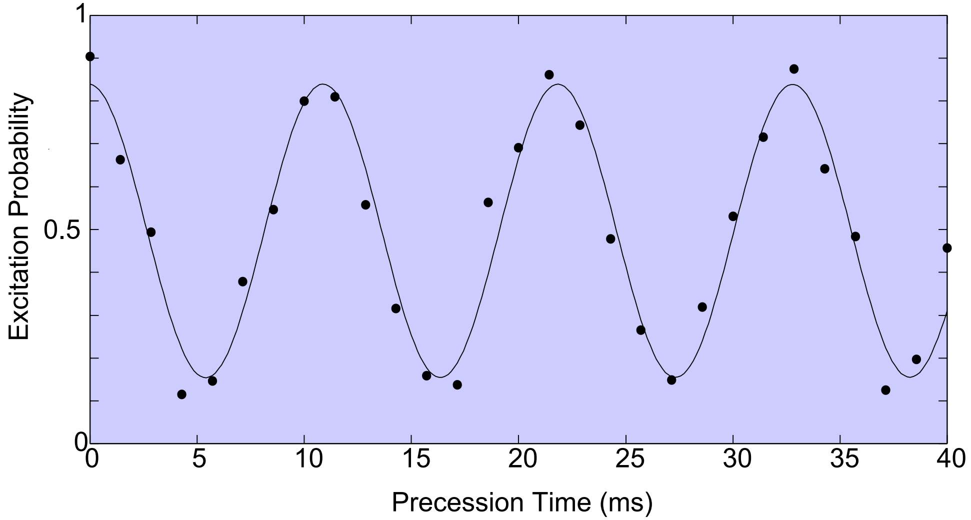
Individual Yb^+-Ion



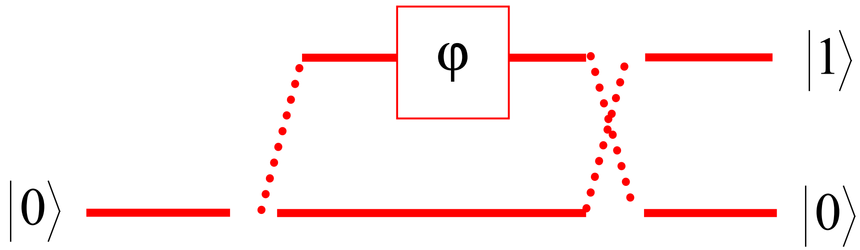
Rabi oscillations

Trapped Yb^+ ions
Coherent preparation of individual quantum systems

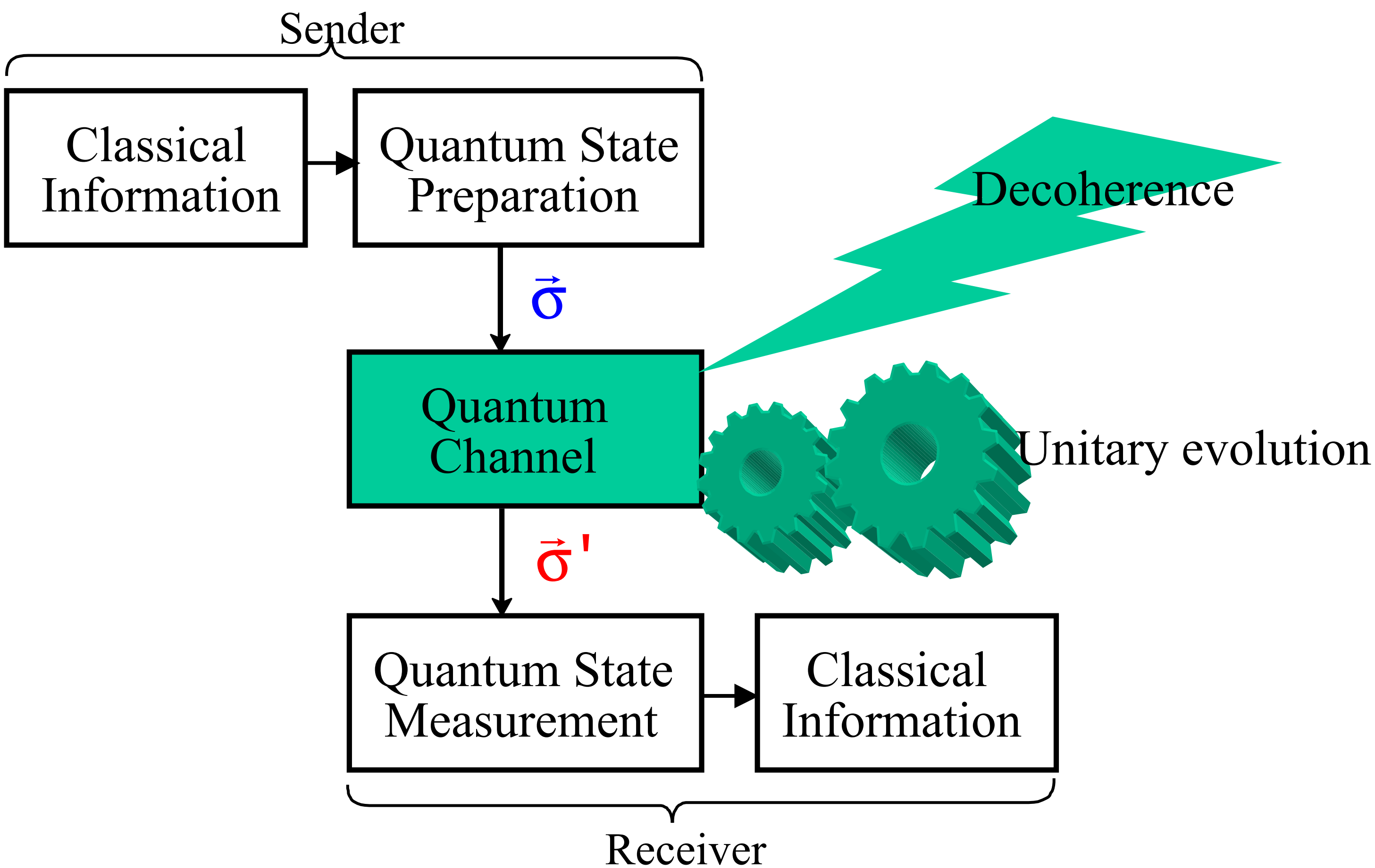




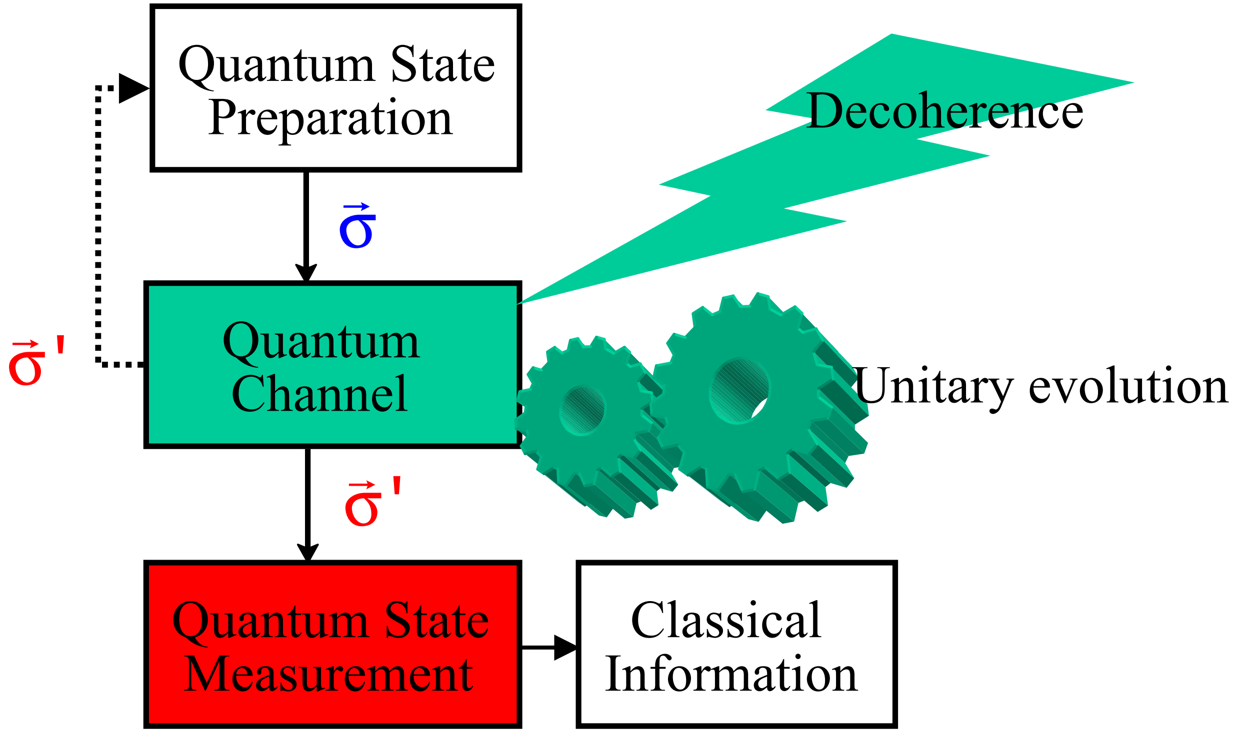
Interferometer



Qubit dynamics



Qubit dynamics

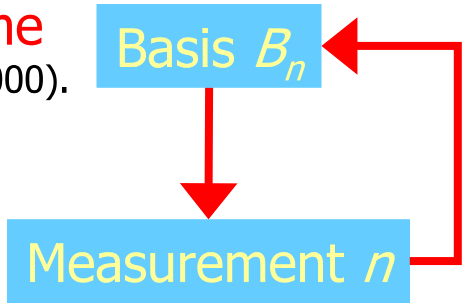


Determination of a quantum state

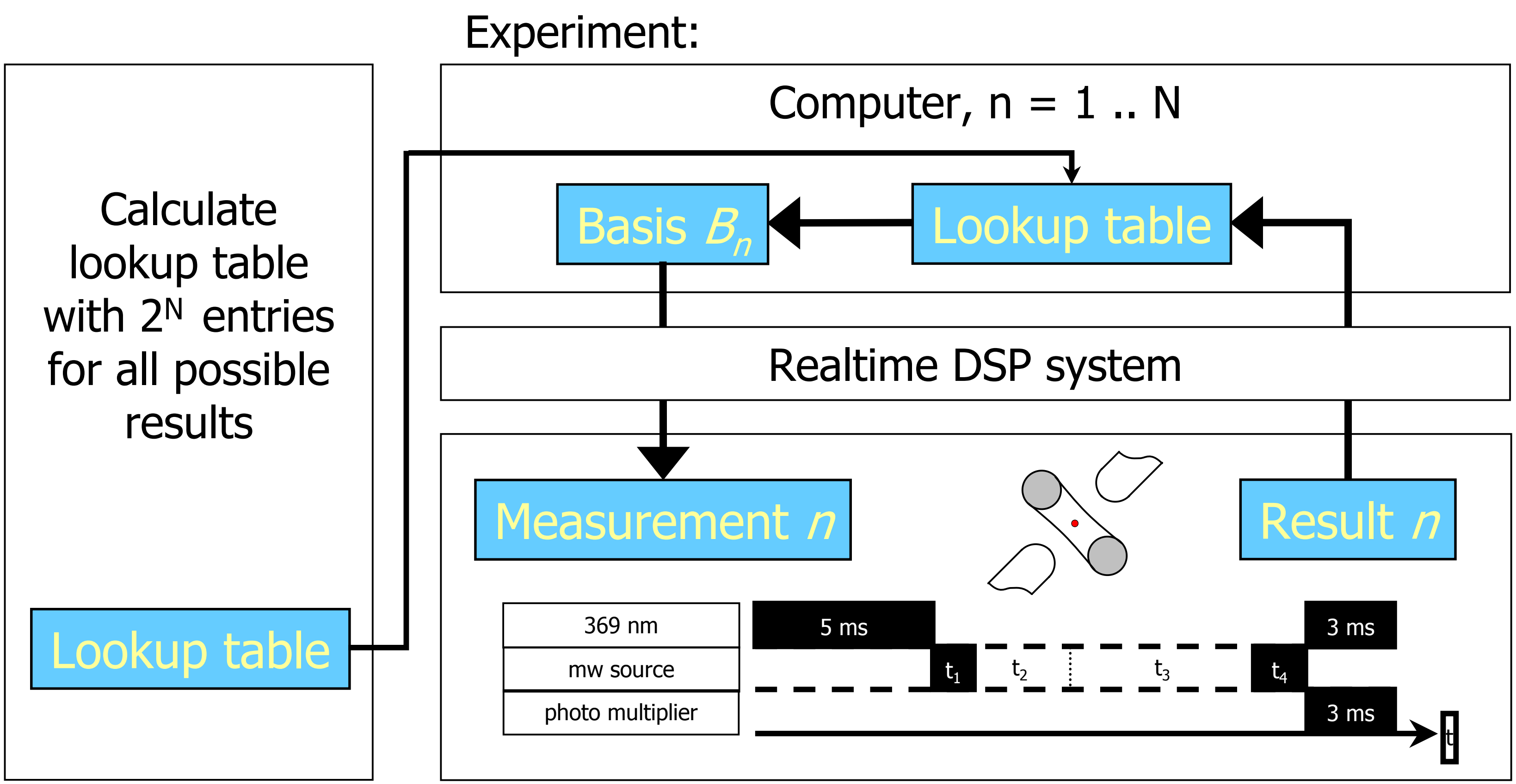
- Tomography: e.g. light fields, motional wave packets
  M. Freyberger, P. Bardroff, C. Leichtle, G. Schrade, W.Schleich, Phys. World **10** No.11, 41 (1997).

- Estimation using a finite number N of identically prepared qubits:
  - Optimal estimation requires entangled basis
    N=2: A. Peres, W.K. Wootters, PRL **66**, 1119 (1991); S. Massar, S. Popescu, PRL **74**, 1259 (1995). N≤5: J. I. Latorre, P. Pascual, and R. Tarrach, PRL **81**, 1351 (1998).
  - First experiments (N=2)
    V. Meyer et al., PRL **86**, 5870 (2001).

- Separate measurements on N qubits: Adaptive scheme
  D. G. Fischer, S. H. Kienle, and M. Freyberger, Phys. Rev. A **61**, 032306 (2000).

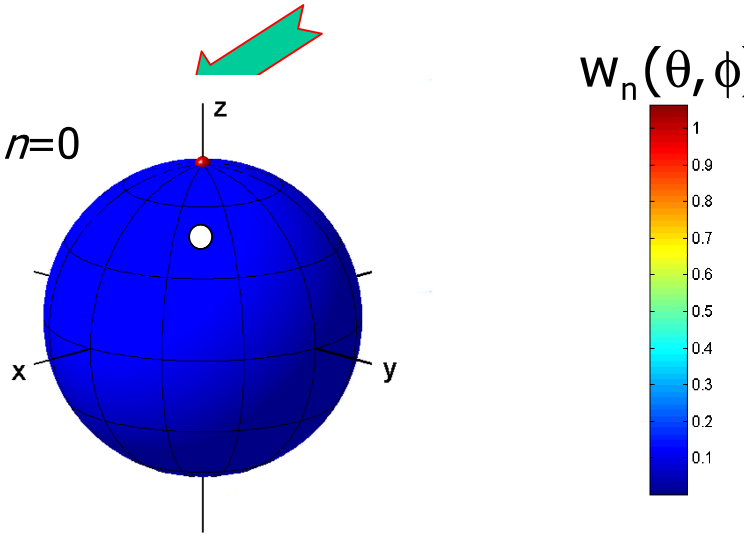


Experiment
Preparation and measurement



Estimating a quantum state

Experiment: self-learning estimation



- Probability density on Bloch sphere after measurement *n*.

$$\rho_n = \int_0^{\pi} d\theta \sin\theta \int_0^{2\pi} d\phi\, w_n(\theta,\phi) |\theta,\phi\rangle\langle\theta,\phi|$$

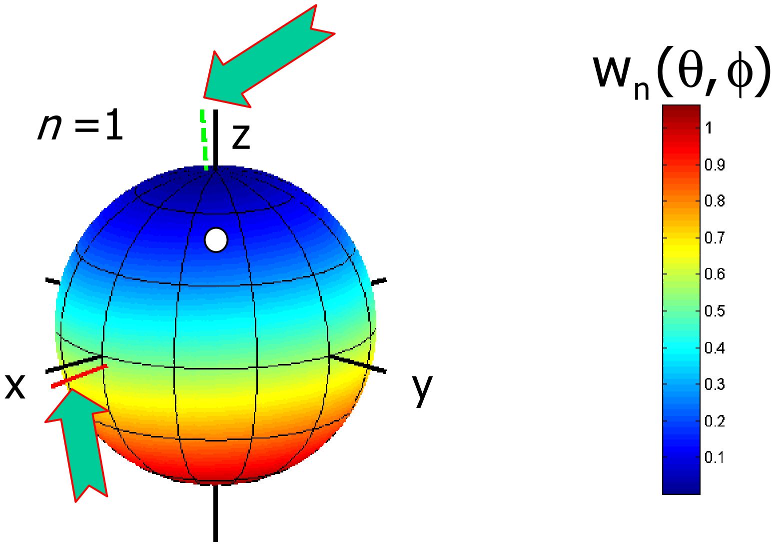
- Calculate direction of next (*n*+1) measurement from $w_n(\theta,\phi)$.

  Maximize classical information gain

Th. Hannemann et al. PRA **65**, 050303(R) (2002)

Estimating a quantum state

Experiment: self-learning estimation



- Probability density on Bloch sphere after measurement *n.*

$$\rho_n = \int_0^{\pi} d\theta \sin\theta \int_0^{2\pi} d\phi\, w_n(\theta,\phi) \left|\theta,\phi\right\rangle\left\langle\theta,\phi\right|$$

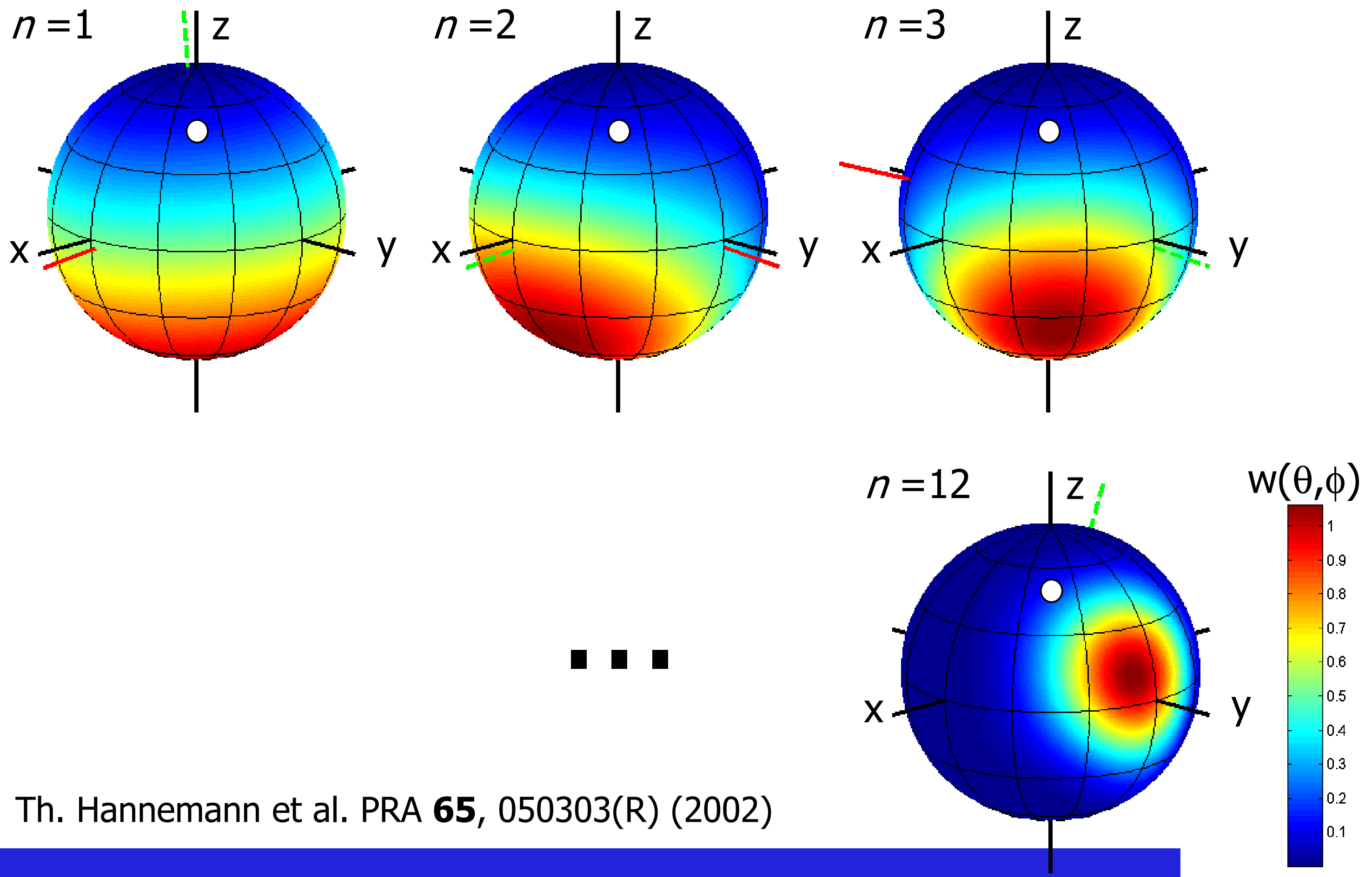
- Calculate direction of next (n+1) measurement from $w_n(\theta,\phi)$.

Better: Maximize expected Fidelity

$$F_{n+1}(\theta,\phi) = \left\langle\theta,\phi\right|\rho_{n+1}\left|\theta,\phi\right\rangle$$

Th. Hannemann et al. PRA **65**, 050303(R) (2002)

Estimating a quantum state
Experiment: self-learning estimation

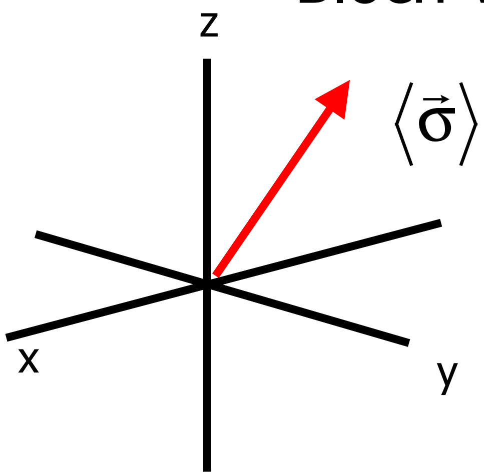


Th. Hannemann et al. PRA **65**, 050303(R) (2002)

Estimating a quantum state
Comparison with theory

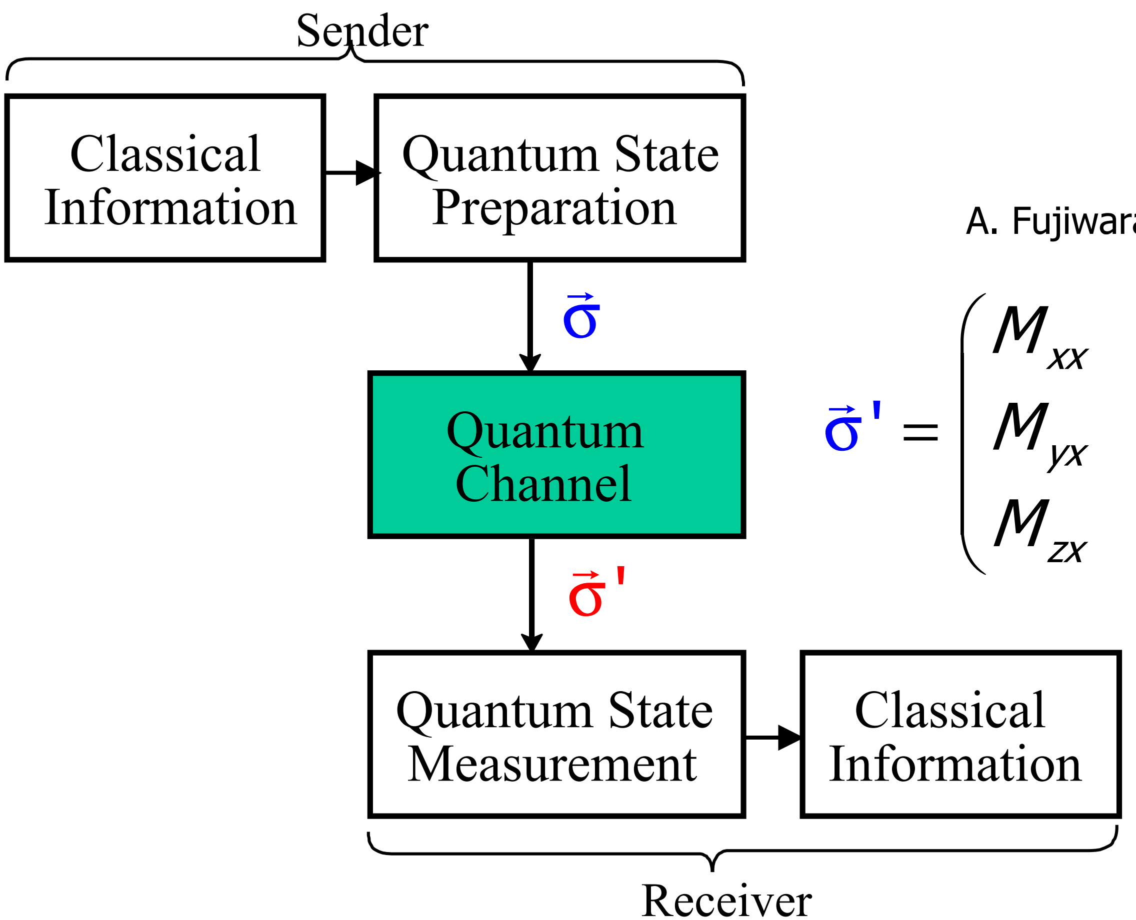
- Account for decoherence:
  - Preparation η_{prep} = 89 %
  - Detection η_{det} = 97 %

Bloch vector



$\langle F \rangle_{Exp}$	$\left\| \langle \vec{\sigma} \rangle \right\|$	$\langle F \rangle_{Theo} \left(\left\| \langle \vec{\sigma} \rangle \right\| \right)$
(85.0±0.6) %	(74.8±2.1) %	(85.4±0.7) %

Realization of quantum channels

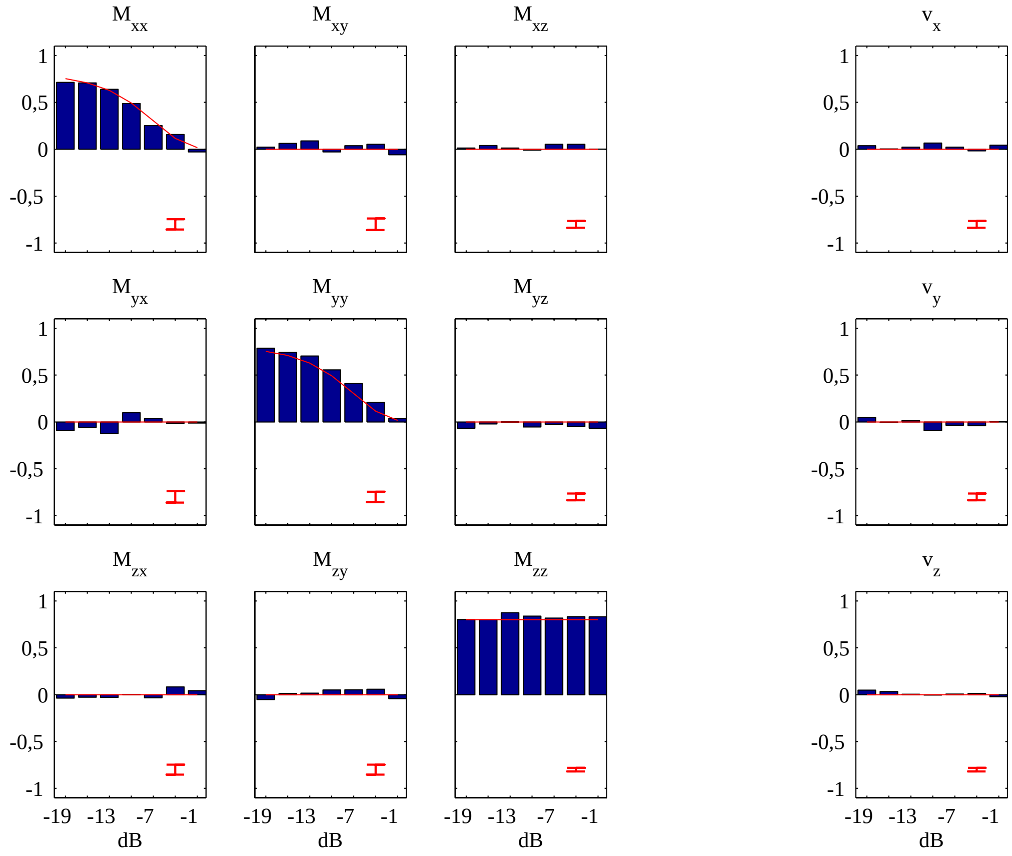


A. Fujiwara, P. Algoet, PRA **59**, 3290 (1999):

$$\vec{\sigma}' = \begin{pmatrix} M_{xx} & M_{xy} & M_{xz} \\ M_{yx} & M_{yy} & M_{yz} \\ M_{zx} & M_{zy} & M_{zz} \end{pmatrix} \cdot \vec{\sigma} + \begin{pmatrix} V_x \\ V_y \\ V_z \end{pmatrix}$$

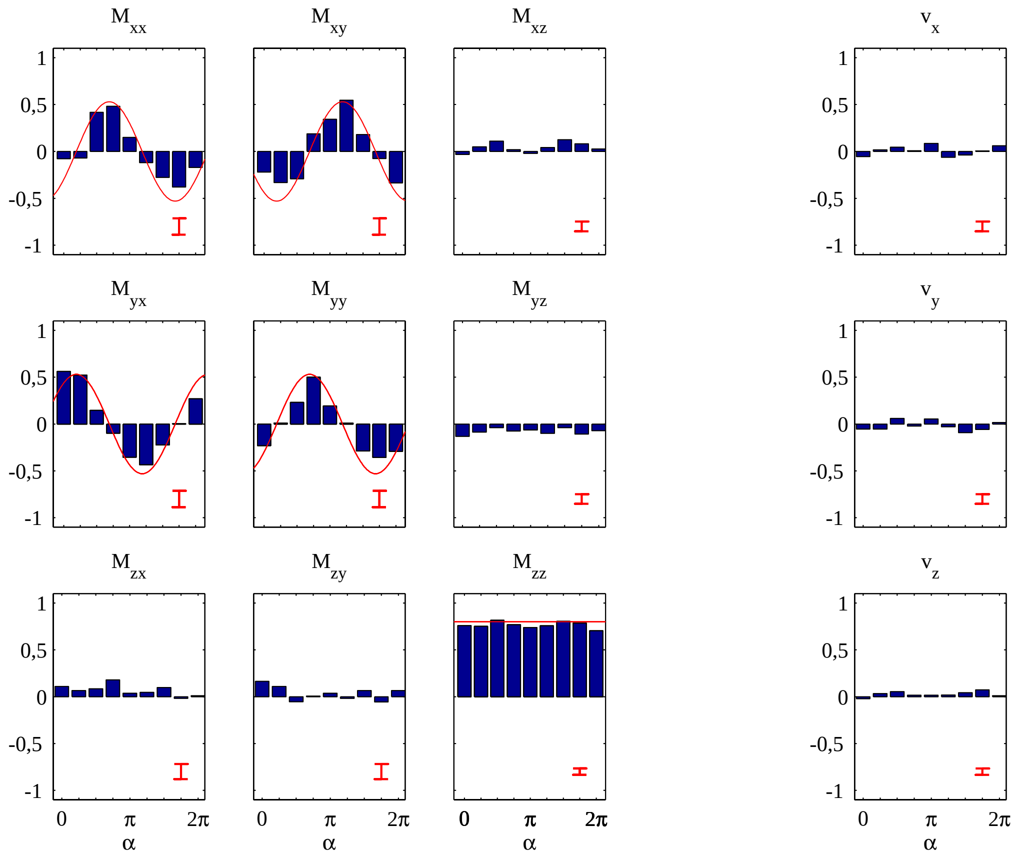
Realization of quantum channels

Variable phase damping



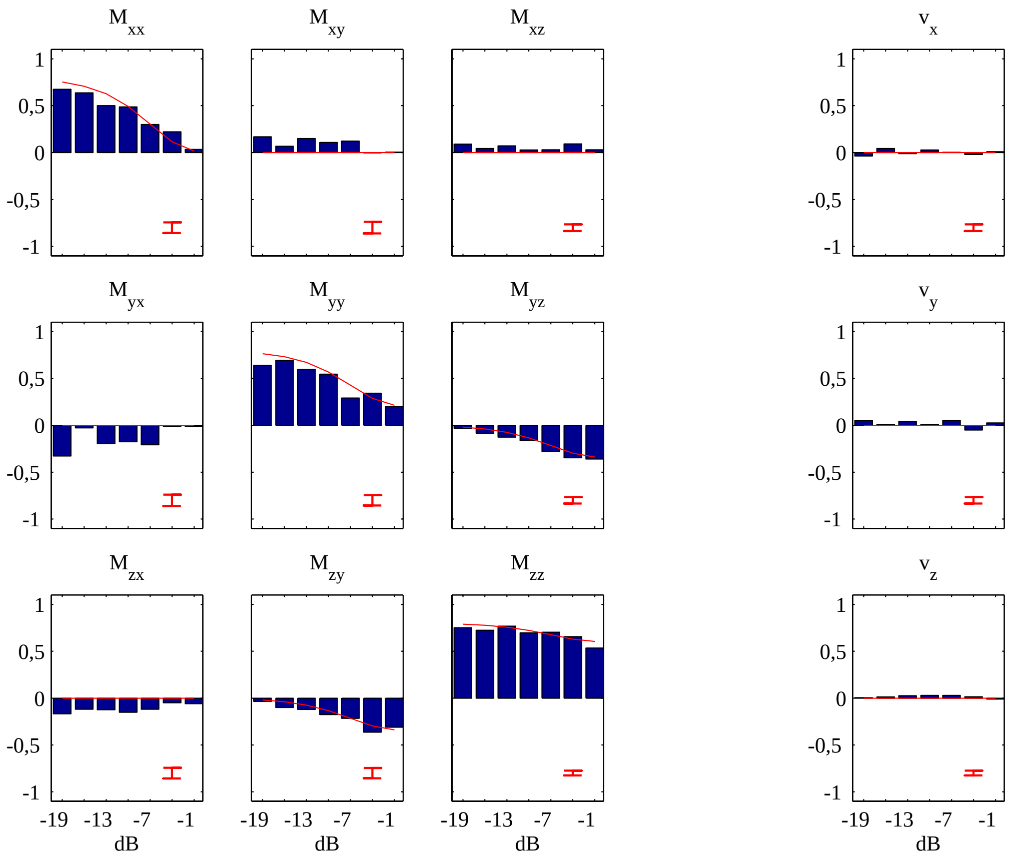
Realization of quantum channels

Fixed phase damping plus arbitrary polarization rotation



Realization of quantum channels

Phase damping in arbitrary plane. Here $\theta=\pi/6$



Universität Hamburg, Institut für Laser-Physik

W. Neuhauser
P.E. Toschek
Ch. Wunderlich

D. Reiß

K. Abich
Ch. Balzer
A. Braun
Th. Hannemann
A. Keil
S. Thöming

Ph. Leick
F. Mintert
M. Riebe
F. Scharnberg

Overview

- New concepts
  - Conditional dynamics in ion traps using microwaves.
  - Spin resonance in ion traps: designed molecules.
  - Simultaneous sideband cooling of all vibrational modes.
- Experiments with Yb^+
  - Self-learning estimation of quantum states.
  - Realization of quantum channels.
  - Quantum Zeno paradox.
- Experiments with Ba^+
  - Efficient, robust Raman cooling.
  - Coherent excitation of E2 transition.