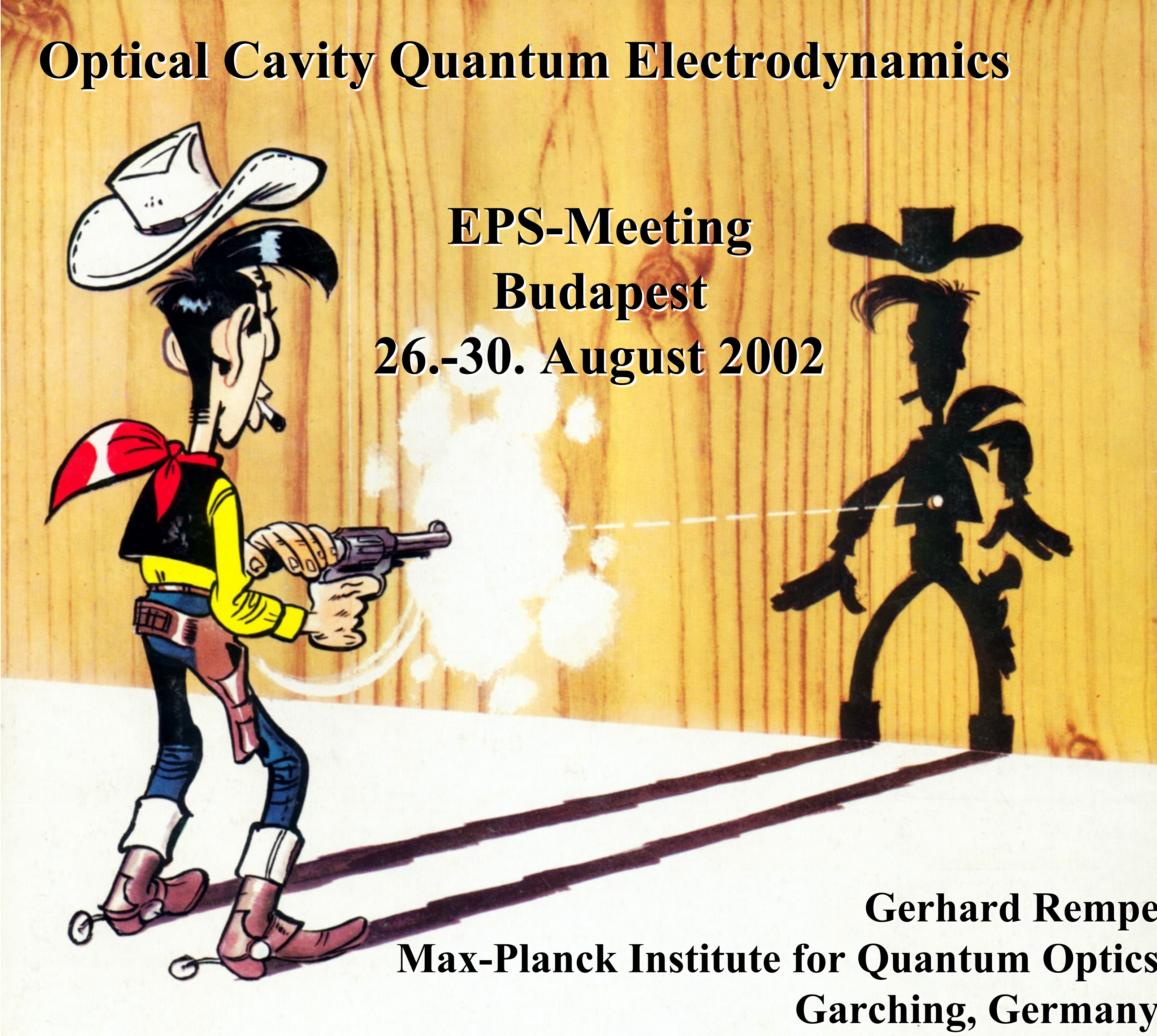
Optical Cavity Quantum Electrodynamics



EPS-Meeting
Budapest
26.-30. August 2002

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Garching, Germany

Optical Cavity Quantum Electrodynamics

why is it interesting ?

- network of **unitary** quantum computers
- control of a **dissipative** quantum system

what has been achieved in the laboratory ?

- example 1: light-matter interface
- example 2: feedback control of atomic motion

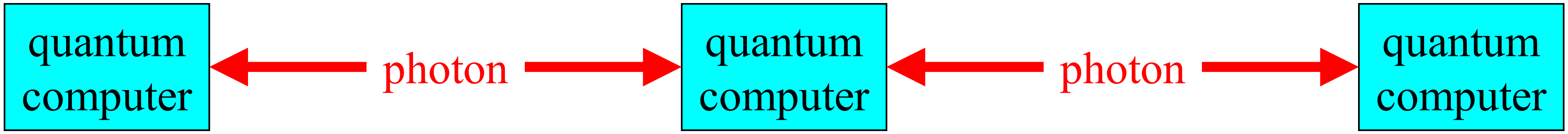
where can it be applied in the future ?

- example 3: microscopy of a moving atom

Distributed Quantum Network

quantum computer

most likely, it will employ a **small** number of qubits



quantum network

adds modularity and scalability

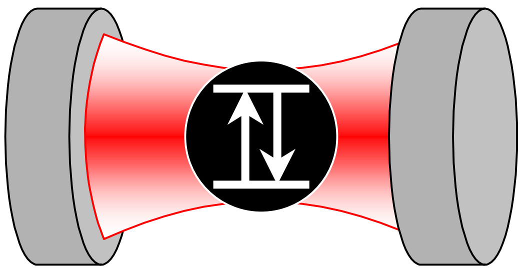
wanted: light-matter interface

a photon source based on a unitary (deterministic and reversible) emission process

Ingredient I: Cavity Quantum Electrodynamics

atomic - dipole decay rate :

$$\gamma = \frac{1}{4\pi\varepsilon_0}\frac{2}{3}\frac{\mu^2\omega^3}{\hbar c^3}$$



cavity - field decay rate :

$$\kappa = \frac{\omega}{2Q} = \frac{c}{2L}\frac{\pi}{F}$$

atom - photon coupling constant :

$$g = \frac{\mu E}{\hbar} = \mu\sqrt{\frac{\omega}{2\varepsilon_0 \hbar V}}$$

$\uparrow$

vacuum - electric field :

$$\frac{\hbar\omega}{2} = \int \varepsilon_0 E^2 dV \quad \Rightarrow \quad E = \sqrt{\frac{\hbar\omega}{2\varepsilon_0 V}}$$

strong coupling g > (γ, κ):

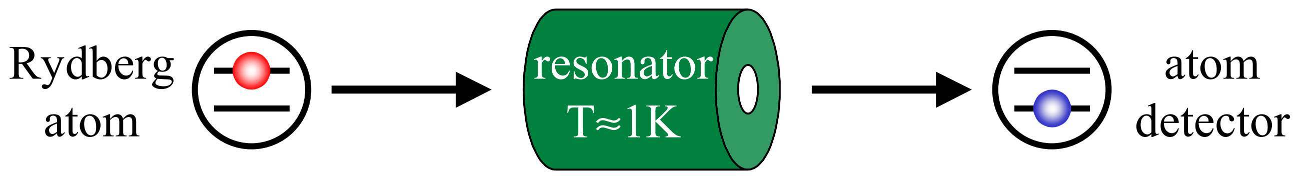
cavity-volume small	**cavity-finesse high**
$\Downarrow$	$\Downarrow$
g large	**κ small**

internal dynamics faster than coupling to the environment

Cavity QED for Quantum Information Processing

microwave domain (ENS, LMU):

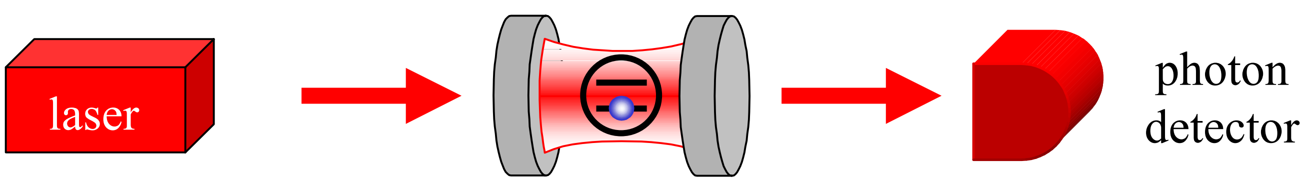
small ω, large μ, large V



+ quantum manipulations at the single-atom and single-photon level
– photons at rest
– poor scalability and poor prospects for quantum communications

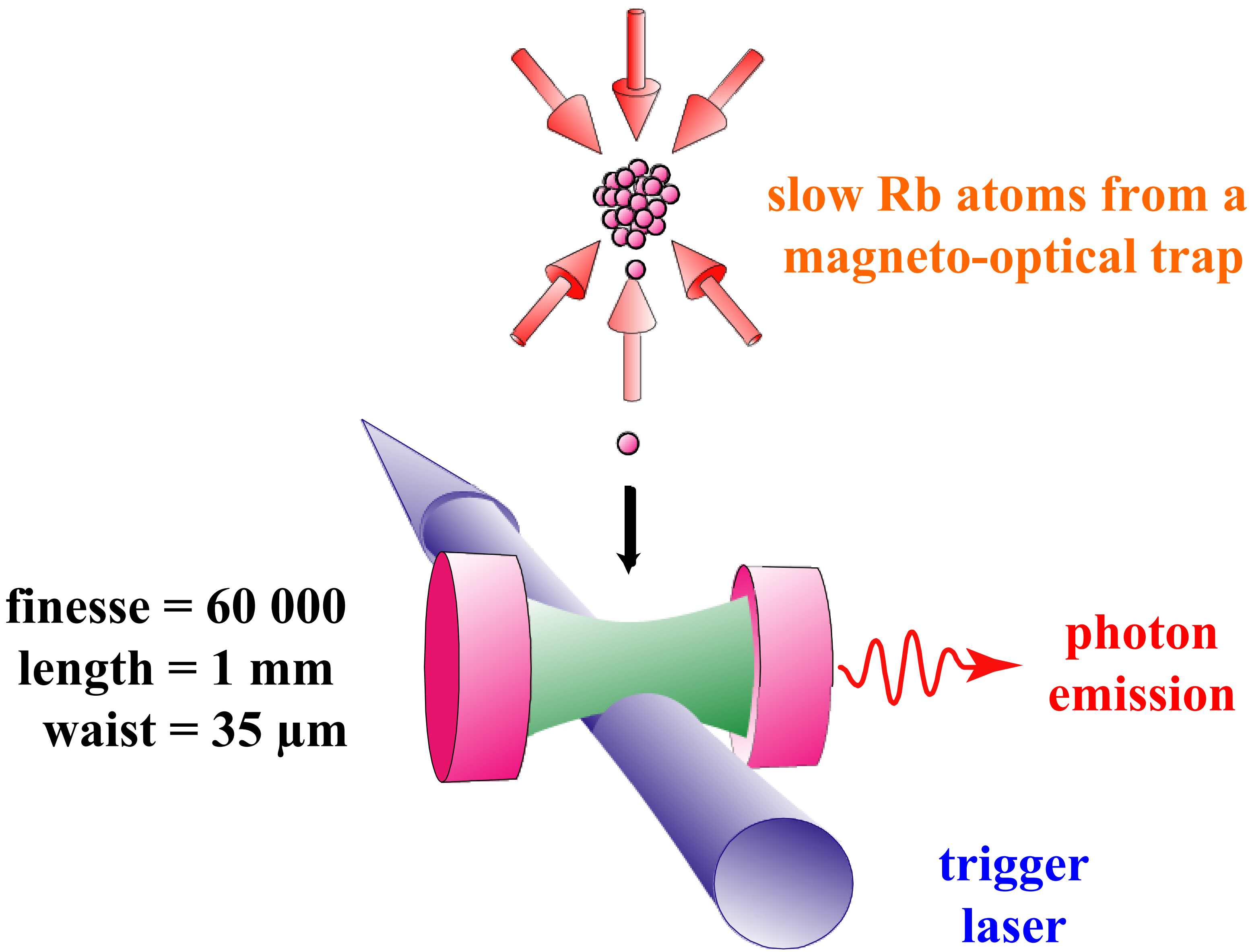
optical domain (Caltech, MPQ, ...):

large ω, small μ, small V

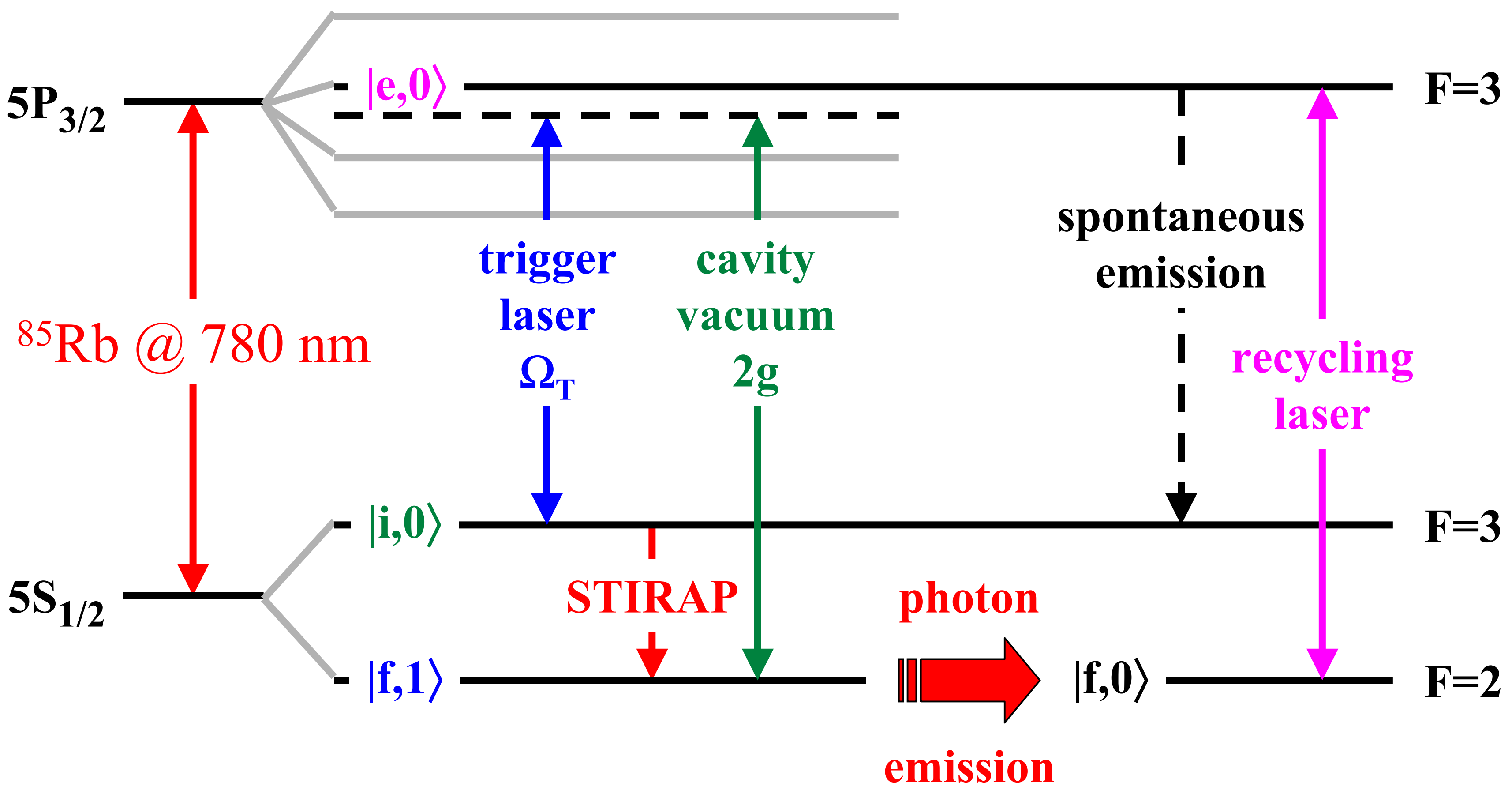


+ flying photons
+ good scalability and good prospects for quantum communications
– limited control over relevant parameters (atomic motion)

Experimental Setup



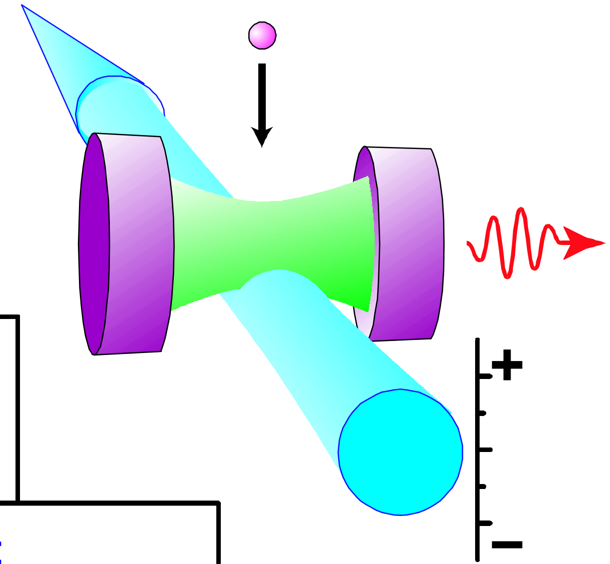
Ingredient II: Stimulated Raman Adiabatic Passage

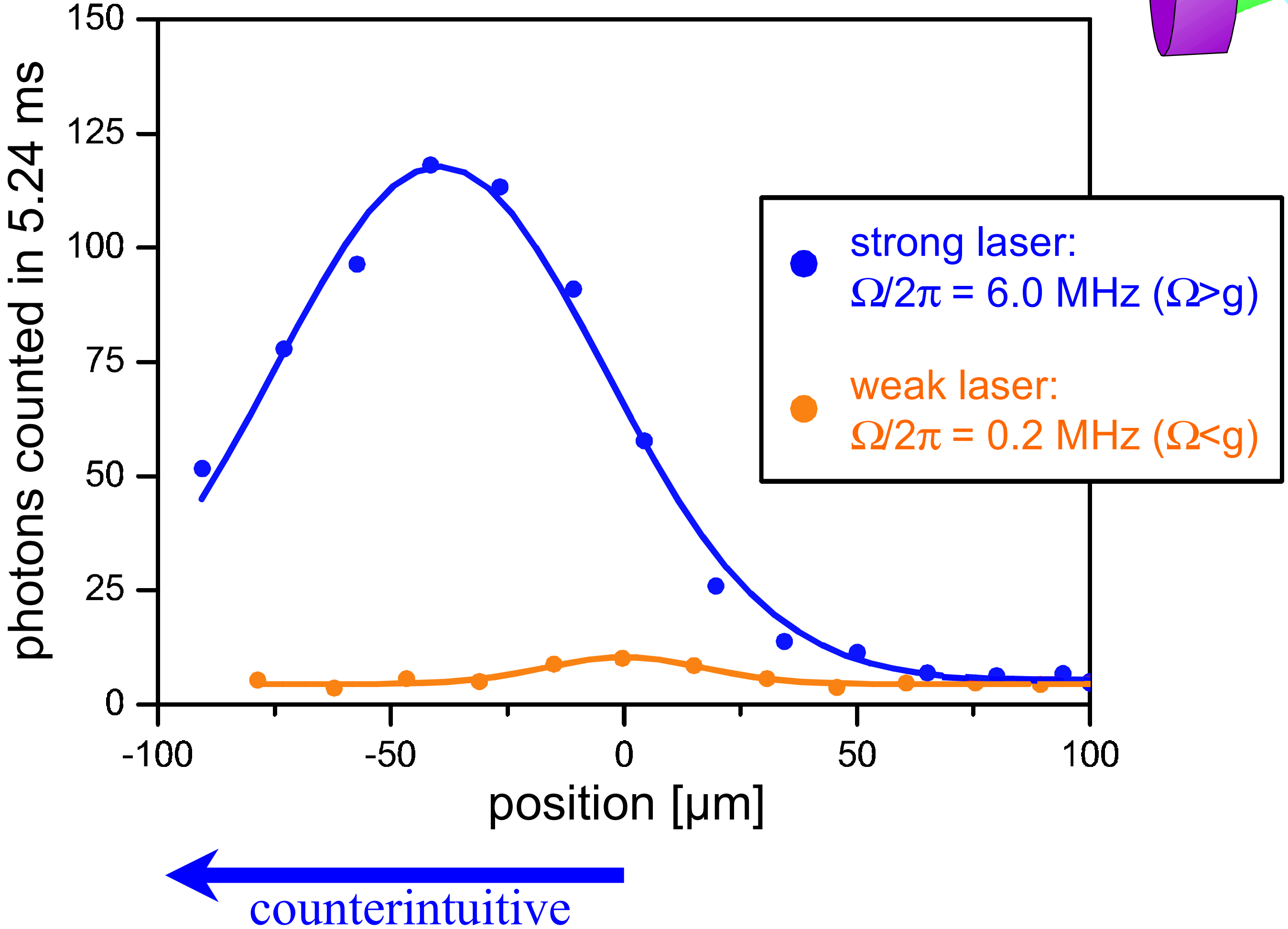


dark state (without contribution from the atom's excited state):

$$|\Psi_0(t)\rangle = \frac{2g(t)\,|\mathrm{i},0\rangle - \Omega_T(t)\,|\mathrm{f},1\rangle}{\sqrt{4g^2 + \Omega_T^2}}$$

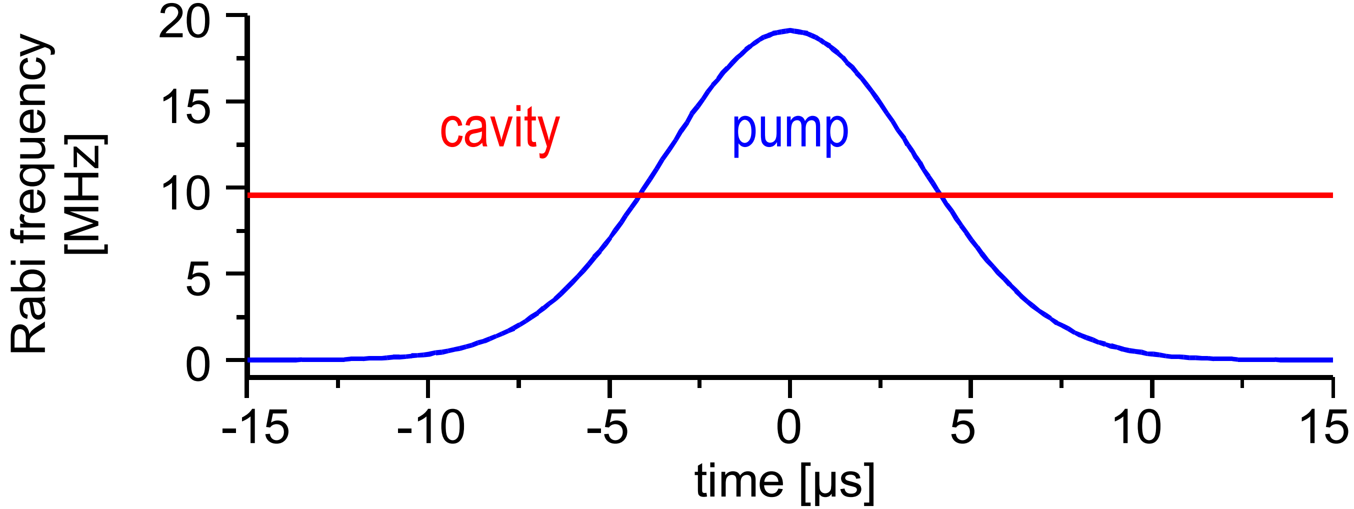
Counterintuitive Interaction Sequence

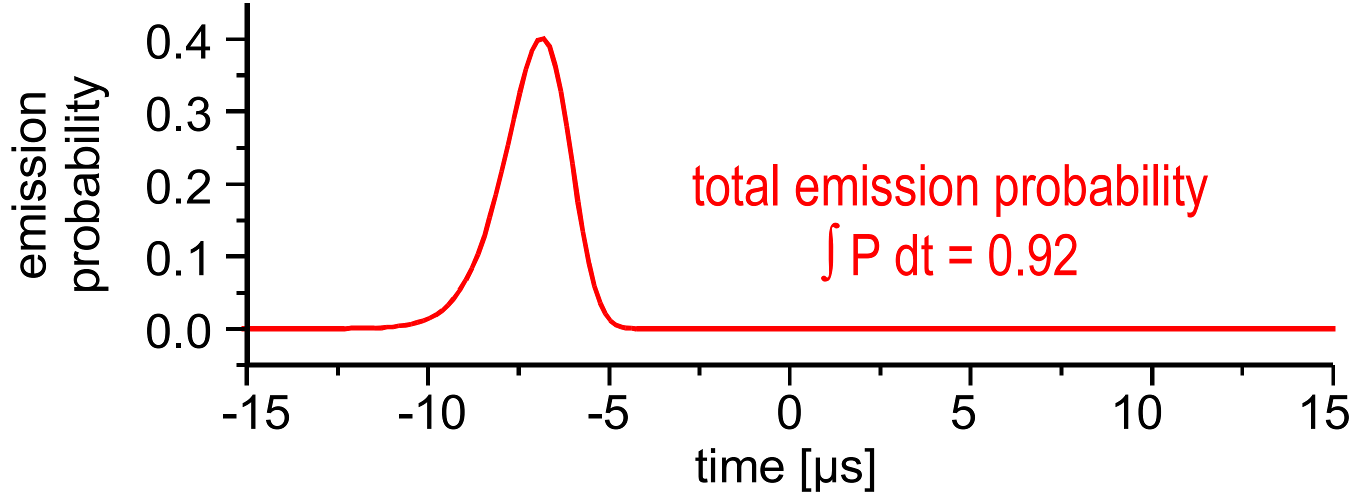




Hennrich et al., Phys. Rev. Lett. **85** (2000) 4872

Numerical Simulation of a Single Shot

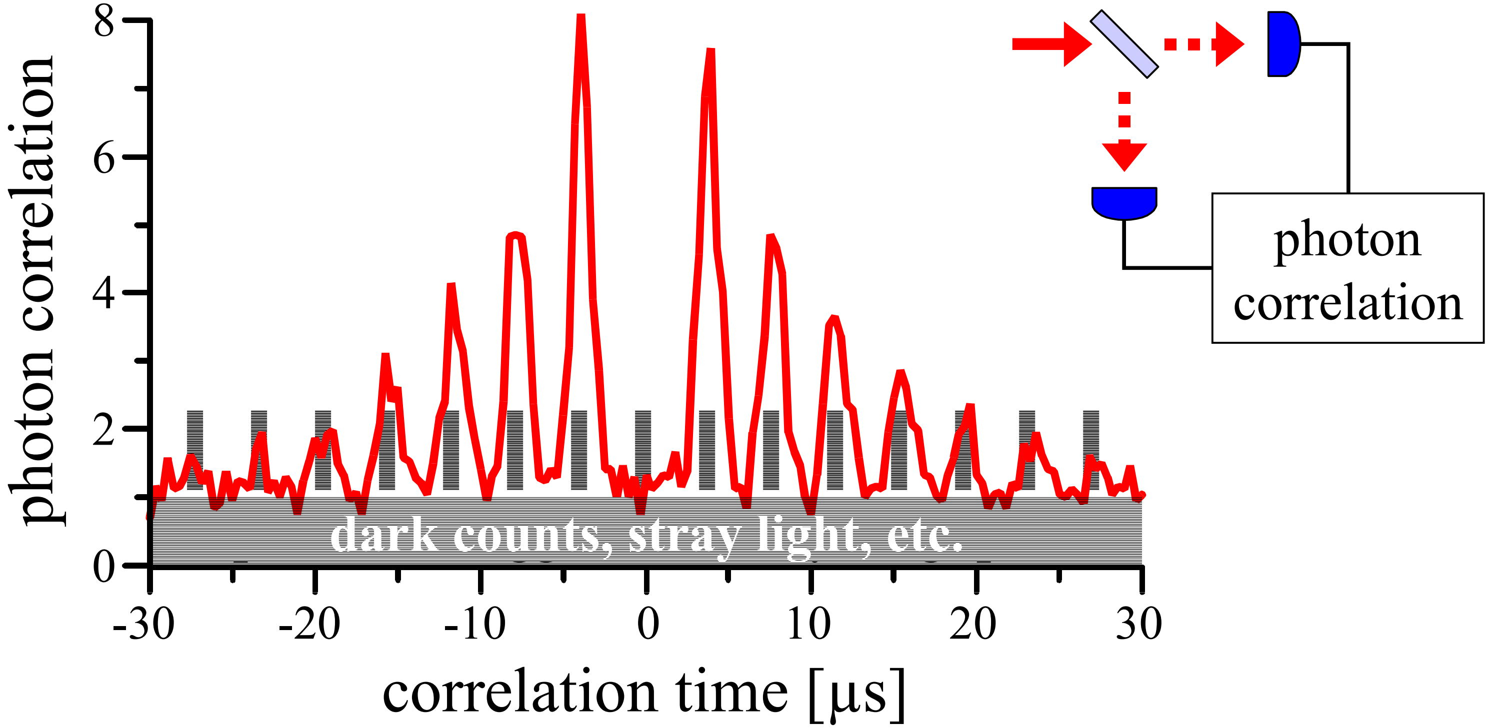




Kuhn et al., Appl. Phys. B **69** (1999) 373

Triggered Stream of Single-Photon Pulses

mean atom number N ≈ 0.06



photon anti-bunching @ τ=0
successive photons @ successive pump pulses
finite atom-cavity interaction time for a moving atom

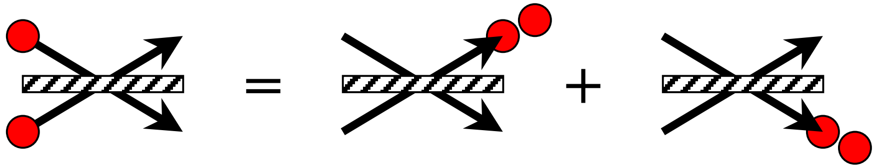
Kuhn et al., Phys. Rev. Lett. **89** (2002) 067901

Single-Photon Physics – An Outlook

Quantum computing:

• quantum gates with linear optics (Knill-LaFlamme-Milburn)

• interference of indistinguishable photons (Hong-Ou-Mandel)

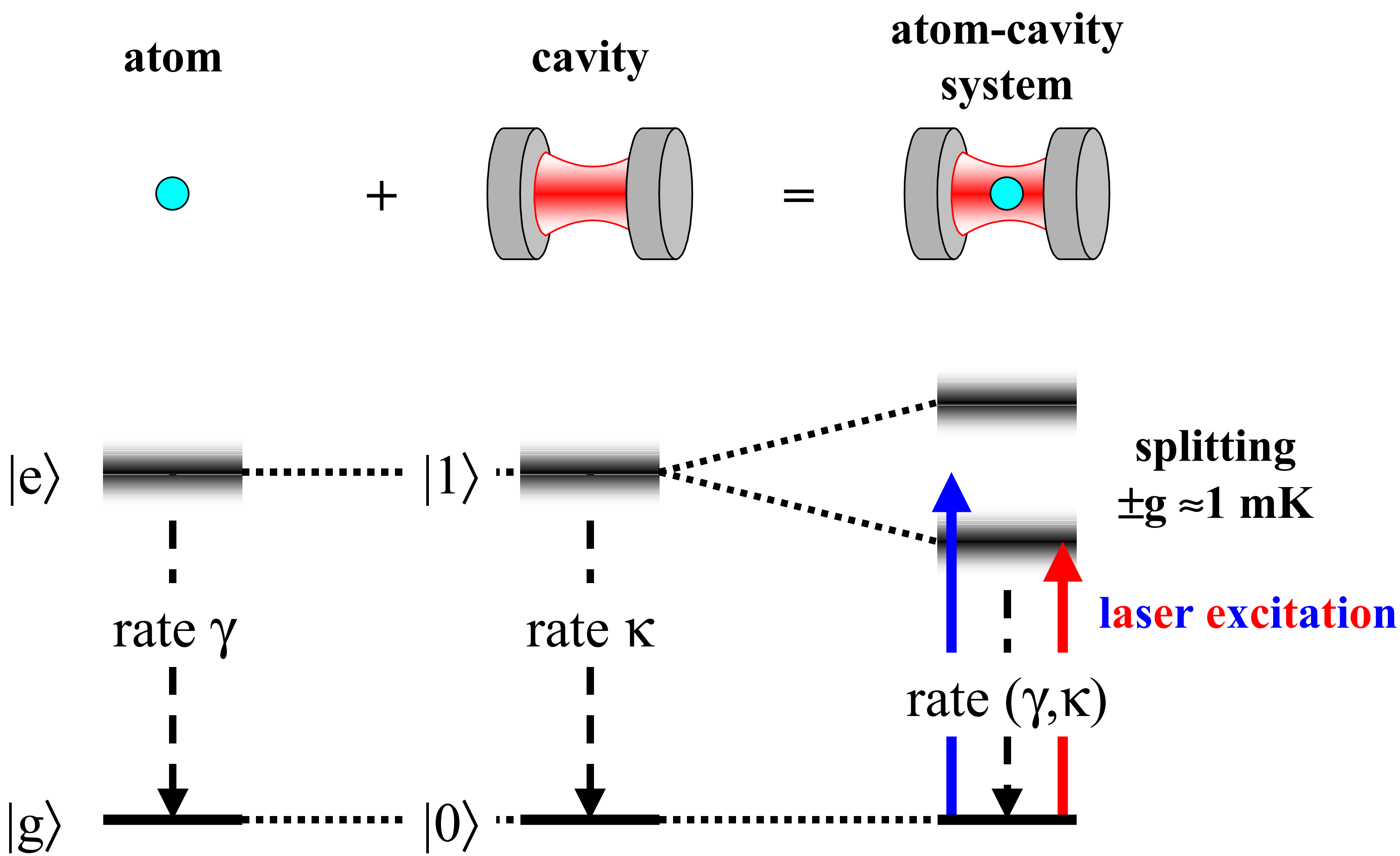


Quantum networking:

• entanglement of two distant intra-cavity atoms

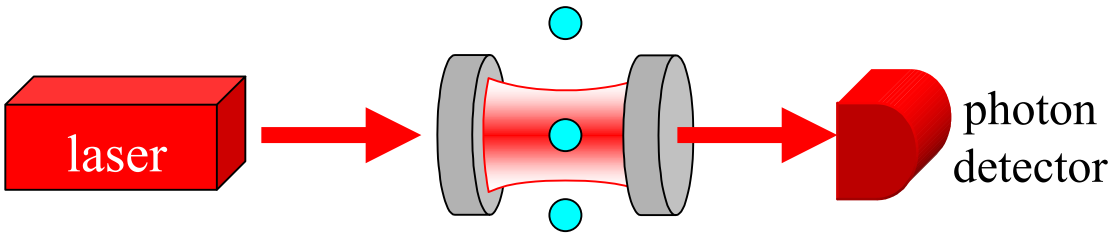
• teleportation of internal and/or external atomic states

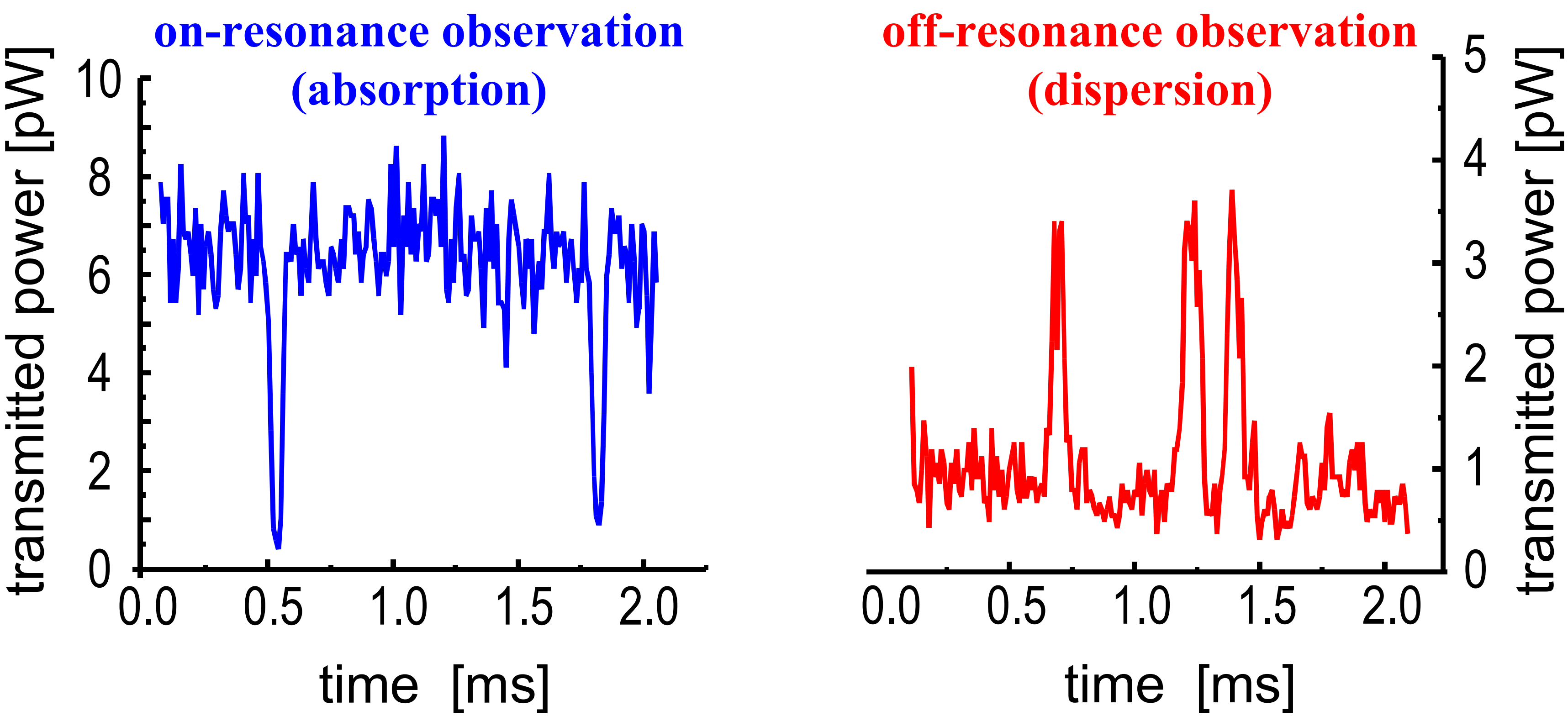
Atom-Photon Molecule



Jaynes and Cummings, IEEE **51** (1963) 89

Real-Time Observation of Individual Atoms





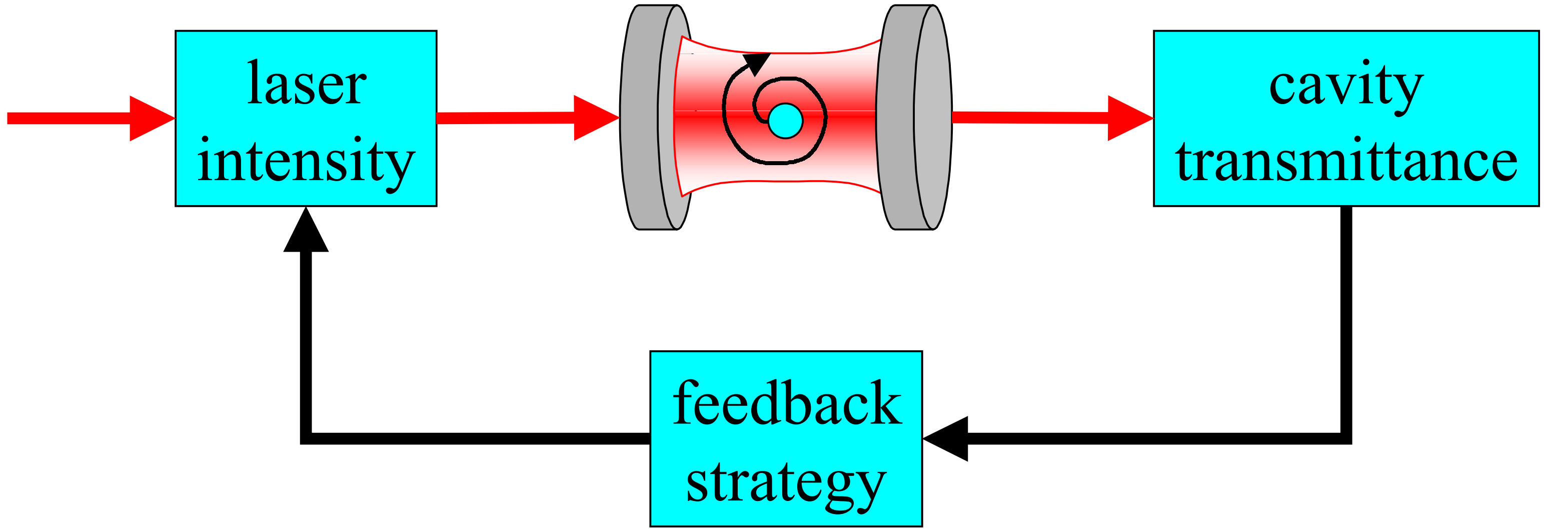
Mabuchi et al., Opt. Lett. **21** (1996) 1393

Münstermann et al., Opt. Commun. **159** (1999) 63

Feedback Control of Atomic Motion

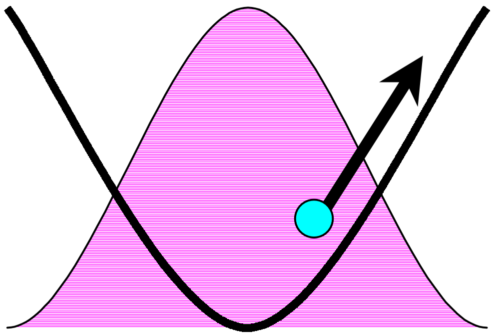
real-time observation and **mechanical binding:**

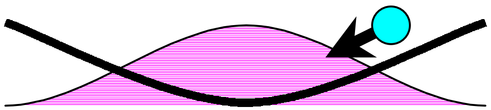
- control an observed (dissipative) quantum system
- explore limits set by quantum noise and measurement-induced back-action



Differentiating Feedback Control

light intensity depends on the atomic velocity





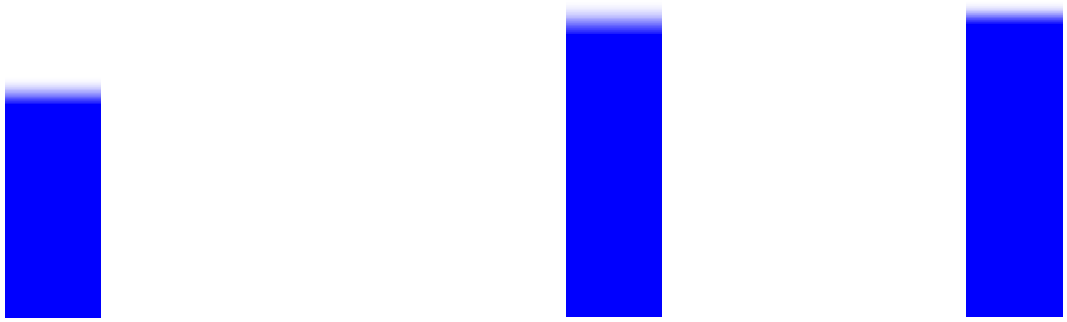
velocity outwards
⇒ 'large' intensity
⇒ 'large' deceleration

velocity inwards
⇒ small intensity
⇒ small acceleration

advantage:
parametric cooling with phase automatically adjusted
(but only one-dimensional cooling along radial direction)

Average Exit Times

predetermined feedback	proportional feedback	differentiating feedback
150 μs + **298(18) μs**	150 μs + **395(23) μs**	150 μs + **401(15) μs**



storage time limited by heating due to random momentum kicks from spontaneous emission events

Fischer et al., Phys. Rev. Lett. **88** (2002) 163002

Single-Atom Physics – An Outlook

continuously observed quantum system:

- quantum-limited position measurement of a free particle

standard quantum limit $$\Delta x_{SQL} = \sqrt{\frac{\hbar \tau}{2m}}$$

high-resolution single-particle microscopy:

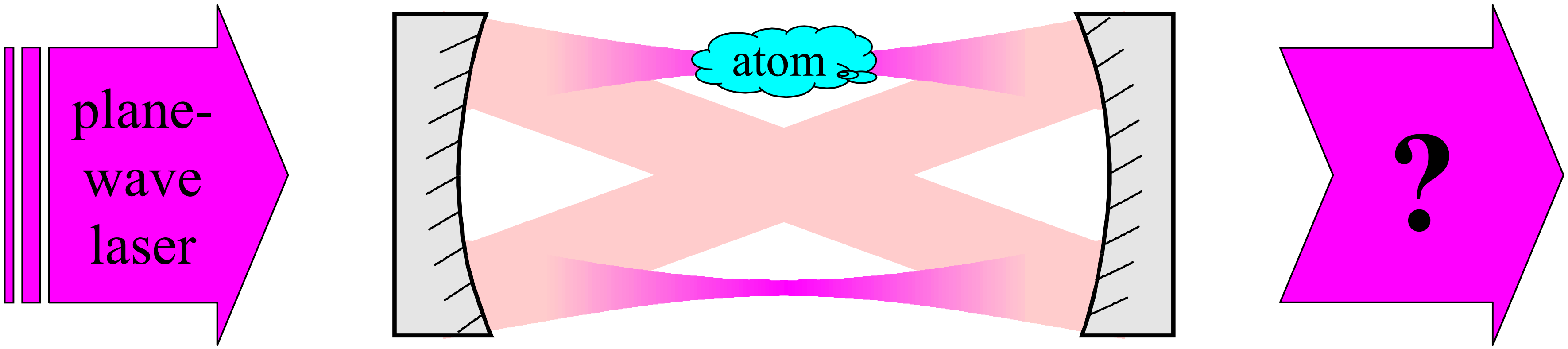
- real-time observation of atomic, biological or chemical processes

Real-time tracking of a single atom

Hood et al.,
Science **287** (2000) 1447

Atomic-Position Measurement

in a resonator with **frequency-degenerate (transverse) modes**, the atom couples to a position-dependent subset of modes

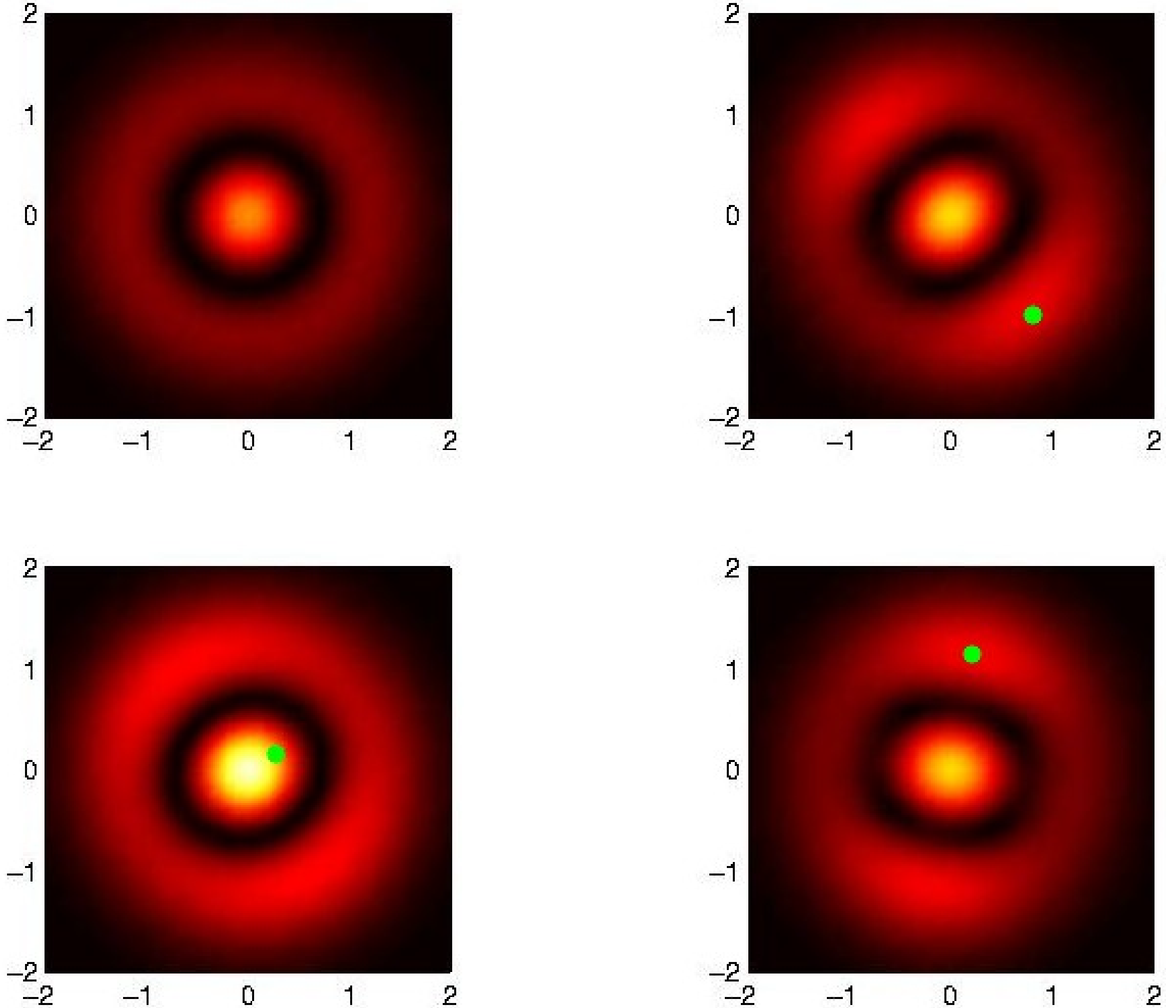


additional advantages:
* small beam waist
* high position resolution
* strong coupling in a long cavity

see also Morin et al., Phys. Rev. Lett. **73** (1994) 1489

Atomic Kaleidoscope (Simulation)

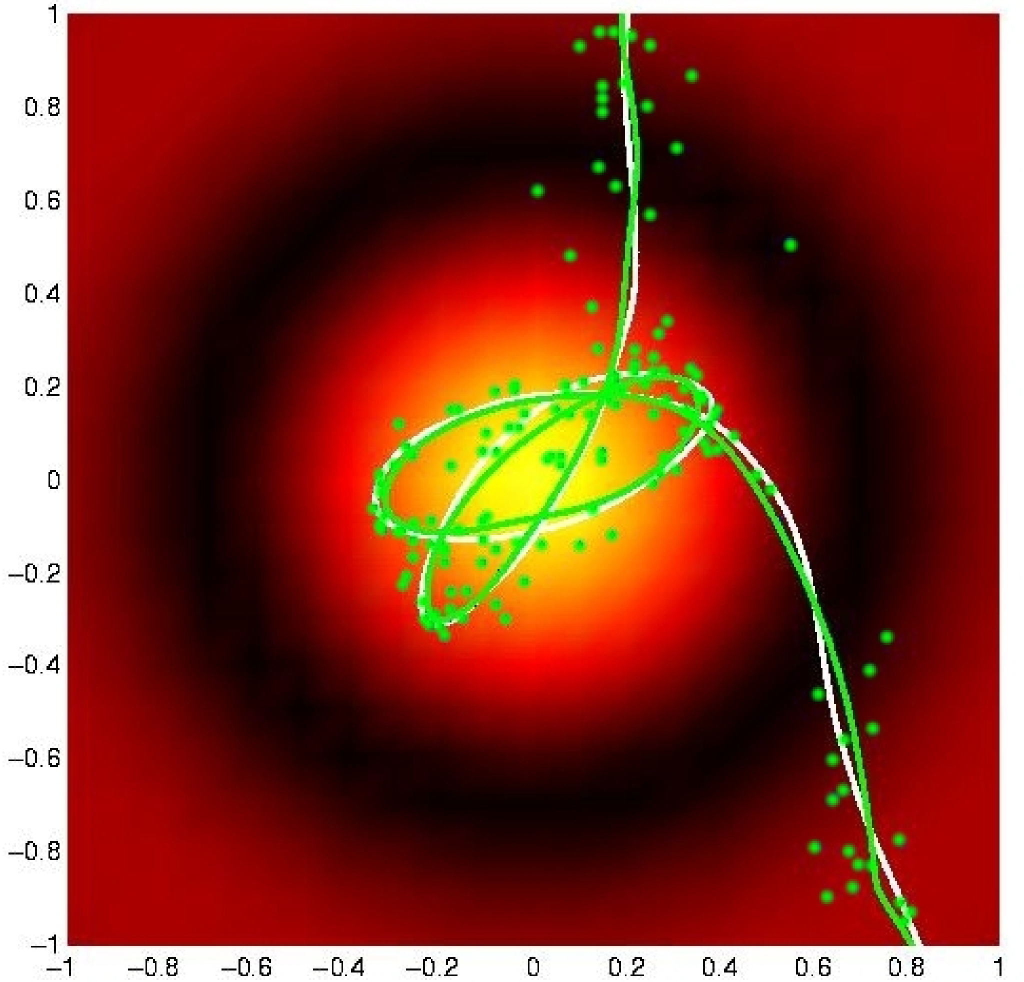
intensity pattern of the light transmitted through a cavity
at the frequency of the transverse modes $TEM_{2,0}$, $TEM_{1,1}$ and $TEM_{0,2}$



Horak et al., Phys. Rev. Lett. **88** (2002) 043601

Reconstruction of an Atomic Trajectory (Simulation)

based on the position-dependent differential phase shift of transverse modes $TEM_{2,0}$, $TEM_{1,1}$ and $TEM_{0,2}$



Horak et al., Phys. Rev. Lett. **88** (2002) 043601

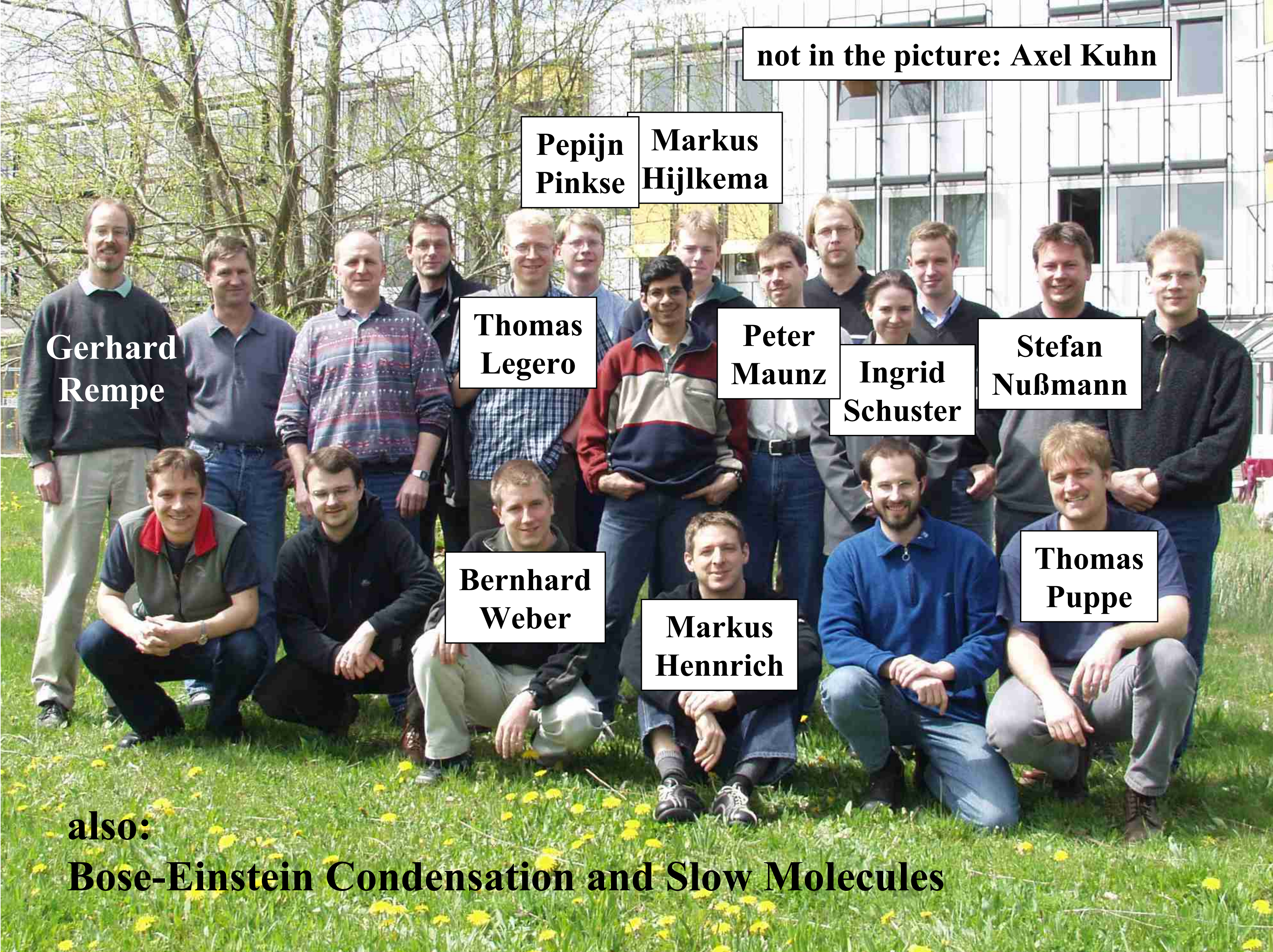
Summary

cavity QED allows one to

- generate by means of
- a unitary process
- single photons
- on demand,

and

- observe
- and control
- with high spatial (μm)
- and temporal (μs) resolution
- the motion of an individual atom.


not in the picture: Axel Kuhn
Pepijn Pinkse
Markus Hijlkema
Gerhard Rempe
Thomas Legero
Peter Maunz
Ingrid Schuster
Stefan Nußmann
Bernhard Weber
Markus Hennrich
Thomas Puppe
also:
Bose-Einstein Condensation and Slow Molecules