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2007-13
INVESTMENTS IN EDUCATION DEVELOPMENT

Single atom – single photon interactions in free space

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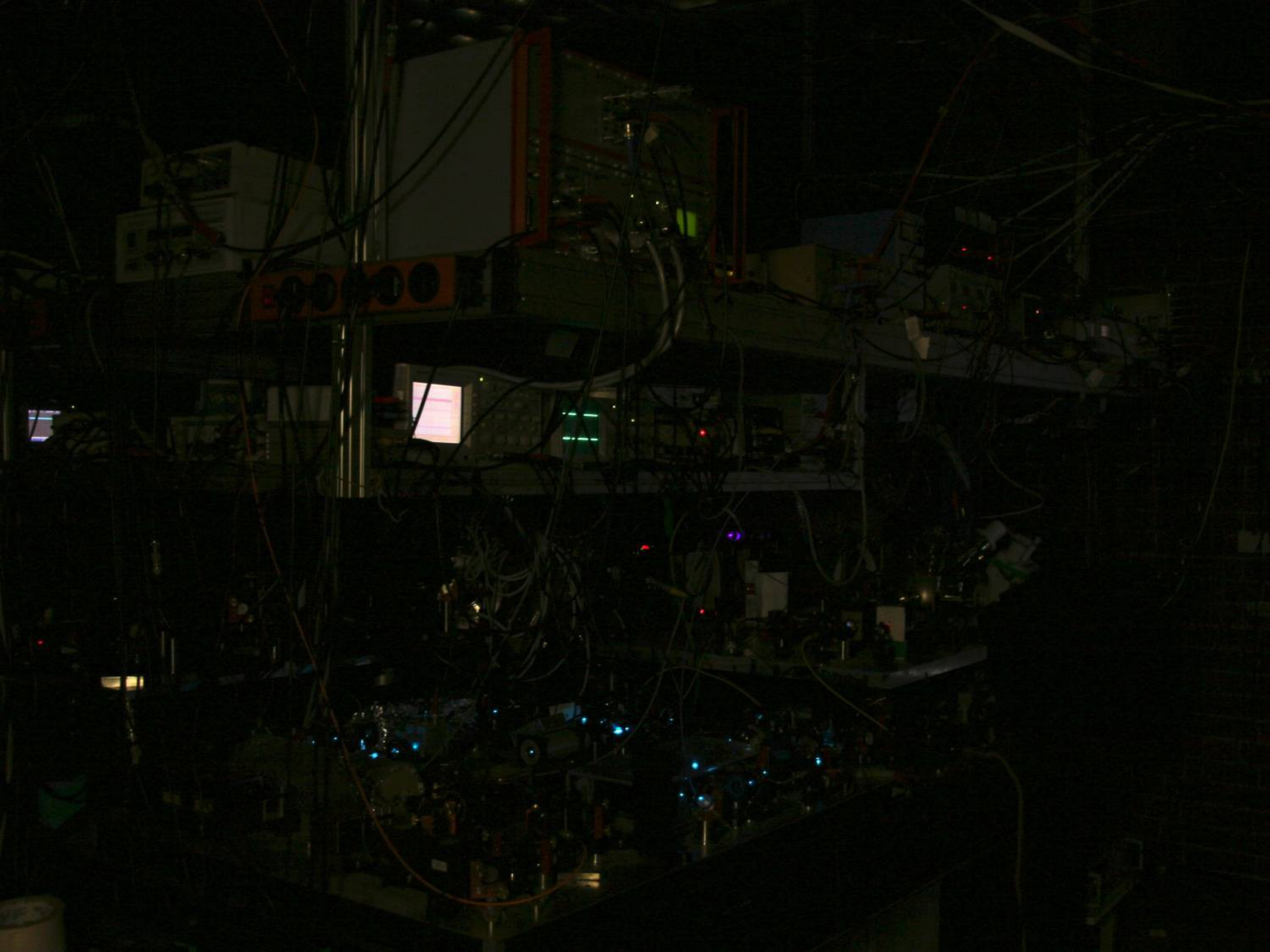
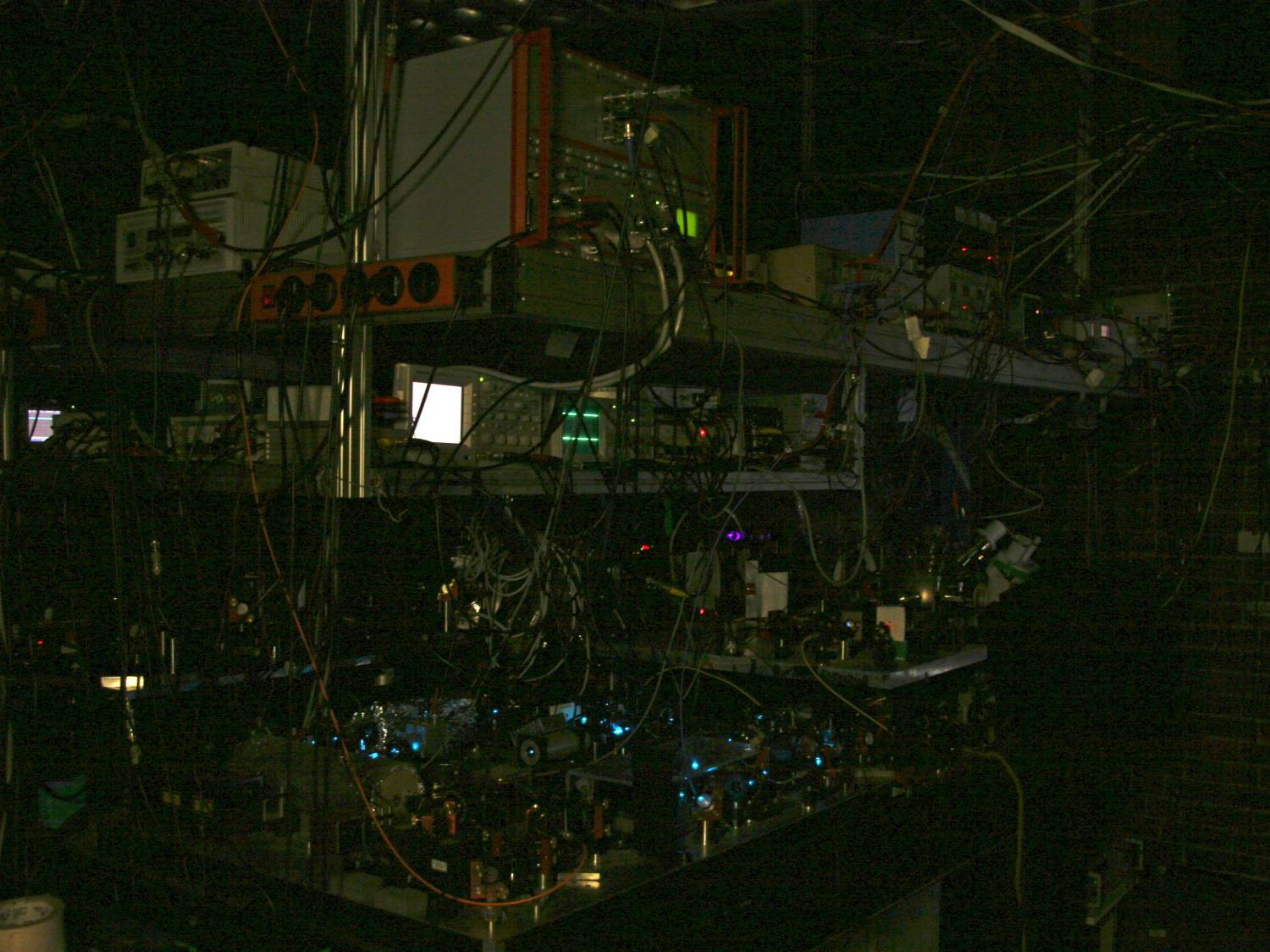
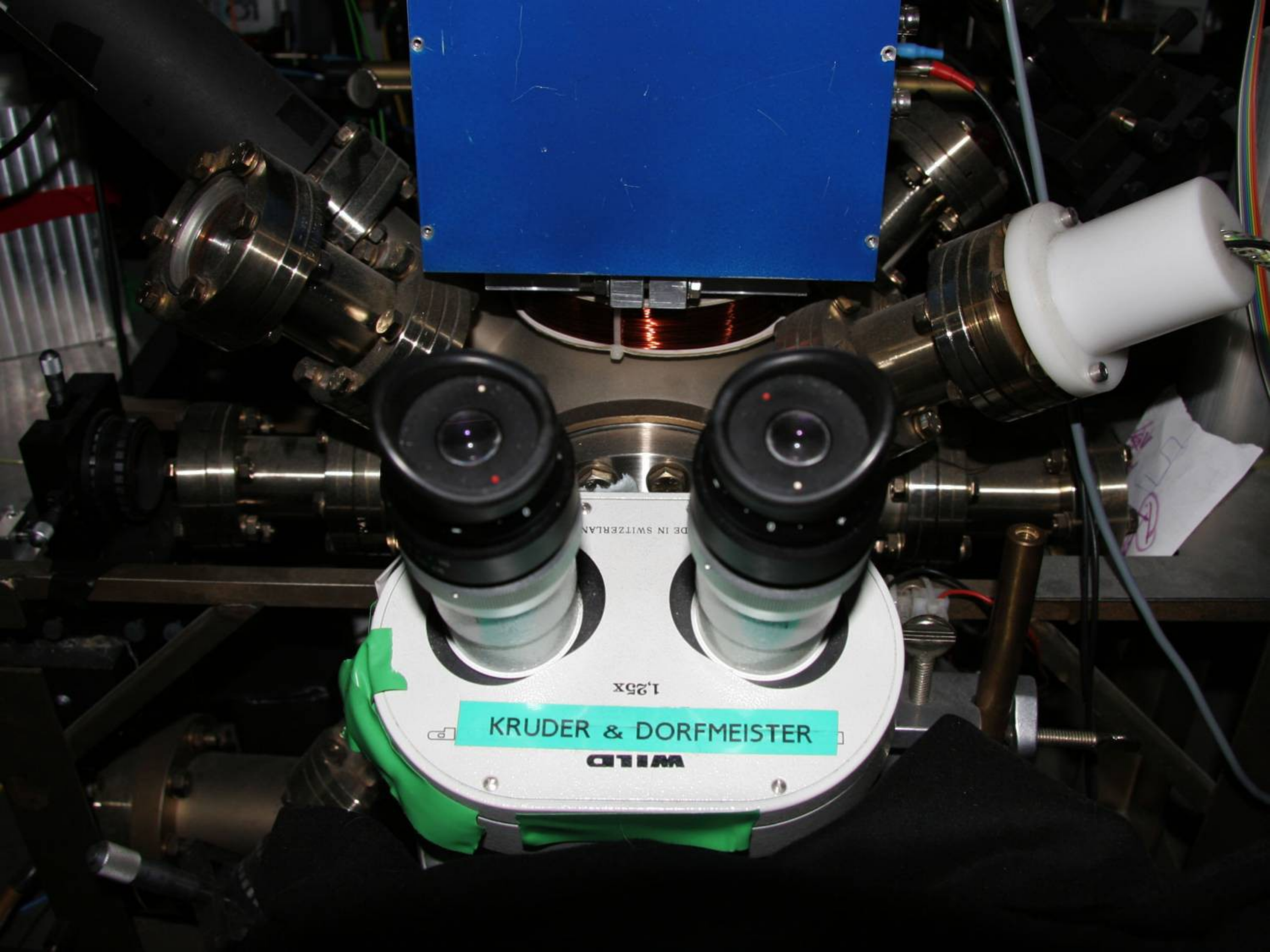
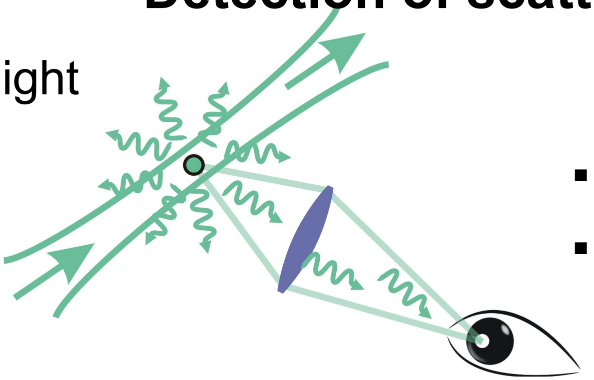





DE IN SWITZERLAN
1,25x
KRUDER & DORFMEISTER
WILD

Observation of single atom in free space

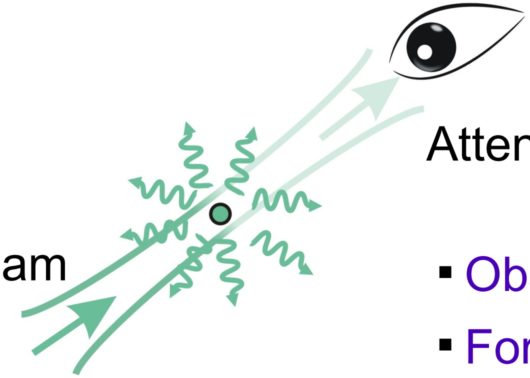
Detection of scattered light



- Resonance fluorescence experiments
- Quantum jumps spectroscopy

Distribution of entanglement by mere observation of scattered photon?

Detection of exciting beam



- Observed with ensembles or atoms in cavities
- For single atoms in free space usually negligible

Can we see a "shadow" of a single atom?

Outline

Ion trapping basics

- Storage – Paul trap
- Classical and quantized motion
- Spectroscopy
- Laser-ion interactions
- Laser cooling

Extinction experiments

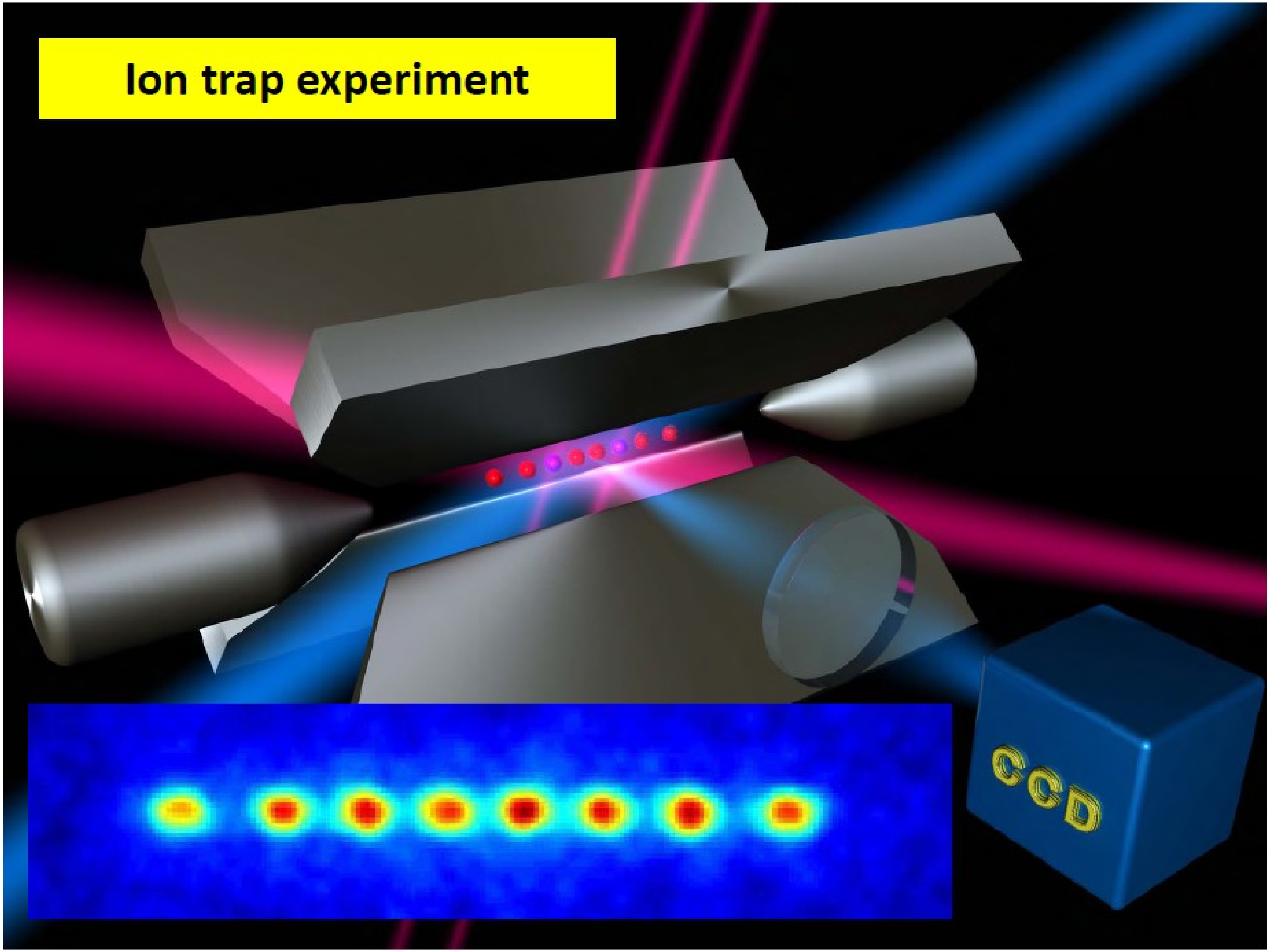
Shadow of a single atom

- Extinction
- Electromagnetically induced transarency
- Single-atom mirror

Atom-atom entanglement

Photon scattering

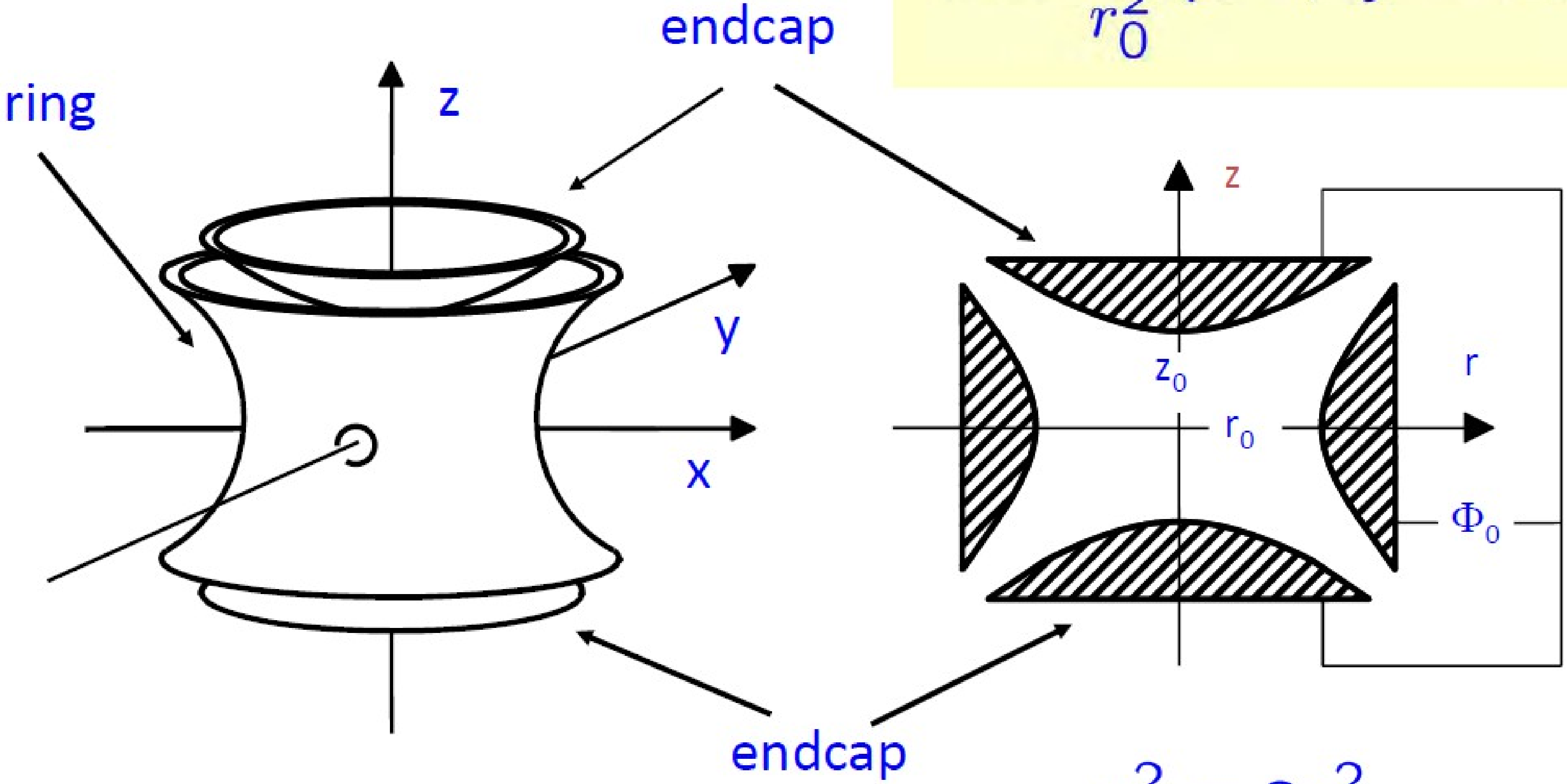
Ion trapping basics



Ion trapping basics

Ion storage – Paul trap

$$\Phi = \frac{\Phi_0}{r_0^2}(x^2 + y^2 - 2z^2)$$

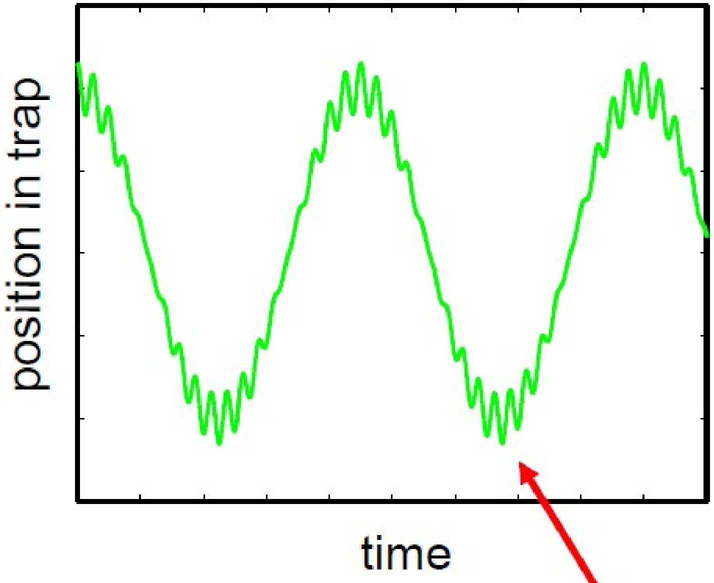


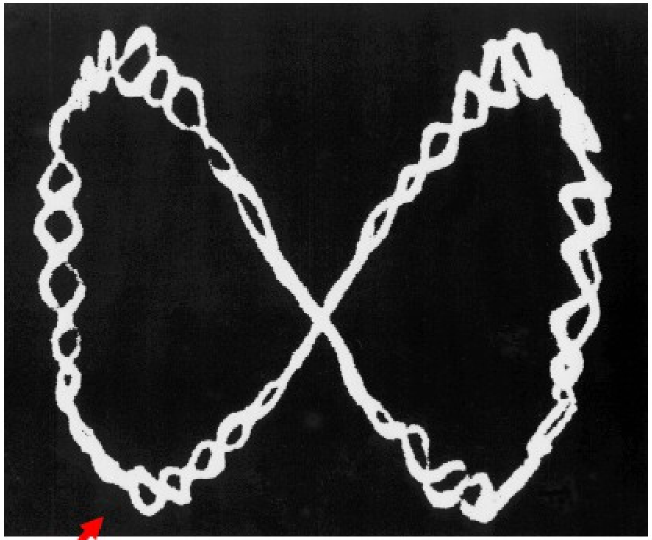
$$r_0^2 = 2z_0^2$$

Ion trapping basics

Classical ion motion

$$r_i(t) \propto \cos(\beta_i \frac{\omega_{\rm rf}}{2} t)(1 - \frac{q_i}{2}\cos(\omega_{\rm rf} t))$$



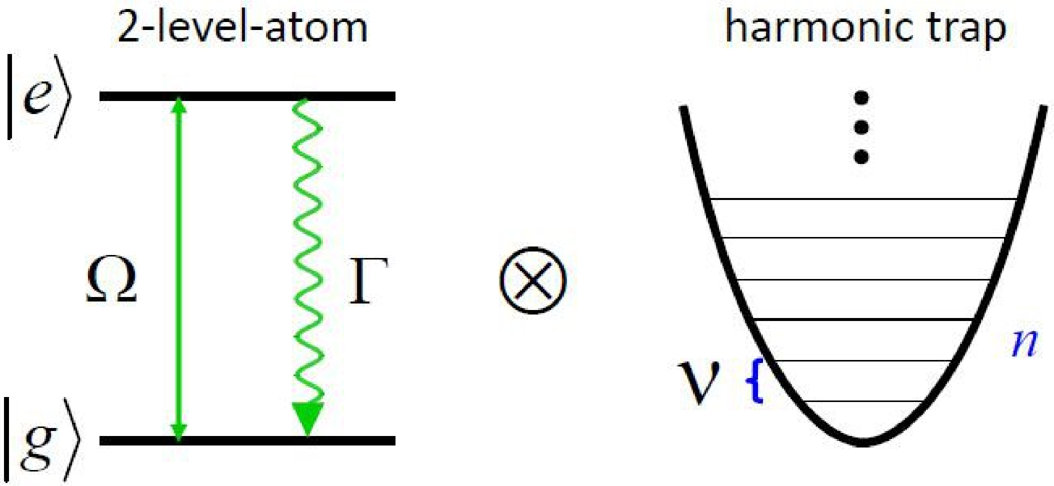


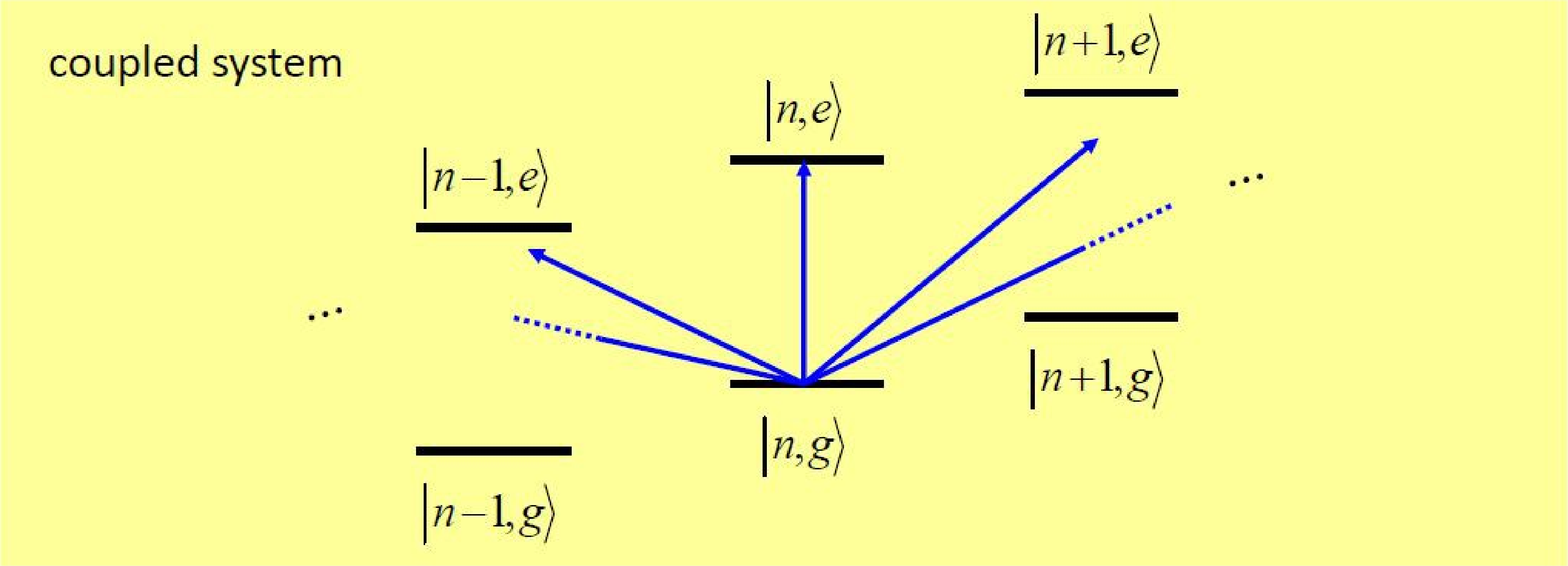
Wuerker, Shelton, Langmuir,
J. Appl. Phys. **30**, 342 (1959)

micromotion

Ion trapping basics

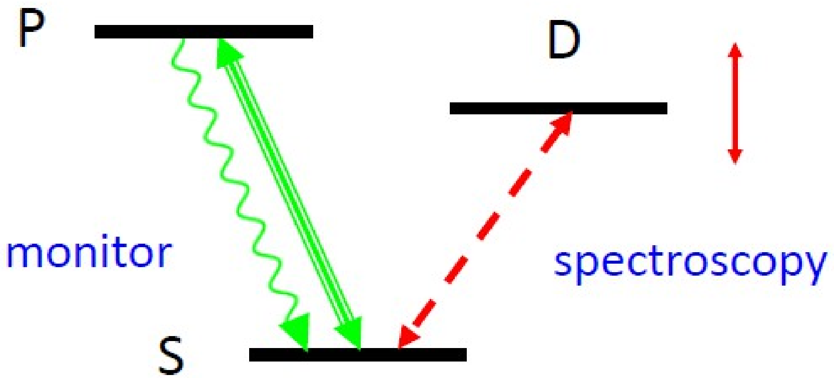
Quantized ion motion



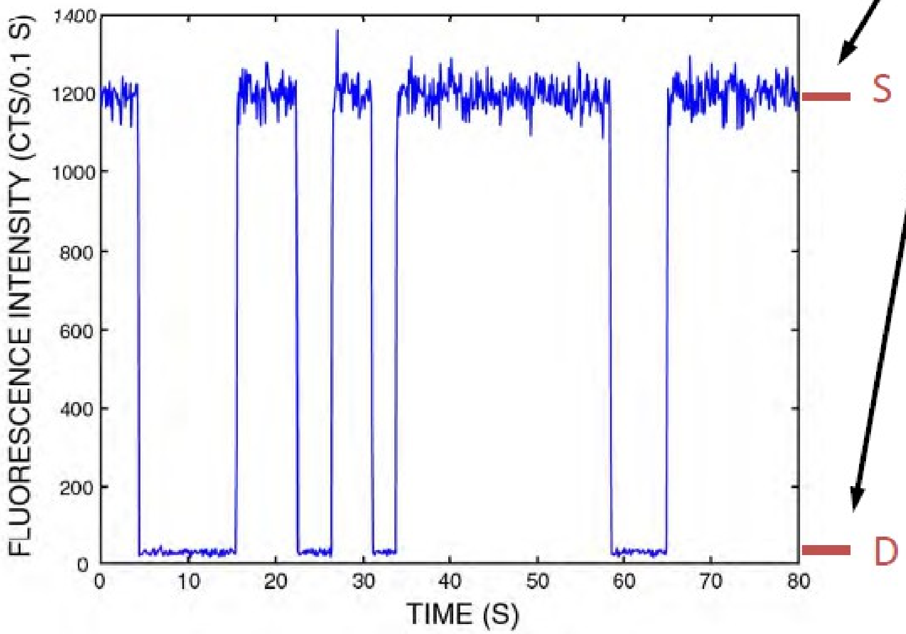


Ion trapping basics

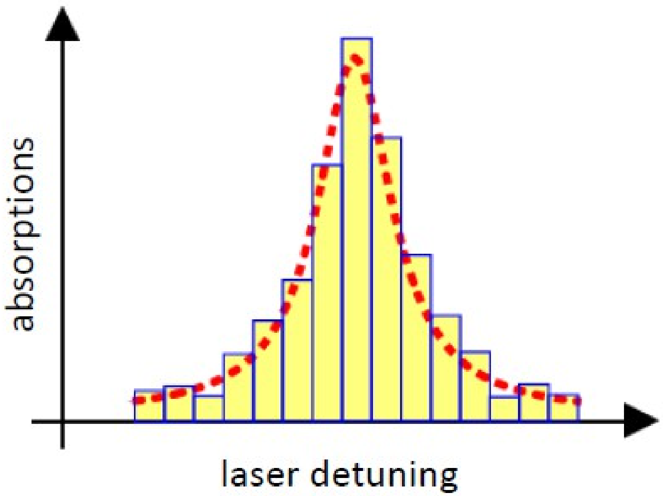
Spectroscopy in ion traps



absorption and emission
cause fluorescence steps
(digital quantum jump signal)

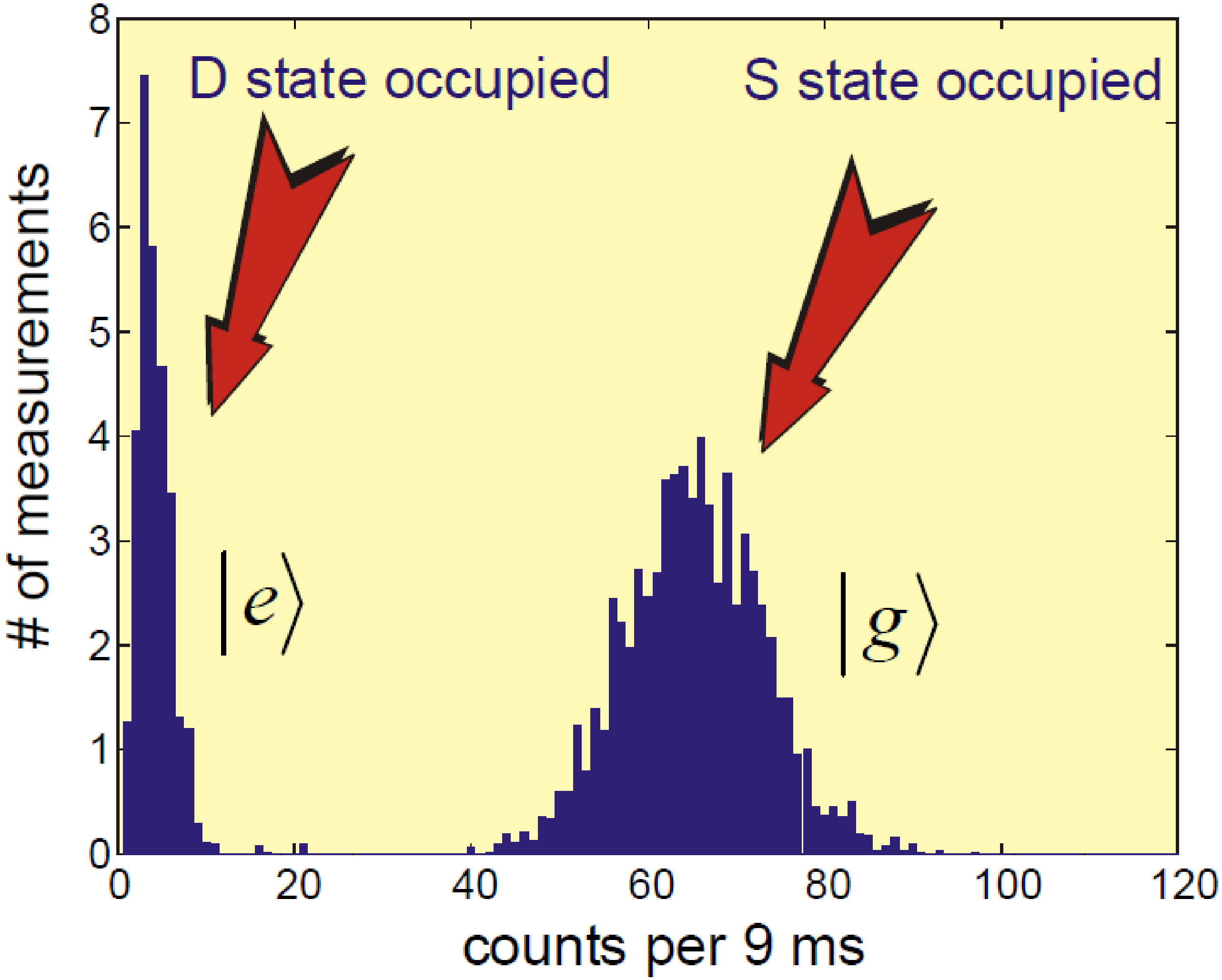


histogram of absorption events



Ion trapping basics

State detection by quantized fluorescence

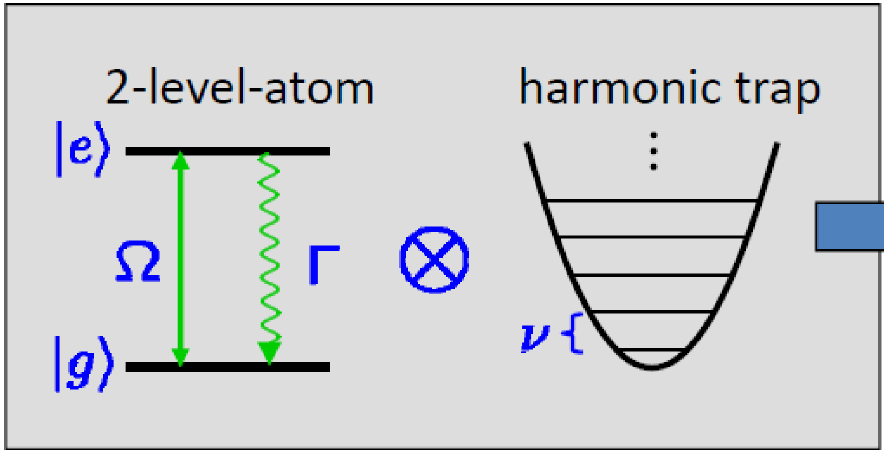


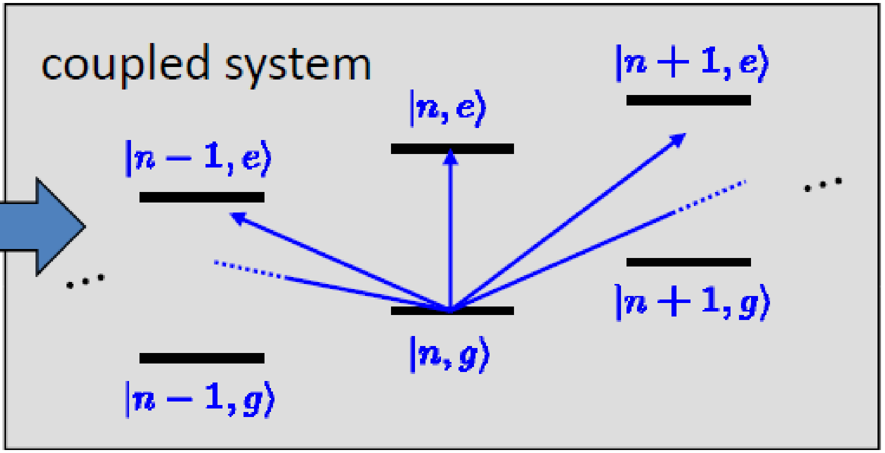
detection efficiency:

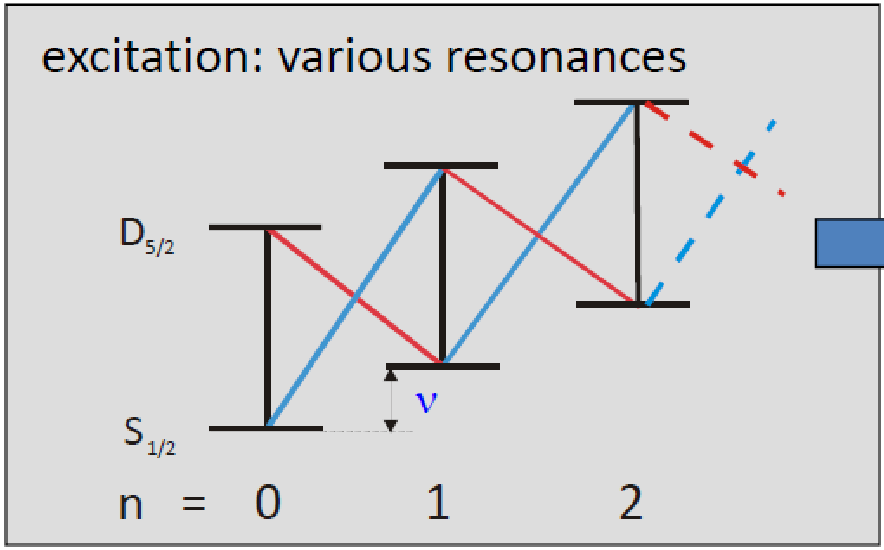
99.85%

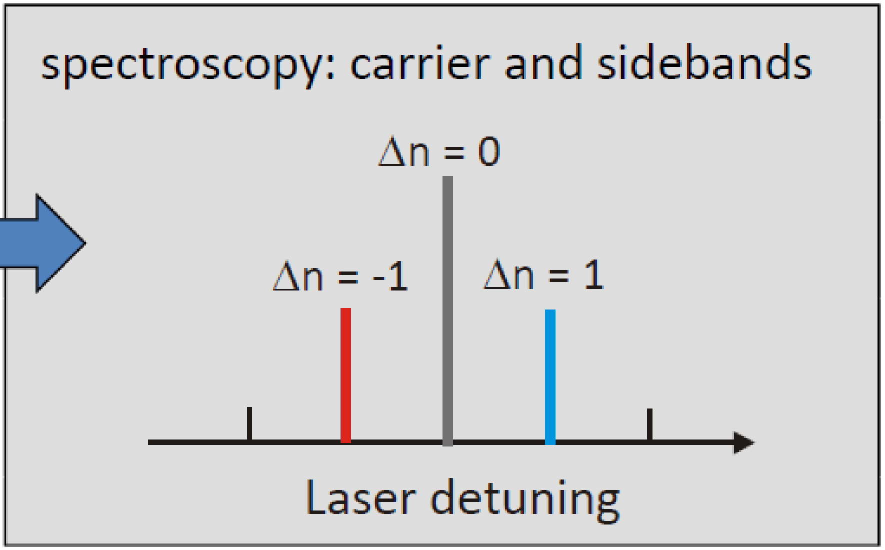
Ion trapping basics

Laser – ion interactions in Lamb-Dicke regime







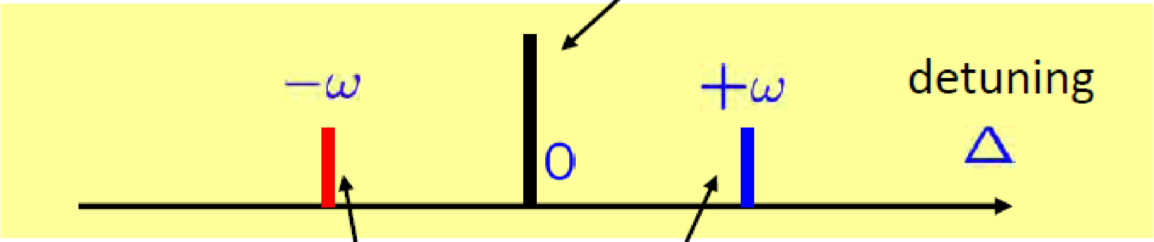


Ion trapping basics

Laser – ion interactions in Lamb-Dicke regime

$$\left.\begin{aligned}\Omega_{n,n} &= (1-\eta^2 n)\Omega \\ H_I &= \frac{1}{2}\hbar\Omega_{n,n}(\sigma^+ e^{i\phi} + \sigma^- e^{-i\phi})\end{aligned}\right\}$$

carrier excitation



$$\Omega_{n-1,n} = \eta\sqrt{n}\Omega$$

$$\underbrace{H_I = \frac{1}{2}\hbar\eta\Omega(a\sigma^+ e^{i\phi} - a^\dagger\sigma^- e^{-i\phi})}$$

red sideband excitation

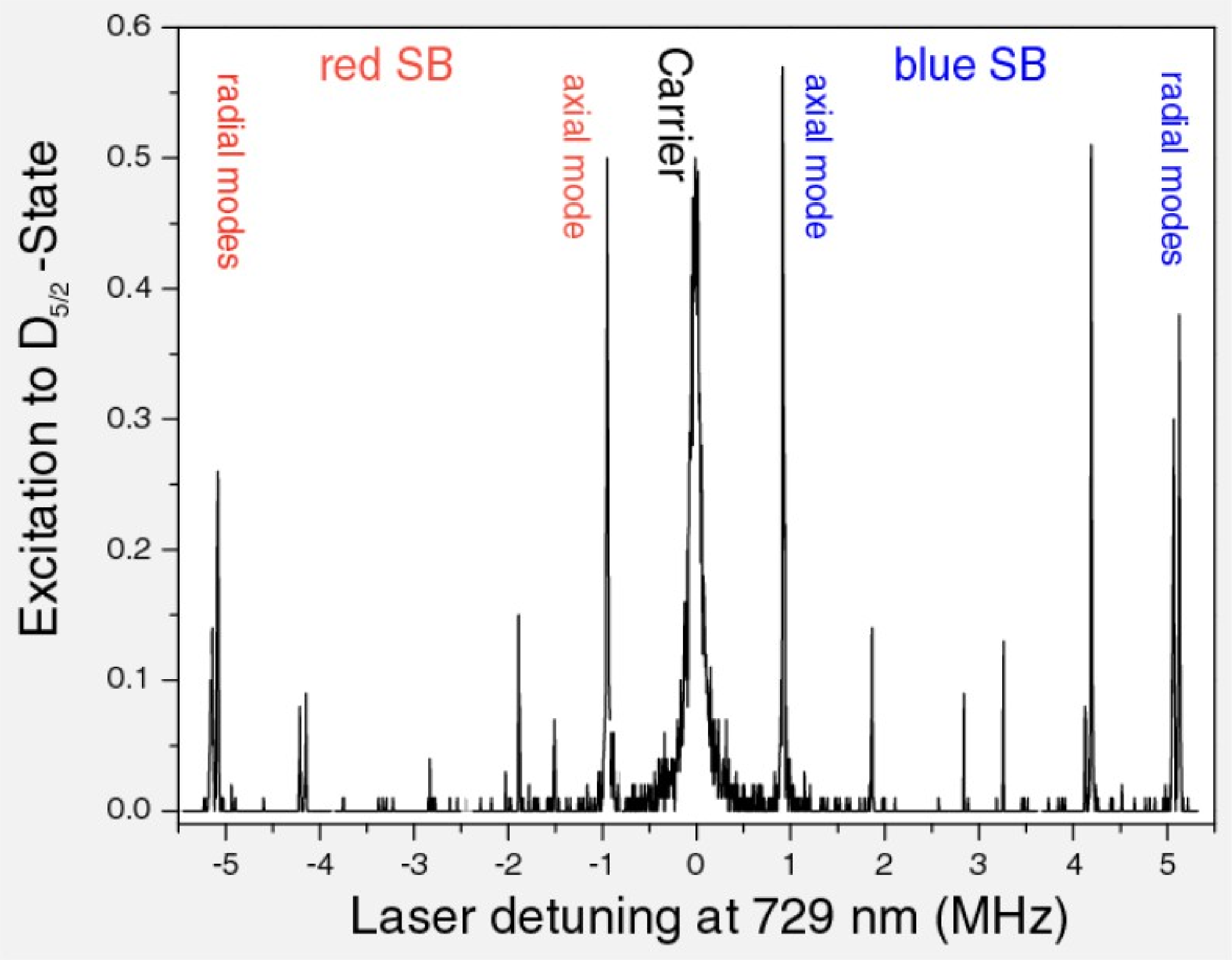
$$\Omega_{n+1,n} = \eta\sqrt{n+1}\Omega$$

$$\underbrace{H_I = \frac{1}{2}\hbar\eta\Omega(a^\dagger\sigma^+ e^{i\phi} - a\sigma^- e^{-i\phi})}$$

blue sideband excitation

Ion trapping basics

Excitation spectrum of the S – D transition



ω_{ax} = 1.0 MHz

ω_{rad} = 5.0 MHz

Ion trapping basics

Laser cooling

Regimes:

$\nu < \Gamma$ **weak** confinement, Doppler cooling

$E_D = \hbar\Gamma/2, \langle n \rangle >> 1$

Doppler cooling

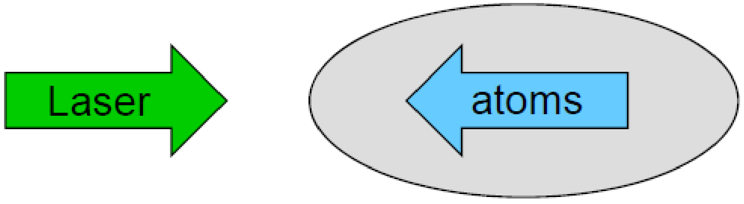
$\nu > \Gamma$ **strong** confinement, sideband cooling

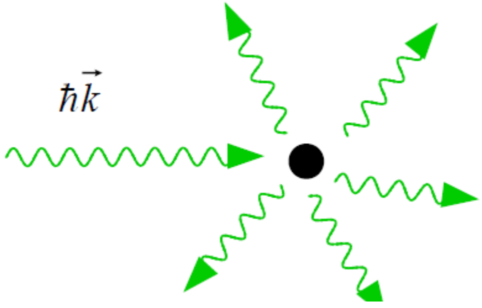
$E_S = \hbar\nu\left(\Gamma^2/4\nu^2 + 1/2\right)$

$\langle n \rangle << 1$

Sideband cooling

Doppler cooling

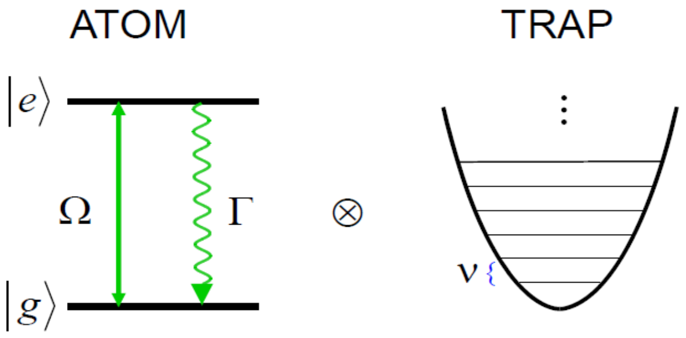


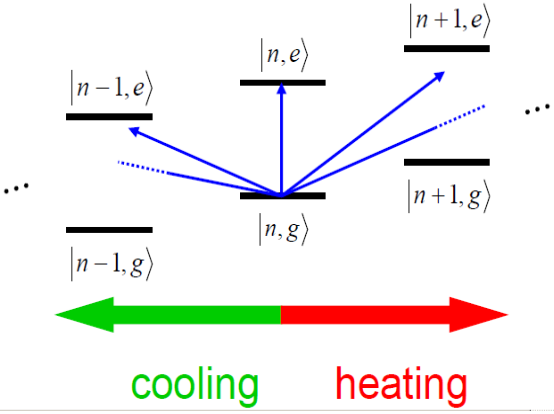


momentum transfer $\hbar\vec{k}_{abs}, -\hbar\vec{k}_{em}$

$$\Delta\vec{p} = n\hbar\vec{k}_{abs} + \underbrace{\sum \hbar\vec{k}_{em}}_{= 0}$$

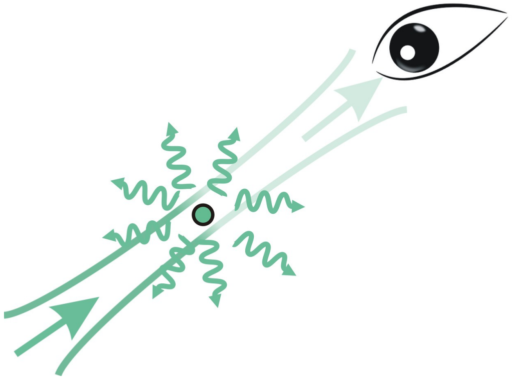
Sideband cooling



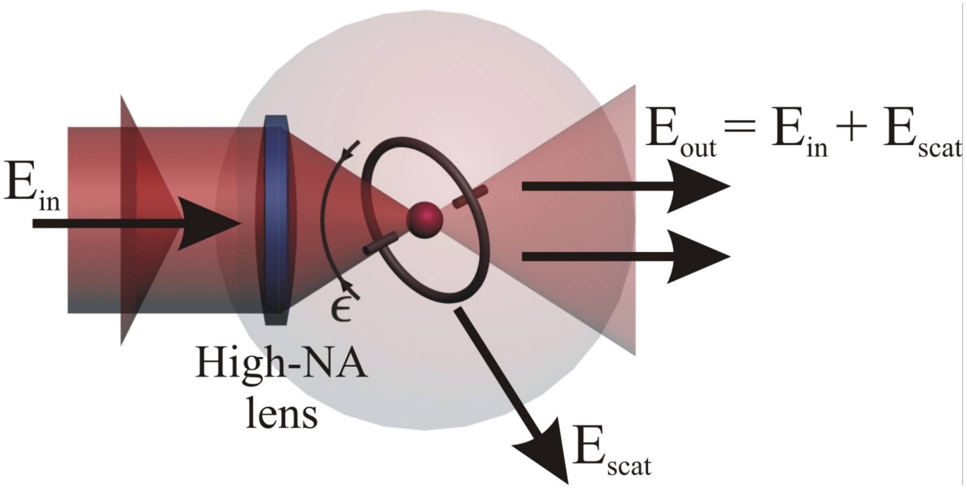


Extinction

Can we see a "shadow" of a single atom?



Extinction from single atom in free space



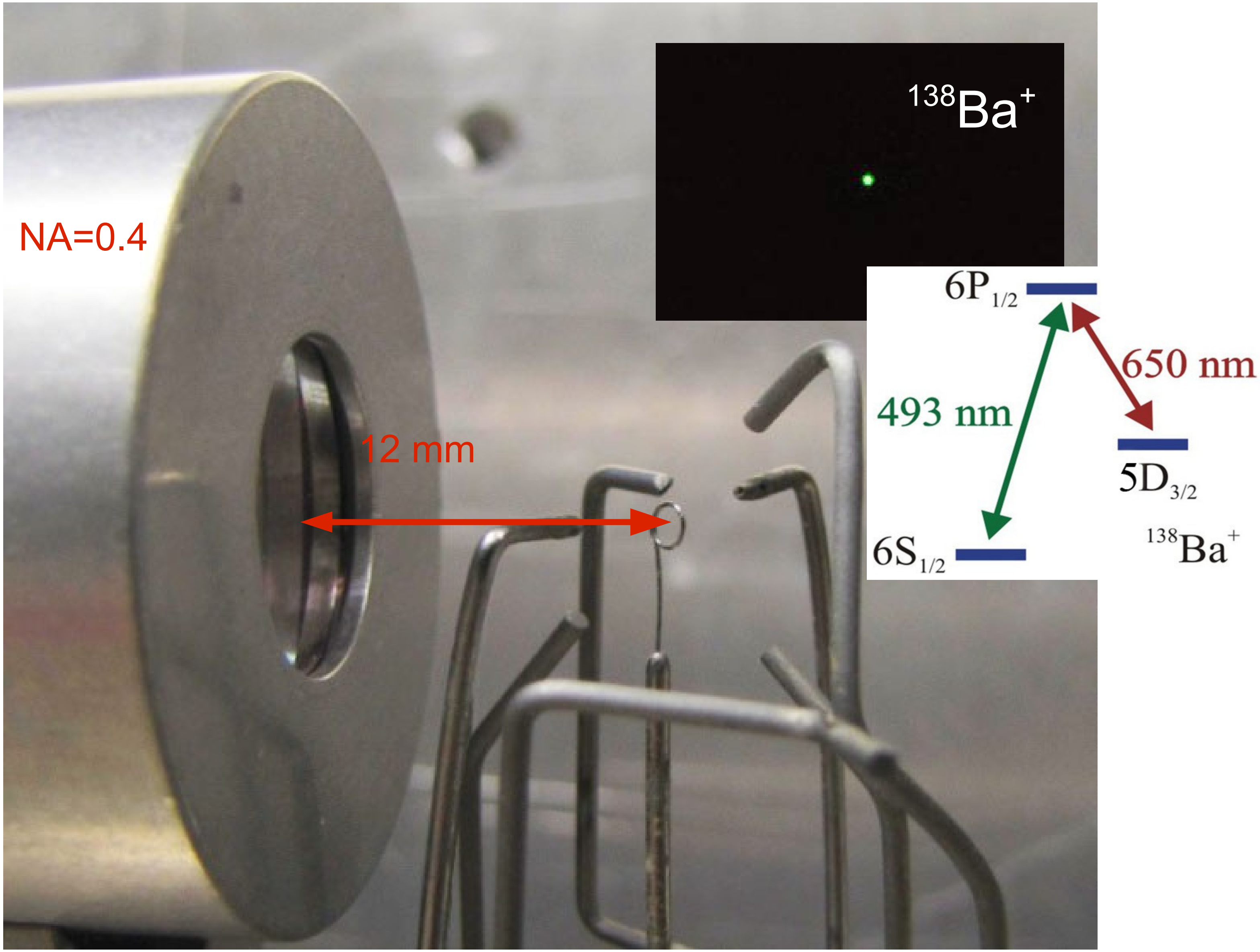
- Destructive interference of scattered and transmited fields!
- In the weak probe limit

$$T = | 1 - 2 \varepsilon |^2$$

Full reflection for lens covering half of the full solid angle!

Extinction

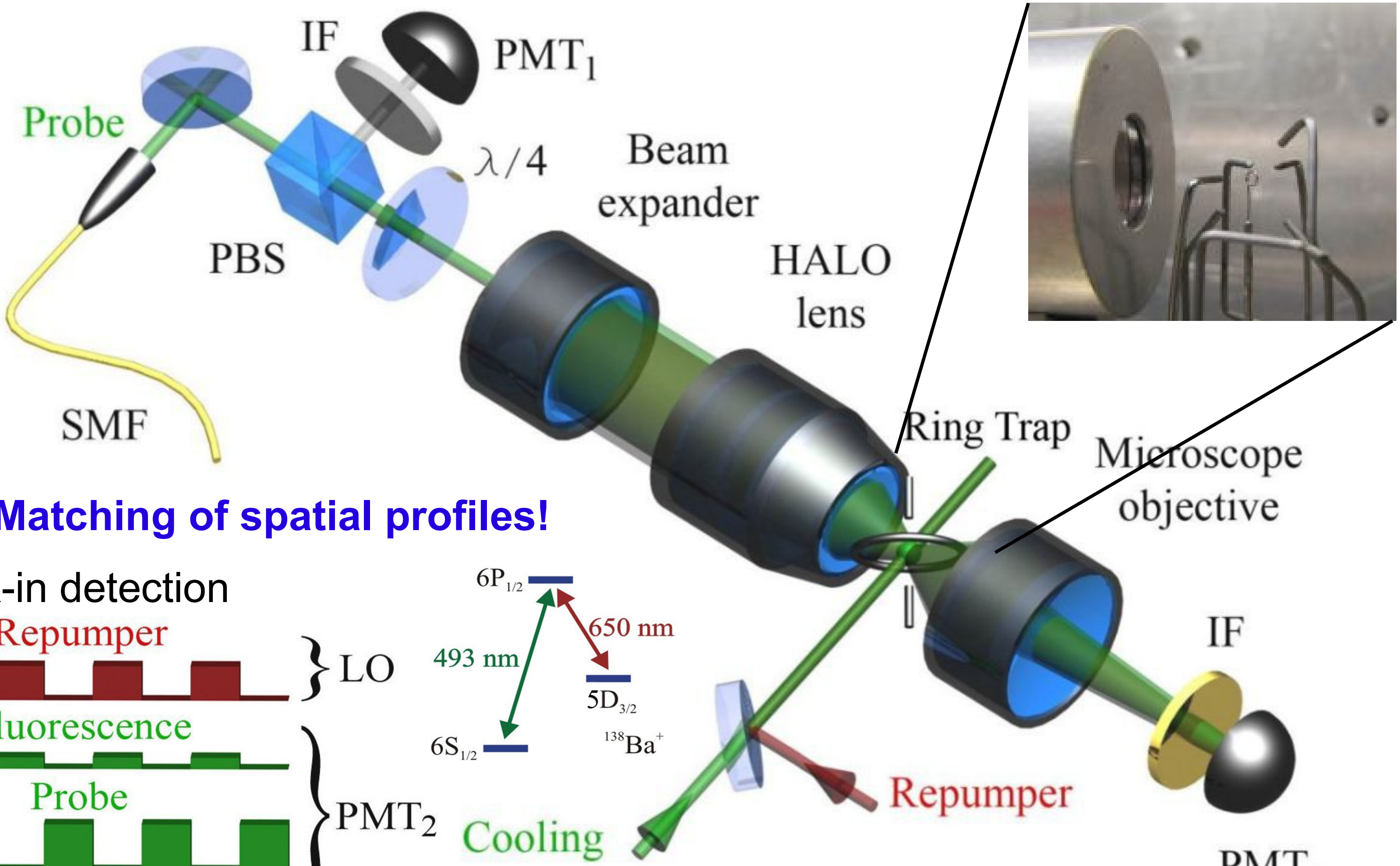
Ring trap



Extinction

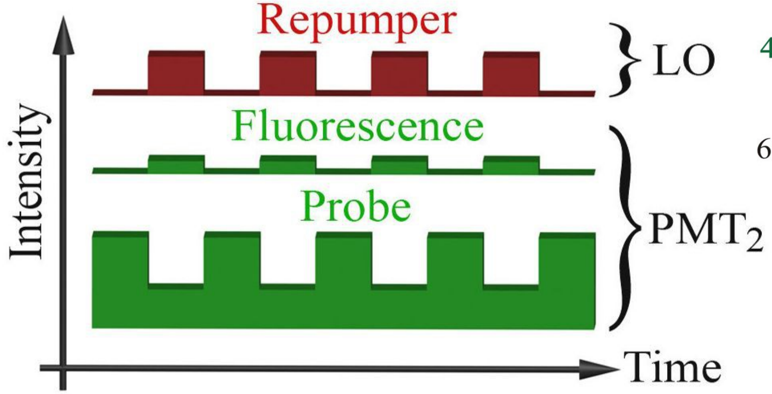
Extinction from single atom in free space

Experimental setup



Matching of spatial profiles!

Lock-in detection

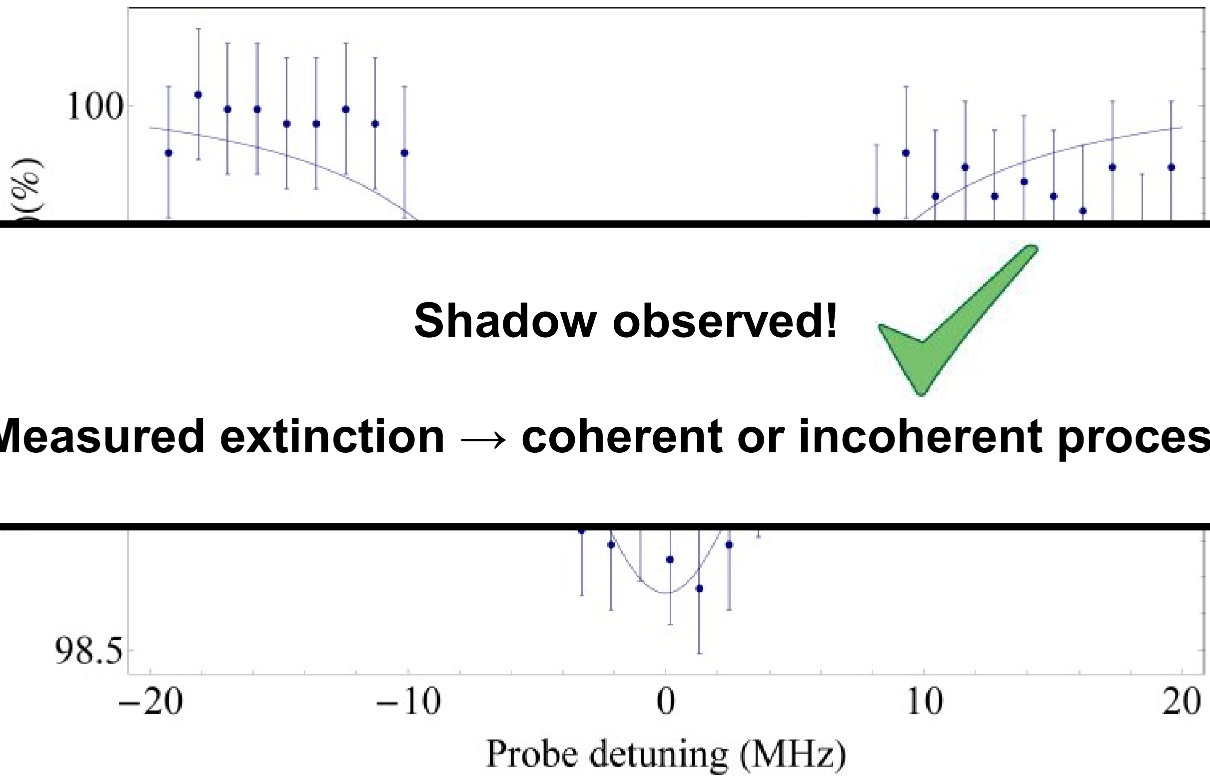


Extinction from single atom in free space

Results

Extinction of 1.35%

Good agreement with our effective solid angle ε~0.01!



Shadow observed! ✓

Measured extinction → coherent or incoherent process?

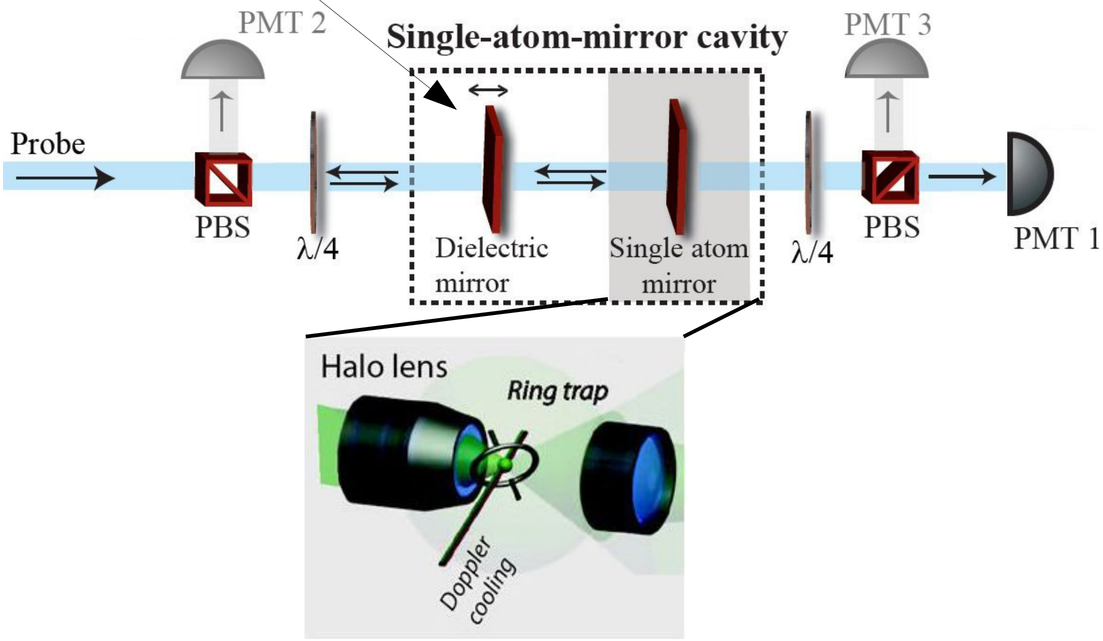
L. Slodička, G. Hétet, S. Gerber, M. Hennrich, and R. Blatt,
Phys. Rev. Lett. **105**, 153604 (2010)

Extinction

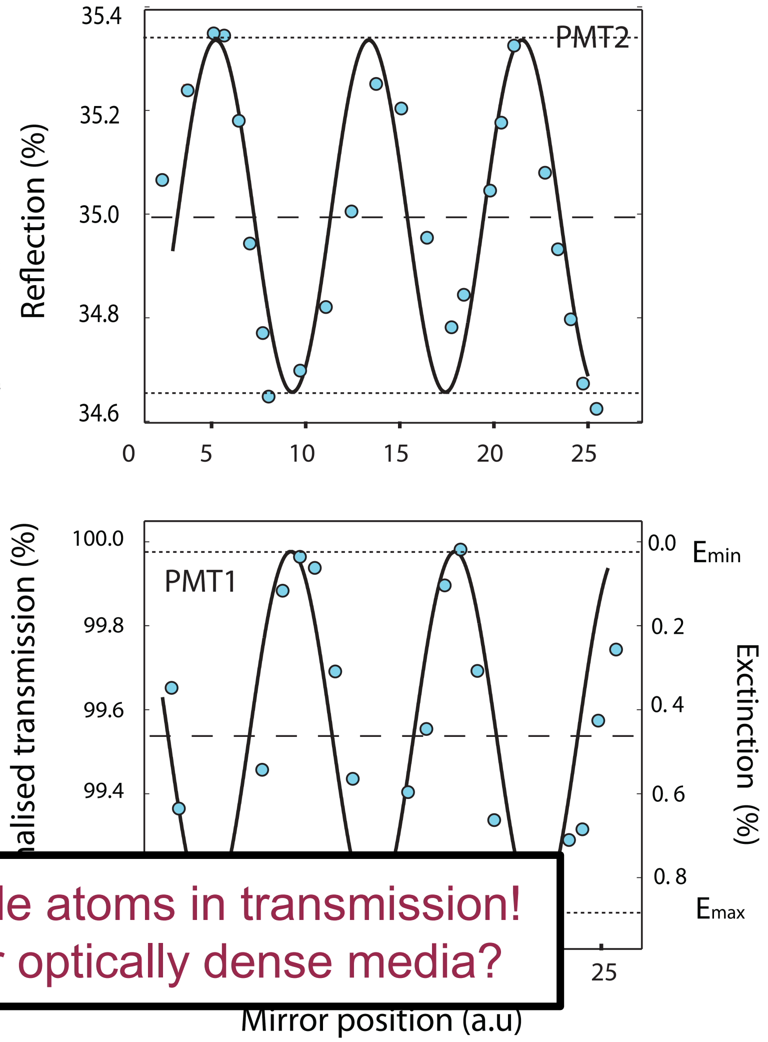
Single-atom-mirror

Fabry-Pérot like cavity setup formed by single atom and dielectric mirror

$|r|^2 = 1 - |t|^2 =$ 0.35



G. Hétet, L. Slodička, M. Hennrich, and R. Blatt,
Phys. Rev. L



We can now observe properties of single atoms in transmission!
Can we now observe effects typical for optically dense media?

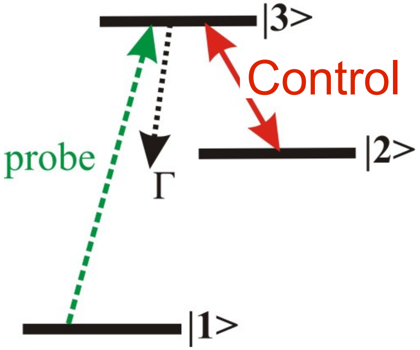
Mergi
and free-space coupling

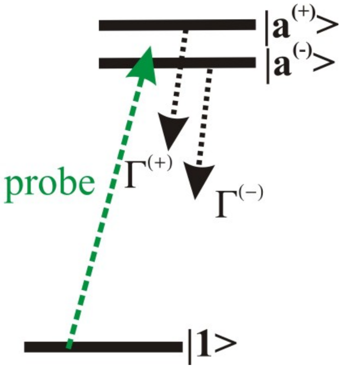
Extinction

Electromagnetically induced transparency

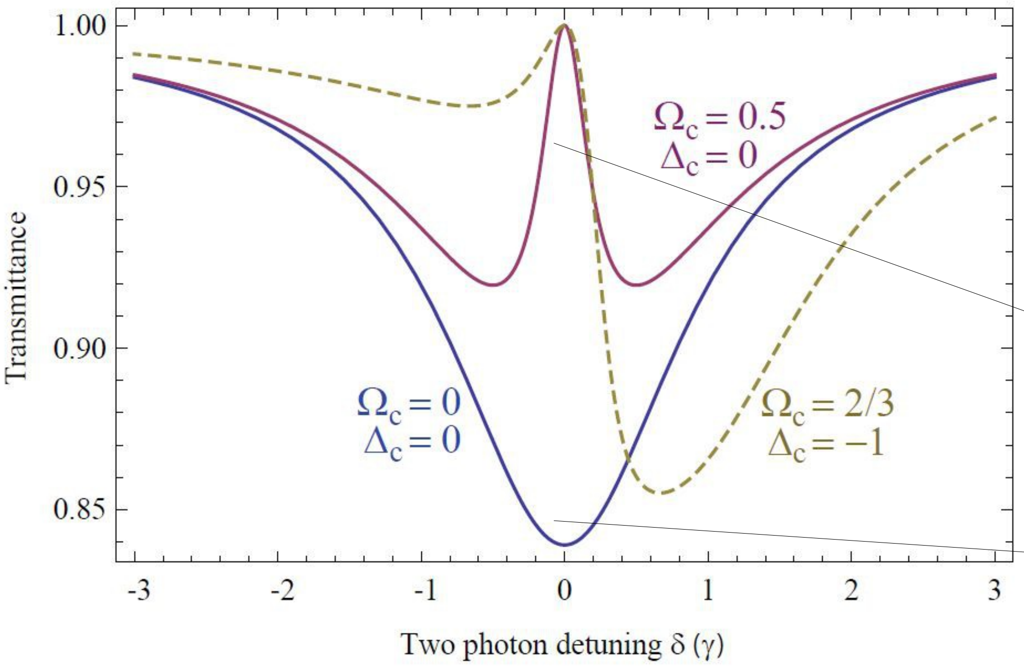
Coherent optical process which renders a medium transparent over a narrow spectral range within an absorption line

Principle





Interference of two decay channels



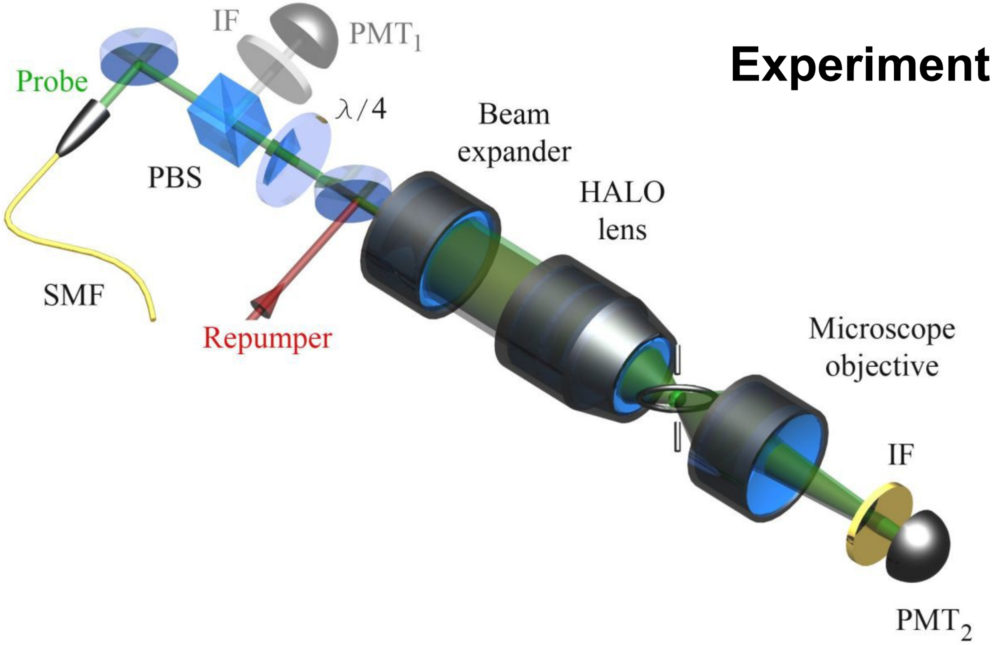
With control beam

EIT window

Without control beam

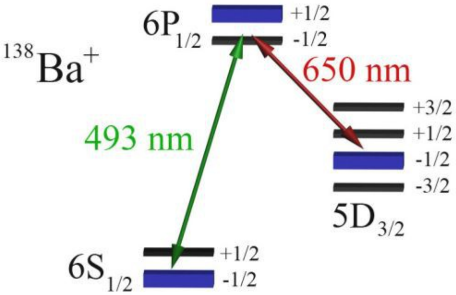
Extinction

Electromagnetically induced transparency

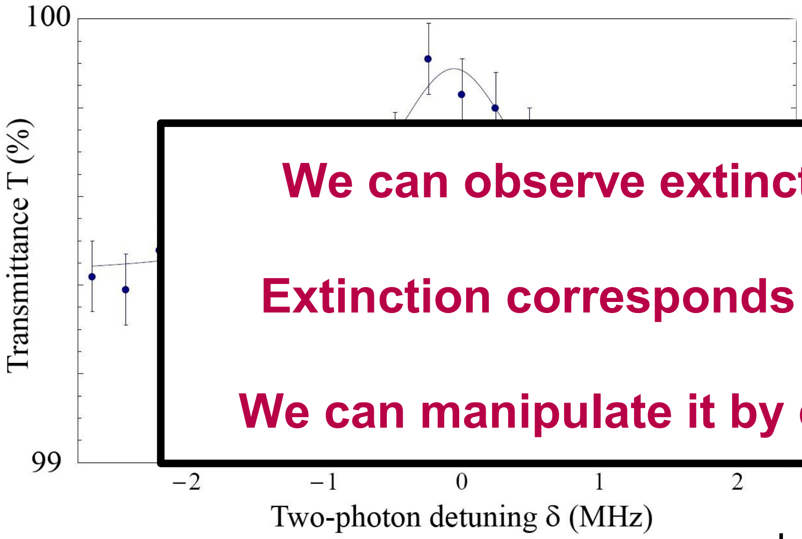


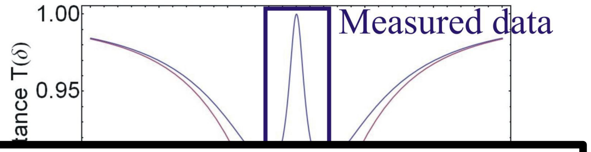
Experimental setup

- Cooling by the probe beam
- Co-propagation of the beams



Results





We can observe extinction from single atom

Extinction corresponds to a coherent process

We can manipulate it by control beam using EIT

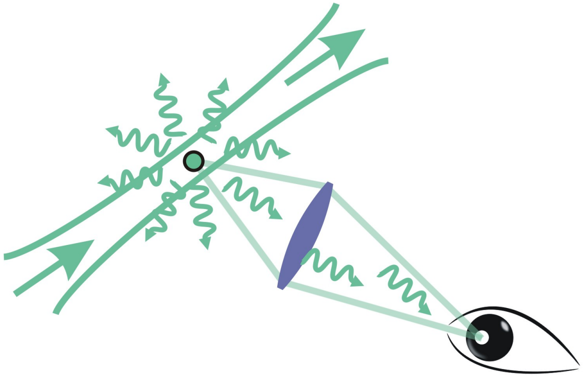
on of 75%

of 1.2MHz

L. Slodička et al., Phys. Rev. Lett. **105**, 153604 (2010)

Atom-atom entanglement

Quantum communication using detection of scattered fluorescence?



Atom-atom entanglement
Quantum communication

- Absolutely secure communication (Quantum cryptography)
- Faithful transfer of unknown quantum state (Quantum teleportation)

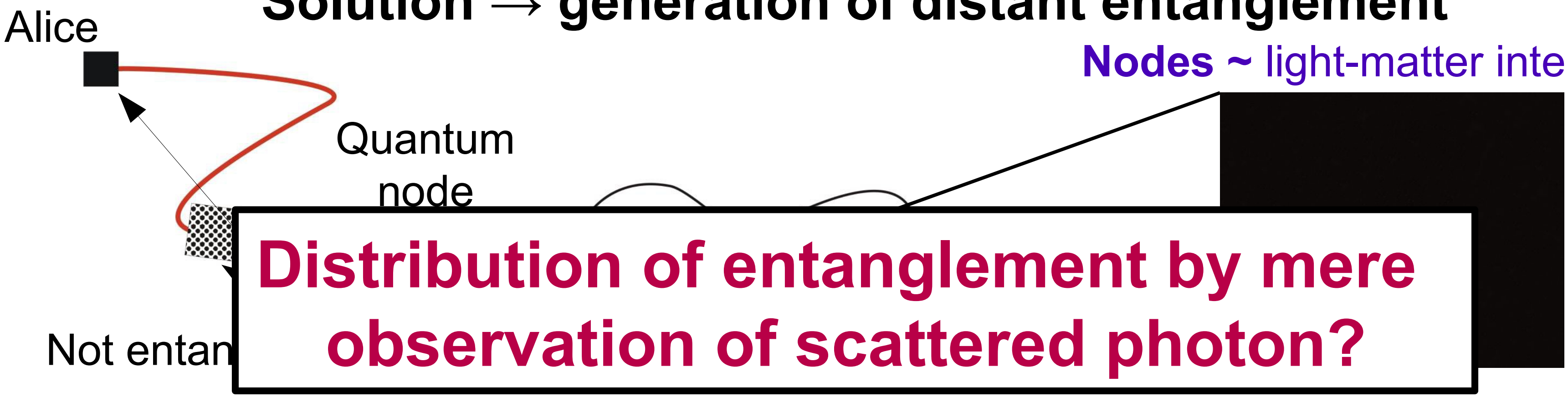
Nature **489**, 269–273 (2012)

New J. Phys. **13** 123001 (2011)

But no quantum analogue of classical amplifier!

Solution → generation of distant entanglement

Nodes ~ light-matter interfaces



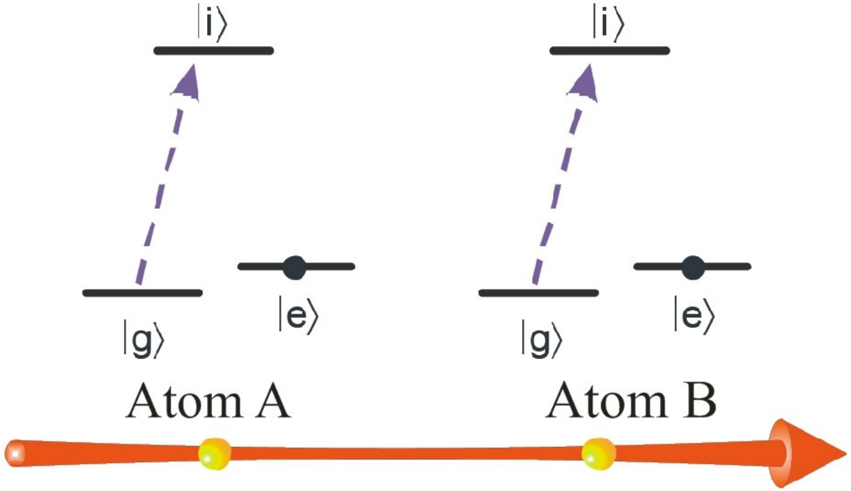
Distribution of entanglement by mere observation of scattered photon?

Atom-atom entanglement

Single-photon scheme

C. Cabrillo et al. PRA 59, 1025-1033 (1999)

Initialization and weak excitation



1. *Initialization*:
   atoms (A,B) in the same state |gg>

2. *Weak excitation:*
   with $p_e << 1$ through a spontaneous Raman process
   → *Atom-photon entanglement:*

Phase acquired from atom to detector

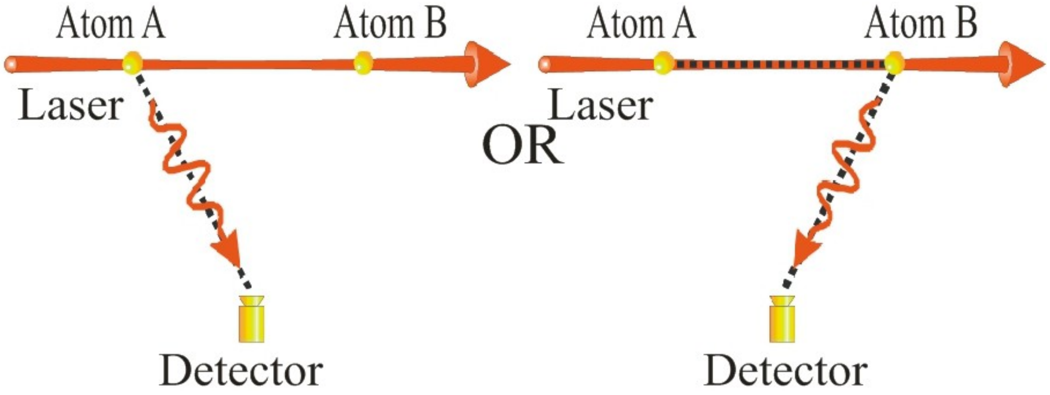
Excitation laser phase

$$\sqrt{1-p_e}|g,0\rangle+\sqrt{p_e}|e,1\rangle e^{i\phi_D - i\phi_L}$$

Atom-atom entanglement

Single-photon scheme

Projective measurement of a Raman scattered photon



3. Overlapping the corresponding photonic modes

$$(1-p_e)e^{i(\phi_{L,A}+\phi_{L,B})}|gg,0\rangle +$$

$$\sqrt{p_e(1-p_e)}\left(e^{i(\phi_{L,A}+\phi_{D,B})}|eg,1\rangle + e^{i(\phi_{L,B}+\phi_{D,A})}|ge,1\rangle\right)+$$

$$p_e e^{i(\phi_{D,A}+\phi_{D,B})}|ee,2\rangle$$

4. Projection by detection:

$$|\Psi^{\phi}\rangle = \frac{1}{\sqrt{2}}(|eg\rangle + e^{i\phi}|ge\rangle)$$

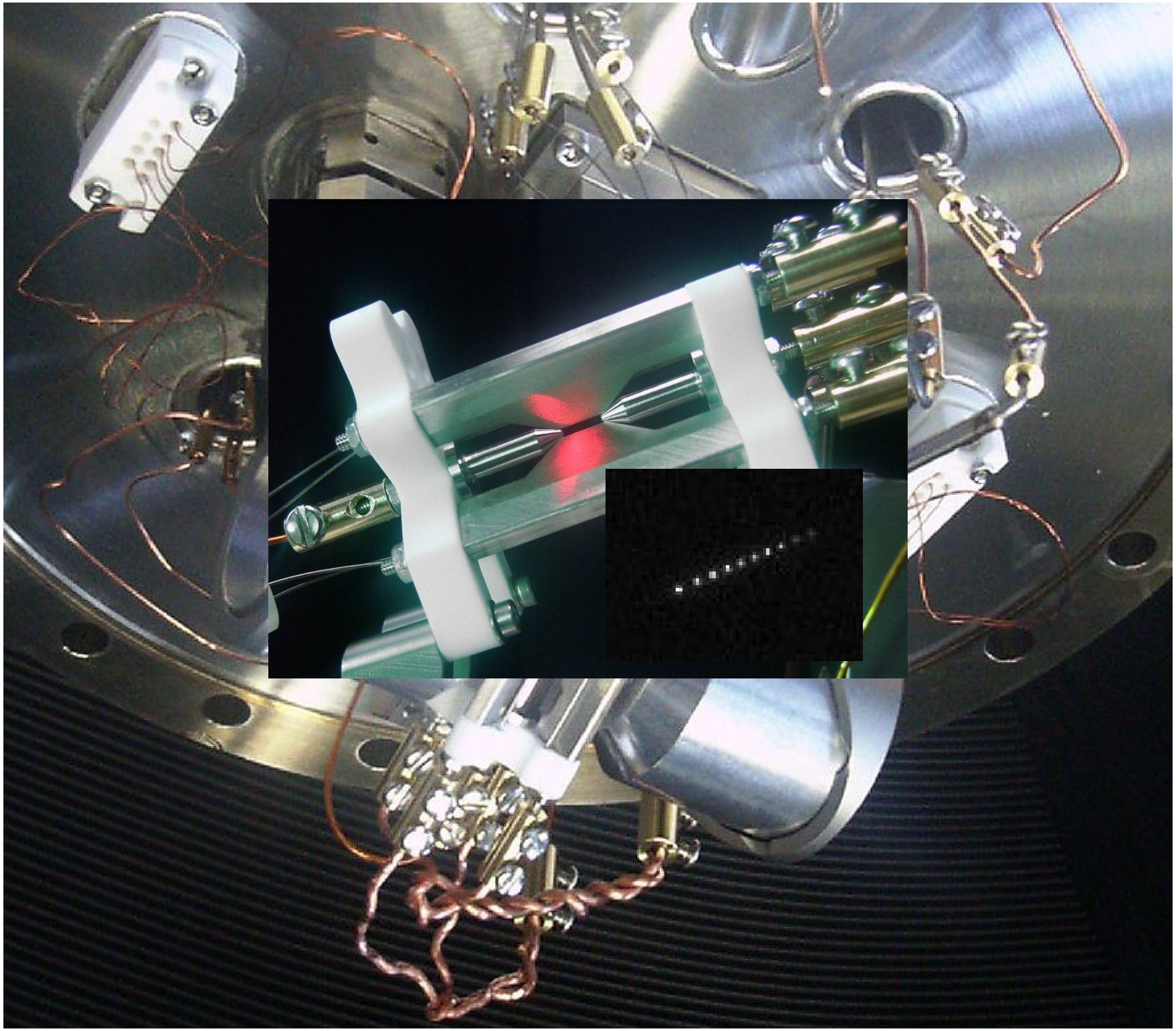
Interference: final entangled state depends on distance between atoms

+

Projective measurement: detection of a *single* Raman-scattered photon

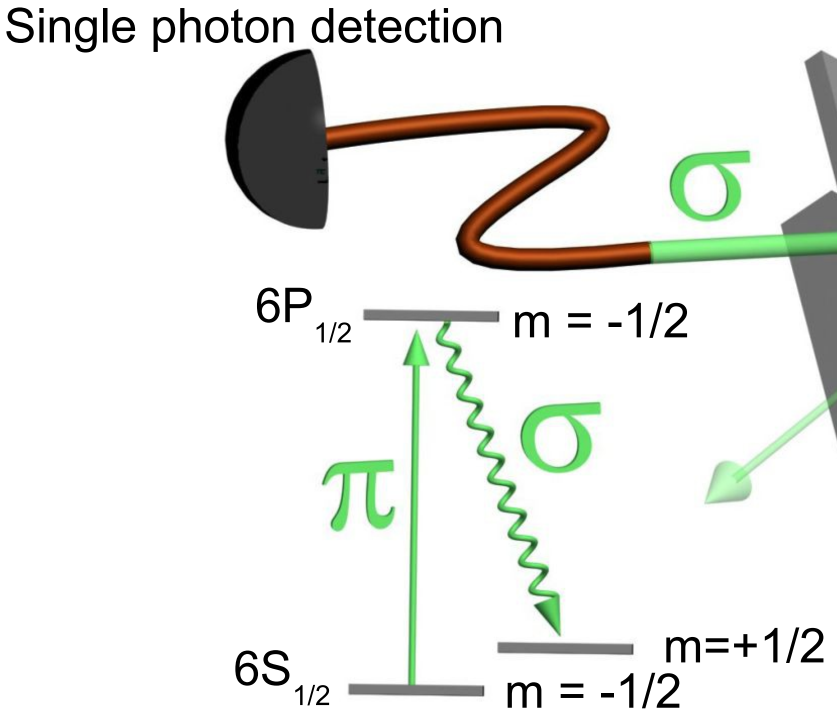
Atom-atom entanglement

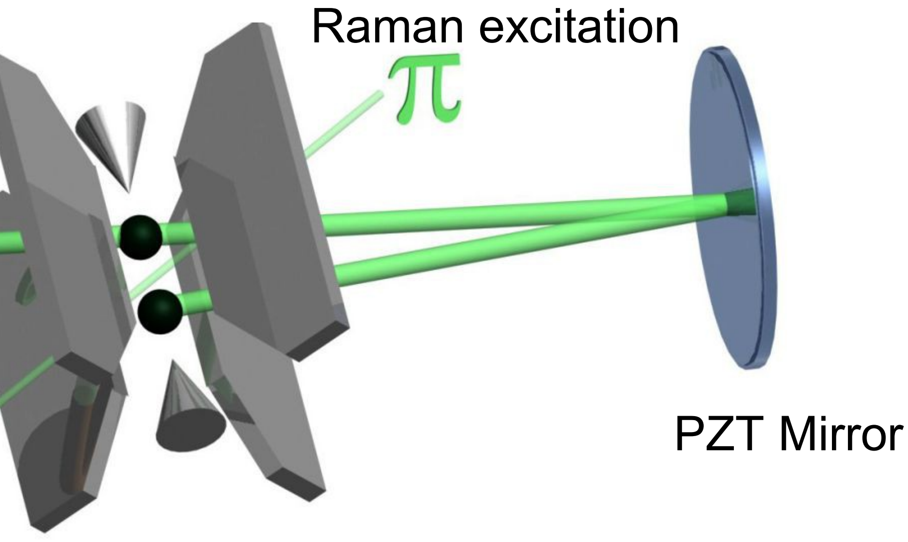
Linear trap



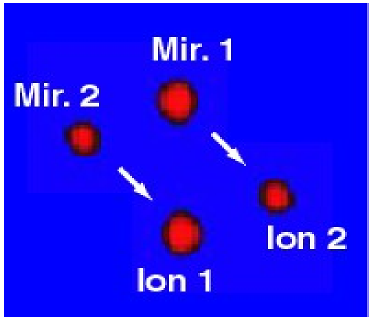
Atom-atom entanglement

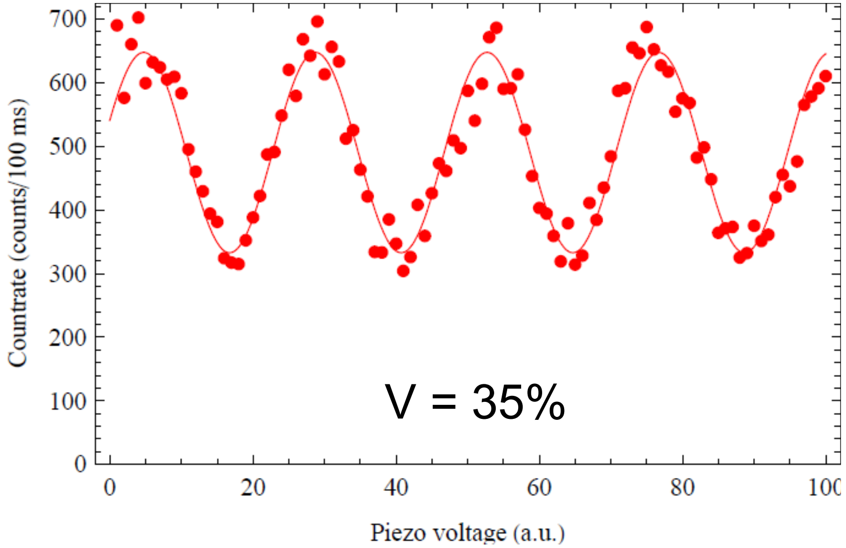
Experimental setup





Two ions interfering with their mirror images





We can hold the phase and control the ion-ion distance to within $\lambda/10$

Atom-atom entanglement

Indistinguishability measurements

- **2nd order coherence**

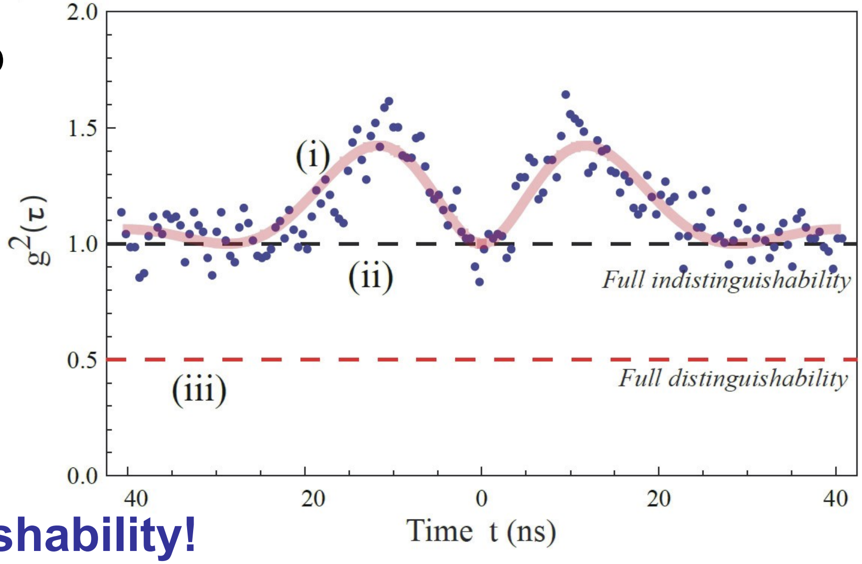
mode overlap

$$g^{(2)}_{\mathrm{Tot}}(\tau) = \frac{1}{2}\left(g^{(2)}(\tau) + |\vec{e_1}\vec{e_2}|^2 |g^{(1)}(\tau)|^2 + 1\right)$$

two-ion $g^{(2)}$

single-ion functions

$$g^{(2)}_{\mathrm{Tot}}(0) = 0.98 \pm 0.07$$



Good spatial and polarization indistinguishability!

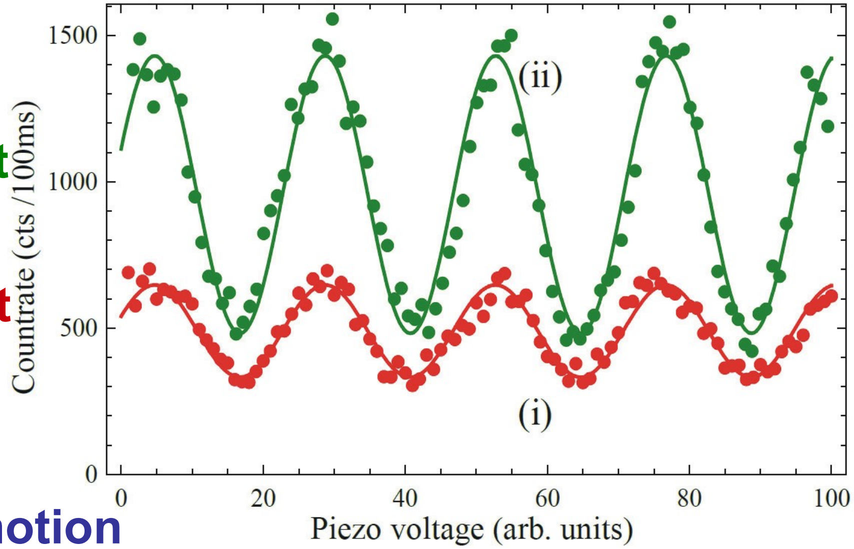
- **1st order coherence**

Interference visibility ~ $e^{-2(k\sigma)^2}$

Mean atomic wavepacket extent

Single ion
~ 60% contrast

Two ions
~ 35 % contast

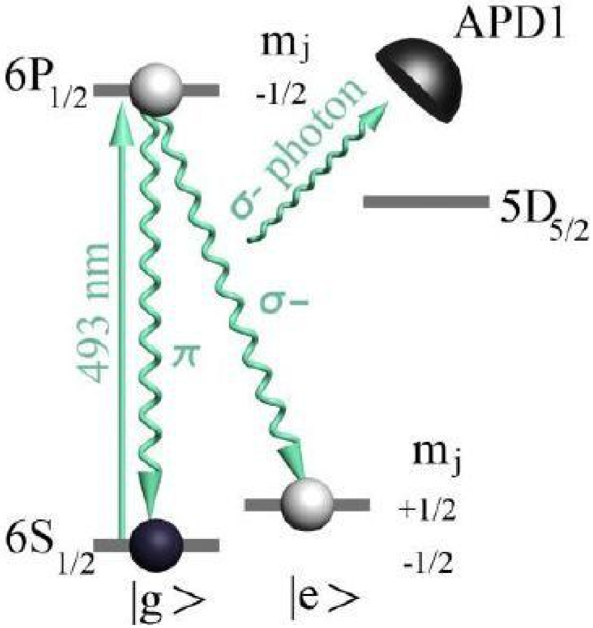


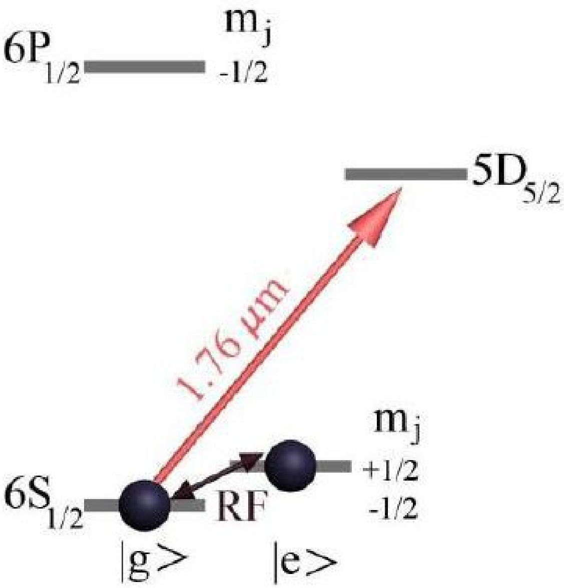
Main source of distinguishability ~ atomic motion
→ excitation along the detection direction

L. Slodička et al., Phys. Rev. A **85**, 043401 (2012)

Atom-atom entanglement

Experimental sequence





Entanglement generation

- Cooling and phase stabilization (4 ms)
- Optical pumping (5 µs)
- Raman excitation (100 ns)
- Single photon detection

NO ? Photon detected ? YES

State analysis

- RF q-bit rotations (6 µs)
- Shelving to D state (2 µs)
- Fluorescence detection (5 ms)

Populations Coherences

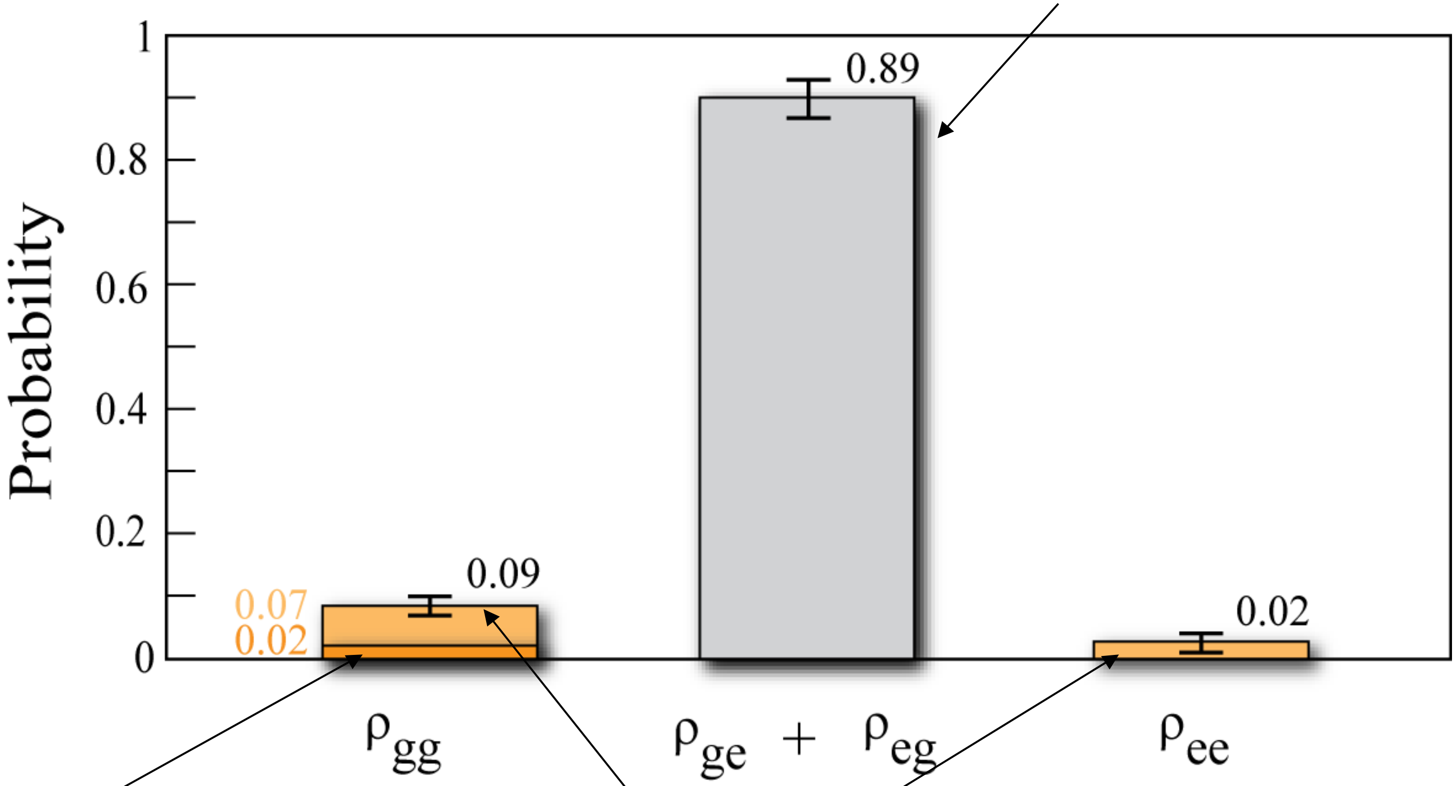
$$F = \langle \Psi^+ | \rho | \Psi^+ \rangle = \frac{1}{2}[\boxed{\rho_{ge} + \rho_{eg}} + \boxed{2\mathrm{Re}(\rho_{eg,ge})}$$

Measured directly (electron shelving) Parity measurement

Atom-atom entanglement

Measurement results

Populations - diagonal elements



Desired correlations

Dark counts

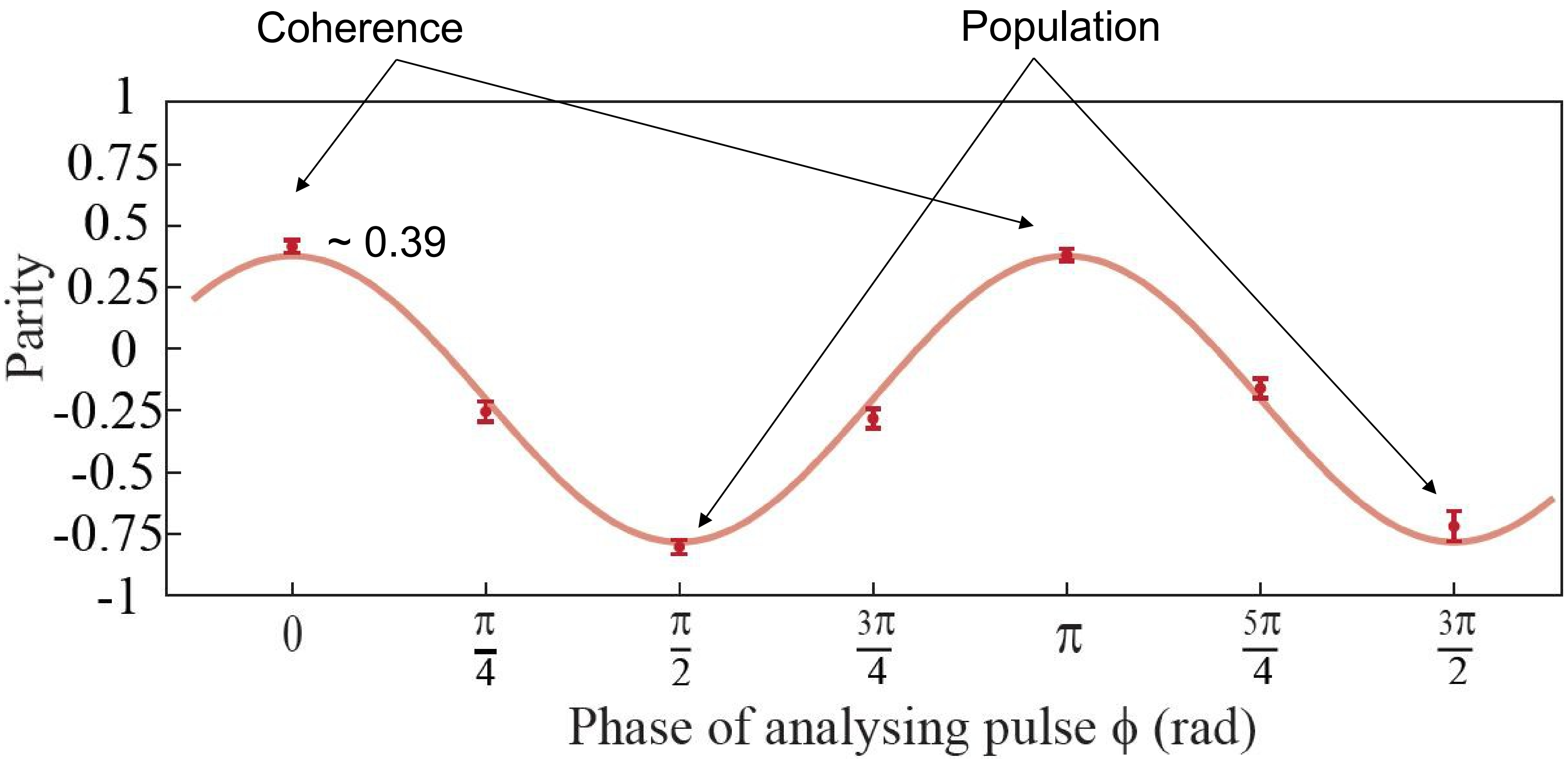
Double excitations

In 89% of the cases correct correlation between atomic states

Atom-atom entanglement

Measurement results

Off diagonal elements - coherences



Measured parity contrast ≈ 58%

Fidelity with $|\Psi^+\rangle$ = 64 ± 2%

Atom-atom entanglement

Results

- **First demonstration** of the single-photon entanglement scheme with single atoms

- **Fidelity** with $|\Psi^+\rangle$ = 64%

  Limited by atomic recoils
  Can be improved by excitation along the detection direction

- Entanglement **generation rate**:

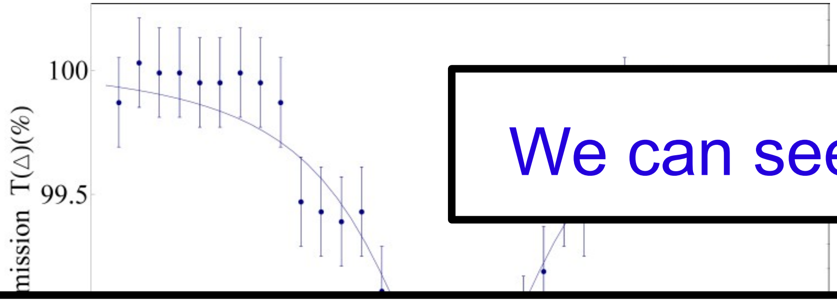
  1 photon is easier to detect than 2!

  With our experimental duty cycle ~ 14 entanglement events/min

  ~ **Two orders of magnitude gain in P_{succ}**

L. Slodička et al., Phys. Rev. Lett. **110**, 083603 (2013)

Summary



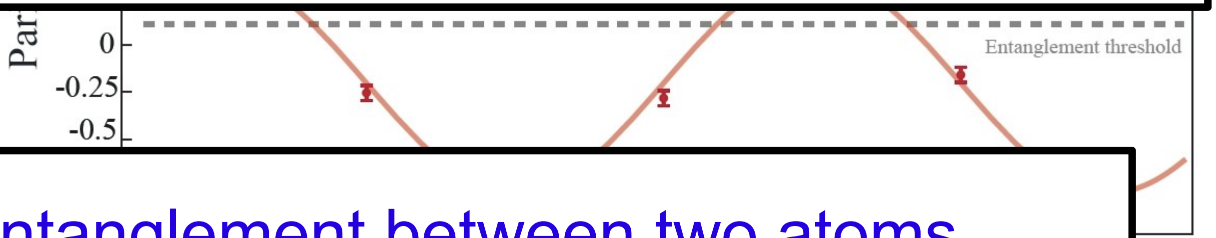
We can see the “shadow“ of a single atom!

Other recent work:

Shot-noise limited monitoring and phase locking of the motion of a single trapped ion
(Phys. Rev. Lett. 110, 133602 (2013))

Free-space read-out and control of single-ion dispersion using quantum interference
(To appear in Phys. Rev. A)

Single ion single photon source
...



We can generate entanglement between two atoms
by mere observation of single photon scattering!

Our group

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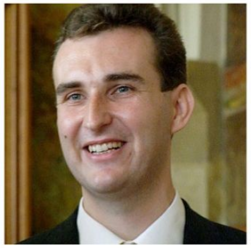


Atom-atom entanglement

State analysis

- We aim to generate $|\Psi^+\rangle = \frac{1}{\sqrt{2}}(|eg\rangle + |ge\rangle)$

All we need to measure!

- Any 2-qubit state $$\hat{\rho} = \begin{pmatrix} \boxed{\rho_{gg}} & \rho_{gg,eg} & \rho_{gg,ge} & \rho_{gg,ee} \\ \rho^*_{gg,eg} & \boxed{\rho_{eg}} & \boxed{\rho_{eg,ge}} & \rho_{eg,ee} \\ \rho^*_{gg,ge} & \boxed{\rho^*_{eg,ge}} & \boxed{\rho_{ge}} & \rho_{ge,ee} \\ \rho^*_{gg,ee} & \rho^*_{eg,ee} & \rho^*_{ge,ee} & \boxed{\rho_{ee}} \end{pmatrix}$$

- Fidelity $$F = \langle\Psi^+|\rho|\Psi^+\rangle = \frac{1}{2}\left[\underbrace{\boxed{\rho_{ge} + \rho_{eg}}}_{\text{Populations}} + \underbrace{\boxed{2\mathrm{Re}(\rho_{eg,ge})}}_{\text{Coherences}}\right]$$

- We measure:

Populations ~ directly (electron shelving)

Coherences ~ the value of parity operator for collective RF rotations R(θ,ϕ)

$$\hat{P} = \hat{p}_{gg} + \hat{p}_{ee} - \hat{p}_{eg} - \hat{p}_{ge}$$

Phase of the pulse

Amplitude of the pulse

Atom-atom entanglement

Measurement results

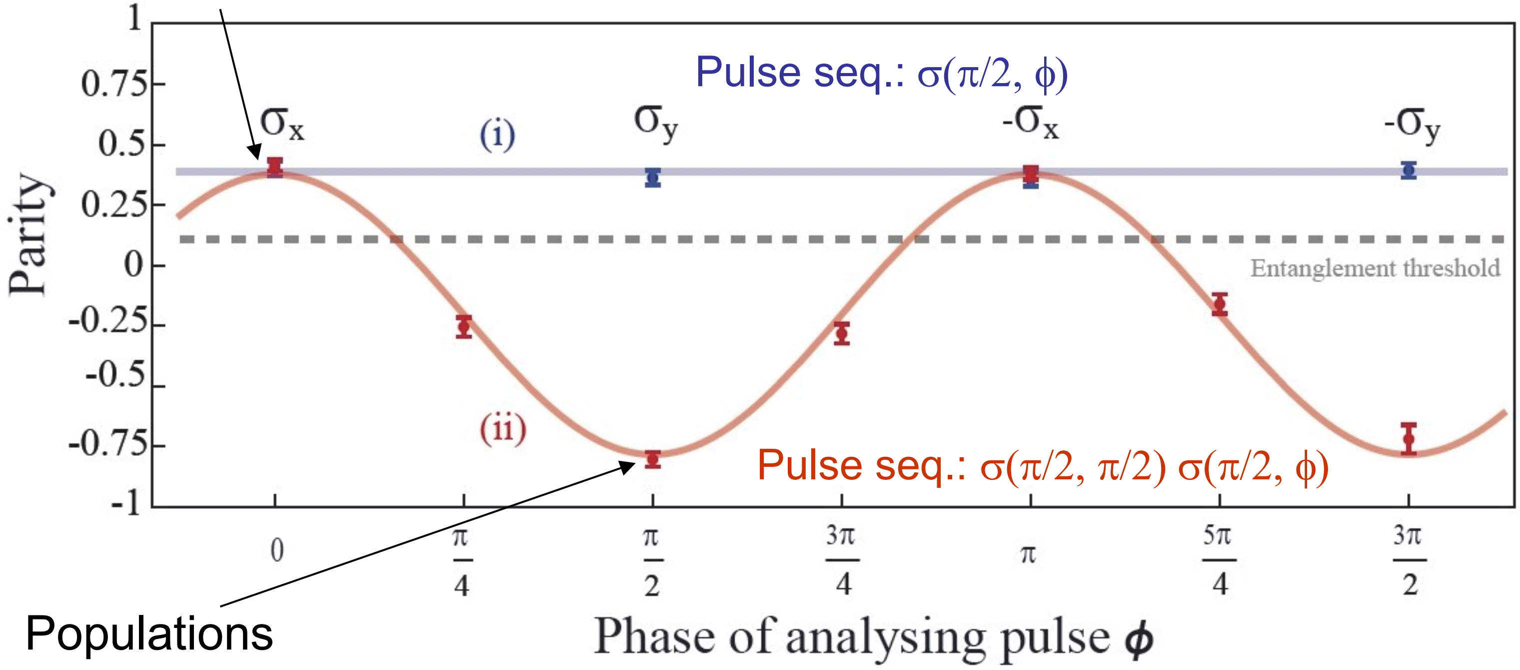
Off diagonal elements - coherences

- We first rotate the output so that

$$|\Psi^+\rangle = |\uparrow\downarrow\rangle + |\downarrow\uparrow\rangle \xrightarrow{R(\pi/2,\,\pi/2)} |\Phi\rangle = |\uparrow\uparrow\rangle - |\downarrow\downarrow\rangle$$

- Parity signal oscillates when applying $R(\pi/2,\phi)$ rotation on this state

Coherences



Pulse seq.: $\sigma(\pi/2, \phi)$

Pulse seq.: $\sigma(\pi/2, \pi/2)\ \sigma(\pi/2, \phi)$

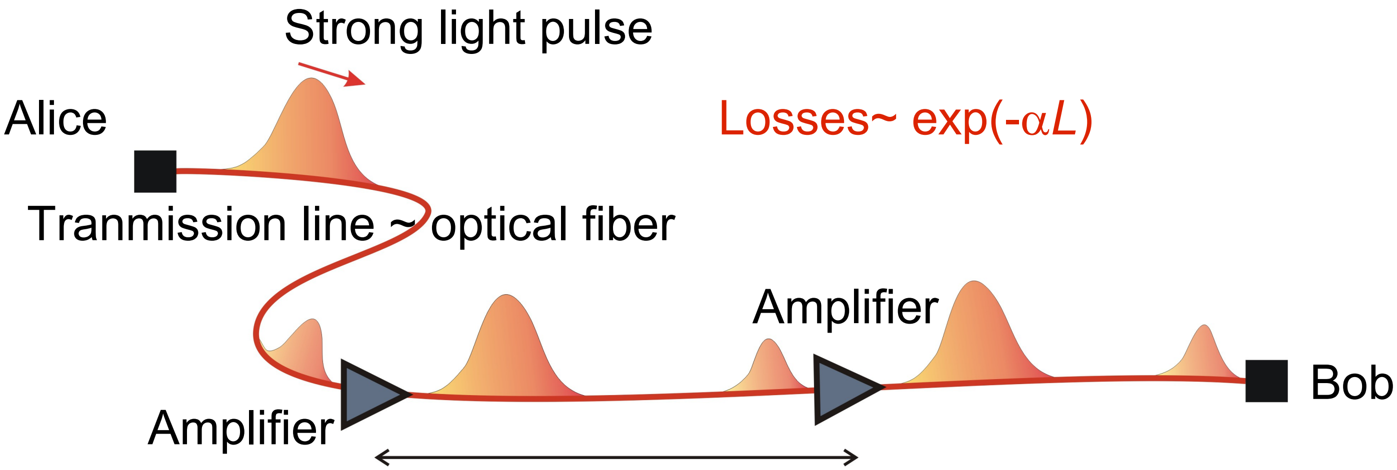
Populations

Measured parity contrast ≈ 58%

Atom-atom entanglement

Motivation

Classical communication

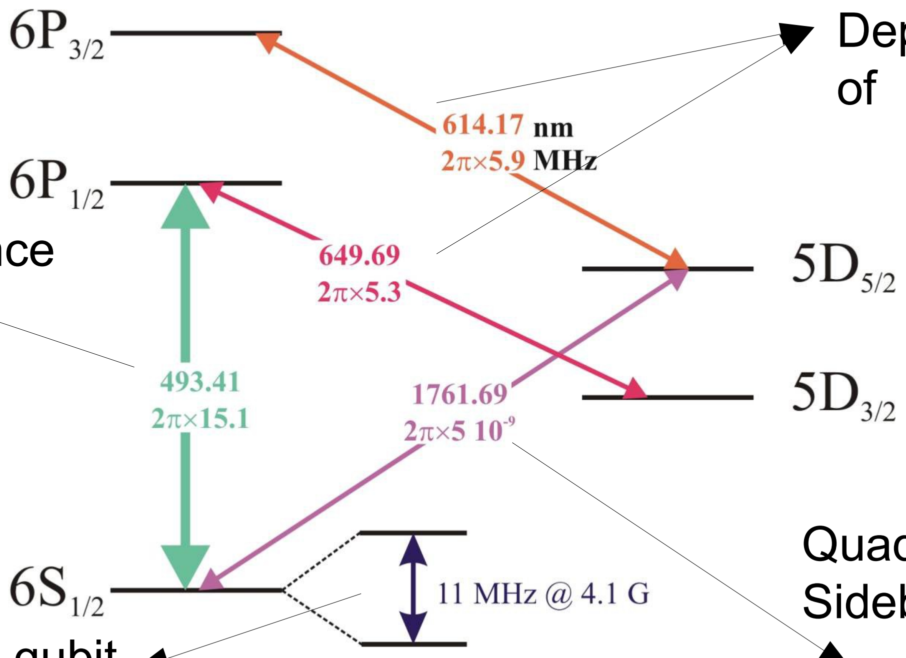


Works well, but quantum physics can offer us more!

- Absolutely secure communication (Quantum cryptography)
- Faithful transfer of unknown quantum state (Quantum teleportation)

Overview

$^{138}Ba^{+}$

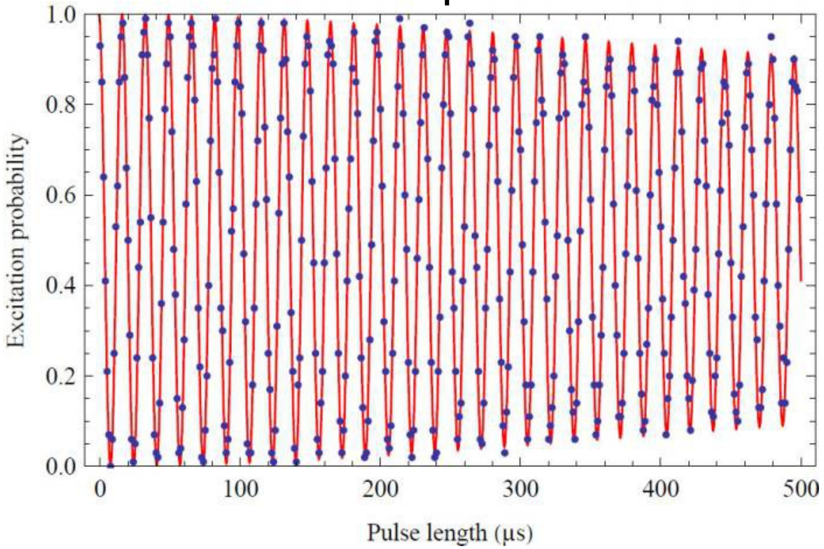


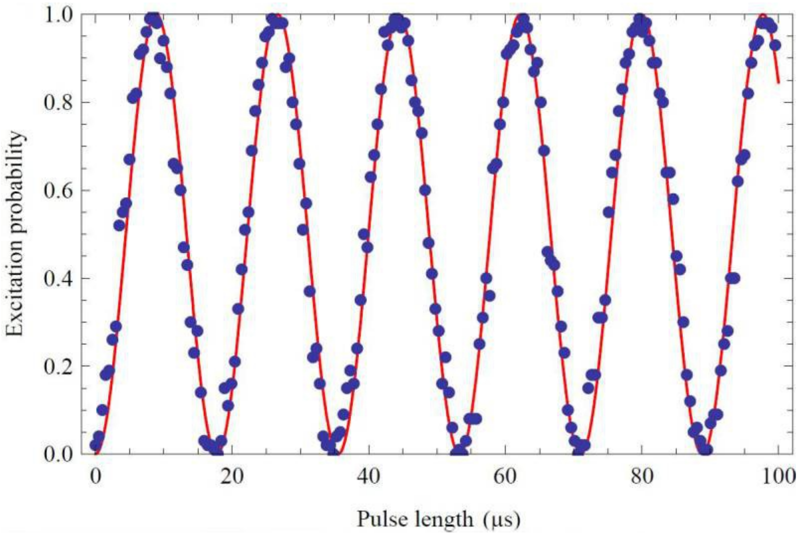
Depopulation of long lived states

Resonance fluorescence
Doppler cooling
State initialization
State detection

Quadrupolar transition qubit
Sideband cooling

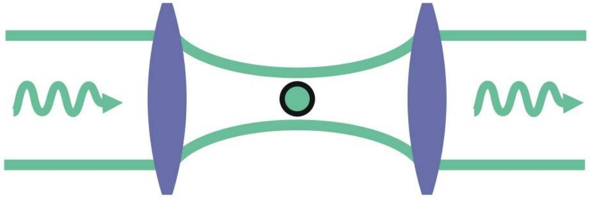
RF transition qubit



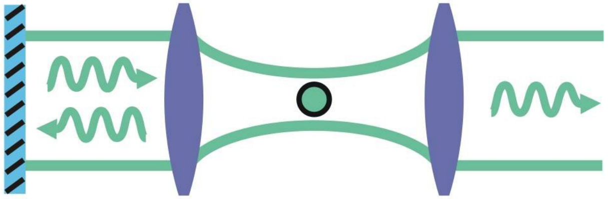


Single atom in free space

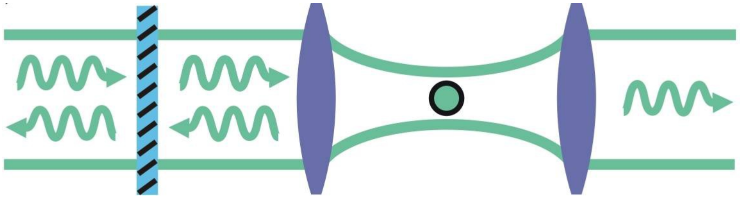
Free space extinction



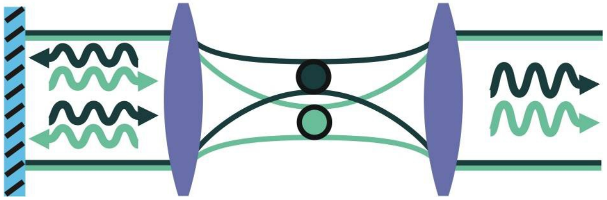
Half-cavity setup



Single-atom mirror



Atom-atom entanglement



Phase interference of scattered light!