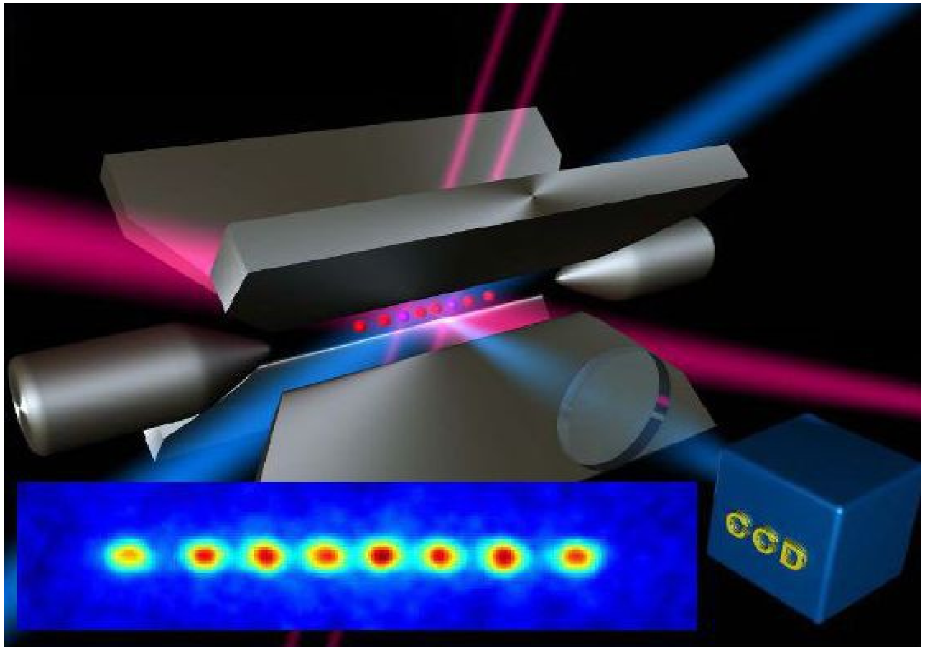
Single atom – light interactions in free space

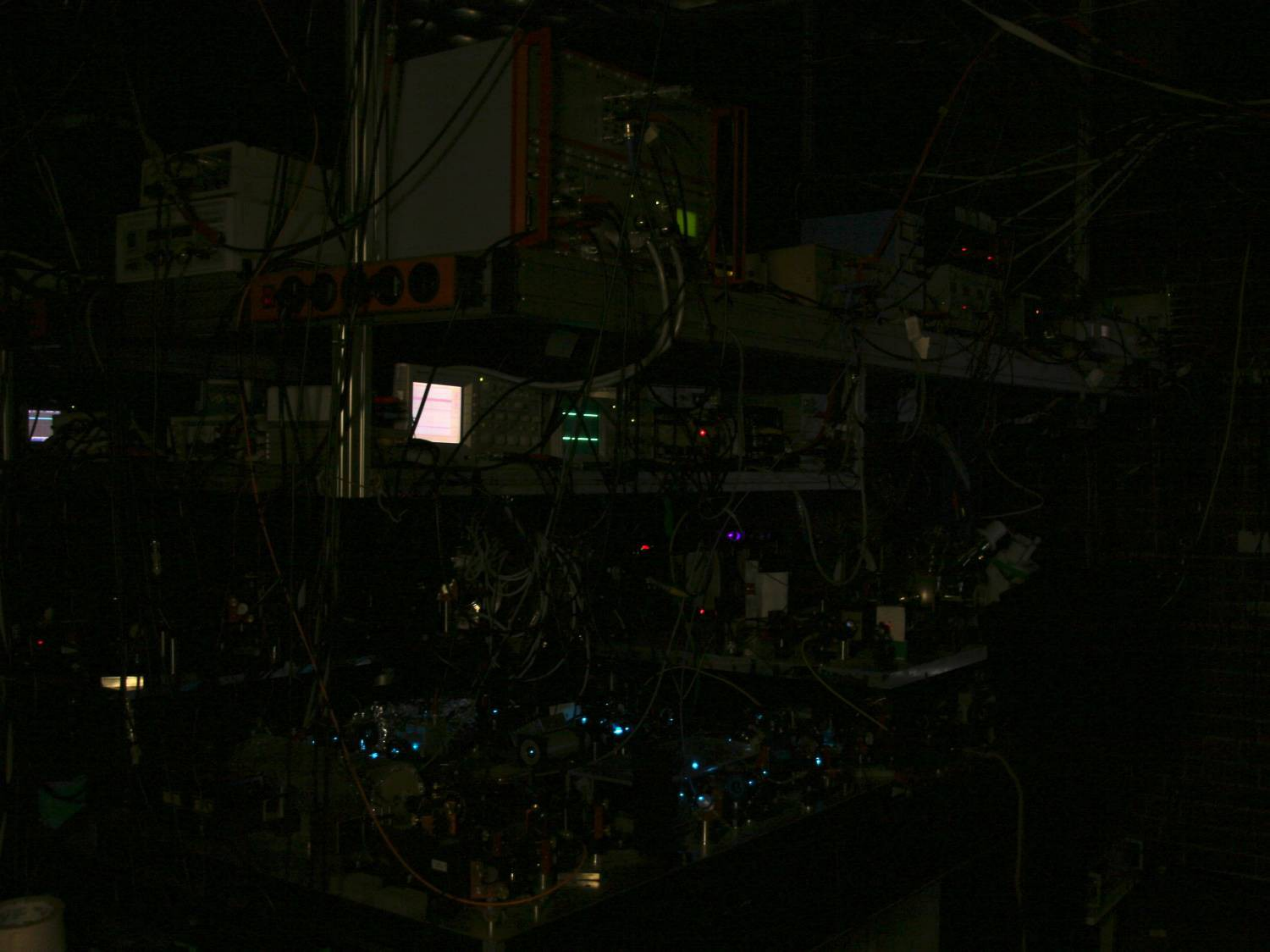
Lukáš Slodička

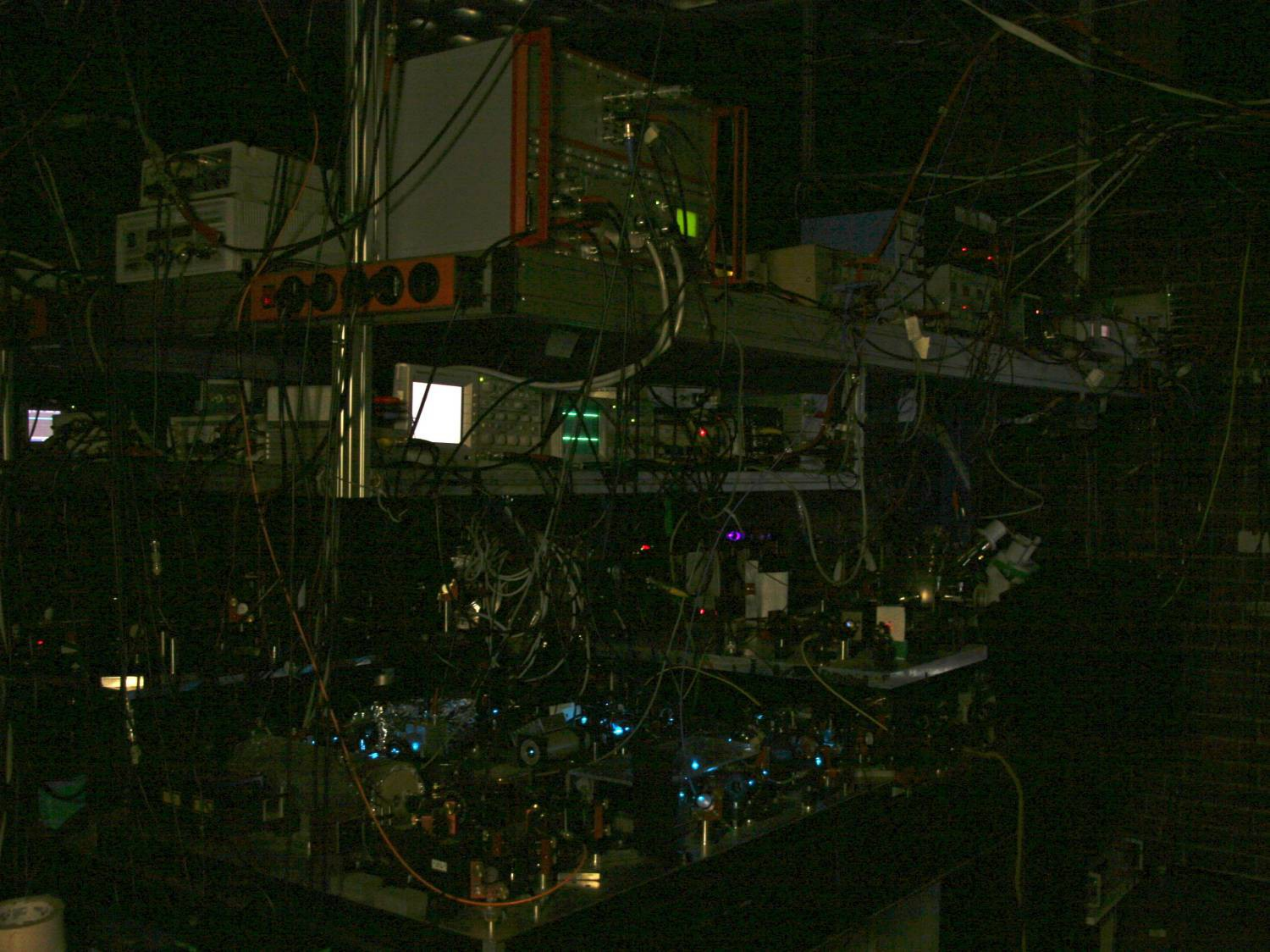
Department of Optics, Faculty of Science, Palacký University,
Olomouc, Czech Republic

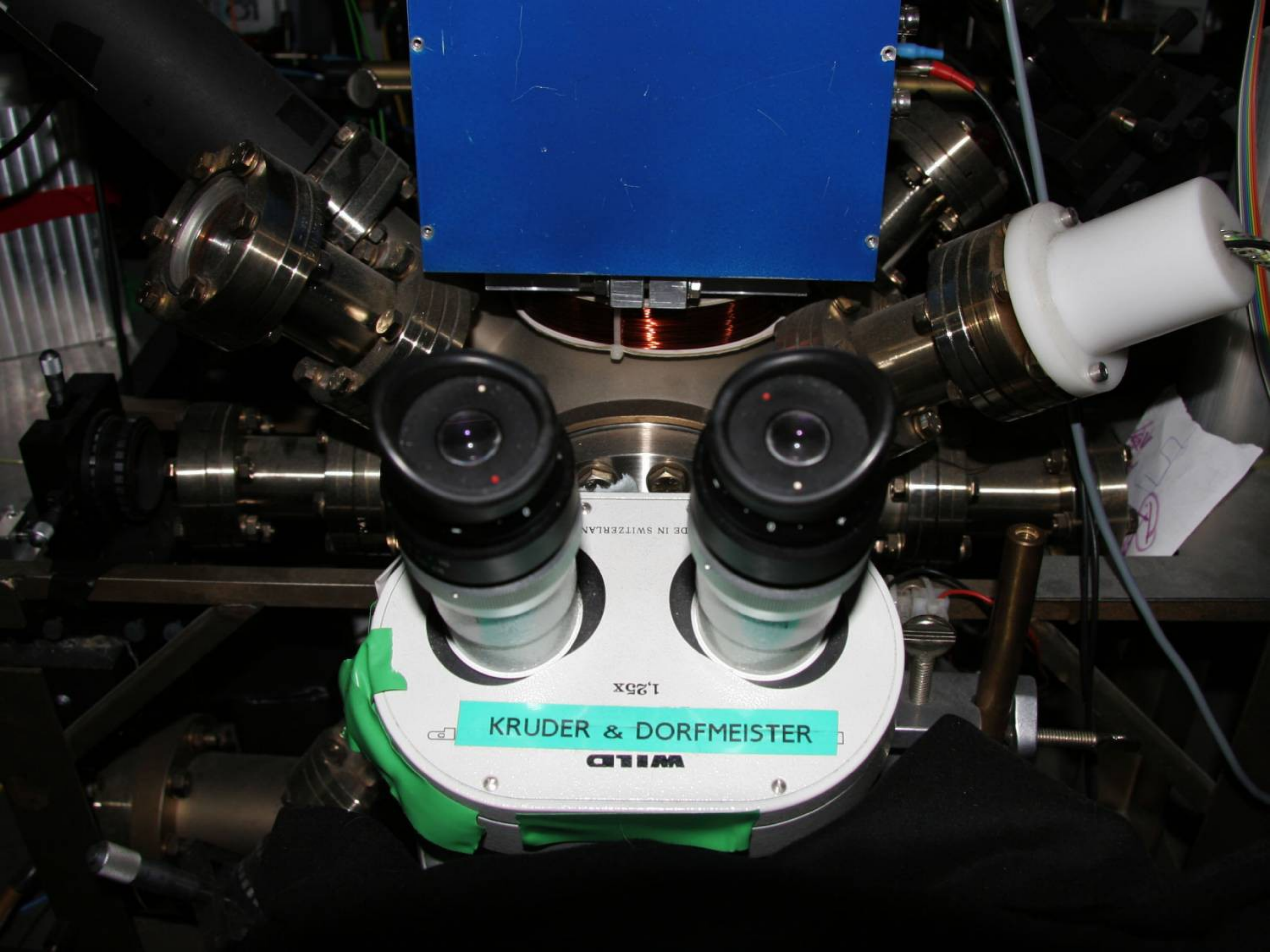


MU, Brno, 20. 5. 2014

evropský sociální fond v ČR
EVROPSKÁ UNIE
MINISTERSTVO ŠKOLSTVÍ, MLÁDEŽE A TĚLOVÝCHOVY
OP Vzdělávání pro konkurenceschopnost
INVESTICE DO ROZVOJE VZDĚLÁVÁNÍ





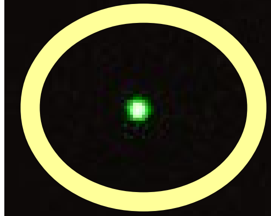

KRUDER & DORFMEISTER
1,25x
WILD

Observation of a single isolated atom!

We never experiment with just one electron or atom or (small) molecule. *In thought-experiments we sometimes assume that we do; this envariably entails ridiculous consequences.*

E. Schrödinger

British Journal of the Philosophy of Science III (10), (**1952**)

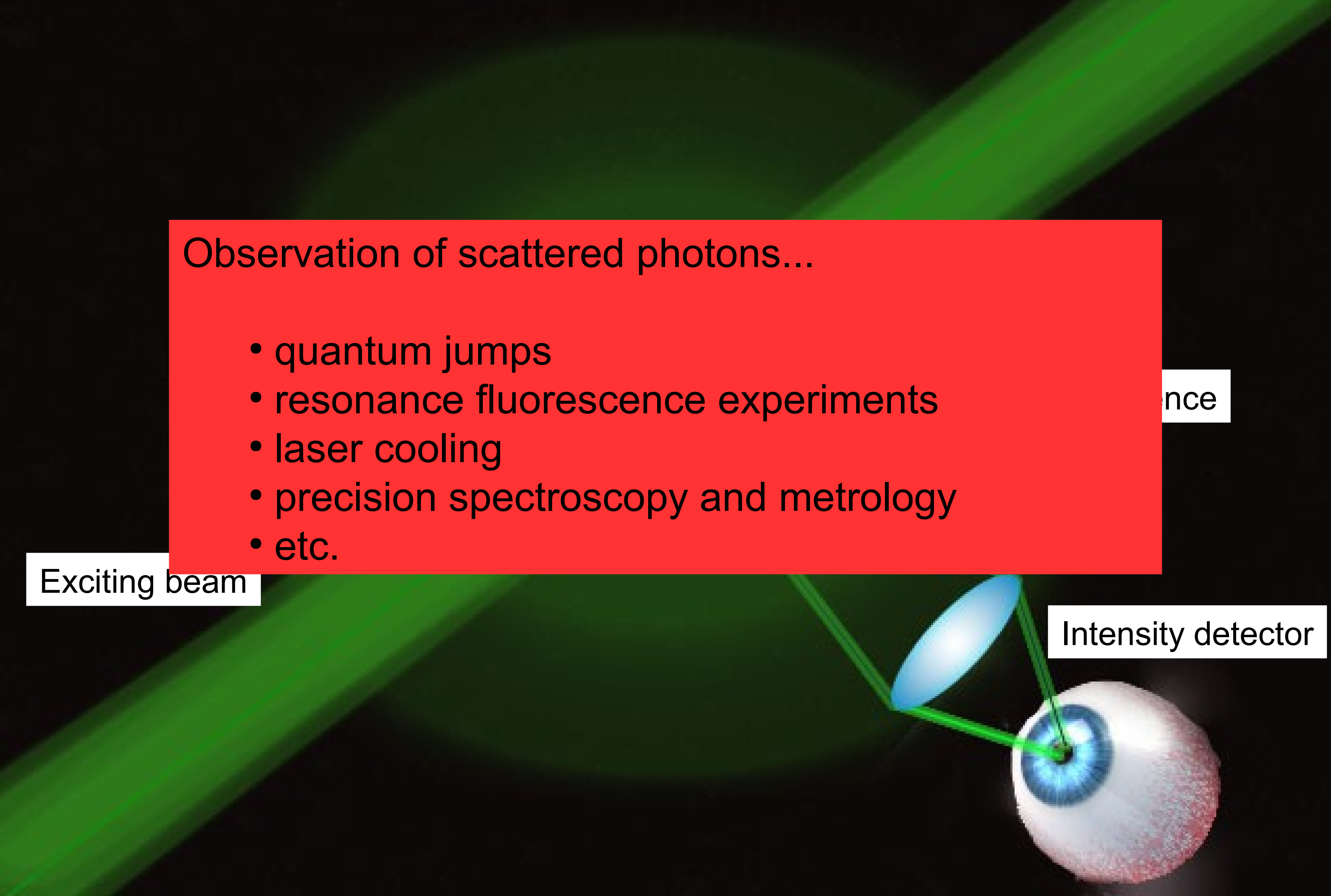


What do we actually see?

Observation of a single atom in free space

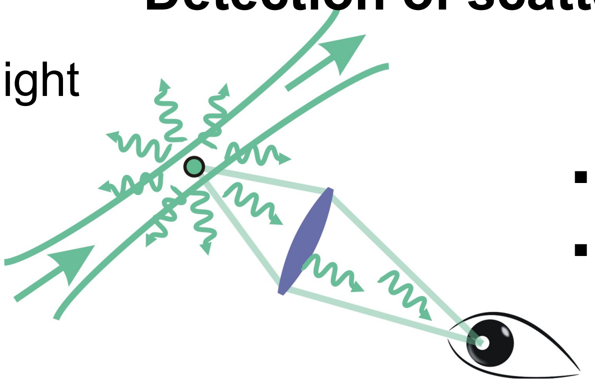
Observation of scattered photons...

- quantum jumps
- resonance fluorescence experiments
- laser cooling
- precision spectroscopy and metrology
- etc.



Observation of single atom in free space

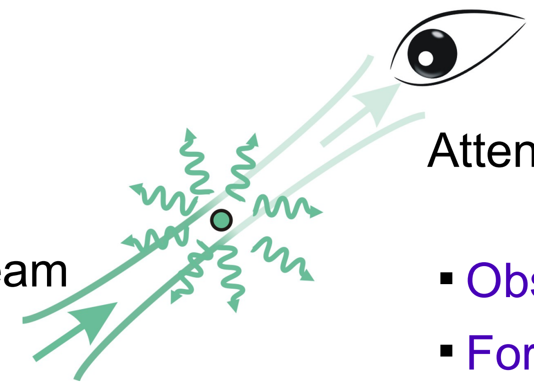
Detection of scattered light



- Resonance fluorescence experiments
- Quantum jumps spectroscopy

Distribution of entanglement by mere observation of scattered photon?

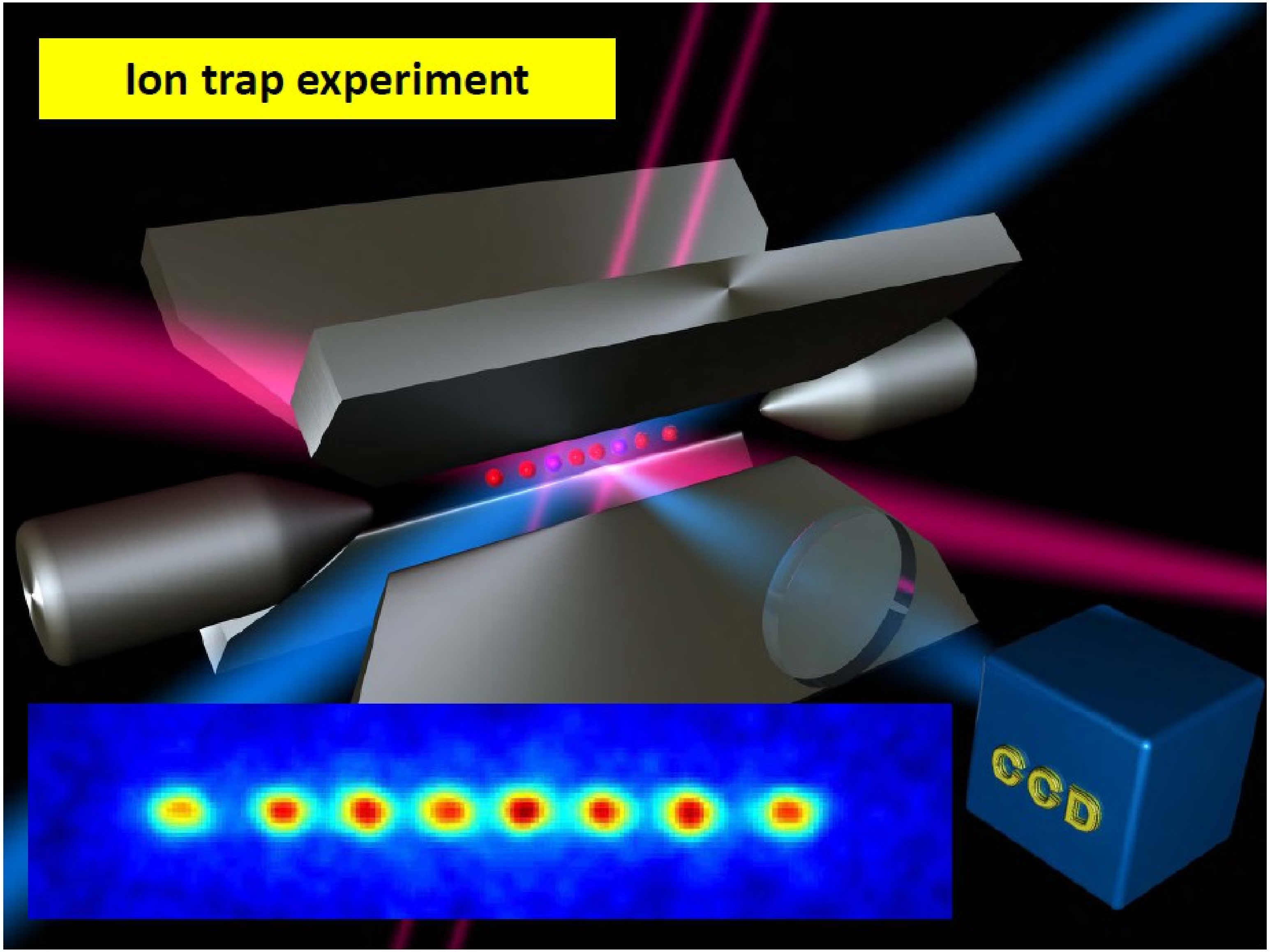
Detection of exciting beam

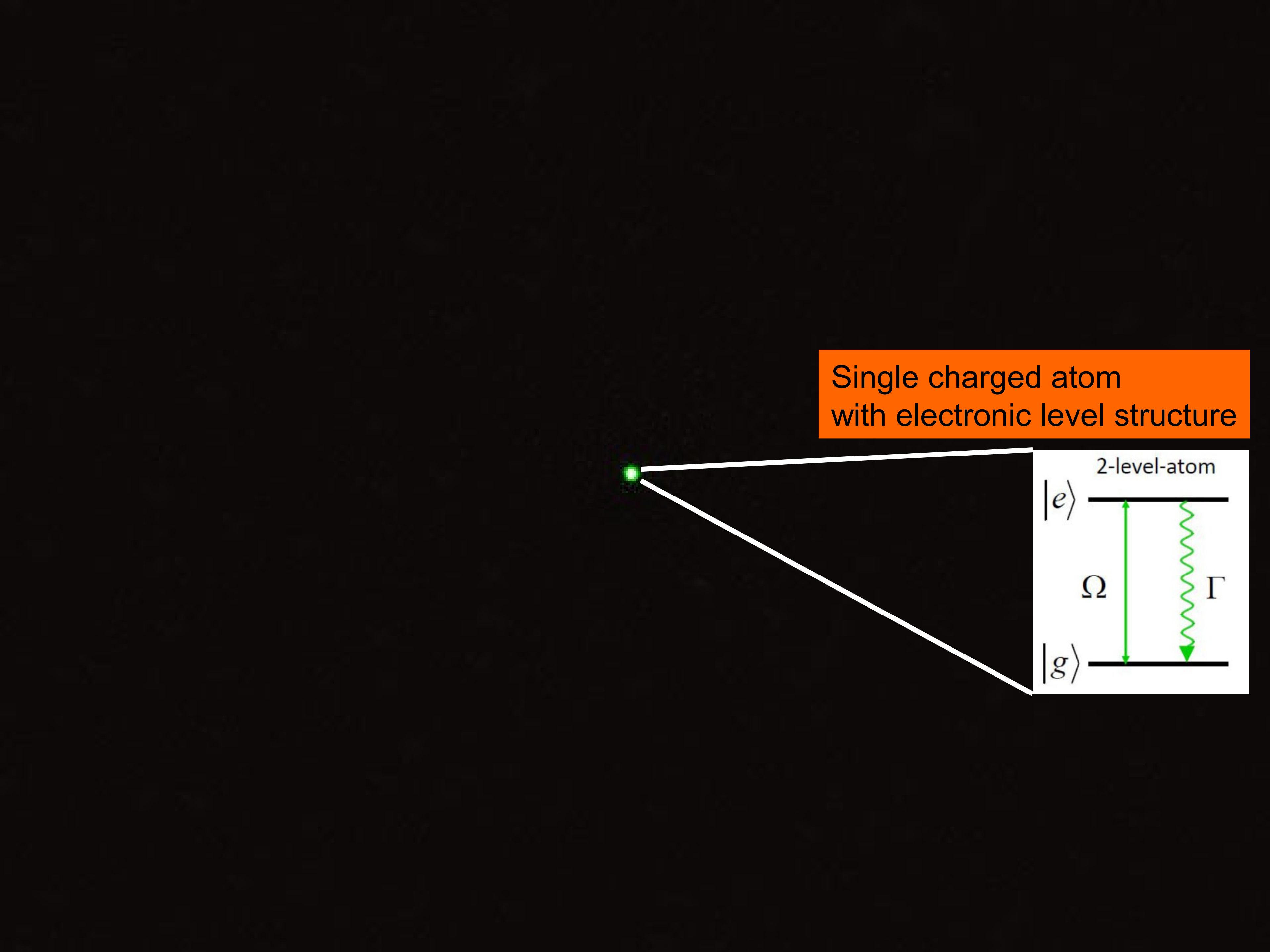


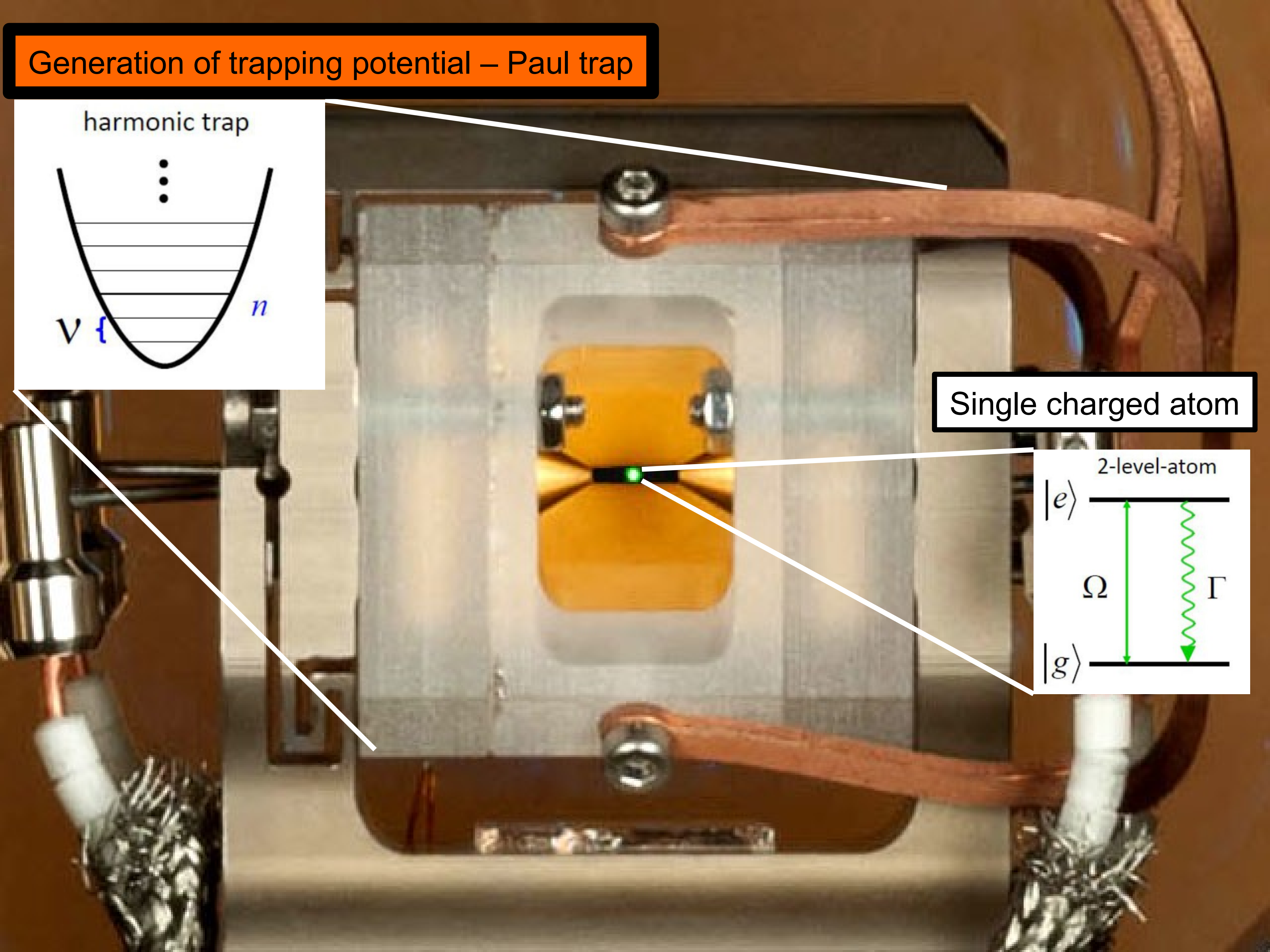
- Observed with ensembles or atoms in cavities
- For single atoms in free space usually negligible

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

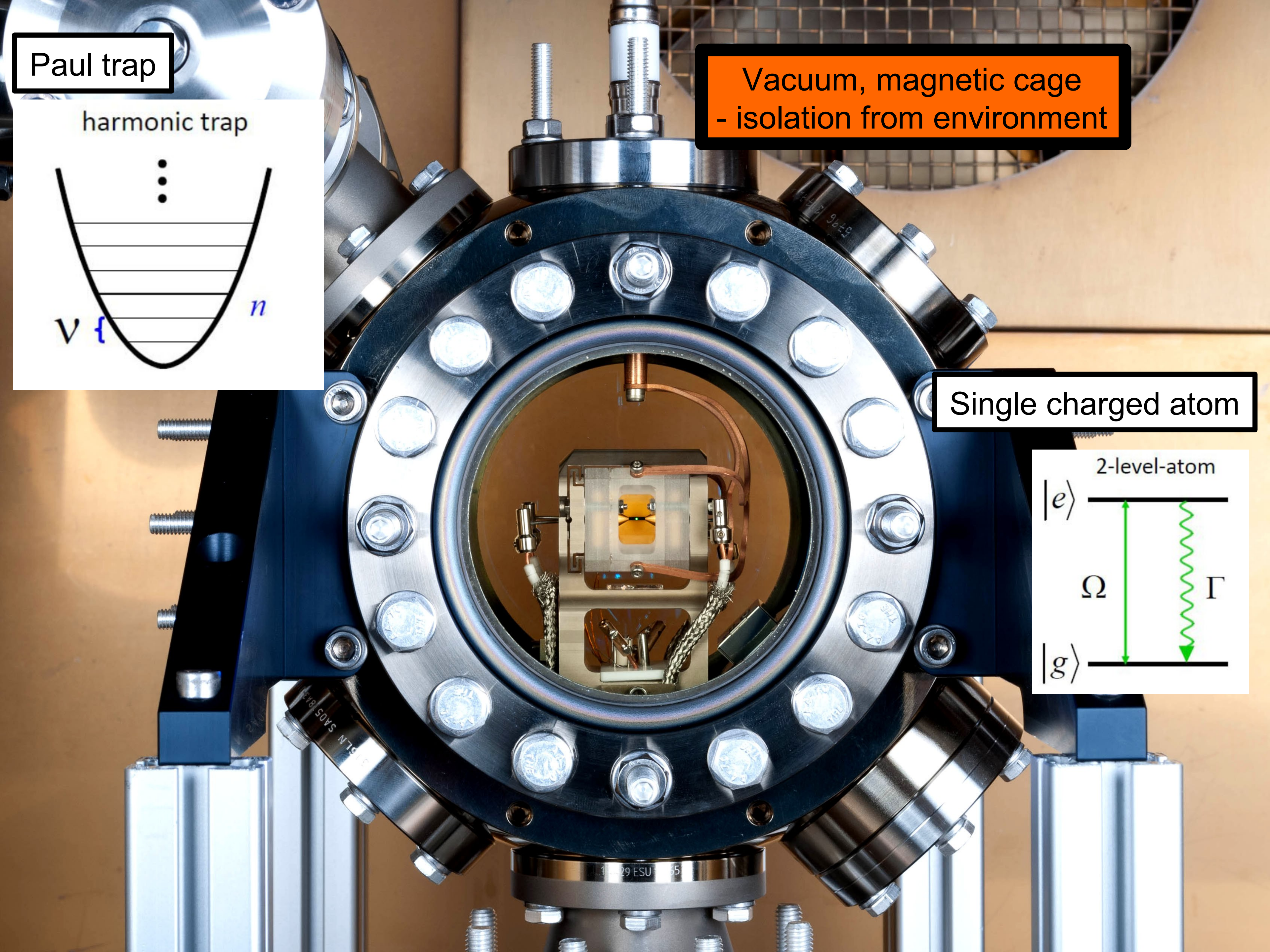
Ion trapping basics



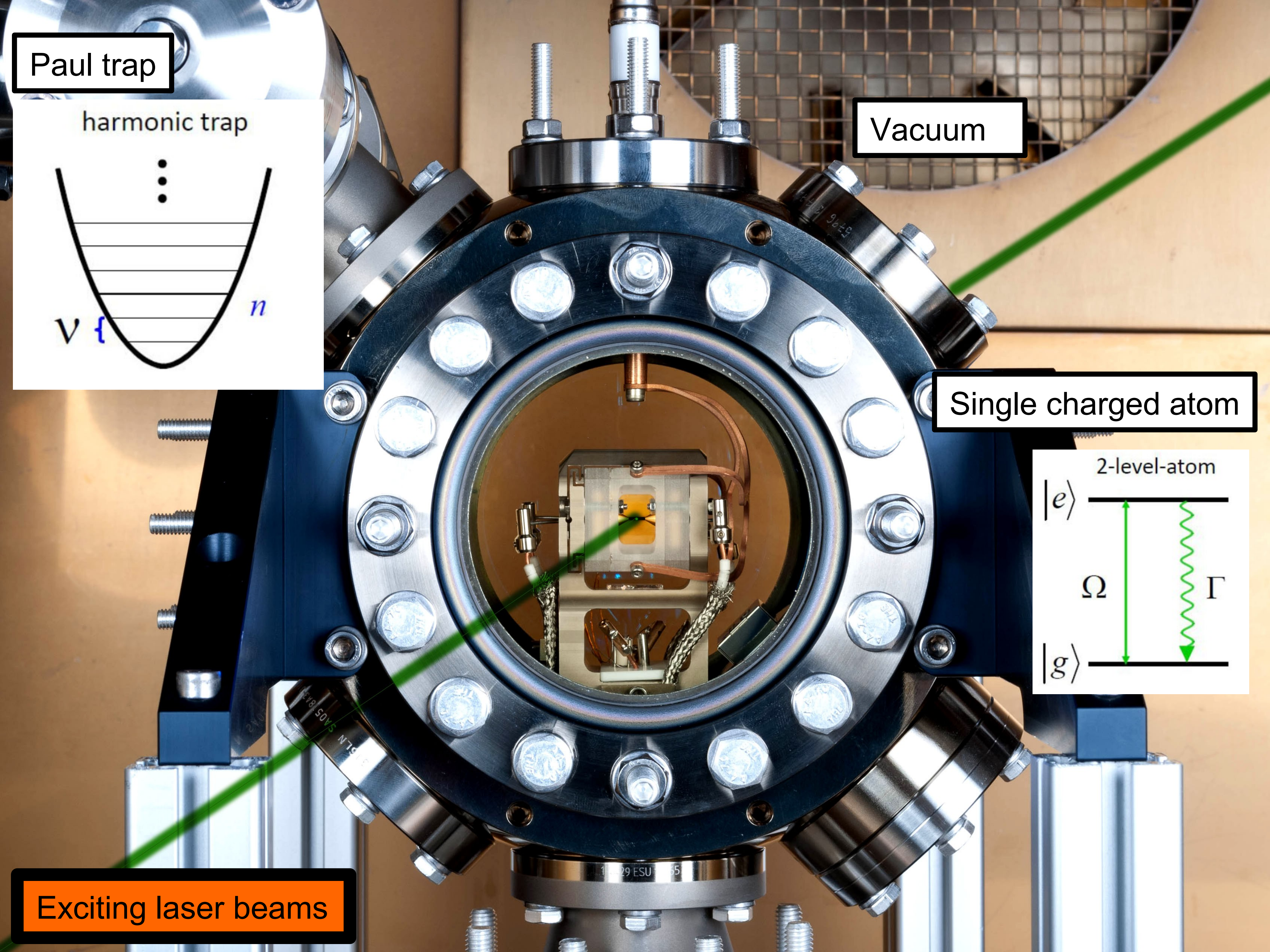

Single charged atom
with electronic level structure
2-level-atom
$|e\rangle$
Ω
Γ
$|g\rangle$



Generation of trapping potential – Paul trap
harmonic trap
ν
n
Single charged atom
2-level-atom
|e⟩
Ω
Γ
|g⟩



Paul trap
harmonic trap
ν
n
Vacuum, magnetic cage
- isolation from environment
Single charged atom
2-level-atom
|e⟩
|g⟩
Ω
Γ



Paul trap
harmonic trap
ν
n
Vacuum
Single charged atom
2-level-atom
|e⟩
Ω
Γ
|g⟩
Exciting laser beams

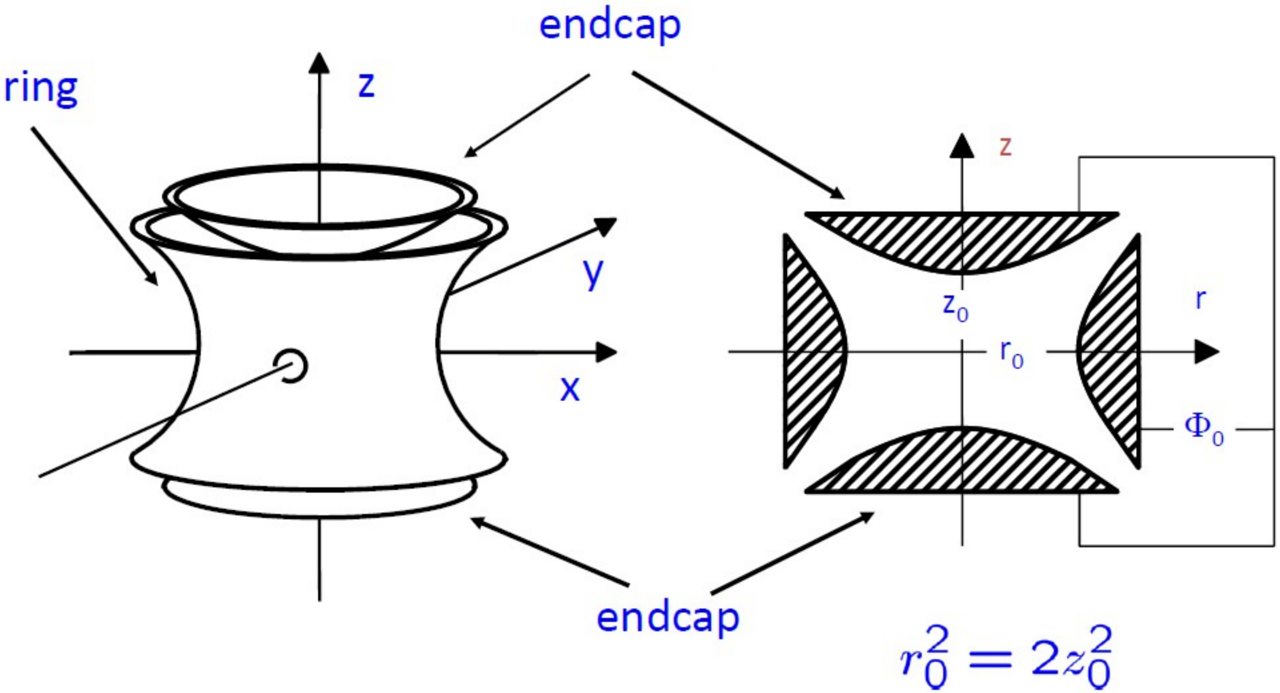
Ion trapping basics

Paul trap

Do it dynamically → Paul trap

time depending potential $\Phi(\overrightarrow{r}, t) = \Phi_0(t) \cdot (x^2 + y^2 - 2z^2)$

with $\Phi_0(t) = (U + V cos(\Omega_{RF} t))/\tilde{r}^2$



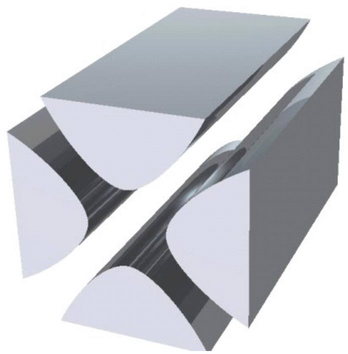
- **Effectively harmonic in all three dimensions**

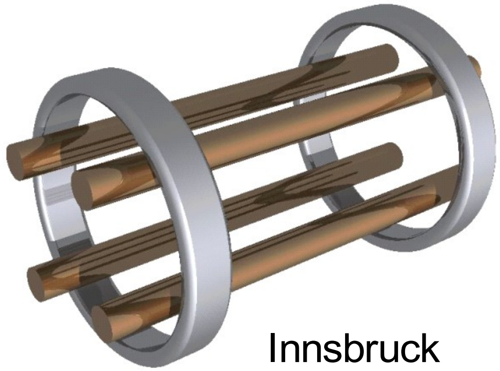
W. Paul

Ion trapping basics

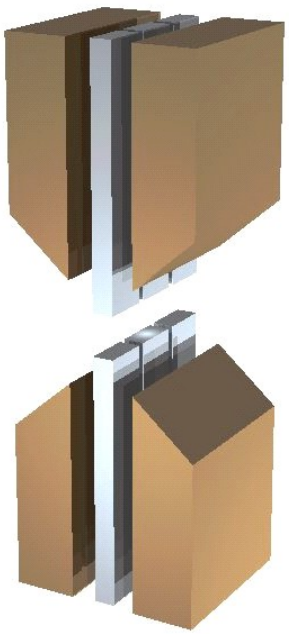
Linear Paul traps

Paul mass filter

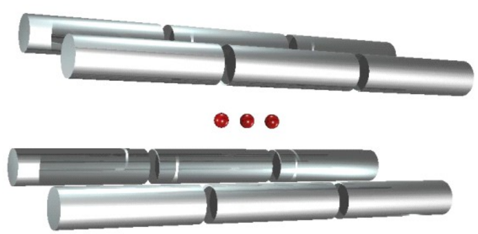




Innsbruck



Munich

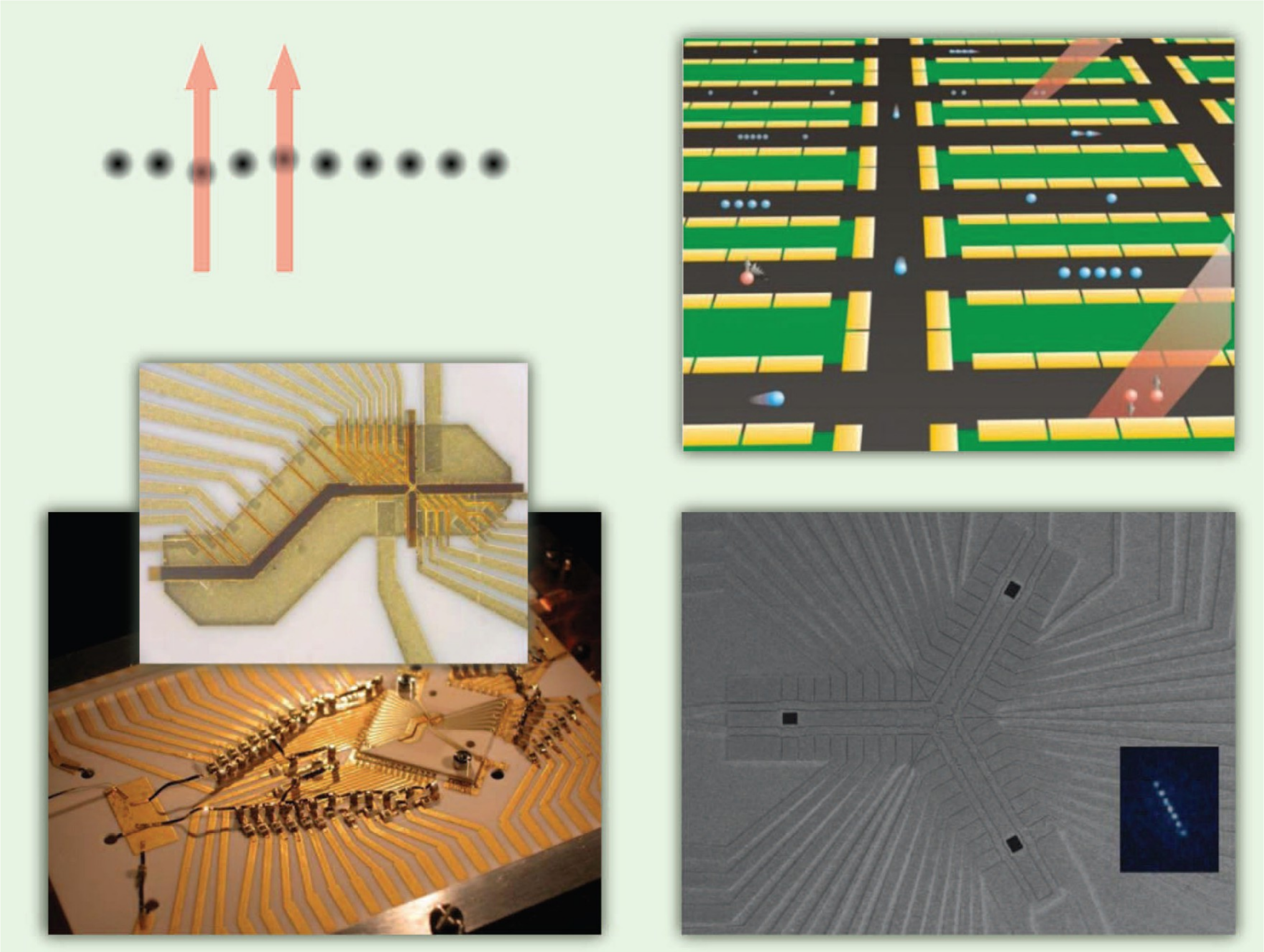


Boulder, Mainz, Aarhus

Ion trapping basics

Quantum charge-coupled device

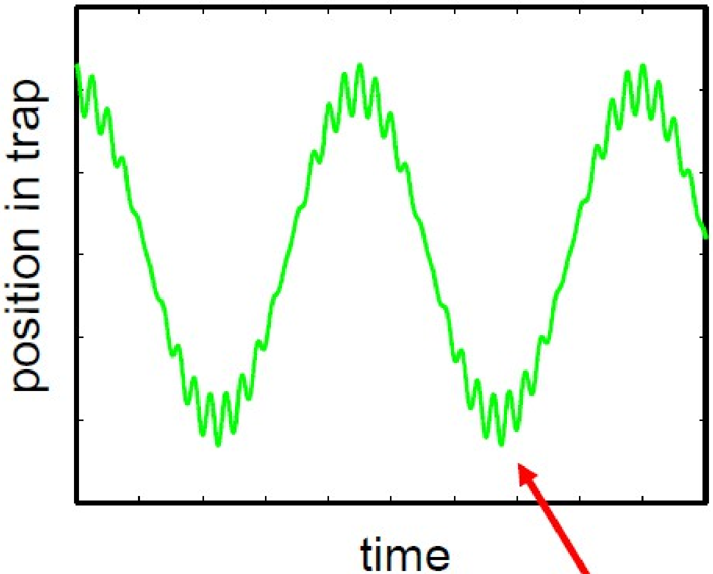
Kielpinsky, Monroe, Wineland (NIST)

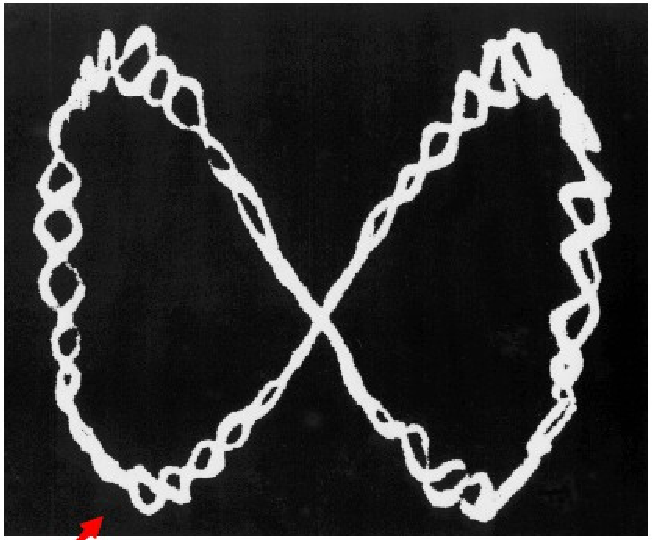


Ion trapping basics

Classical ion motion

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



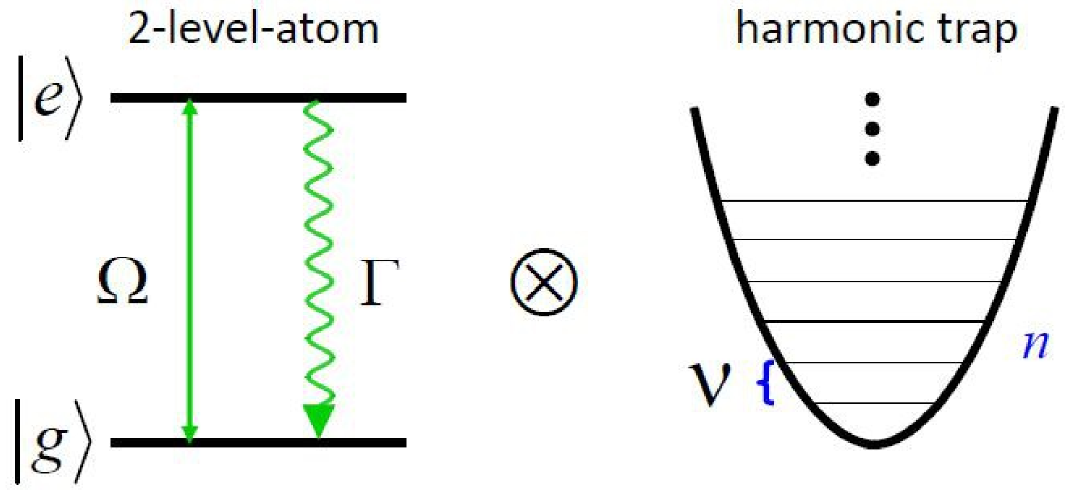


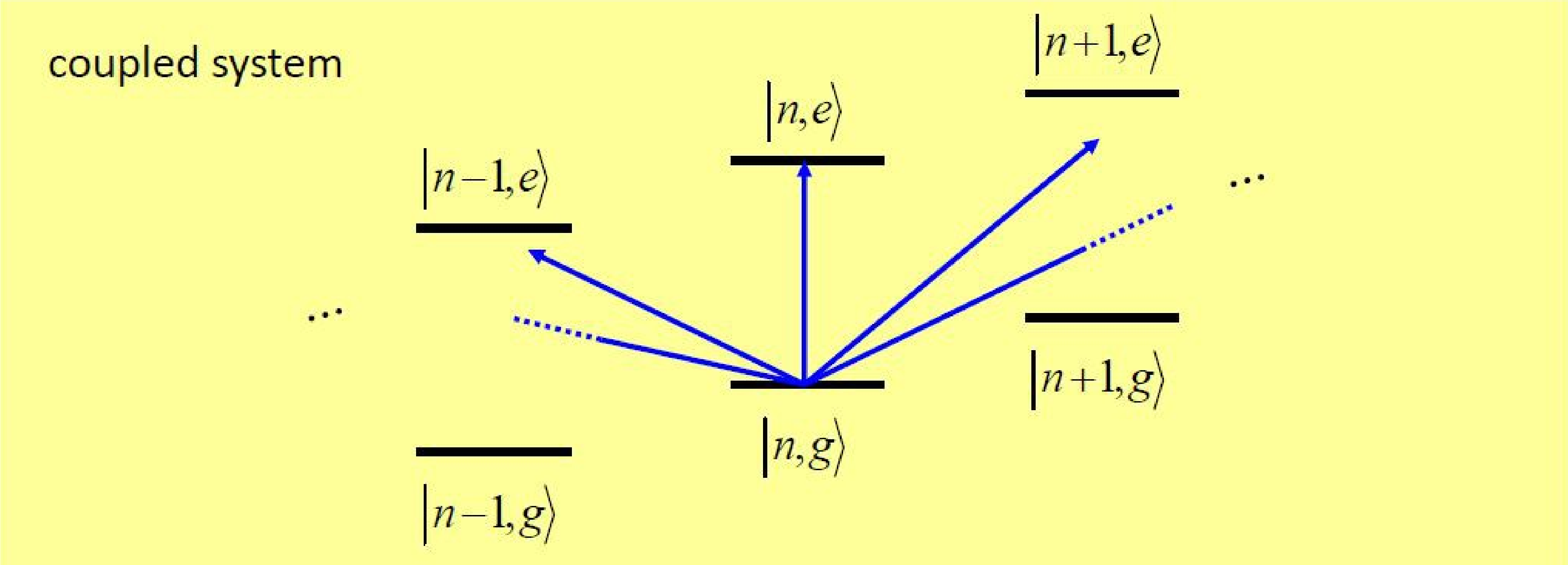
Wuerker, Shelton, Langmuir,
J. Appl. Phys. **30**, 342 (1959)

micromotion

Ion trapping basics

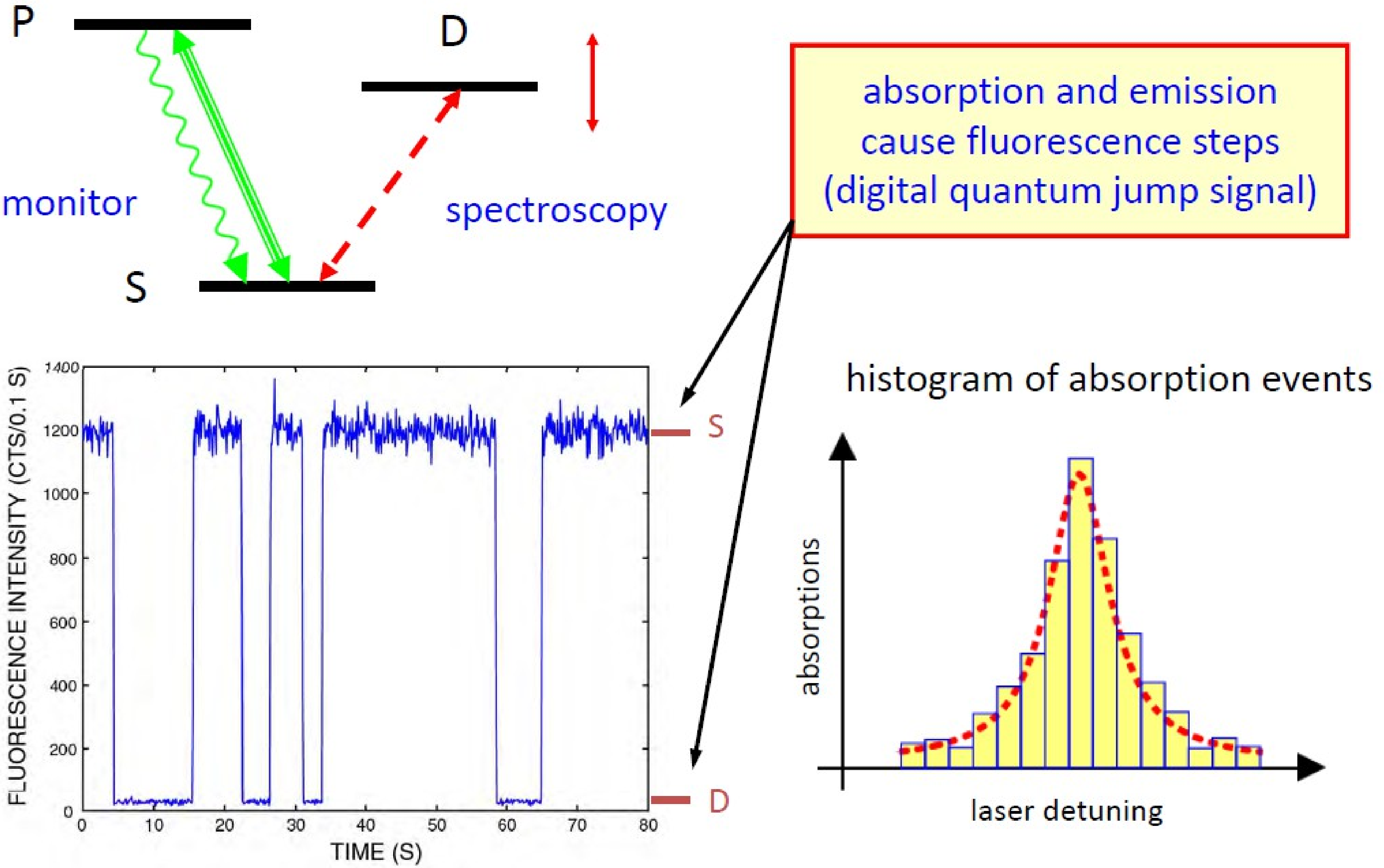
Quantized motion





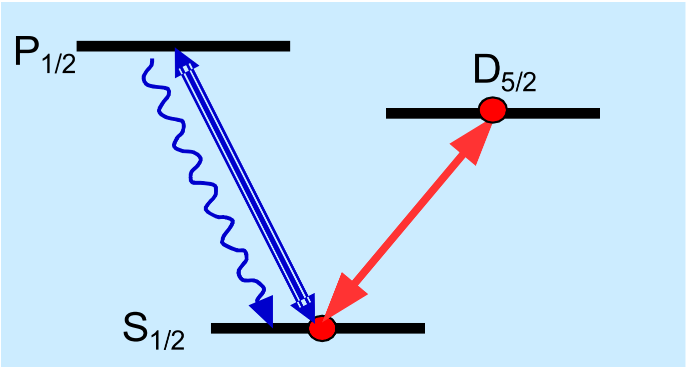
Ion trapping basics
Spectroscopy - electron shelving method

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



Ion trapping basics

Electron shelving

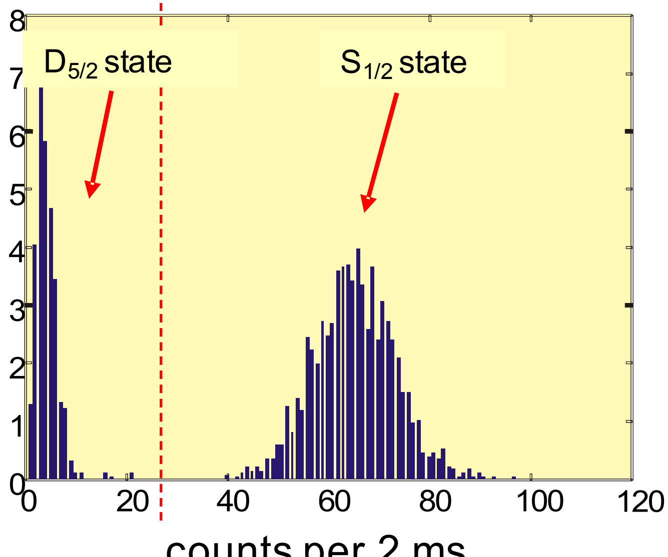


1. Initialization in a pure quantum state

2. Quantum state manipulation on $S_{1/2} - D_{5/2}$ transition

3. Quantum state measurement by fluorescence detection

One ion : Fluorescence histogram



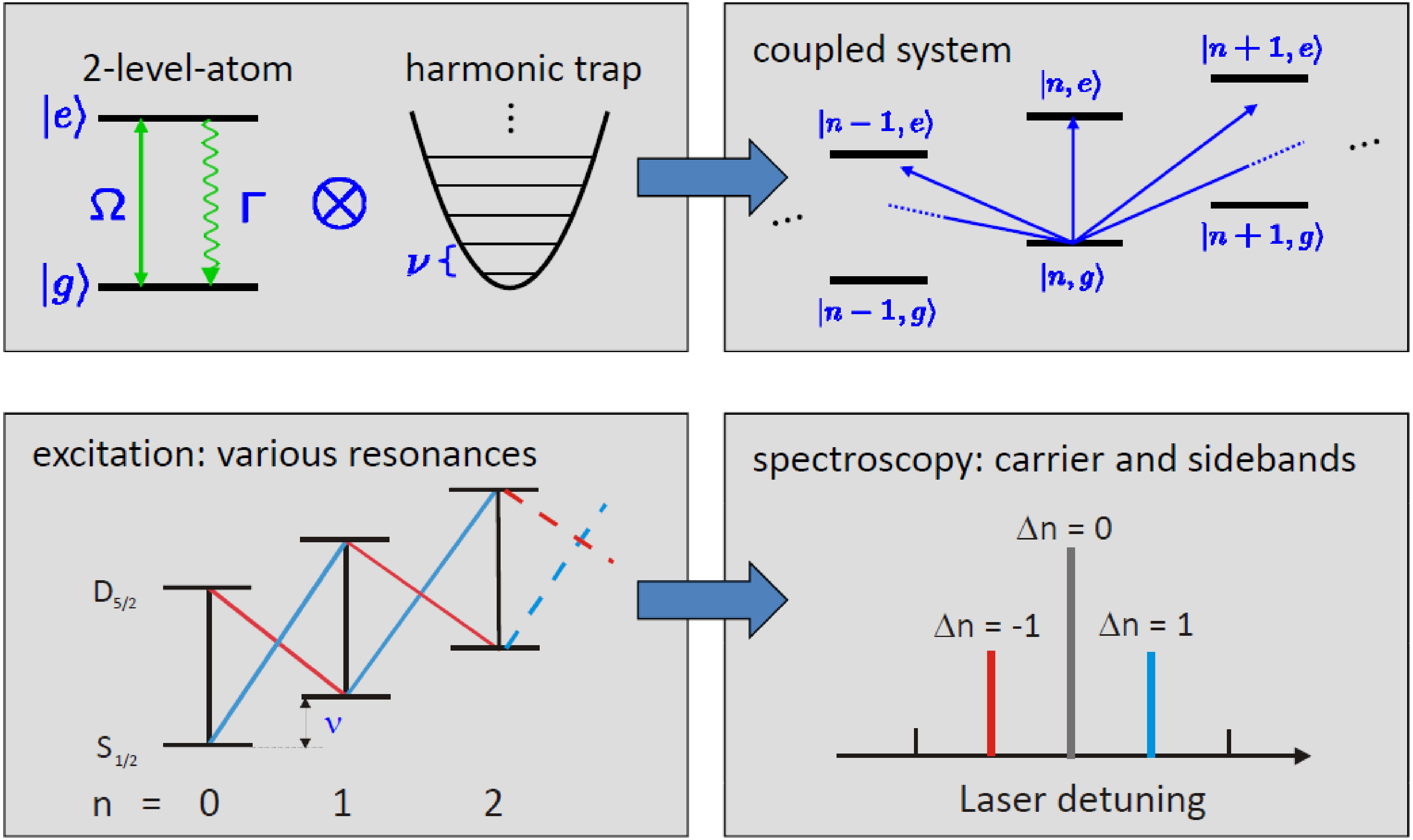
50 experiments / s

Repeat experiments 100-200 times

Detection efficiency → 100 %

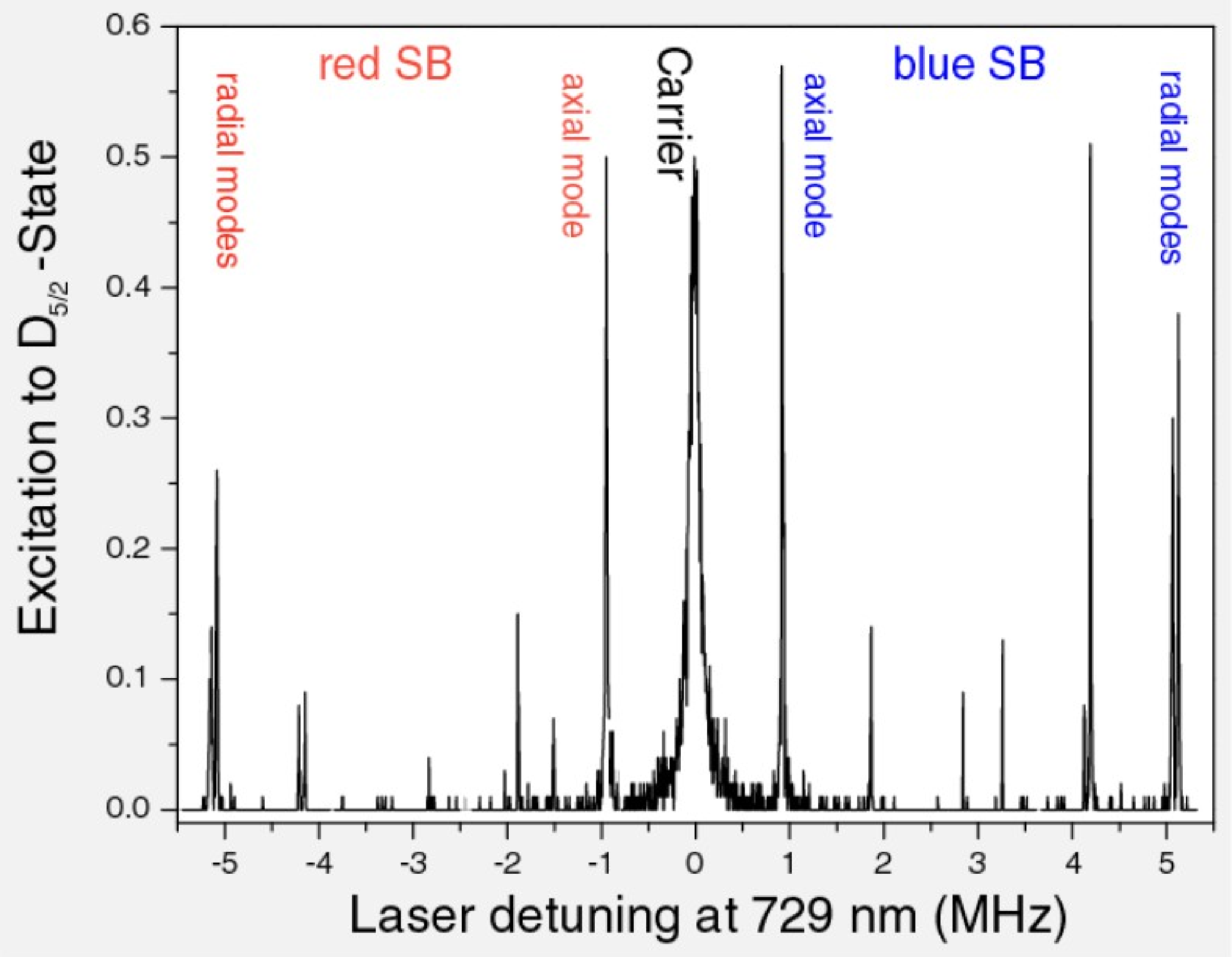
Ion trapping basics

Laser – ion interactions in Lamb-Dicke regime



Ion trapping basics

Excitation spectrum



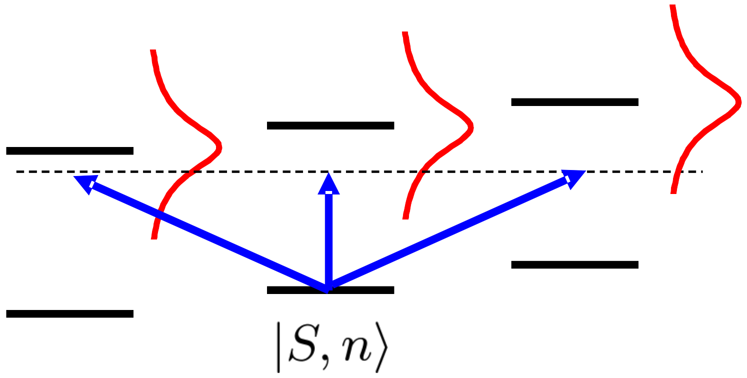
ω_{ax} = 1.0 MHz

ω_{rad} = 5.0 MHz

Ion trapping basics

Laser cooling of ions

Doppler cooling

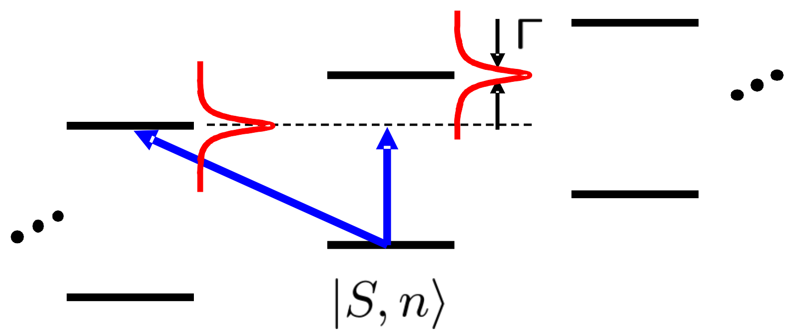


$\nu \ll \Gamma$ **weak** confinement, Doppler cooling

$$\langle n \rangle = \frac{\Gamma}{2\nu} > 1$$

if laser detuned by $\Delta = -\Gamma/2$

Sideband cooling



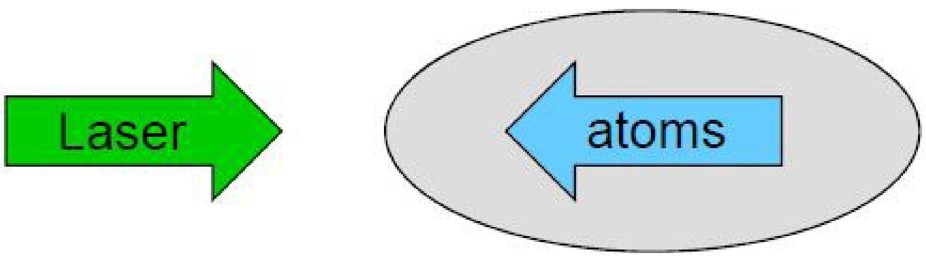
$\nu \gg \Gamma$ **strong** confinement, sideband cooling

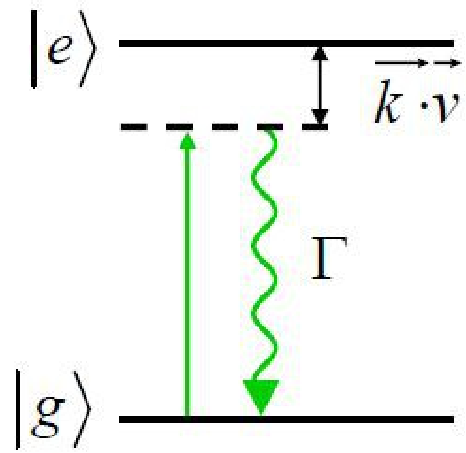
$$\langle n \rangle = \frac{\Gamma^2}{4\nu^2} \ll 1$$

if laser detuned by $\Delta = -\nu$

Ion trapping basics

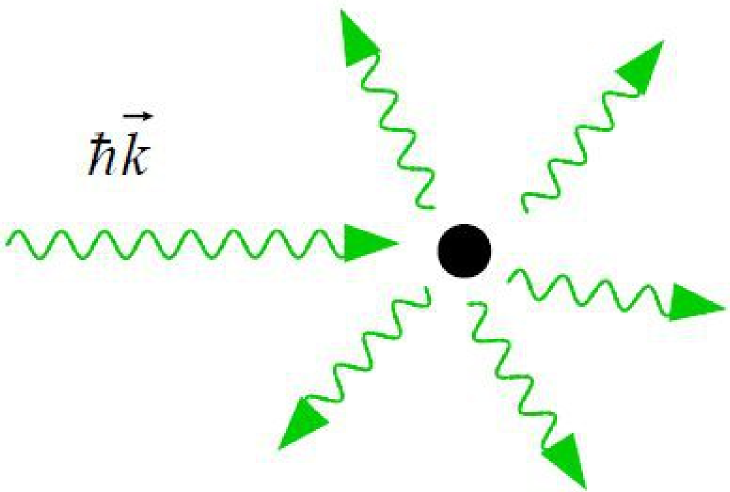
Doppler cooling





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

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

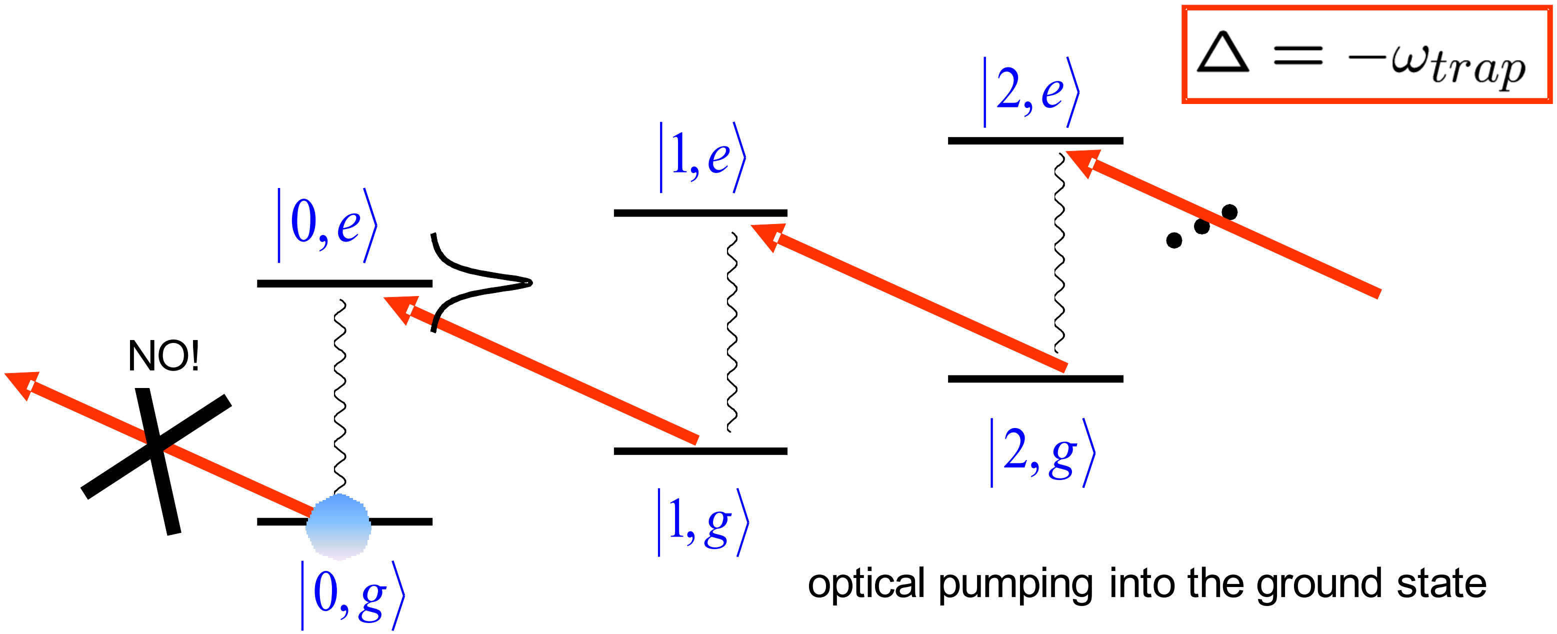


Doppler cooling limit:

$$E_D = \hbar\frac{\Gamma}{2}$$

Ion trapping basics

Sideband cooling

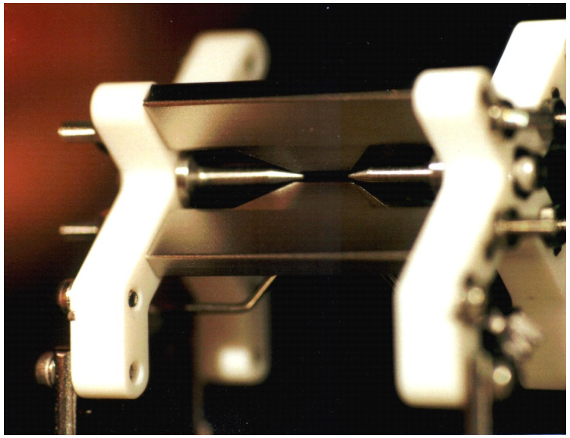


optical pumping into the ground state

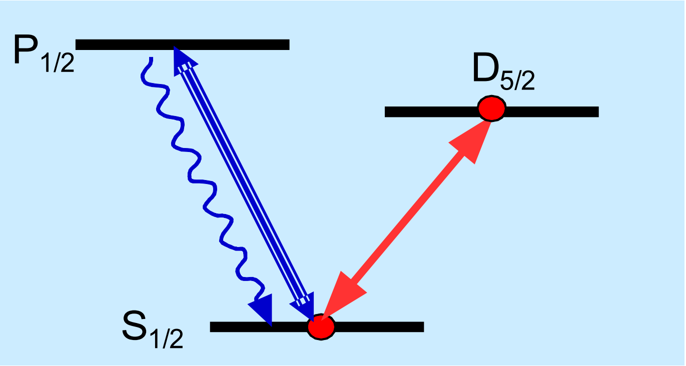
Signature: no further excitation possible
„dark state“ |0>

Summary – ion trapping basics

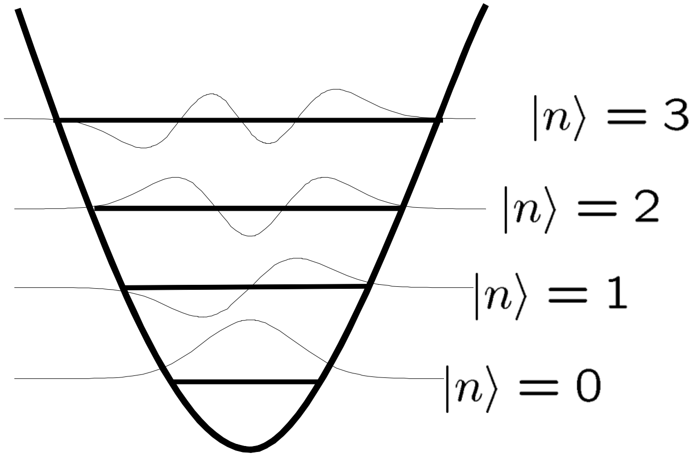
Trapping of charged particles → Paul traps

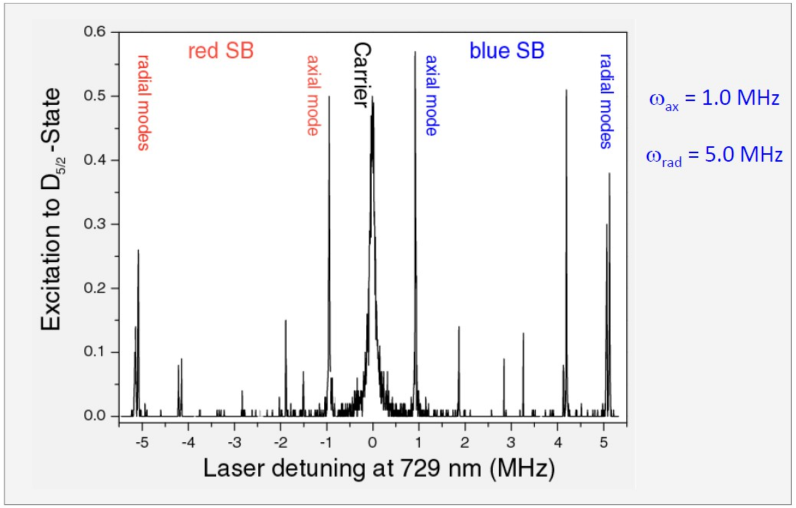


Precise spectroscopy → electron shelving



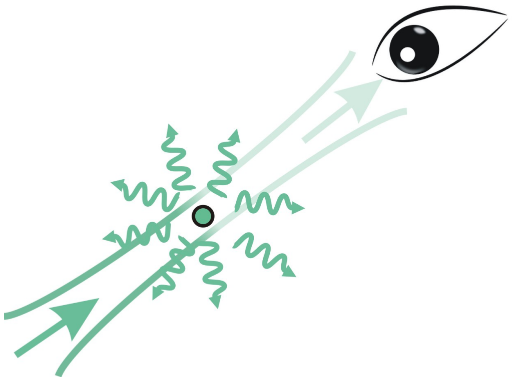
Ion's motion → Quantum harmonic oscillator





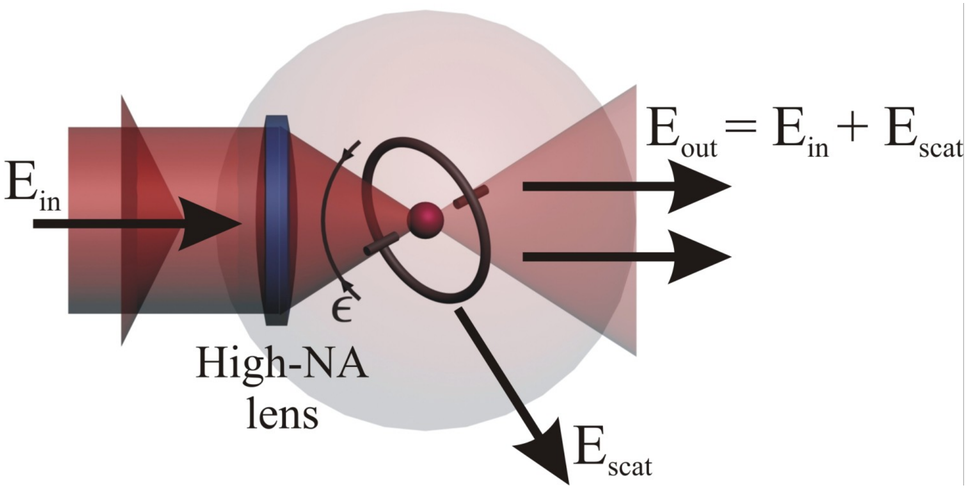
Extinction

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



Extinction

Extinction from single atom in free space



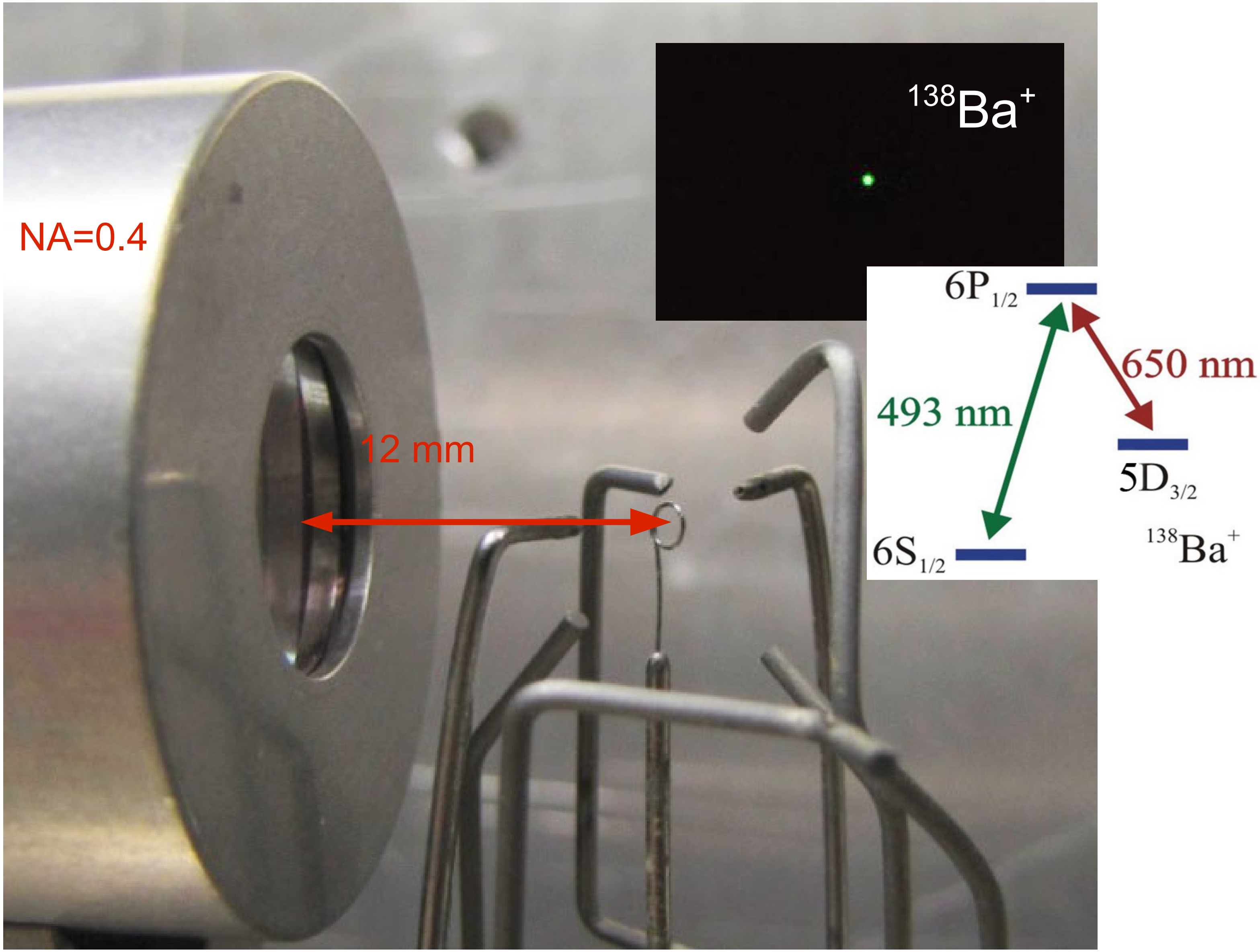
- Destructive interference of scattered and transmited fields!
- In the weak probe limit

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

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

Extinction

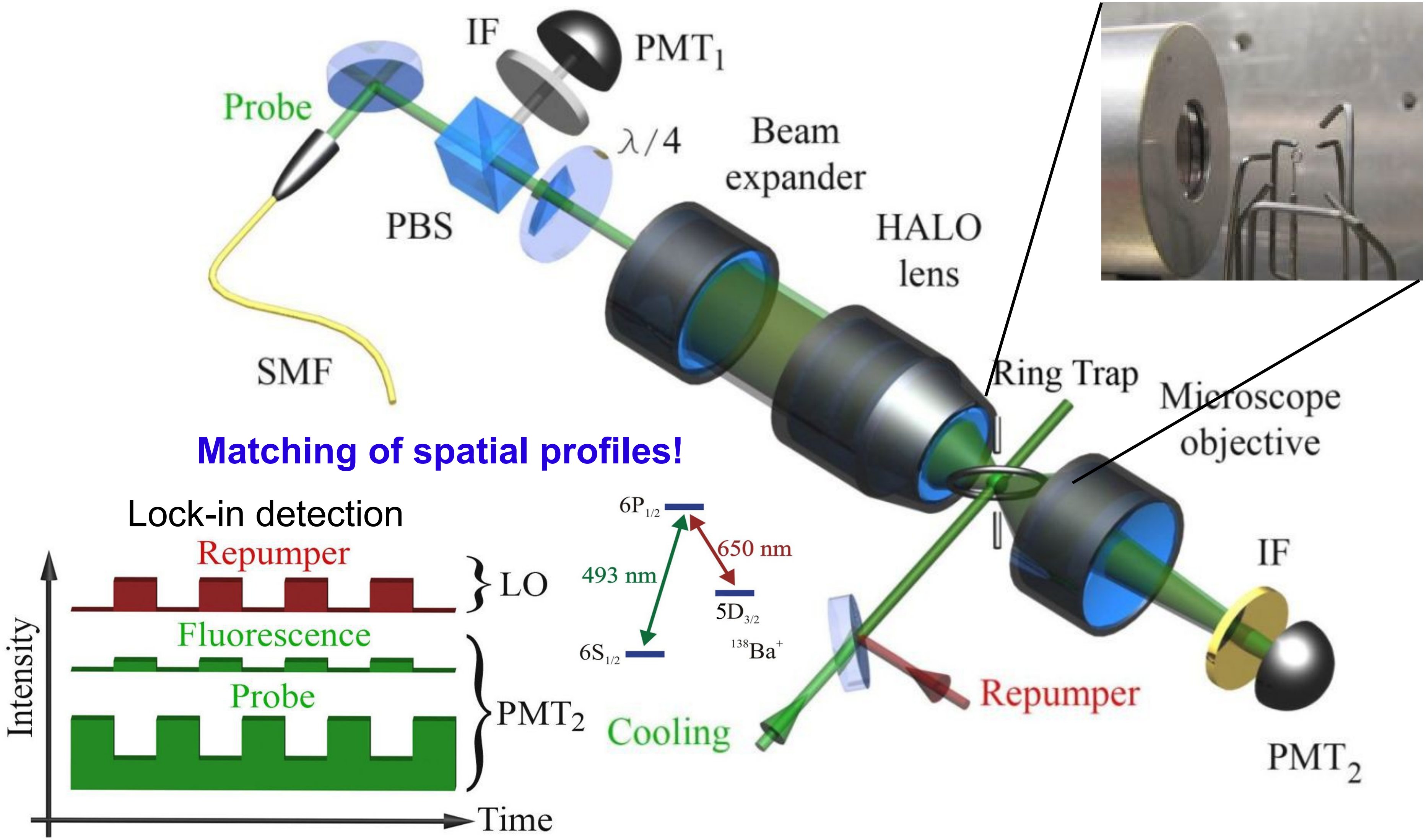
Ring trap



Extinction from single atom in free space

Experimental setup

Matching of spatial profiles!

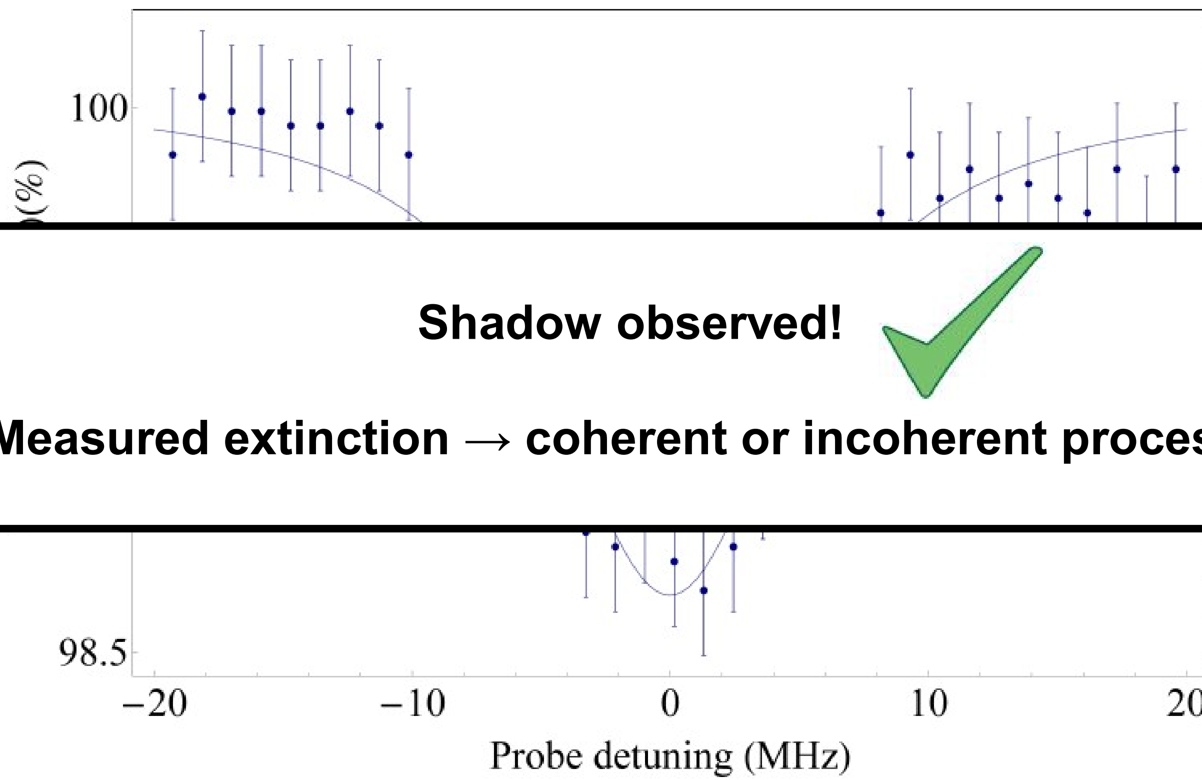


Extinction from single atom in free space

Results

Extinction of 1.35%

Good agreement with our effective solid angle ε~0.01!



Shadow observed!

Measured extinction → coherent or incoherent process?

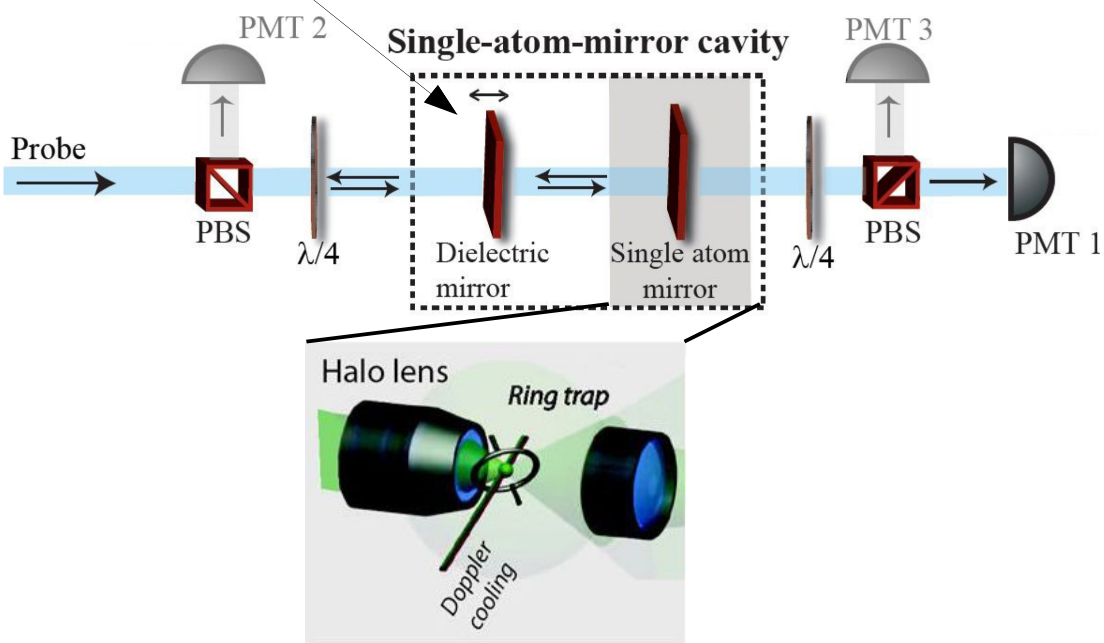
L. Slodička, G. Hétet, S. Gerber, M. Hennrich, and R. Blatt,
Phys. Rev. Lett. **105**, 153604 (2010)

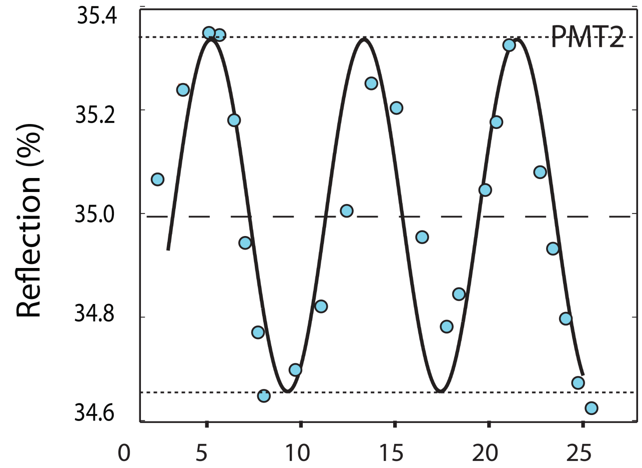
Extinction

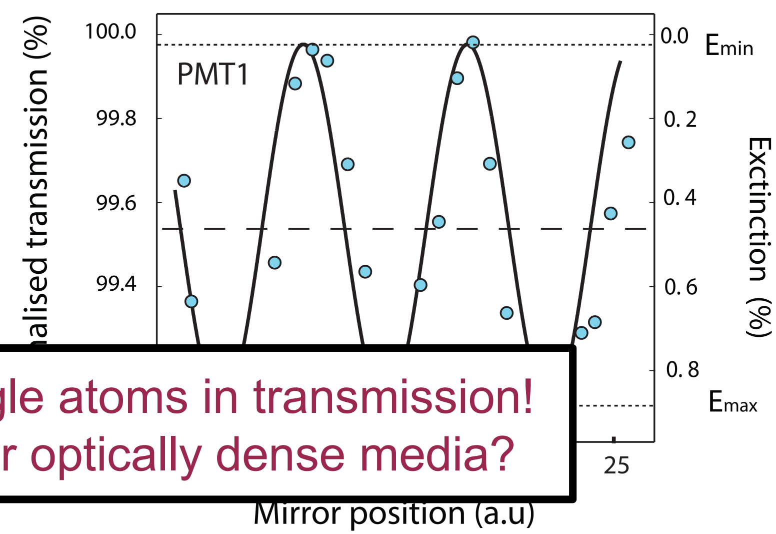
Single-atom-mirror

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?

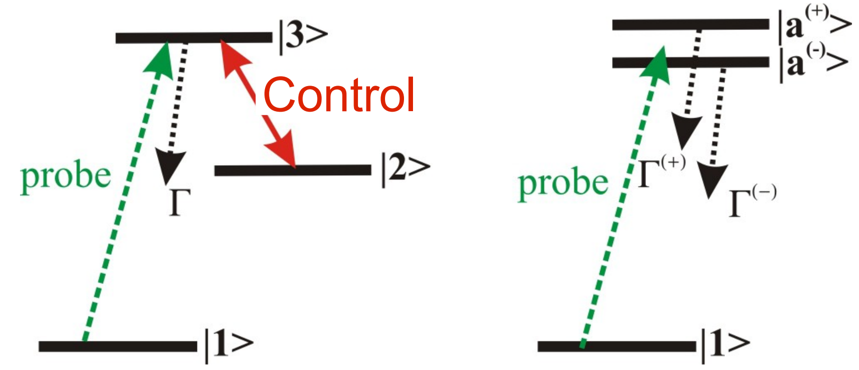
Mergi
and free-space coupling

Extinction

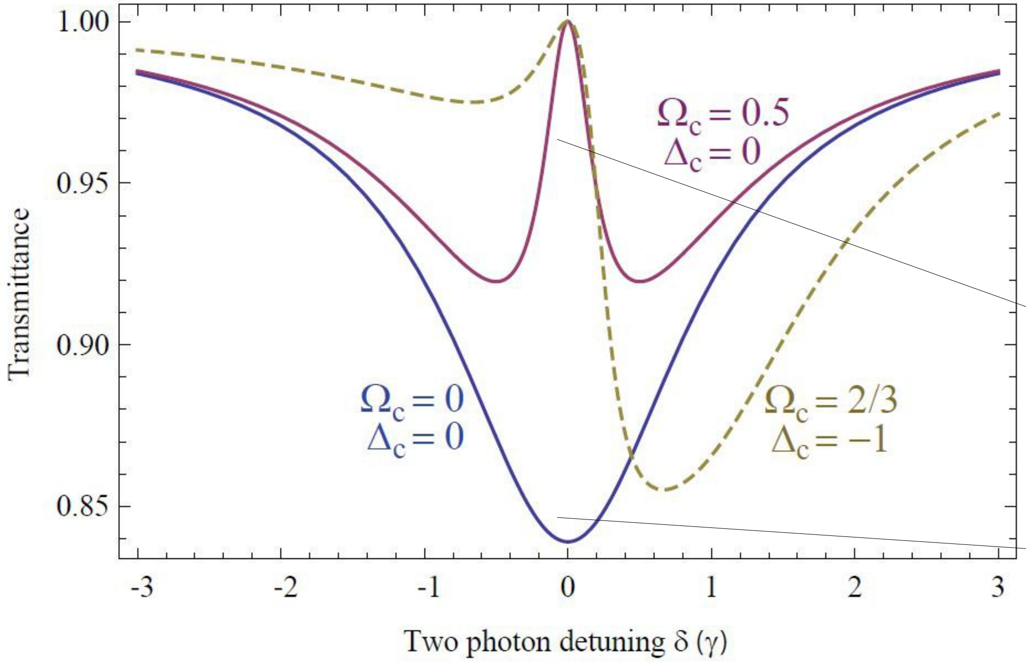
Electromagnetically induced transparency

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

Principle



Interference of two decay channels



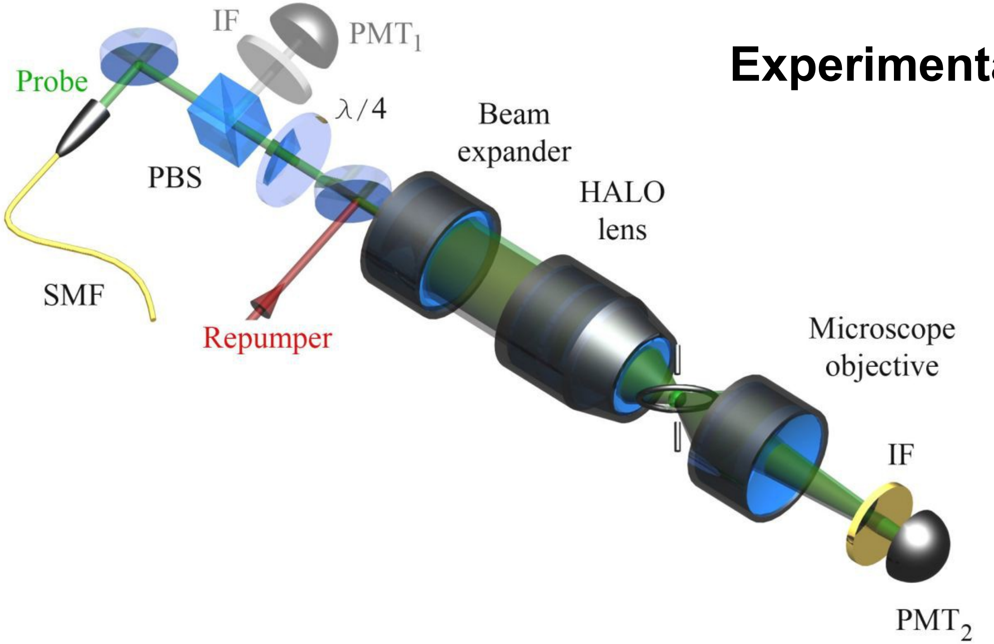
With control beam

EIT window

Without control beam

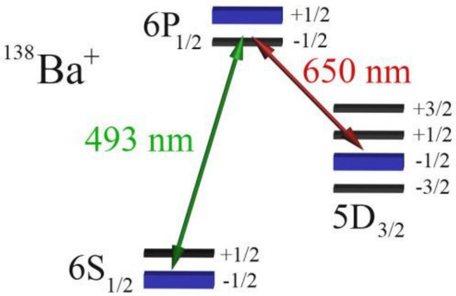
Extinction

Electromagnetically induced transparency

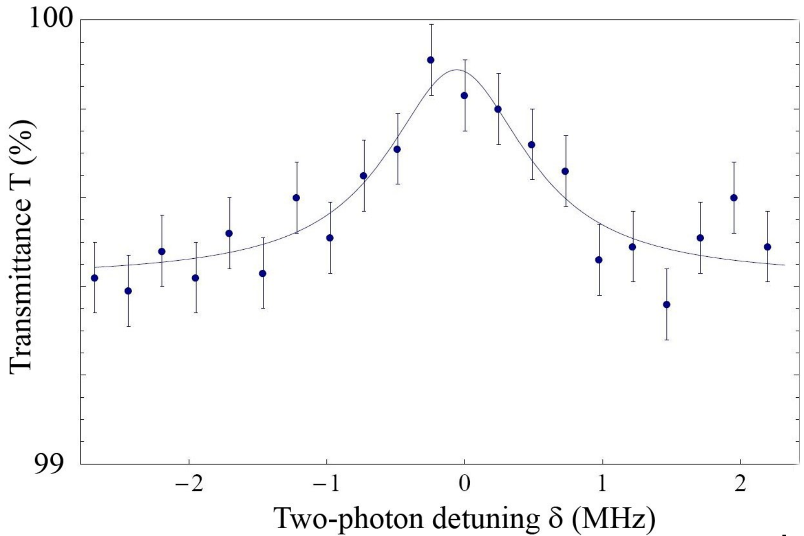


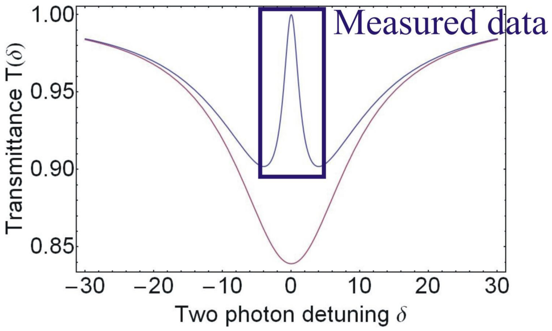
Experimental setup

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



Results





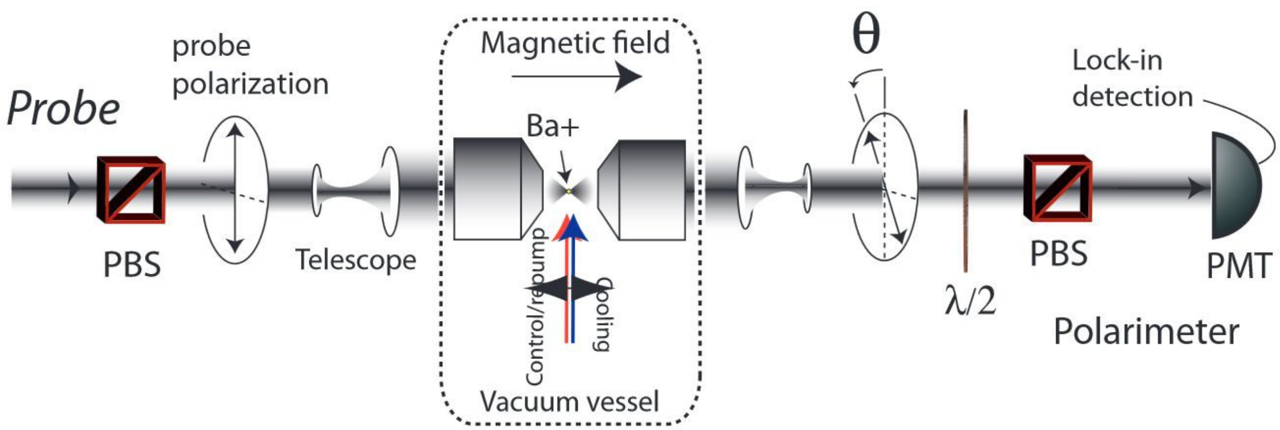
Extinction suppression of 75%
Subnatural linewidth of 1.2MHz

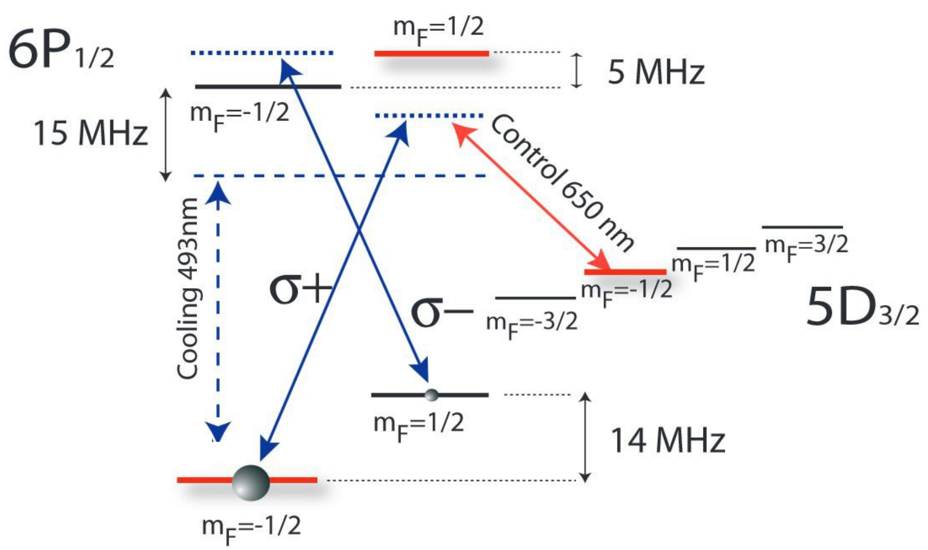
L. Slodička et al., Phys. Rev. Lett. **105**, 153604 (2010)

Extinction

Phase-shift measurements

Experimental setup

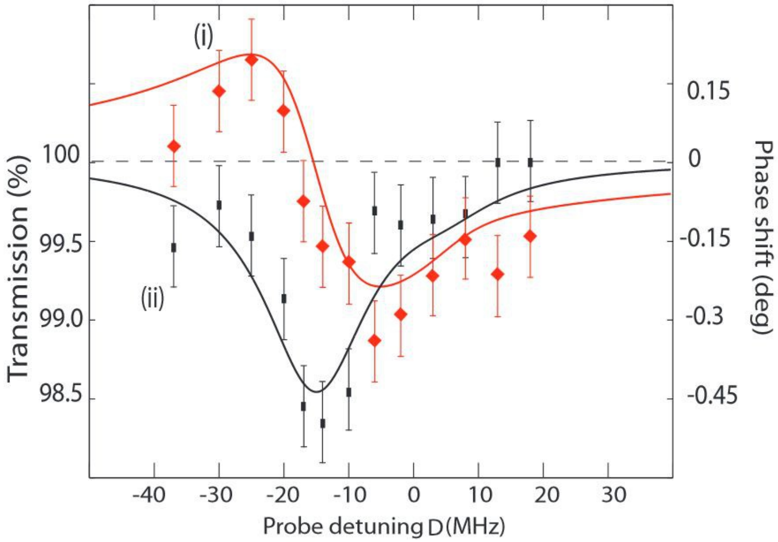




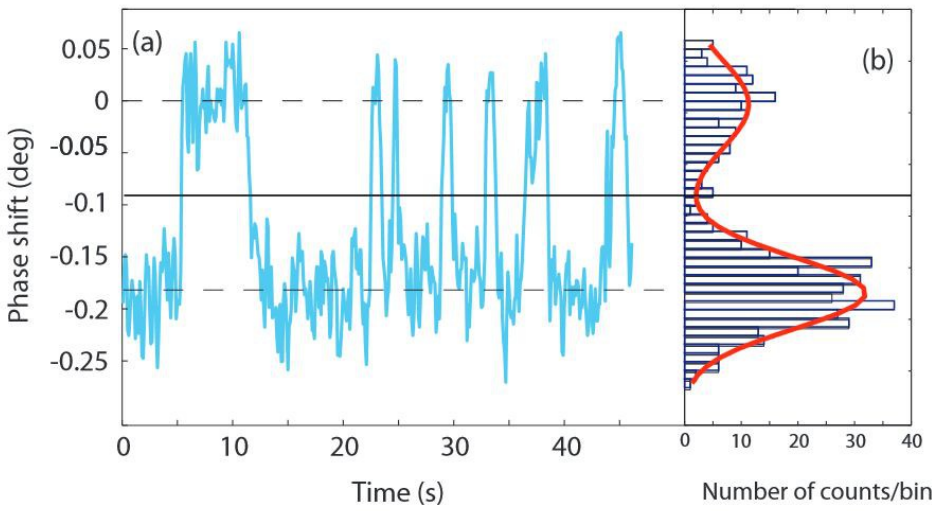
Extinction

Phase-shift measurements

Faraday Rotation



State read-out



We can observe extinction from single atom

Extinction corresponds to a coherent process

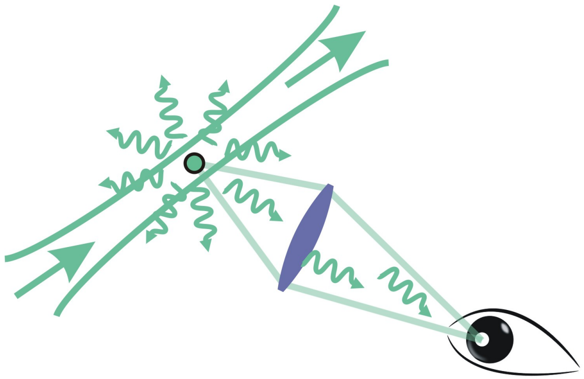
We can manipulate it by control beam using EIT

We can measure phase shift induced by single atom

G. Hétet et al., Phys. Rev. A **88**, 041804 (R) (2013)

Atom-atom entanglement

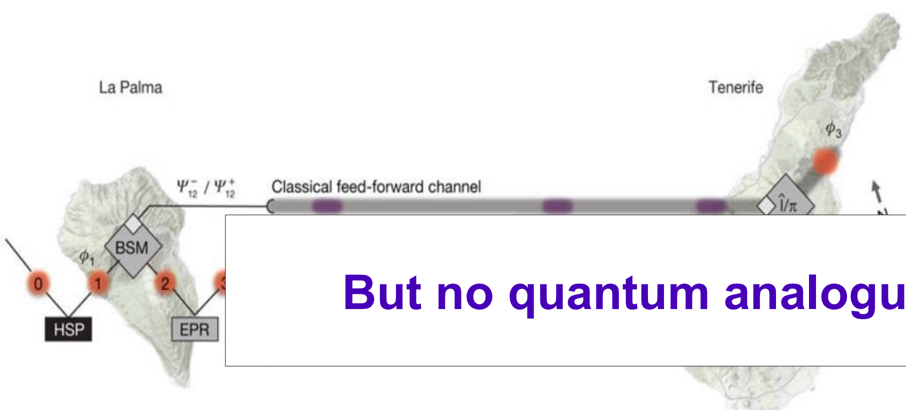
Quantum communication using detection of scattered fluorescence?



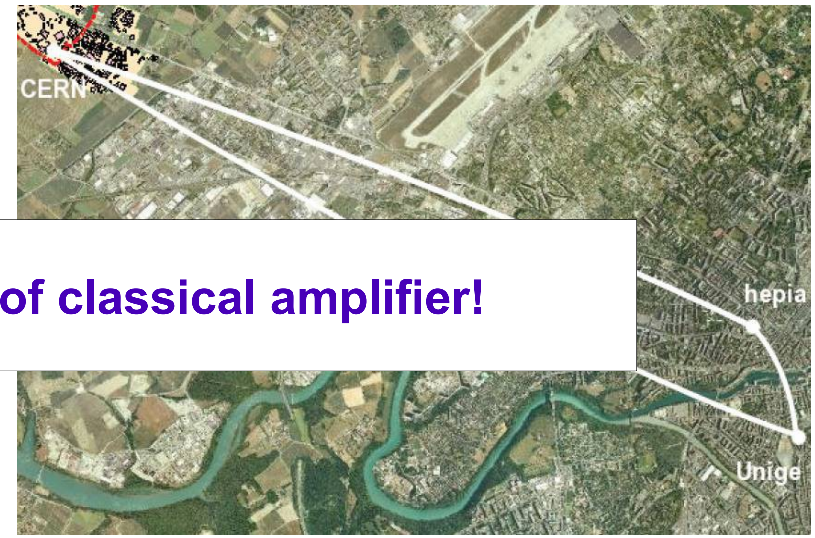
Atom-atom entanglement

Quantum communication

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



Nature **489**, 269–273 (2012)



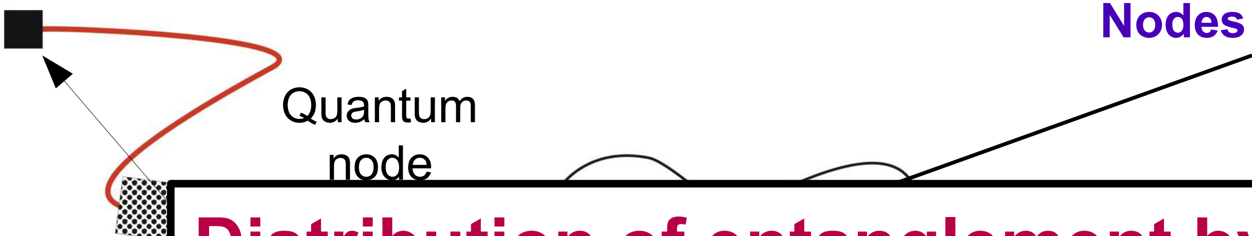
New J. Phys. **13** 123001 (2011)

But no quantum analogue of classical amplifier!

Solution → generation of distant entanglement

Alice

Nodes ~ light-matter interfaces



Quantum node

Not entan

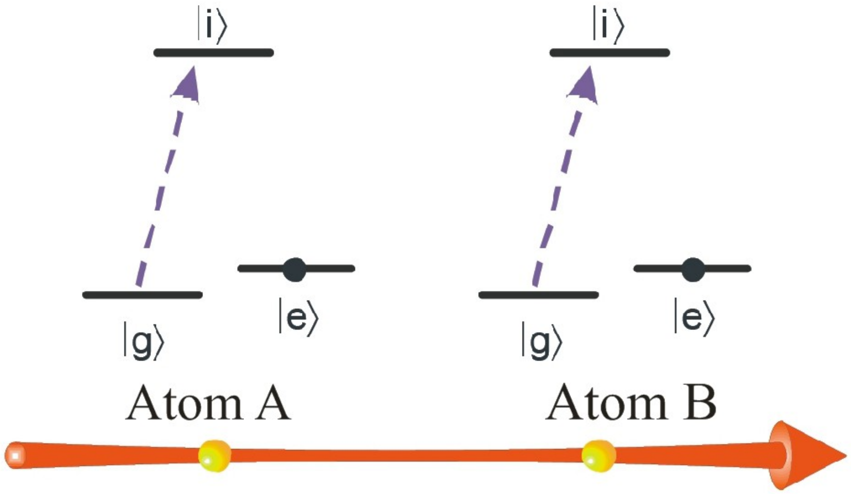
Distribution of entanglement by mere observation of scattered photon?

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:*

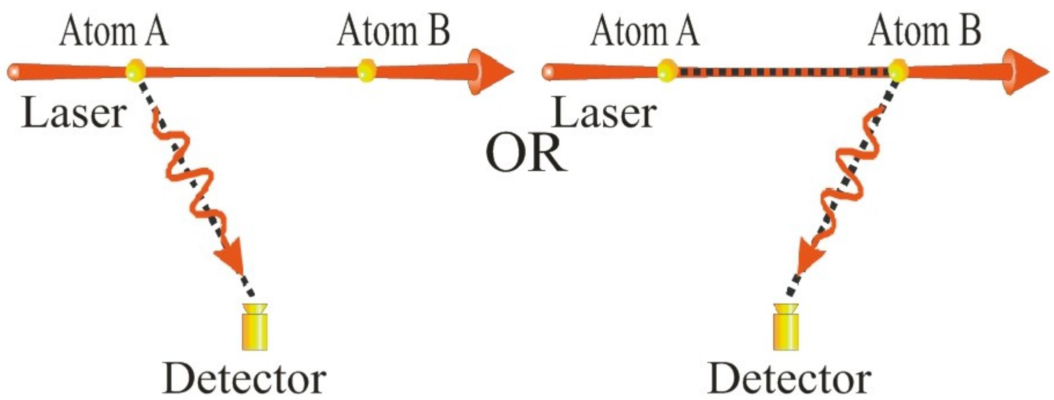
Phase acquired from atom to detector

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:

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

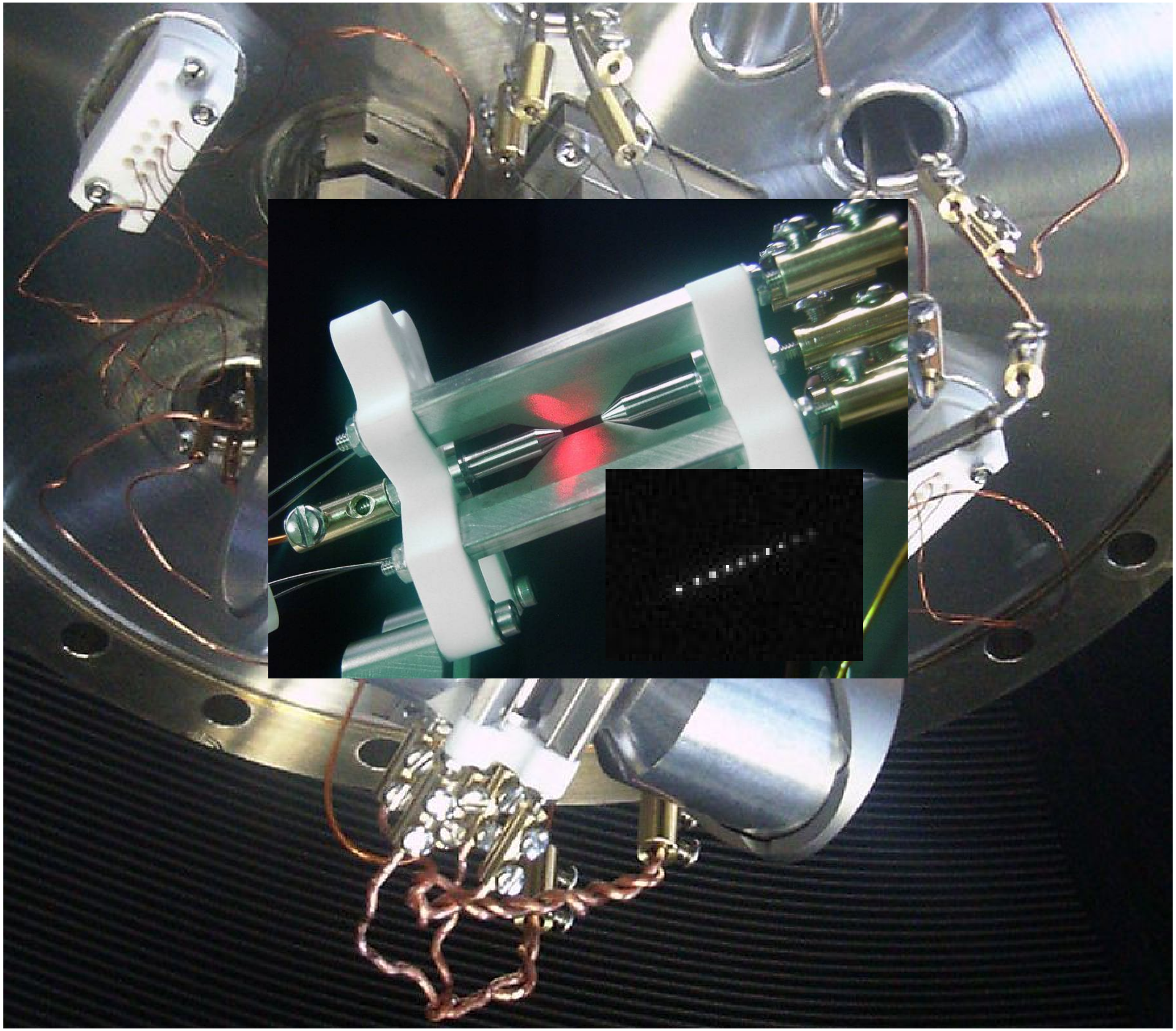
Interference: final entangled state depends on distance between atoms

+

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

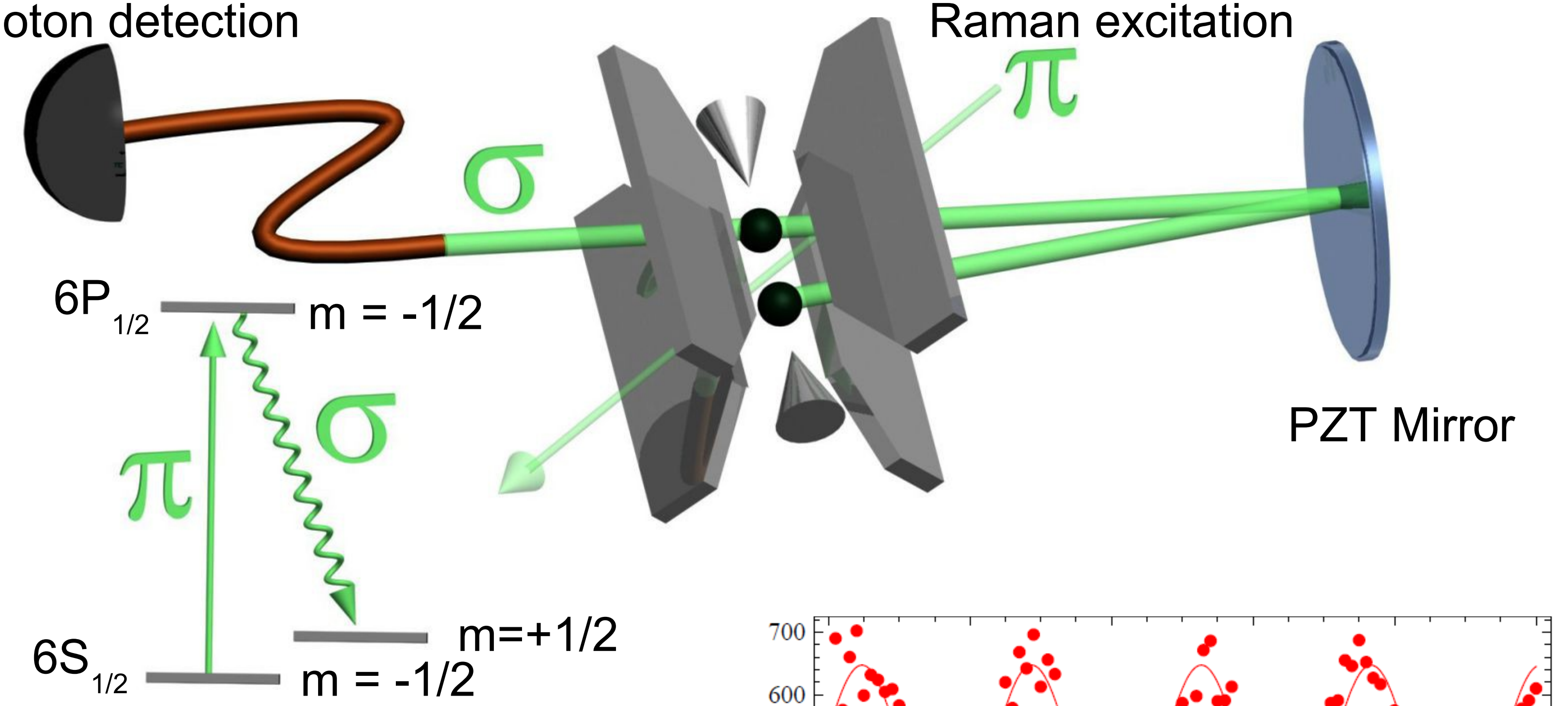
Atom-atom entanglement

Linear trap

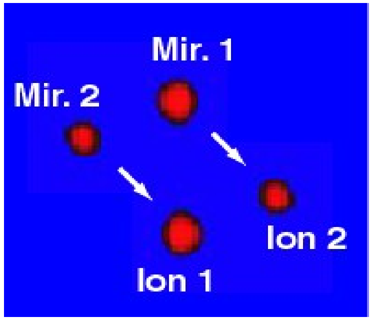


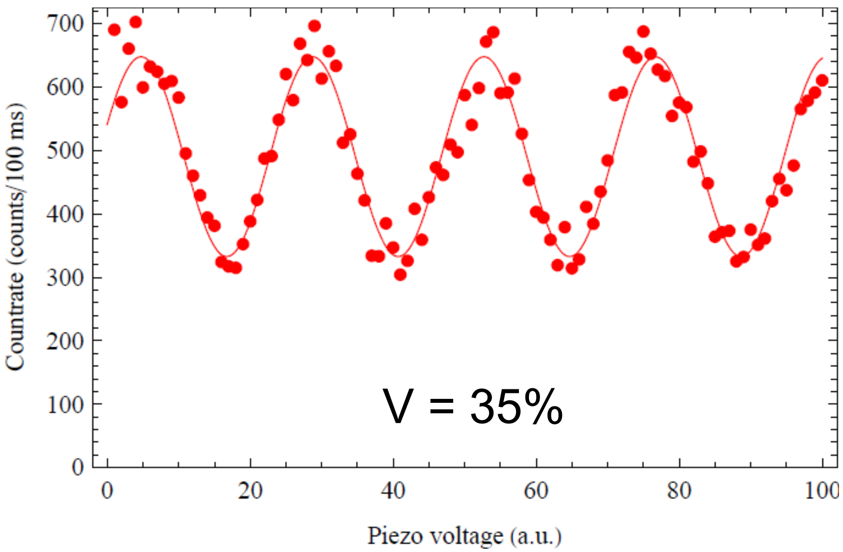
Atom-atom entanglement

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**

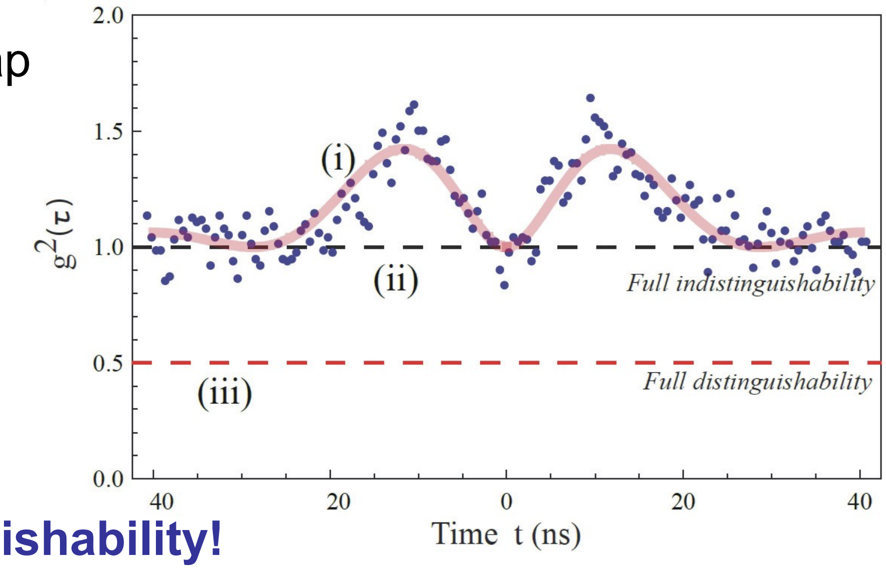
$$g^{(2)}_{\mathrm{Tot}}(\tau) = \frac{1}{2}(g^{(2)}(\tau) + |\vec{e_1}\vec{e_2}|^2 |g^{(1)}(\tau)|^2 + 1)$$

mode overlap

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

single-ion functions

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



Good spatial and polarization indistinguishability!

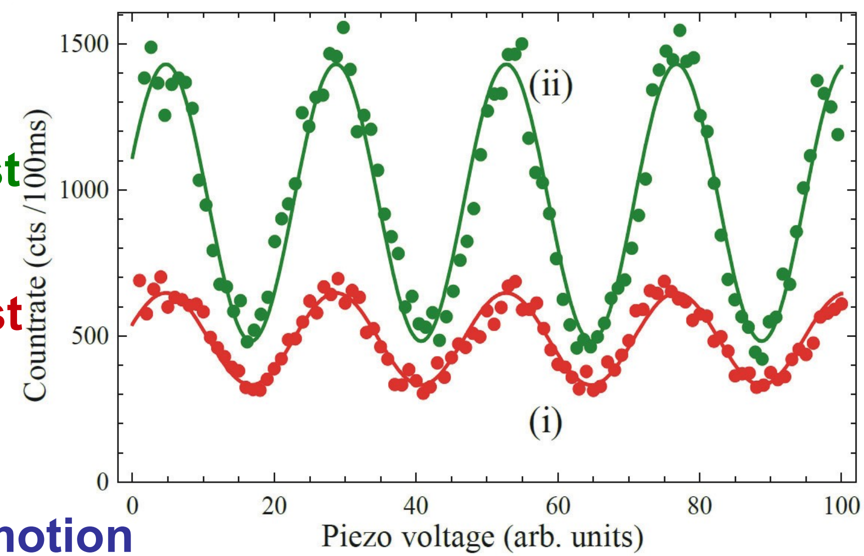
- **1st order coherence**

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

Mean atomic wavepacket extent

Single ion ~ 60% contrast

Two ions ~ 35 % contast



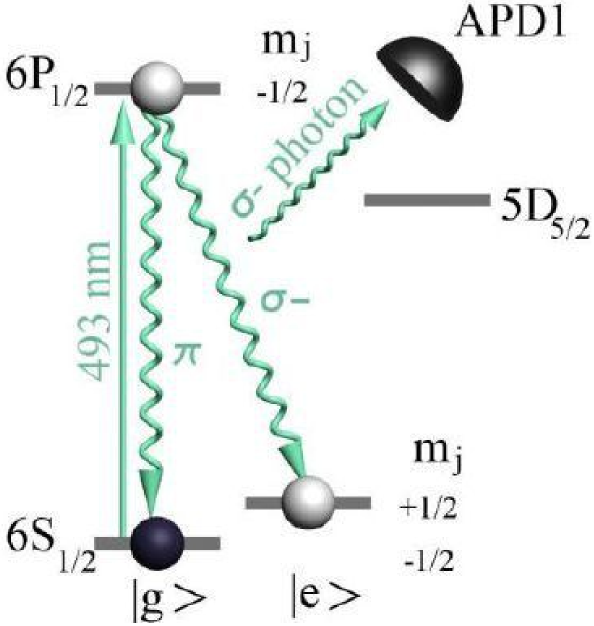
Main source of distinguishability ~ atomic motion

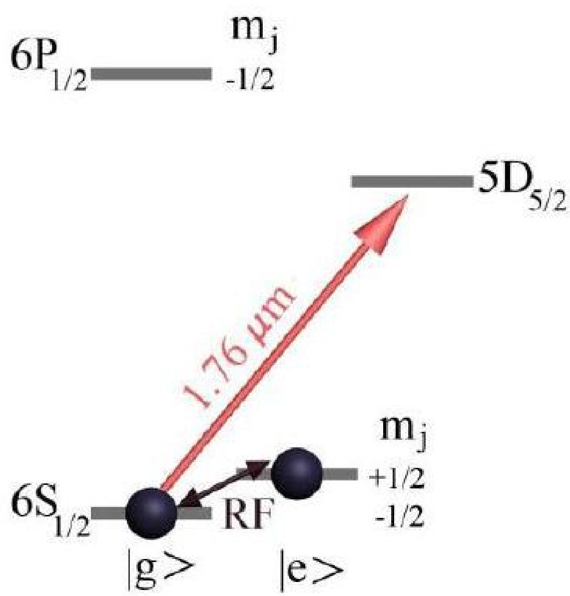
→ excitation along the detection direction

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

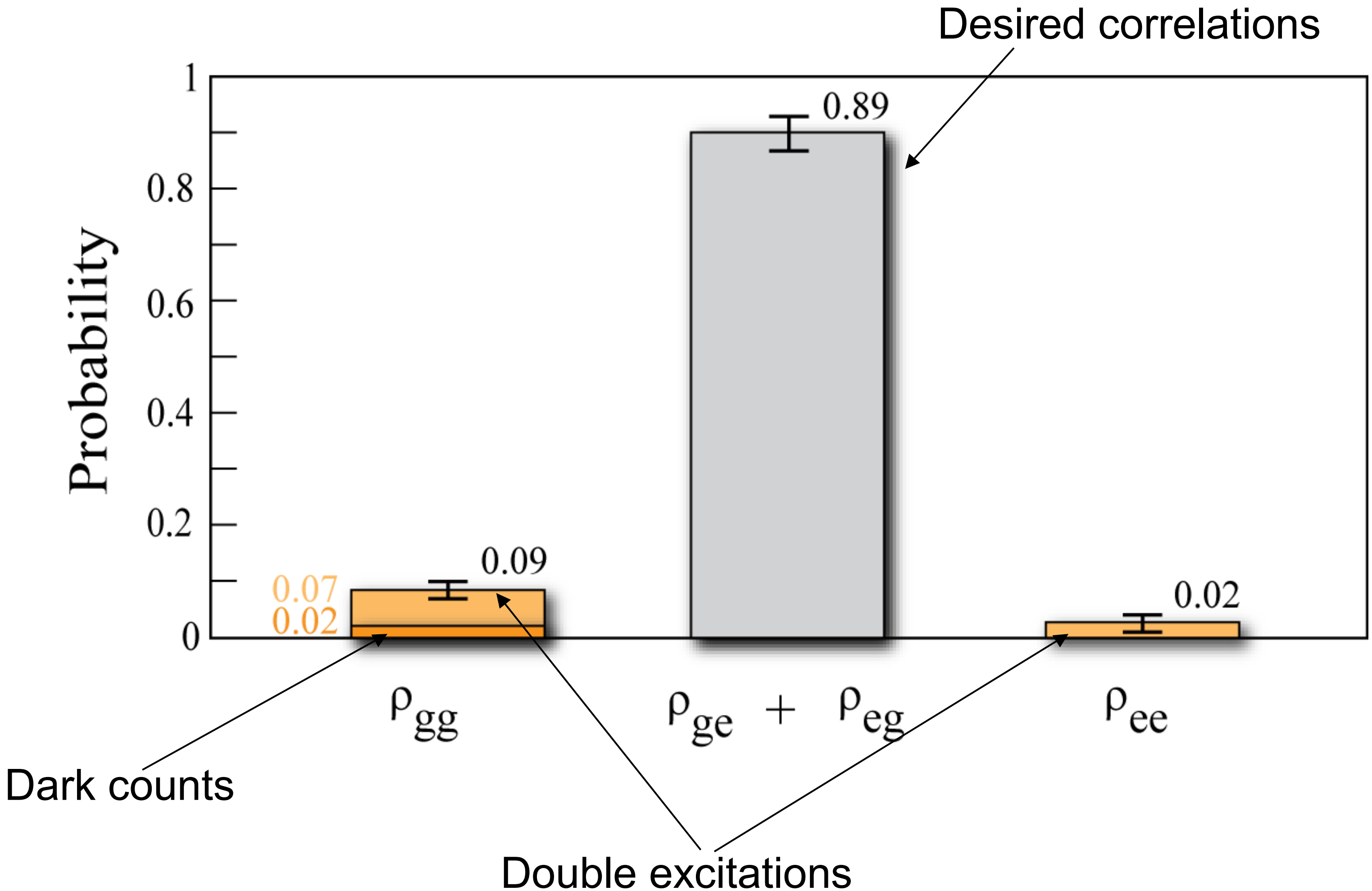
$$F = \langle \Psi^+ | \rho | \Psi^+ \rangle = \frac{1}{2}\left[\rho_{ge} + \rho_{eg} + 2\mathrm{Re}(\rho_{eg,ge})\right]$$

Measured directly (electron shelving) Parity measurement

Atom-atom entanglement

Measurement results

Populations - diagonal elements

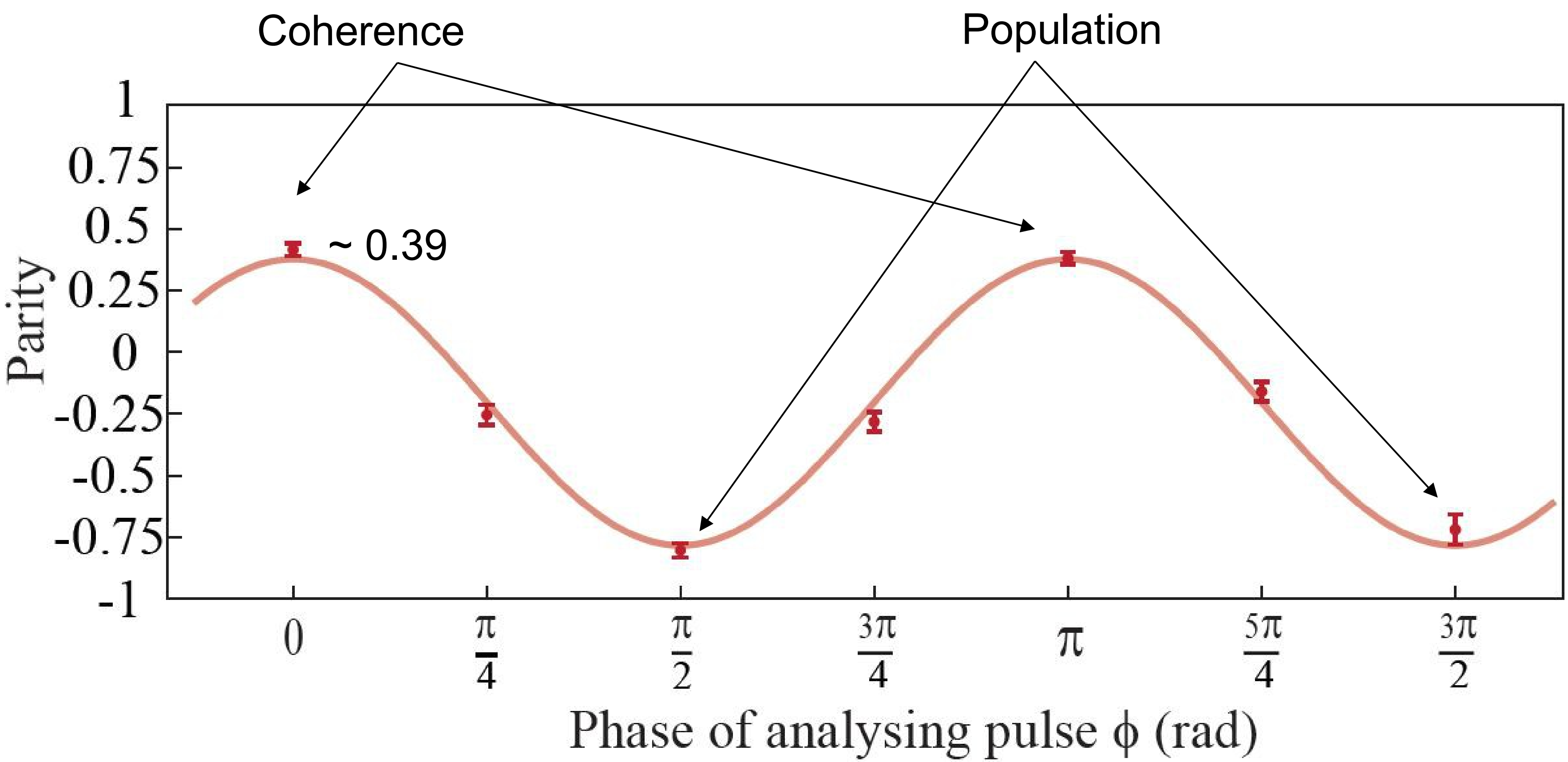


In 89% of the cases correct correlation between atomic states

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**:

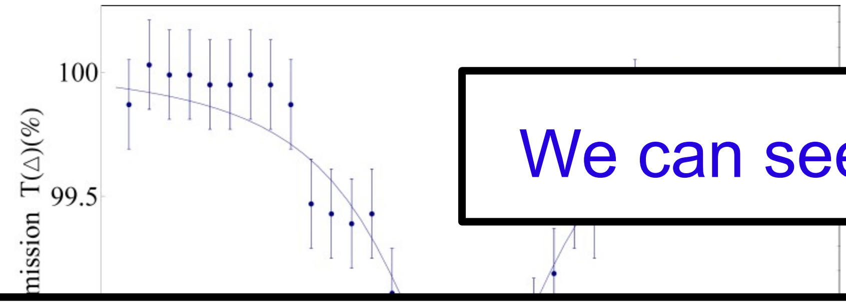
  1 photon is easier to detect than 2!

  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



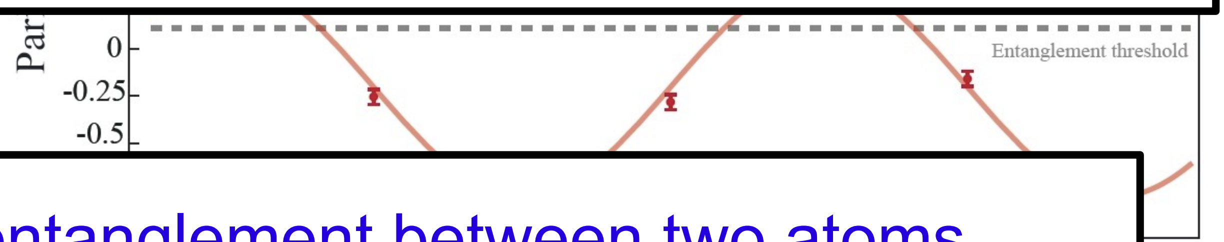
We can see the “shadow“ of a single atom!

Other recent work:

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

Single ion single photon source

...



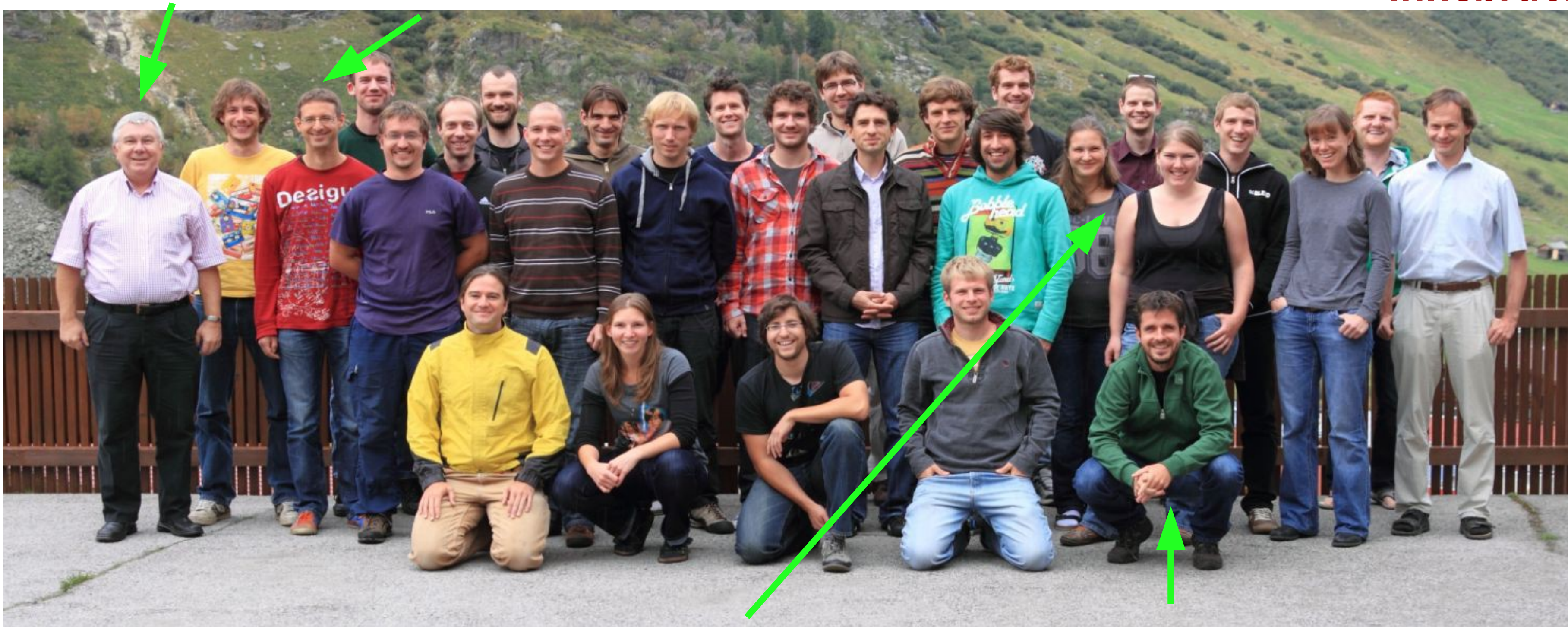
We can generate entanglement between two atoms by mere observation of single photon scattering!

Our group

Innsbruck

Rainer Blatt

Markus Hennrich



Nadia Röck

Gabriel Hétet

Olomouc

Miroslav Ježek

Michal Mičuda

Martina Miková

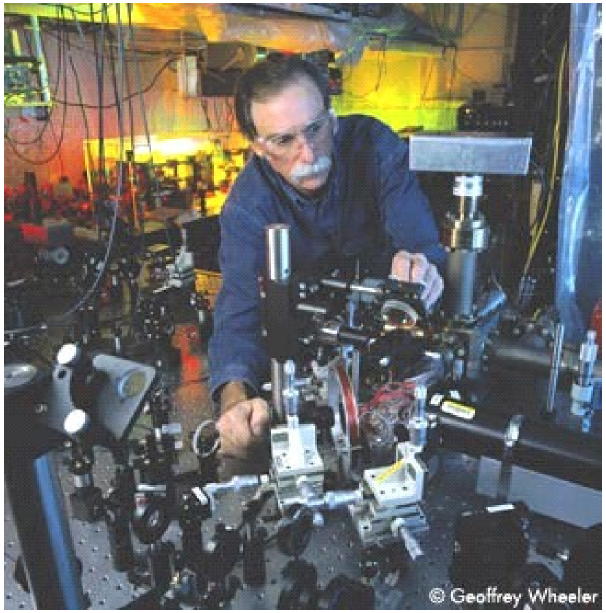
Ivo Straka

Miloslav Dušek

Radim Filip

Jaromír Fiurášek

D. Wineland (NIST)



“Ion trappers are encouraged because we can at least see a straightforward path to making a large processor, but the technical problems are extremely challenging. It might be fair to say that ion traps are currently in the lead; however, a good analogy might be that we’re leading in a marathon race, but only one metre from the start line.”

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 $$\hat{\rho} = \begin{pmatrix} \rho_{gg} & \rho_{gg,eg} & \rho_{gg,ge} & \rho_{gg,ee} \\ \rho^*_{gg,eg} & \rho_{eg} & \rho_{eg,ge} & \rho_{eg,ee} \\ \rho^*_{gg,ge} & \rho^*_{eg,ge} & \rho_{ge} & \rho_{ge,ee} \\ \rho^*_{gg,ee} & \rho^*_{eg,ee} & \rho^*_{ge,ee} & \rho_{ee} \end{pmatrix}$$

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

Populations Coherences

- We measure:

Populations ~ directly (electron shelving)

Coherences ~ the value of parity operator for collective RF rotations $\mathrm{R}(\theta,\phi)$

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

Phase of the pulse

Amplitude of the pulse

Atom-atom entanglement

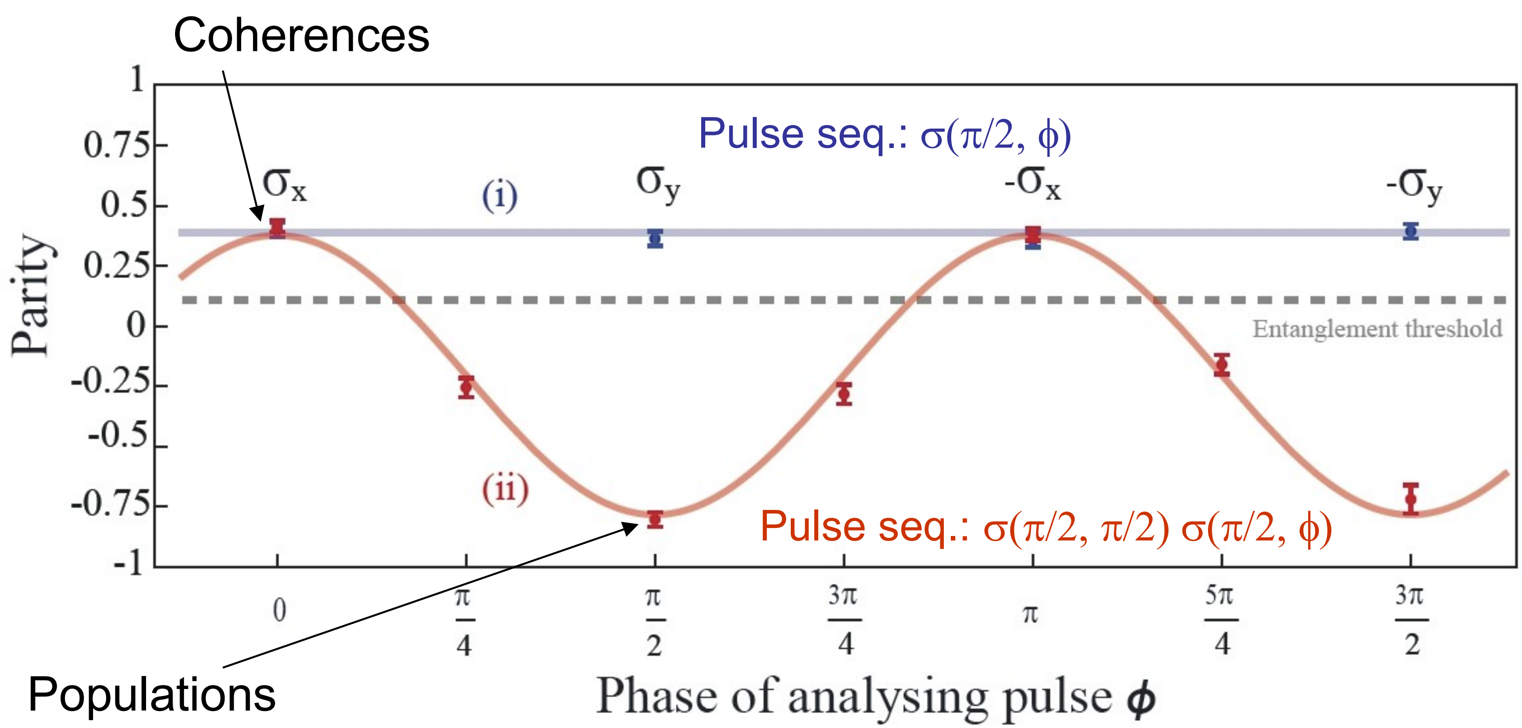
Measurement results

Off diagonal elements - coherences

- We first rotate the output so that

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

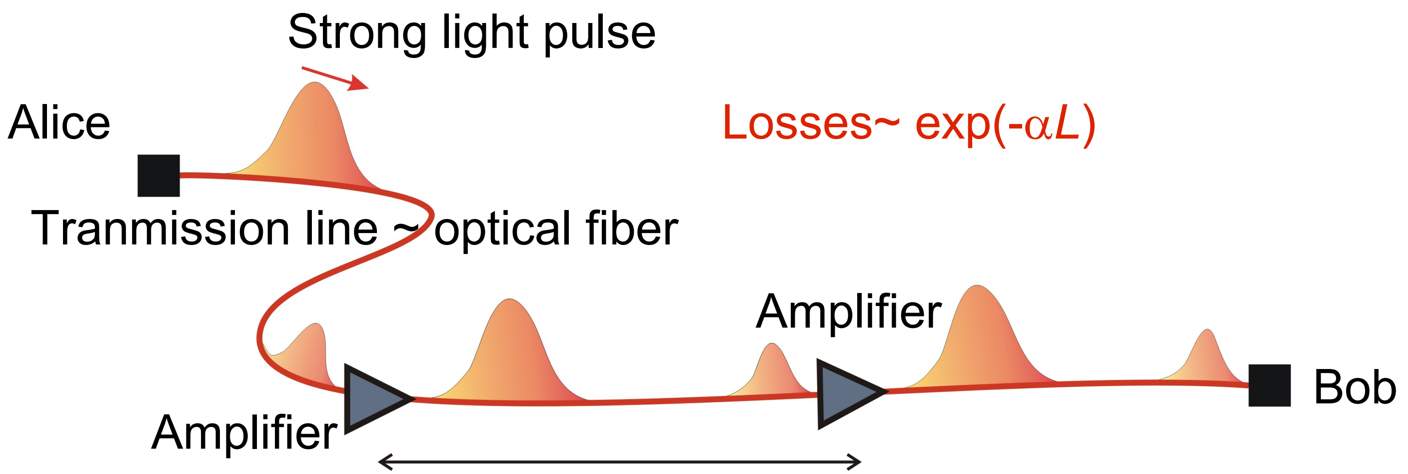
- Parity signal oscillates when applying R(π/2,ϕ) rotation on this state



Measured parity contrast ≈ 58%

Atom-atom entanglement
Motivation

Classical communication



Works well, but quantum physics can offer us more!

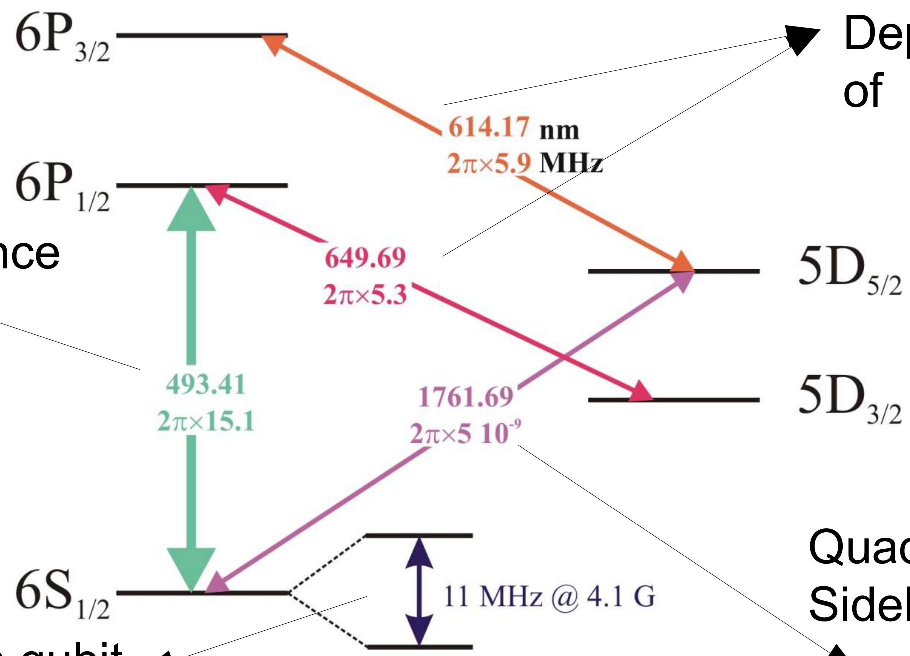
- Absolutely secure communication (Quantum cryptography)
- Faithful transfer of unknown quantum state (Quantum teleportation)

Overview

$^{138}Ba^+$

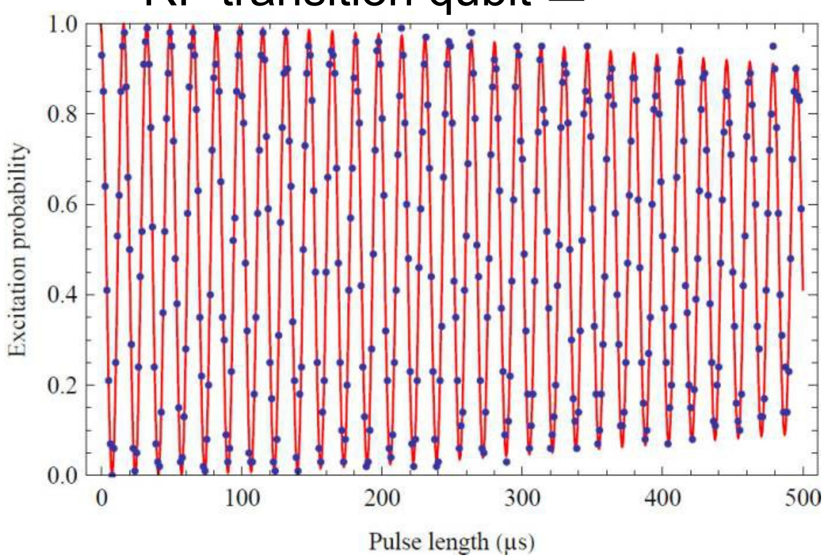
Depopulation of long lived states

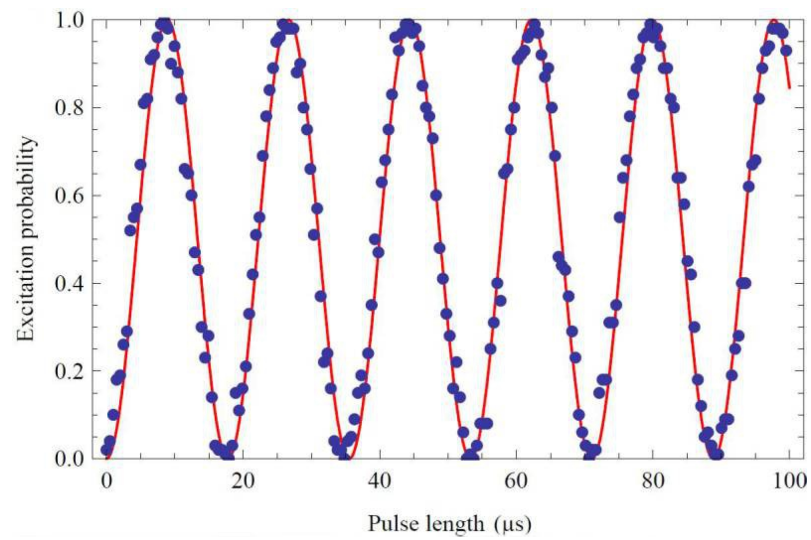
Resonance fluorescence
Doppler cooling
State initialization
State detection



Quadrupolar transition qubit
Sideband cooling

RF transition qubit

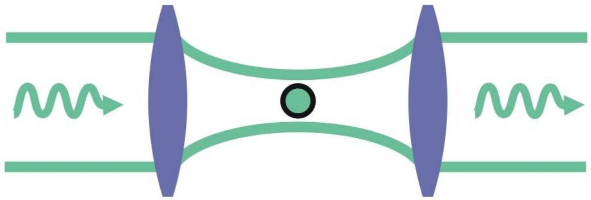




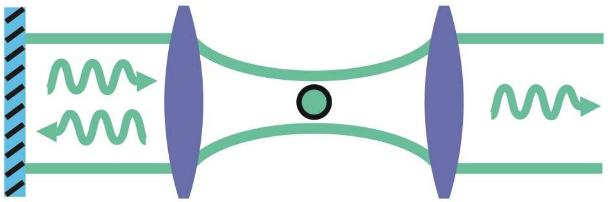
Overview

Single atom in free space

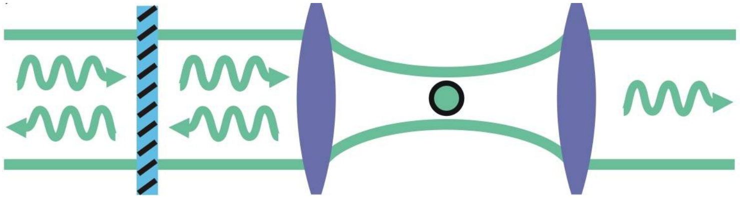
Free space extinction



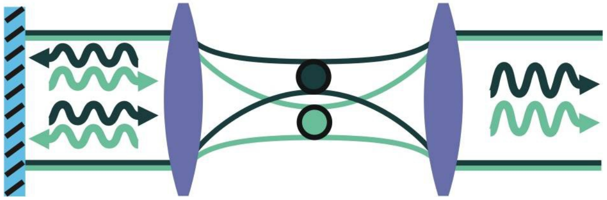
Half-cavity setup



Single-atom mirror



Atom-atom entanglement



Phase interference of scattered light!