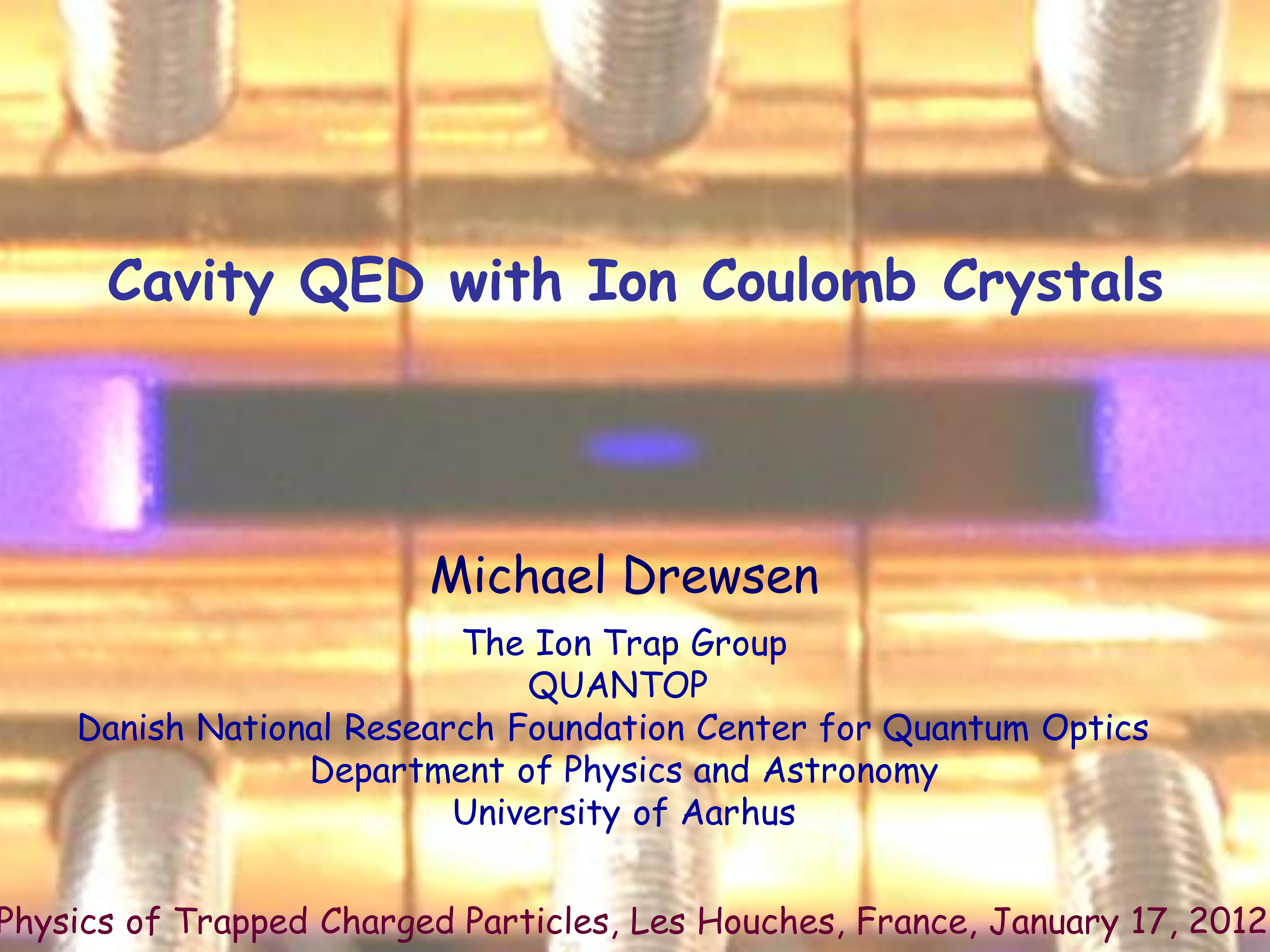


Cavity QED with Ion Coulomb Crystals

Michael Drewsen

The Ion Trap Group
QUANTOP
Danish National Research Foundation Center for Quantum Optics
Department of Physics and Astronomy
University of Aarhus

Physics of Trapped Charged Particles, Les Houches, France, January 17, 2012

Why cavity QED with ion Coulomb crystals ?

I) Quantum information:

Stable and faithful light-matter interfaces for coupling of flying and stationary qubits

I) Single photon sources
II) Quantum memories
III) Quantum repeaters

II) Cavity optomechanics:

I) Cavity mediated cooling of at. and mol. ion
II) Cavity optomechanics with Coulomb crystals
III) Simulations of systems based on usual solids

III) Plasma physics:

A tool to investigate the properties of strongly coupled one component plasmas (OCPs).

Outline

I) Brief introduction to ion Coulomb crystals

II) Cavity Quantum ElectroDynamics (CQED) in short

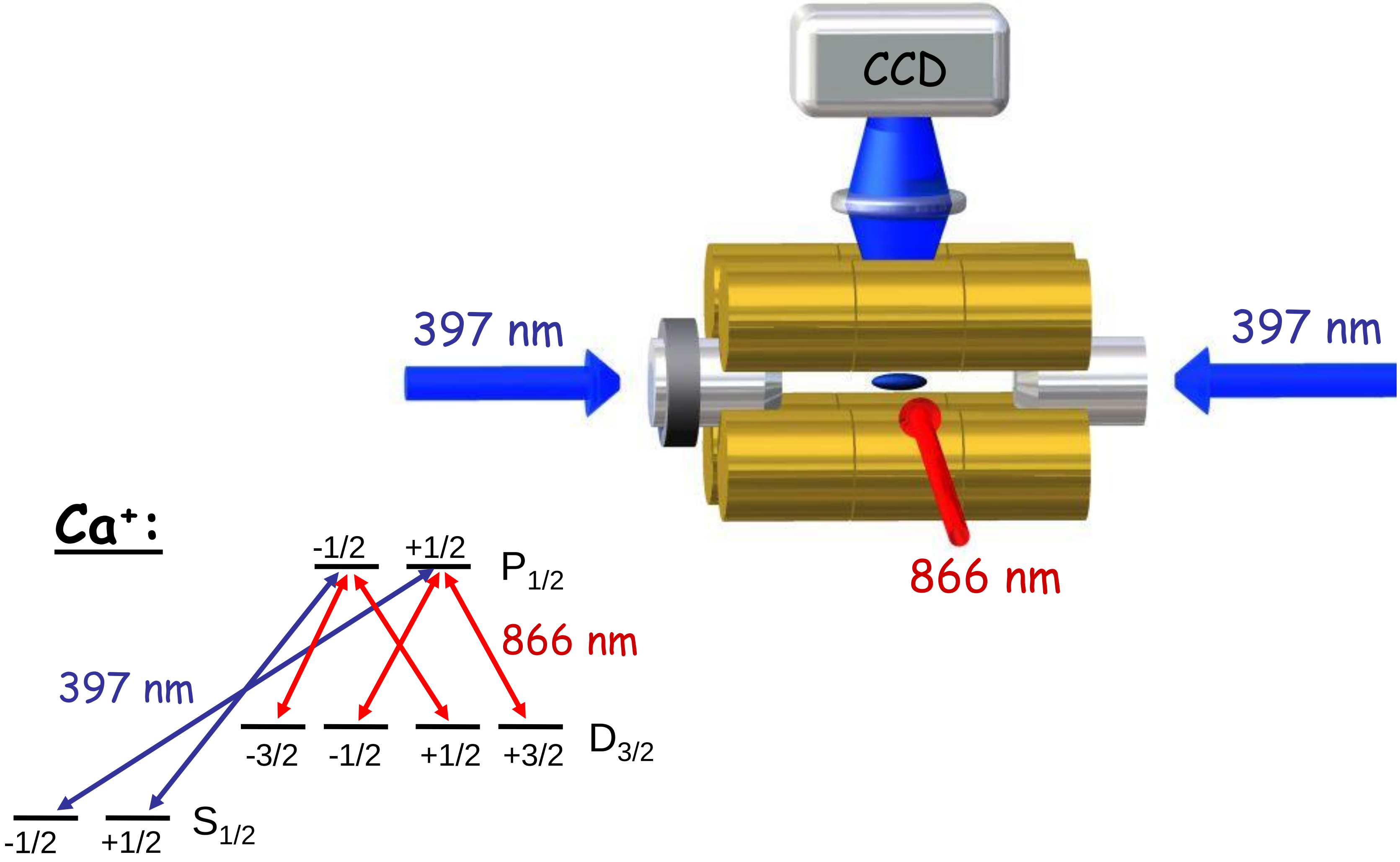
III) CQED experiments with Coulomb crystals

- Collective strong coupling
- Cavity EIT
- Cross Kerr effect and photon blockade

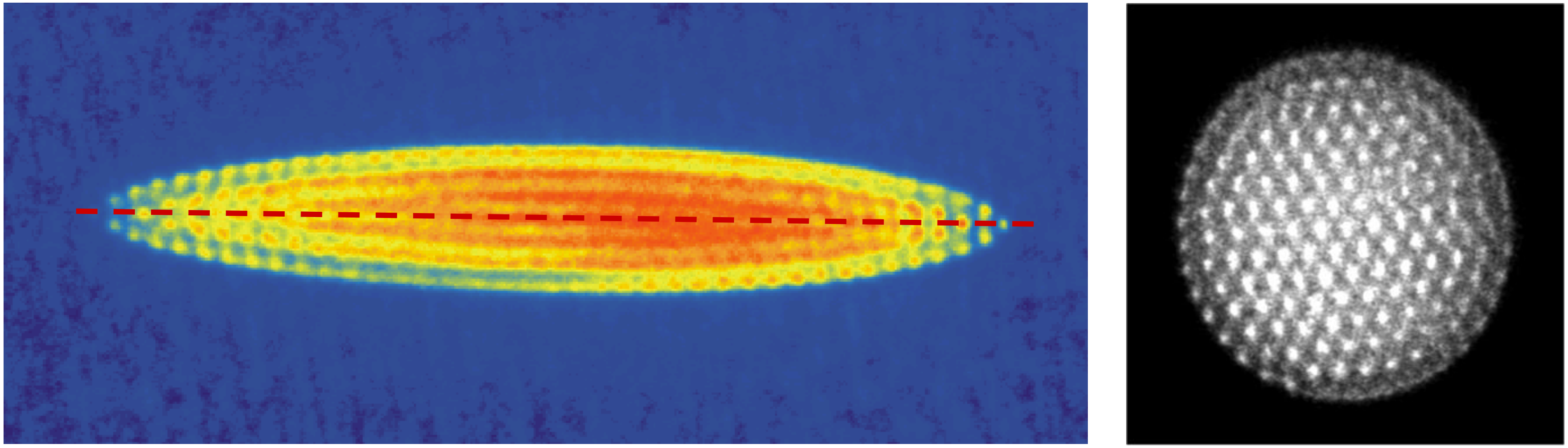
IV) Conclusion

I) Brief introduction to ion Coulomb crystals

Laser cooling of trapped ions:



Ion Coulomb crystals



Phys. Rev. Lett. **96**, 103001 (2006)

Properties:

Uniform density	~10^8 - 10^9 ions/cm^3
Melting point	~100 mK
Life times of	~hours @ P~10^{-10} mBar

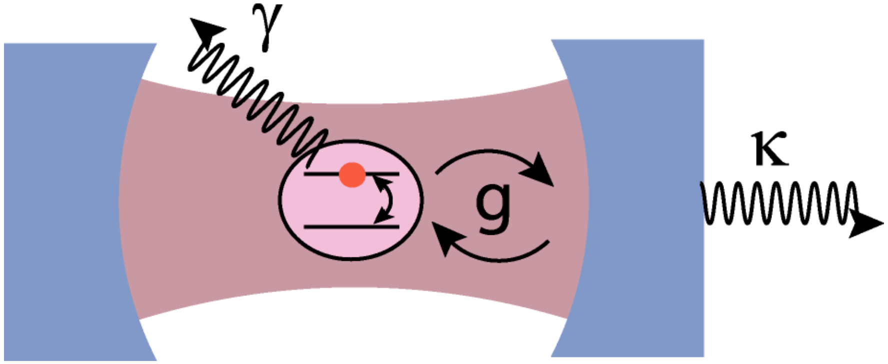
Unique feature of these solids:

The internal state of individual ions are "unperturbed" by the presence of other ions as well as the trapping fields !

II) Cavity Quantum ElectroDynamics in short

Exploration of the coupling of a quantized cavity EM-field to electromagnetic transitions in a quantum system.

A few important parameters (2-level system)



Strong coupling regime:

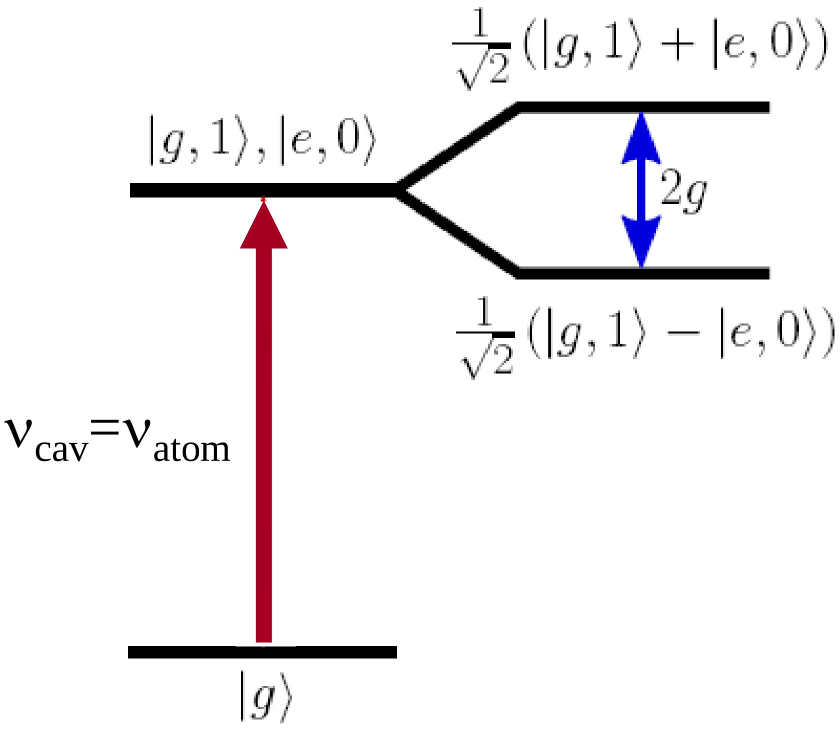
$$\boxed{g > \gamma, \kappa}$$

Coupling rate of a single photon to the atomic system: g

Quantum system dipole decay rate: γ

Cavity field decay rate: κ

Atomic interaction with a single photon



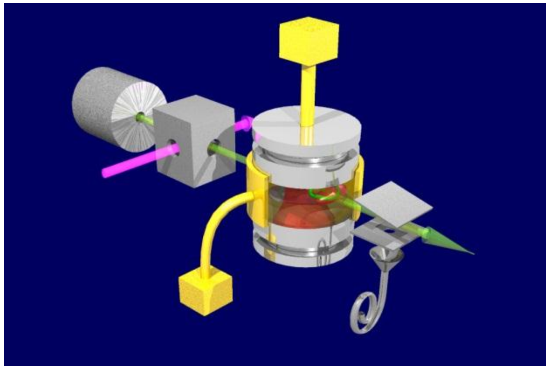
Single photon
Rabi splitting

Hallmark of CQED !

Pioneering CQED work

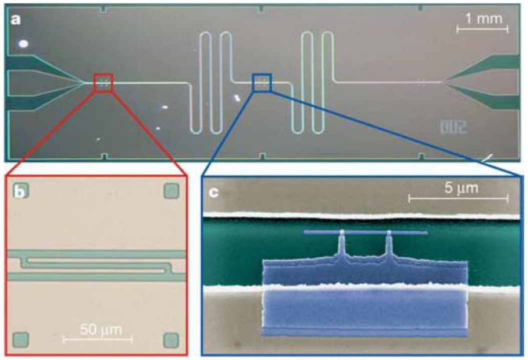
Microwaves:

Atoms



Haroche, ENS; Walther, MPQ

CPB's

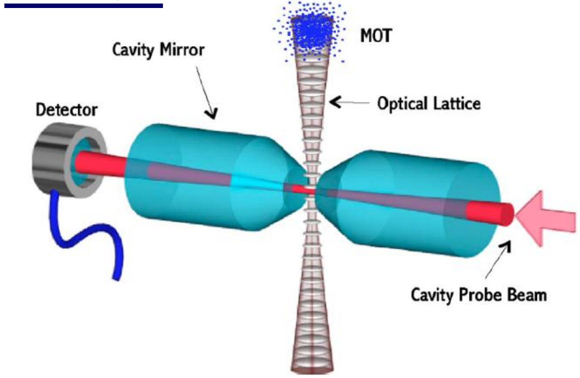


Schoelkopf, YALE;
Wallraff, ETH
Martinis, UCSB
Vion, Saclay

Optical range:

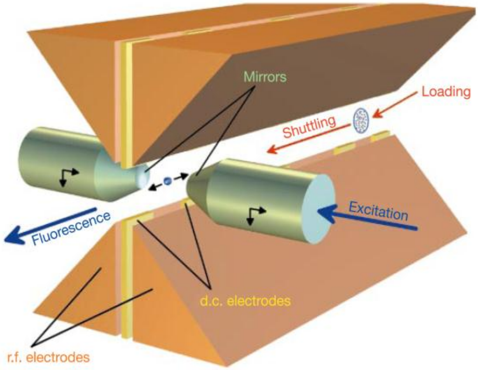
$$\boxed{g = \mu_{eg} \cdot \epsilon \sqrt{\frac{\hbar\omega_1}{2\epsilon_0 V}}}$$

Atoms



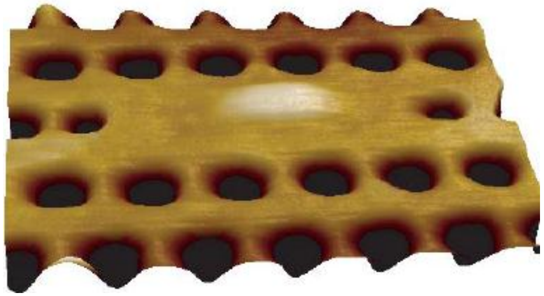
Rempe, MPQ;
Kimble, Caltec

Ions



Walther, MPQ;
Blatt, Innsbruck

Qdots

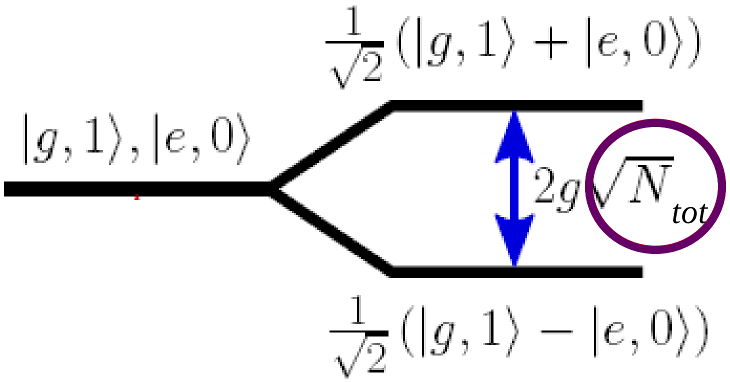


Imamoglu, ETH
Yamamoto, Stanford

III) CQED experiments with Coulomb crystals

Why Coulomb crystals ?

Interaction with a single photon



$\frac{1}{\sqrt{2}}(|g,1\rangle + |e,0\rangle)$

$|g,1\rangle, |e,0\rangle$

$2g\sqrt{N_{tot}}$

$\frac{1}{\sqrt{2}}(|g,1\rangle - |e,0\rangle)$

For multi-particle states:

$$\left|g,1\right\rangle \equiv \left|g_1,\ldots,g_{N_{tot}},1\right\rangle$$

Ideally: $\left|e,0\right\rangle \equiv \frac{1}{\sqrt{N_{tot}}}\sum_{i=1}^{N_{tot}}\left|g_1,g_2,\ldots,e_i,\ldots,g_{N_{tot}},0\right\rangle$

Actually: $\left|e,0\right\rangle \equiv \sum_{i=1}^{N_{tot}} c_i\left|g_1,g_2,\ldots,e_i,\ldots,g_{N_{tot}},0\right\rangle,$ $\sum_{i=1}^{N_{tot}}\left|c_i\right|^2 = 1$

Effective number of ions: $\boxed{N \equiv \sum_{i=1}^{N_{tot}} \psi^2(\vec{r}_i)}$, with

$$\psi^2(\mathbf{r}) = \left(\frac{w_0}{w(z)}\right)^2 \exp(-2(x^2+y^2)/w(z)^2)\sin^2\left[kz - \tan(z/z_0) + k(x^2+y^2)/2R(z)\right]$$

being the cavity mode function (TEM_{00})

Why Coulomb crystals ?

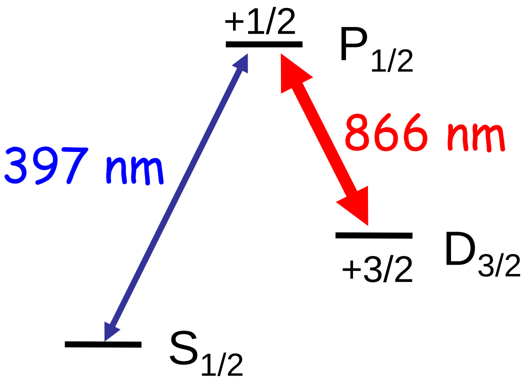
Collective coupling: $g_{eff} = gN^{1/2}$ => Collective strong coupling regime accessible ($g_{eff} > \kappa, \gamma$)

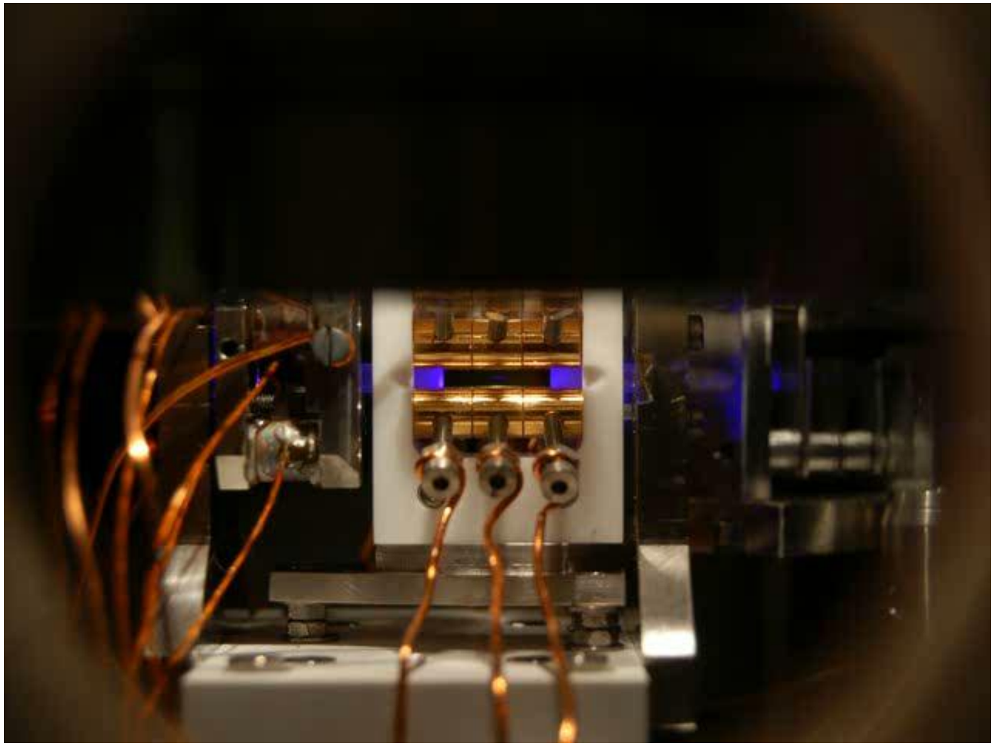
N can be varied "continuously" from 1 to ~ 2000

Good overlap between cavity mode and ions in Coulomb crystals
Micro-meter positioning control

J. Phys. B, 42, 154008 (2009)

The $^{40}Ca^{+}$ ion:





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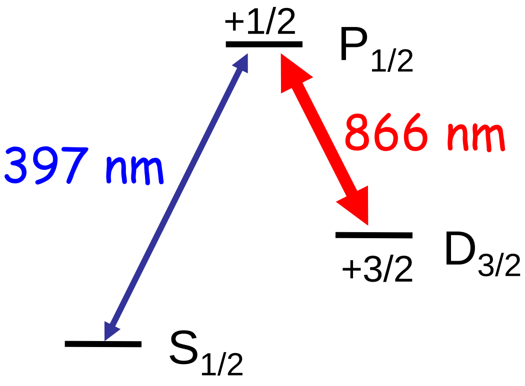
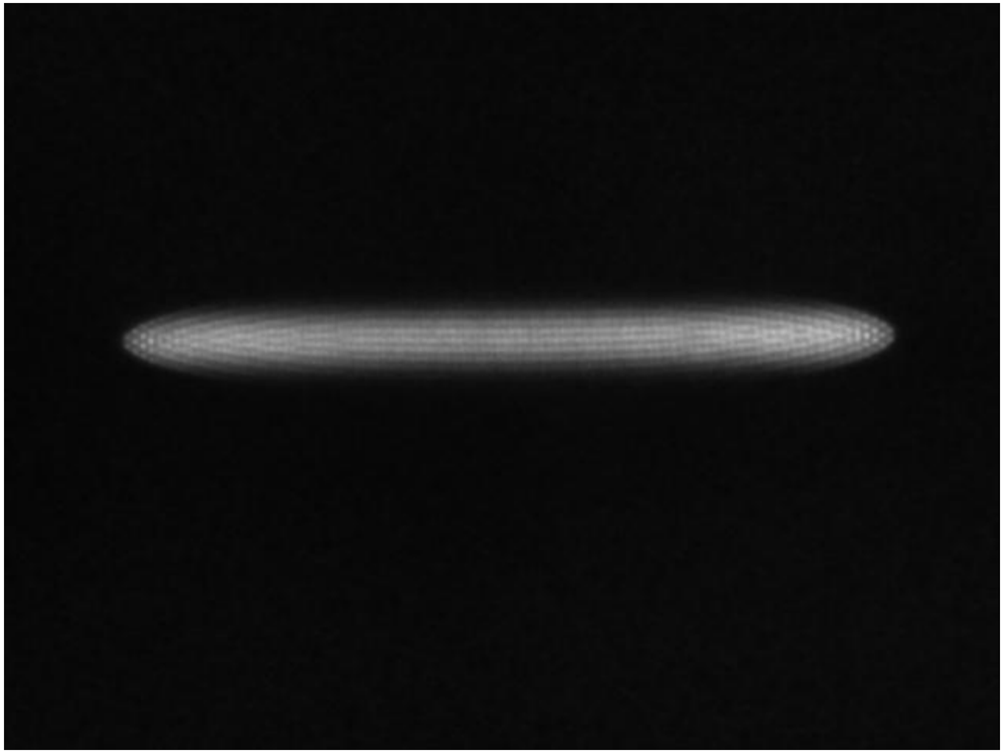




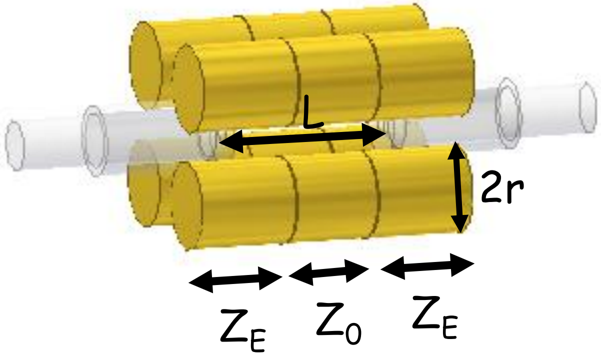
The Cavity Trap Setup

The cavity:

$L = 11$ mm
$w_0 = 37\ \mu m$
$R_1 \approx 99.85\%$
$R_2 > 99.99\%$

$F \sim 3200$

$\boxed{\kappa = 2\pi \times 2.1 \text{ MHz}}$

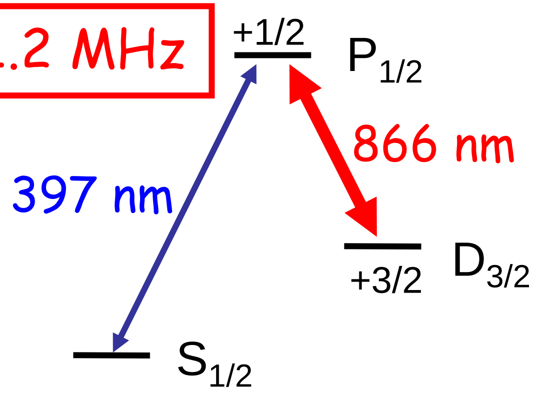


The trap:

$2r = 5.2$ mm
$z_0 = 5.0$ mm
$z_E = 5.9$ mm

The $^{40}Ca^+$ ion:

$\boxed{\gamma = 2\pi \times 11.2 \text{ MHz}}$



The cavity-atom coupling:

$\boxed{g = 2\pi \times 0.53 \text{ MHz}}$

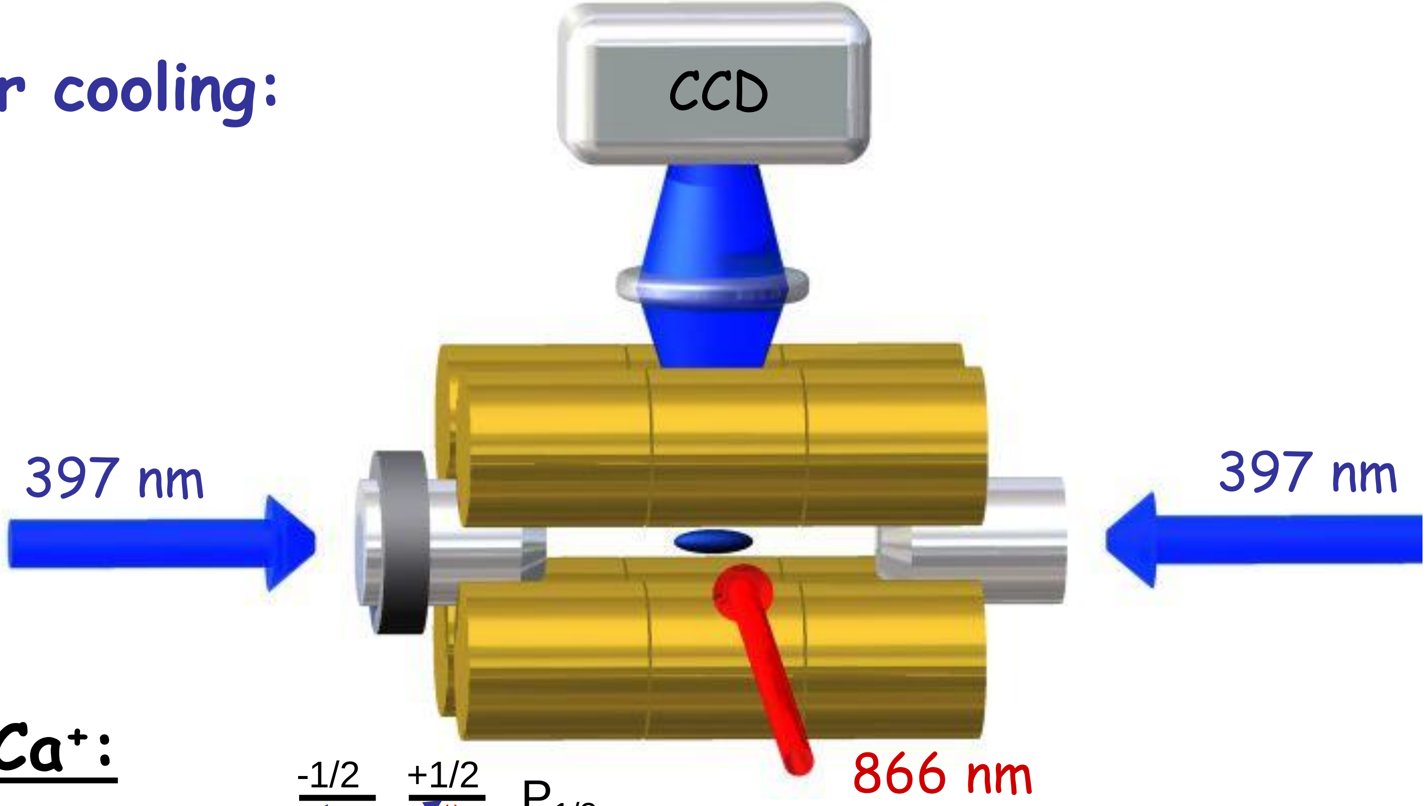
$\boxed{g_{eff} = gN^{1/2} > \gamma, \kappa \Rightarrow N > \sim 430}$

Coop. par.: $C = Ng^2/(2\kappa\gamma)$:

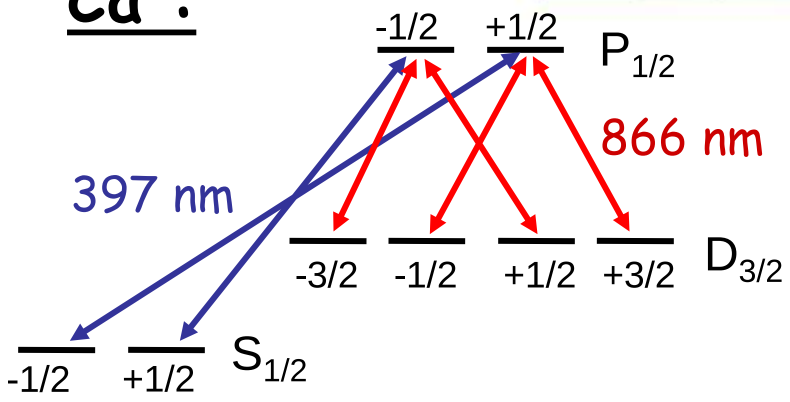
$C \approx 0.006$ ($N = 1$) -> $C \approx 10$ ($N = 1500$)

Experimental Sequence

Laser cooling:

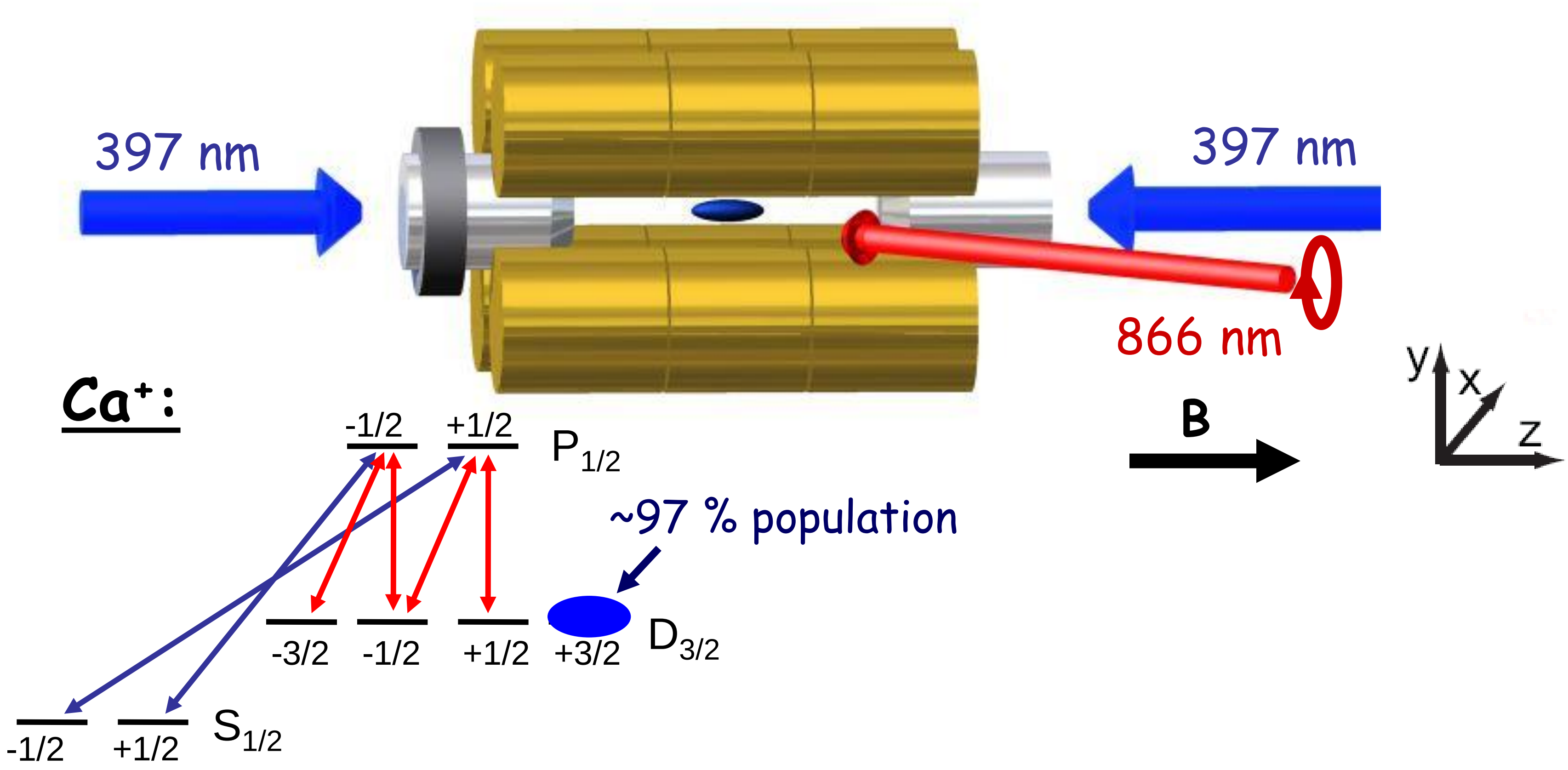


Ca$^+$:



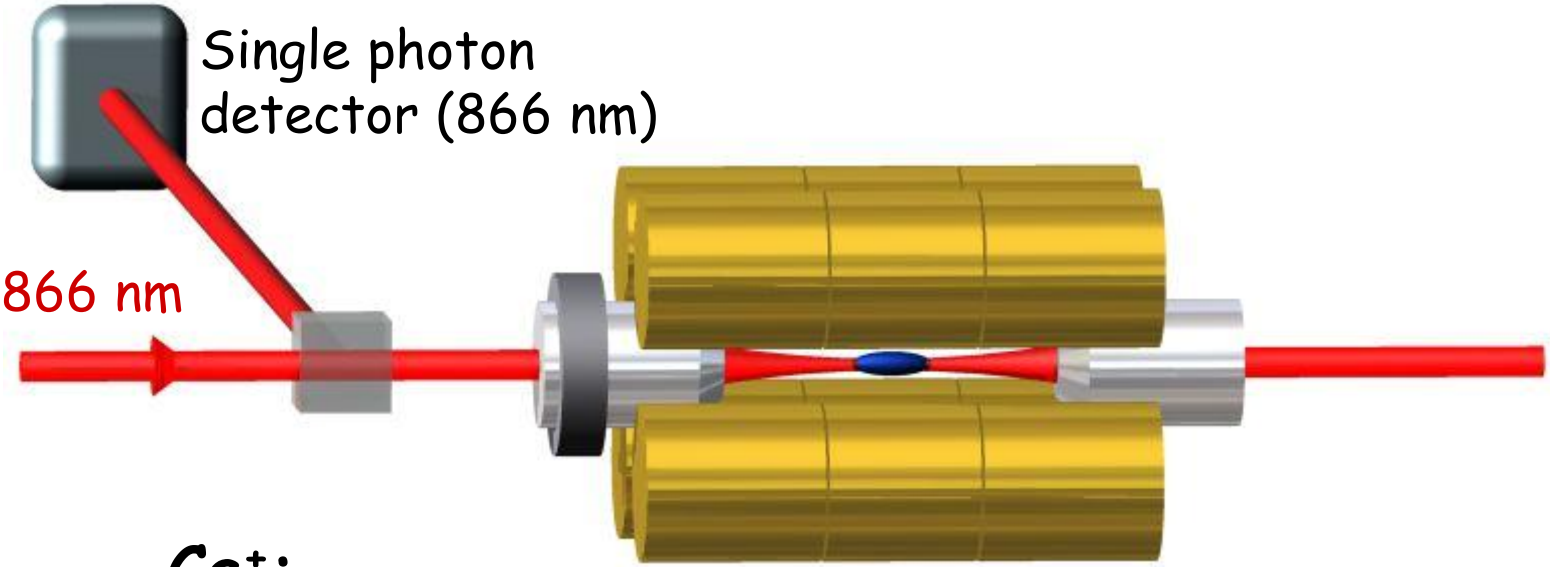
Experimental Sequence

Optical pumping:

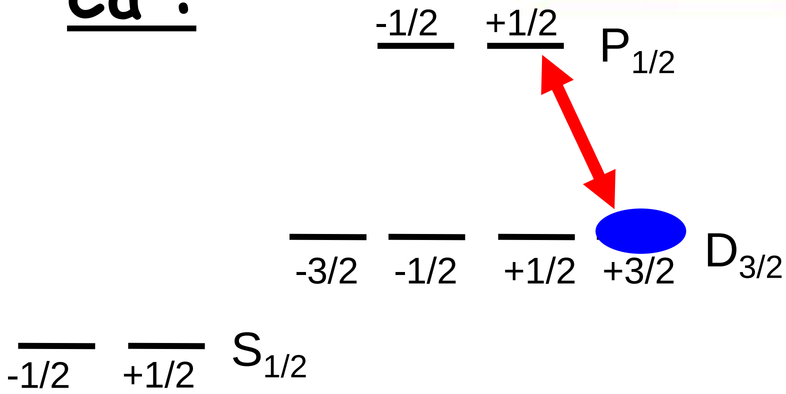


Experimental Sequence

Cavity probing:

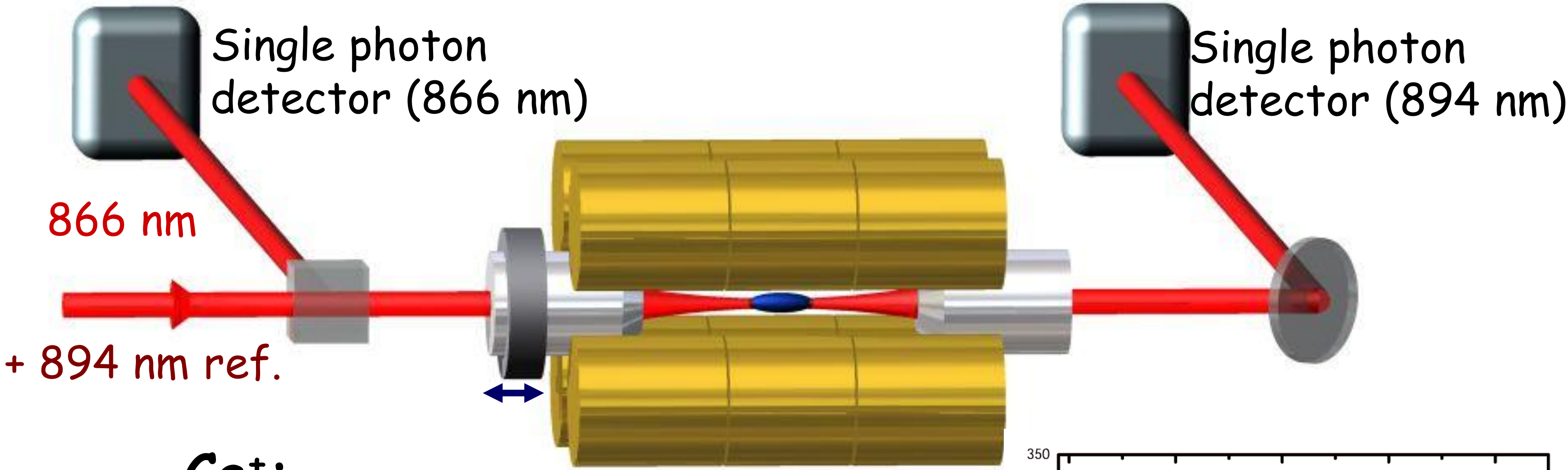


Ca$^+$:

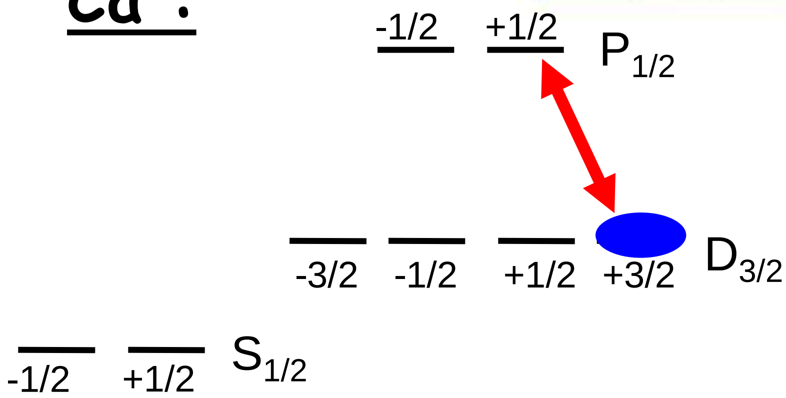


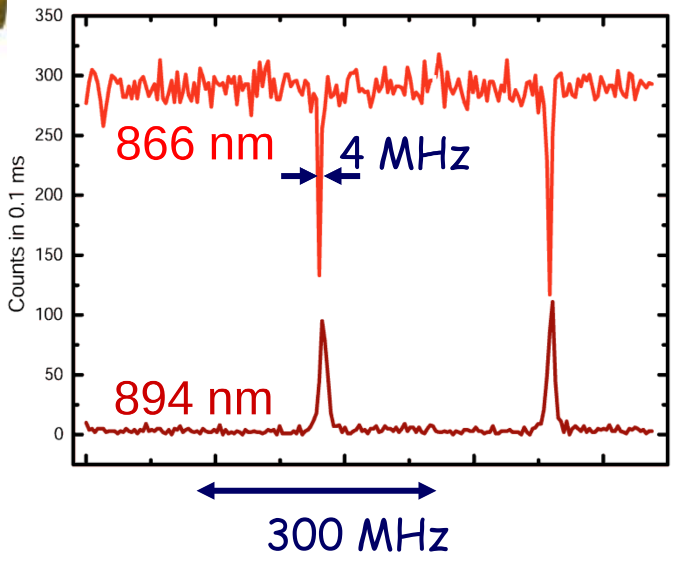
Experimental Sequence

Cavity probing:

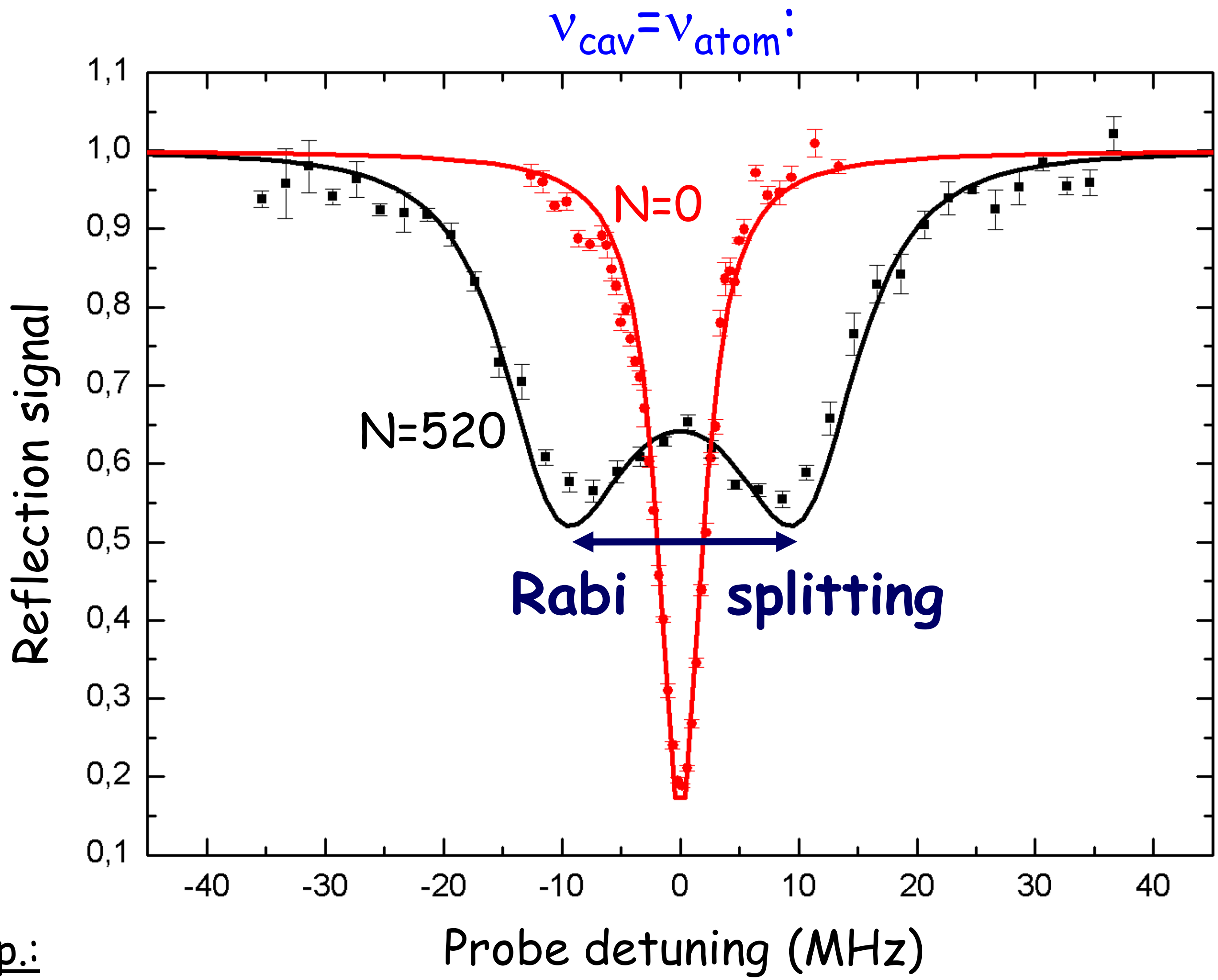


Ca⁺:





Observation of single photon Rabi splitting



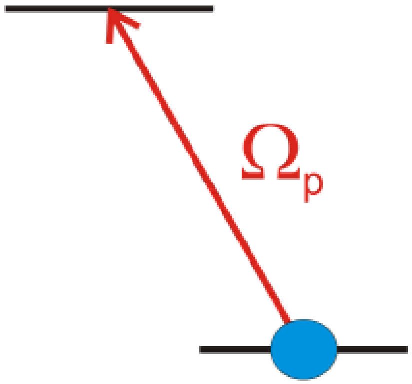
First exp.:

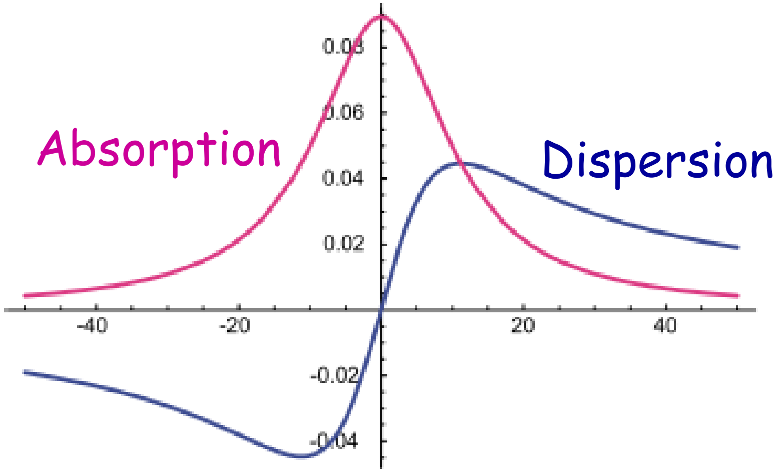
R. J. Thompson, G. Rempe & H. J. Kimble,
Phys. Rev. Lett. 68, 1132-1135 (1992)

Nature Physics **5**, 494 (2009)

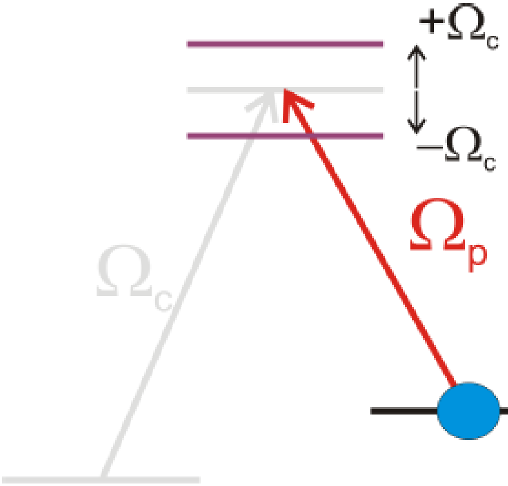
Electromagnetically Induced Transparency (EIT)

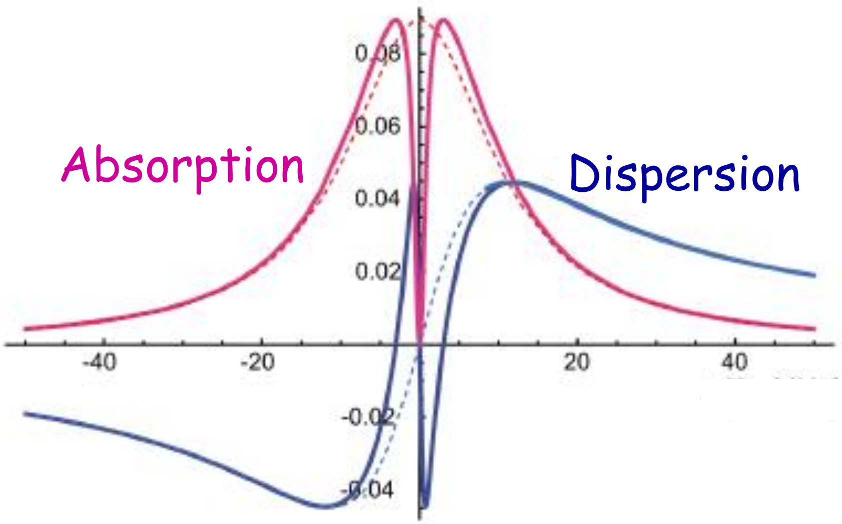
2-level atoms





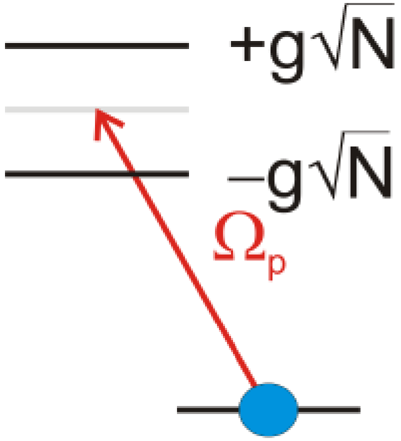
3-level atoms



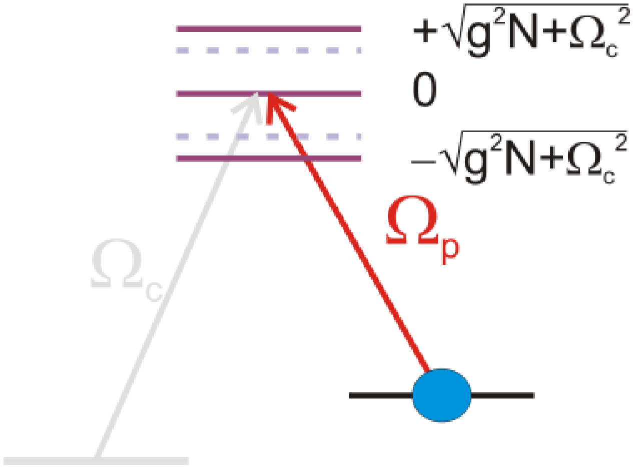


EIT in a cavity

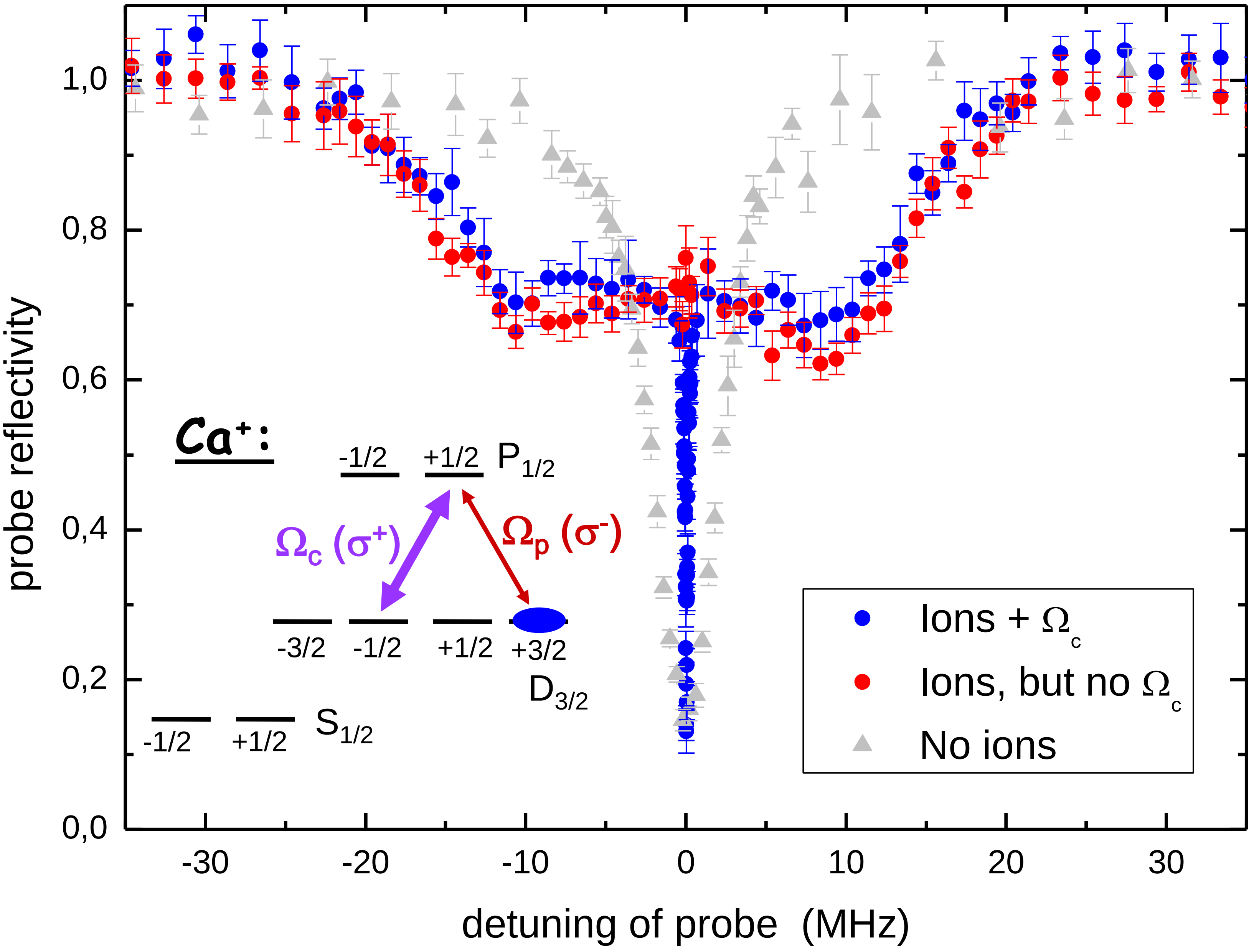
2-level atoms in cavity



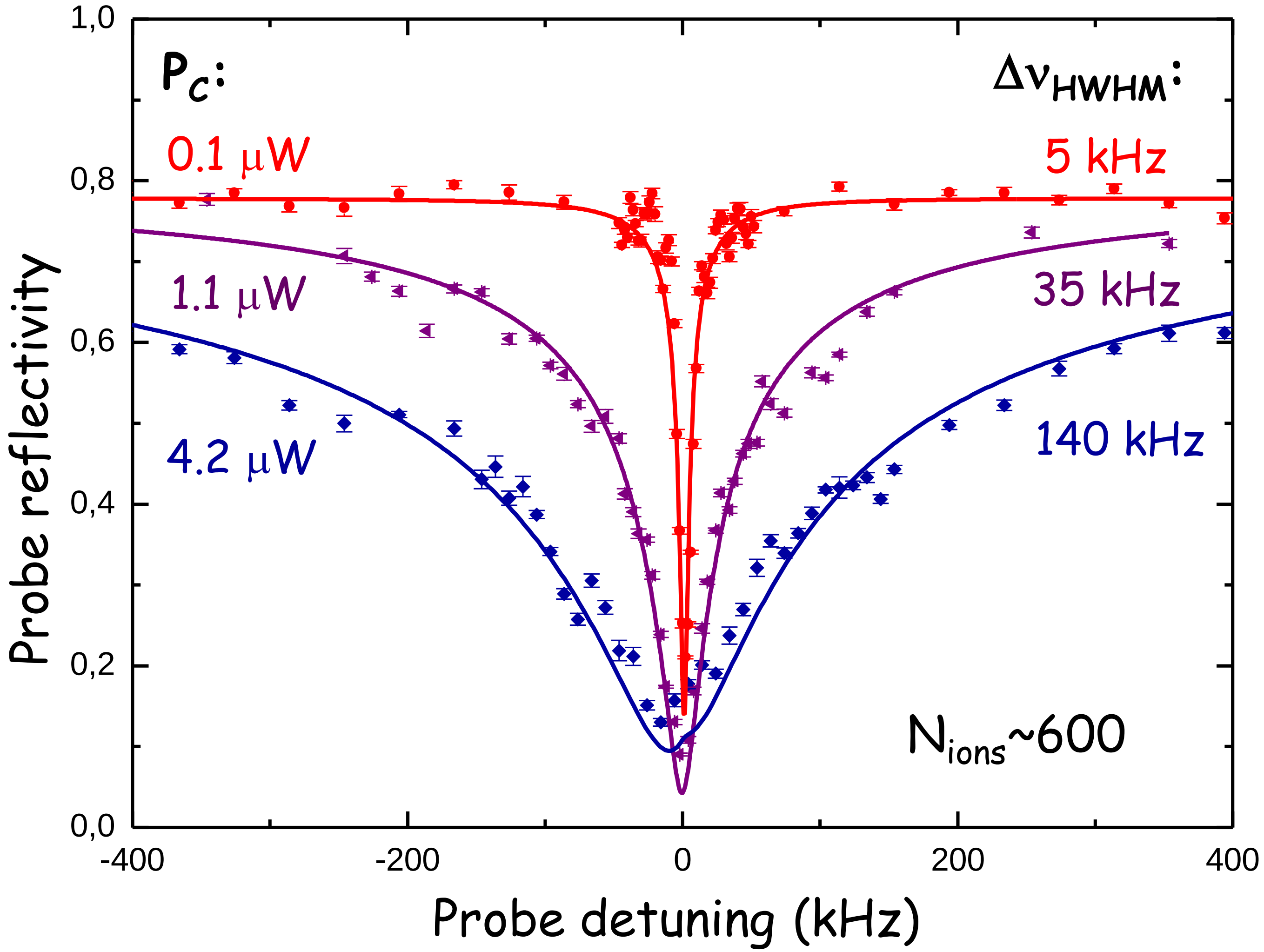
3-level atoms in cavity



Observation of triplet structure in reflection

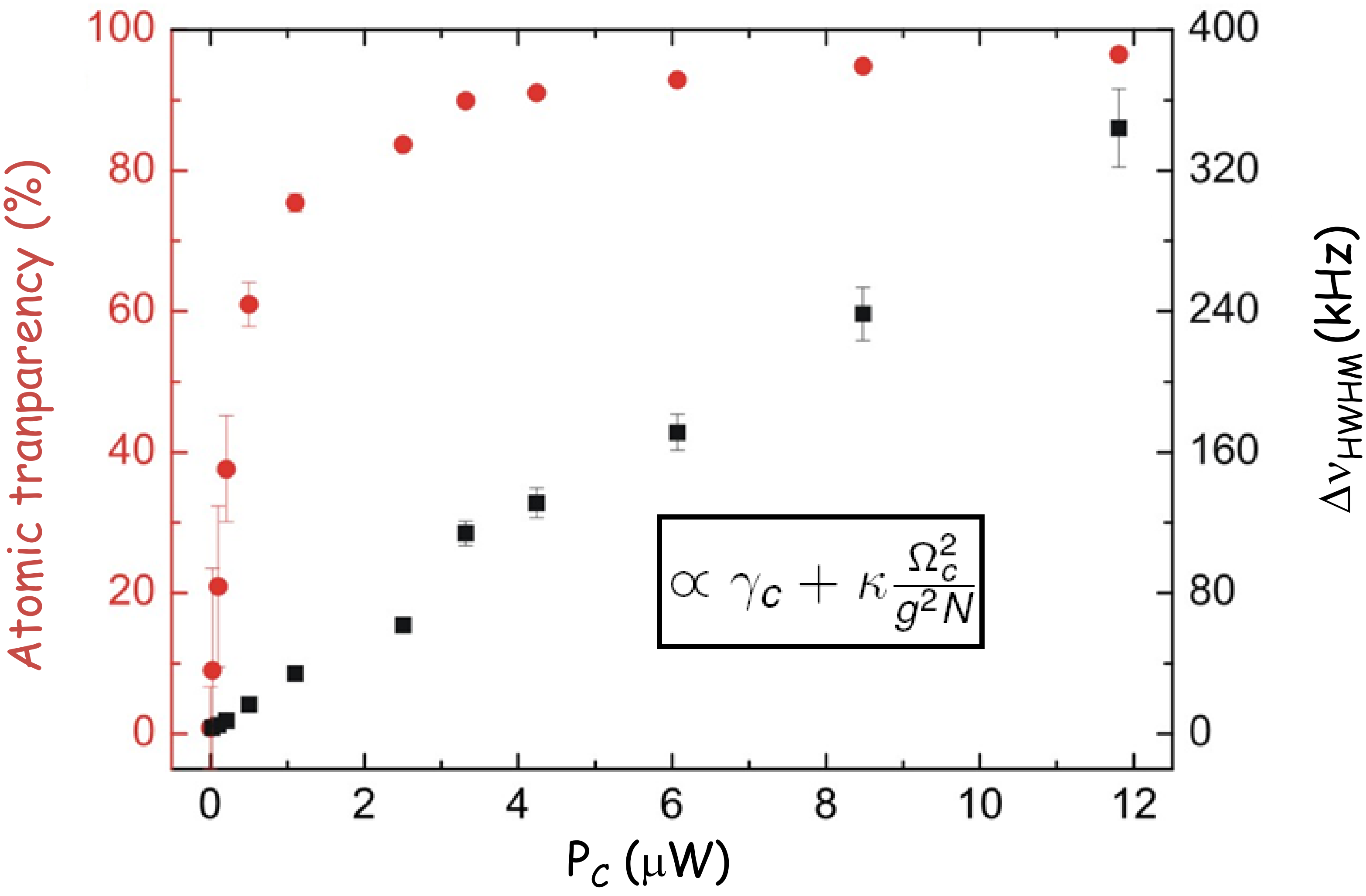


EIT feature vs. coupling laser power



Non-Lorenzian line shapes due to Gaussian mode profile

EIT feature vs. coupling laser power



> 90 % transperency for $\Delta\nu_{HWHM}$ ~100 kHz

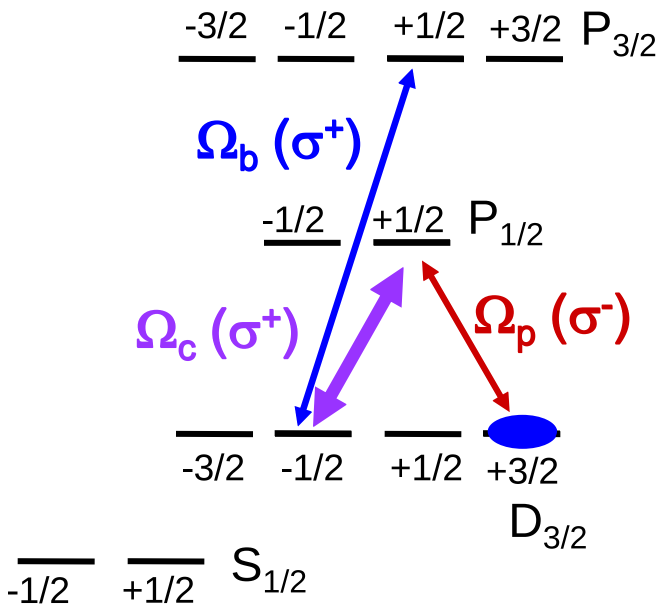
γ_c ~ 1 kHz

Nature Photonics, **5**, 633 (2011)

Cross Kerr effect and photon blockade

Schmidt and Imamoglu, opt. Lett. 21, 1936 (1996);
Imamoglu *et al.*, Phys. Rev. Lett **79**, 1467 (1997)

Ca⁺:



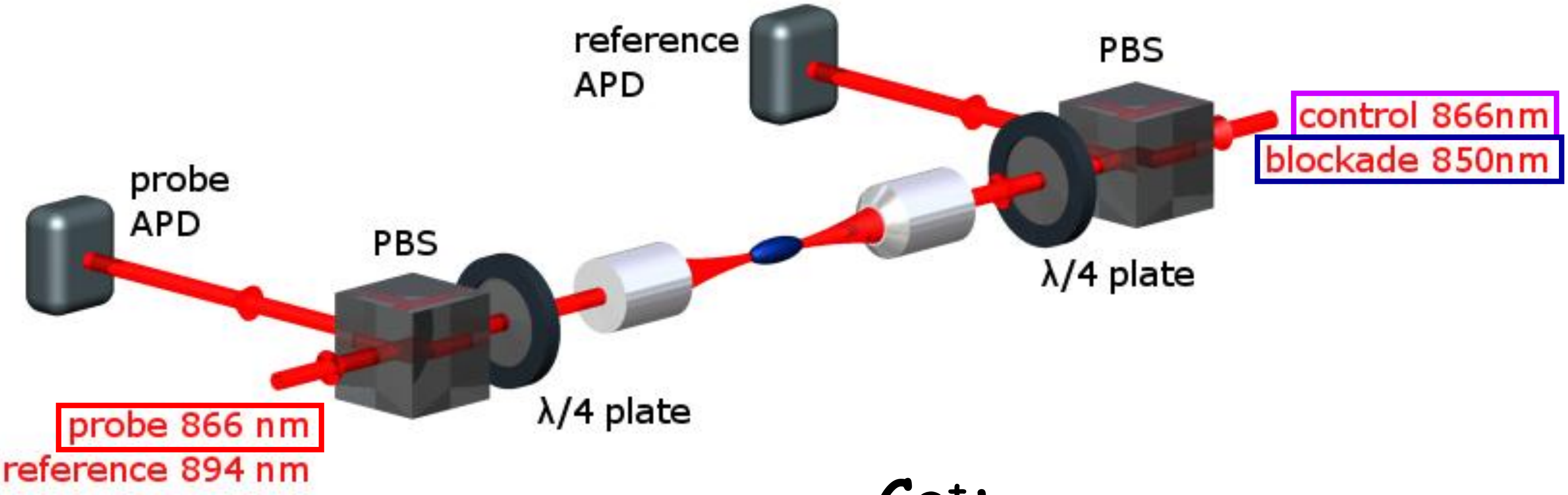
If the light shift due to Ω_b is larger than the EIT width then EIT ceases => Photon blockade !

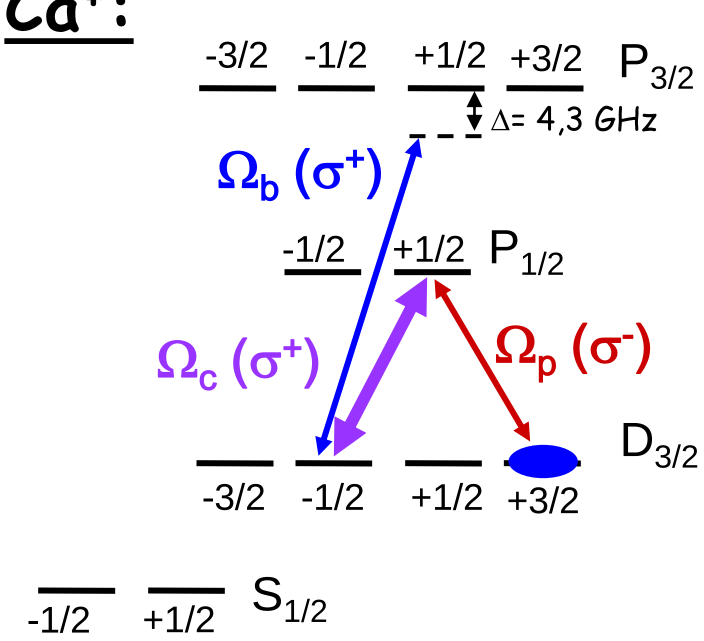
At the single photon level this would enable

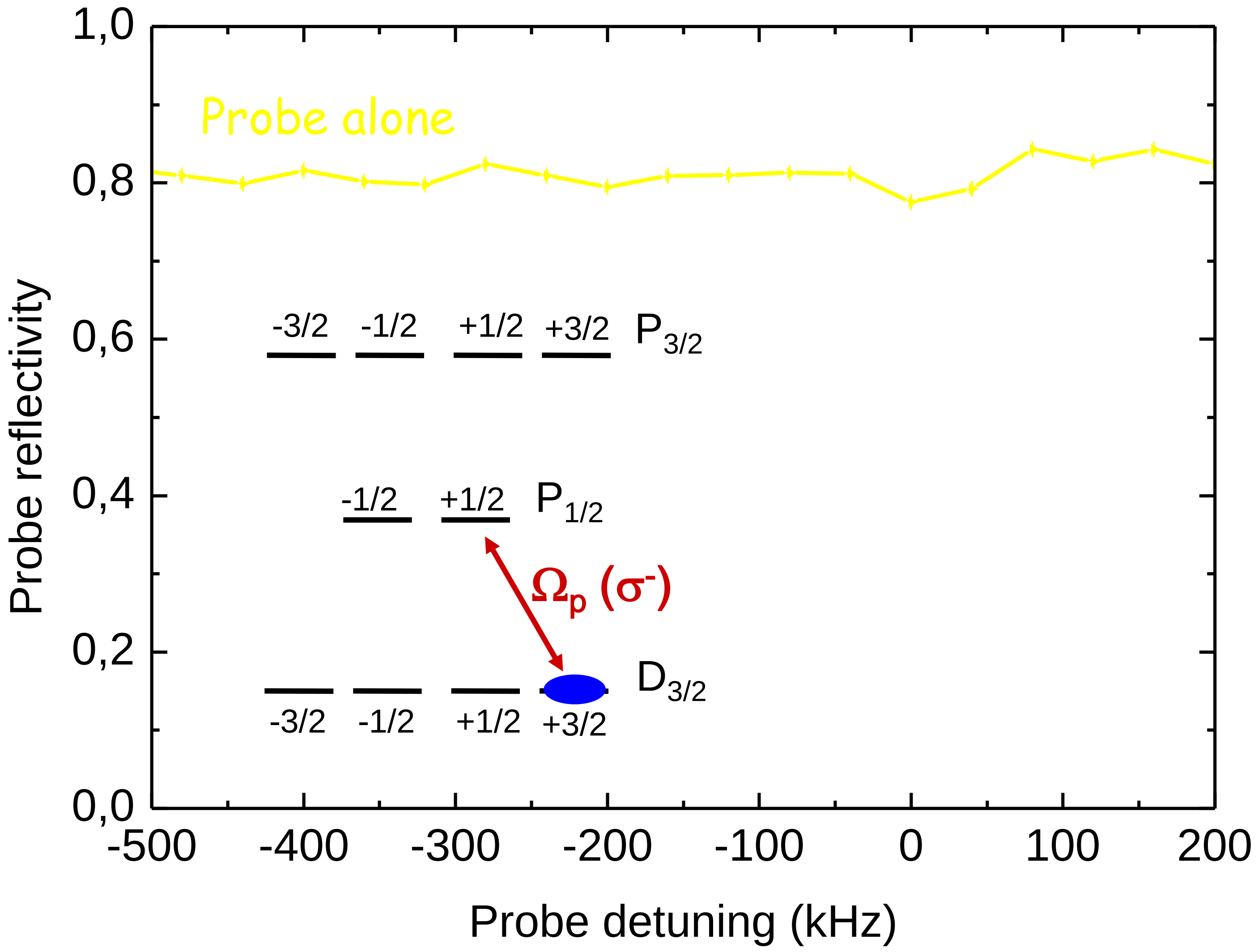
I) Single photon transistor

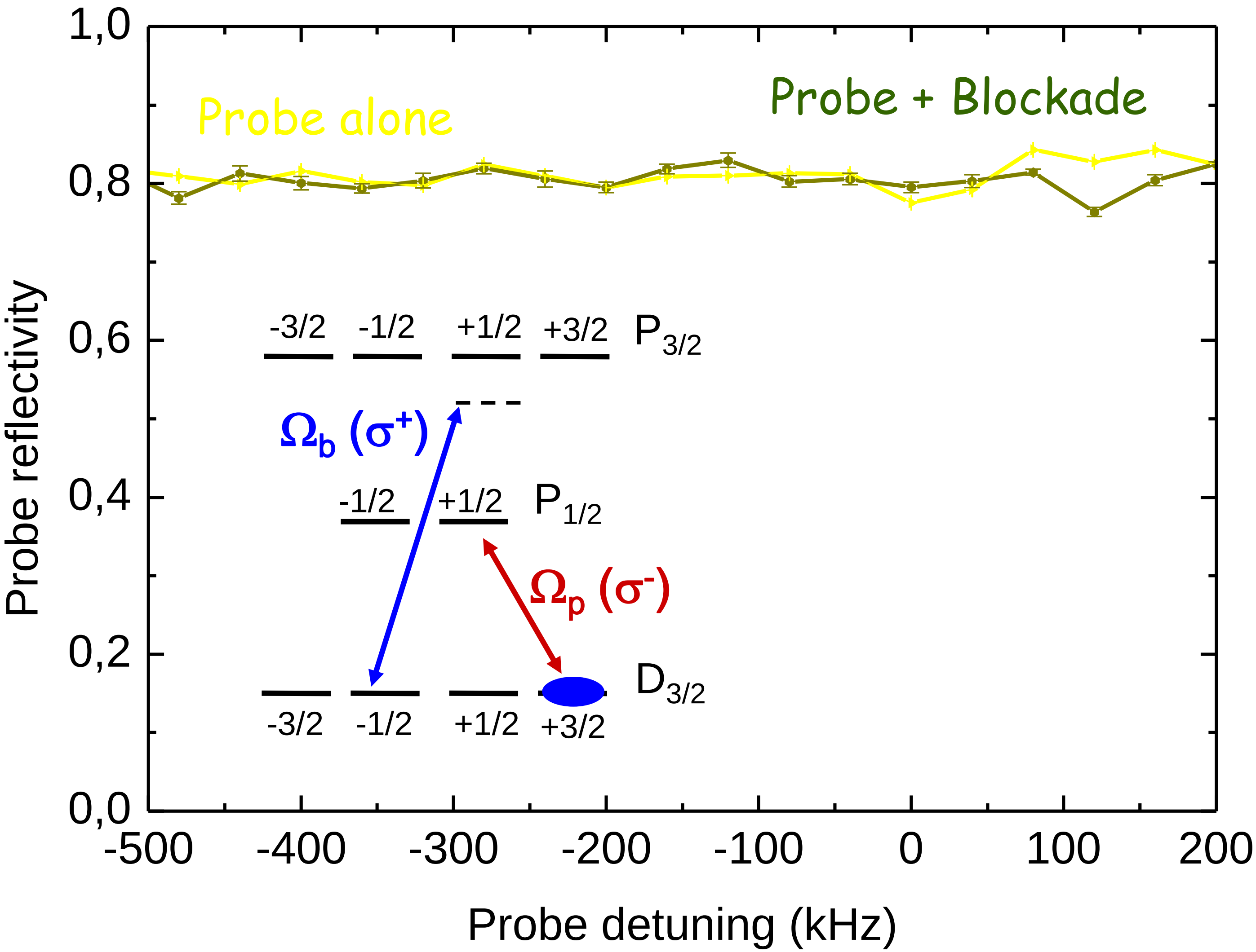
Very challenging !!

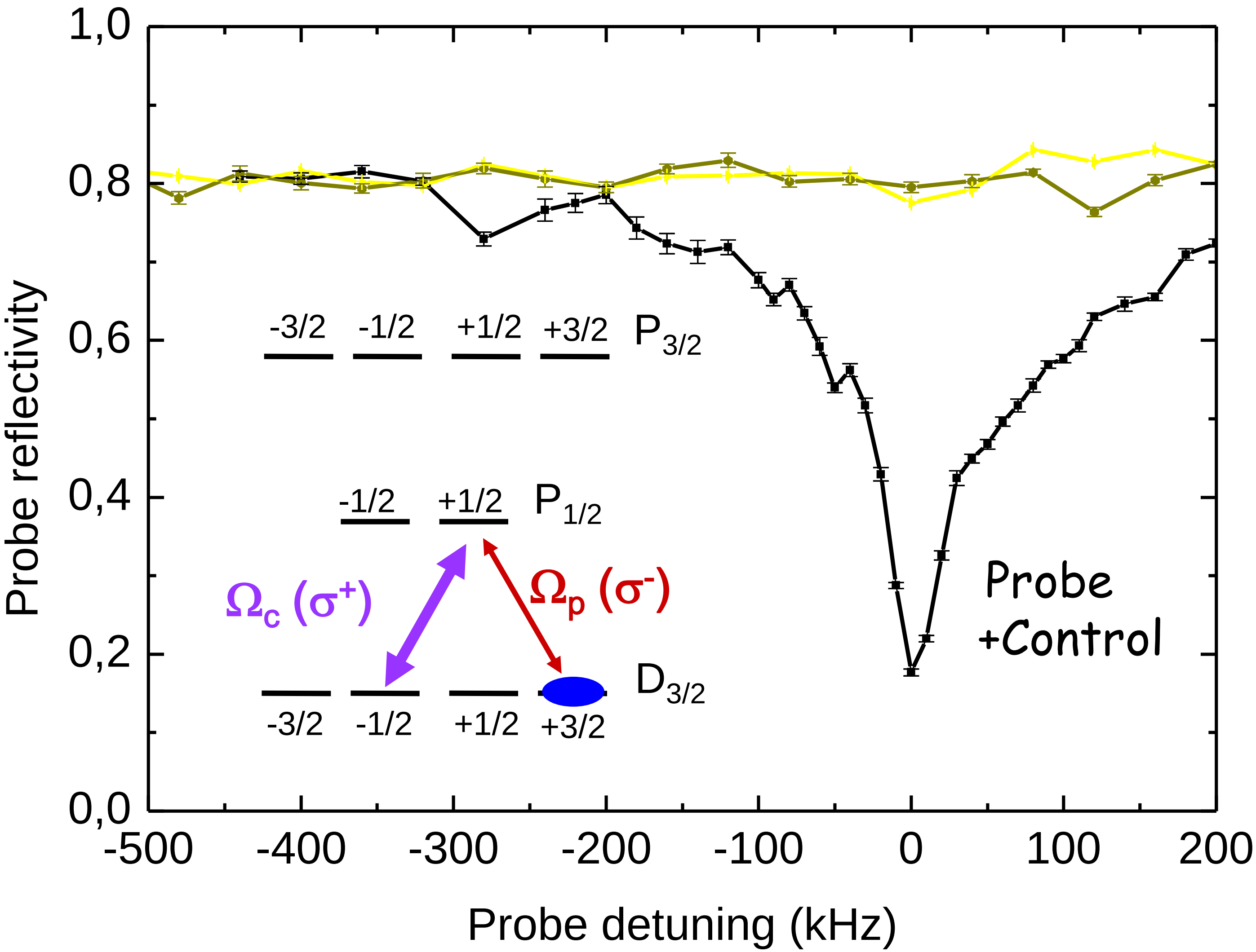
Sketch of experimental setup






1,0
0,8
0,6
0,4
0,2
0,0
-500
-400
-300
-200
-100
0
100
200
Probe reflectivity
Probe detuning (kHz)
Probe alone
-3/2
-1/2
+1/2
+3/2
$P_{3/2}$
-1/2
+1/2
$P_{1/2}$
Ω_p (σ^-)
$D_{3/2}$
-3/2
-1/2
+1/2
+3/2


Probe alone
Probe + Blockade
1,0
0,8
0,6
0,4
0,2
0,0
Probe reflectivity
-500
-400
-300
-200
-100
0
100
200
Probe detuning (kHz)
-3/2
-1/2
+1/2
+3/2
P3/2
Ωb (σ+)
-1/2
+1/2
P1/2
Ωp (σ-)
D3/2
-3/2
-1/2
+1/2
+3/2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0
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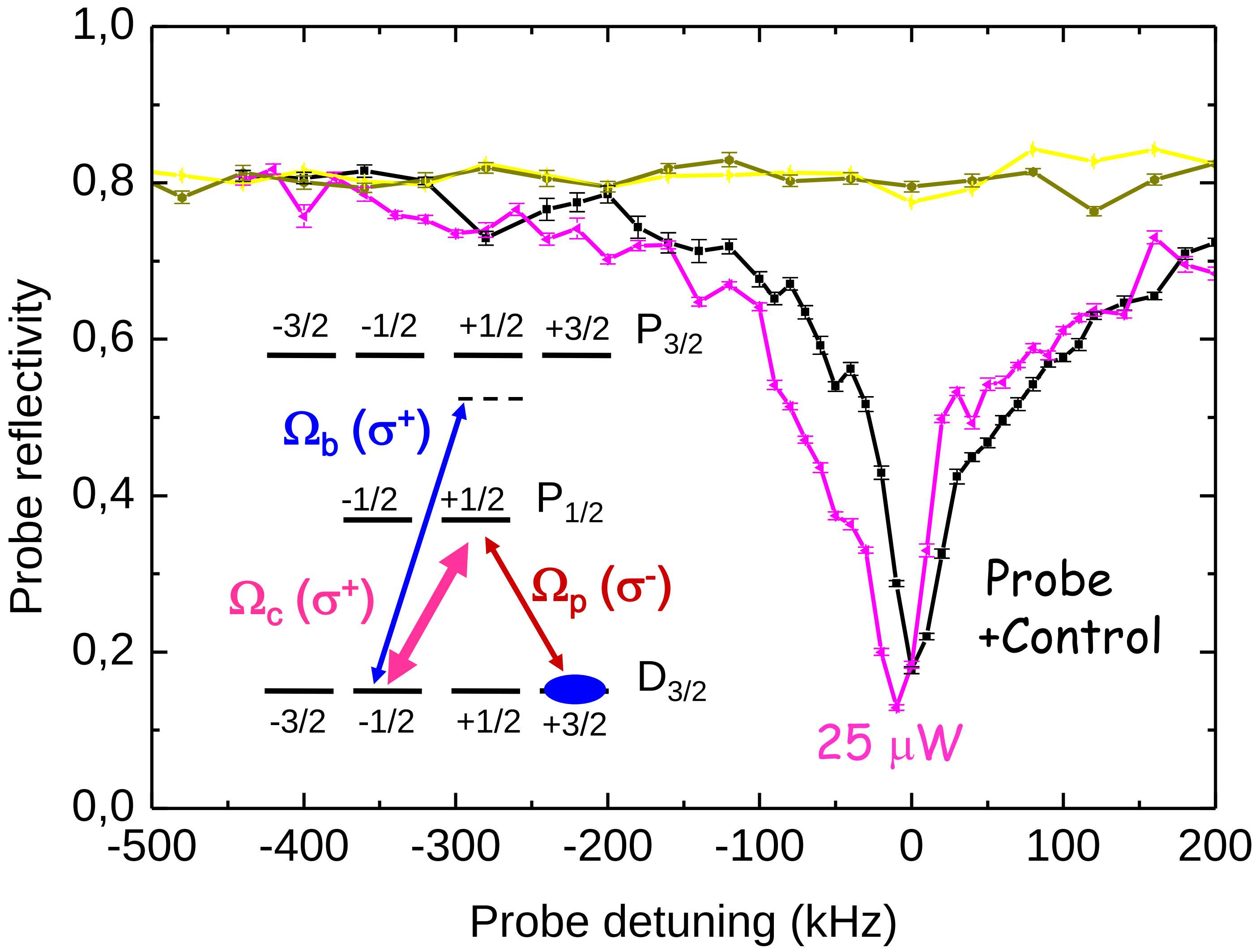
200
Probe reflectivity
Probe detuning (kHz)
-3/2
-1/2
+1/2
+3/2
$P_{3/2}$
-1/2
+1/2
$P_{1/2}$
Ω_c (σ^+)
Ω_p (σ^-)
$D_{3/2}$
-3/2
-1/2
+1/2
+3/2
Probe
+Control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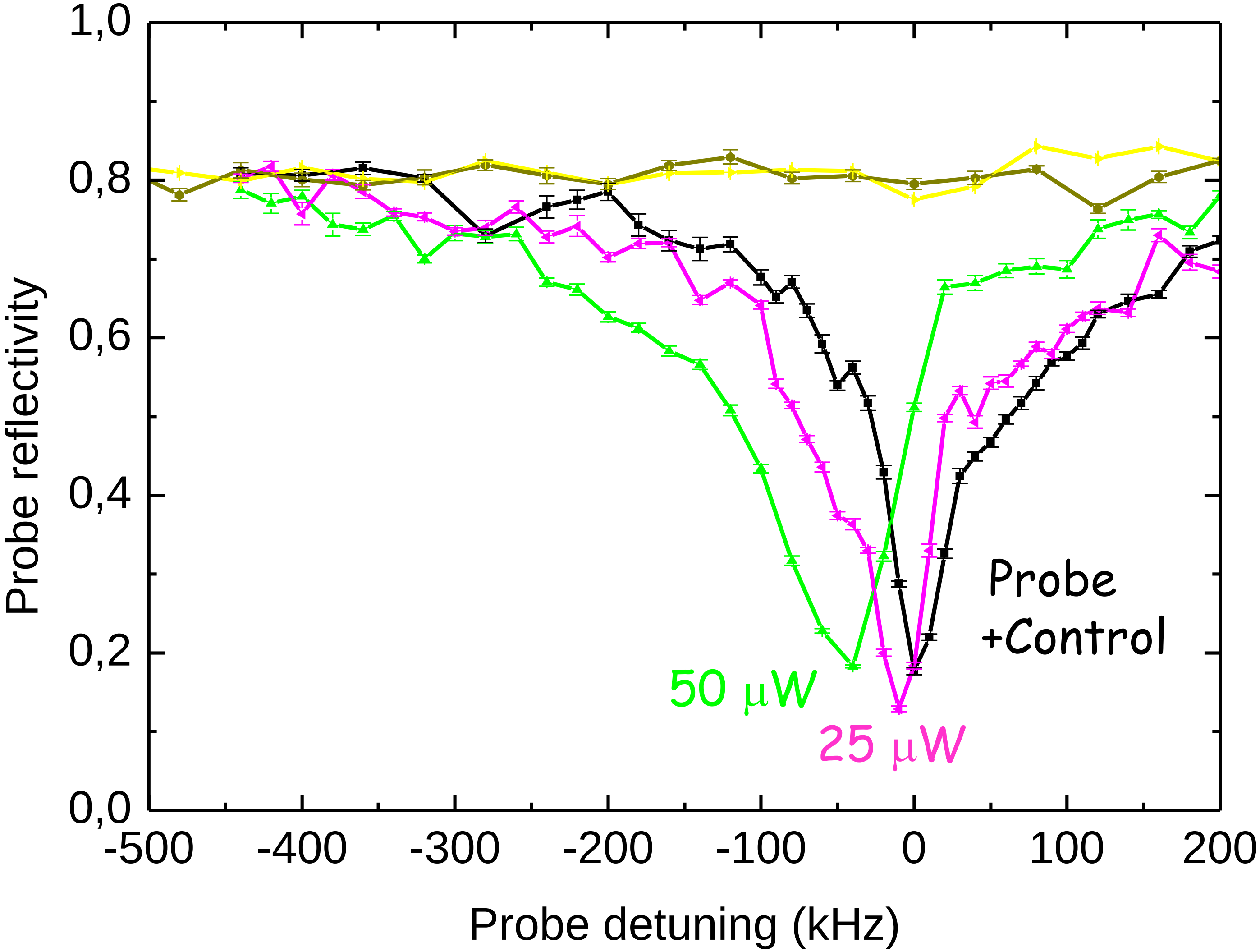
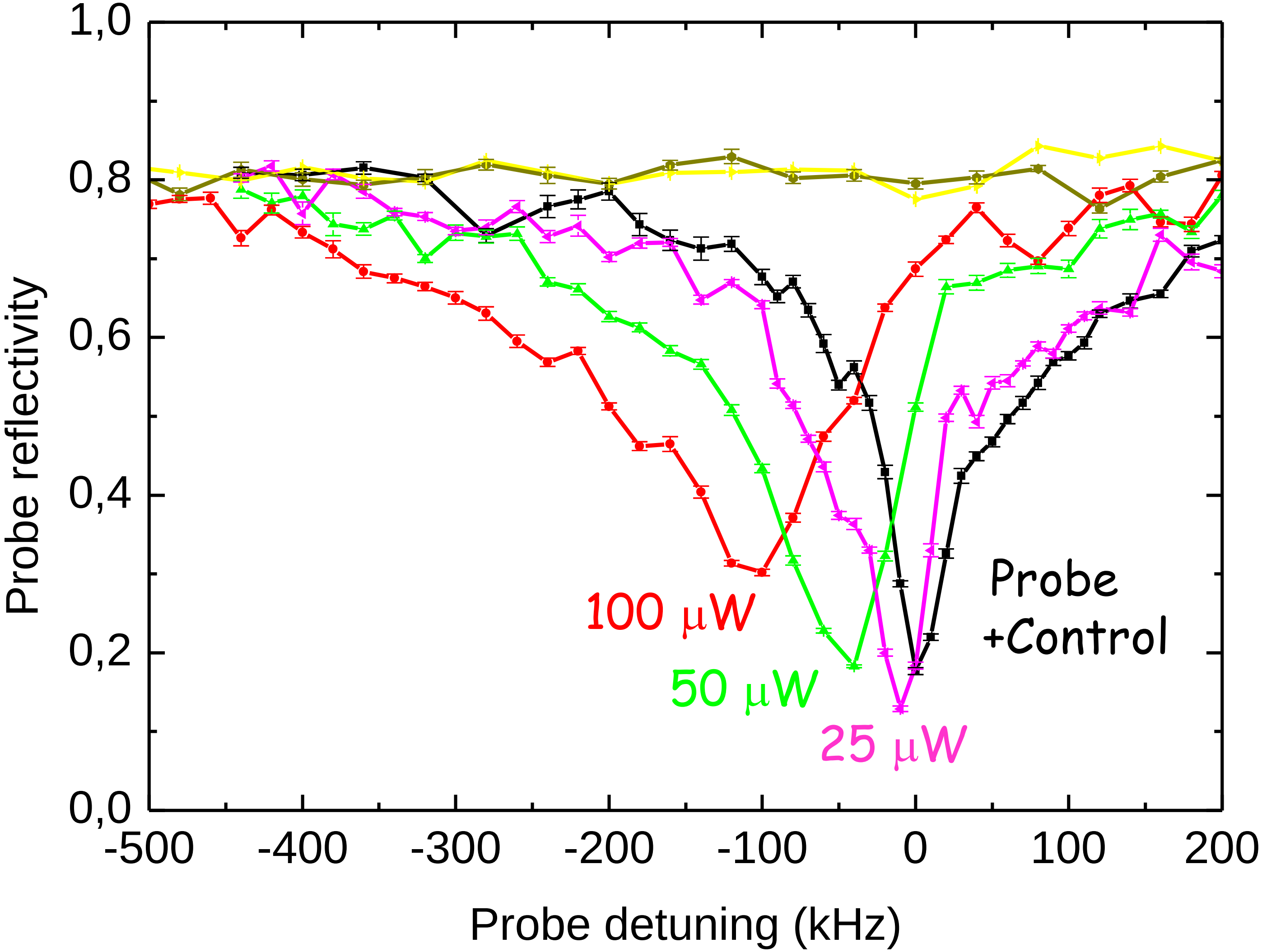
0,4
0,2
0,0
Probe reflectivity
-500
-400
-300
-200
-100
0
100
200
Probe detuning (kHz)
-3/2
-1/2
+1/2
+3/2
$P_{3/2}$
Ω_b (σ^+)
-1/2
+1/2
$P_{1/2}$
Ω_c (σ^+)
Ω_p (σ^-)
$D_{3/2}$
-3/2
-1/2
+1/2
+3/2
Probe
+Control
25 μW


1,0
0,8
0,6
0,4
0,2
0,0
-500
-400
-300
-200
-100
0
100
200
Probe reflectivity
Probe detuning (kHz)
Probe
+Control
50 μW
25 μW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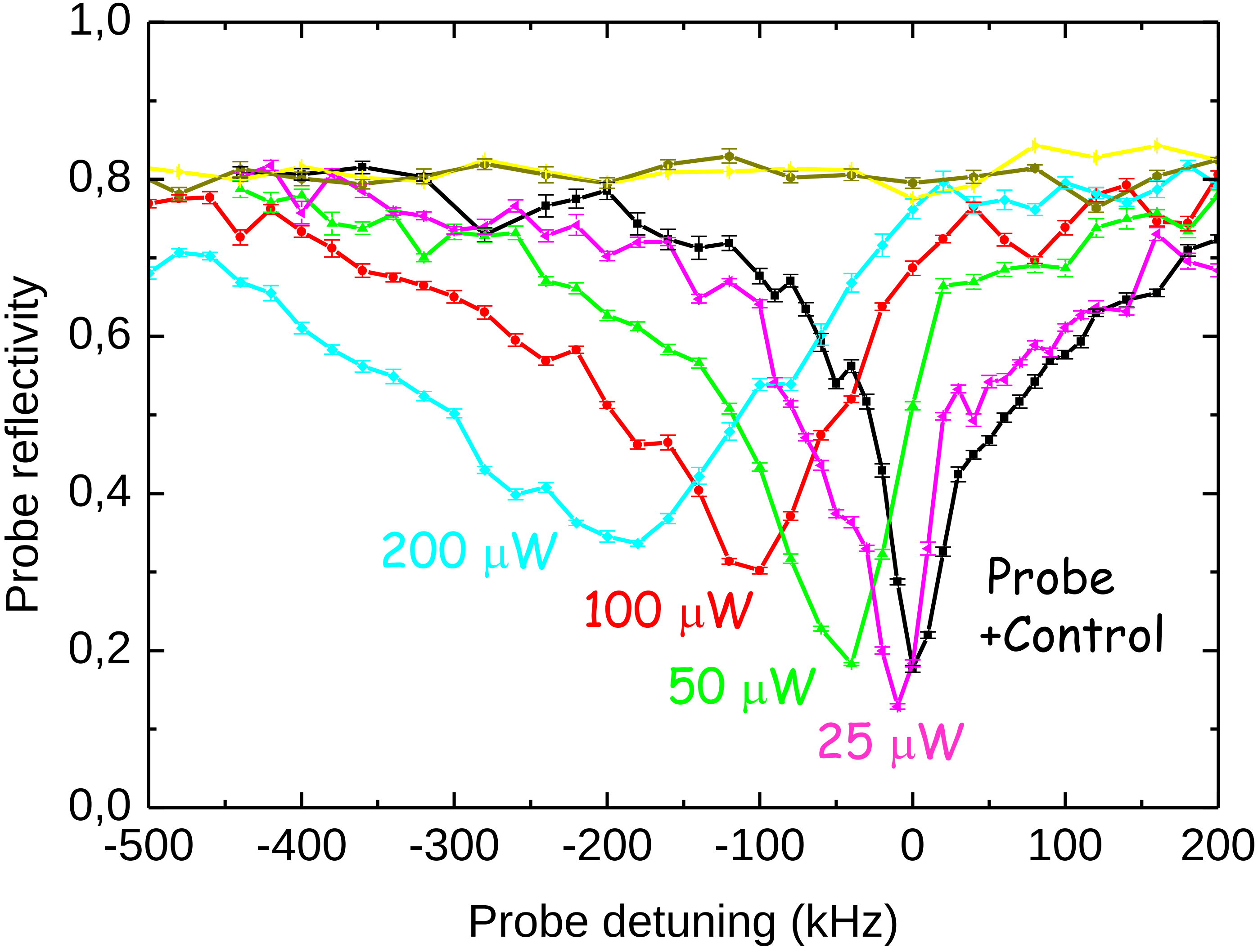
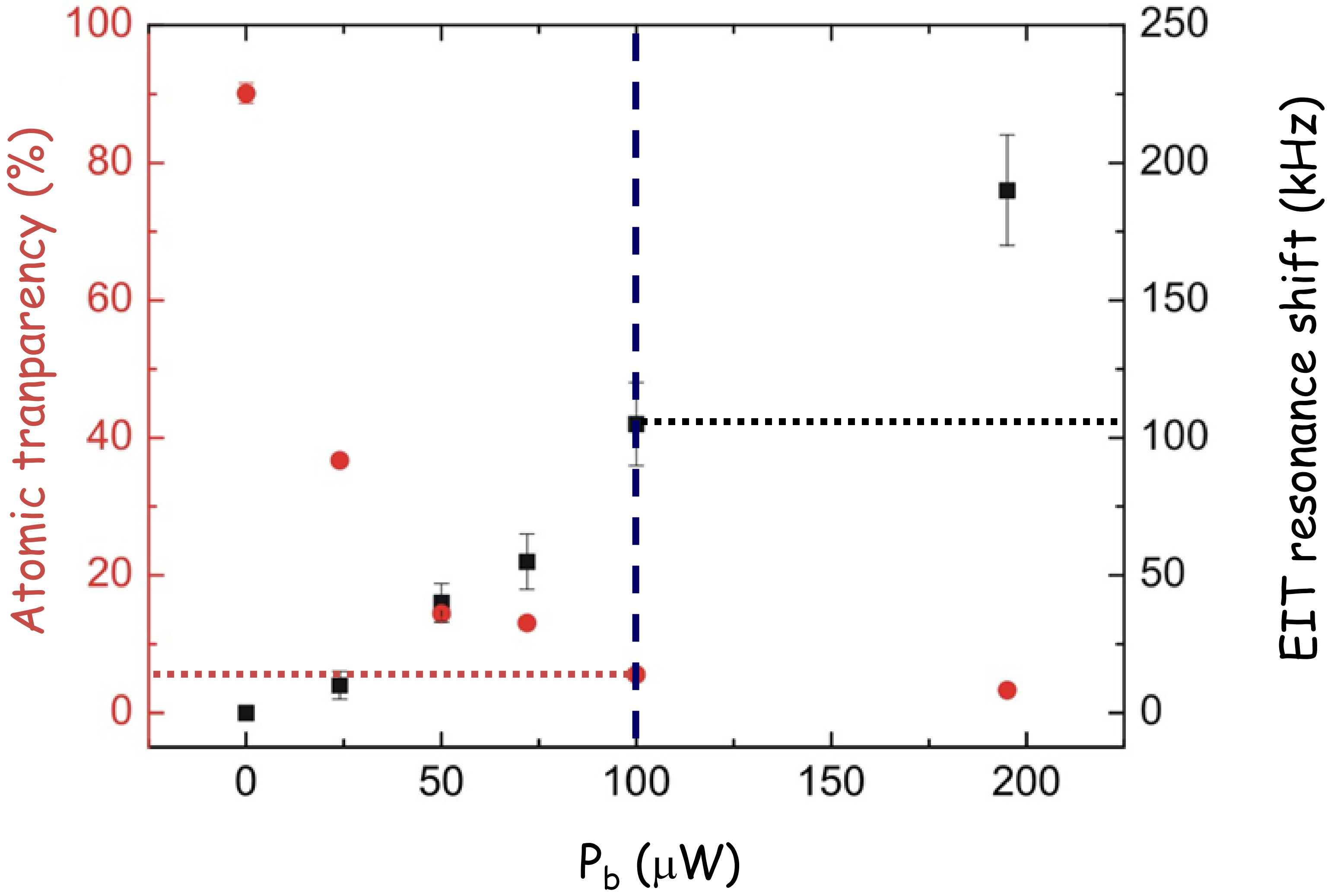
Probe reflectivity
Probe detuning (kHz)
100 μW
50 μW
25 μW
Probe
+Control


1,0
0,8
0,6
0,4
0,2
0,0
Probe reflectivity
-500
-400
-300
-200
-100
0
100
200
Probe detuning (kHz)
200 μW
100 μW
50 μW
25 μW
Probe
+Control

Photon blockade vs. blockade laser power



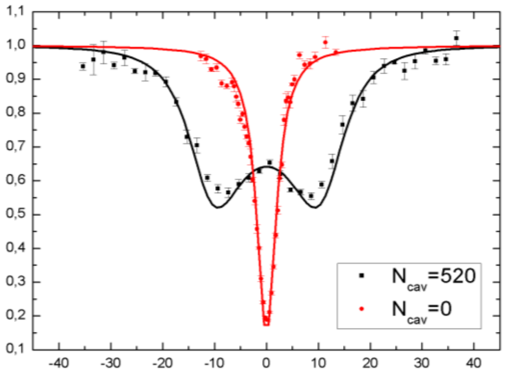
Corresponds to ~25.000 blockade photons in cavity at a detuning of 4.3 GHz

The same shift obtainable for a few photons tuned close to resonance !

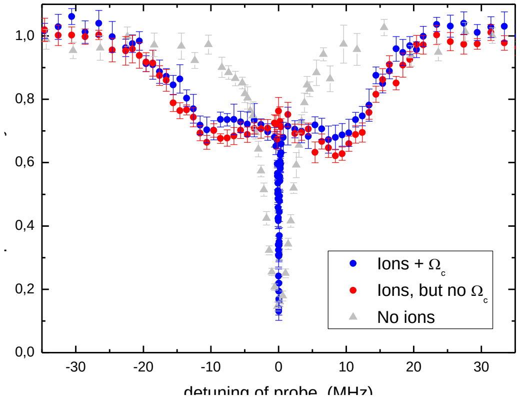
Nature Photonics, **5**, 633 (2011)

IV) Conclusion

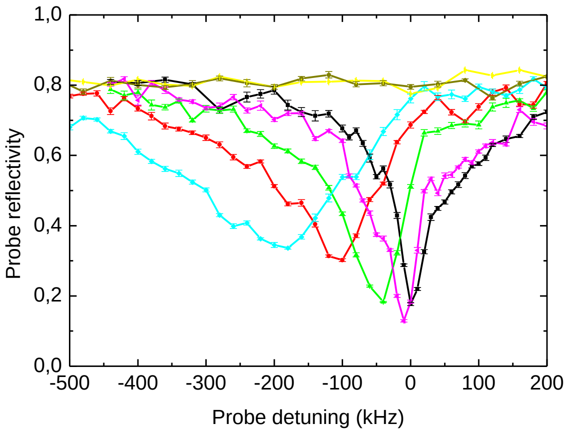
- Collective strong coupling has been realized with ion Coulomb crystals.



- Cavity EIT in the collective strong coupling regime has been demonstrated.



- A photon blockade mechanism has been demonstrated via a 4-level scheme in the $^{40}Ca^+$ ion.



- More to come …

People involved:

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Joan Marler (Post Post Doc)
Peter Herskind (Post PhD)
Magnus Albert (PhD)
Rasmus B. Linnet (PhD)
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