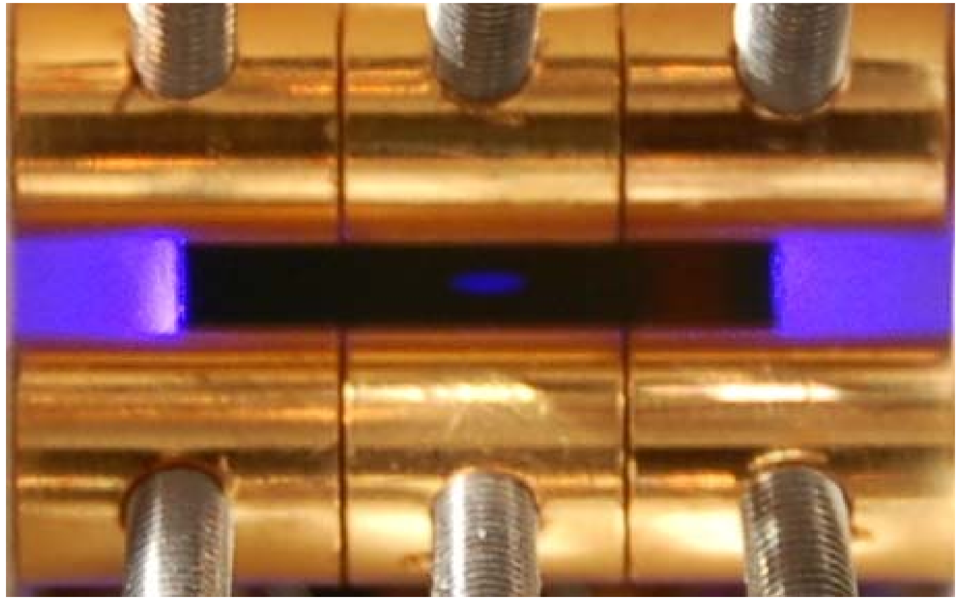
Cavity QED with ion Coulomb crystals



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2010 European Conf. on Trapped Ions , Redworth Hall, UK, Sept. 22, 2010

Why cavity QED with ion Coulomb crystals ?

I) Quantum information:

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

II) Cavity optomechanics:

III) Plasma physics:

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

Outline

I) Brief introduction to the production of ion Coulomb crystals

II) Cavity Quantum ElectroDynamics (CQED) in short

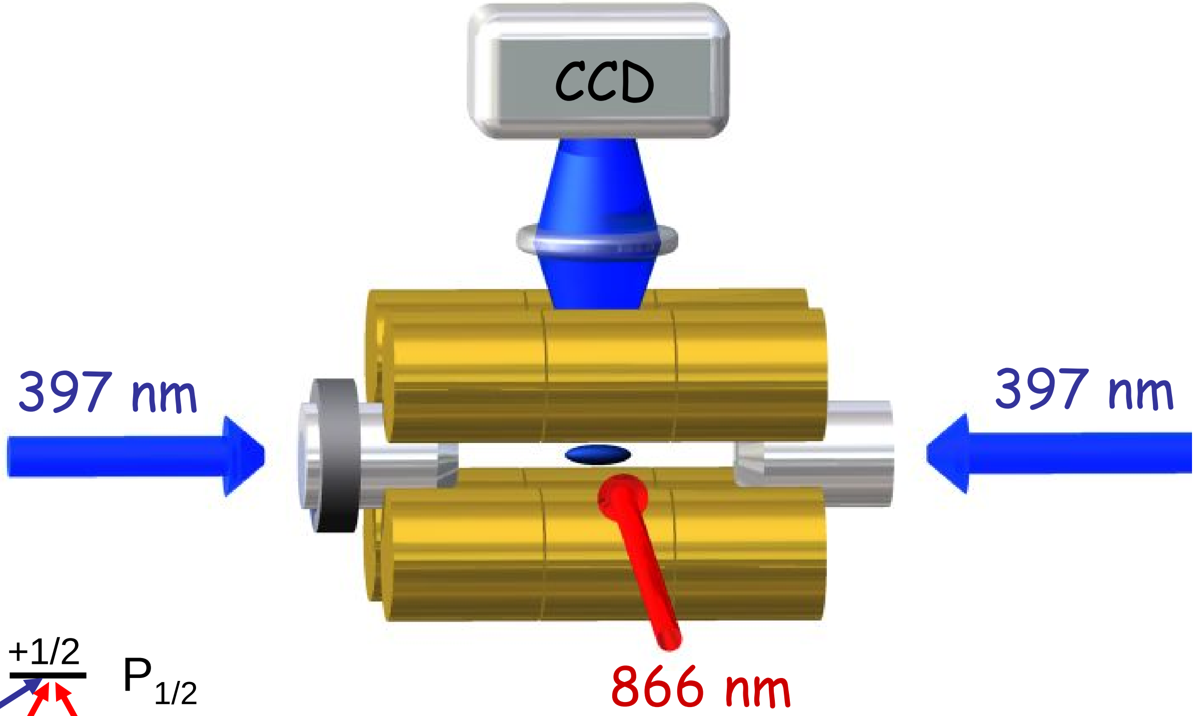
III) CQED experiments with Coulomb crystals

- Collective strong coupling
- Crystal normal-mode spectroscopy
- Cavity EIT
- Weak field induced photon blockade

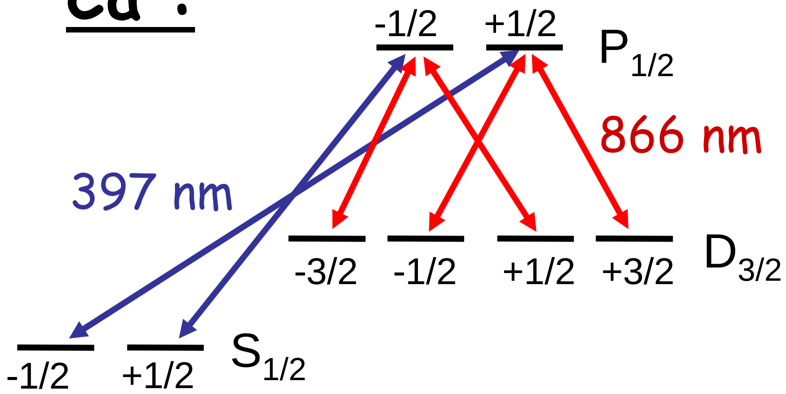
IV) Conclusion

I) Brief introduction to our production of ion Coulomb crystals

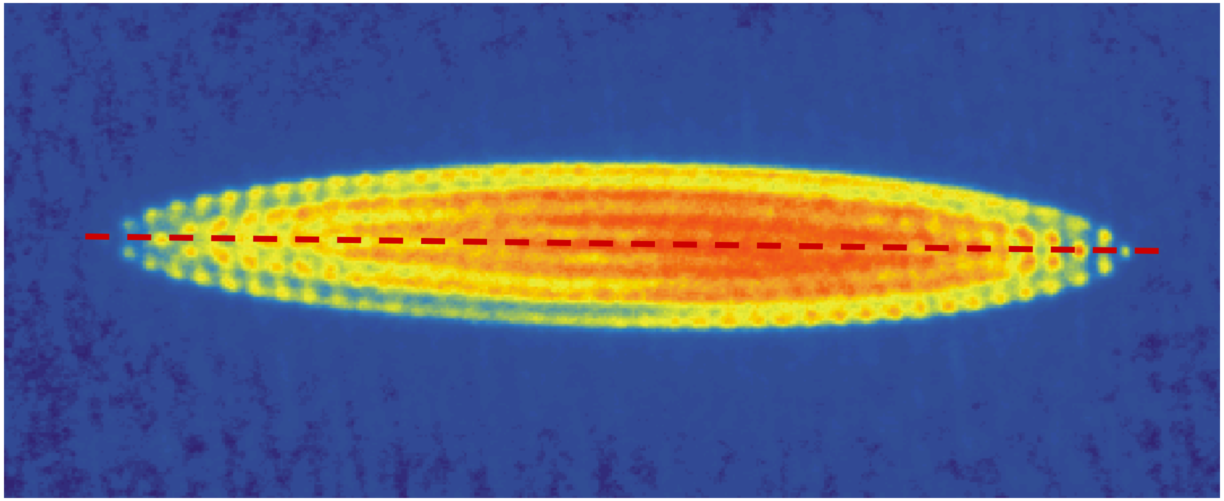
Laser cooling of trapped ions:

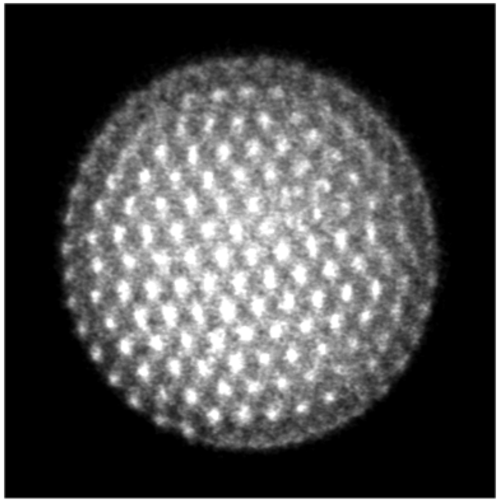


Ca⁺:



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

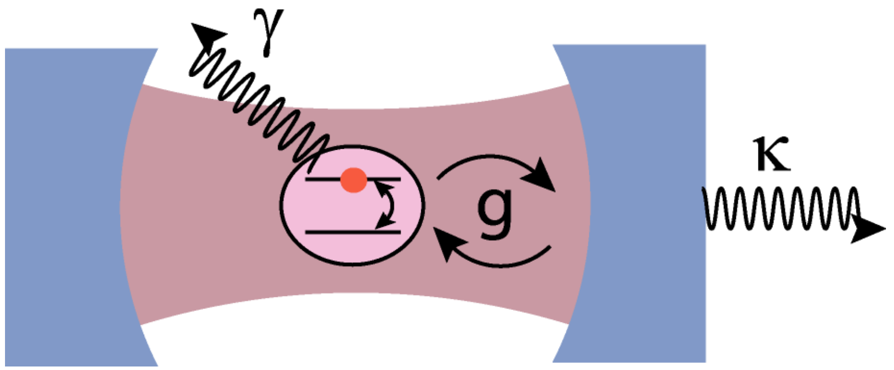
Unique feature of these solids:

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

Exploring 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:

$g > \gamma, \kappa$

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

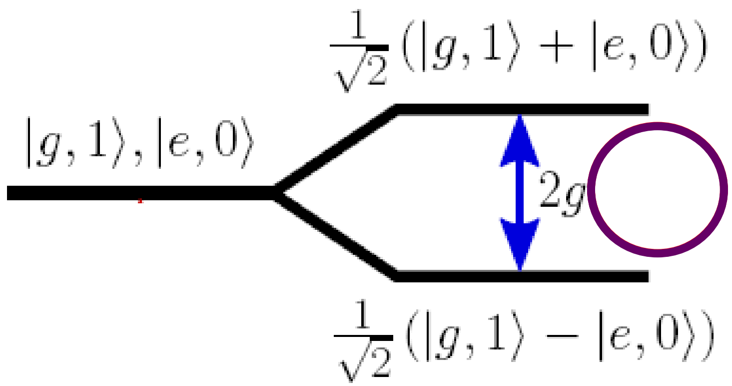
Single photon
Rabi splitting

Hallmark of CQED !

III) CQED experiments with Coulomb crystals

Why Coulomb crystals ?

Interaction with a single photon



For multi-particle states:

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

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

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

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

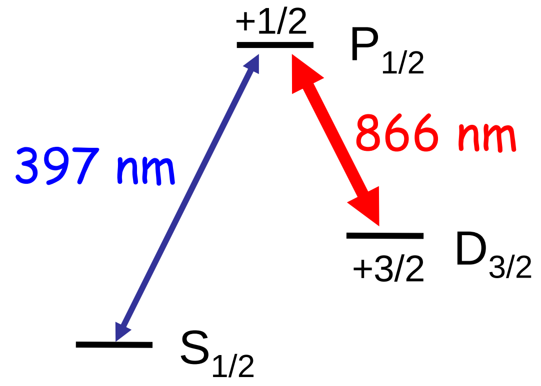
Collective coupling: $g_{eff} = gN^{1/2}$ => Collective strong coupling regime accessible ($g_{eff} > \kappa, \gamma$)

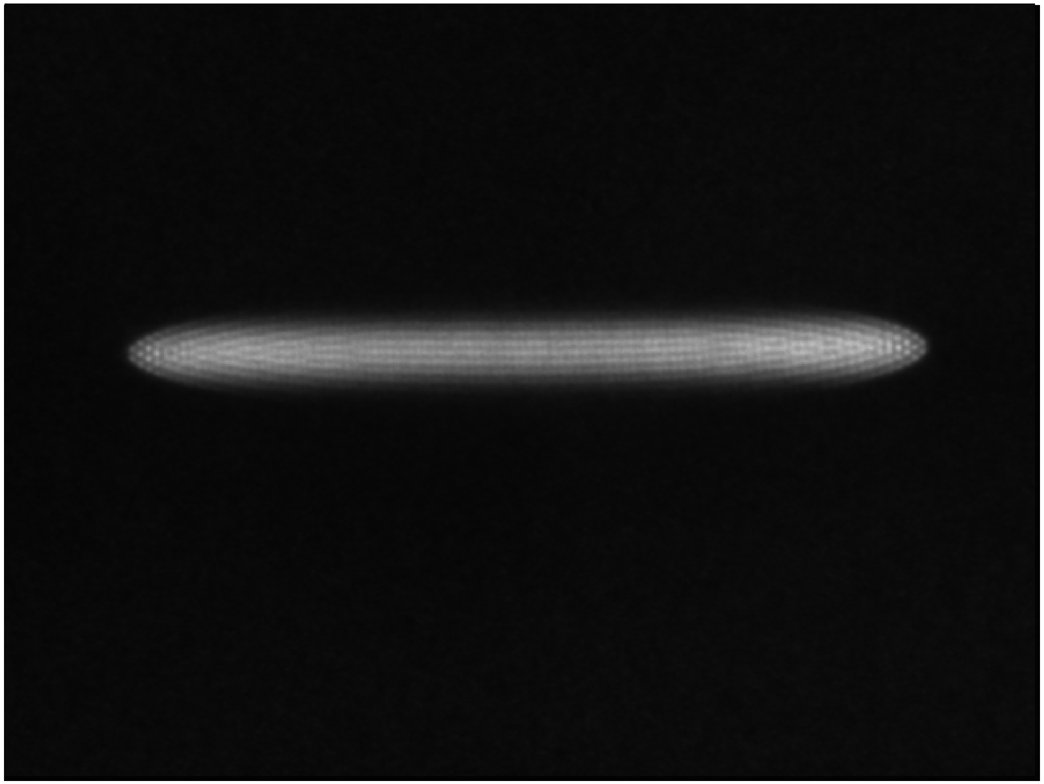
N can be varied "continuously" from 1 to ~ 2000

Good overlap between cavity mode and ions in Coulomb crystals

Micro-meter positioning control: J. Phys. B, 42, 154008 (2009)

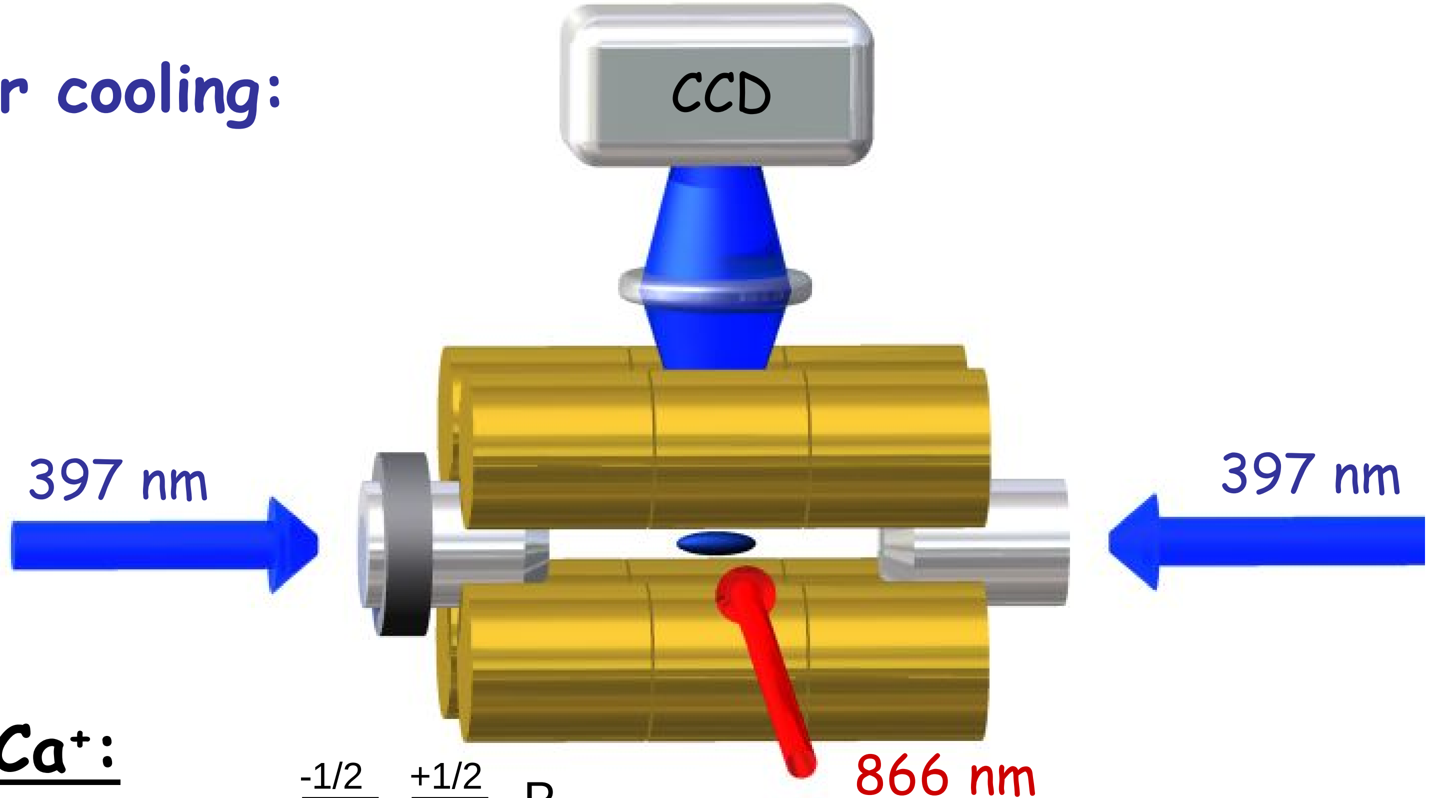
The $^{40}Ca^{+}$ ion:

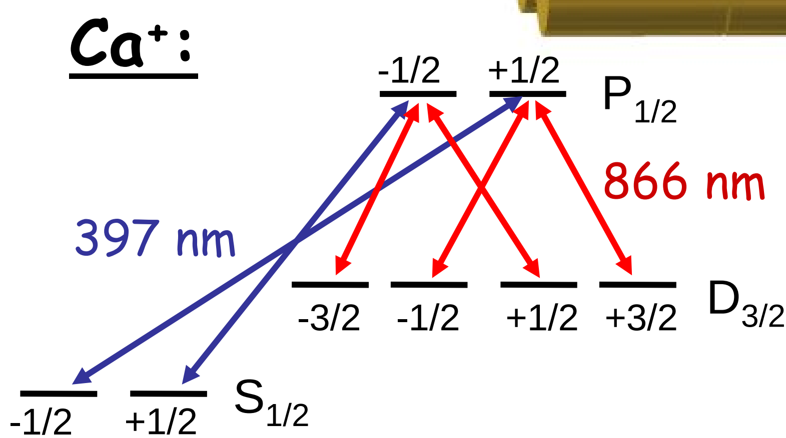




Experimental Sequence

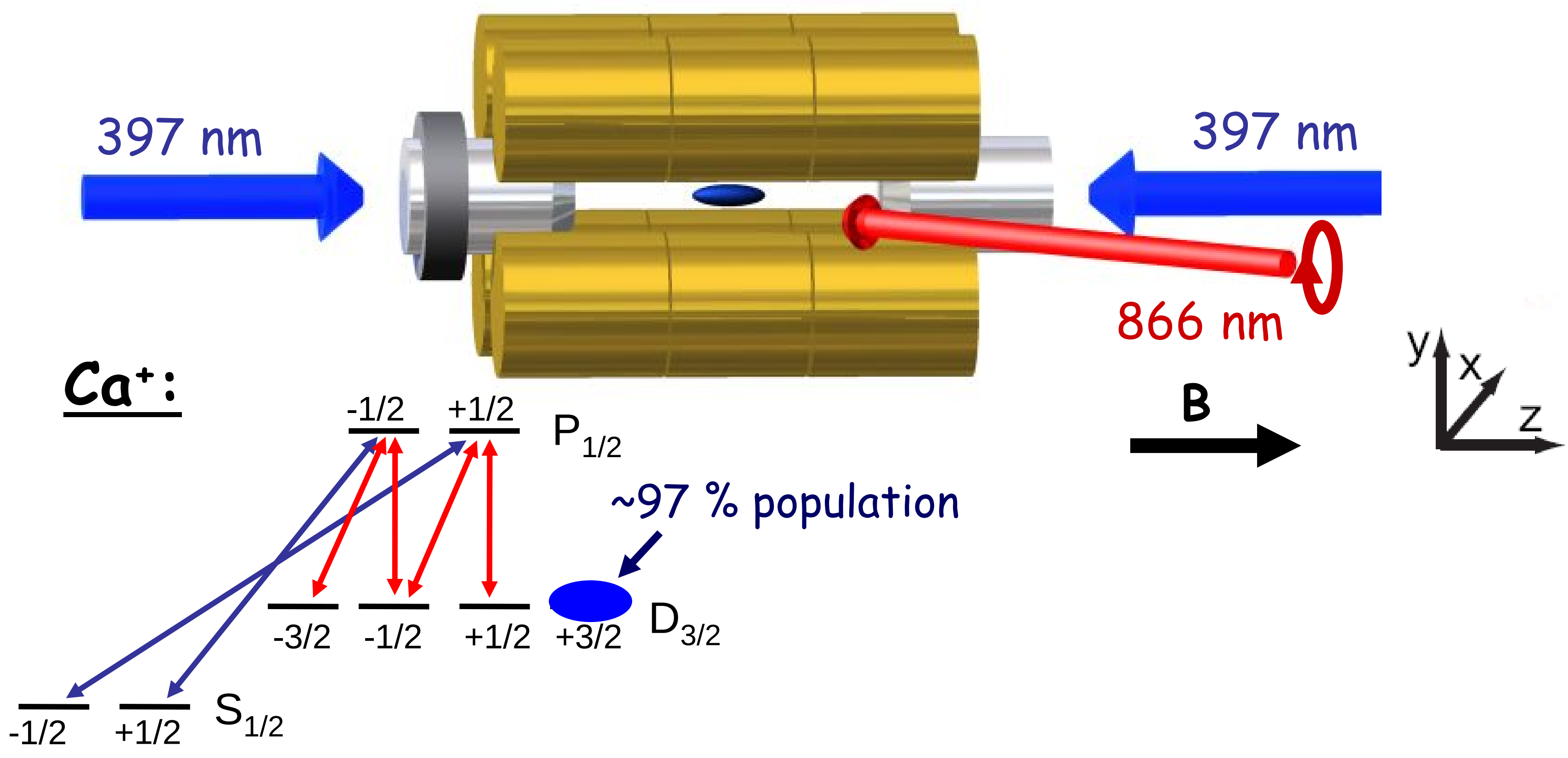
Laser cooling:





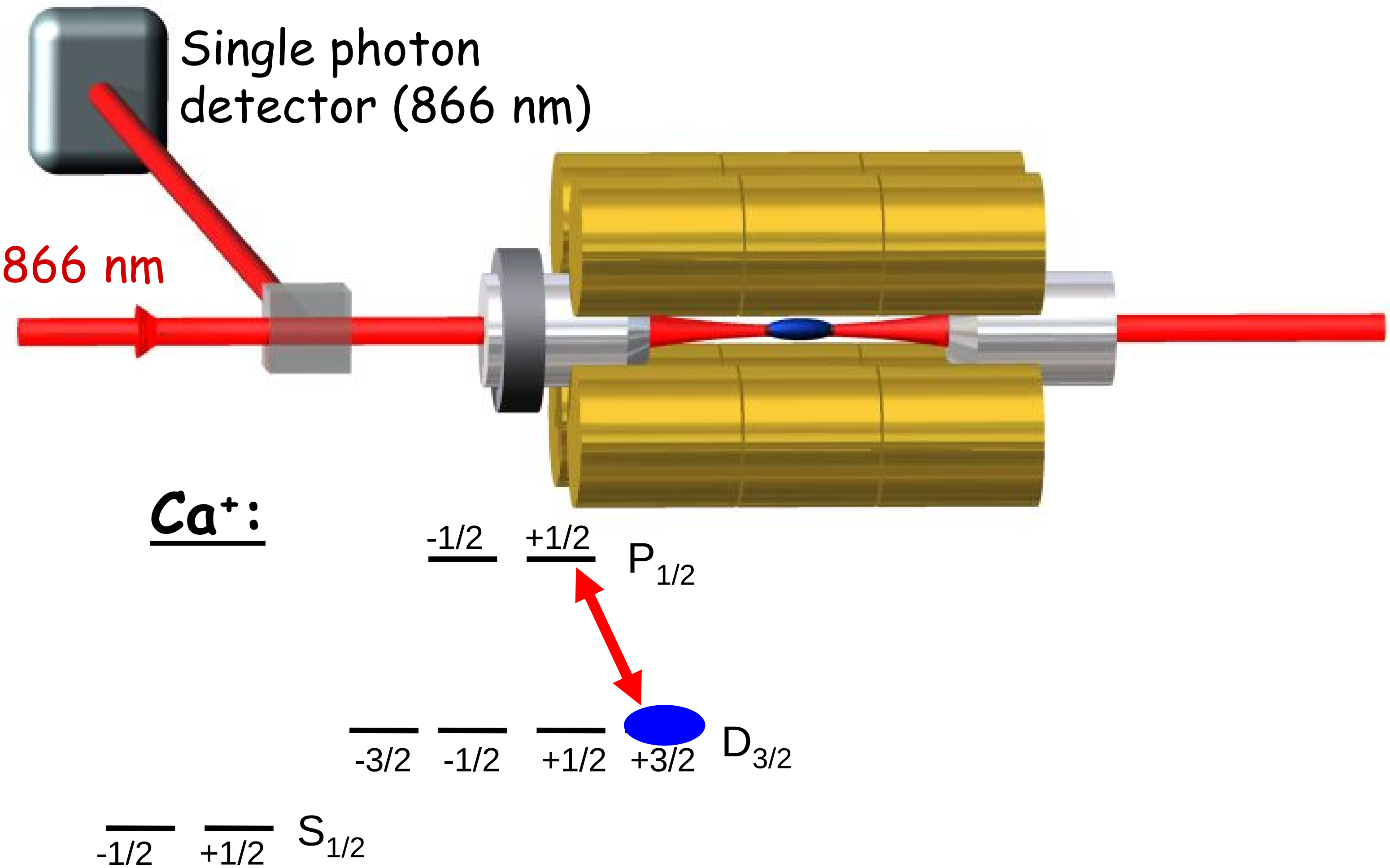
Experimental Sequence

Optical pumping:



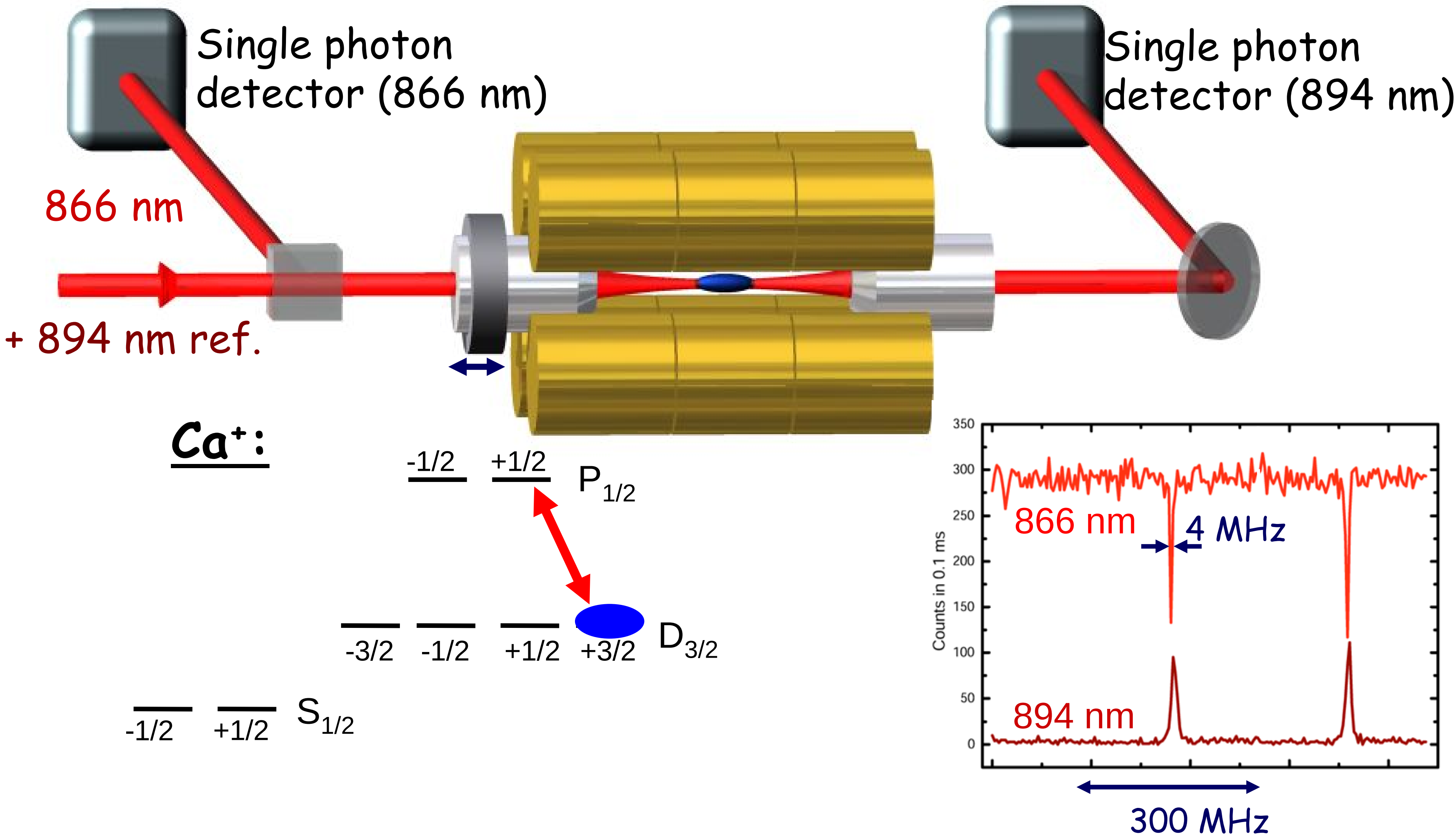
Experimental Sequence

Cavity probing:

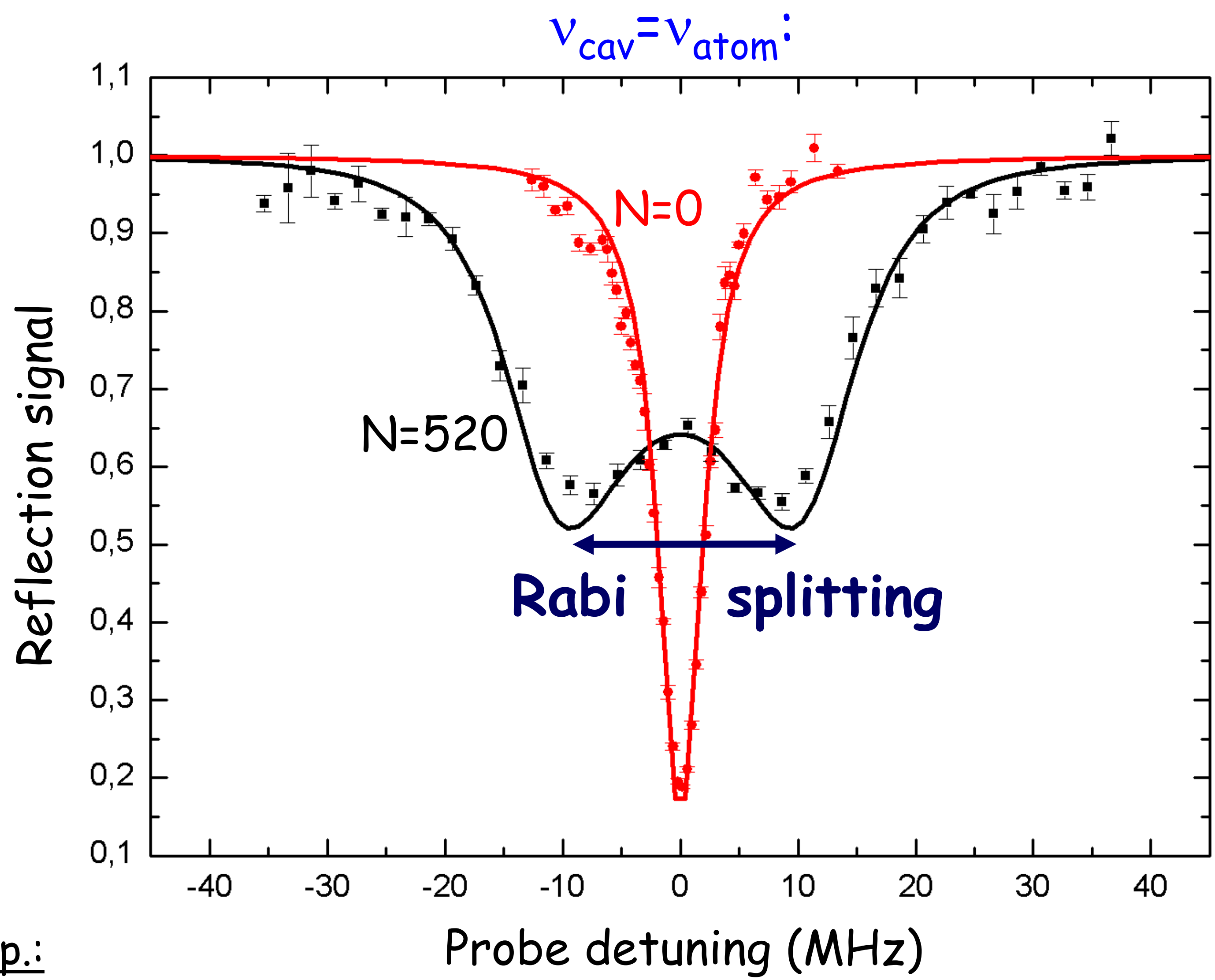


Experimental Sequence

Cavity probing:



Observation of single photon Rabi splitting

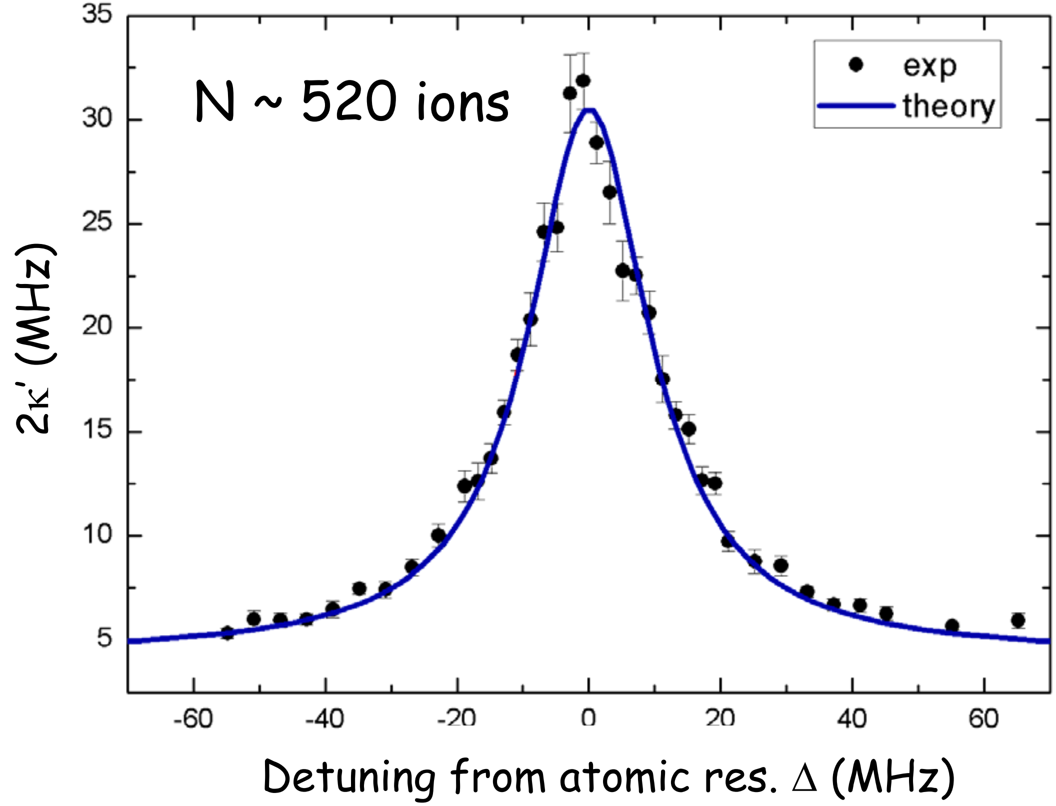


<u>First exp.:</u>

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

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

Reflection signals for a *scanning* cavity



Resonance half-width

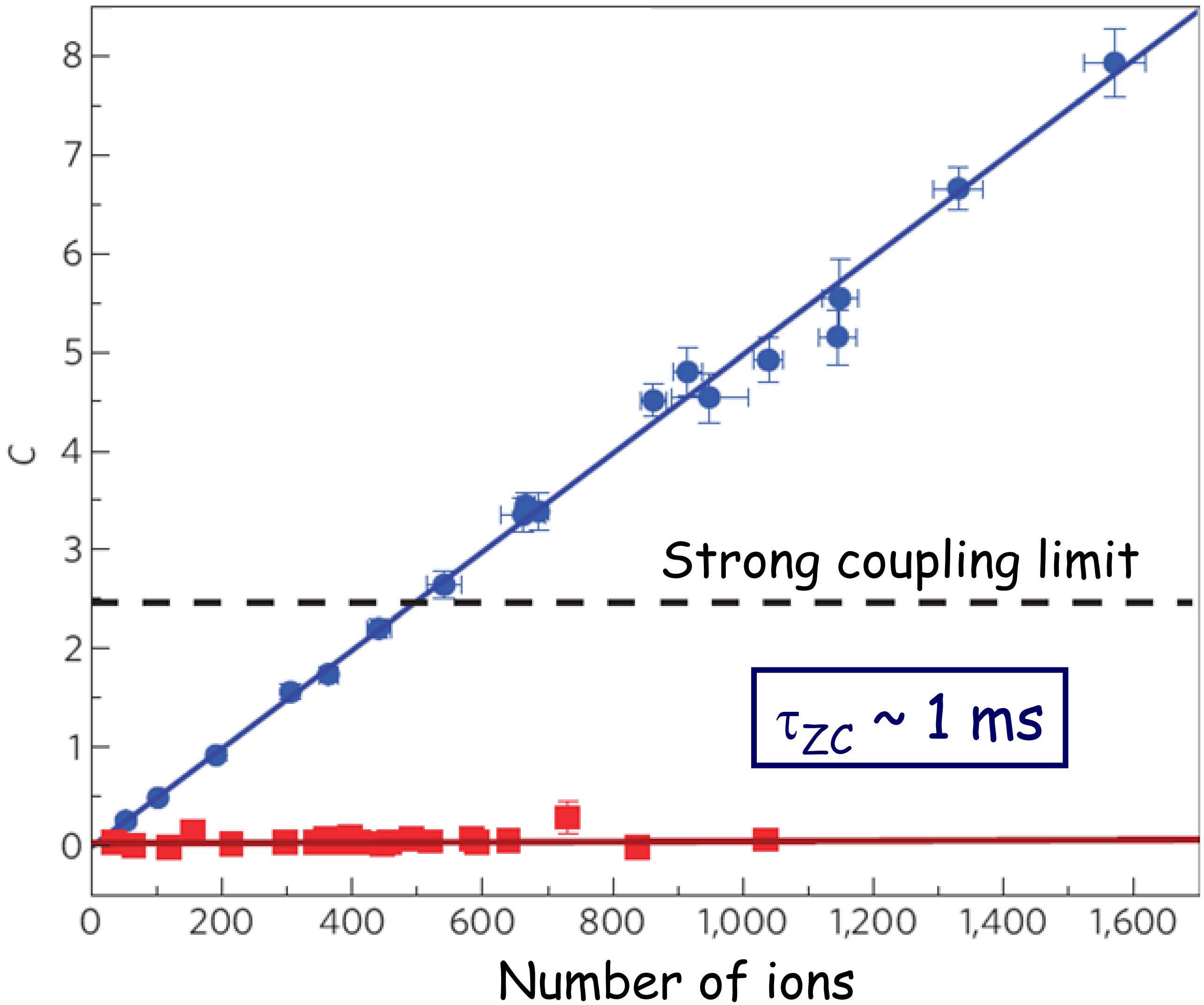
$$\kappa' = \kappa\left(1 + C\frac{1}{1+(\Delta/\gamma)^2}\right)$$

$$C = \frac{Ng^2}{2\kappa\gamma}$$ (Cooperativity)

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

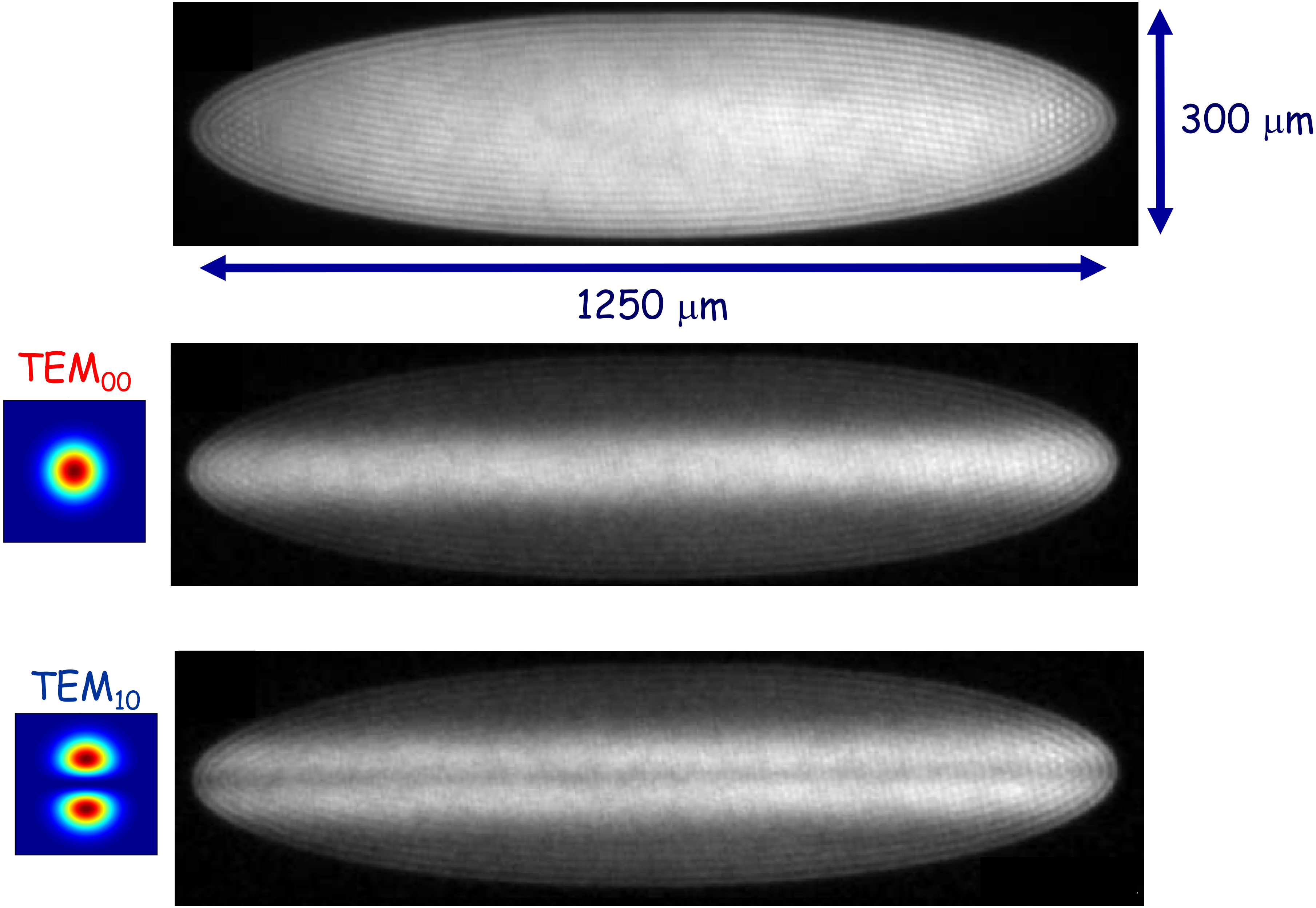
Cooperativity C vs. number of ions

$$C = \frac{Ng^2}{2\kappa\gamma}$$ ~ 95% of expected value

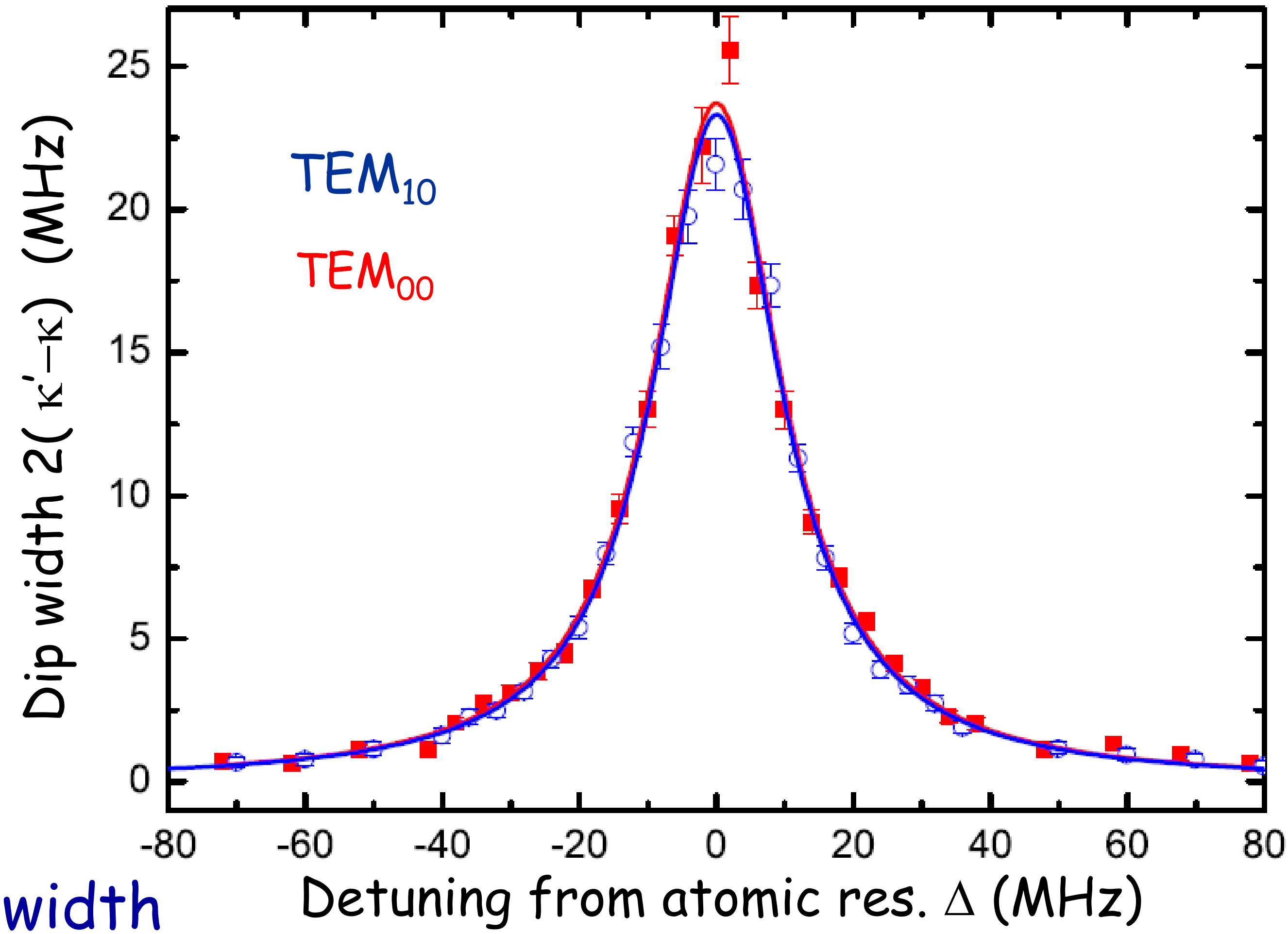


Nature Physics **5**, 494 (2009)

Collective coupling for different TEM_{nm} modes



Collective coupling strength with a large crystal



Dip half-width

$$\kappa' = \kappa = \kappa C \frac{1}{1+(\Delta/\gamma)^2}$$

$$C = \frac{Ng^2}{2\kappa\gamma}, \quad Ng^2 \equiv G_{nm}$$

$G_{00} = 2\pi\,(11.6 \pm 0.1)$ MHz.

$G_{10} = 2\pi\,(11.5 \pm 0.1)$ MHz.

Phys. Rev. A, 041802 (R) (2009)

Crystal normal-mode spectrocopy

Crystal eigenmodes

Discrete charges:

3N normal modes (N particles)

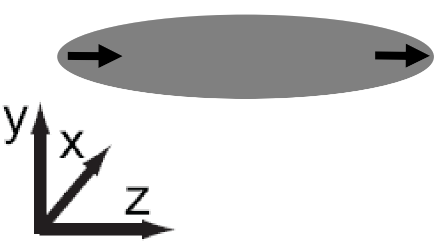
Charged Spheroidal fluids:

(l,m)-modes, l=1,2,3,... ; m=-l,-l+1,...,0,,...,l-1,l

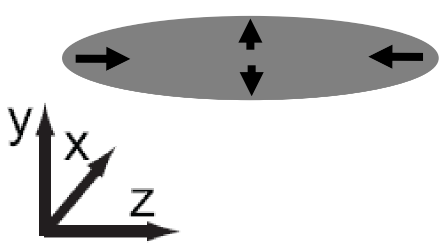
D. H. E. Dubin, Phys. Rev. Lett. **66**, 2077 (1991)
D. H. E. Dubin and J. P. Schiffer, Phys. Rev. E. **53**, 5249 (1996)
D. H. E. Dubin, Phys. Rev. E. **53**, 5268 (1996)

Ex. (l,0)-modes:

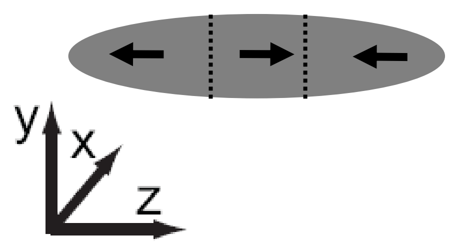
(1,0)



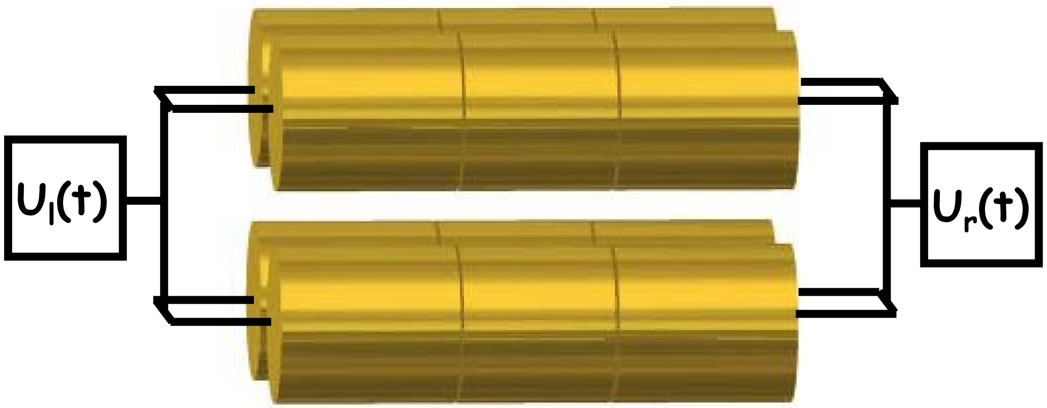
(2,0)



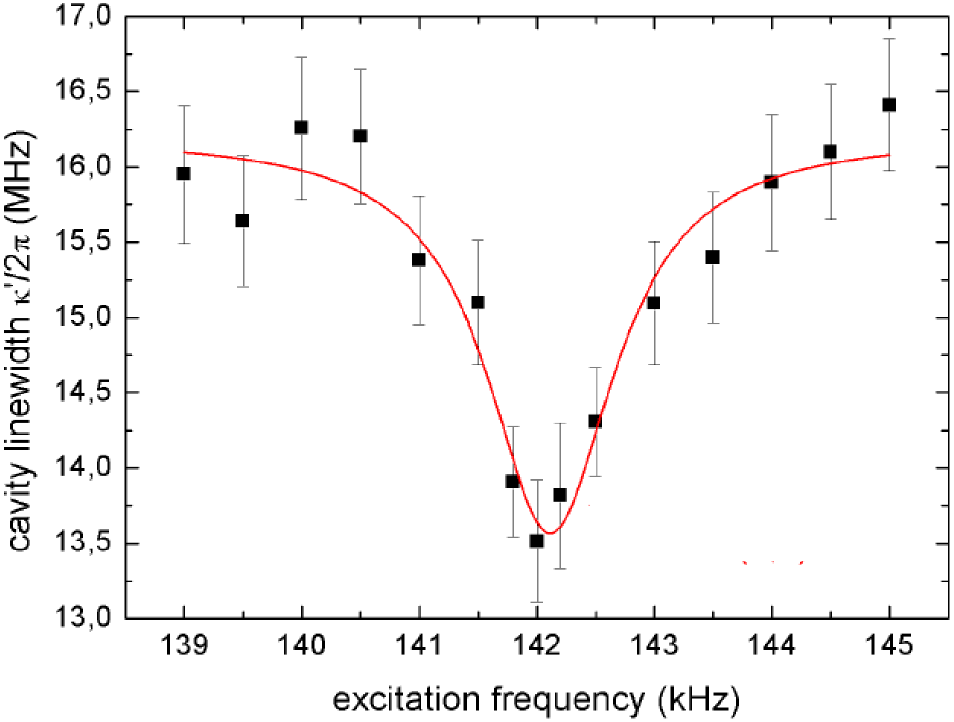
(3,0)



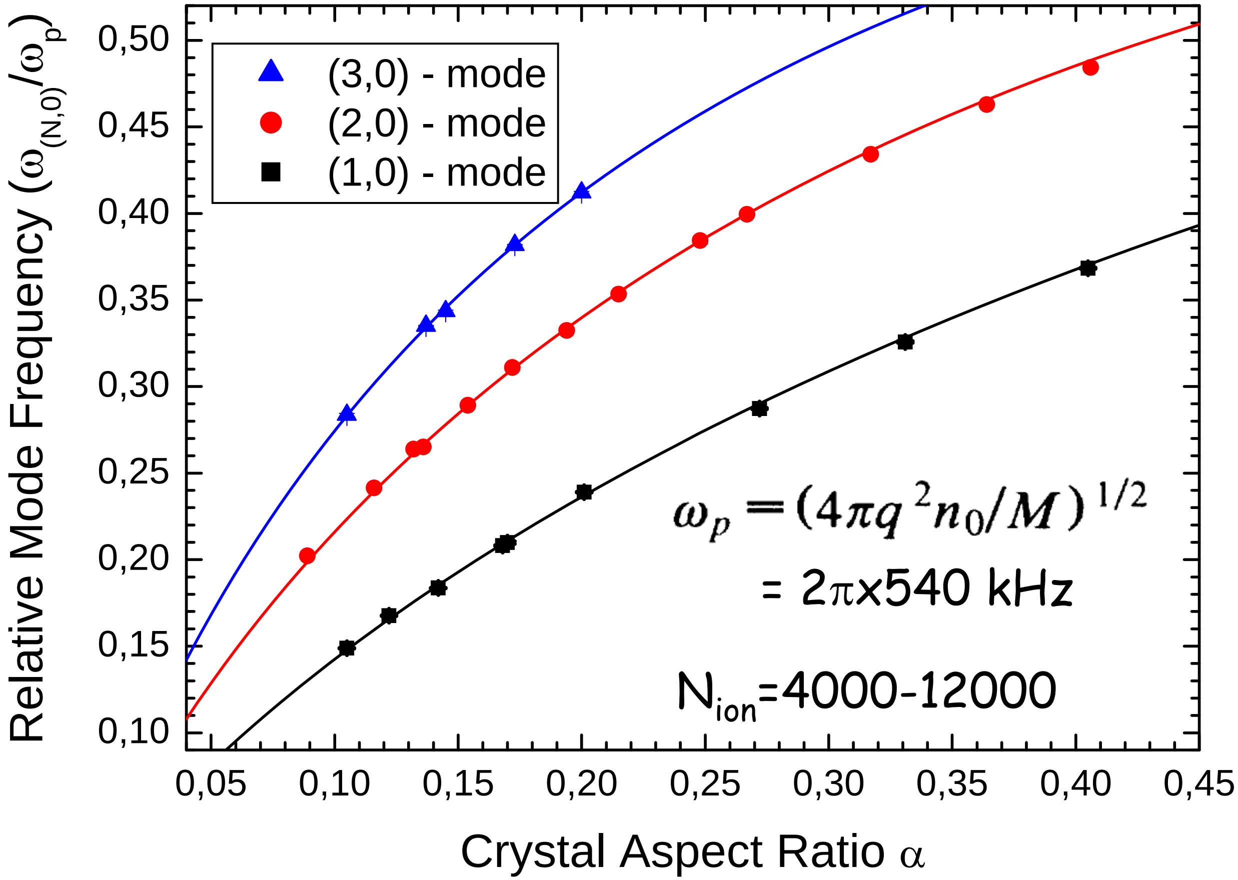
Exciation of the (l,0)-modes



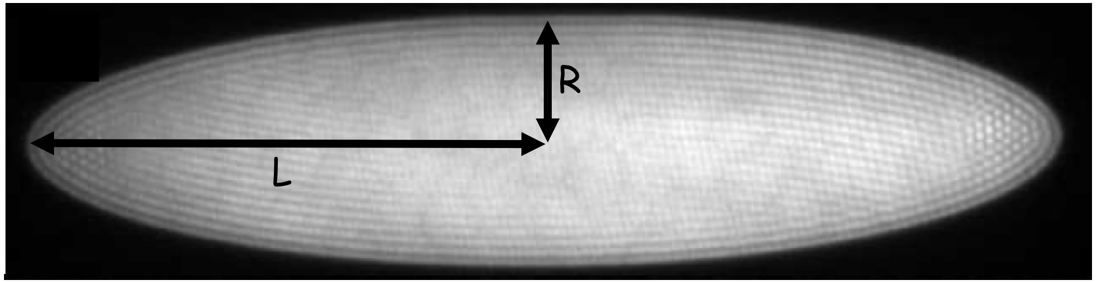
$$U_l(t) = U_0 \cos(wt) = \pm U_r(t)$$



Crystal mode frequencies vs. crystal aspect ratio



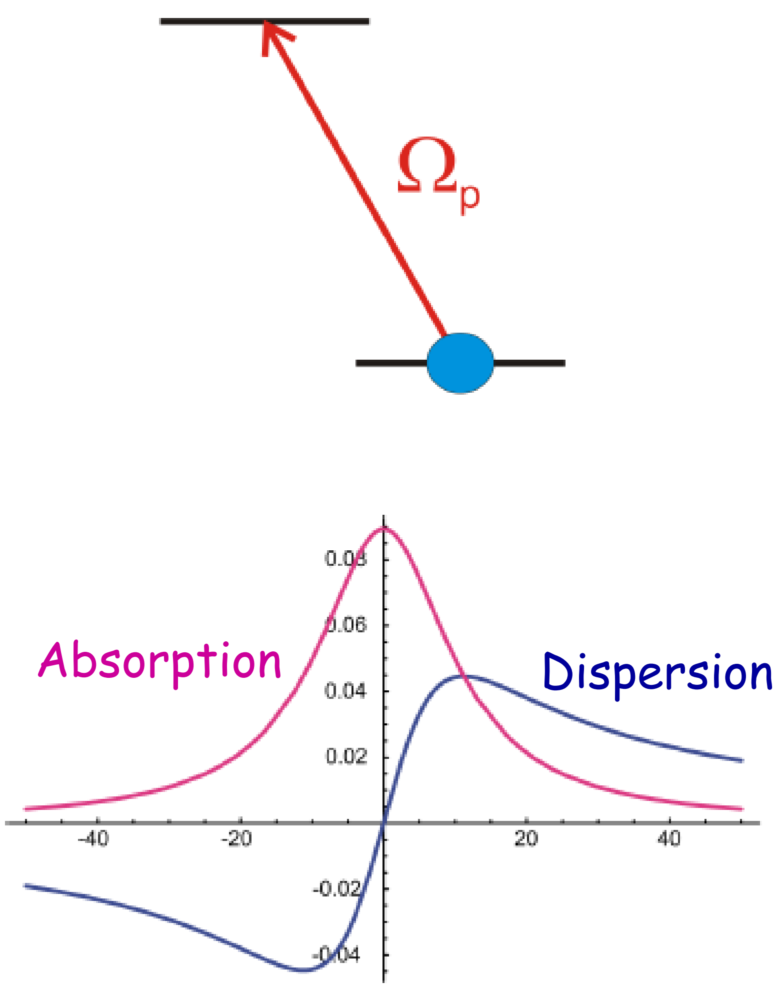
$\alpha \equiv R/L$:



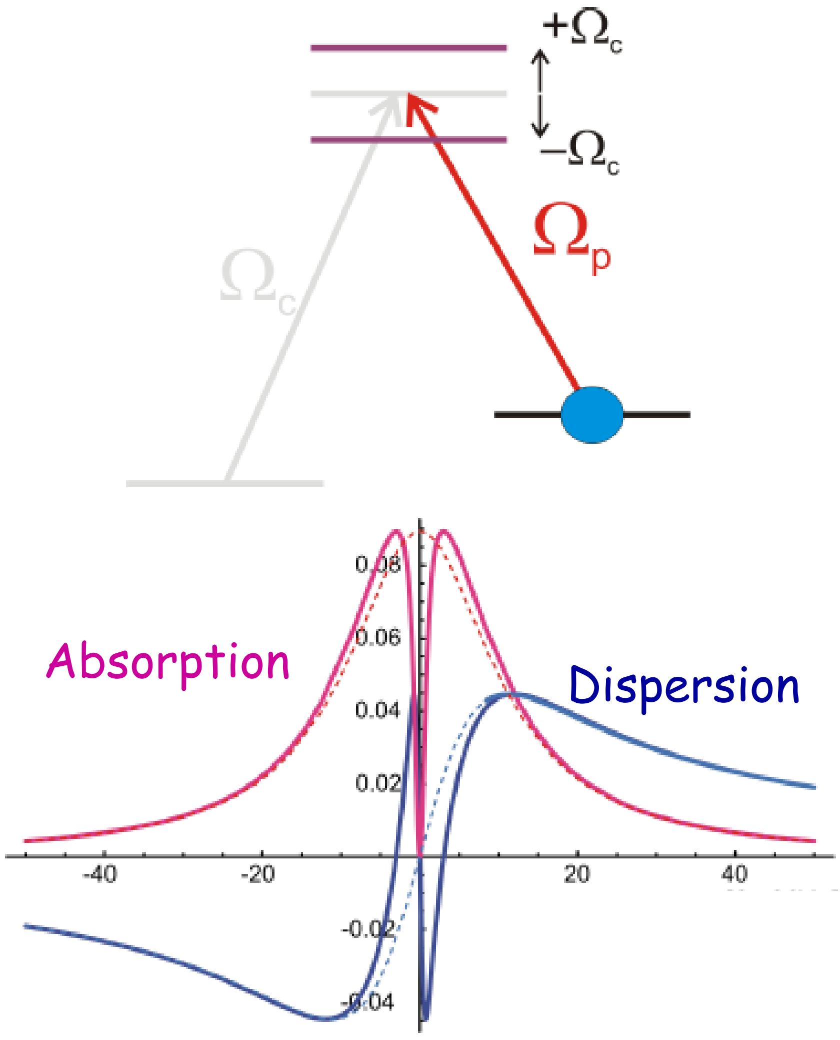
Phys. Rev. Lett. **105**, 103001 (2010)

Electromagnetically Induced Transparency (EIT)

2-level atoms

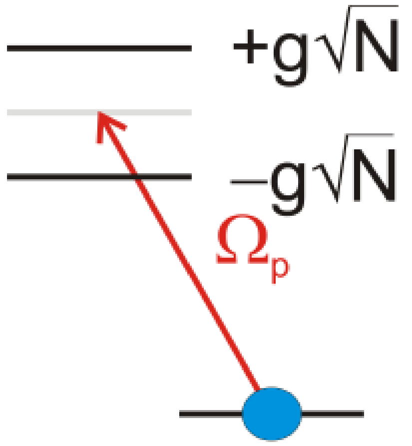


3-level atoms

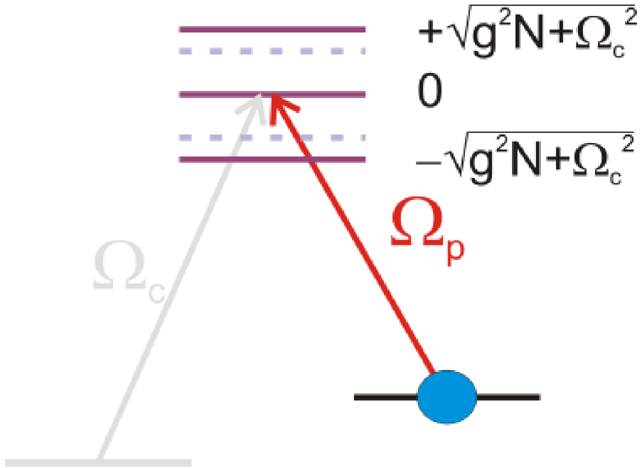


EIT in a cavity

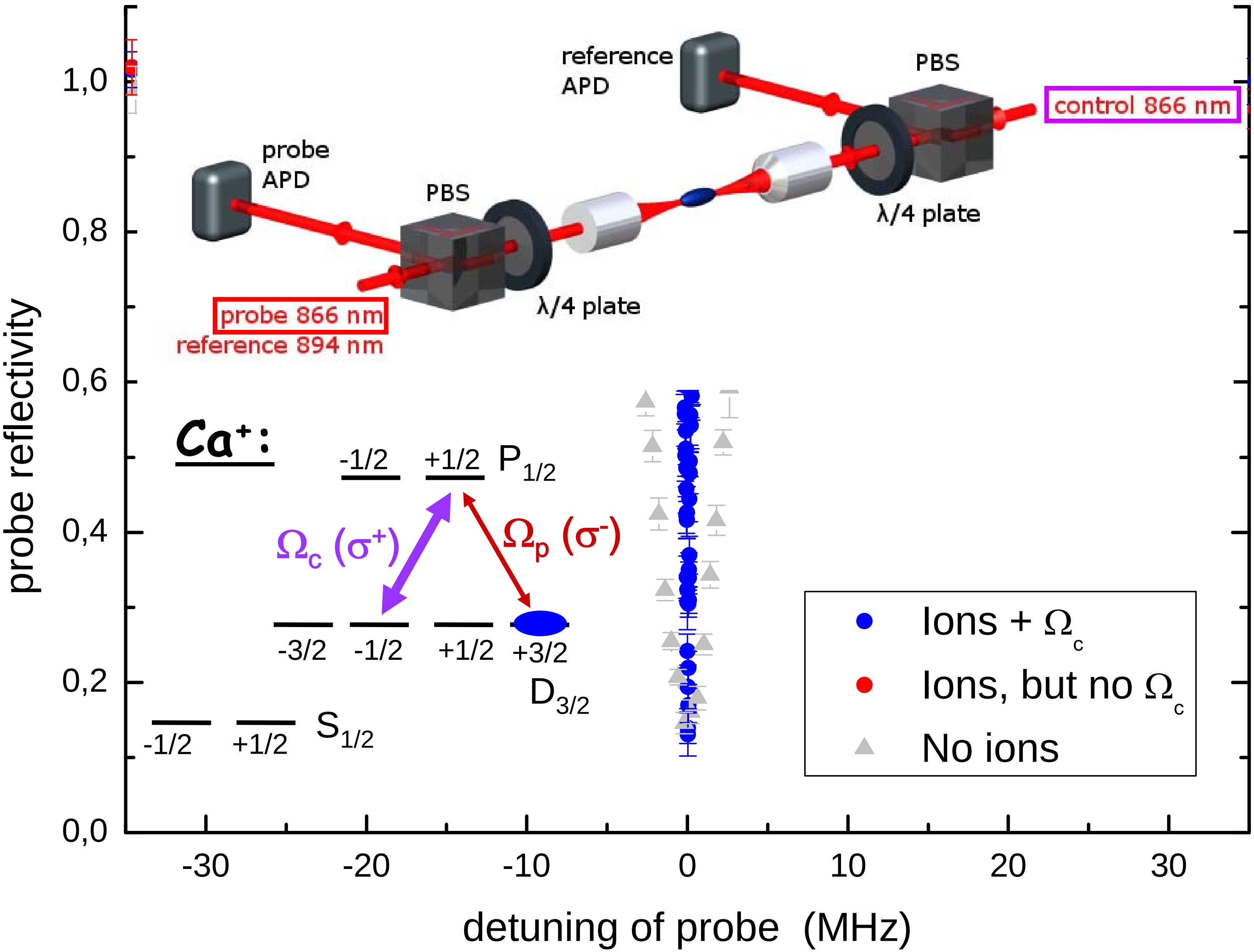
2-level atoms in cavity



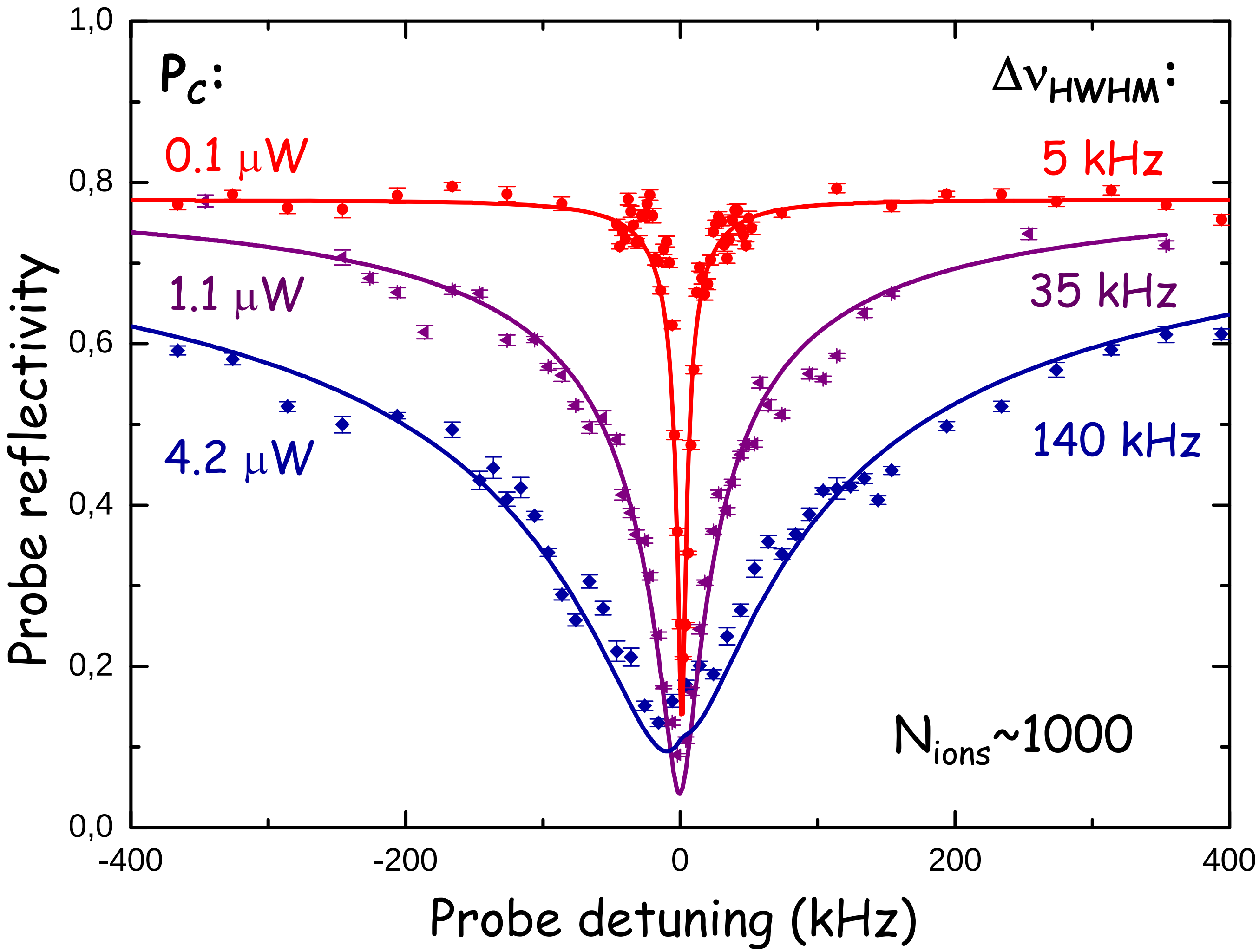
3-level atoms in cavity



Observation of triplet structure in reflection

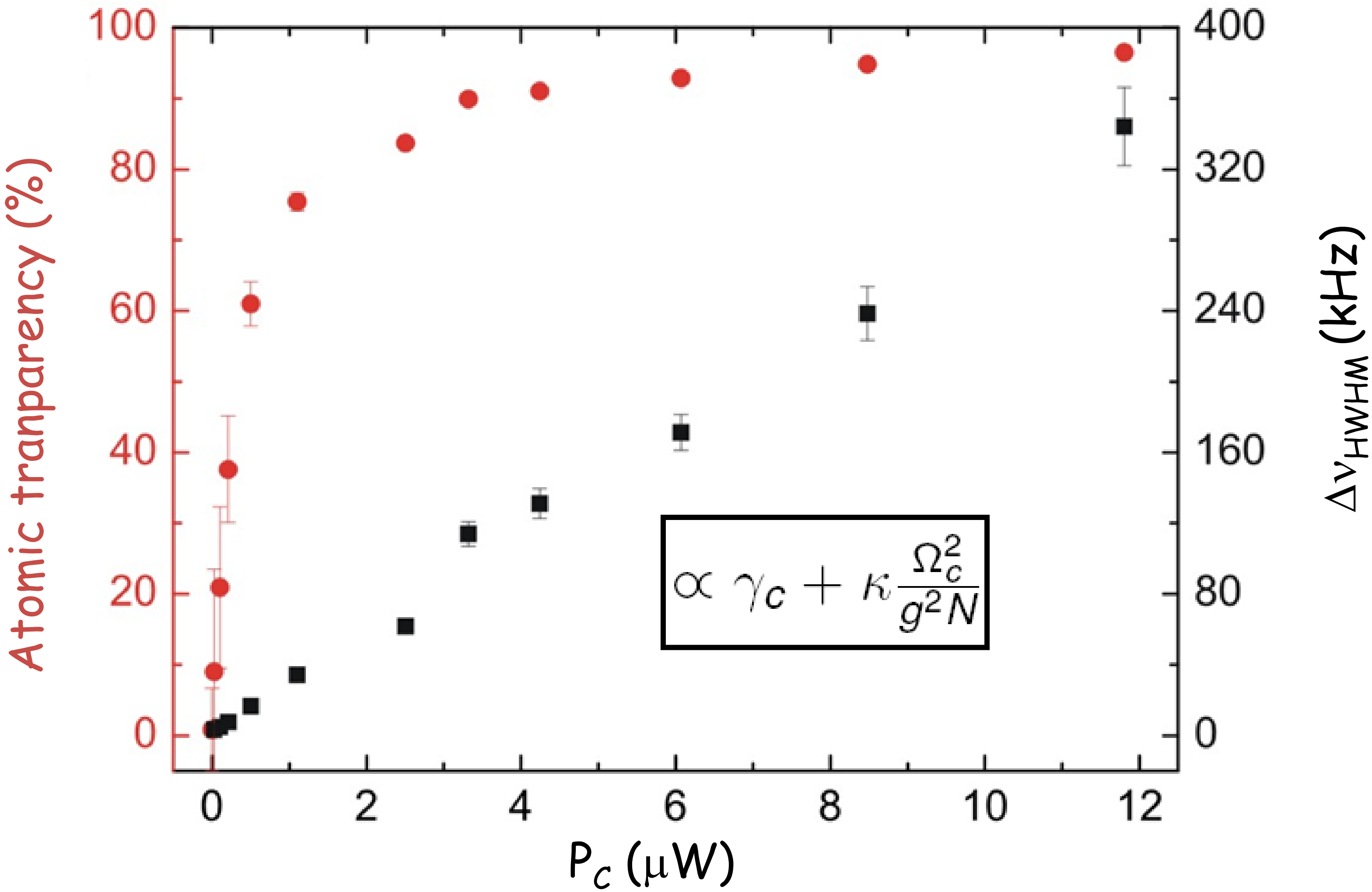


EIT feature vs. coupling laser power



Non-Lorenzian line shapes due to Gaussian mode profile

EIT feature vs. coupling laser power



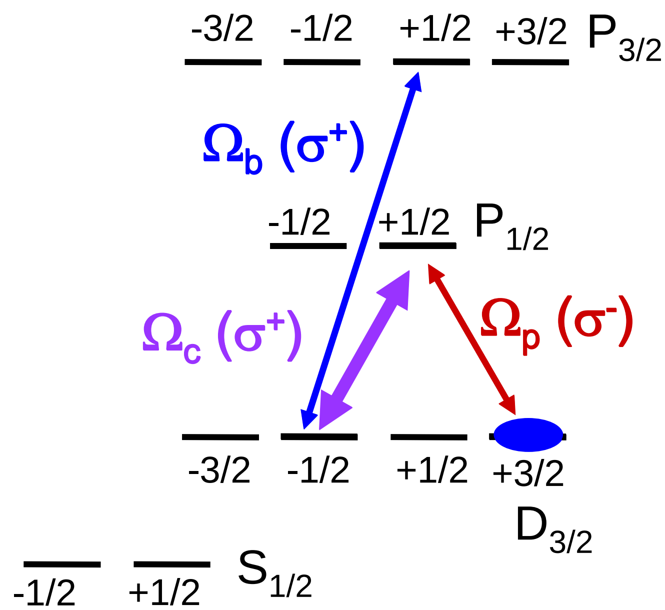
> 90 % transperency for $\Delta\nu_{HWHM}$ ~100 kHz

γ_c ~ 1 kHz

Photon blockade

Imamoglu *et al.*, Phys. Rev. Lett **79**, 1467 (1997)

Ca⁺:



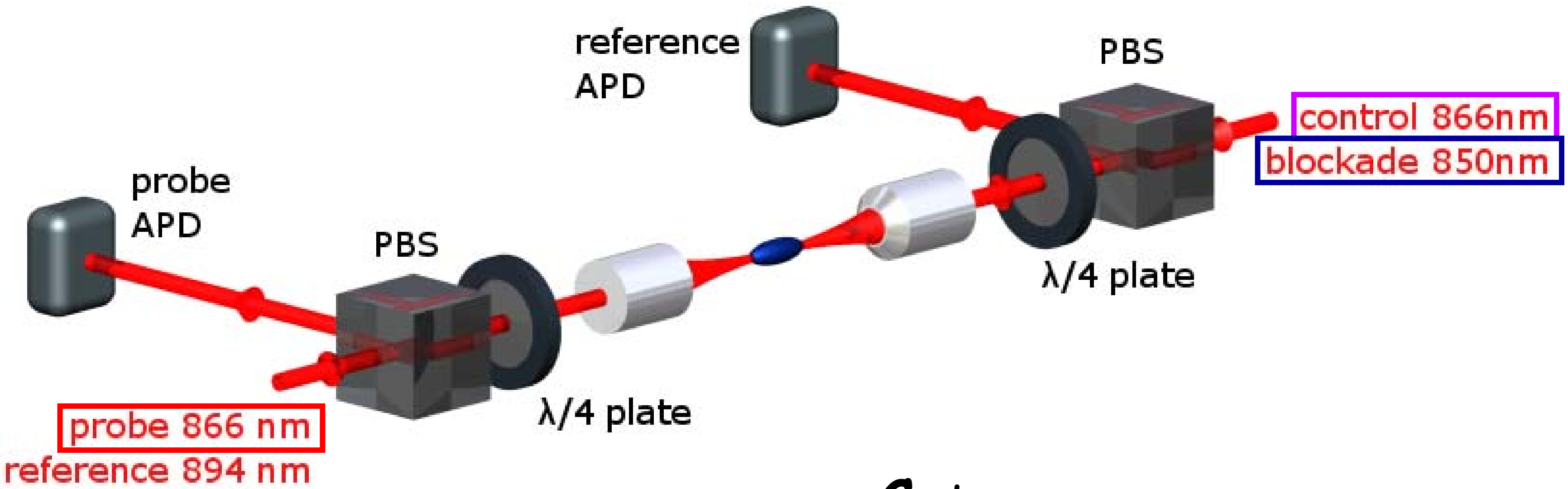
If the light shift due to Ω_b is larger than the EIT width then EIT ceases => Photon blockade !

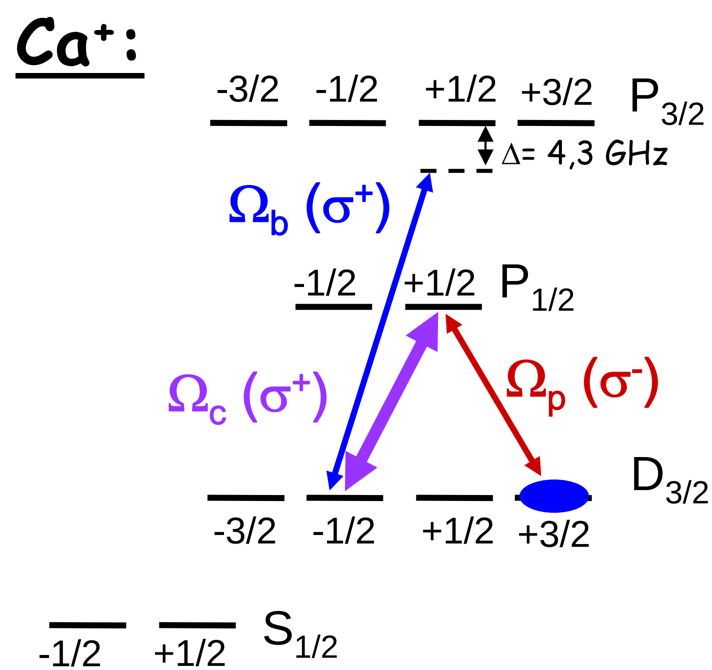
At the single photon level this would enable

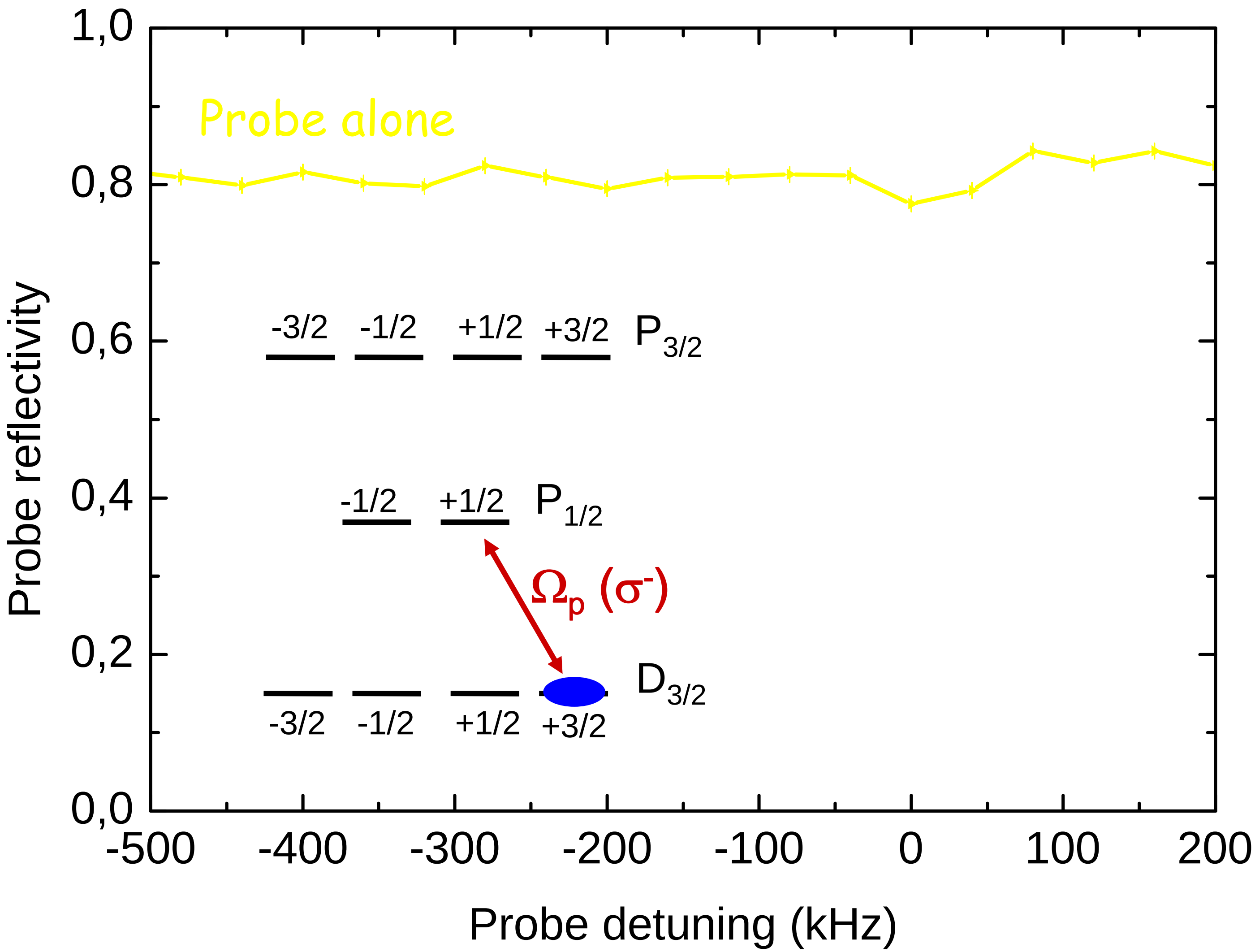
I) Single photon transistor

Very challenging !!

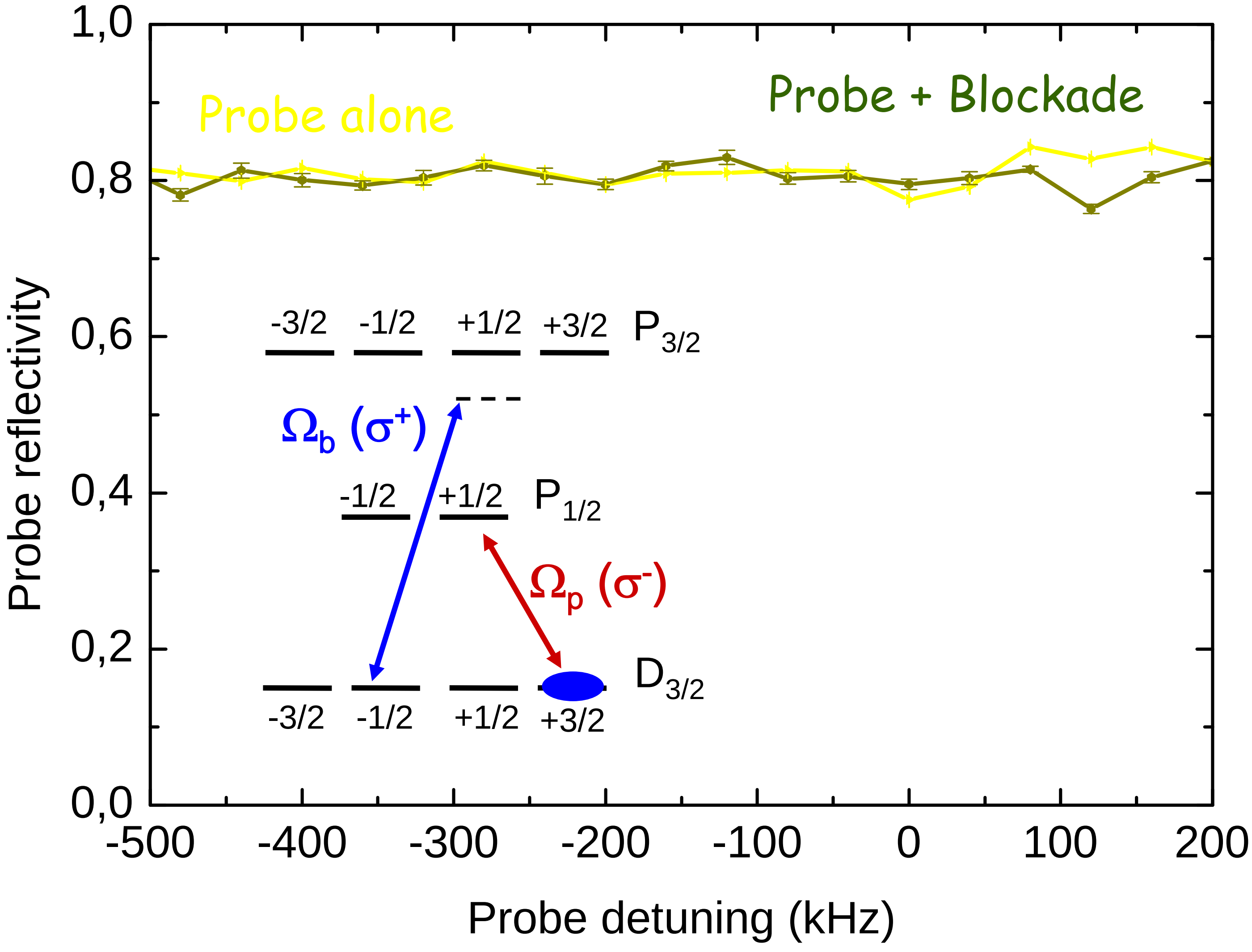
Sketch of experimental setup



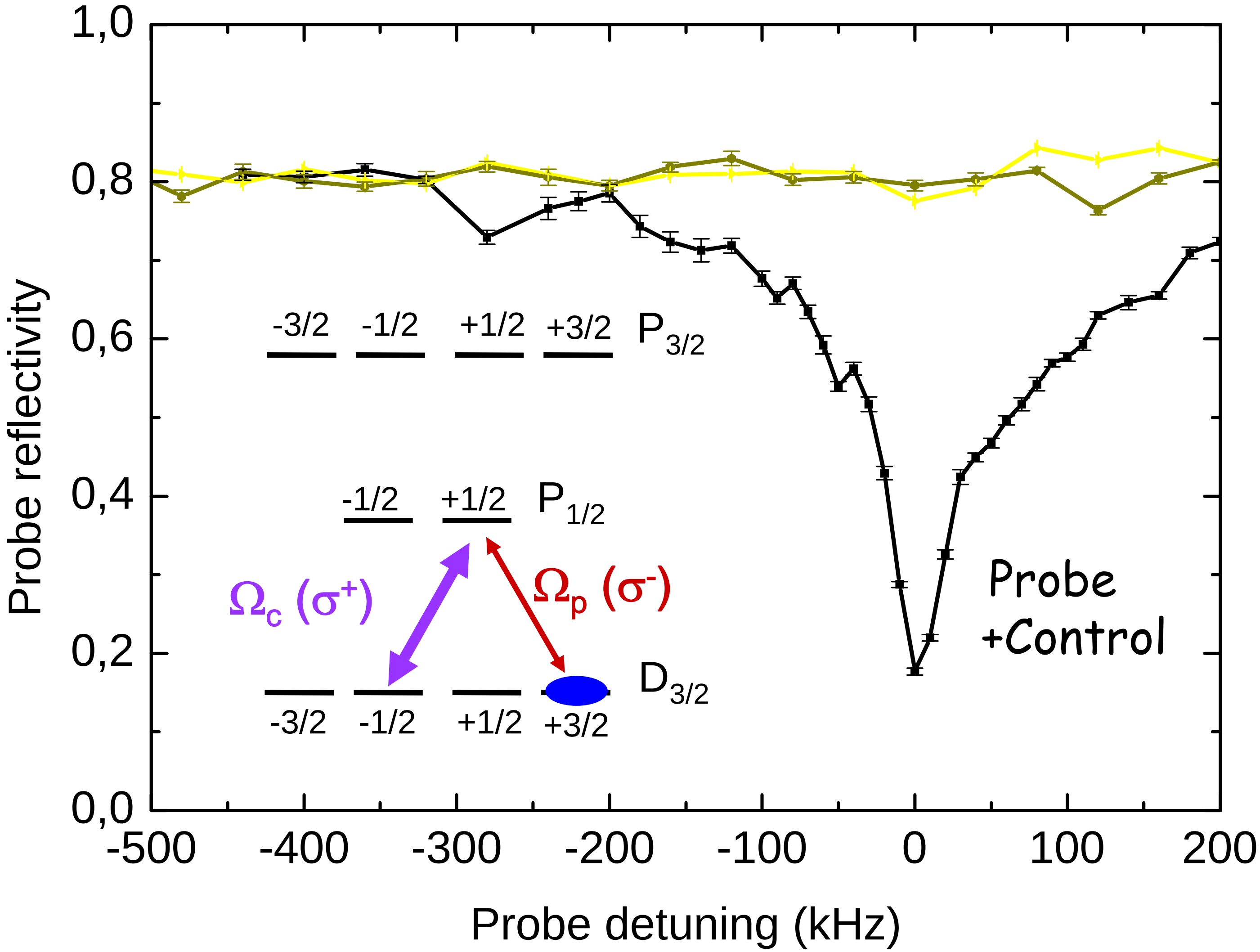




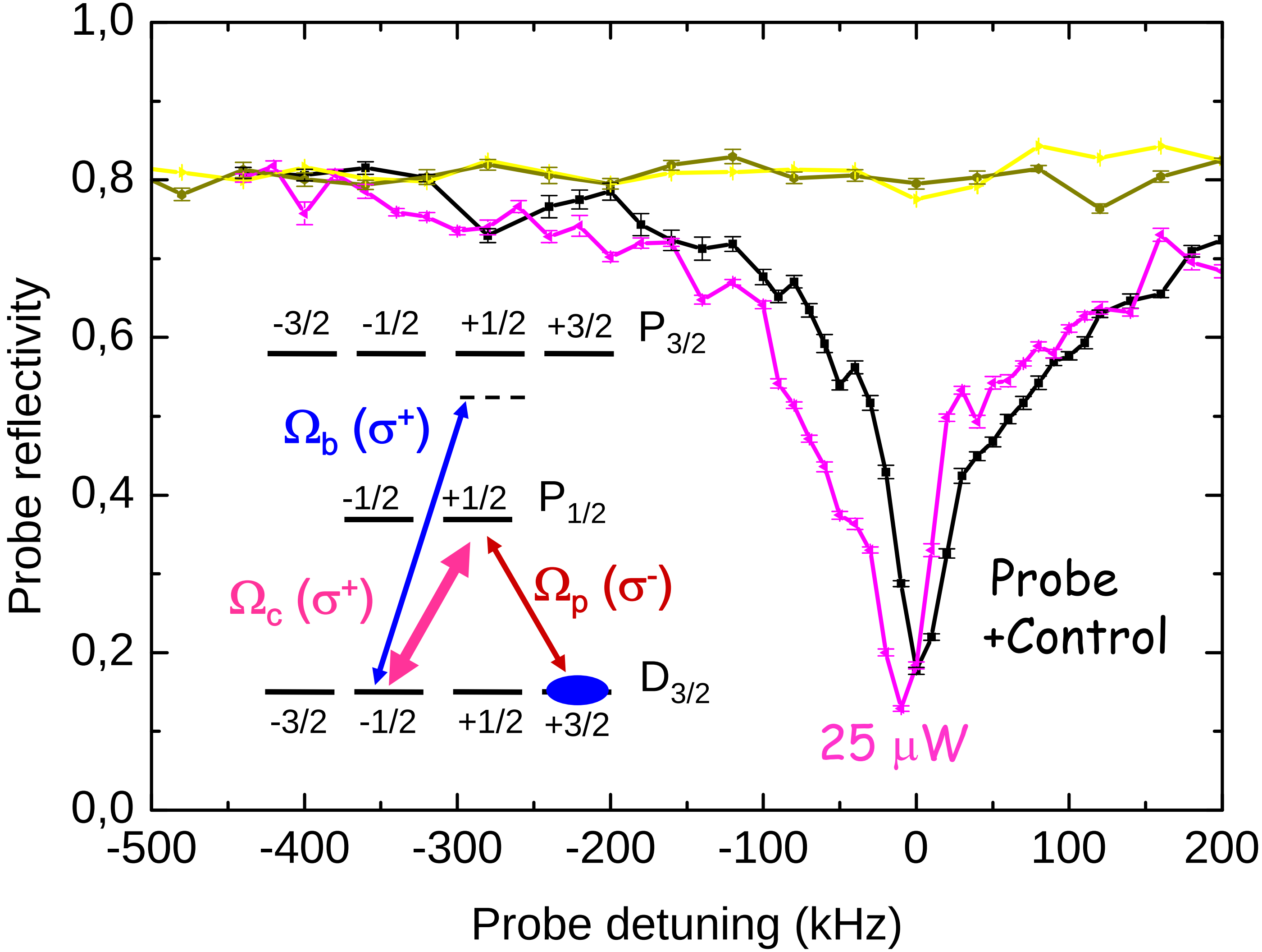
Probe alone
-3/2
-1/2
+1/2
+3/2
$P_{3/2}$
-1/2
+1/2
$P_{1/2}$
Ω_p (σ^-)
$D_{3/2}$
-3/2
-1/2
+1/2
+3/2
1,0
0,8
0,6
0,4
0,2
0,0
Probe reflectivity
-500
-400
-300
-200
-100
0
100
200
Probe detuning (kHz)



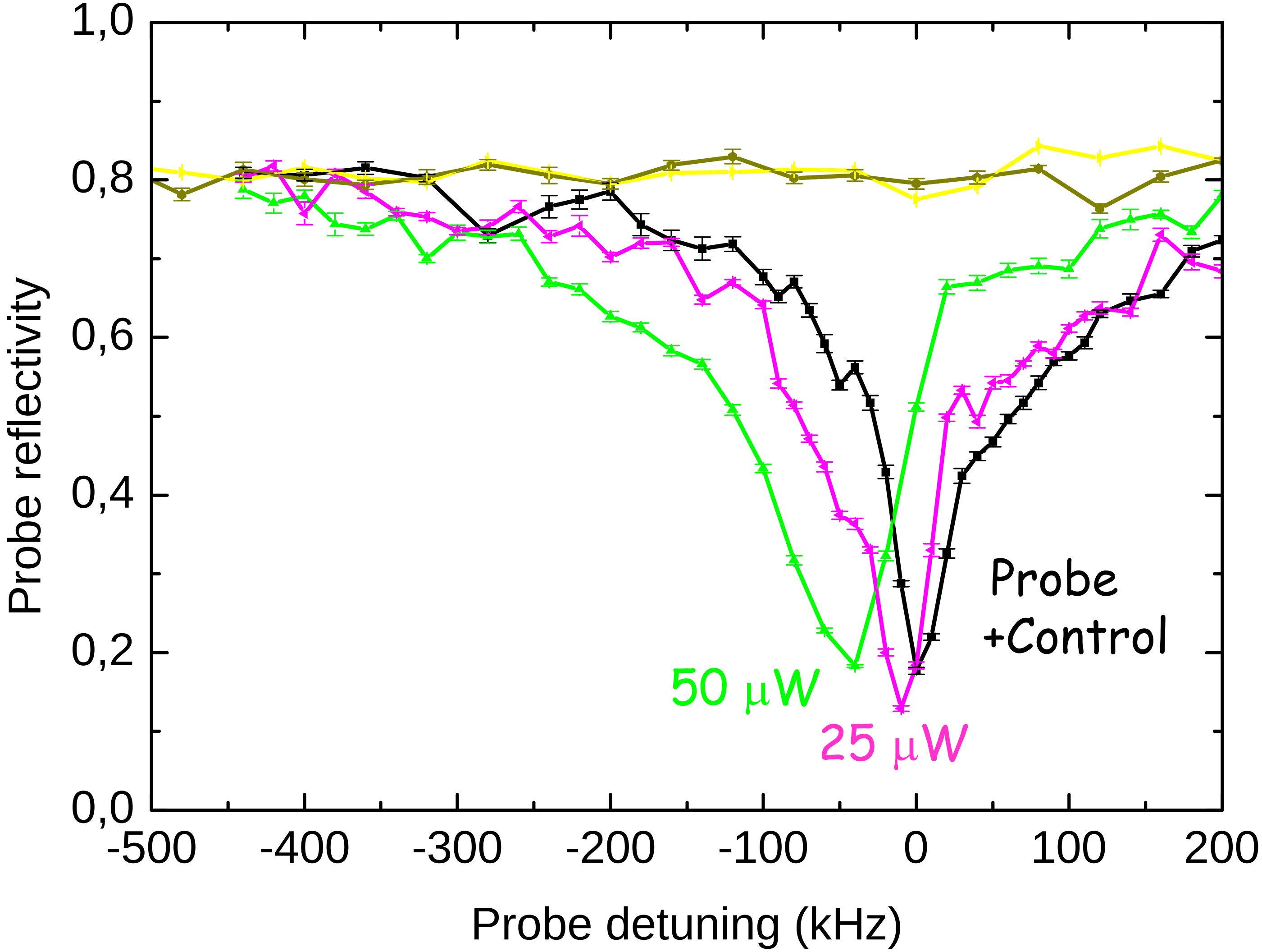
1,0
0,8
0,6
0,4
0,2
0,0
-500
-400
-300
-200
-100
0
100
200
Probe reflectivity
Probe detuning (kHz)
Probe alone
Probe + Blockade
-3/2
-1/2
+1/2
+3/2
$P_{3/2}$
Ω_b (σ^+)
-1/2
+1/2
$P_{1/2}$
Ω_p (σ^-)
$D_{3/2}$
-3/2
-1/2
+1/2
+3/2



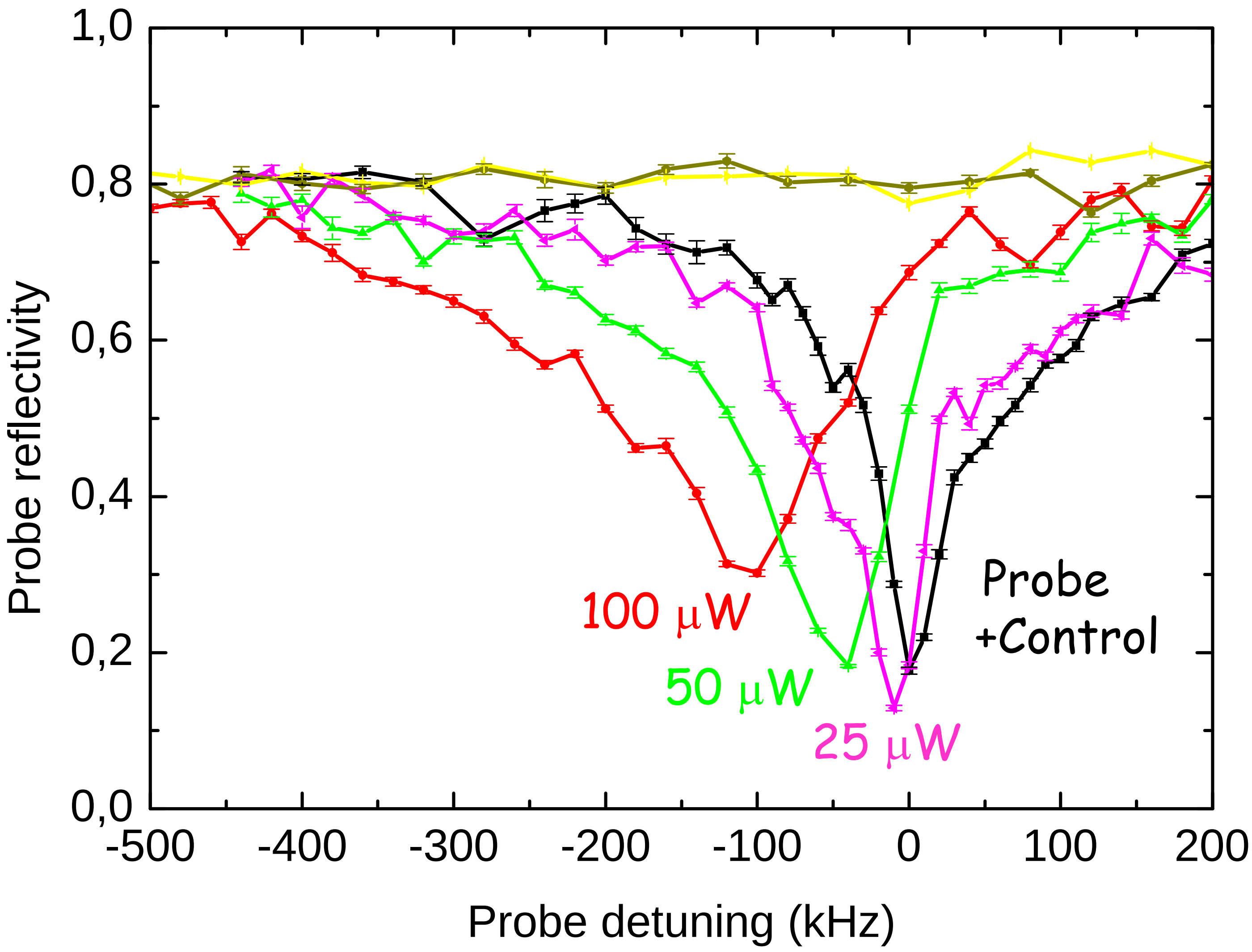
1,0
0,8
0,6
0,4
0,2
0,0
-500
-400
-300
-200
-100
0
100
200
Probe detuning (kHz)
Probe reflectivity
-3/2
-1/2
+1/2
+3/2
P3/2
-1/2
+1/2
P1/2
Ωc (σ+)
Ωp (σ-)
-3/2
-1/2
+1/2
+3/2
D3/2
Probe
+Control



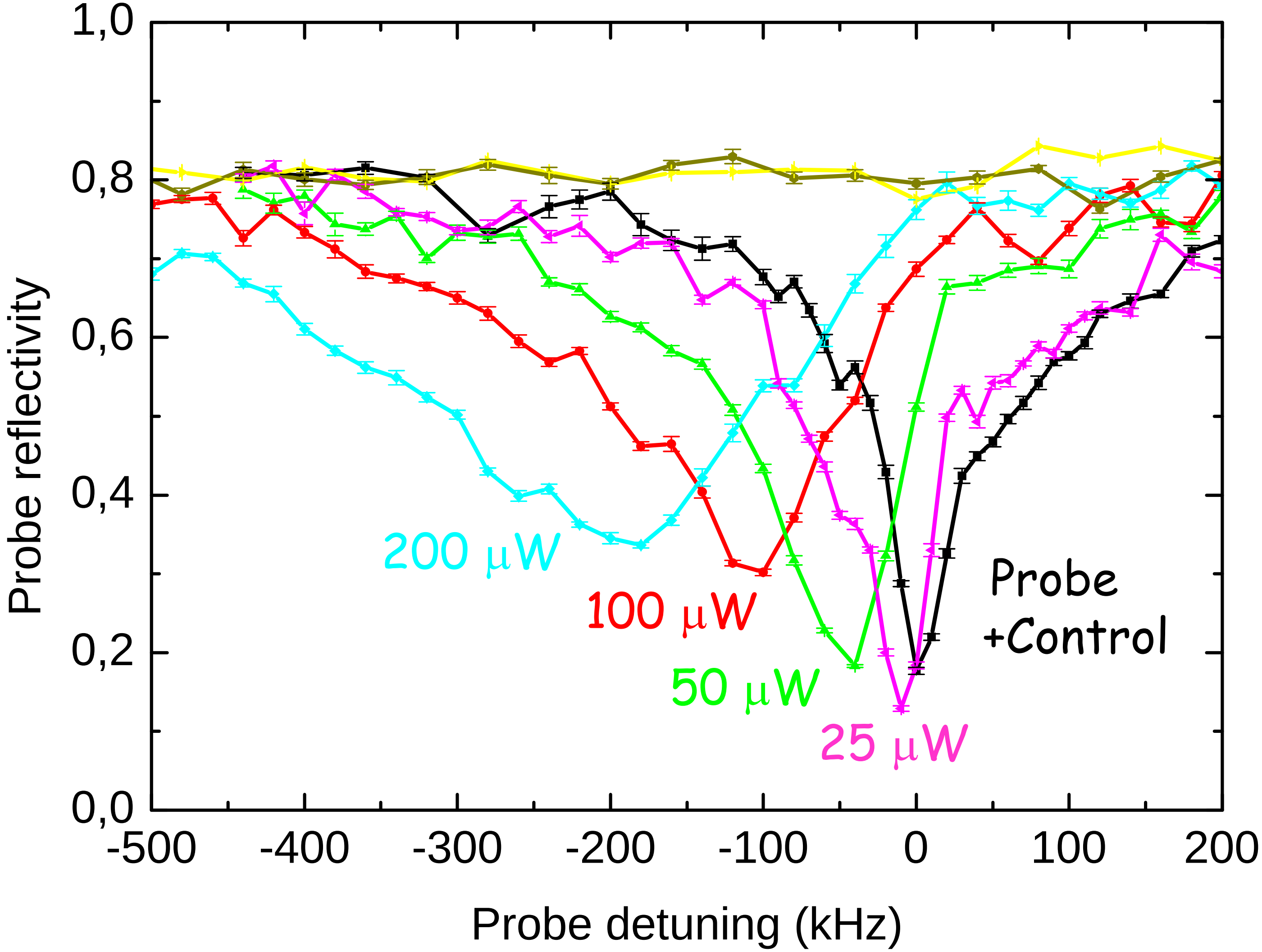
1,0
0,8
0,6
0,4
0,2
0,0
Probe reflectivity
-500
-400
-300
-200
-100
0
100
200
Probe detuning (kHz)
-3/2
-1/2
+1/2
+3/2
$P_{3/2}$
Ω_b (σ^+)
-1/2
+1/2
$P_{1/2}$
Ω_c (σ^+)
Ω_p (σ^-)
-3/2
-1/2
+1/2
+3/2
$D_{3/2}$
Probe
+Control
25 μW



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

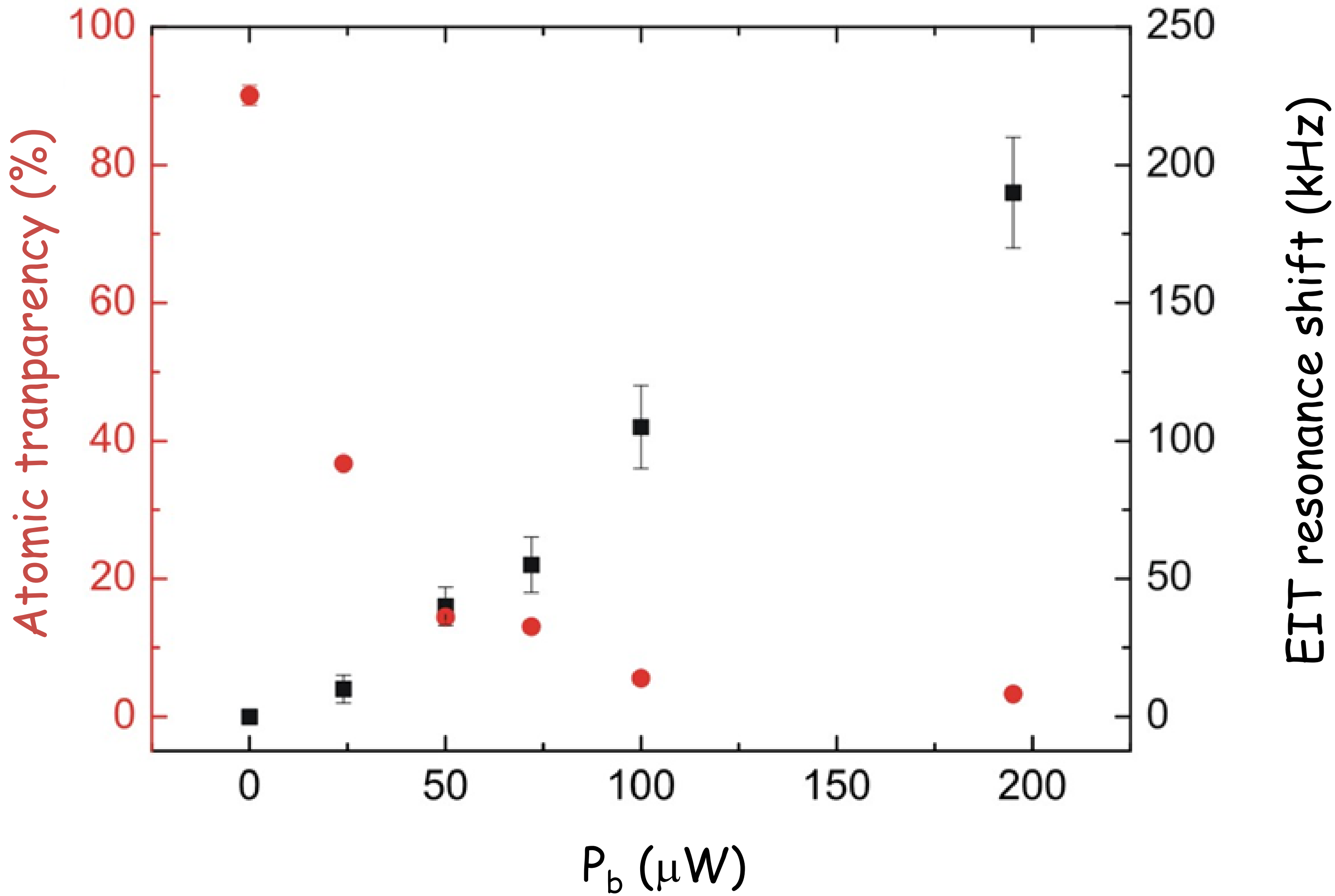


1,0
0,8
0,6
0,4
0,2
0,0
-500
-400
-300
-200
-100
0
100
200
Probe reflectivity
Probe detuning (kHz)
100 μW
50 μW
25 μW
Probe
+Control



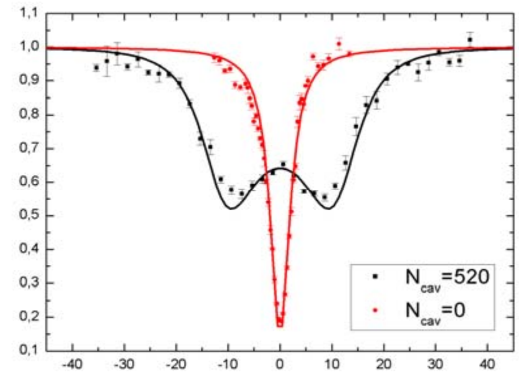
1,0
0,8
0,6
0,4
0,2
0,0
-500
-400
-300
-200
-100
0
100
200
Probe reflectivity
Probe detuning (kHz)
200 μW
100 μW
50 μW
25 μW
Probe
+Control

Photon blockade vs. blockade laser power

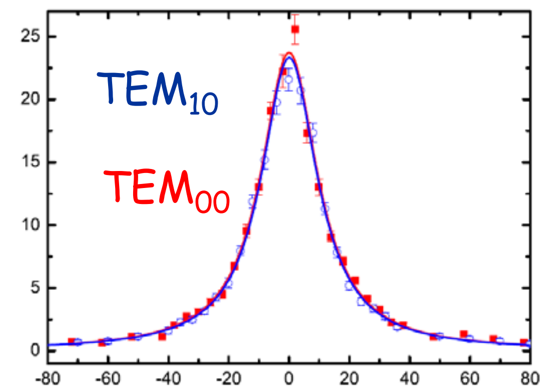


IV) Conclusion

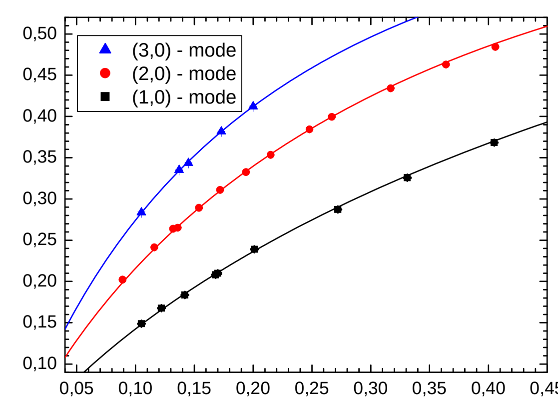
- Collective strong coupling has been realized with ion Coulomb crystals.



- Same collective coupling to different TEM_{nm} modes

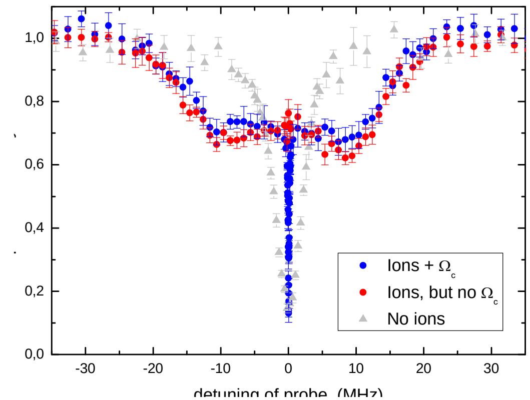


- Crystal normal-mode spectroscopy through coupling strength measurements

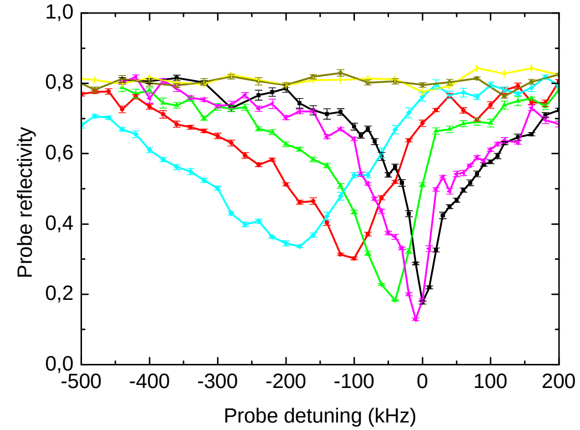


IV) Conclusion (cont')

- 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.



People involved:

Aurelien Dantan (Post Doc)

Joan Marler (Post Post Doc)

Peter Herskind (Post PhD)

Magnus Albert (PhD)

Rasmus B. Linnet (PhD)

Martin Larsen (MSc)

Jens Lykke Sørensen (Post Doc)

Anders Mortensen (PhD/Post Doc)

Maria Langkilde-Lauesen (MSc)

Esben S. Nielsen (MSc)

Open PhD position!!

(January 2011)

EU ITN on
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