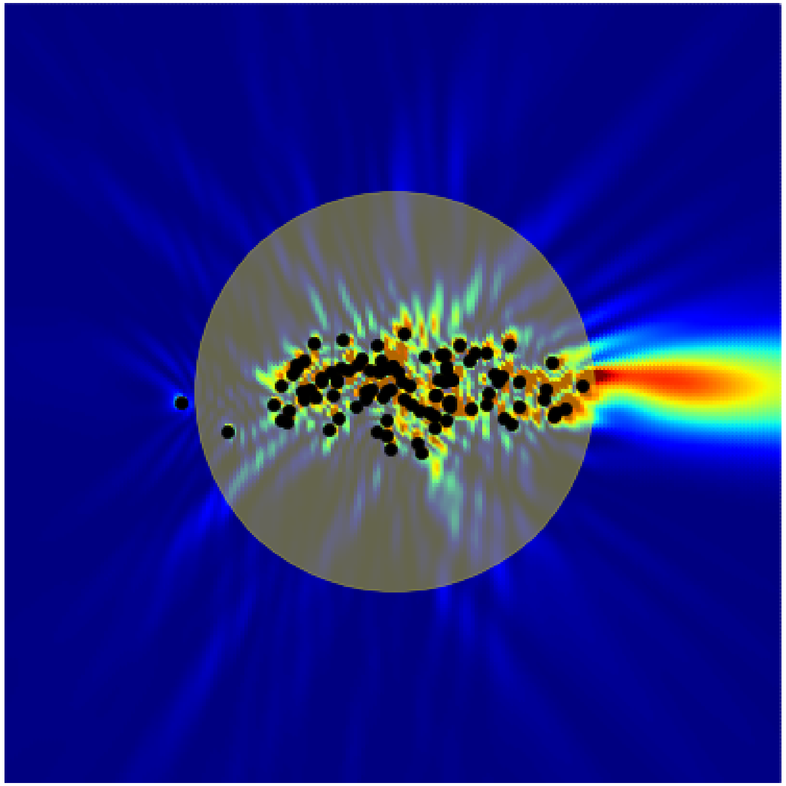


$$k_{\mathrm{L}}^{-1} < N^{-1/3} < k_{\mathrm{R}}^{-1}$$

Rydberg Atom-Light Interactions
(**RALI**)

Rydberg Atom-Light Interactions
(**RALI**)

$$E_{\rm scat} \propto \frac{k^2}{r}$$

Rydberg Atom-Light Interactions
(**RALI**)

$$E_z = \frac{d}{4\pi\epsilon_0}\left[\left(\frac{1}{r^3} - \frac{\mathrm{i}k}{r^2}\right)(3\cos^2\theta - 1) - \frac{k^2}{r}\sin^2\theta\right]\mathrm{e}^{\mathrm{i}(kr-\omega t)}$$

Rydberg Atom-Light Interactions
(**RALI**)

$$E_z = \frac{d}{4\pi\epsilon_0}\left[\left(\frac{1}{r^3} - \frac{ik}{r^2}\right)(3\cos^2\theta - 1) - \frac{k^2}{r}\sin^2\theta\right] e^{i(kr-\omega t)}$$

Near field Far field

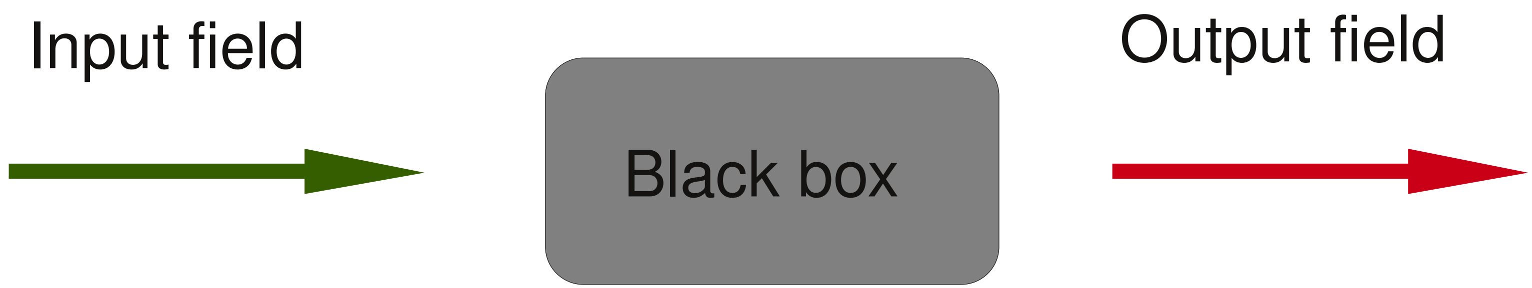
Rydberg Atom-Light Interactions (**RALI**)

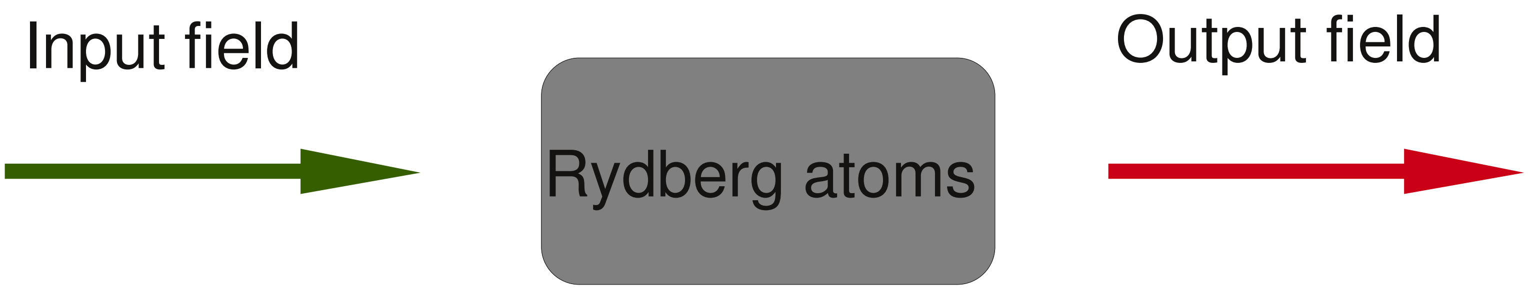
$$E_z = \frac{d}{4\pi\epsilon_0}\left[\left(\frac{1}{r^3} - \frac{ik}{r^2}\right)(3\cos^2\theta - 1) - \frac{k^2}{r}\sin^2\theta\right] e^{i(kr-\omega t)}$$

Near field   Far field

$$k_{\mathrm{L}}^{-1} < N^{-1/3} < k_{\mathrm{R}}^{-1}$$

Both

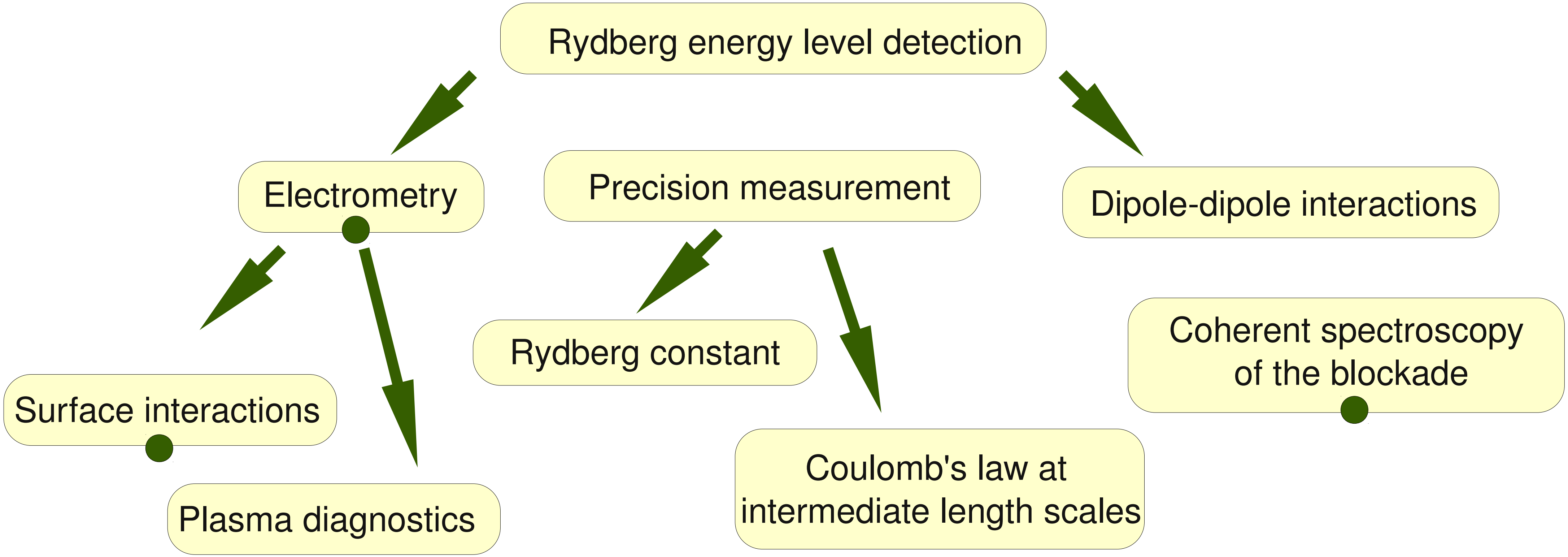

Input field
Black box
Output field



Can we exploit the extraordinary properties of Rydberg atoms to modify a light field in a useful way?

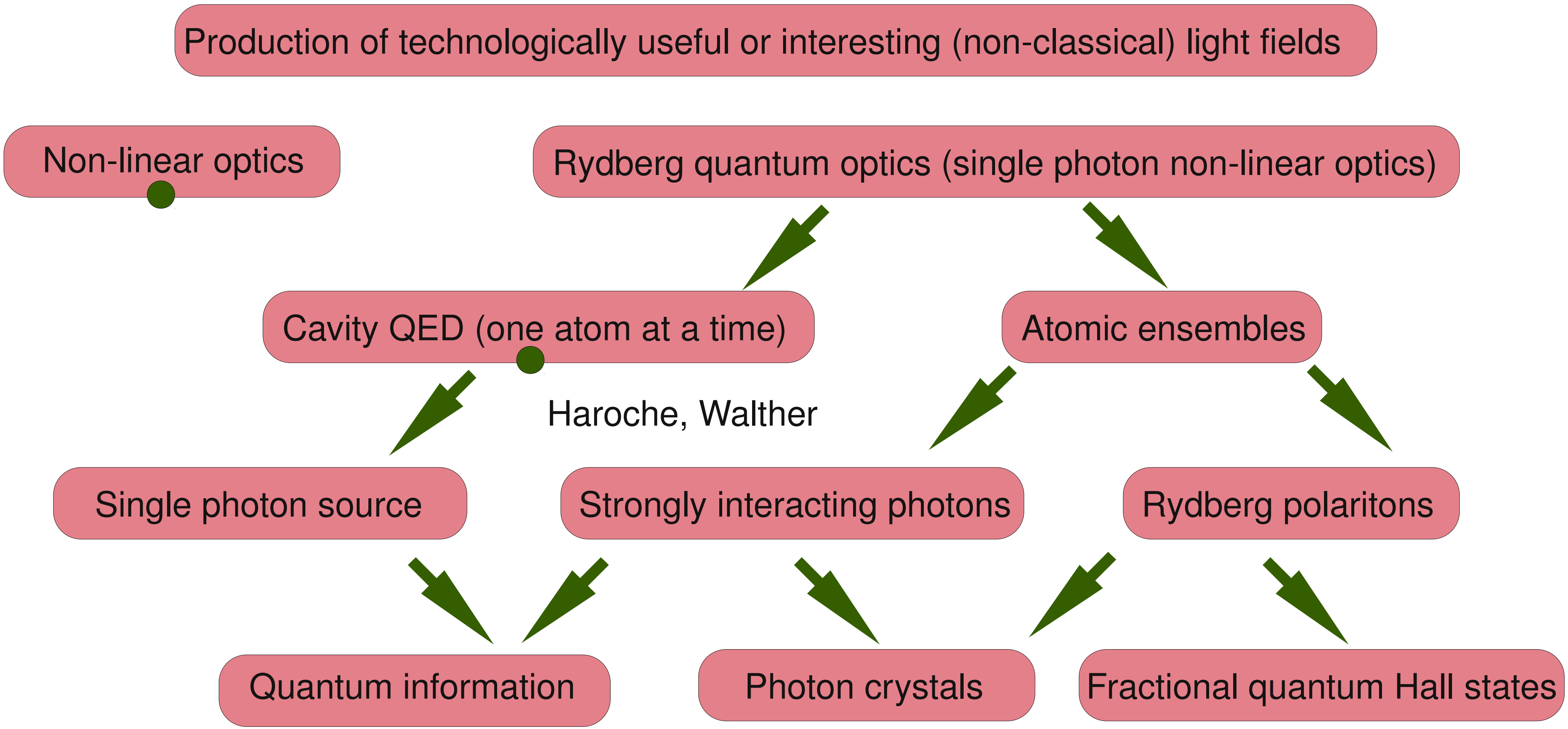
Can we exploit the extraordinary properties of Rydberg atoms to modify a light field in a useful way?

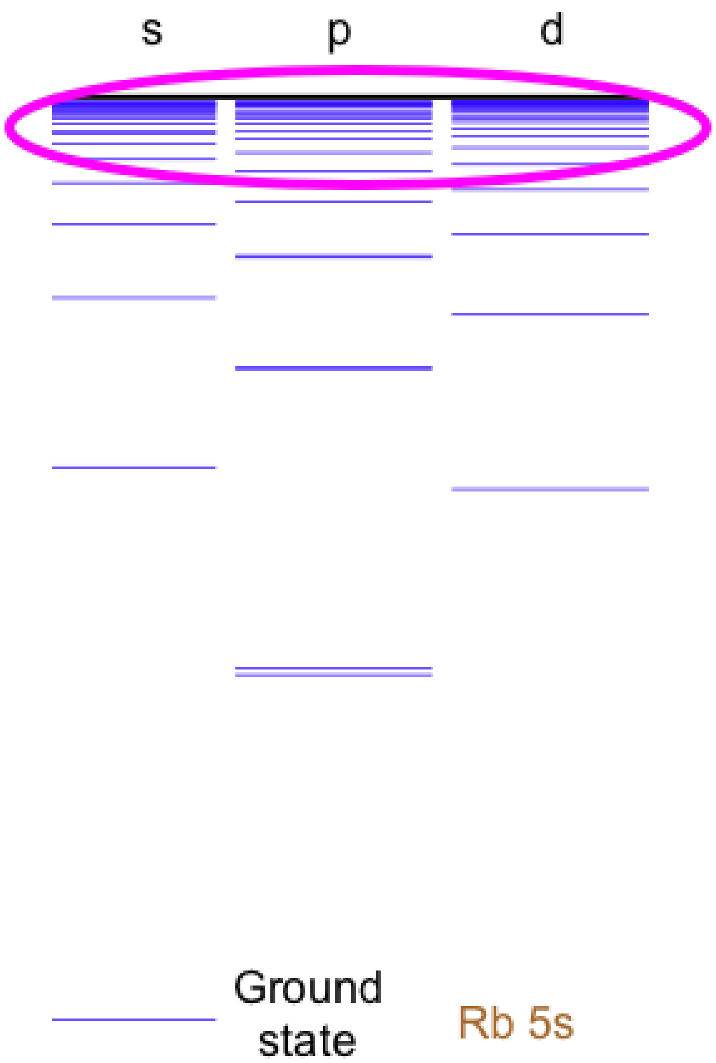
1. What does the output field tells us about the Rydberg atom or the environment of each Rydberg atom?



Applications II

Can we exploit the extraordinary properties of Rydberg atoms to modify a light field in a useful way?





Rydberg states: large *n*

Scaling with principal quantum number *n* (low ℓ)

Size	n^2	
Dipole moment	n^2	
Lifetime	n^3	Long lived
Polarizability	n^7	Sensitivity to electric fields
van der Waals	n^{11}	Strong atom - atom interactions
Dipole moment 5s - np	$n^{-3/2}$	Weak atom light interactions

1. Rydberg energy level detection

'Precision' measurement

2. Rydberg non-linear optics

Giant Kerr effect

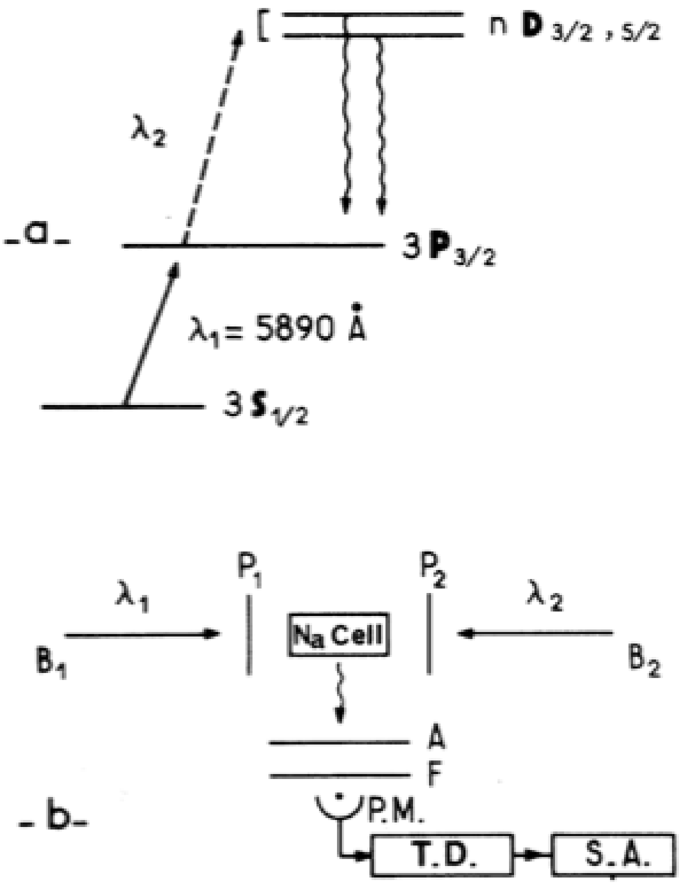
3. Effects dipole – dipole interactions on the optical response

Coherent spectroscopy of the blockade

4. Rydberg quantum optics

Light induced fluorescence

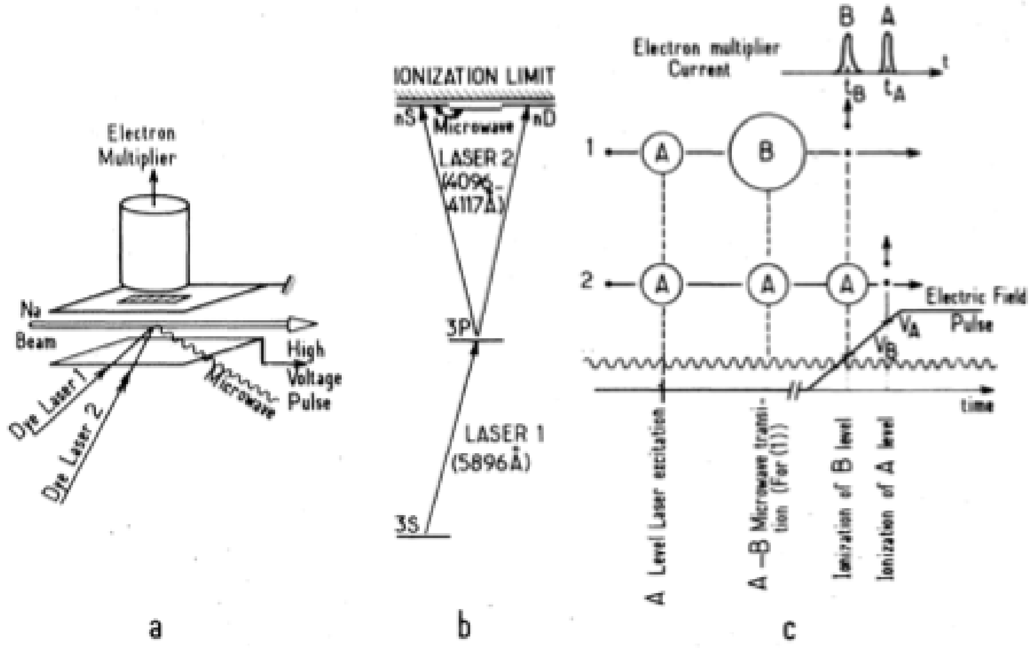
Low n < 20



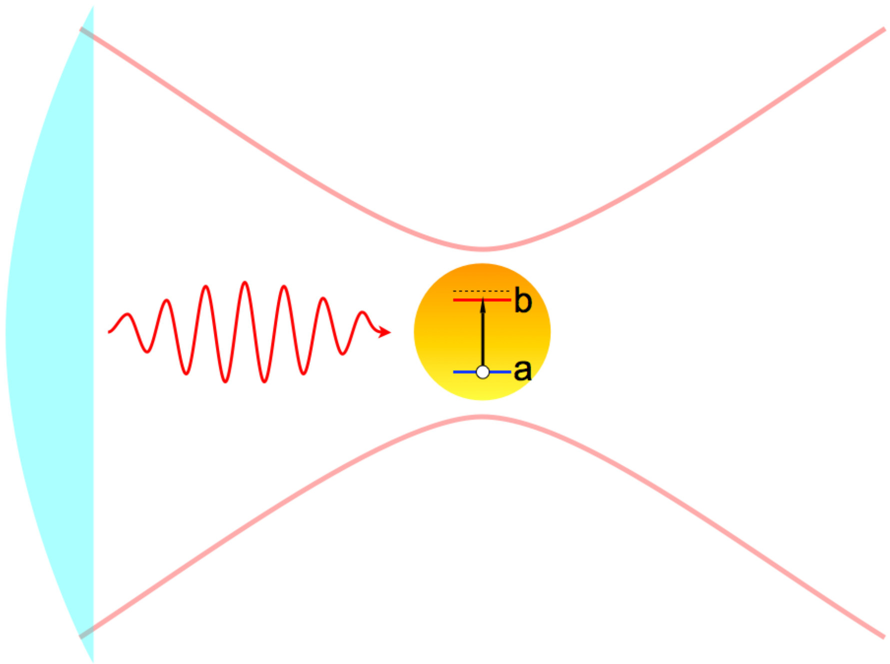
Haroche, Gross, Silverman, PRL **18**, 1063 (1974).

Field ionization

High n > 20



Fabre, Haroche, Goy, PRA **18**, 229 (1978).



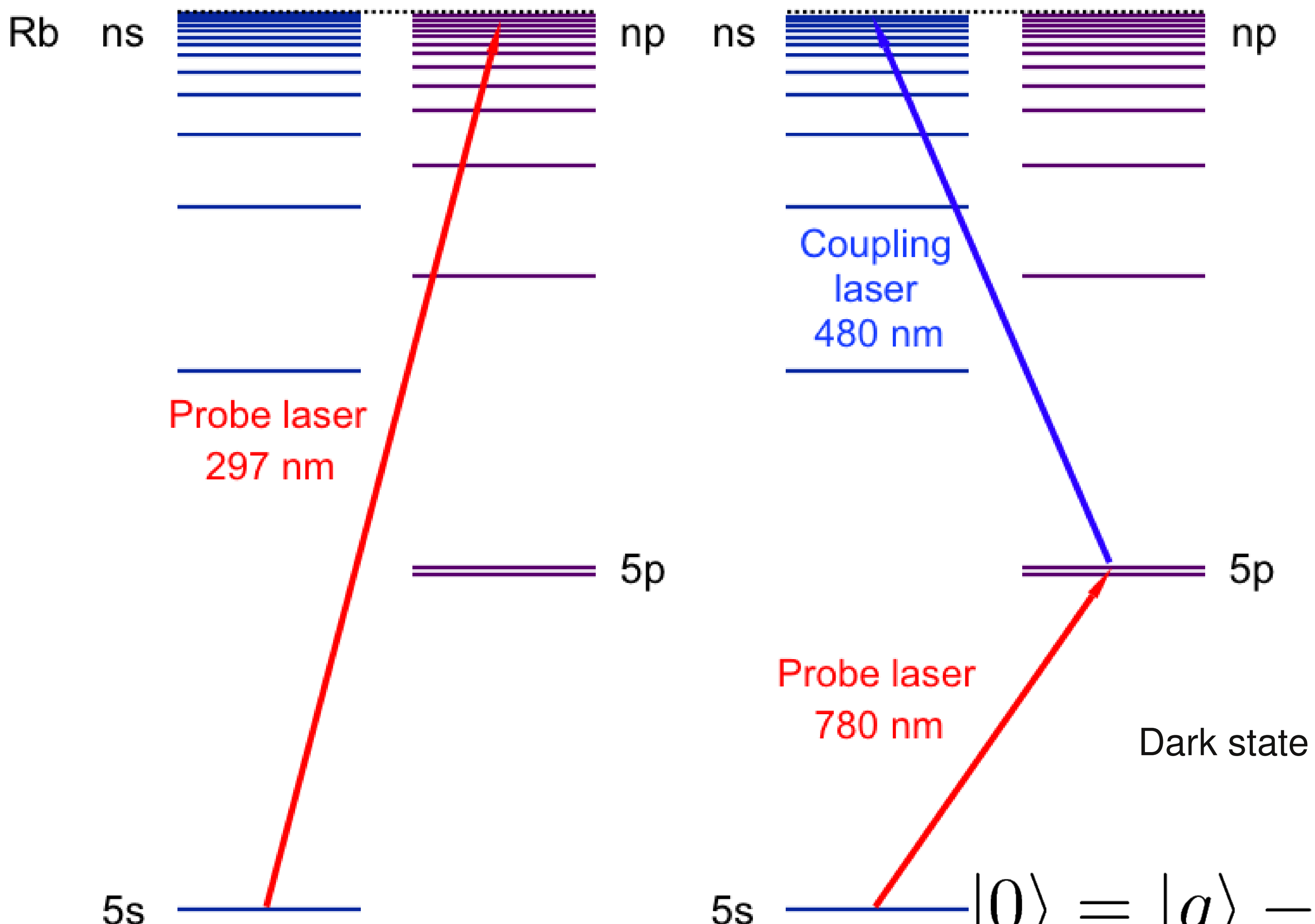
Weak excitation: single atom response

Two-level

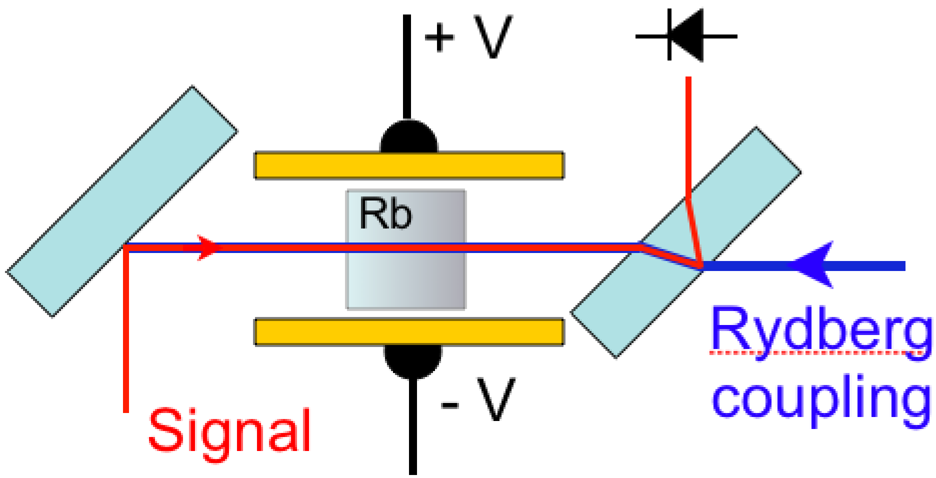
$$\chi_1 = \frac{\mathrm{i}}{V}\frac{d_{\mathrm{ab}}^2}{\epsilon_0\hbar}\frac{1}{\gamma_{\mathrm{ab}} - \mathrm{i}\Delta}$$

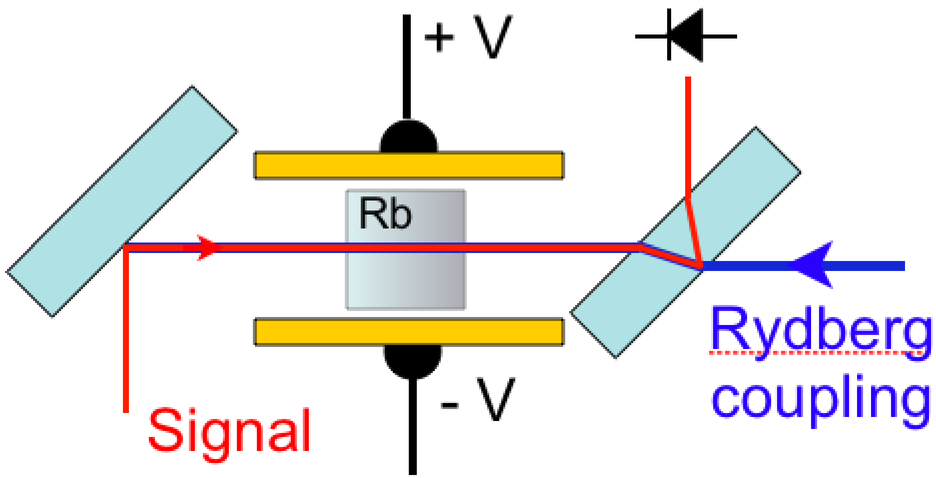
Multi-level

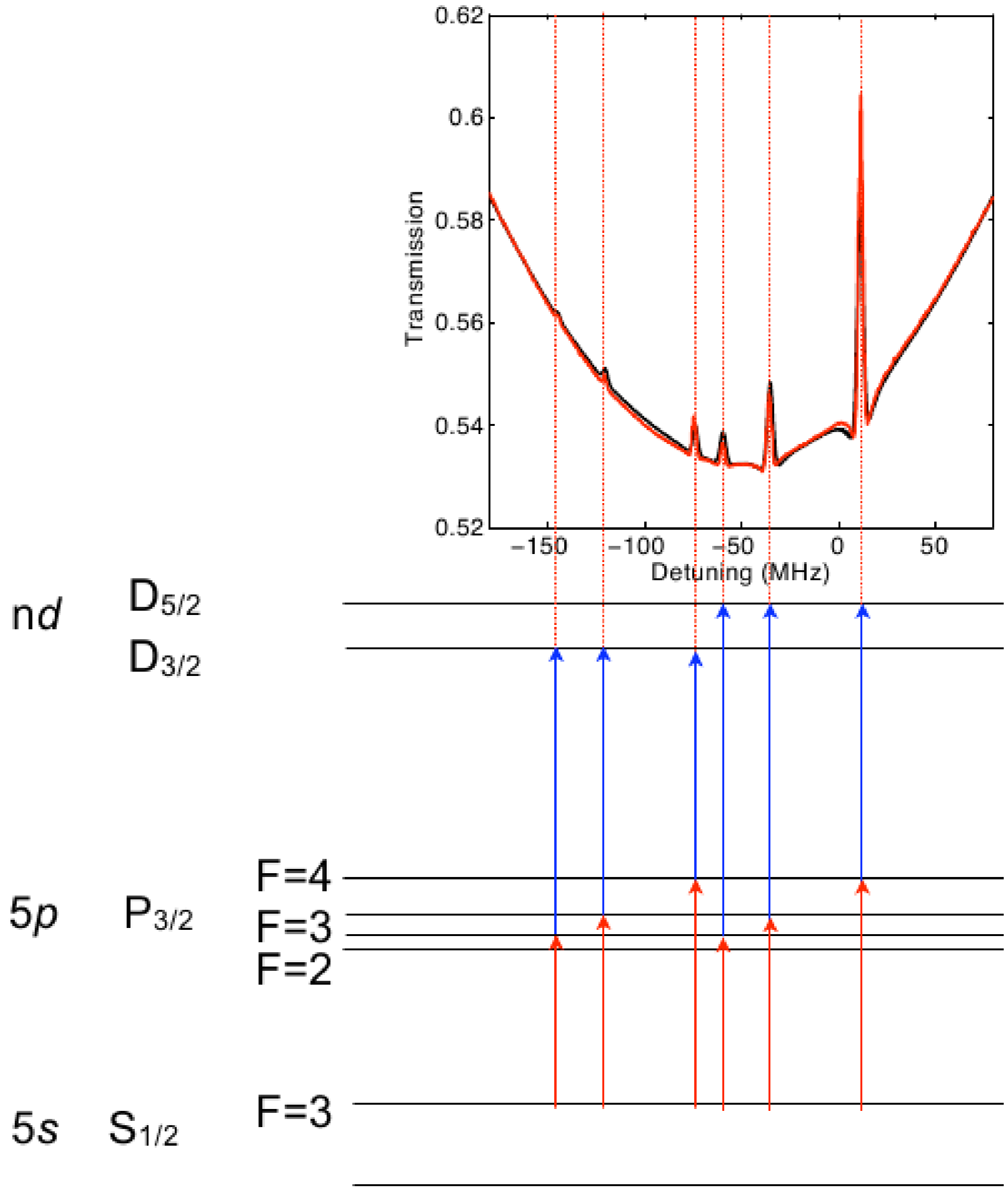
$$\chi_1 = \frac{\mathrm{i}}{V}\frac{d_{\mathrm{ab}}^2}{\epsilon_0\hbar}\frac{1}{\gamma - \mathrm{i}\Delta}$$

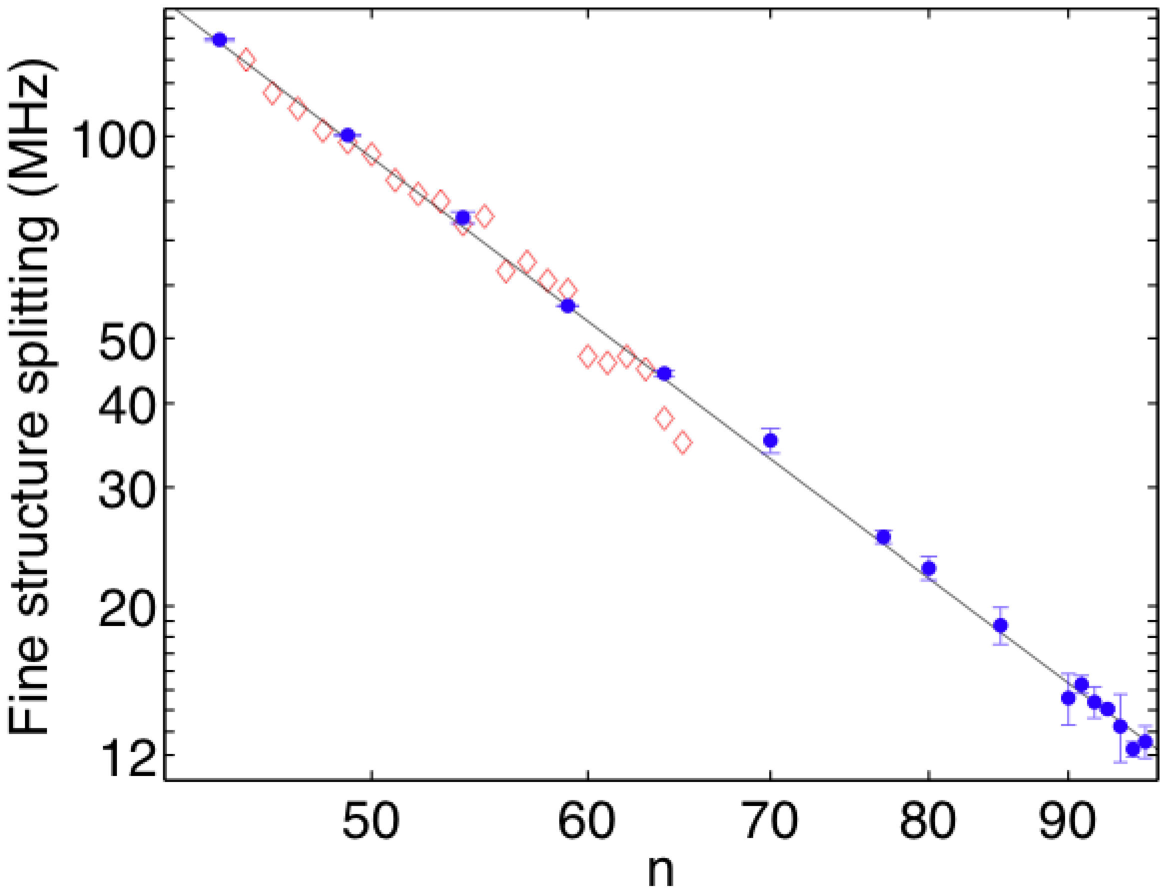


$$|0\rangle = |g\rangle - \mathrm{e}^{\mathrm{i}\phi}|r\rangle$$


+ V
Rb
Signal
- V
Rydberg
coupling


+ V
Rb
- V
Signal
Rydberg
coupling

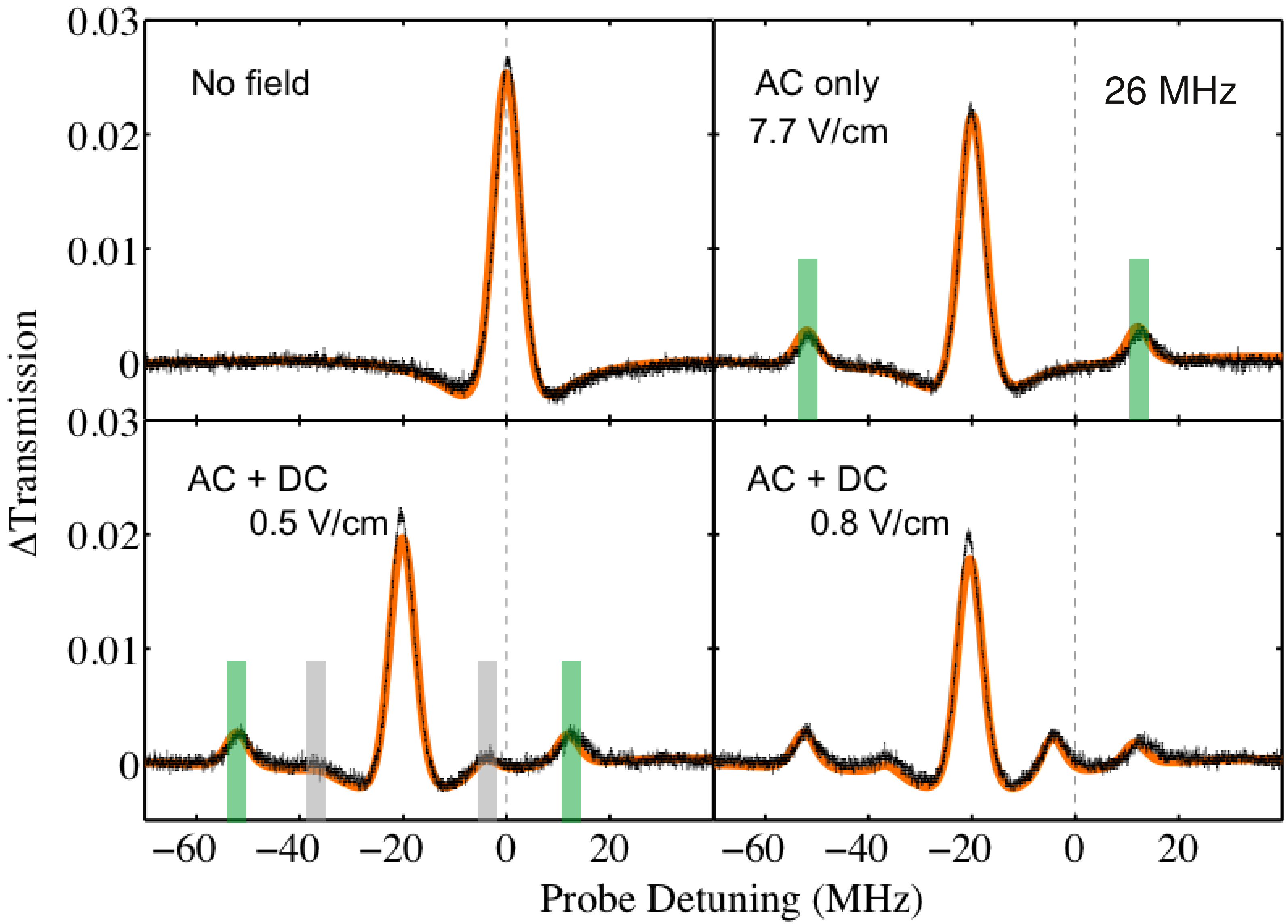

0.62
0.6
0.58
0.56
0.54
0.52
Transmission
−150
−100
−50
0
50
Detuning (MHz)
nd
D5/2
D3/2
5p
P3/2
F=4
F=3
F=2
5s
S1/2
F=3



◊ K. C. Harvey and B. P. Stoicheff, Phys. Rev. Lett. **38**, 537 (1977).

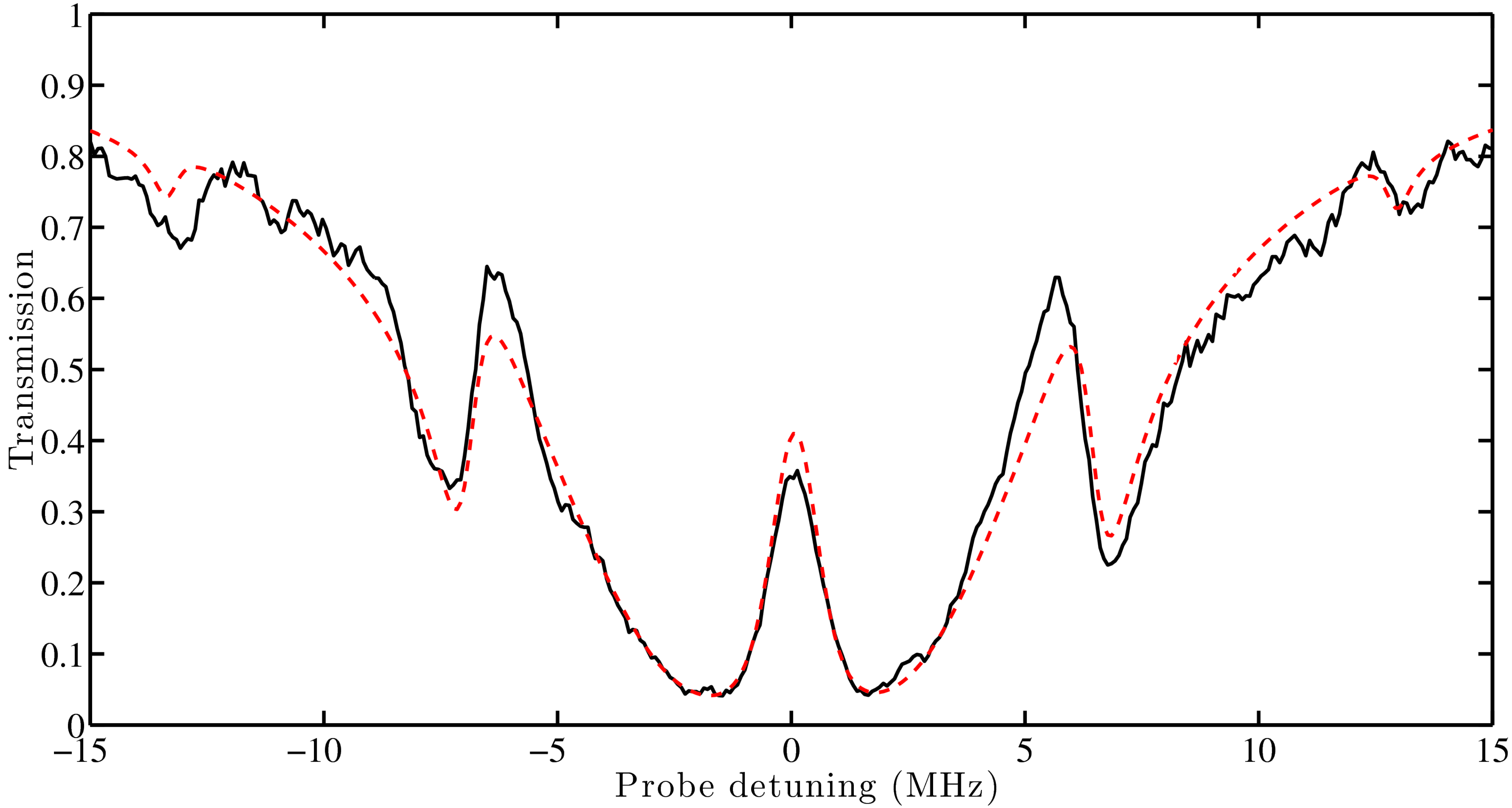
— W. Li, I. Mourachko, M. W. Noel, and T. F. Gallagher, Phys. Rev. A **67**, 052502 (2003).

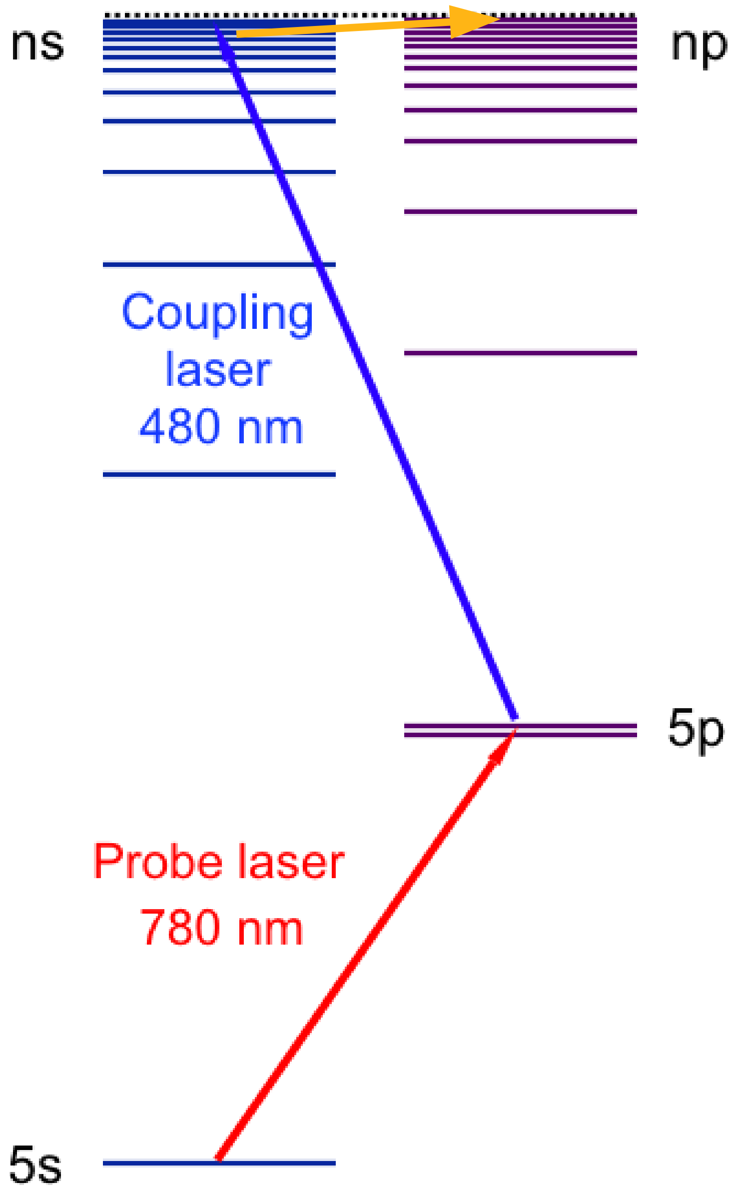
● A. Mohapatra, T. R. Jackson, CSA, Phys. Rev. Lett. **98**, 113003 (2007).



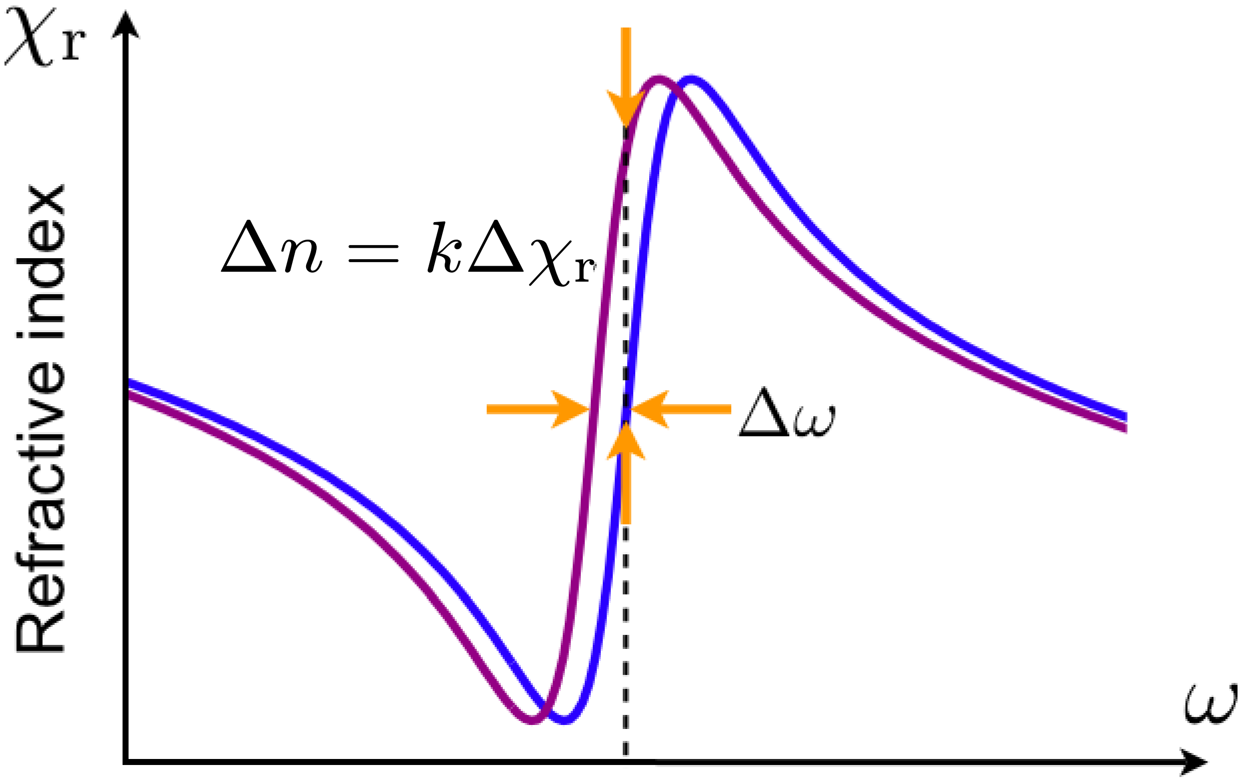
Bason et al. New J. Phys. 12, 065015 (2010)

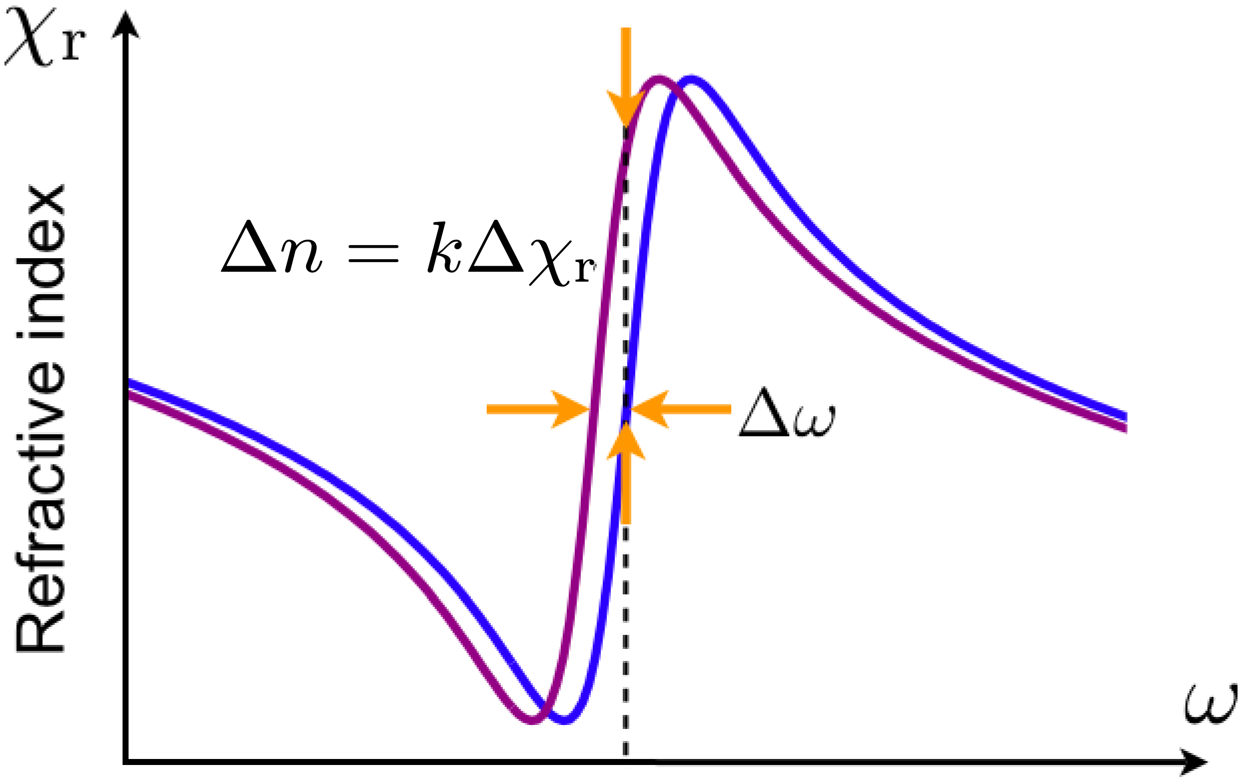
5s – 5p – 46s - 46p


Transmission
Probe detuning (MHz)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
−15
−10
−5
0
5
10
15



5s – 5p – 180s – 500s


χ_r
Refractive index
$\Delta n = k\Delta\chi_r$
$\Delta\omega$
ω



$$\chi_{\rm r} = \chi_{\rm r}^{(1)} + \chi_{\rm r}^{(3)}\mathcal{E}^2$$

$$\chi_{\rm r} = \chi_{\rm r}^{(1)} + \frac{\partial\chi_{\rm r}}{\partial\omega}\Delta\omega$$

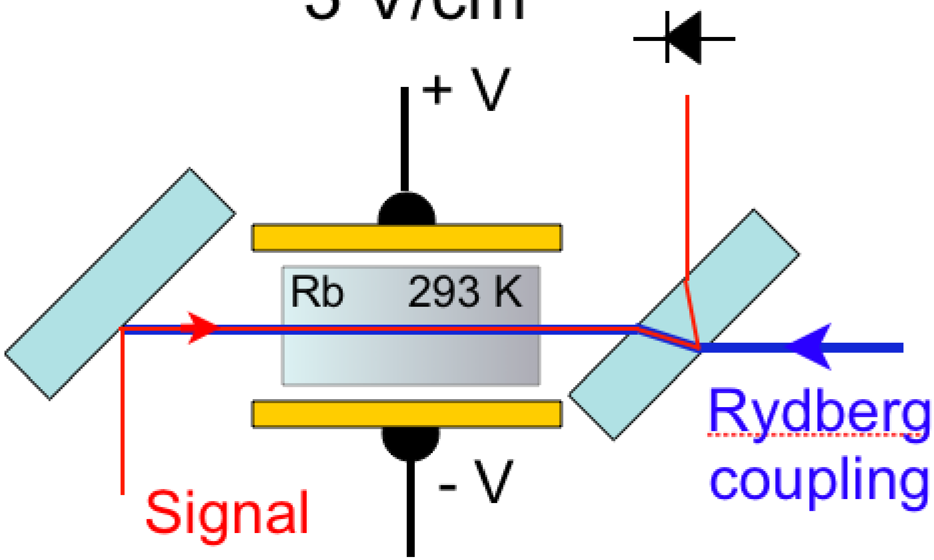
$$n_{\rm g} = 1 + \frac{\omega}{2}\frac{\partial\chi_{\rm r}}{\partial\omega}$$

$$\Delta\omega = -\frac{1}{2}\frac{\alpha\mathcal{E}^2}{\hbar}$$

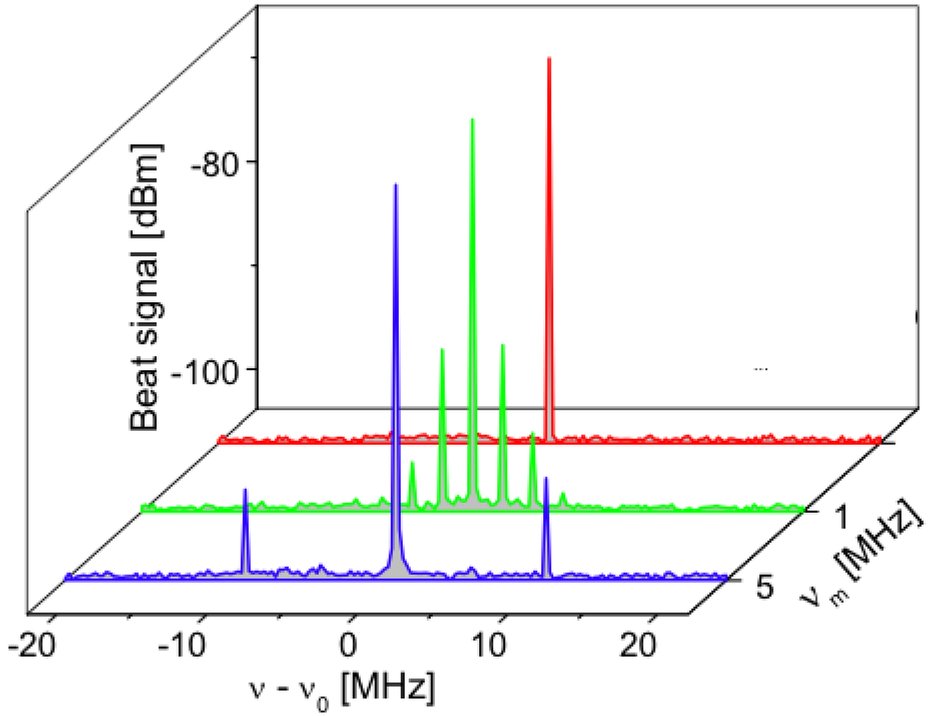
$$\chi^{(3)} = \frac{(n_{\rm g}-1)\alpha}{\hbar\omega}$$

$\nu_{\rm m}$ 1 - 10 MHz

3 V/cm



Low field electro-optic modulator



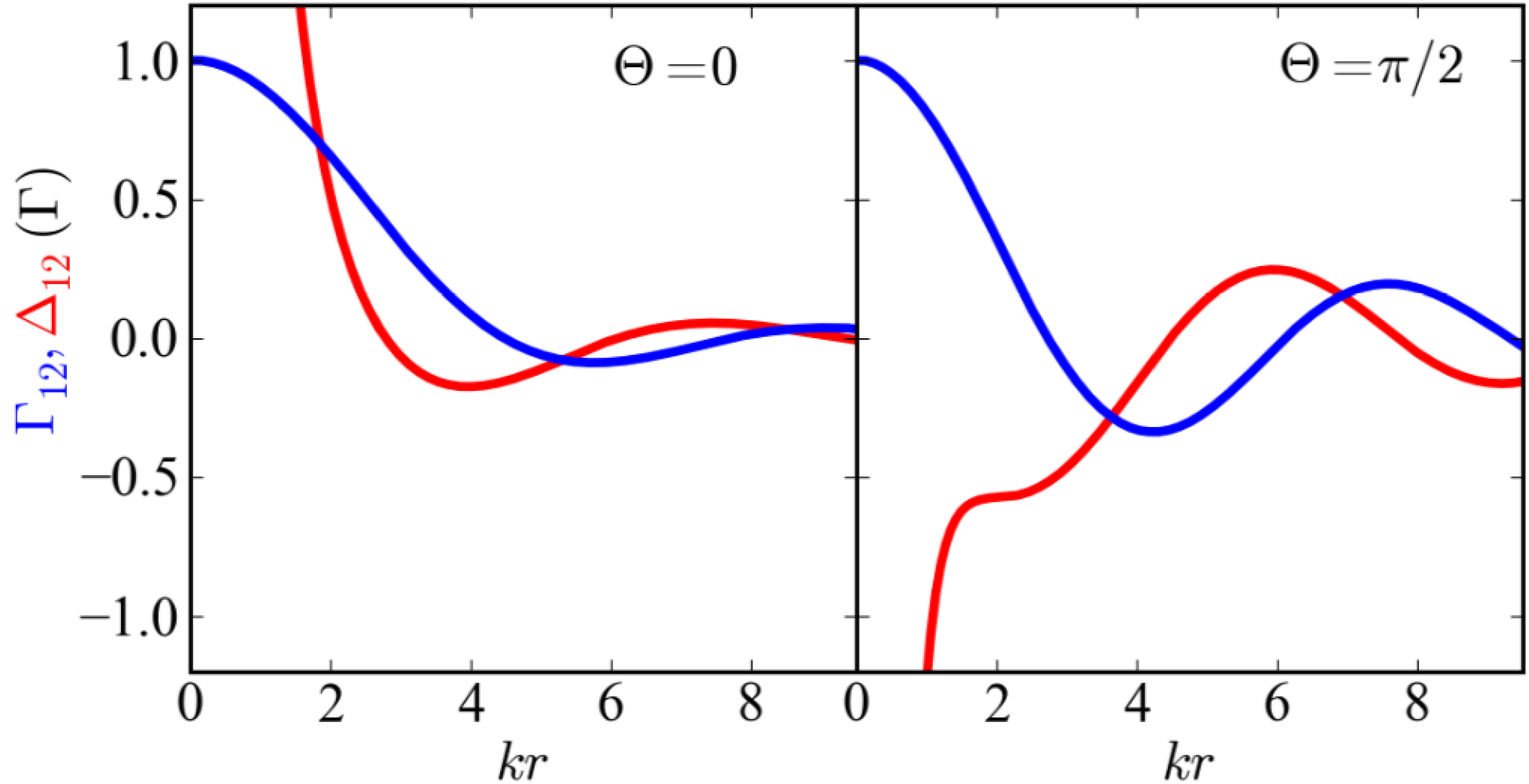
Kerr effect ($\chi^{(3)}$) 10^6 times larger than Kerr liquids (nitrobenzene)

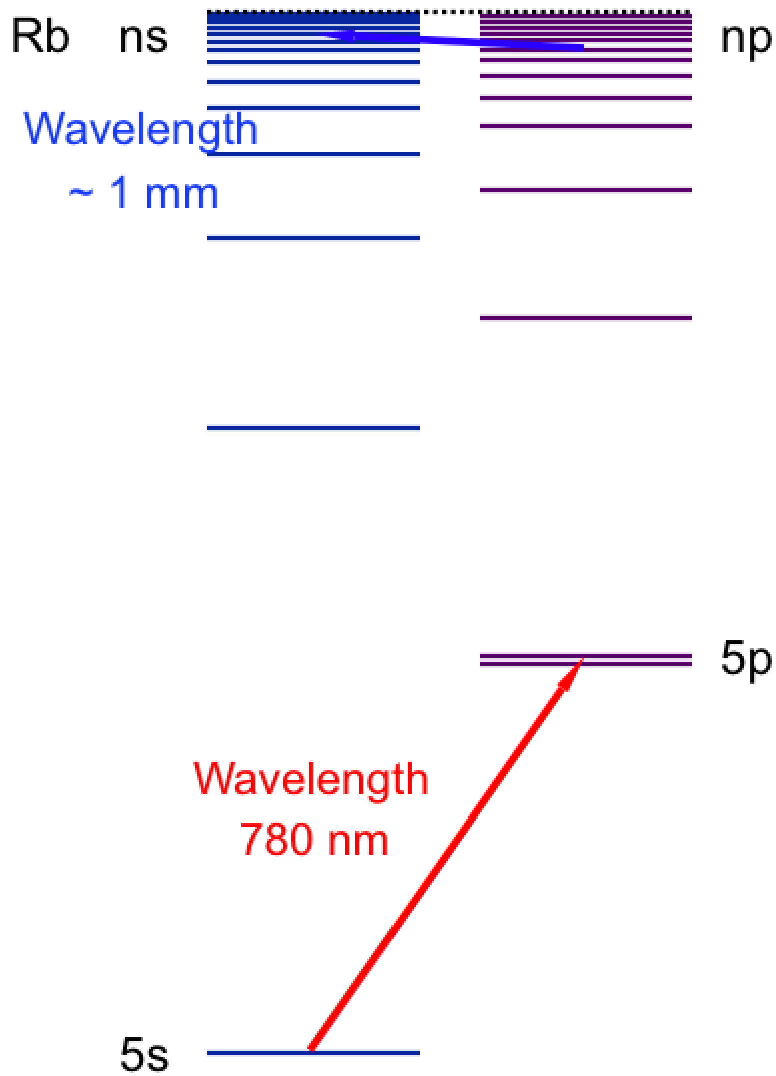
Giant dc Kerr effect, Mohapatra *et al*. Nature Phys. **4**, 890 (2008).

Electric field of a single oscillating dipole

$$E_z = \frac{d}{4\pi\epsilon_0}\left[\left(\frac{1}{r^3} - \frac{\mathrm{i}k}{r^2}\right)(3\cos^2\theta - 1) - \frac{k^2}{r}\sin^2\theta\right]\mathrm{e}^{\mathrm{i}(kr-\omega t)}$$

Imaginary part	**Width**
Real part	**Shift**

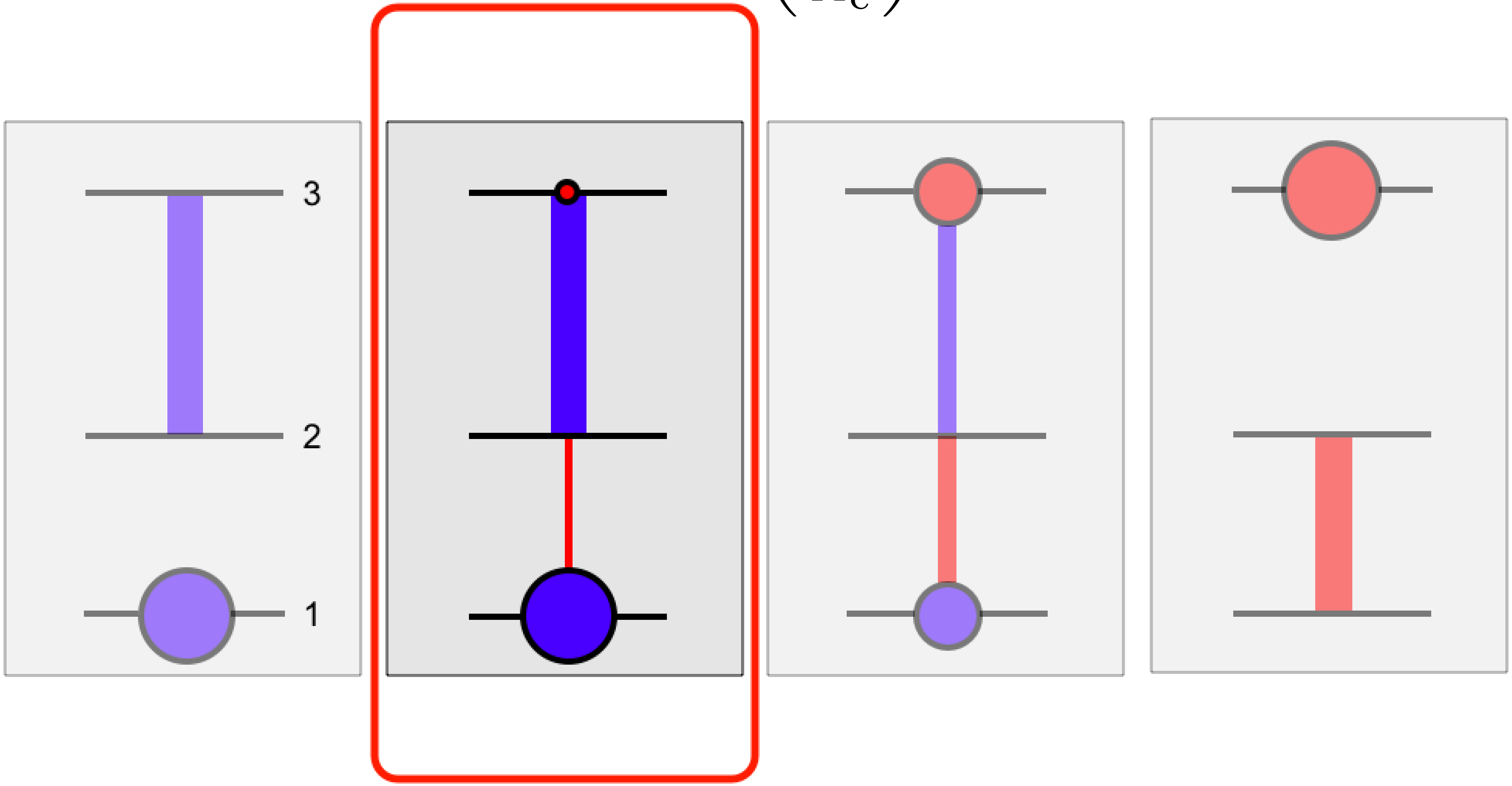

$\Theta = 0$
$\Theta = \pi/2$
$\Gamma_{12}, \Delta_{12}\,(\Gamma)$
1.0
0.5
0.0
−0.5
−1.0
0
2
4
6
8
kr
kr



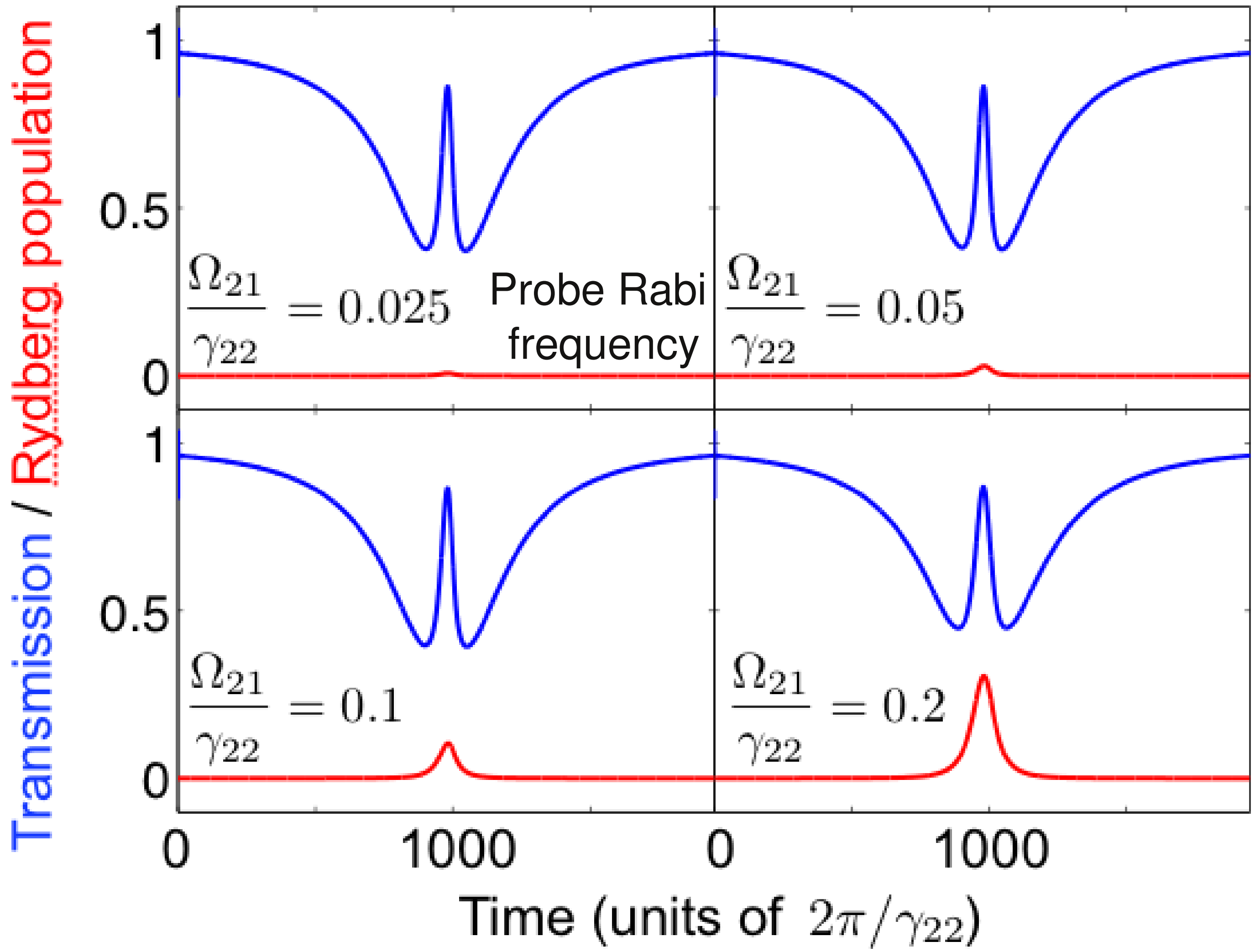
$$N \gg 1 \times 10^{9}\ \mathrm{cm}^{-3}$$

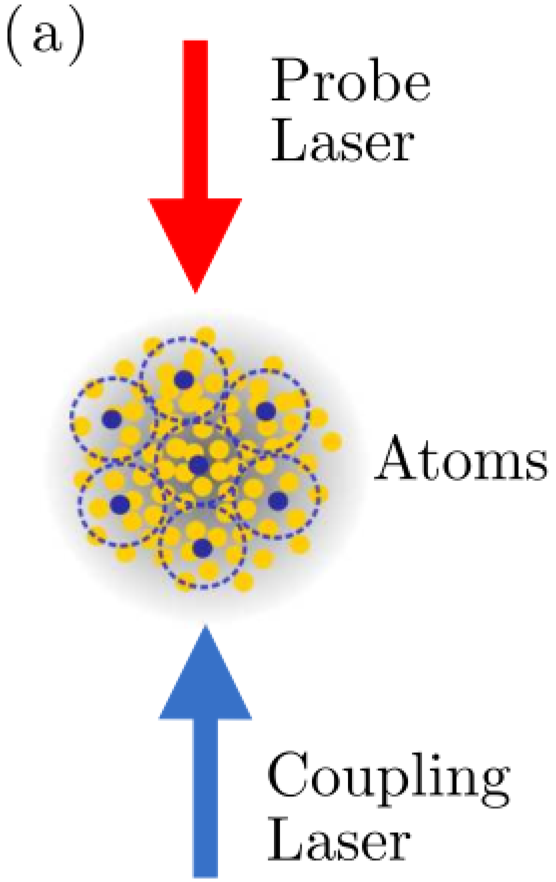
$$N \gg 2 \times 10^{15}\ \mathrm{cm}^{-3}$$

Rydberg fraction $\left(\frac{\Omega_p}{\Omega_c}\right)^2$

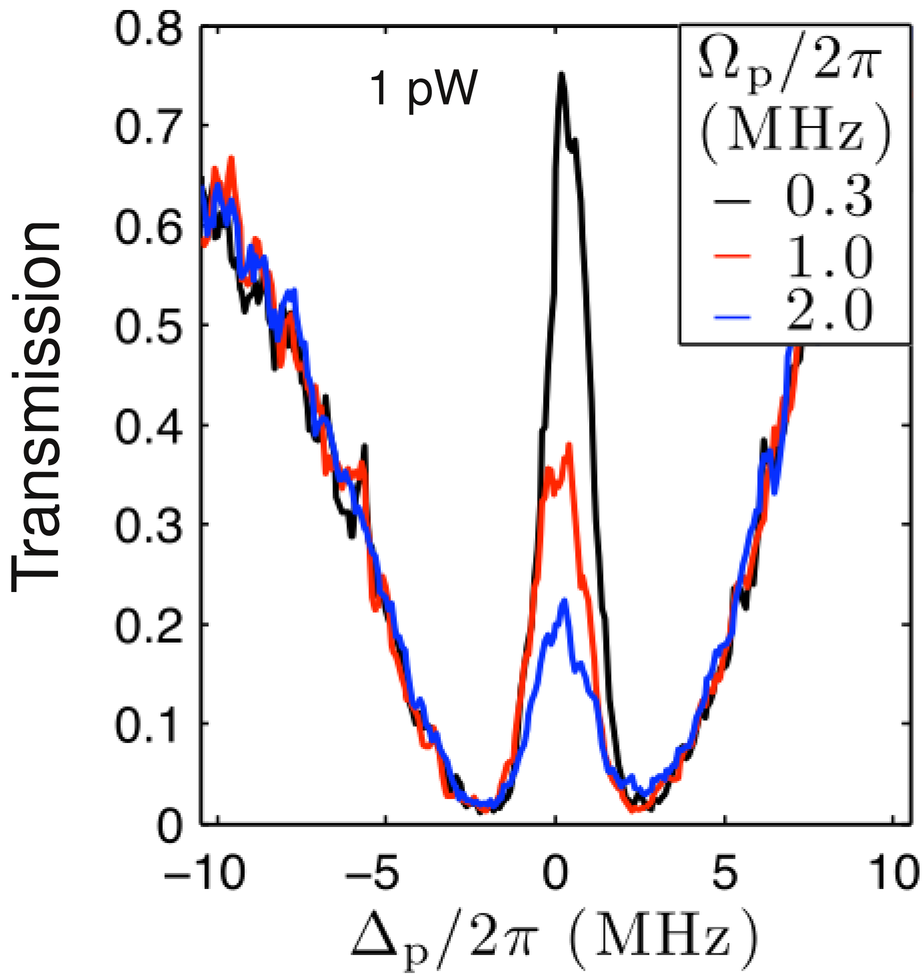


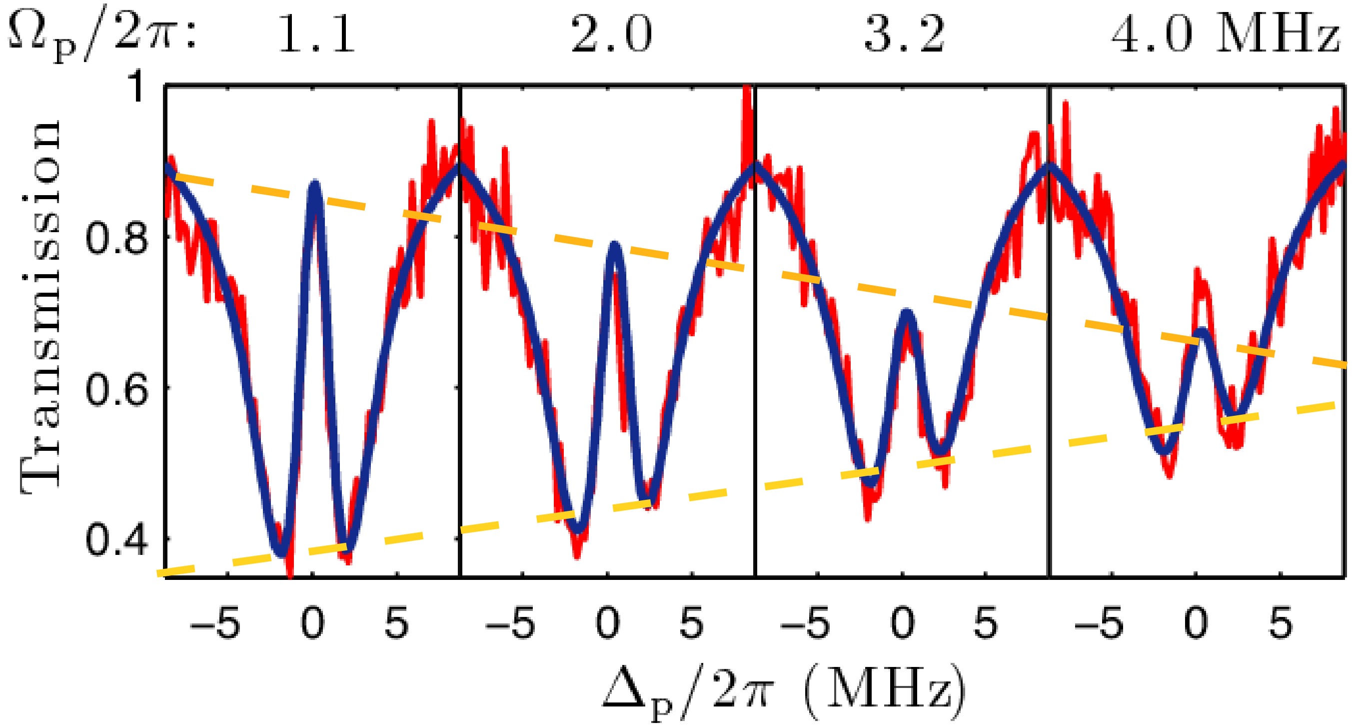
Coupling Rabi frequency $\frac{\Omega_{32}}{\gamma_{22}} = 0.25$





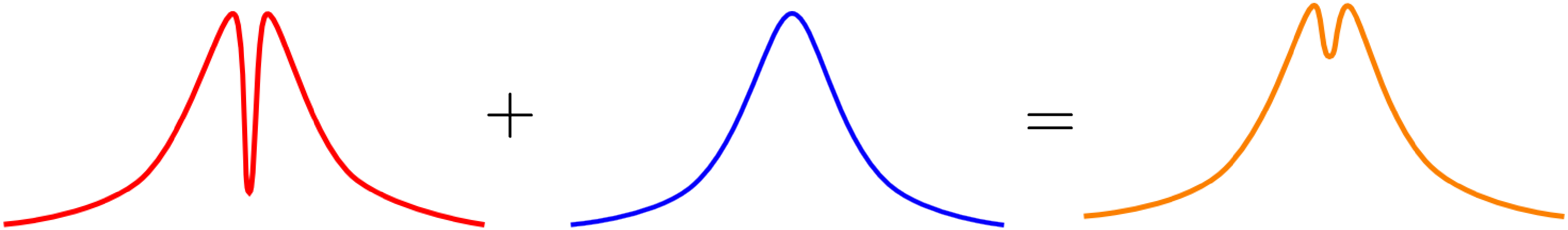
$N = 2 \times 10^{10}\ \mathrm{cm}^{-3}$




Ωp/2π: 1.1
2.0
3.2
4.0 MHz
Transmission
1
0.8
0.6
0.4
–5 0 5 –5 0 5 –5 0 5 –5 0 5
Δp/2π (MHz)

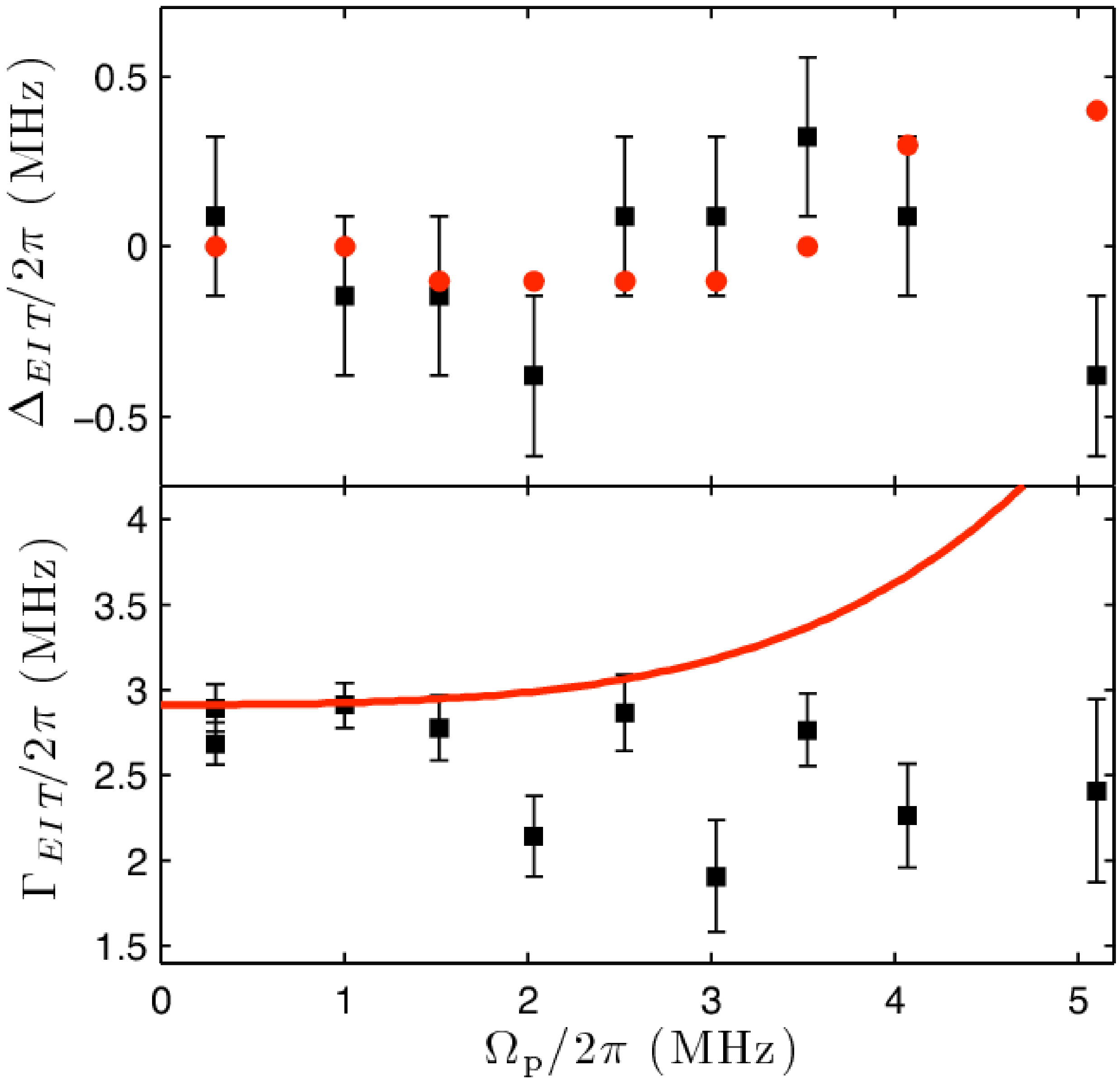
Simple picture of suppression

$$\frac{1}{N} \qquad \frac{N-1}{N}$$

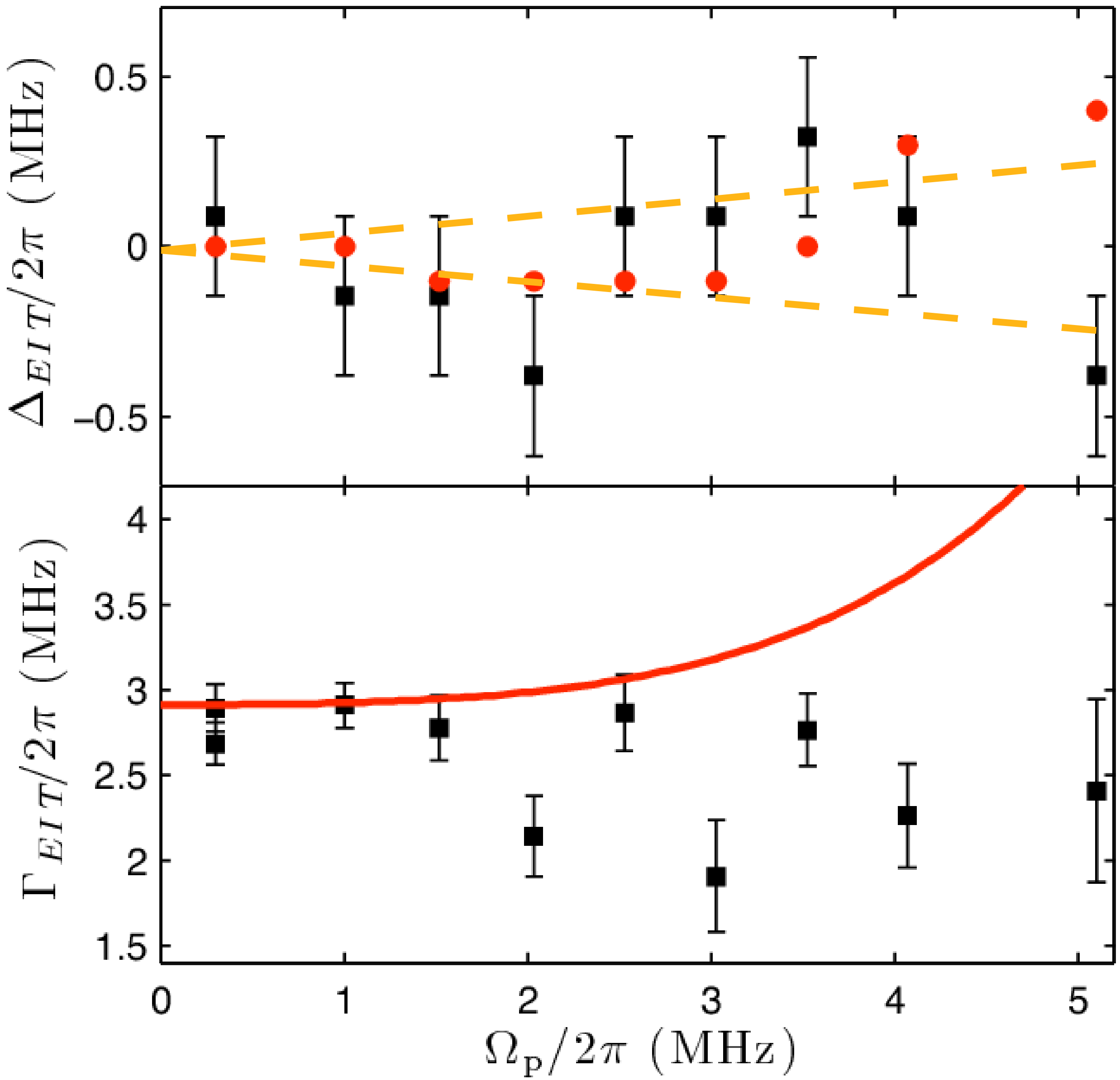


Level shift

Broadening

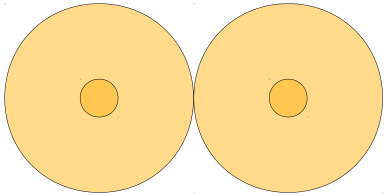


Dephasing model



$$r_b = \left(\frac{C_6}{\hbar\Omega_c}\right)^{1/6}$$

5.6 microns



Shift is less than 500 kHz

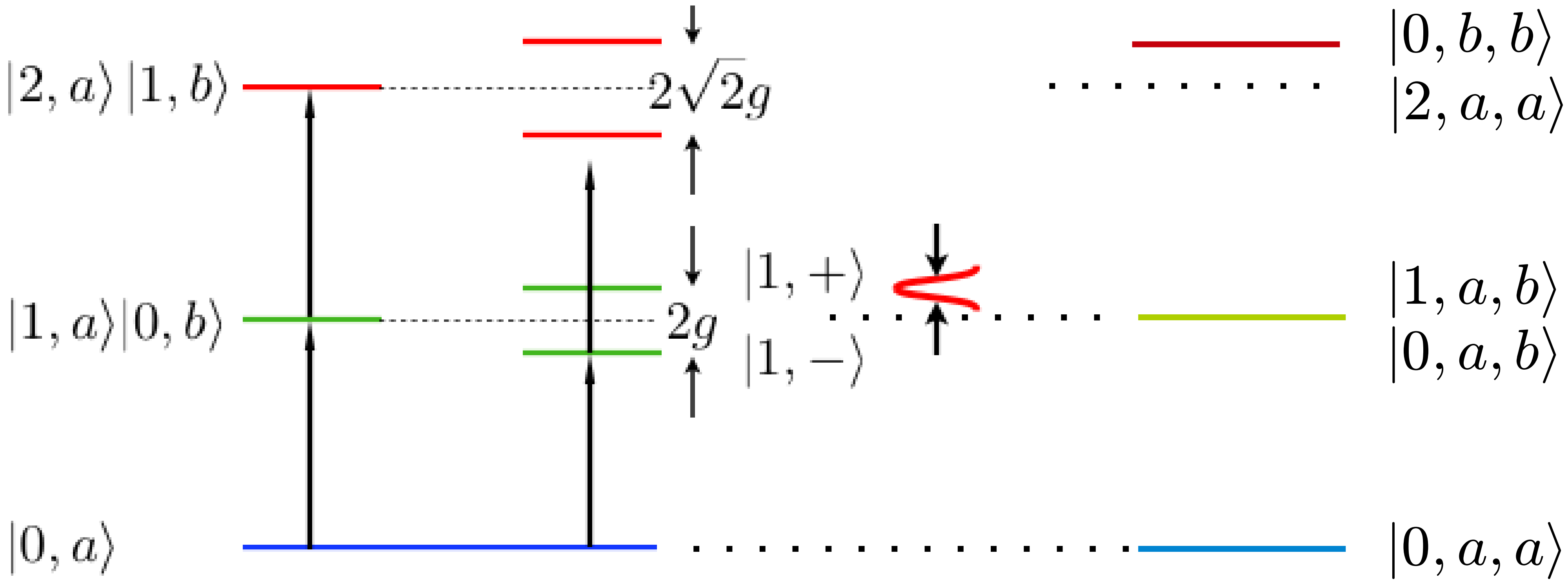
Mean superatom spacing

8.0 microns

Dephasing of superatoms < 200 kHz

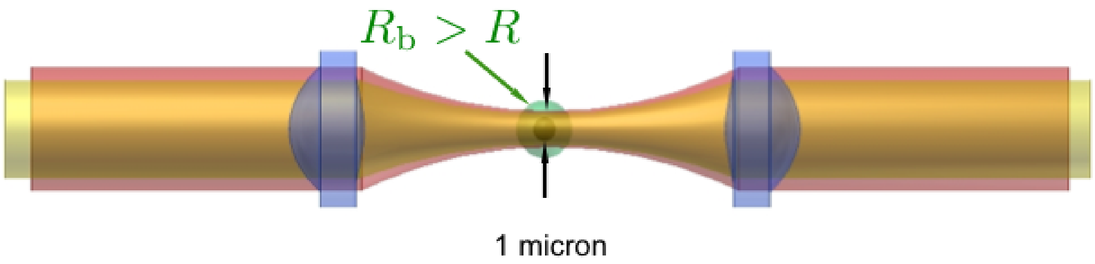
Strong coupling

Level **shift** due to a single quanta is larger than the line **width**.



$$V > \hbar\Omega$$

Single blockade volume



High optical depth per blockade

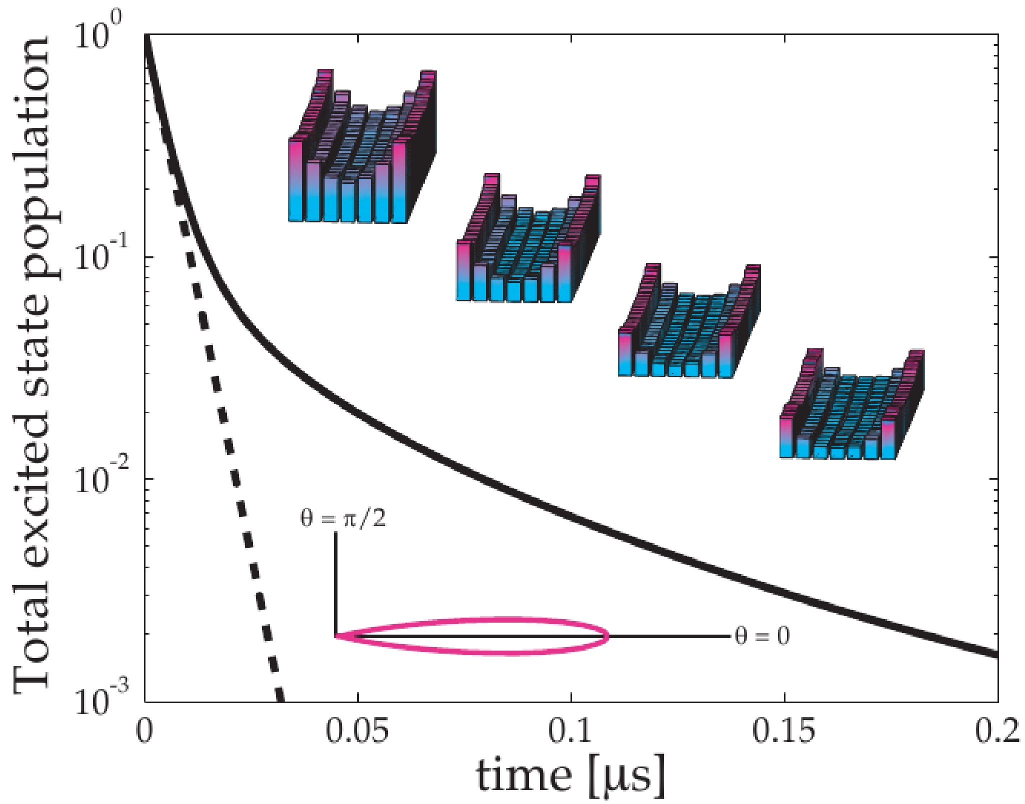
or a cavity

Single photon source

Single photon non-linear optics

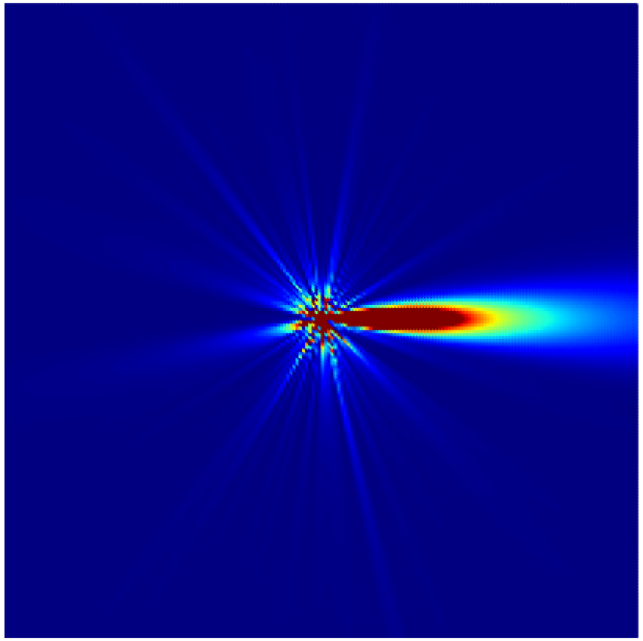
Pedersen and Molmer
Phys. Rev. A, **79**, 012320 (2009)
7 x 7 x 20 atoms

Olmos and Lesanovsky
ring lattice



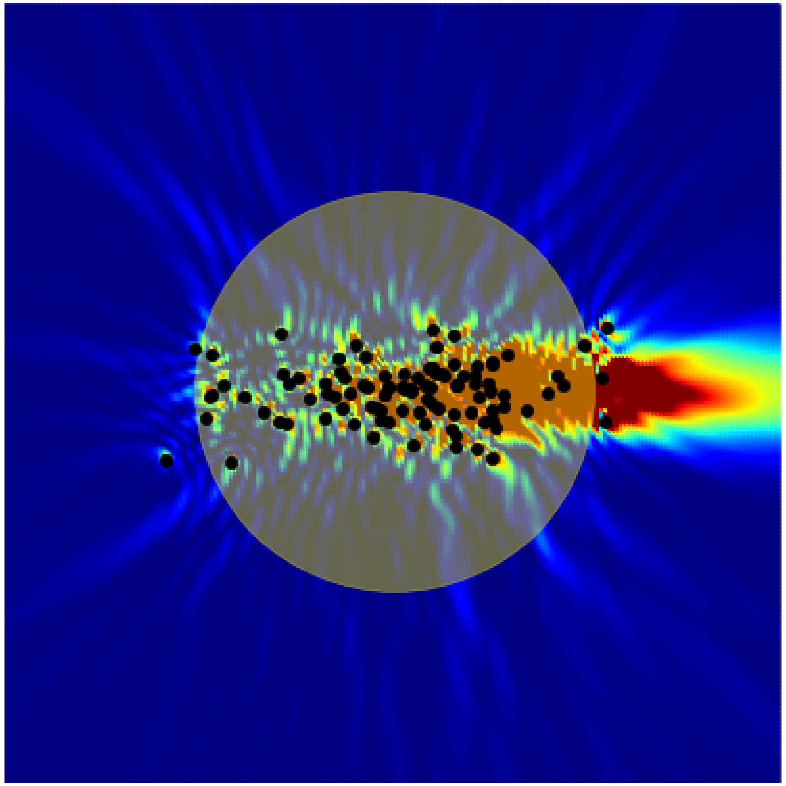
100 atoms randomly distributed in 3 x 1 micron

100 atoms randomly distributed in 3 x 1 micron

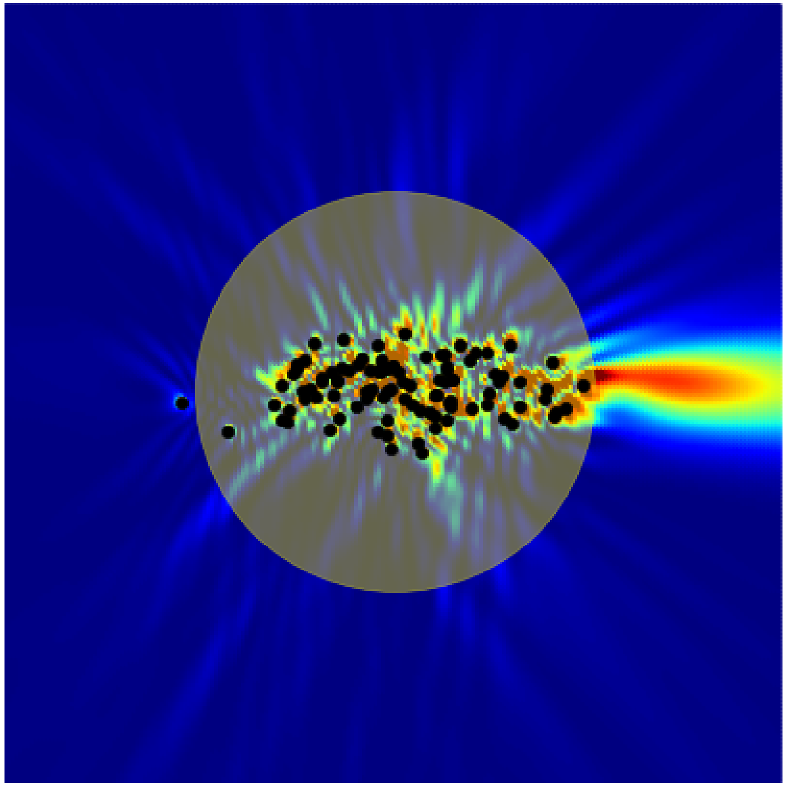


$$\mathcal{E}(x,y,z)=\mathcal{E}_0\frac{w_0}{w}\mathrm{e}^{\mathrm{i}kz}\mathrm{e}^{-\mathrm{i}\alpha}\mathrm{e}^{\mathrm{i}\rho^2/2R}\mathrm{e}^{-\rho^2/w^2} \qquad \alpha=\tan^{-1}\left(\frac{2z}{kw_0^2}\right)$$

Without Gouy phase



With Gouy phase



Large effect in the near field but not so apparent in the far field

Summary

Rydberg non-linear optics

Input field → Rydberg atoms → Output field

Electrometry

E-field inside cells

Stuttgart
Durham

E-field close to surfaces

Amsterdam

Spectroscopy of the blockade

Heidelberg
Durham

Rydberg quantum optics

Acknowledgements

Jon Pritchard

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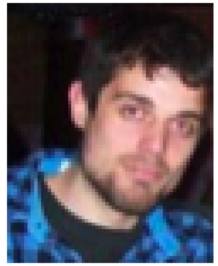
Matt Jones



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EPSRC

Durham University