Joint Quantum Centre (JQC) Durham - Newcastle

Joint Quantum Centre
JQC.ORG.UK

Current PhD:

H. Busches
C. Carr
J. Keaveney
D. Maxwell
D. Parades

Current PDRA:

D. Szwer

Collaborators:

M. P. A. Jones (Durham)
I. G. Hughes (Durham)
R. M. Potvliege (Durham)
K. J. Weatherill (Durham)
D. Sarkisyan (Yerevan)
M. Tanasittikosol (Bangkok)

Sr Rydberg:

G. Lochead
D. Boddy
D. Saddler
C. Vaillant

Recent PhD:

R. Abel (2011)
J. D. Pritchard (2011)

Recent PDRA:

A. Gauguet (Toulouse)
U. Krohn (Durham)
A. Mohapatra (Bhubanesqar)

EPSRC

Durham University

ITN - COHERENCE
MARIE CURIE ACTIONS

SEVENTH FRAMEWORK PROGRAMME

In DIPOLES we deLIGHT

Summary

Part I

Light field and one dipole

Dipole – dipole interactions

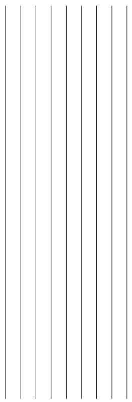
Part II

Non-linear optics

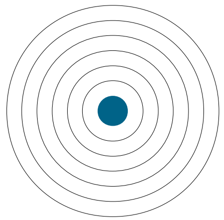
Incident field $\mathcal{E}_{\mathrm{i}}$

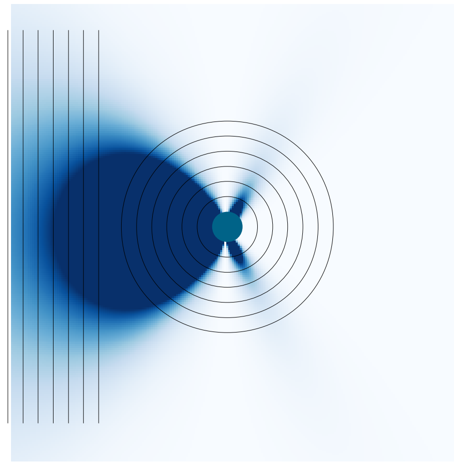
Induced dipole field $\mathcal{E}_{\mathrm{d}}$

Total field $\mathcal{E}_{\mathrm{t}} = \mathcal{E}_{\mathrm{i}} + \mathcal{E}_{\mathrm{d}}$

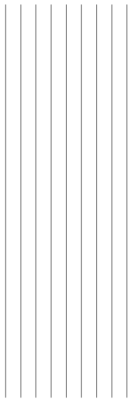


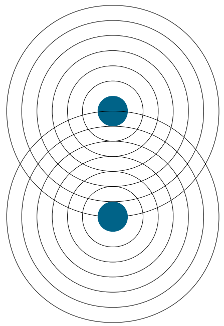
One dipole





Two dipoles

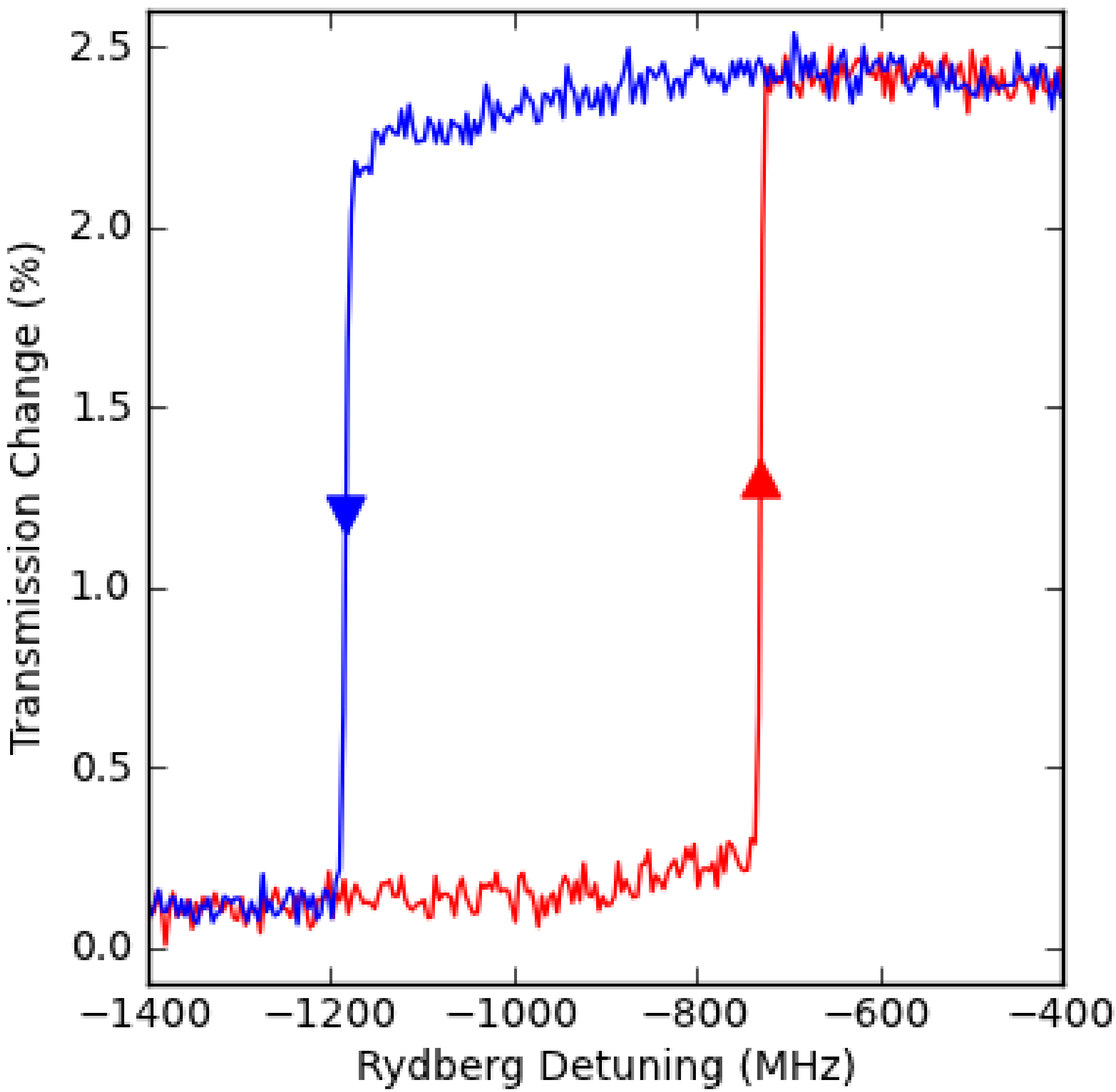




Cooperative effects:

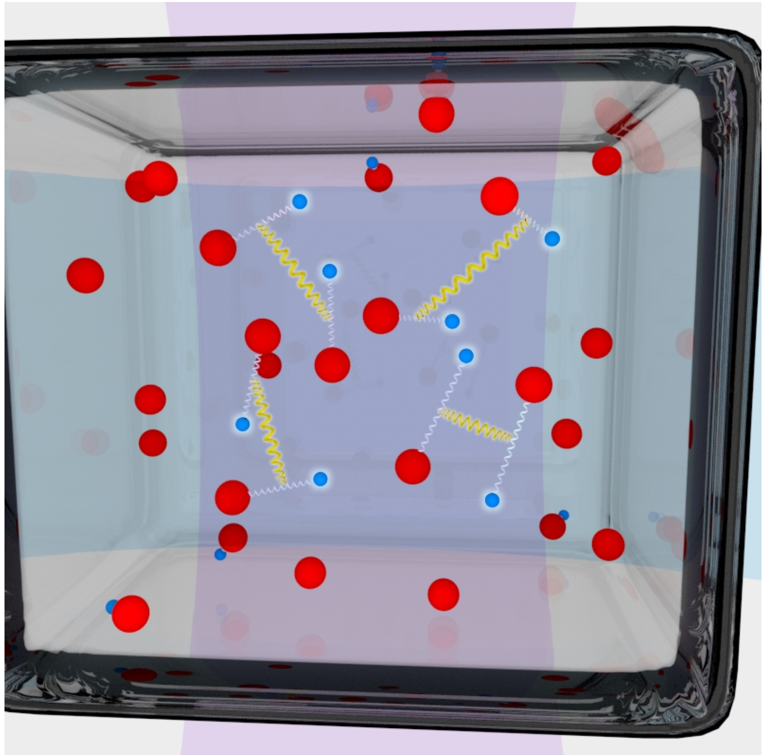
level shift/splitting, sub/superradiance

Strongly correlated quantum many body system!



2.5
2.0
1.5
1.0
0.5
0.0
Transmission Change (%)
−1400
−1200
−1000
−800
−600
−400
Rydberg Detuning (MHz)

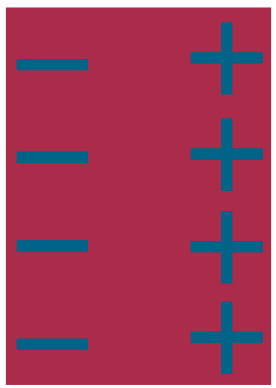
For intuition look to classical physics



Dipoles and dielectrics

Force → $\mathcal{E}$

Dielectric

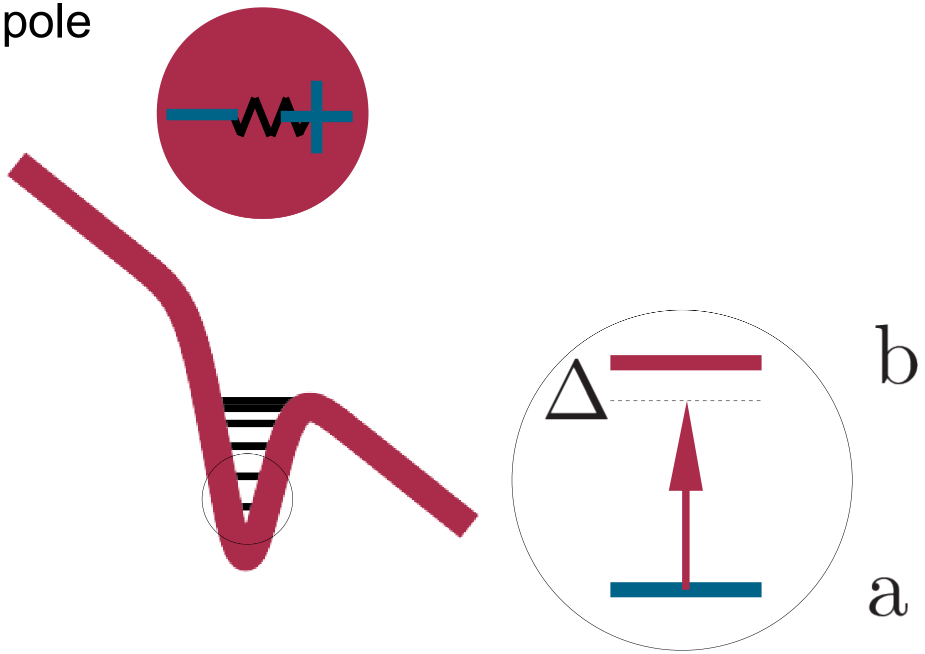


Displacement Force

$$P = N\langle d\rangle = \epsilon_0 \chi \mathcal{E}$$

Susceptibility: dimensionless

Dipole



No dipole-dipole

$$\frac{\langle d\rangle}{4\pi\epsilon_0} = \alpha_{\rm p}\mathcal{E} \qquad \chi = 4\pi N \alpha_{\rm p}$$

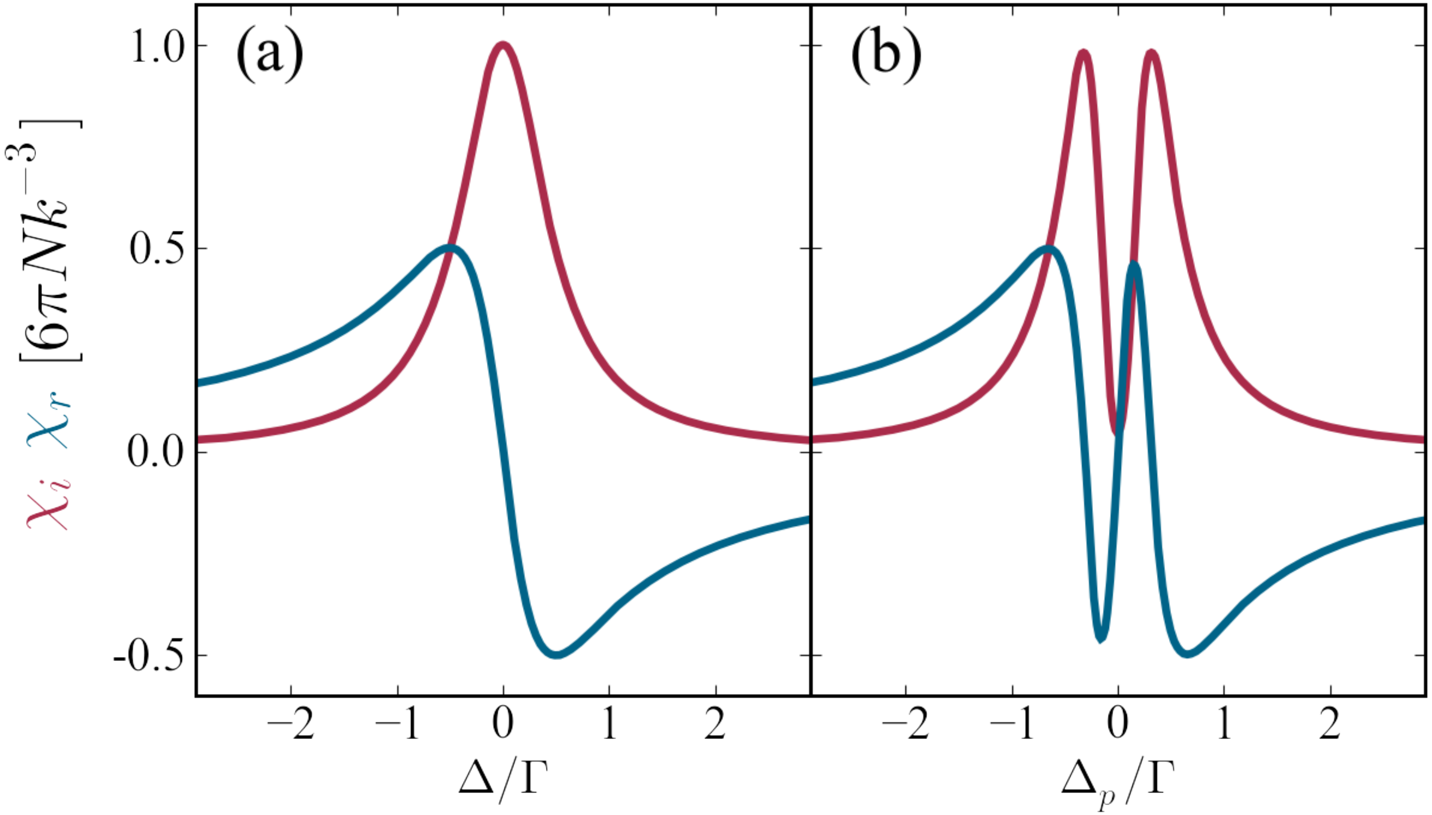
Medium Single dipole

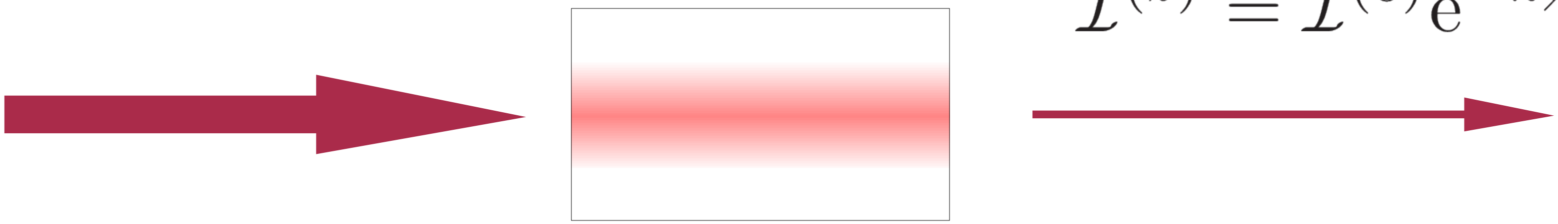
$$\alpha_{\rm p} = -\frac{1}{4\pi\epsilon_0}\frac{d_{\rm ab}^2}{\hbar(\Delta + {\rm i}\gamma_{\rm ab})}$$

2-level

3-level

See Notes 5.4





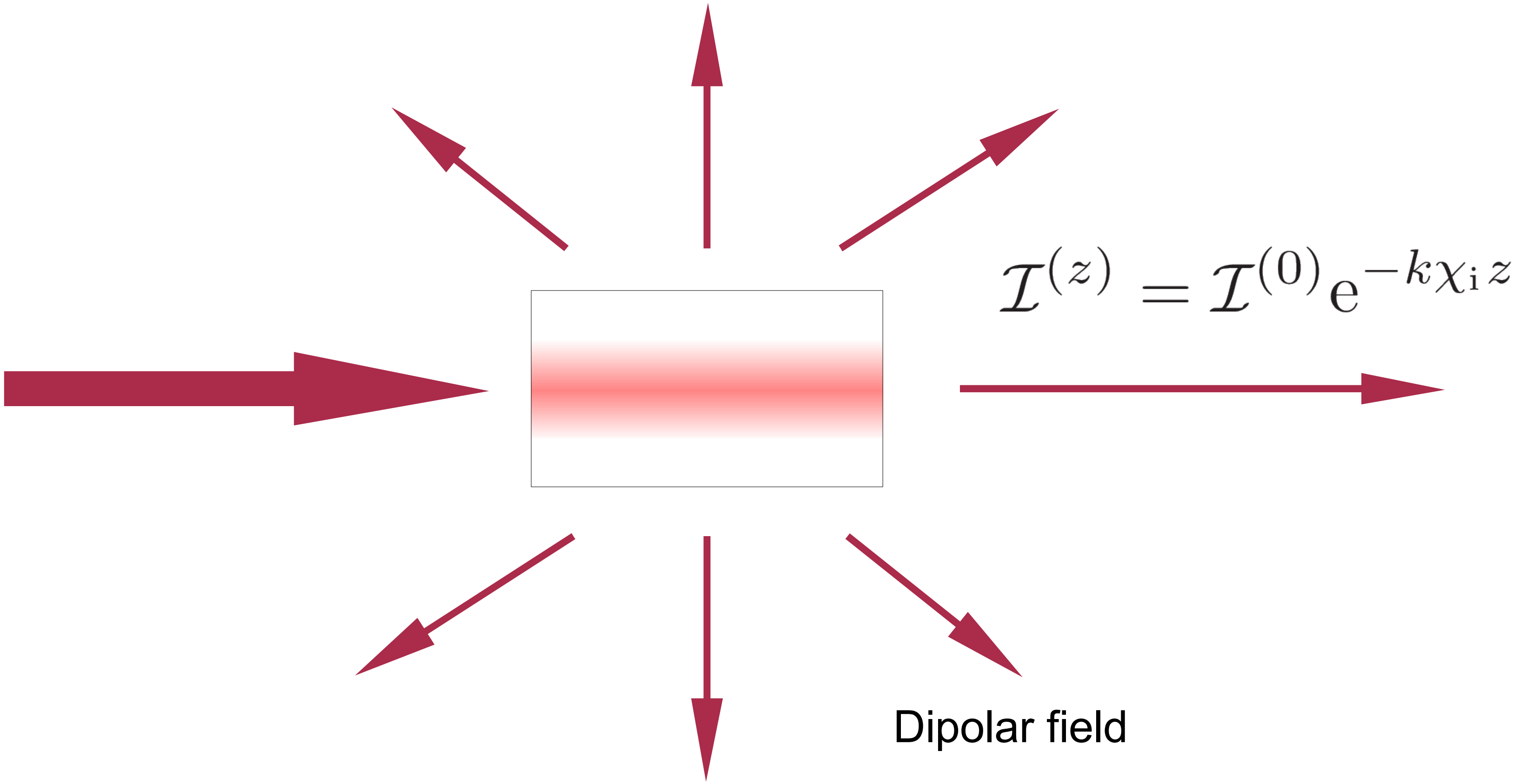
$$\mathcal{I}^{(z)} = \mathcal{I}^{(0)} \mathrm{e}^{-k\chi_\mathrm{i} z}$$

Aha! The light has been absorbed.

$$\alpha = k\chi_\mathrm{i}$$

Where has the light gone?

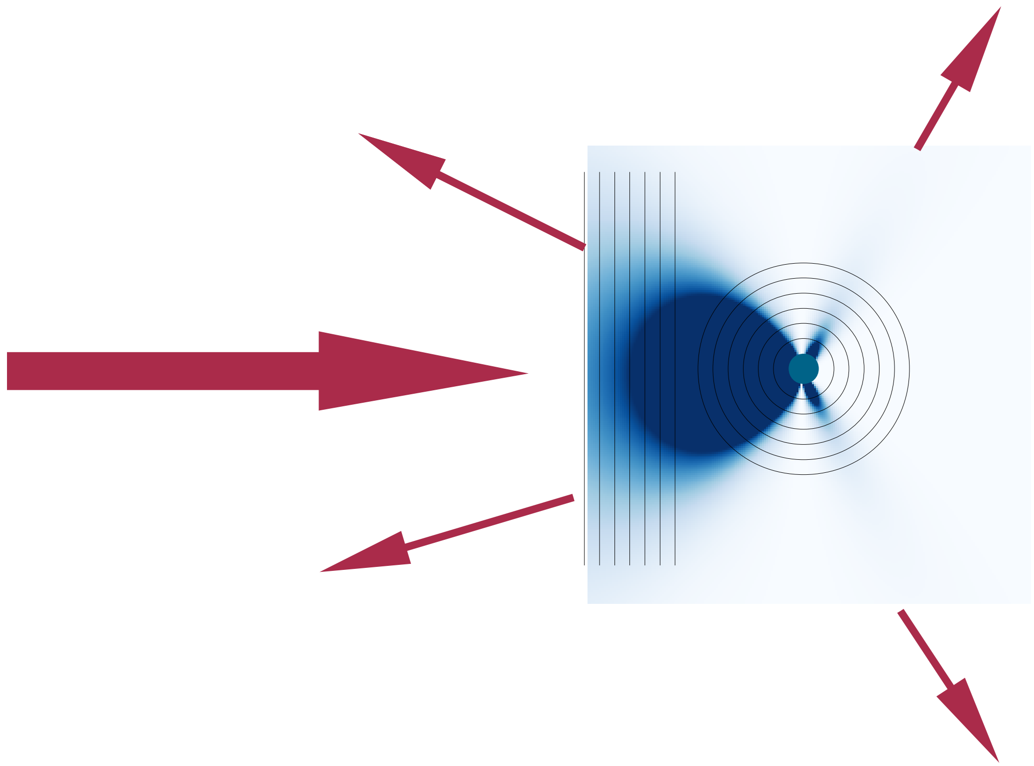
Light propagation through a dipolar medium.



No absorbed! Just scattered.

Is it possible to reduce the transmission to zero?

For a single dipole?

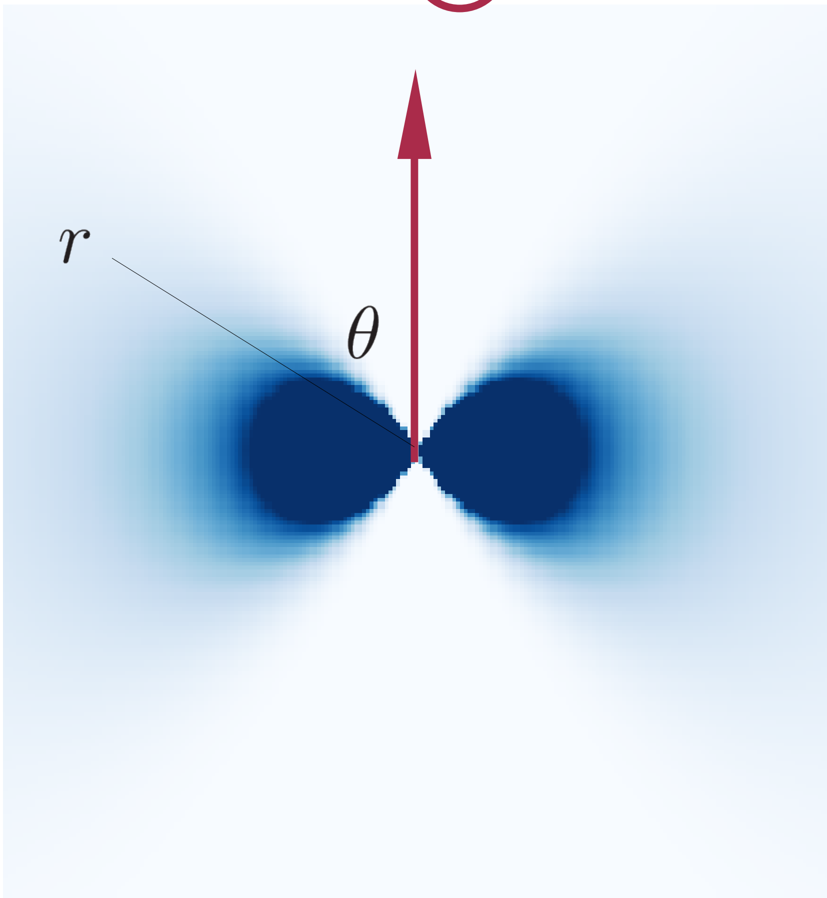


$$\mathcal{E}_{\rm t} = \mathcal{E}_{\rm i} + \mathcal{E}_{\rm d}$$

Destruction interference
in the
forward scattering direction

Electric field of a dipole

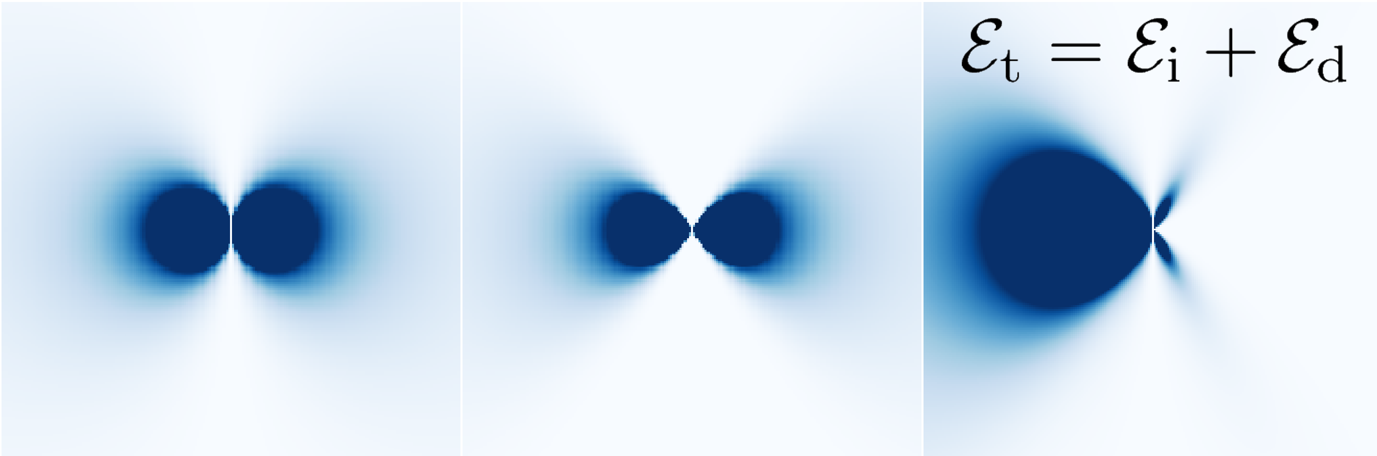
$$\mathcal{E}_z = \frac{d}{4\pi\epsilon_0}\left[\left(\frac{1}{r^3}-\frac{\mathrm{i}k}{r^2}\right)(3\cos^2\theta-1)+\frac{k^2}{r}\sin^2\theta\right]\mathrm{e}^{\mathrm{i}(kr-\omega t)}$$



Focussed Gaussian

$$\mathcal{E}_\mathrm{i}^{(z)} = -\mathrm{i}\frac{z_\mathrm{R}}{z}\mathcal{E}_0\mathrm{e}^{\mathrm{i}kz}\mathrm{e}^{\mathrm{i}k\rho^2/2z}\mathrm{e}^{-\rho^2/w_0^2}$$

A diffraction light field acquires a phase of $\pi/2$

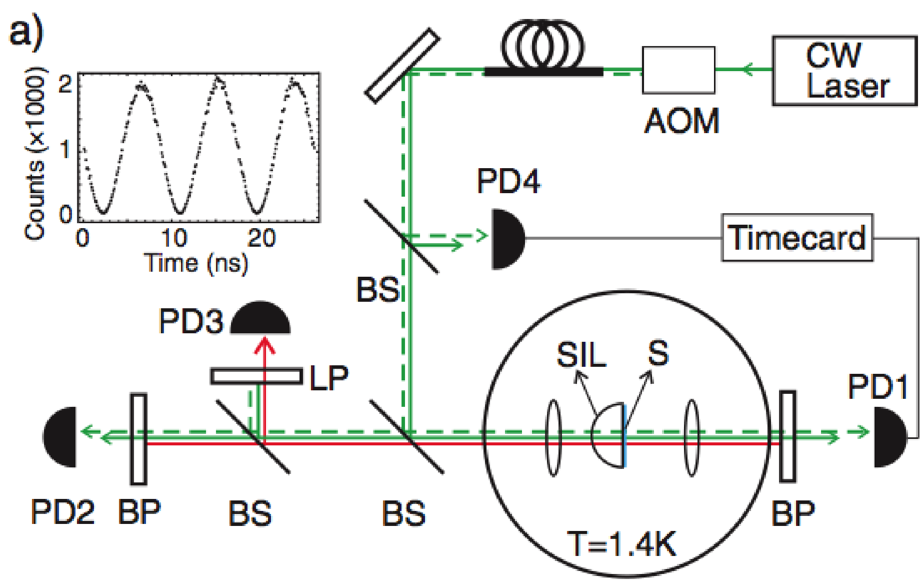


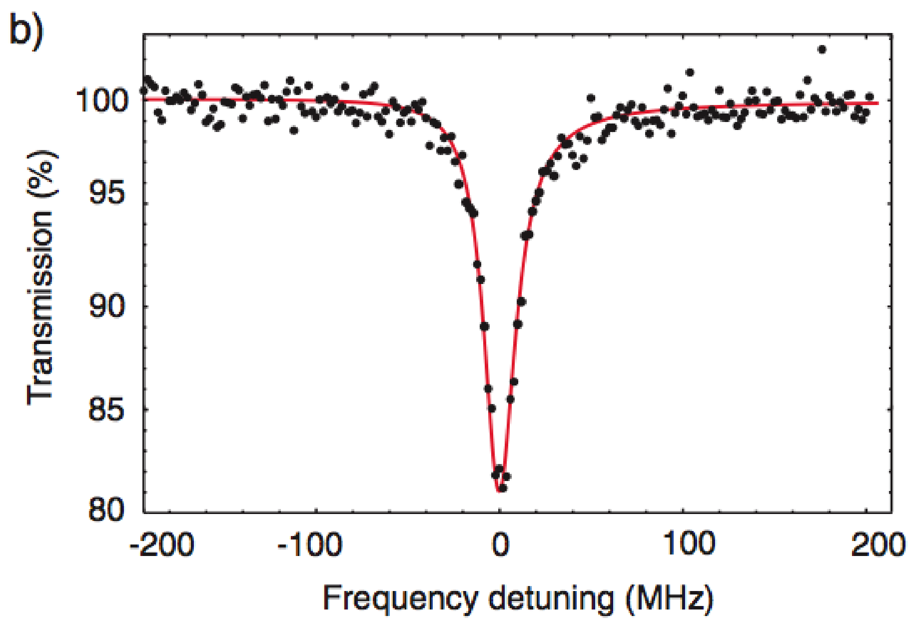
Dipole field

$$\mathcal{E}_\mathrm{d} = \mathrm{i}\frac{3}{2}\frac{1}{kr}\mathcal{E}_0\sin^2\theta\,\mathrm{e}^{\mathrm{i}(kr-\omega t)}$$

On resonance a driven oscillator lags the driving field by $\pi/2$

State of the art





Pototschnig *et al.*
Phys. Rev. Lett. **107**, 063001 (2012).

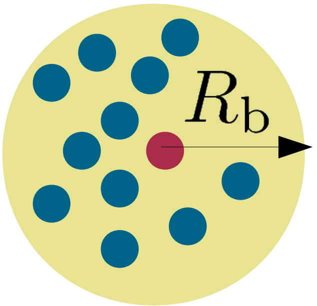
See also work by:

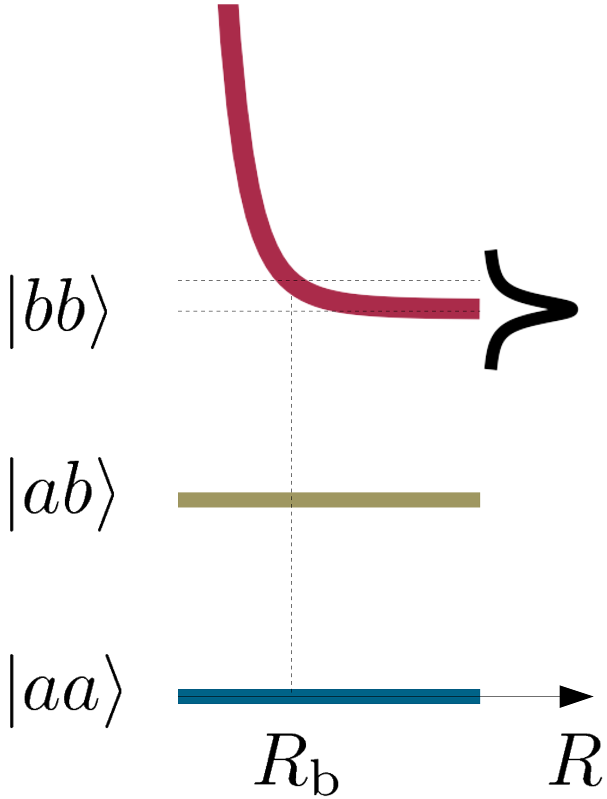
Kurtsiefer (Singapore)
Leuch (Erlangen)

An ensemble of *N* dipoles that only support a single excitation.

An ensemble of *N* dipoles that only support a single excitation.

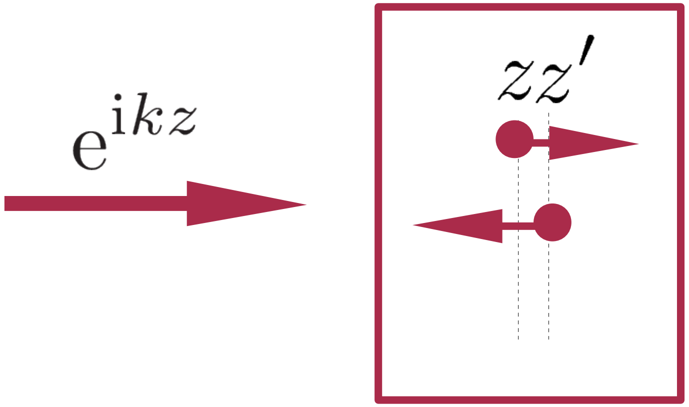
A Rydberg superatom





$$|\psi\rangle = \frac{1}{\sqrt{N}} \sum_{j=1}^{N} |a_1 \ldots b_j \ldots a_N\rangle \qquad \sigma = N\frac{3\lambda^2}{2\pi}$$

Extinction in an ensemble: the Ewald-Oseen extinction theorem



$$\mathcal{E}_0' \mathrm{e}^{\mathrm{i}k'z} = \mathcal{E}_0 \mathrm{e}^{\mathrm{i}kz} + \mathrm{i}\frac{k\chi}{2}\mathrm{e}^{\mathrm{i}kz}\int_z^\infty \mathrm{d}z' \mathcal{E}_0' \mathrm{e}^{\mathrm{i}(k'-k)z'} + \mathrm{i}\frac{k\chi}{2}\mathrm{e}^{-\mathrm{i}kz}\int_0^z \mathrm{d}z' \mathcal{E}_0' \mathrm{e}^{\mathrm{i}(k'+k)z'}$$

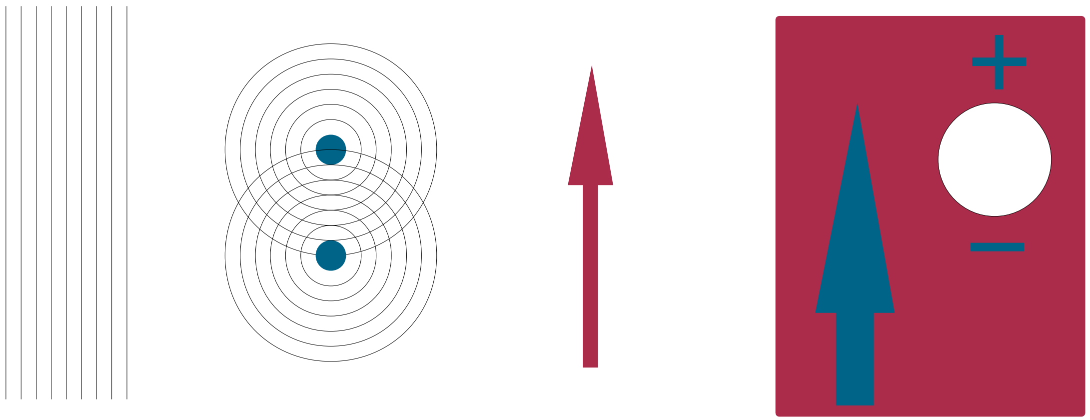
Incident field — Forward dipolar field — Backward dipolar field

$$\mathcal{E}_\mathrm{t}^{(z)} = \mathcal{E}_0 \mathrm{e}^{\mathrm{i}kz} - \mathcal{E}_0 \mathrm{e}^{\mathrm{i}kz} + \frac{2}{n+1}\mathcal{E}_0 \mathrm{e}^{\mathrm{i}nkz}$$

$$n = \sqrt{1+\chi}$$

The superposition of the incident field and the dipolar field inside the medium is plane wave with reduced amplitude and modified phase velocity.

The Lorentz local field correction



$$\mathcal{E}_{\rm loc} = \mathcal{E} + \frac{\mathcal{P}}{3\epsilon_0}$$

$$\mathcal{P} = \epsilon_0 \chi \mathcal{E} \qquad\qquad \mathcal{P} = 4\pi\epsilon_0 N \alpha_{\rm p} \mathcal{E}_{\rm loc}$$

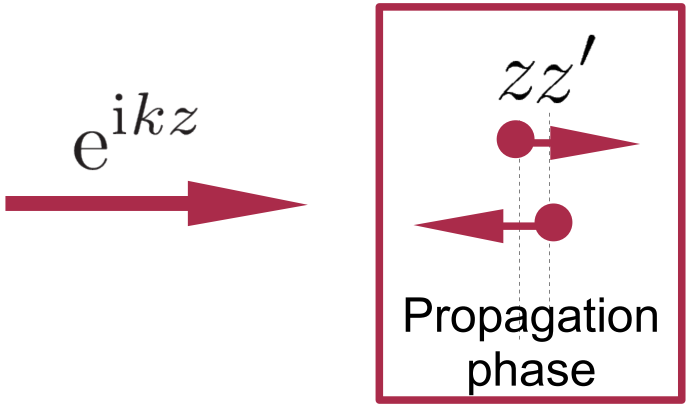
$$\chi = \frac{4\pi N \alpha_{\rm p}}{1 - \frac{4}{3}\pi N \alpha_{\rm p}}$$

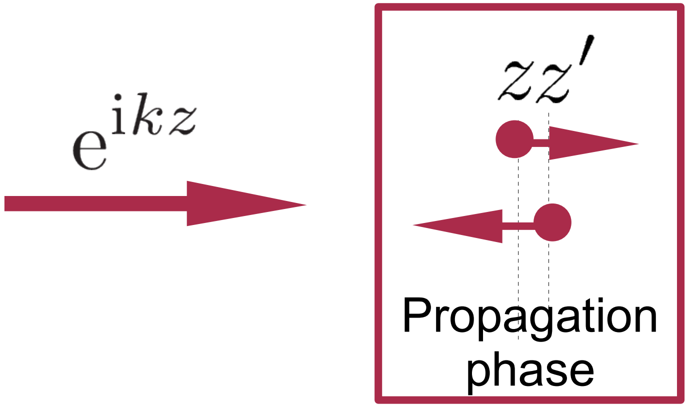
Lorentz-Lorenz law

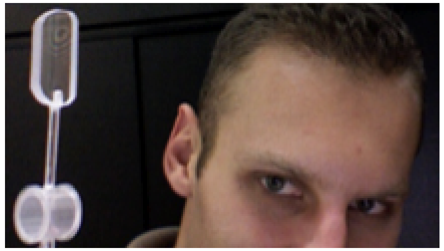
Also Clausius Mossotti

$$\chi = -\frac{Nd^2/\epsilon_0\hbar}{\Delta + {\rm i}\gamma_{\rm ab} + Nd^2/3\epsilon_0\hbar}$$

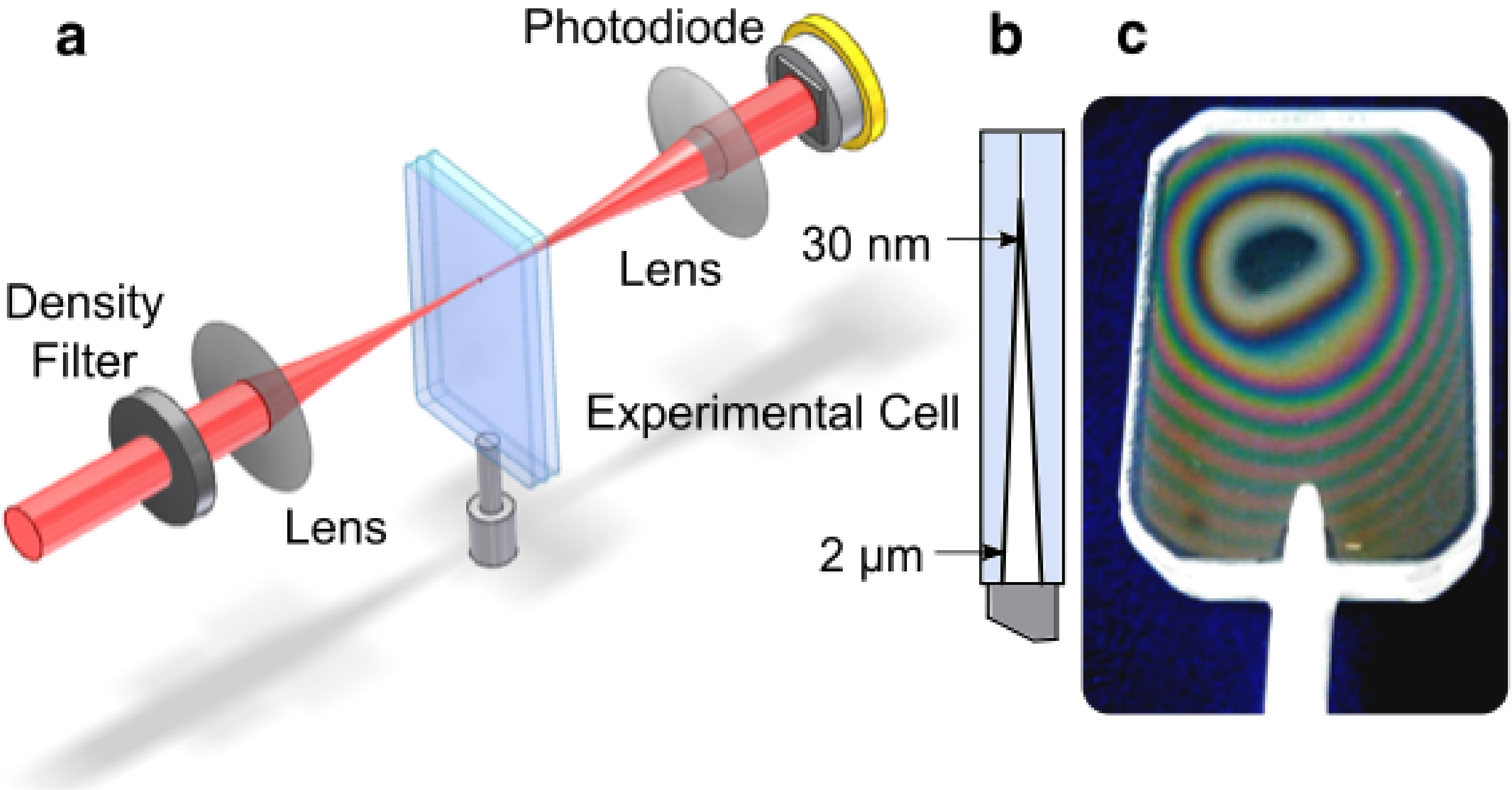
Lorentz shift

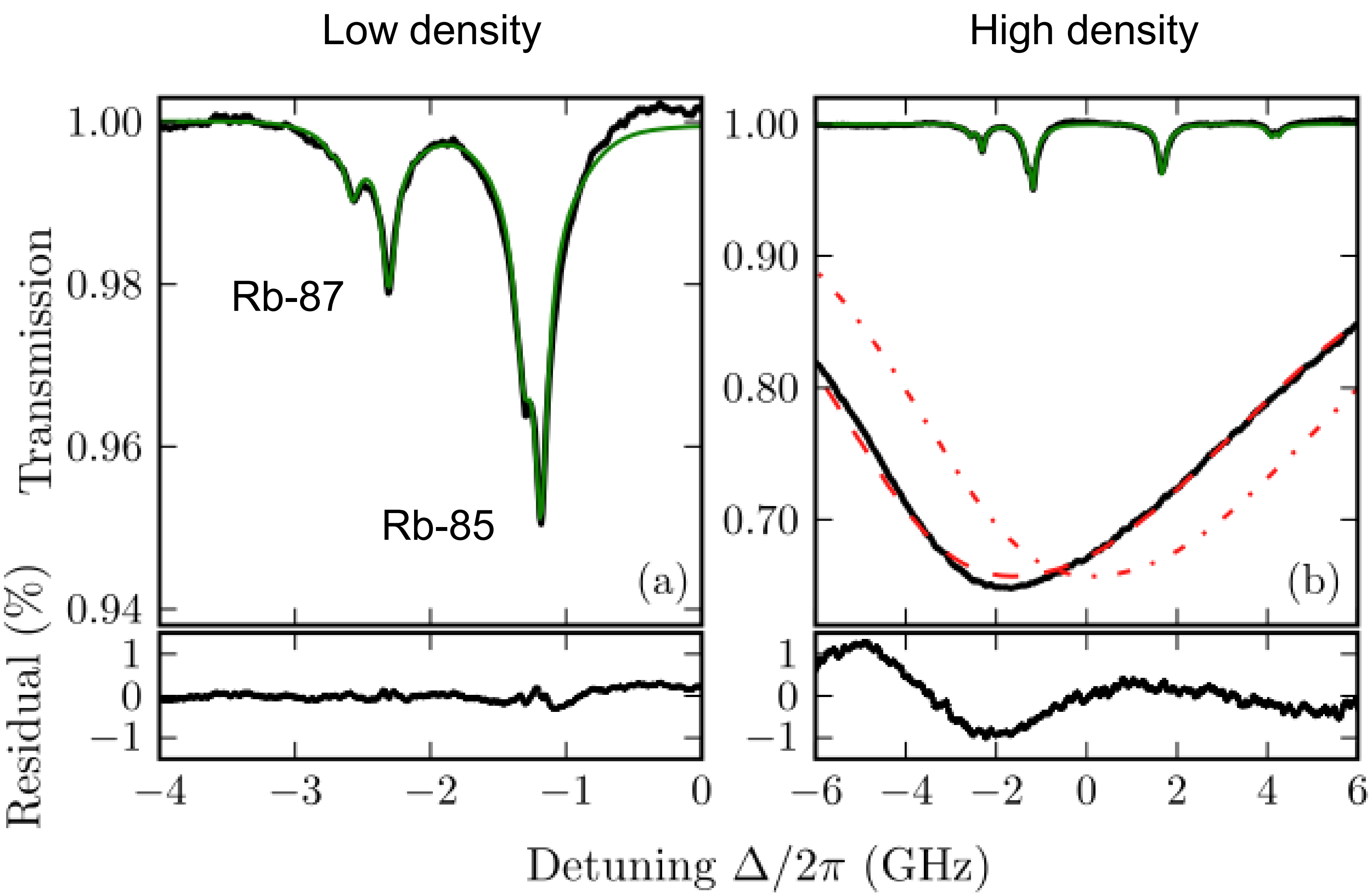

e^{ikz}
$z z'$
Propagation phase





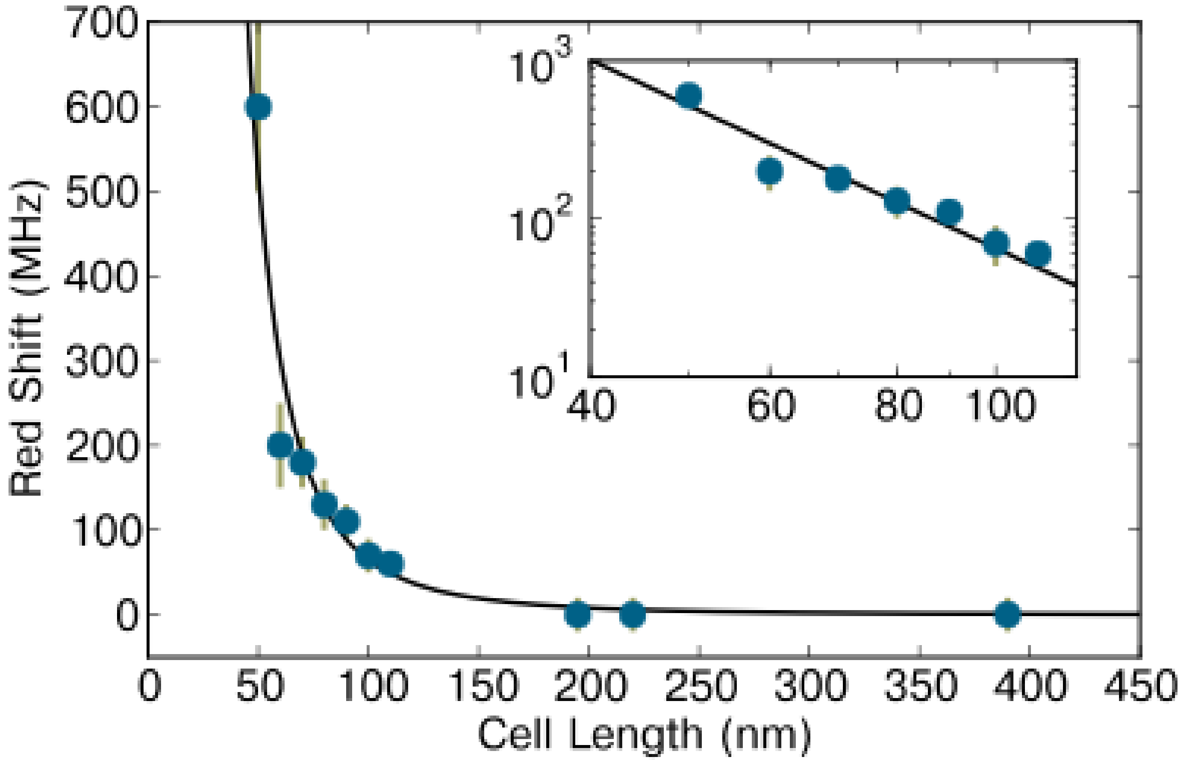
David Sarkisyan, Armen Sargsyan,
Armenian Academy of Sciences

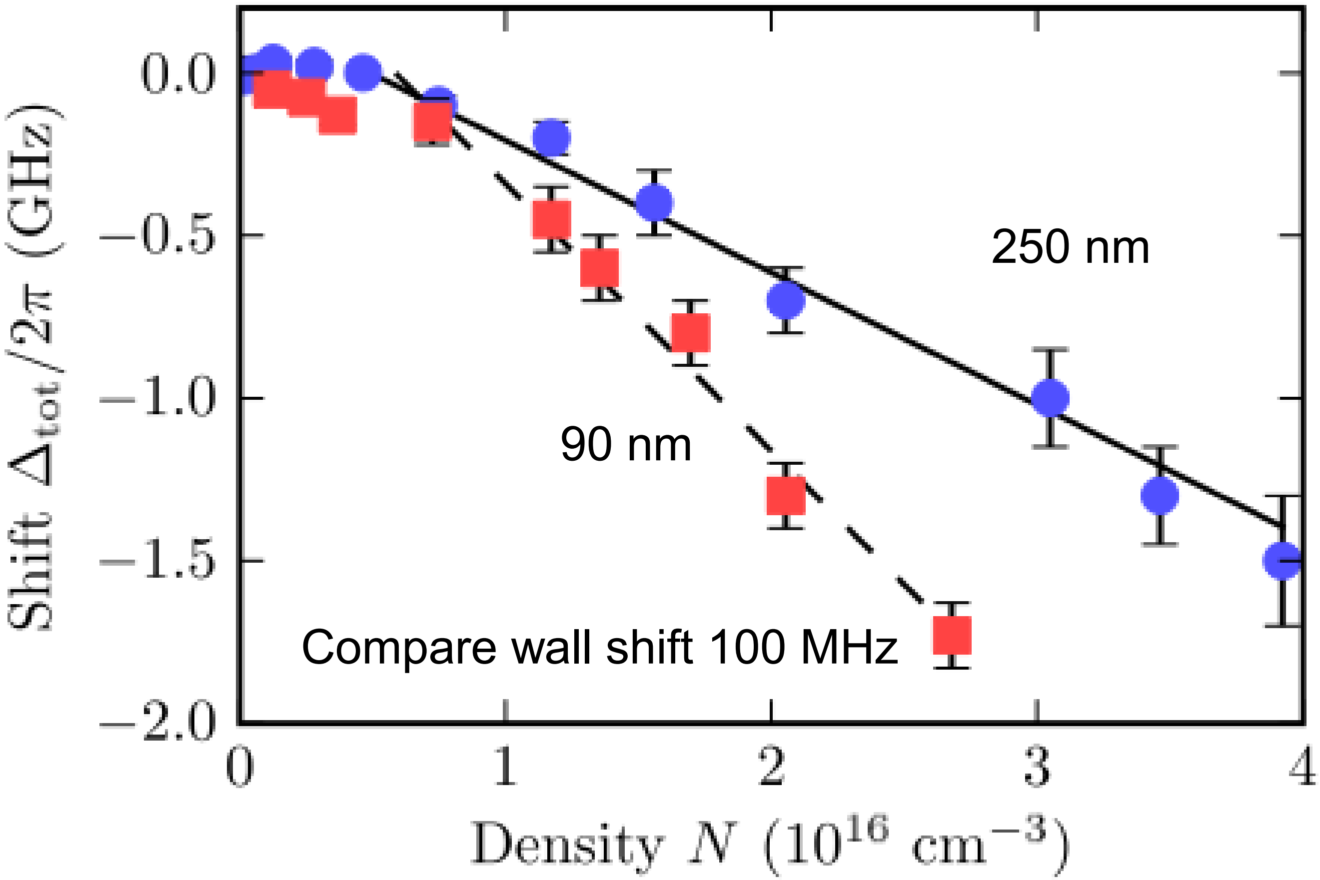




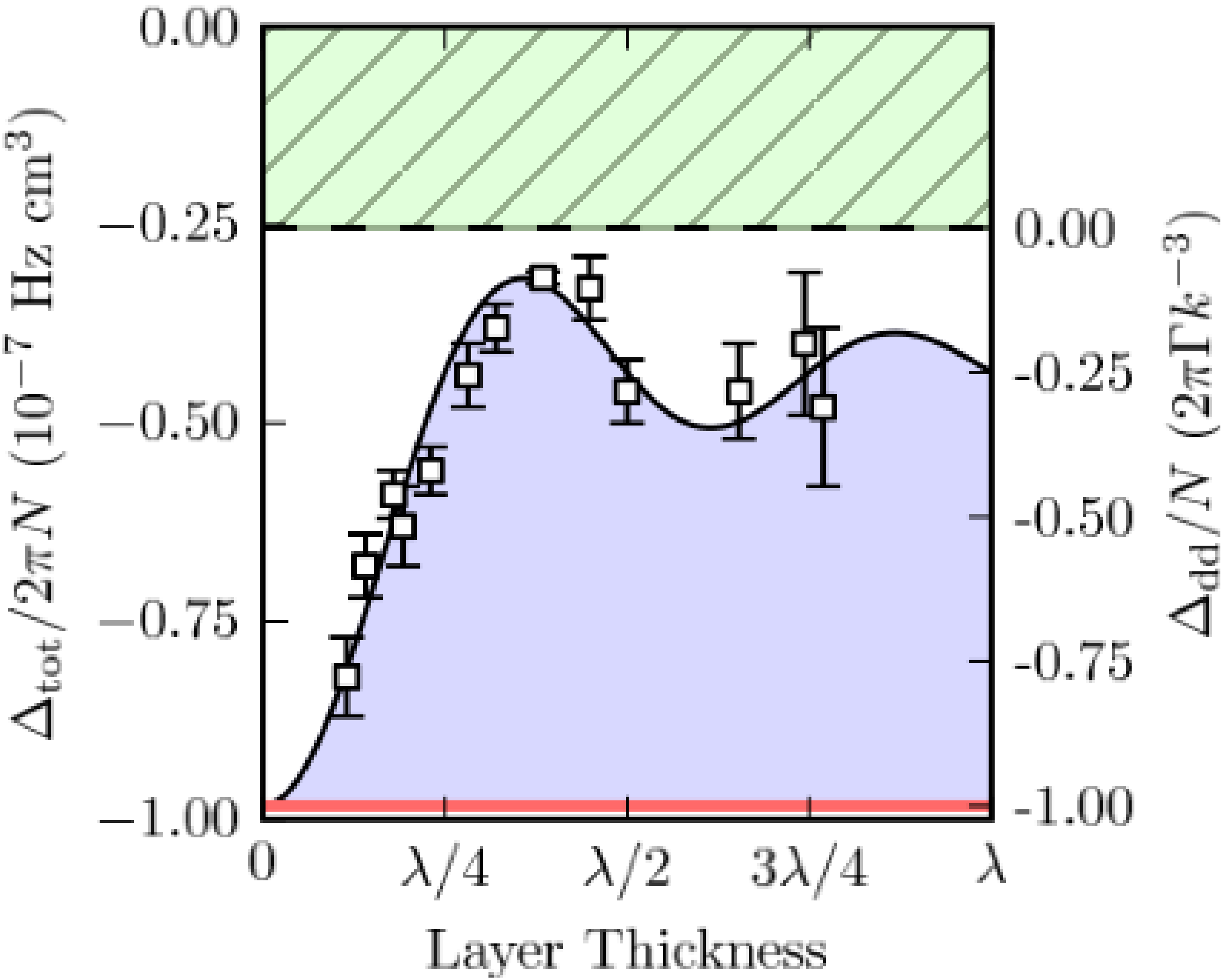
J. Keaveney *et al.*, arXiv:1201.5251

Wall shift: van der Waals: low density vary only length

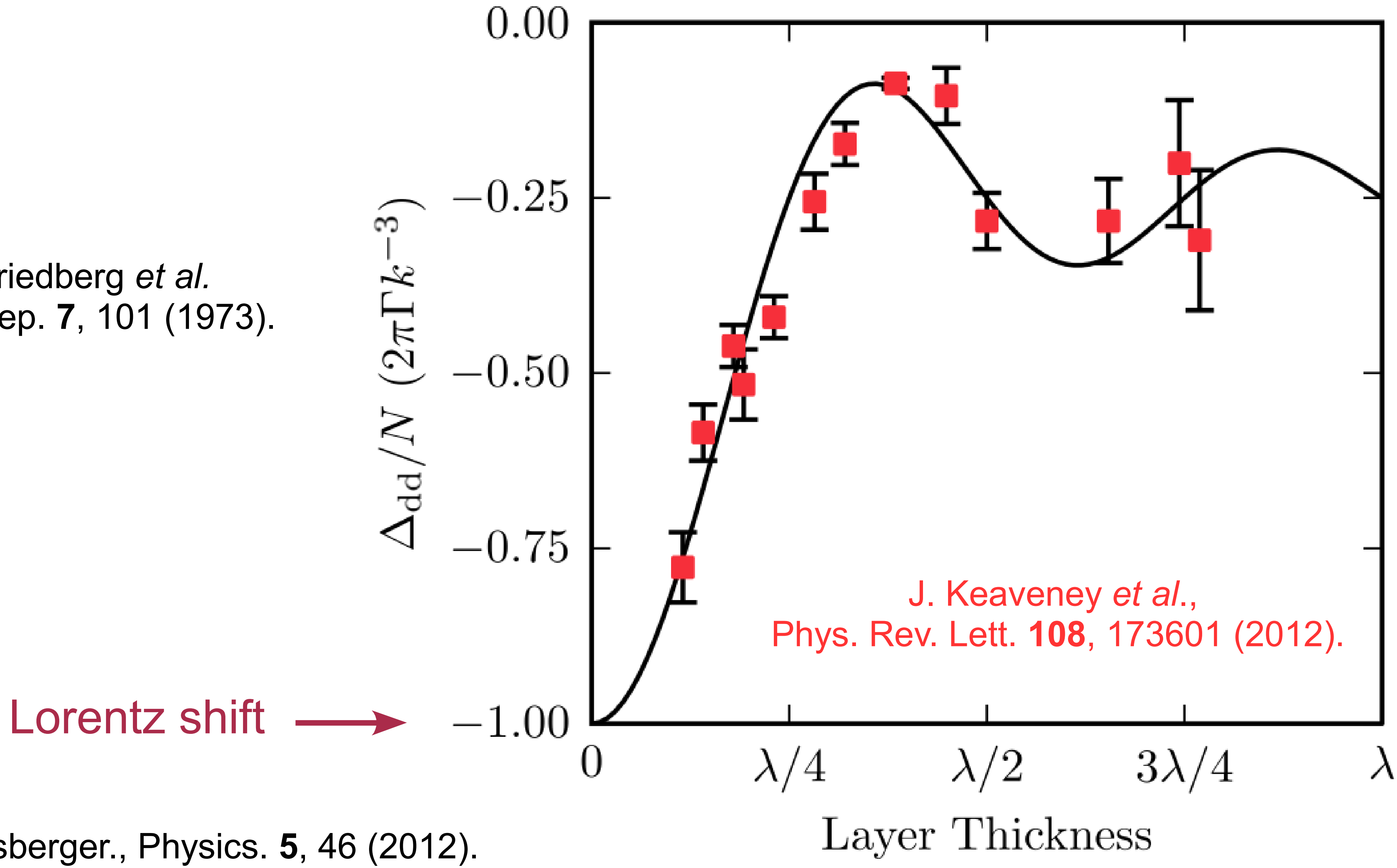




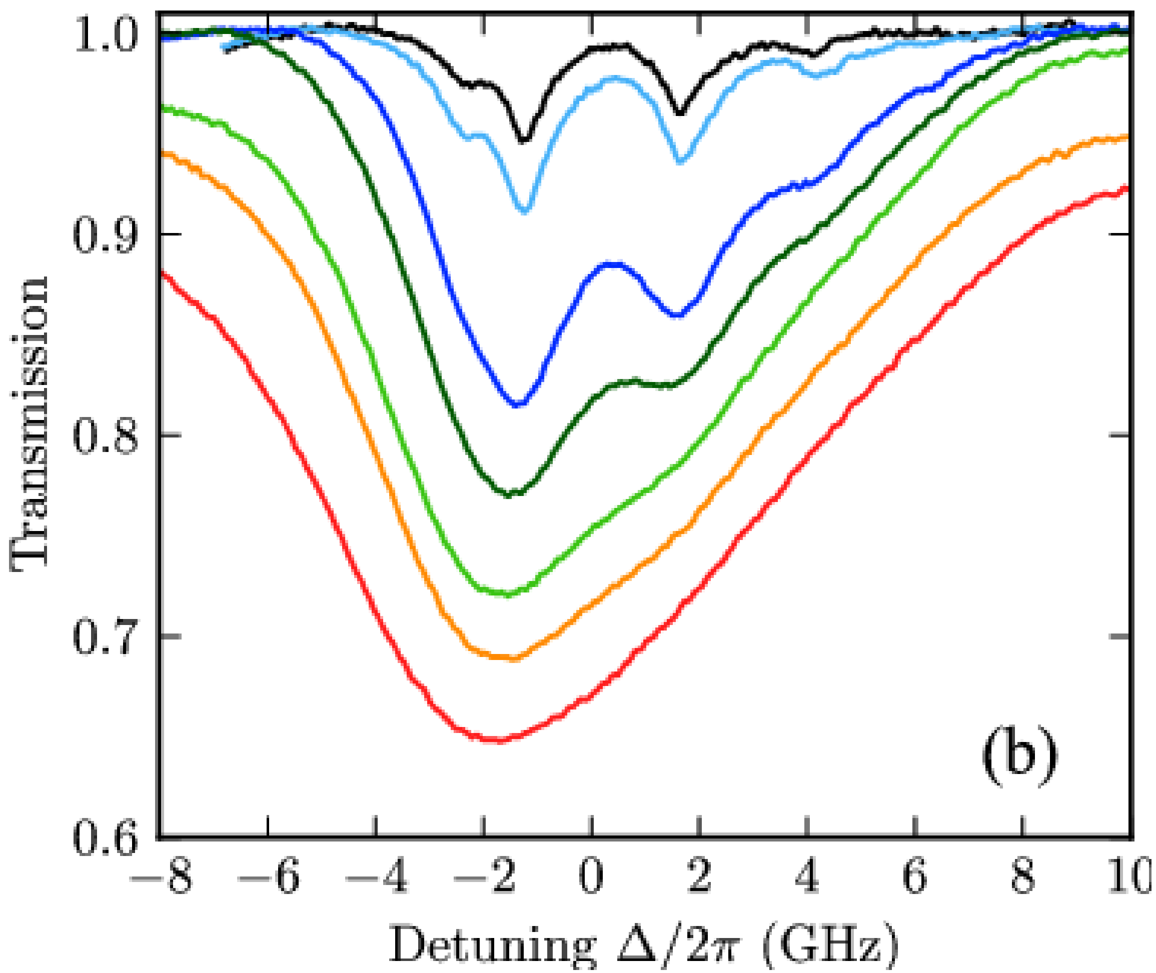
Note the high density!


0.00
−0.25
−0.50
−0.75
−1.00
$\Delta_{\rm tot}/2\pi N$ (10^{-7} Hz cm^3)
0.00
-0.25
-0.50
-0.75
-1.00
$\Delta_{\rm dd}/N$ ($2\pi\Gamma k^{-3}$)
0
$\lambda/4$
$\lambda/2$
$3\lambda/4$
λ
Layer Thickness

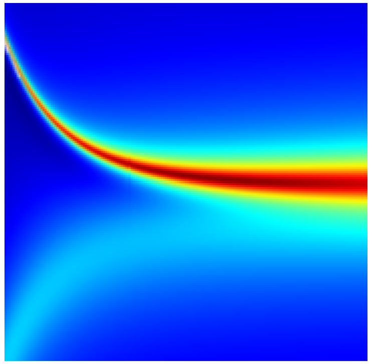
R. Friedberg *et al.*
Phys. Rep. **7**, 101 (1973).



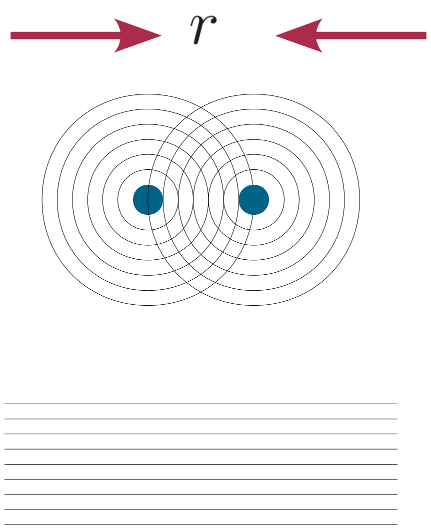
R. Rohlsberger., Physics. **5**, 46 (2012).

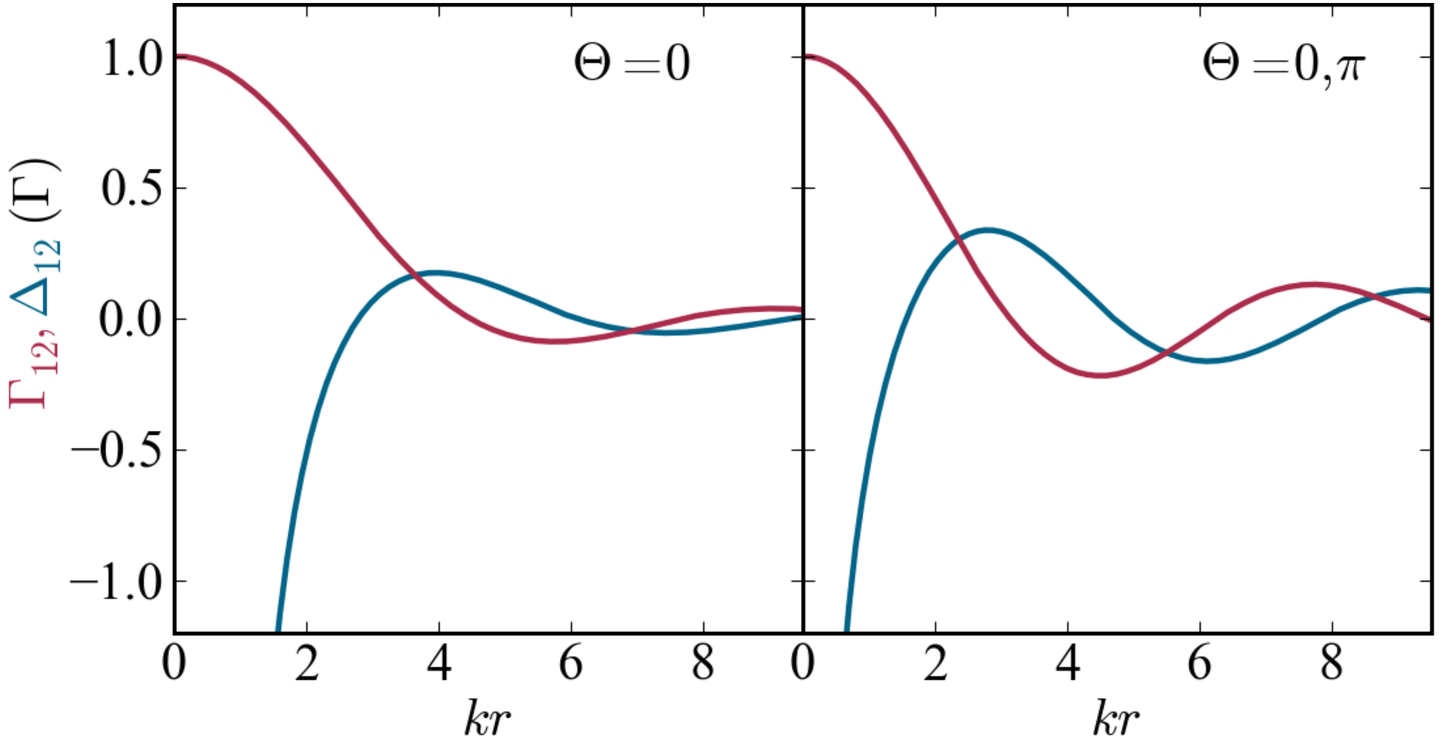


1.0
0.9
0.8
0.7
0.6
Transmission
−8 −6 −4 −2 0 2 4 6 8 10
Detuning Δ/2π (GHz)
(b)

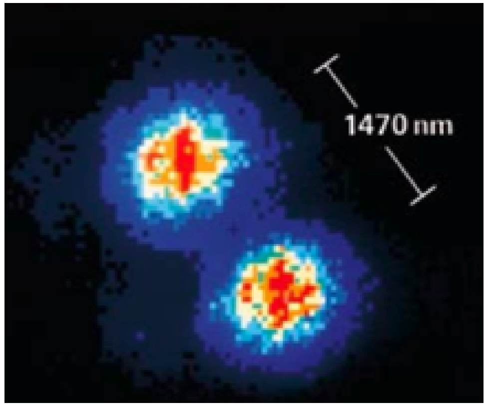


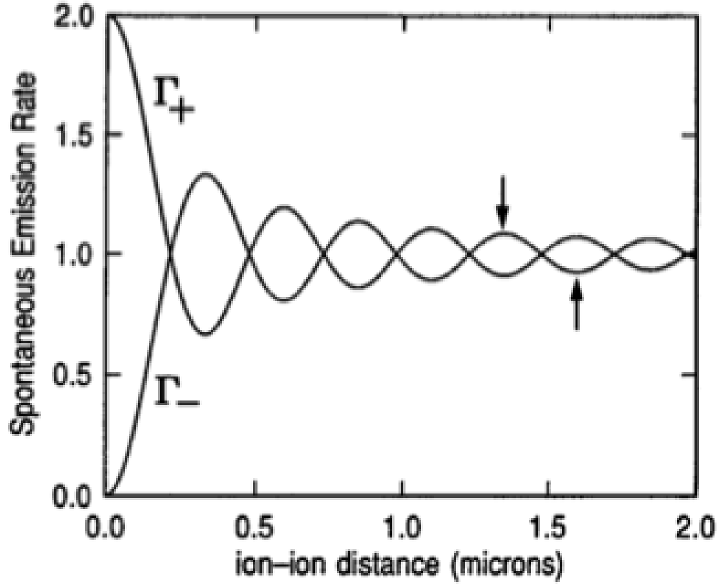
$$|\psi\rangle = \frac{1}{\sqrt{2}}(|ab\rangle \pm |ba\rangle)$$

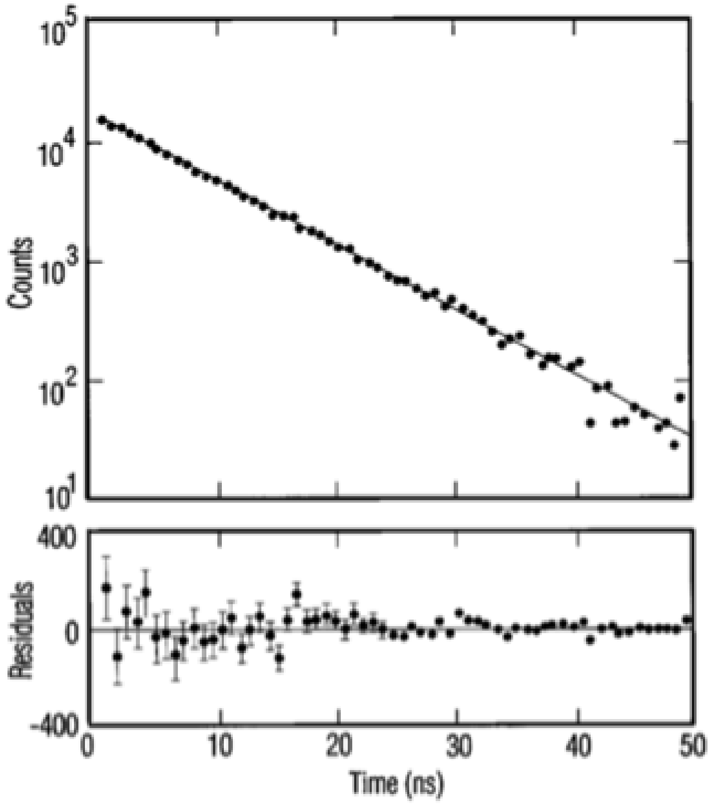


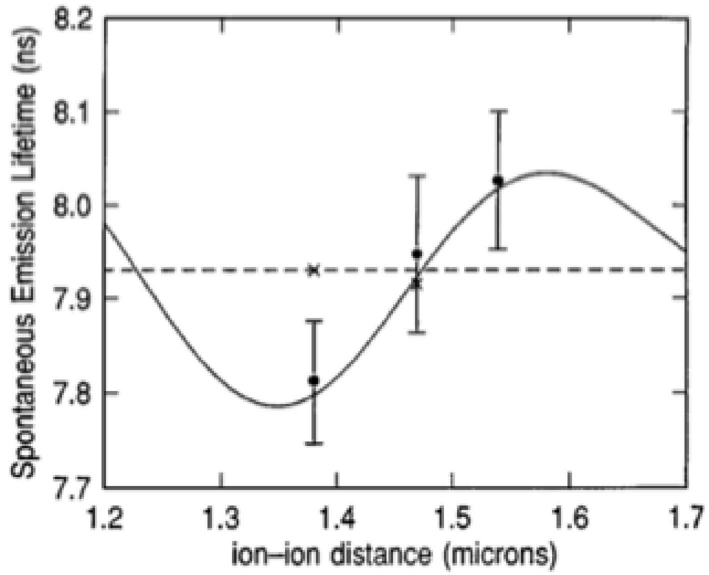


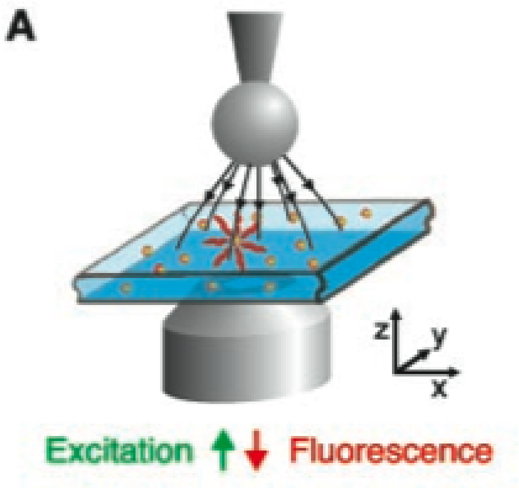
Near field $kr < 1$ Optical dipoles $r < 100$ nm Rydberg dipoles $r < 1$ mm

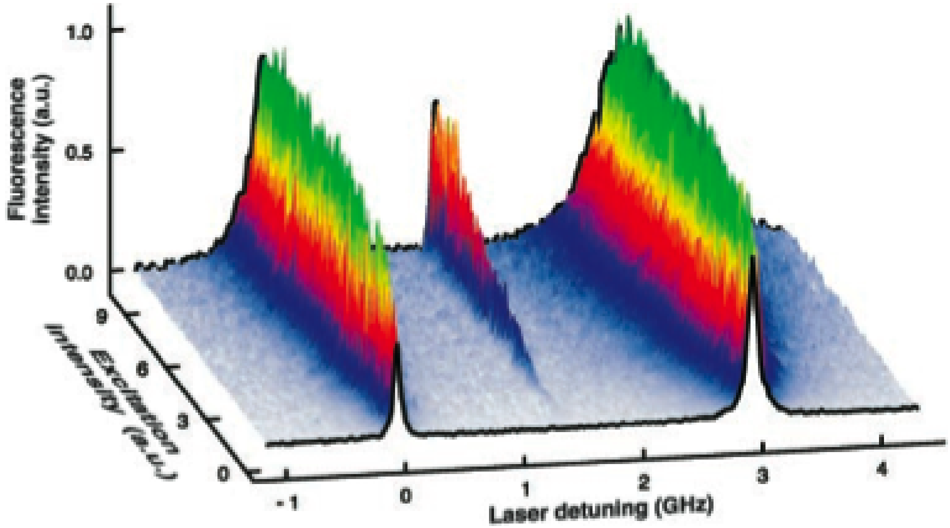

1470 nm

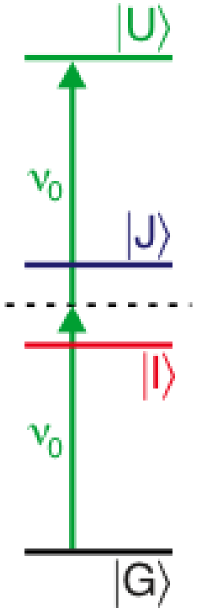

Spontaneous Emission Rate
ion–ion distance (microns)
Γ_+
Γ_-
2.0
1.5
1.0
0.5
0.0
0.0
0.5
1.0
1.5
2.0


Counts
10^5
10^4
10^3
10^2
10^1
Residuals
400
0
-400
0
10
20
30
40
50
Time (ns)

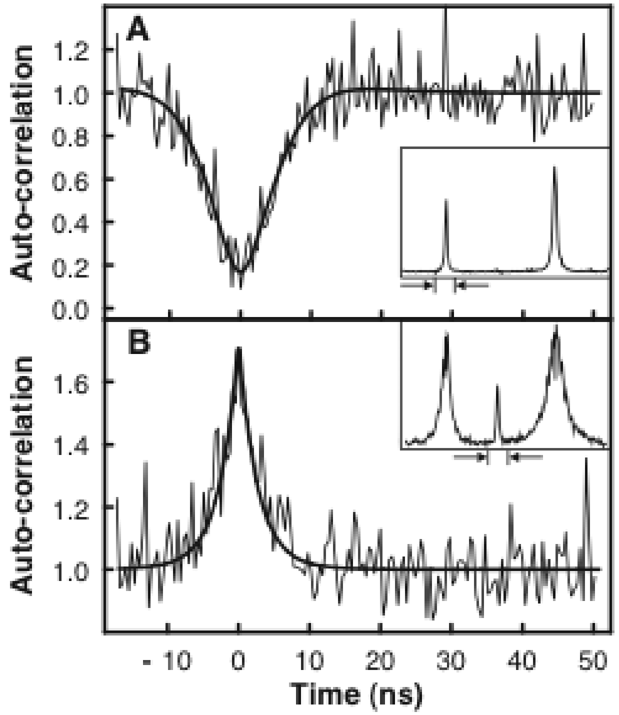

Spontaneous Emission Lifetime (ns)
8.2
8.1
8.0
7.9
7.8
7.7
1.2
1.3
1.4
1.5
1.6
1.7
ion–ion distance (microns)







Coupled system



1. Always think in terms of the superposition of the incident field and the induced dipole field.

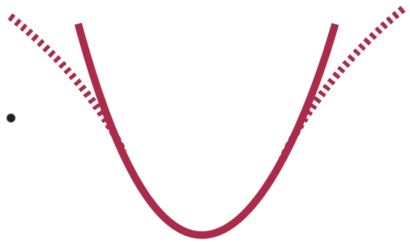
2. There is no absorption!
   Only destructive interference in the forward scattering direction.

3. The extinction problem.
   Imperfect coupling between a photon and a single dipole.

The interaction depends on the incident light intensity.

Linear optics $$P = \epsilon_0 \chi \mathcal{E}$$ Displacement is linearly proportional to the force

Non-linear optics $$P = \epsilon_0 \chi^{(1)} \mathcal{E} + \epsilon_0 \chi^{(3)} \mathcal{E}^3 + \ldots$$



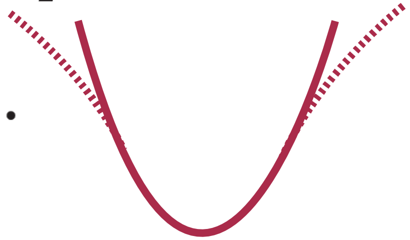
Non-linear optics

The interaction depends on the incident light intensity.

Linear optics $$P = \epsilon_0 \chi \mathcal{E}$$ Displacement is linearly proportional to the force

$\frac{1}{2} m\omega^2 (x^2 + \epsilon x^4)$

Non-linear optics $$P = \epsilon_0 \chi^{(1)} \mathcal{E} + \epsilon_0 \chi^{(3)} \mathcal{E}^3 + \ldots$$

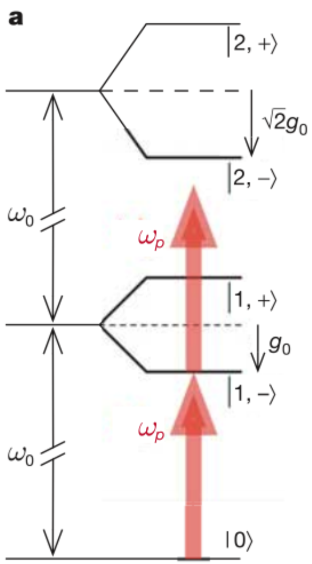


Quantum: single photon non-linearity anharmonic level spacing.

1. ac Stark shift

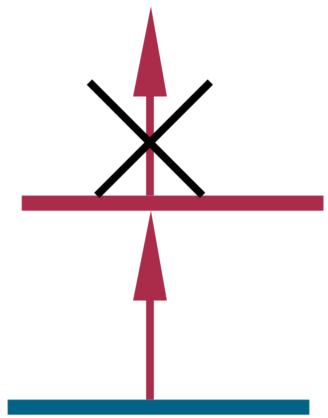
Cavity QED

Birnbaum *et al.*
Nature **436**, 101 (2005).



2. Saturation

Single dipole

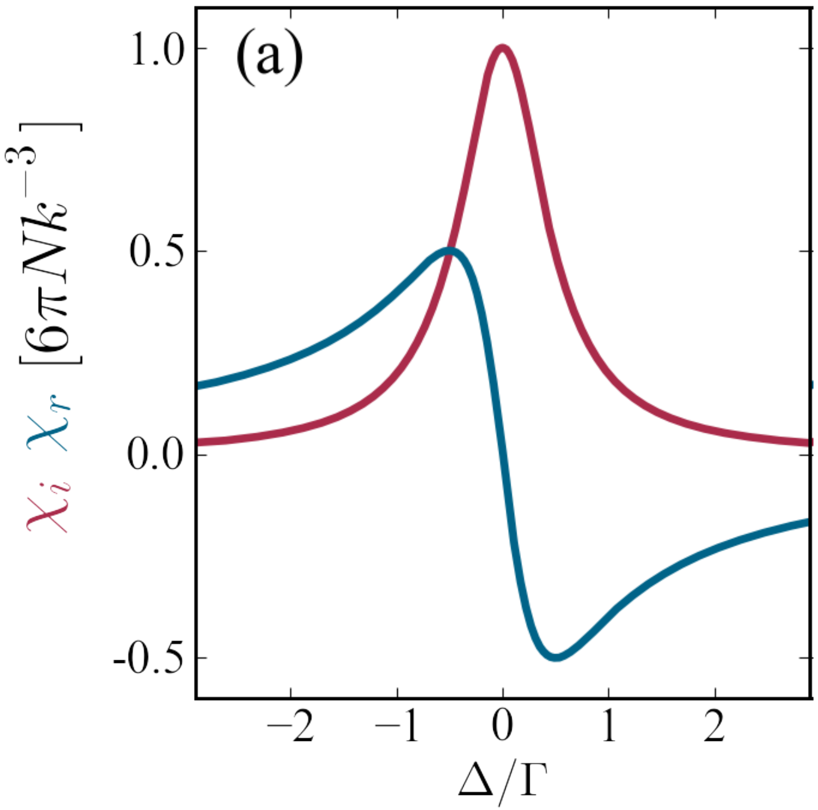


Single atom

Single molecule

The extinction problem

Rydberg superatom



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

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

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

ac Stark shift

$$\Delta\omega = -\frac{1}{2}\frac{\alpha_{\rm p}\mathcal{E}^2}{\hbar}$$

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

Far off resonance

$$\chi_{\rm r}^{(3)} = \chi_{\rm r}^{(1)} \frac{d_{\rm ab}^2}{(\hbar\omega_0)^2} \qquad \mathcal{E}_{\rm at} = \hbar\omega_0/d_{\rm ab}$$

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

Binding field

$$\mathcal{E}_{\rm at} \sim \tfrac{1}{2} e/4\pi\epsilon_0 a_0^2 \sim 5\times 10^{11}\ {\rm Vm}^{-1}$$

Non-linear term

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

Ratio of incident field to binding field squared

$$\left|\chi_{\rm r}^{(3)}\right| \leq 10^{-23}{\rm V}^{-2}{\rm m}^2$$

Water

$$\chi_{\rm r}^{(3)} = 2.5\times 10^{-22}{\rm V}^{-2}{\rm m}^2$$

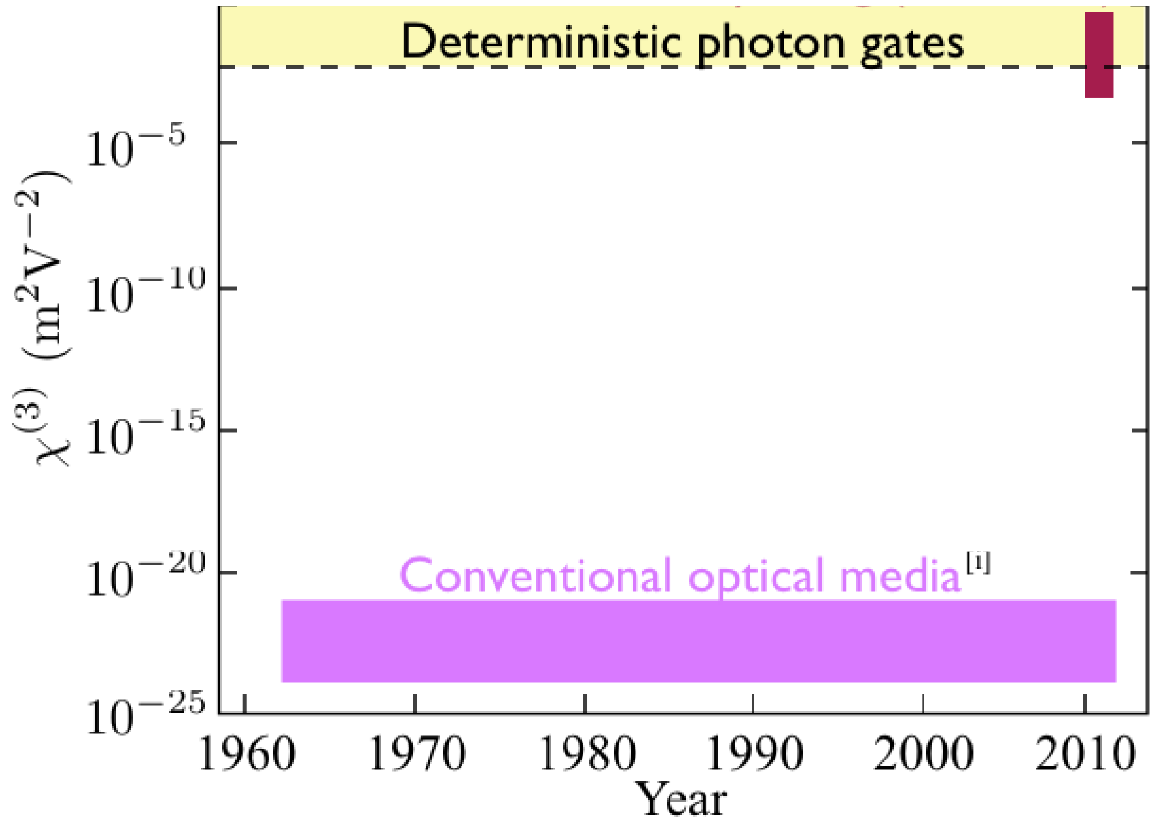
E field of a photon $\hbar\omega_0 = \frac{1}{2}\epsilon_0\mathcal{E}^2\pi w_0^2\ell$

Length 1 MHz bandwidth 1 micron in a fibre

$\mathcal{E} \sim 3 \times 10^1\ \mathrm{Vm}^{-1}$

$\mathcal{E}_{\mathrm{at}} \sim 5 \times 10^{11}\ \mathrm{Vm}^{-1}$

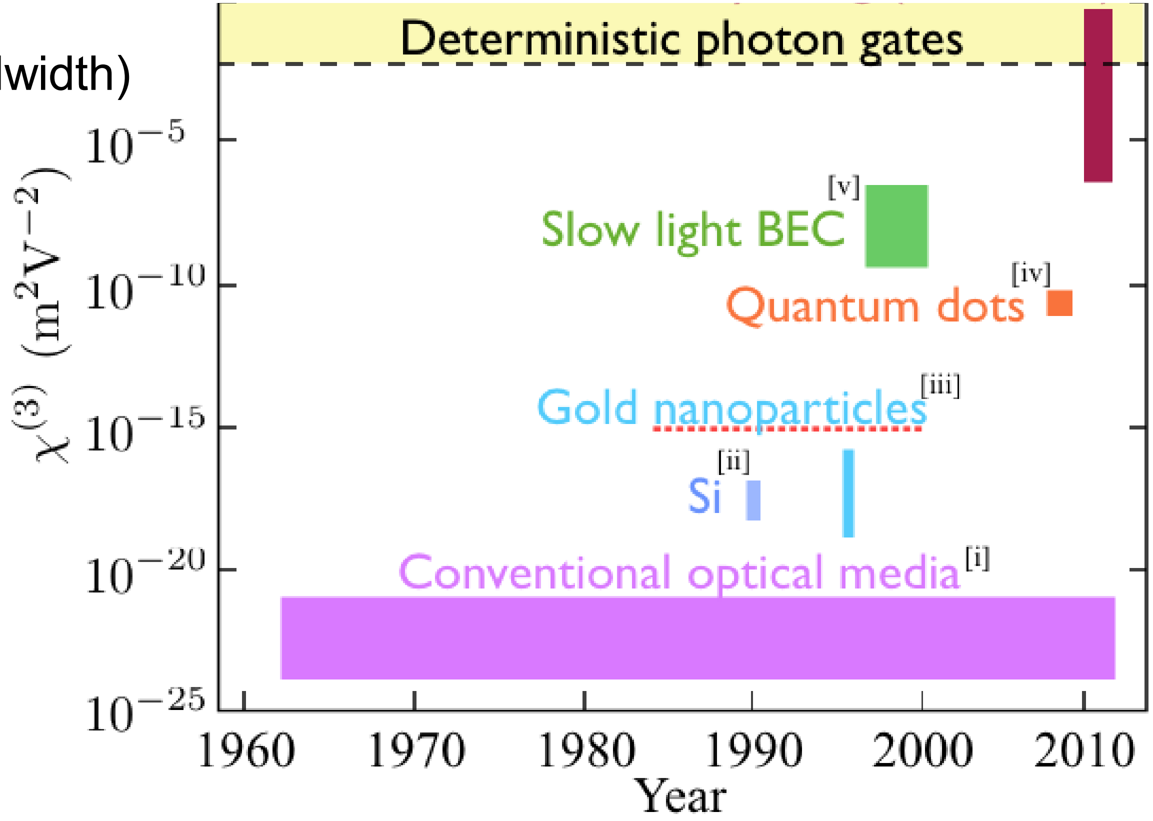
$$\chi_{\mathrm{r}}^{(3)}\mathcal{E}^2 = \frac{\chi_{\mathrm{r}}^{(1)}}{\mathcal{E}_{\mathrm{at}}^2}\mathcal{E}^2$$



$$\chi^{(3)} = \frac{(n_g - 1)\alpha_p}{\hbar\omega}$$

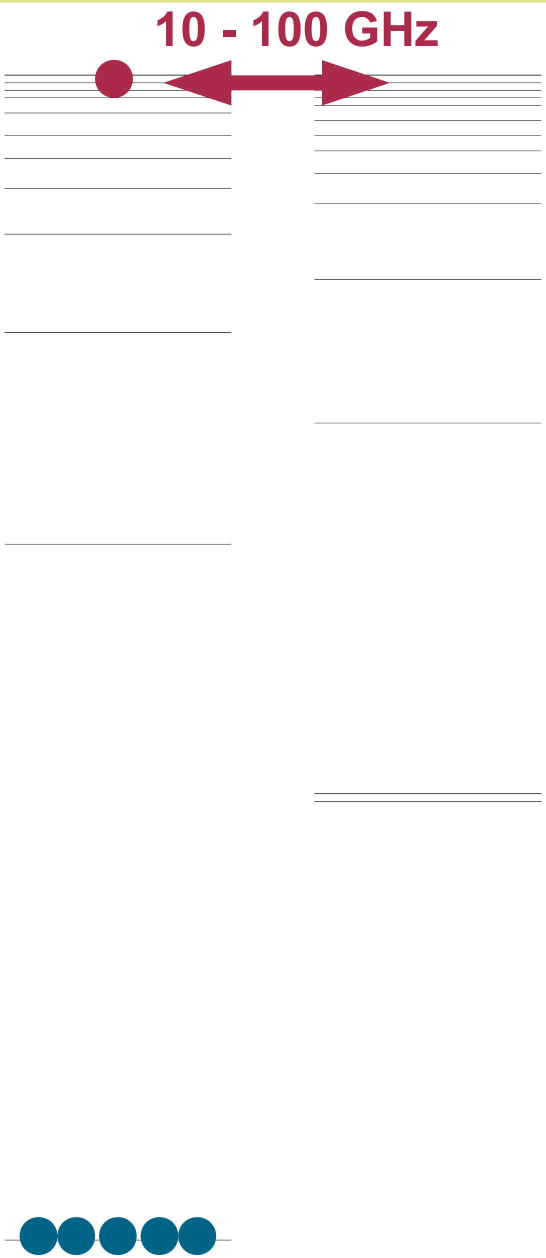
Resonance (enhancement but reduced bandwidth)

$$\chi^{(3)} \sim \chi^{(1)} \frac{\Gamma}{\Delta} \left(\frac{d\mathcal{E}_{ph}}{\hbar\Omega_c} \right)^2$$



Rydberg states

$n > 30$



Ground state

$n = 5$

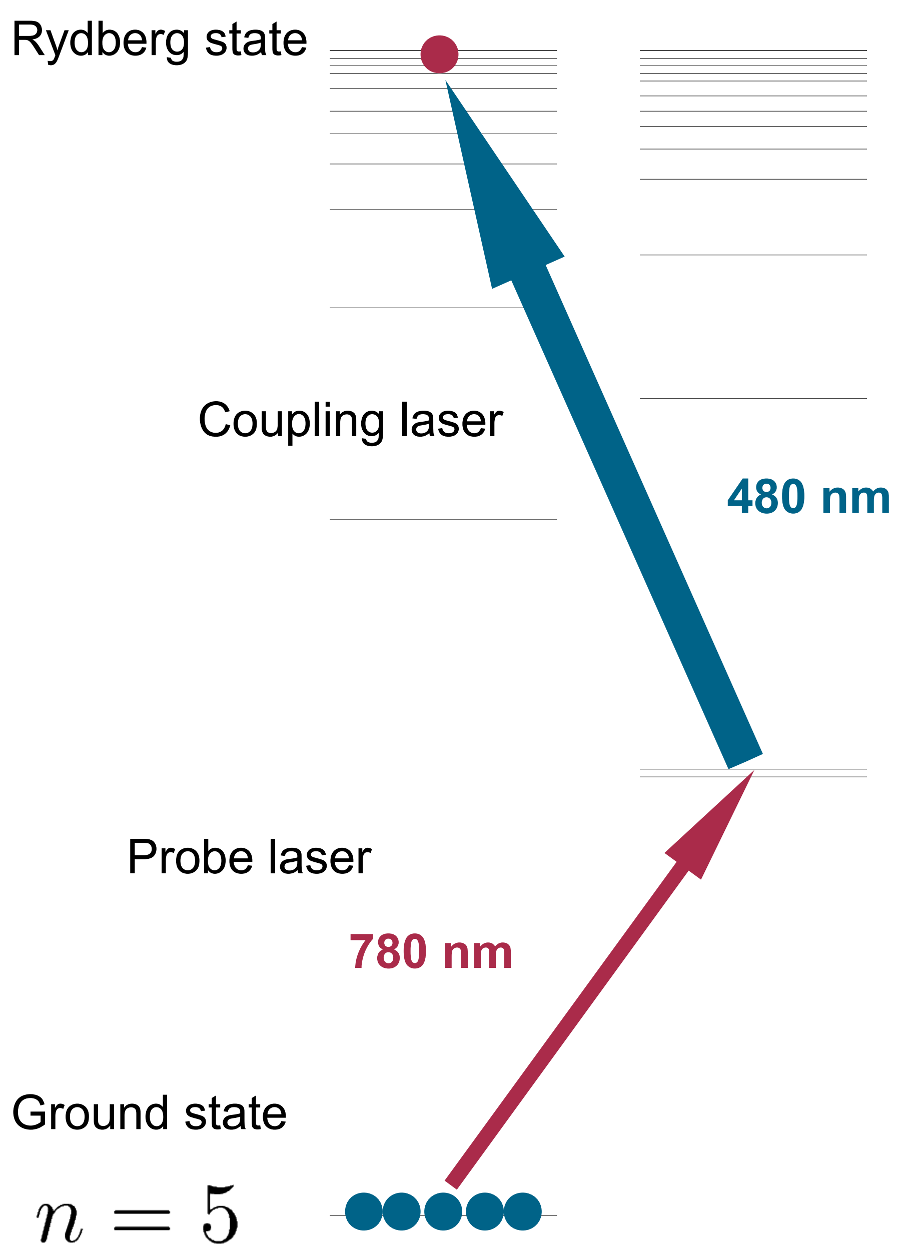
Rydberg states

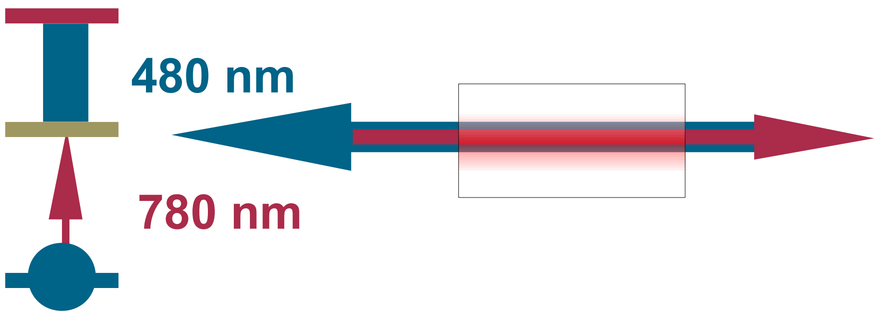
Size $\langle r \rangle \sim n^2 a_0$

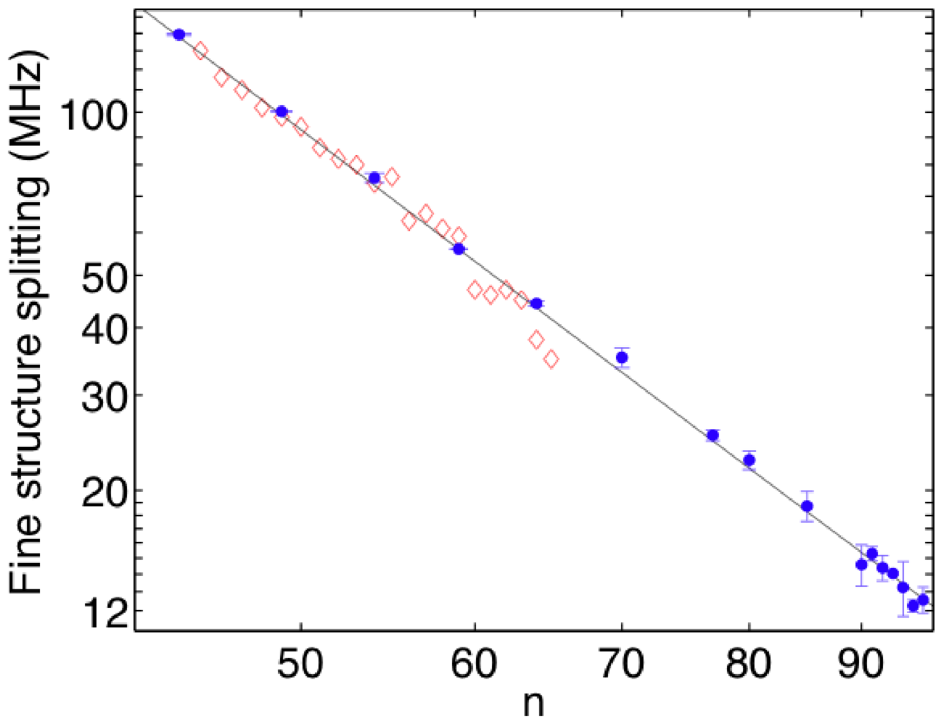
Dipole moment $\langle d \rangle \sim n^2 e a_0$

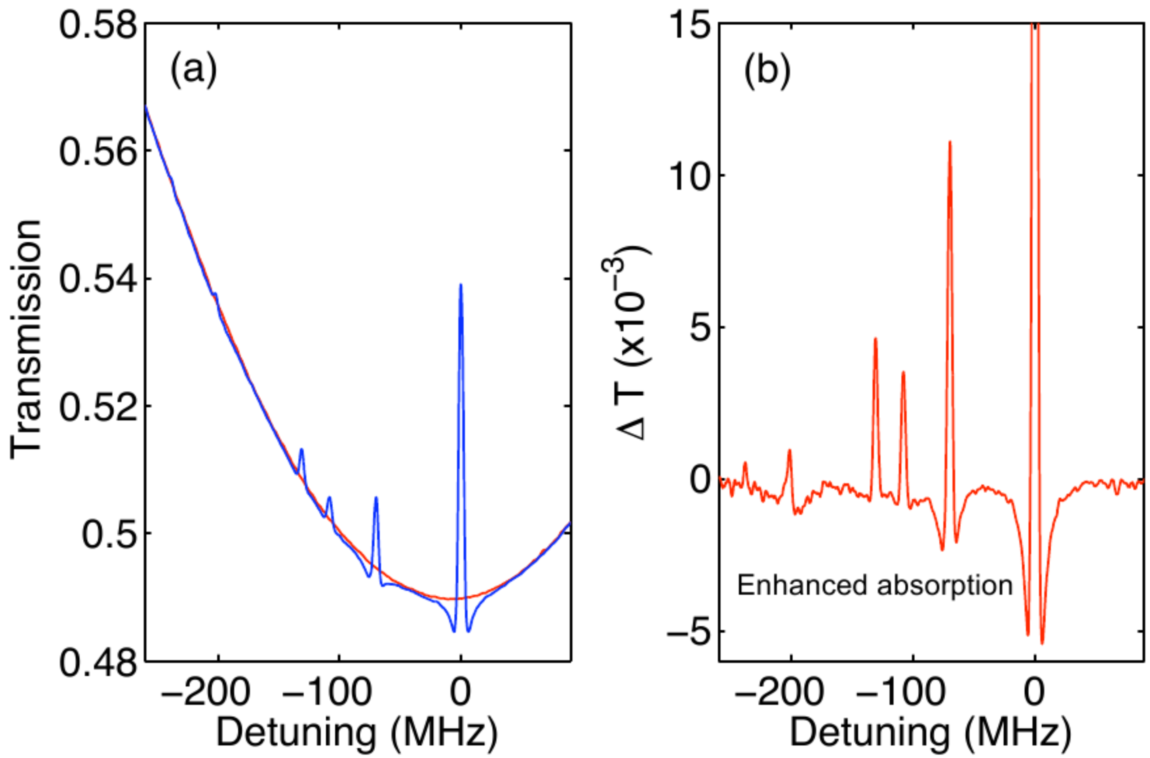
$$\mathcal{E}_{\rm at} \sim \tfrac{1}{2} e / 4\pi\epsilon_0 n^4 a_0^2 \sim 5 \times 10^3\ \mathrm{Vm}^{-1}$$

Near field $kr < 1$ Rydberg dipoles $r < 1$ mm


Rydberg state
Coupling laser
480 nm
Probe laser
780 nm
Ground state
$n = 5$





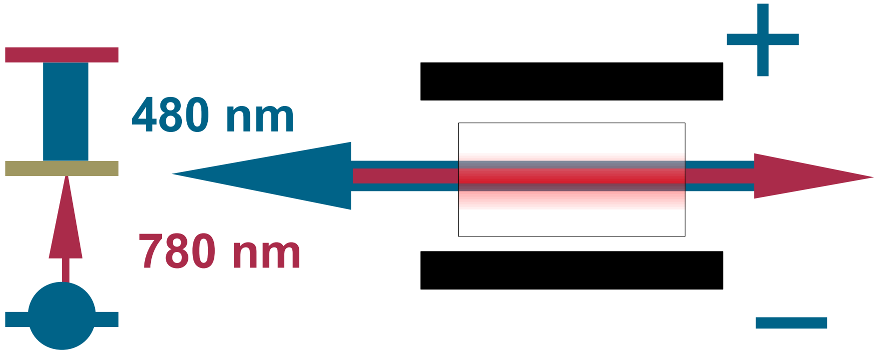


Narrow resonance – long lived coherence between ground and Rydberg states!

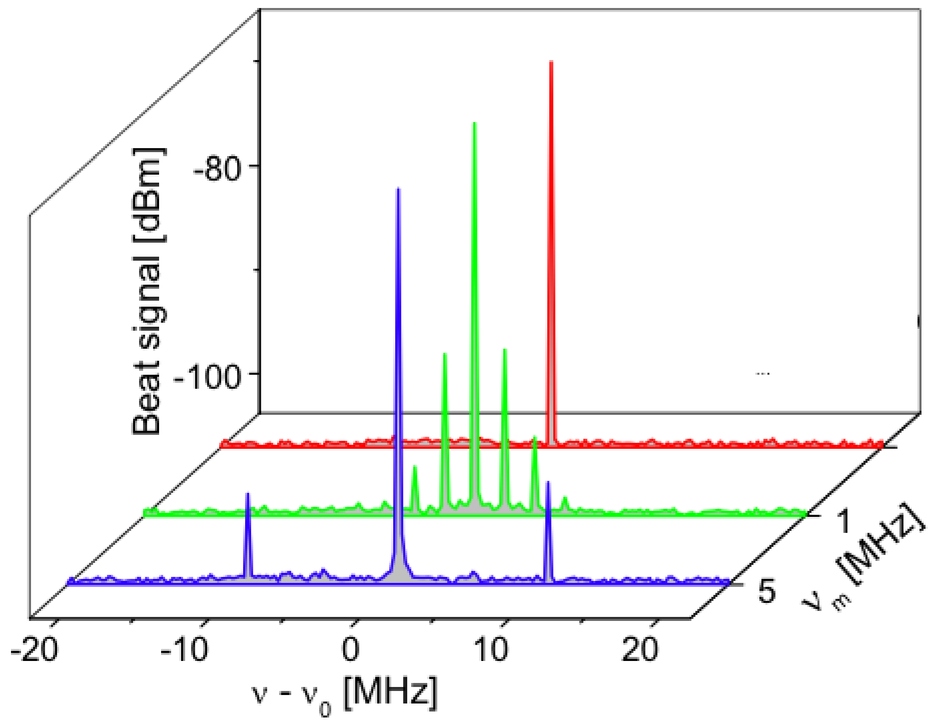
◊ K. C. Harvey and B. P. Stoicheff, Phys. Rev. Lett. **38**, 537 (1977).

— 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).

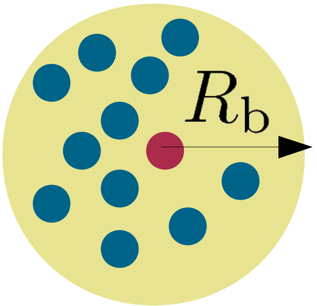


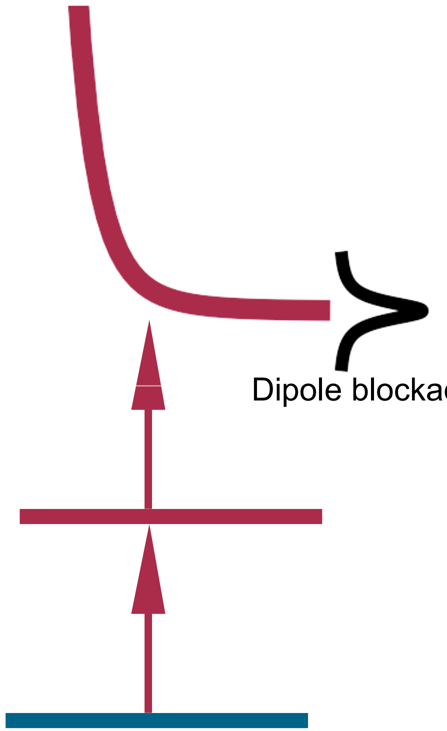
Low field electro-optic modulator



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

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



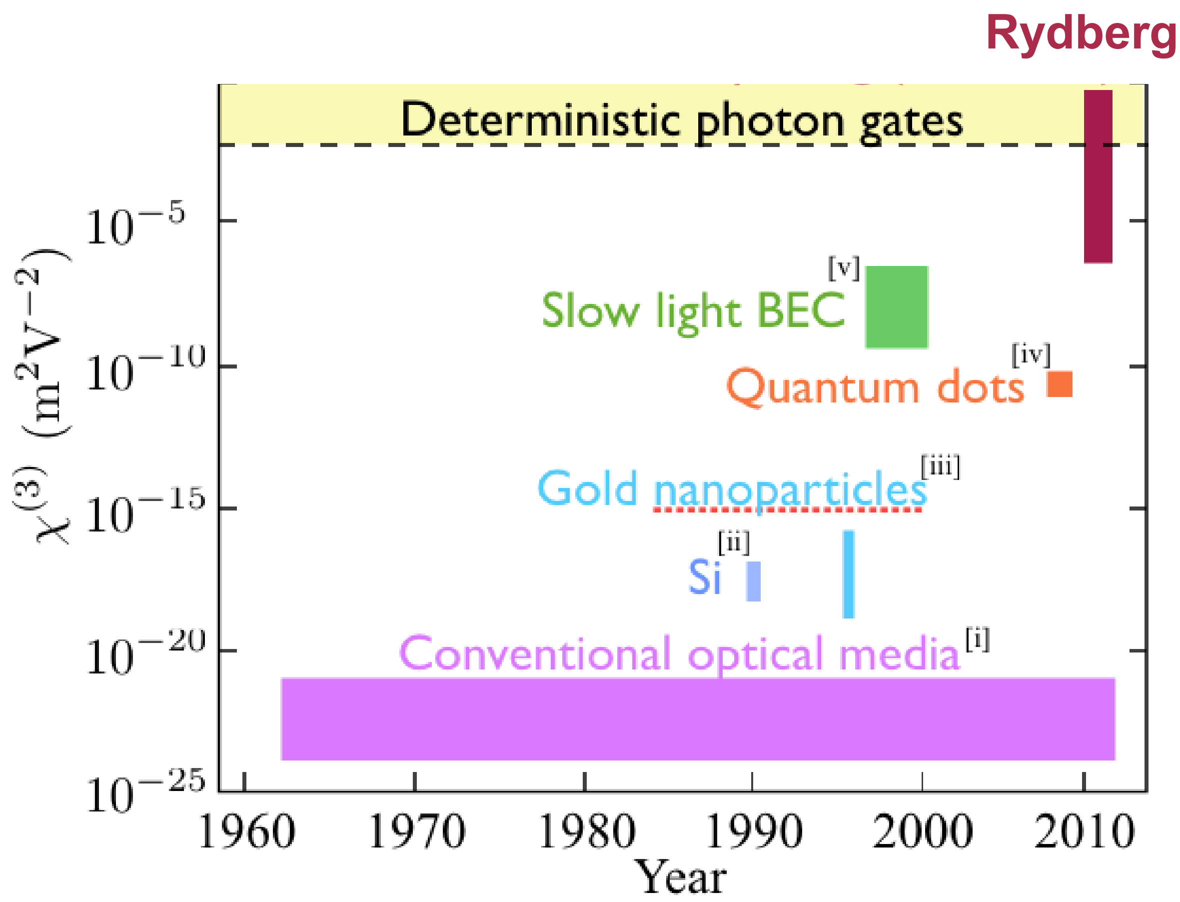


Dipole blockade: Lukin *et al*. Phys. Rev. Lett. **87**, 037901 (2001)

Excitation induced shift larger than the excitation linewidth

$$\chi^{(3)} = \frac{(n_g - 1)\alpha_p}{\hbar\omega}$$

Rydberg

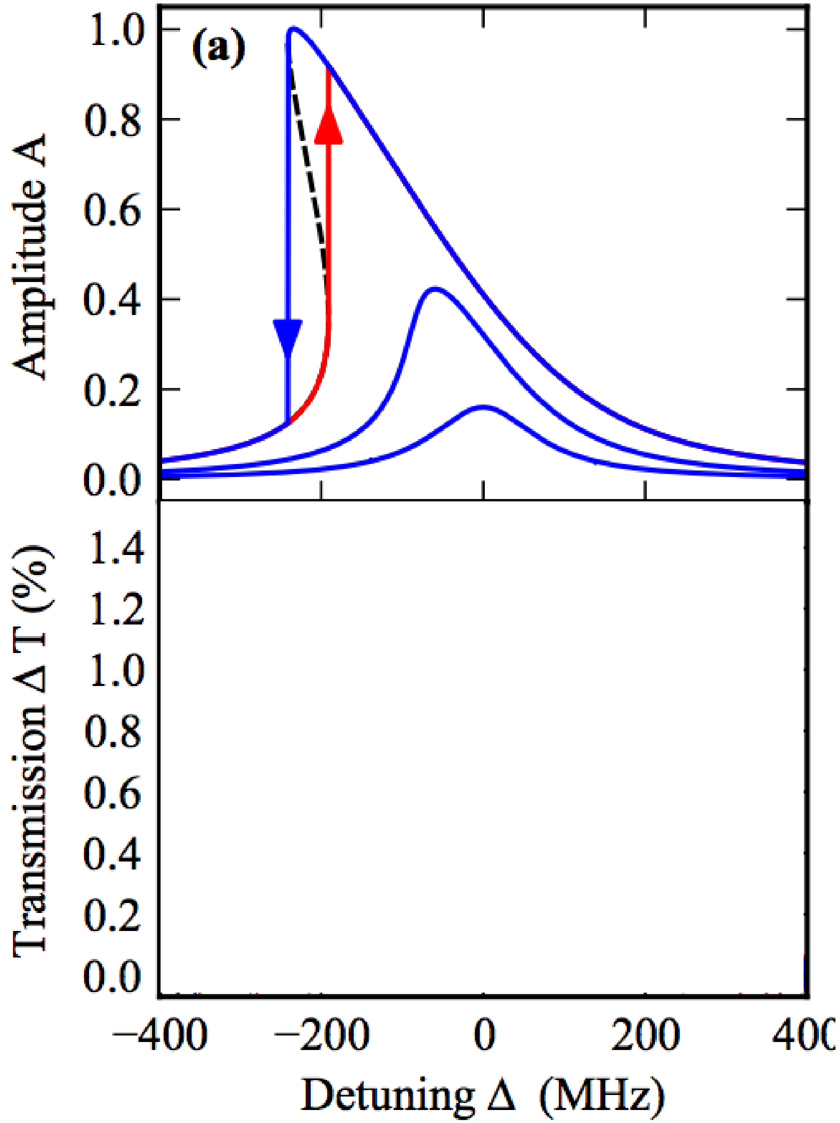


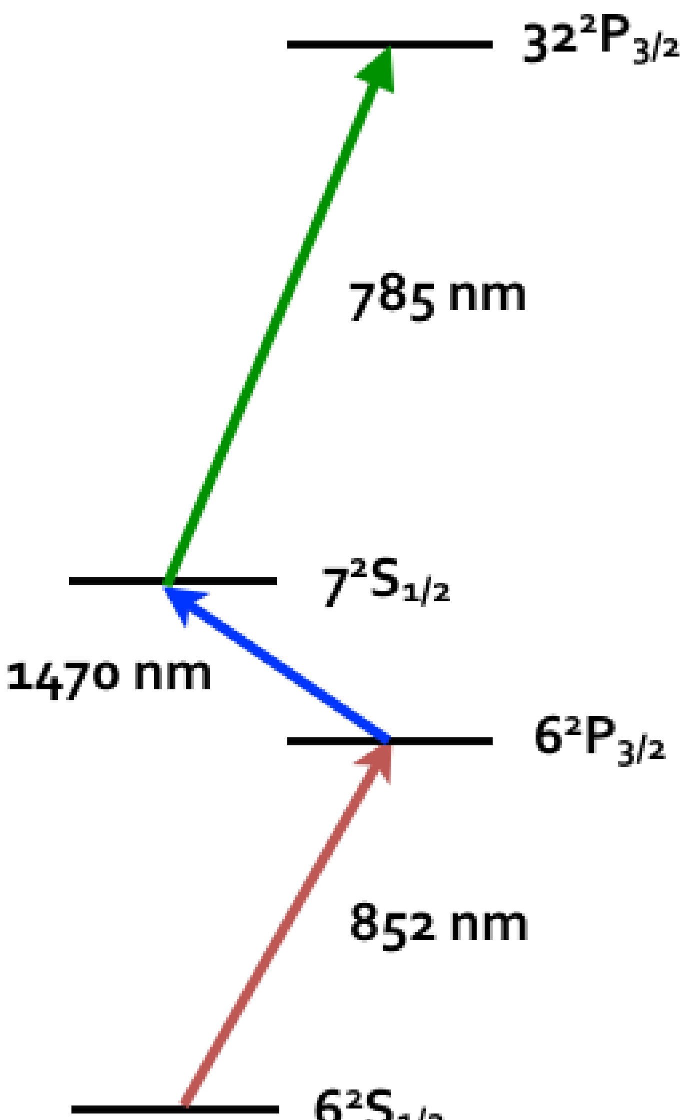
Rydberg

$$\chi^{(3)} \sim \mathcal{N}_b \chi^{(1)} \left(\frac{d\mathcal{E}_{ph}}{\hbar\Omega_c} \right)^2$$

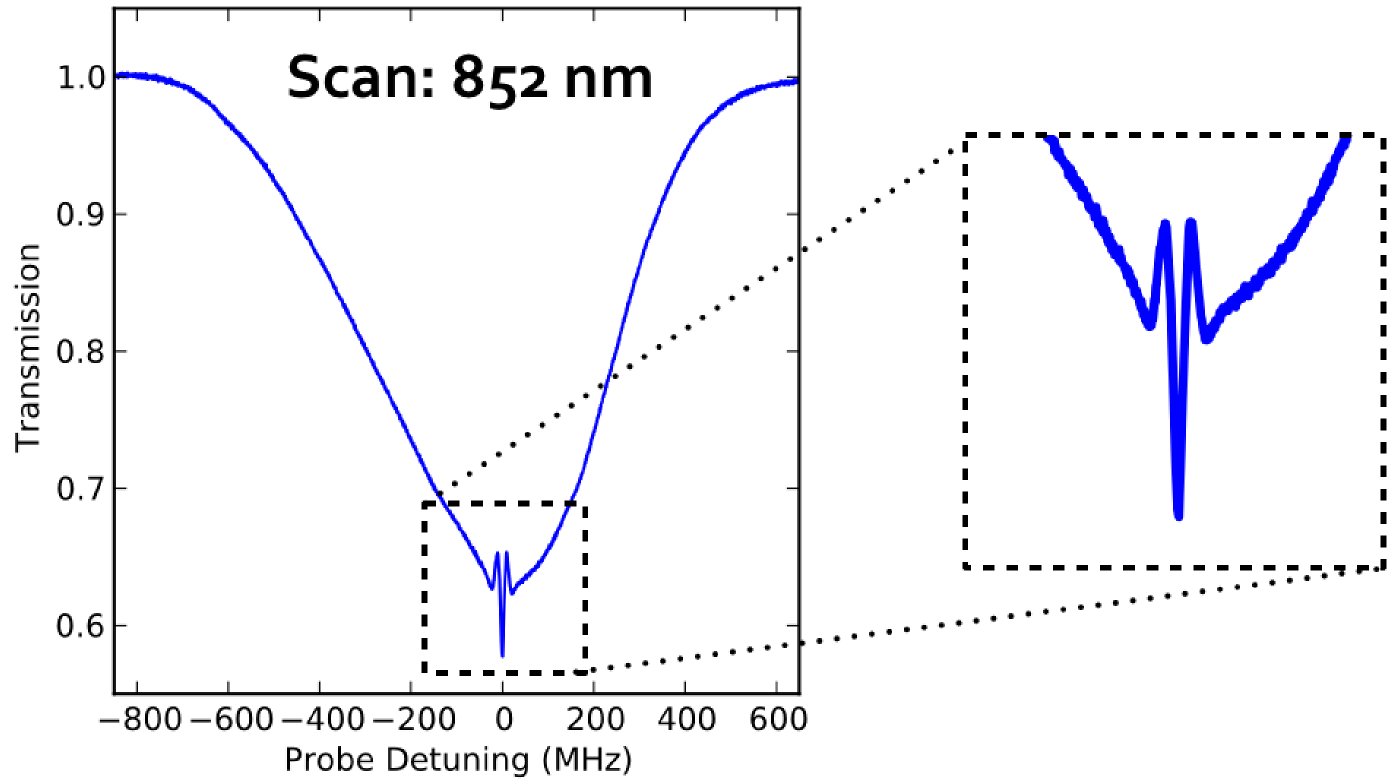
Classical model: The Duffing Oscillattor

$$m\ddot{x} + \gamma\dot{x} + kx^2 + \epsilon x^3 = F cos \omega_0 t$$

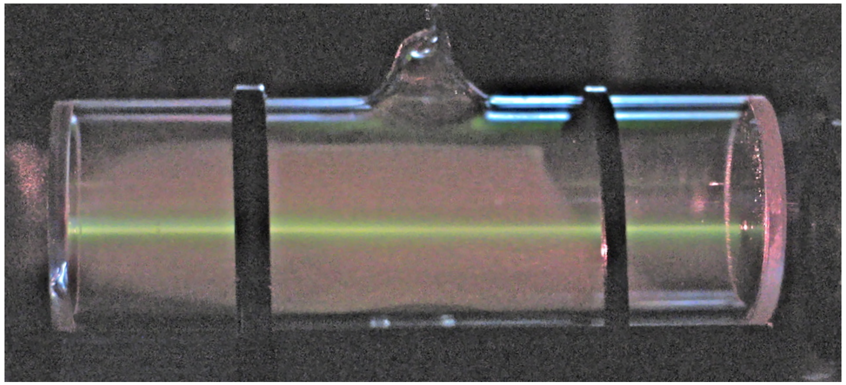


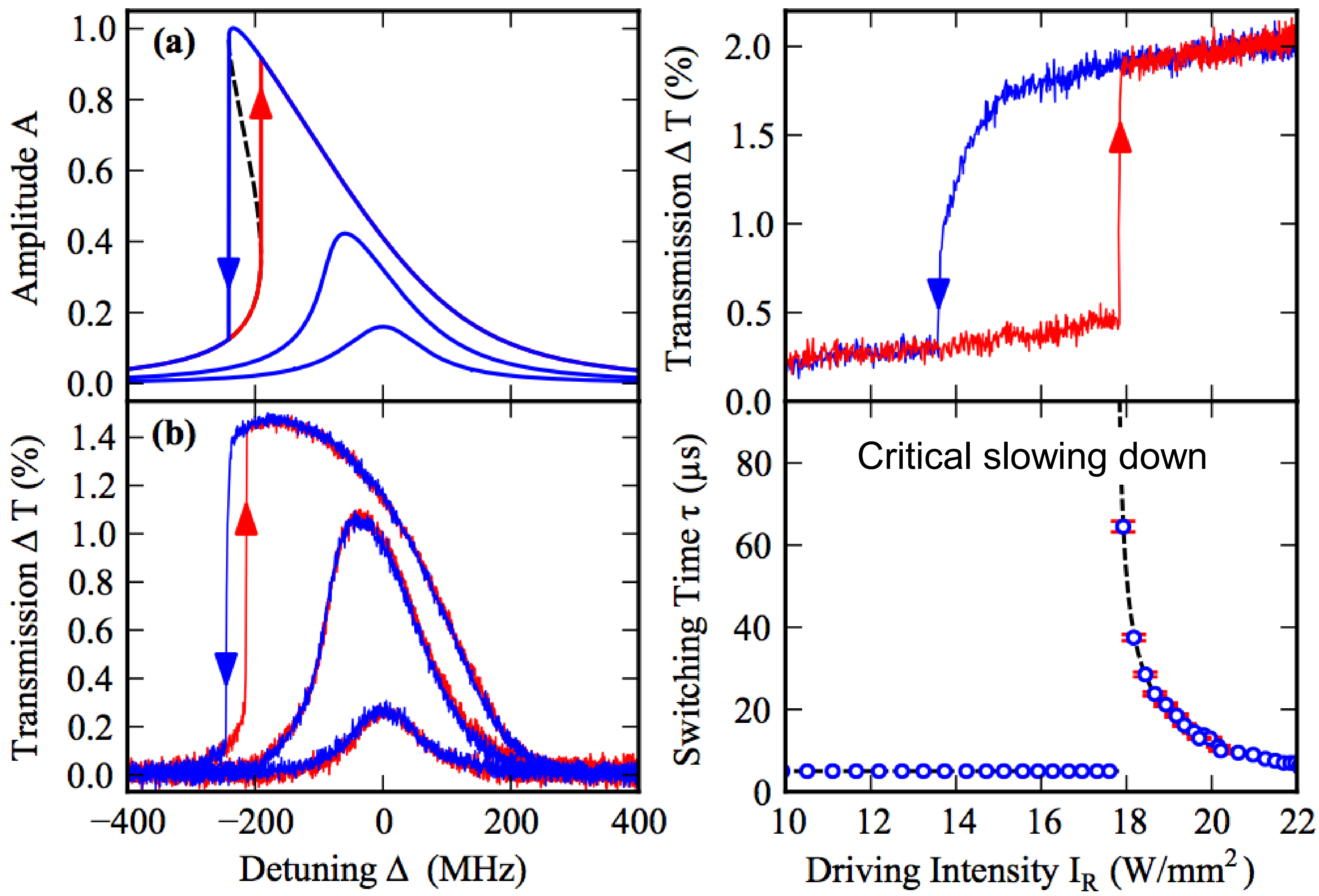


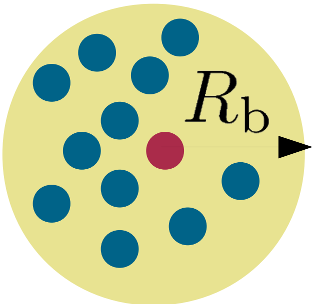
$32^2P_{3/2}$
785 nm
$7^2S_{1/2}$
1470 nm
$6^2P_{3/2}$
852 nm
$6^2S_{1/2}$

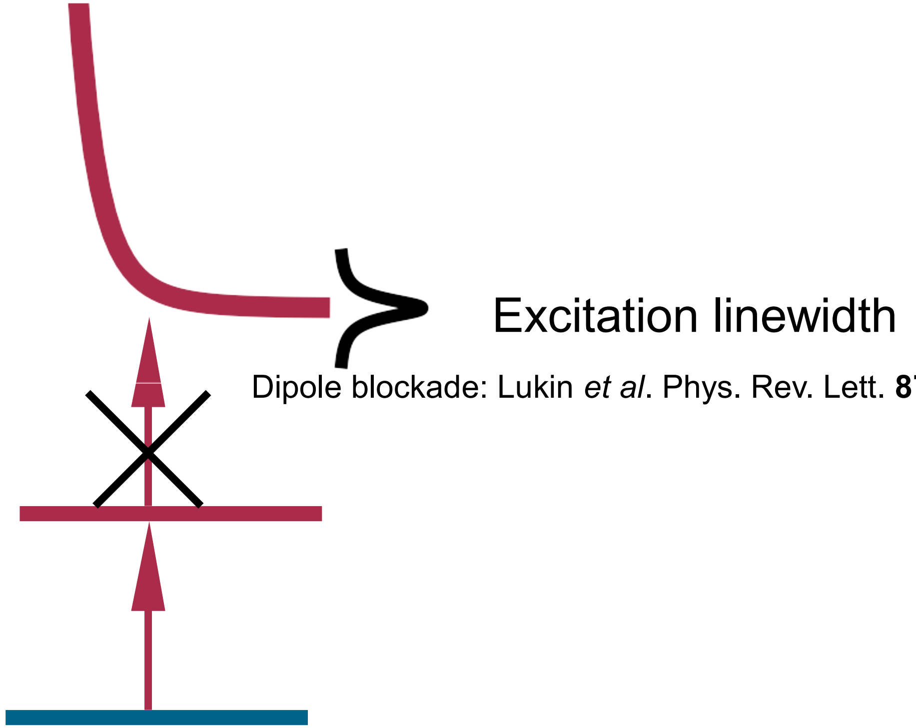


Scan: 852 nm
Transmission
1.0
0.9
0.8
0.7
0.6
−800 −600 −400 −200 0 200 400 600
Probe Detuning (MHz)




(a)
(b)
Amplitude A
Transmission Δ T (%)
Detuning Δ (MHz)
−400
−200
0
200
400
Transmission Δ T (%)
Switching Time τ (μs)
Critical slowing down
Driving Intensity I_R (W/mm²)
10
12
14
16
18
20
22

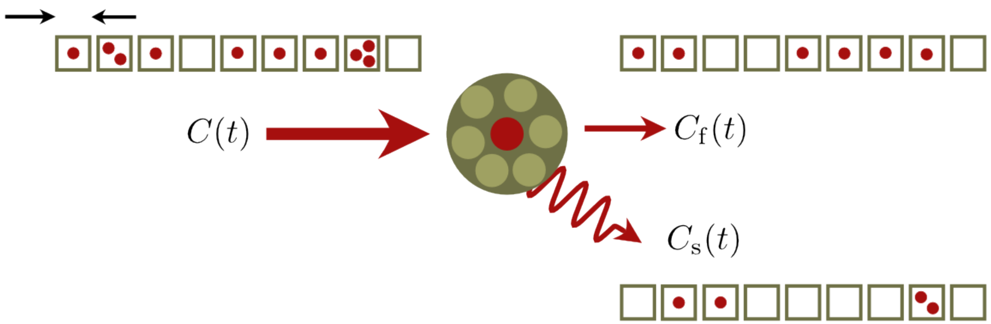




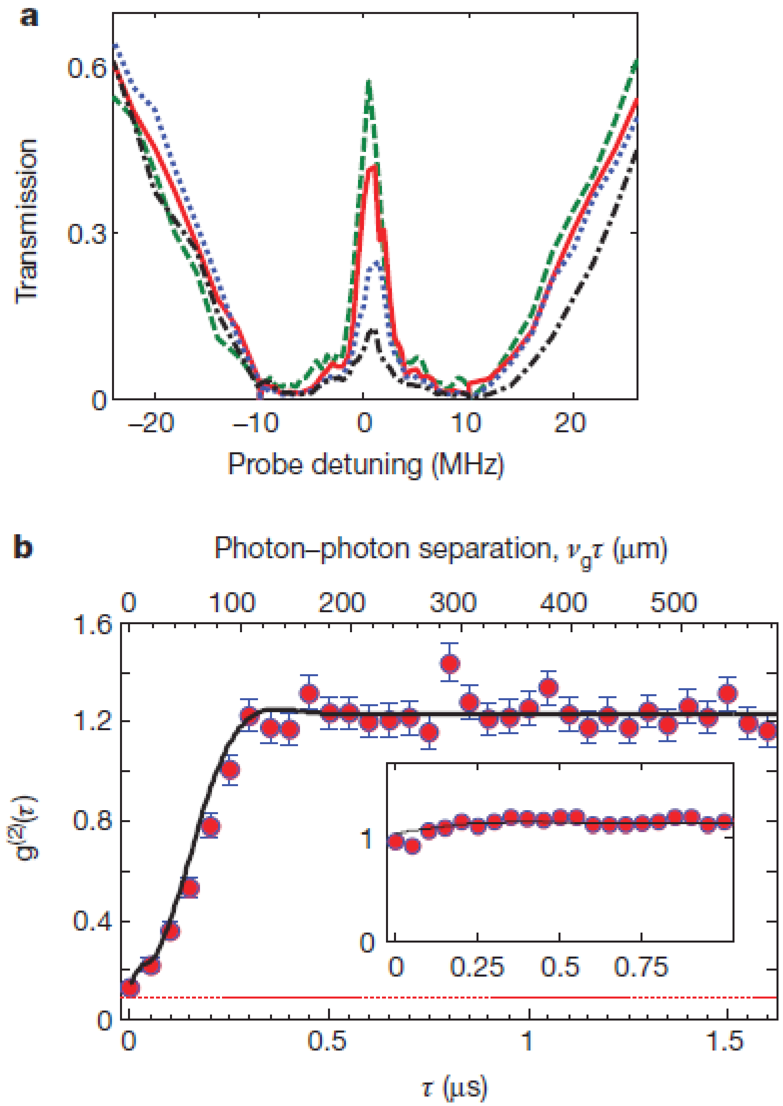
Dipole blockade: Lukin *et al*. Phys. Rev. Lett. **87**, 037901 (2001)

Excitation induced interaction must be larger than the excitation linewidth

Pritchard *et al*. Phys. Rev. Lett. **105**, 193603 (2010).



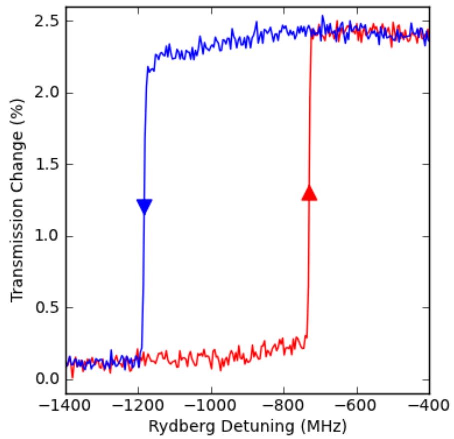
Peyronel *et al*. Nature 488, 57 (2012).



1. Typically optical non-linearities are small.

$$\chi_{\mathrm{r}}^{(3)}\mathcal{E}^2 = \chi_{\mathrm{r}}^{(1)}\frac{\mathcal{E}^2}{\mathcal{E}_{\mathrm{at}}^2}$$

2. We can solve this with Rydberg atoms.



3. Optical bistabilty.

4. Photon-photon interactions.