Joint Quantum Centre Durham/Newcastle

Durham

Acknowledgements

Durham (Current)

Staff: MPA Jones, KJ Weatherill

PDRA: **P Huillery**

PhD: H Busche, S Ball, T Ilieva
C Wade, N Sibalic

Theory Collaborations

Nottingham: I Lesanovsky. Dresden T Pohl

Finance

EPSRC

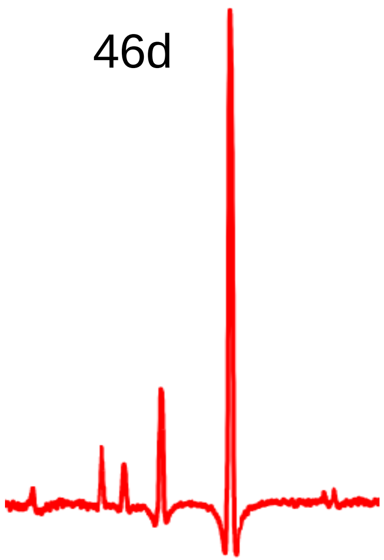
Former members

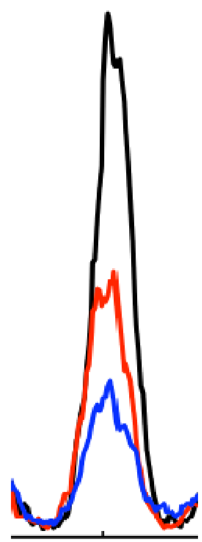
PDRA: A Mohapatra (NISER), A Gauguet (Toulouse), U Krohn
D Szwer (NPL)

PhD: MG Bason (Aarhus), JD Pritchard (Wisc), RP Abel
D Maxwell (CERN),
D Paredes (ICFO)

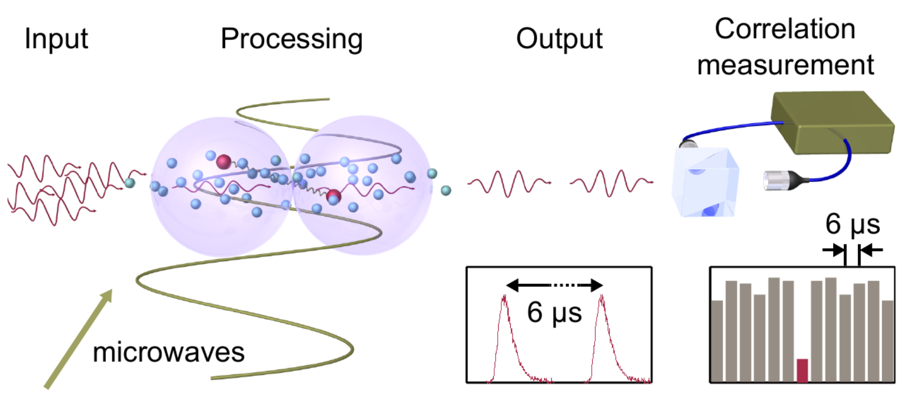
From Rydberg EIT to quantum non-linear optics

2006	2010	2012	2013
Rydberg EIT	Giant optical non-linearity		Non-equilibrium phase transition

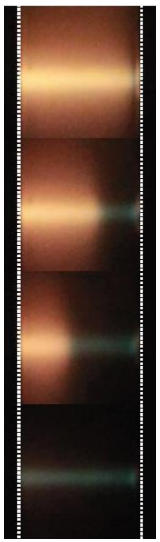




Rydberg quantum optics



Maxwell *et al*., Phys. Rev. Lett. **110**, 103003 (2013).



XXZ model

Carr *et al*., Phys. Lev. Lett. **111**, 113901 (2013).

Mohapatra *et al*., Phys. Rev. Lett. **98**, 113003 (2007).

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

Rydberg non-linear optics, Pritchard *et al*., Annual Review of Cold Atoms and Molecules, **1**, 301 (2013).

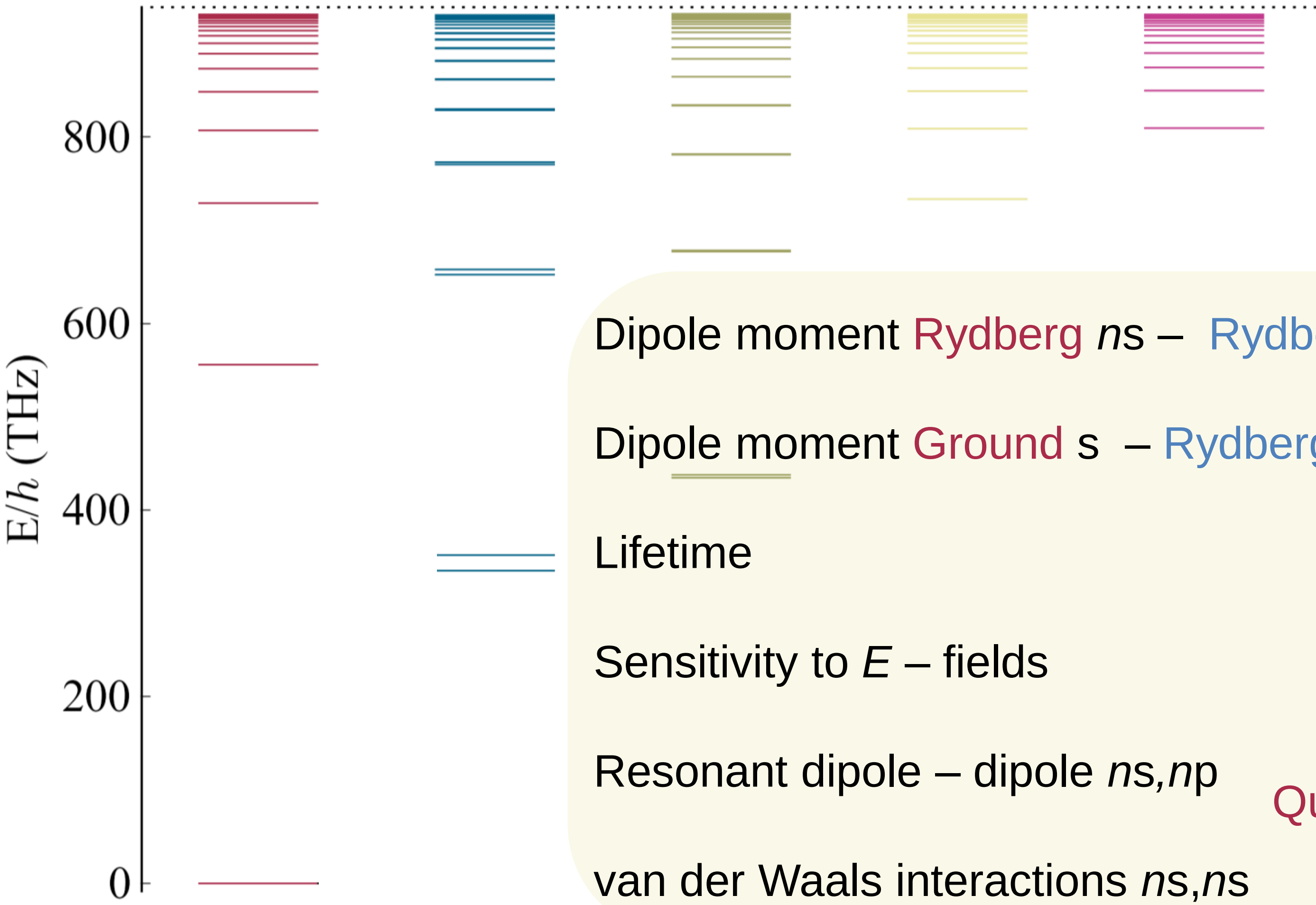
Durham University

Ground states to highly-excited Rydberg states

$$E_n = -\frac{R_{\mathrm{Rb}}}{n^{*2}}$$

$$n^* = n - \delta$$

Ground states to highly-excited Rydberg states



$$E_n = -\frac{R_{\mathrm{Rb}}}{n^{*2}}$$

$$n^* = n - \delta$$

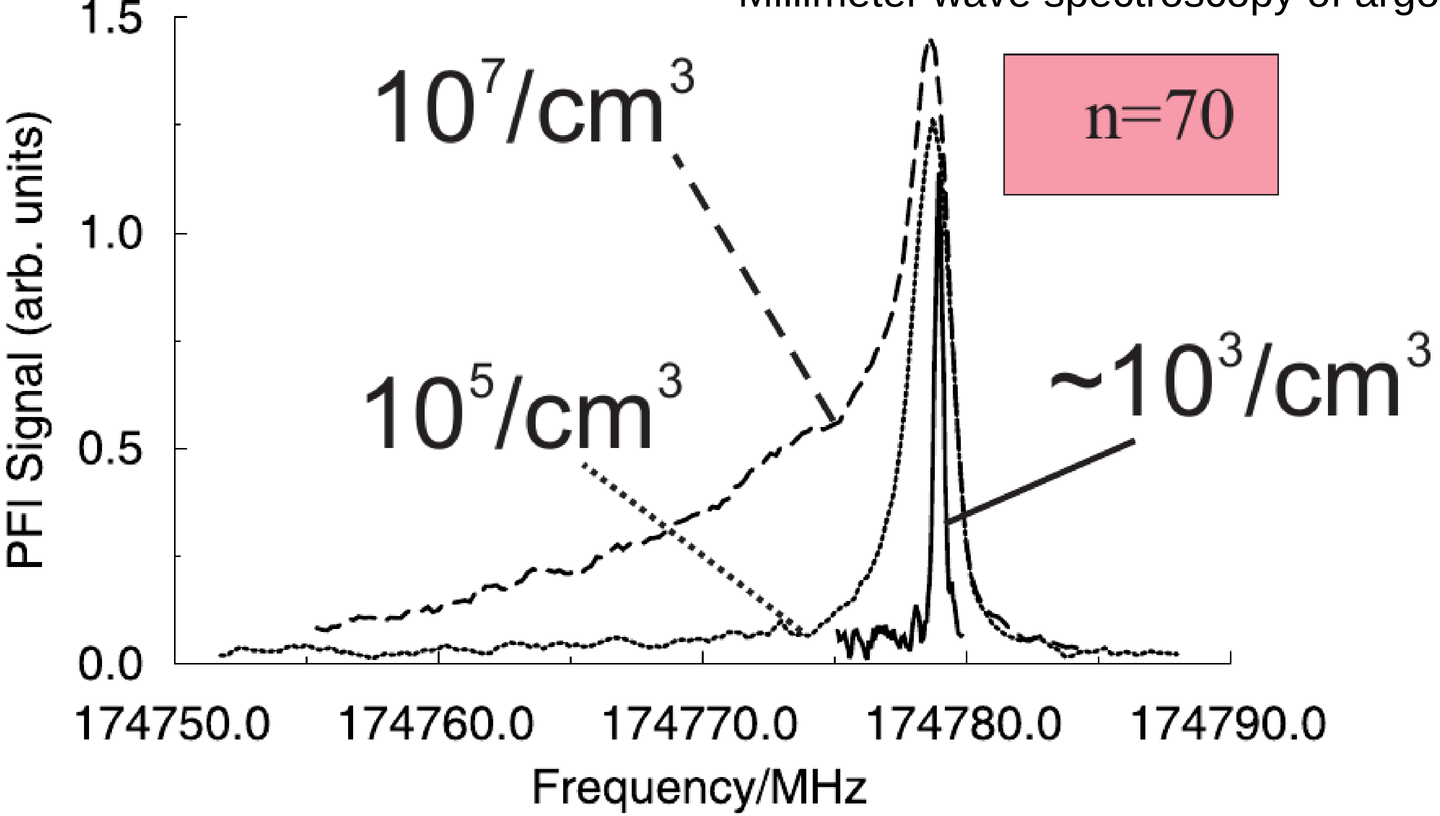
Dipole moment Rydberg *n*s – Rydberg *n*p		n^{*2}
Dipole moment Ground s – Rydberg *n*p		$n^{*-3/2}$
Lifetime		n^{*3}
Sensitivity to *E* – fields	Sensors	n^{*7}
Resonant dipole – dipole *ns*,*n*p	Quantum optics many body	n^{*4}
van der Waals interactions *ns*,*ns*		n^{*11}

Rydberg inspiration! 2004

Frederick Merkt, ETH

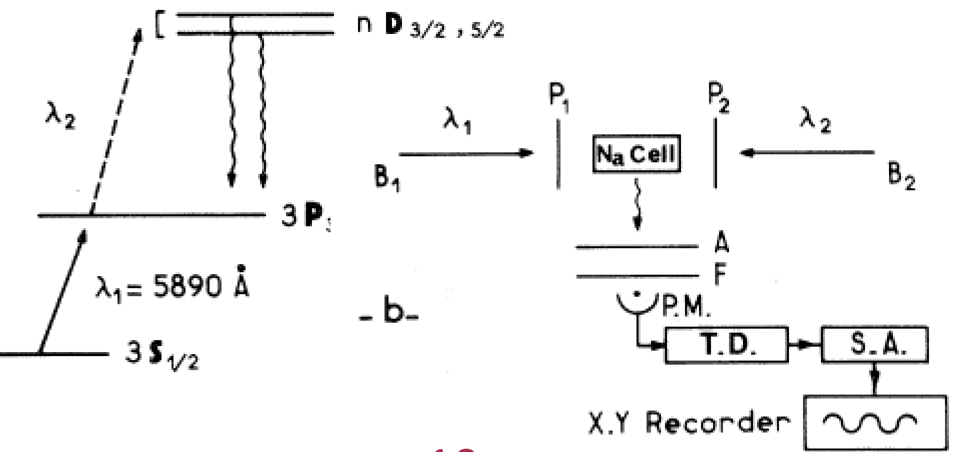
ECAMP Rennes 2004

Millimeter wave spectroscopy of argon



Rydberg atom detection

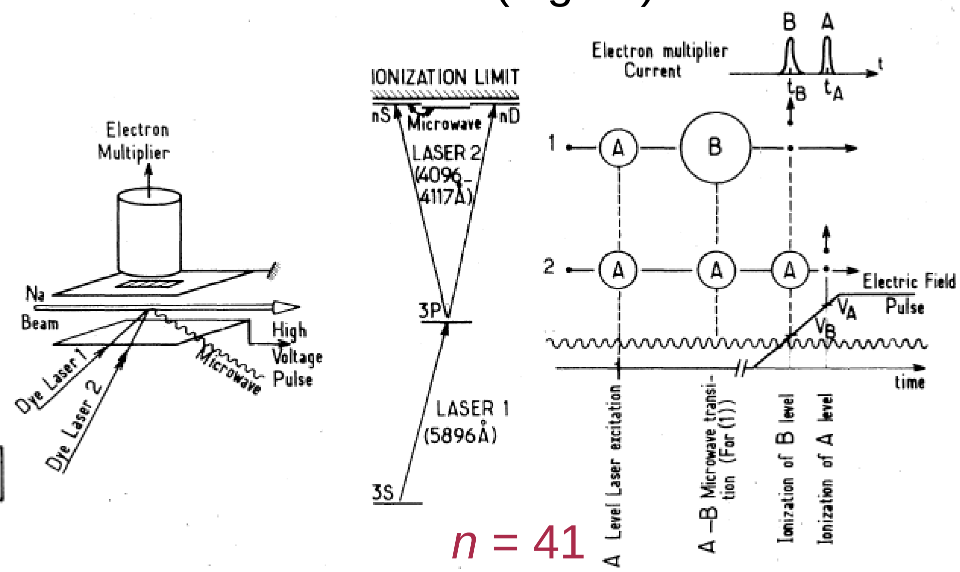
Fluorescence (low *n*)



$n = 10$

Haroche *et al*., Phys. Rev. Lett. **33**, 1063 (1974).

Ionisation (high *n*)



$n = 41$

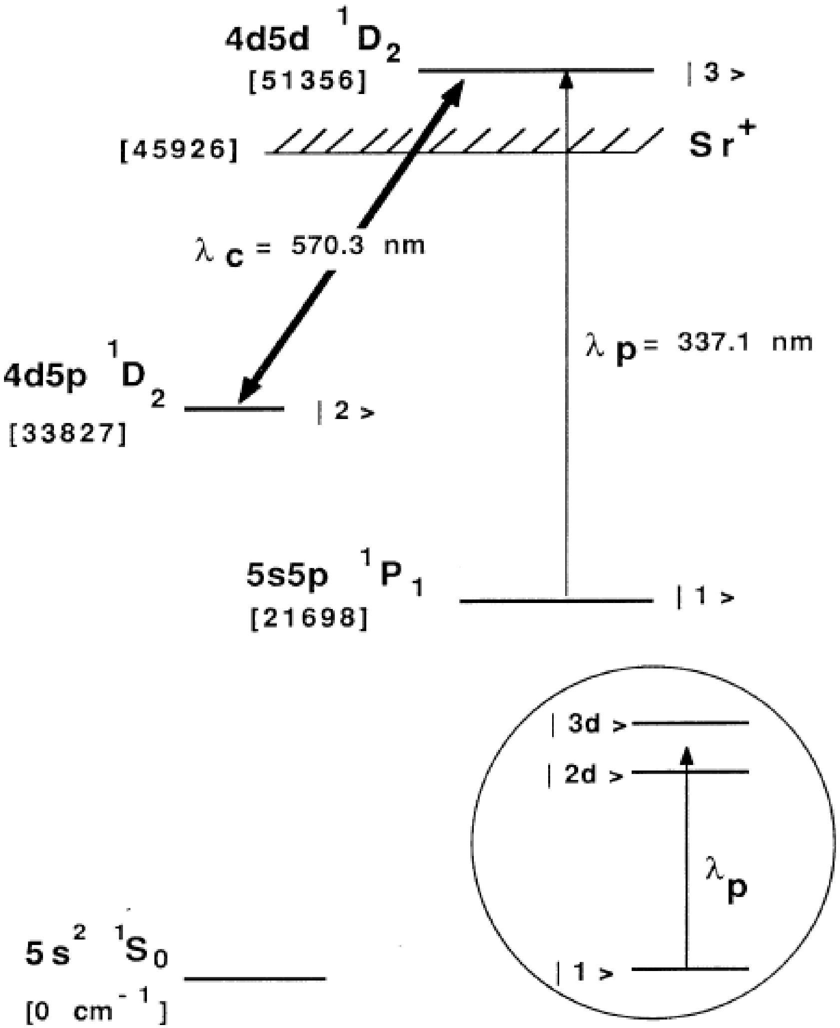
Fabre *et al*., Phys. Rev. A **18**, 229 (1978).

Some notes on the Rydberg project (date 06/07/06)

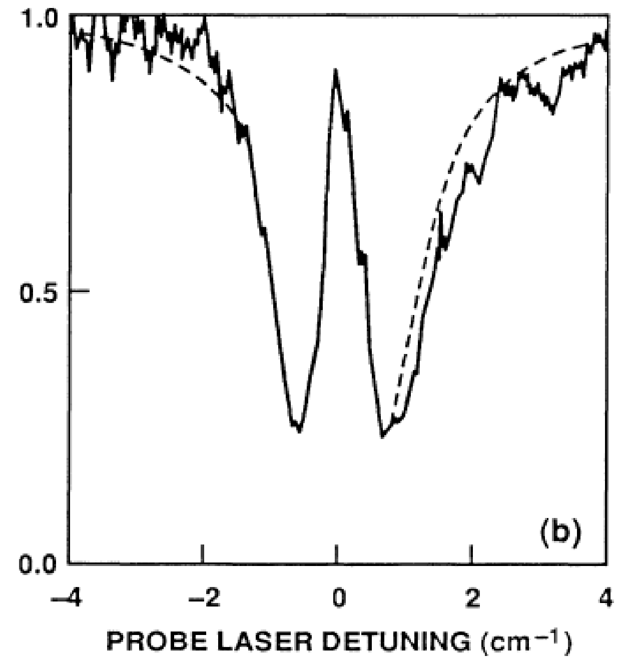
Unique features of our experiment.

1. Aim to **detect Rydberg excitation purely optically**, all other groups use ionisation. Why do other groups use ionisation? Because it offers very efficient detection (a micro-channel plate can detect ions with approaching 100% efficiency).

Electromagnetically induced transparency



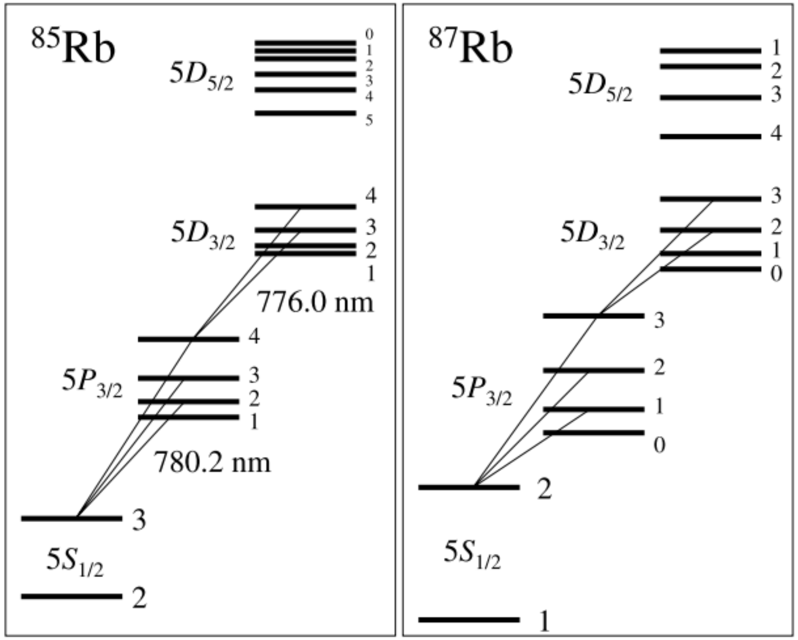
Boller, Imamoglu and Harris, Phys. Rev. Lett. **66**, 2593 (1991).

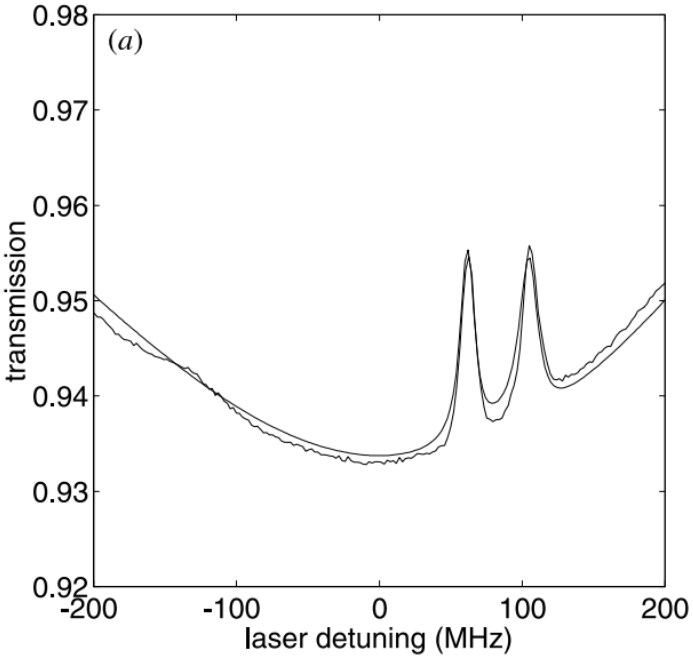


Ladder EIT with Rydbergs?

J Gea Banacloche, Y Li, S Jin, M Xiao, Phys Rev A **51**, 576 (1995).

S Badger, IG Hughes and CS Adams, J. Phys. B **34**, L749 (2001).





Ladder EIT: limited utility?

REVIEWS OF MODERN PHYSICS, VOLUME 77, APRIL 2005

Electromagnetically induced transparency: Optics in coherent media

Michael Fleischhauer

Fachbereich Physik, Technische Universität Kaiserslautern, D-67663 Kaiserslautern, Germany

Atac Imamoglu

Institute of Quantum Electronics, ETH-Hönggerberg, HPT G12, CH-8093 Zürich, Switzerland

Jonathan P. Marangos

Quantum Optics and Laser Science Group, Blackett Laboratory, Imperial College, London SW7 2BW, United Kingdom

the ladder and vee configurations illustrated in Fig. 6 are of more limited utility

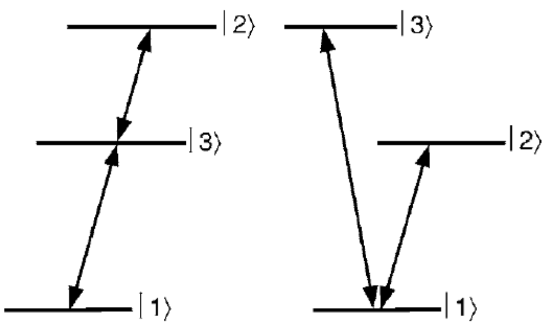
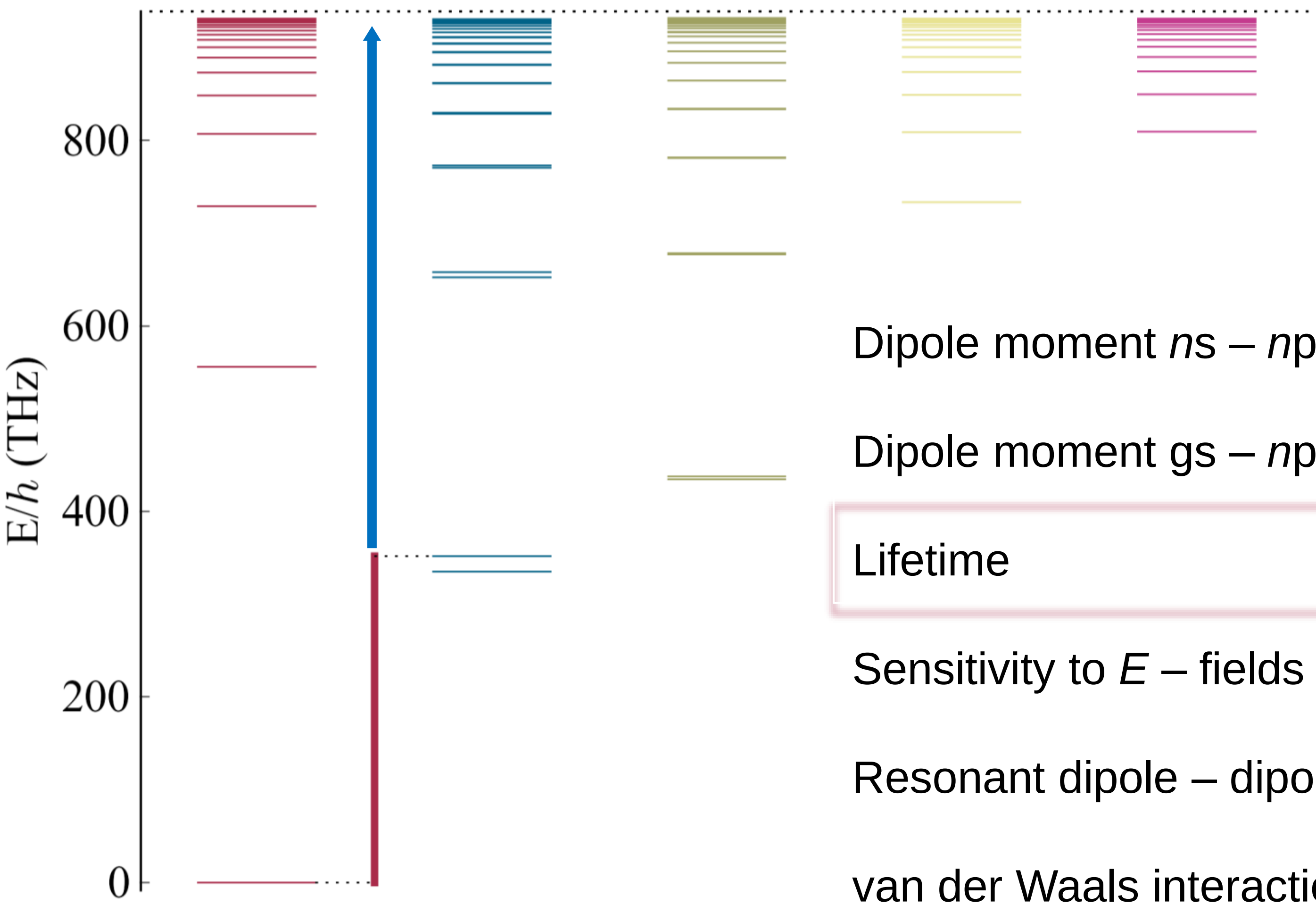


FIG. 6. Ladder (left) and vee-type (right) three-level schemes. These do not show EIT in the strict sense because of the absence of a (meta)stable dark state.

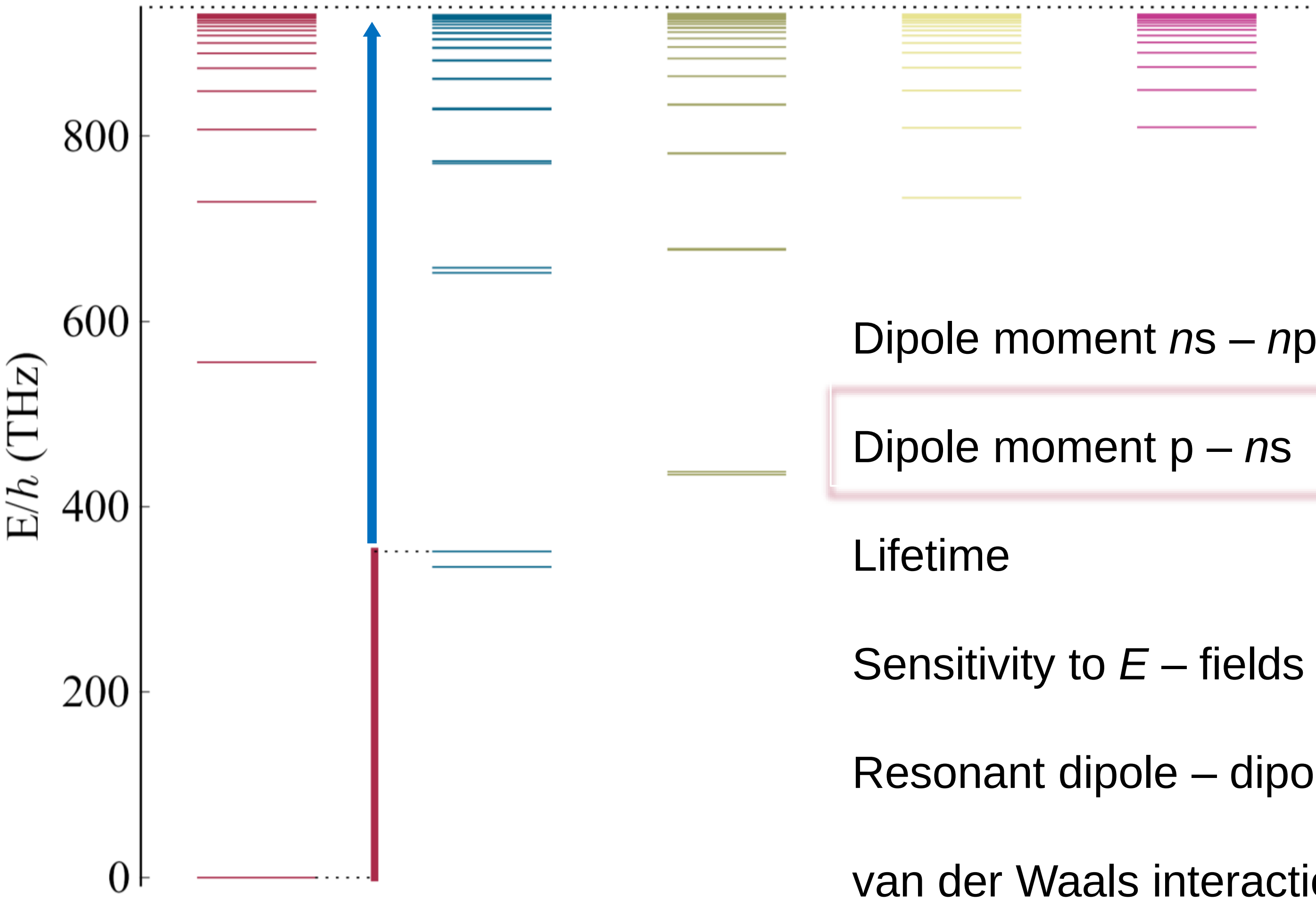
Ladder EIT with Rydbergs?



$$n^* = n - \delta$$

Dipole moment *n*s – *n*p	n^{*2}
Dipole moment gs – *n*p	$n^{*-3/2}$
Lifetime	n^{*3}
Sensitivity to *E* – fields	n^{*7}
Resonant dipole – dipole *n*s,*n*p	n^{*4}
van der Waals interactions *n*s,*n*s	n^{*11}

Ladder EIT with Rydbergs? A problem

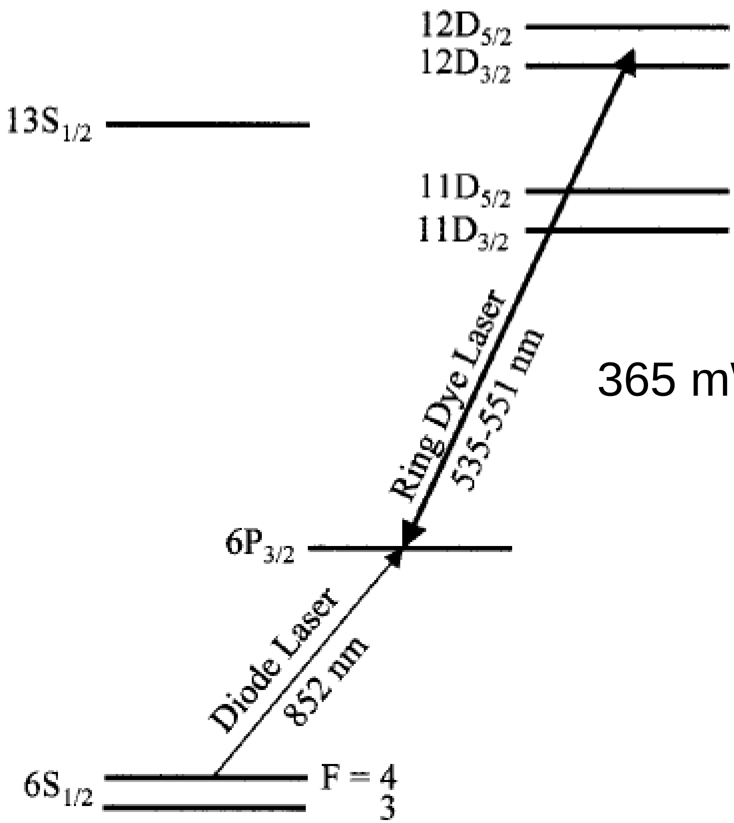


$$n^* = n - \delta$$

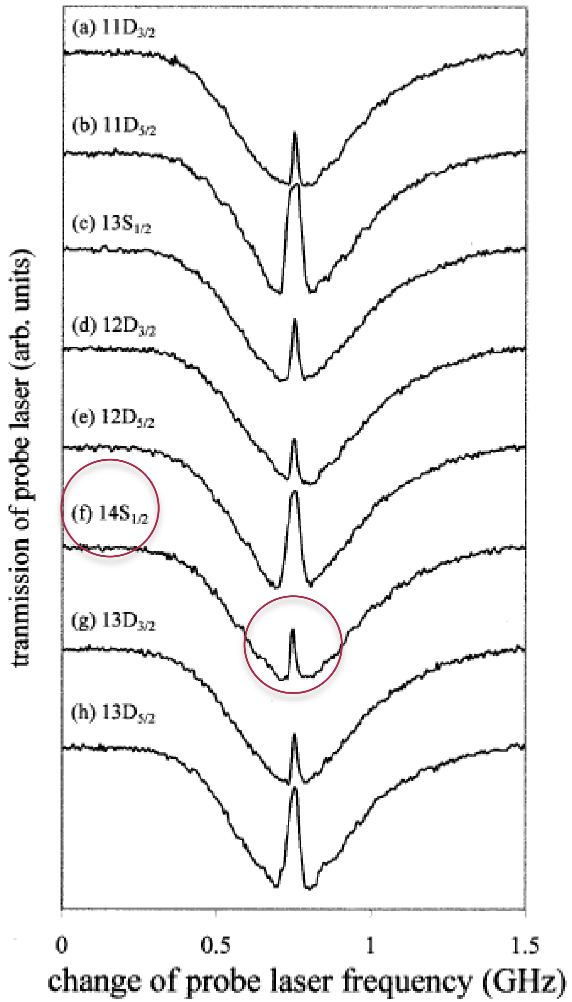
Dipole moment *n*s – *n*p	n^{*2}
Dipole moment p – *n*s	$n^{*-3/2}$
Lifetime	n^{*3}
Sensitivity to *E* – fields	n^{*7}
Resonant dipole – dipole *n*s,*n*p	n^{*4}
van der Waals interactions *n*s,*n*s	n^{*11}

Ladder EIT?

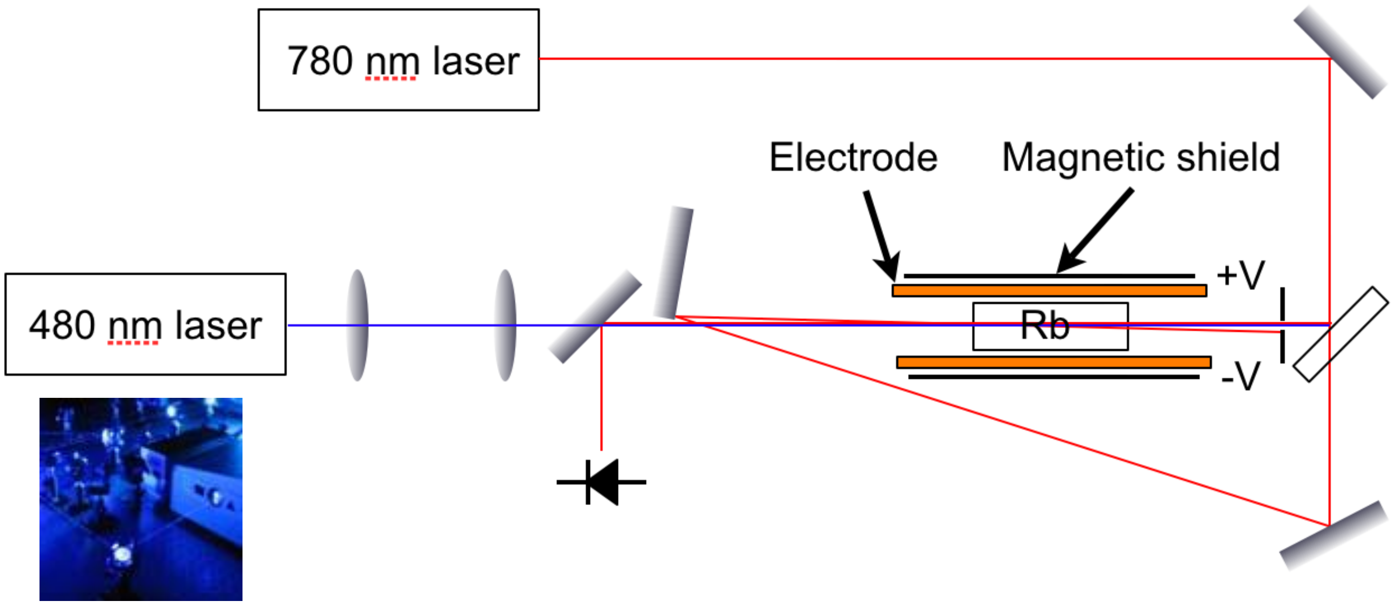
Clarke and van Wijngaarden, Phys. Rev. A **64**, 023818 (2001).



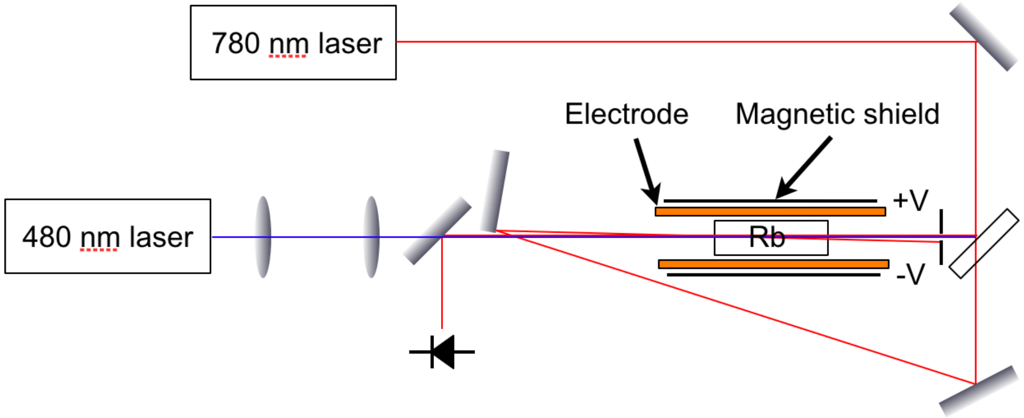
365 mW



Experiment summer 2006

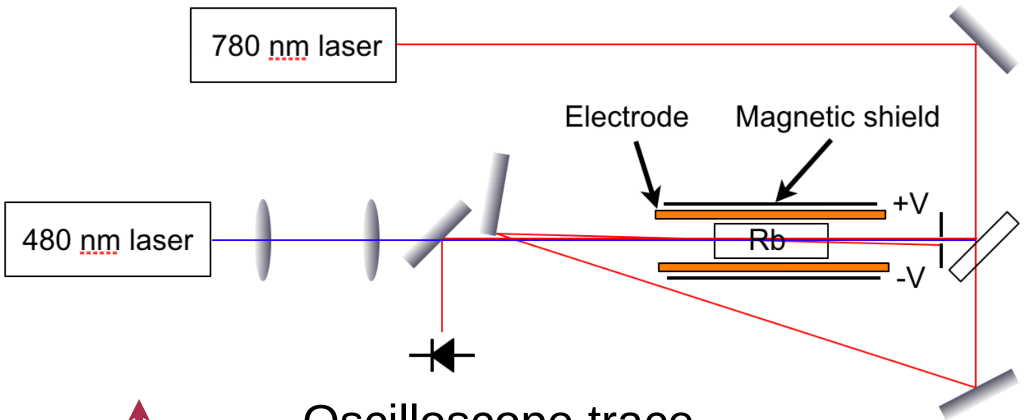


1st Rydberg EIT (06.11.06)



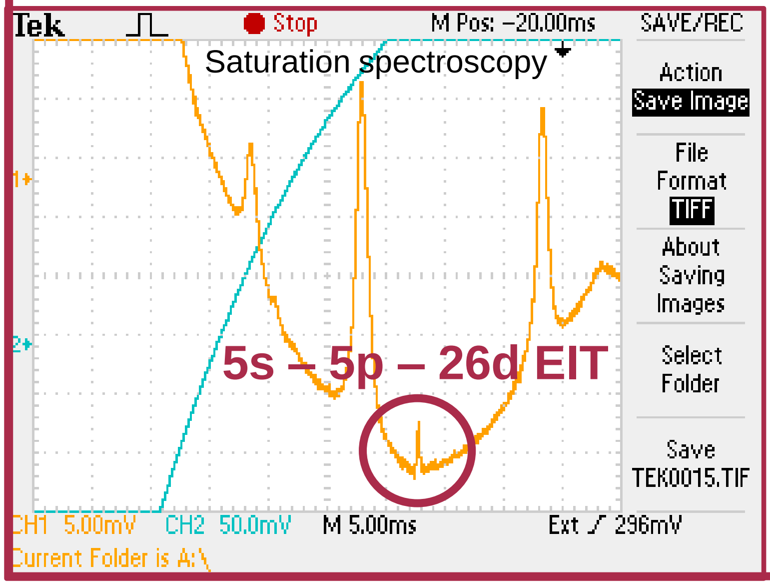
Thermal vapour

1st Rydberg EIT (06.11.06)



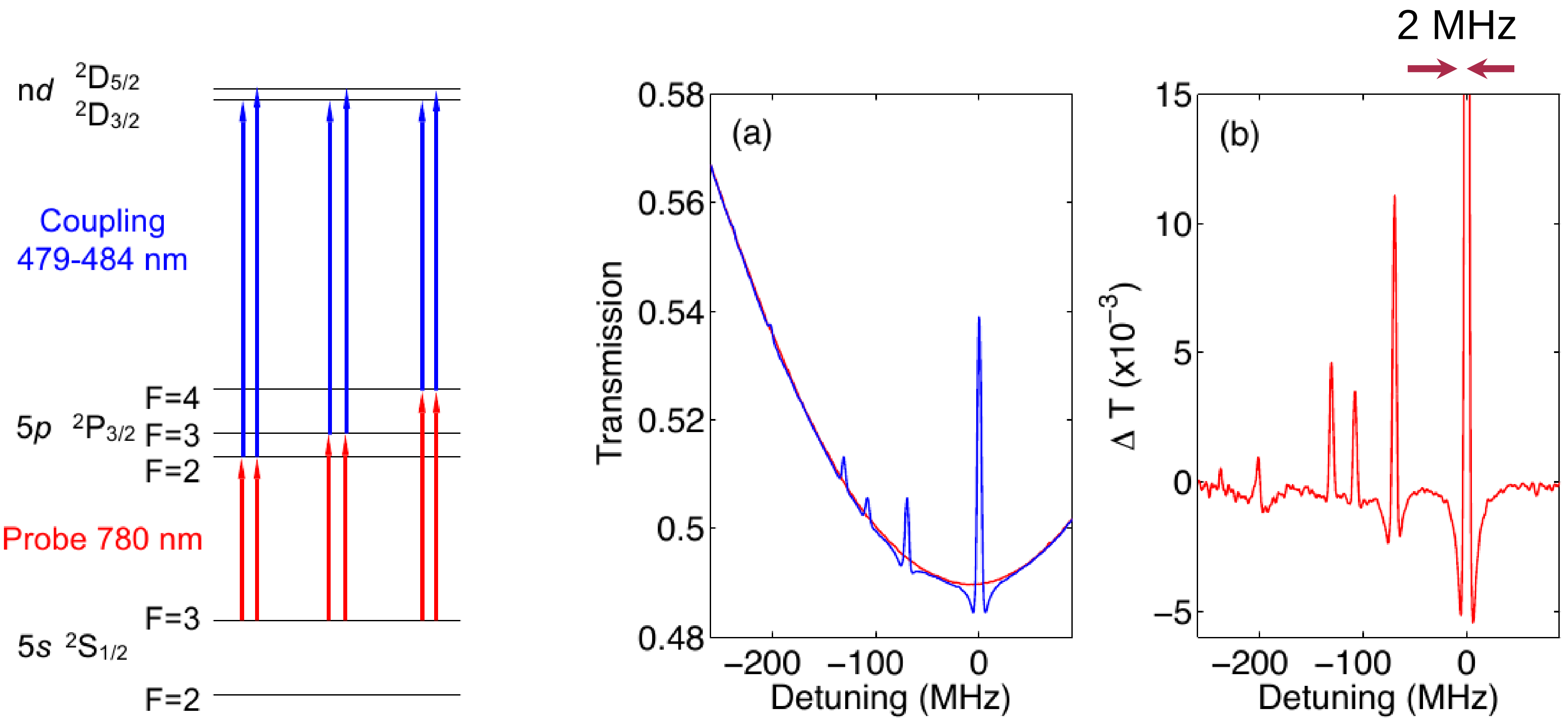
Photodiode signal

Oscilloscope trace



Laser detuning

Rydberg EIT *n* = 46 d



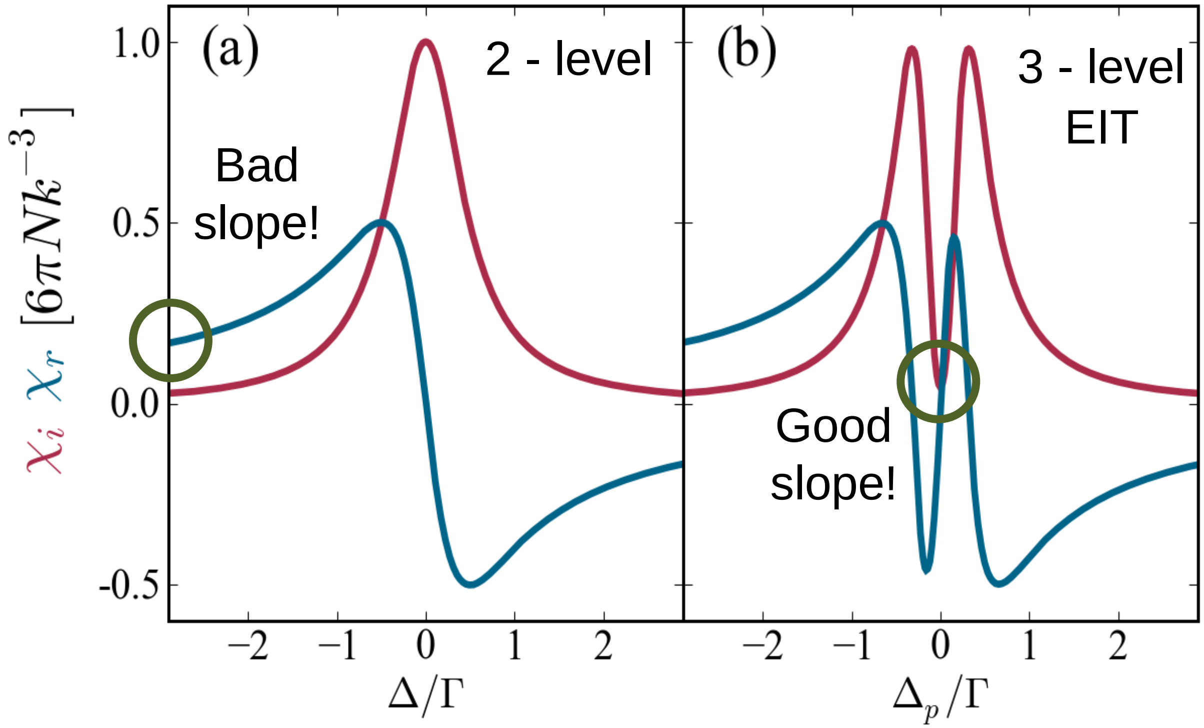
Mohapatra *et al*., Phys. Rev. Lett. **98**, 113003 (2007).

Rydberg EIT: giant Kerr effects

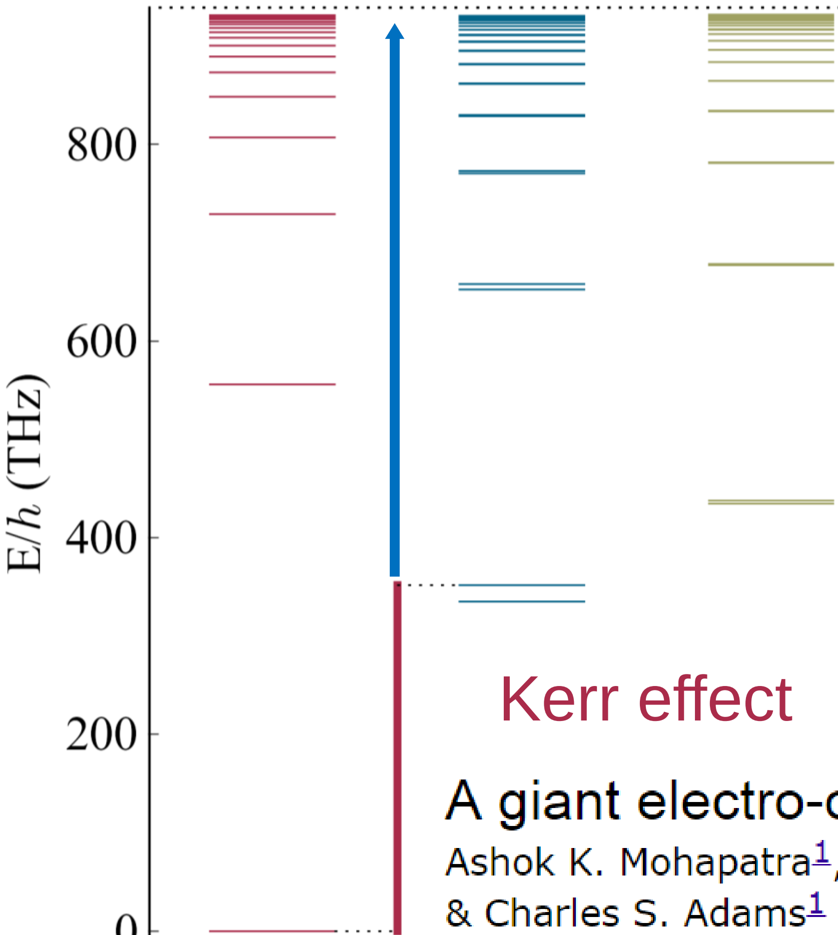
$$\chi \rightarrow \chi^{(1)} + \frac{\partial \chi^{(1)}}{\partial \omega}\left(-\frac{1}{2}\alpha\mathcal{E}^2\right)$$

Non-linearity

Slope (EIT) Shift (Rydberg)



Ladder EIT with Rydbergs: non-linearity



$$n^* = n - \delta$$

Dipole moment *n*s – *n*p	n^{*2}
Dipole moment p – *n*s	$n^{*-3/2}$
Lifetime	n^{*3}
Sensitivity to *E* – fields	n^{*7}

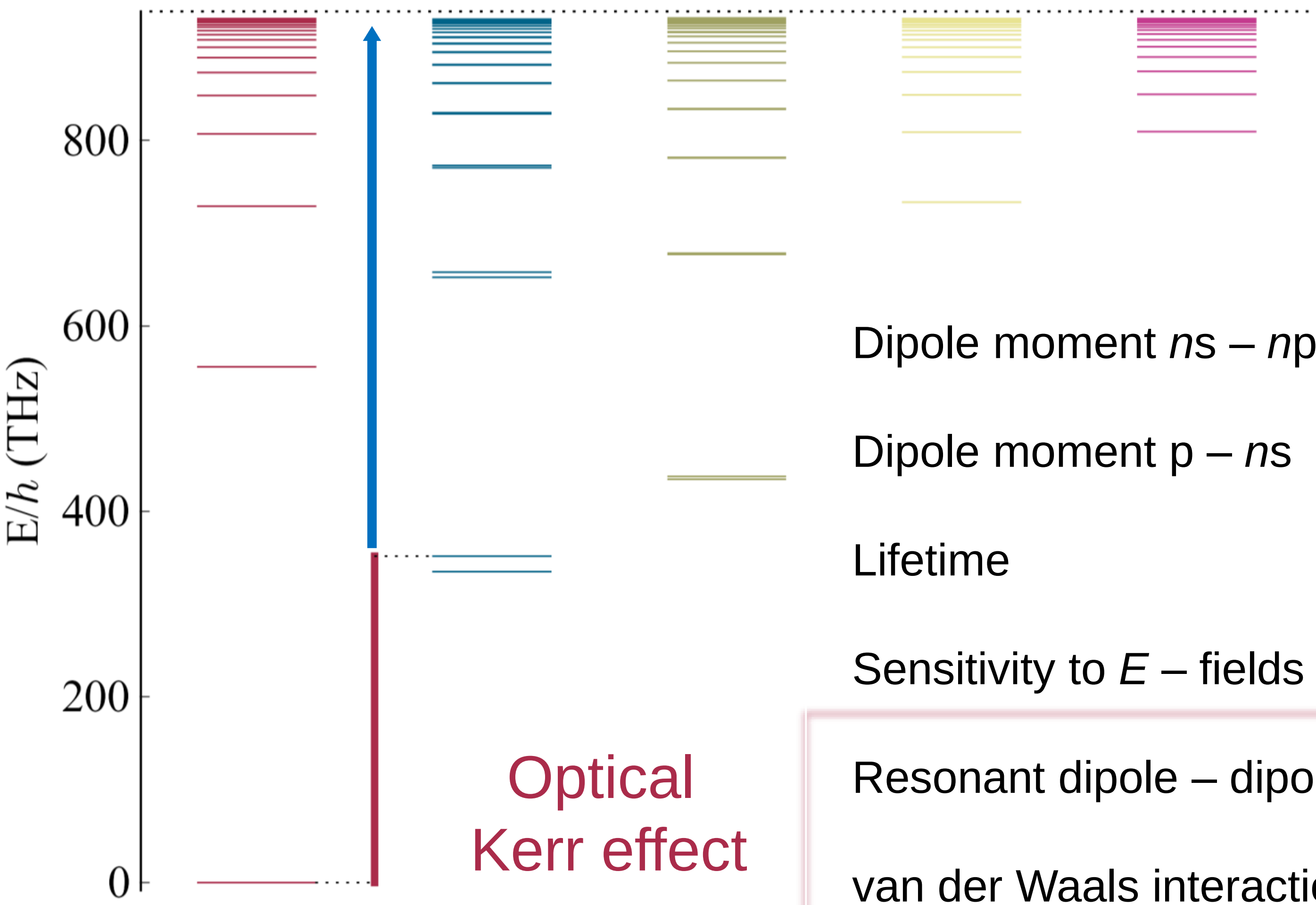
Kerr effect

A giant electro-optic effect using polarizable dark states

Ashok K. Mohapatra[1], Mark G. Bason[1], Björn Butscher[2], Kevin J. Weatherill[1] & Charles S. Adams[1]

Nature Physics **4**, 890 - 894 (2008)

Ladder EIT with Rydbergs: non-linearity



Optical Kerr effect

$$n^* = n - \delta$$

Dipole moment *n*s – *n*p	n^{*2}
Dipole moment p – *n*s	$n^{*-3/2}$
Lifetime	n^{*3}
Sensitivity to *E* – fields	n^{*7}
Resonant dipole – dipole *ns*,*np*	n^{*4}
van der Waals interactions *ns*,*ns*	n^{*11}

Early theory

PHYSICAL REVIEW A **72**, 043803 (2005)

Long-range interactions and entanglement of slow single-photon pulses

Inbal Friedler,[1] David Petrosyan,[2] Michael Fleischhauer,[3] and Gershon Kurizki[1]
[1]*Department of Chemical Physics, Weizmann Institute of Science, Rehovot 76100, Israel*
[2]*Institute of Electronic Structure & Laser, FORTH, GR-71110 Heraklion, Crete, Greece*
[3]*Fachbereich Physik, Universität Kaiserslautern, D-67663 Kaiserslautern, Germany*
(Received 7 March 2005; published 5 October 2005)

We show that very large nonlocal nonlinear interactions between pairs of colliding slow-light pulses can be realized in atomic vapors in the regime of electromagnetically induced transparency. These nonlinearities are mediated by strong, long-range dipole-dipole interactions between Rydberg states of the multilevel atoms in a ladder configuration. In contrast to previously studied schemes, this mechanism can yield a homogeneous conditional phase shift of π even for weakly focused single-photon pulses, thereby allowing a deterministic realization of the photonic phase gate.

1^{st} Rydberg EIT in cold atoms (2008)

J. Phys. B: At. Mol. Opt. Phys. **41** (2008) 201002

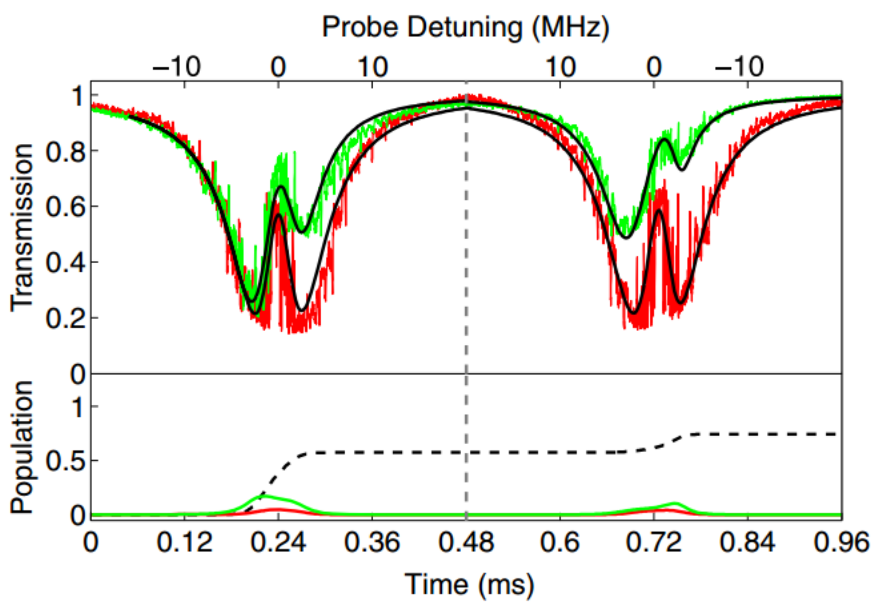


Figure 3. Top: double-scan EIT for the $|1\rangle \rightarrow |2\rangle \rightarrow |3\rangle = 19d$ system for probe powers of 450 nW (red) and 3.4 μW (green). The

J. Phys. B: At. Mol. Opt. Phys. **41** (2008) 201002

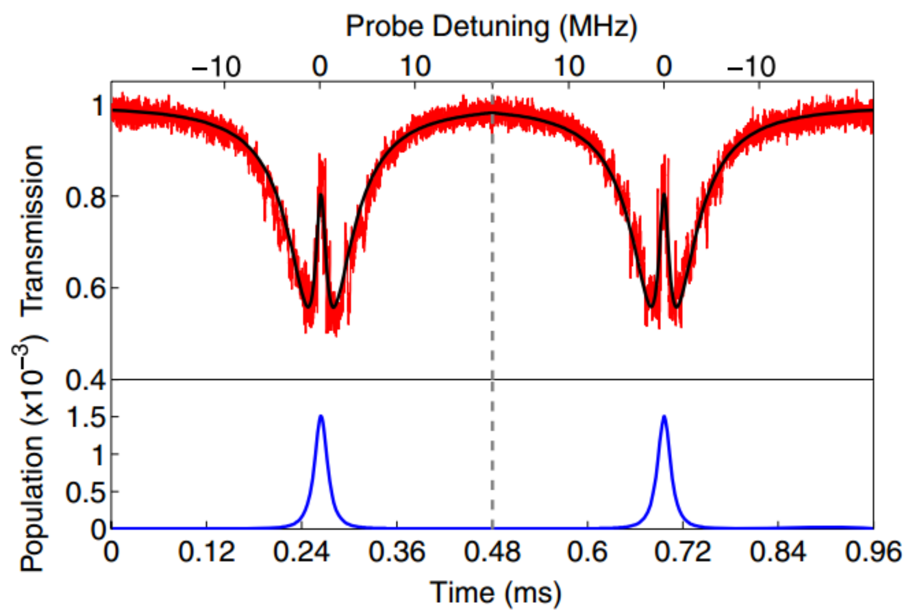


Figure 4. Top: double-scan EIT for the $|1\rangle \rightarrow |2\rangle \rightarrow |3\rangle = 26d$ system with a probe power of 200 nW and coupling beam power of 60 mW. The solid line (black) is the theoretical line of best fit giving an EIT linewidth of 0.58 ±0.04 MHz. Bottom: population of the Rydberg state as a function of time for the duration of the scan.

Rydberg EIT (2010)

J. Phys. B: At. Mol. Opt. Phys. **41** (2008) 201002

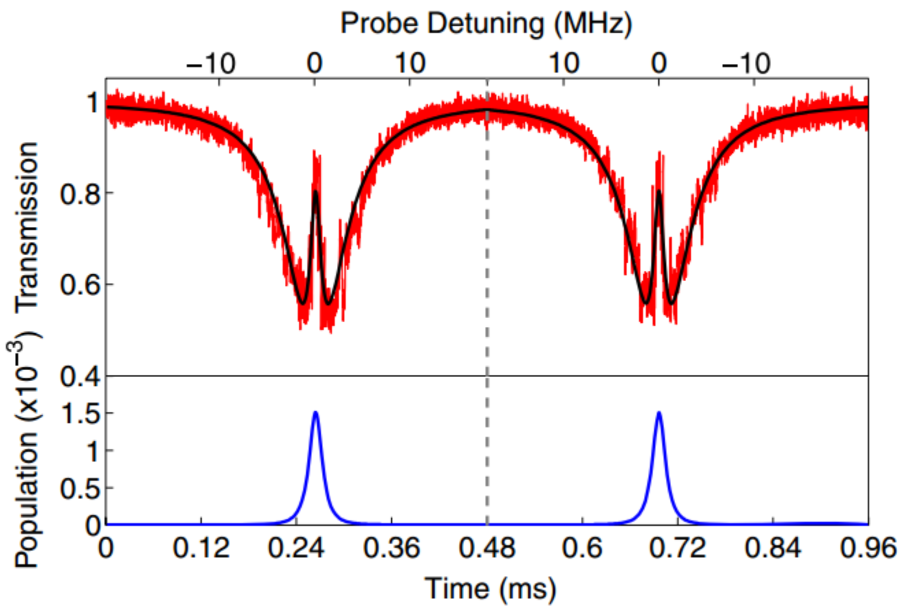
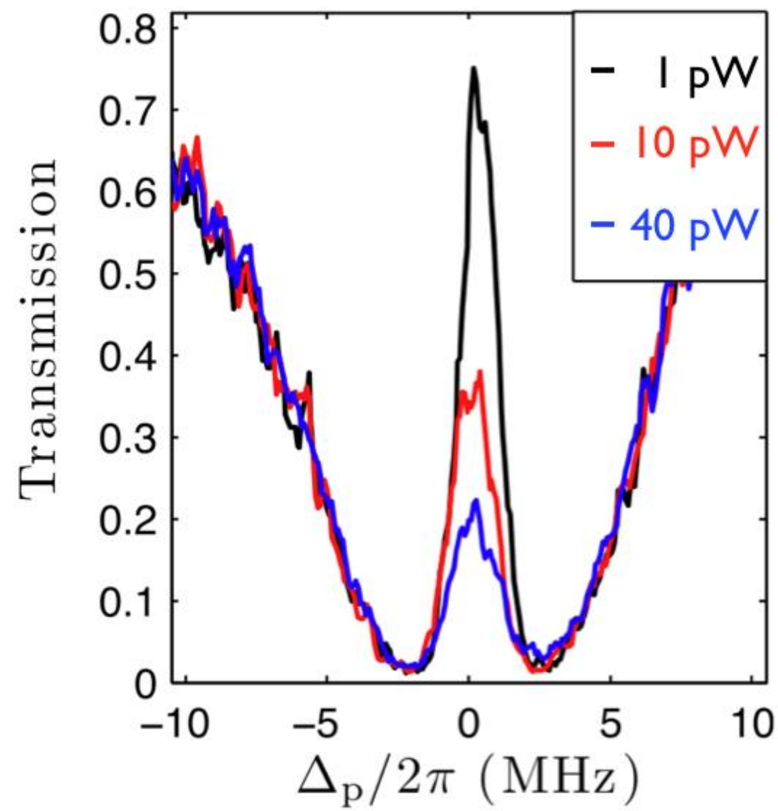


Figure 4. Top: double-scan EIT for the $|1\rangle \rightarrow |2\rangle \rightarrow |3\rangle = 26d$ system with a probe power of 200 nW and coupling beam power of 60 mW. The solid line (black) is the theoretical line of best fit giving an EIT linewidth of 0.58 ±0.04 MHz. Bottom: population of the Rydberg state as a function of time for the duration of the scan.

Pritchard *et al*, PRL **105**, 193603 (2010)

***n* = 46 s**



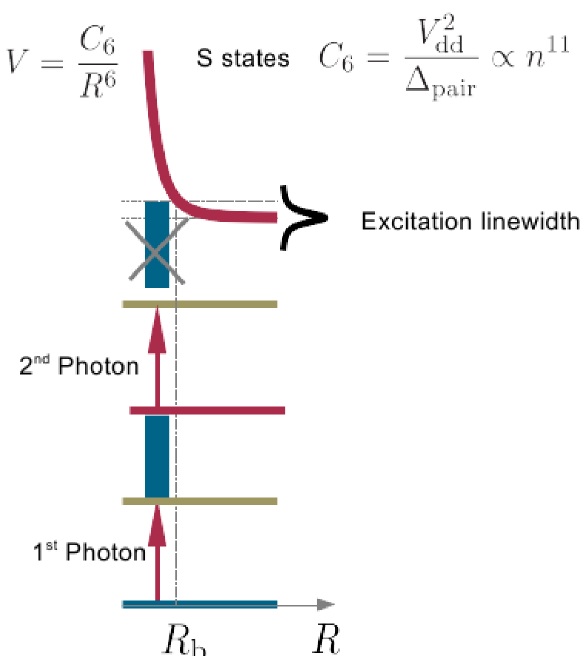
Dipole blockade and Rydberg EIT

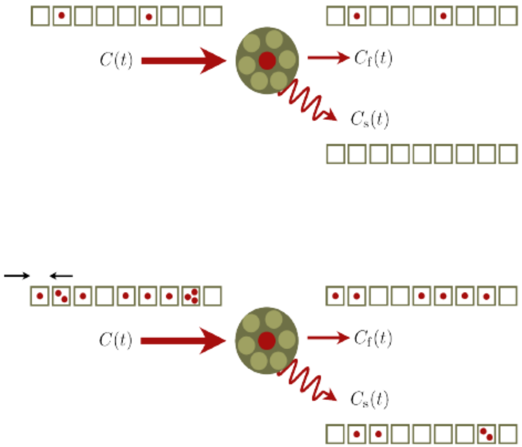
Nonlocal Nonlinear Optics in Cold Rydberg Gases

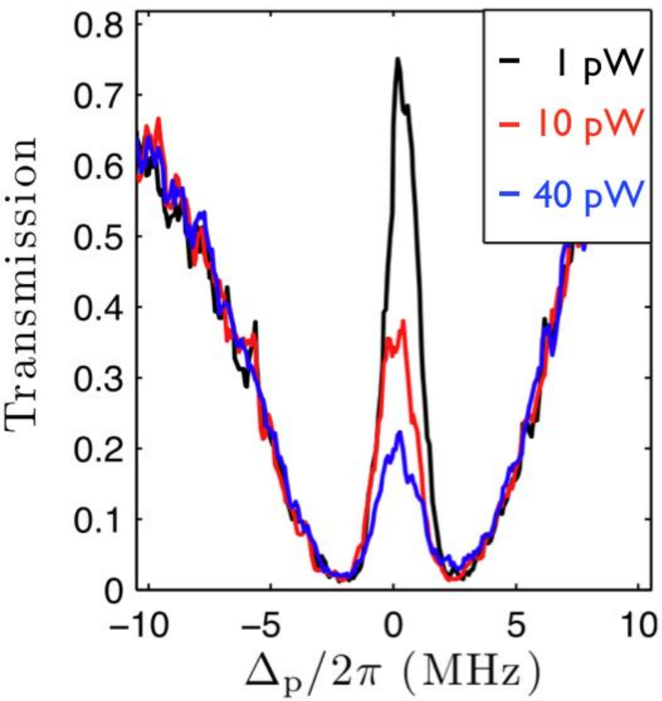
Phys. Rev. Lett. **107**, 153001 – Published 3 October 2011

S. Sevinçli, N. Henkel, C. Ates, and T. Pohl

Rydberg polaritons







Pritchard *et al*, PRL **105**, 193603 (2010)

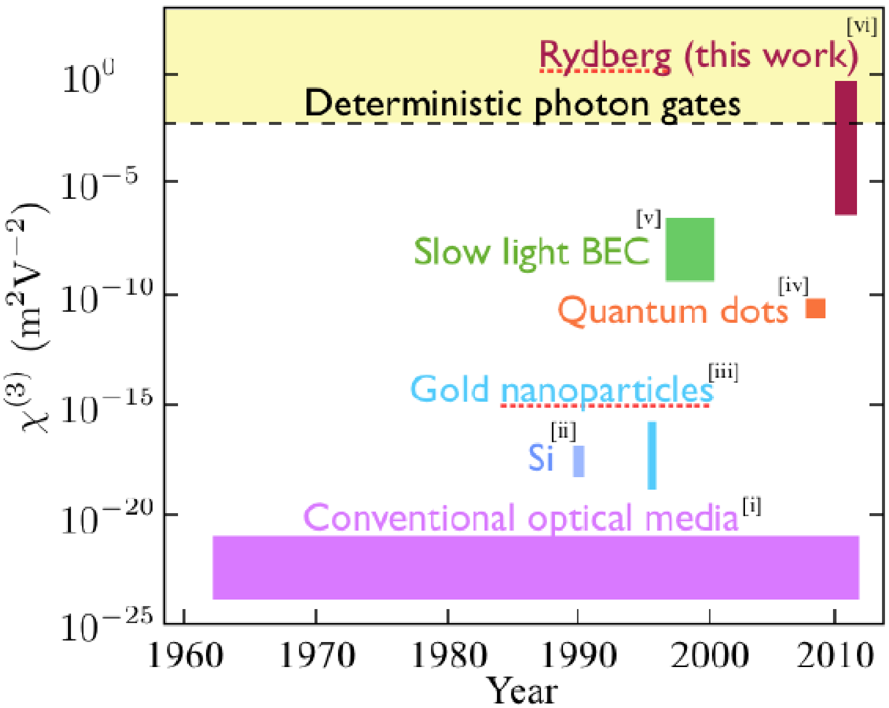
Giant optical non-linearity

Rydberg non-linear optics,
Pritchard *et al*.,
Ann. Rev. of Cold Atoms and Mol., **1**, 301 (2013).
arXiv:1205.4890

Optical Kerr effect

$$\Delta\phi = k\chi^{(3)}|\mathcal{E}_{\rm ph}|^2\ell$$

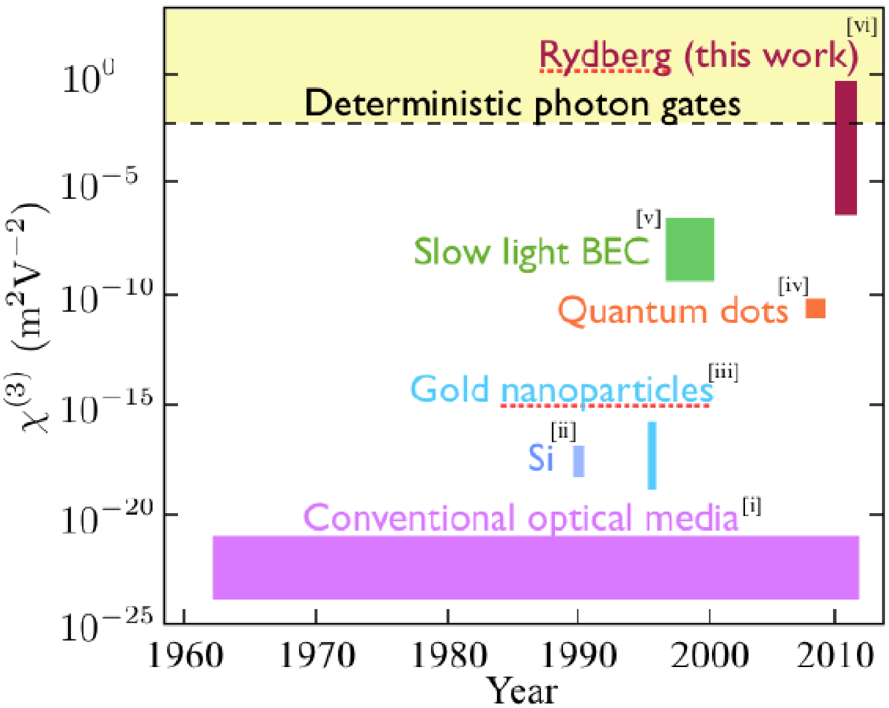
Kerr non-linearity



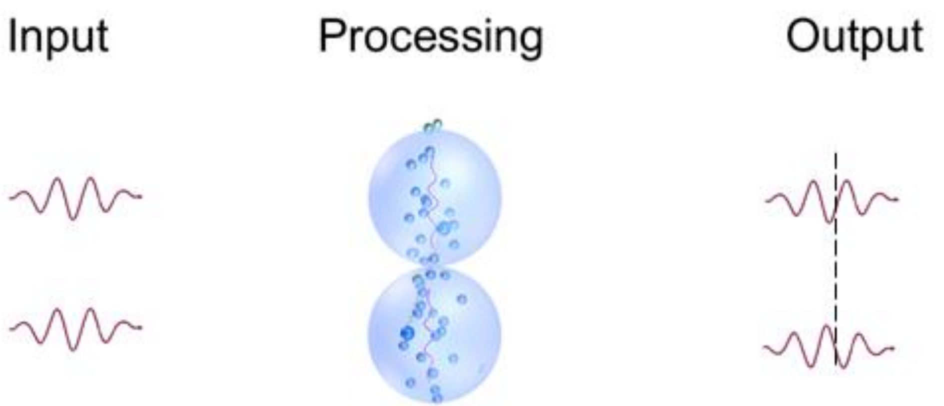
A photon-photon processor?

Rydberg non-linear optics,
Pritchard *et al.*,
Ann. Rev. of Cold Atoms and Mol., **1**, 301 (2013).
arXiv:1205.4890

Kerr non-linearity



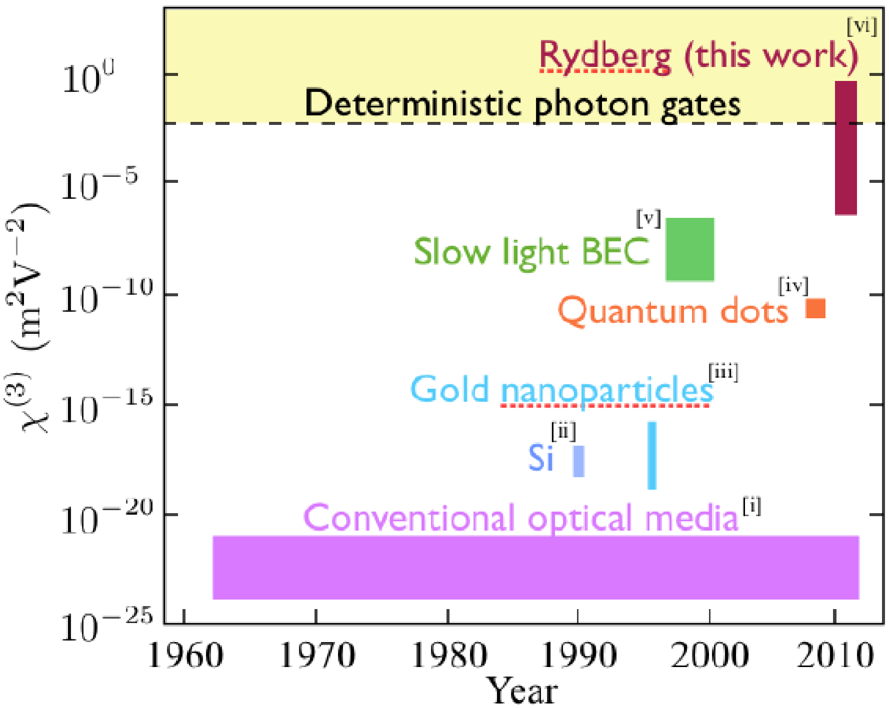
$$\Delta\phi = k\chi^{(3)}|\mathcal{E}_{\rm ph}|^2\ell$$



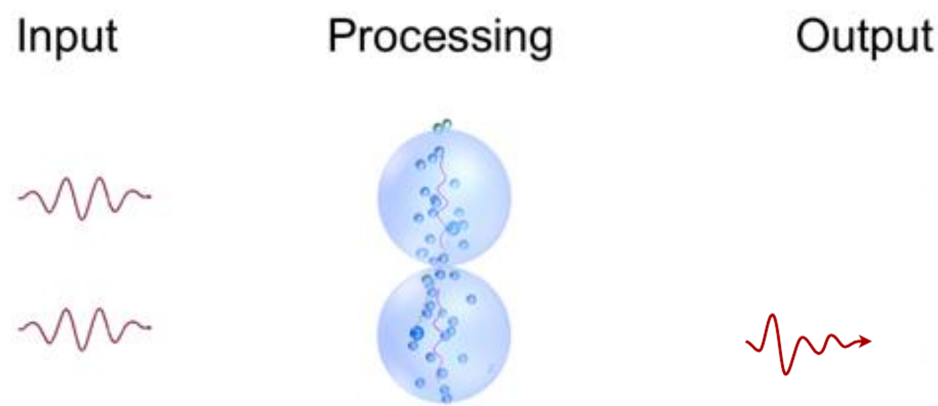
A photon-photon processor?

Rydberg non-linear optics,
Pritchard *et al.*,
Ann. Rev. of Cold Atoms and Mol., **1**, 301 (2013).
arXiv:1205.4890

Kerr non-linearity



$$\Delta\phi = k\chi^{(3)}|\mathcal{E}_{\rm ph}|^2\ell$$



JH Shapiro,
Single-photon Kerr nonlinearities do not help quantum computation,
Phys Rev A **76**, 062305 (2006)

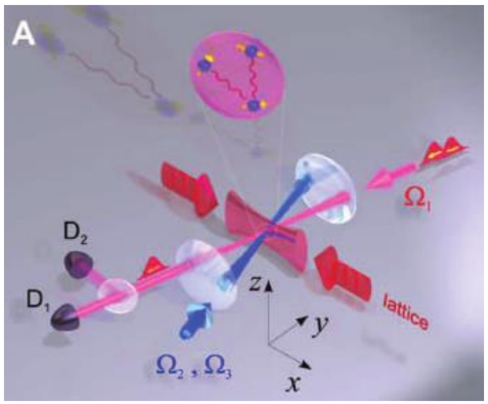
J Gea Banacloche,
Impossibility of large phase shifts via the giant Kerr effect with single-photon wave packets, Phys Rev A **81**, 043823 (2010)

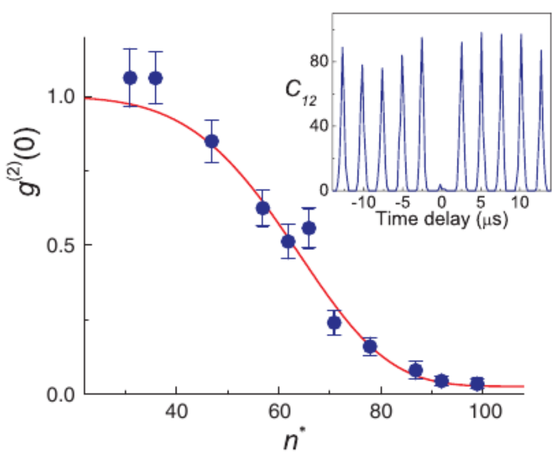
Nonlocal Nonlinear Optics in Cold Rydberg Gases
Phys. Rev. Lett. **107**, 153001 – Published 3 October 2011
S. Sevinçli, N. Henkel, C. Ates, and T. Pohl

Rydberg quantum optics

Georgia Tech

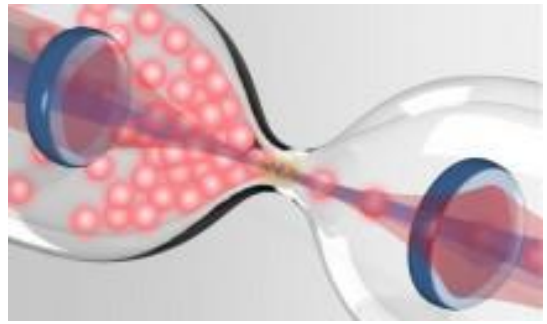
Dudin *et al*, Science **336**, 887 (2012)

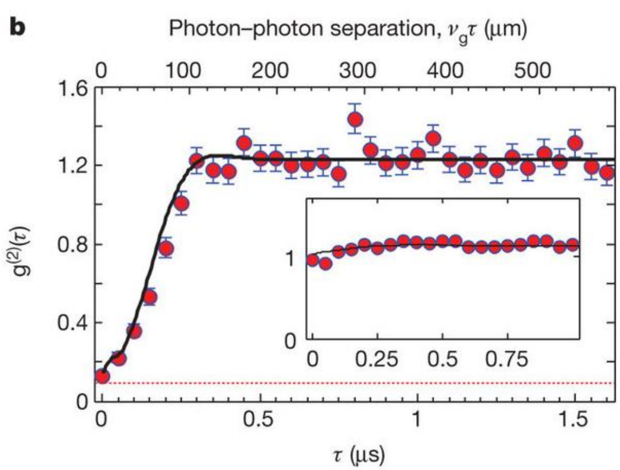




Harvard/MIT

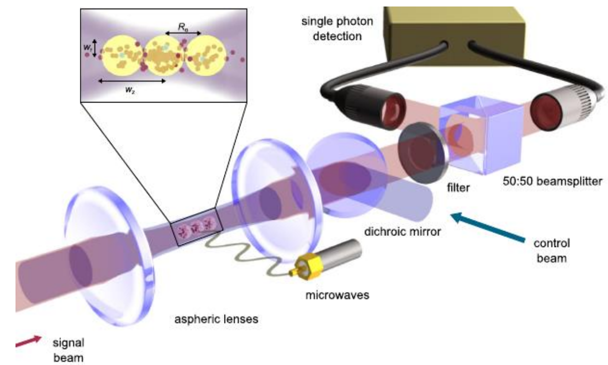
Peyronel *et al*, Nature **488**, 57 (2012)

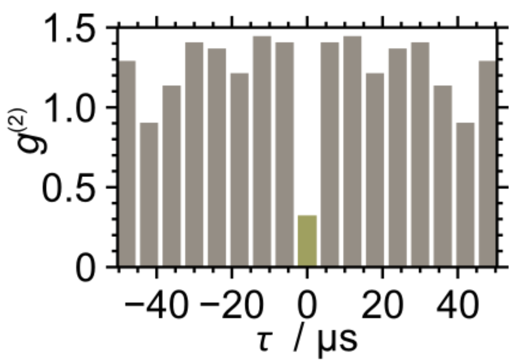




Durham

Maxwell *et al*, PRL **110**, 103001 (2013)

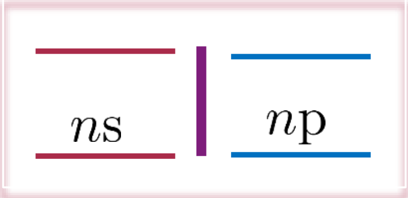




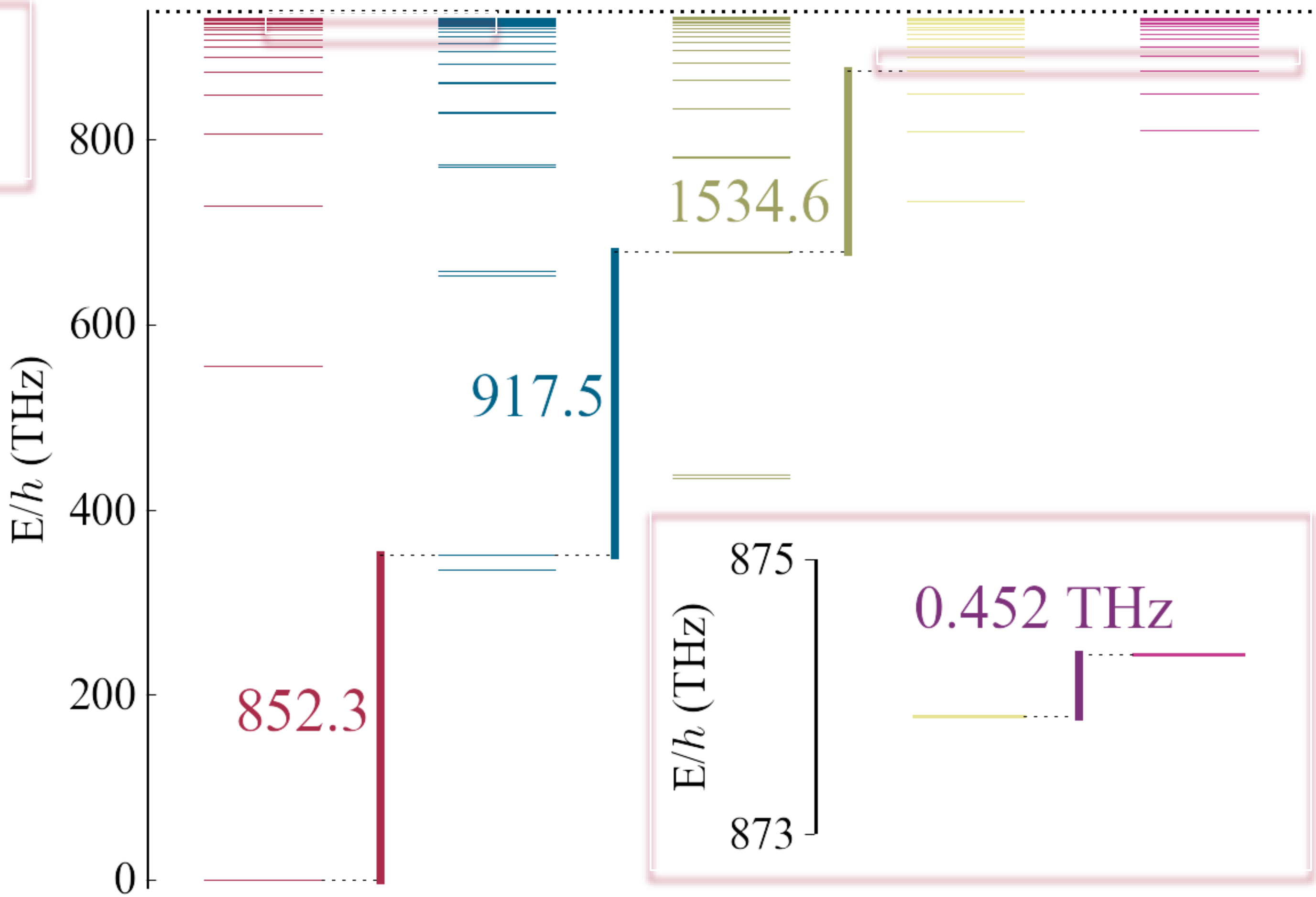
plus Heidelberg, Garching, Stuttgart, Paris, ICFO

Interface: optical, THz, microwave and rf

1 – 100 GHz



Cs levels



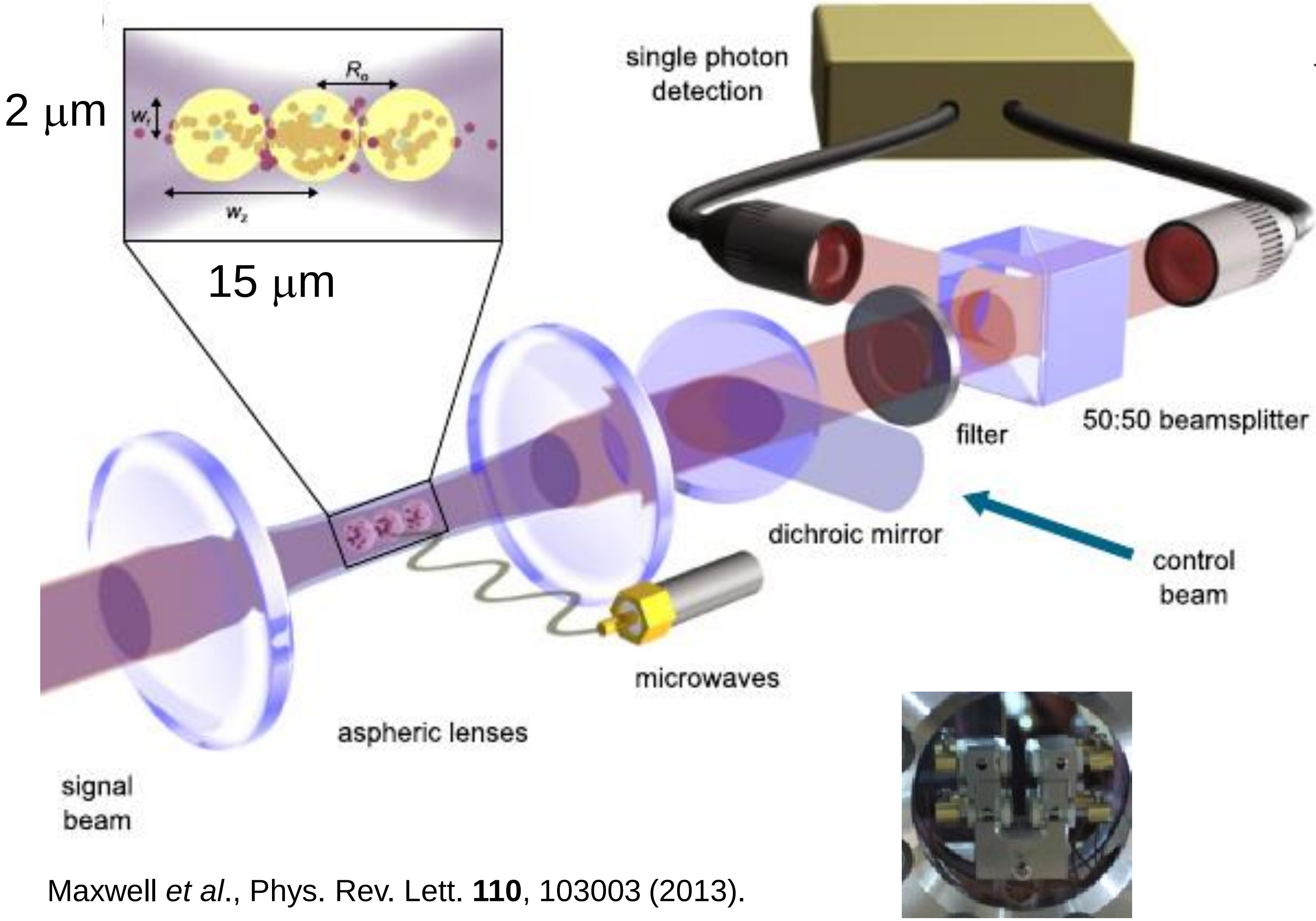
Experiment: laser cooled Rb atoms

See D Maxwell, PhD thesis www.jqc.org.uk

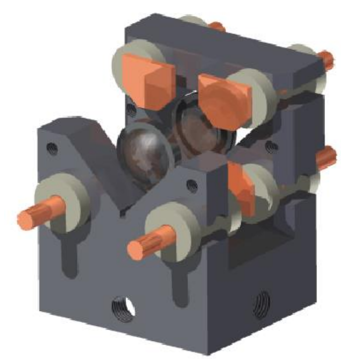
Optically trapped ultracold Rb atoms

$$R_{\rm opt} = \left(\frac{C_6}{\hbar\Omega}\right)^{1/6}$$

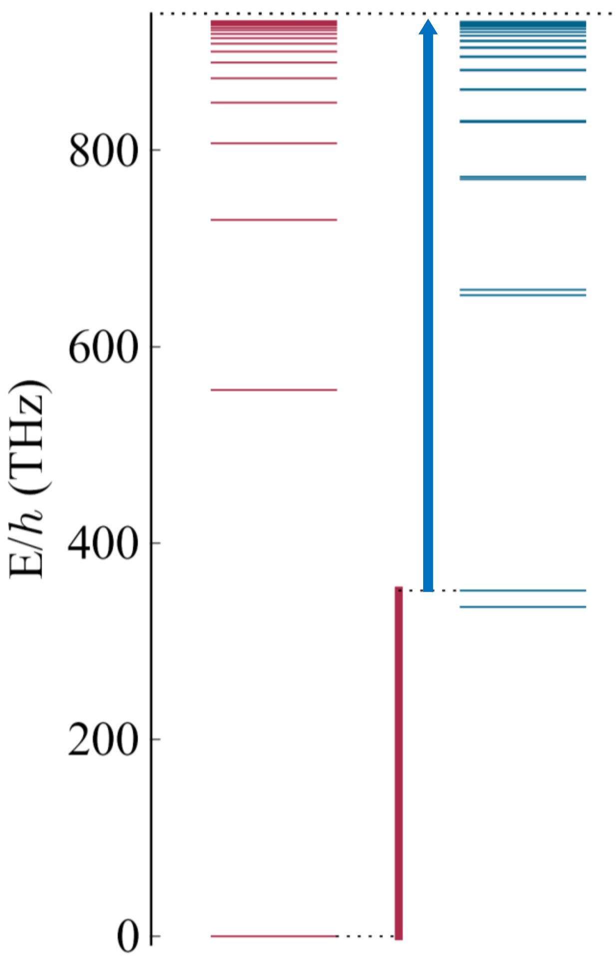
5 μm

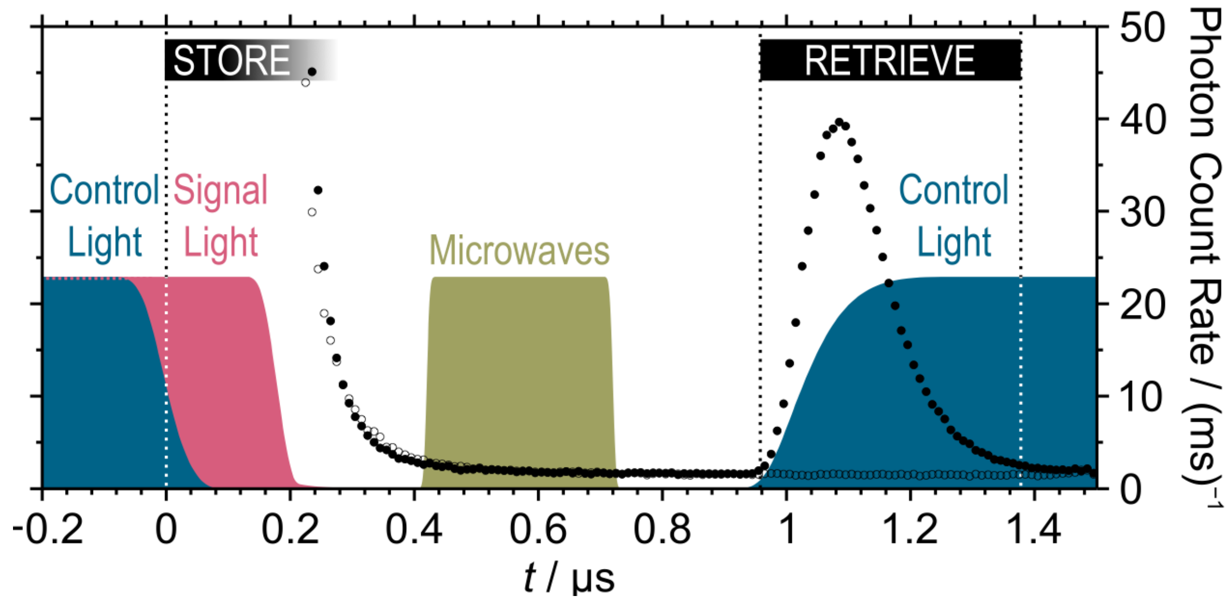


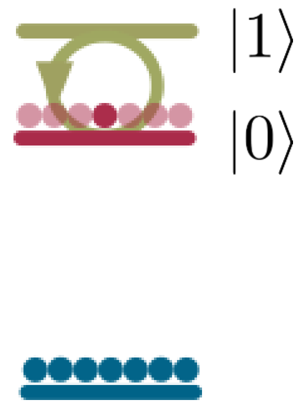
Maxwell *et al*., Phys. Rev. Lett. **110**, 103003 (2013).



Rydberg quantum memory







60s

Rydberg polaritons!

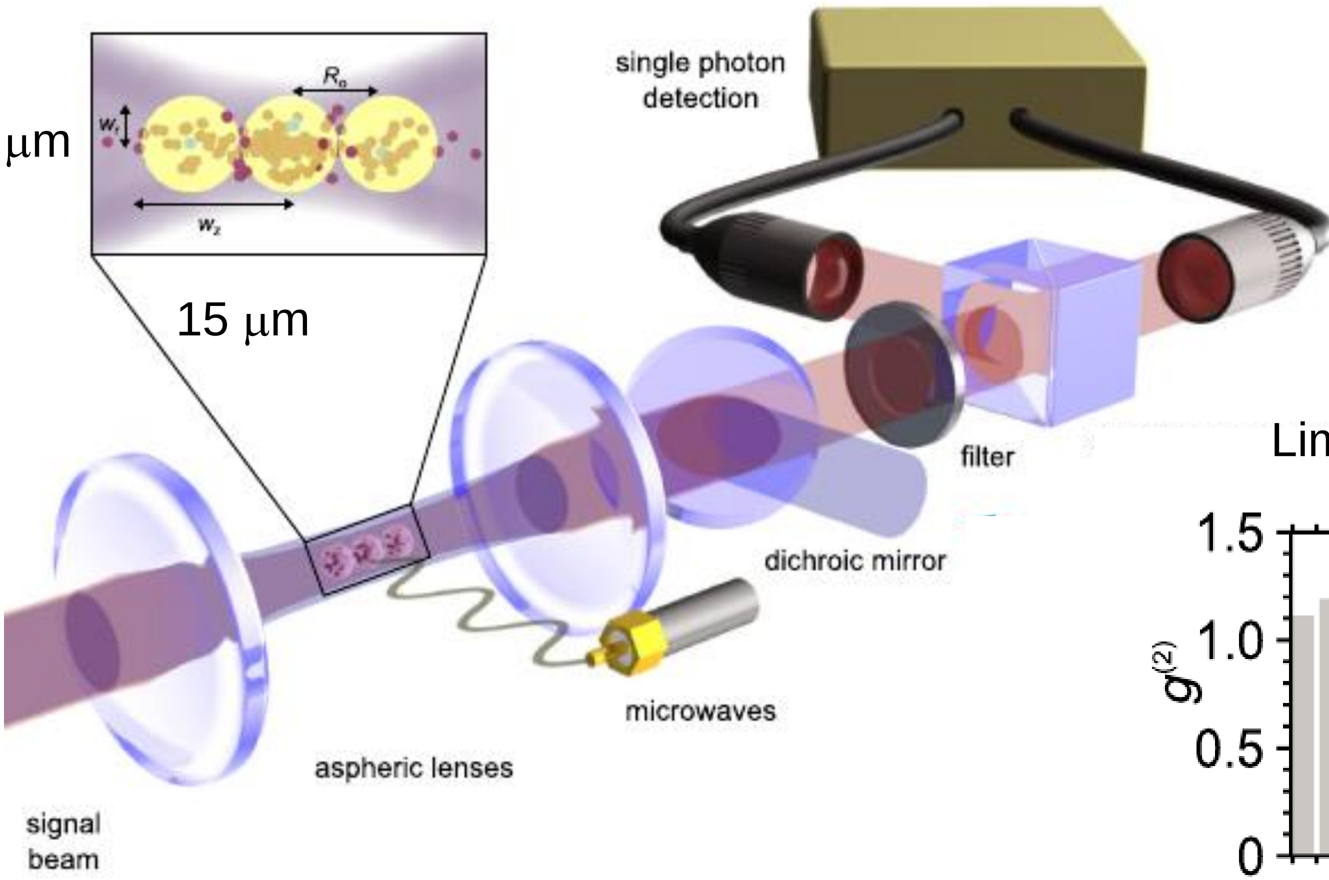
$$|\psi\rangle = \frac{1}{\sqrt{N}} \sum_{\nu} \mathrm{e}^{\mathrm{i}\underline{k}.\underline{r}} |b_\nu\rangle$$

Maxwell *et al*., Phys. Rev. Lett. **110**, 103003 (2013).

Anti-bunching: memory is blockaded

2 µm

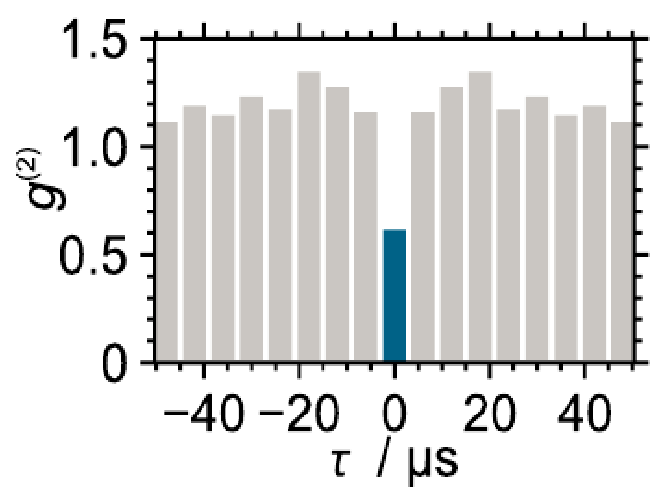
15 µm



$$R_{\text{opt}} = \left(\frac{C_6}{\hbar\Omega}\right)^{1/6}$$

5 µm

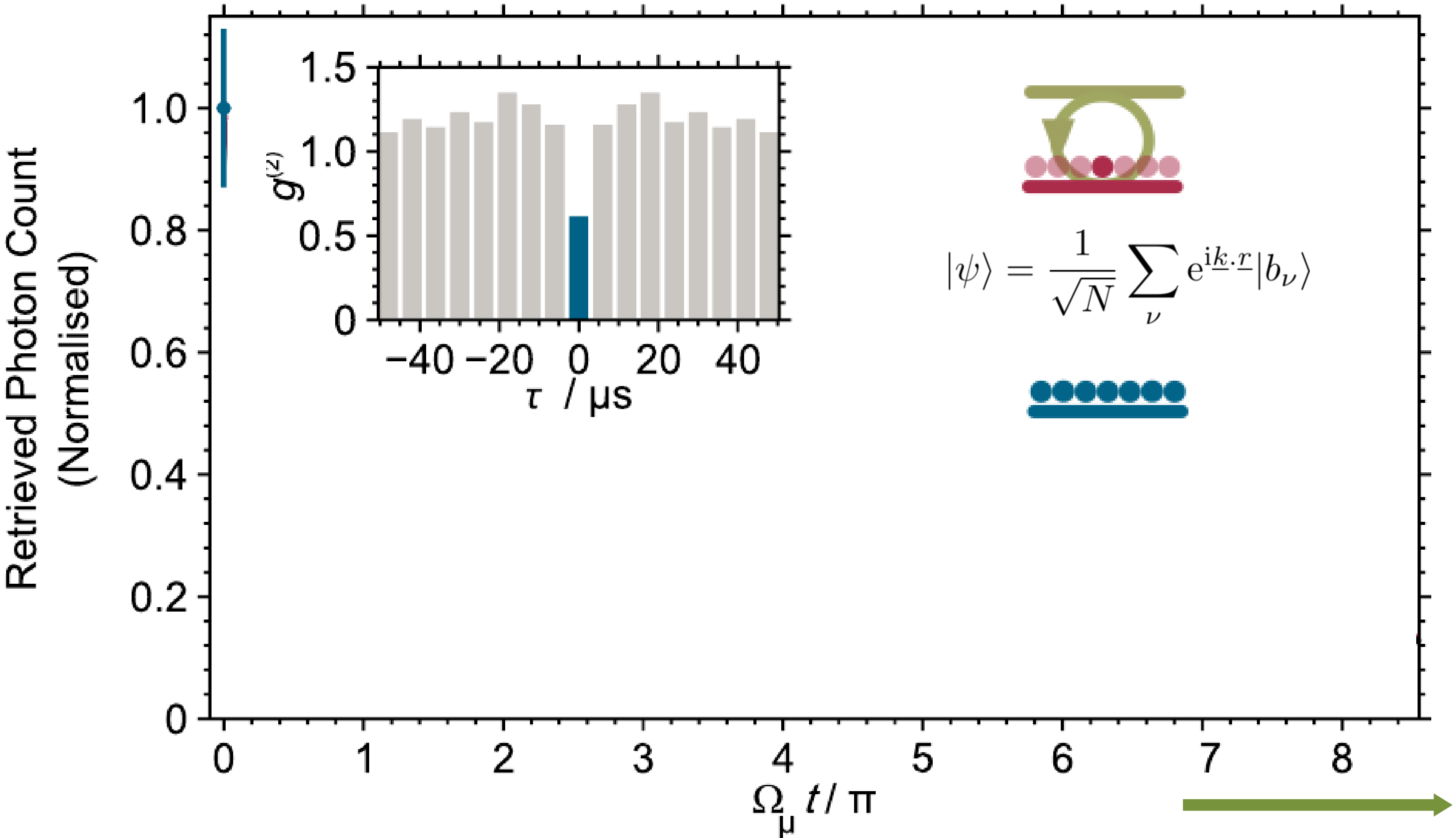
Limited to 3 polaritons!



Maxwell *et al*., Phys. Rev. Lett. **110**, 103003 (2013).

Microwave control of photon-photon interactions

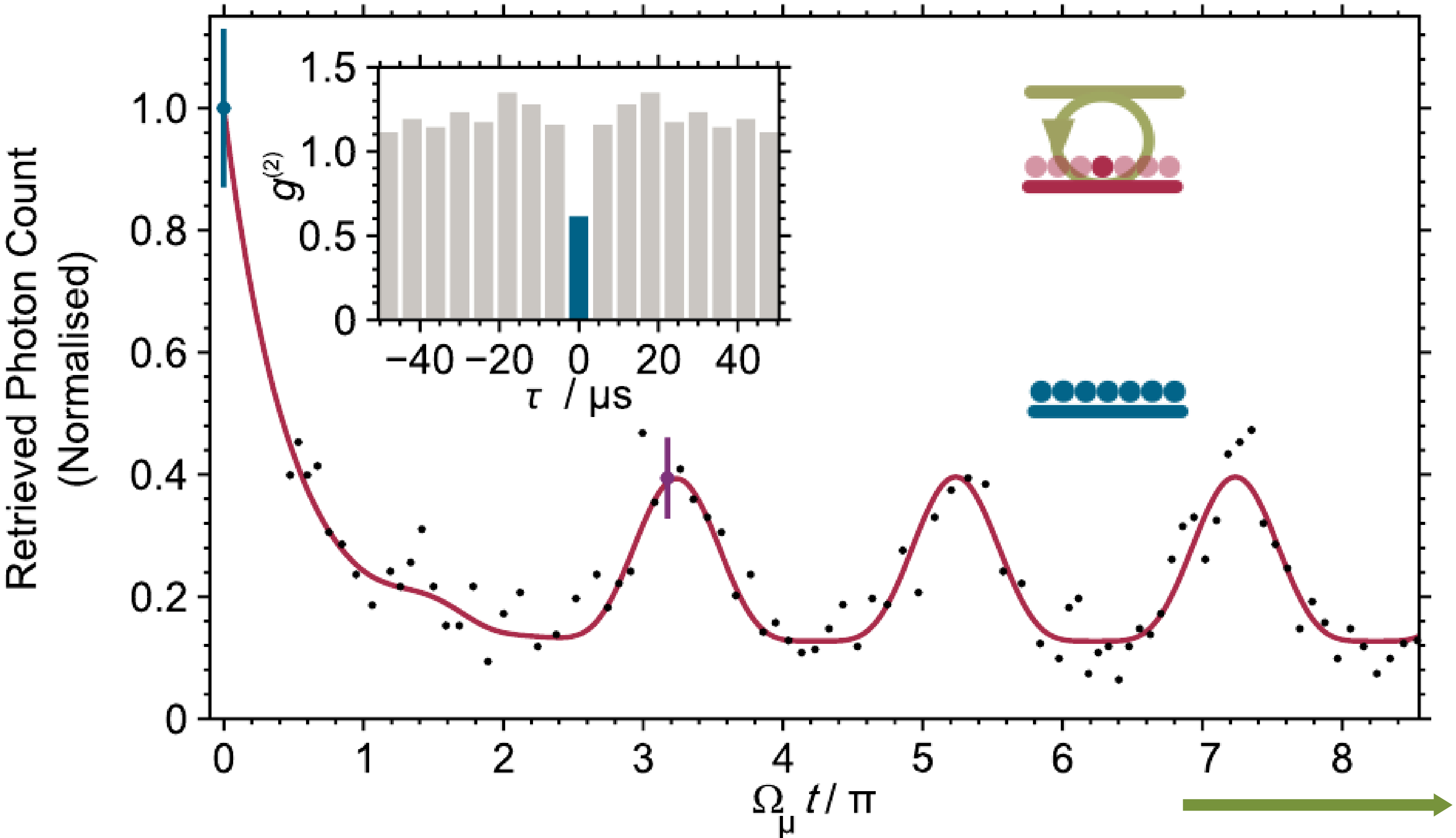
Maxwell *et al.*, Phys. Rev. A **110**, 043827 (2014).



Increasing microwave power

Microwave control of photon-photon interactions

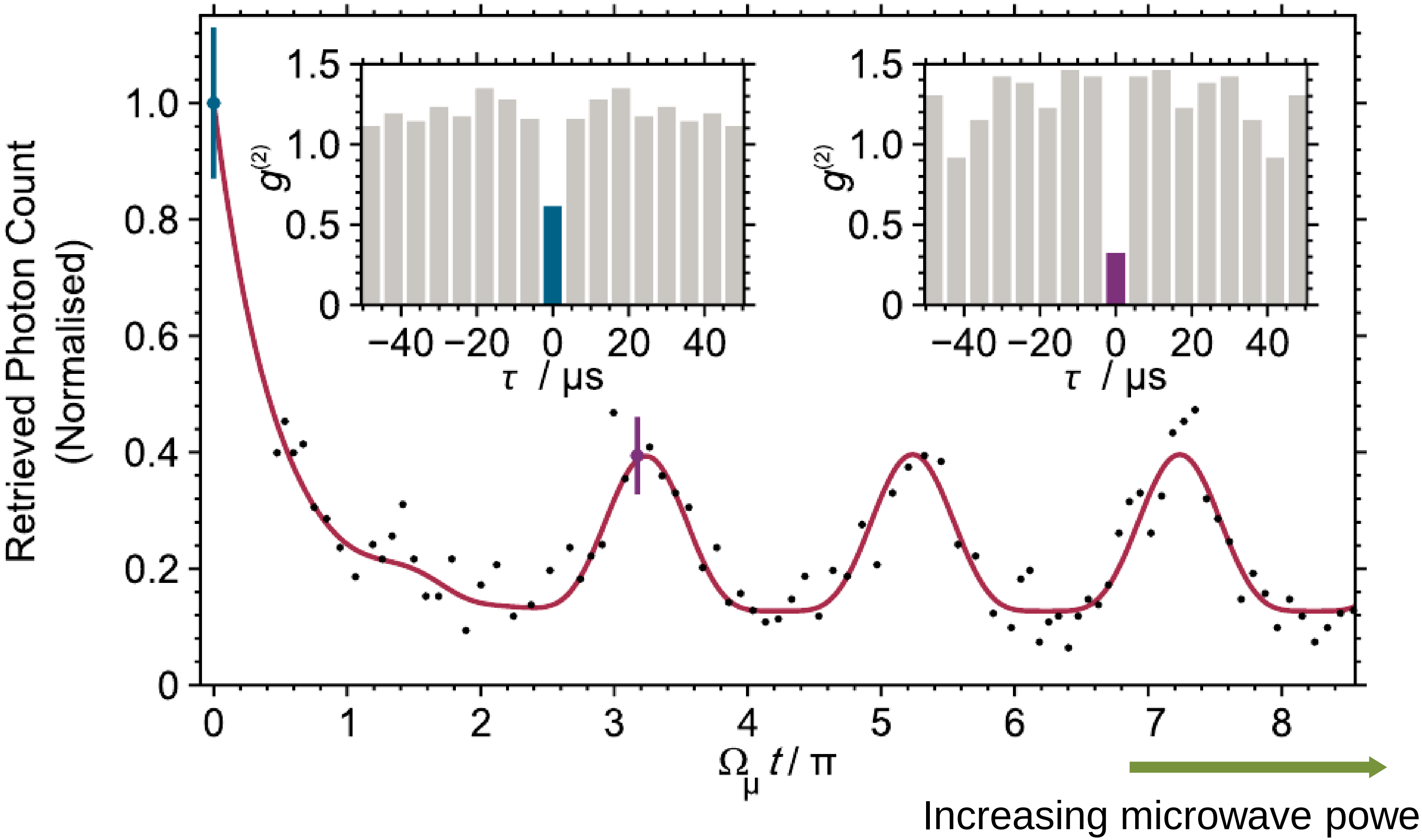
Maxwell *et al*., Phys. Rev. A **110**, 043827 (2014).



Increasing microwave power

Microwave control of photon-photon interactions

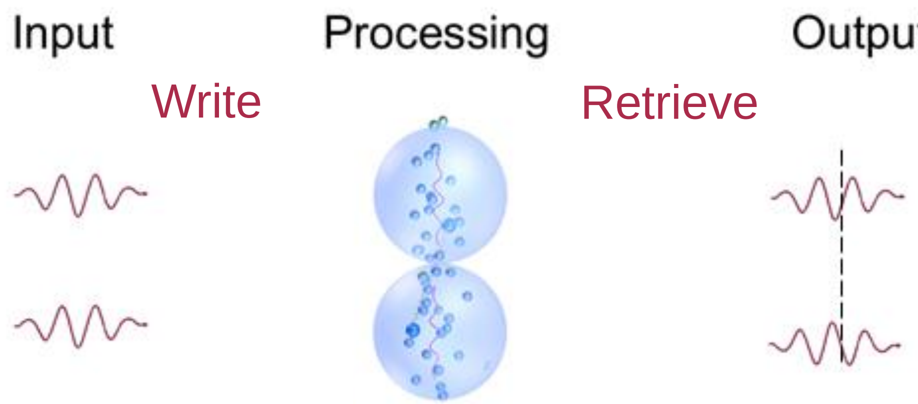
Maxwell *et al*., Phys. Rev. A **110**, 043827 (2014).



Theory: dephasing of spin waves. Bariani *et al*., Phys. Rev. Lett. **108**, 030501 (2012).

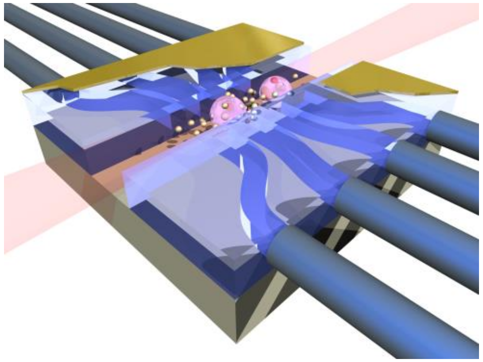
A photon-photon processor

Paredes-Barato *et al.*, Phys. Lev. Lett. **112**, 040501 (2014).

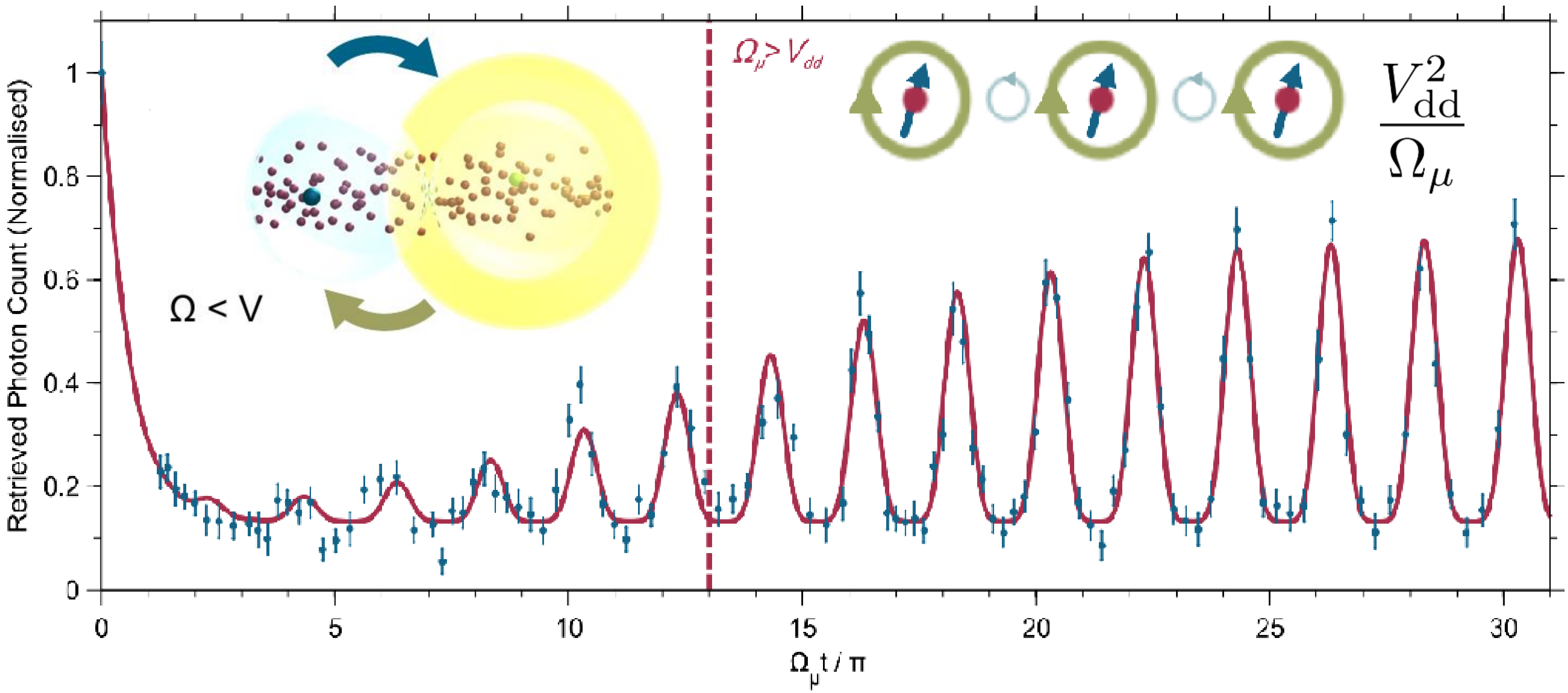


JH Shapiro,
Single-photon Kerr nonlinearities do not help quantum computation,
Phys Rev A **76**, 062305 (2006)

J Gea Banacloche,
Impossibility of large phase shifts via the giant Kerr effect with single-photon wave packets, Phys Rev A **81**, 043823 (2010)



Excitation hopping: XXZ spin model



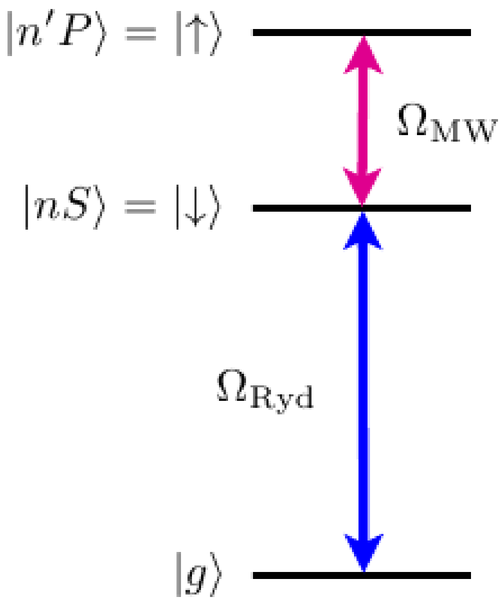
Hopping between single atoms: Barredo *et al.*, arXiv:1408:1055

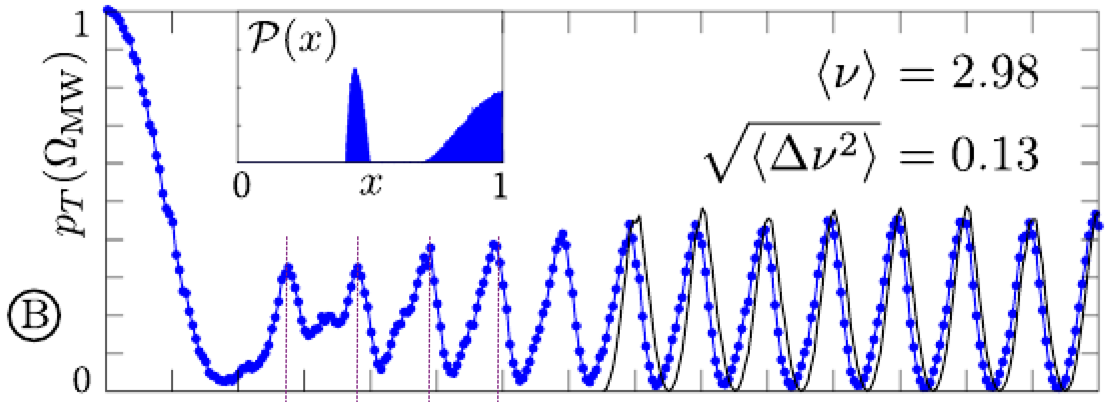
Exciton dynamics: XXZ spin model

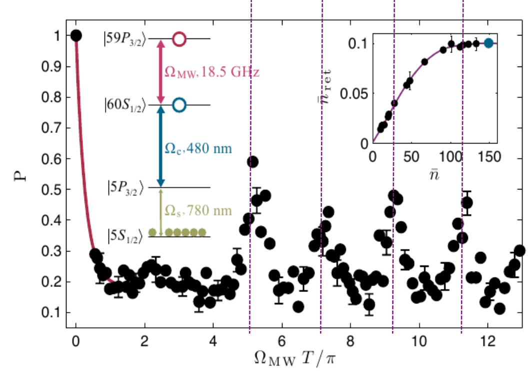
S Bettelli *et al*, PRA **88**, 043436 (2013)

Driving Hopping

$$\mathcal{H}_{\rm eff} = \frac{1}{2}\hbar\sum_i \Omega_i \sigma_i^x + \sum_{i\neq j} V_{ij}(\sigma_i^+\sigma_j^- + \sigma_i^-\sigma_j^+)$$



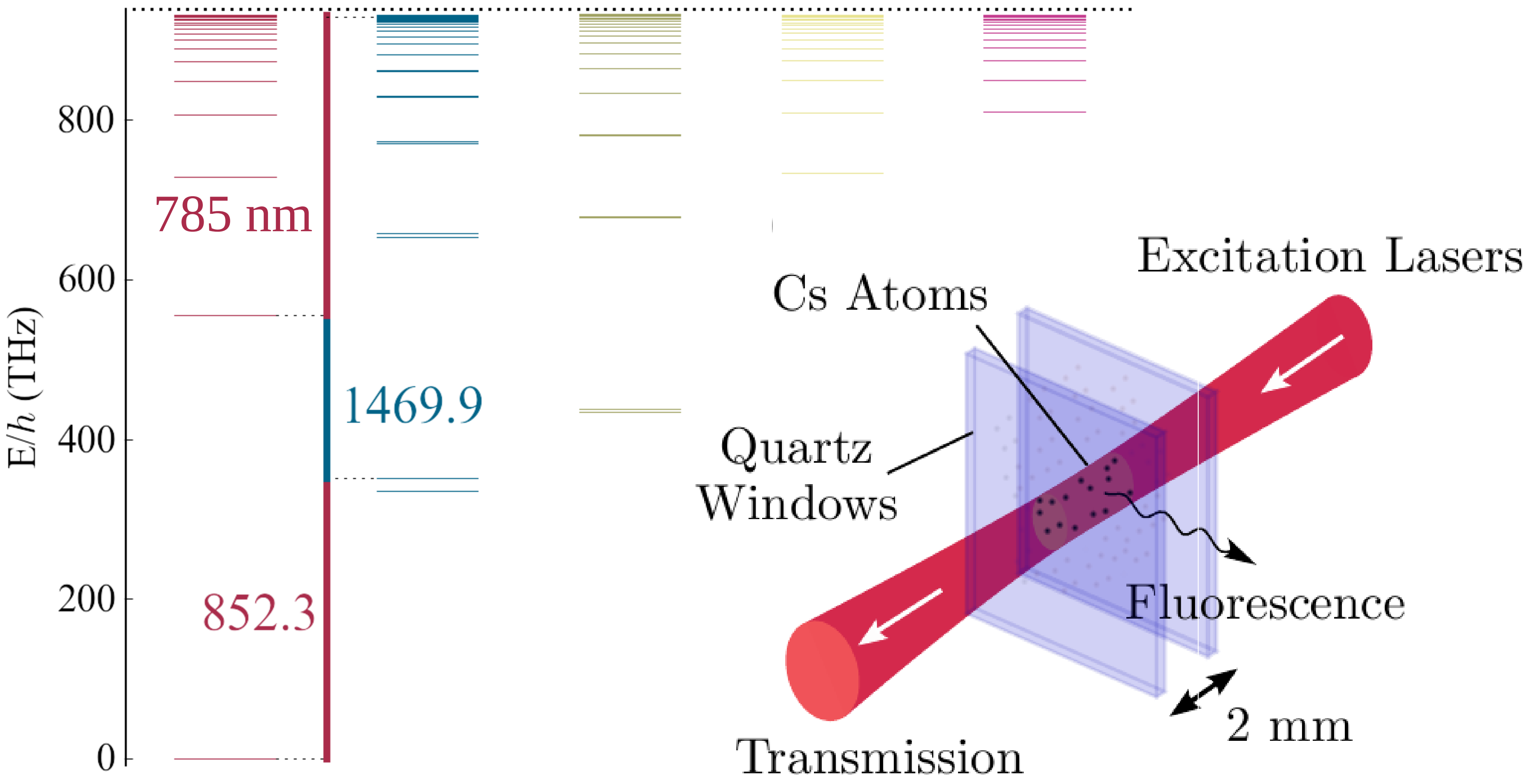




XXZ model

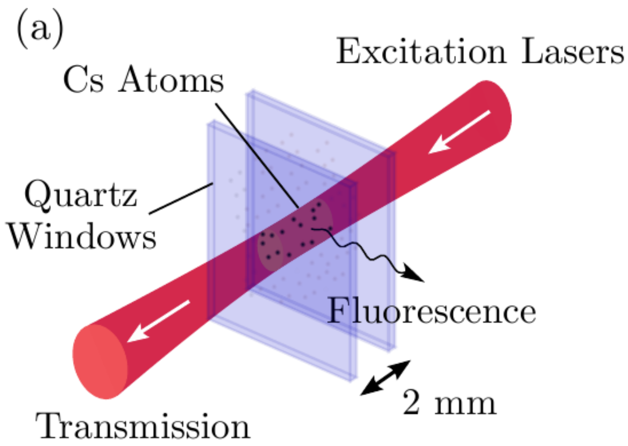
$$\mathcal{H}_{\rm eff} = \frac{1}{2}\hbar\sum_i \Omega_i \sigma_i^z + \sum_{i\neq j} V_{ij}(\sigma_i^x\sigma_j^x + \sigma_i^y\sigma_j^y + 2\sigma_i^z\sigma_j^z)$$

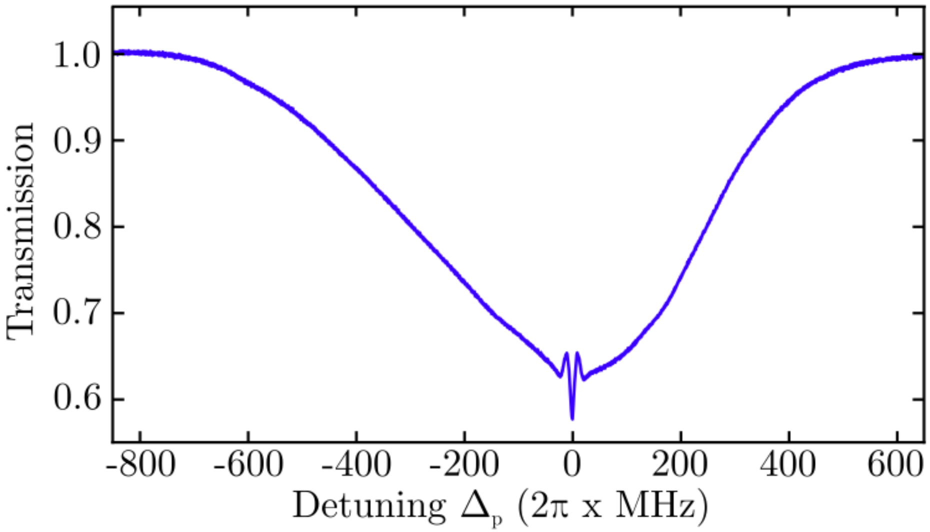
3 photon Rydberg EIT: 6s – 6p – 7s – 26p



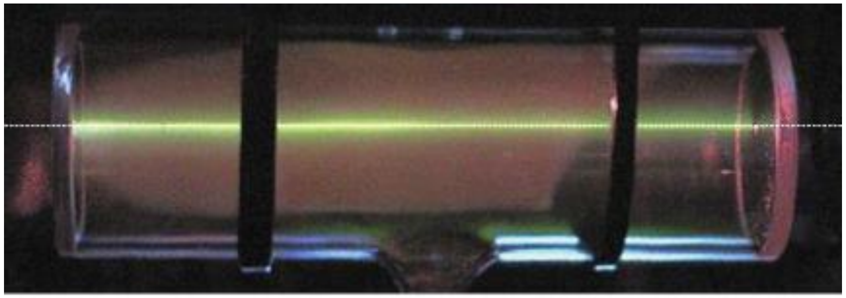
3 – photon EIT

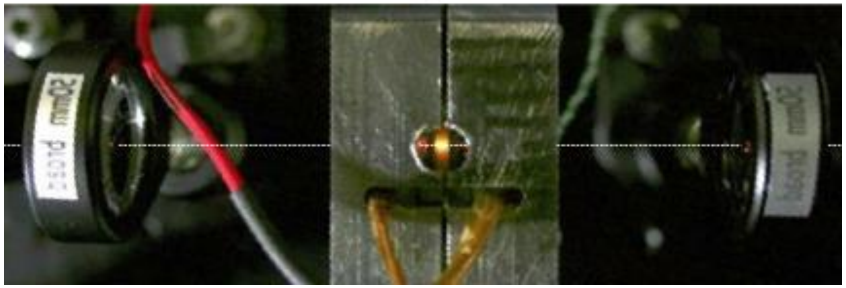
C. Carr *et al*. Opt. Lett. **37**, 3858 (2012).



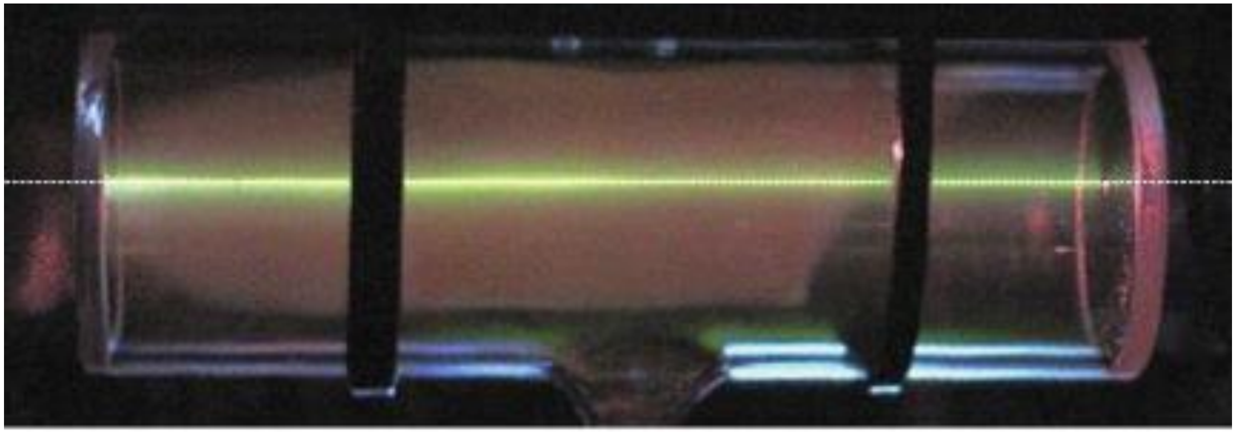


Long cell (low density)

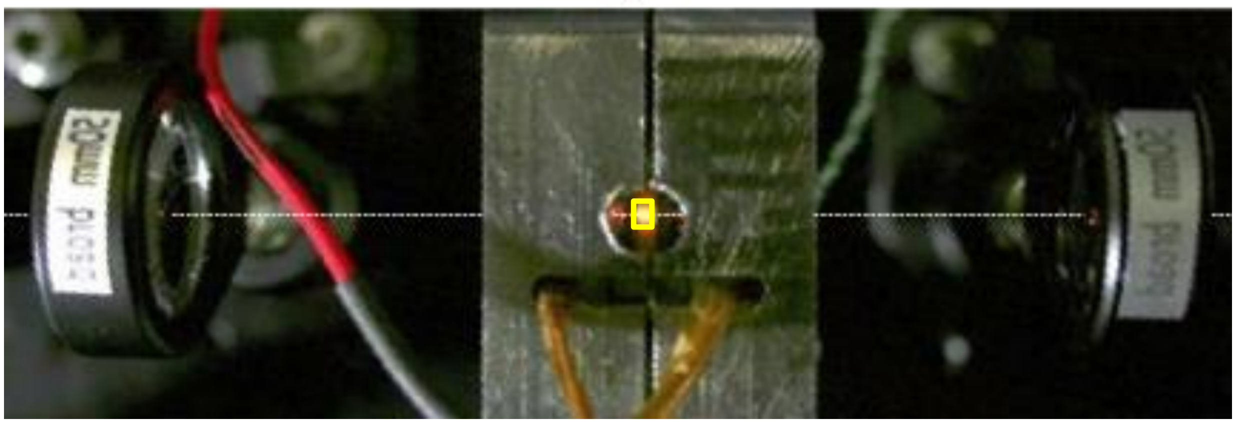


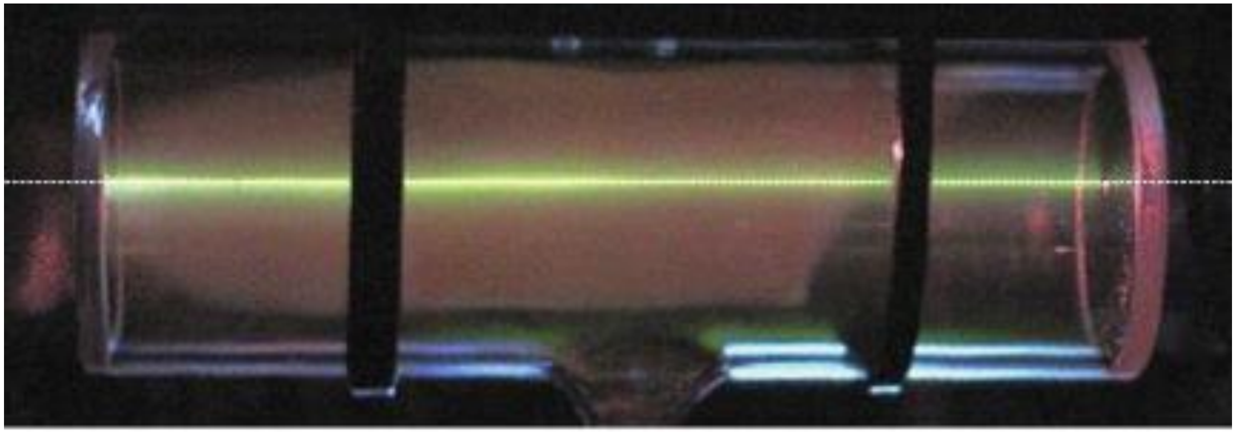


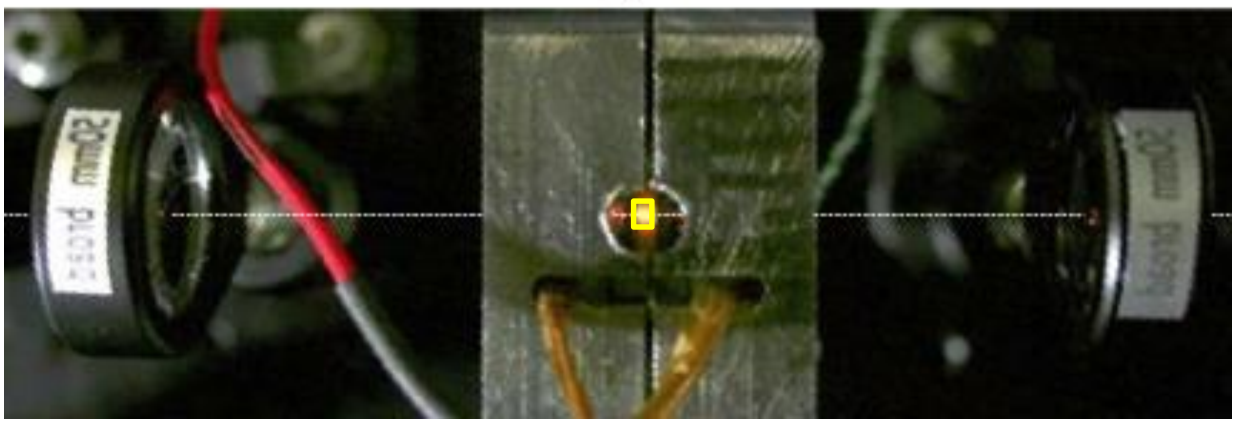
Short cell (higher density)

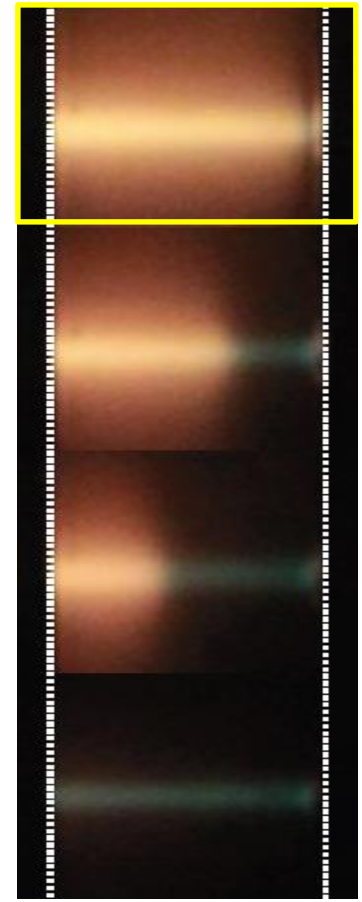


(a)

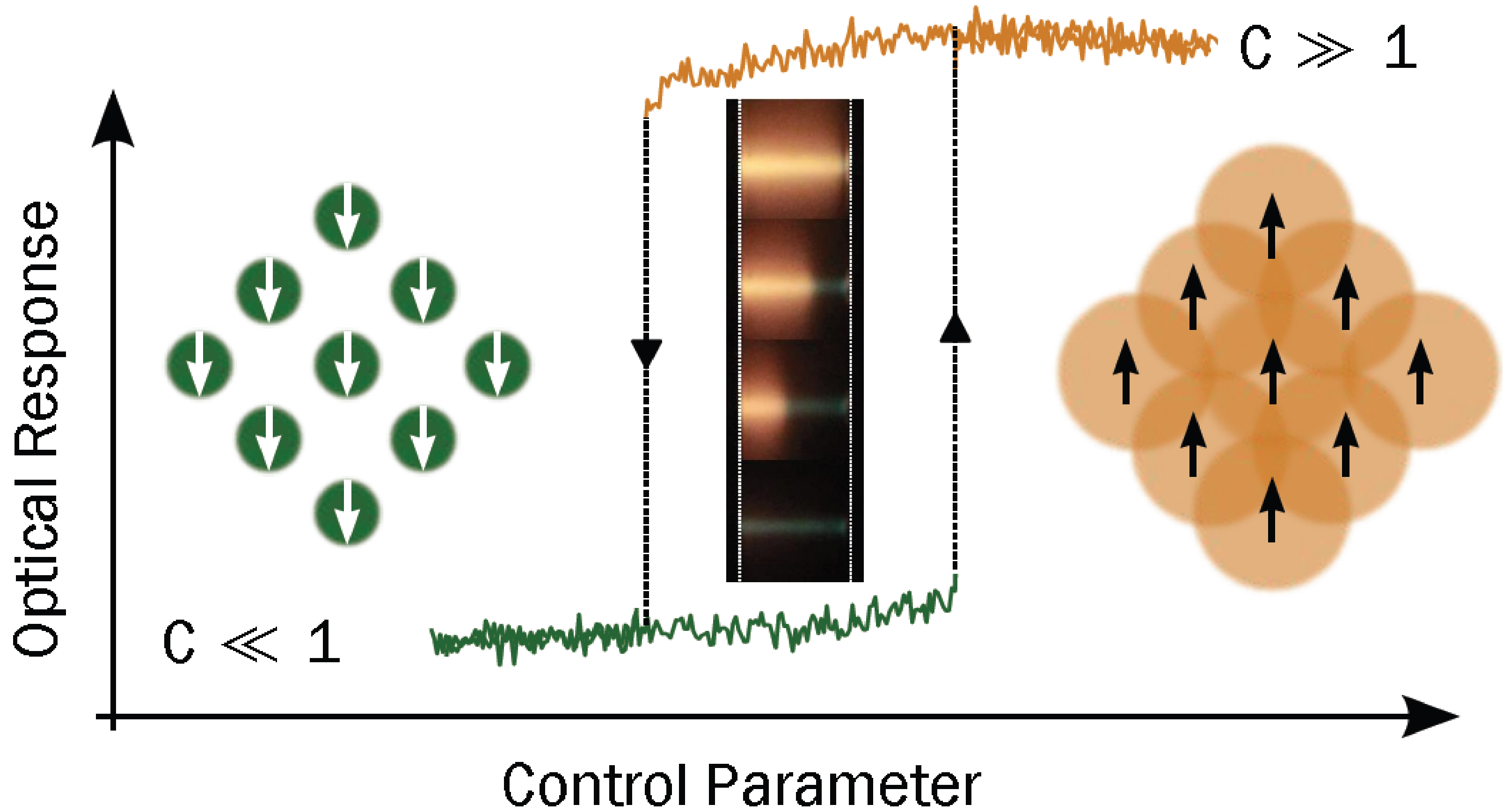




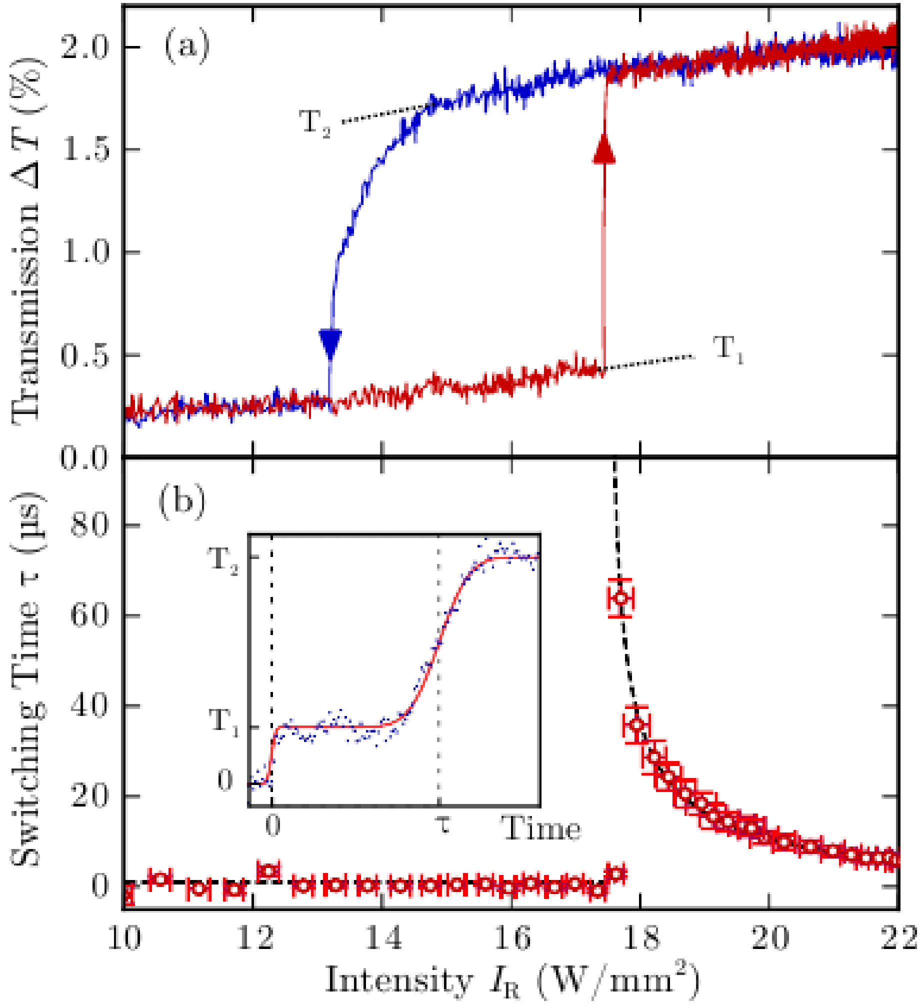


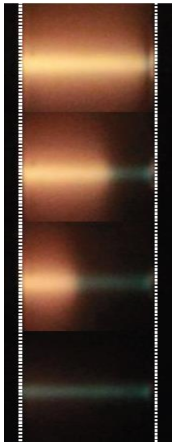


Phase transition

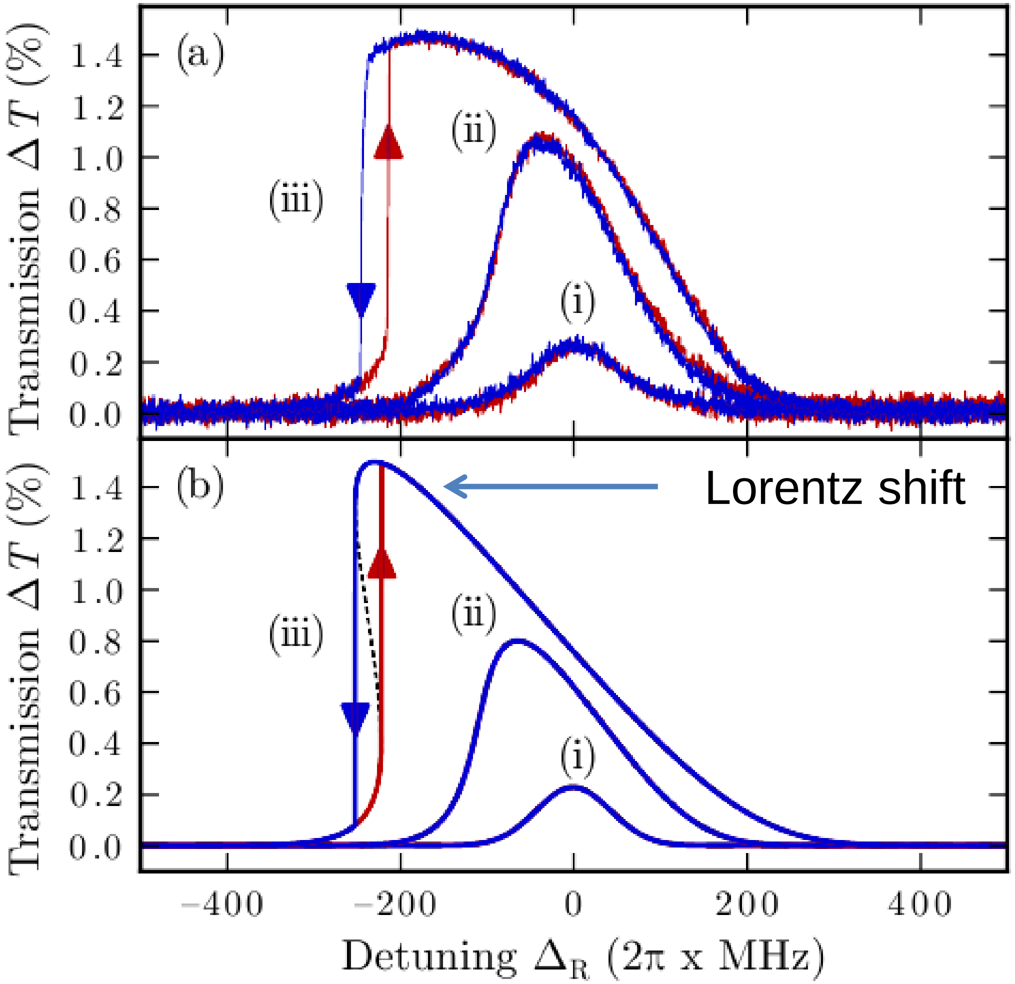


Non-equilibrium phase transition



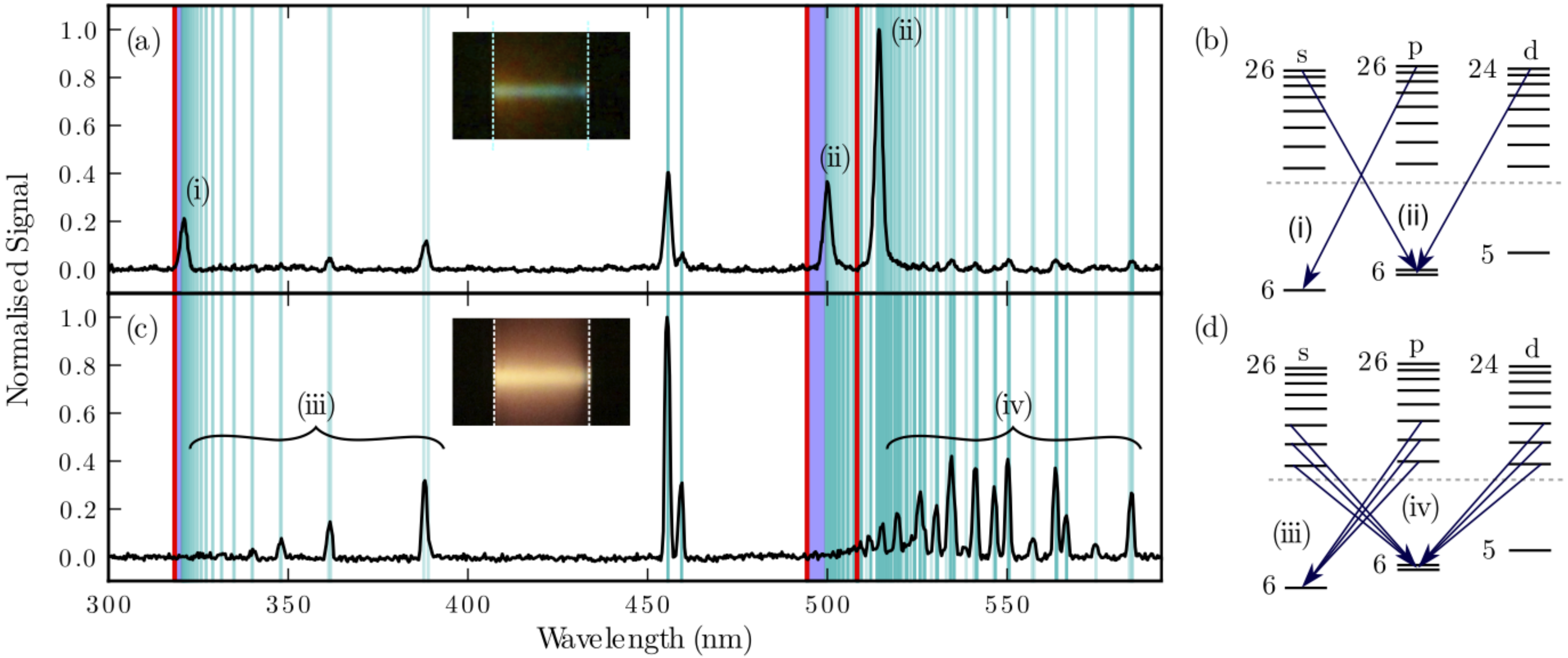


Intrinsic optical bistability



$$\Delta' = -N_r \frac{d^2}{\epsilon_0 \hbar}$$

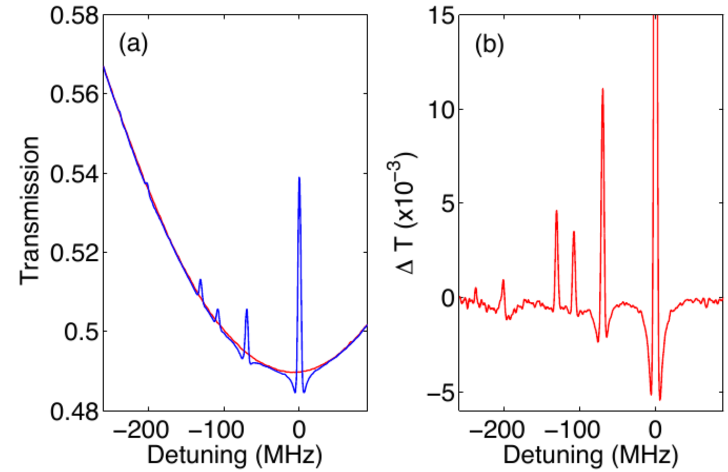
Superradiant cascade



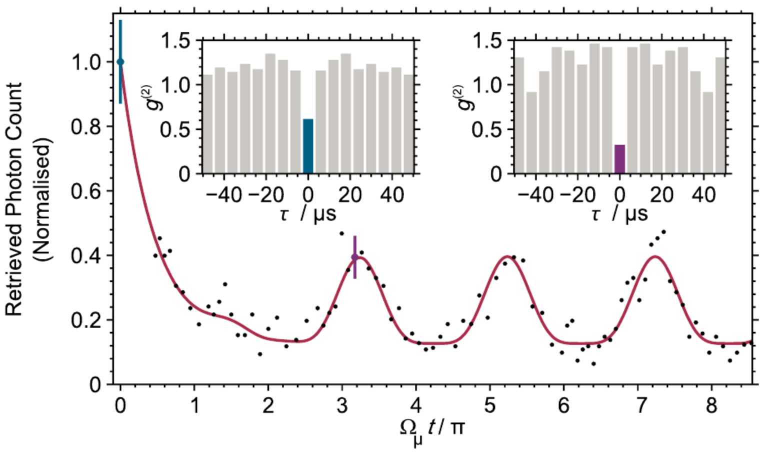
Summary

Rydberg non-linear optics,
Pritchard *et al*.,
Ann. Rev. of Cold Atoms and Mol., **1**, 301 (2013).

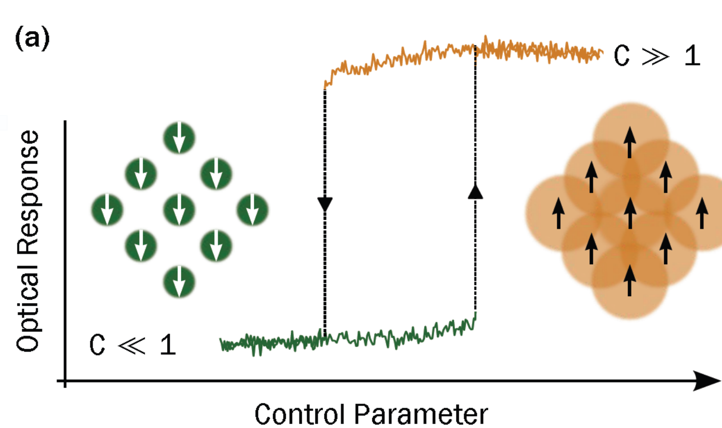
1. Rydberg EIT:



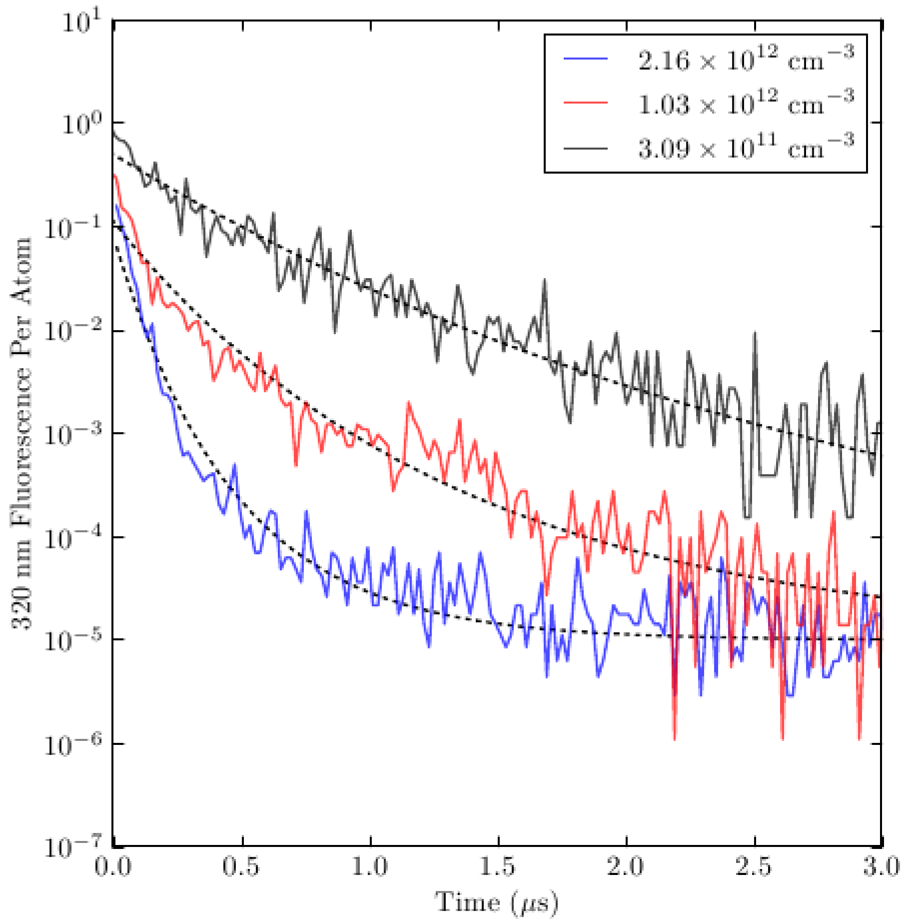
2. Microwave to optical interface



3. Phase transition



Superradiant [?] depopulation of 26p



Superradiant cascade [?]