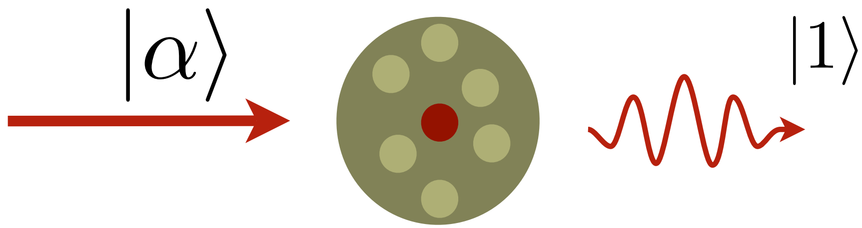
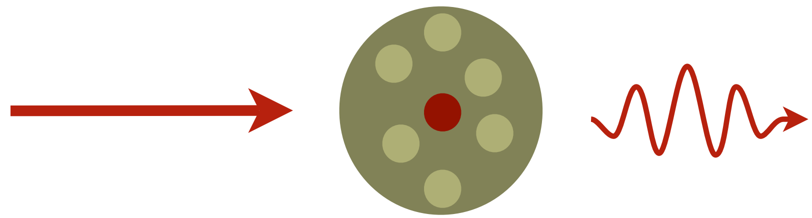
Cooperative atom-light interaction in a blockaded Rydberg ensemble



Jonathan Pritchard

University of Durham, UK

Overview



1. Cooperative optical non-linearity due to dipole-dipole interactions

2. Observation of cooperativity in an ultra-cold Rydberg ensemble

3. Towards single photon non-linearities

Photonic Quantum Computer

Single Photon Gate

$\frac{\lambda}{2}$

Photon Source

Photon Detector

Two Photon Gate

No free-space photon-photon interaction

Nonlinear atom-light interaction

KLM Linear Optics

E. Knill *et al.*
Nature **409**, 46 (2001)

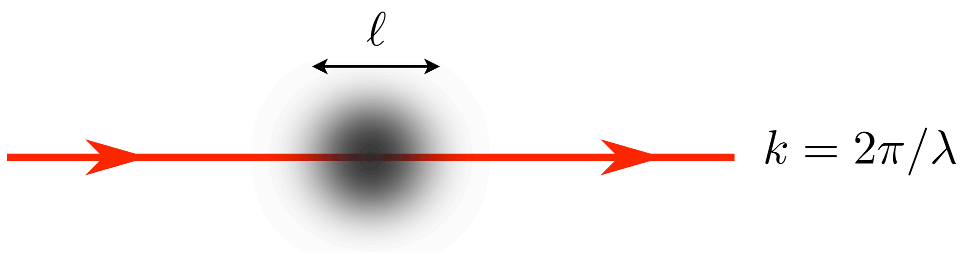
Rydberg atoms

I. Freidler *et al.*
PRA **72**, 043803 (2005)

Optical Non-linearity

Optical response expressed in terms of complex susceptibility:

$$\chi = \chi^{(1)} + \chi^{(2)}\mathcal{E} + \chi^{(3)}\mathcal{E}^2 + \cdots$$



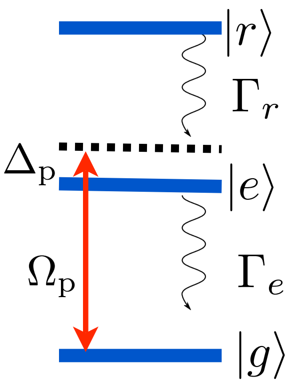
Observe back-action on light :

Transmission $T = \exp\{-k\chi_I \ell\}$

Dispersion $\Delta\phi = k\chi_R \ell/2$

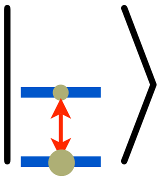
Electromagnetically Induced Transparency

Consider a three level atom in ladder EIT scheme

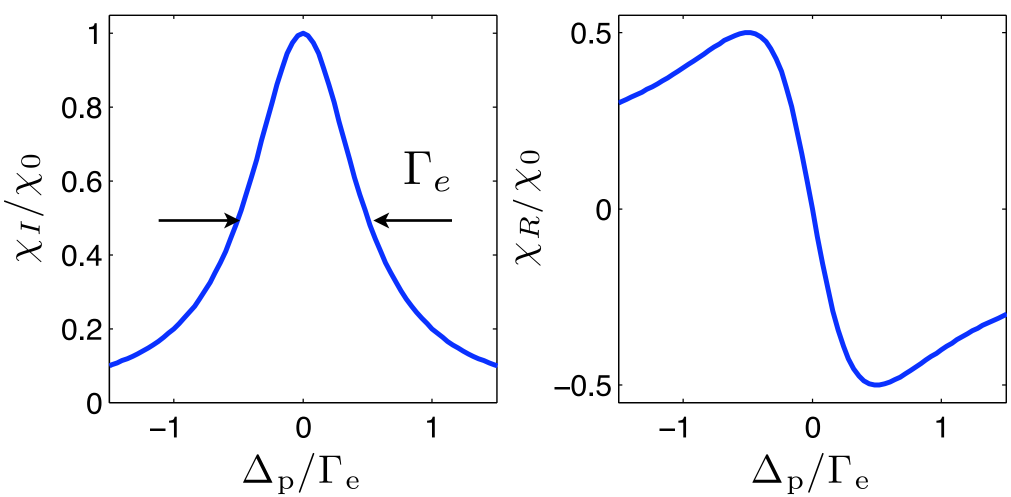


On resonance eigenstate is:

$$|\Psi\rangle = \frac{(\Omega_{\mathrm{p}}^2 + \Gamma_e^2)^{1/2}|g\rangle - \Omega_{\mathrm{p}}|e\rangle}{2(\Omega_{\mathrm{p}}^2/2 + \Gamma_e^2/4)^{1/2}}$$

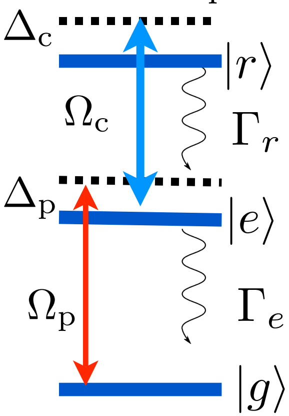
$|\Psi\rangle =$ 

Susceptibility:



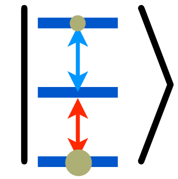
Consider a three level atom in ladder EIT scheme

$\Omega_\mathrm{c} > \Omega_\mathrm{p}$



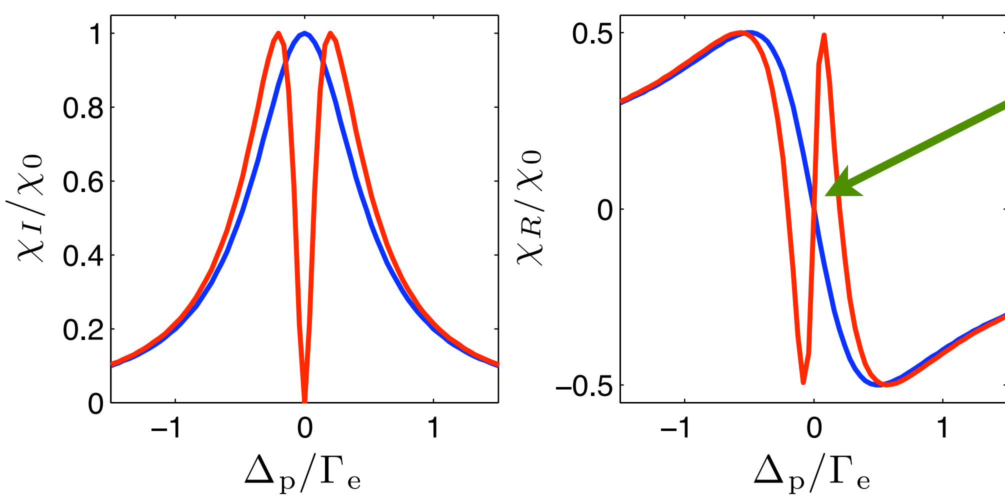
On two-photon resonance populate **dark state**:

$$|\Psi_\mathrm{D}\rangle = \frac{\Omega_\mathrm{c}|g\rangle - \Omega_\mathrm{p}|r\rangle}{(\Omega_\mathrm{p}^2 + \Omega_\mathrm{c}^2)^{1/2}}$$

$|\Psi_\mathrm{D}\rangle =$ 

M. Fleischhauer *et al.*, RMP **77**, 633 (2005).

Susceptibility:



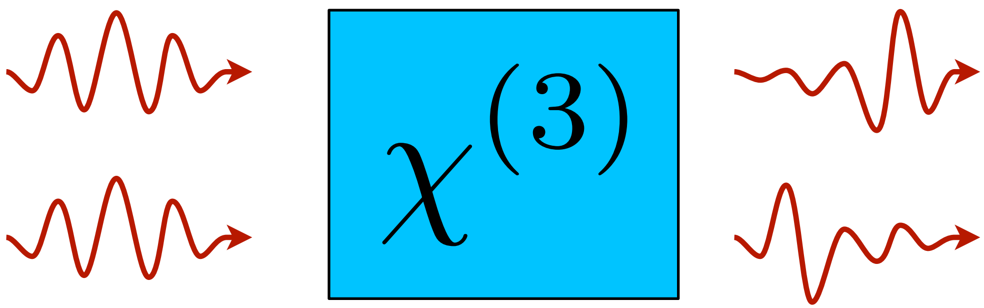
Intensity dependent

Giant Kerr $\chi^{(3)}$

H. Schmidt and A. Imamoğlu
Opt. Lett. **21**, 1936 (1996)

A. Mohapatra *et al.*
Nature Phys. **4**, 890 (2008)

Apply Kerr effect to two photon gate:



Phase shift changes across envelope - destroys fidelity

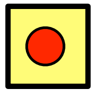
Single-photon Kerr non-linearities do not help quantum computation,
J. H. Shapiro, PRA **76**, 062305 (2006)

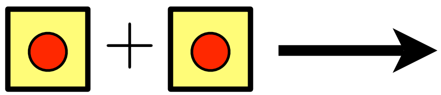
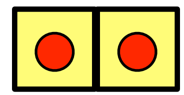
Impossibility of large phase shift via the giant Kerr effect with single photon wavepackets,
J. Gea-Banacloche, PRA **81**, 043823 (2010).

⇒ Require novel non-linearity

Cooperative Non-linearity

“Ordinary” Non-linearity

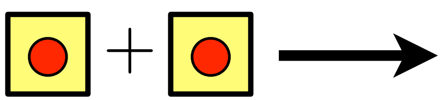
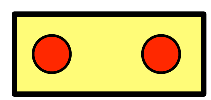
Single dipole  χ_1

Two dipoles  **Dipoles Independent**  $\chi = 2\chi_1$

From single dipole response derive response of ensemble $\chi = N\chi_1$

Cooperative non-linearity

Introduce strong dipole-dipole interactions

Two dipoles  **Dipoles Correlated**  $\chi \neq 2\chi_1$

Optical response of single dipole modified by neighbouring dipoles

Rydberg Atoms

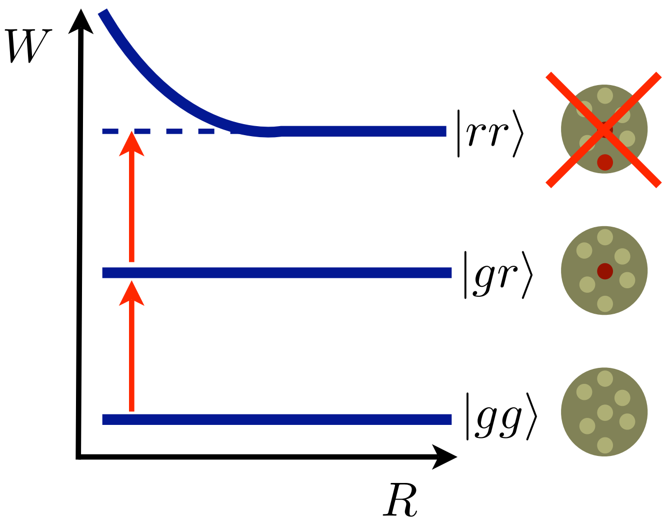
AtMol. Durham Atomic & Molecular Physics

Cooperativity requires strong dipole-dipole interactions ⇒ **Rydberg Atoms**

Dipole moment $\mu \propto n^2$

Interaction $V(R) = -\frac{C_6}{R^6} \propto n^{11}$

'Strong' dipole-dipole interactions ⇒ **Blockade** $V(R) > \Omega_c$



Blockade radius

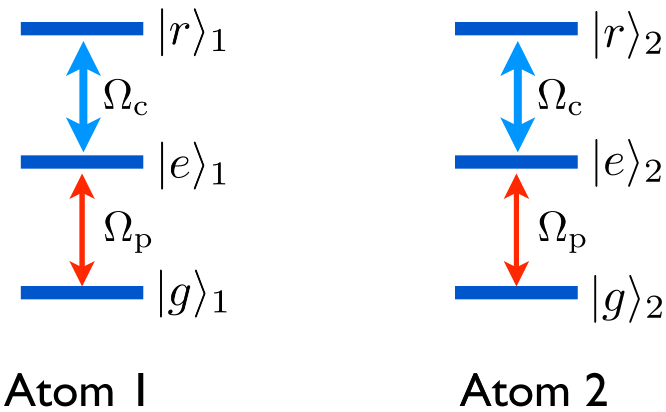
$$R_b = \sqrt[6]{\frac{C_6}{\Omega_c}} \simeq 5\ \mu\mathrm{m} \qquad (60S_{1/2},\ \Omega_c \sim 4\ \mathrm{MHz})$$

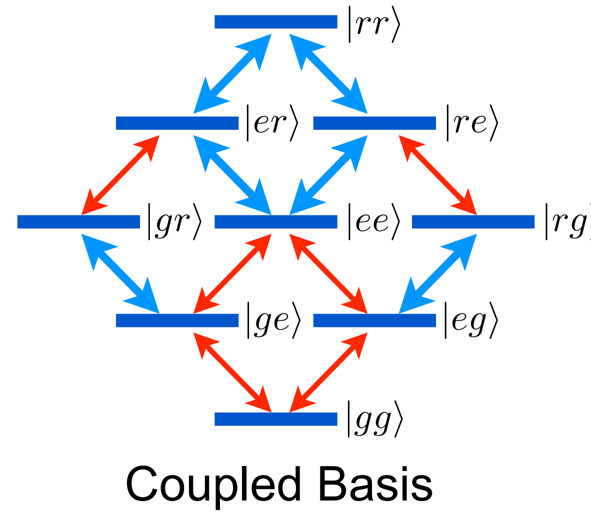
Average Number of atoms / blockade

$$\bar{N}_b = 4/3\pi R_b^3 \rho$$

Rydberg EIT without interactions

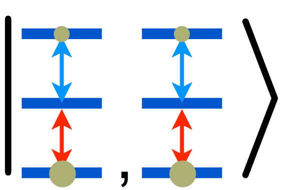
Consider a pair of atoms $R \gg R_{\mathrm{b}}$

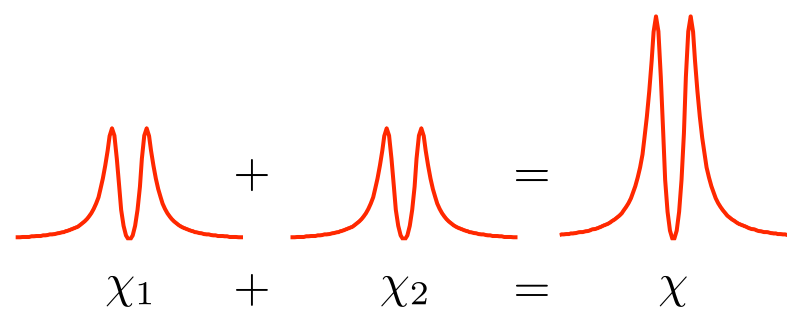




Large separation : Observe ordinary dark state $|\Psi_{\mathrm{D}}\rangle = |\psi_{\mathrm{D}}\rangle_1 \otimes |\psi_{\mathrm{D}}\rangle_2$

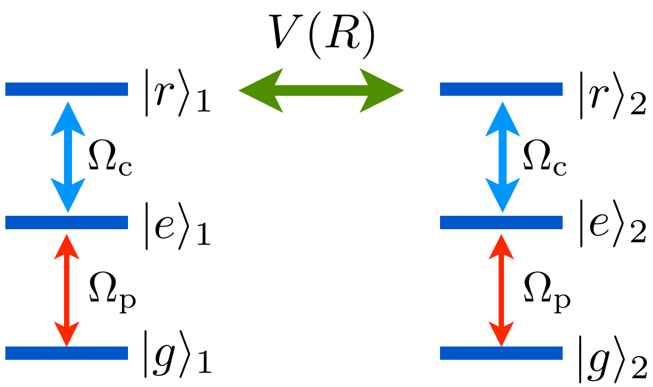
$|\Psi_{\mathrm{D}}\rangle =$



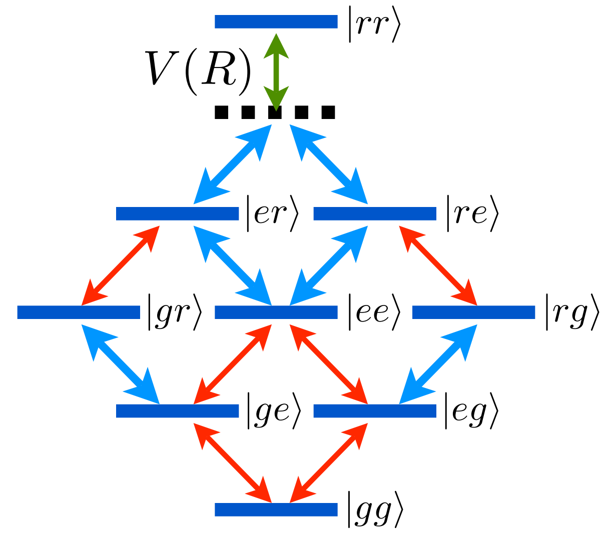


Rydberg EIT with interactions

Move atoms closer $R < R_\mathrm{b}$



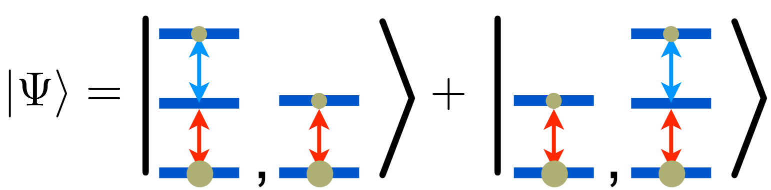
Atom 1 Atom 2

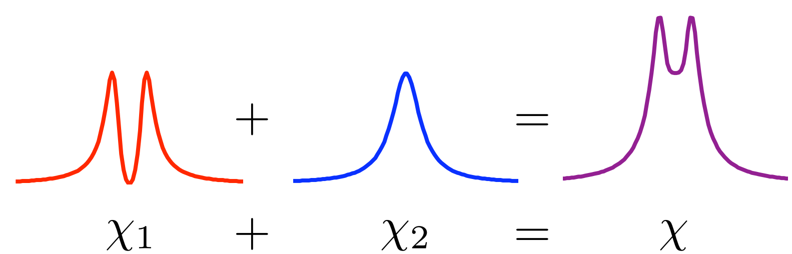


Coupled Basis

$V(R) \gg \Omega_\mathrm{c}$: Blockade creates new state $|\Psi\rangle$

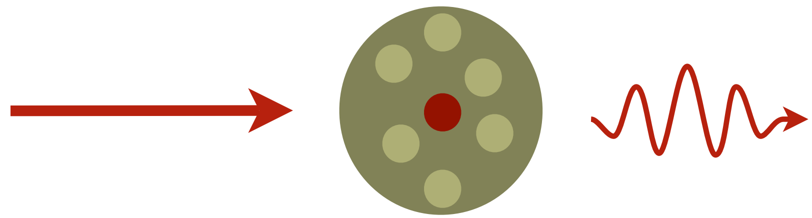
D. Møller *et al.* PRL **100**, 170504 (2008)





Tuneable cooperative atom-light interaction ⇒ $\Omega_\mathrm{c}, \Omega_\mathrm{p}, V(R)$

Overview



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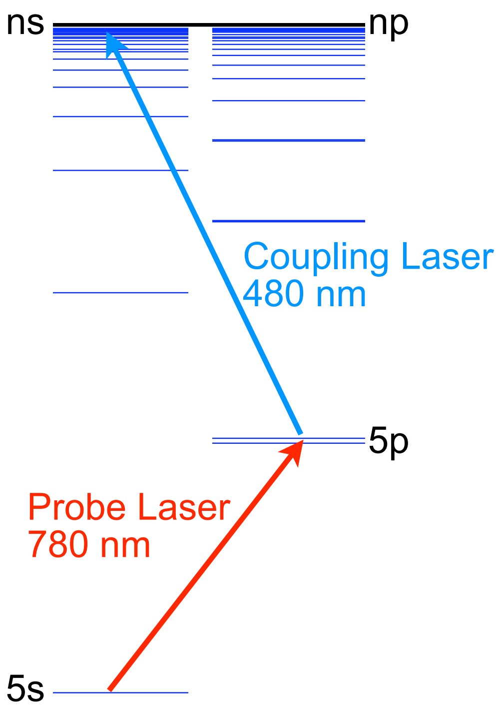
EIT Locking Scheme



R. P. Abel *et al.*, Appl. Phys. Lett. **94**, 071107 (2009)

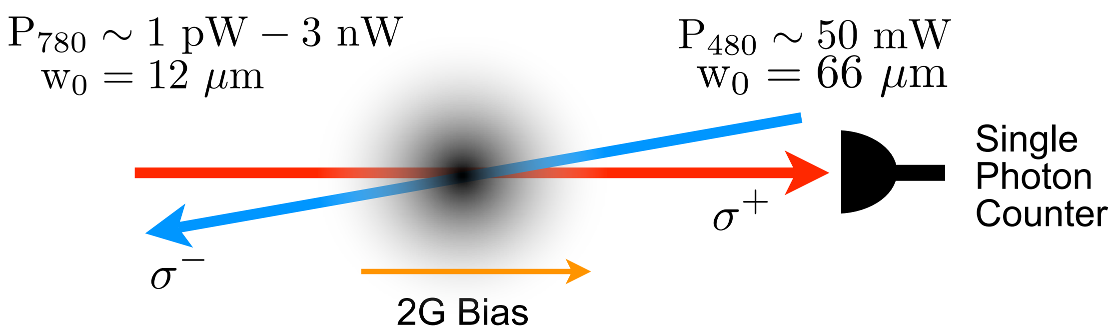
Choice of Rydberg State

$V(R) > \Omega_c > \Omega_p$

$C_6 \propto n^{11}$ $\Omega_c \propto n^{-3/2}$ ⇒ n = 50 - 60

Experimental Setup

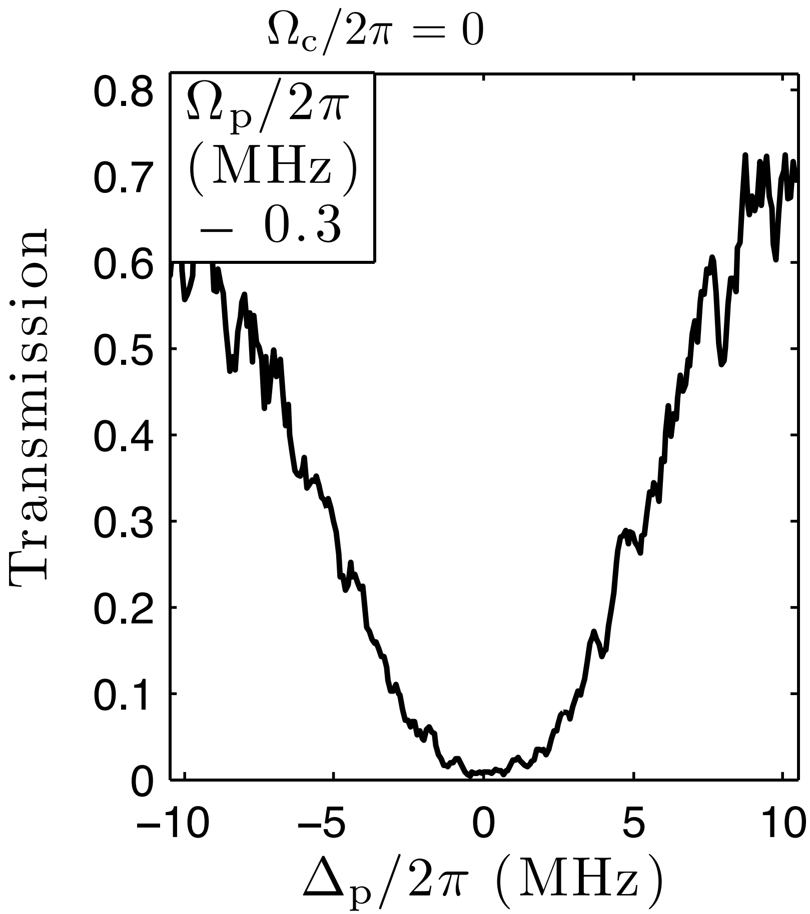
^{87}Rb atoms prepared in $5S_{1/2}$ $|F=2, m_F=2\rangle$



Scan probe $\Delta_p/2\pi = -20 \rightarrow 20$ MHz in 500 μs

K. J. Weatherill *et al.*, J. Phys. B **41**, 201002 (2008).

Record transmission for $60S_{1/2}$ at $\rho \sim 1.2 \times 10^{10}\ \mathrm{cm}^{-3}$

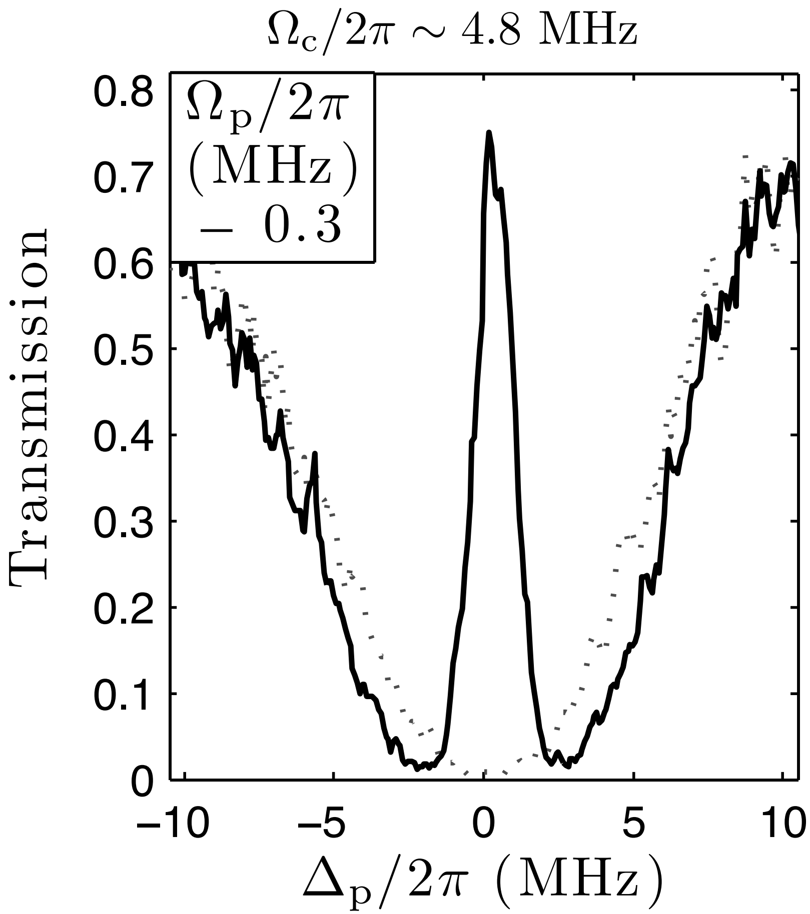


Data recorded from 100 averages

Weak probe :

J. D. Pritchard *et al.* arXiv:1006.4087 (2010)

Record transmission for $60S_{1/2}$ at $\rho \sim 1.2 \times 10^{10}\ \mathrm{cm}^{-3}$



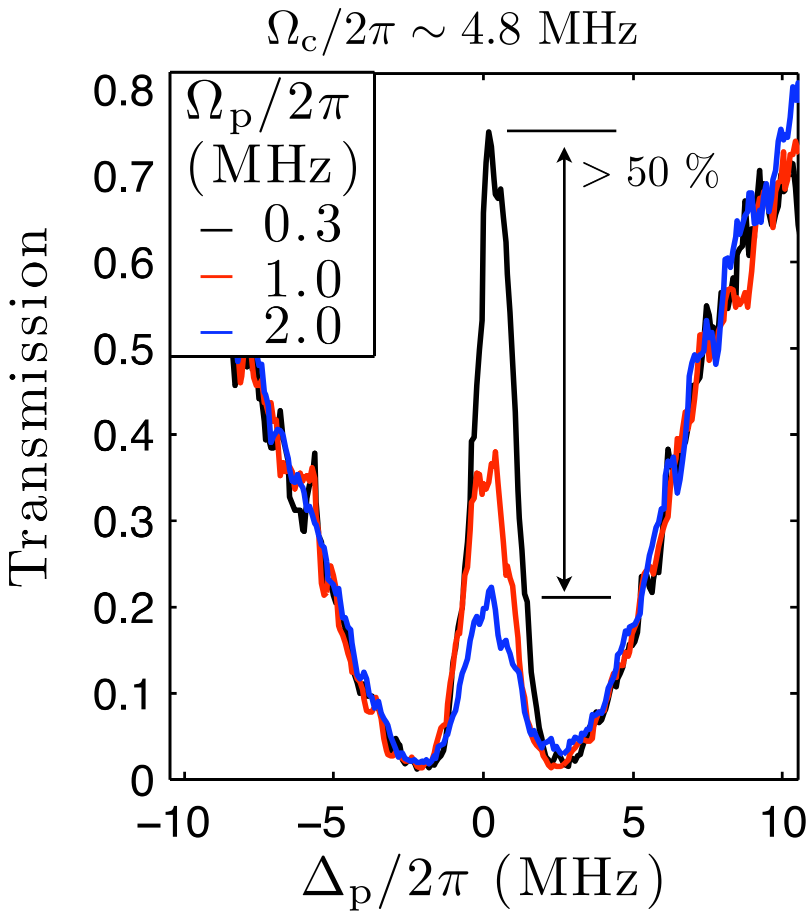
Data recorded from 100 averages

Weak probe : No Rydberg population

Narrow probe of Rydberg state frequency

J. D. Pritchard *et al.* arXiv:1006.4087 (2010)

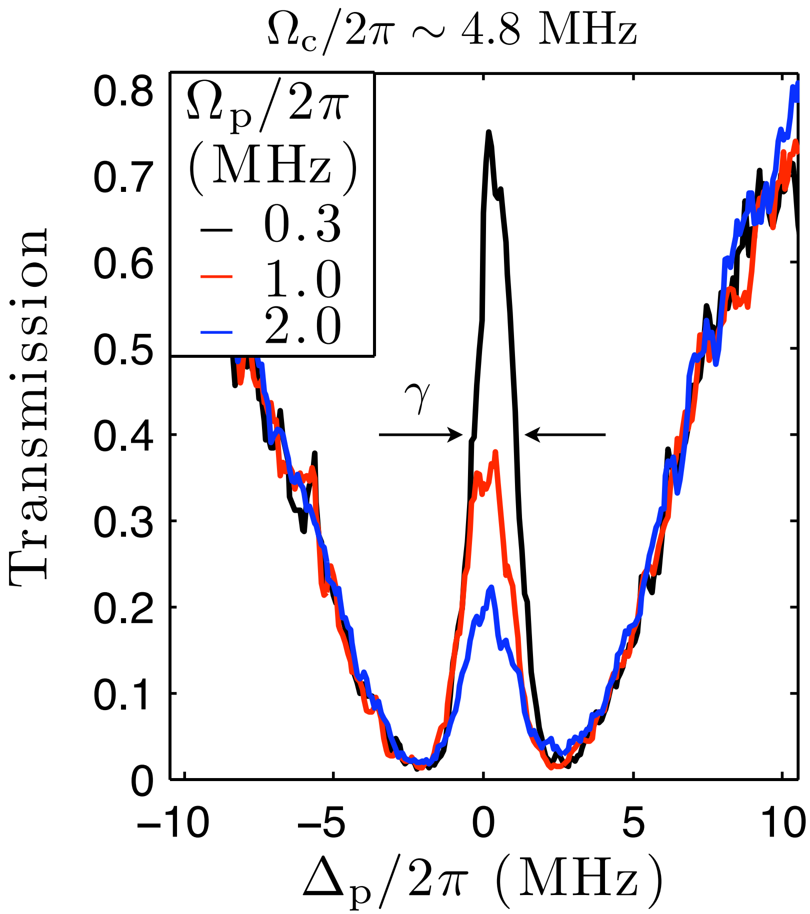
Record transmission for $60S_{1/2}$ at $\rho \sim 1.2 \times 10^{10}\ \mathrm{cm}^{-3}$



+ Suppression

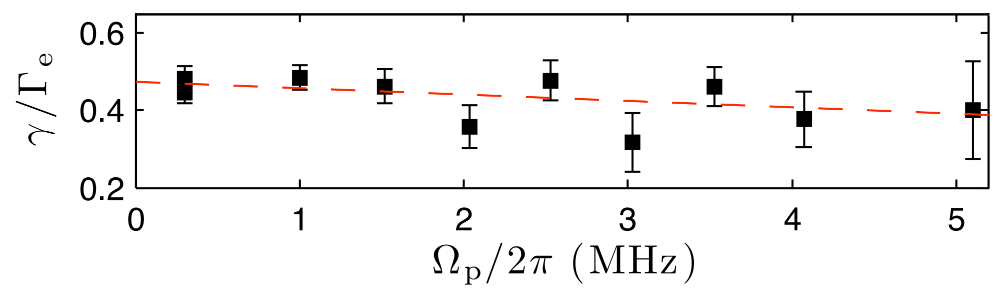
J. D. Pritchard *et al.* arXiv:1006.4087 (2010)

Record transmission for $60S_{1/2}$ at $\rho \sim 1.2 \times 10^{10}\ \mathrm{cm}^{-3}$



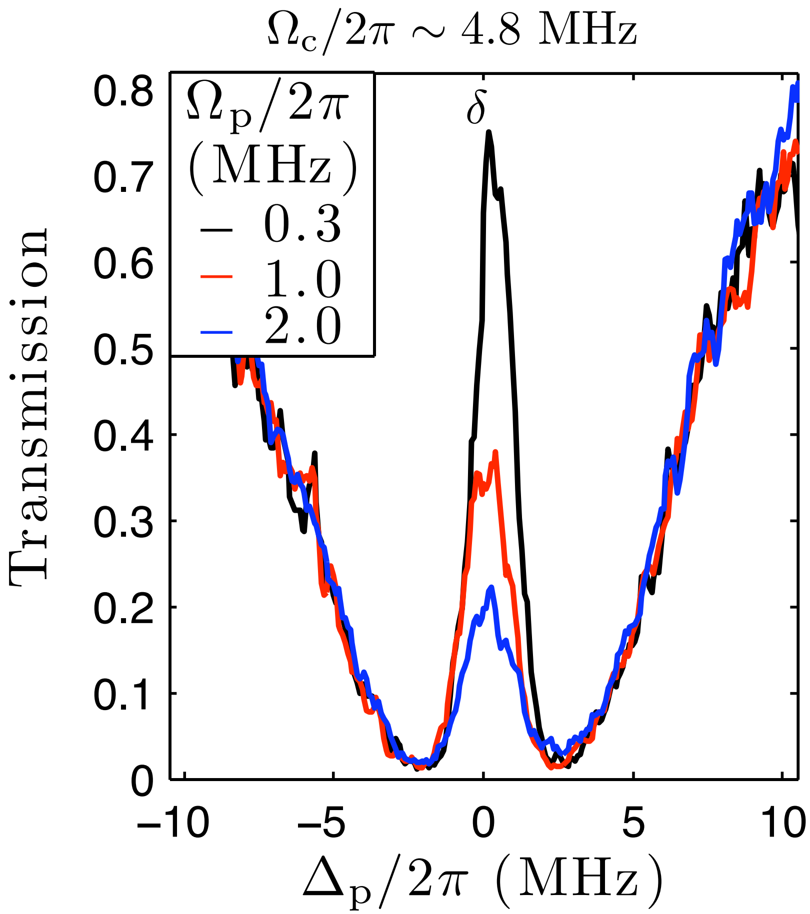
+ Suppression

+ No broadening

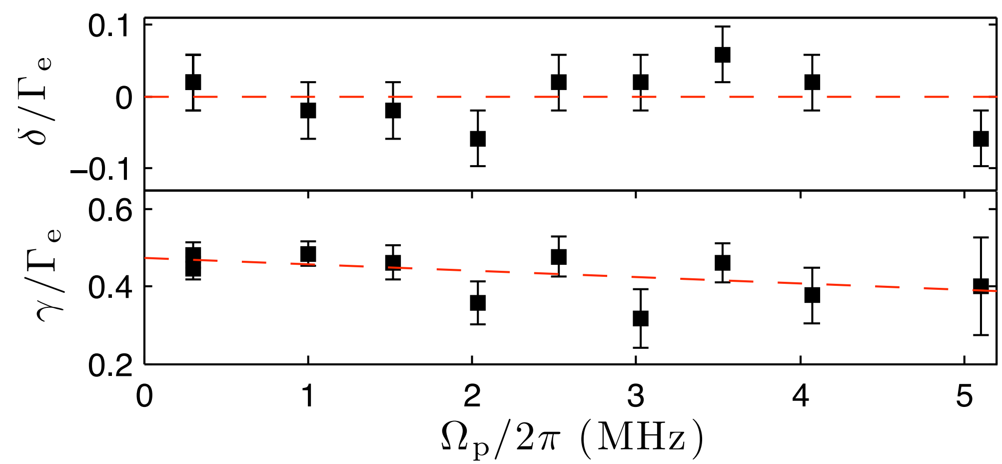


J. D. Pritchard *et al.* arXiv:1006.4087 (2010)

Record transmission for $60S_{1/2}$ at $\rho \sim 1.2 \times 10^{10}\ \mathrm{cm}^{-3}$



- **+ Suppression**
- **+ No broadening**
- **+ No shift**



J. D. Pritchard *et al.* arXiv:1006.4087 (2010)

Mechanisms for suppression

Observations: Suppression | No Shift | No Broadening

Mechanisms:

- Ion Creation
- Mean-field interaction
- Van der Waals dephasing
- Cooperative Nonlinearity

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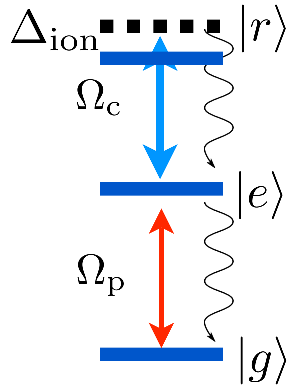
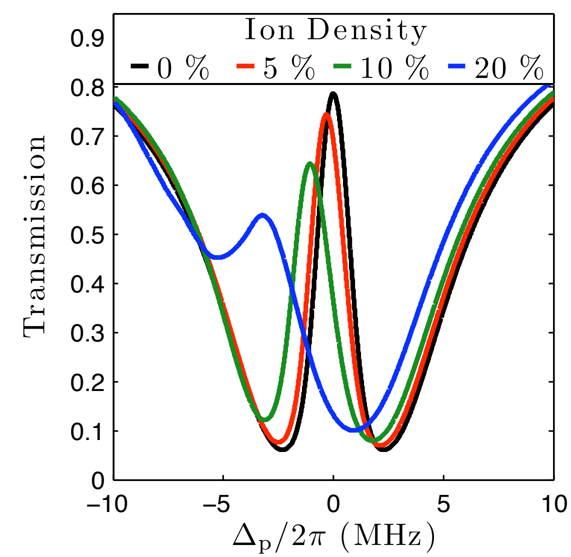


Stark shift of atom *i*

$$\Delta^i_{\text{ion}} = -\frac{1}{2}\alpha_0 \sum_j^{N_{\text{ion}}} \mathcal{E}^2(R_{ij})$$

Ions cause red shift and broadening

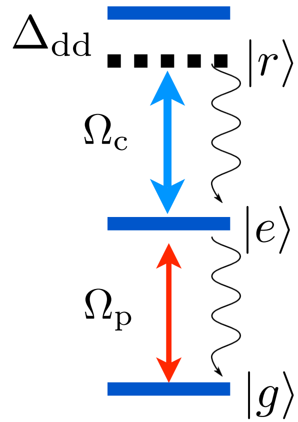


Mechanisms for suppression

Observations: Suppression — No Shift — No Broadening

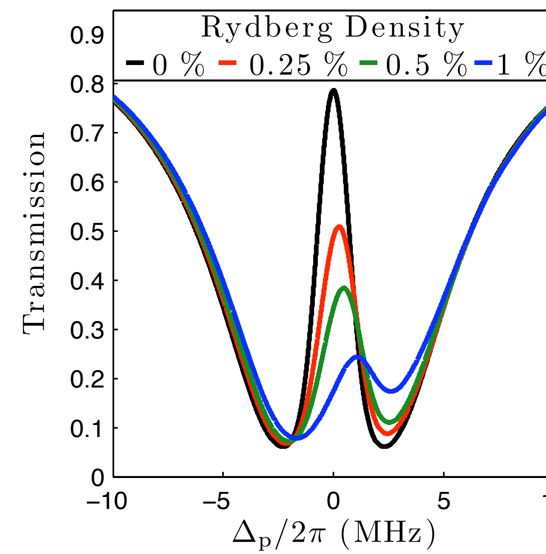
Mechanisms:

- ~~Ion Creation~~
- **Mean-field interaction**
- Van der Waals dephasing
- Cooperative Nonlinearity



Dipole-dipole shift of atom *i*

$$\Delta^{i}_{\rm dd} = \sum_{i\neq j}^{N} -\frac{C_6}{R_{ij}^6}$$



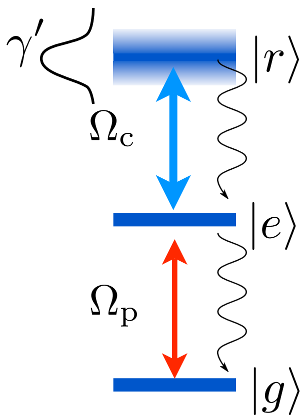
Mean-field causes blue shift and broadening

H. Schempp *et al.* PRL **104**, 173602 (2010)

Observations: Suppression | No Shift | No Broadening

Mechanisms:

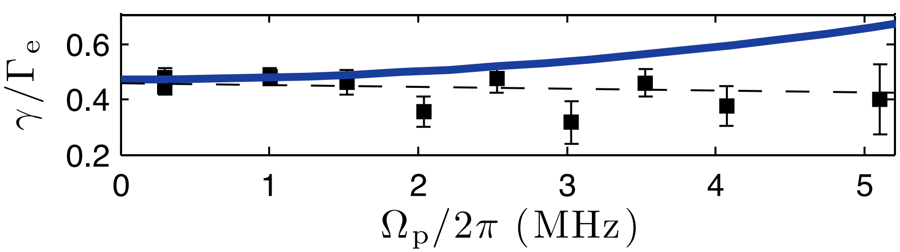
- ~~Ion Creation~~
- ~~Mean-field interaction~~
- **Van der Waals dephasing**
- Cooperative Nonlinearity

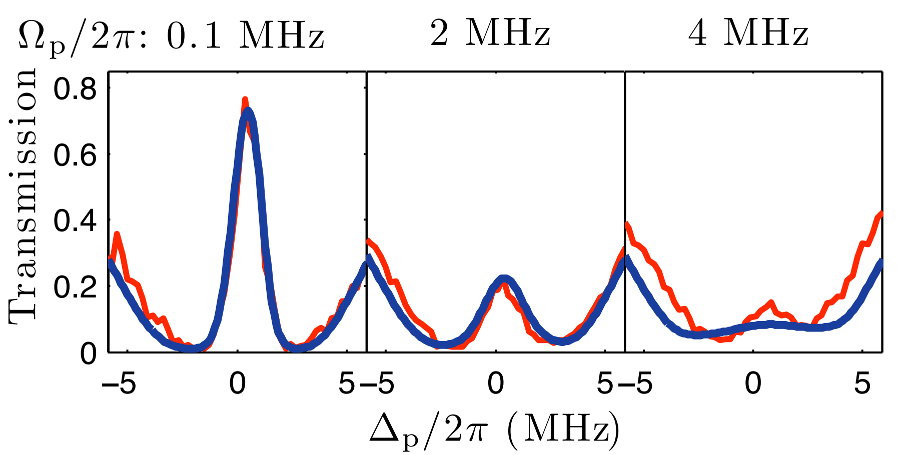


Dephasing Rate

$$\gamma' = \gamma_{\rm vdW} N_r$$

Fit 60S data: $\gamma_{\rm vdW} \sim 7\Gamma_e$





vdW predicts significant broadening

M. Gross and S. Haroche Phys. Rep. **93**, 301 (1982)

Mechanisms for suppression

Observations: Suppression | No Shift | No Broadening

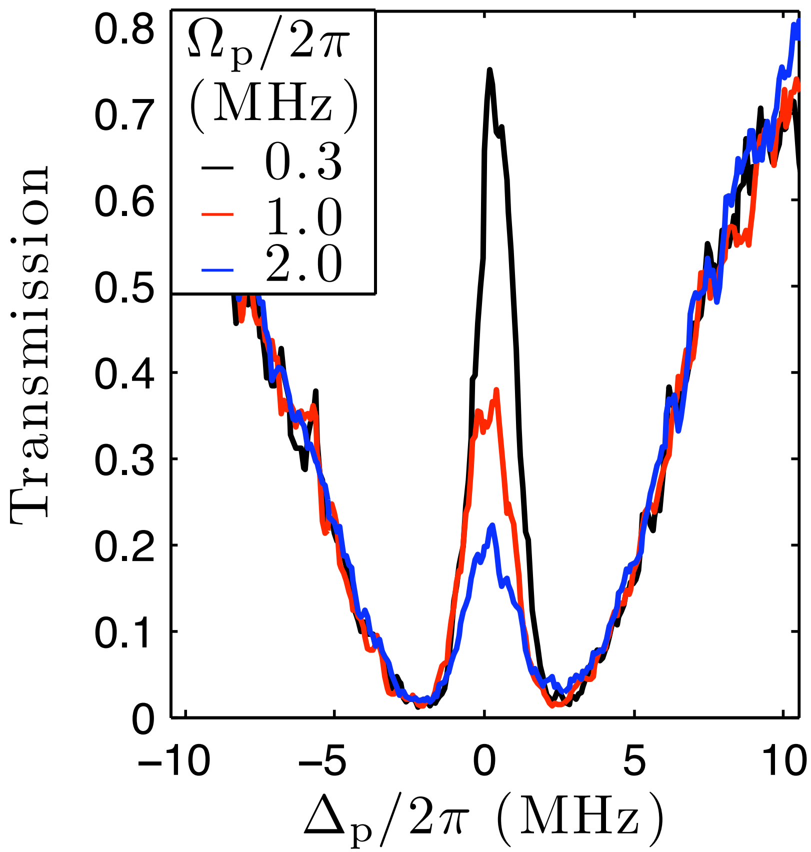
Mechanisms:

- ~~Ion Creation~~
- ~~Mean-field interaction~~
- ~~Van der Waals dephasing~~
- **Cooperative Nonlinearity**

Require model for all atoms in blockade

$$\rho \sim 1.2 \times 10^{10}\ \mathrm{cm}^{-3} \quad \Rightarrow \bar{N}_\mathrm{b} \sim 9$$

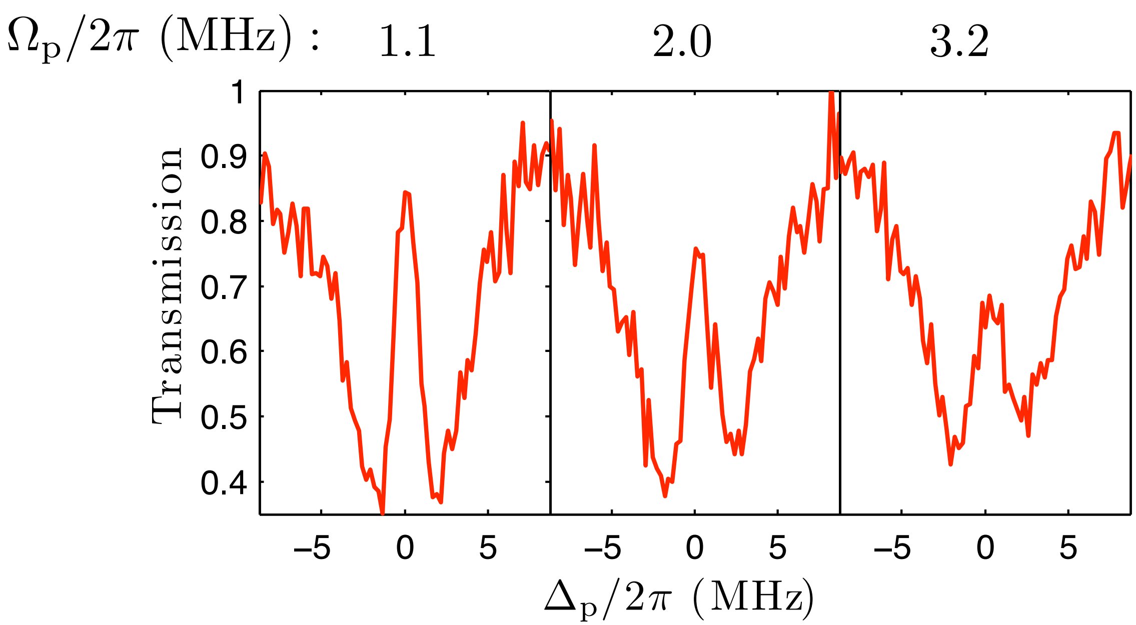
Too big to model!



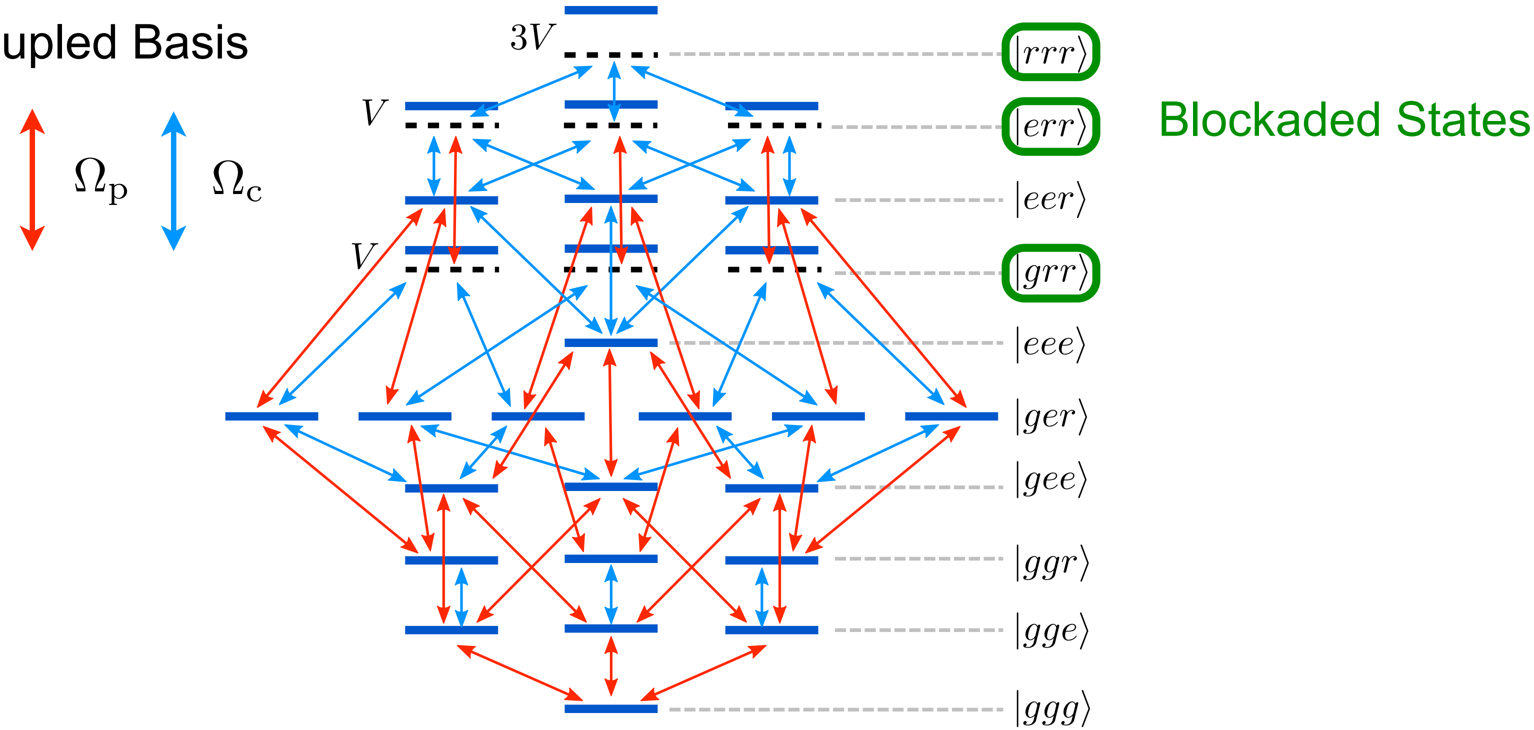
Reduce atomic density

$$\rho \sim 0.35 \times 10^{10}\ \mathrm{cm}^{-3} \Rightarrow \bar{N}_b \sim 3$$

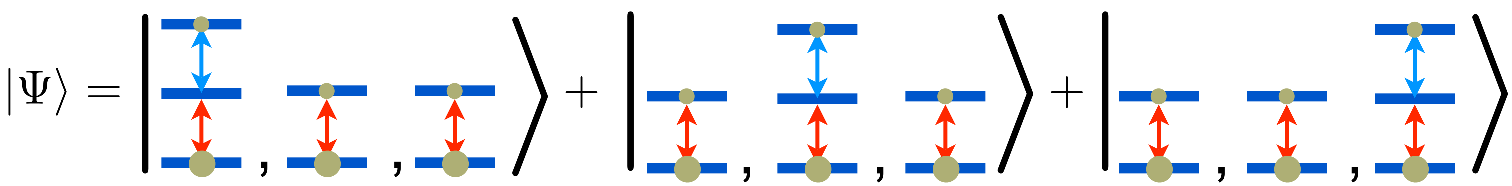
Require 3-atom model



Three Atom Coupled Basis



Entangled state on two-photon resonance:



Model transmission using Liouville eq. $\dot{\sigma} = \frac{i}{\hbar}[\sigma, \mathscr{H}] - \gamma\sigma$

Three Atom Model (2)

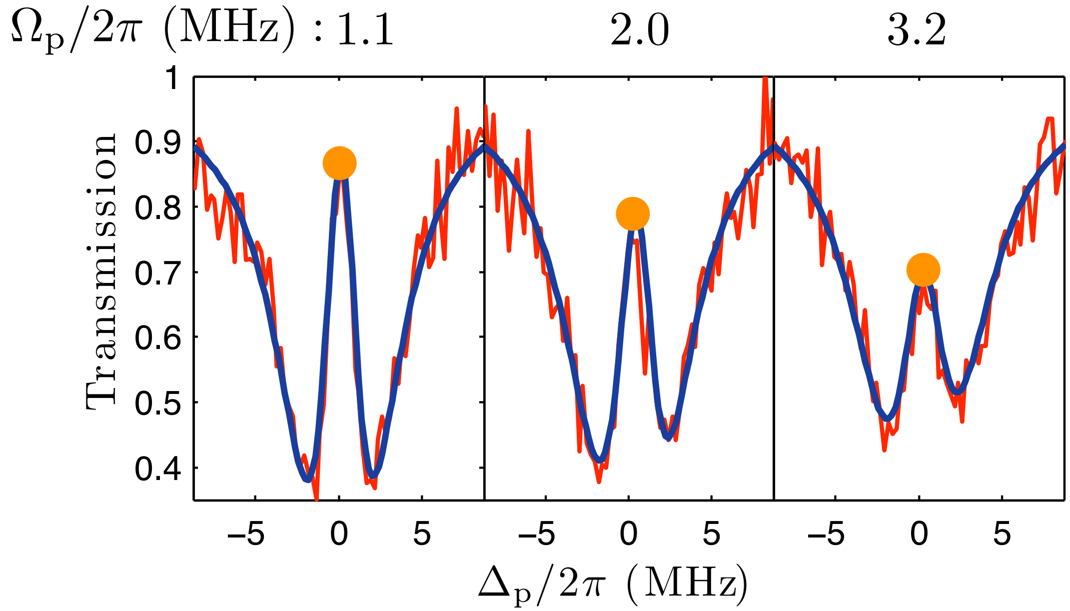
Parameters: weak-probe data

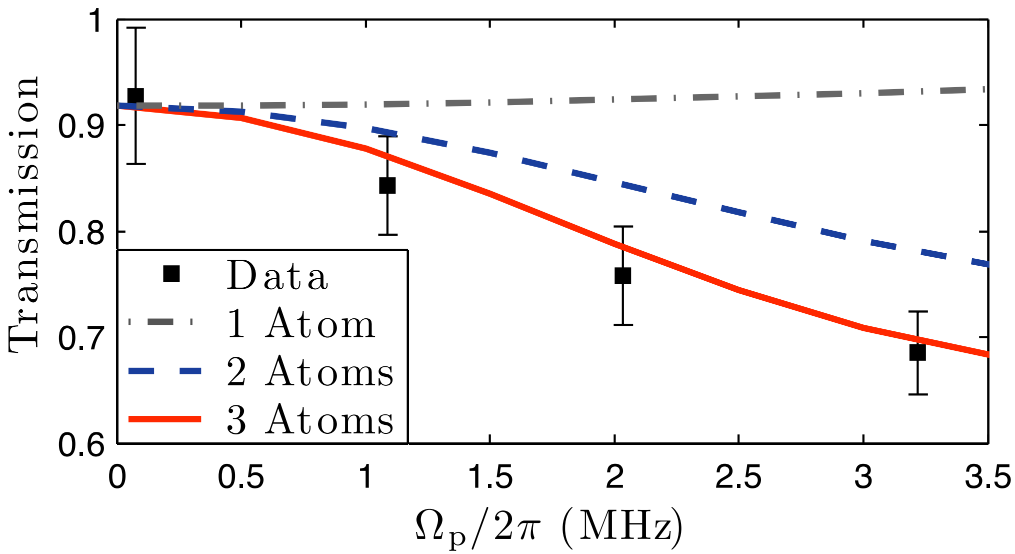
$$\Omega_c/2\pi = 3.8\ \text{MHz}$$

$$\gamma_{gr}/2\pi = 110\ \text{kHz}$$

Interaction strength:

$$V/2\pi = 15\ \text{MHz}$$

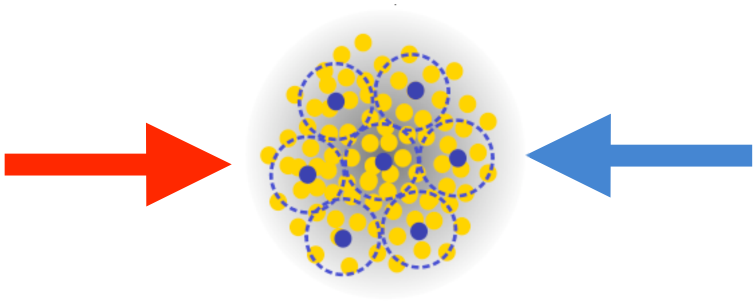


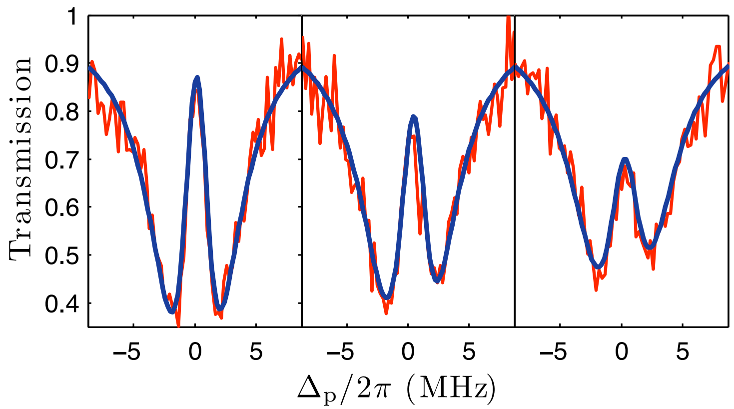


Cooperative Nonlinearity :

- ✓ Suppression
- ✓ No Shift
- ✓ No Broadening

J. D. Pritchard *et al.* arXiv:1006.4087(2010)





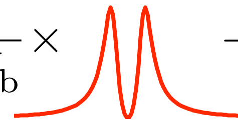
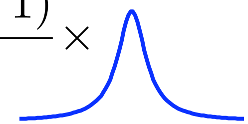
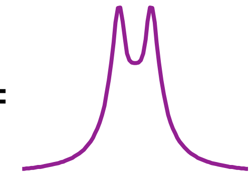
Cooperative model:

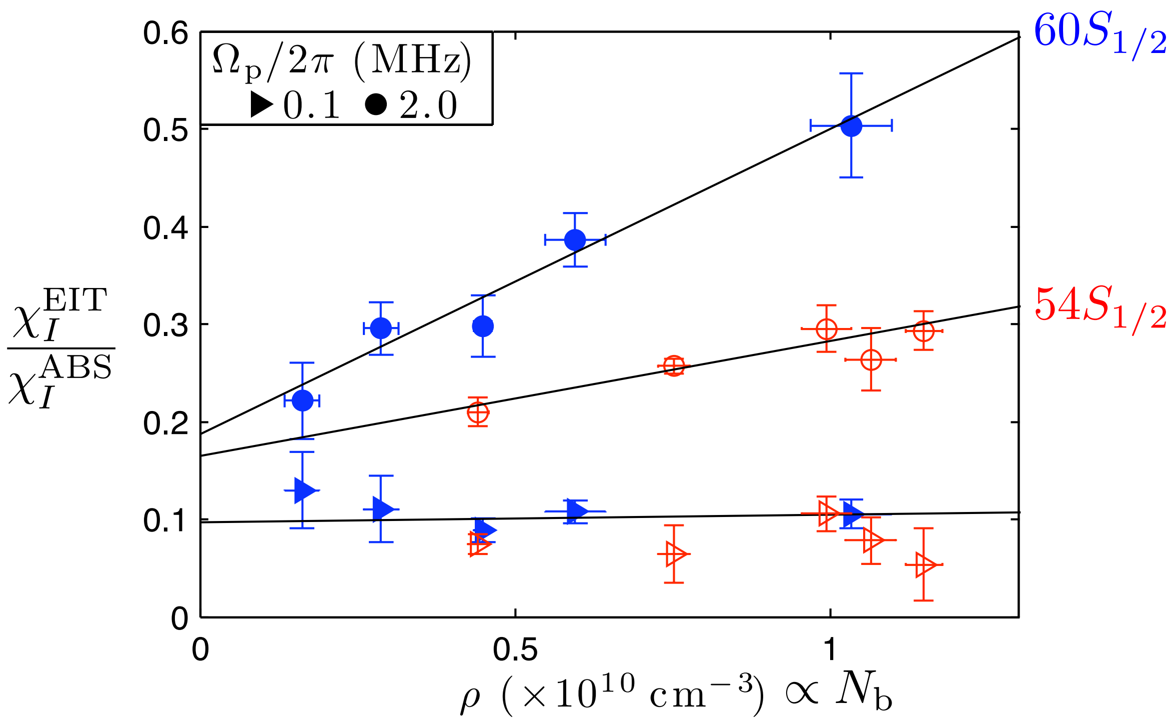
Model single blockade to reproduce ensemble

No additional broadening ⇒ EIT width limited by relative laser linewidth γ_{gr}

Blockade dephasing rate

$$\gamma_b/2\pi < 100 \text{ kHz}$$

Non-linear density scaling: $\frac{1}{N_\mathrm{b}} \times$  $+ \frac{(N_\mathrm{b}-1)}{N_\mathrm{b}} \times$  = 



Number of atoms / blockade:

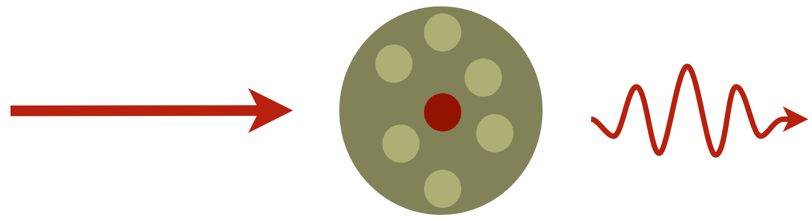
$$N_\mathrm{b} \sim \rho R_\mathrm{b}^3 \propto n^{*6.25}$$

$$\Rightarrow \frac{N_\mathrm{b}^{60}}{N_\mathrm{b}^{54}} = 2.0$$

Measured ratio 2.6 ± 0.7

J. D. Pritchard *et al.* arXiv:1006.4087(2010)

Overview

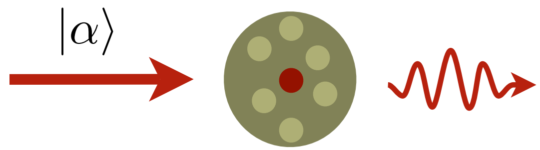


1. Cooperative optical non-linearity due to dipole-dipole interactions

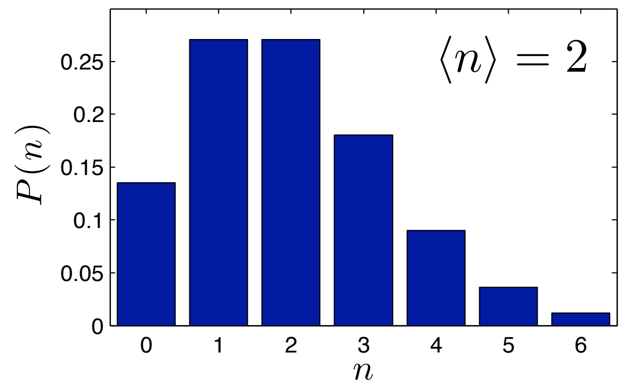
2. Observation of cooperativity in an ultra-cold Rydberg ensemble

3. **Towards single photon non-linearities**

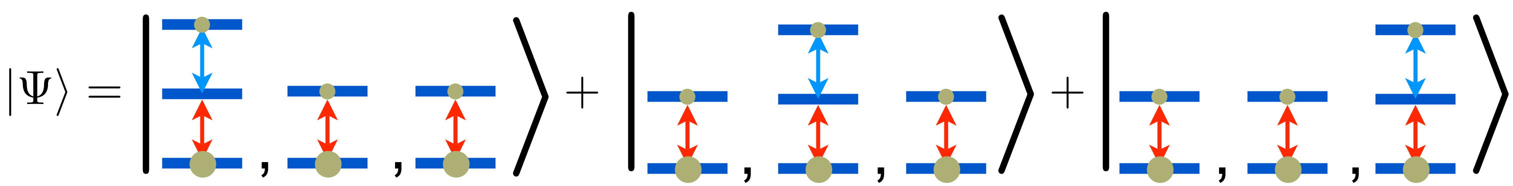
Photon Blockade



Input light in coherent state $|\alpha\rangle$



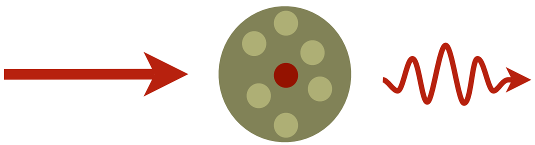
Ensemble transparent to single photon



Measure changes in photon statistics due to cooperative interaction

Blockaded Ensemble

➡ Single Photon source



M. Saffman and T. Walker, PRA **66**, 065403 (2002)

➡ Cooperative emission of a single photon

D. Porras and J. I. Cirac, PRL **78**, 053816 (2009)

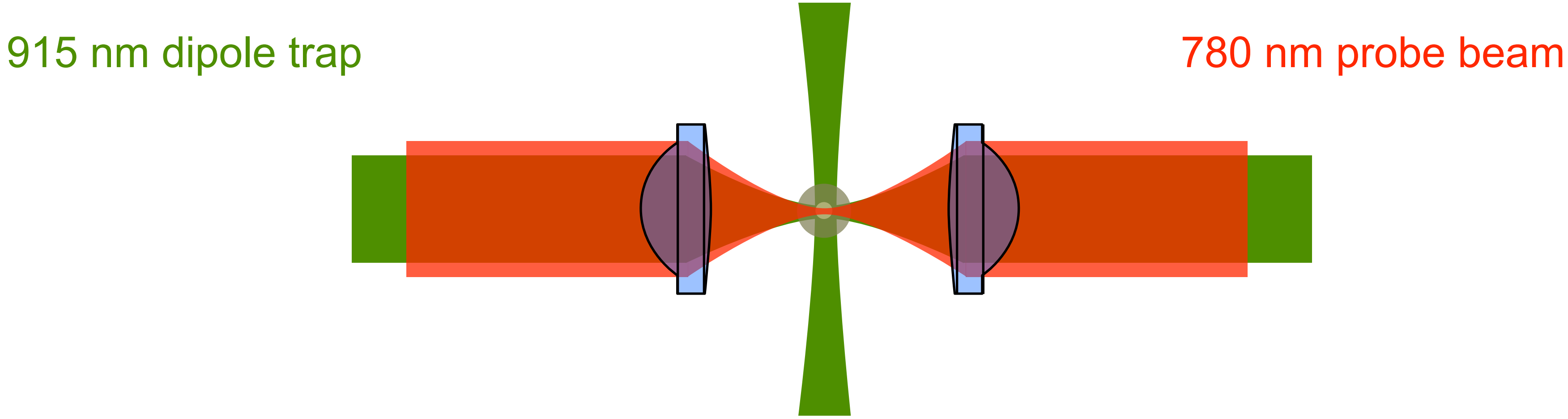
L. H. Pedersen and K. Mølmer, PRA **79**, 012320 (2009)

Requirements:

+ Large single photon Rabi frequency

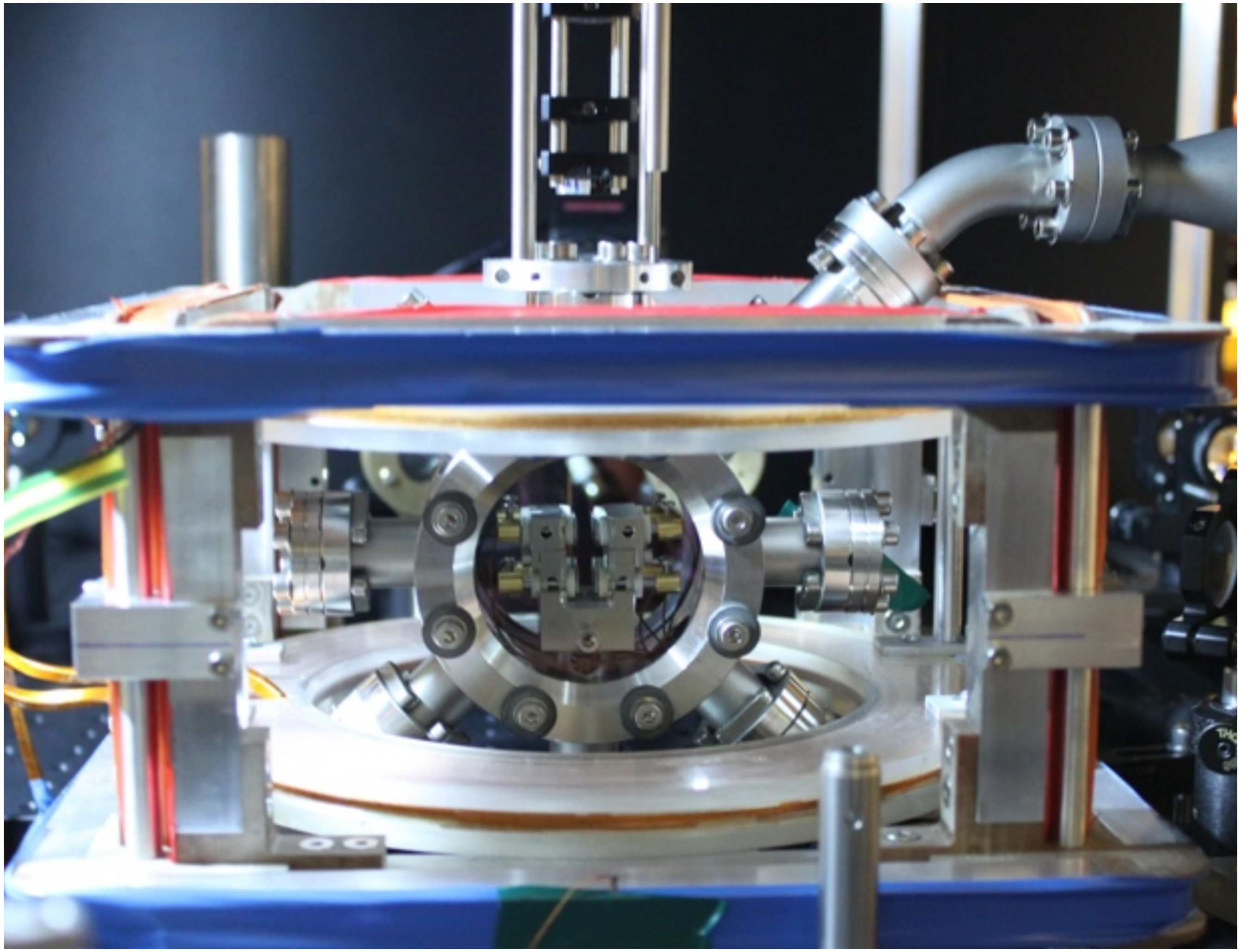
+ All atoms confined within single blockade sphere $R < R_{\rm b} \sim 5\ \mu{\rm m}$

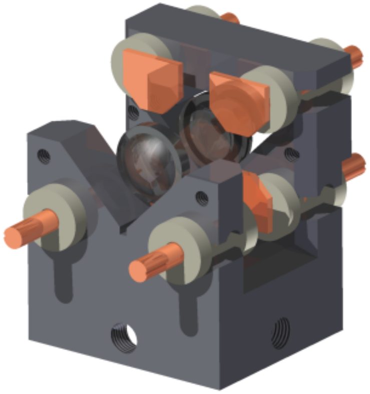
Solution: Microscopic Dipole Trap



Transverse trap $w = 6\ \mu{\rm m}$

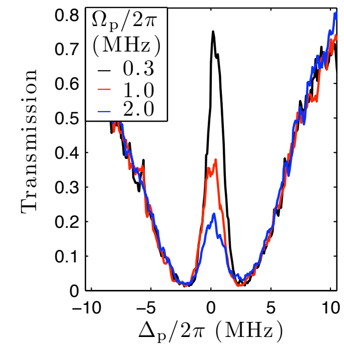
Vacuum Chamber





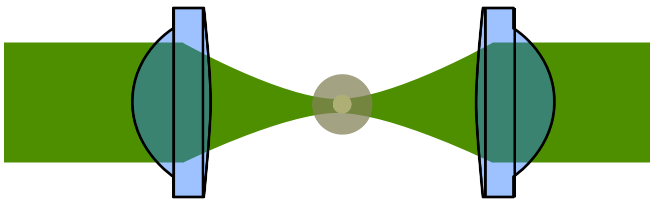
Cooperative atom-light interaction due to dipole-dipole interactions

✓ Done



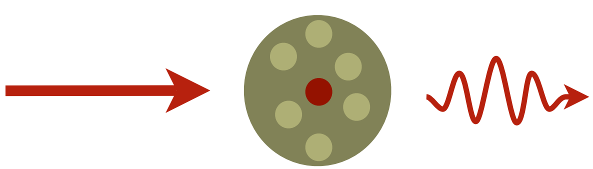
Require single blockade sphere

✓ Built



Explore photon statistics

☛ In progress



Acknowledgements


Dan Maxwell


Dr. Alex Gauguet


Dr. Kevin Weatherill


Dr. Matt Jones


Prof. Charles Adams

EPSRC
Pioneering research and skills

Durham University