Non-linear optics using Rydberg atoms

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Outline

- Basics of non-linear optics
- Rydberg blockade interaction (enhanced optical non-linearity)
- Rydberg EIT
- Review on measurement of non-linear refractive index of Rydberg EIT medium
- Our experiment on measurement of non-linearity of Rydberg EIT in thermal vapor
- Conclusion

Optical non-linearity
(Non-linear refractive index)

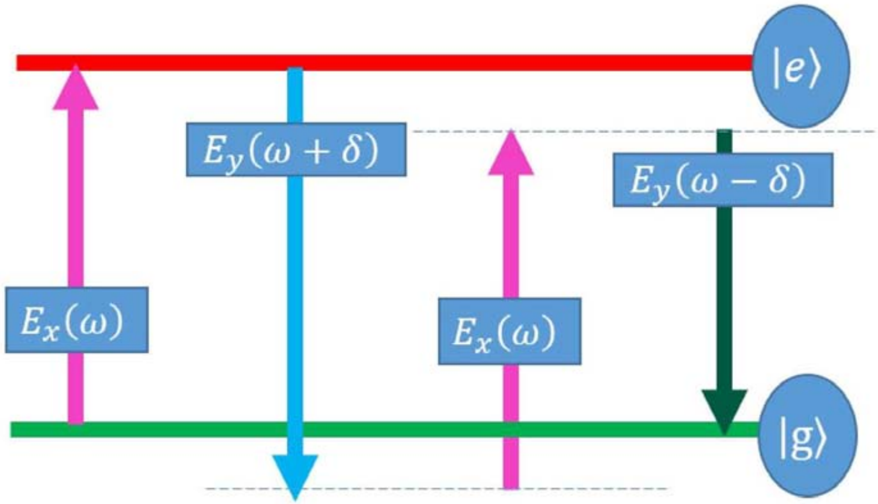
Kerr non-linearity of a medium $n = n_0 + n_2 I$ where $n_2 \propto \chi^{(3)}$

***n_2* ≈ 10^{-20} m^2/W** for typical glass (typical observed with high intensity of the laser)

- **A medium with very large *n_2* is necessary to see the effect at a single photon level which will be useful for quantum computation and to study the foundational issues of quantum mechanics.**

- **Standard EIT medium doesn‘t provide sufficient non-linearity to observe at a single photon level (Rydberg EIT can enhance the non-linearity)**

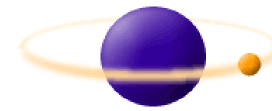
Optical non-linearity
(Four wave mixing)



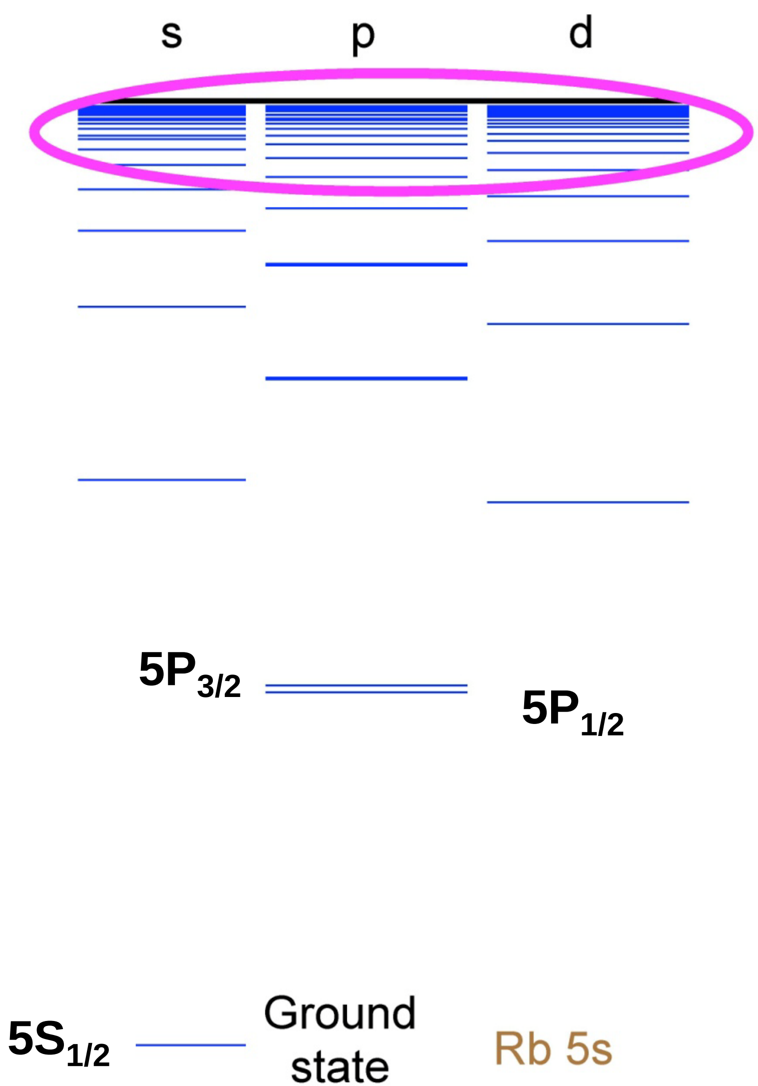
Parametric process
Energy and momentum conservation of the copropagating beams gives
$\omega-\delta=2\omega-(\omega+\delta)$

- **Four wave mixing can be used to generate quantum state of light**
  (e.g. Rydberg excitation in atomic vapor can be used as single photon source)

Rydberg atoms



Alkali atom energy levels

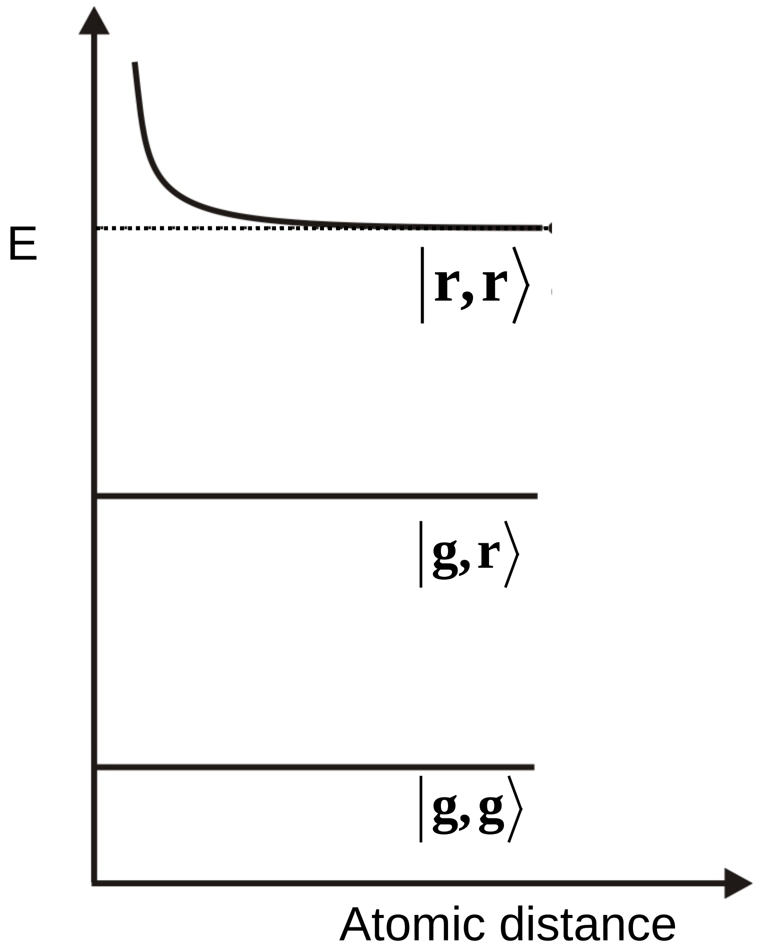


Rydberg states: large *n*

Scaling with principal quantum number *n* (low)

Size	n^2	Few 100 nm
Dipole moment	n^2	**Strong dipolar interaction**
Lifetime	n^3	**Long lived** **100 μsec for *n* > 40**
Polarizability Sensitivity to electric fields	n^7	**Giant Kerr effect**
van der Waals Atom - atom interactions	n^{11}	Strongly interacting (QIP)

Rydberg Rydberg interaction

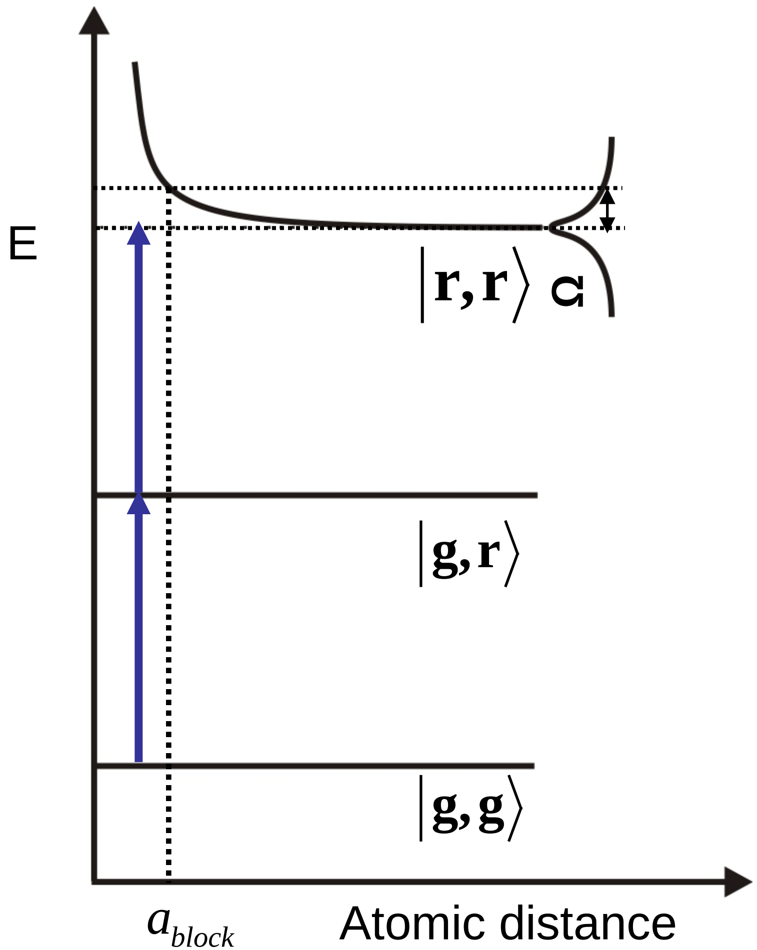


Simplest case: van der Waals

$$V(r) = \frac{C_6}{r^6}$$

$C_6 \rightarrow n^{11}$

Rydberg blockade



Simplest case: van der Waals

$$V(r) = \frac{C_6}{r^6}$$

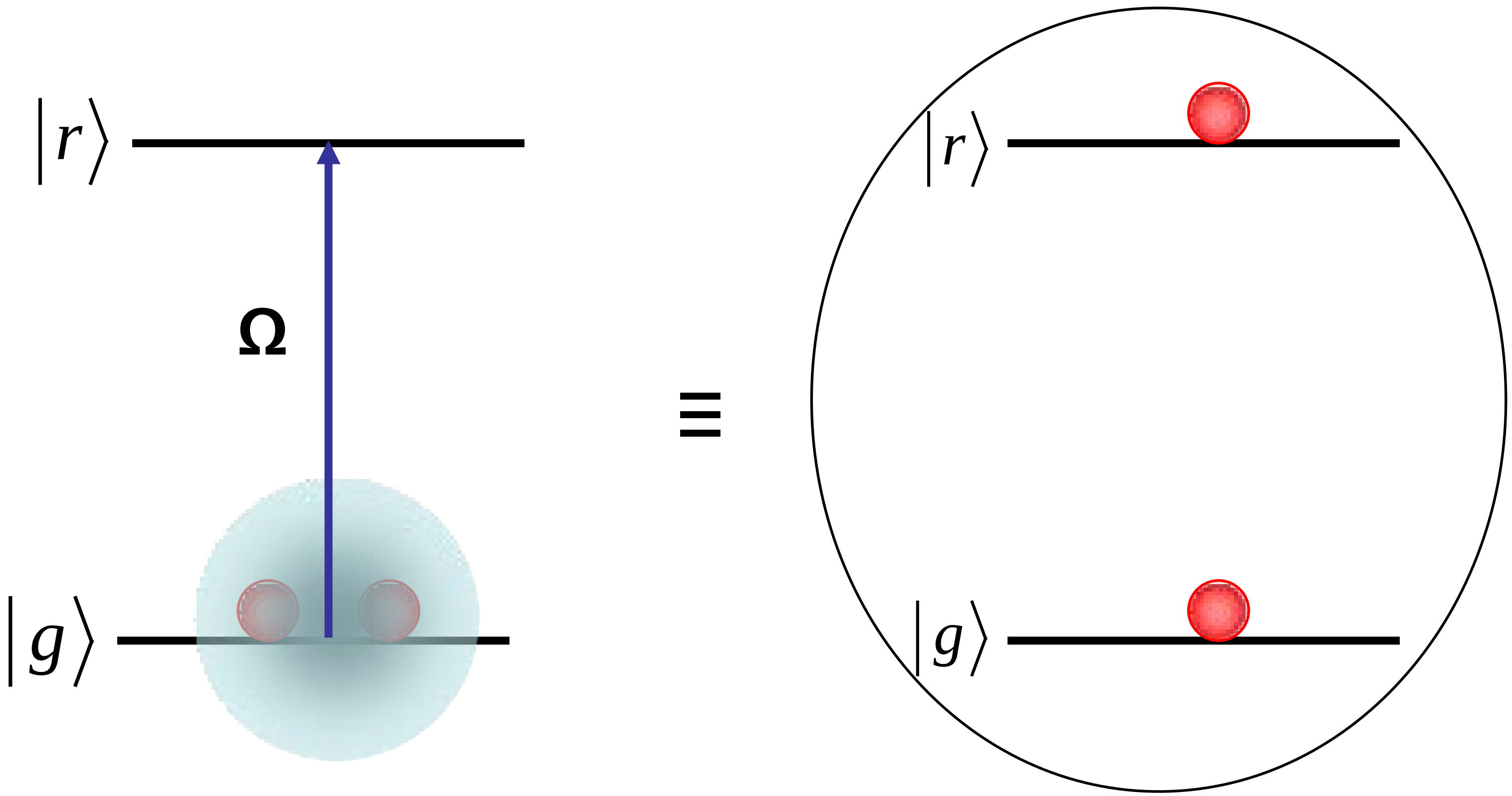
$C_6 \rightarrow n^{11}$

blockade condition

$$\frac{C_6}{a_{block}^6} \gg \hbar\Omega$$

$a_{block} \approx$ few μm

Rydberg blockade



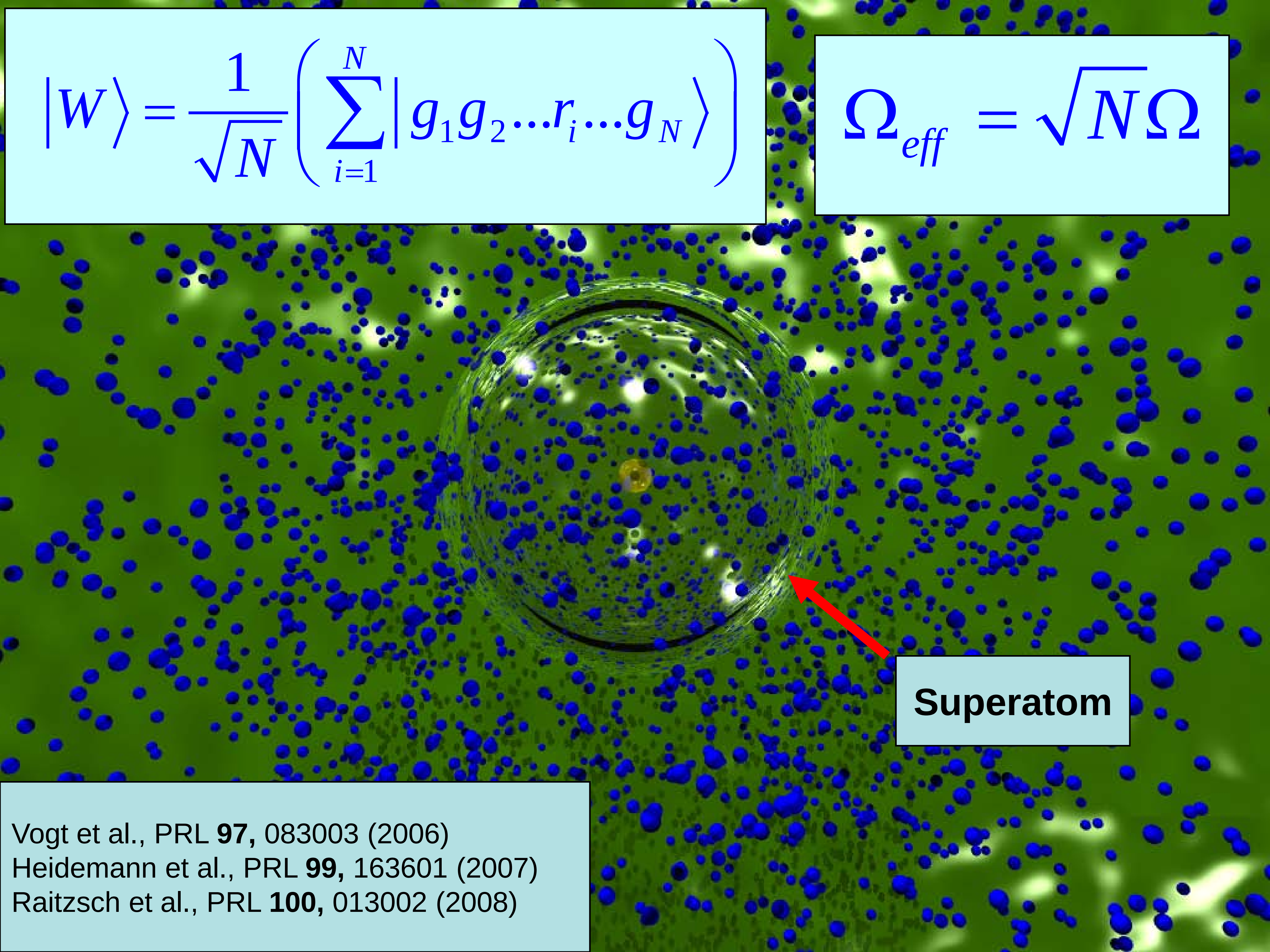
$$|\Psi\rangle = \frac{1}{\sqrt{2}}\left(|g,r\rangle + e^{i\varphi}|r,g\rangle\right)$$

Urban et al., Nature Phys. **5,** 110 (2009)
Gaetan et al., Nature Phys. **5,** 115 (2009)
Wilk et al., Phys. Rev. Lett. **104,** 010502 (2010)

$$\Omega_{eff} = \sqrt{2}\Omega$$

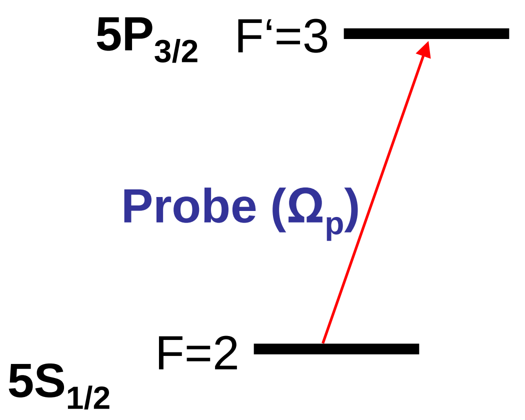
$$|W\rangle = \frac{1}{\sqrt{N}}\left(\sum_{i=1}^{N}|g_1 g_2 \ldots r_i \ldots g_N\rangle\right)$$

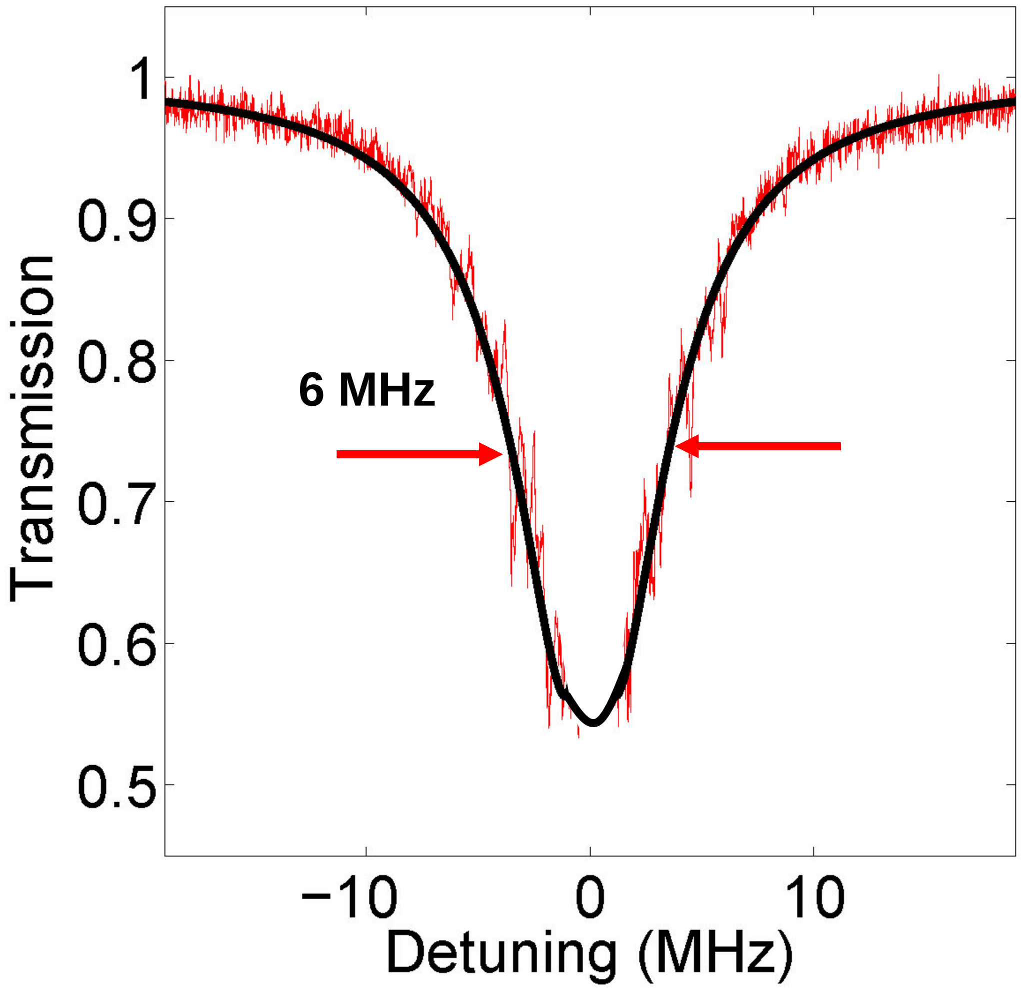
$$\Omega_{eff} = \sqrt{N}\Omega$$



Vogt et al., PRL **97,** 083003 (2006)
Heidemann et al., PRL **99,** 163601 (2007)
Raitzsch et al., PRL **100,** 013002 (2008)

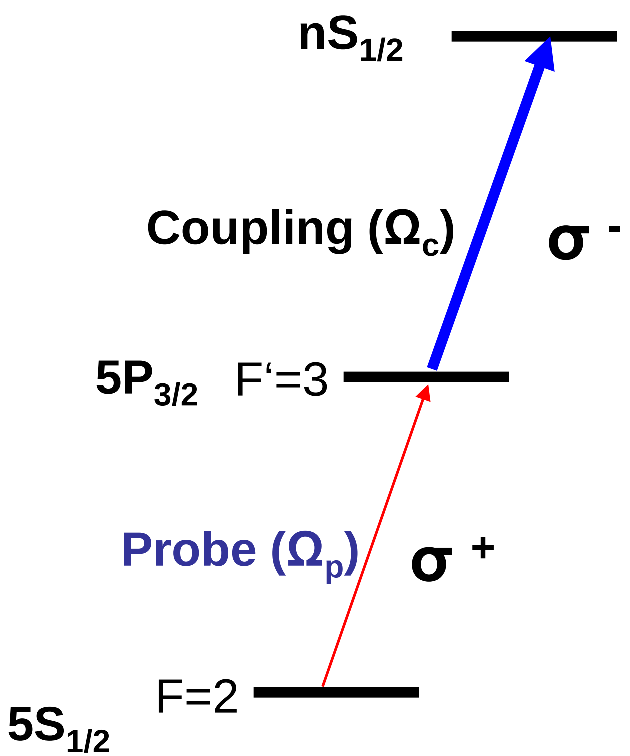
Electromagnetically induced transparency (EIT)



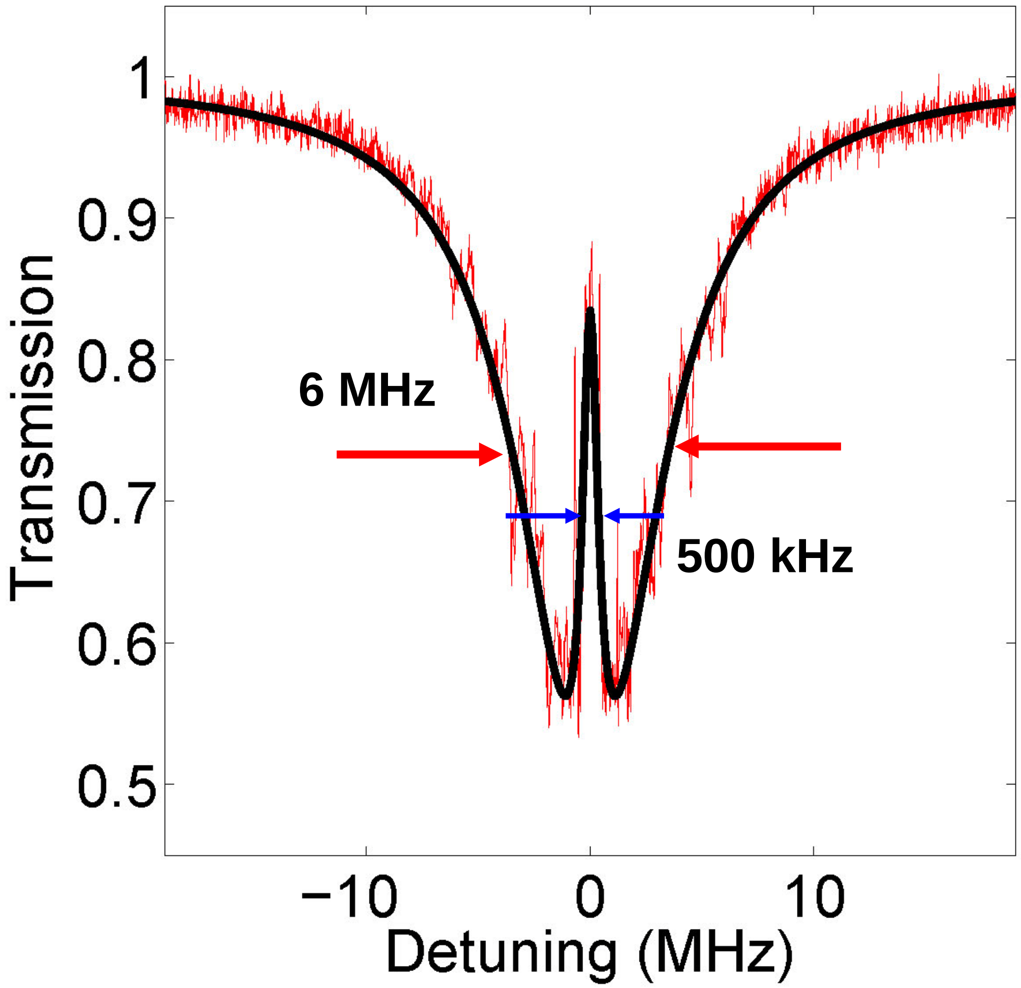


^{87}Rubidium

Electromagnetically induced transparency (EIT)

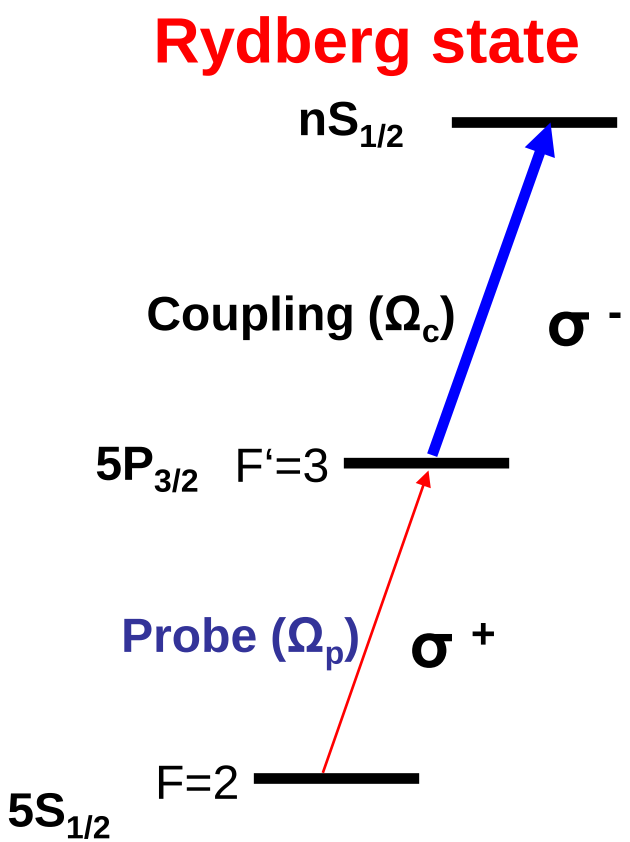


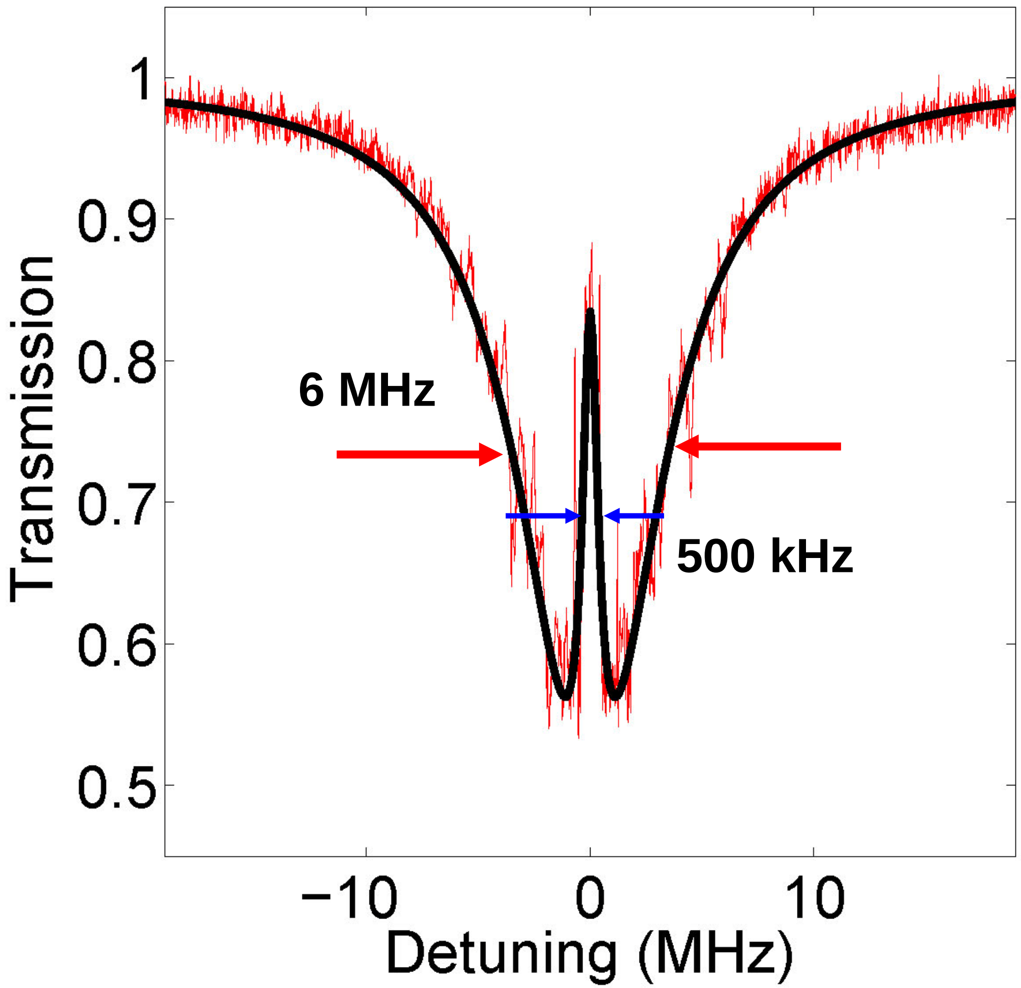
^{87}Rubidium



EIT still doesn‘t provide enough non-linearity at single photon level

Rydberg EIT

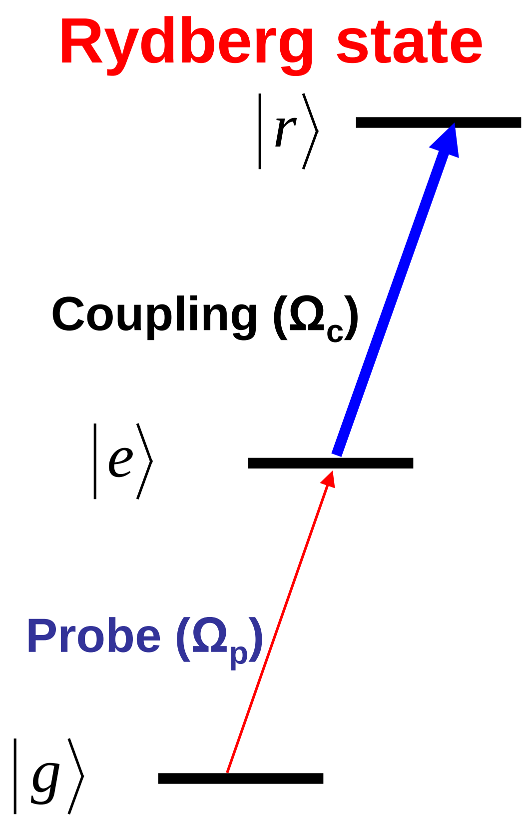


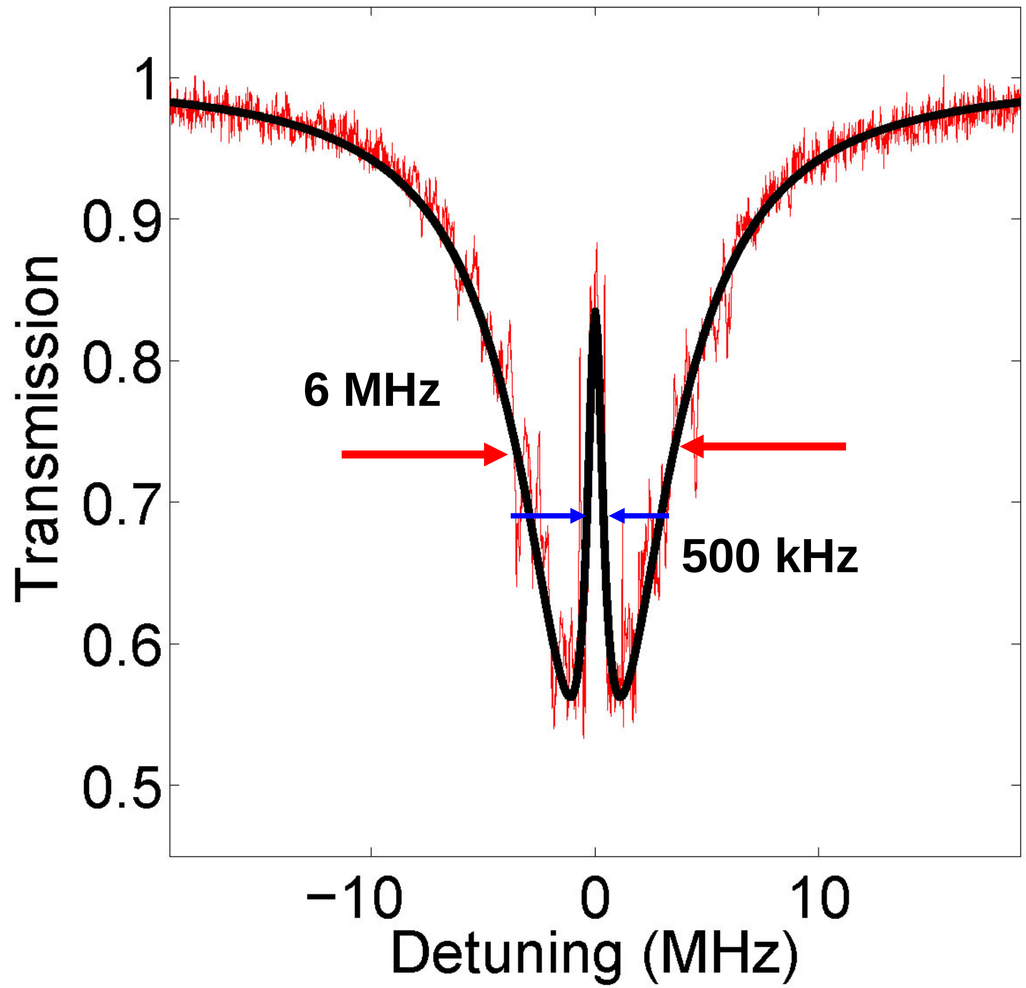


^{87}Rubidium

Rydberg EIT:
Mohapatra et al., PRL, **98,** 113003 (2007) (Thermal atoms)
Weatherill et al., J. Phys. B, **41,** 201002 (2008) (Cold atoms)

Non-linearity of Rydberg EIT





$$|D\rangle = \frac{\Omega_c}{\sqrt{\Omega_p^2 + \Omega_c^2}}|g\rangle - \frac{\Omega_p}{\sqrt{\Omega_p^2 + \Omega_c^2}}|r\rangle$$

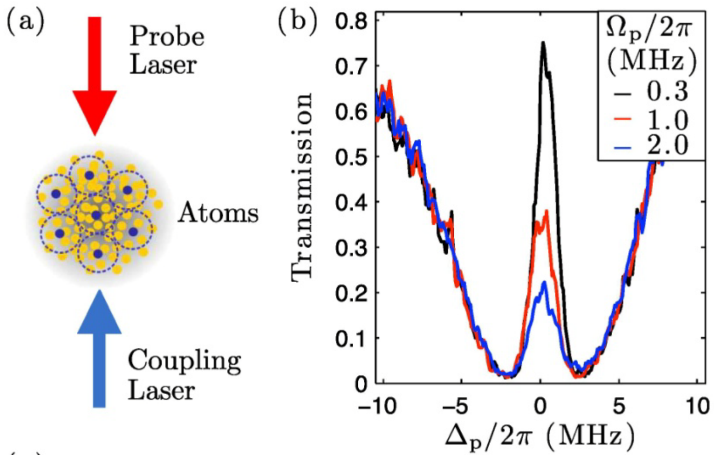
Dark state that doesn‘t couple to the probe
beam and hence probe beam become transparent

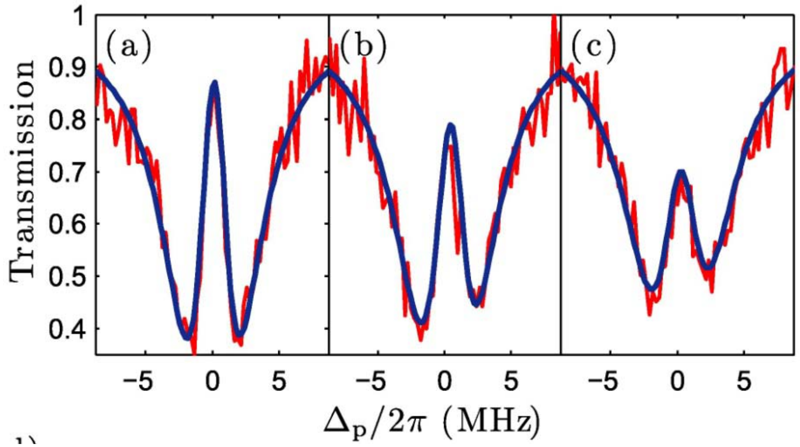
Non-linearity of Rydberg EIT

In the blockade sphere, more than one atom can not be excited which makes the dark state very fragile and get mixed with intermediate state.

$$|D\rangle = \frac{\Omega_c}{\sqrt{\Omega_p^2 + \Omega_c^2}}|g\rangle - \frac{\Omega_p}{\sqrt{\Omega_p^2 + \Omega_c^2}}|r\rangle + k|e\rangle$$

For large probe power, the EIT peak reduces with larger probe absorption.

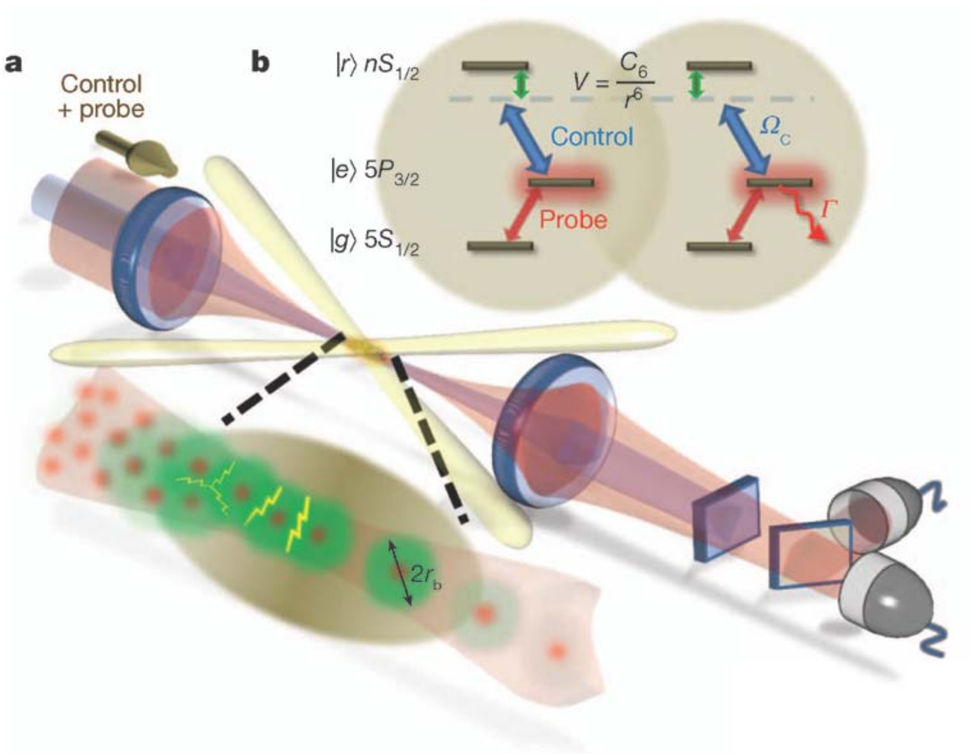


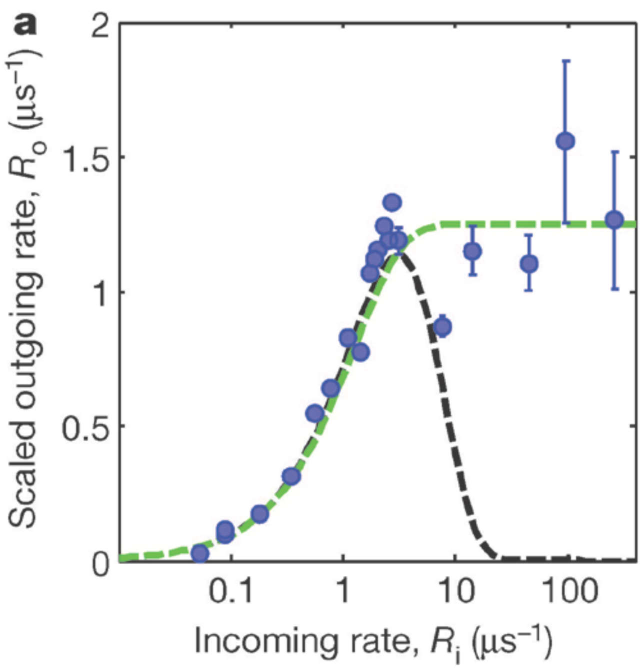


(a) One, (b) two, (c) three atoms per blockade sphere

Durham university, UK group
Pritchard et al. PRL, **105,** 193603 (2010)

Non-linearity of Rydberg EIT (Pushing to single photon level)





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

Optical non-linearity of Rydberg EIT in thermal vapor

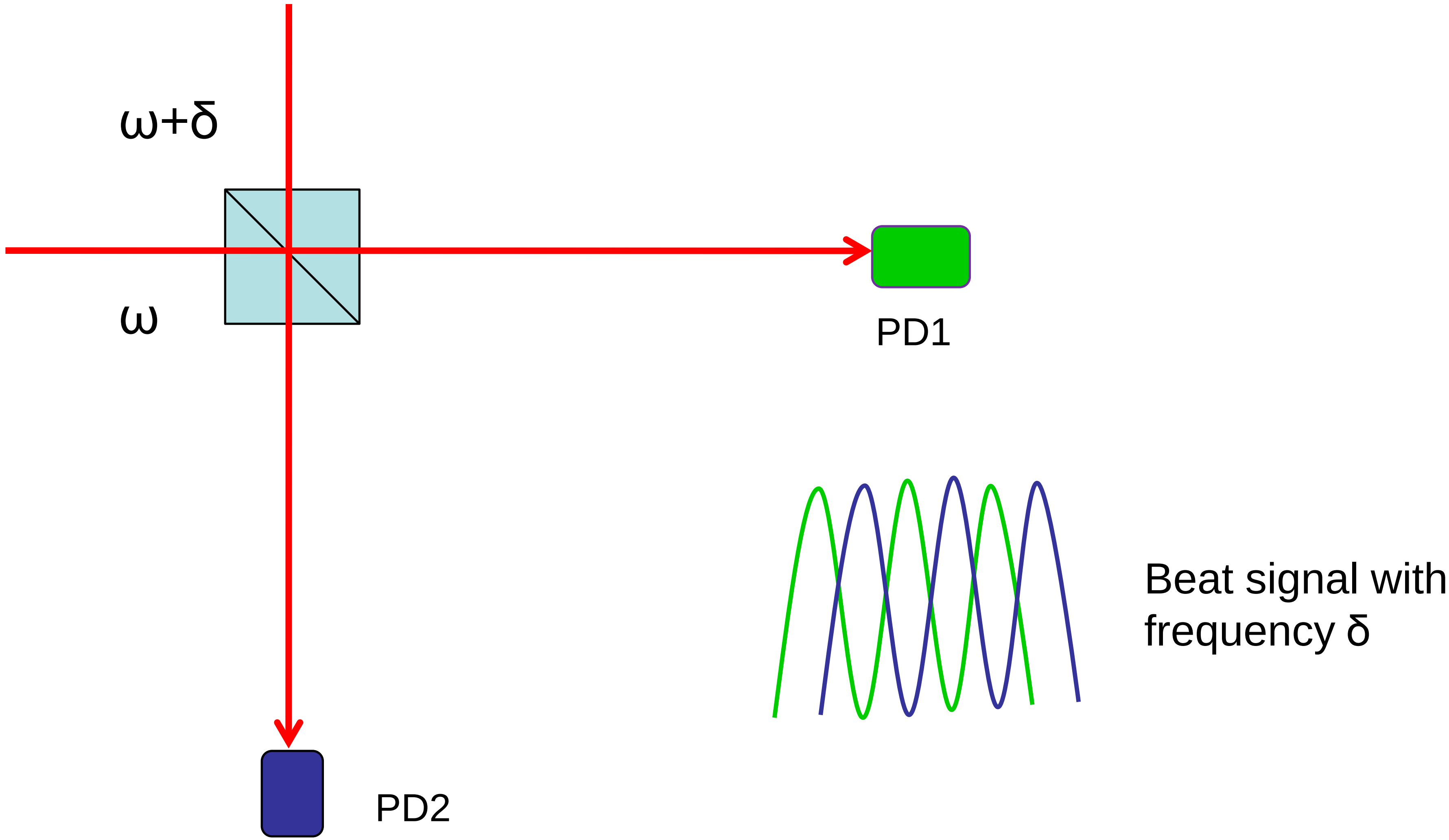
- Rydberg blockade radius is only scaled approximately by a factor of 3 in thermal vapor

$$a_{block}^{6} \approx \frac{C_6}{\hbar \Delta \omega_D}$$

  - Kuebler et al. Nature Photo. **4,** 112 (2010)

- Optical pumping rate to the dark state is much faster than the transit time of the atoms

Optical heterodyne technique to measure refractive index



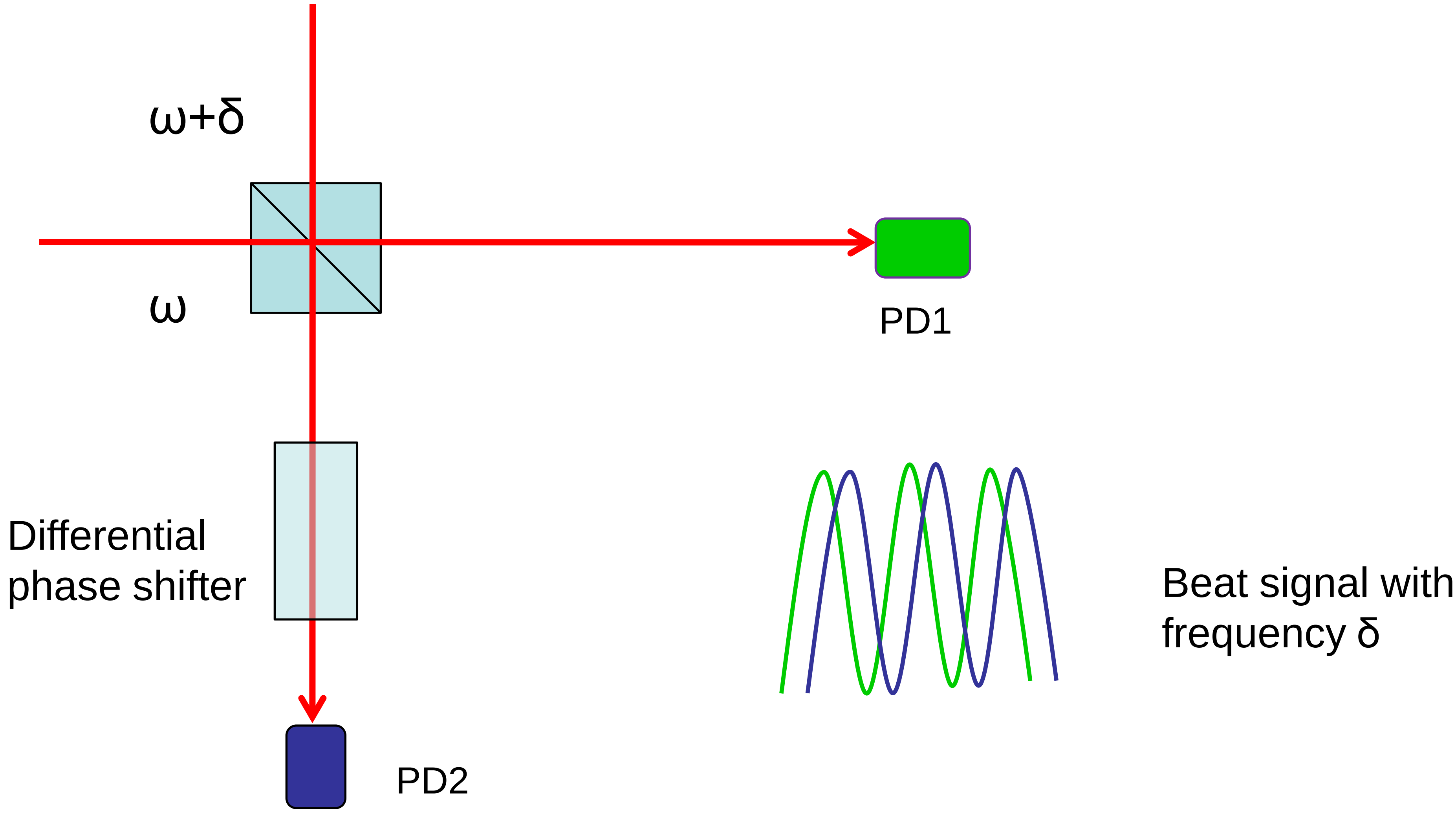
$$a_1 \cos(\delta t) a_2 \cos(\delta t + \varphi)$$

$$= \frac{a_1 a_2}{2}\left(\cos(2\delta t + \varphi)\right) + \frac{a_1 a_2}{2}\cos(\varphi)$$

Low pass filter →

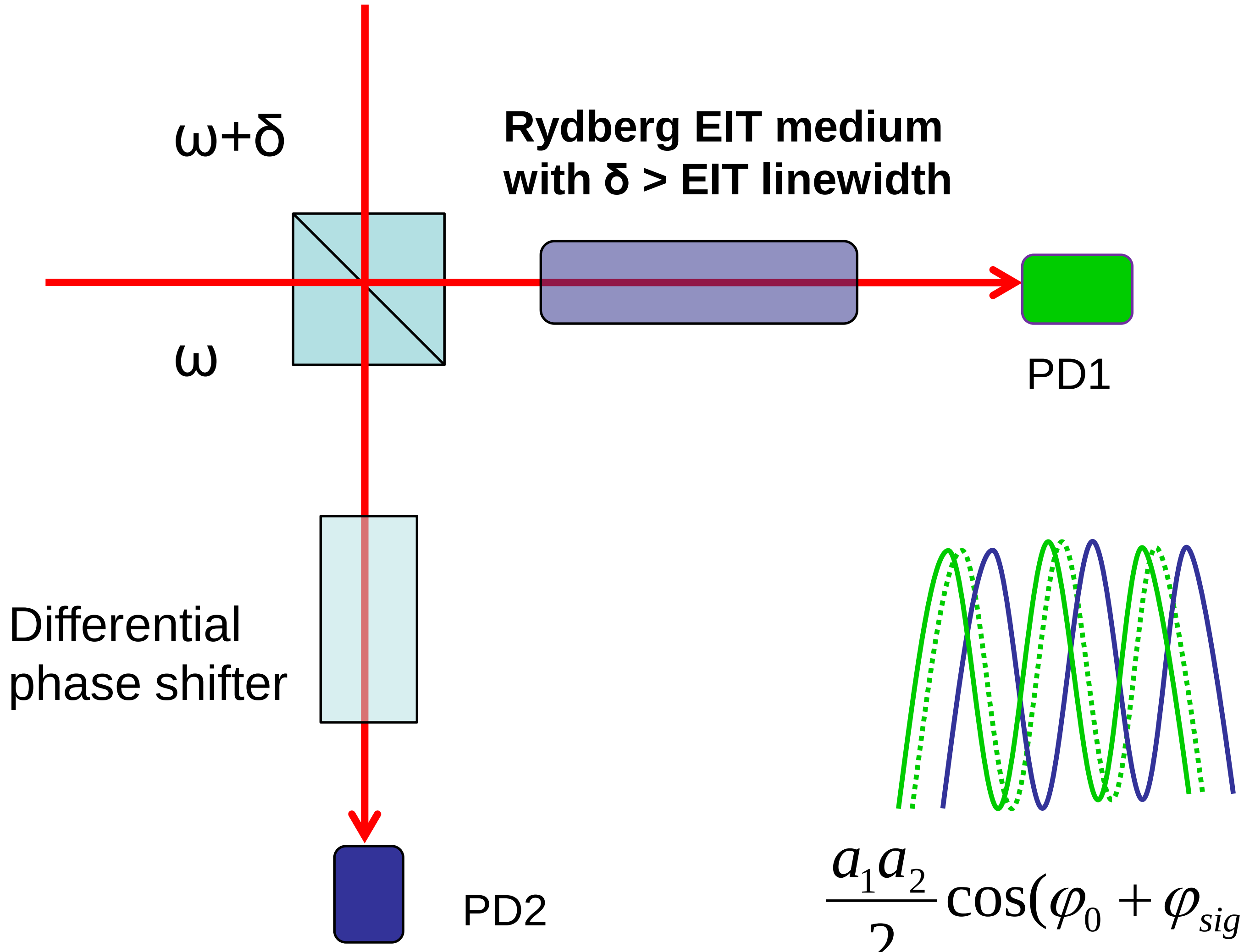
$$\frac{a_1 a_2}{2}\cos(\varphi)$$

Optical heterodyne technique to measure refractive index



$$\frac{a_1 a_2}{2}\cos(\varphi_0)$$

Optical heterodyne technique to measure refractive index



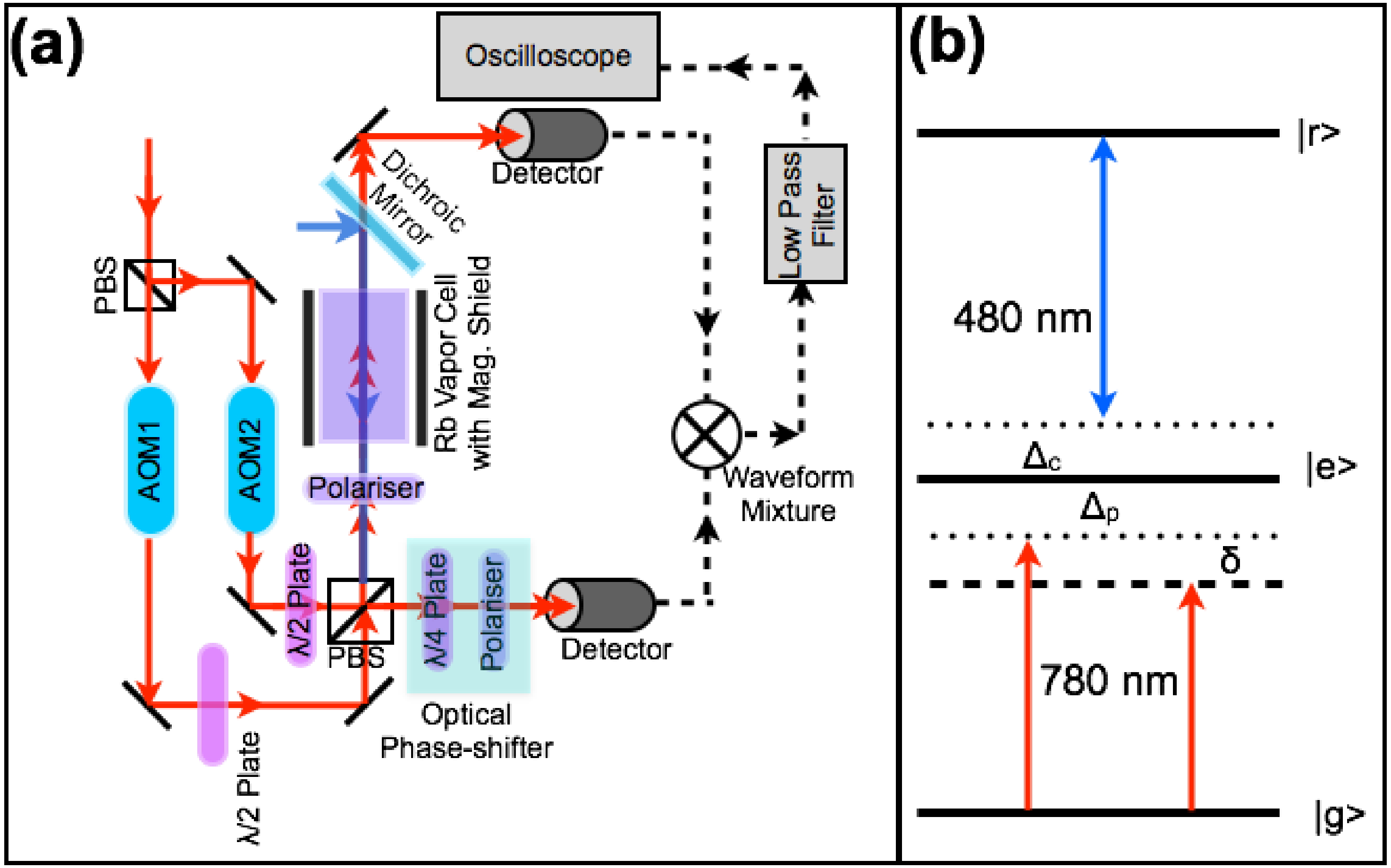
Beat signal with frequency δ

$$\frac{a_1 a_2}{2}\cos(\varphi_0 + \varphi_{sig})$$

$\varphi_0 = 90^0$ Sensitive to phase, refractive index

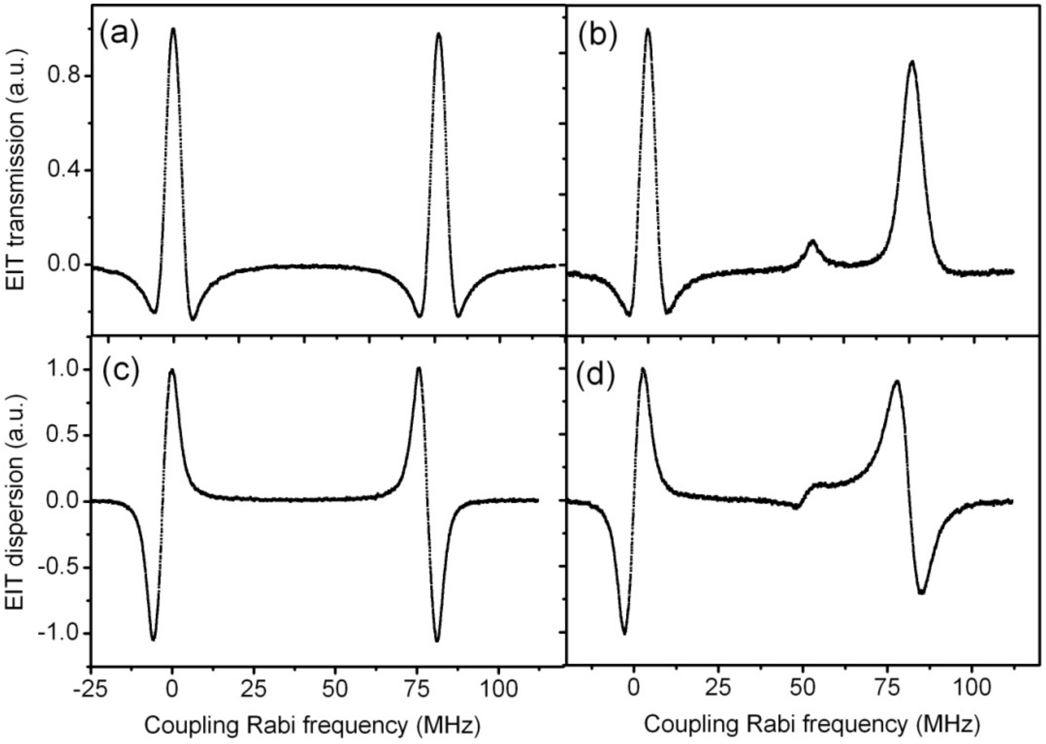
$\varphi_0 = 0^0, 180^0$ Sensitive to amplitude, transmission

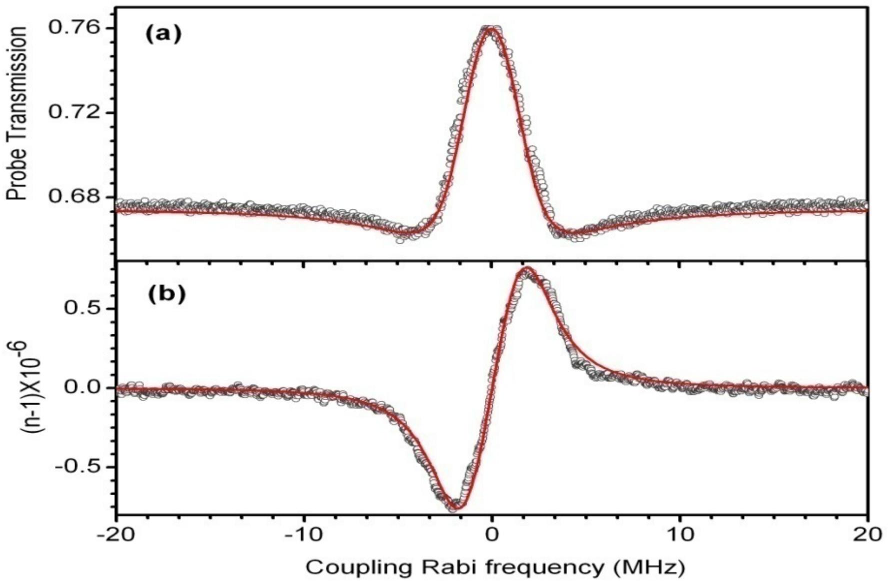
Non-linear refractive index of Rdberg EIT



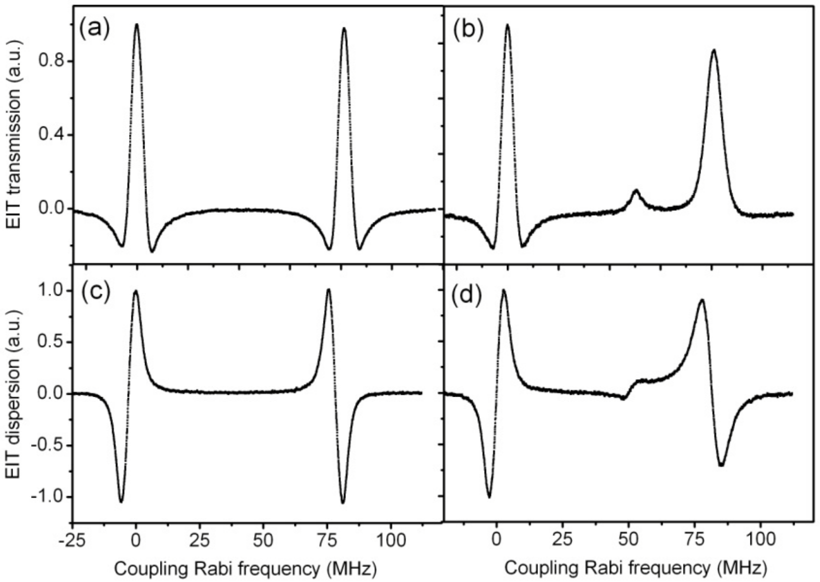
Details in Arup's poster

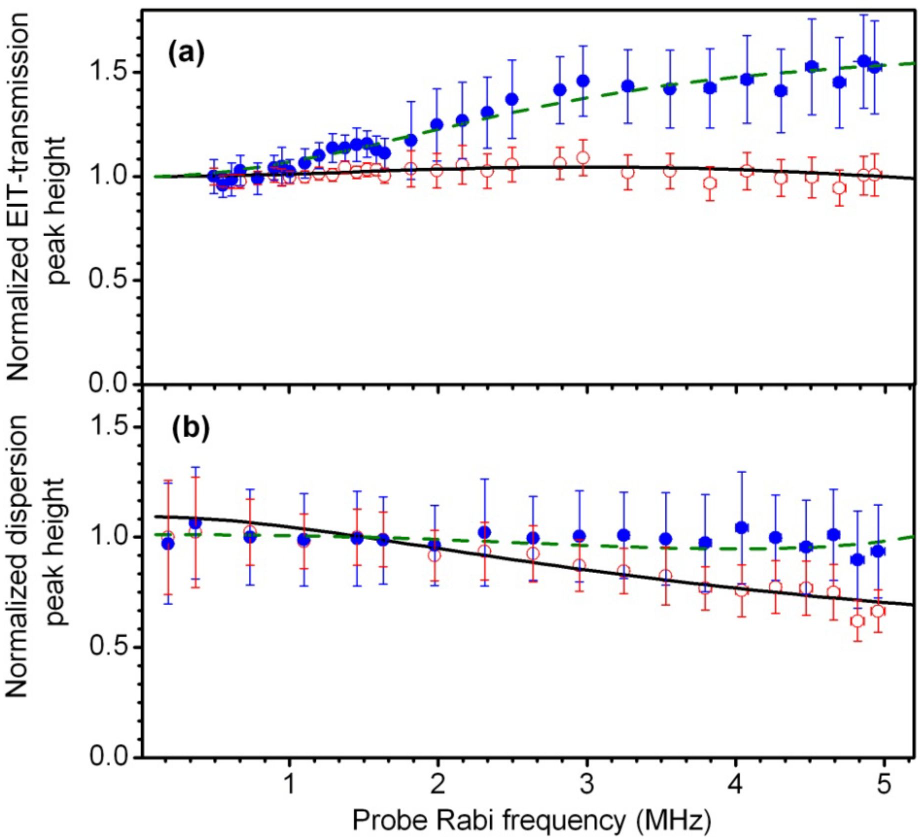
Non-linear refractive index of Rdberg EIT





Non-linear refractive index of Rdberg EIT





There is no blockade interaction present here due to very low density.
We need a micron sized vapor cell to observe the blockade induced non-linearity.

Arup's Poster
Blockade induced non-linearity is observed by keeping probe outside Doppler profile

Acknowledgement

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Thank You