

Efficient All-Optical Switching Using Slow Light within a Hollow Fiber

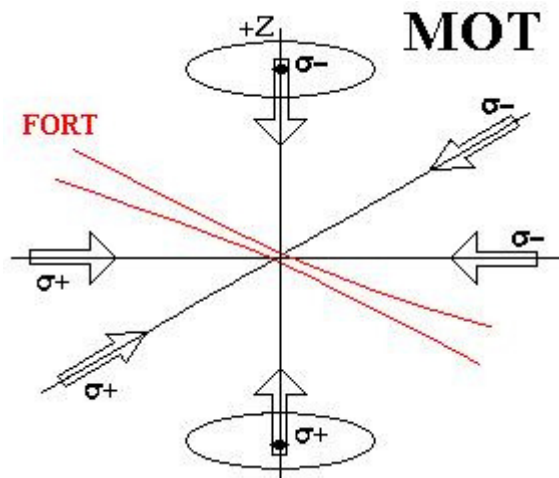
M. Bajcsy,¹ S. Hofferberth,¹ V. Balic,¹ T. Peyronel,² M. Hafezi,¹ A. S. Zibrov,¹ V. Vuletic,² and M. D. Lukin¹

¹Harvard-MIT Center for Ultracold Atoms, Department of Physics, Harvard University, Cambridge, Massachusetts 02138, USA

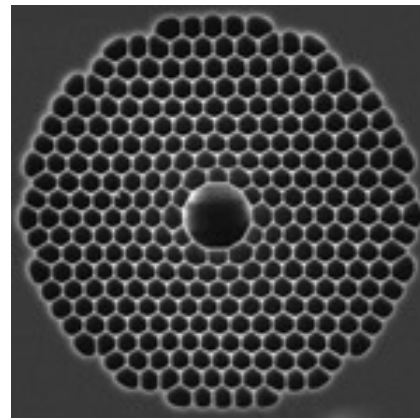
²Harvard-MIT Center for Ultracold Atoms, Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA

(Received 3 January 2009; published 18 May 2009)

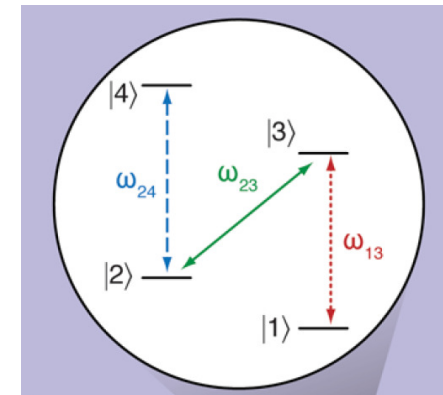
We demonstrate a fiber-optical switch that is activated at tiny energies corresponding to a few hundred optical photons per pulse. This is achieved by simultaneously confining both photons and a small laser-cooled ensemble of atoms inside the microscopic hollow core of a single-mode photonic-crystal fiber and using quantum optical techniques for generating slow light propagation and large nonlinear interaction between light beams.



Cold Atoms



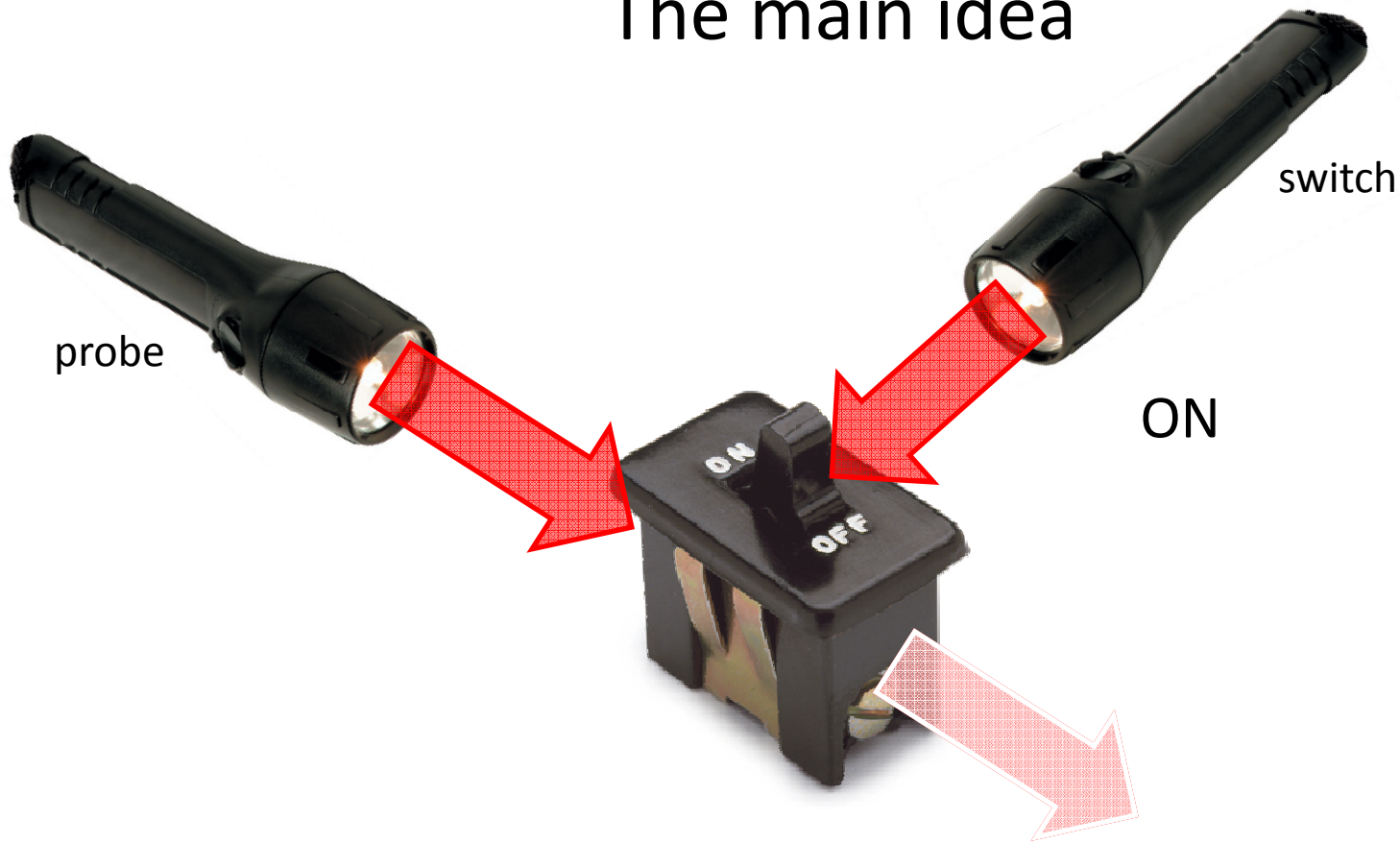
Hollow Fiber



EIT

Luciano Cruz

The main idea



“Optical switches operating at a fundamental limit of **one photon** per switching event would further enable the realization of key protocols from quantum information science”

Background References

"Giant Kerr nonlinearities obtained by electromagnetically induced transparency" – H. Schmidt and A. Imamoglu, Opt. Lett. , **21**, 1936 (1996)

"Photon Switching by quantum interference" – SE Harris and Y Yamamoto, PRL. , **81**, 3611(1998)

"Nonlinear Optics at Low Light Levels", SE Harris and LV Hau, PRL, **82**, 4611 (1999)

"Nonlinear Optics and Quantum Entanglement of Ultraslow Single Photons", MD Lukin and A Imamoglu, PRL, **84**, 1419 (2000)

...

"Observation of Large Kerr Nonlinearity at Low Light Intensities", H Kang and Y Zhu, PRL 91, 093601 (2003)

"Low light level nonlinear optics with slow light", DA Braje, V Balic, GY Yin, and SE Harris , PRA 68, 041801 (2003)

What do we need to have optical switches in few photons regime?

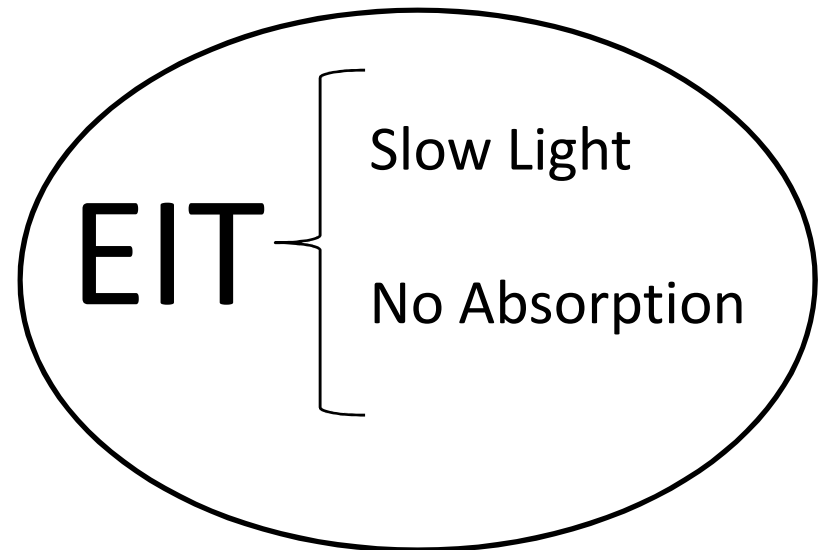
❑ Large optical nonlinearity

$$n = n_0 + n_2 I$$

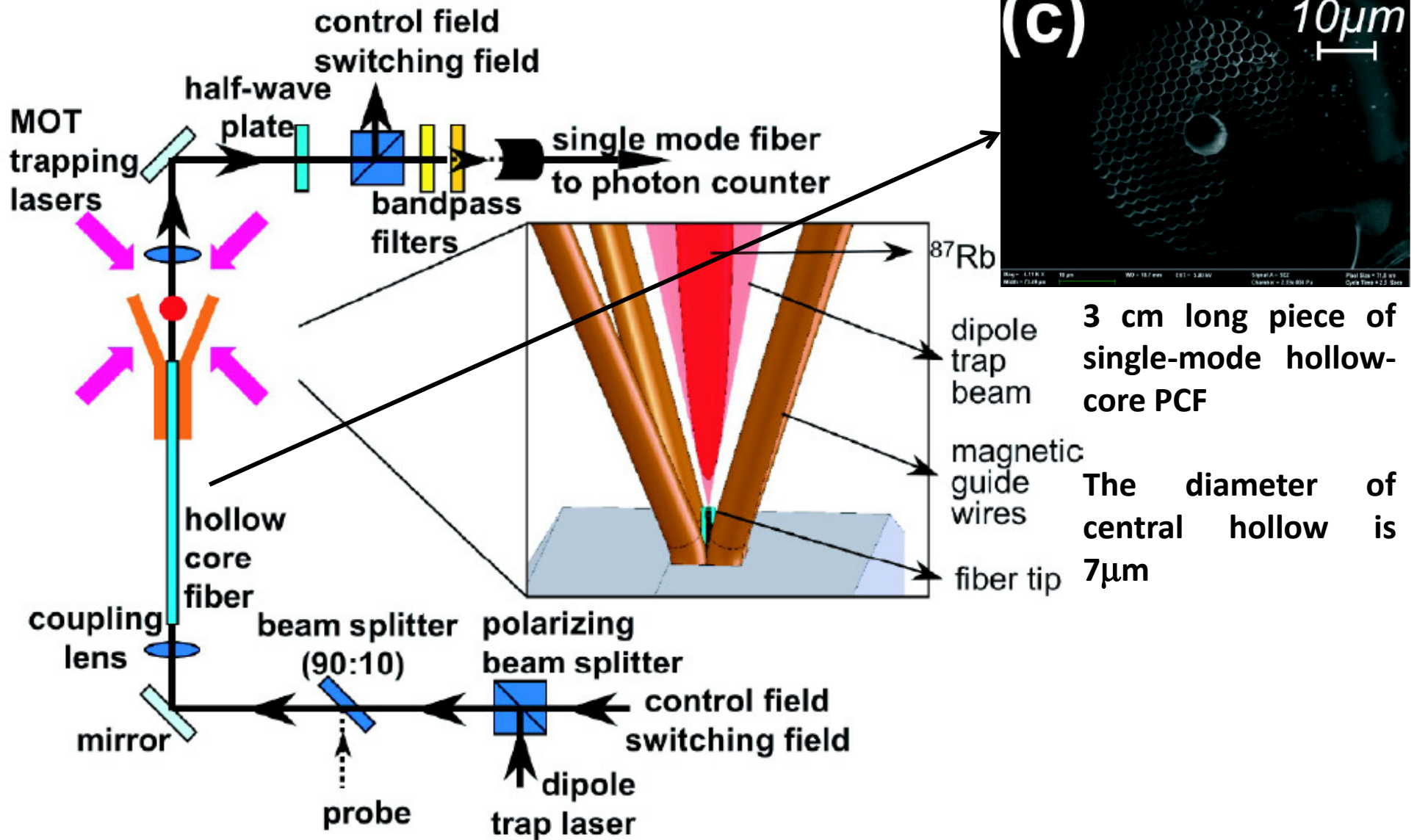
❑ Tight confinement of the light beams

❑ Long interaction time

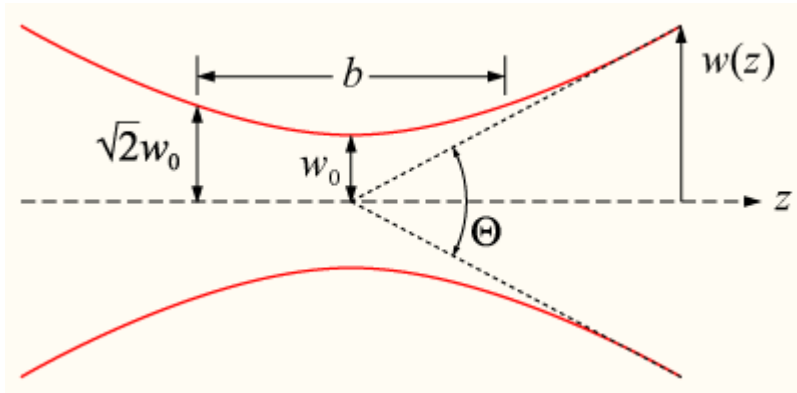
❑ Low photon loss



The Experiment Setup



A little about gaussian beams....

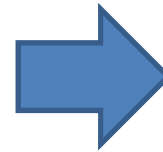


$$w(z) = w_0 \sqrt{1 + \left(\frac{z}{z_R}\right)^2}$$

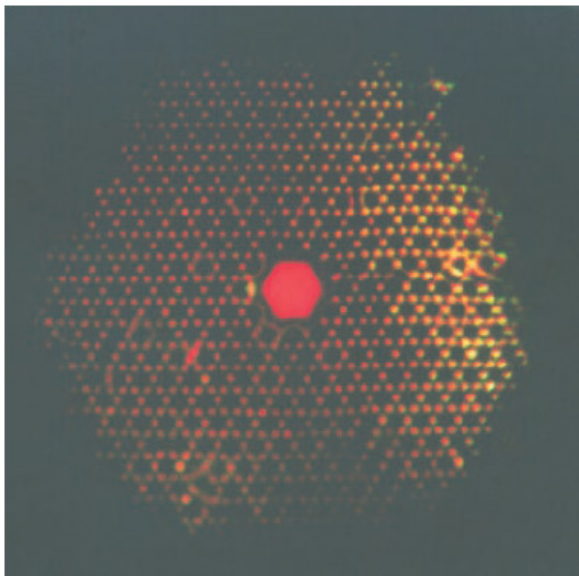
$$z_R = \frac{\pi w_0^2}{\lambda}$$

$$I = \frac{P}{\pi w^2(z)}$$

How to get 'effective' long z_R and small w_0 ?



Hollow Core Photonic Crystal Fibers



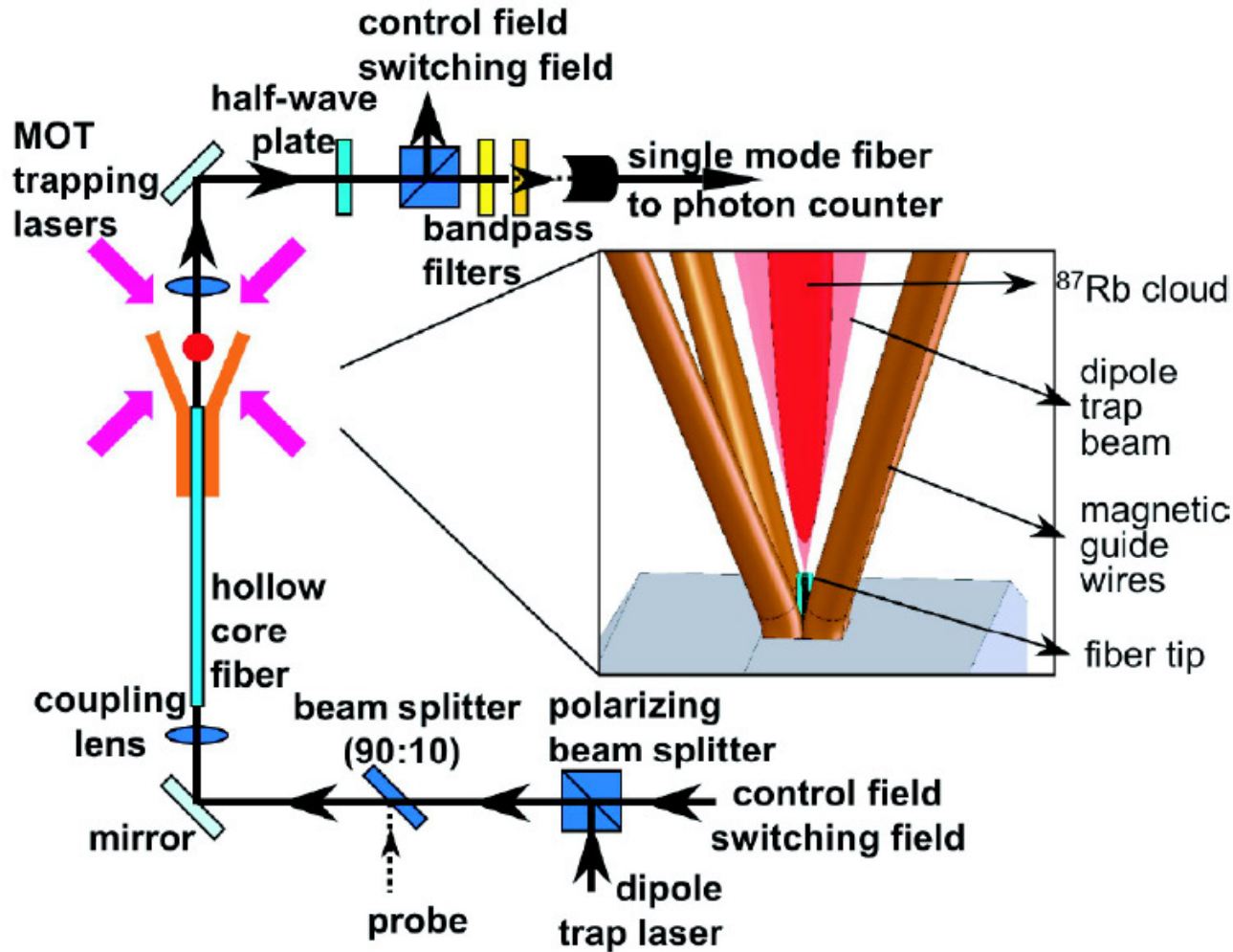
Single-Mode Photonic Band Gap Guidance of Light in Air

R. F. Cregan,¹ B. J. Mangan,¹ J. C. Knight,¹ T. A. Birks,¹
P. St. J. Russell,^{1*} P. J. Roberts,² D. C. Allan³

The confinement of light within a hollow core (a large air hole) in a silica-air photonic crystal fiber is demonstrated. Only certain wavelength bands are confined and guided down the fiber, each band corresponding to the presence of a full two-dimensional band gap in the photonic crystal cladding. Single-mode vacuum waveguides have a multitude of potential applications from ultrahigh-power transmission to the guiding of cold atoms.

Science, **285**, 1537 (1999)

The Experiment Setup



^{87}Rb cold atoms

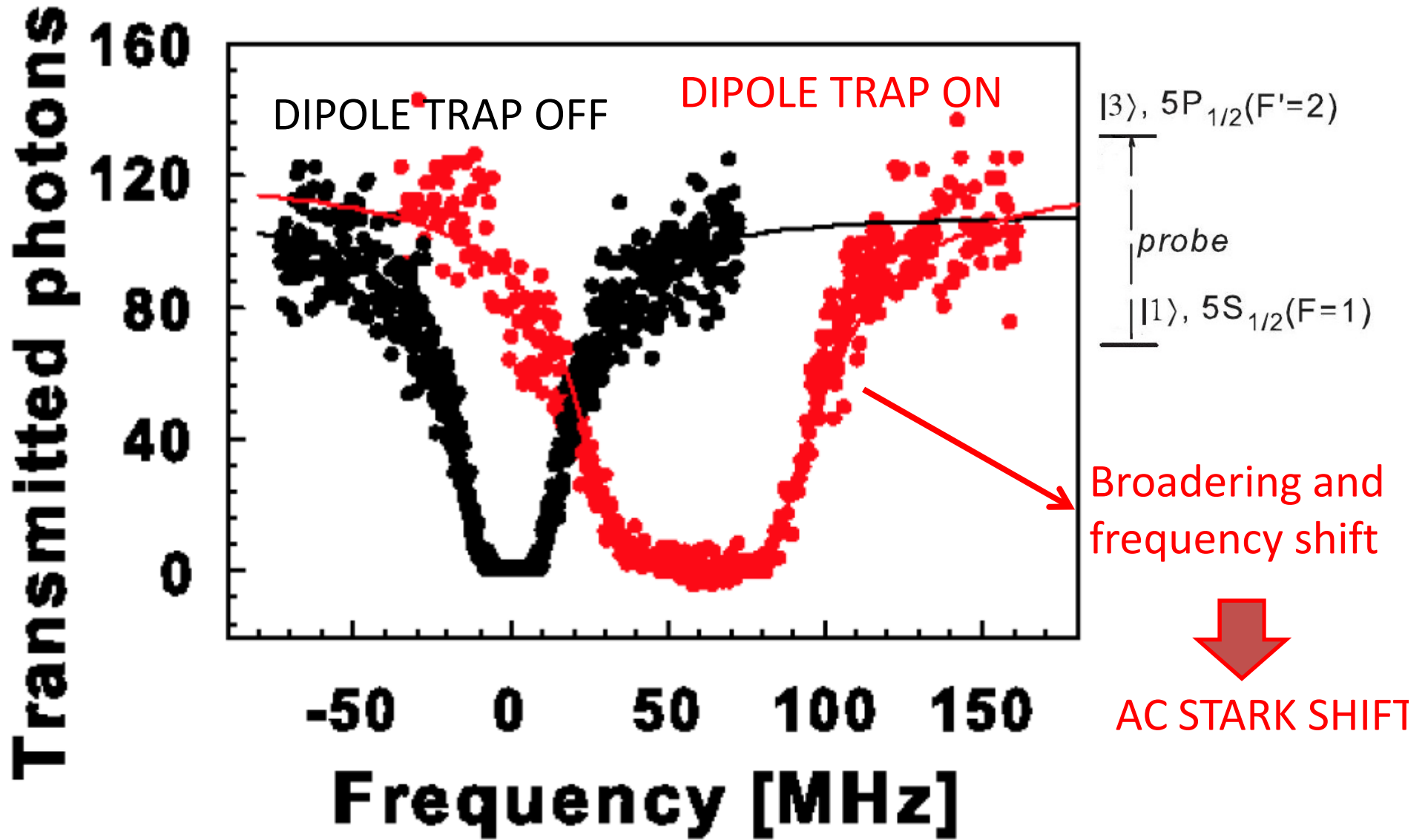
$$w_0 = 1.9 \pm 0.2 \mu\text{m}$$

$$\text{OD (100 atoms)} \sim 1$$

Strong transverse confinement ($\omega_t / 2\pi \sim 50\text{-}100$ kHz)

Deep trap potential ~ 10 mK@ few mW

Signature of cold atoms inside of PCF



OD (3000 atoms) \sim 30

AC Stark Shift

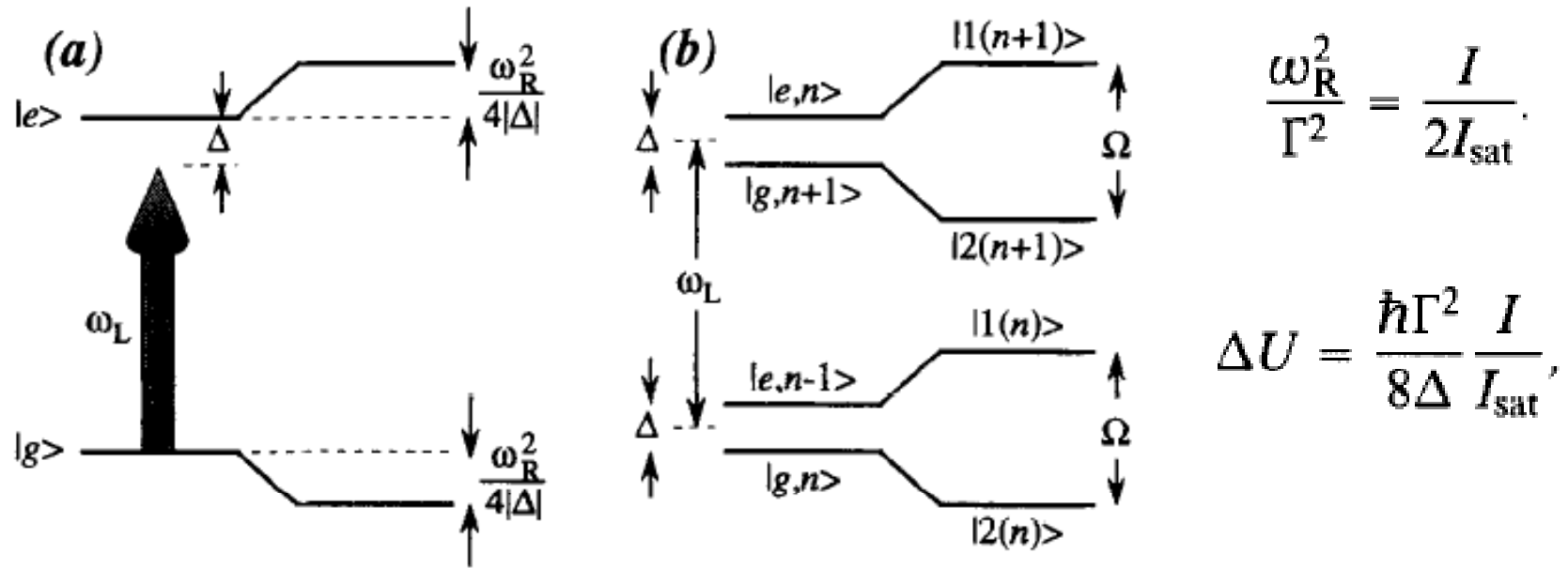
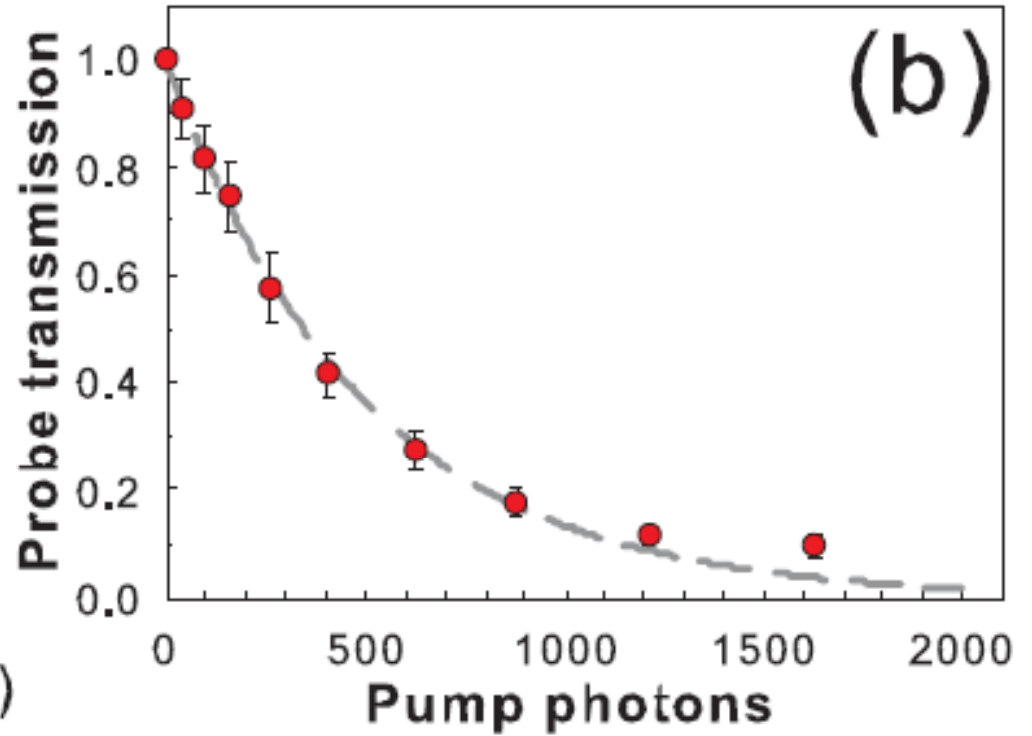
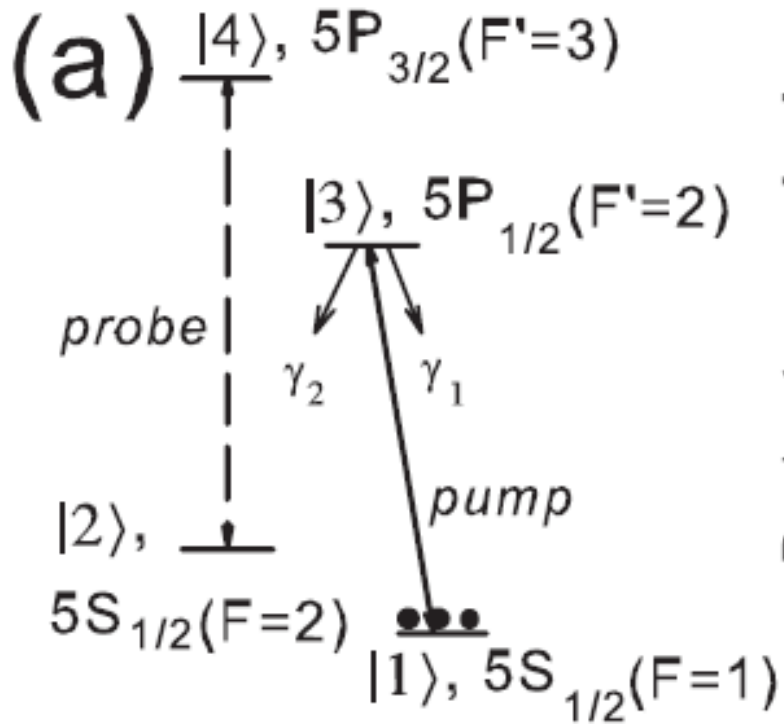


Fig. 7. (a) Two atomic levels $|g\rangle$ and $|e\rangle$ are coupled by a light field with frequency ω_L . The coupling strength is characterised by the Rabi frequency ω_R . If the laser is tuned below resonance, the ac-Stark shift causes the levels to repel. For $\omega_R \ll \Delta$ the energy shift is $\hbar\omega_R^2/4|\Delta|$. (b) In the dressed atom picture, the atom and the laser field are considered jointly. The energy of a ground state atom and n photons is almost degenerate with that of an excited atom and $n - 1$ photons. The dressed energy levels form a ladder of manifolds separated by the photon energy $\hbar\omega_L$. The atom-field interaction splits the levels within each manifold by $\hbar\Omega = \hbar\sqrt{\omega_R^2 + \Delta^2}$. The eigenstates for the coupled system ($|1(n)\rangle$, $|2(n)\rangle$, etc.) are linear combinations of the uncoupled states ($|g, n\rangle$, $|e, n - 1\rangle$, etc.).

Non linear saturation based on incoherent population transfer

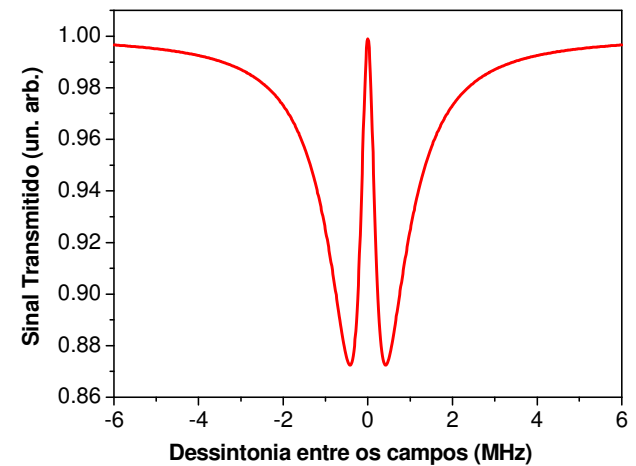
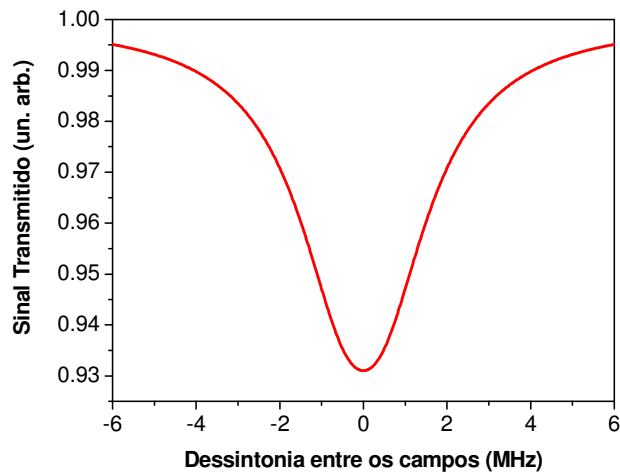
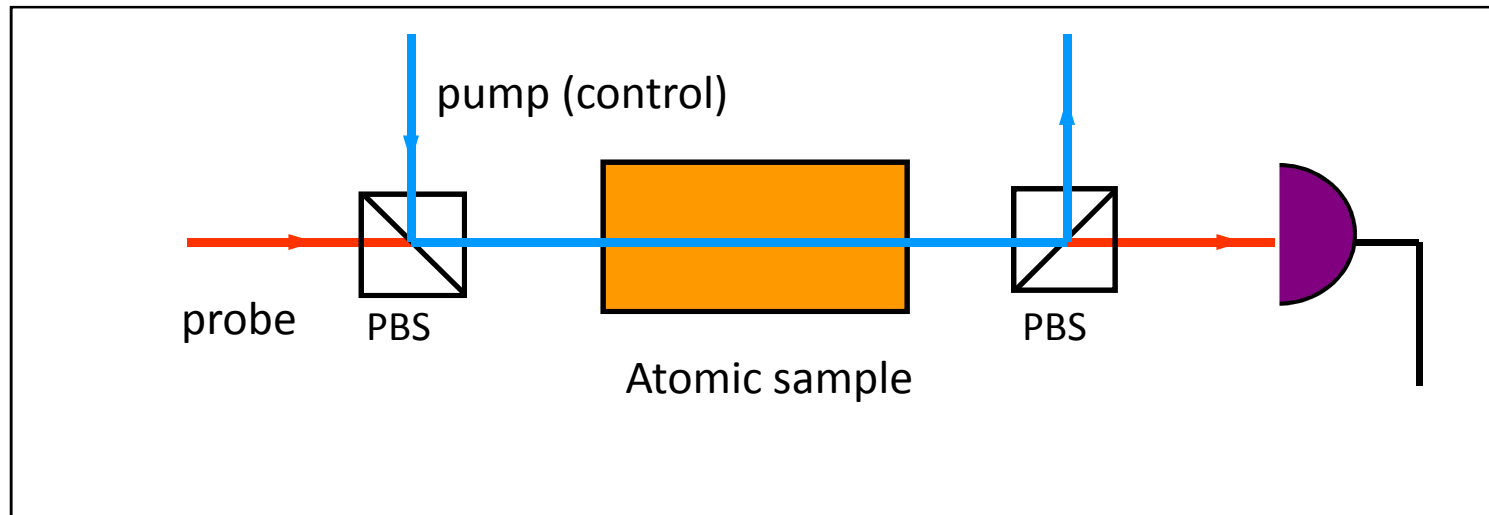


50% reduction of probe transmission is achieved with **~ 300 photons**

Electromagnetically Induced Transparency (EIT)

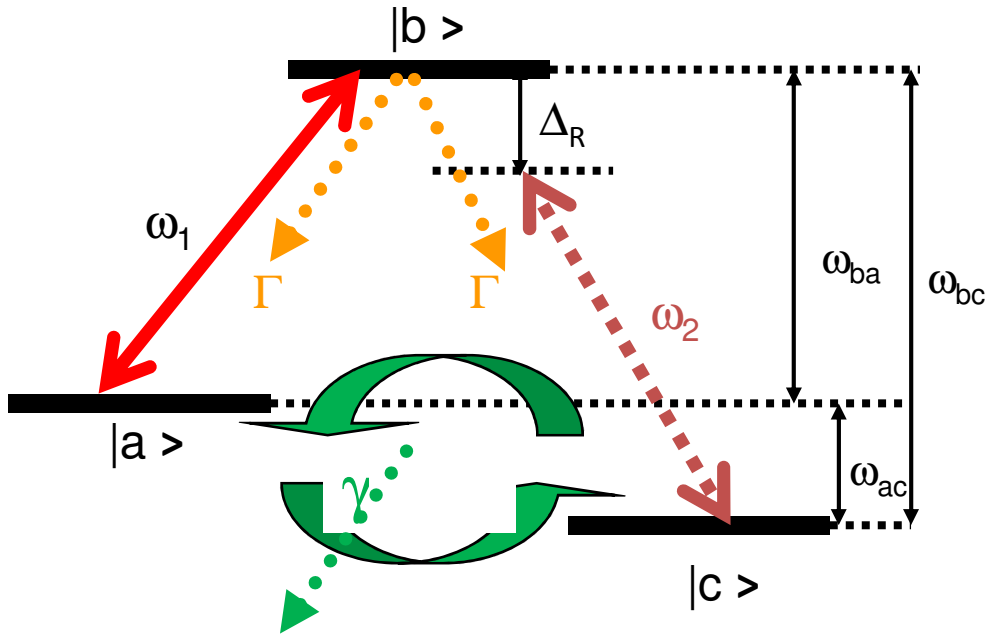
“Electromagnetically Induced Transparency is a *quantum* interference effect that permits the propagation of light through an otherwise opaque atomic medium...”

C. Liu *et al.*, Nature **409**, 490 (2001)

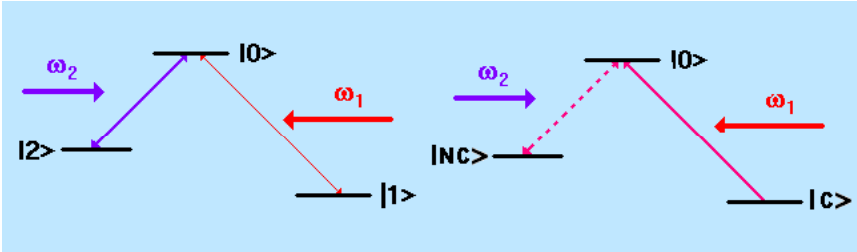


Electromagnetically Induced Transparency (EIT)

Dark State



$$|NC\rangle = \frac{\Omega_1|a\rangle - \Omega_2|c\rangle}{\sqrt{|\Omega_1|^2 + |\Omega_2|^2}}$$

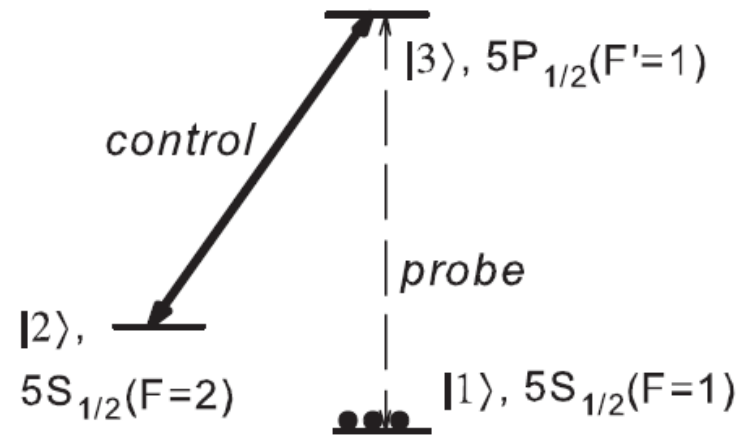
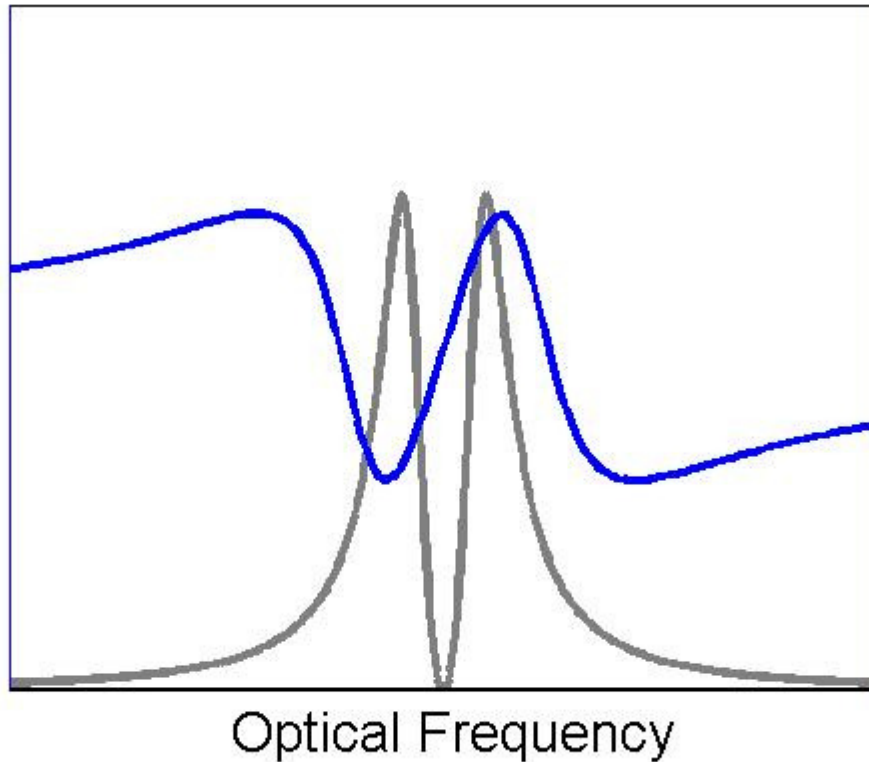


$$H_\Lambda = \hbar[\omega_a|a\rangle\langle a| + \omega_b|b\rangle\langle b| + \omega_c|c\rangle\langle c|]$$

$$V_\Lambda = \hbar[\Omega_1|a\rangle\langle b|e^{i(\omega_1 t + \phi_1)} + \Omega_2|c\rangle\langle b|e^{i(\omega_2 t + \phi_2)}] + h.c.$$

"Electromagnetically Induced Transparency: Optics in coherent media", M Fleischhauer, A Imamoglu, J P Marangos, RMP, **77**, 633 (2005)

Others consequences of EIT: nonlinearity and slow light

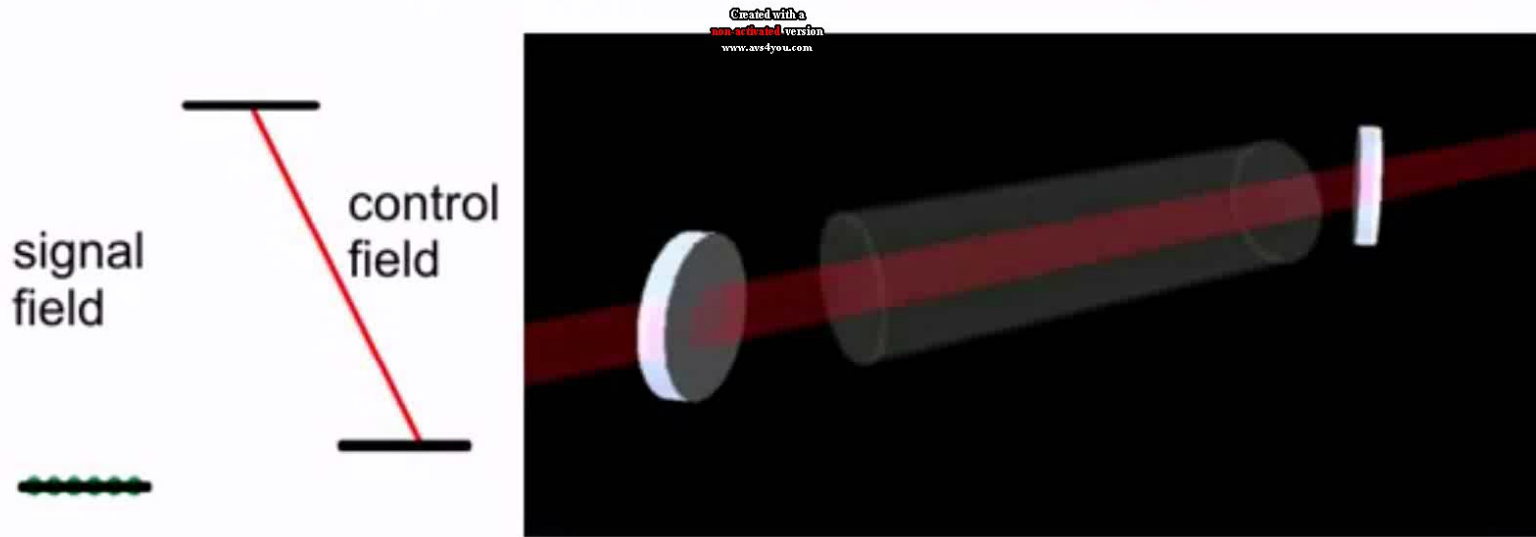
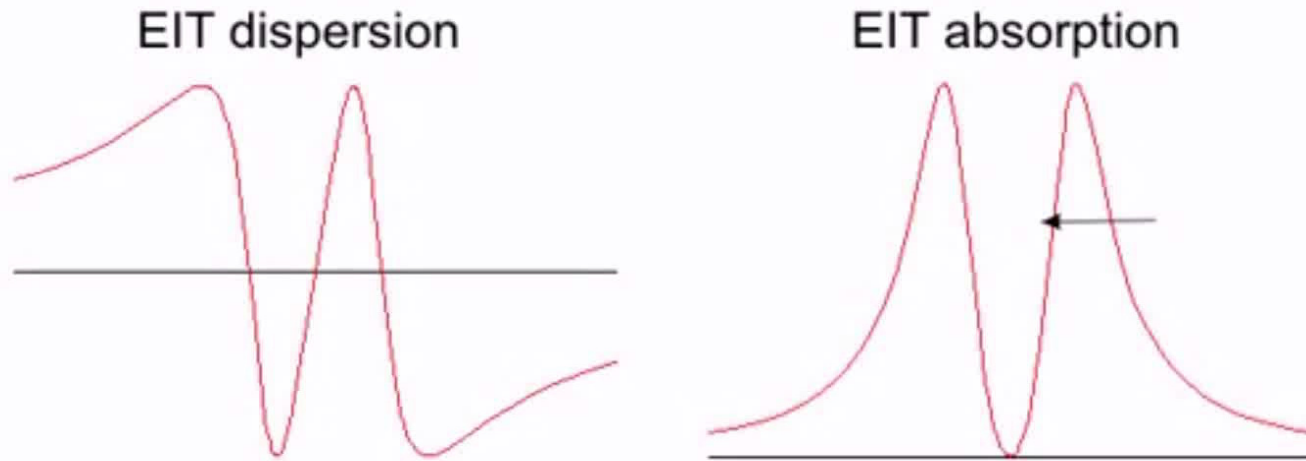


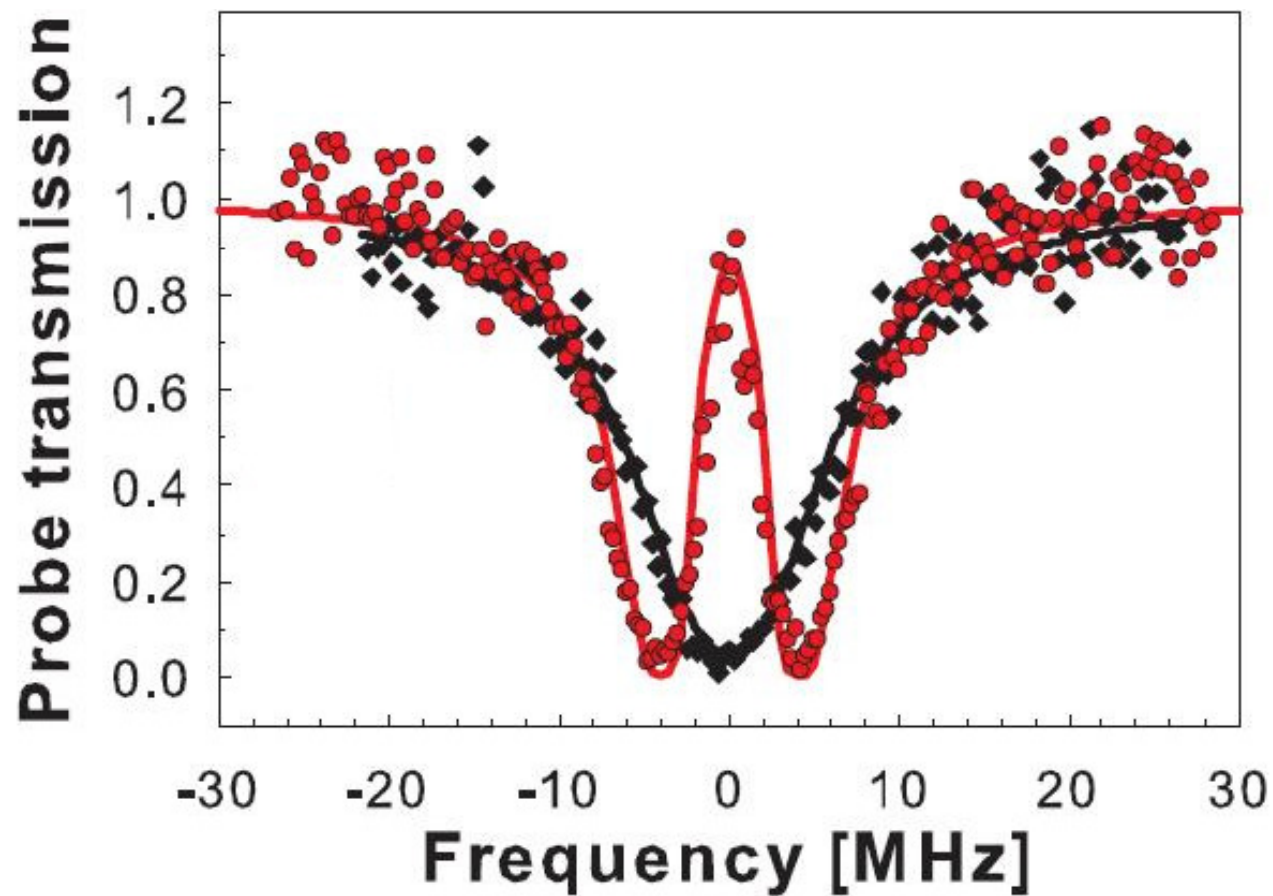
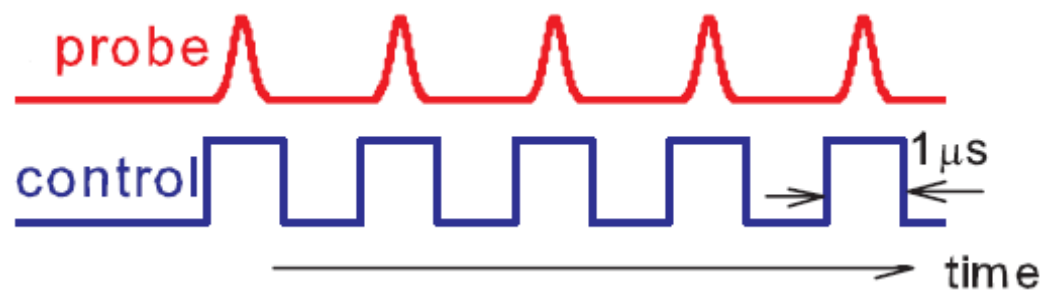
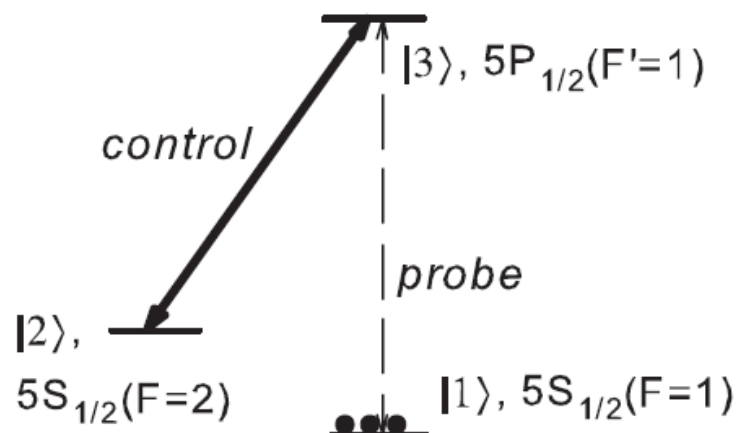
$$v_g = \frac{c}{n(\omega_p) + \omega_p \frac{dn}{d\omega_p}} \approx \frac{\hbar c \epsilon_0}{2\omega_p} \frac{\Omega_c^2}{|\mu_{13}|^2 N}$$

LV Hau, et al, Nature, 397, 594 (1999) [BEC; $v_g \sim 17$ m/s]

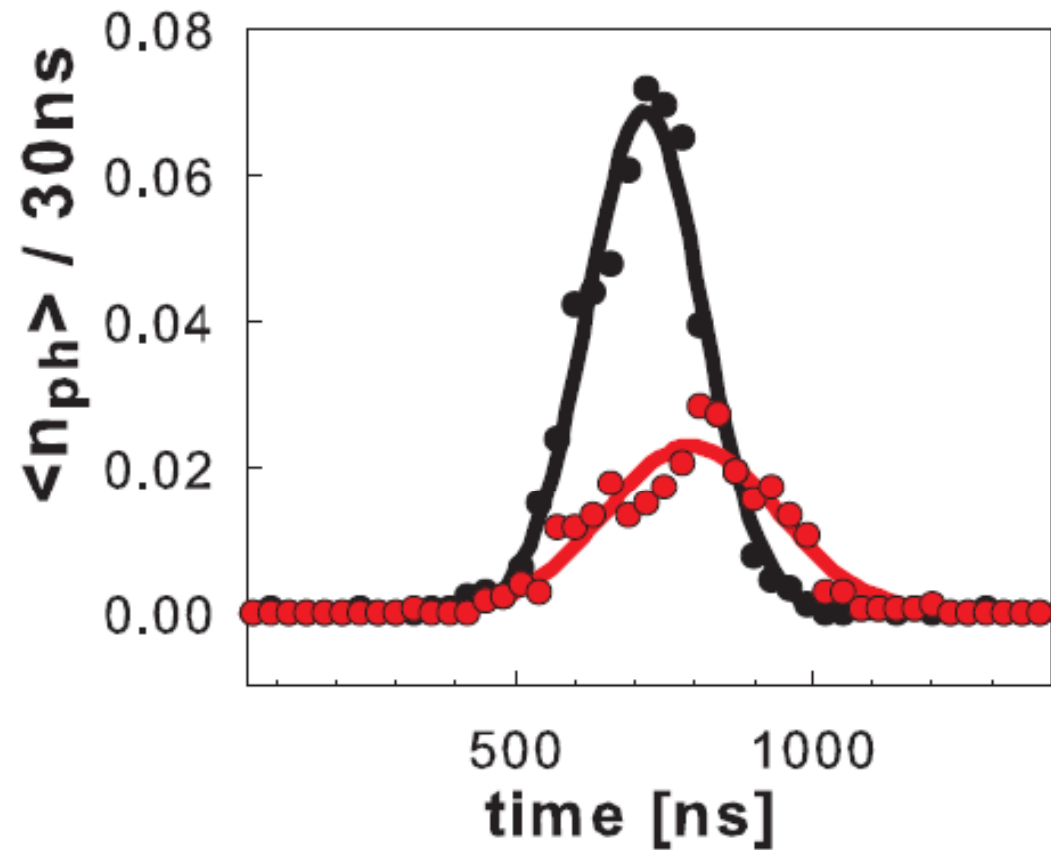
MM Kash, et al, PRL, 82, 5229 (1999) [hot vapor; ; $v_g \sim 90$ m/s]

Storage light





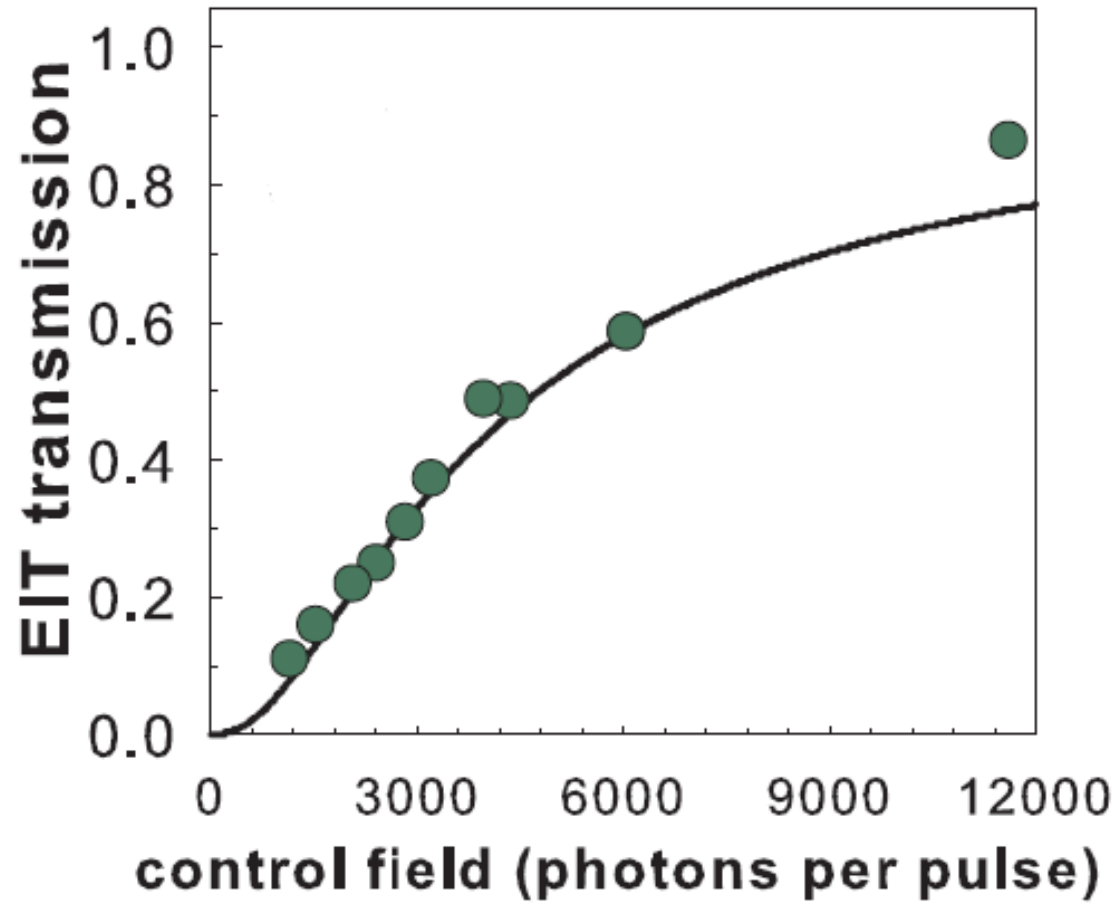
Slow light



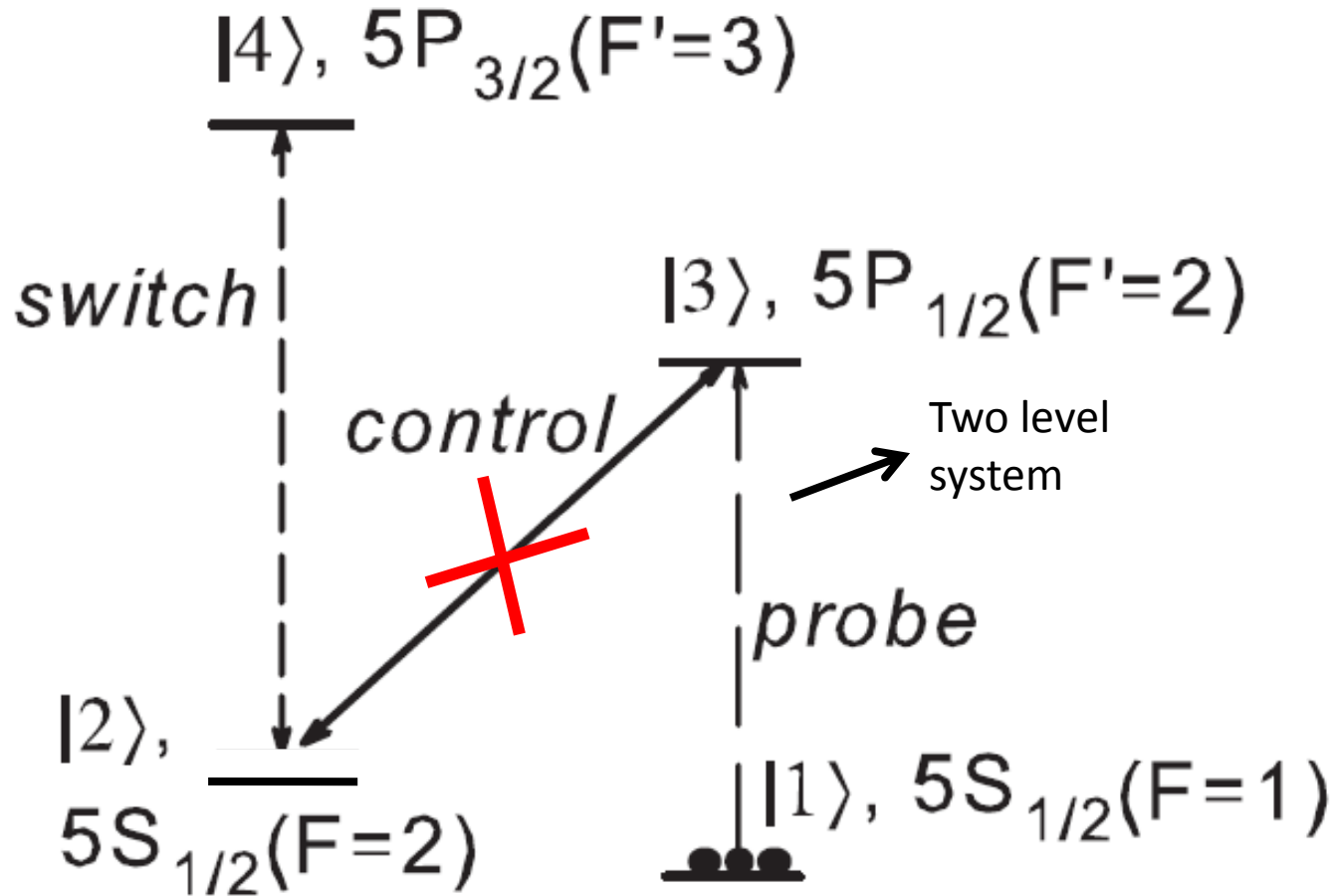
The EIT pulse (red) is delayed \sim 100 ns for control pulse containing \sim 3500 photons

$$v_g \sim 3 \text{ km/s}$$

Transmission in the EIT resonance



Four level N scheme



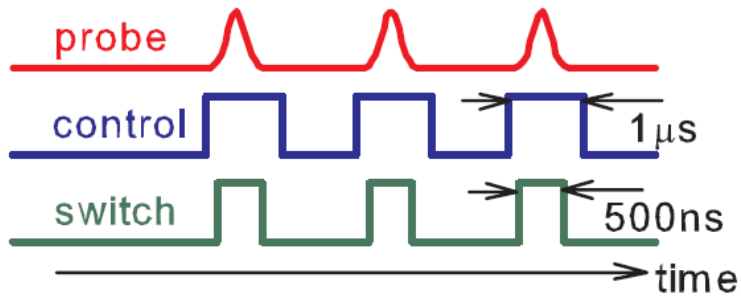
When switch is ON:

AC Stark Shift in $|2\rangle$

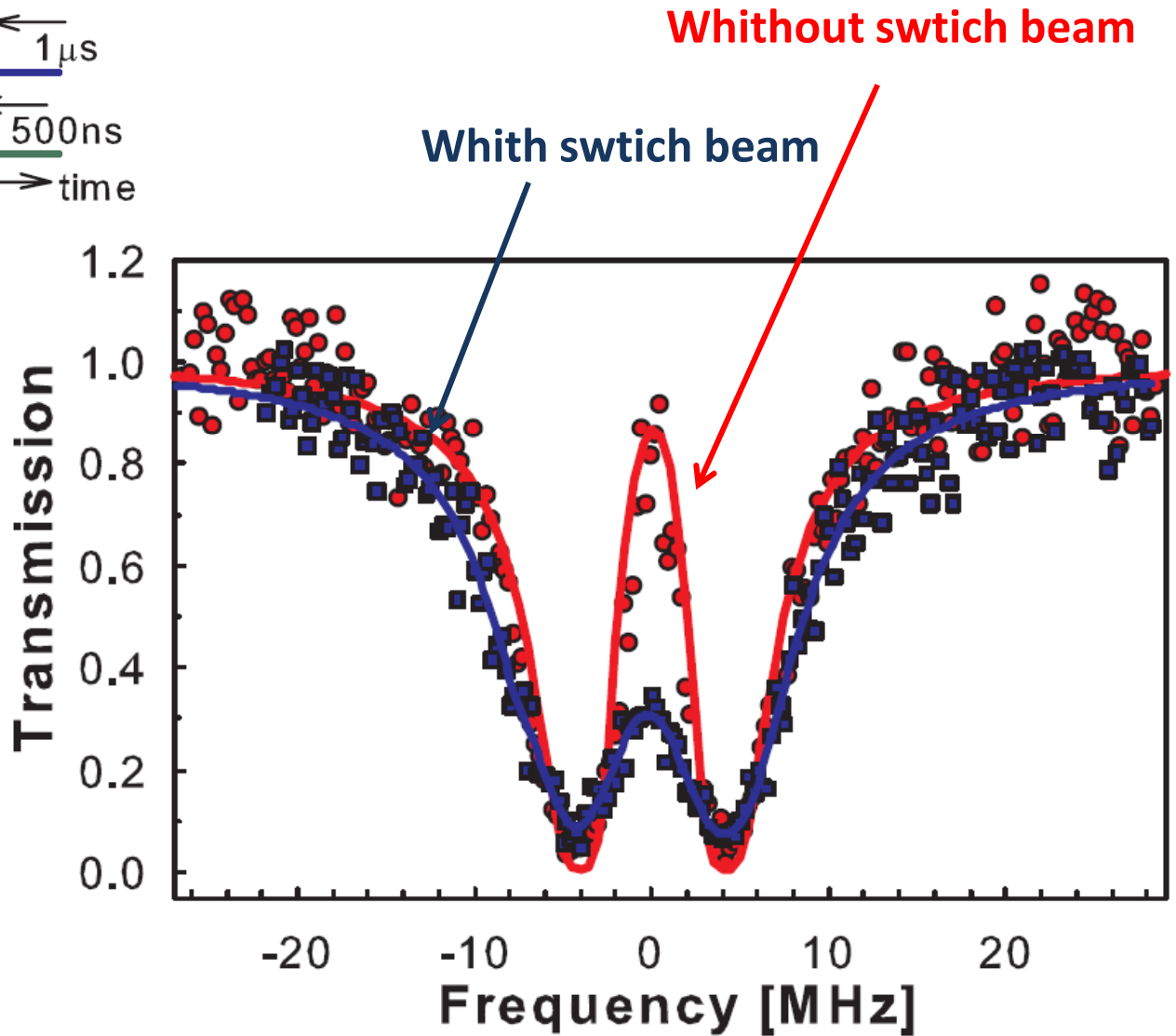
NO EIT effect

$$\chi^*(\omega_p) = \frac{K(|\Omega_{24}|^2 - 4\Delta\tilde{\omega}_c\Delta\tilde{\omega}_{24})}{4\Delta\tilde{\omega}_p\Delta\tilde{\omega}_c\Delta\tilde{\omega}_{24} - |\Omega_c|^2\Delta\tilde{\omega}_{24} - |\Omega_{24}|^2\Delta\tilde{\omega}_p}$$

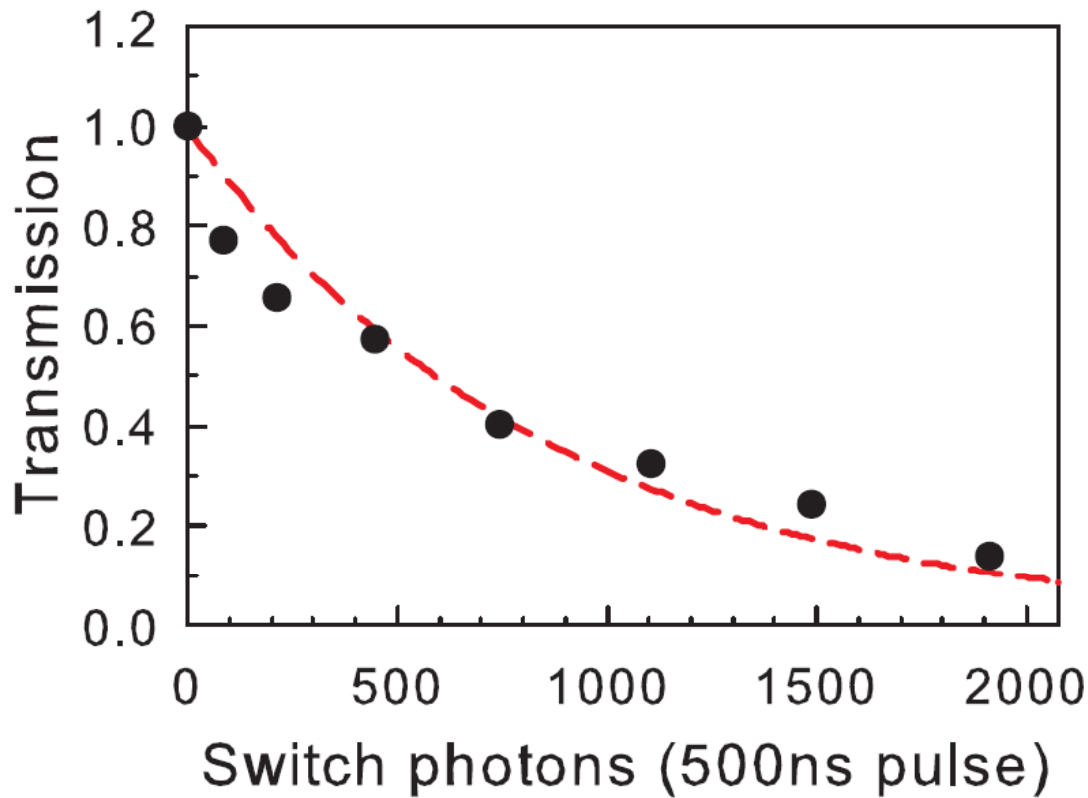
Switch using 4 level system



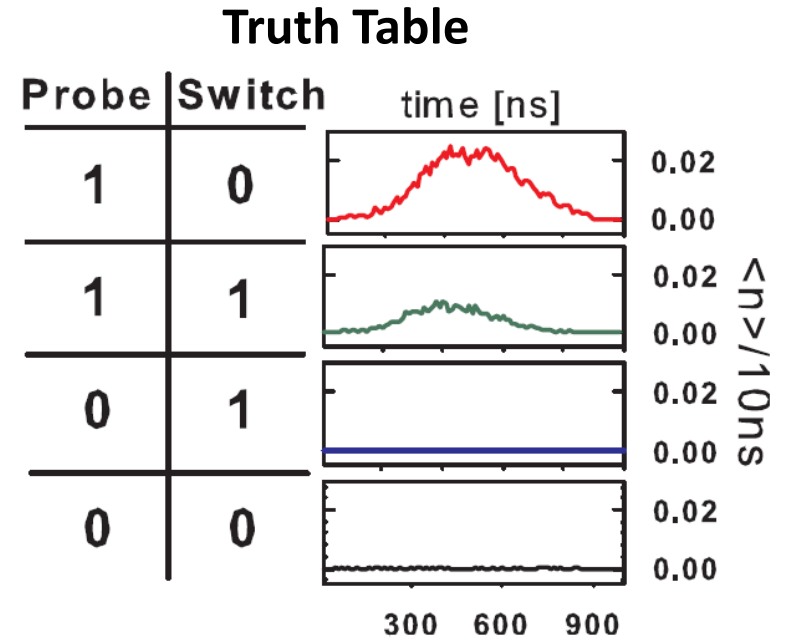
50% reduction
for 700 switch
photons



“ON” and “OFF” states of the switch



A contrast of over 90% between the “on” and “off” state of the switch is undesirable for practical applications.



Probe pulse containing on average 2 photons

1/e attenuation in presence of switch photons (~ 400 switch photons)

Summary

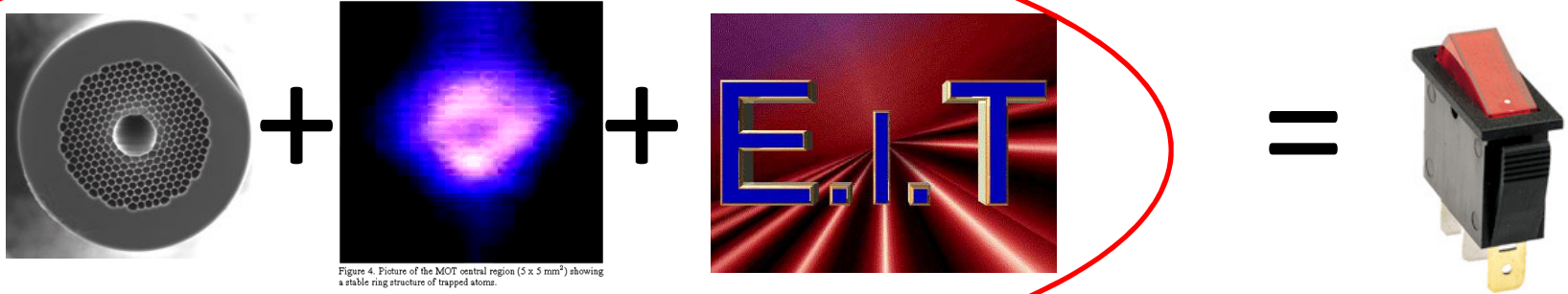
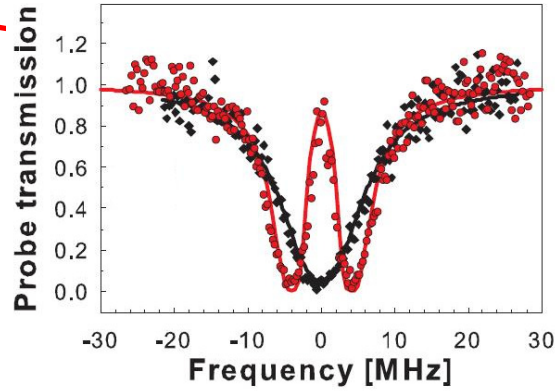


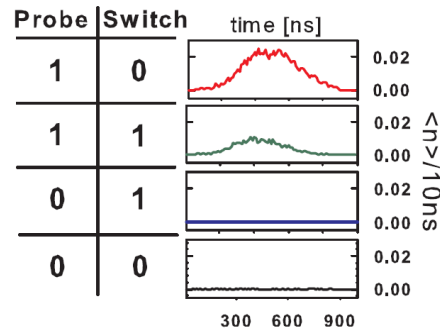
Figure 4. Picture of the MOT central region (5 x 5 mm²) showing a stable ring structure of trapped atoms.

Observed



with few photons

Implemented



with ~ 400 photons