Photon-Photon Interactions

VIT, One-photon transistor

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Rydberg polaritons

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Outline

- How to induce deterministic photon-photon interactions?

  For

  - All-optical switches (classical and quantum)
  - Photon-photon quantum gates
  - Quantum gas of interacting photons

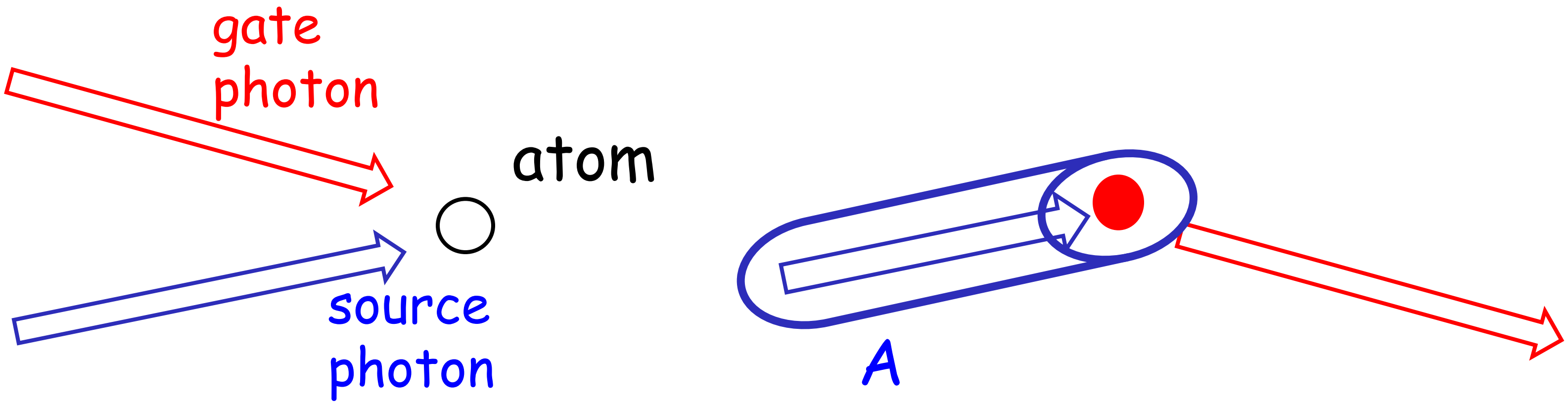
Outline

- Vacuum-induced transparency (VIT)
  - Induce transmission with an electromagnetic vacuum field;
- All-optical one-photon transistor
  - One photon controls one or many photons;
- Quantum nonlinear medium via Rydberg states
  - Optical medium that transmits one but absorbs two photons;
  - Attracting photons.

Goal: nonlinear optics with single-photons

How can one make light interact influence the propagation of other light?

Convert red photon into an atomic excitation, atom in other state can influence the propagation of blue photon, read out the red photon.

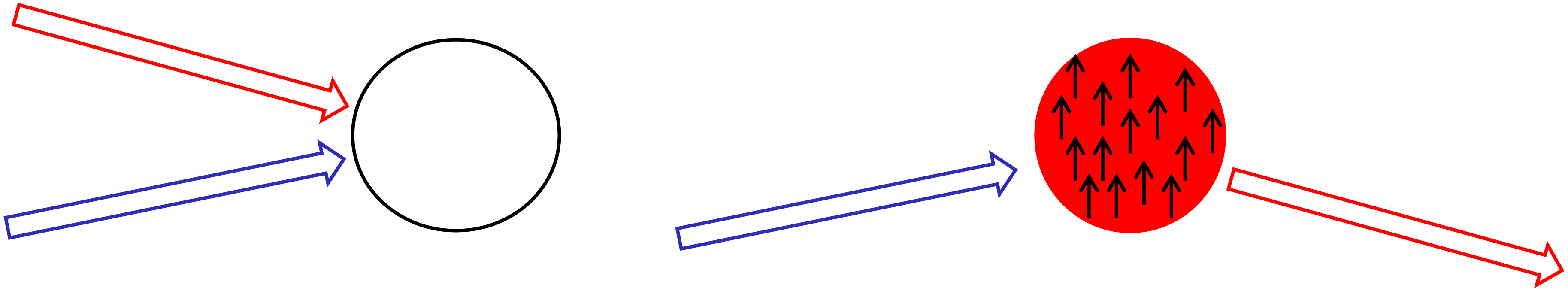


Two problems: i) one atom does not influence strongly the propagation of a light beam: $\sigma/A < \lambda^2/A < 1$.

ii) A single atom emits a red photon uniformly, not into incident mode.

Goal: nonlinear optics with single-photons

- **Mode-matching problem:** Convert atomic excitation coherently back to light propagating in definite direction: array of phased dipoles – electromagnetically induced transparency (EIT)



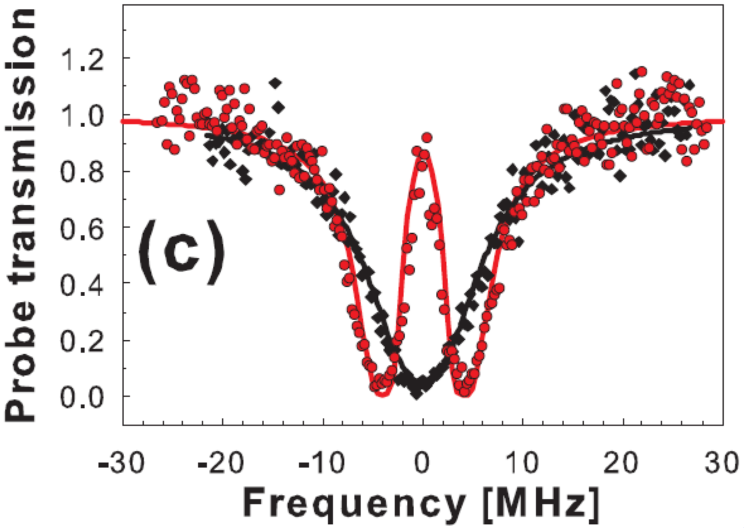
Strong interaction problem:

use cavity to multiply σ/A by number of photon round trips.

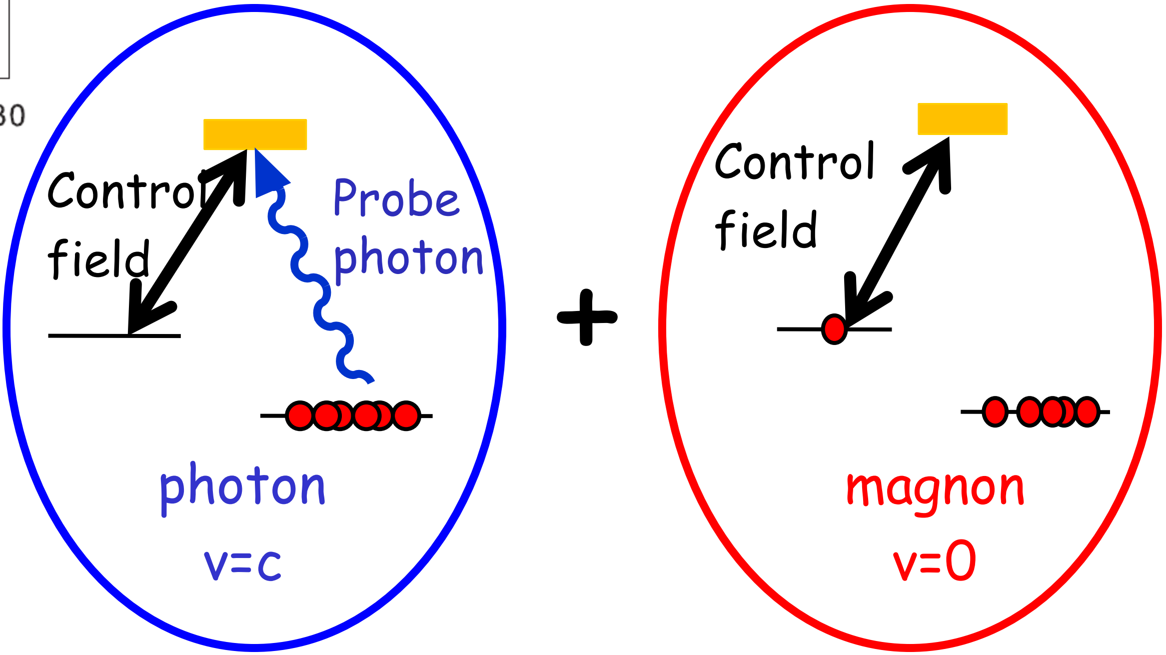
or

Use strongly interacting atomic states (Rydberg).

Electromagnetically Induced Transparency



- EIT produces slow light by converting photons into collective atomic (spin) excitations



slow-light polariton 0 < v < c = photon + magnon

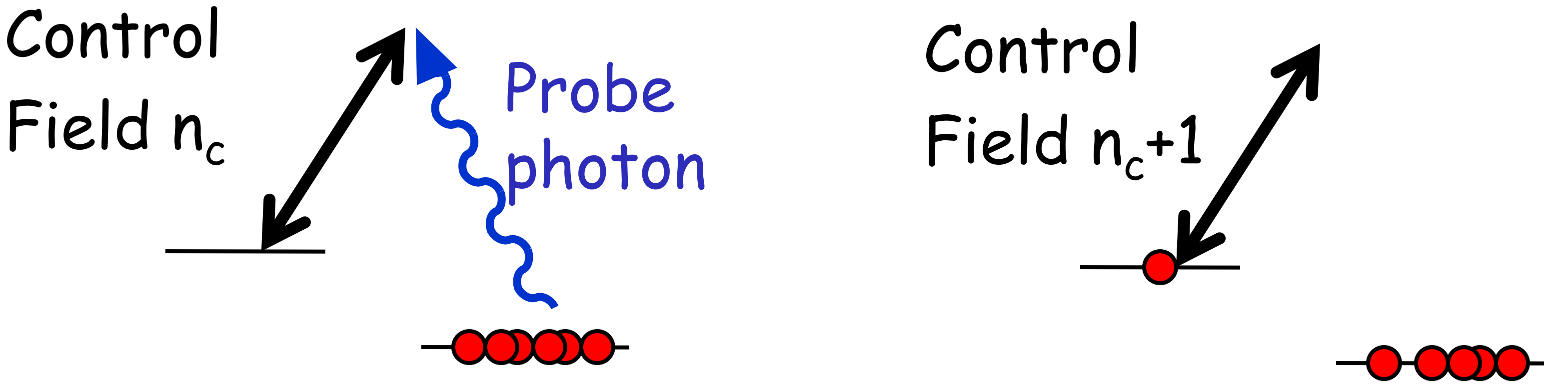
Strength of control field determines probability amplitudes and speed of polariton: EIT linear in probe field

Vacuum-induced transparency

H. Tanji-Suzuki, W. Chen, R. Landig, J. Simon, and V. Vuletic, Science **333**, 1266 (2011).

From EIT to VIT

- EIT is linear because control field is classical, i.e. $n_c \approx n_c+1$
- If n_c could be made small, then there would be strong nonlinearity:
- $n_c = 0$: vacuum-induced transparency, VIT



Control Field n_c

Probe photon

Control Field n_c+1

Vacuum-induced transparency

- J. E. Field, Phys. Rev. A 47, 5064 (1993).

Strongly coupled cavity can play role of control field.

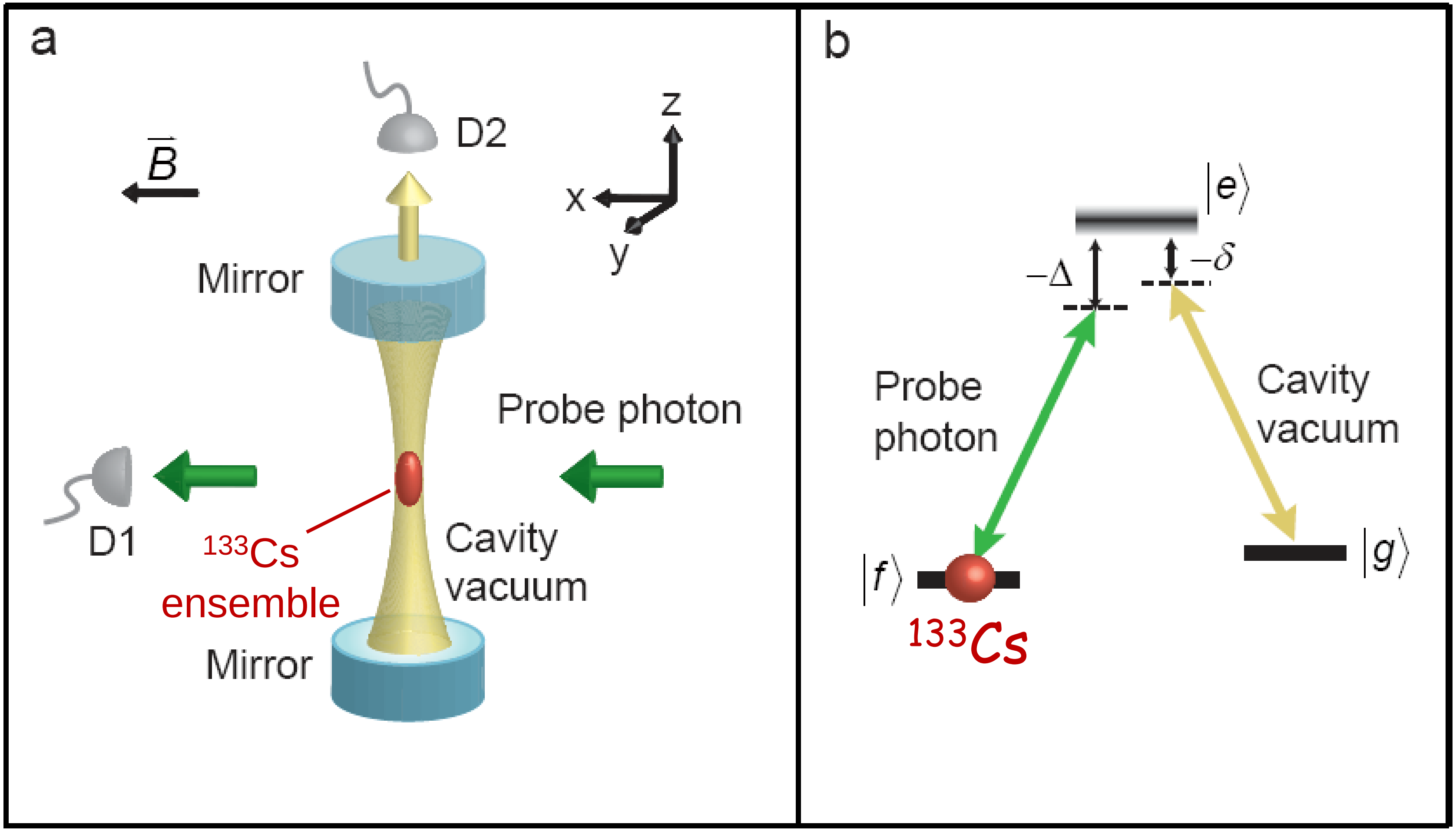
- Nikoghosyan and Fleischhauer, PRL **104**, 013601 (2010):

nonlinearity can be used for dispersive photon Fock state filter

Single-atom work on EIT with cavity

- Rempe group: M. Mucke, *et al.*, *Nature* **465**, 755 (2010).
- Meschede group: T. Kampschulte, et al., Phys. Rev. Lett. **105**, 153603 (2010).
- Blatt group: L. Slodicka *et al.*, Phys. Rev. Lett. **105**, 153604 (2010).
- Above systems use cavity on probe leg to enhance the probe interaction with single atom
- Vacuum-induced transparency is different: cavity replaces control field, rather than enhancing probe field.

Setup for observing VIT



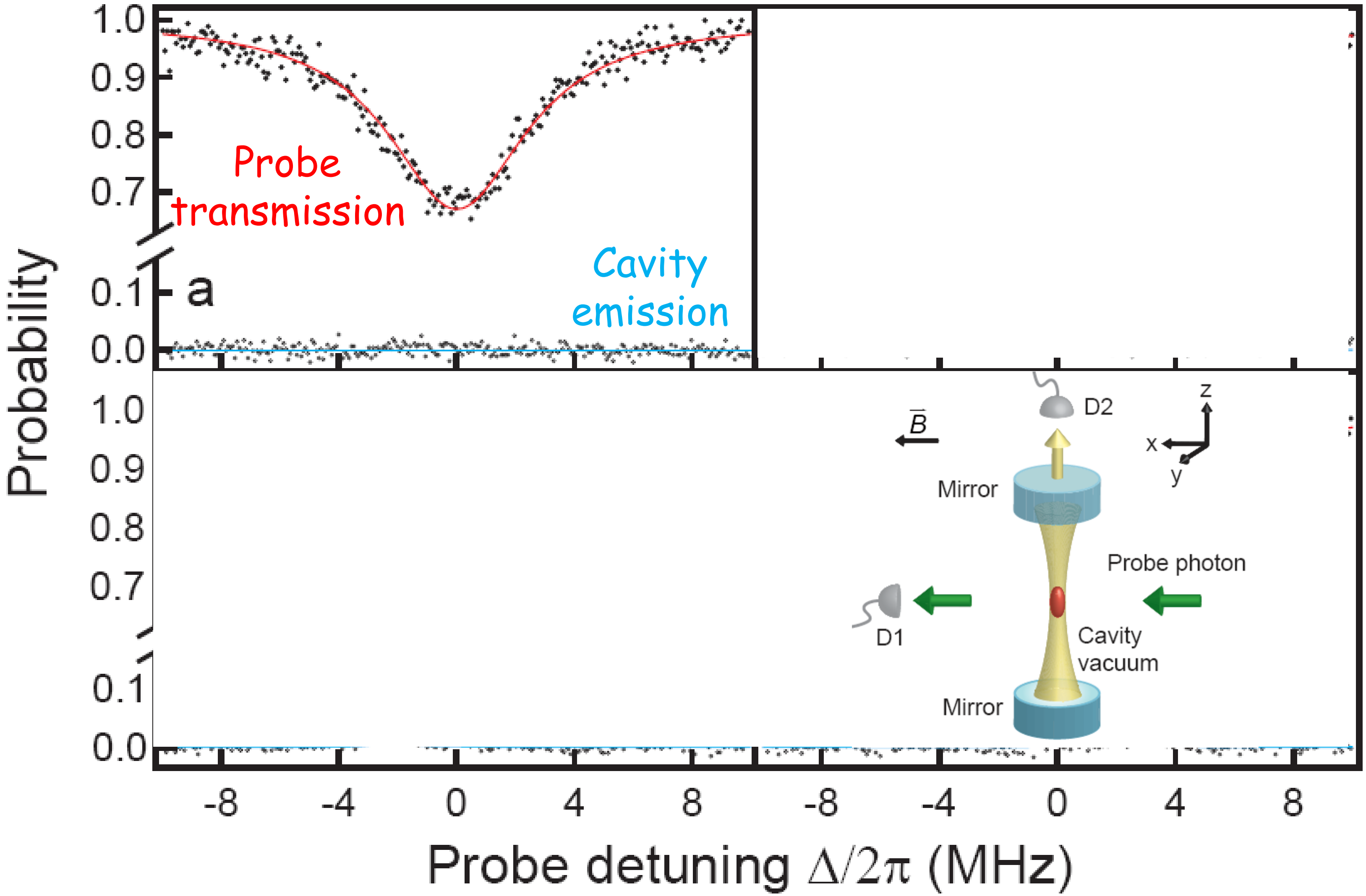
Large strongly coupled cavity

Cavity parameters:

Length	1.4 cm
Finesse	6×10^4
Waist	35 μm
Cavity linewidth	2π 160 kHz
Atomic linewidth	2π 5.2 MHz
vacuum Rabi freq.	2π 1.3 MHz
Cooperativity	8.1

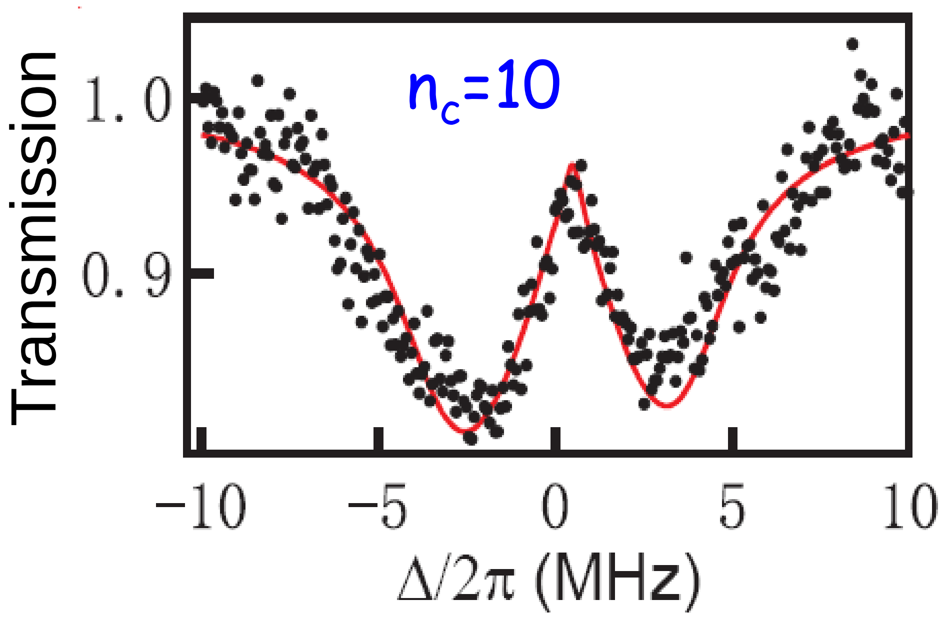
$\Gamma > g > \kappa$

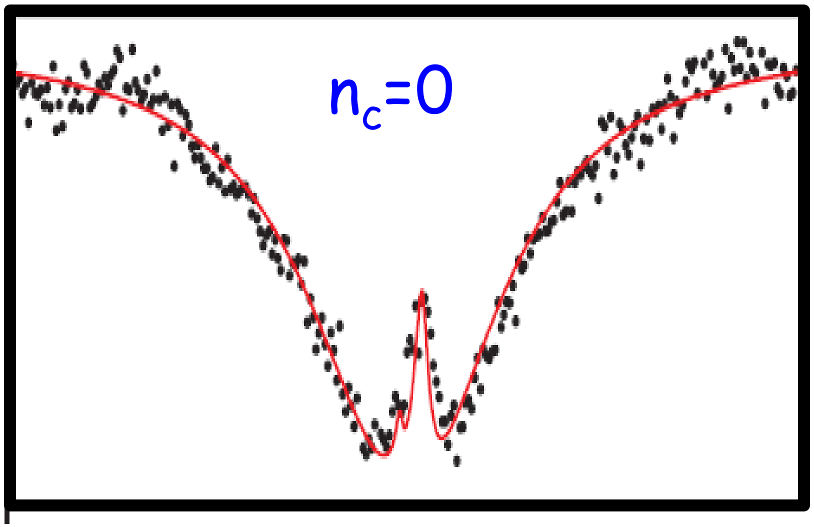
Probe transmission and VIT

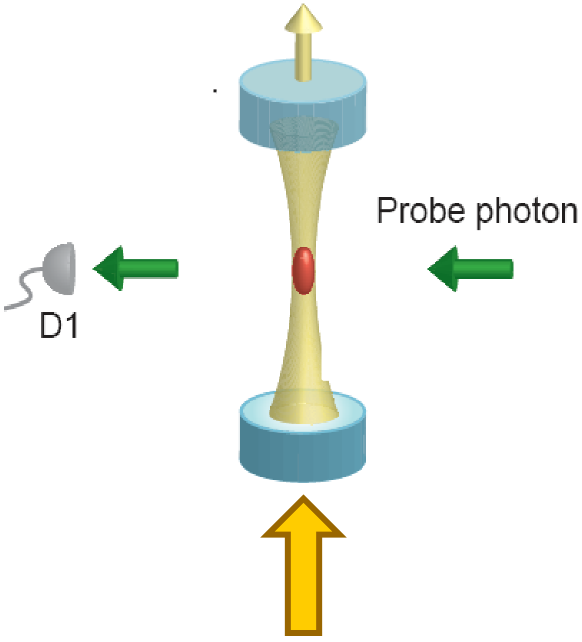


H. Tanji-Suzuki, W. Chen, R. Landig, J. Simon, and V. Vuletic, Science **333**, 1266 (2011).

From VIT to EIT: $n_c>0$

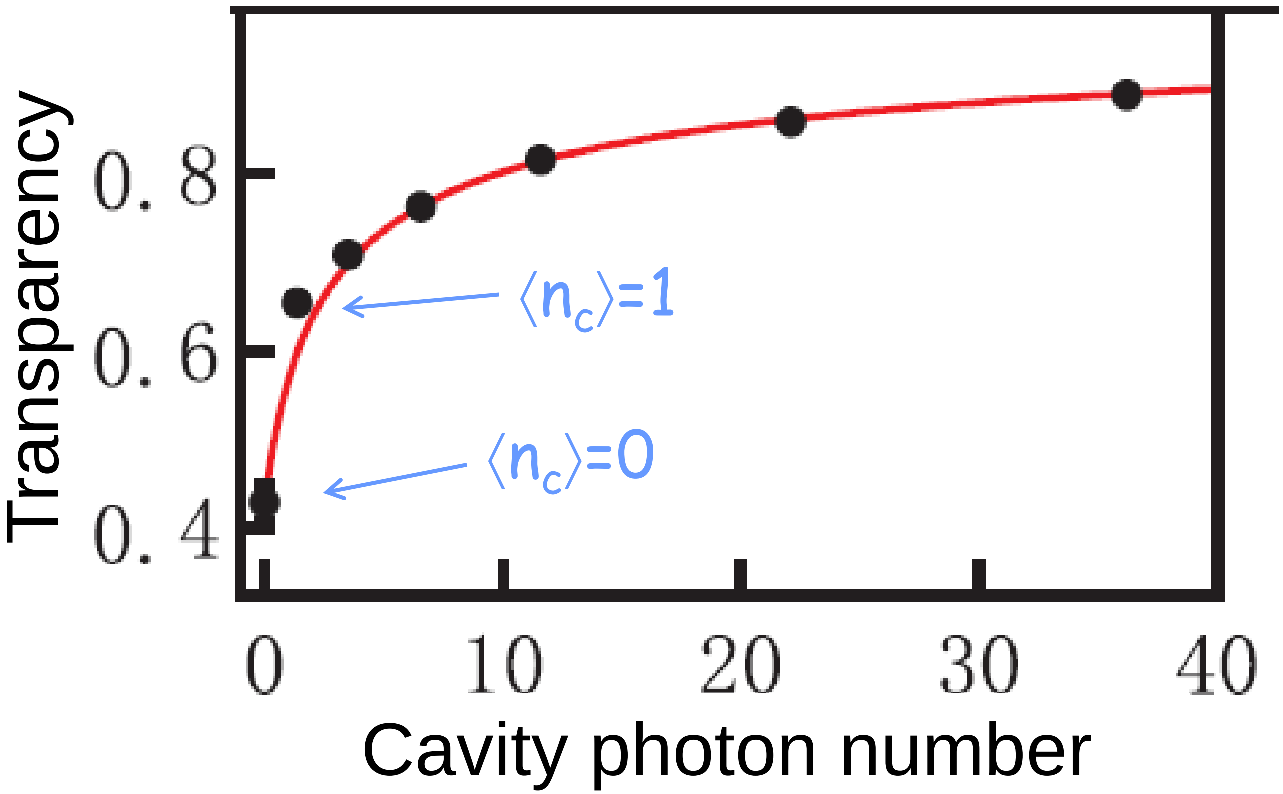






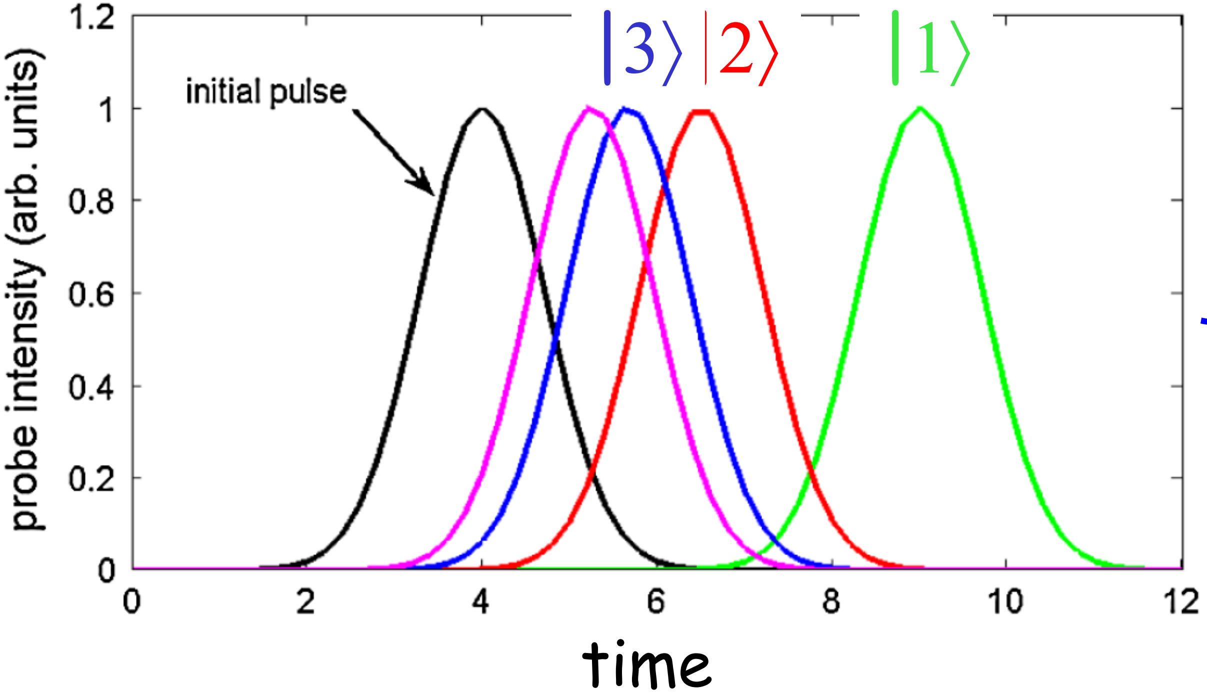
Fill cavity with control photons

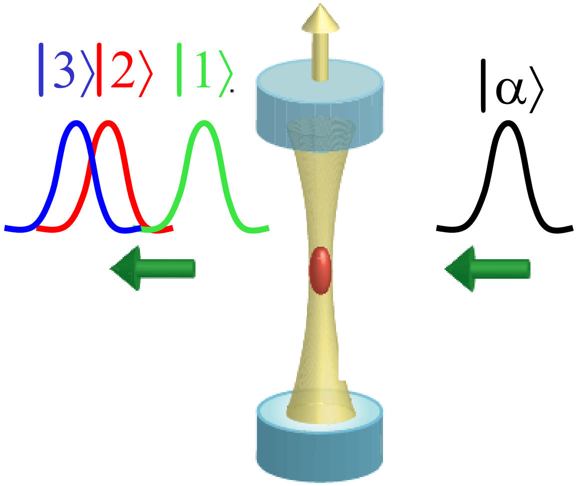
From VIT to EIT: transparency vs. cavity photon number



Strong nonlinearity: One cavity photon substantially changes probe transmission

Dispersive photon Fock state filter



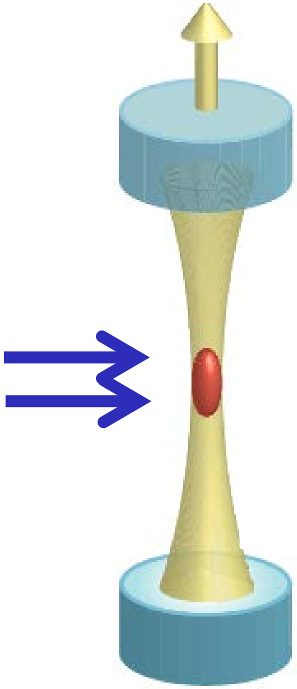


Nikoghosyan and Fleischhauer, PRL **104**, 013601 (2010).

Requires large cooperativity and large optical depth

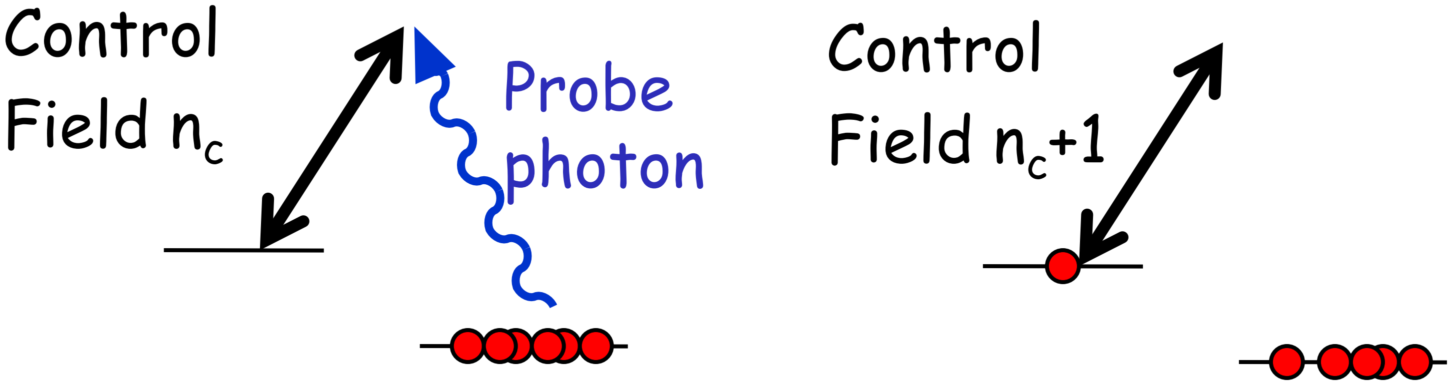
$\eta \sim OD \gg 1$

Infinite-range photon-photon interaction



Two photons incident on different parts of the ensemble interact via the cavity mode:

Each photon influences the other's group velocity, phase.

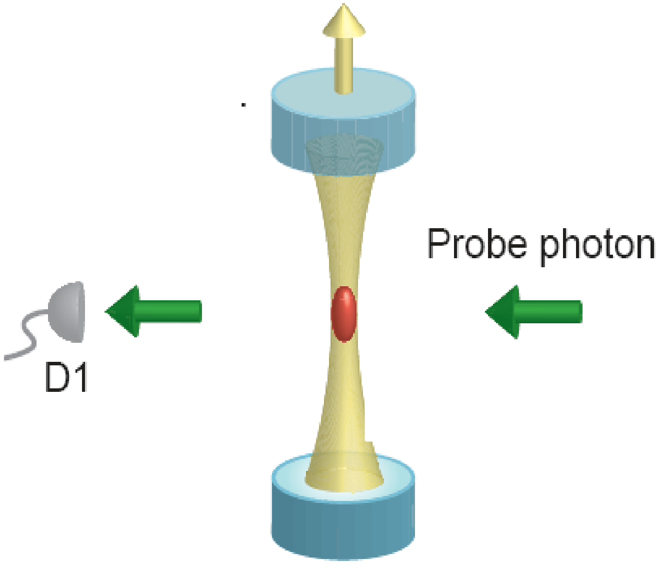


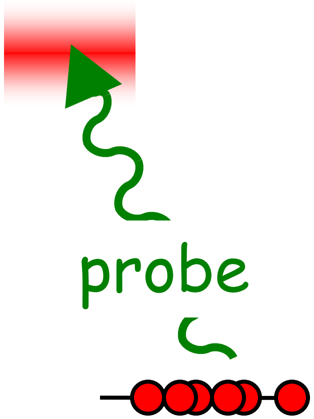
Control Field n_c

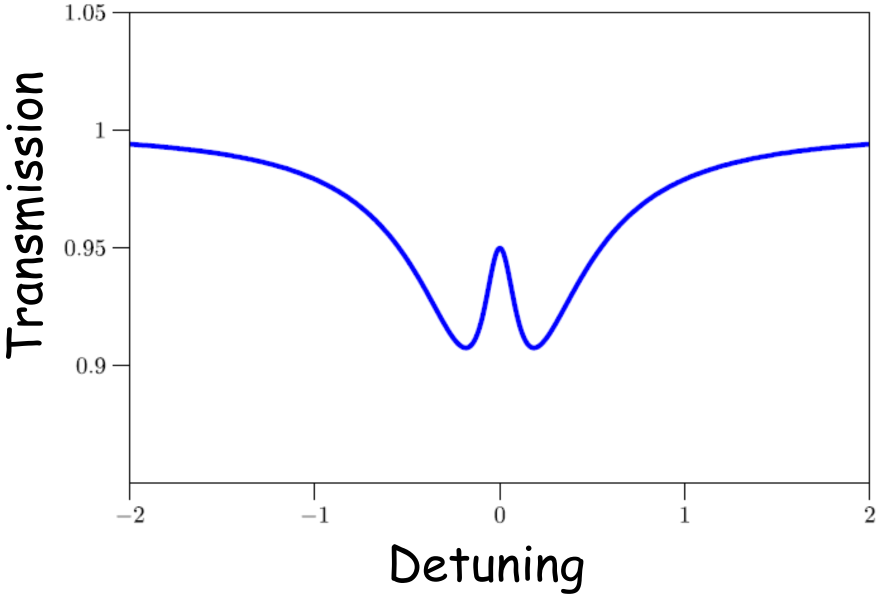
Probe photon

Control Field n_c+1

Vacuum-induced transparency for two-level atoms?







Transparency as cavity field cancels incident field at atom:

free space emission suppressed, dominant decay via cavity

Alsing, Cardimona, and Carmichael, PRA **45**, 1793 (1992).

P. R. Rice, R. J. Brecha, Opt. Comm. **126**, 230 (1996).

Classical description: Tanji-Suzuki et al., Adv. At. Mol. Opt. Phys. **60**, 201-237 (2011), quant-ph 1104.3594.

One-photon optical switch and transistor

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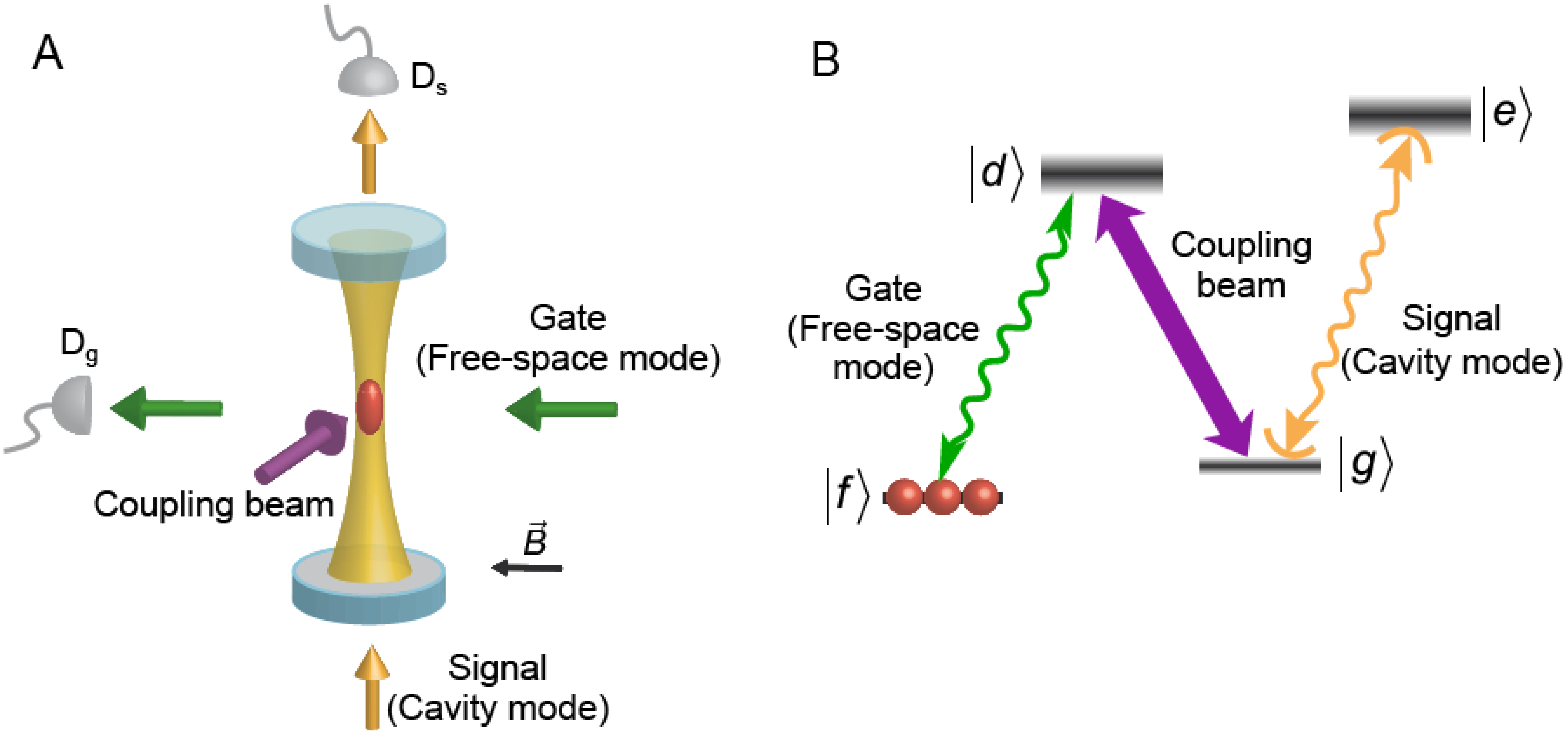
Michael Gullans
Mikhail Lukin

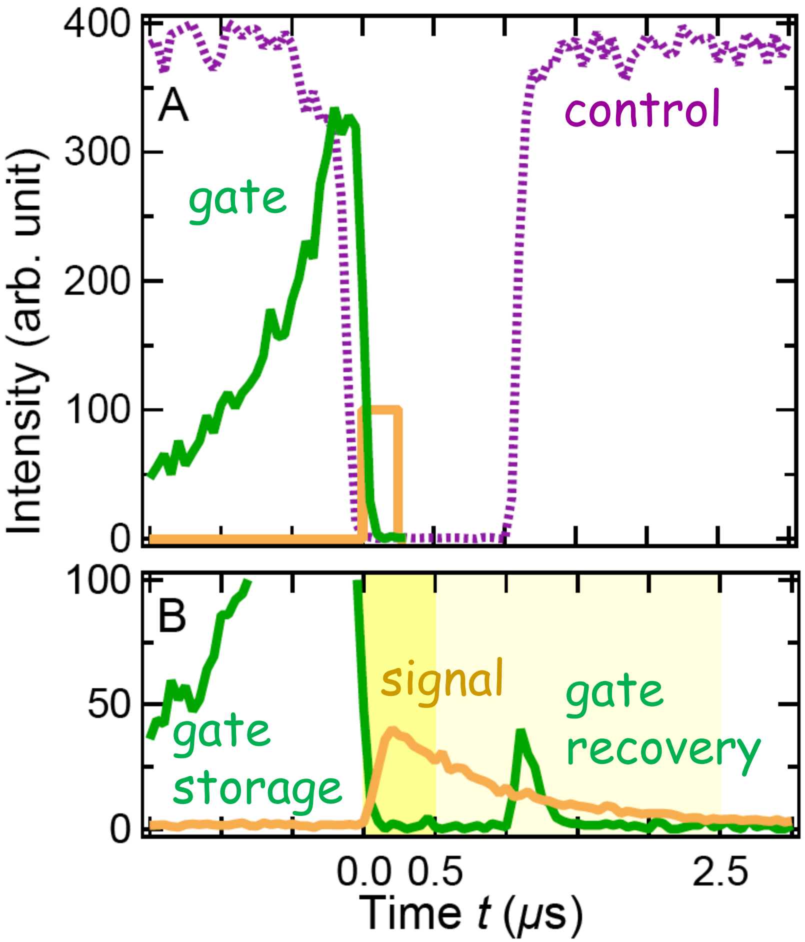
Wenlan Chen, Kristin Beck, Michael Gullans, Mikhail Lukin, Haruka Tanji-Suzuki, and Vladan Vuletic, submitted (2013).

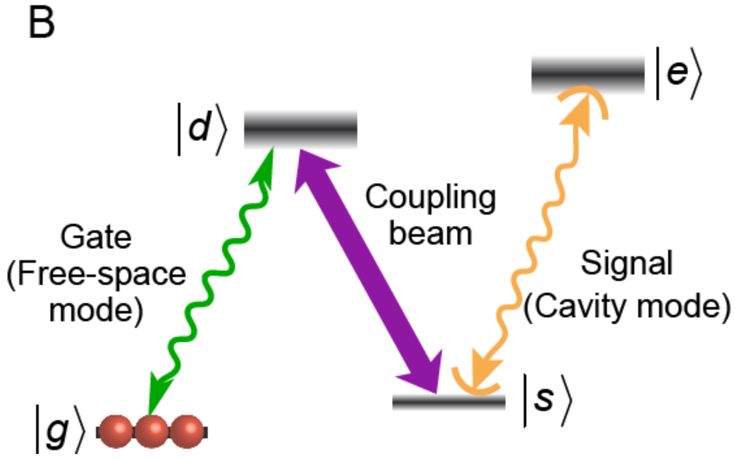
EIT nonlinearity in four-level system



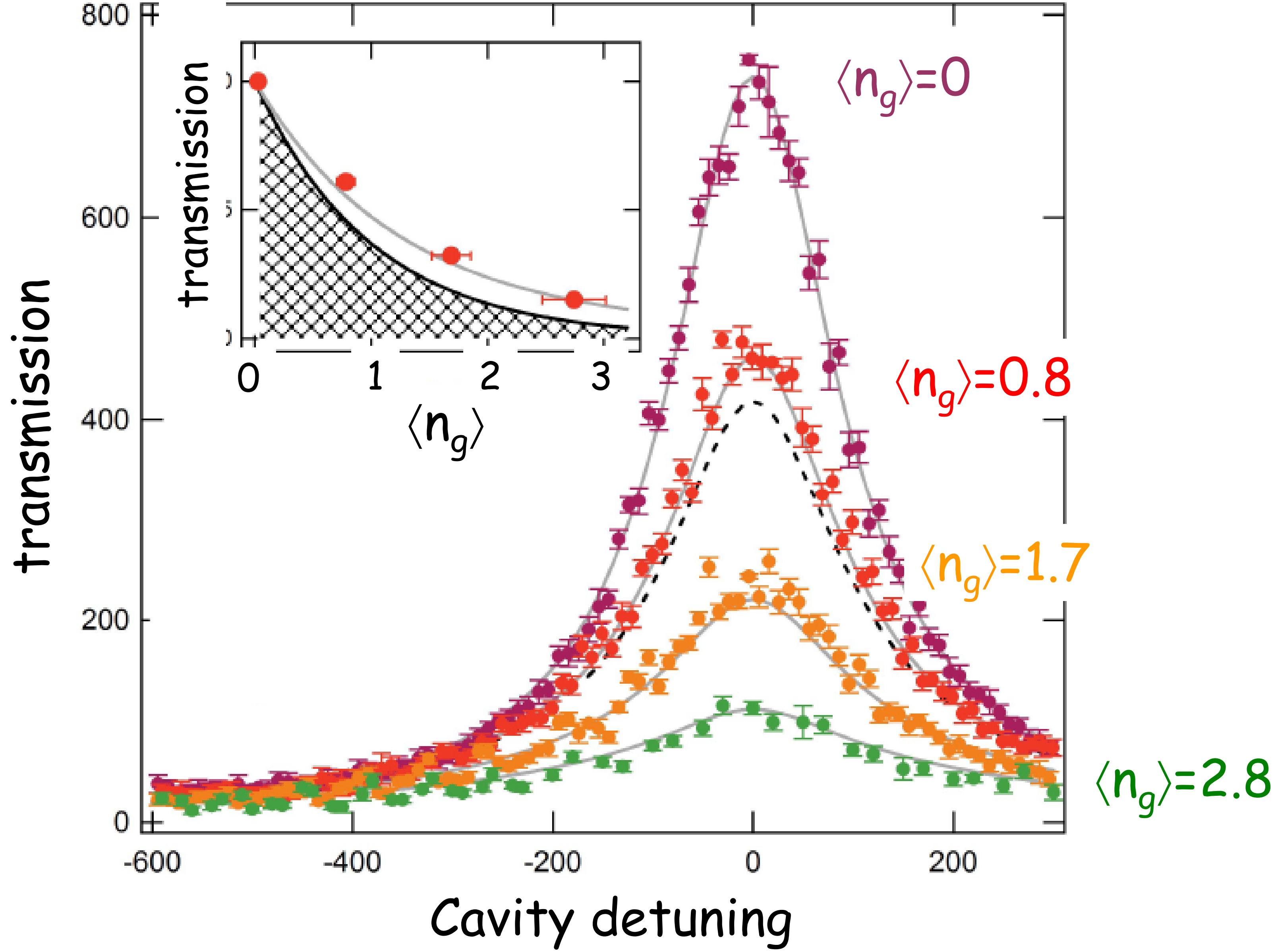
e.g., Imamoglu, Woods, Schmidt & Deutsch, PRL **79**, 1467 (1997);
S. Harris & Y. Yamamoto, PRL **81**, 3611 (1998);

Transistor with stored gate photon

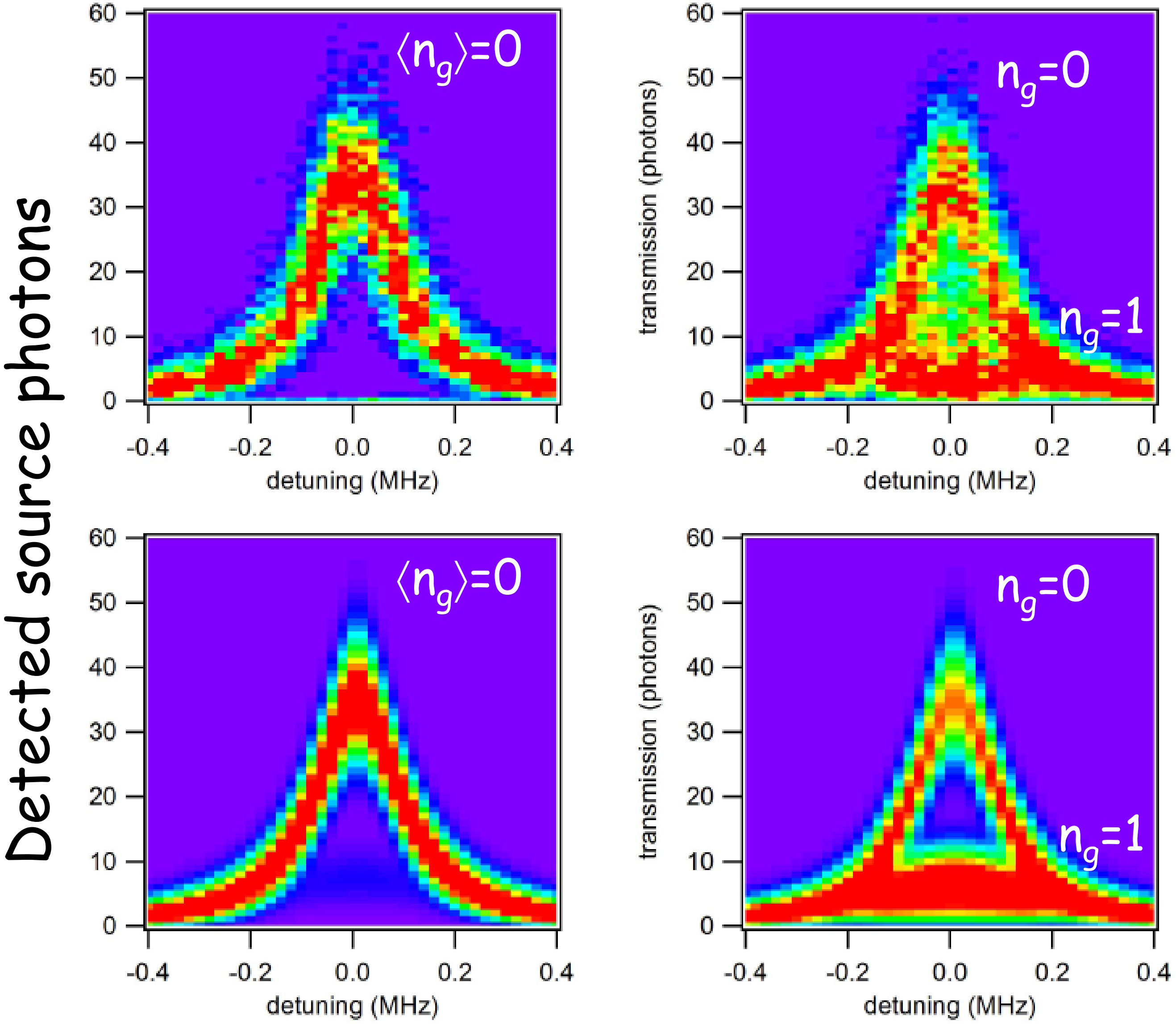




Cavity transmission vs. gate photon number



Histograms of cavity transmission

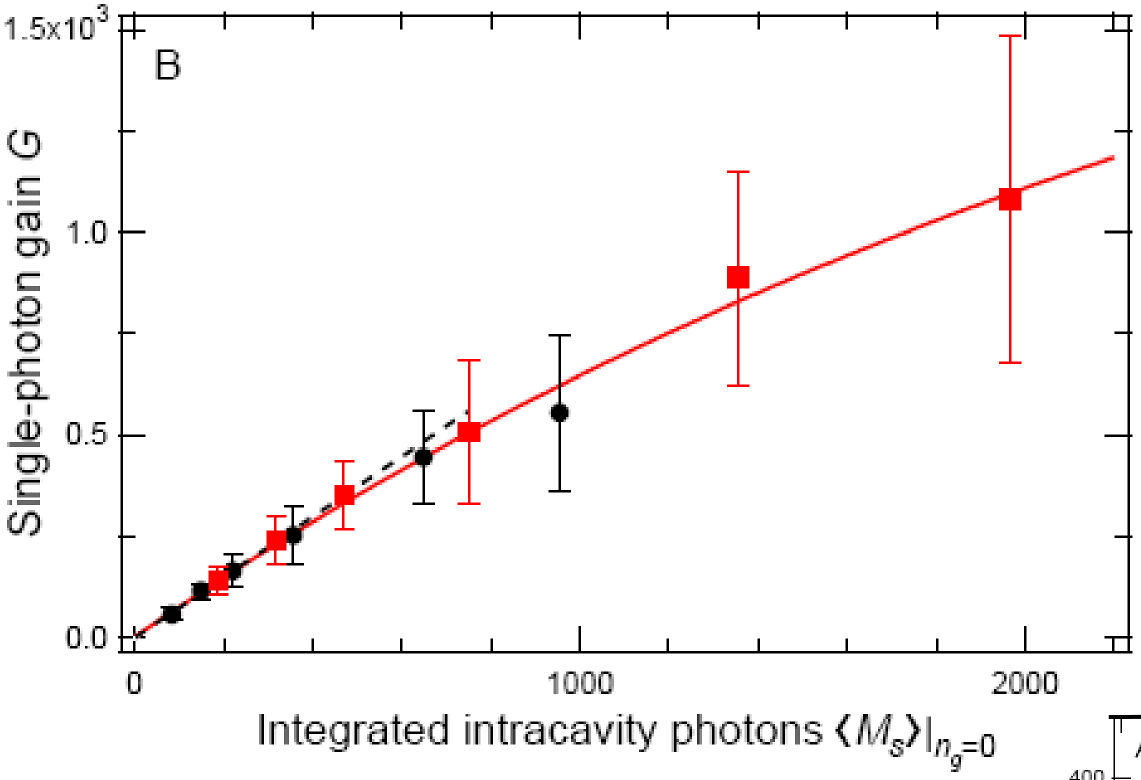


experiment

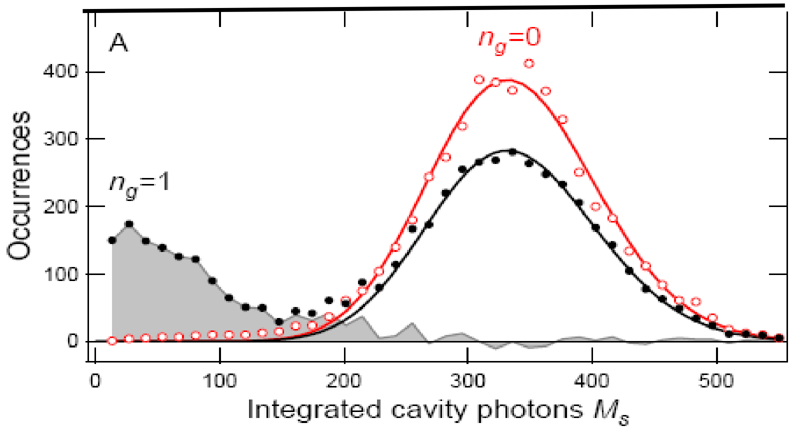
Clear separation of gate photon number states zero and one.

theory

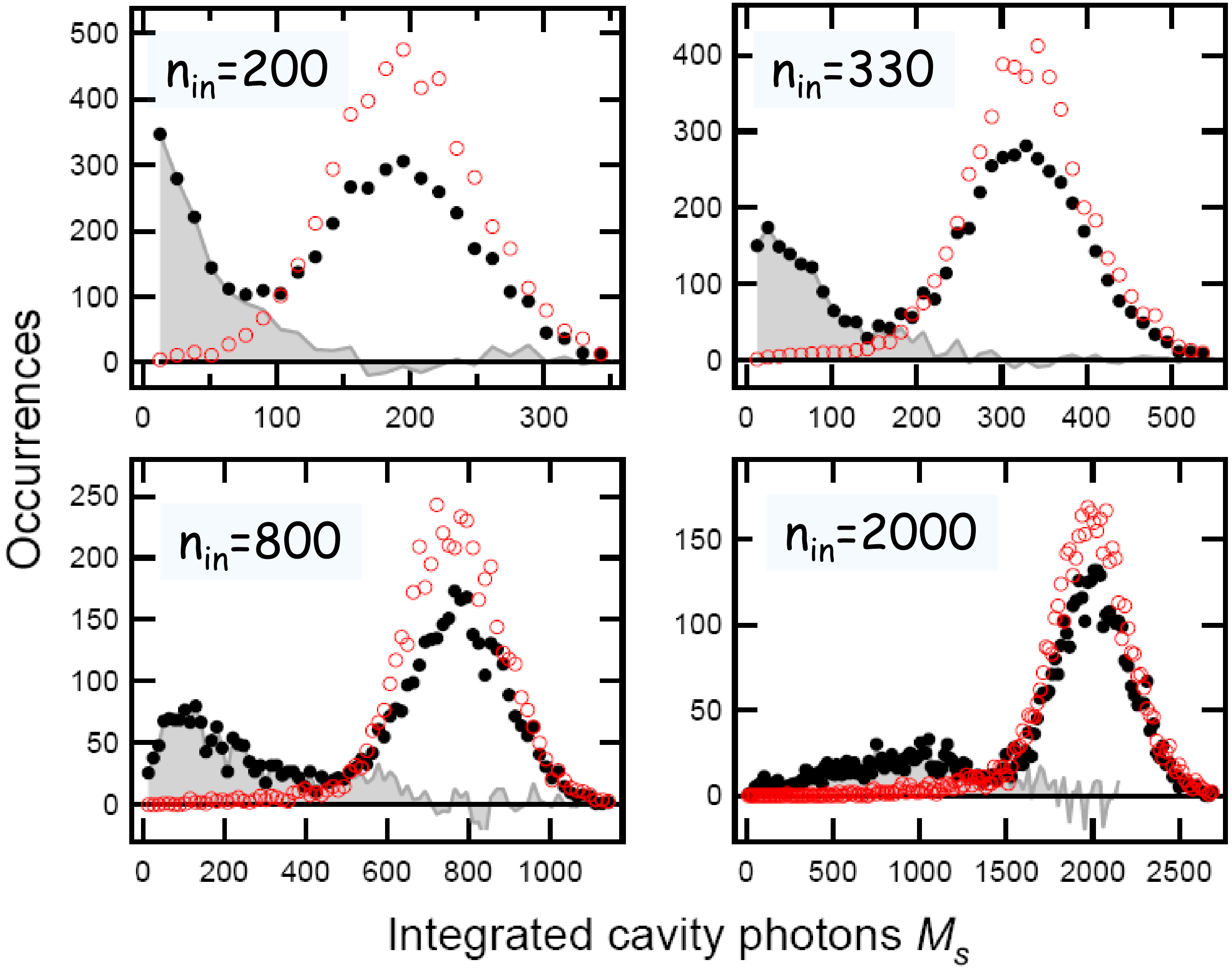
Single-photon transistor with gain: switching 1000 photons with one



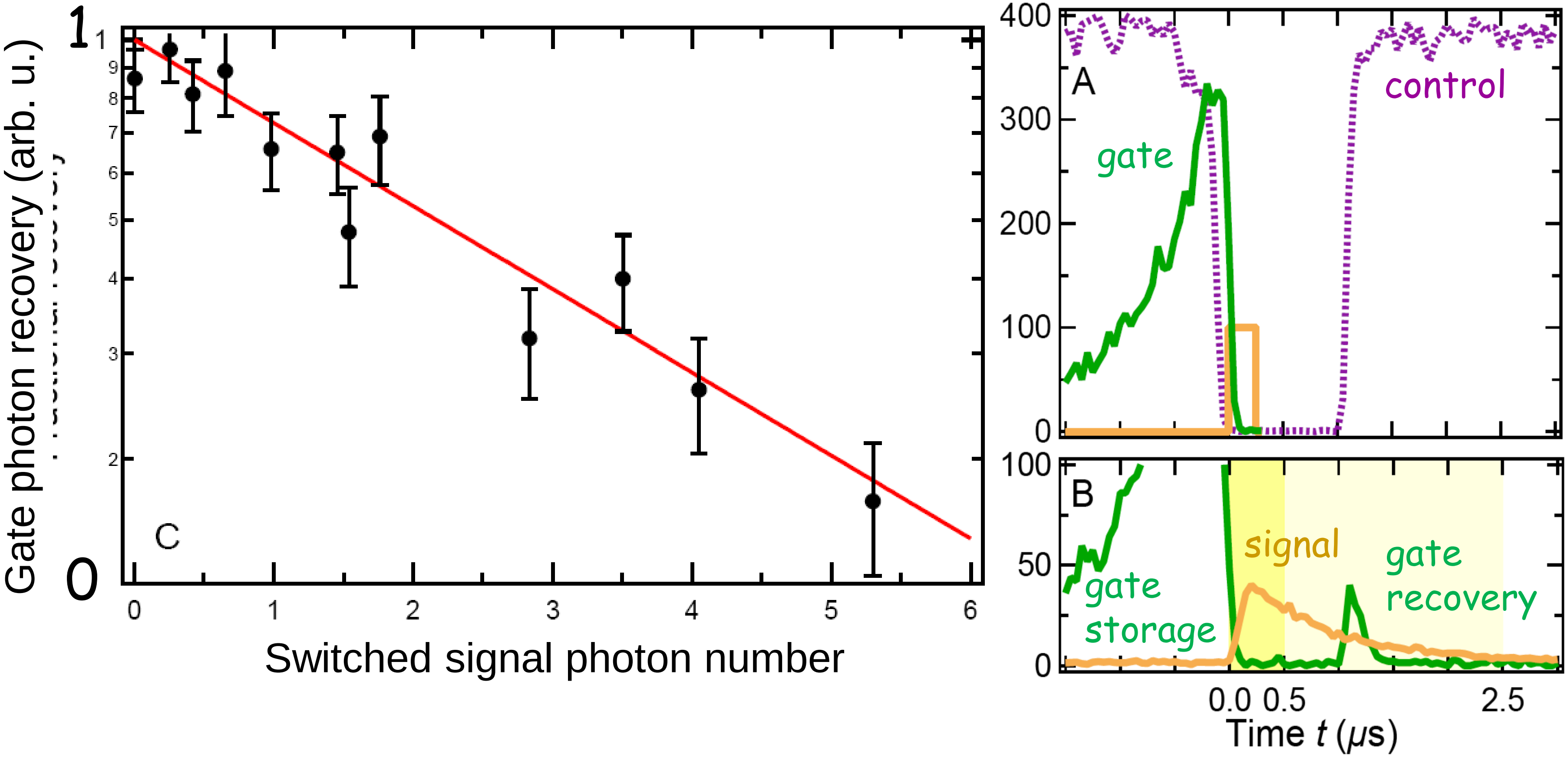
Gain saturation at G~2000 presumably due to optical pumping to other sublevels with weaker coupling to cavity.



Gain saturation: optical pumping



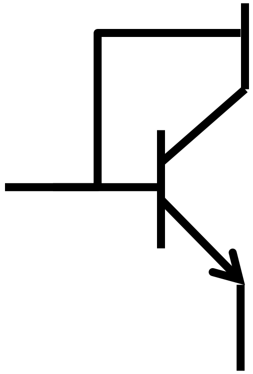
Transistor with recovered gate photon

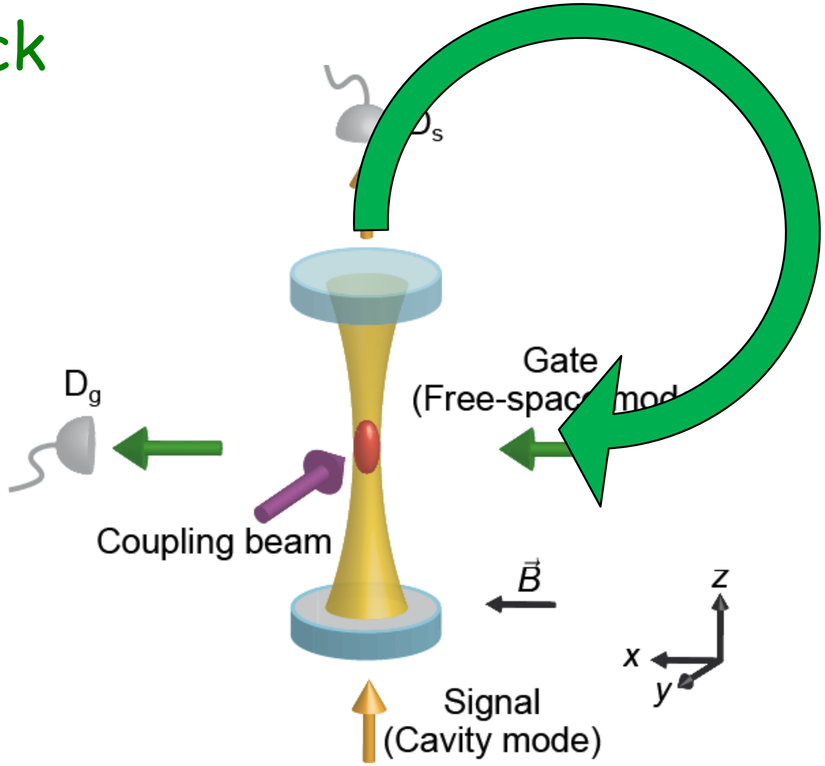


Non-demolition gain: 2.3 signal photons can be switched while recovering gate photon with 1/e probability.

Future possibilities

- Quantum non-demolition detector for traveling optical photons
- NOON state preparation
- Photon-photon quantum gates?
- All-optical circuits with feedback and gain in analogy to electronic circuits





Single-photon nonlinearity by means of Rydberg polaritons

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Ofer Firstenberg
Thomas Pohl

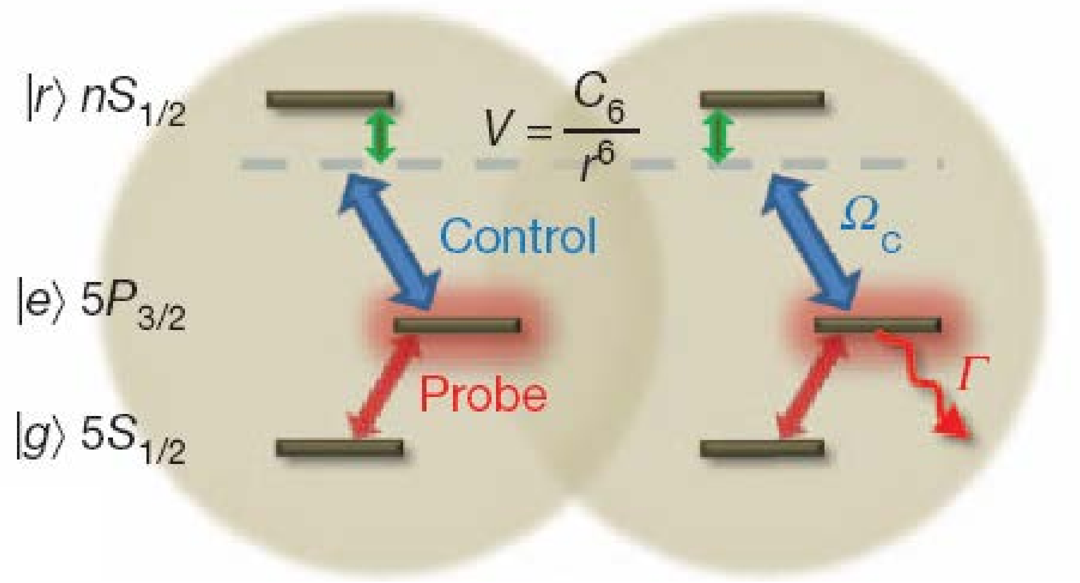
Qiyu Liang
Alexey Gorshkov
Mikhail Lukin

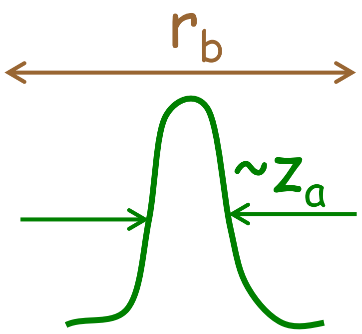
T. Peyronel, O. Firstenberg, Q.-Y. Liang, S. Hofferberth, A.V. Gorshkov, T. Pohl, M.D. Lukin, and V. Vuletic, Nature **488**, 57-60 (2012).

Rydberg atoms for quantum control

- Nonlinearities in Rydberg excitation
  - Tong, D. et al. Local blockade of Rydberg excitation in an ultracold gas. PRL **93**, 063001 (2004);
  - Singer et al., PRL **93**, 163001 (2004);
  - Liebisch et al., PRL **95**, 253002 (2005);
  - Heidemann et al. , PRL **100**, 033601 (2008).
- Quantum gate between two Rydberg atoms
  - Urban et al., Nature Phys. **5**, 110–114 (2009);
  - Gaetan et al., Nature Phys. **5**, 115–118 (2009).
- EIT with Rydberg atoms (classical regime, but same idea as this work)
  - Pritchard et al., PRL **105**, 193603 (2010).
- Theory work
  - Lukin et al., PRL **87**, 037901 (2001);
  - Petrosyan, Otterbach, & Fleischhauer, PRL **107**, 213601 (2011);
  - Gorshkov et al., PRL **107**, 133602 (2011);
  - Muller, Lesanovsky, Weimer, Buechler, & Zoller, PRL **102**, 170502 (2009).

EIT with interacting Rydberg atoms





Very strong Rydberg-Rydberg interaction (~THz at 1 μm) prevents excitation of two Rydberg atoms within some blockade radius r_b

-> Rydberg slow-light polaritons cannot coexist within r_b.

Size of Rydberg polariton ~ resonant attenuation length $z_a \times \sqrt{OD}$

-> expect single photon nonlinearity for $z_a < r_b$, i.e. at high atomic density.

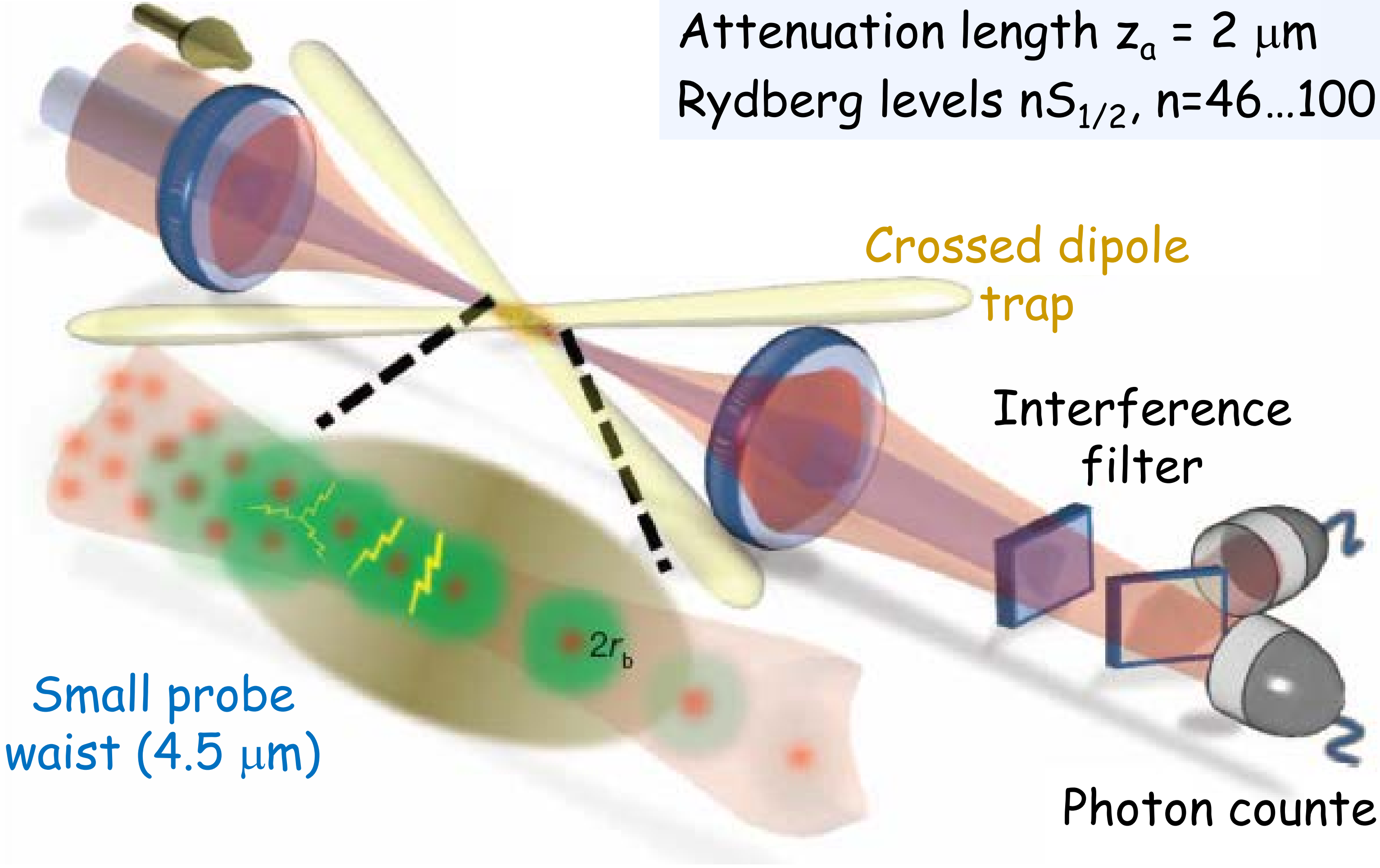
Our system: $z_a < 2\mu m$ $r_b \geq 10\mu m$

Experimental setup

Ultracold high-density ^{87}Rb ensemble (10^{12} cm^{-3})

Attenuation length z_a = 2 μm

Rydberg levels $nS_{1/2}$, n=46…100



Continuous probe and control beams

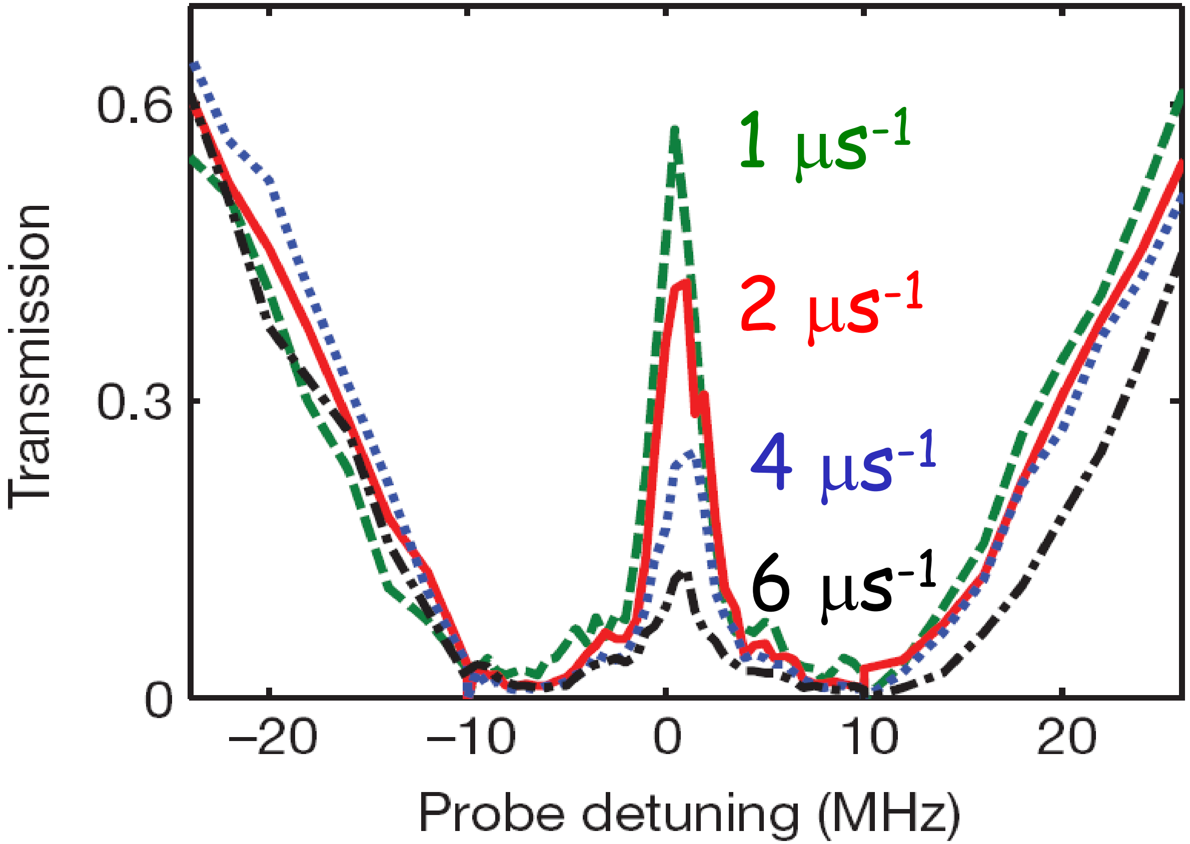
Crossed dipole trap

Interference filter

Photon counters

Small probe waist (4.5 μm)

Rydberg EIT spectra for different probe photon rates

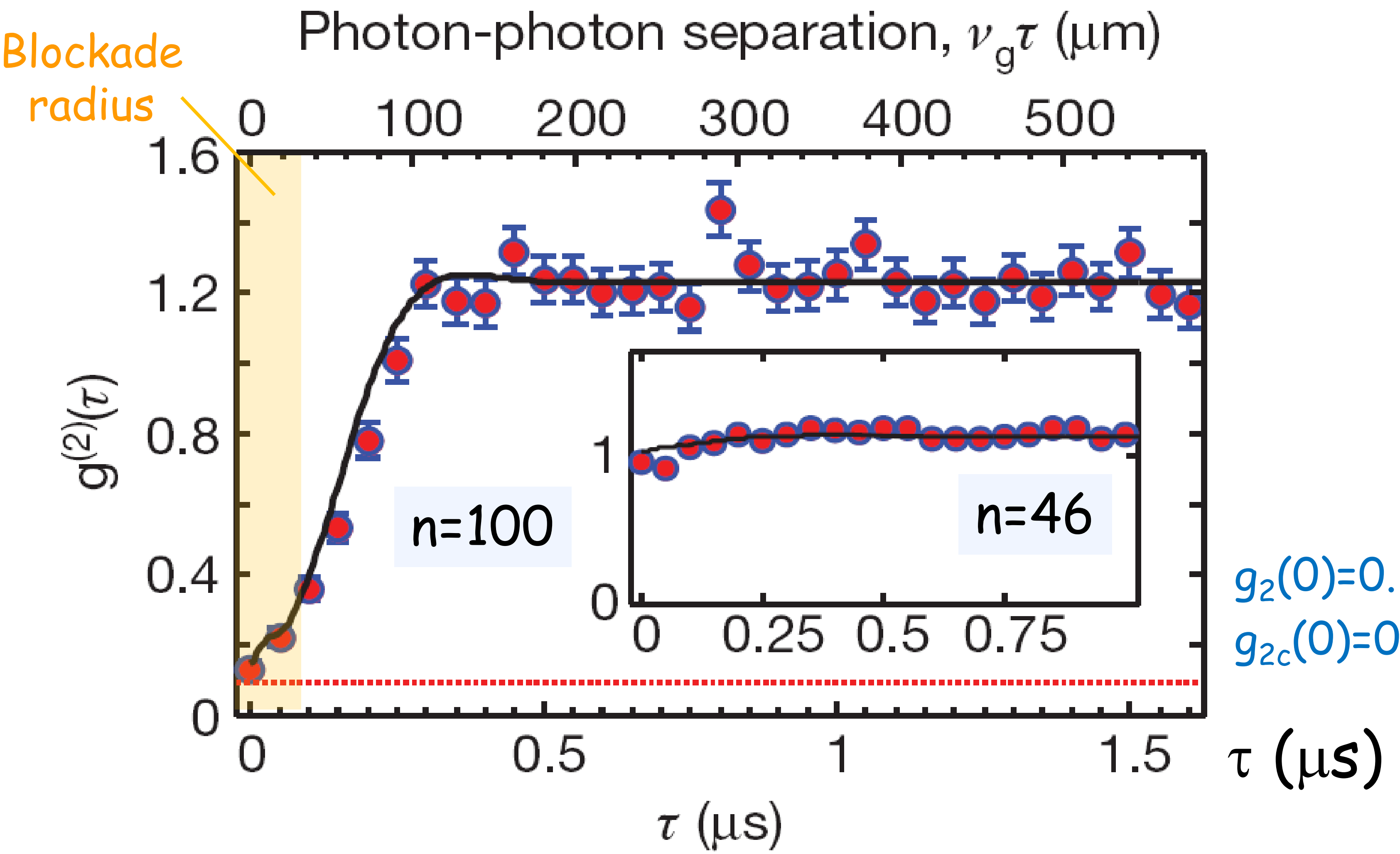


$|n=100\ S_{1/2}\rangle$
Optical depth OD=40
Attenuation length 2μm
Blockade radius 13μm

Similar measurements of large optical nonlinearity (in classical regime attenuation length > blockade radius):

Pritchard, Maxwell, Gauguet, Weatherill, Jones, and Adams, Phys. Rev. Lett. **105**, 193603 (2010).

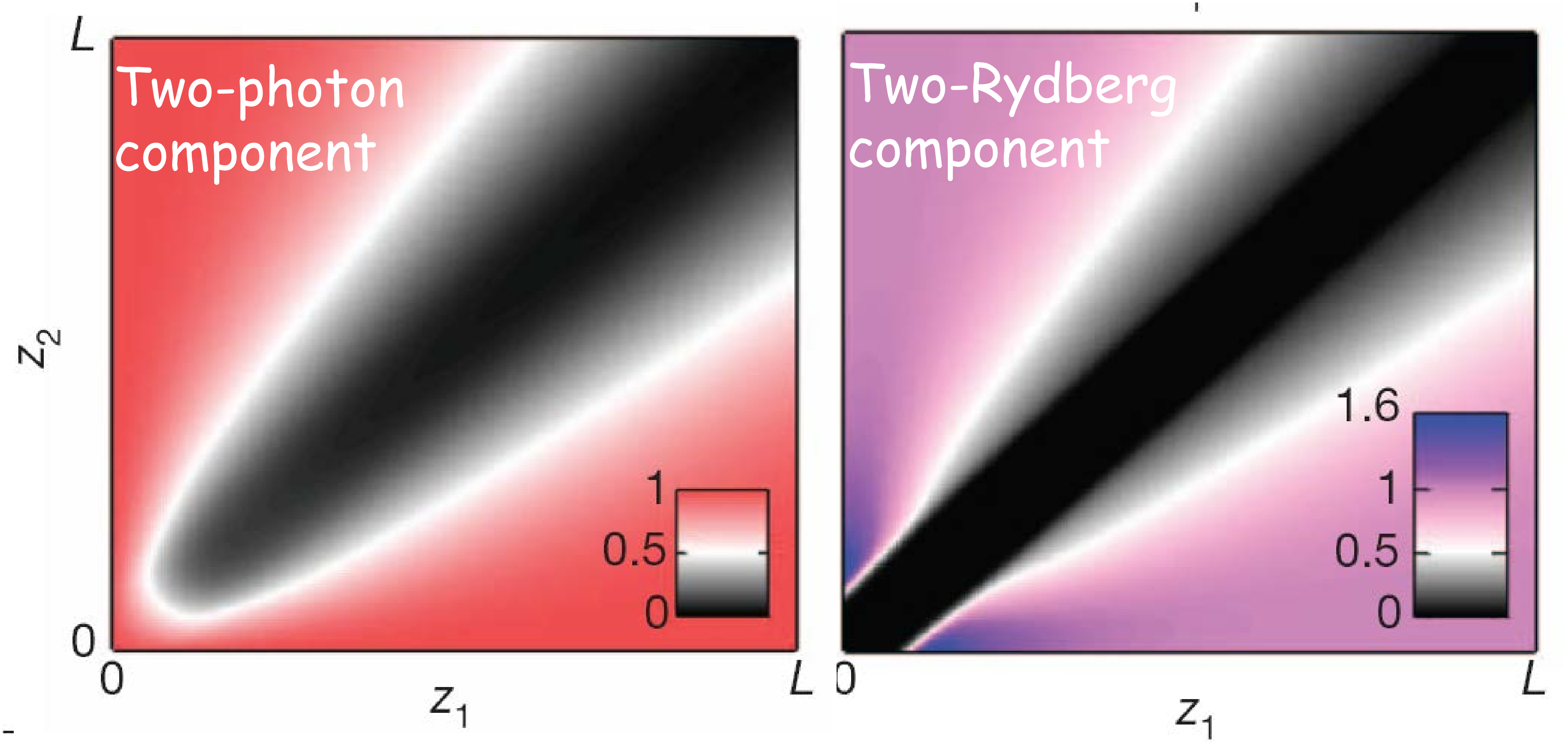
One-photon transmission and two-photon loss



$g_2(0)$=0.13(2)
$g_{2c}(0)$=0.04(3)

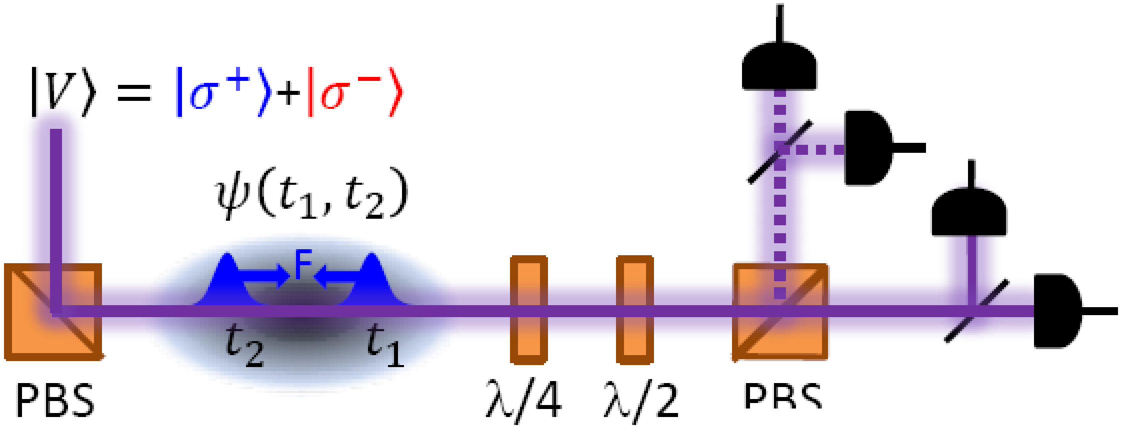
T. Peyronel, O. Firstenberg, Q.-Y. Liang, Alexey Gorshkov, T. Pohl, M. Lukin, and V. Vuletic, Nature Advance online publication (7/25/2012).

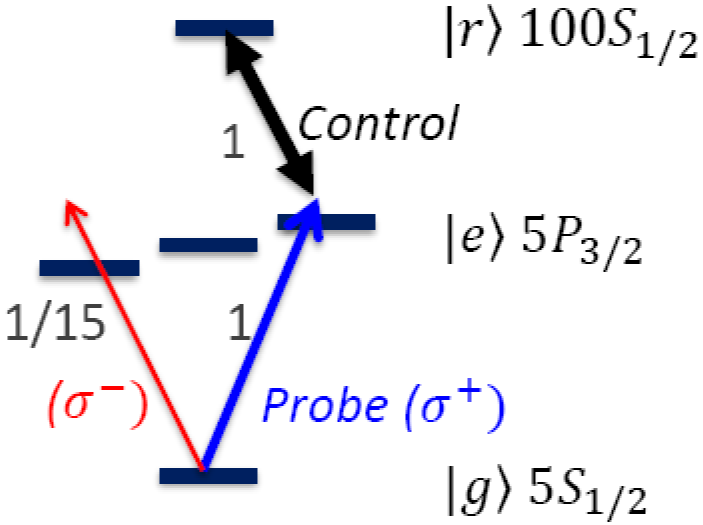
Propagation of two-excitation wavefunction inside Rydberg EIT medium: theory calculation

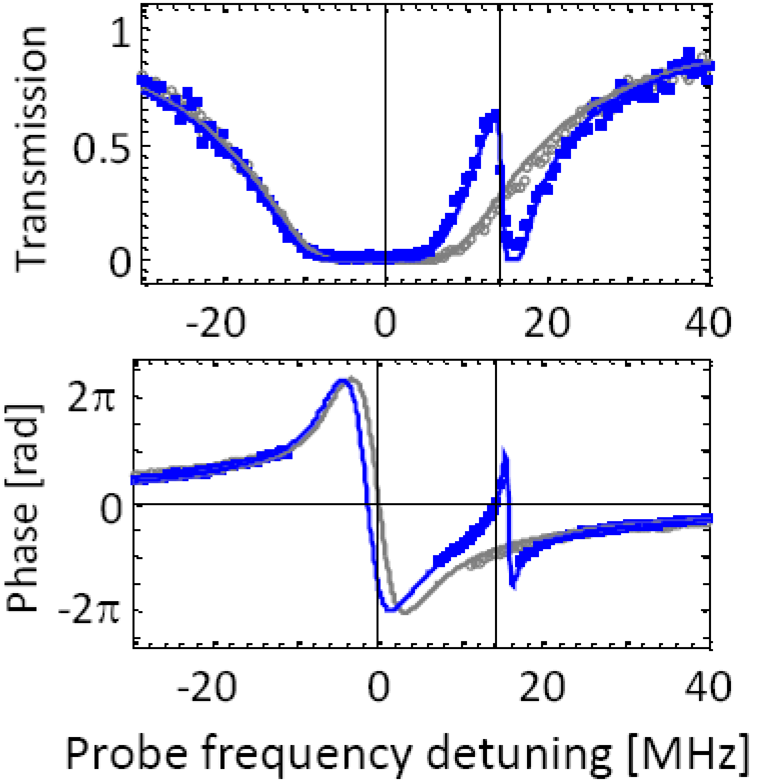


Broadening of exclusion range during propagation through optically dense medium (OD=50) due to dispersion.

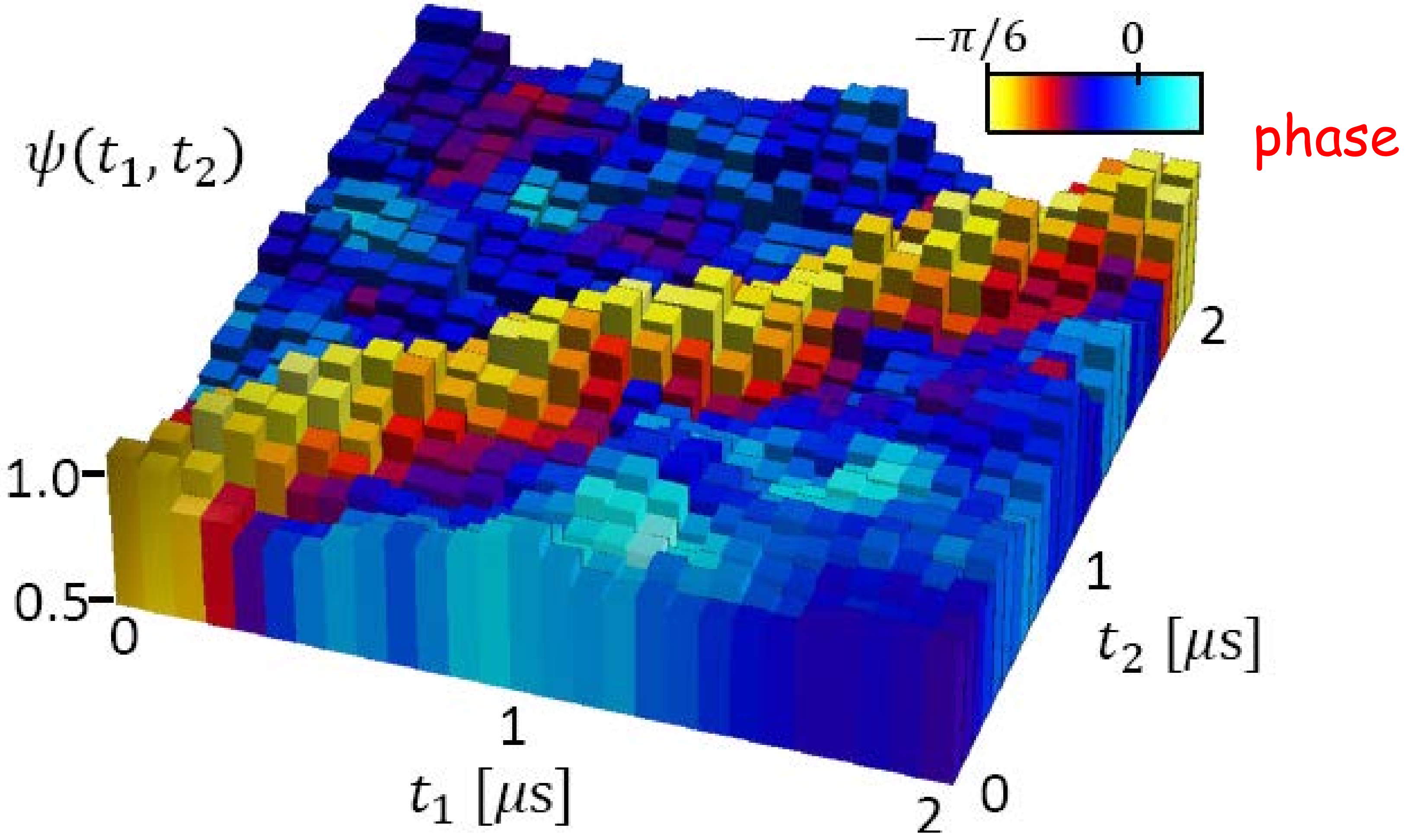
Detuned EIT: Forces between photons





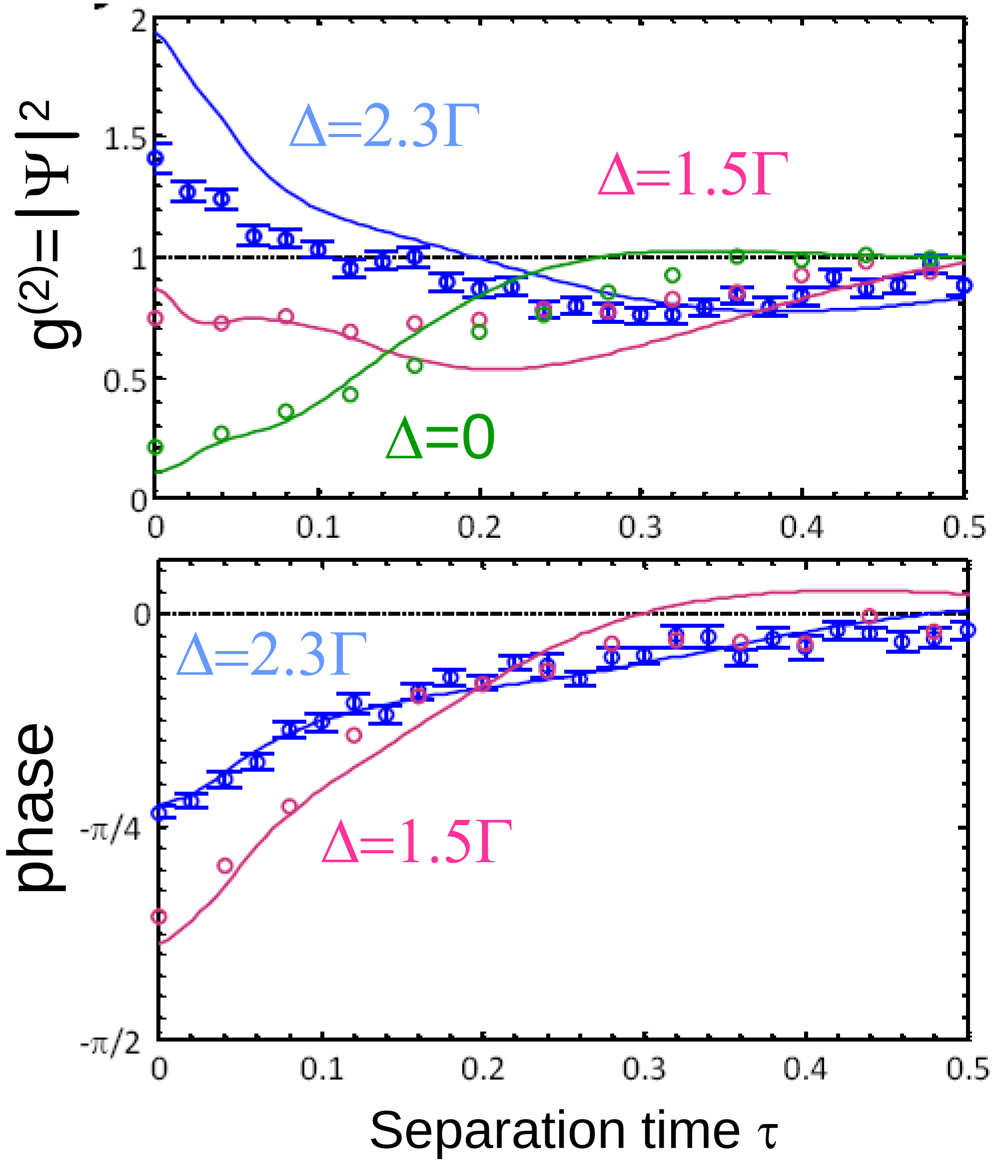


Attractive force between two photons

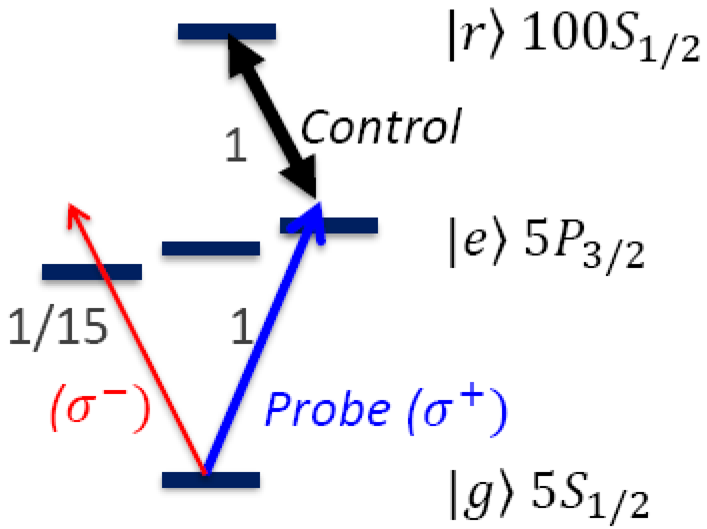


Measured two-photon wavefunction

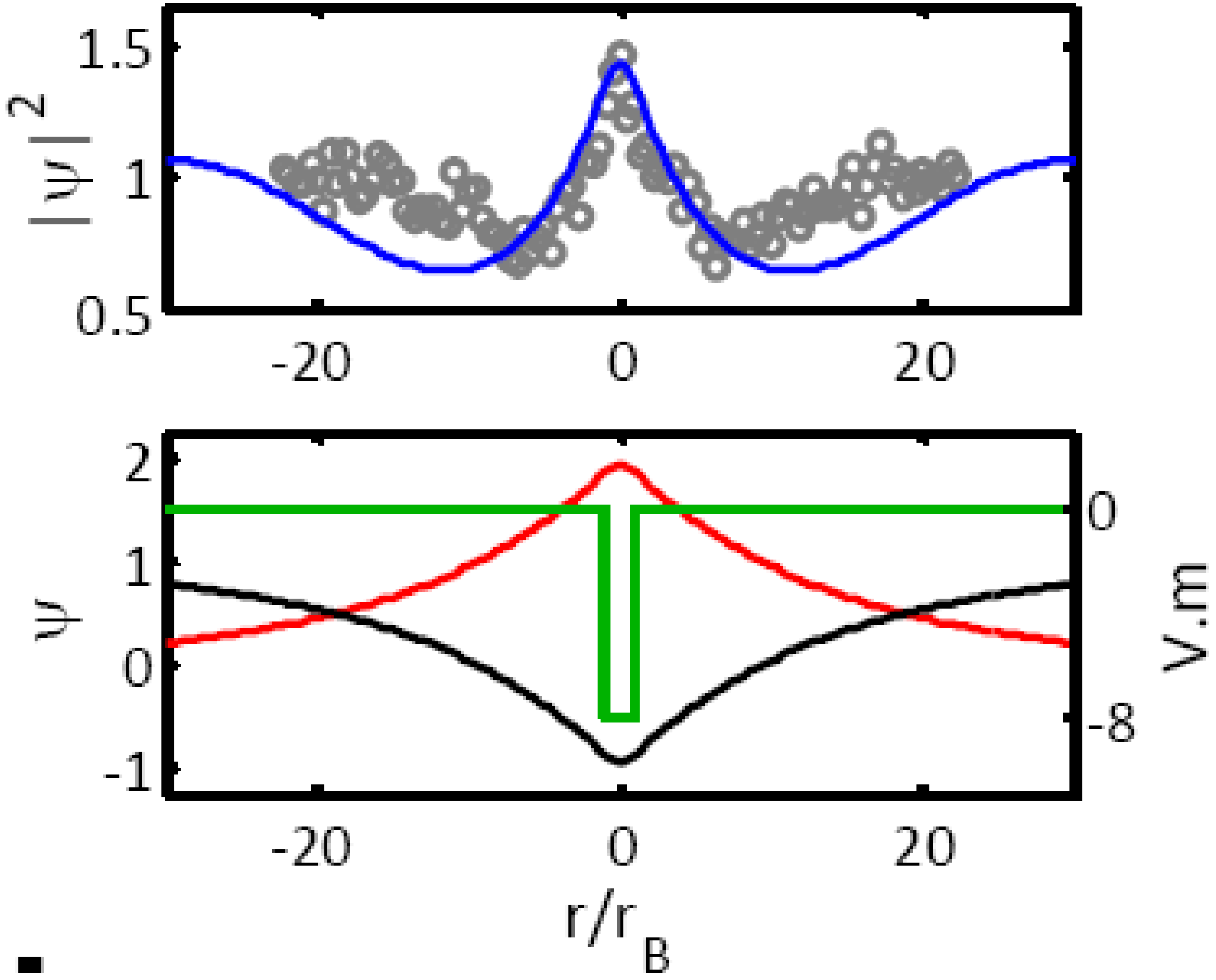
Transition from photon antibunching (dissipation) to bunching (forces)



Incident photons linearly polarized, measure correlation function in different polarization bases, quantum state tomography



Two-photon bound state



Experiment

Simple theoretical picture (Schrodinger equation)

Future Rydberg polariton research

- Colliding interacting photons: photonic quantum gates?
- Three-photon correlation functions: photonic solitons?
- Tuning the interactions: 1D photon crystal?

Summary

- Cavity-free quantum nonlinear medium with different response for one and two photons.
- Cavity-based one-photon transistor where one photon can switch 1000 photons.
- Various possible applications:
  - photonic quantum gates
  - quantum non-demolition detector for photon
  - 1D quantum gas of interacting photons (crystal?)