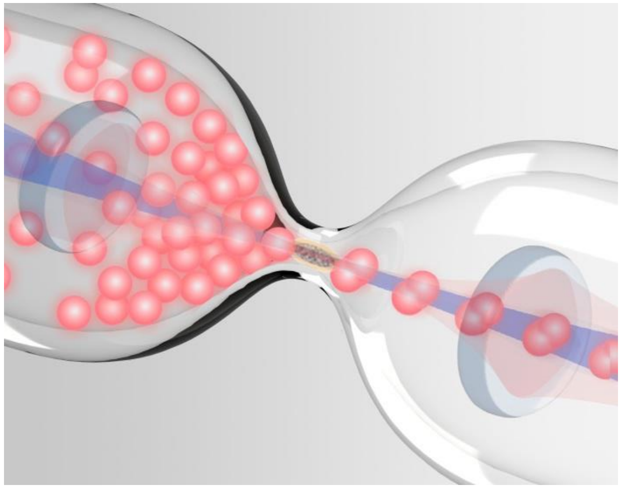
Quantum nonlinear optics with Rydberg polaritons



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with:
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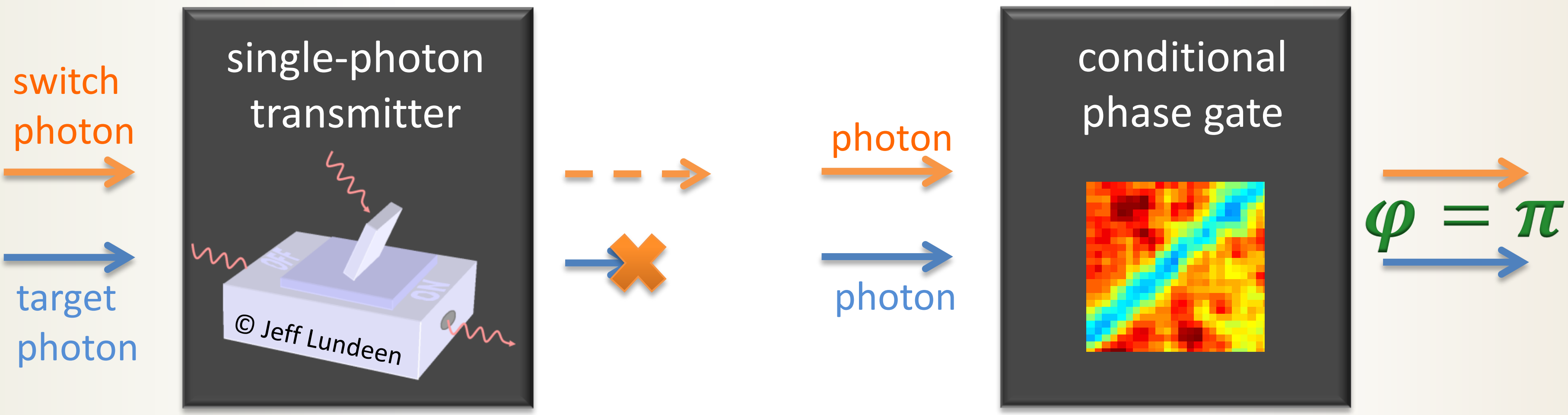
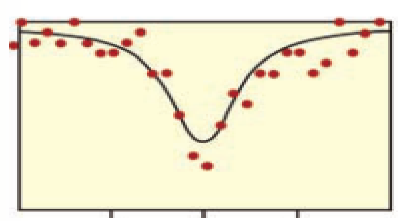
A. Gorshkov, S. Hofferberth,
T. Pohl, V. Vuletic, M. D. Lukin

The goal:
strong interactions between photons

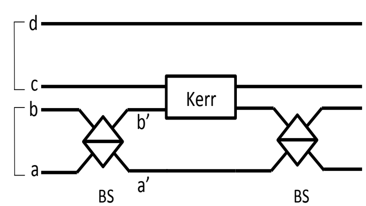


photonic transistors

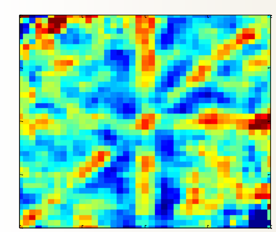
metrology & non-demolition measurements



quantum computation



many-body physics with photons



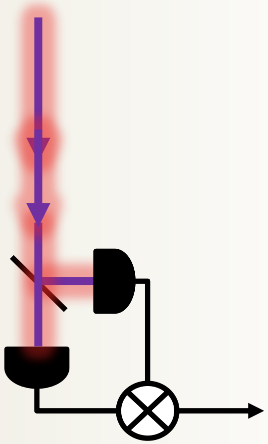
Quantum nonlinear optics

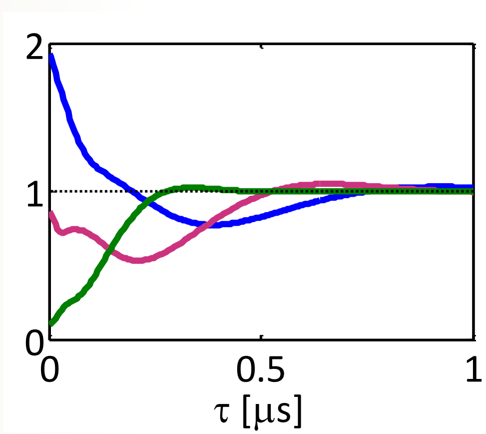
$$|\mathrm{in}\rangle = |0\rangle + \epsilon|1\rangle + \frac{\epsilon^2}{\sqrt{2}}|2\rangle + \cdots$$

$$|\mathrm{out}\rangle = |0\rangle + \epsilon\eta|1\rangle + \frac{\epsilon^2\eta^2\psi}{\sqrt{2}}|2\rangle + \cdots$$

Linear: η

Nonlinear: $\psi \neq 1$





2-photon correlation:

$$g^{(2)}(\tau) = \frac{\langle 2p\rangle}{\langle 1p\rangle\langle 1p\rangle} = |\psi(\tau)|^2$$

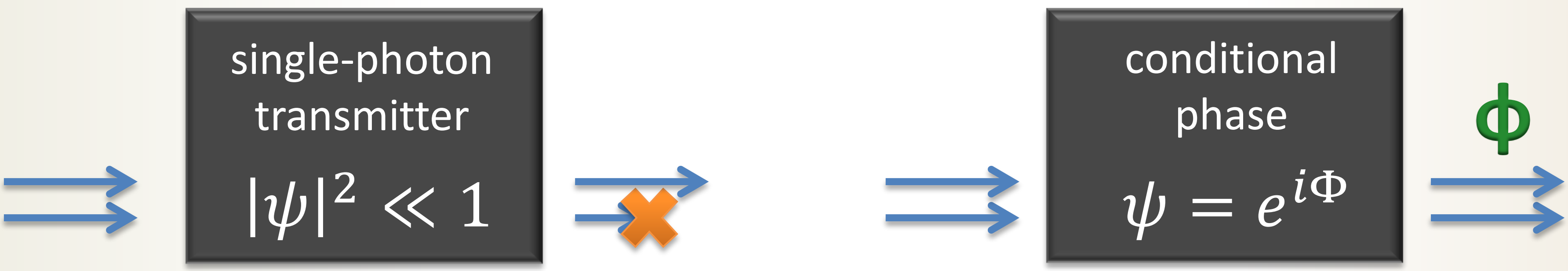
Quantum nonlinear optics

$$|\text{in}\rangle = |0\rangle + \epsilon|1\rangle + \frac{\epsilon^2}{\sqrt{2}}|2\rangle + \cdots$$

$$|\text{out}\rangle = |0\rangle + \epsilon\eta|1\rangle + \frac{\epsilon^2\eta^2\psi}{\sqrt{2}}|2\rangle + \cdots$$

Linear: η

Nonlinear: $\psi \neq 1$



$(1 - |\psi|^2) = 95\%$ blockade probability

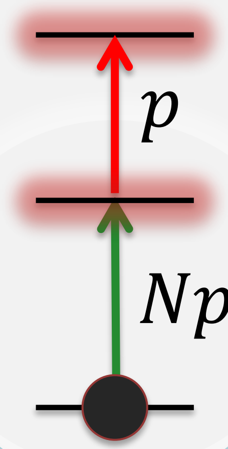
($\eta^2 = 50\%$ linear transmission)

$\Phi \cong \pi/4$

($\eta^2 = 50\%$ linear transmission)

The challenge of QNLO

- Photons interact weakly with each other
- Photons are easily lost

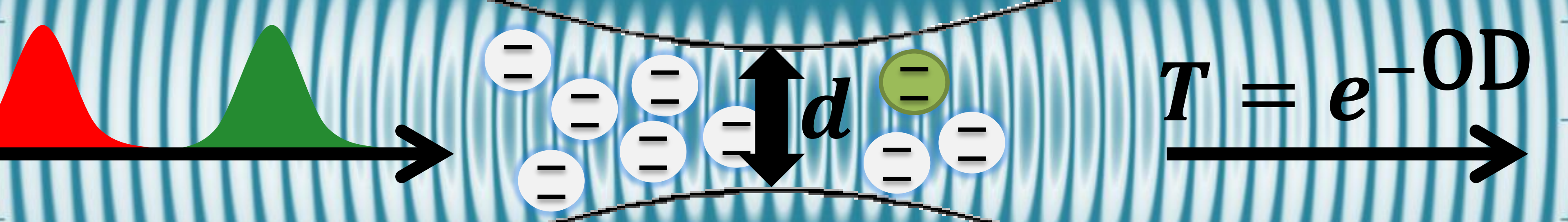


Single-photon – Single-atom interaction probability:

$$p \lesssim \frac{\lambda^2}{d^2}$$

←resonant absorption cross-section

←transverse localization



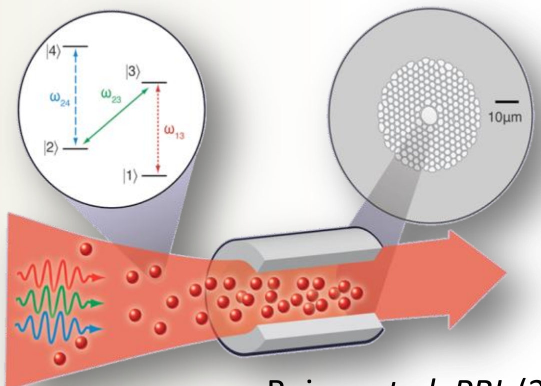
optical depth → $\mathrm{OD} \sim Np$

Schmidt & Imamoglu *Opt Lett* (1996), Harris & Yamamoto *PRL* (1998)

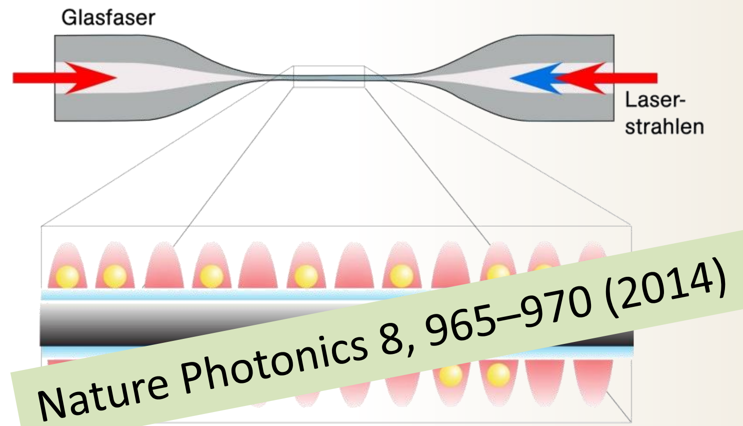
Confinement

Waveguides (fibers) $d \sim \lambda$

"Transmission lines" $d \ll \lambda$



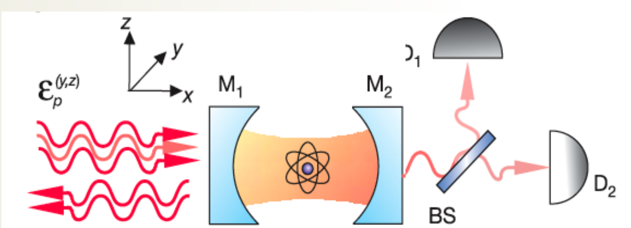
Bajcsy *et al. PRL* (2009)



Nature Photonics 8, 965–970 (2014)

Rauschenbeutel (Vienna)

Cavities

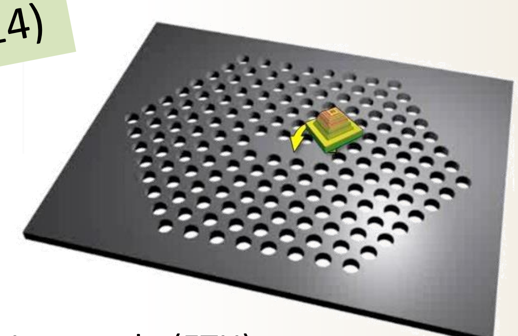


Kimble (Caltech) Birnbaum *et al. Nature* (2005)

Science **345**, 903-906 (2014)

Dayan (Weizmann)

Thompson, Tiecke, Lukin, Vuletic (2013)

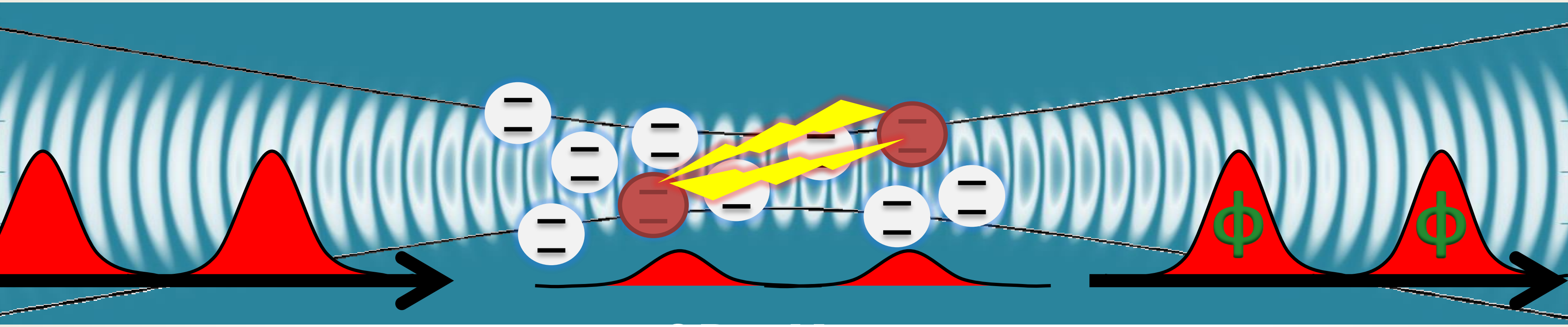


Imamoglu (ETH)
Reinhard *et al. Nat. Phot.* (2012)

Rydberg-mediated interactions

strong **photon-atom** interactions via **slow light**

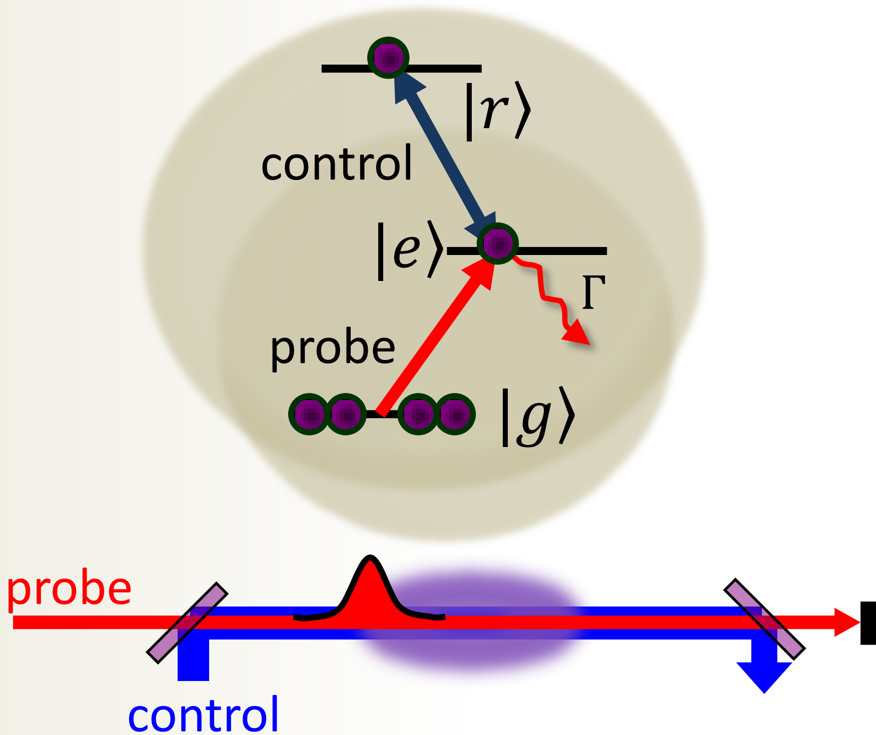
strong **atom-atom** interactions via **Rydberg states**

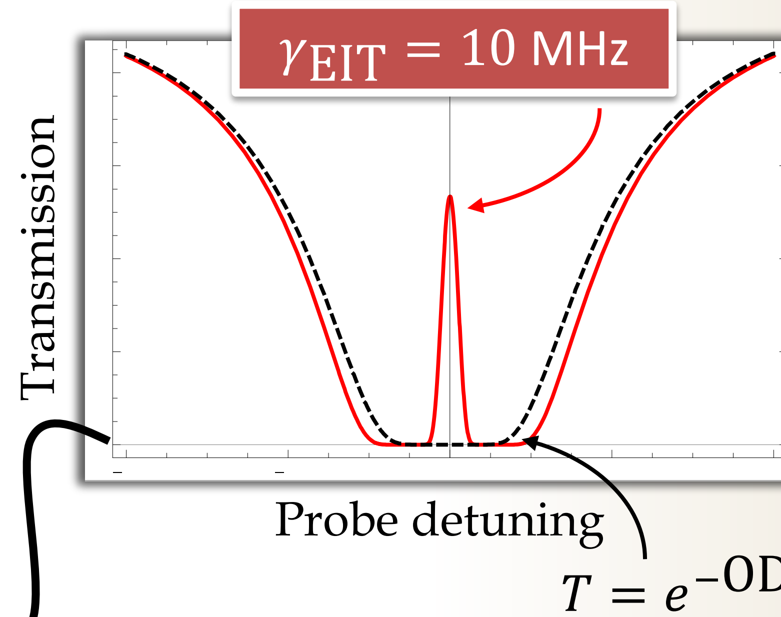


For now: effectively **1D channel** via focusing

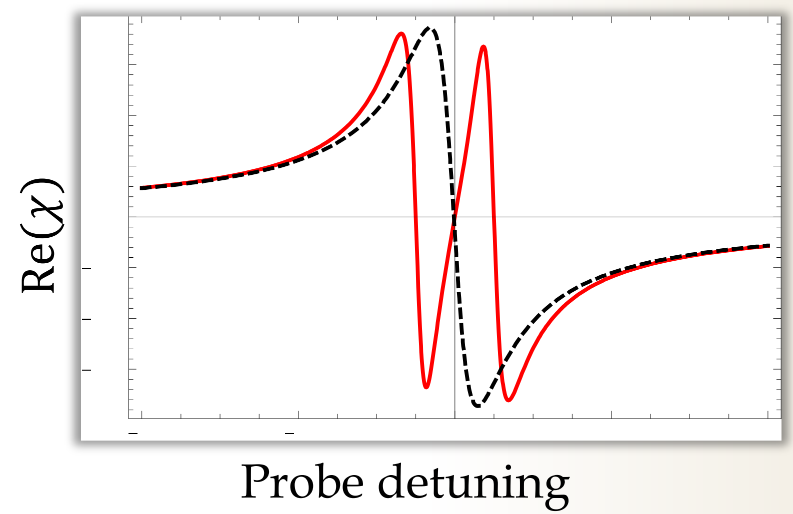
Theory: Lukin, Petrosyan, Kurizki, Pohl, Molmer, Gorshkov, Lesanovsky , Fleischhauer, Demler
Experiments: Adams, Grangier, Saffman, Weidemüller, Rempe, Pfau, Kuzmich, Bloch,

Slow-light polaritons



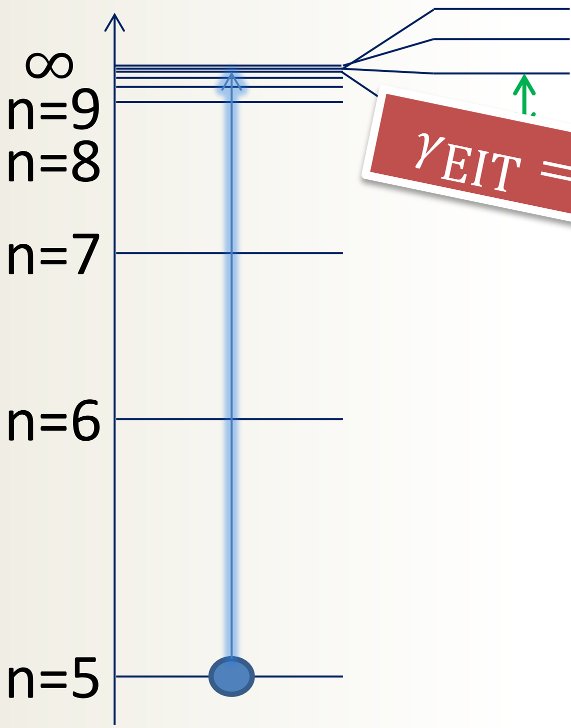


$$v_g = \frac{c}{n + \omega \frac{dn}{d\omega}} \cong 100 \frac{m}{s}$$



Coupled propagation of photonic (v_g/c) and spin wave: "polariton"

Rydberg n=100 (rubidium)



Level spacing $\Delta E \propto n^{*-3}$

$$E_{101s} - E_{100s} = 6\ \text{GHz}$$

$\gamma_{EIT} = 10$ MHz

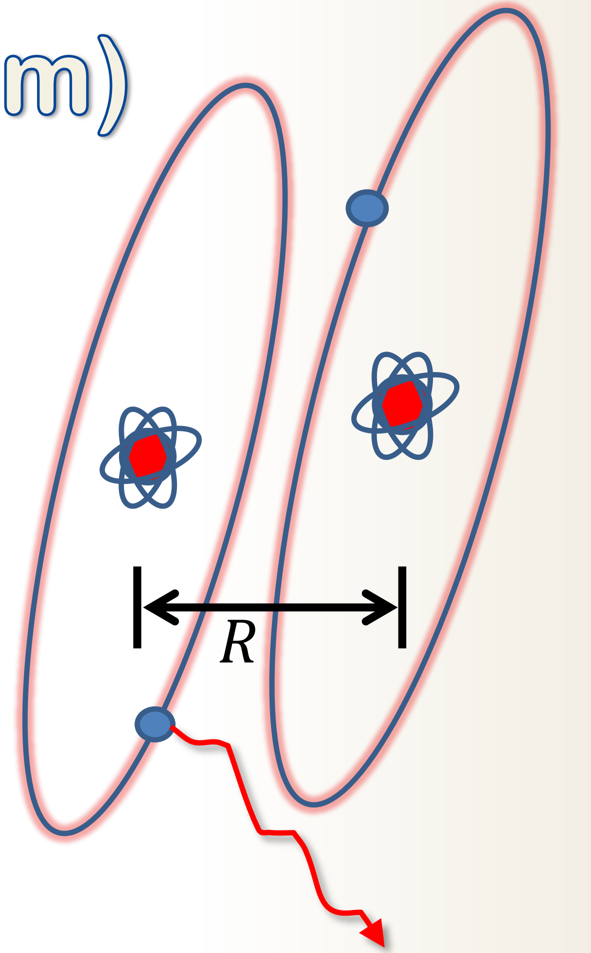
Mesoscopic object:

Orbit radius $\approx a_0 n^{*2}$

$$r_{5s} = 0.2\ \text{nm}$$

$$r_{100s} = 250\ \text{nm}$$

Dipole $\mu \approx e a_0 n^{*2}$



Long-range Van der Waals interaction:

$$V(R) \sim \frac{(\mu^2/R^3)^2}{\Delta E} = -\frac{C_6}{R^6} \propto \frac{n^{11}}{R^6}$$

Long lifetime $\propto n^{*3}$

$$\tau_{5p} = 30\ \text{ns}$$

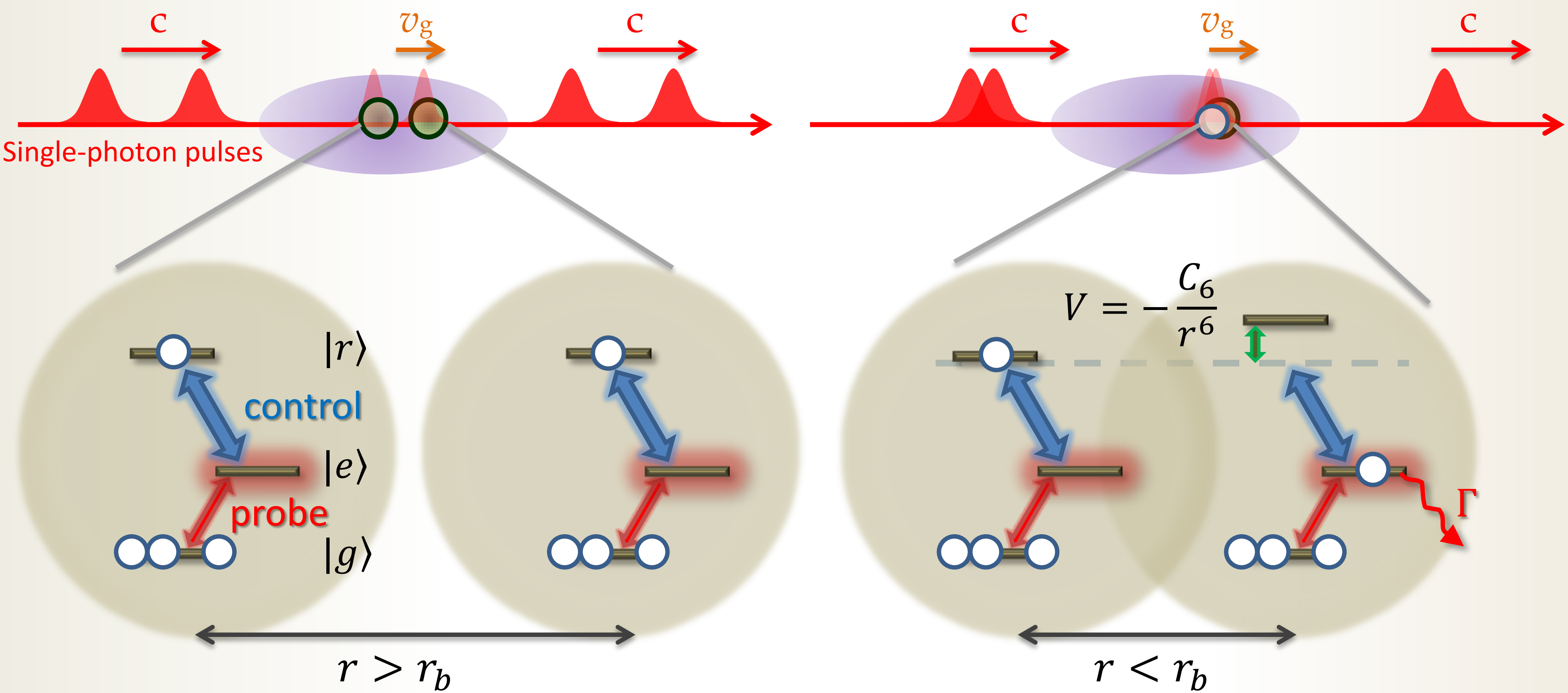
$$\tau_{100s} = 0.1\sim1\ \text{ms}$$

$\gamma_{EIT} = 10$ MHz

$$\mathbf{100S_{1/2} - 100S_{1/2}:}\ \ C_6 = -56\ \text{THz}\ \mu\text{m}^6$$

Saffman *et al.*, RMP (2010)

Rydberg polaritons



Blockade radius = r_b

distance at which the excitation linewidth equals the interaction shift

$$V_{VdW}(r_b) \approx \hbar\,\gamma_{\mathrm{EIT}}$$

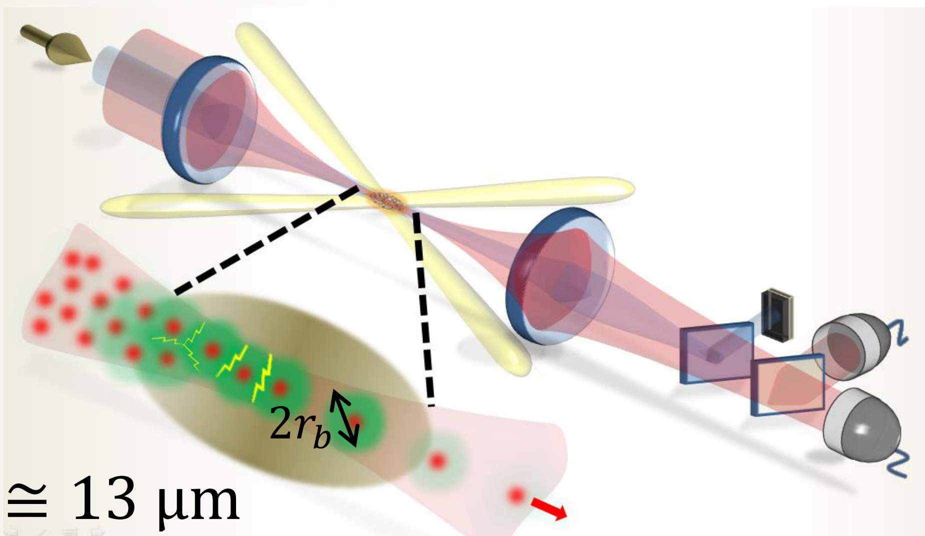
Design a blockade experiment

1. Strong attenuation within one blockaded sphere (OD_b):

$$\mathrm{OD}_b \cong 5$$

2. 1D limit (focusing):

$$\text{probe waist} = 5\ \mu\text{m}$$

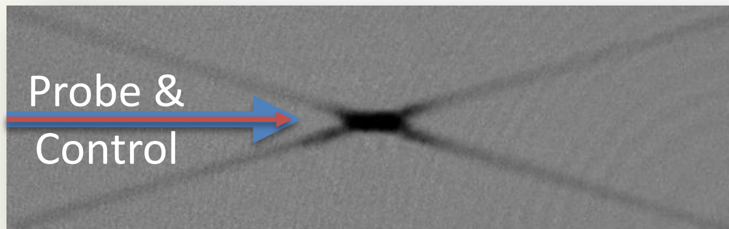


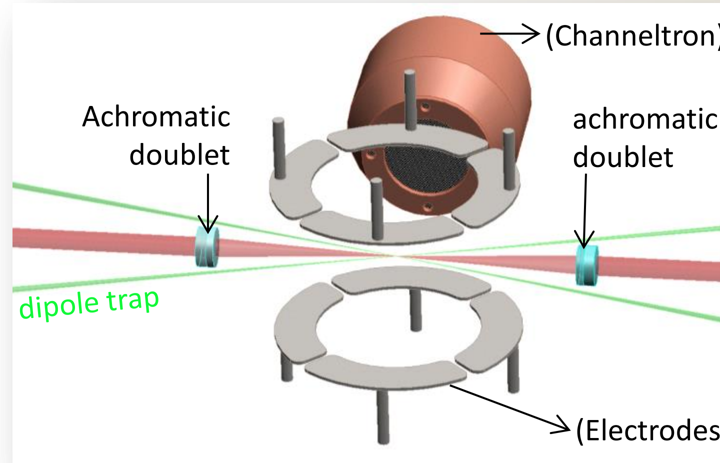
$r_b \cong 13\ \mu\text{m}$

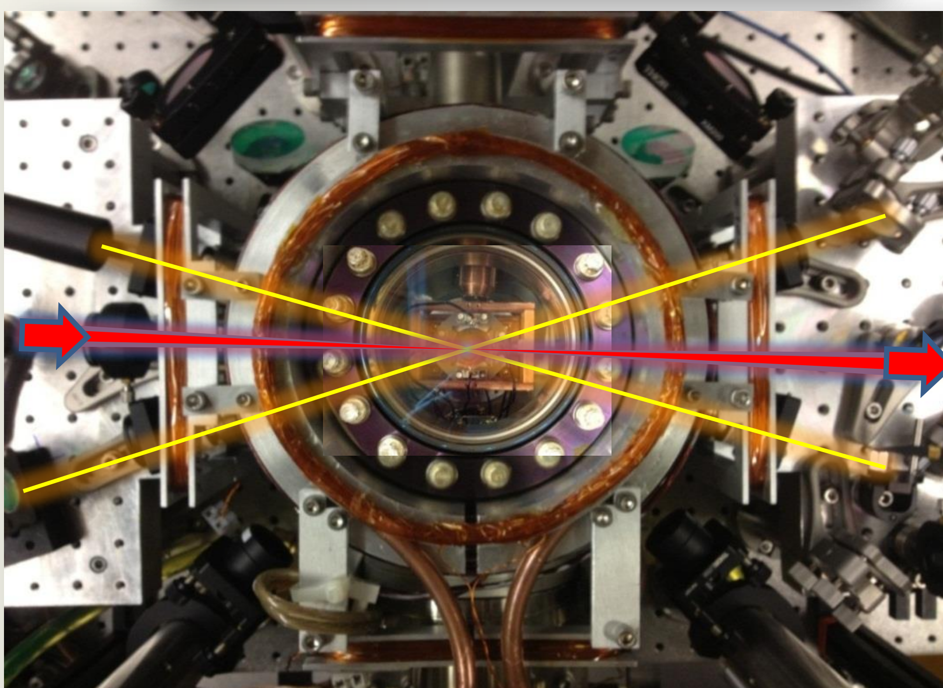
Experimental setup

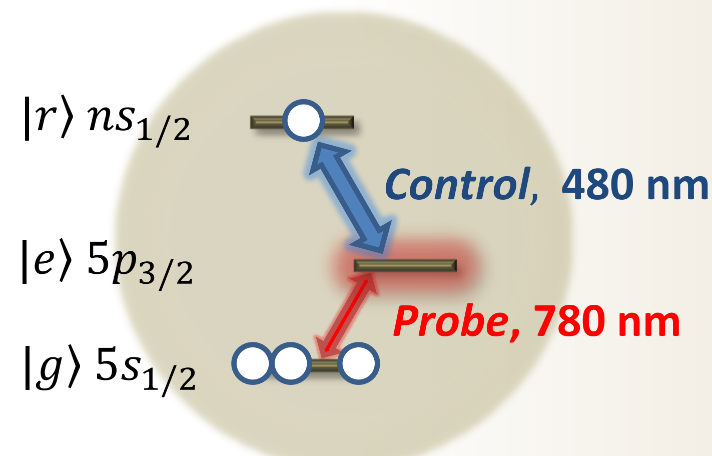
Optically trapped cold rubidium (T=50 μK)

(100 μm)X(25 μm), 10^5 atoms, OD = 30-50







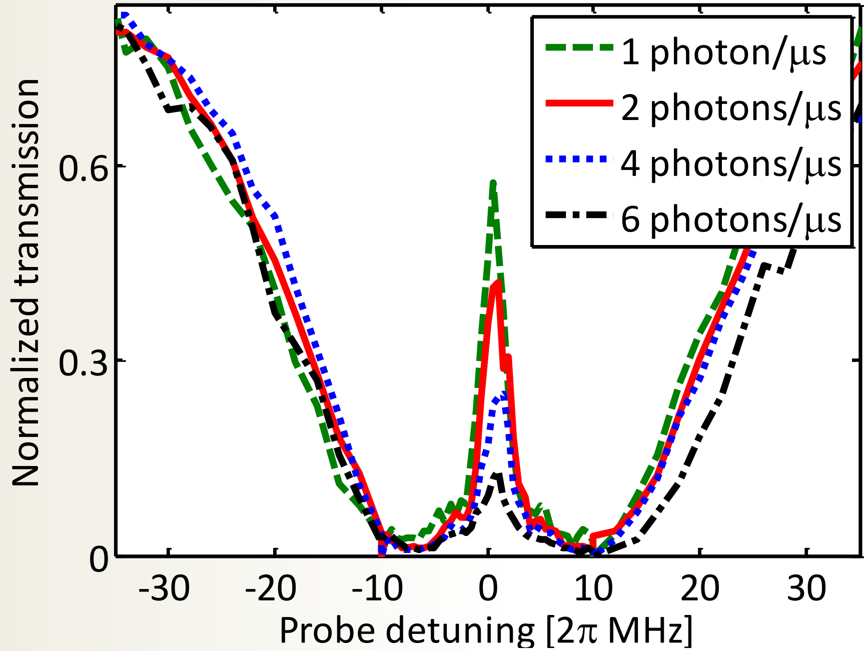


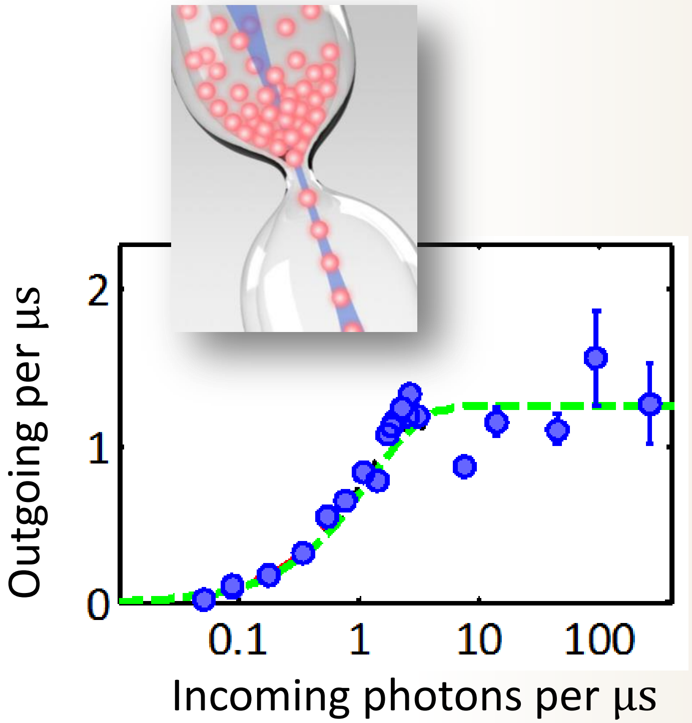
Delay time in the medium:

$\tau_d = 340$ ns

Non-linearity at low probe power

Transmission for increasing incoming photon rate



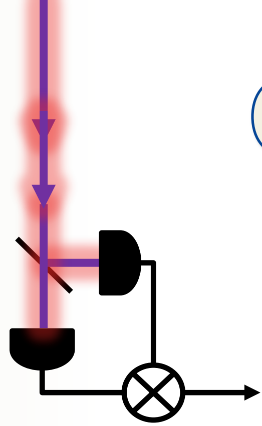


- High (~60%) transmission for (very) weak probe
- Rapid saturation: extraordinary nonlinearity

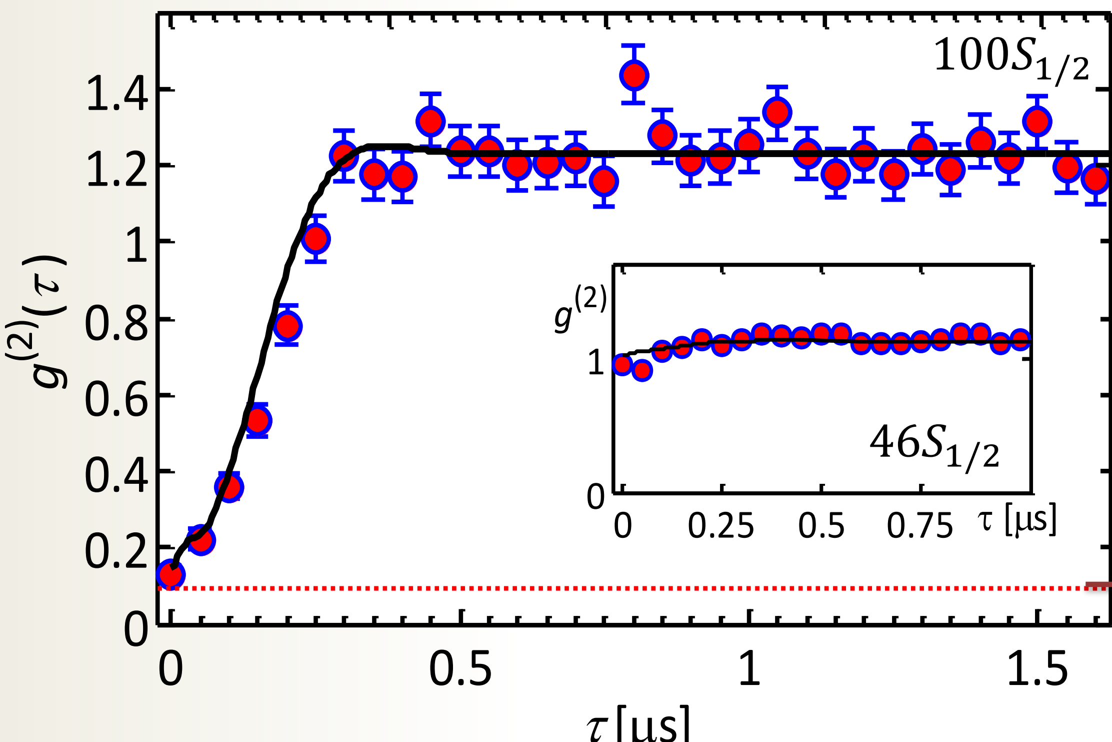
Sub-pico-Watt ⟺ Quantum regime?

Nature **488**, 57-60 (2012)

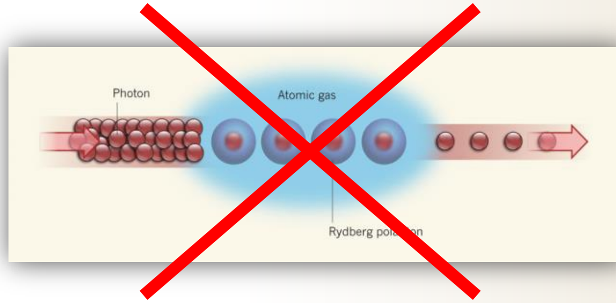
Quantum nonlinearity



$$g^{(2)}(\tau) = \frac{\langle 2p \rangle}{\langle 1p \rangle \langle 1p \rangle} = |\psi(\tau)|^2$$



$g^{(2)}(0) = 0.04$ (+0.07 noise)

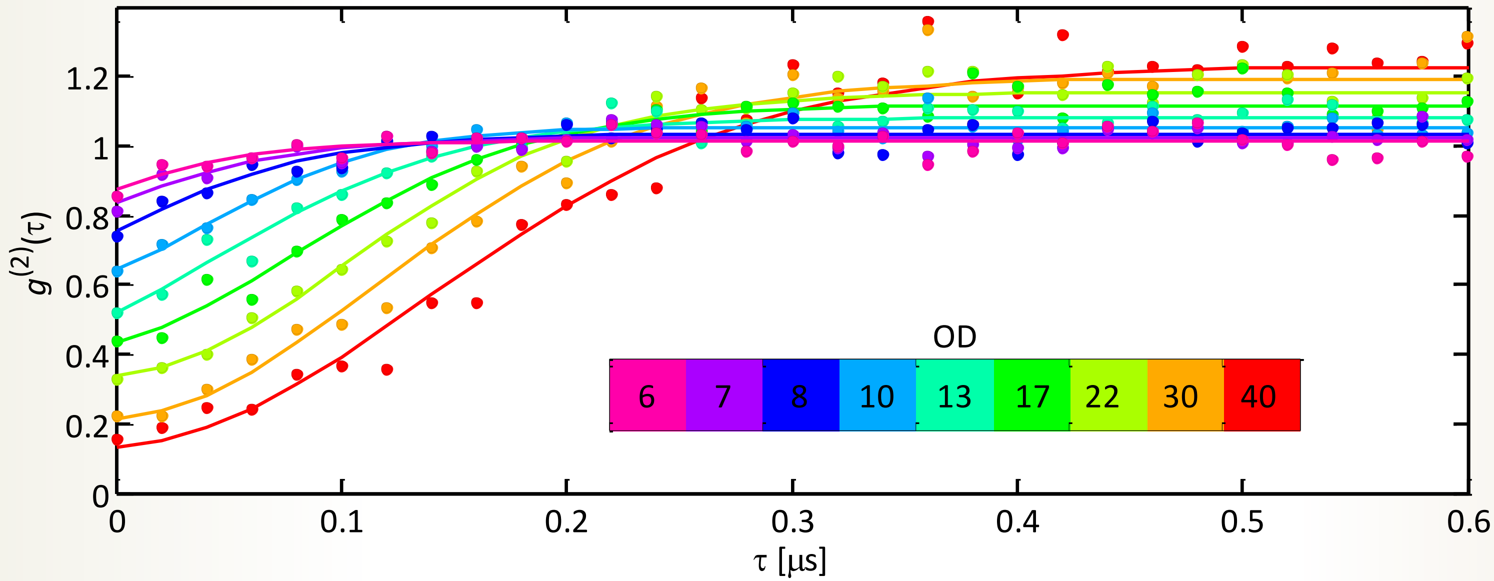


Sub-Poissonian: **Yes**

"crystallized" train: **No**

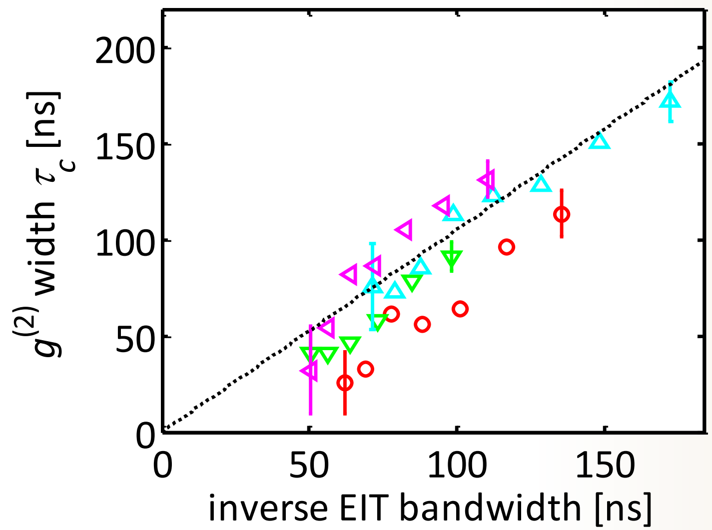
Nature **488**, 57-60 (2012)

Effect of EIT bandwidth



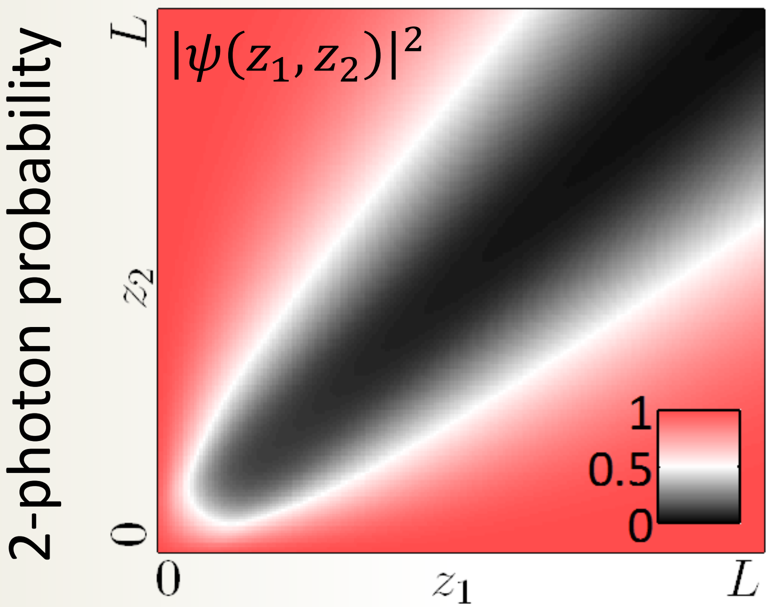
Sharp temporal features are filtered due to finite bandwidth:

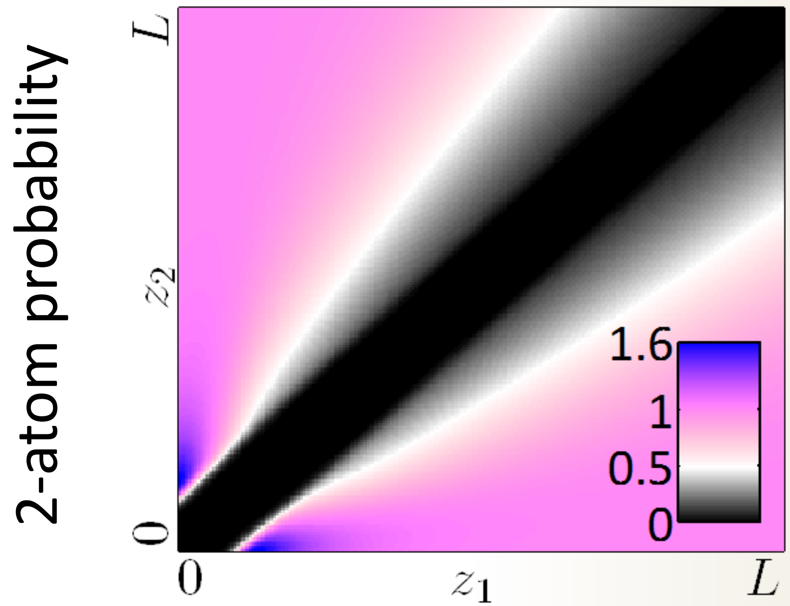
$$B = \frac{\gamma_{EIT}}{\sqrt{8 \cdot \mathrm{OD}}}$$



Physics at resonance – diffusion

Probability directly observed by $g^{(2)}(\tau)$



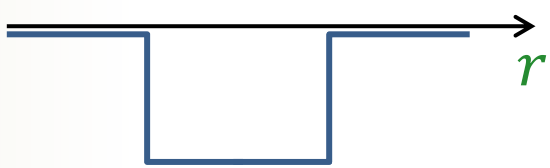


An effective diffusion equation for $\psi(R, r)$:

$$R = \frac{(z_1 + z_2)}{2} \qquad r = z_1 - z_2$$

$$\frac{\partial \psi}{\partial R} = -\frac{q(r)}{l_a}\psi + 4 l_a \frac{\partial^2 \psi}{\partial r^2}$$

$$-\frac{q(r)}{l_a} =$$

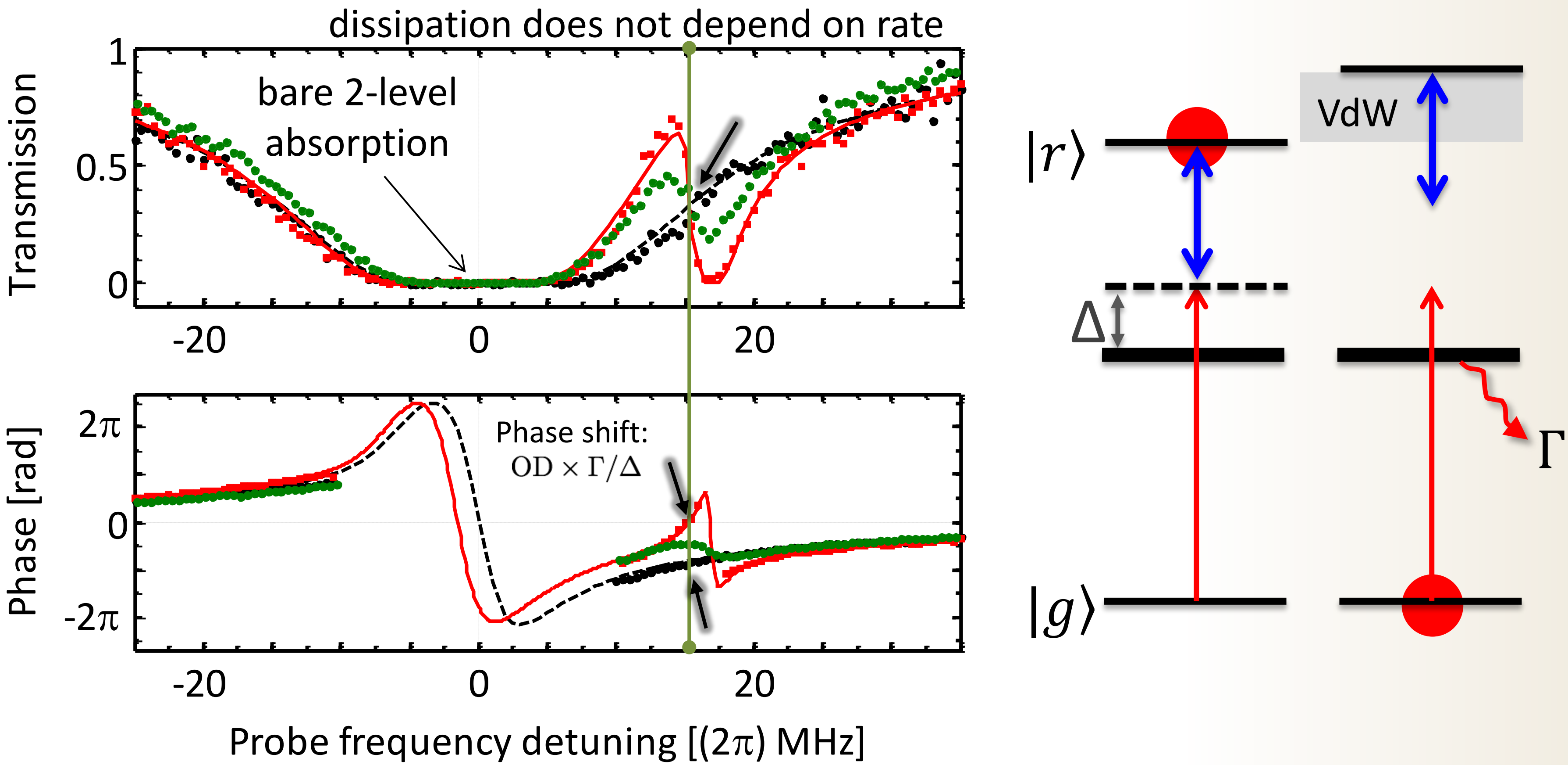


Attenuation length:

$$l_a = L/OD$$

Dispersive nonlinearity

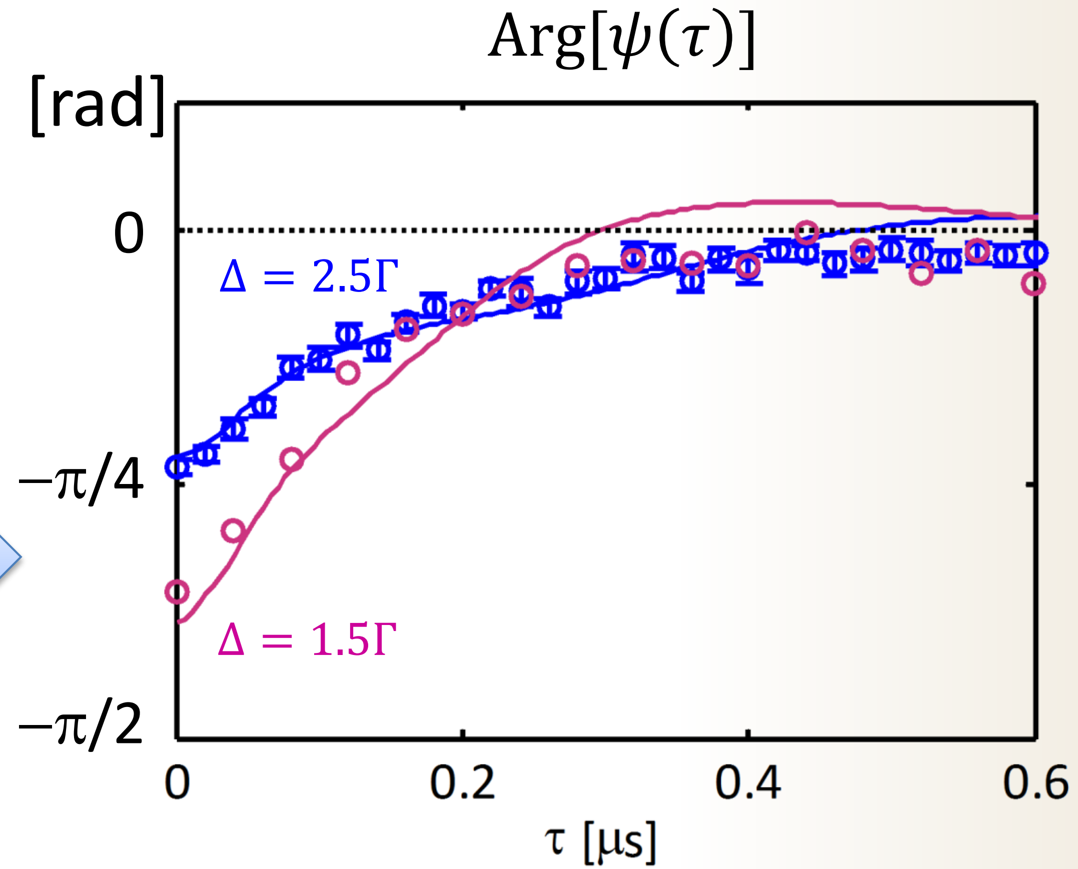
At large detuning:



→ Conservative interaction between the photons

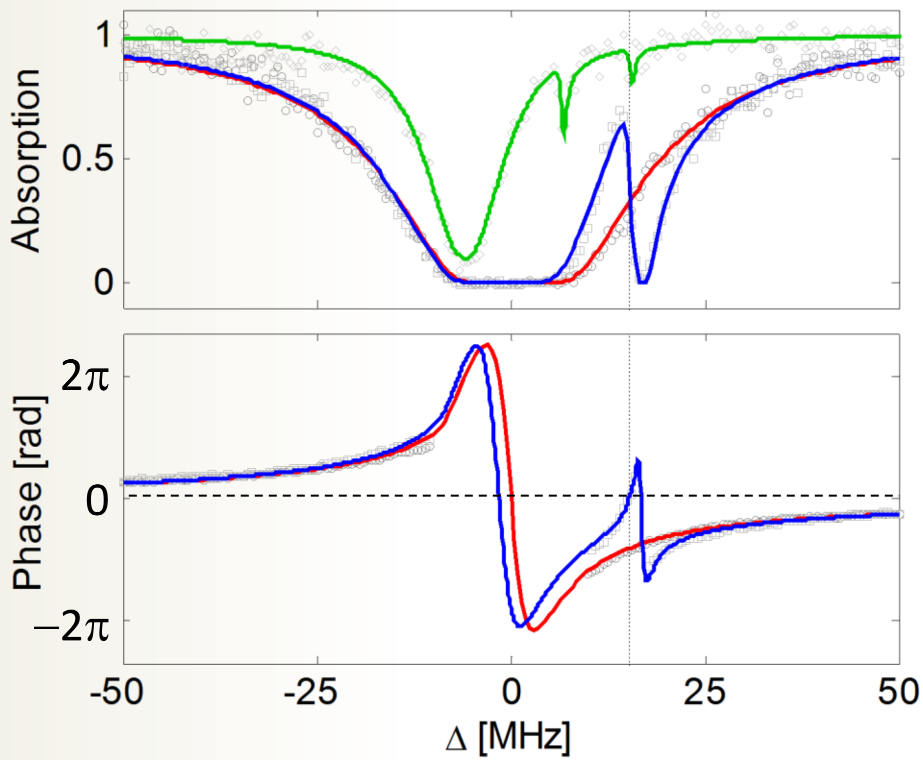
Conservative potential: Phase

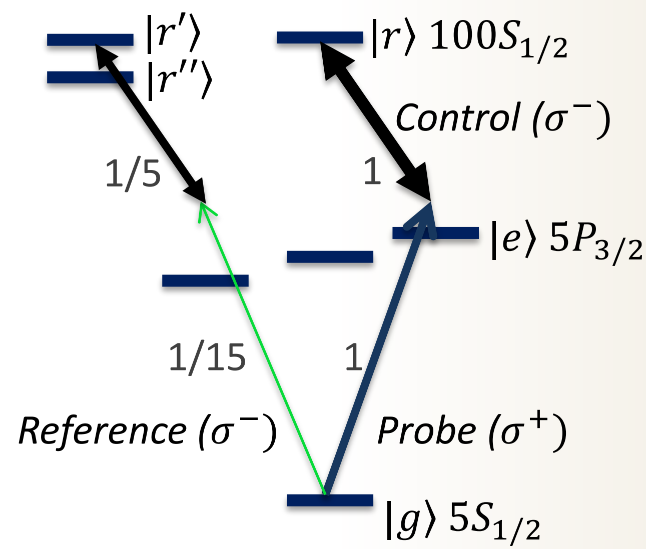
Conditional two-photon phase shift of $\sim \boldsymbol{\pi/4}$ at $\sim \mathbf{50}\%$ transmission

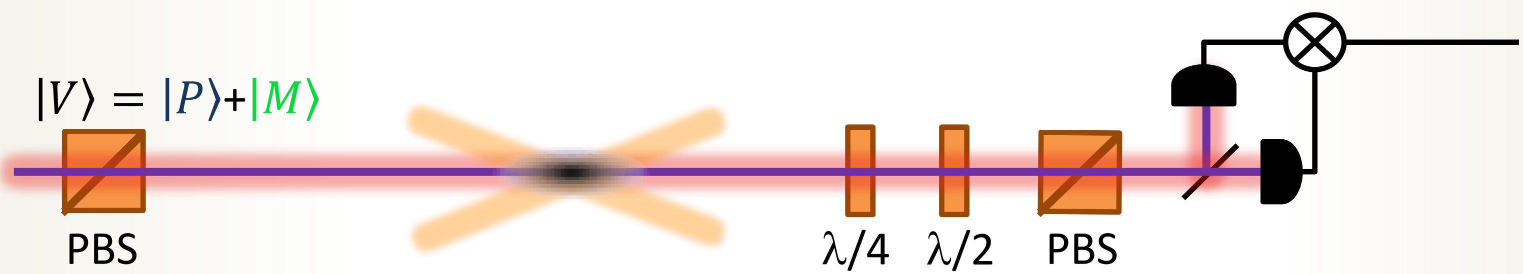


Nature **502**, 71-75-60 (2013)

Retrieval of the conditional phase







Retrieval of the conditional phase

$$|\mathrm{in}\rangle = |V\rangle = \frac{|P\rangle + |M\rangle}{\sqrt{2}} \;\Longrightarrow\; |\mathrm{out}\rangle = \frac{\eta|P\rangle + |M\rangle}{\sqrt{2}}$$

(On perfect EIT, $\eta \sim 1$)

$$|\mathrm{in}\rangle = |VV\rangle = \frac{|PP\rangle + |MP\rangle + |PM\rangle + |MM\rangle}{2} \;\Longrightarrow\; |\mathrm{out}\rangle = \frac{\psi(\tau)|PP\rangle + |MP\rangle + |PM\rangle + |MM\rangle}{2}$$

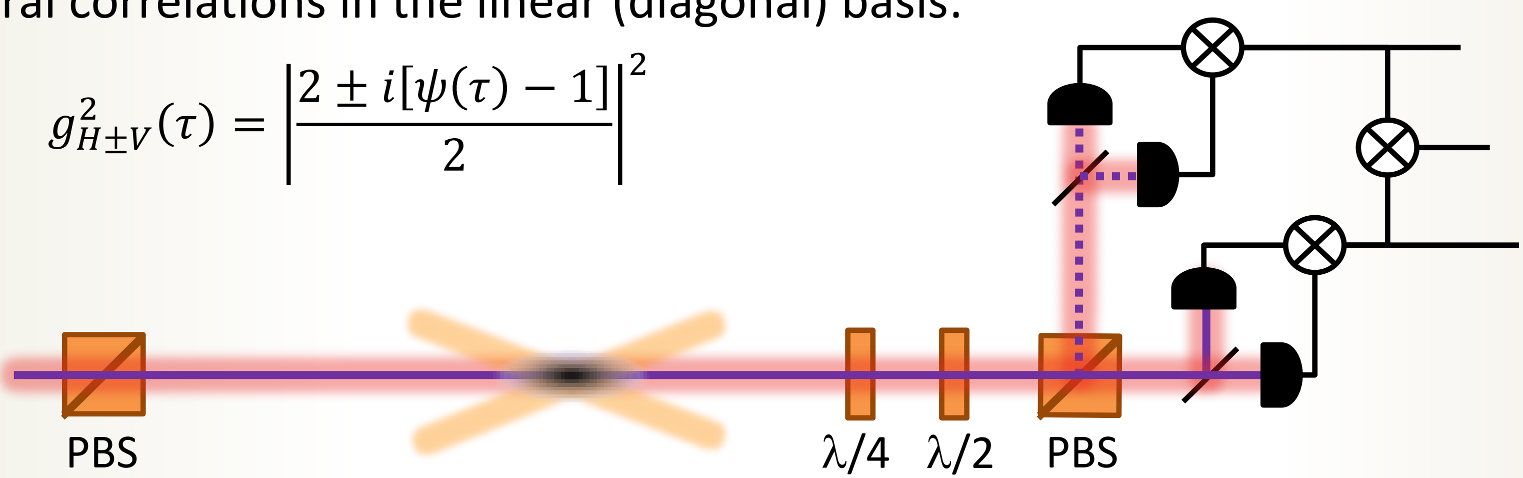
Complex amplitude to retrieve

Temporal correlations in the circular basis:

$$g^2_{PP}(\tau) = |\psi(\tau)|^2$$

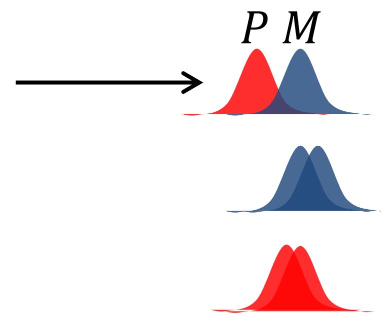
Temporal correlations in the linear (diagonal) basis:

$$g^2_{H\pm V}(\tau) = \left|\frac{2 \pm i[\psi(\tau) - 1]}{2}\right|^2$$



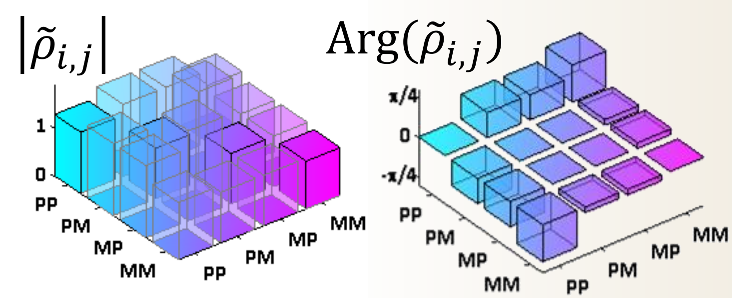
Two-photon state tomography

- Why full tomography?
  - Linear absorption and rotation
  - (Weak) interaction with σ^-
  - depolarization (decoherence)



- Single mode → 10 degrees of freedom
- 2-photon density matrix:

$$\rho^{(2)} = \begin{pmatrix} \rho_{PP,PP} & \rho_{PP,PM_+} & \rho_{PP,MM} & 0 \\ \rho_{PM_+,PP} & \rho_{PM_+,PM_+} & \rho_{PM_+,MM} & 0 \\ \rho_{MM,PP} & \rho_{MM,PM_+} & \rho_{MM,MM} & 0 \\ 0 & 0 & 0 & \rho_{PM_-,PM_-} \end{pmatrix}$$



Interaction matrix:

$$\tilde{\rho}_{i,j} = \frac{\rho^{(2)}{}_{i,j}}{\left[\rho^{(1)} \otimes \rho^{(1)}\right]_{i,j}}$$

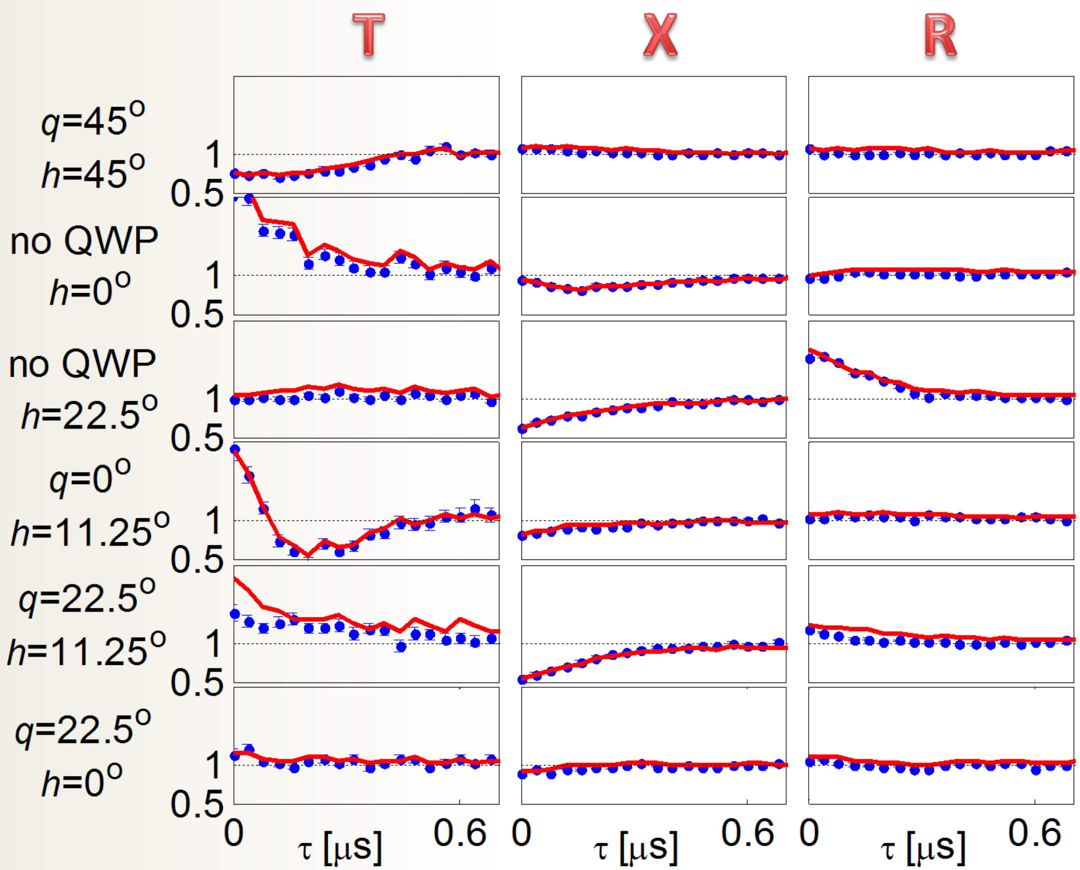
(All $\tilde{\rho}_{i,j} = 1$ in the absence of non-linearity)

- 1-photon density matrix:

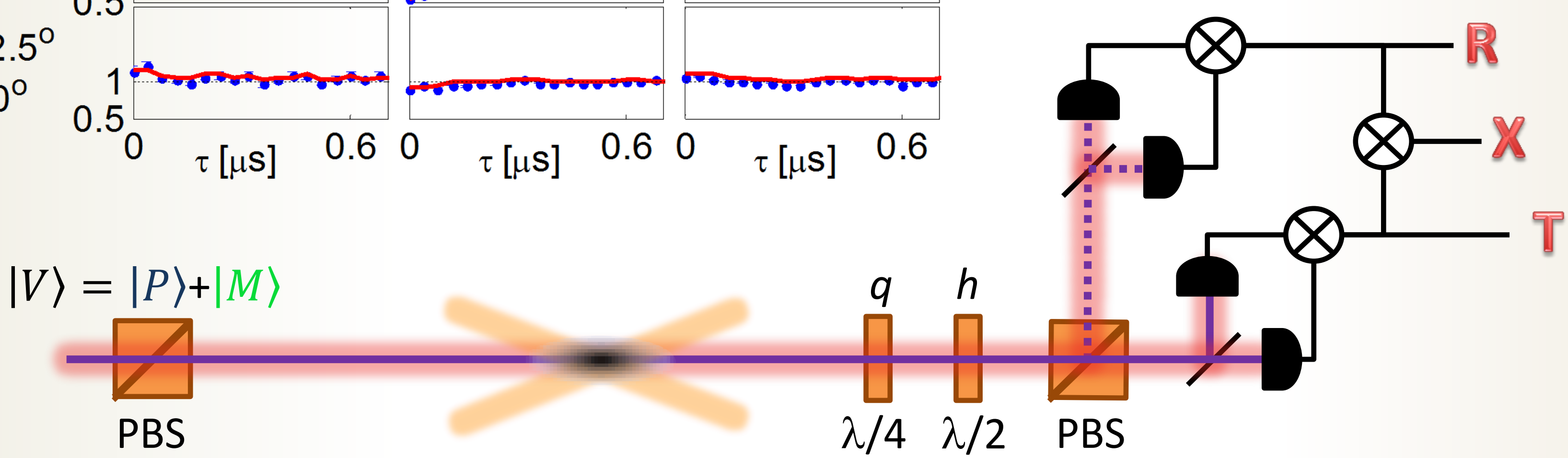
$$\rho^{(1)} = \begin{pmatrix} \rho_{P,P} & \rho_{P,M} \\ \rho_{M,P} & \rho_{M,M} \end{pmatrix}$$

Adamson et al. *PRL* **98,** 043601 (2007)
James et al. *PRA* **64**, 052312 (2001)

Measuring the conditional phase



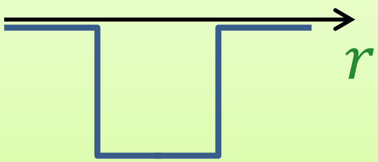
Reconstructed $g^{(2)}$ in 6 bases by quantum state tomography



Interacting photon gas

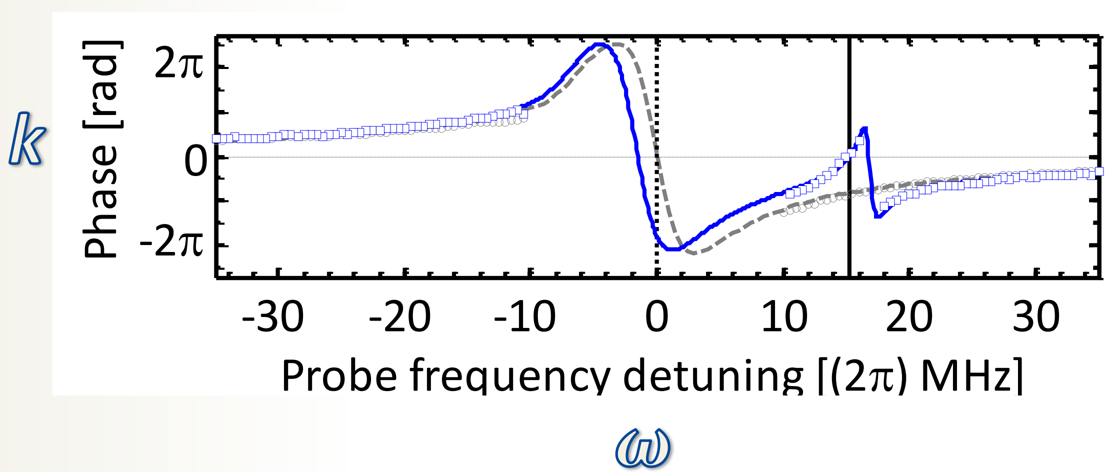
At $|\Delta| \gg \Gamma, \Omega$ Mass:

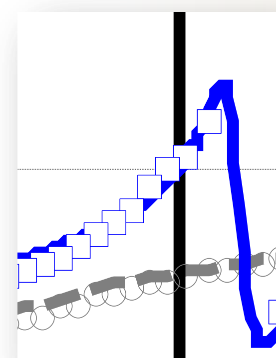
$$\tilde{m} = \frac{1}{16 l_a}\frac{\Gamma}{\Delta}$$



A potential well of width $2r_B$:

$$V(r) = -\frac{1}{2 l_a}\frac{\Gamma}{\Delta} \times \begin{cases} 1 & r \ll r_B \\ 0 & r \gg r_B \end{cases}$$





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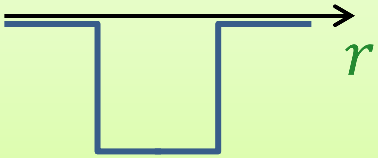


A potential well of width $2r_B$:

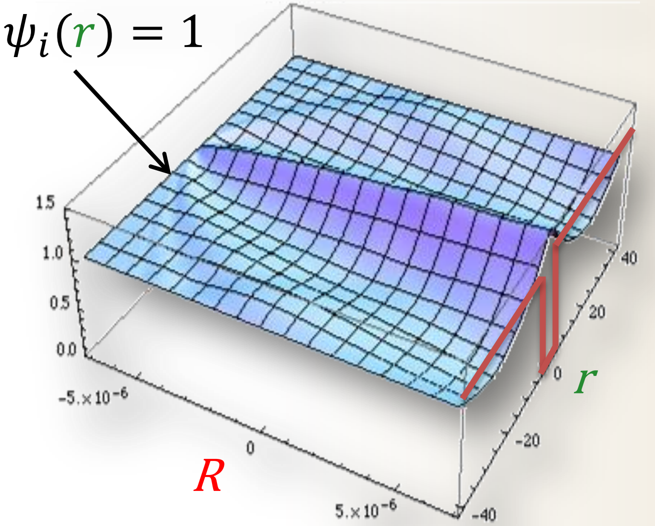
$$V(r) = -\frac{1}{2 l_a} \frac{\Gamma}{\Delta} \times \begin{cases} 1 & r \ll r_B \\ 0 & r \gg r_B \end{cases}$$

Evolution of the two-photon probability amplitude $\psi(R, r)$:

$$i \frac{\partial \psi}{\partial R} = V(r)\psi + \frac{1}{2\tilde{m}} \frac{\partial^2 \psi}{\partial r^2}$$

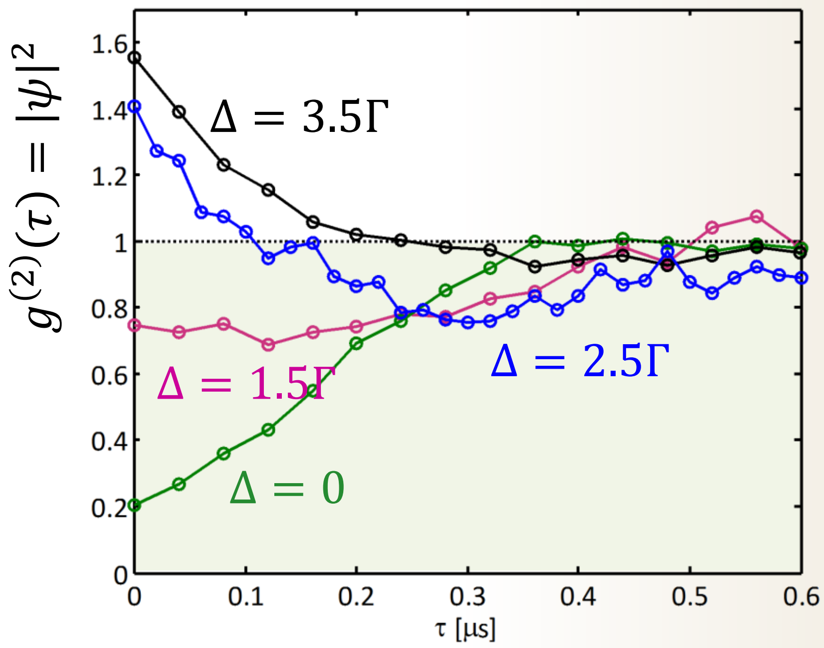
$$R = \frac{(z_1 + z_2)}{2} = 0 \dots L \qquad r = z_1 - z_2$$

Initial conditions: $\psi_i(r) = 1$

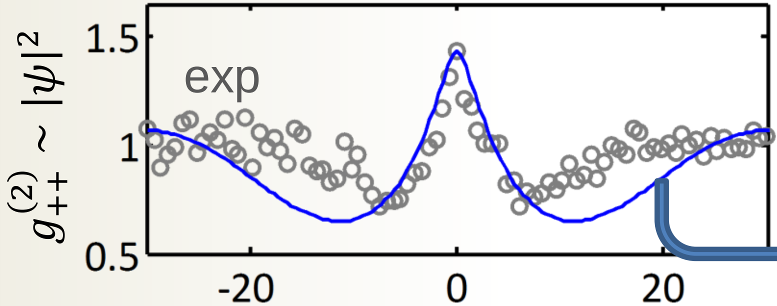


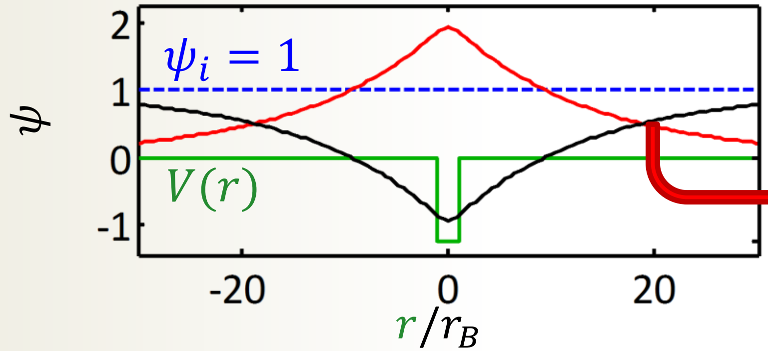
Bunching and 2-photon bound state

$$i\frac{\partial\psi}{\partial R} = \frac{1}{2\widetilde{m}}\frac{\partial^2\psi}{\partial r^2} + V(r)\psi$$



For our experimental parameters, the system has a single bound-state:



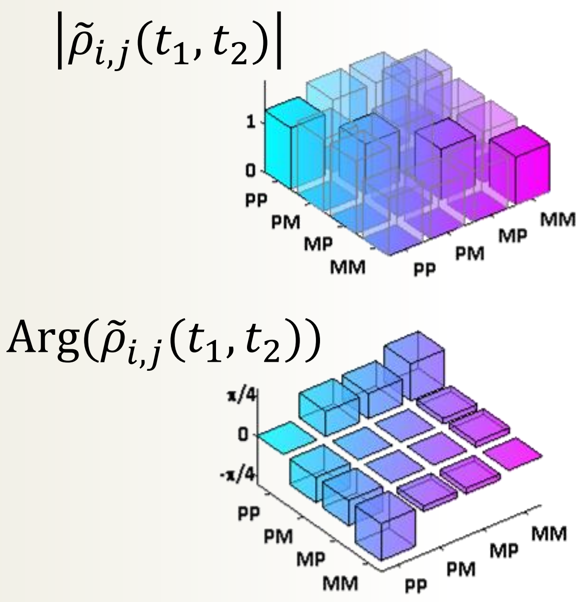


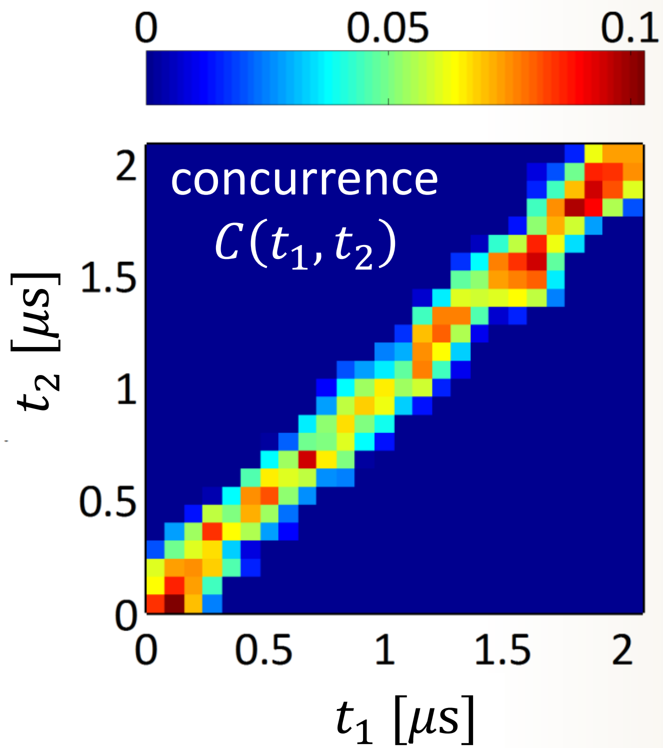
$|\psi(r)|^2$ = Solution of the Schrödinger-equation approximation

$\psi_{B.S}(r)$= two-photon bound state

Related theory: S. Fan / Baranger / D. Chang / Drummond

Entanglement in polarization basis





deterministic entanglement of previously-independent photons

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Gorshkov / Thursday 11 AM:
Repulsive potentials,
Coulomb-like potentials,
Many-body physics.

Looking for **postdocs** for the new quantum nonlinear optics lab at the Weizmann Institute

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