Observation of three-photon bound states in a quantum nonlinear medium

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Oh Seunghoon

Journal club

The research group

QUANTUM OPTICS

Liang et al., Science 359, 783–786 (2018)

Observation of three-photon bound states in a quantum nonlinear medium

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Vladan Vuletic

Principal investigator in the Research Laboratory of Electronics (RLE) at the Massachusetts Institute of Technology (MIT)

In 1992 - Earned the Physics Diploma with highest honors from the Ludwig-Maximilians-Universität München

In 1997 - Earned a Ph.D. in Physics from the same institution.

His interests lie in many-body quantum mechanics and the experimental implementation of entangled many-body states.

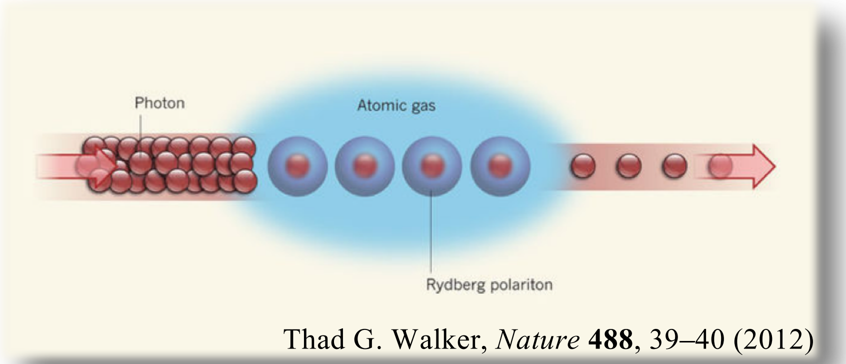
Research Interests

Laser cooling and trapping, quantum physics, quantum entanglement, quantum optics, quantum information processing

Selected publication

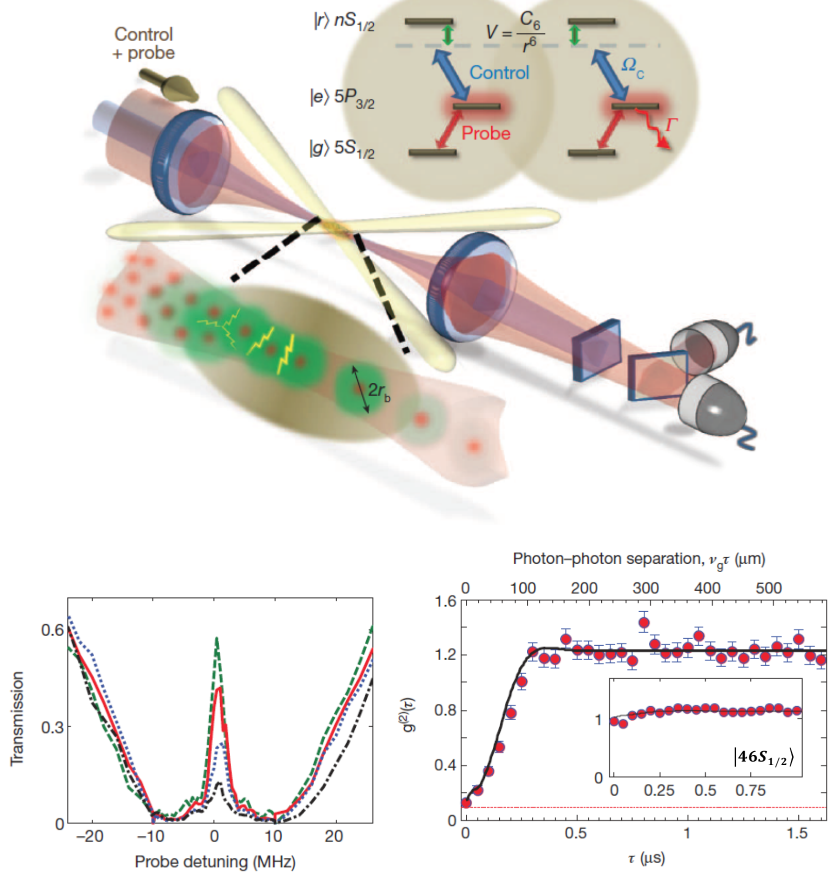
- All-optical switch and transistor gated by one stored photon (Science)
- Nanophotonic quantum phase switch with a single atom (Nature)
- Atom-by-atom assembly of defect-free one-dimensional cold atom array

Rydberg polaritons



Thad G. Walker, *Nature* **488**, 39–40 (2012)

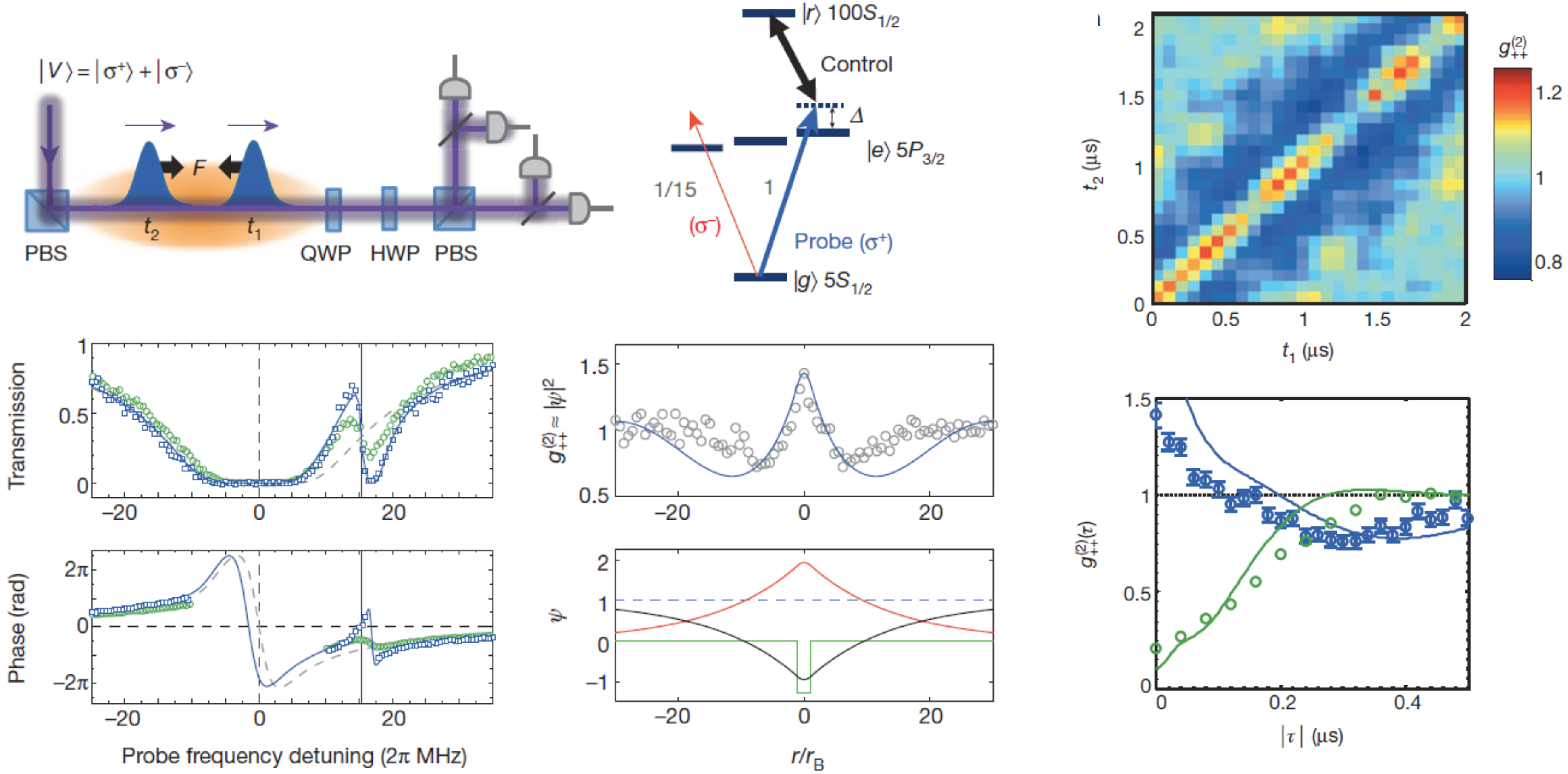
Finite group velocity & low loss
via strong interaction between Rydberg atoms



on atomic resonance

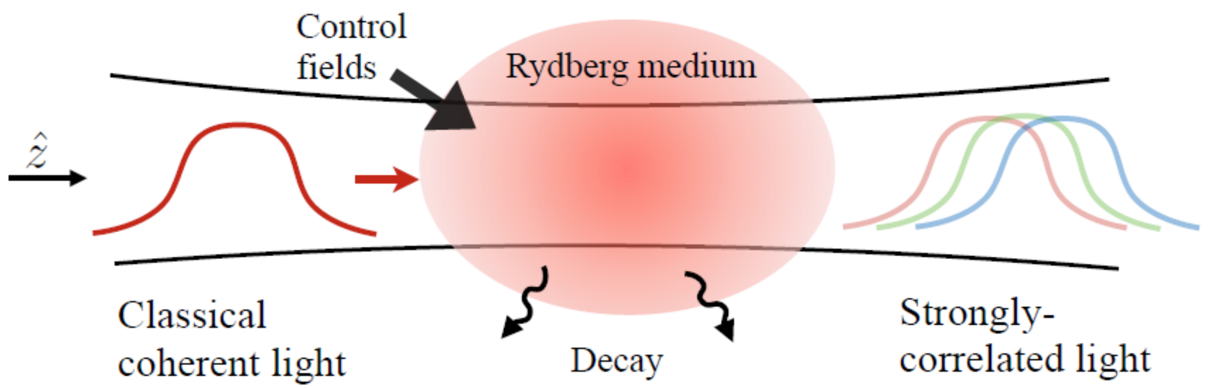
V. Gorshkov, J. Otterbach, M. Fleischhauer, T. Pohl, M. D. Lukin, Phys. Rev. Lett. 107, 133602 (2011)
T. Peyronel et al., Nature 488, 57–60 (2012)

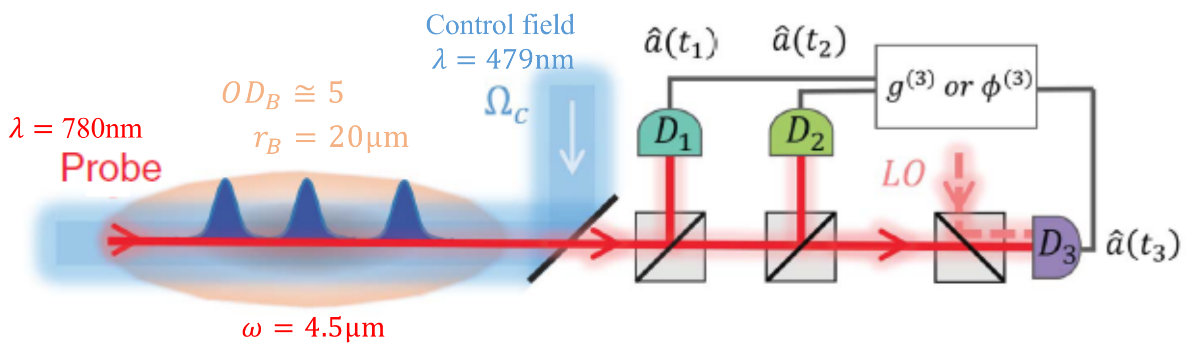
Photon bound state (dimer)

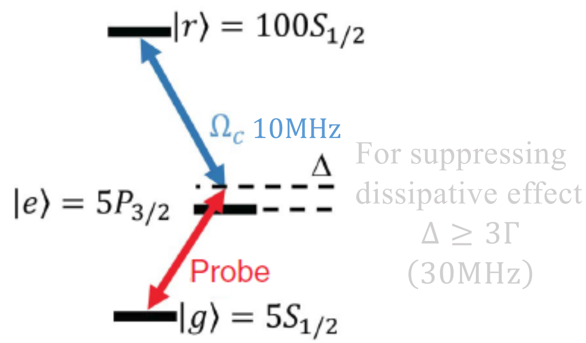


O. Firstenberg et al., Nature 502, 71–75 (2013)

Experimental setup

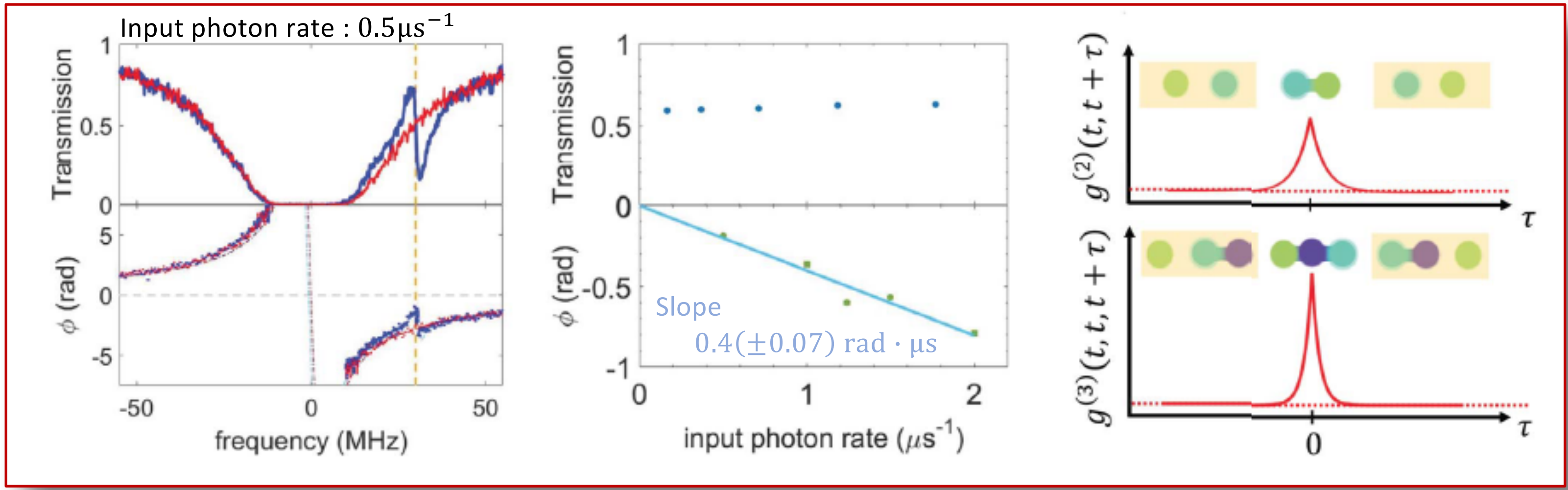


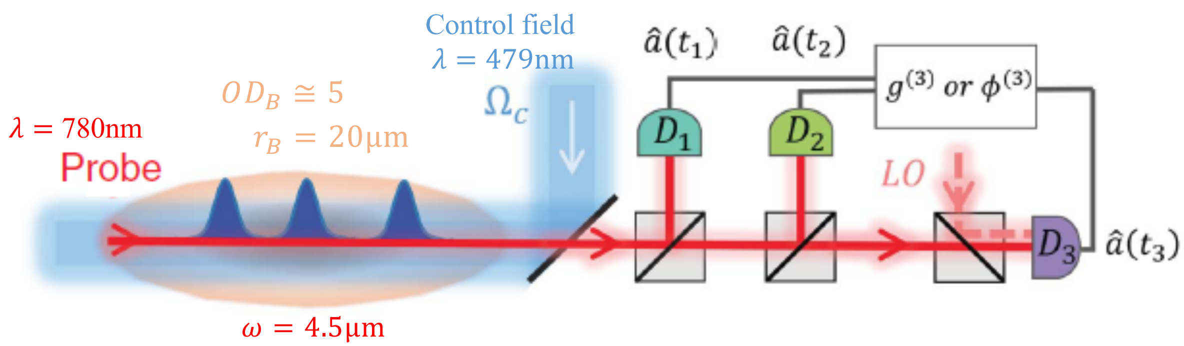


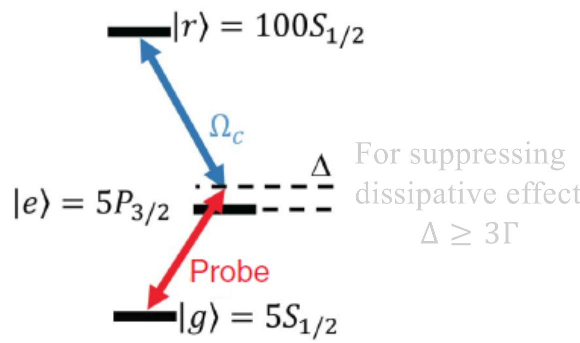


EIT-configuration of ^{87}Rb

Experimental setup







EIT-configuration of ^{87}Rb

The quantum dynamics of interacting photons ($g^{(N)}$ & $\phi^{(N)}$)

Considering the state containing up to the three photon

$$|\Psi\rangle$$
$$= |0\rangle + \int dt_1 \Psi_1(t_1)|t_1\rangle + \int dt_1 dt_2 \Psi_1(t_1,t_2)|t_1,t_2\rangle + \int dt_1 dt_2 dt_3 \Psi_1(t_1,t_2,t_3)|t_1,t_2,t_3\rangle$$

$|t_1,\cdots,t_N\rangle = \frac{1}{N!}a^\dagger(t_1)\cdots a^\dagger(t_N)|0\rangle$, N : number of photons

$a^\dagger(t)$: photon creation operator of the time bin mode 't'

The correlation function

$$g^{(2)}(t_1,t_2) = \frac{|\Psi_2(t_1,t_2)|^3}{|\Psi_1(t_1)|^2|\Psi_1(t_2)|^2} \qquad g^{(3)}(t_1,t_2,t_3) = \frac{|\Psi_3(t_1,t_2,t_3)|^2}{|\Psi_1(t_1)|^2|\Psi_1(t_2)|^2|\Psi_1(t_3)|^2}$$

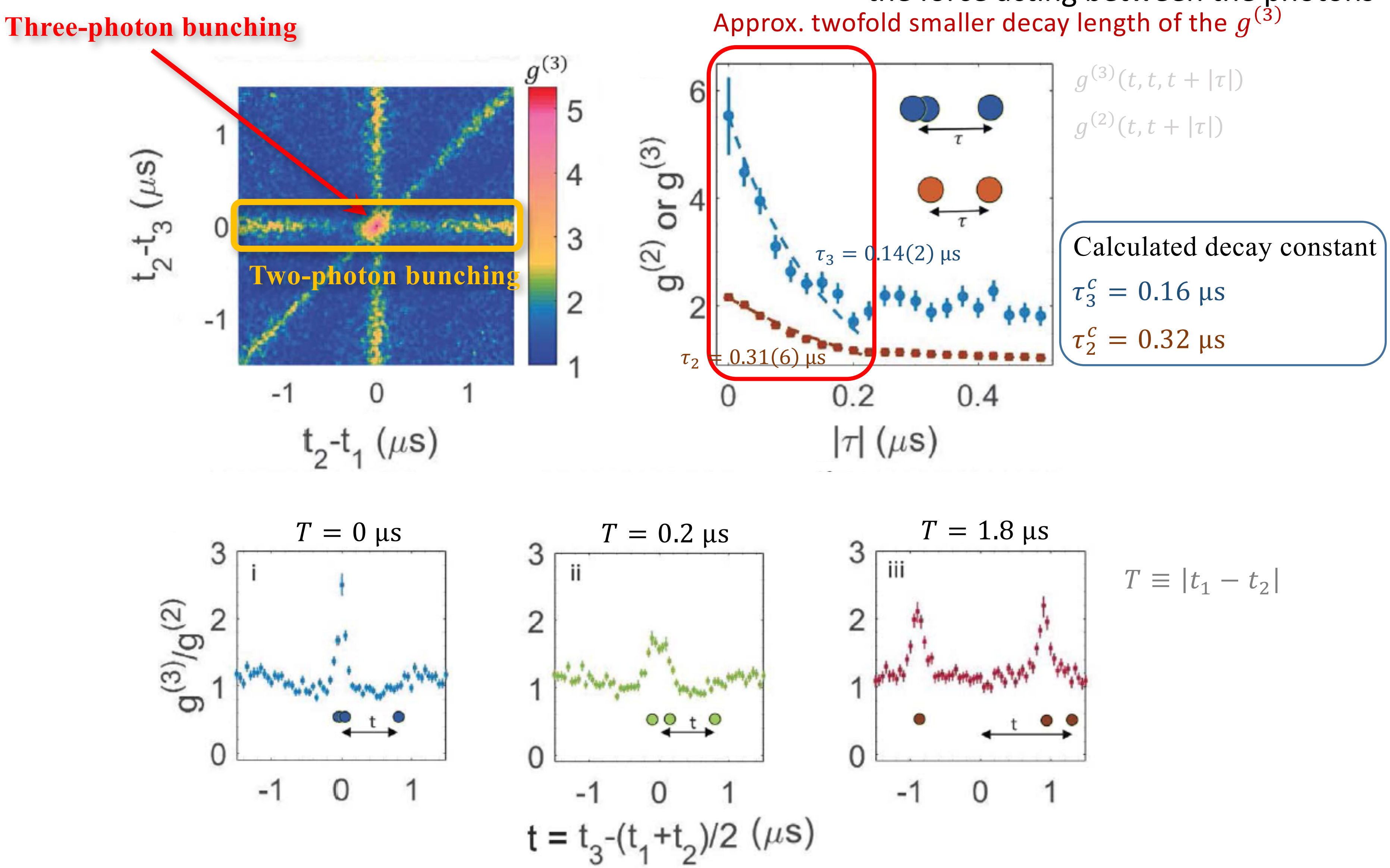
Ψ_N : N-photon wave function

Phase of the N-photon wave function, $\tilde{\phi}^{(N)}$

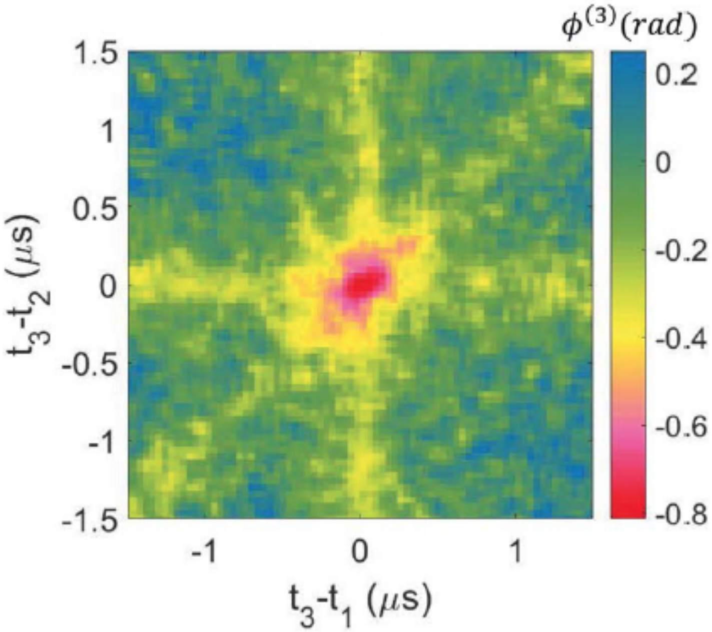
$$\tilde{\phi}^{(1)}(t_1) = \mathrm{Arg}[\Psi_1(t_1)\,]$$
$$\tilde{\phi}^{(2)}(t_1,t_2) = \mathrm{Arg}[\Psi_1(t_1,t_2)\,]$$
$$\phi^{(3)}(t_1,t_2,t_3) = \mathrm{Arg}[\Psi_1(t_1,t_2,t_3)\,]$$

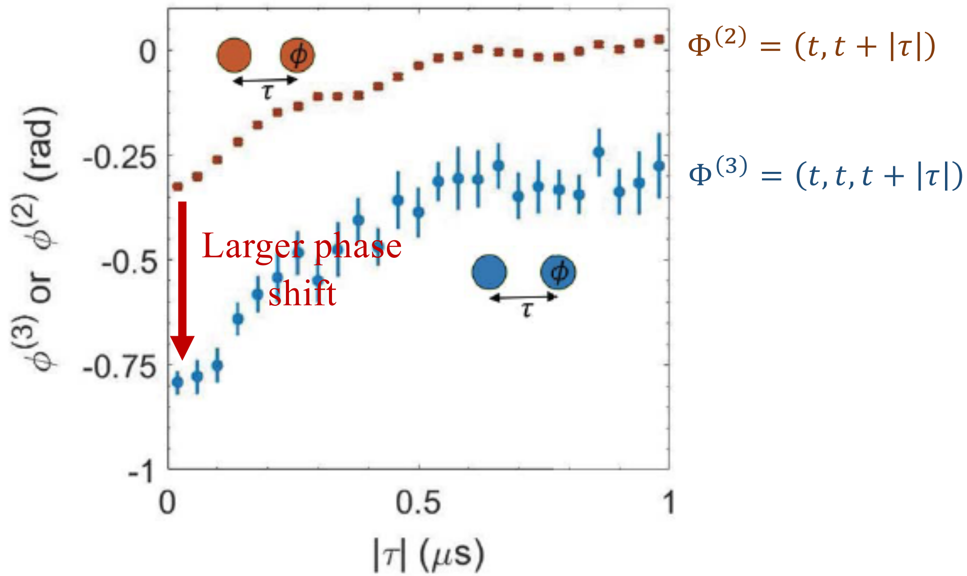
Three-photon correlation function

- The decay length is closely related to the force acting between the photons



Three-photon phase ($\Phi^{(3)}$)





The interaction between a photon and a dimer is stronger than that between two photons

Summary

- They have shown that three-photon bounded state, or quantum photonic soliton, in a way of measuring $g^{(3)}$ and $\phi^{(3)}$.

- Comparing to two-photon case(photonic dimer), three-photon case(photonic trimer) much more likely to attract the other photon to be bounded together.

- Increasing interacting medium length with larger τ, it would retain only the solitonic bound-state component by means of quantum destructive interference.

- With improved detection efficiency and data-acquisition rate, larger photonic molecules could be observed.

- With the probe beam engineering, the system con be extended to 2,3D.

Thank you

Effective field theory (EFT)

1D slow-light Hamiltonian density

$$\boxed{\mathcal{H} = -\hat{\Psi}^{\dagger}\left(i\hbar v_g \frac{\partial}{\partial_z} + \frac{\hbar^2}{2m}\frac{\partial^2}{\partial_z^2}\right)\hat{\Psi} - \frac{\hbar^2}{ma}\hat{\Psi}^{\dagger 2}\hat{\Psi}^2}$$

$m = -\frac{\hbar\Omega_c^2}{8\Delta v_g^2}$: effective photon mass

v_g : group velocity $\qquad$ Ω_c : control laser Rabi frequency

a : scattering length $\qquad$ Δ : one-photon detuning

For weak interaction,

$$a \approx 15.28\left(\frac{1}{OD_B}\frac{\Delta}{\Gamma}\right)^2 r_B$$

$$(a \gg r_B \rightarrow a \gtrsim 10\, r_B)$$

Effective field theory (EFT)

The photon correlation function

$$g^{(3)}(t_1, t_2, t_3) \propto e^{-\frac{|t_1 - t_2|}{a/(2v_g)}} e^{-\frac{|t_2 - t_3|}{a/(2v_g)}} e^{-\frac{|t_3 - t_1|}{a/(2v_g)}} \qquad g^{(2)}(t_1, t_2) \propto e^{-\frac{|t_1 - t_2|}{a/(2v_g)}}$$

$$g^{(3)}(t, t, t + |\tau|) \propto e^{-2\frac{|\tau|}{a/(2v_g)}}$$

half width wave packet
for the same experimental condition
0.32 μs & 0.16 μs

The dimer & trimer binding energy (estimated)

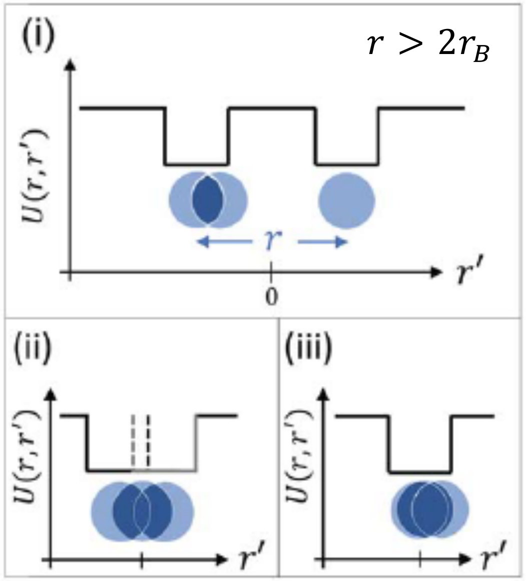
$$E_2 = -\frac{\hbar^2}{ma^2} = h \times 0.2\ \mathrm{MHz}$$

$$E_3 = 4E_2$$

The phase ratio $(\phi^{(3)}/\phi^{(2)})$ is expected to be **4**, independent of the atom-light detuning(Δ)

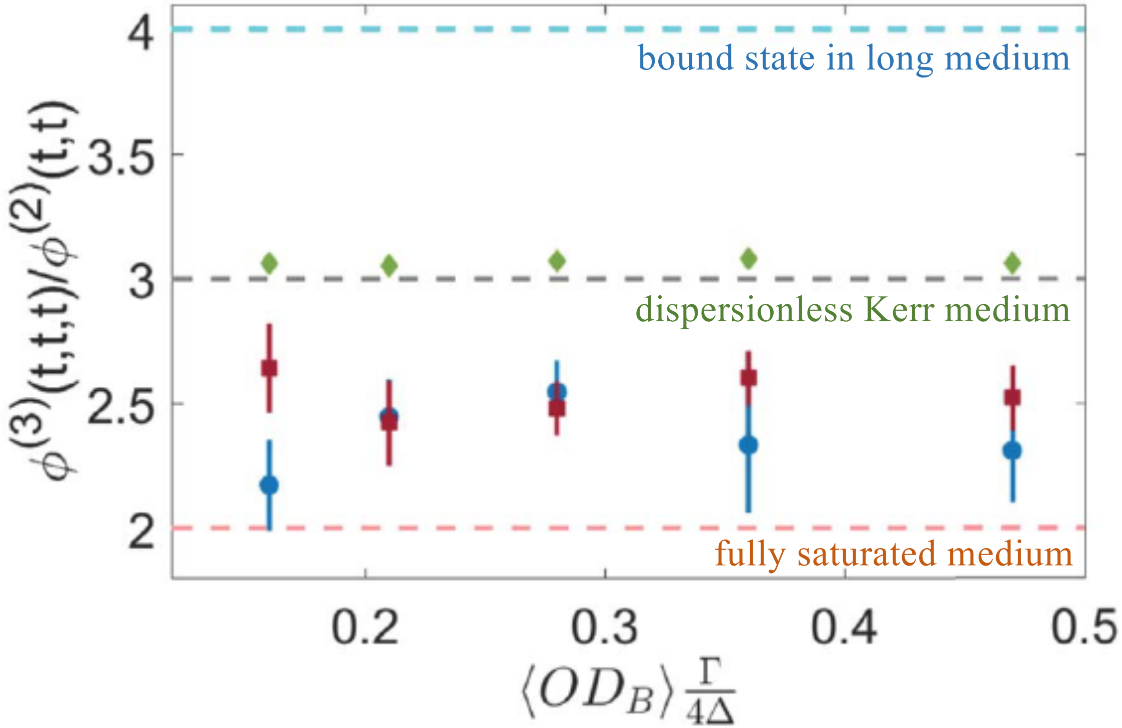
EFT and experimental result

Interaction potential between two photons



$2r_B > r > r_B$ $\quad$ $r < r_B$

Repulsive effect for saturation of the Rydberg blockade



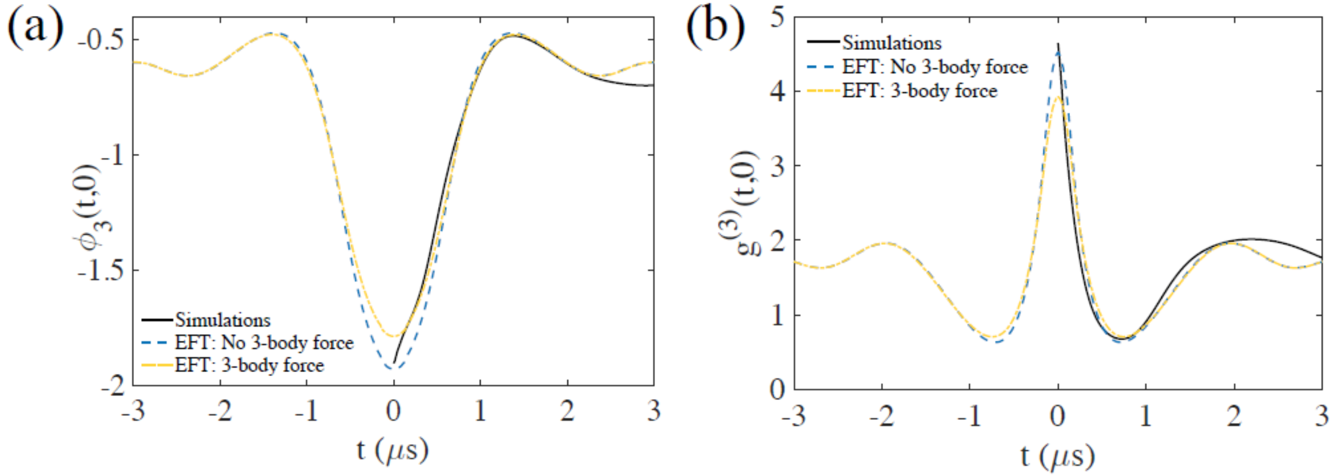


FIG. S3: Comparison between EFT and simulations

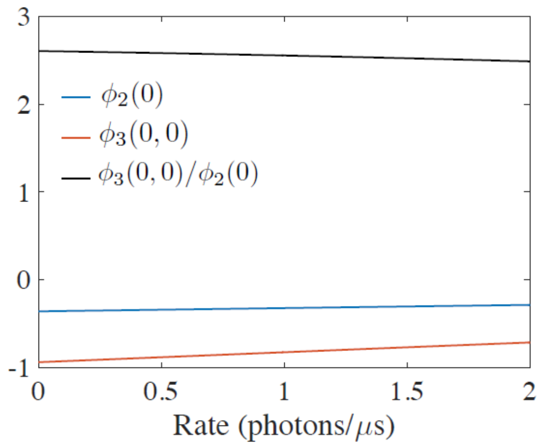


FIG. S4: Rate dependent corrections within the EFT

Model	$\phi_3(0,0)/\phi_2(0)$
Simulations	2.90
EFT: No 3-body force	3.13
EFT: 3-body force	$2.85 \pm .11$

TABLE S1: Comparison of phase ratio between EFT and simulations.

$\langle\varphi\rangle$=$\langle \mathrm{OD}_B\rangle\Gamma/4\Delta$	0.16	0.21	0.28	0.36	0.47
Measured $\phi_3(0,0)/\phi_2(0)$	$2.17 \pm .18$	$2.45 \pm .15$	$2.55 \pm .13$	$2.33 \pm .27$	$2.31 \pm .21$
EFT: 3-body force	$2.64 \pm .18$	$2.42 \pm .17$	$2.48 \pm .11$	$2.60 \pm .11$	$2.52 \pm .13$
Simulations	2.77	2.66	2.72	2.63	2.60
EFT: No 3-body force	3.06	3.05	3.07	3.08	3.06
Fitted δ ($2\pi\cdot$MHz)	0.6	0.6	0	-0.2	-0.4

TABLE S2: Comparison of phase ratio between EFT, simulations and experimental data.