Quantum nonlinear optics in the strong photon-photon interaction regime

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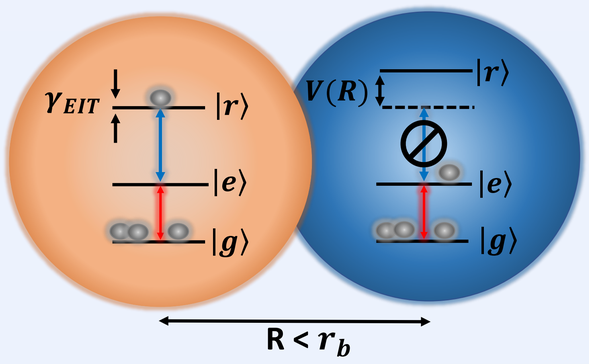
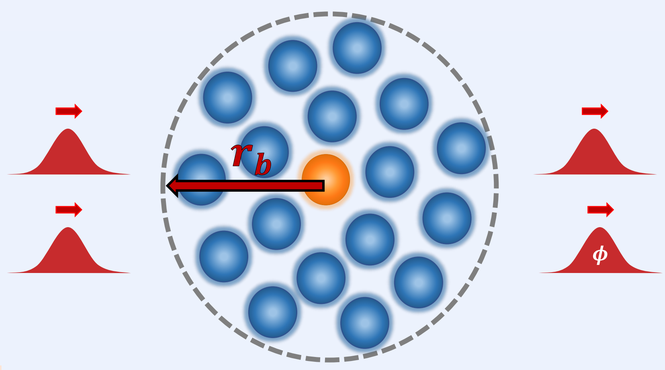
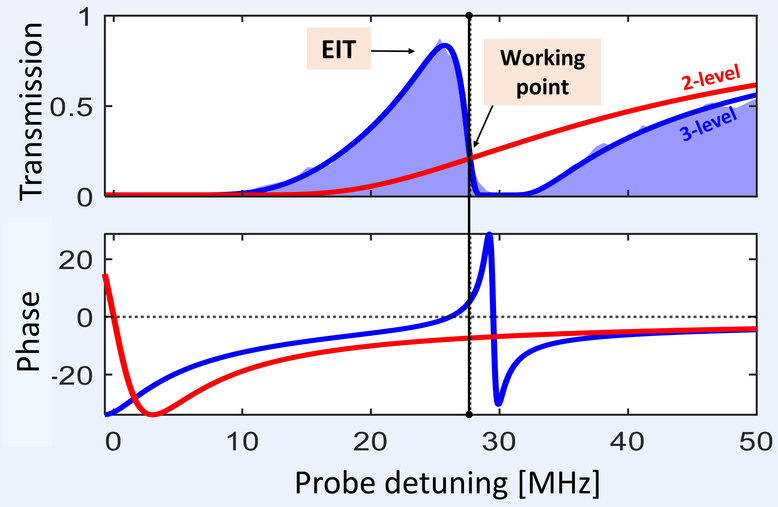
Abstract

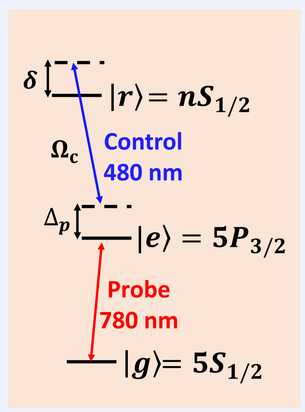
We explore effective photon-photon interactions by coupling light to cold Rydberg atoms.
In the strong-interaction regime, we observe a large (>π) two-photon phase, genuine three-photon interactions and optical quantum vortices.

Background: interaction between photons induced by interaction between Rydberg atoms







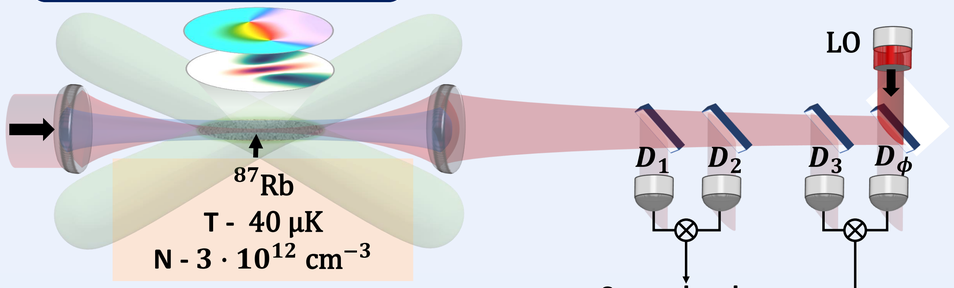


$$V(R) = -\frac{C_6}{R^6} \propto \frac{n^{11}}{R^6}$$

$$r_b = \left(\frac{|C_6|}{\gamma_{EIT}}\right)^{1/6}$$

$$OD_b = OD \cdot \frac{r_b}{L}$$

Experimental Setup



OD – Optical Depth~90

n - Principal quantum number = 100

$\tilde{r}_b$- Blockade radius ~ 16 μm

OD_b - Blockaded optical depth ~19

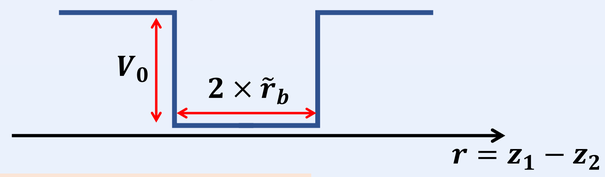
Simple Model

The dynamics can be described approximately by a Schrodinger-like equation:

$$\frac{i\partial\psi(R,r)}{\partial R} = -\frac{1}{2m}\frac{\partial^2\psi(R,r)}{\partial r^2} + U(r)\psi(R,r)$$

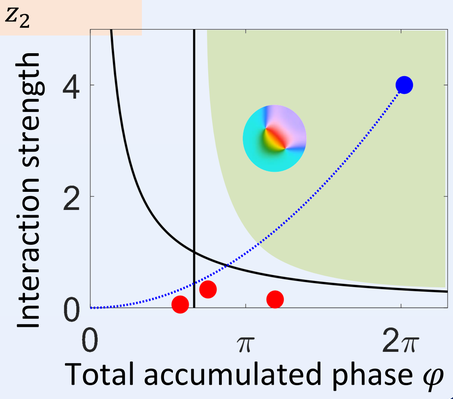
$R = \frac{z_1+z_2}{2}$, R: $[0, L]$.
$r = z_1 - z_2$

Two – photon interaction U(r):



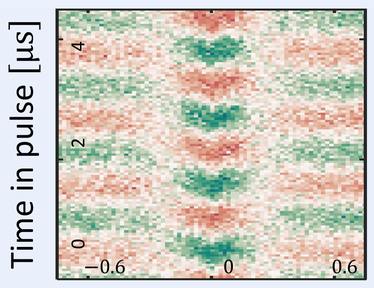
Interaction strength:
$$\lambda = 2m\tilde{r}_b^{\,2}U = \left(\frac{OD_b \cdot \Gamma}{2\Delta_p}\right)^2 \cdot \left(\frac{\Delta_p}{\Gamma}\right)^{\frac{2}{6}}$$

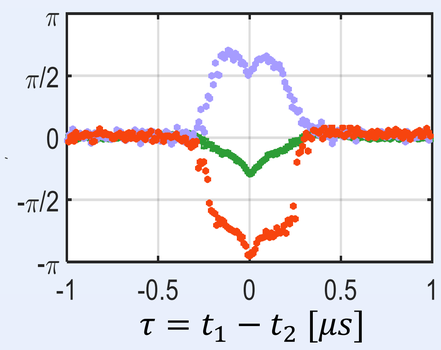
Effective mass:
$$\omega - v_{group}k \propto \frac{1}{m}k^2$$



Conditional π phase shift

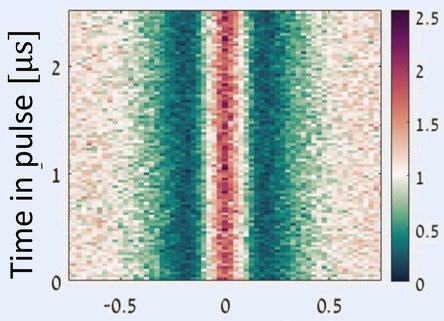
Conditional beat signal

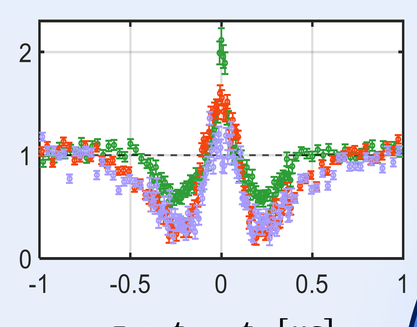




OD ≈ 50
OD ≈ 75
OD ≈ 95

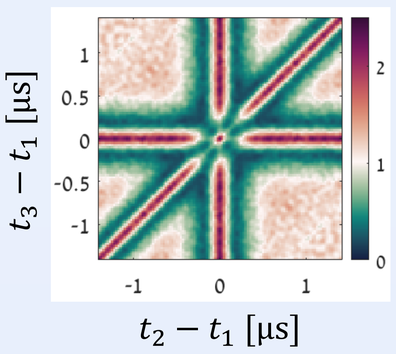
Second order intensity correlation $g^{(2)}$





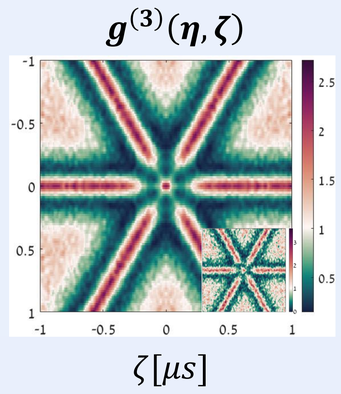
Strong photon-photon interaction regime

Three photon interactions



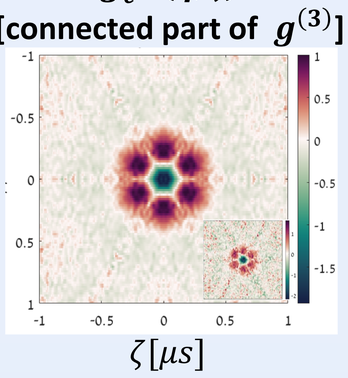
$$\eta = \frac{t_2 - t_1}{\sqrt{2}}$$

$$\zeta = \sqrt{\frac{2}{3}}\left(\frac{t_1 + t_2}{2} - t_3\right)$$



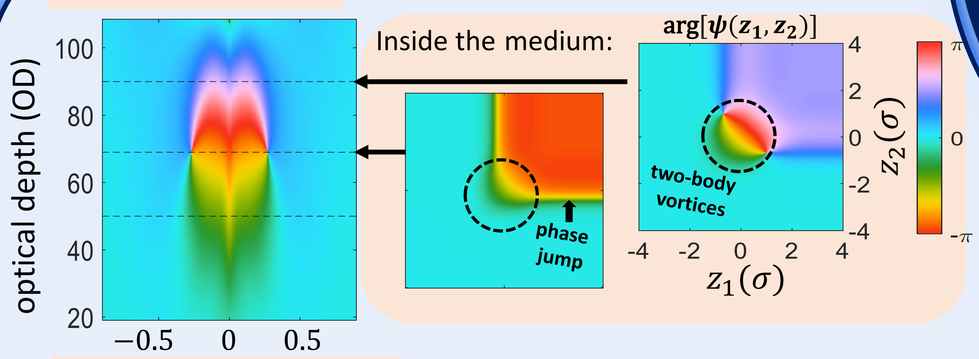
$$g_c^{(3)}(\eta,\zeta) = g^{(3)}(\eta,\zeta) - g^{(2)}(t_2 - t_1) - g^{(2)}(t_3 - t_1) - g^{(2)}(t_3 - t_2) + 2$$

$g_c^{(3)}(\eta, \zeta)$ [connected part of $g^{(3)}$]



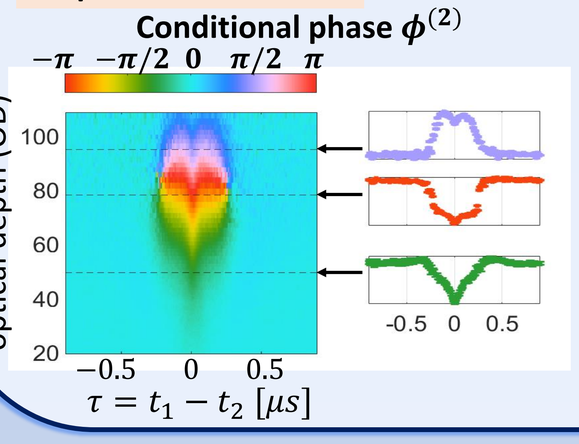
Two photon vortices

Simulation results

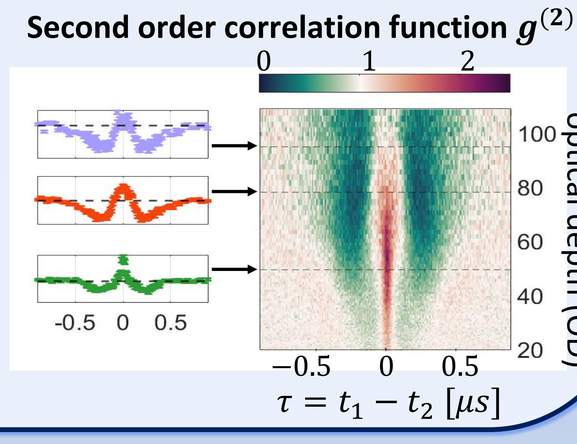


Experimental results

Conditional phase $\phi^{(2)}$

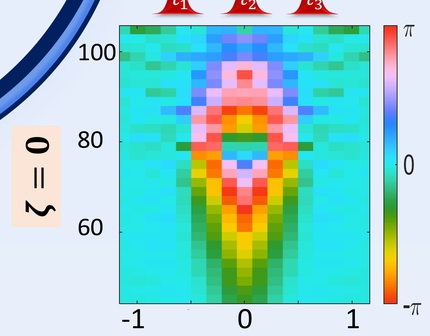


Second order correlation function $g^{(2)}$

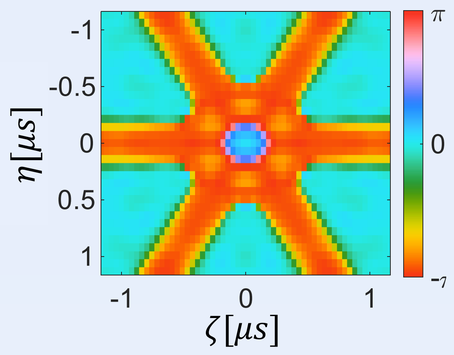


Three photon vortex line and ring

$\phi^{(3)}$ along η



@ critical OD ≈ 75



$\phi^{(3)}$ along ζ