META 2018: Session 3A13 (Wednesday, 27th June, 17:00-19.15)
Quantum Nanophotonics for Applications in Quantum Information Science

Technische Universität Berlin

Correlation of cascaded photons: Two-photon processes in the Mollow Regime

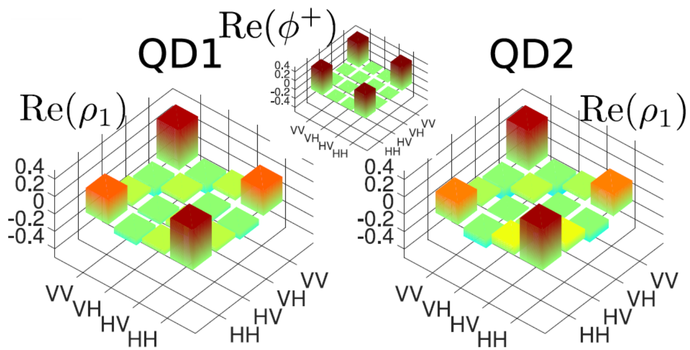
Alexander Carmele, Julian Schleibner, and Andreas Knorr
Technische Universität Berlin, Institut für Theoretische Physik

Samir Bounouar, Max Strauß, and Stephan Reitzenstein
Technische Universität Berlin, Institut für Festkörperphysikk

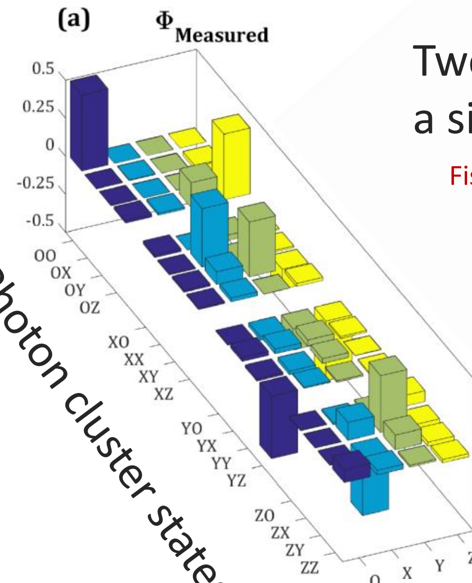
Recent successes in the field of semiconductor quantum optics

Recent highlights in Semiconductor Quantum Optics

Generation of highly **entangled** photon pairs



Bounouar et al, Appl.Phys.Lett. 112, 153107 (2018)
Winik et al, Phys. Rev. B 95, 235435 (2017).

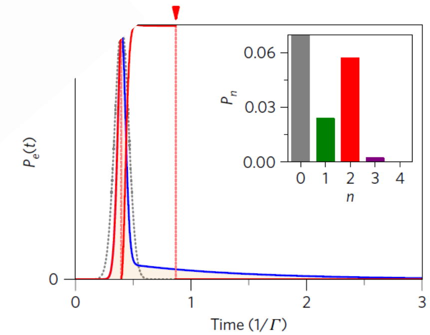


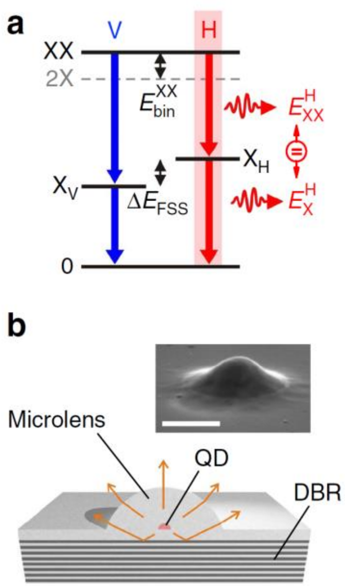
Photon cluster states

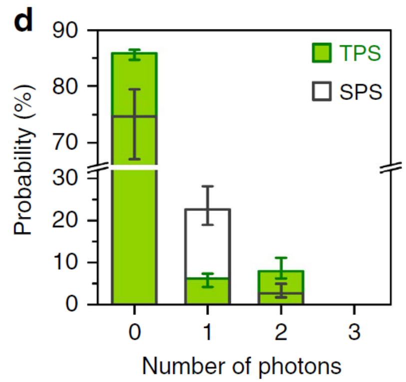
Schwartz et al, Science 354, 434 (2016)

Two-photon processes of a single Quantum dot

Fisher et al, Nat.Physics 13, 649 (2017)

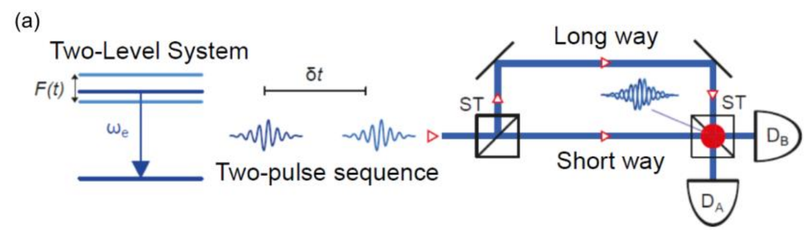


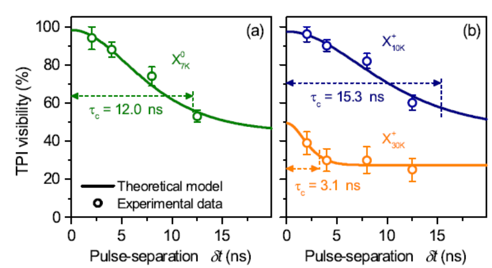




Deterministic **twin**-photon source

Heindel et al, Nat. Comm. 8, 14870 (2017)





Thoma et al, PRL 116, 033601 (2016)

Generation of indistinguishable photons (up to 99% visibility)

Ding et al, PRL 116, 020401 (2016)
Kim et al, Optica 3, 577 (2016)
Wang et al, PRL 116, 213601 (2016)

N-Photon bundles in cascade processes: Two-Photon resonance fluorescence

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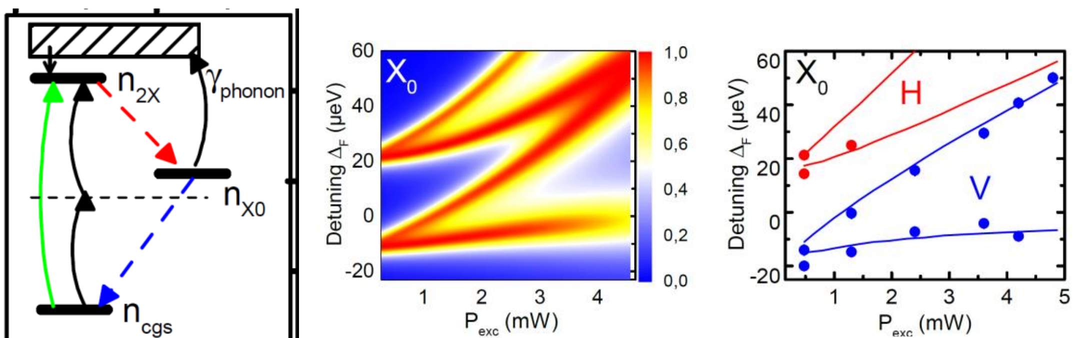
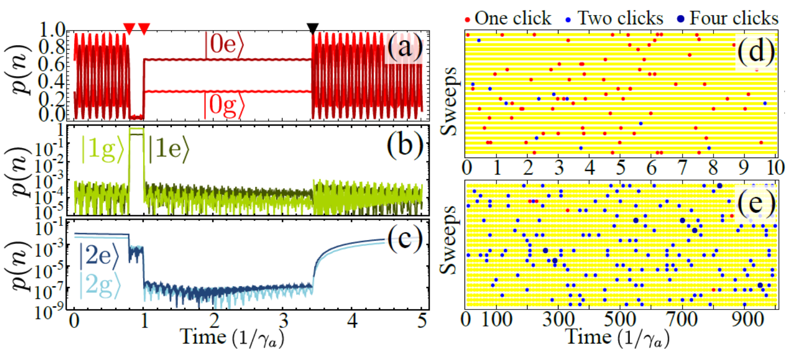


Cavity-assisted two-photon excitation with directionality in the nonlinear excitation regime

Hargart et al, Phys. Rev. B 93, 115308 (2016)

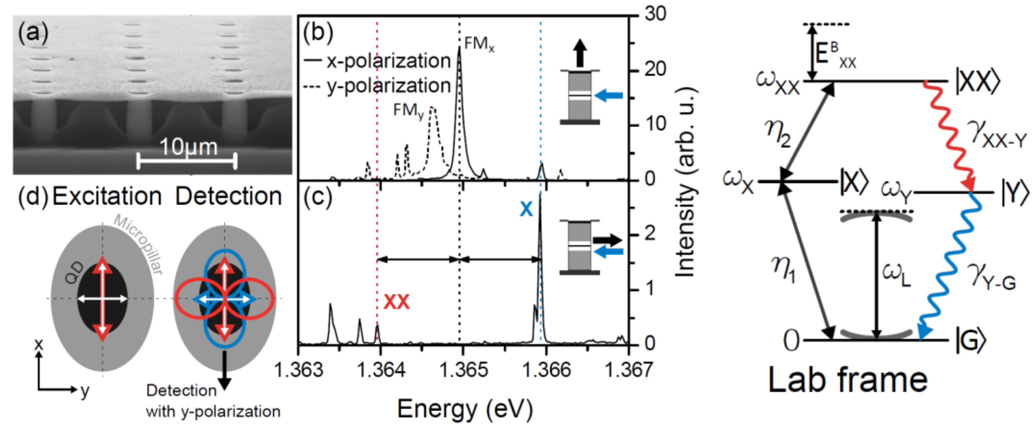
Ardelt et al, Phys. Rev. B 90, 241404 (R) (2014)

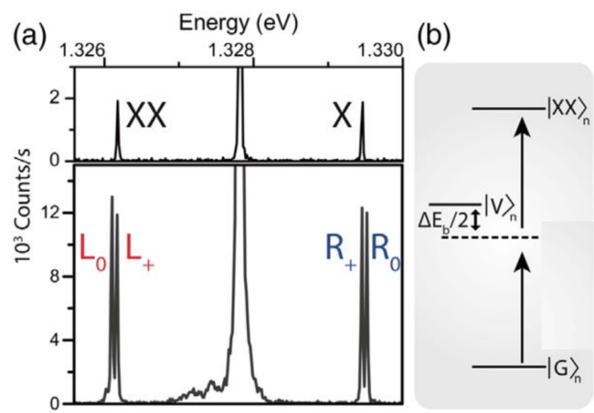
Phonon-assisted emission processes and comparison between single-photon and two-photon excitations



Theoretical proposal via N-photon bundles in leapfrog processes

Munoz et al, Nat.Photonics 8, 550 (2014)

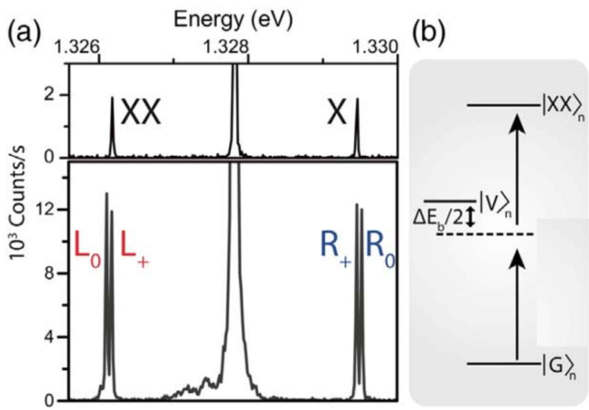




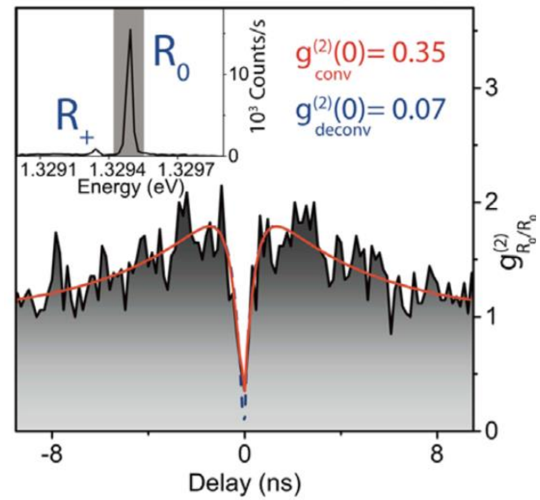
Mollow physics in cascade processes

Bounouar et al, PRL 118, 233601 (2017)

Mollow physics in the two-photon regime – polarization selective

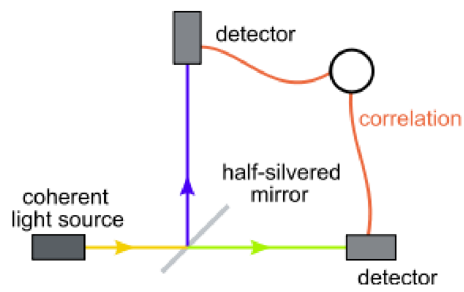


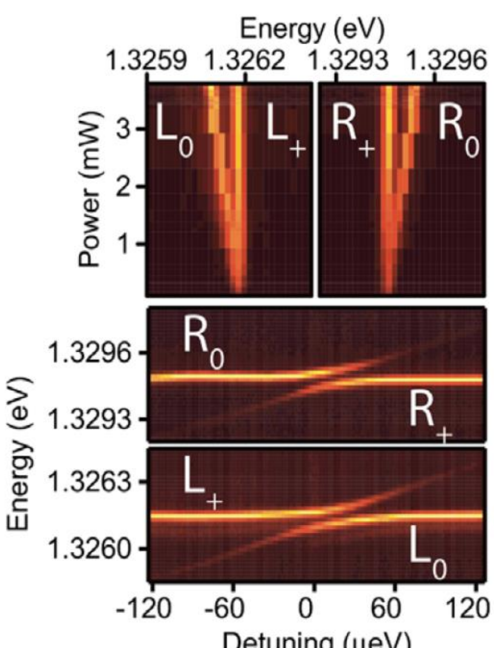
Bounouar et al, PRL 118, 233601 (2017)



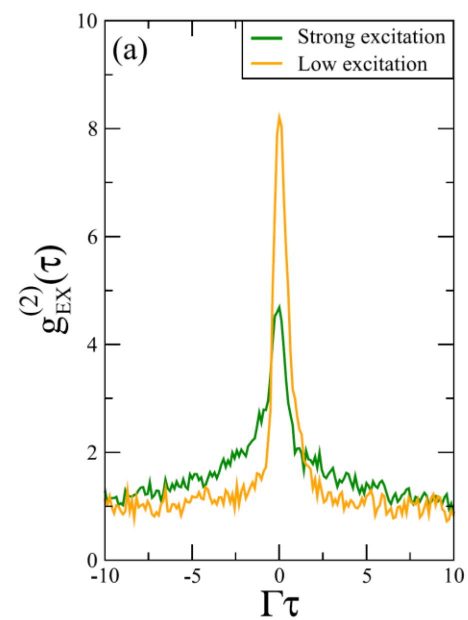
Antibunching for single lines confirm the non-classical character of the quantum light source

Two-photon driving in resonance with biexciton and off-resonant with exciton





Unexpected behavior for combined biexciton and exciton photons – no antibunching is visible



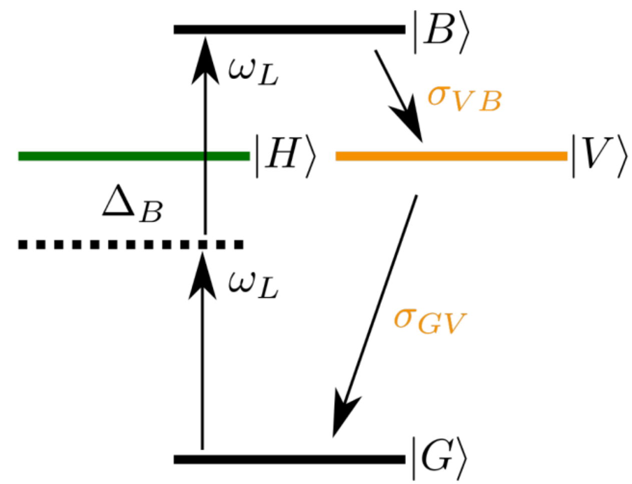
Theory of two-photon Mollow physics

Theoretical model

Hamiltonian in two-photon resonance with exciting laser field and radiative decay and master equation approach:

$$H = \Delta\left(\sigma_{HH} + \sigma_{VV}\right) + \Omega_L(\sigma_{GH} + \sigma_{HB} + \text{h.c.})$$

$$\dot{\rho} = -i\,[H, \rho] + \Gamma_X \sum_{i=H,V} \left(\mathcal{D}[\sigma_{Gi}] + \mathcal{D}[\sigma_{iB}]\right)\rho$$



Schleibner, submitted, arXiv: 1710.03031

Set of differential equation can be drastically reduced if symmetries and time-scales are taken into accout

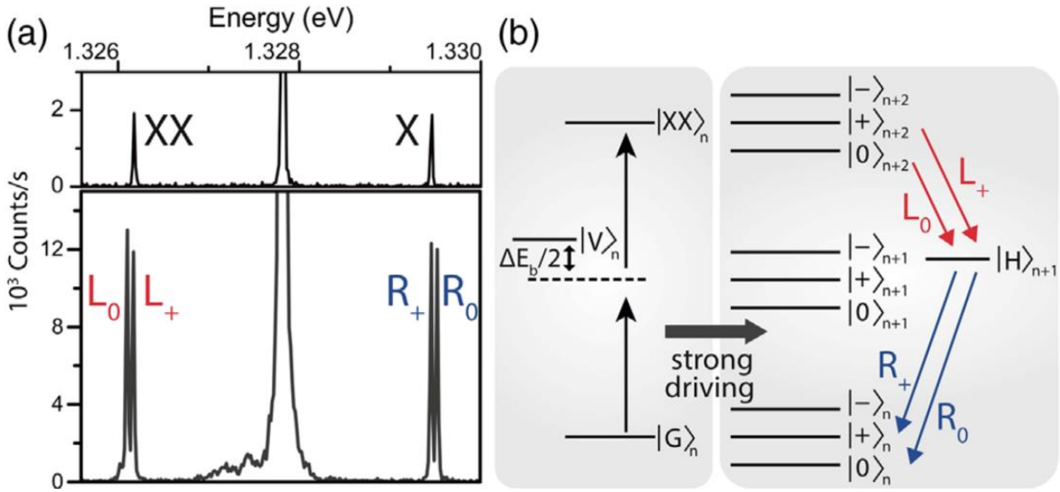
$$\begin{aligned}
\dot{\rho}_{GG} &= 2\Gamma_X\left(\rho_{HH} + \rho_{VV}\right) - i\Omega_L\left(\rho_{HG} - \rho_{GH}\right),\\
\dot{\rho}_{HG} &= -\left(\Gamma_X + i\Delta\right)\rho_{HG} - i\Omega_L\left(\rho_{BG} + \rho_{GG} - \rho_{HH}\right),\\
\dot{\rho}_{HH} &= -2\Gamma_X\left(\rho_{HH} - \rho_{BB}\right) - i\Omega_L\left(\rho_{GH} - \rho_{HG} + \rho_{BH} - \rho_{HB}\right),\\
\dot{\rho}_{BG} &= -2\Gamma_X\rho_{BG} - i\Omega_L\left(\rho_{HG} - \rho_{BH}\right),\\
\dot{\rho}_{BH} &= -\left(3\Gamma_X - i\Delta\right)\rho_{BH} - i\Omega_L\left(\rho_{HH} - \rho_{BB} - \rho_{BG}\right),\\
\dot{\rho}_{BB} &= -4\Gamma_X\rho_{BB} - i\Omega_L\left(\rho_{HB} - \rho_{BH}\right),\\
\dot{\rho}_{VV} &= -2\Gamma_X\left(\rho_{VV} - \rho_{BB}\right).
\end{aligned}$$

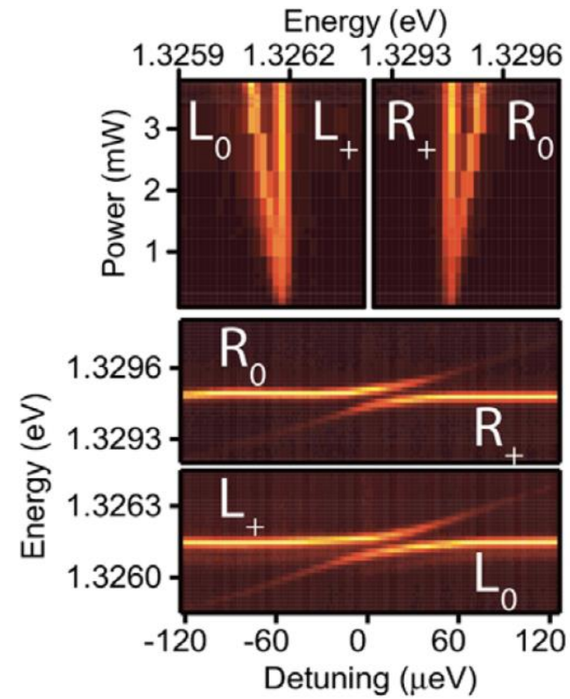
$$\begin{aligned}
\dot{D}(t) &= -\Gamma\left[D(t) + \Sigma_0\right] - i\Omega B(t)\\
\dot{B}(t) &= -\Gamma B(t) - i\Omega D(t).
\end{aligned}$$

Benchmark the quantum optical power spectrum signal:

$$S_i(\omega) = \text{Re}\left[\lim_{t\to\infty}\int_0^{\infty}\langle c_i^{\dagger}(t)c_i(t+\tau)\rangle\, e^{i(\omega-\omega_L)\tau}\, d\tau\right] \qquad c_i(t) = \sigma_{iB}(t) + \sigma_{Gi}(t)$$

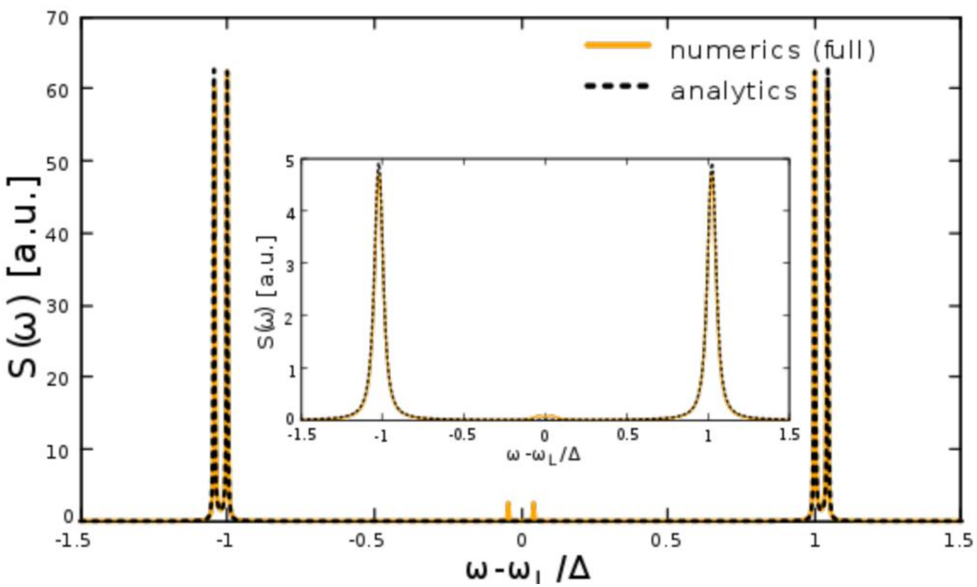
Benchmark the experimental signal with theoretical modelling





Bounouar et al, PRL 118, 233601 (2017)

Splitting occurs for strong driving, but only one peak shifts



Two-photon spectrum solution:
In the strong-driving limit, one peak does not shift, splitting proportional to the square of the Rabi energy

But what about the correlation function?

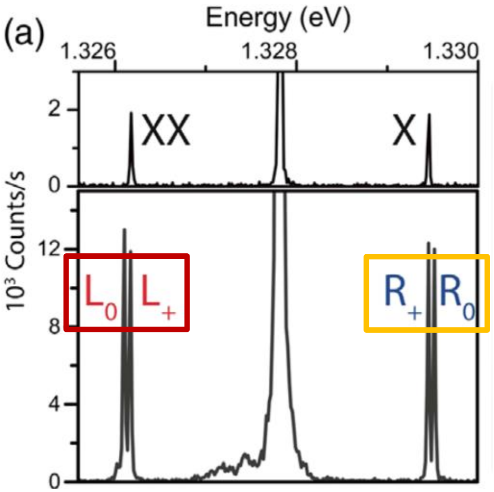
$$S_{BV}(\omega) = \alpha\left(\frac{\Omega_R\Gamma + \frac{\Gamma}{2}(\omega - \omega_L + \Delta + \frac{\Omega}{2} + \Omega_R)}{\Gamma^2 + [\omega - \omega_L - (-\Delta - \frac{\Omega}{2} - \Omega_R)]^2} + \frac{\Omega_R\Gamma - \frac{\Gamma}{2}(\omega - \omega_L + \Delta + \frac{\Omega}{2} - \Omega_R)}{\Gamma^2 + [\omega - \omega_L - (-\Delta - \frac{\Omega}{2} + \Omega_R)]^2}\right)$$

$$S_{VG}(\omega) = \alpha\left(\frac{\Omega_R\Gamma + \frac{\Gamma}{2}(\omega - \omega_L - \Delta - \frac{\Omega}{2} + \Omega_R)}{\Gamma^2 + [\omega - \omega_L - (\Delta + \frac{\Omega}{2} - \Omega_R)]^2} + \frac{\Omega_R\Gamma - \frac{\Gamma}{2}(\omega - \omega_L - \Delta - \frac{\Omega}{2} - \Omega_R)}{\Gamma^2 + [\omega - \omega_L - (\Delta + \frac{\Omega}{2} + \Omega_R)]^2}\right)$$

Schleibner, submitted, arXiv: 1710.03031

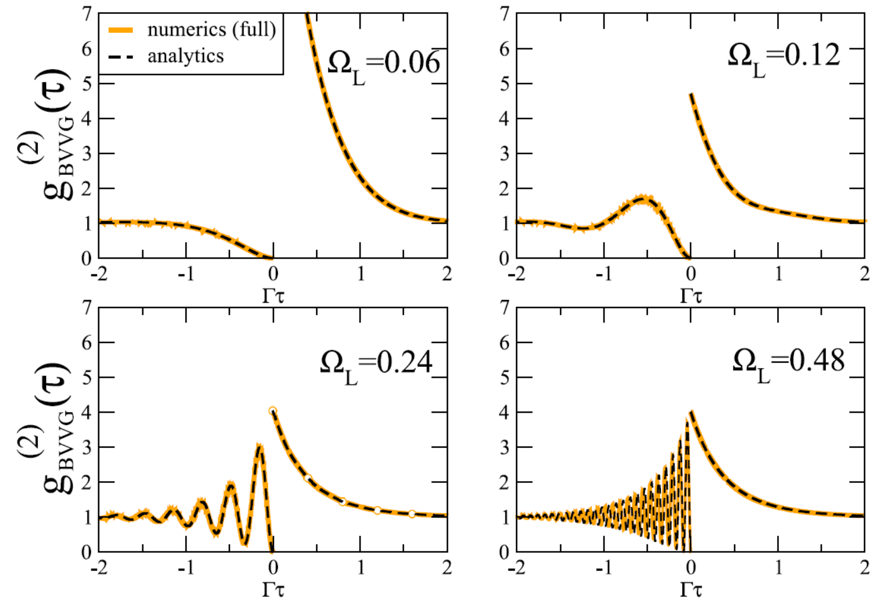
Photon-photon correlation function in the bare-state basis

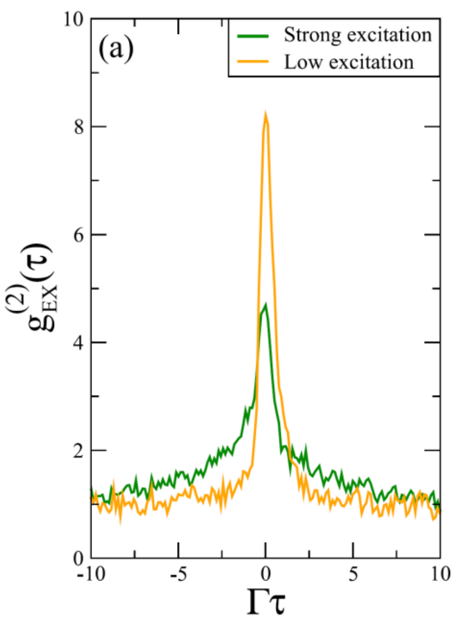
Hanbury Brown-Twiss setup to probe photon-photon correlations



$$g^{(2)}_{ijkl}(\tau) = \frac{\rho_{ii}(\infty)\rho^{jj}_{kk}(\tau)}{\rho_{ii}(\infty)\rho_{kk}(\infty)} = \frac{\rho^{jj}_{kk}(\tau)}{\rho_{kk}(\infty)}$$

Biexciton and exciton photon correlation show in theory bunching and antibunching





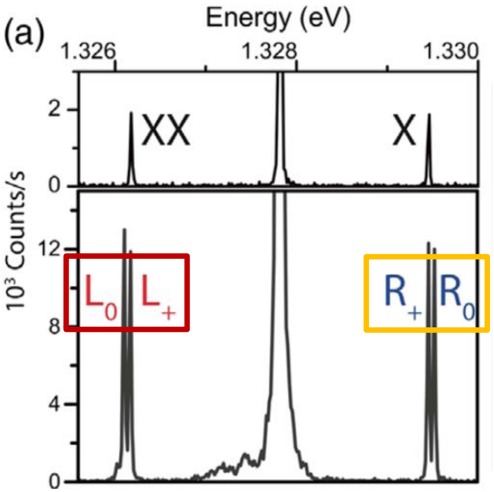
$$g^{(2)}_{BVVG}(\tau) = 2e^{-\Gamma\tau}\left(1 + \cosh(\Gamma\tau) + \alpha[1 + \cos(\Omega\tau)]\right)$$

$$g^{(2)}_{VGBV}(\tau) = 1 + e^{-\Gamma\tau}\left(e^{-\Gamma\tau} - 2\cos(\Omega\tau)\right)$$

$$\alpha = \Gamma^2/\Omega^2$$

Not the full amount of biexciton and exciton photon emission is taken into account

Photon-photon correlation in the dressed-state basis



$$|0\rangle = \frac{1}{\sqrt{2}}\left(|B\rangle - |G\rangle\right),$$

$$|+\rangle = \frac{\Omega}{\sqrt{2\Omega^2 + e_+^2}}\left(|G\rangle + \frac{e_+}{\Omega}|H\rangle + |B\rangle\right)$$

$$|-\rangle = \frac{\Omega}{\sqrt{2\Omega^2 + e_-^2}}\left(|G\rangle + \frac{e_-}{\Omega}|H\rangle + |B\rangle\right)$$

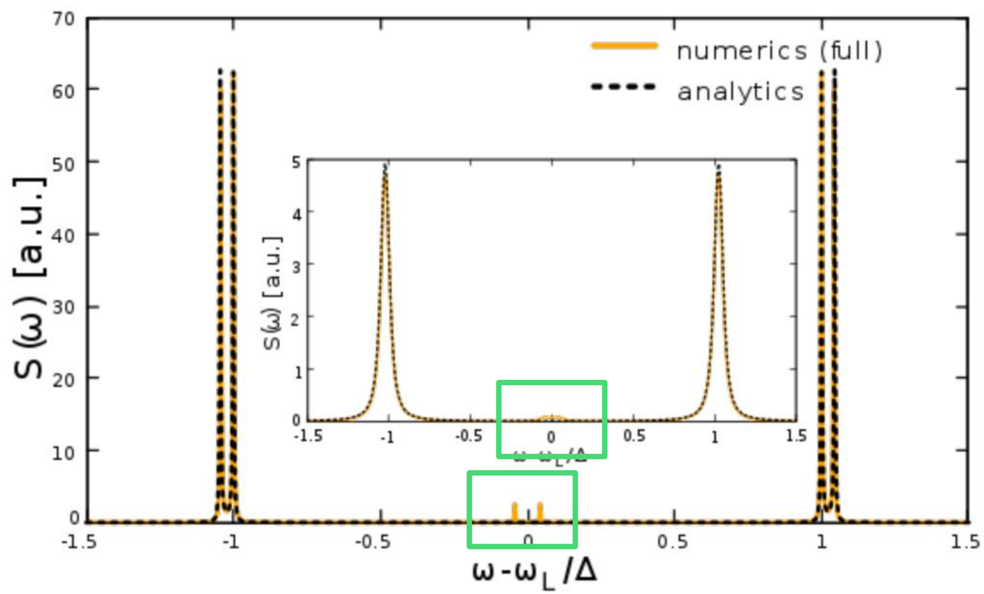
Only two out of three eigenstate enter into the measured signal (+,0)

Biexciton photons (τ≤0)

$$g^{(2)}_{\mathrm{EX}}(\tau) = \frac{1}{4}\sum_{i,j=+,0} g^{(2)}_{\mathrm{iVVj}}(\tau)$$

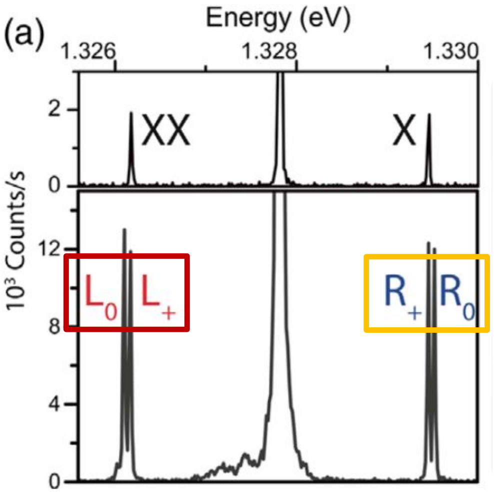
Exciton photons (τ>0)

$$g^{(2)}_{\mathrm{EX}}(\tau) = \frac{1}{4}\sum_{i,j=+,0} g^{(2)}_{\mathrm{VijV}}(\tau)$$



Schleibner, submitted, arXiv: 1710.03031

Photon-photon correlation in the dressed-state basis



$$|0\rangle = \frac{1}{\sqrt{2}}\left(|B\rangle - |G\rangle\right),$$

$$|+\rangle = \frac{\Omega}{\sqrt{2\Omega^2 + e_+^2}}\left(|G\rangle + \frac{e_+}{\Omega}|H\rangle + |B\rangle\right)$$

$$|-\rangle = \frac{\Omega}{\sqrt{2\Omega^2 + e_-^2}}\left(|G\rangle + \frac{e_-}{\Omega}|H\rangle + |B\rangle\right)$$

Only two out of three eigenstate enter into the measured signal (+,0) and superponing this signal leads to very good agreement between theory and experiment

Biexciton photons (τ≤0)

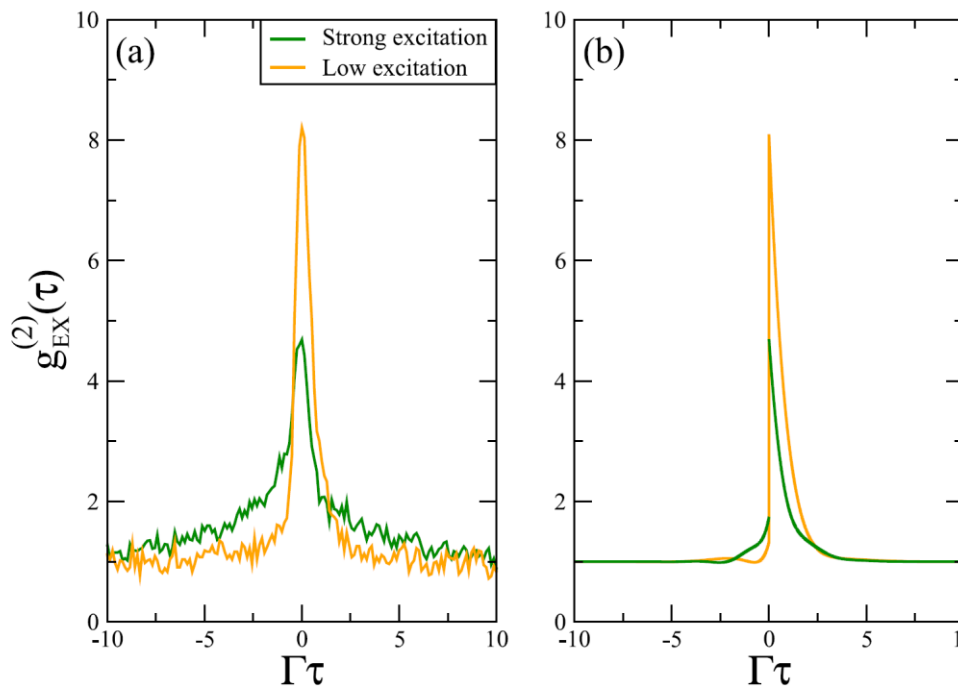
$$g^{(2)}_{\mathrm{EX}}(\tau) = \frac{1}{4}\sum_{i,j=+,0} g^{(2)}_{\mathrm{iVVj}}(\tau) \qquad \alpha = \Gamma^2/\Omega^2$$

$$g^{(2)}_{\mathrm{EX}}(\tau) = 1 + e^{-2\Gamma\tau} - \frac{2\alpha\cos(\Omega\tau)}{1+2\alpha}e^{-\Gamma\tau}$$

Exciton photons (τ>0)

$$g^{(2)}_{\mathrm{EX}}(\tau) = \frac{1}{4}\sum_{i,j=+,0} g^{(2)}_{\mathrm{VijV}}(\tau)$$

$$g^{(2)}_{\mathrm{EX}}(\tau) = \frac{\rho^{VV}_{VV}(\tau)}{\rho^{VV}_{VV}(\infty)} = 3 + e^{-2\Gamma\tau} + 2\alpha e^{-\Gamma\tau}[1+\cos(\Omega\tau)]$$

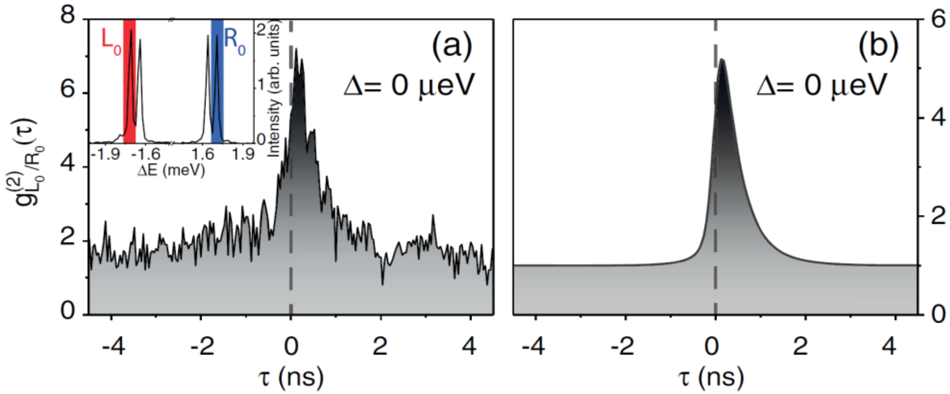


Deep antibunching only visible in this setup with in phase superposition of all possible photon paths

Schleibner, submitted, arXiv: 1710.03031

Path-controlled vanishing and reestablished time-ordering

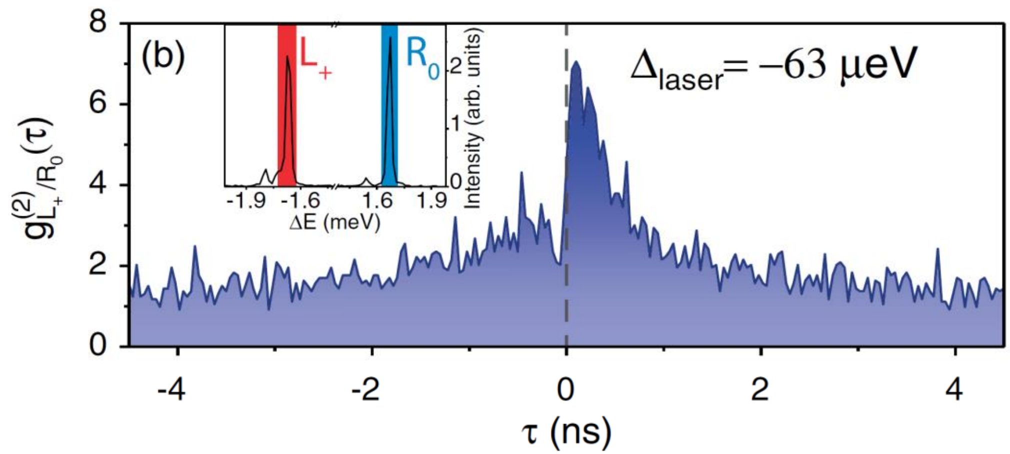
In resonance, vanishing time-order in the strong driving limit



The correlation function loses information which photon has been emitted first (biexciton or exciton photon) – interesting for time-bin application and heralding

Bounouar et al, PRL 118, 233601 (2017)

Detuning shifts the weight in between the Eigenvalues to path-control the cascade process



Of resonance, time-order is restablished – theory becomes due to detuning hard, even numerically due to transcendental Eigenvalue equations

Thank you for the attention!

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