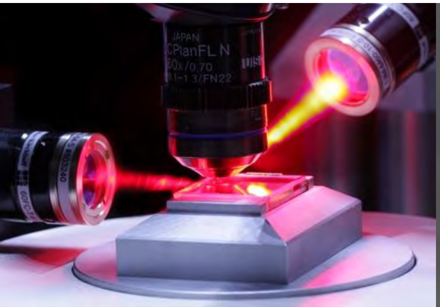
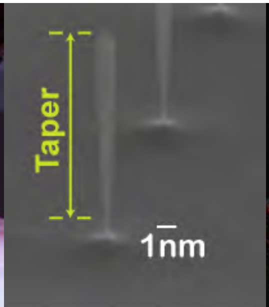
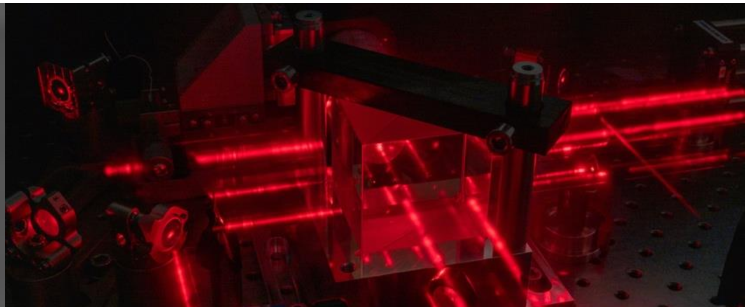
Stockholm University
Knut och Alice Wallenbergs Stiftelse
QUANTERA
DFG Deutsche Forschungsgemeinschaft
Carl Tryggers Stiftelse för Vetenskaplig Forskning
Vetenskapsrådet

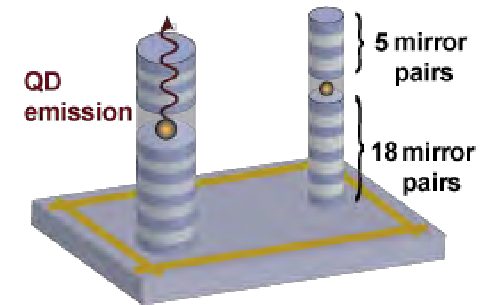
Quantum light from quantum emitters: efficiency, characterization, and entanglement generation

Ana Predojević
Stockholm University







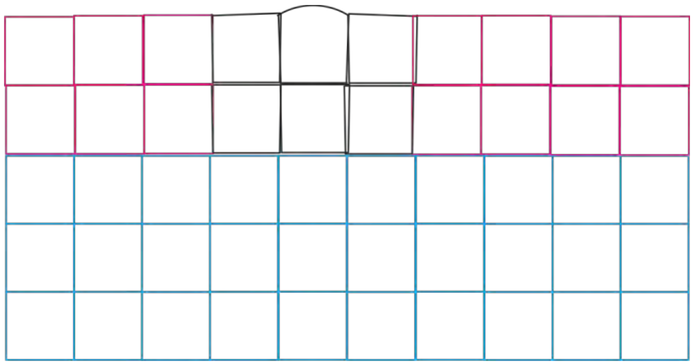


Why quantum dots?

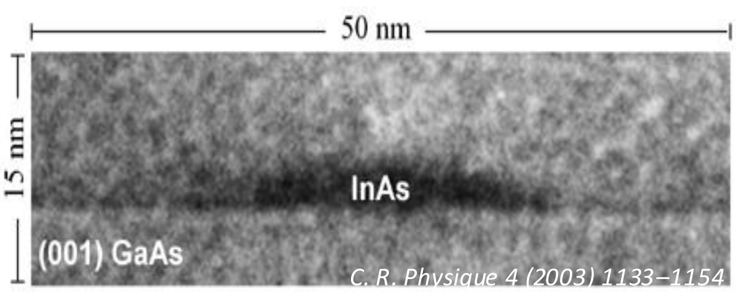
Fabrication method:

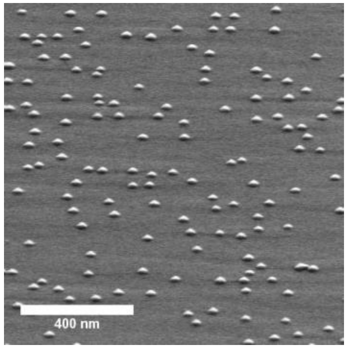
- Self-assembled quantum dots
- Colloidal quantum dots

InAs - 6.0583 A

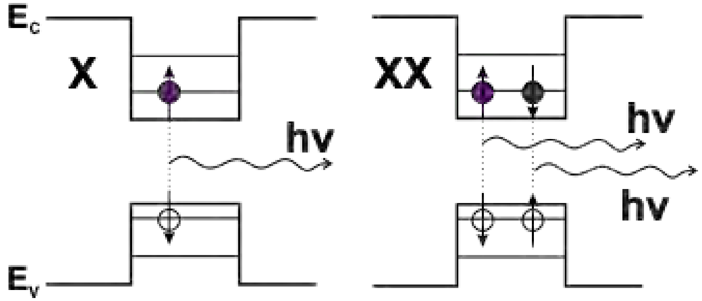


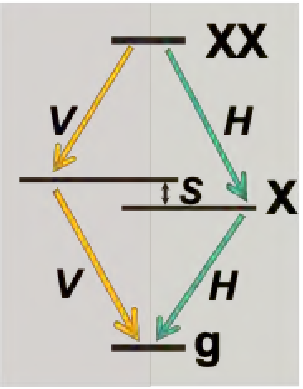
GaAs - 5.65325 A



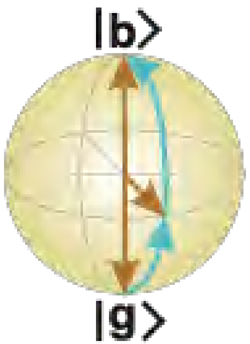


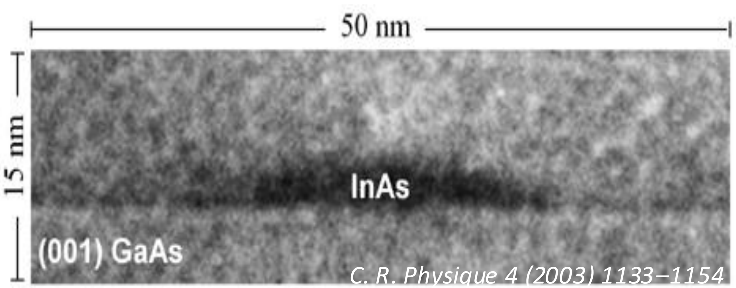
Quantum emitters - high performance sources of quantum light



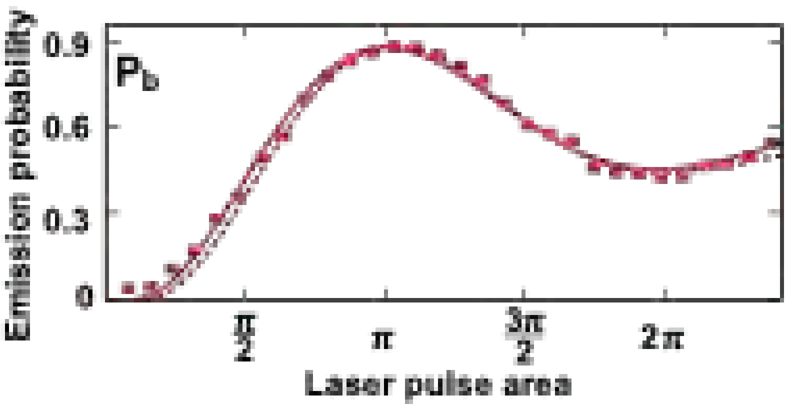


XX – Biexciton
X – Exciton
g – ground state

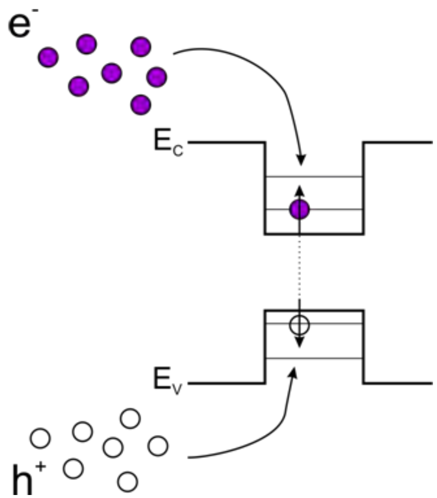


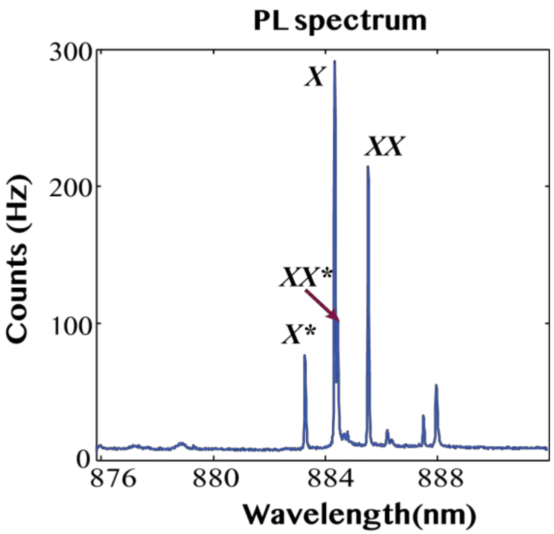


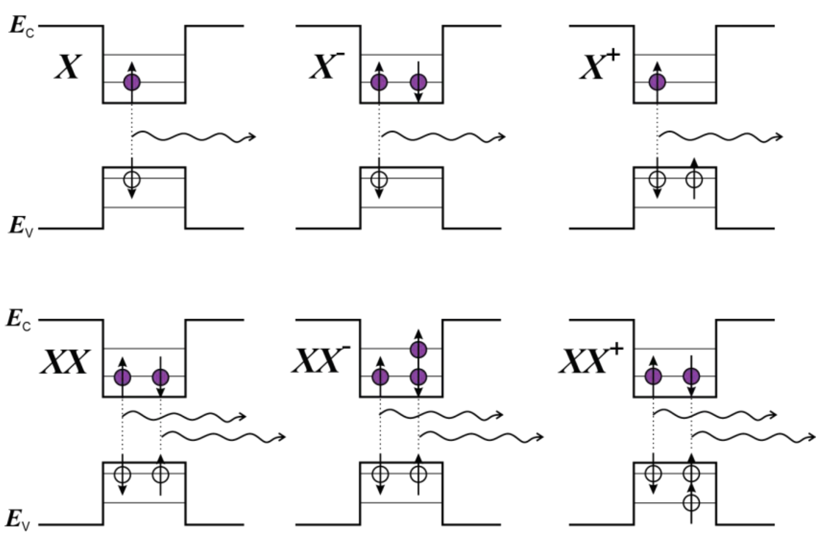
- high photon generation probability
- sub-Poissonian statistics



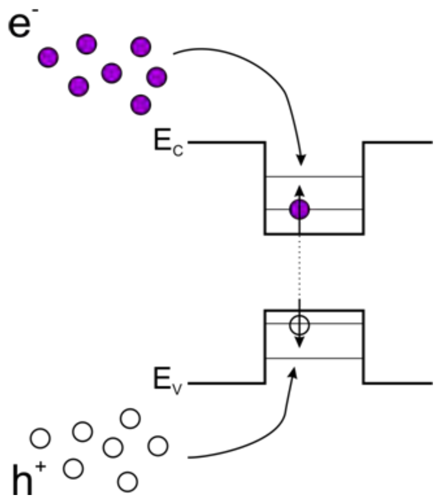
Excitation – emission: simplest approach

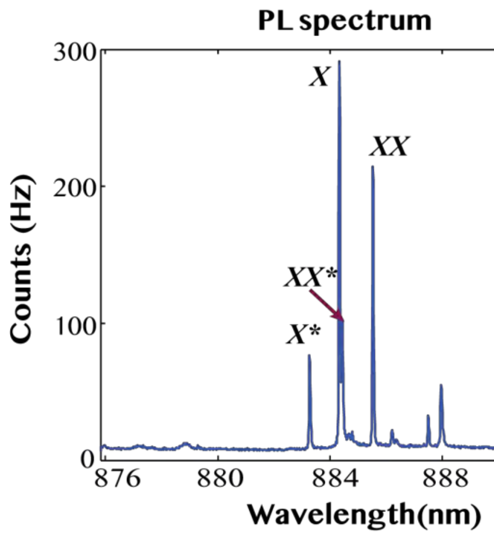


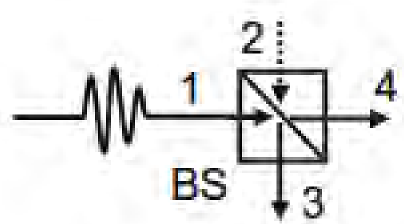


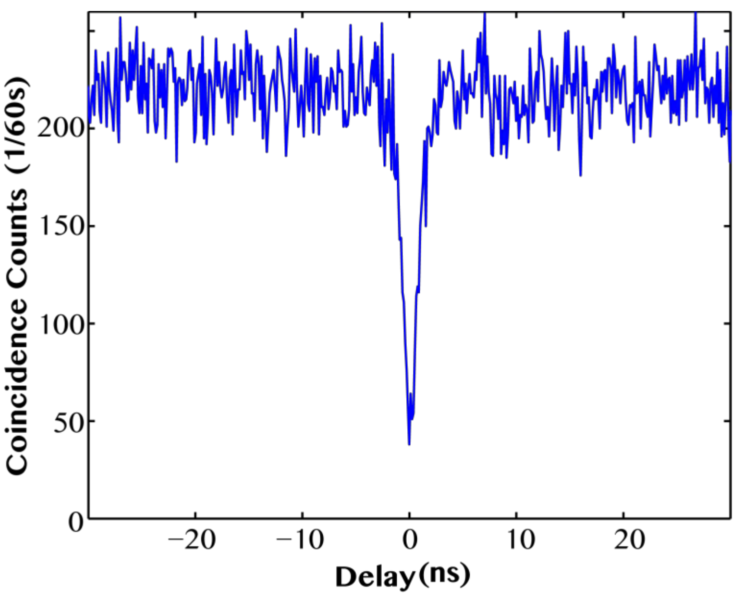


Excitation – emission: simplest approach





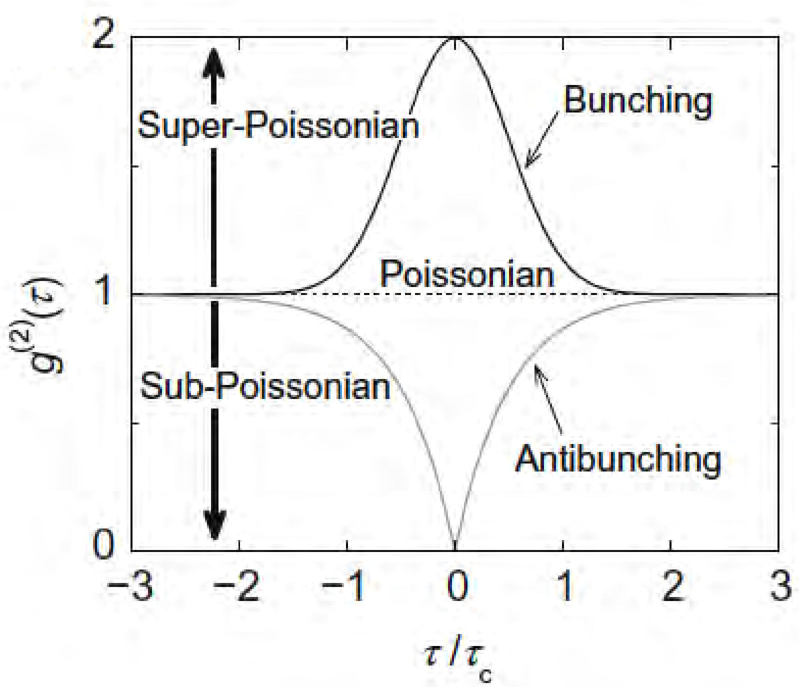


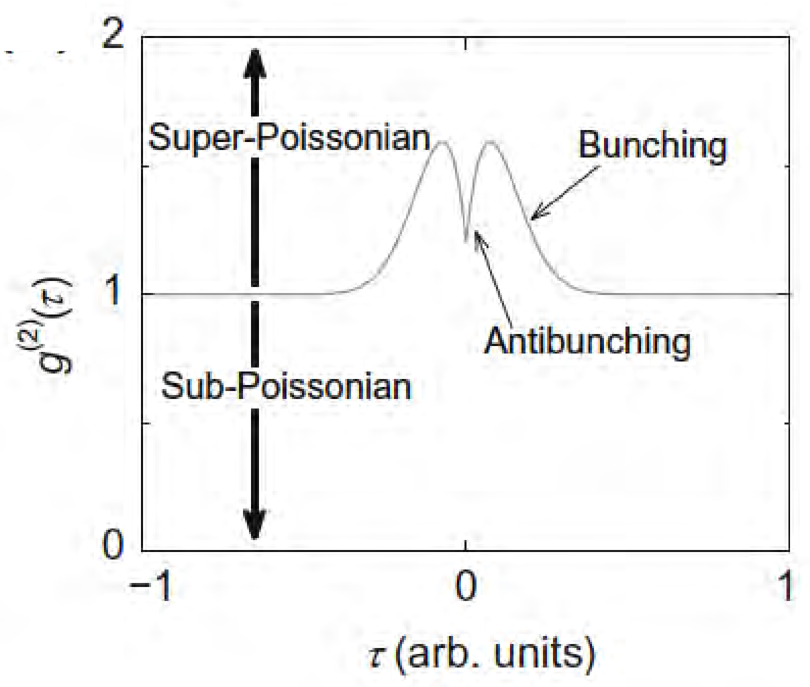


Excitation – emission: simplest approach

$$g^{(2)}(\tau) = \frac{\langle \hat{a}^\dagger(t)\hat{a}^\dagger(t+\tau)\hat{a}(t+\tau)\hat{a}(t)\rangle}{\langle \hat{a}^\dagger(t)\hat{a}(t)\rangle^2}$$

$$g^{(2)}(0) = \frac{\langle \hat{n}(t)(\hat{n}(t)-1)\rangle}{\langle \hat{n}(t)\rangle^2}$$

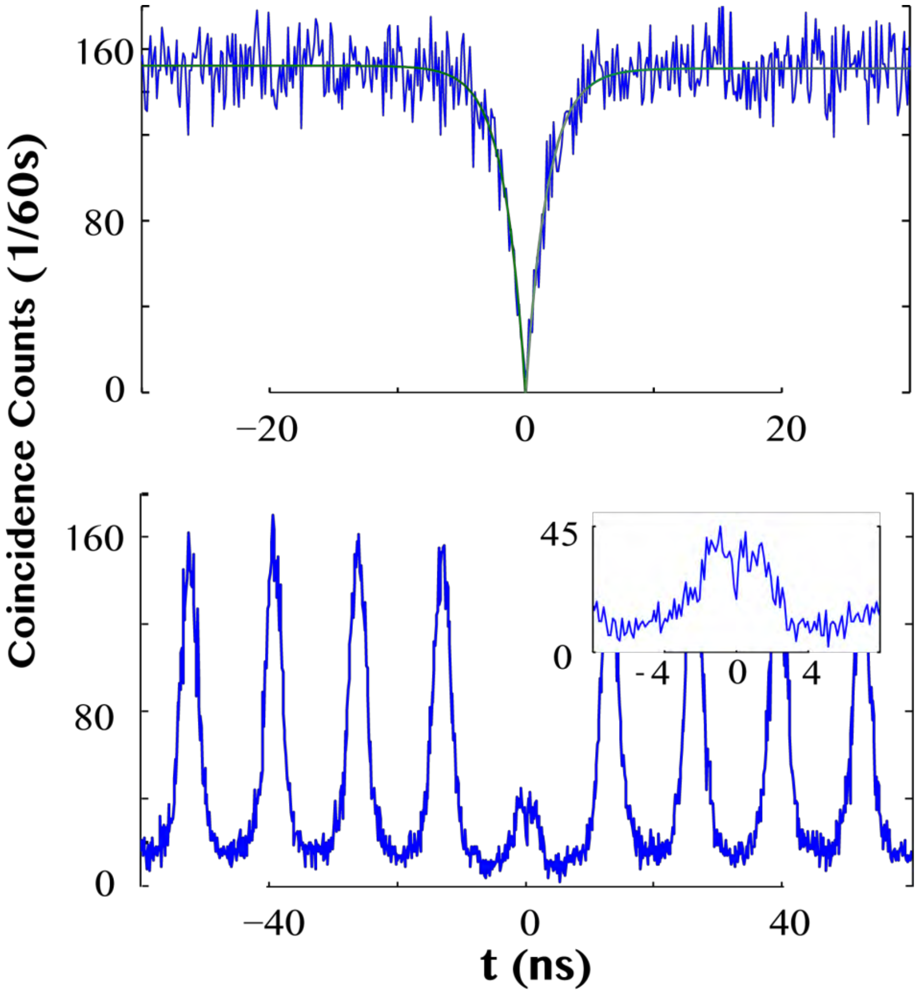




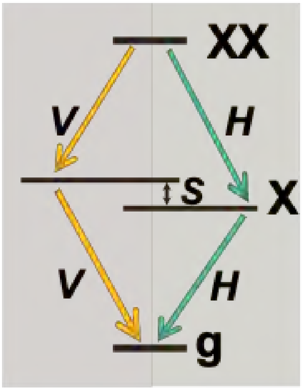
Single-Photon Generation and Detection ISBN: 978-0-12-387695-9

Phys. Rev. A 41, 475

Excitation – emission: simplest approach



Excitation – emission: simplest approach



XX – Biexciton
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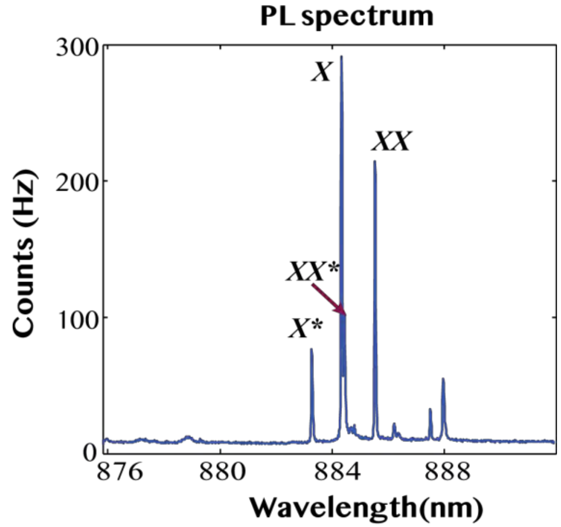
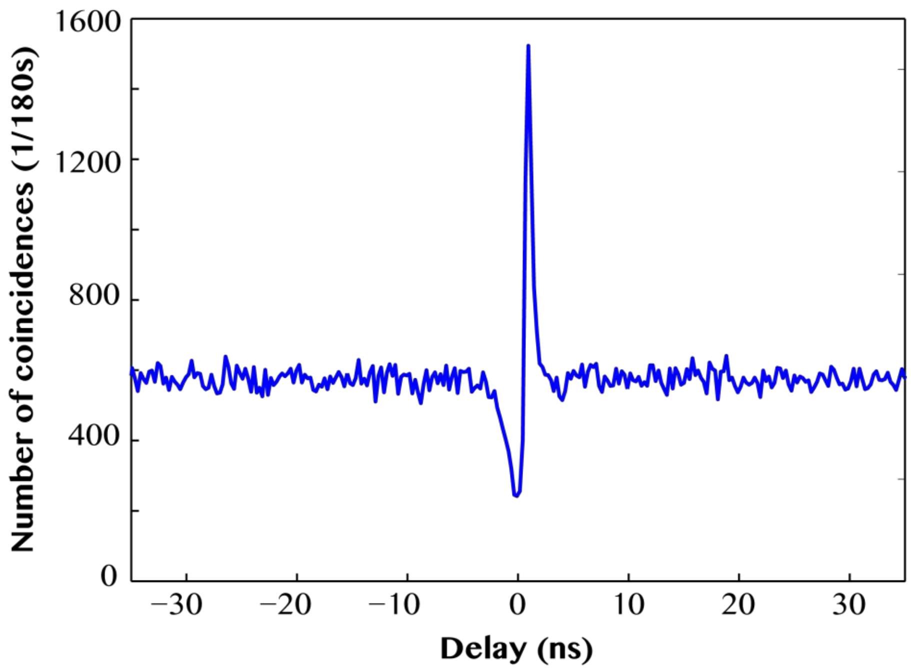
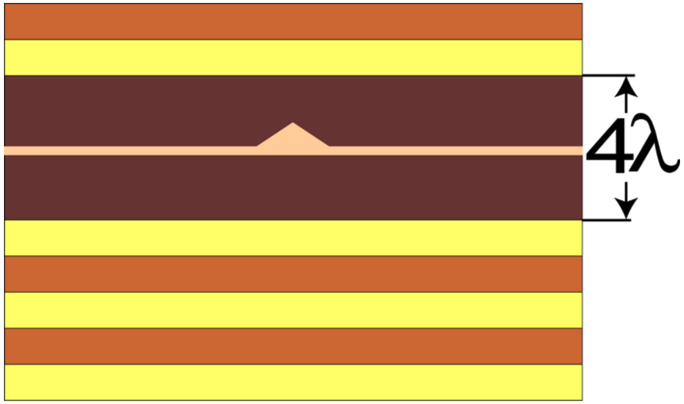




Collection: simplest approach

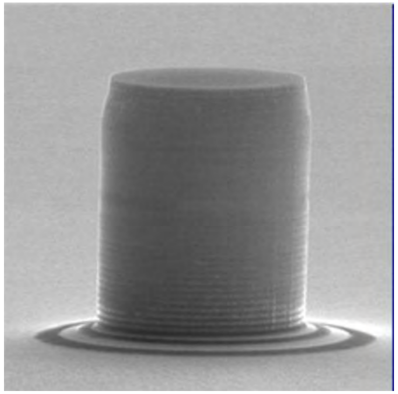
absence of engineered photonic environment 1%



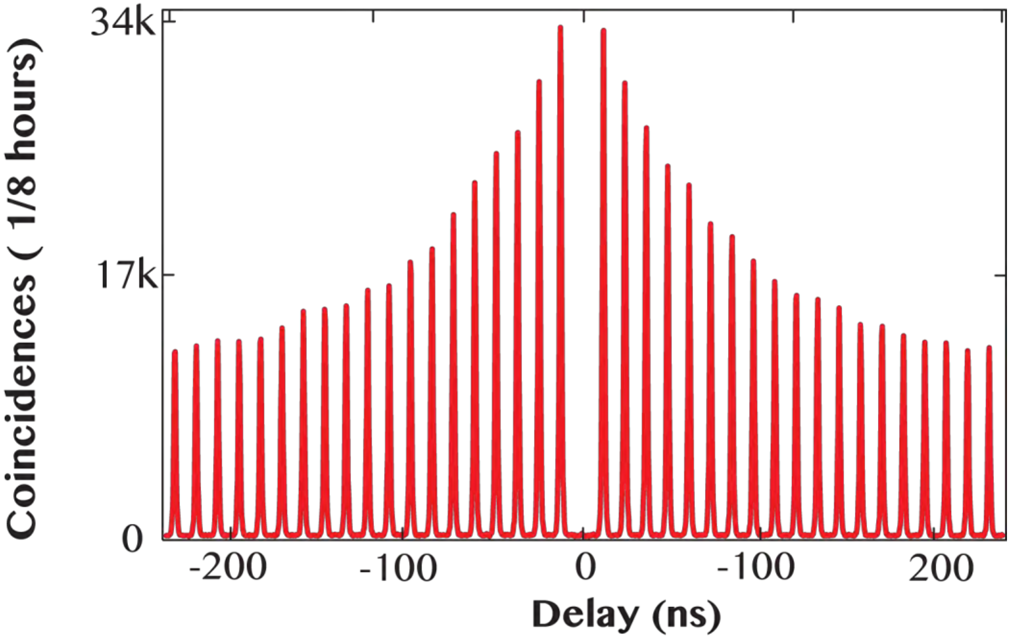
planar cavity <10%

nanohills on the sample surface

[Optics express 22, 8136–8142 (2014)]) 42%

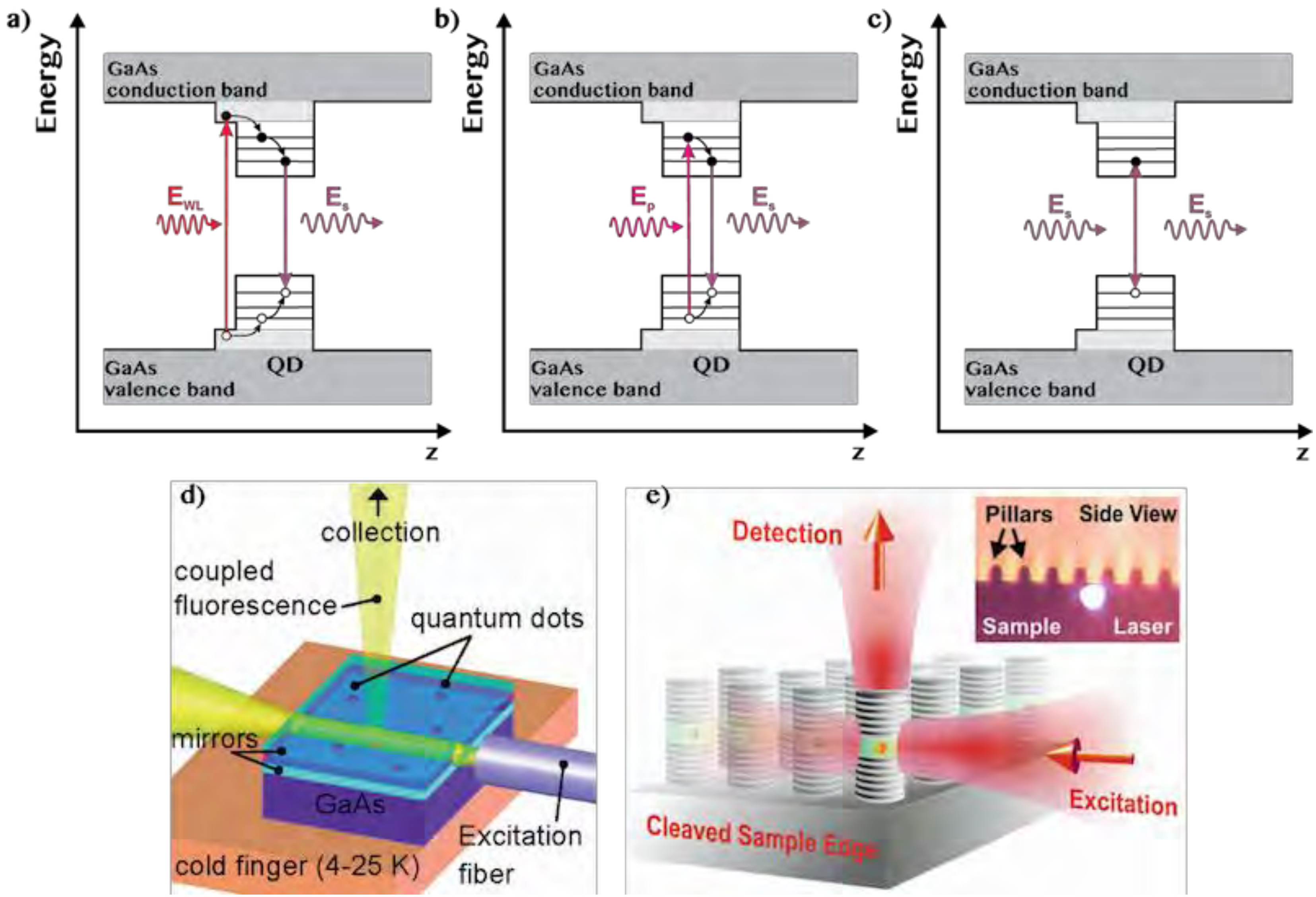


Better photon statistics: resonant excitation



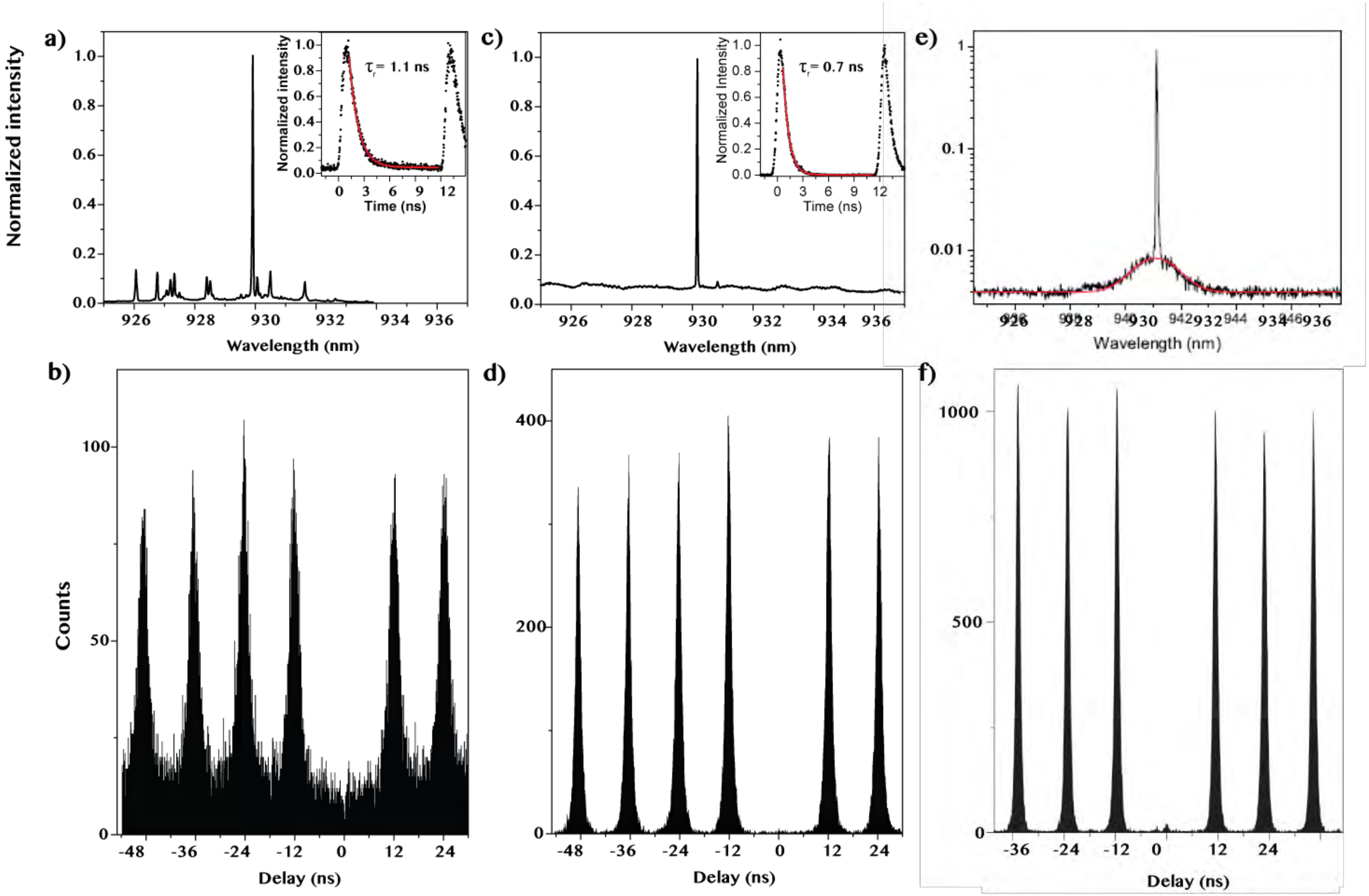
Optics Express 22, 4789, 2014

Better photon statistics: resonant excitation



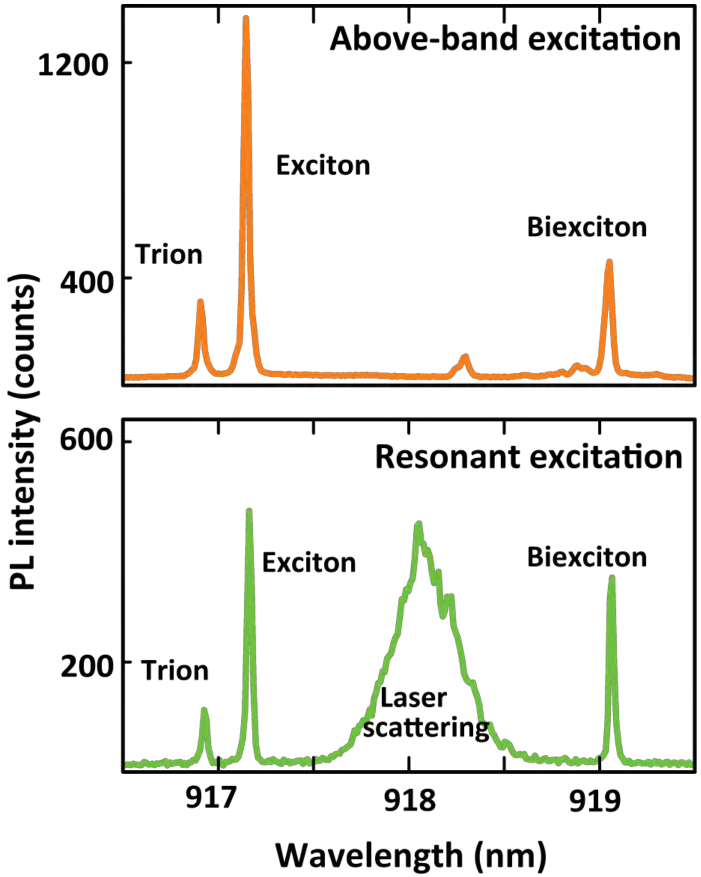
arXiv:1502.00160

Better photon statistics: resonant excitation

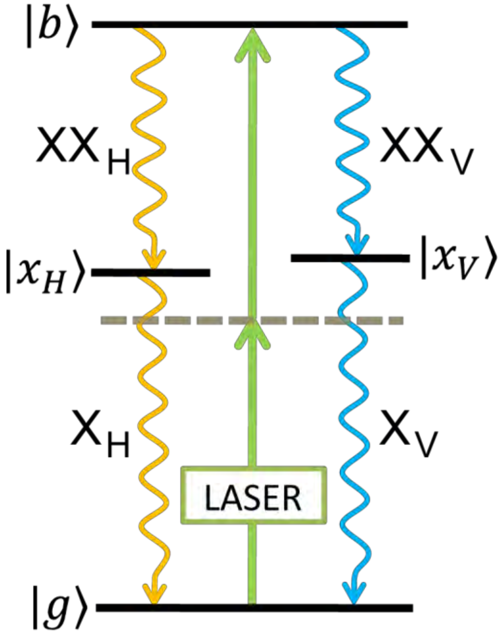


arXiv:1502.00160

Resonant excitation of biexciton



S. Stufler, et al. Phys. Rev. B. 73, 125304 (2006).

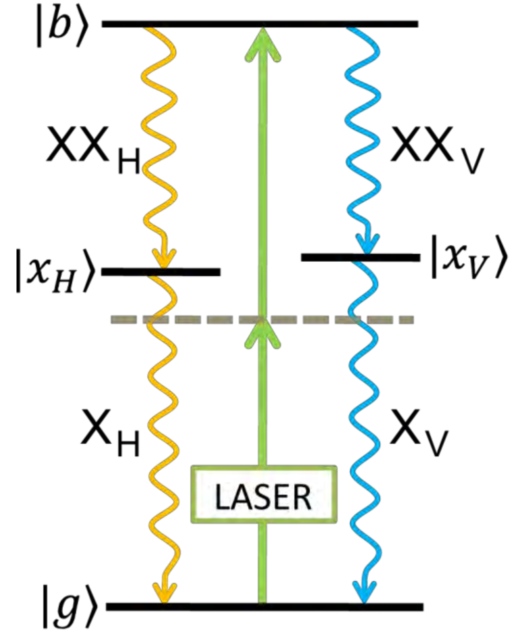


H. Jayakumar et al. Phys. Rev. Lett. 110, 135505 (2013)

Resonant excitation of biexciton

$$H = \hbar \begin{pmatrix} 0 & \frac{\Omega_1(t)}{2} & 0 \\ \frac{\Omega_1(t)}{2} & -\Delta_b + \Delta_e & \frac{\Omega_2(t)}{2} \\ 0 & \frac{\Omega_2(t)}{2} & -2\Delta_b \end{pmatrix}$$

$$\dot{\rho} = -\frac{i}{\hbar}[H, \rho] + \sum_{i=1}^{4} \mathcal{L}_i(\rho)$$



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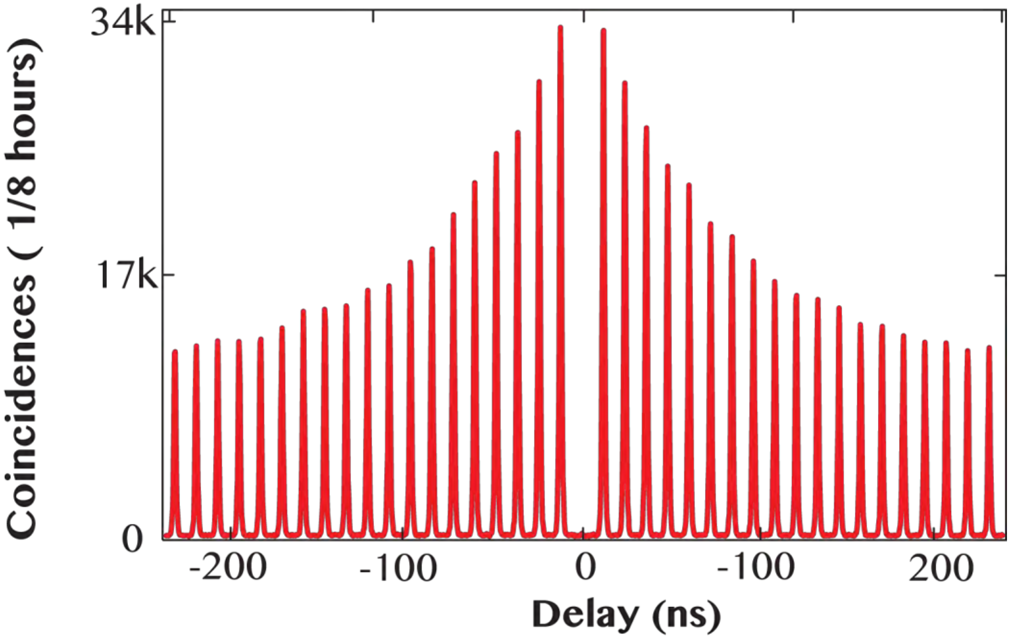
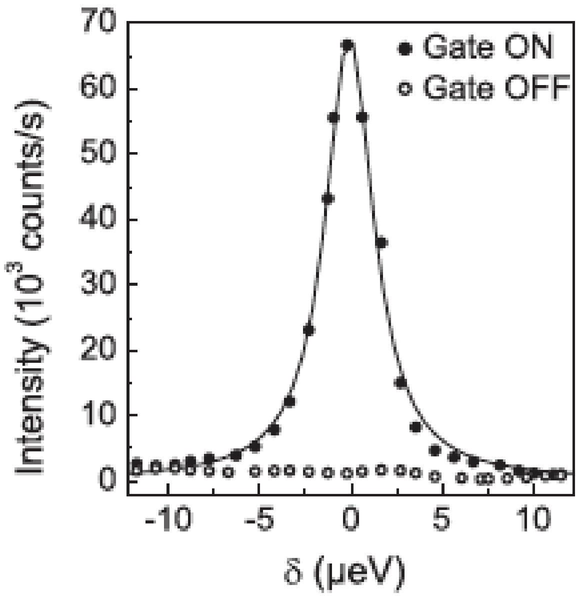


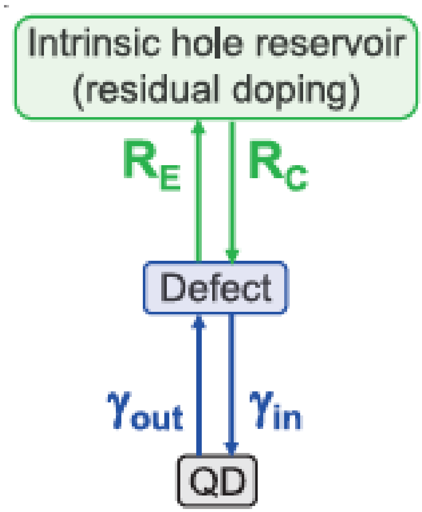
[Optics Express 22, 4789, 2014]()

Reduction of blinking

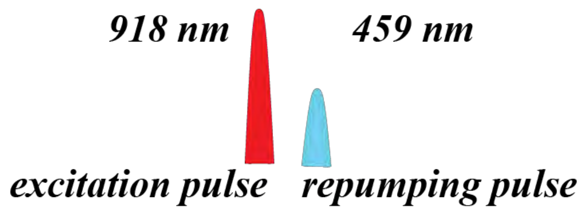
*H. S. Nguyen et al. PRB **87**, 115305 (2013)*.

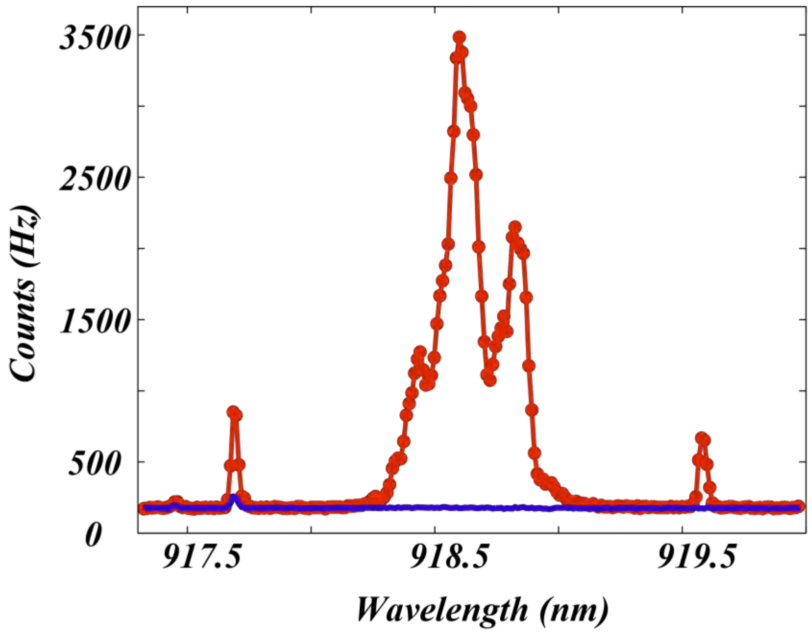
*H. S. Nguyen et al. PRL **108**, 057401 (2012)*.

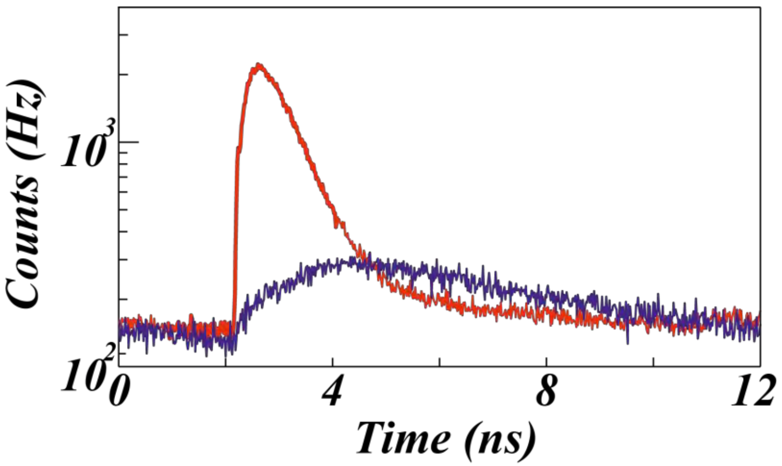




Reduction of blinking







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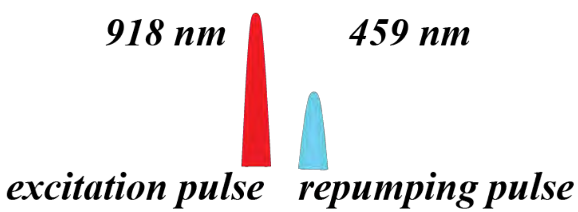
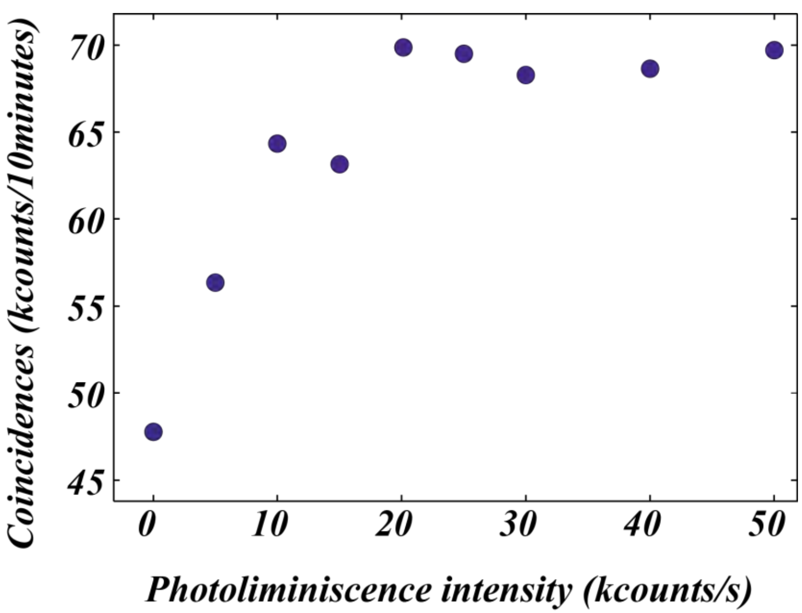
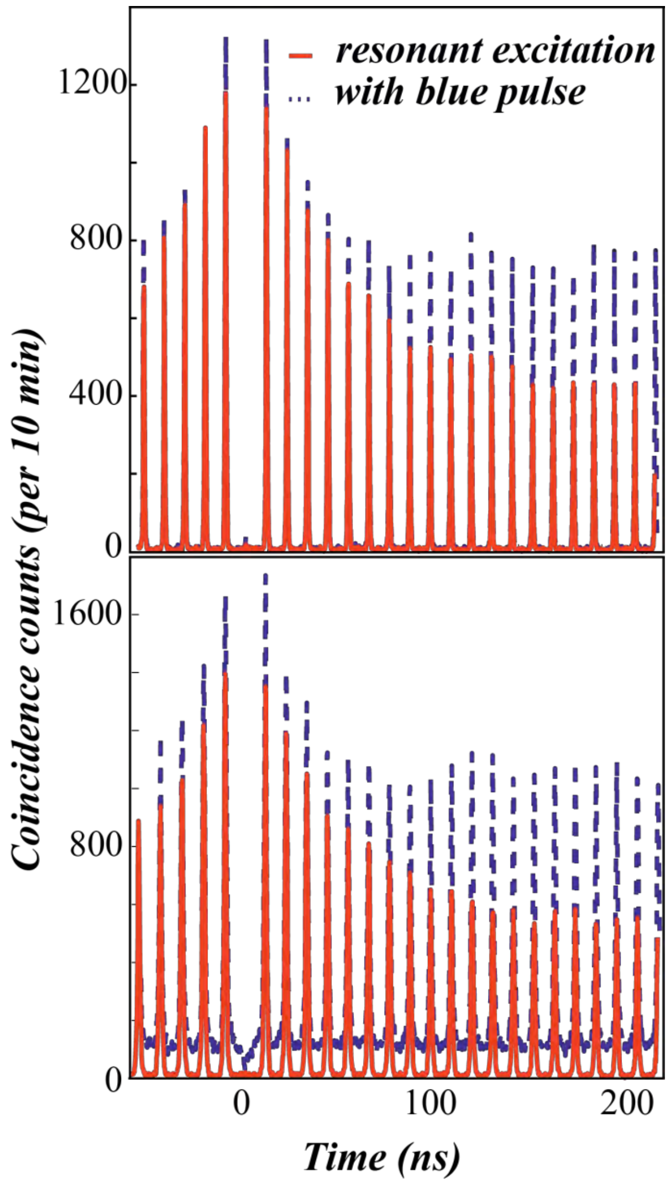
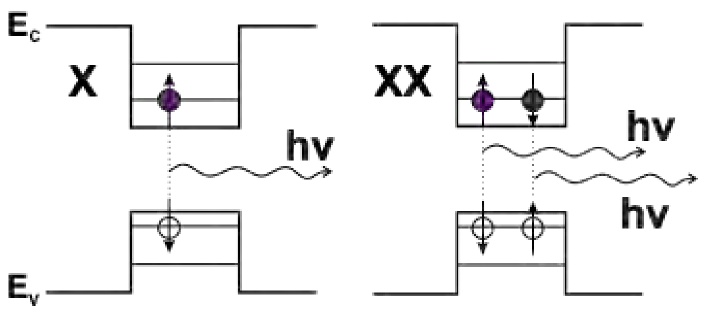


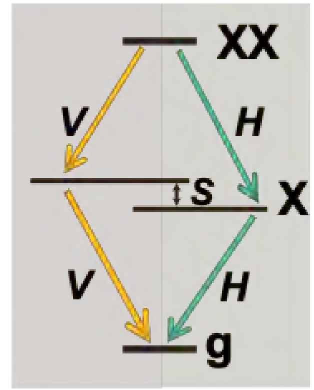


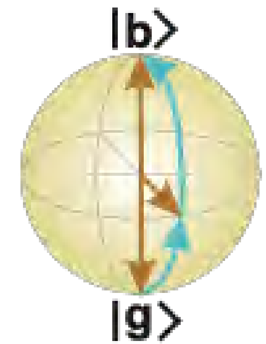


[Optics Express Vol. 24, Issue 19, pp. 21794-21801 (2016)]

Quantum emitters - high performance sources of quantum light







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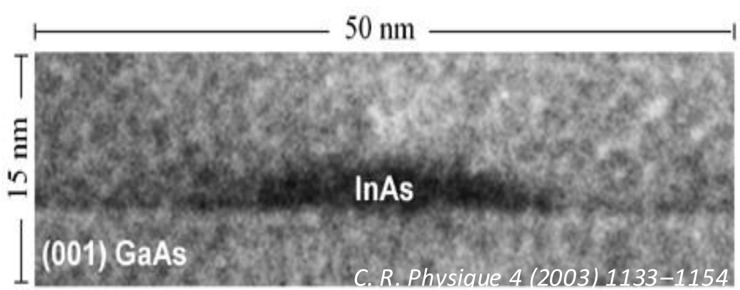
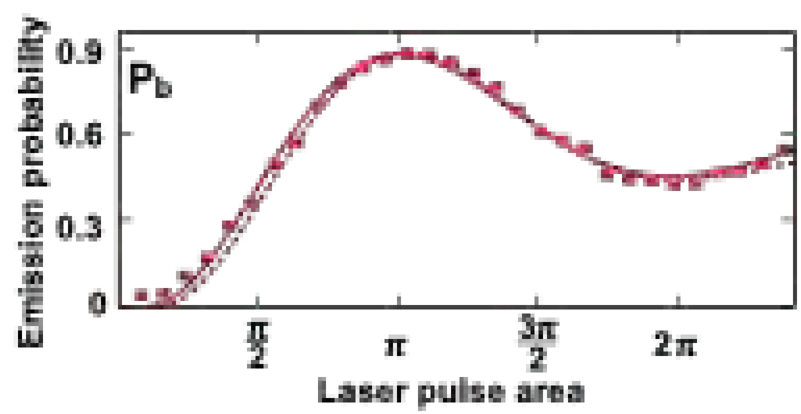
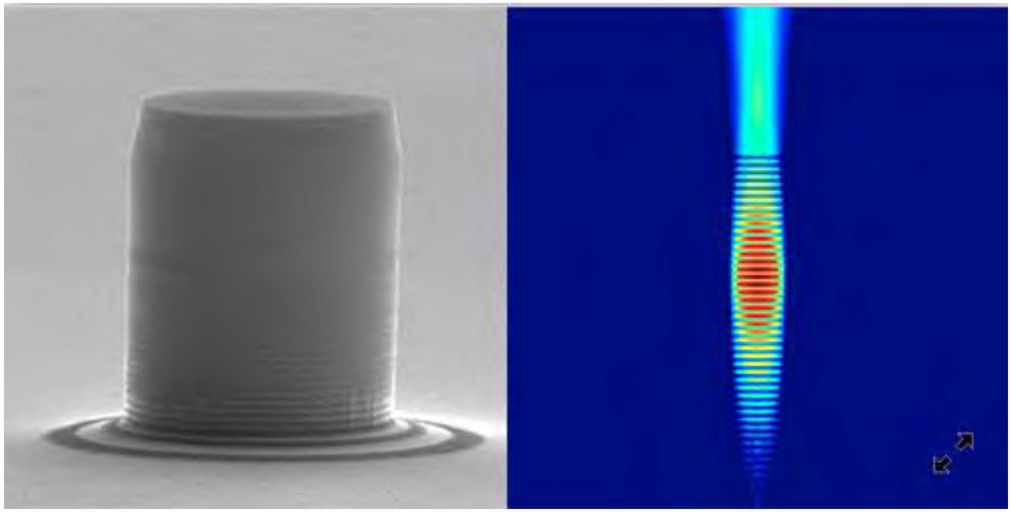


- high photon generation probability
- sub-Poissonian statistics



Increasing the extraction efficiency



Phys. Rev. Lett.116, 020401(2016)

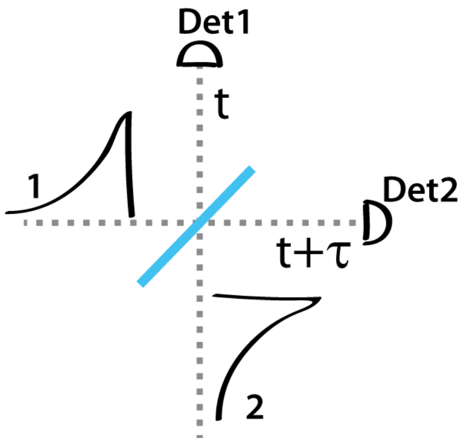
moderate to Q-factor: 1000 – 10000

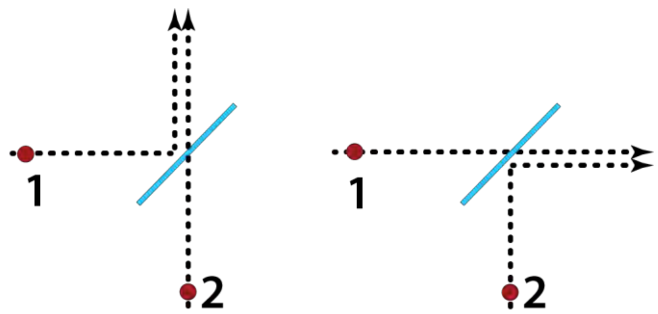
linewidth < 0.5nm

Purcell factor up to 7

N. Somaschi, et al. Nature Photonics10, 340–345 (2016)
X. Ding, et al. Phys. Rev. Lett.116, 020401(2016)
S. Gerhardt, et al. Phys. Rev. B100, 115305 (2019)

Two – photon interference





$$G^{(2)}(t,\tau) = \frac{1}{4}\left[I_1(t)\, I_2(t+\tau) + I_2(t) I_1(t+\tau) - G_1^{(1)}(t,\tau)\left(G_2^{(1)}(t,\tau)\right)^* - \left(G_1^{(1)}(t,\tau)\right)^* G_2^{(1)}(t,\tau) \right]$$

- in the case the photon 1 and photon 2 are identical

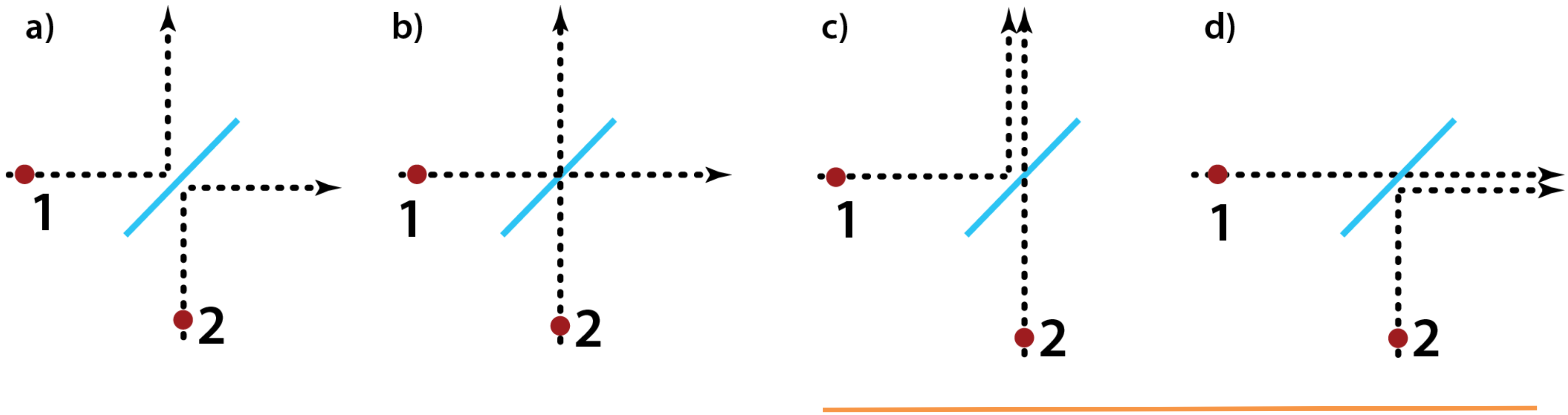
$$G^{(2)}(t,\tau) = \frac{1}{4}\left[2I(t)I(t+\tau) - 2|G^{(1)}(t,\tau)|^2 \right]$$

- importance of two-photon interference:

- **quantum teleportation and entanglement swapping**
- **quantum photonic processors**

Two – photon interference

- two photon interference effect demonstrated/used by Hong, Ou, and Mandel in 1987



Indistinguishability (easy):

- polarization
- arrival time
- energy

Indistinguishability (complicated):

- "shape" of the wave packet
- coherence of photons

Two – photon interference

VOLUME 59, NUMBER 18 PHYSICAL REVIEW LETTERS 2 NOVEMBER 1987

Measurement of Subpicosecond Time Intervals between Two Photons by Interference

C. K. Hong, Z. Y. Ou, and L. Mandel
Department of Physics and Astronomy, University of Rochester, Rochester, New York 14627
(Received 10 July 1987)

A fourth-order interference technique has been used to measure the time intervals between two photons, and by implication the length of the photon wave packet, produced in the process of parametric down-conversion. The width of the time-interval distribution, which is largely determined by an interference filter, is found to be about 100 fs, with an accuracy that could, in principle, be less than 1 fs.

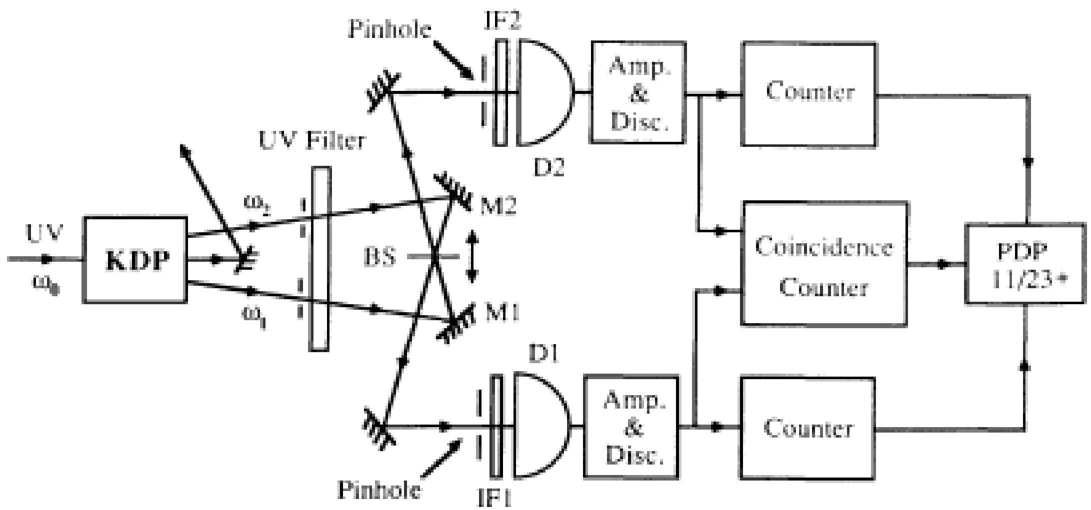


FIG. 1. Outline of the experimental setup.

Phys. Rev. A 56, 1627 (1997)

Two – photon interference

VOLUME 59, NUMBER 18 PHYSICAL REVIEW LETTERS 2 NOVEMBER 1987

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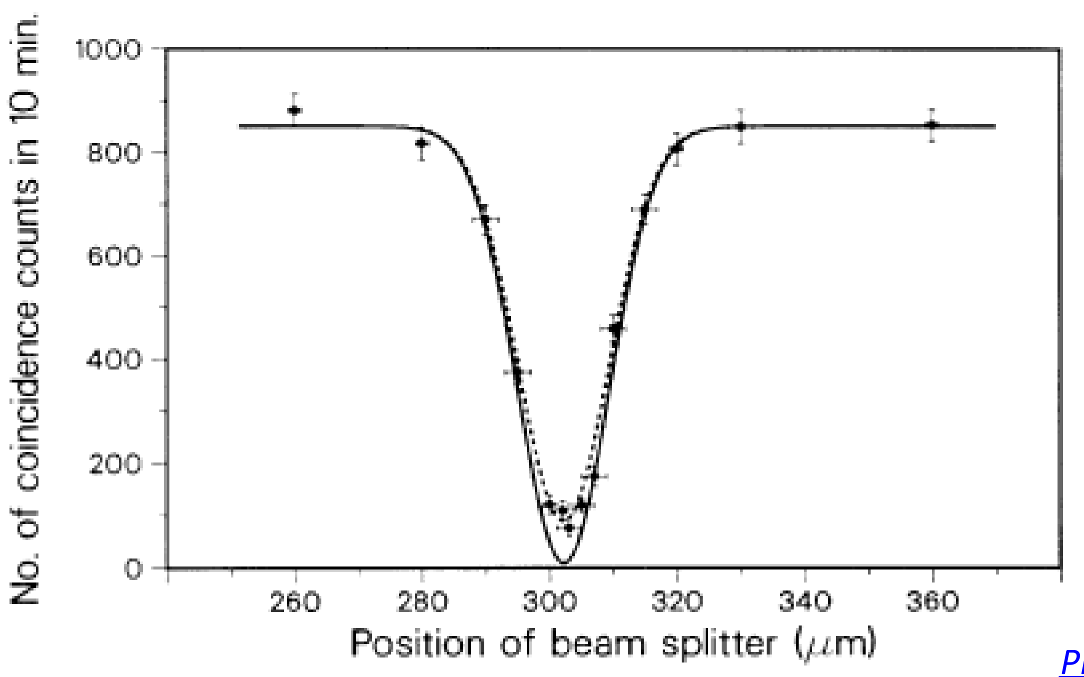
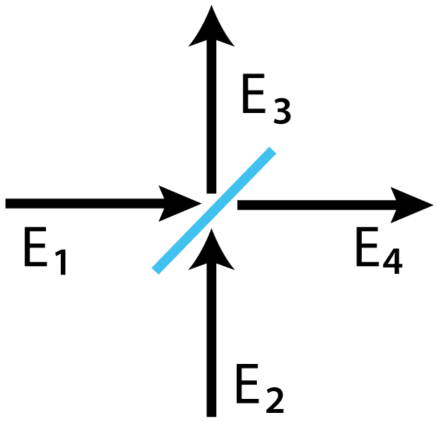


Phys. Rev. A 56, 1627 (1997)

Two – photon interference



$$E_3^{(+)} = \frac{1}{\sqrt{2}} (iE_1^{(+)} + E_2^{(+)})$$

$$E_4^{(+)} = \frac{1}{\sqrt{2}} (E_1^{(+)} + iE_2^{(+)})$$

$$G^{(2)}(t,\tau) = \langle E_3^{(-)}(t) E_4^{(-)}(t+\tau) E_4^{(+)}(t+\tau) E_3^{(+)}(t) \rangle$$

- correlation of photons leaving the beamsplitter

$$= \frac{1}{4} [\langle (-E_1^{(-)}(t) + E_2^{(-)}(t)) \cdot (E_1^{(-)}(t+\tau) - iE_2^{(-)}(t+\tau))$$
$$\cdot (E_1^{(+)}(t+\tau) + iE_2^{(+)}(t+\tau)) \cdot (iE_1^{(+)}(t) + E_2^{(+)}(t)) \rangle]$$

Two – photon interference

- assuming that only single photons are impinging on the beamsplitter

$$\left.\begin{array}{l}\langle E_1^{(-)}(t)E_1^{(-)}(t+\tau)E_1^{(+)}(t+\tau)E_1^{(+)}(t)\rangle \\ \langle E_2^{(-)}(t)E_2^{(-)}(t+\tau)E_2^{(+)}(t+\tau)E_2^{(+)}(t)\rangle \\ \ldots\end{array}\right\} = 0$$

- there are four remaining terms:

$$\begin{aligned}G^{(2)}(t,\tau) = &\langle \underline{E_1^{(-)}(t)}E_2^{(-)}(t+\tau)E_2^{(+)}(t+\tau)\underline{E_1^{(+)}(t)}\rangle \\ &+\langle E_2^{(-)}(t)E_1^{(-)}(t+\tau)E_1^{(+)}(t+\tau)E_2^{(+)}(t)\rangle \\ &-\langle \underline{E_1^{(-)}(t)}E_2^{(-)}(t+\tau)\underline{E_1^{(+)}(t+\tau)}E_2^{(+)}(t)\rangle \\ &-\langle E_2^{(-)}(t)E_1^{(-)}(t+\tau)E_2^{(+)}(t+\tau)E_1^{(+)}(t)\rangle\end{aligned}$$

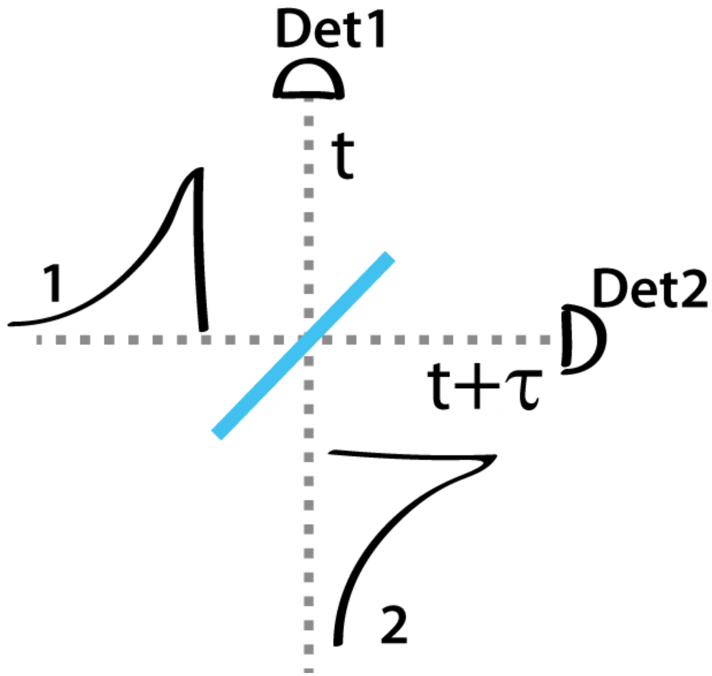
Two – photon interference

$$G^{(2)}(t,\tau)= \frac{1}{4}[\langle E_1^{(-)}(t)E_1^{(+)}(t)\rangle\langle E_2^{(-)}(t+\tau)E_2^{(+)}(t+\tau)\rangle$$
$$+\langle E_2^{(-)}(t)E_2^{(+)}(t)\rangle\langle E_1^{(+)}(t+\tau)E_1^{(+)}(t+\tau)\rangle$$
$$-\langle E_1^{(-)}(t)E_1^{(+)}(t+\tau)\rangle\langle E_2^{(-)}(t+\tau)E_2^{(+)}(t)\rangle$$
$$-\langle E_1^{(-)}(t+\tau)E_1^{(+)}(t)\rangle\langle E_2^{(-)}(t)E_1^{(+)}(t+\tau)\rangle]$$

$$G^{(2)}(t,\tau)= \frac{1}{4}[I_1(t)\, I_2(t+\tau)+I_2(t)I_1(t+\tau)$$
$$-G_1^{(1)}(t,\tau)(G_2^{(1)}(t,\tau))^*-(G_1^{(1)}(t,\tau))^*G_2^{(1)}(t,\tau)]$$

Appl. Phys. B 77, 797-802 (2003)

Two – photon interference

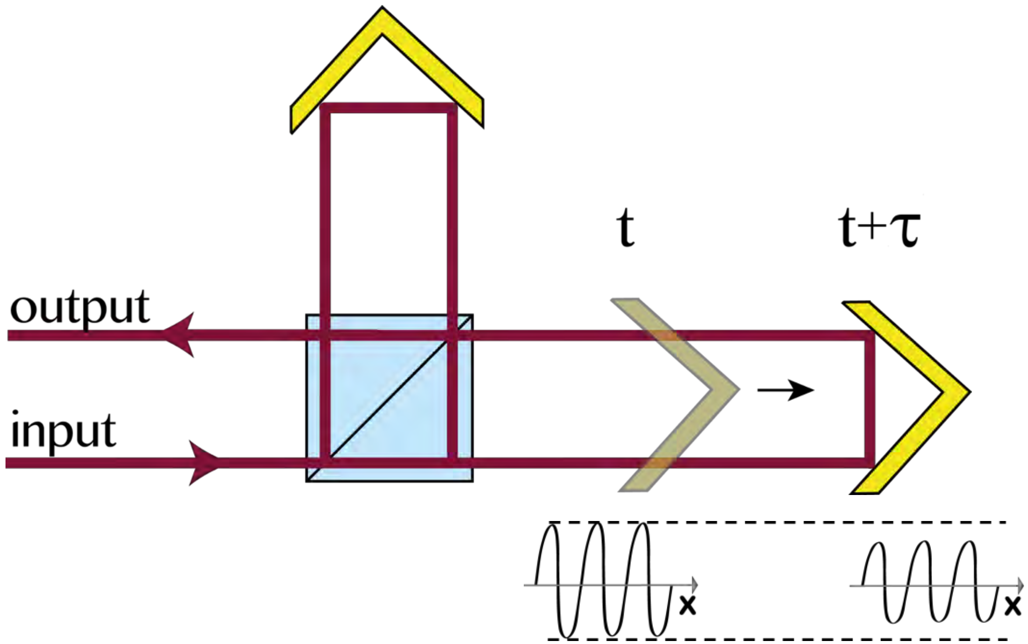


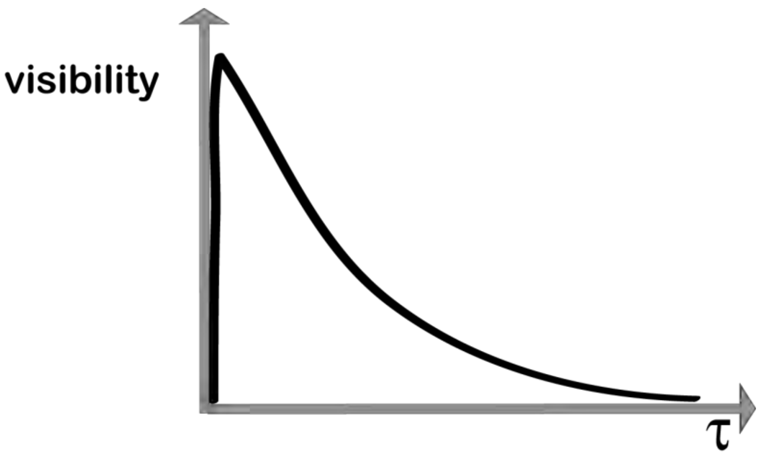
$$G^{(2)}(t,\tau) = \frac{1}{4}[I_1(t)\, I_2(t+\tau) + I_2(t) I_1(t+\tau) - G_1^{(1)}(t,\tau)(G_2^{(1)}(t,\tau))^* - (G_1^{(1)}(t,\tau))^* G_2^{(1)}(t,\tau)]$$

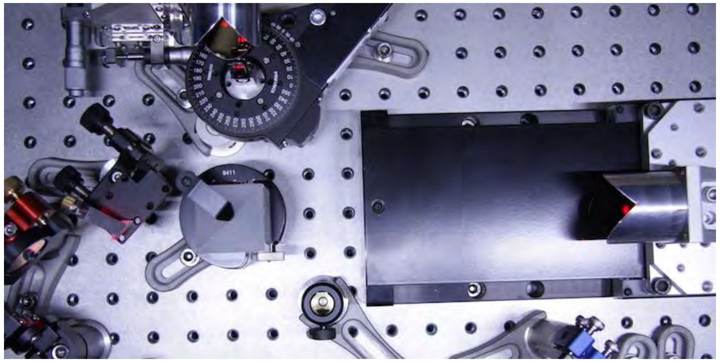
- in the case the photon 1 and photon 2 are identical

$$G^{(2)}(t,\tau) = \frac{1}{4}[2I(t)I(t+\tau) - 2|G^{(1)}(t,\tau)|^2]$$

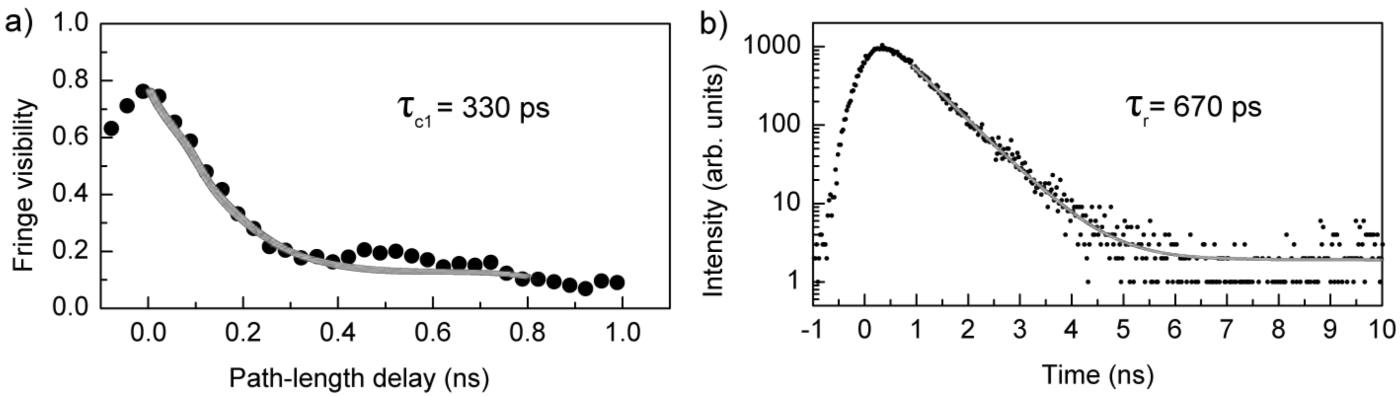
Field correlations



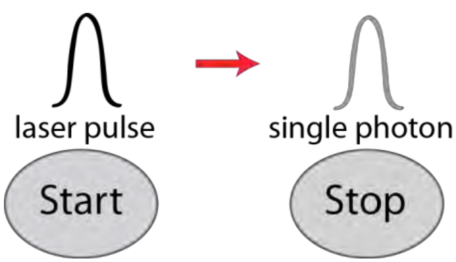


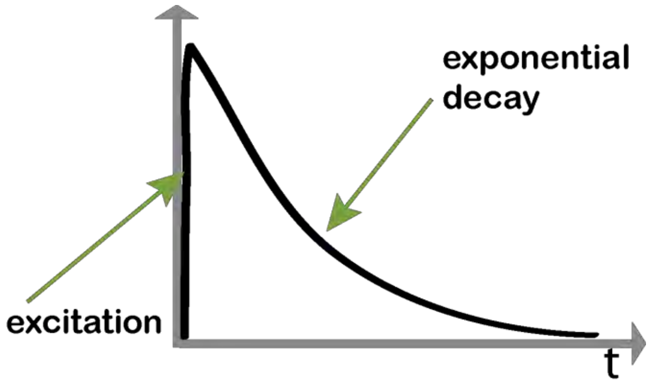


Intensity correlations



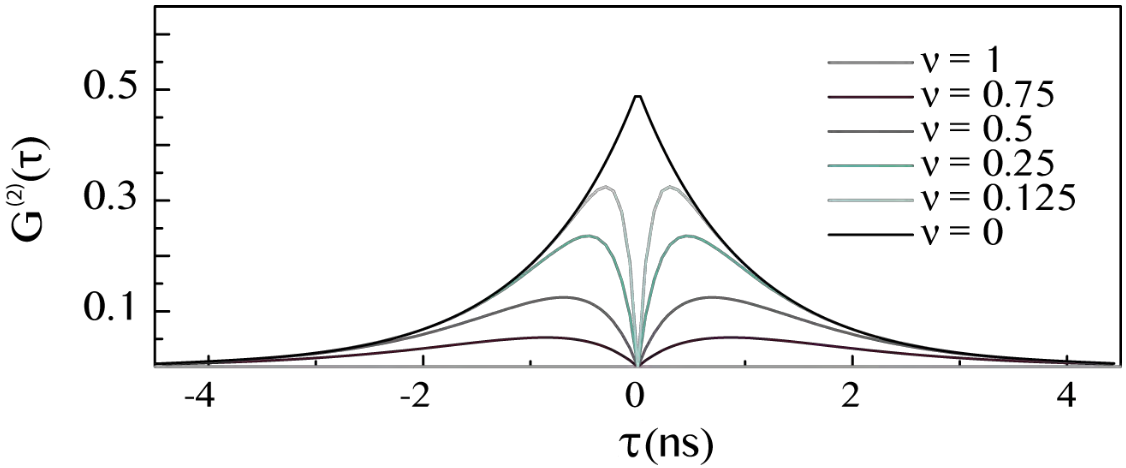
a) Coherence time and b) Life time of photons emitted by a quantum dot





arXiv:1502.00160

Indistinguishability of photons

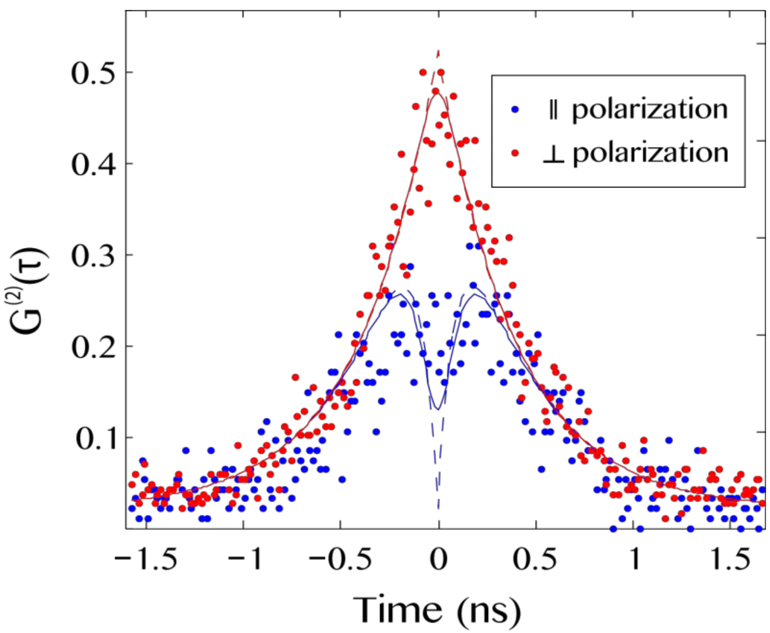


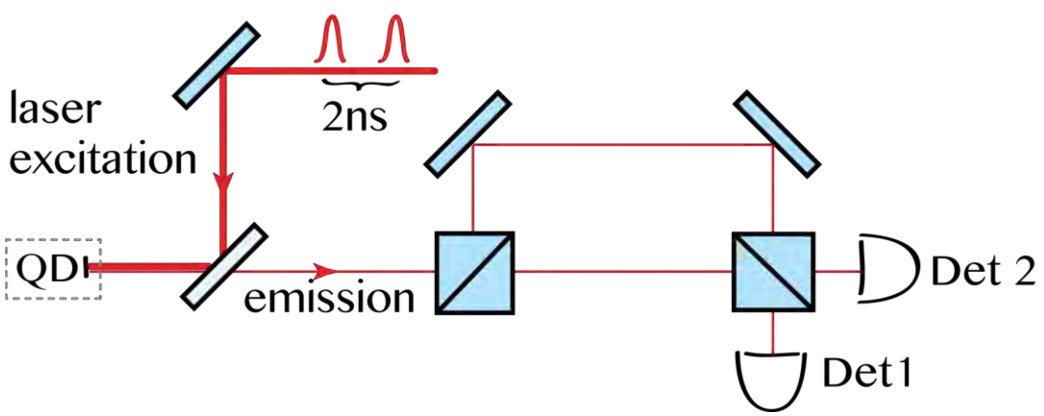
Calculated correlation function $G^{(2)}(\tau)$ for photons with radiative lifetime τ_r = 1ns, and different visibilities $\nu = \tau_c/2\tau_r$.

$$G^{(2)}(t,\tau) = \frac{1}{4}\left[2I(t)I(t+\tau) - 2|G^{(1)}(t,\tau)|^2\right]$$

arXiv:1502.00160

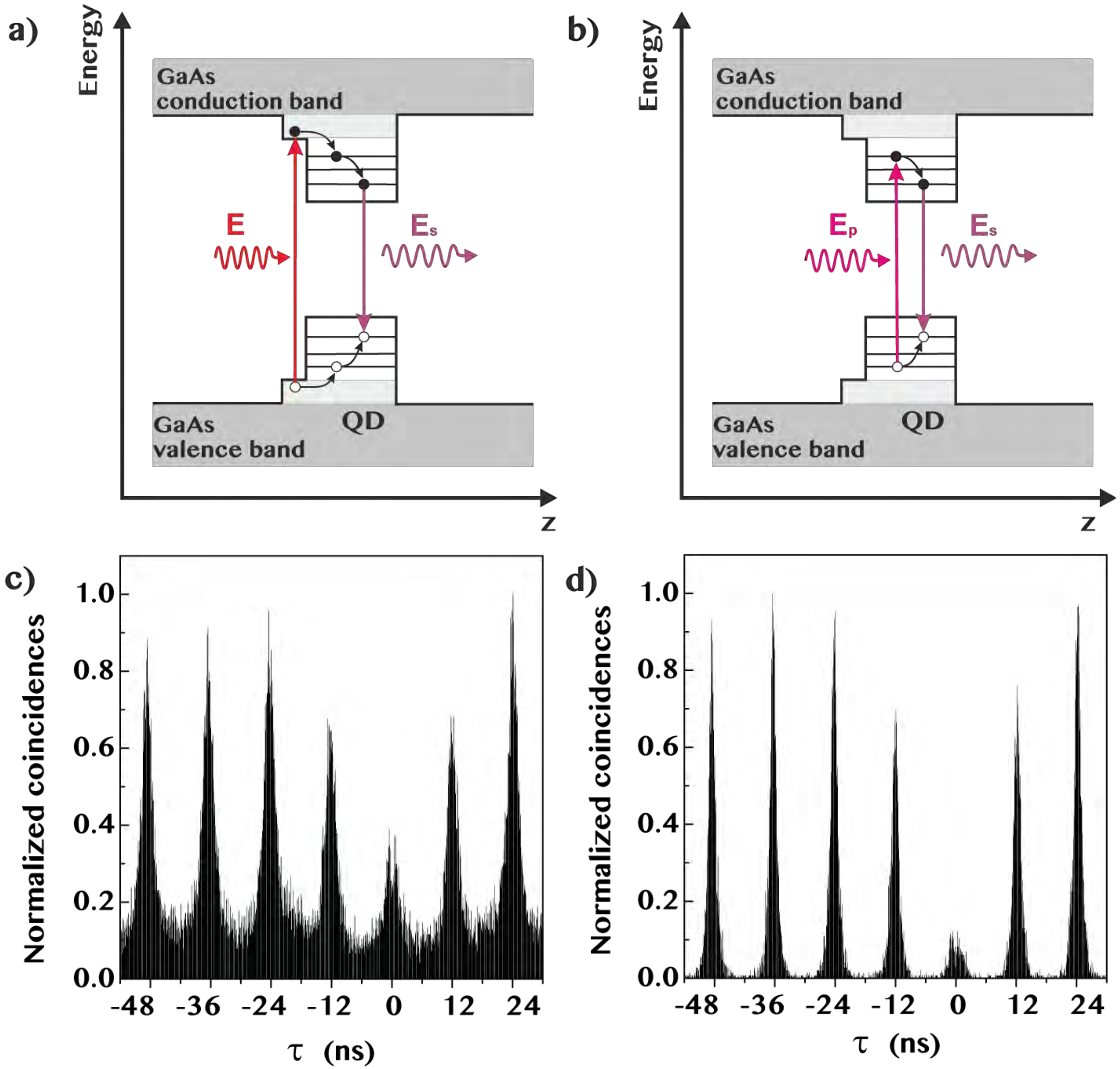
Indistinguishability of photons





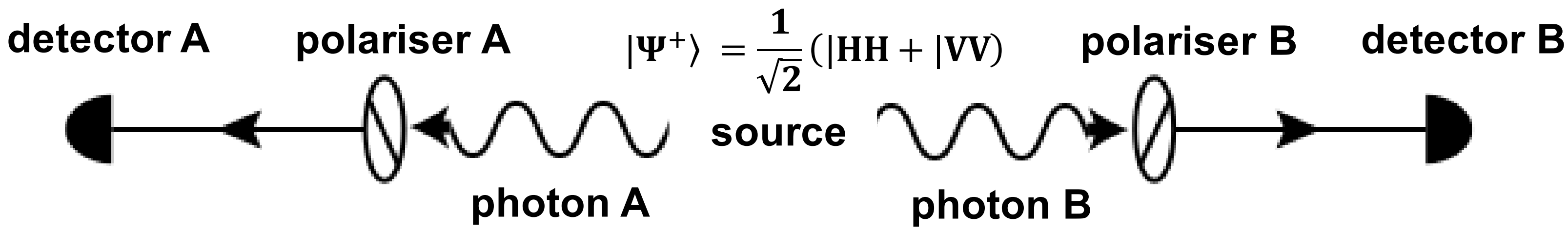
New Journal of Physics 17, 123025 2015

Indistinguishability of photons vs excitation method



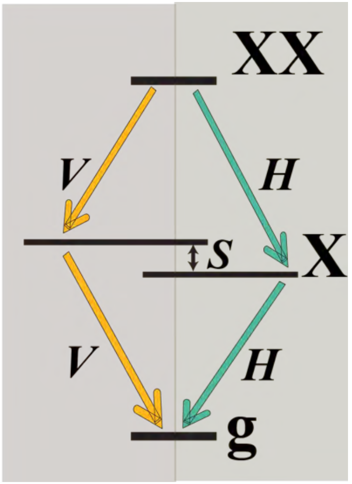
arXiv:1502.00160

Entangled photon pairs: Aspect/Zeilinger experiment



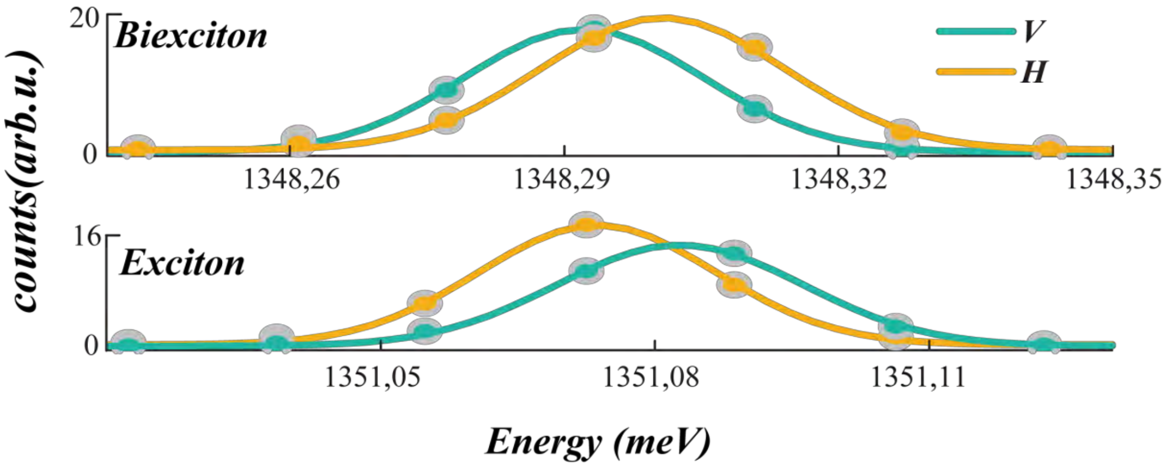
Entangled photon pairs emitted by quantum dot

XX– Biexciton
X– Exciton
g – ground state

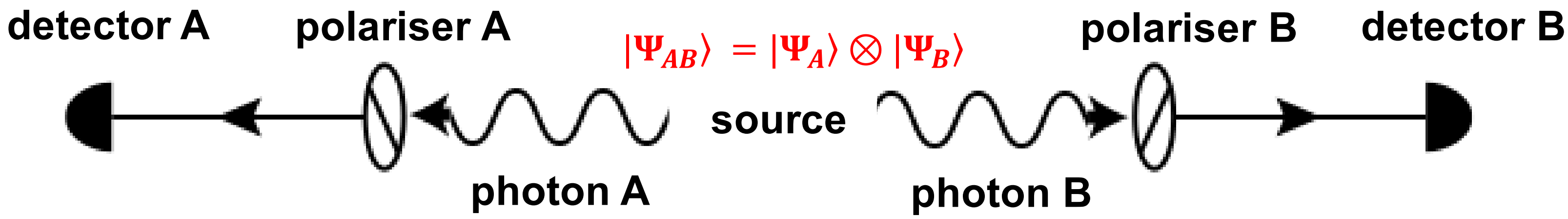


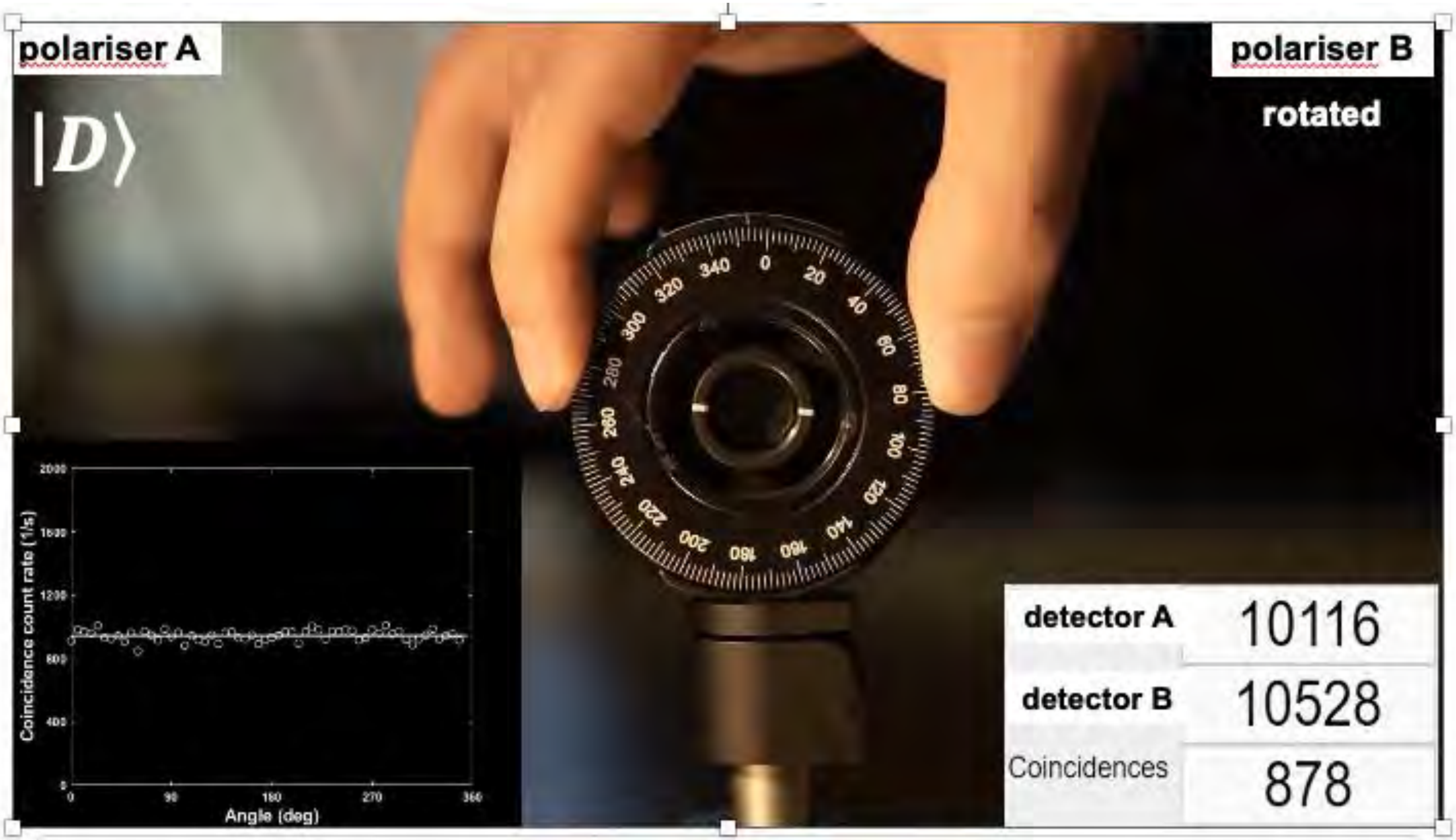
Recovery of the level degeneracy:

- electric field, magnetic filed tuning
- optical Stark effect
- growth
- strain tuning



Pair of photons that are in a separable state





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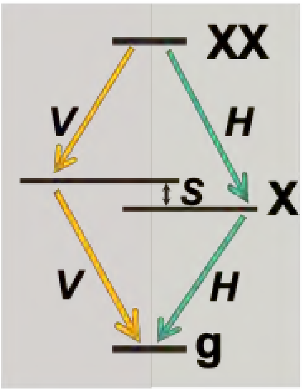

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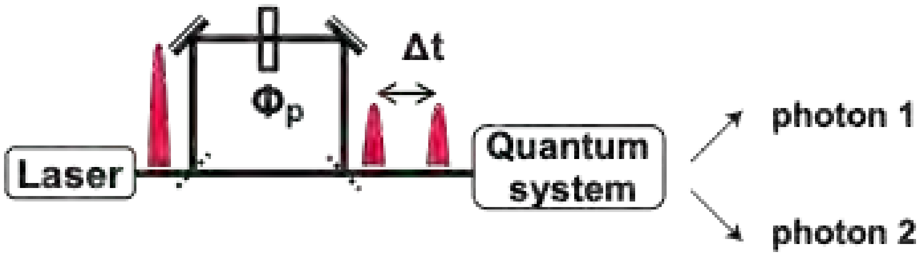
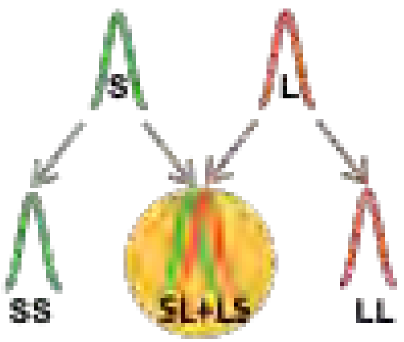


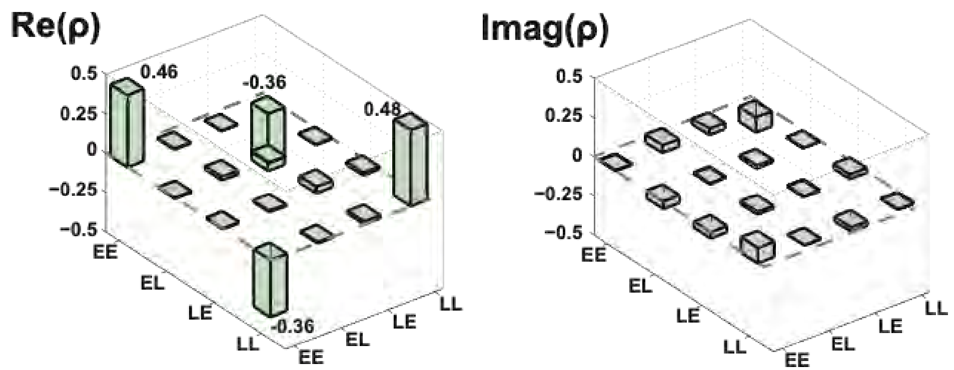
$$|\Phi\rangle_{\mathrm{pump}} = \frac{1}{\sqrt{2}}\left(|\mathrm{early}\rangle_{\mathrm{p}} + e^{i\Phi_{\mathrm{p}}}|\mathrm{late}\rangle_{\mathrm{p}}\right)$$

- **single spacial mode linear optical quantum computing,** *Phys. Rev. Lett.* **111**, 150501 (2013).
- **quantum communication,** *Nature Physics* **3**, 692 - 695 (2007).
- **long-distance entanglement distribution via optical fiber,** *Optics Express*, **17**, 11440 (2009).

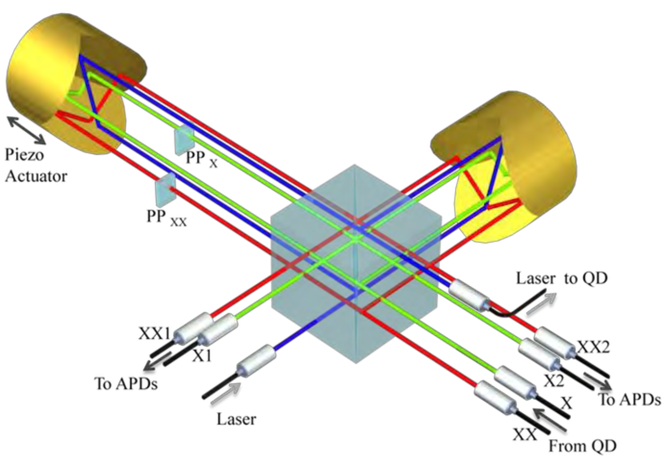
Time-bin entanglement

$$|\Phi^+\rangle = \frac{1}{\sqrt{2}}\left(|\mathrm{early}\rangle_X|\mathrm{early}\rangle_{XX} + e^{i\Phi_p}|\mathrm{late}\rangle_X|\mathrm{late}\rangle_{XX}\right)$$





visibility	concurrence	fidelity
80(5)%	0.78(6)	0.88(3)



H. Jayakumar, et al. *Nature Communications* **5**, 4251 (2014).

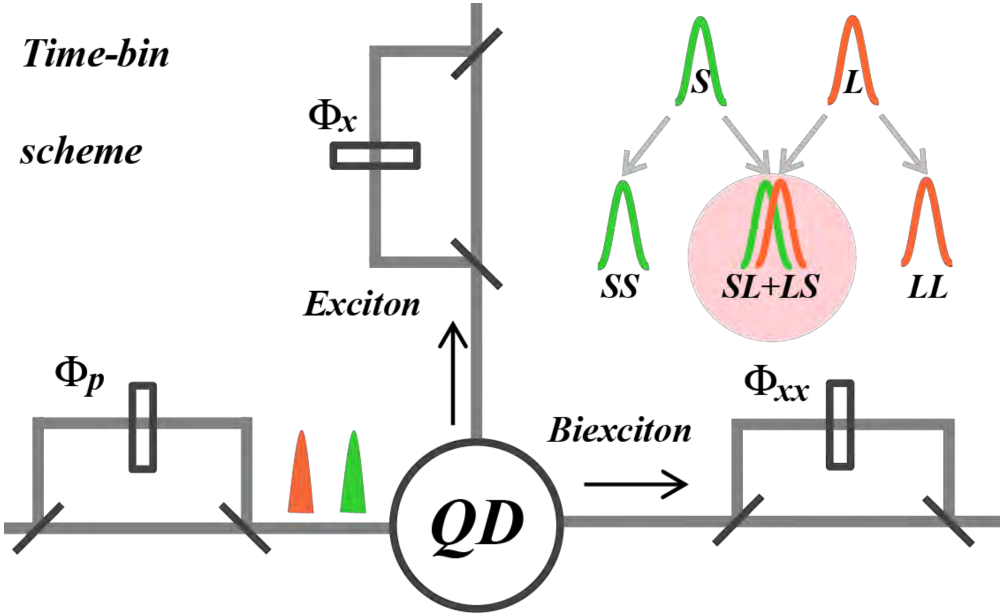
M. Prilmüller, et al. *Phys. Rev. Lett.* **121**, 110503 (2018).

L. Ginés, et al. *Opt. Express* **29**, 4174 (2021).

L. Ginés, et al. *Phys. Rev. Lett.* **129**, 033601 (2022).

T. Huber, et al. *Phys. Rev. B*, **93** 201301(R) (2016).

Time-bin entanglement - analysis



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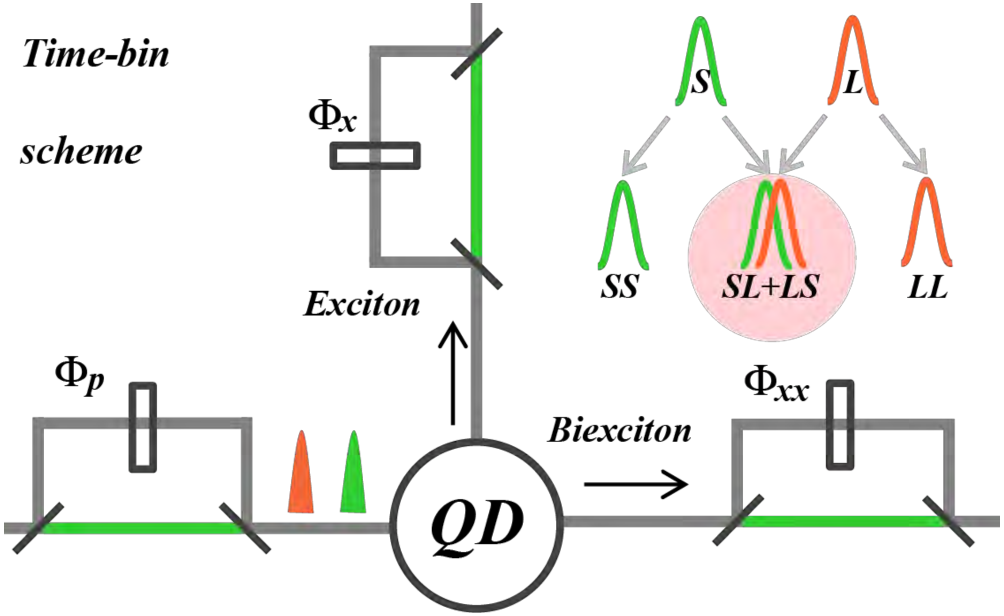

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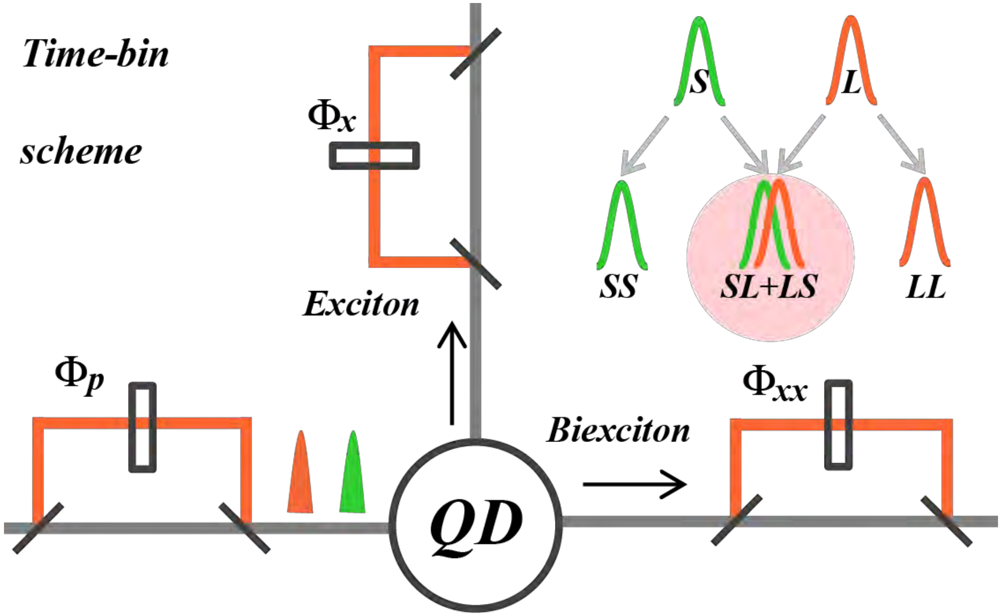

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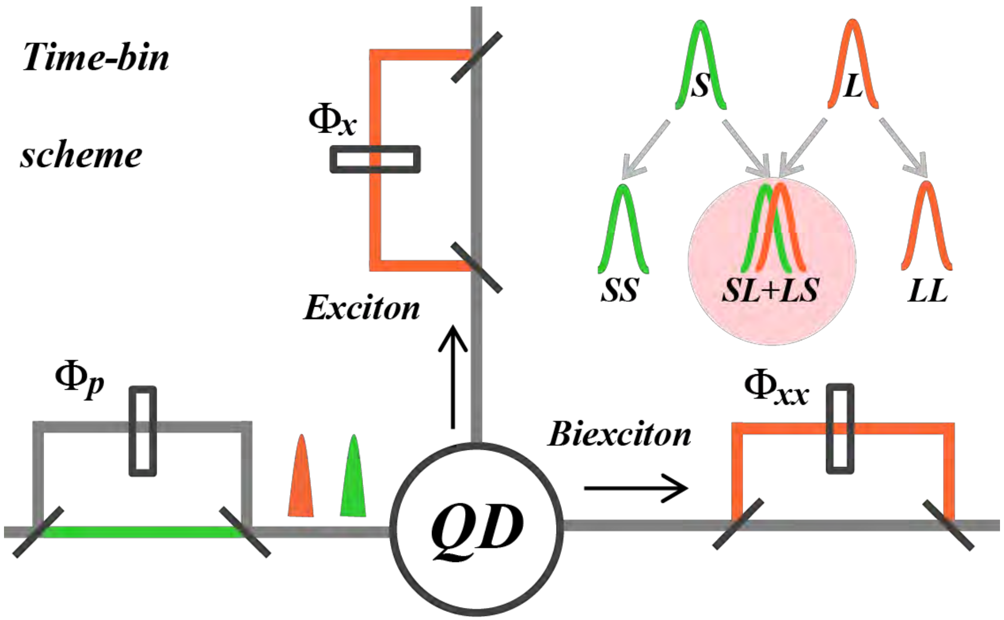

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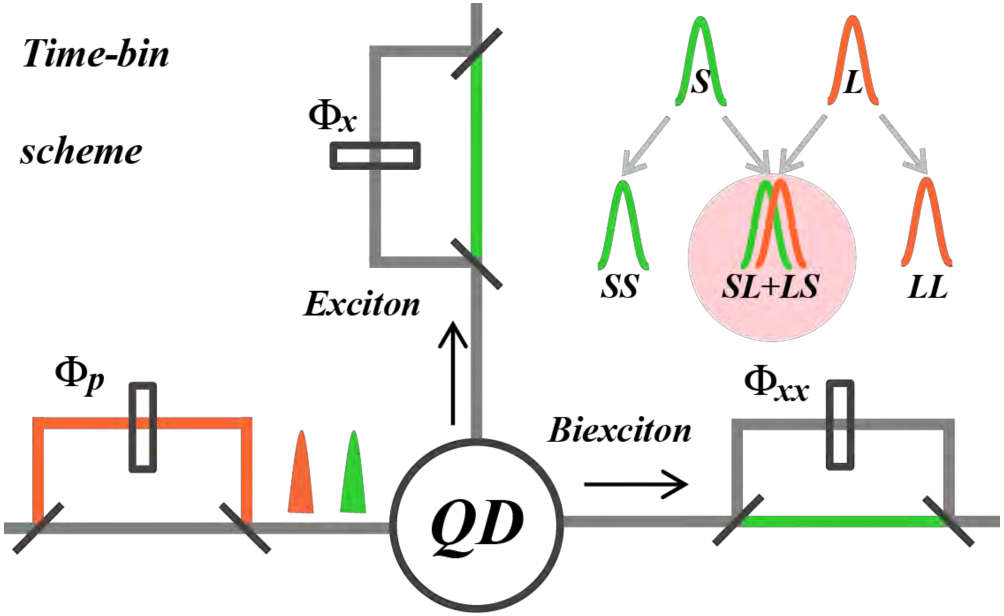

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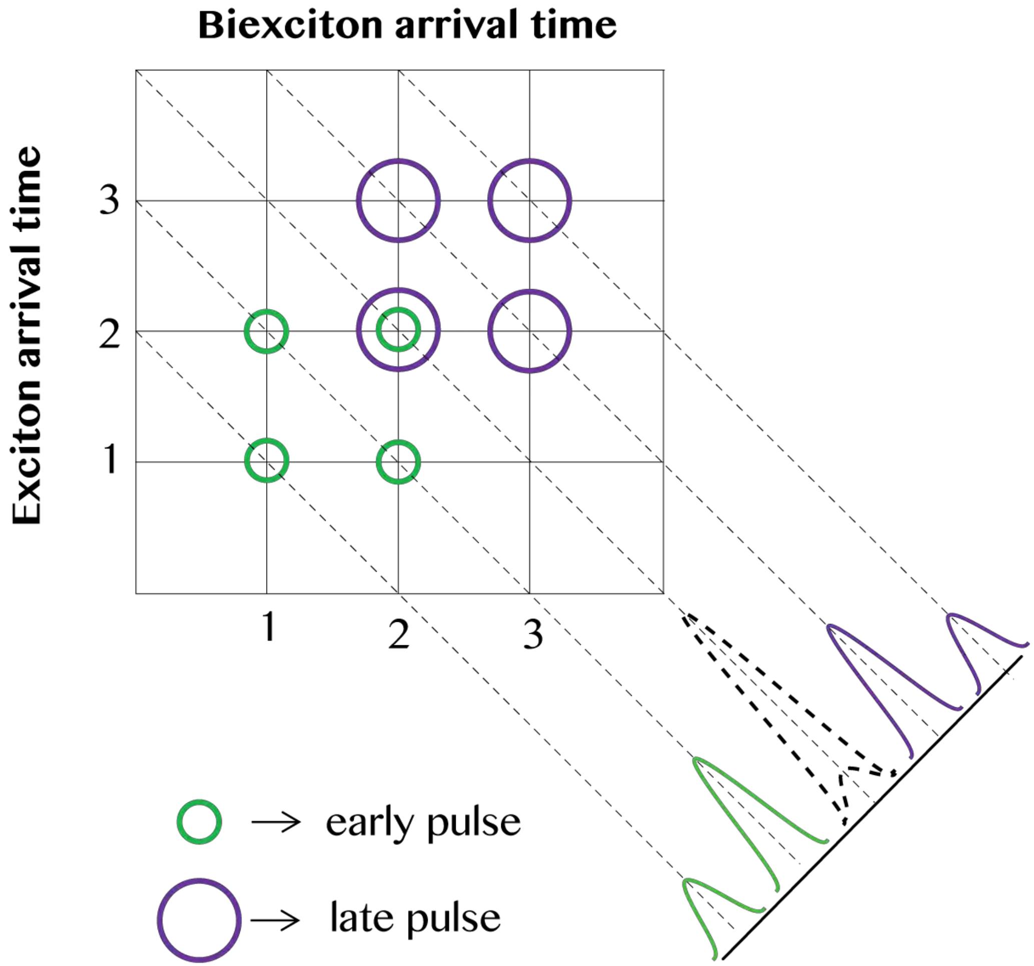
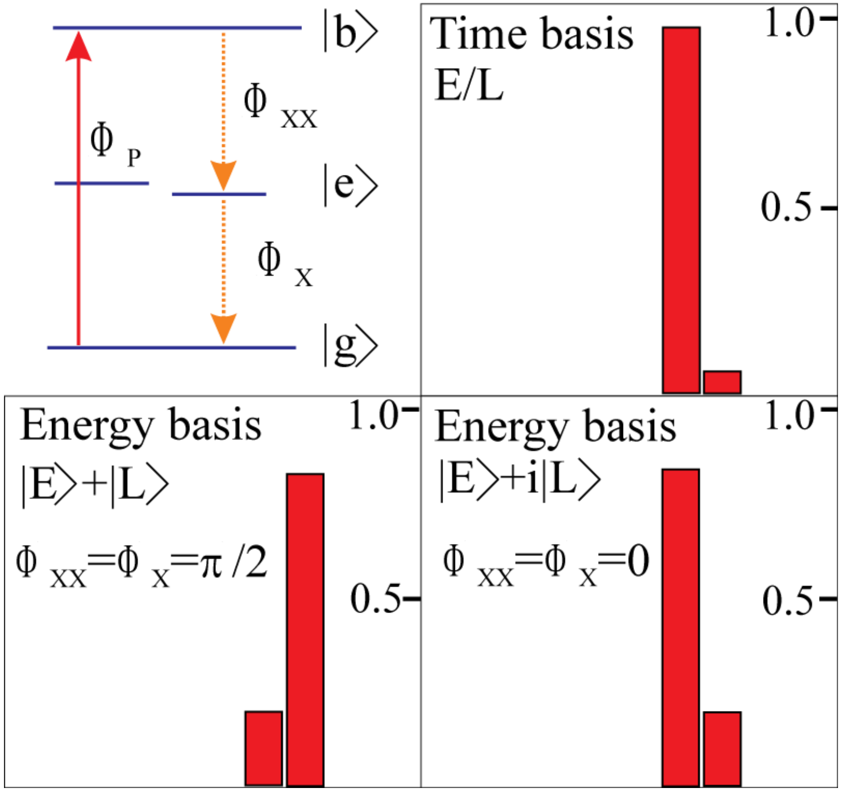
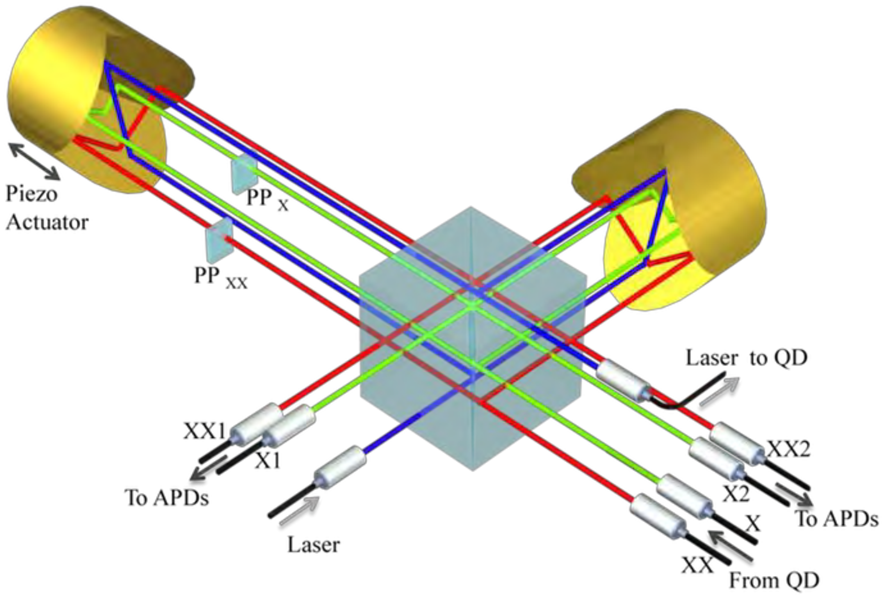


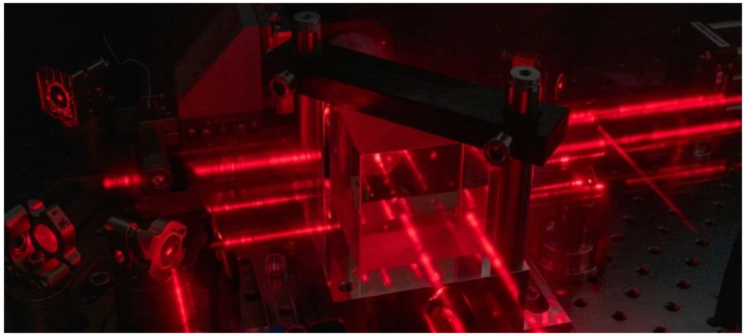
arXiv:1503.00352



pulse length (ps)	E/L	E+L/E-L	E+iL/E-iL
12	94(2)%	74(5)%	67(5)%

Time-bin entanglement





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