Single Photon Generation & Application in Quantum Cryptography

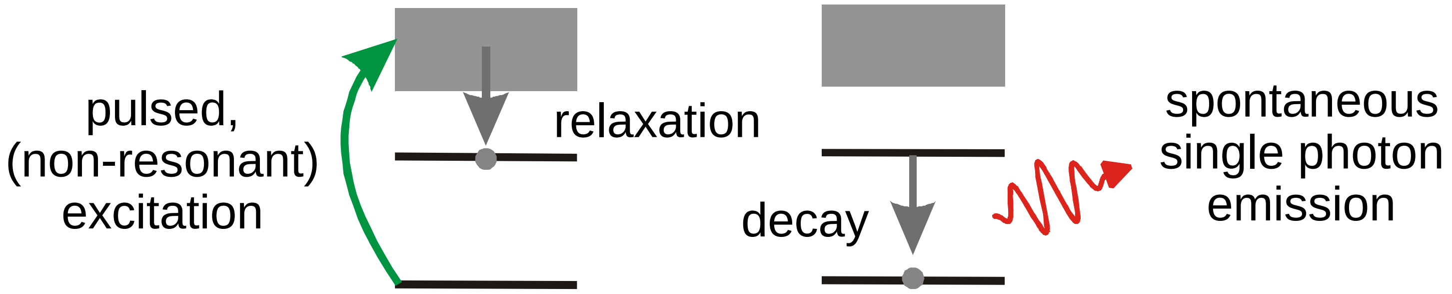
- Single Photon Sources
- Photon Cascades
- Quantum Cryptography

Single Photon Sources

Methods to Generate Single Photons on Demand

Spontaneous emission (single emitters)

- atoms, molecules, quantum dots, defect centers
- optical, electrical and STIRAP excitation



pulsed,
(non-resonant)
excitation

relaxation

decay

spontaneous
single photon
emission

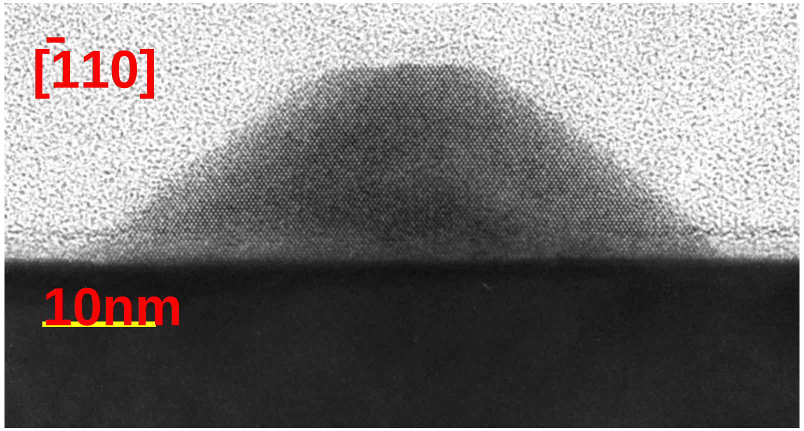
M: Brunel et al., PRL 83, 2722 (1999)
Lounis & Moerner, Nature 407, 491 (2000)

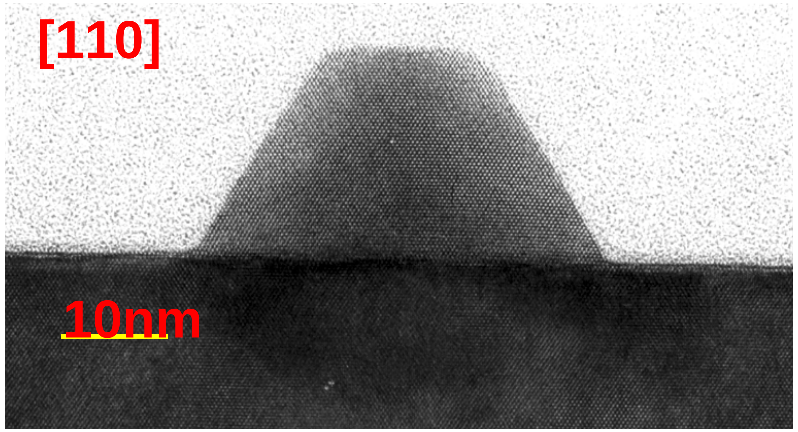
DC: Kurtsiefer et al., PRL 85, 290 (2000)
Beveratos et al., PRA 64, 061802(R) (2001)

QD: Kim et al., Nature 397, 500 (1999)
Michler et al., Science 290, 2282 (2000)
Santori et al., PRL 86, 1502 (2001)
Yuan et al., Science 295, 102 (2002)

Single Photon Sources
Quantum Dots

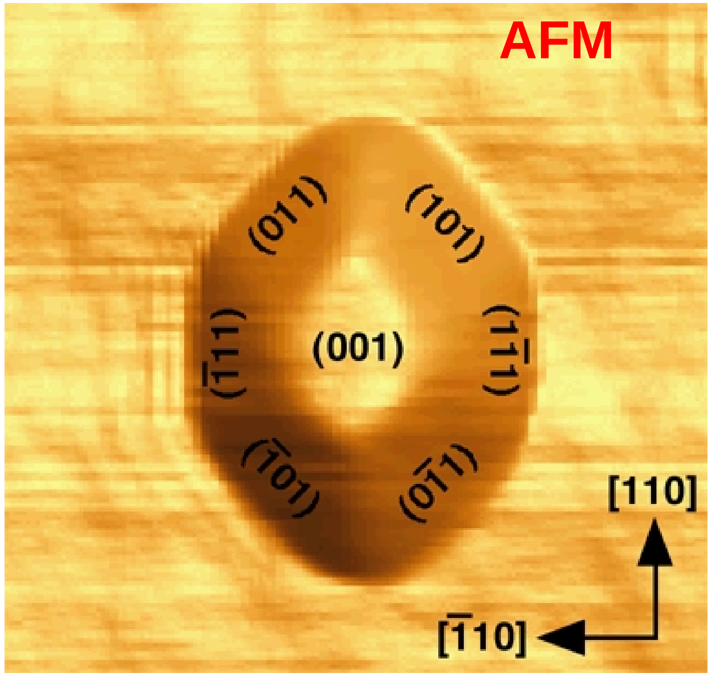
Transmission electron microscope images





K. Georgsson et al., Appl. Phys. Lett. 67, 2981 (1995)

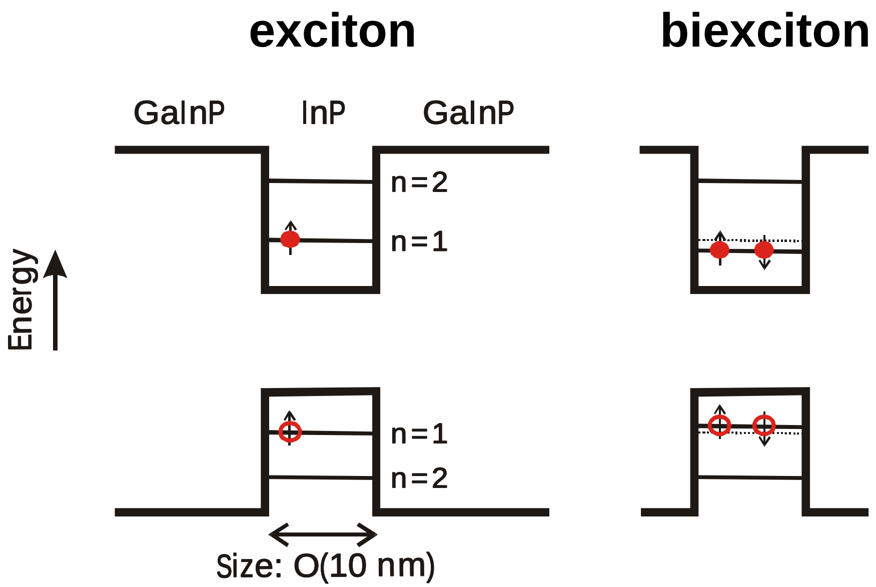
Atomic force microscope image

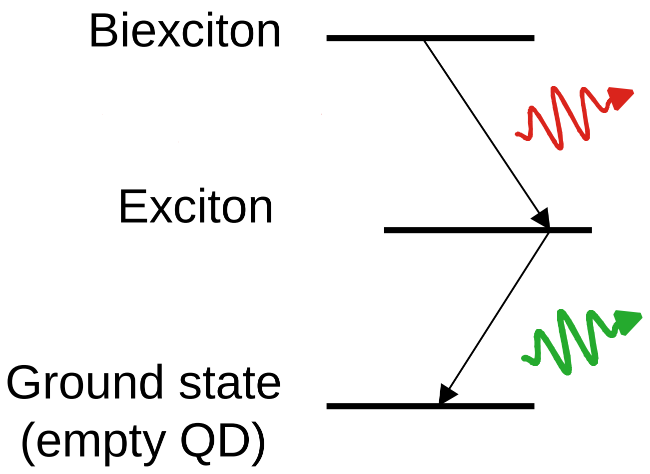


Contains ~10000 atoms

InP dots grown on GaInP

Single Photon Sources
Quantum Dots

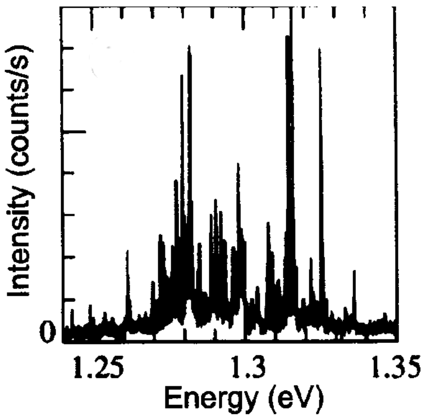



Biexciton

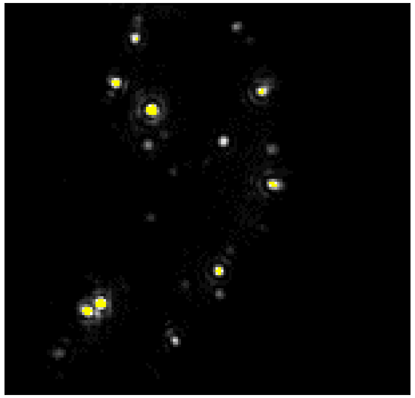
Exciton

Ground state
(empty QD)

Photoluminescence of an ensemble of InAs quantum dots



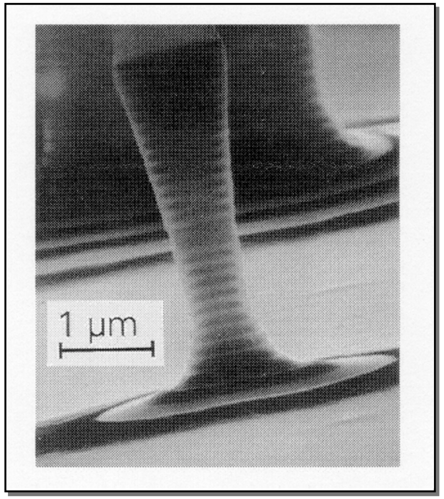
Photoluminescence image of a set of InP quantum dots



Single Photon Sources
Quantum Dots

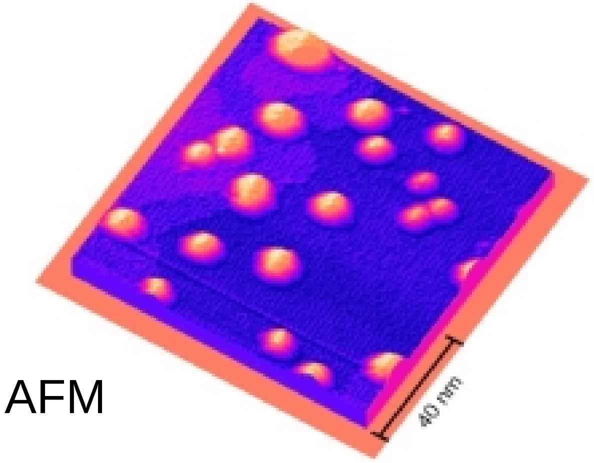
Specific advantages of single quantum dots

- Stability
- Compatible with chip-technology
- Wide spectral range
- Electrical Pumping
- High repetition rate
- Strong interactions “available”



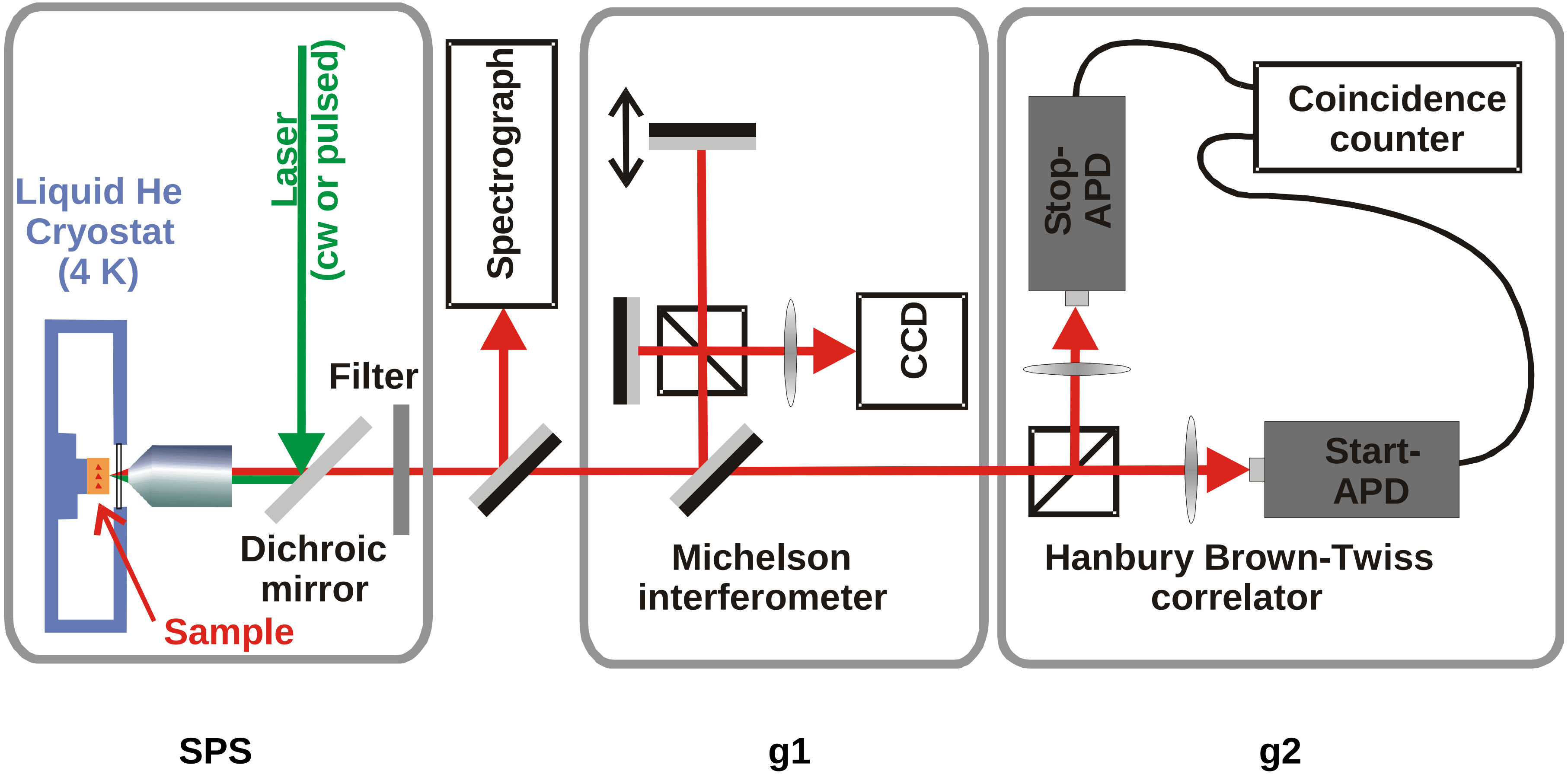
Specific disadvantages of single quantum dots

- Low temperature operation
- Non-uniformity
- Device production yield
- Decoherence
- Efficiency



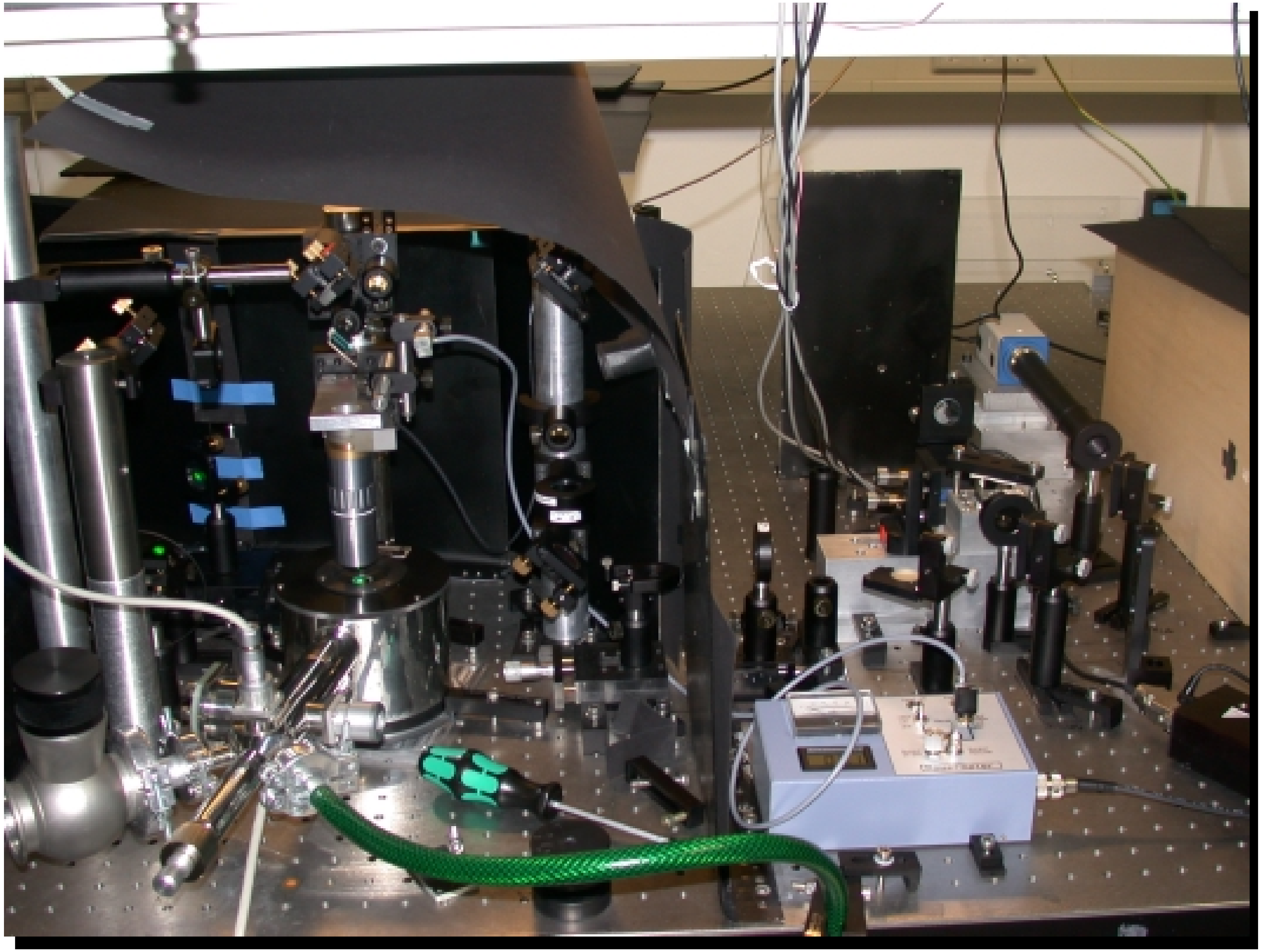
AFM

Single Photon Sources
Experimental Setup



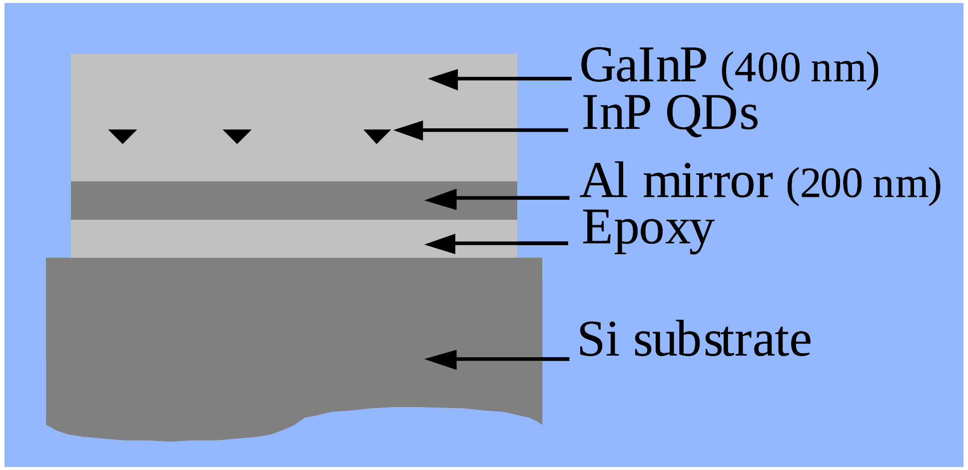
Single Photon Sources

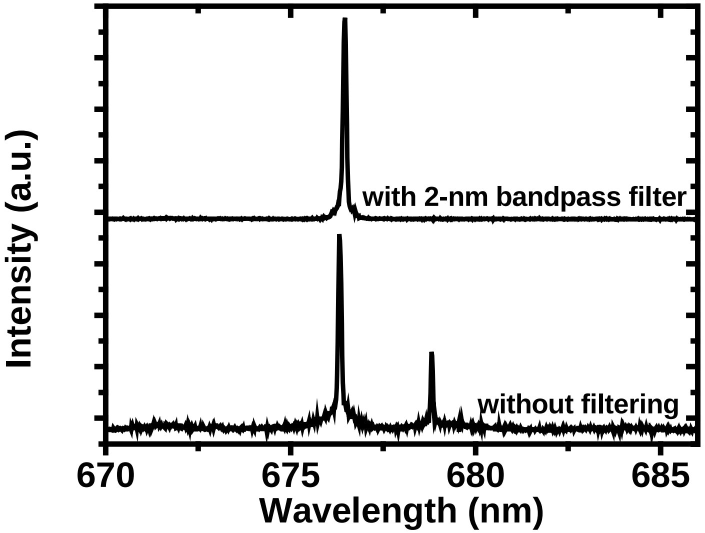
Experimental Setup



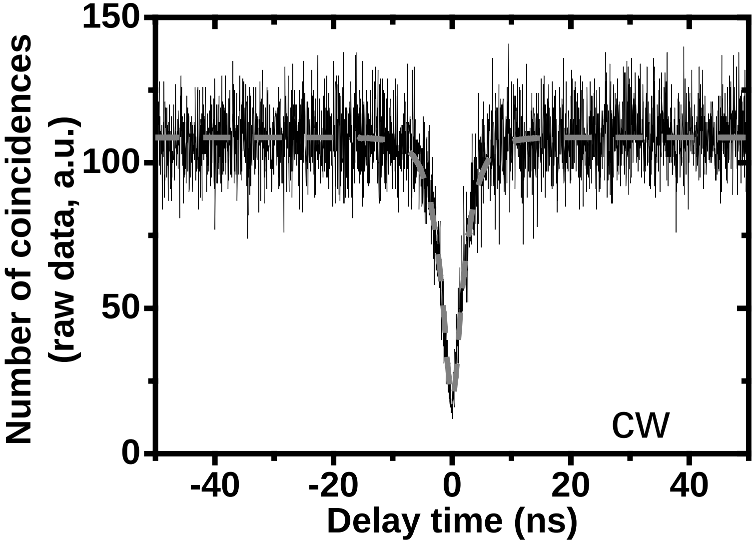
Single Photon Sources
InP Quantum Dots in GaInP

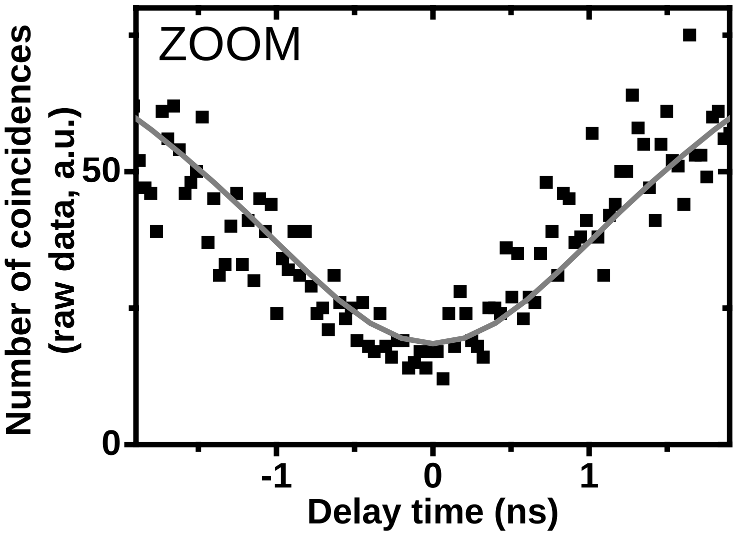
- Emission around 690 nm
  (@ maximum detection efficiency of Si detectors)
- Lifetime around 1 ns
- Dot density: 10^8 cm^{-2} through 2 nm bandpass filter
- Linewidth around 100 µeV

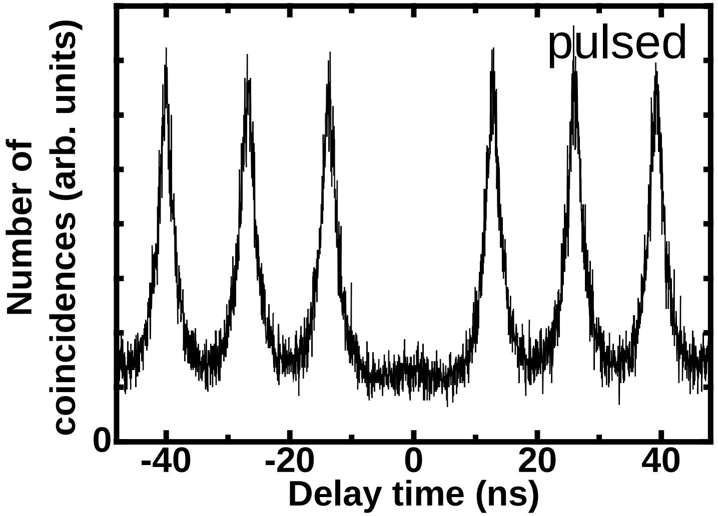




Single Photon Sources
Intensity Correlation Measurements







- Central peak vanishes nearly completely

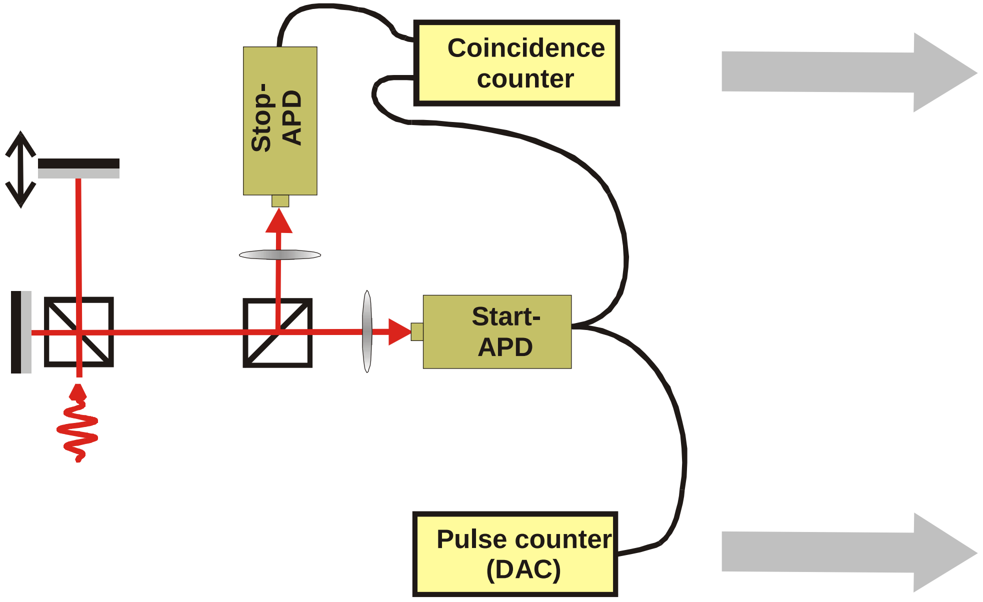
⇨ generation of only one photon per pulse

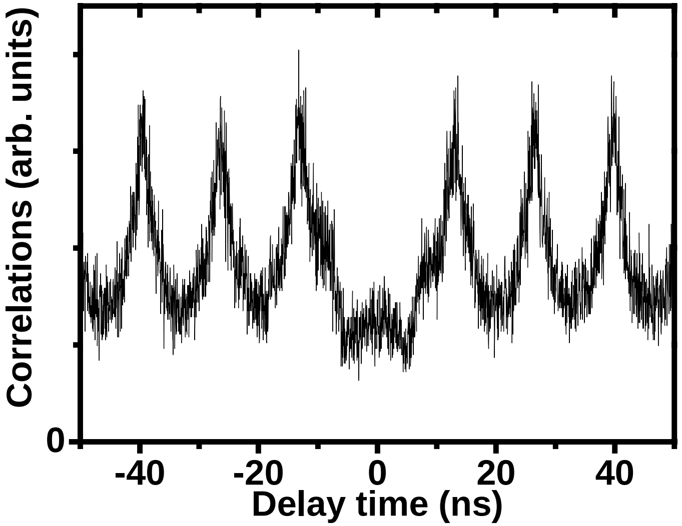
- Single photon generation observed up to 40 K

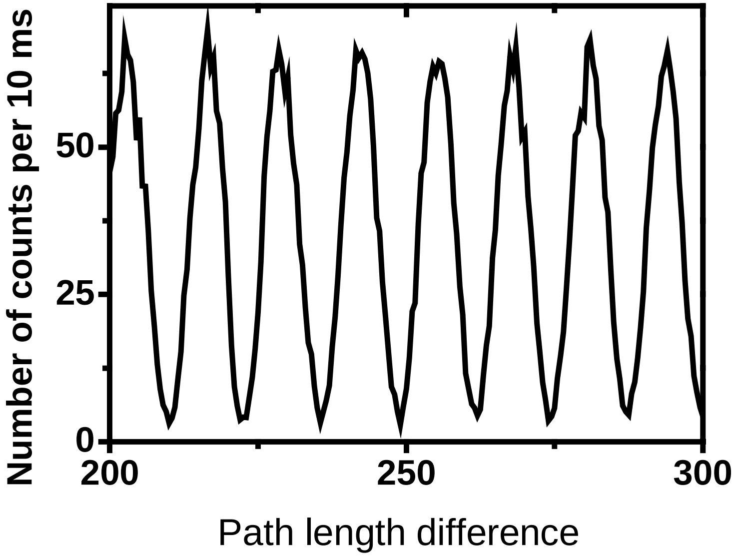
V. Zwiller, et al., Appl. Phys. Lett. 82, 1509 (2003)

Single Photon Sources

Wave and Particle Aspects





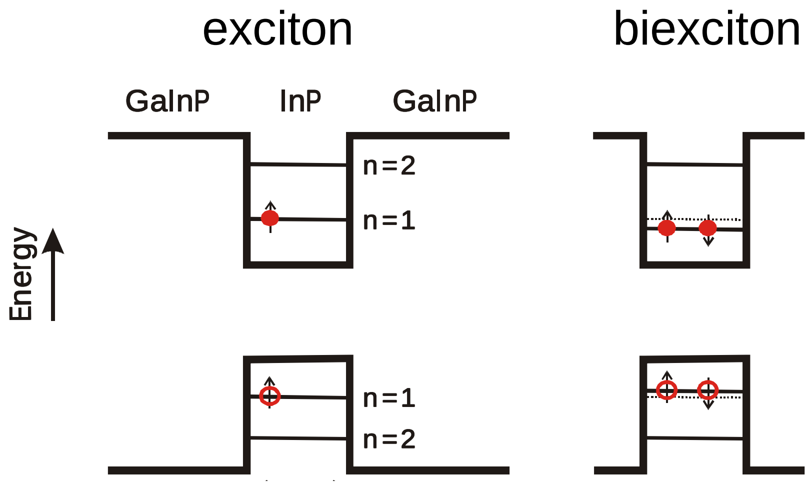


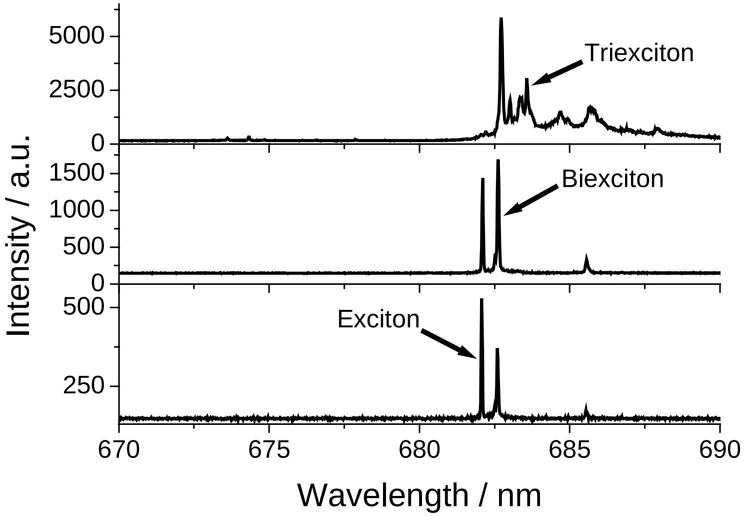
Taylor-experiment (1906)

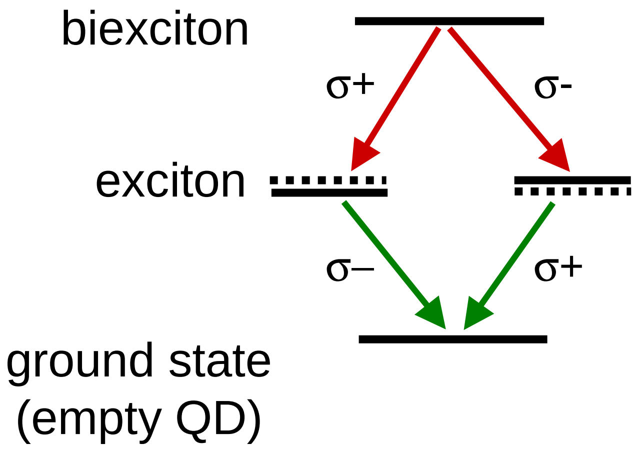
T. Aichele, et al., AIP proc. Vol. 750, 35 (2005)
V. Jacques, et al. Eur. Phys. J. D 35, 561 (2005)
J. T. Höffges, et al. *Opt. Comm.*, 133, 170–174 (1997)

Photon Cascades

Cascaded Emission



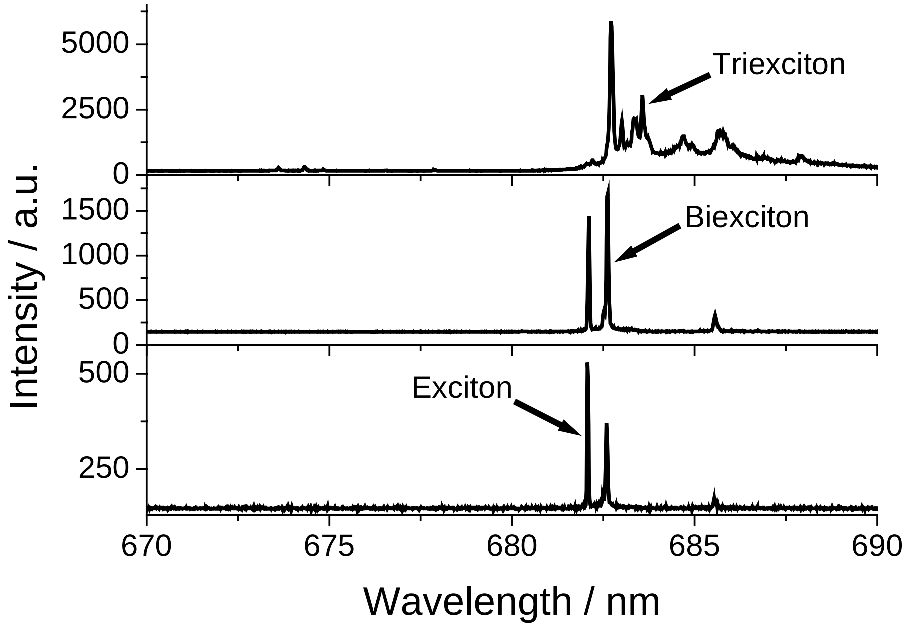


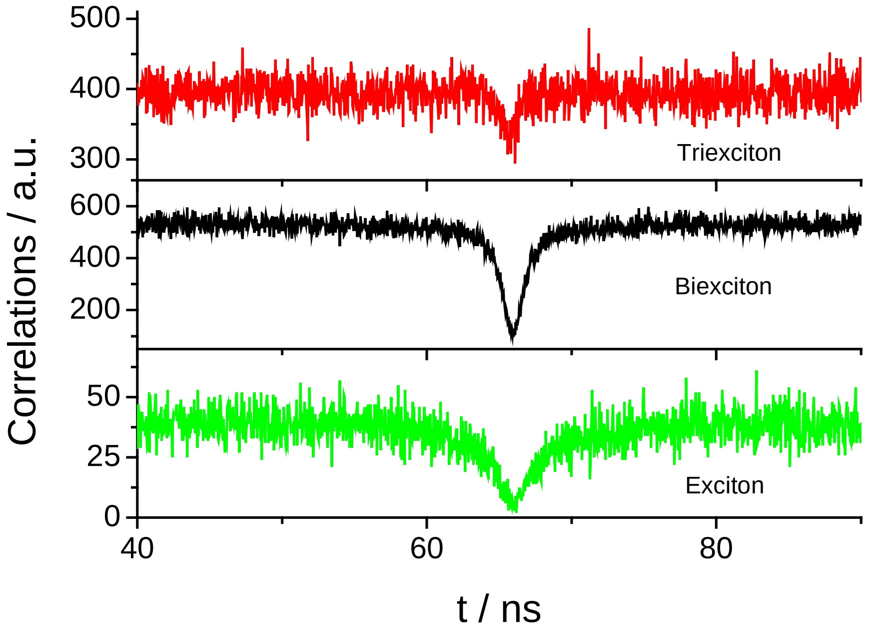


Different energy of exciton, biexciton, triexciton, ...
due to Coulomb interaction

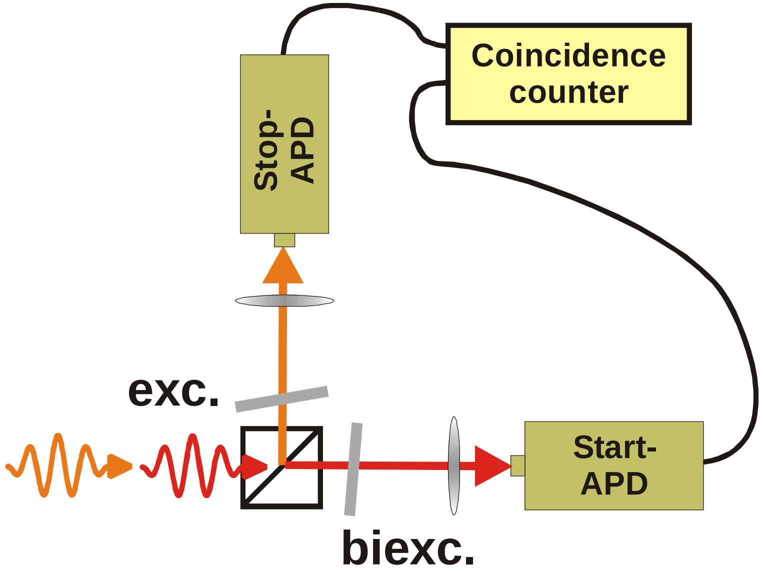
Photon Cascades
Cascaded Emission

Spectra and anti-bunching in photon cascades:



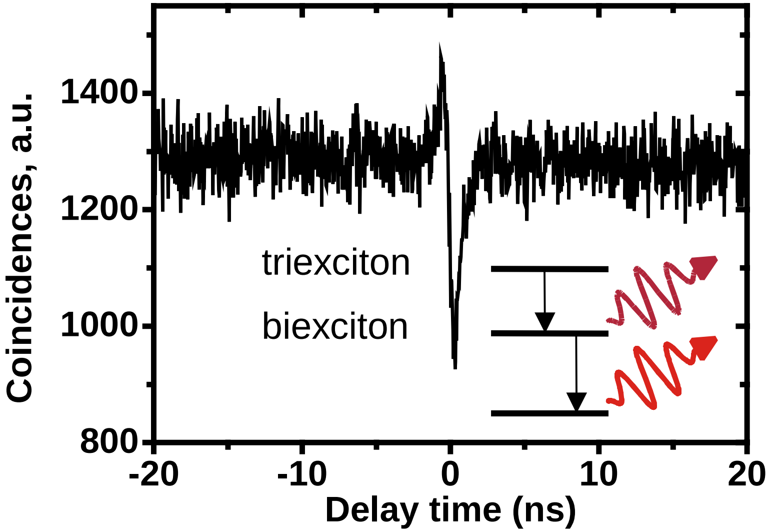


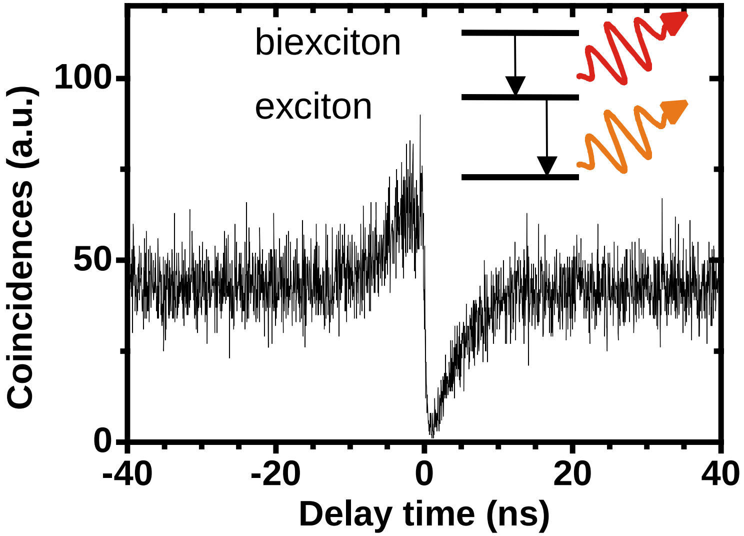
Photon Cascades
Cascaded Emission



Correlation measurements reveal dynamics of multiphoton cascades

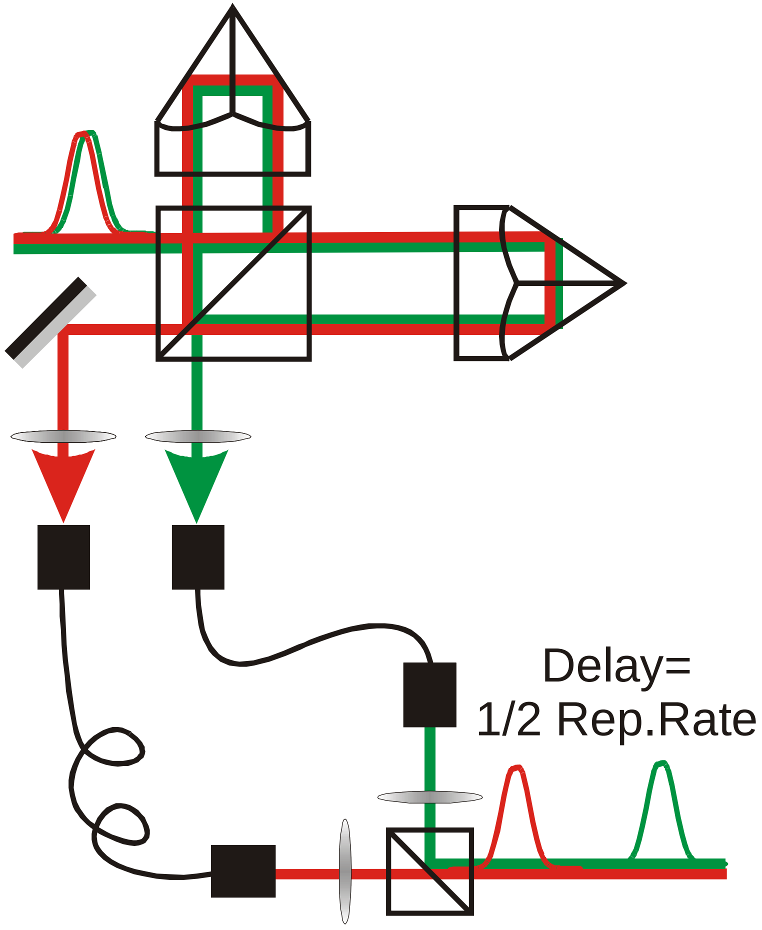
J. Persson et al., Phys. Rev. B 69, 233314 (2004)
D. V. Regelmann, et al. Phys. Rev. Lett. 87, 257401 (2001)
E. Moreau et al., Phys. Rev. Lett. 87, 163601 (2001)
A. Kiraz et al. Phys. Rev. B 65, 161303 (2002)

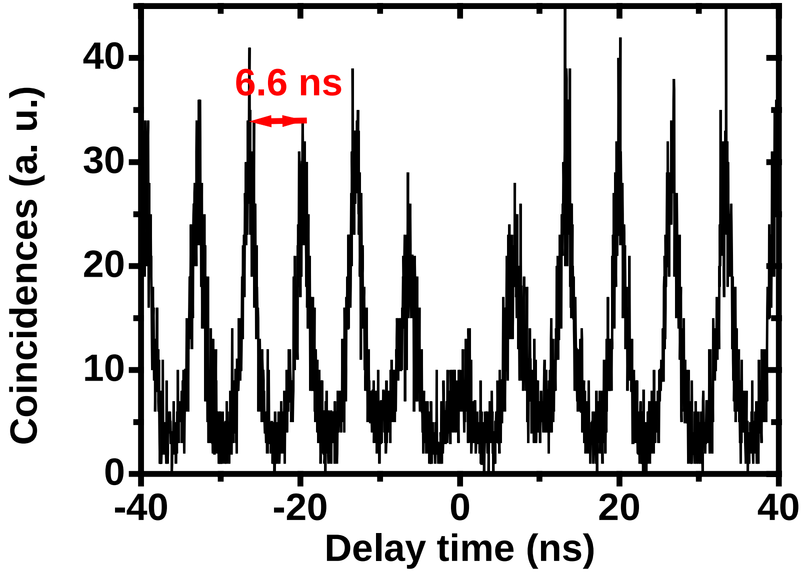




Photon Cascades
Single Photon Multiplexing

Separating spectral lines using a Michelson interferometer



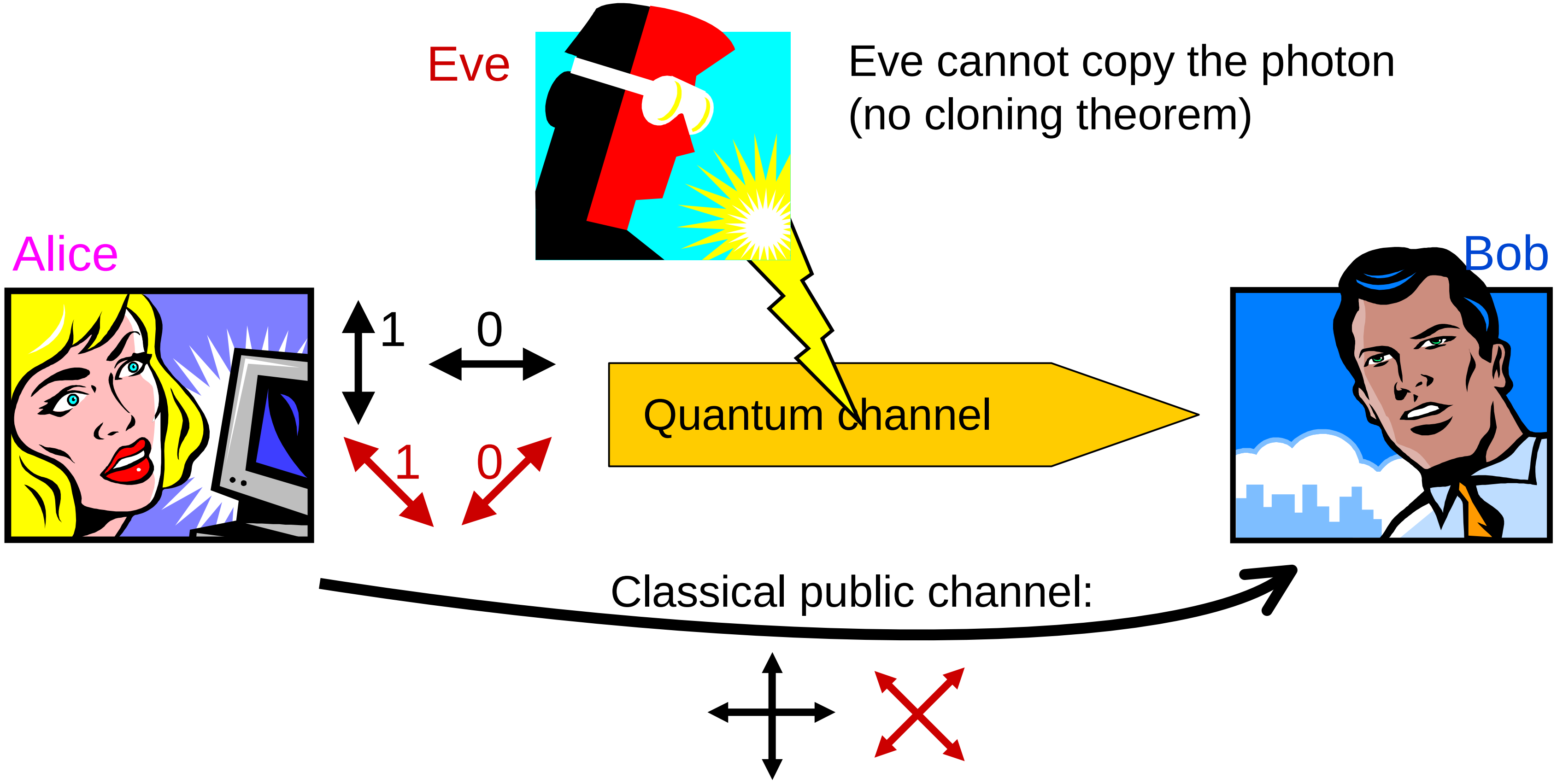


One quantum emitter acts as two independent single photon sources.

Delaying the two photons by half the excitation repetition time doubles the photon rate.

Quantum Cryptography

The BB84 Protocol



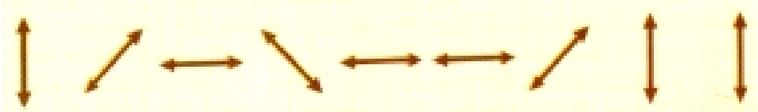
Eve cannot copy the photon
(no cloning theorem)

Bennett, Brassard, Proc. IEEE Int. Conf. on Computers, Systems & Signal Processing (1984),
First realization with QDs: Waks et al., Nature 420, 762 (2002)

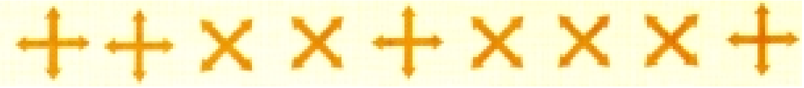
Quantum Cryptography

BB84 Protocol

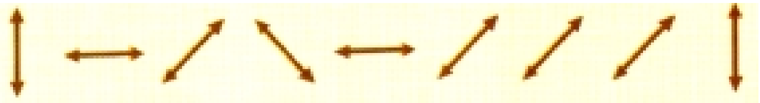
- Alice sends randomly polarized photons (0, 45, 90 or 135°) to Bob.



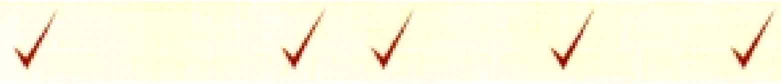
- Bob randomly measures in the straight or diagonal base.



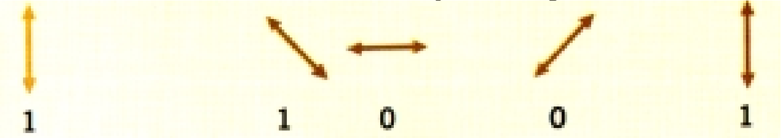
- Bob keeps his results secret.



- Bob publically tells his measurement bases (not the results!). Alice publically tells him if he chose the right base.



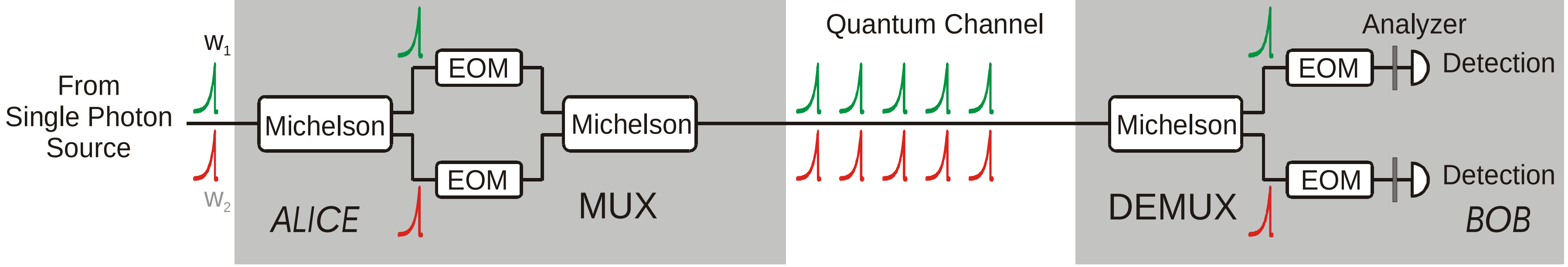
- Alice and Bob keep only the results with the common bases.

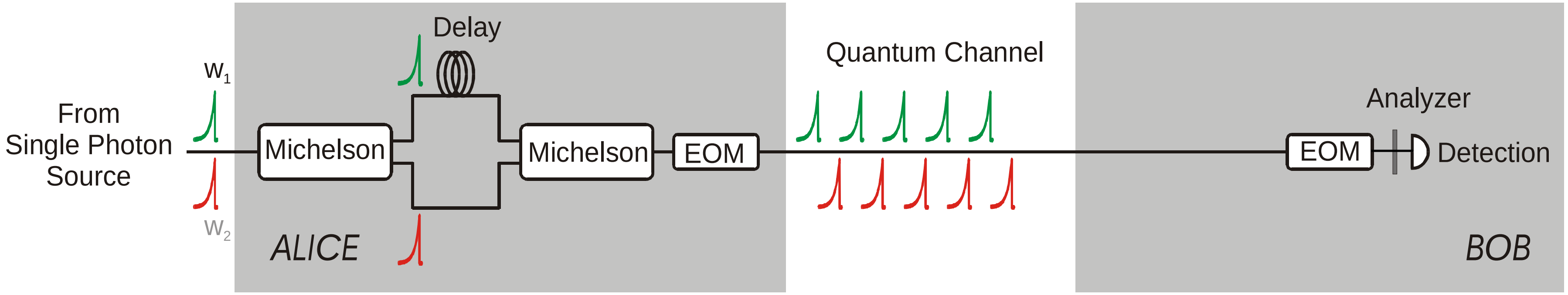


- They both have now a common and random key: 1 1 0 0 1 ...

Quantum Cryptography

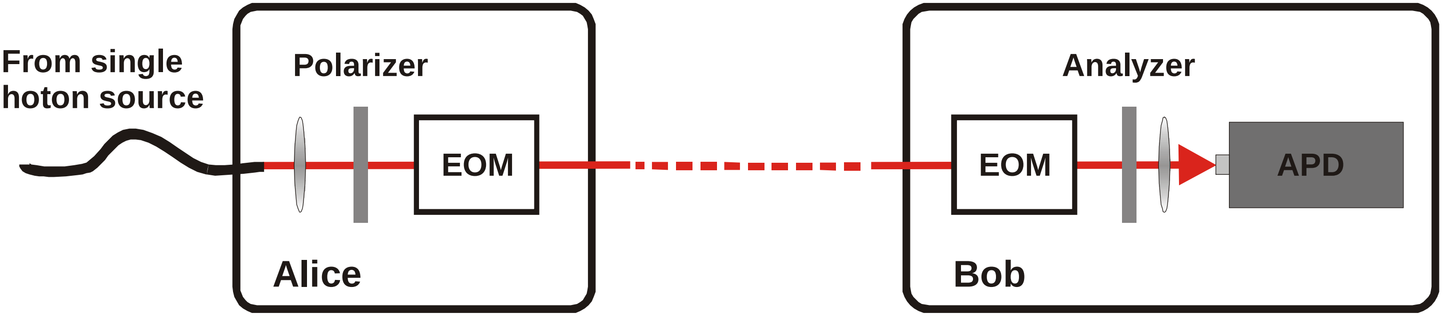
Multiplexed Quantum Cryptography





Quantum Cryptography

Multiplexed Quantum Cryptography



Transmission to Bob: 30 successfull counts/s at a laser modulation of 20 kHz

Similarity between Alice´s and Bob´s keys: 95%

T. Aichele, G. Reinaudi, O. Benson, Phys. Rev. B, 70, 235329 (2004)