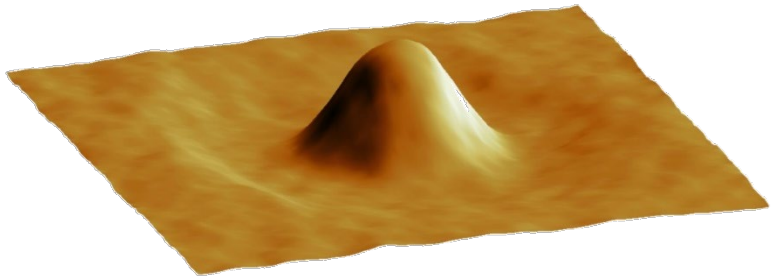
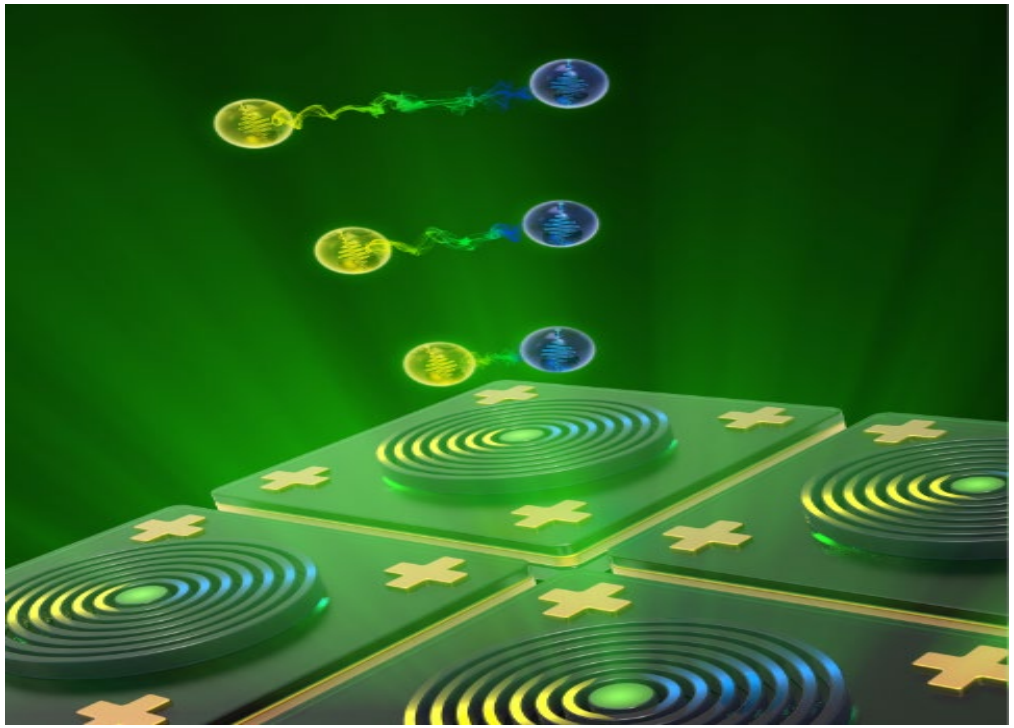
Halbleiter-basierte Quellen einzelner Photonen und verschränkter Photonenpaare



Armando Rastelli

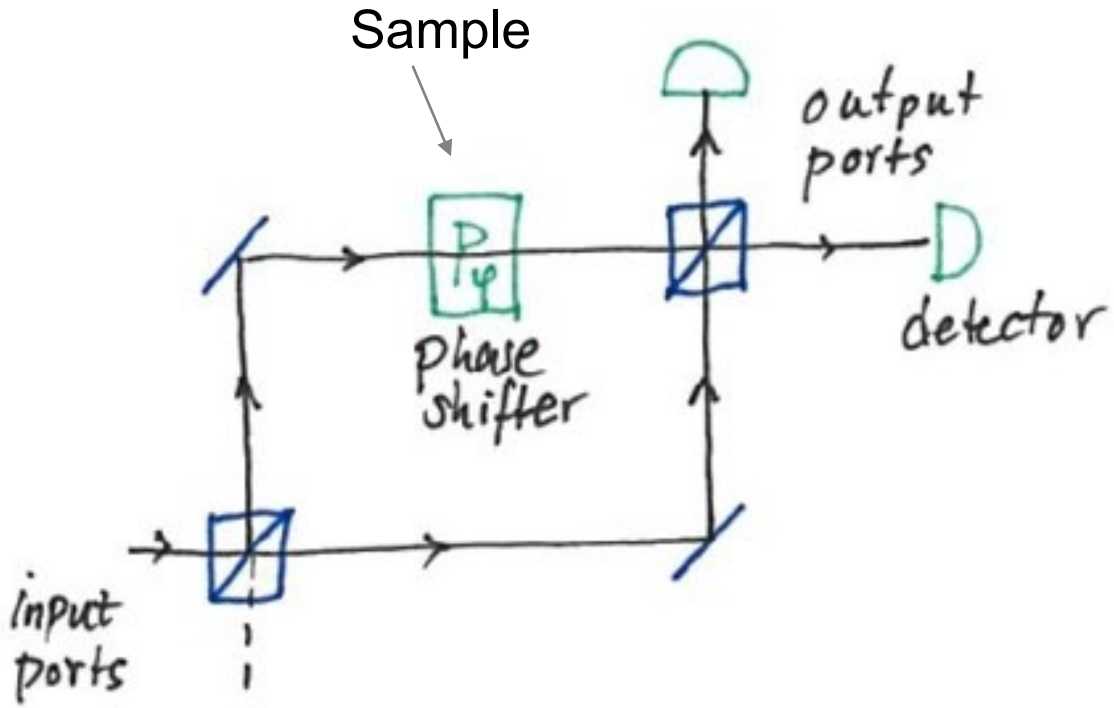
Institute of Semiconductor and Solid-State Physics
Linz Institute of Technology (LIT)

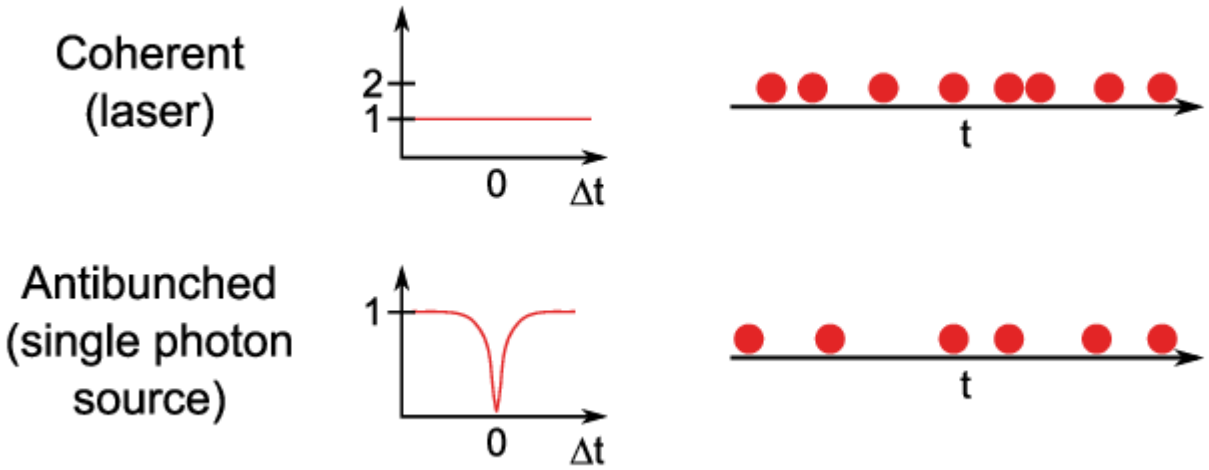


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Quantum-optical metrology

- High-precision measurements based on optical interference (based on phase shifts)
- Quantum states of light can improve sensitivity in phase detection beyond standard quantum limit $\Delta\phi = 1/\sqrt{N}$ towards the Heisenberg limit $\Delta\phi = 1/N$, with N the number of photons.
- Examples of quantum states of light: single photons, N00N states, entangled photon pairs





New sources of non-classical light are required!

https://qt.eu/applications/quantum-optical-metrology-imaging-and-sensing

Entangled photons and their use

- Entangled state of two particles: state which cannot be factorized as a product of single-particle wavefunctions.
- Example of polarization-entangled two-photon state:

$$|\Phi^+\rangle = \frac{1}{\sqrt{2}}(|H\rangle_1|H\rangle_2 + |V\rangle_1|V\rangle_2) =$$

$$= \frac{1}{\sqrt{2}}(|D\rangle_1|D\rangle_2 + |A\rangle_1|A\rangle_2) =$$

$$= \frac{1}{\sqrt{2}}(|R\rangle_1|L\rangle_2 + |L\rangle_1|R\rangle_2)$$

- Key resource for quantum technologies (enables establishing correlations among separate/remote locations) → Applications in quantum key distribution and quantum-enhanced sensing

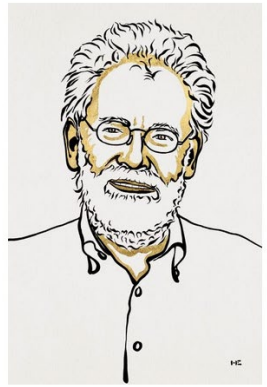
The Nobel Prize in Physics 2022



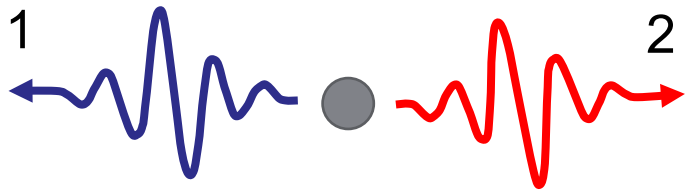
Ill. Niklas Elmehed © Nobel Prize Outreach
Alain Aspect
Prize share: 1/3



Ill. Niklas Elmehed © Nobel Prize Outreach
John F. Clauser
Prize share: 1/3



Ill. Niklas Elmehed © Nobel Prize Outreach
Anton Zeilinger
Prize share: 1/3

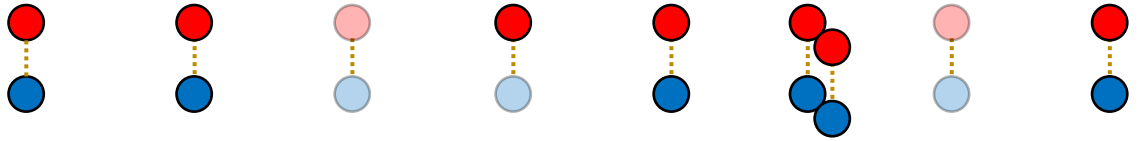


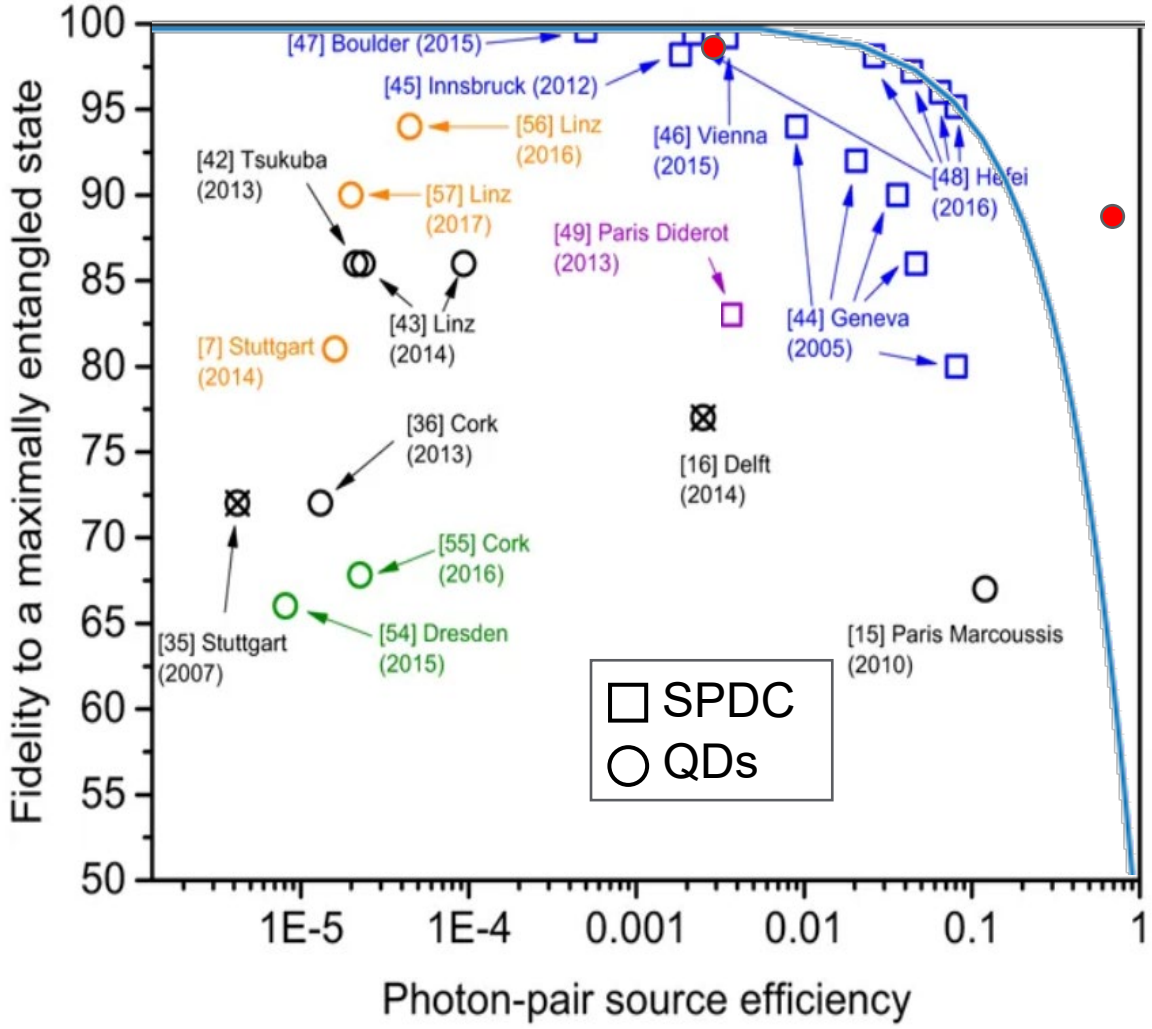
A. Aspect, et al., Phys. Rev. Lett. 47, 460-463 (1981)

See Mark Fox, *Quantum Optics – An Introduction,* Oxford Univ. Press (2006)

Sources of entangled photon pairs

Commonly used sources based on parametric down-conversion (probabilistic)





← Liu, J., et al.,
Nat. Nanotech. 14, 586–593 (2019)

ARTICLES
https://doi.org/10.1038/s41565-019-0435-9
nature nanotechnology

A solid-state source of strongly entangled photon pairs with high brightness and indistinguishability

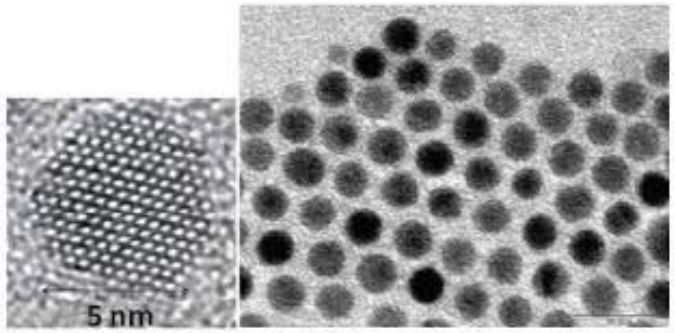
Jin Liu[1,6], Rongbin Su[1,6], Yuming Wei[1], Beimeng Yao[1], Saimon Filipe Covre da Silva[2], Ying Yu[3], Jake Iles-Smith[4], Kartik Srinivasan[5], Armando Rastelli[2*], Juntao Li[1*] and Xuehua Wang[1*]

K. Jöns, et al., Sci. Rep. 7, 1700 (2017)

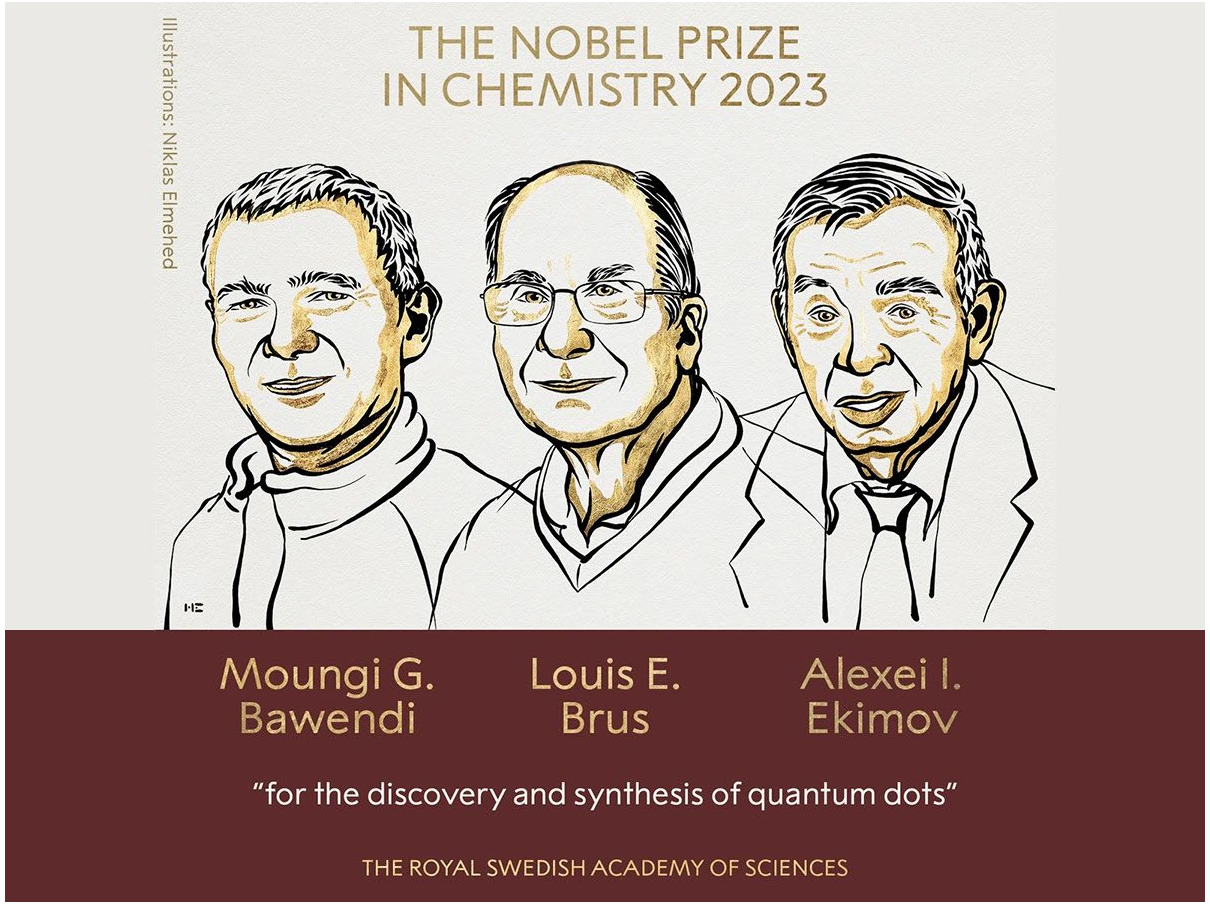
Semiconductor quantum dots

Definition: a QD is a system which confines the motion of charge carriers in all directions and in a region of space that is small enough to make quantization effects apparent

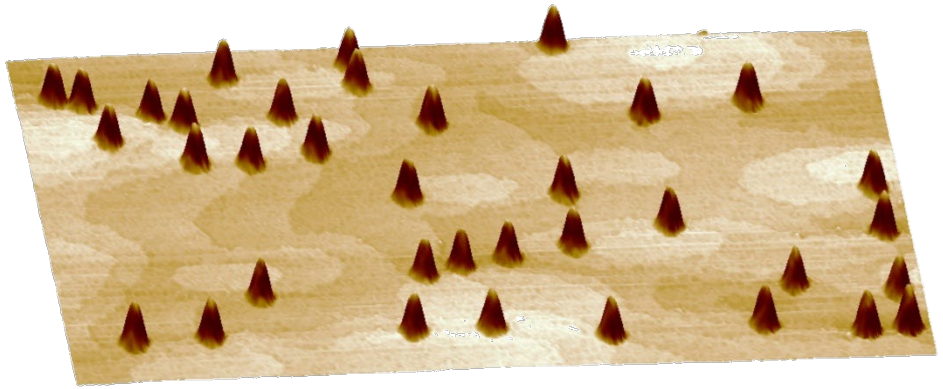
Example: CdSe nanocrystals (or colloidal QDs) in solution. Different size → different color



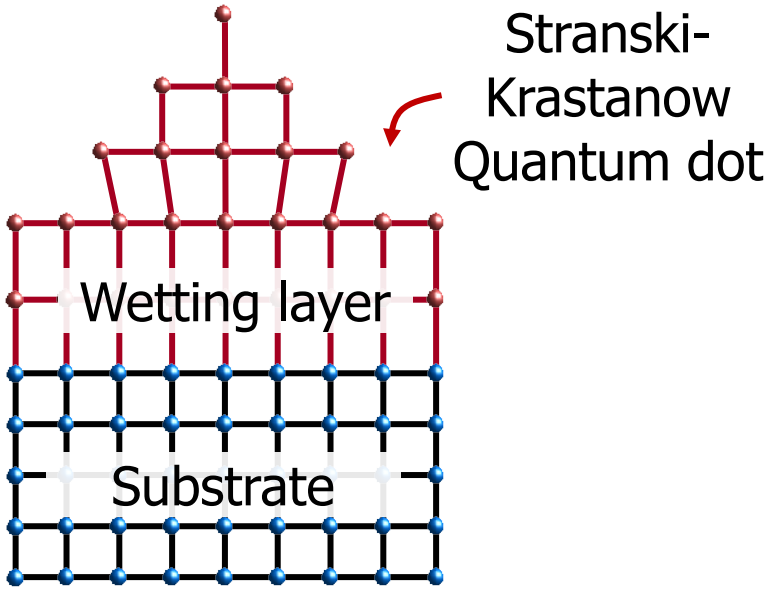


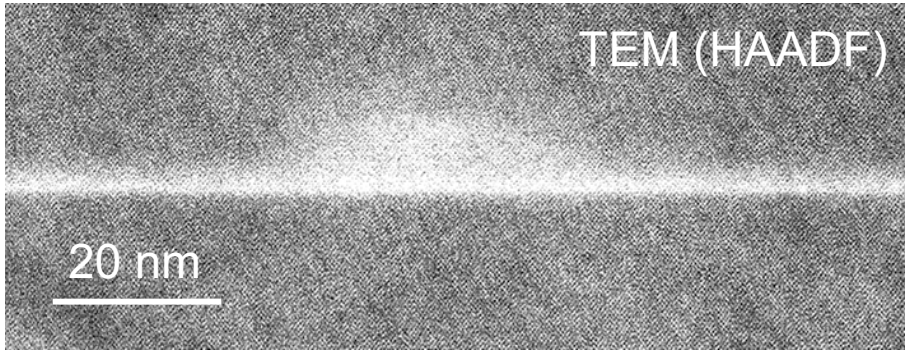


Epitaxial semiconductor Quantum Dots



AFM of SK-InGaAs/GaAs QDs
scale 1400x700x12 nm^3





F. Ding *et al.* APL 90, 173104 (2007)

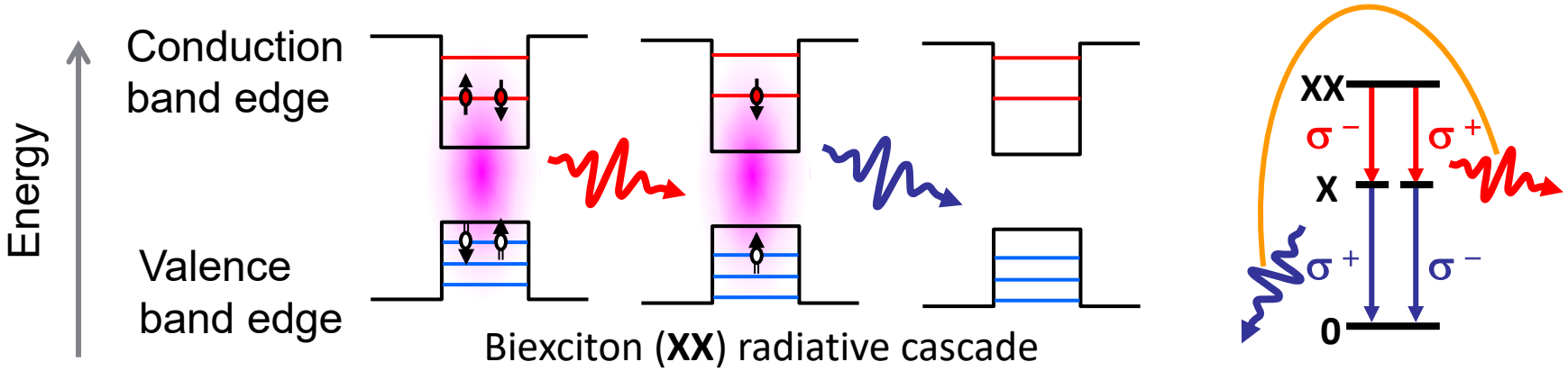
- 3D confinement → „artificial atom“ → Quantum emitter
- Easy to integrate in optoelectronic devices
- Short radiative lifetimes → GHz photon generation rates possible

Reviews: I. Aharonovich, D. Englund, M Toth, Nat. Photon. 10, 631 (2016)

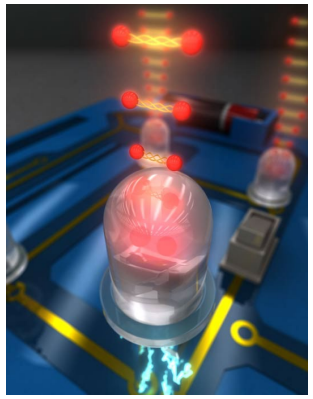
P. Senellart, G. Solomon and A. White, Nat. Nanotechnol. 12, 1026 (2017)

T Heindel, JH Kim, N Gregersen, A Rastelli, S Reitzenstein, Advances in Optics and Photonics 15, 613-738 (2023)

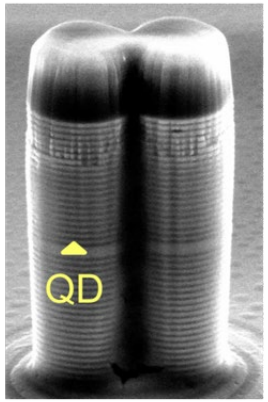
Entangled photon pairs from quantum dots



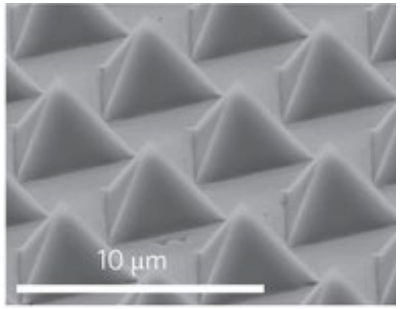
Biexciton (**XX**) radiative cascade



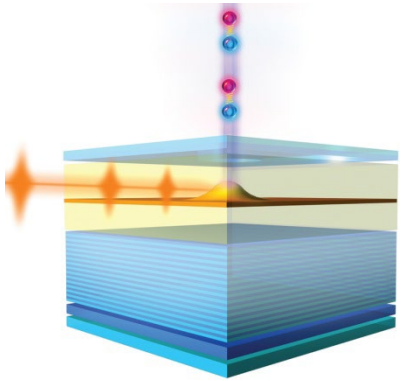
Nature **465**, 594 (2010)
(Shields group)



Nature **466**, 217 (2010)
(Senellart Group)



Nature Photon. **4**, 302 (2010)
(Pelucchi Group)

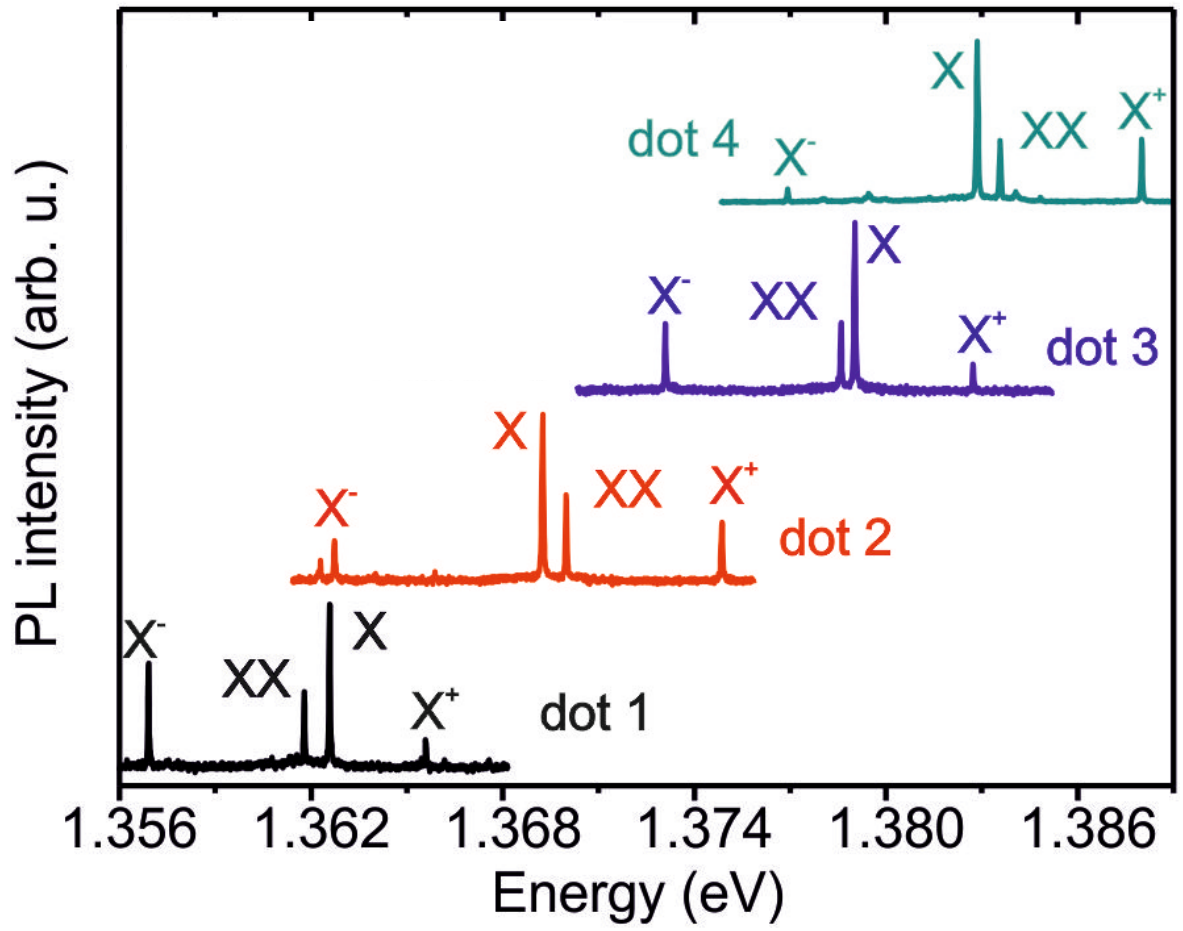


Nature Phot. **8**, 224 (2014)
(Michler Group)

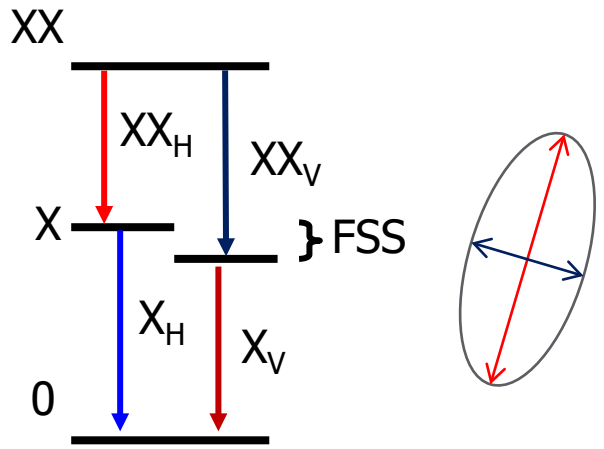
QDs **could** become „**the perfect source of entangled photons**“
Nature Photon. **8**, 174 (2014), C.-Y. Lu and J.-W. Pan

Problem: time-averaged fidelity to Bell state mostly limited to ~0.8

Problems of conventional epitaxial QDs: Spread in QD emission properties



- QD potential varies from QD to QD

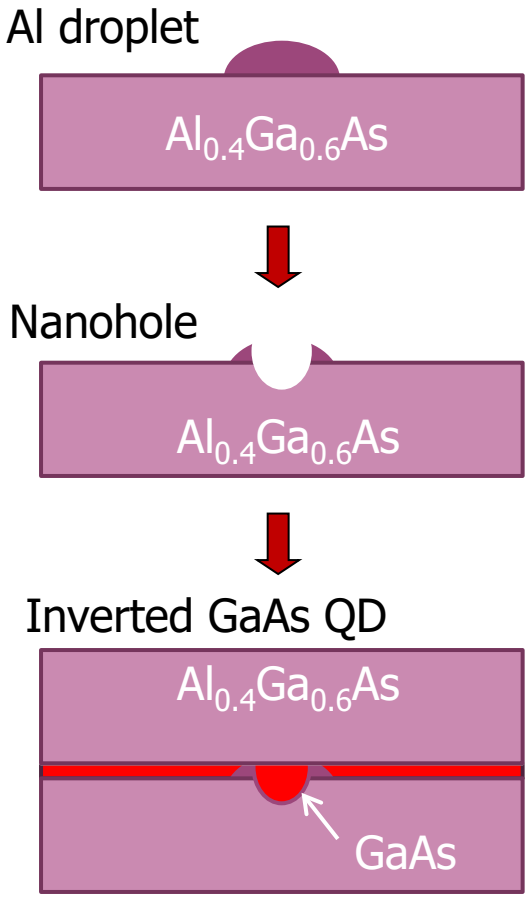


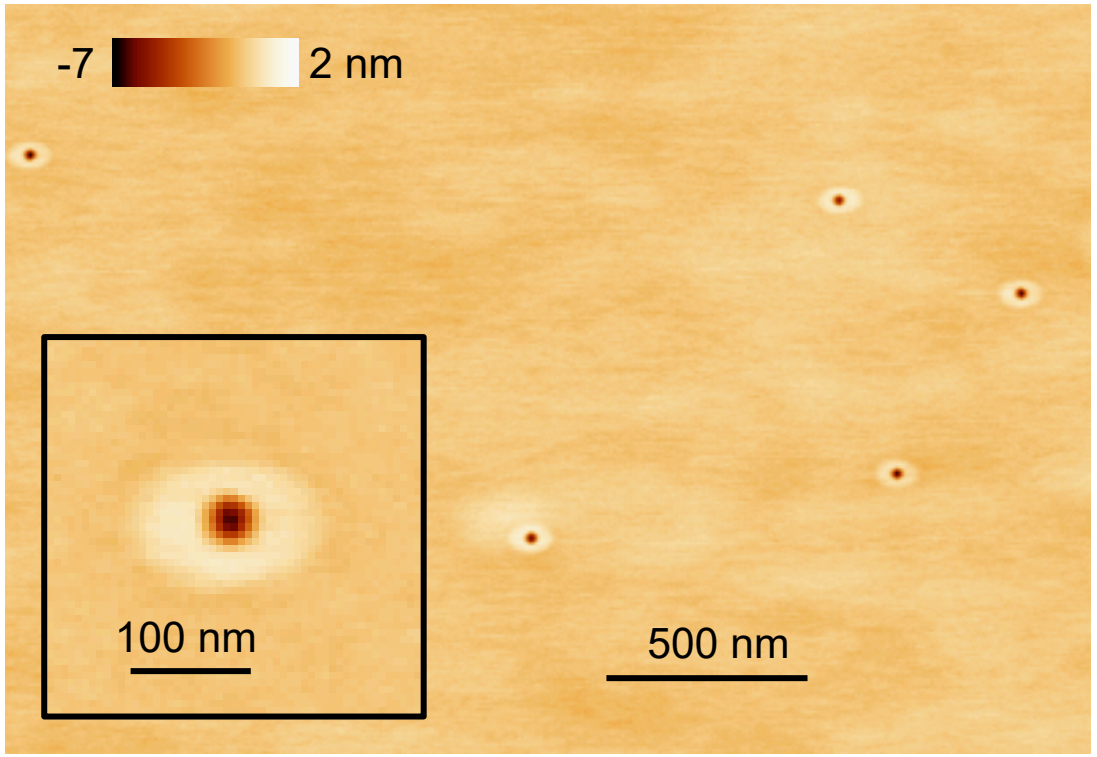
- FSS stemming from in-plane anisotropies hinders using most QDs as sources of entangled photon pairs

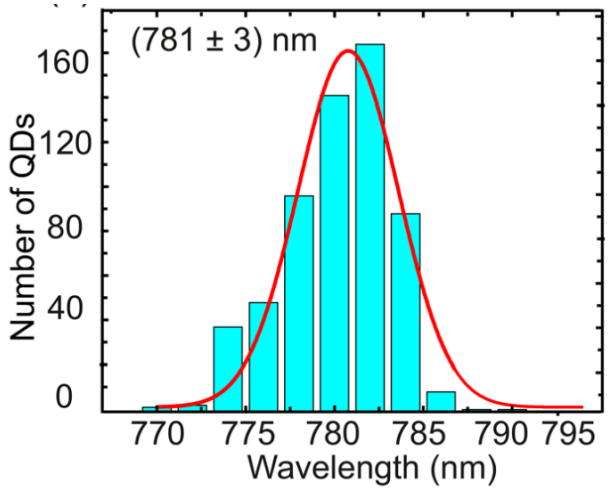
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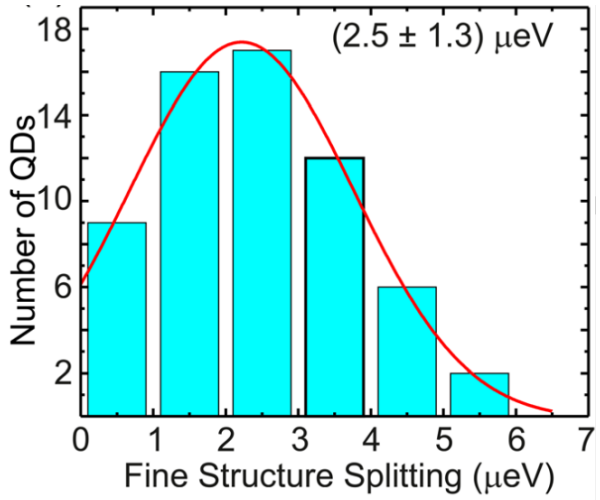
R. Trotta, E. Zallo, E. Magerl, O. G. Schmidt, AR, Phys. Rev. B (2013) and refs. therein

Material system: GaAs QDs in AlGaAs matrix by local droplet etching







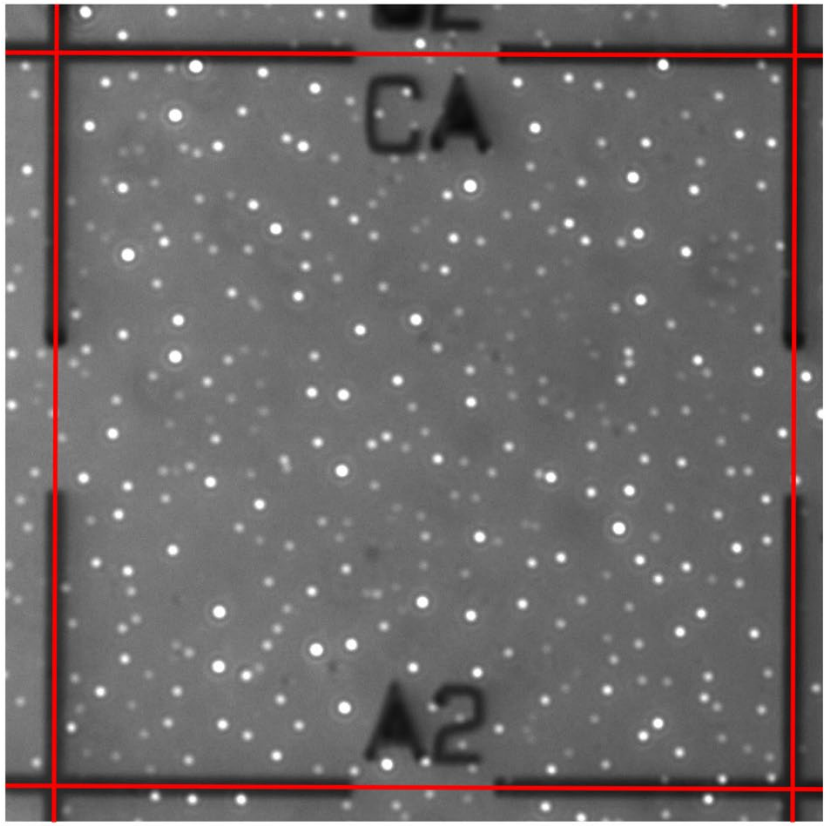


- Improved ensemble homogeneity and symmetry over InGaAs QDs → easier to find entanglement-ready QDs

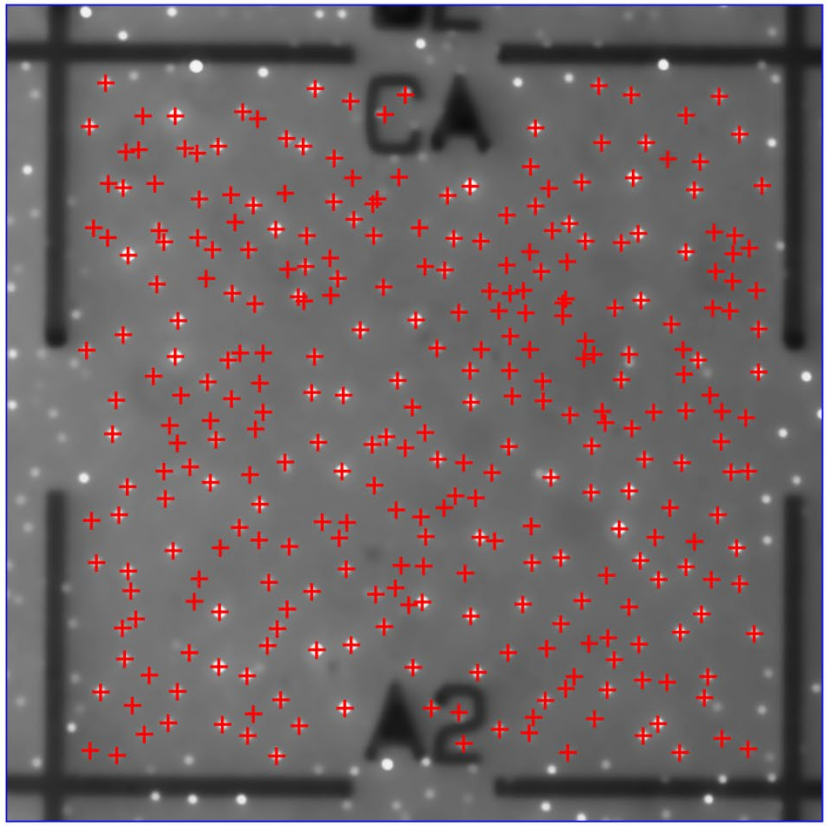
A. Rastelli et al. Phys. Rev. Lett. 92, 166104 (2004)
Y. Huo, A. Rastelli, O. G. Schmidt, APL 102, 152105 (2013)
Reviews: M. Gurioli, Z Wang, A Rastelli, T Kuroda, S Sanguinetti *Nature Mater.* ***18,*** *799* (2019),
S. F. Covre da Silva et al. Appl. Phys. Lett. 119, 120502 (2021)

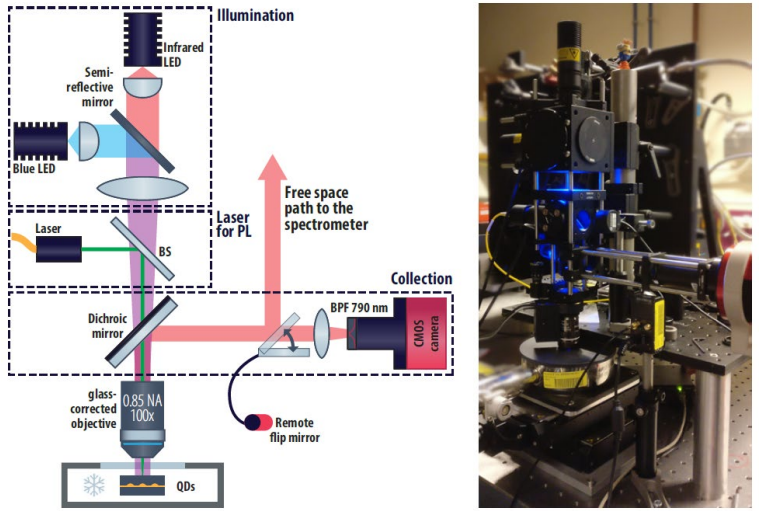
QD fluorescence imaging for deterministic fabrication

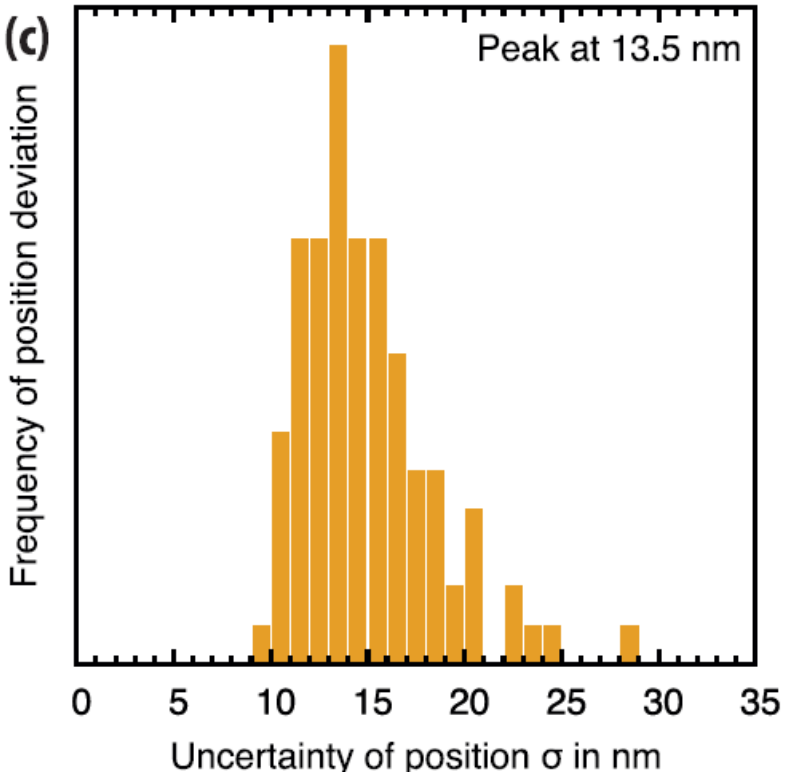
Fit and linear regression detection



Detected peaks







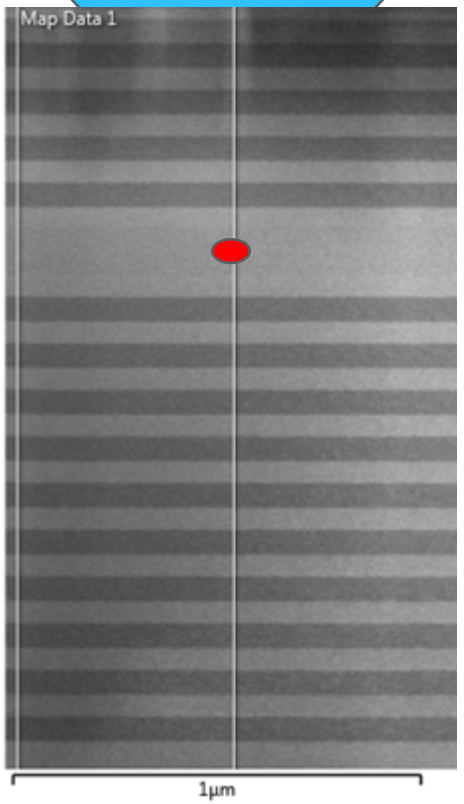
QD density sufficiently low to address single QDs and locate them with ~10 nm accuracy via far-field optics

M. Rota, T. Krieger et al. arXiv:2212.12506

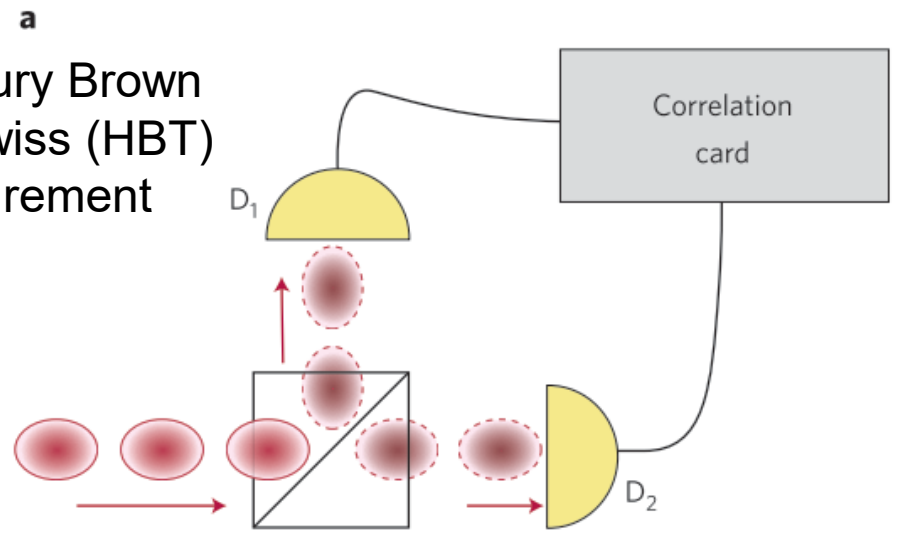
Similar to J. Liu, M. Davanco, L. Sapienza et al. Rev. Sci. Instruments **88**, 023116 (2017)

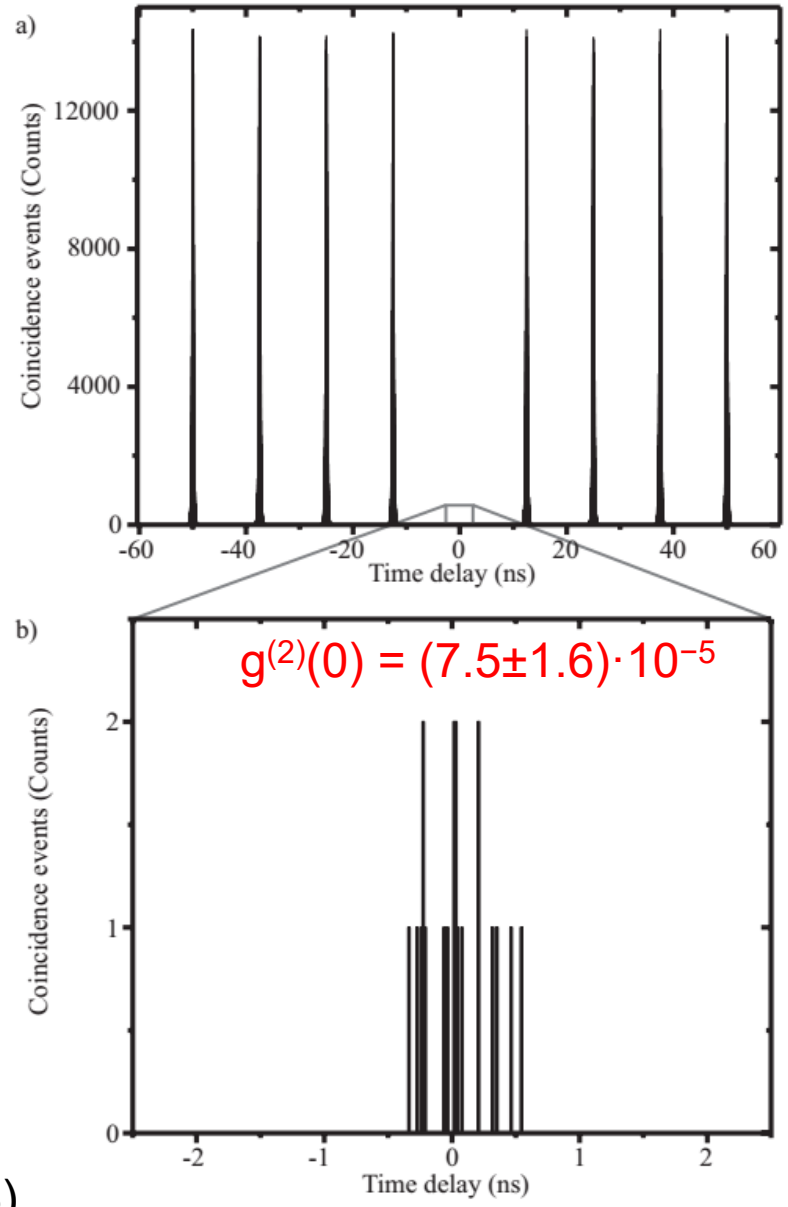
BACKGROUND-FREE SINGLE PHOTONS USING GaAs QDs EMBEDDED IN A PLANAR CAVITY

Solid-immersion lens



Hambury Brown and Twiss (HBT) measurement





At least as good as real atoms!

For single trapped ions:

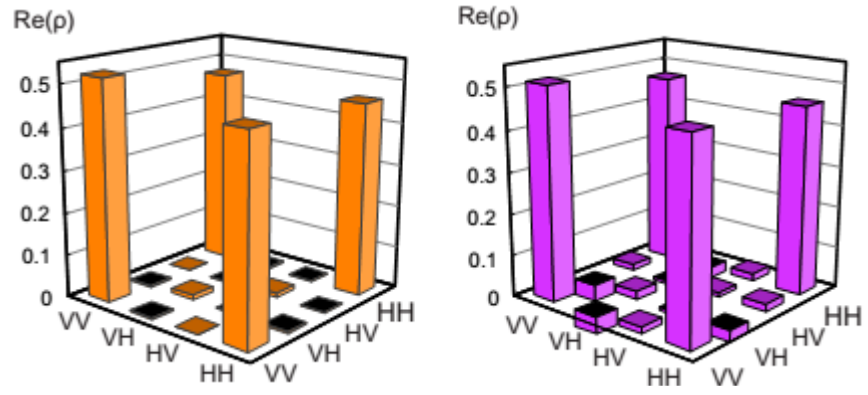
$g^{(2)}(0) = (8.1 \pm 2.3) \cdot 10^{-5}$

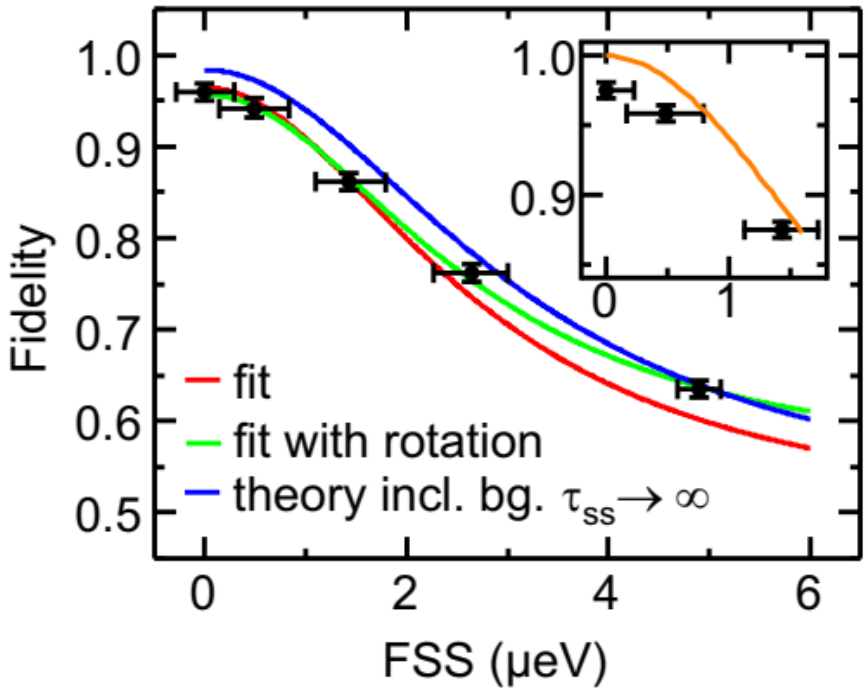
C. Crocker et al. Opt. Express **27,** 28143 (2019)

L. Schweickert, K.D. Jöns, K. Zeuner, S.F. Covre da Silva, H. Huang, M. Reindl, R. Trotta, A. Rastelli, V. Zwiller, Appl. Phys. Lett. 112, 093106 (2018)

NEARLY MAXIMALLY ENTANGLED PHOTONS FROM GaAs QDS

Reconstructed density matrix for 2 independent QDs with FSS<0.2 μeV (lifetime-limited homogeneous linewidth 2.3 μeV)







- Fidelity to ψ up to 97.8(0.5)%

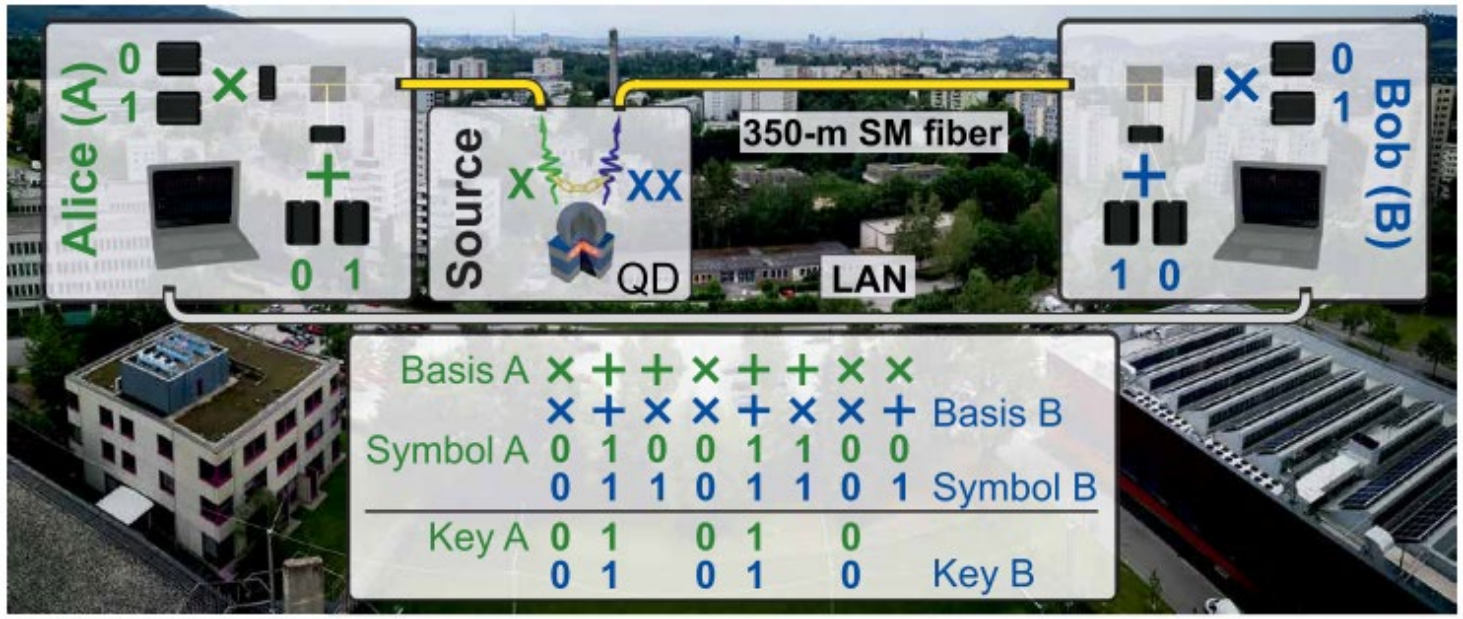
Highest reported so far for QD sources with no temporal nor spectral filtering. Reasons:

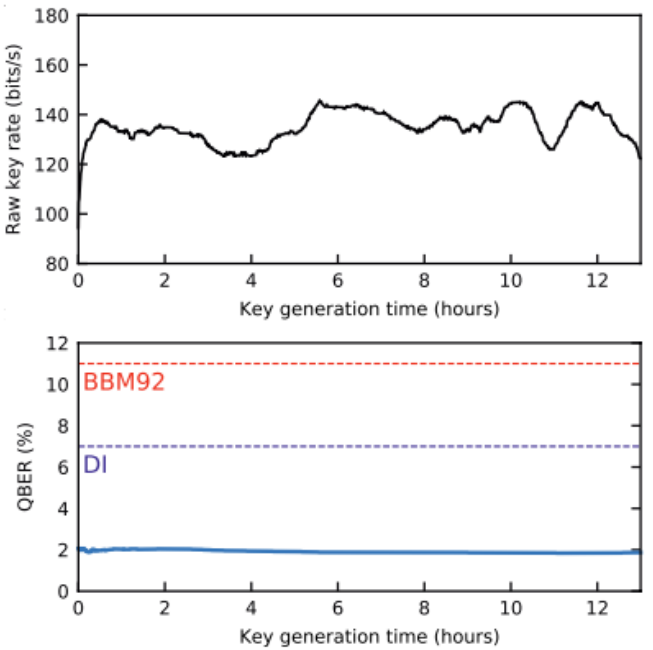
- ☐ Short X lifetime (250 ps)
- ☐ Full control of FSS via multiaxial strain
- ☐ Reduced spin dephasing

- Residual imperfections?
  - ☐ TPE: T. Seidelmann et al, Phys. Rev. Lett. 129, 193604 (2022); F. Basso Basset et al. Phys. Rev. Lett. 131 (16), 166901 (2023)
  - ☐ Temperature: B. U. Lehner et al., Nano Lett. 23, 1409 (2023)
  - ☐ Spin noise: C. Schimpf et al, Physical Review B 108 (8), L081405 (2023)

D. Huber, et al. Phys. Rev. Lett. 121, 033902 (2018)

Entanglement-based QKD @ JKU/LIT







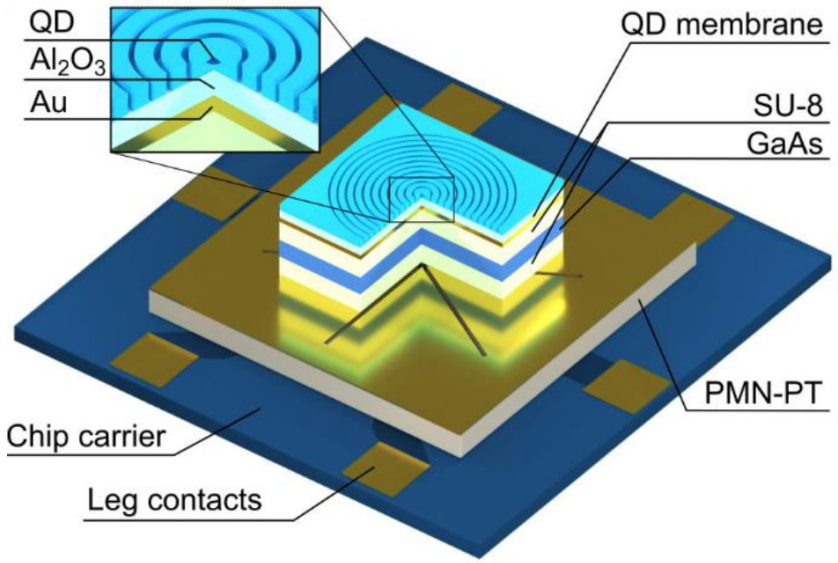
C. Bennett, G. Brassard, N. Mermin, Phys. Rev. Lett. **68**, 557-559 (1992)

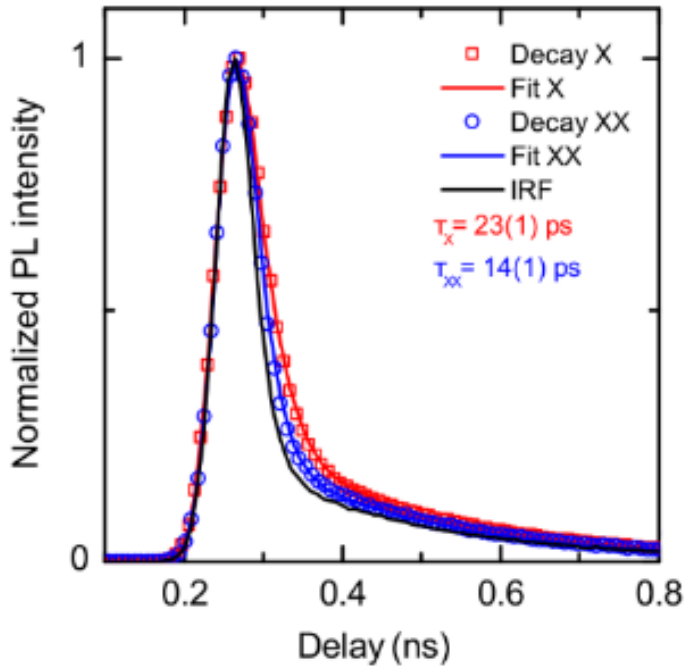
C. Schimpf et al., Sci. Adv. **7**, aebe8905 (2021)

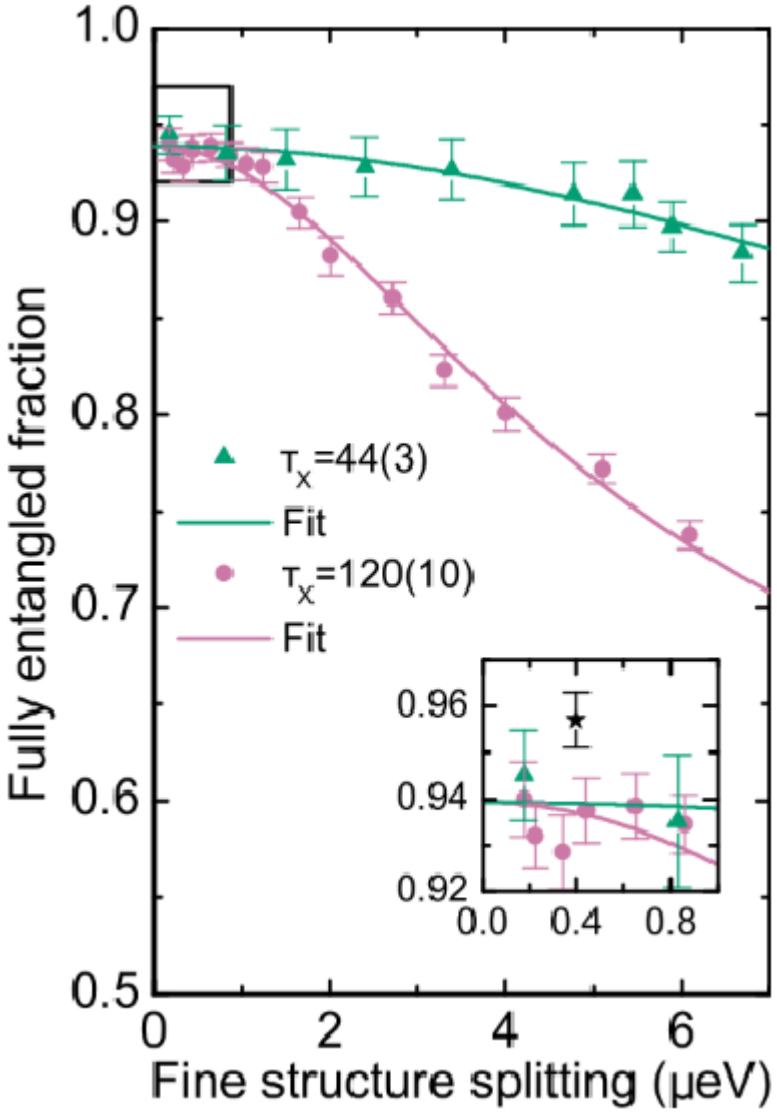
Average raw keyrate at 80 MHz pump rate:	**135 bits/s**
Average QBER:	**1.91%**
Key rate after error correction and privacy amplification:	**86 bits/s**

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BOOSTING BRIGHTNESS AND RADIATIVE RATES THROUGH STRAIN-TUNABLE CIRCULAR BRAGG GRATINGS RESONATORS







- Light extraction efficiency up to 75%
- Purcell enhanced emission up to 10 →
  - Radiative decay rate of >20 GHz
  - Increased tolerance to FSS
  - Increased tolerance to noise sources

J. Liu et al. Nature Nanotech. 14, 586 (2019)

M. M Rota et al. arXiv:2212.12506

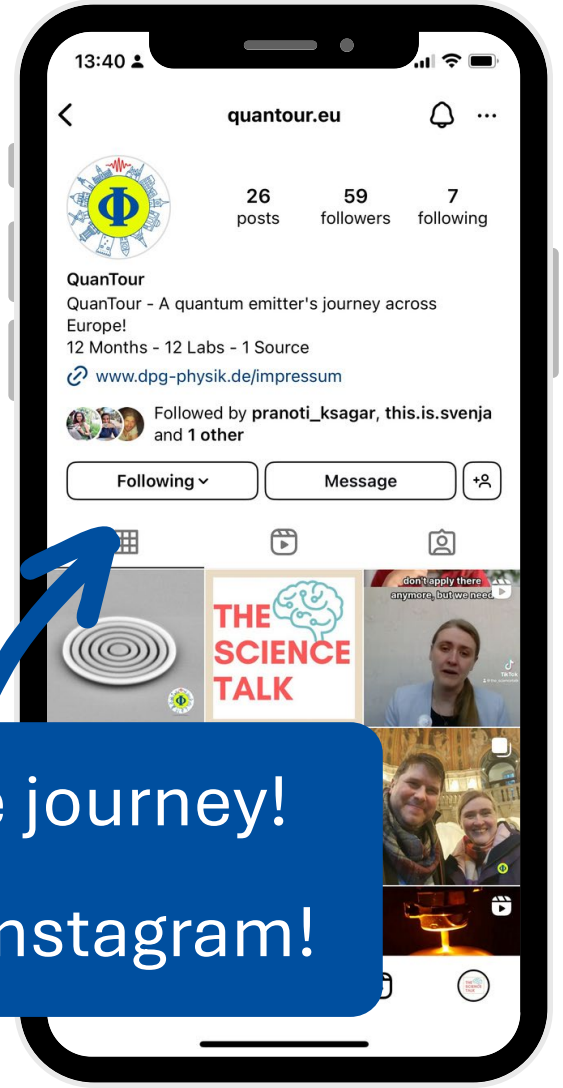
QuanTour - 12 months. 12 labs. 1 source.



A Quantum Emitter's journey through Europe

#QTorch #QuanTour #SUPERquantum

QUANTOUR.EU



Be part of the journey!

Follow us on Instagram!

Deutsche Physikalische Gesellschaft

INTERNATIONAL YEAR OF Quantum Science and Technology

Quantum2025

THE SCIENCE TALK

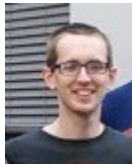
thesciencetalk.com/quantour/

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JKU
C. Schimpf, I. Brytavskyi, S.F. Covre da Silva, S. Manna, J. Martín-Sánchez (Univ. Oviedo), D. Huber, M. Reindl, Y. Huo (USTC) X. Yuan (Univ. Nanjn), H. Huang, G. Undeutsch, B. Lehner, J. Freund, T. M. Krieger, M. Aigner

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P. Walther
M. Vyvlecka

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S. Stroj

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R. Trotta, F. Basso Basset, M. Rota

SYSU Guangzhou
J. Liu

Univ. Stuttgart
S. Portalupi, J. Weber, P. Michler

Univ. Paderborn
K. Jöns

Univ. Basel
R. J. Warburton

Univ. Bayreuth
T. Seidelmann, M. Axt

KTH Stockholm
V. Zwiller, T. Lettner, L. Schweickert

Univ. Münster
D. Reiter

Univ. Innsbruck
G. Weihs, R. Keil

Univ. Cambridge
L. Zaporski, D. Gangloff, C. Le Galle, M. Atatüre

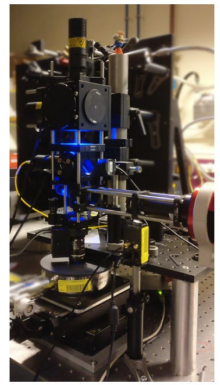
Univ. Sheffield, E. Chekhovich

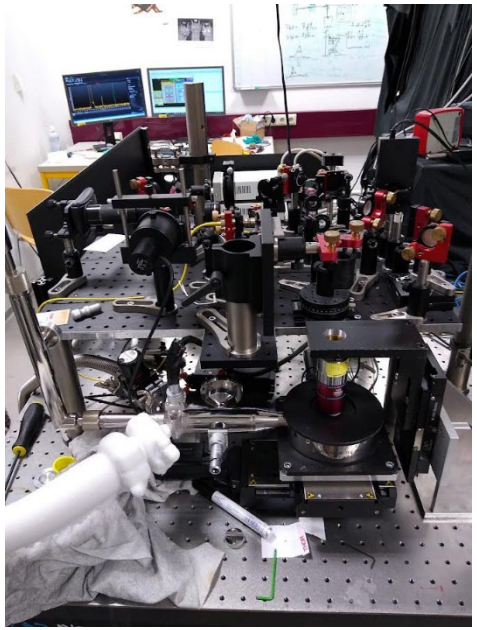
JOHANNES KEPLER UNIVERSITY LINZ
FWF
bmwfw Bundesministerium für Wissenschaft, Forschung und Wirtschaft
aws erp-fonds
Deutsche Forschungsgemeinschaft DFG
HORIZON 2020

Quantum research at JKU

Semiconductor heterostructure fabrication (epitaxial growth via MBE)

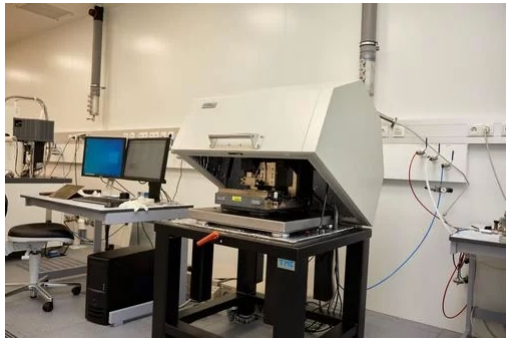


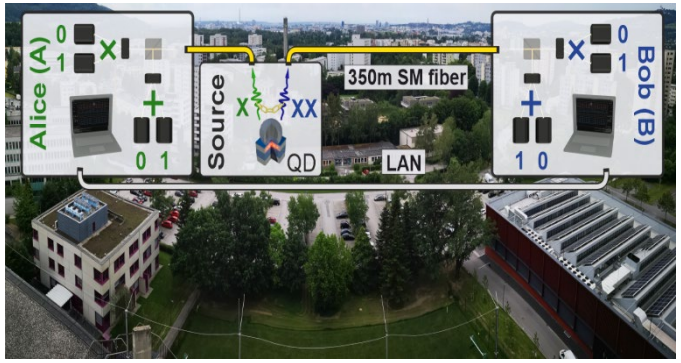




Quantum optics and entanglement-based quantum key distribution

Characterization (AFM, photoluminescence)





Modeling and device fabrication

