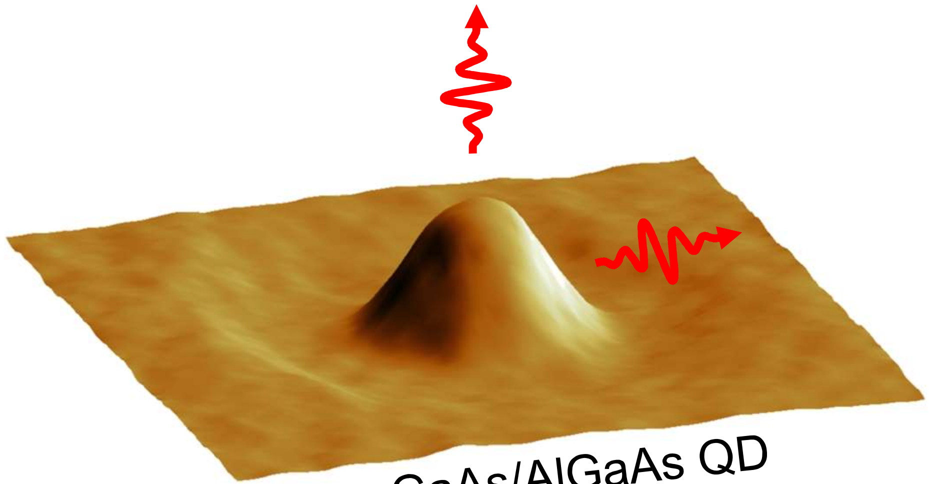
SEMICONDUCTOR-BASED SOURCES OF QUANTUM LIGHT

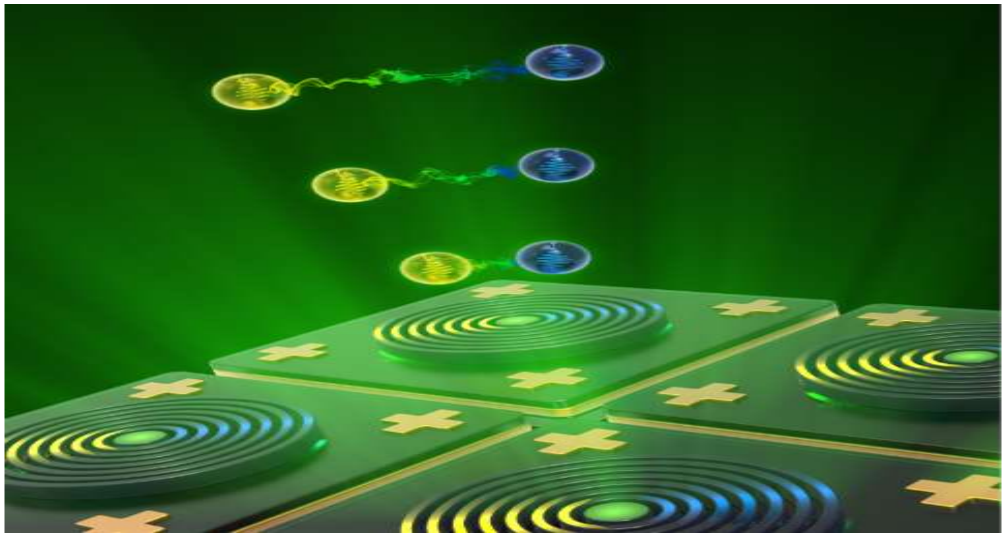


GaAs/AlGaAs QD

Armando Rastelli

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

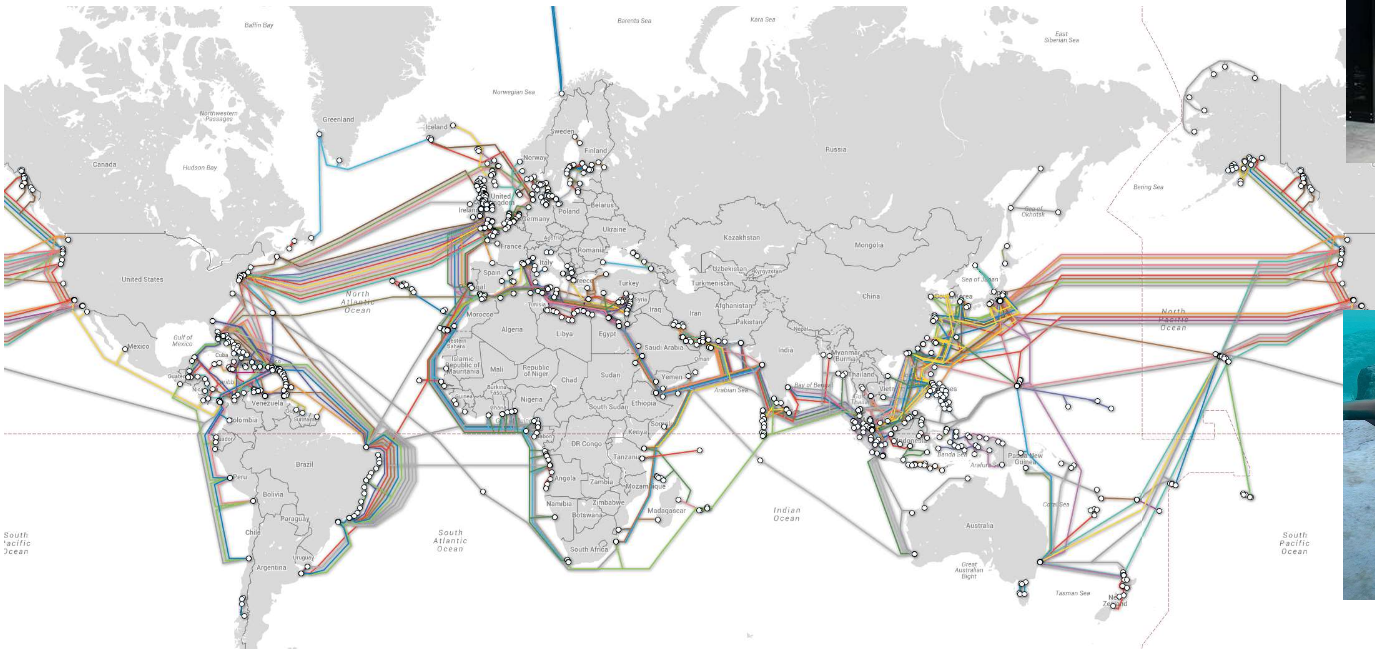
JOHANNES KEPLER UNIVERSITY LINZ

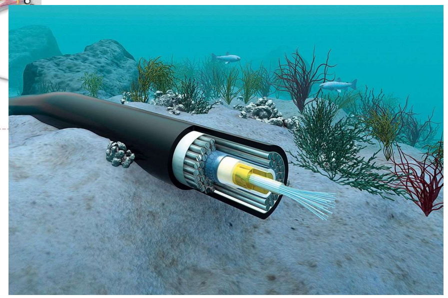


INTRODUCTION - PHOTONICS

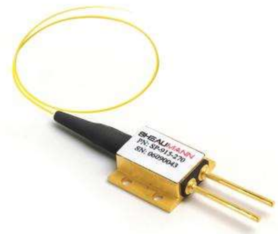
Example of application:

- Light as information carrier for short and long-distance communication: low attenuation in optical fibers, high speed and large bandwidth



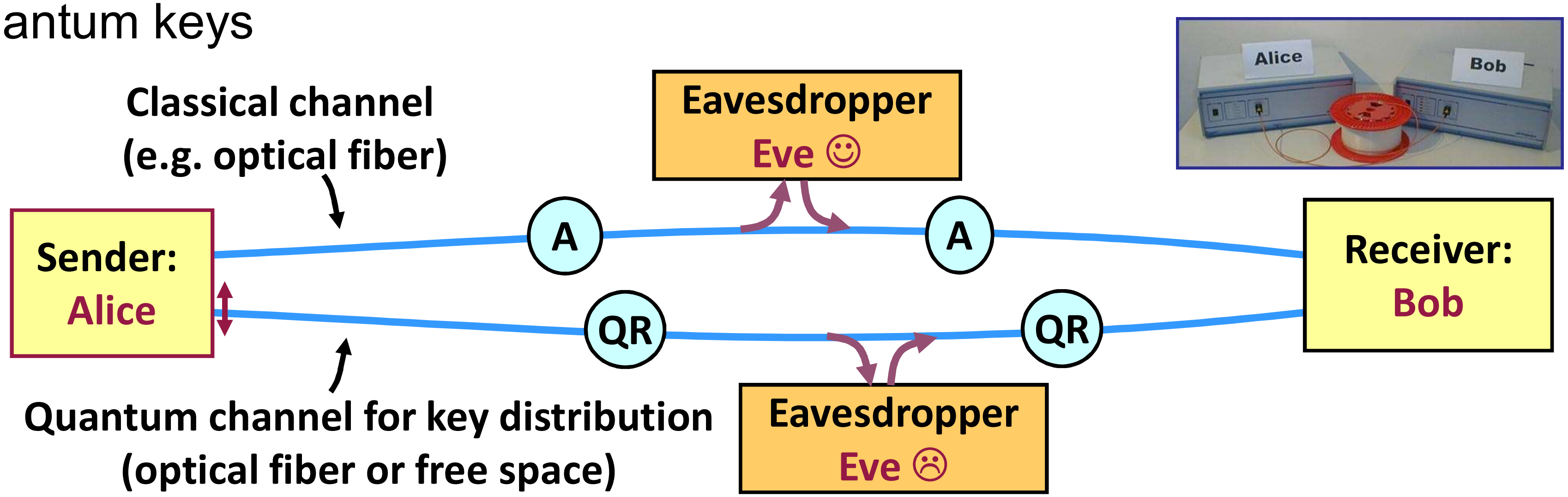


- Light sources: Semiconductor laser diodes



INTRODUCTION - QUANTUM PHOTONICS

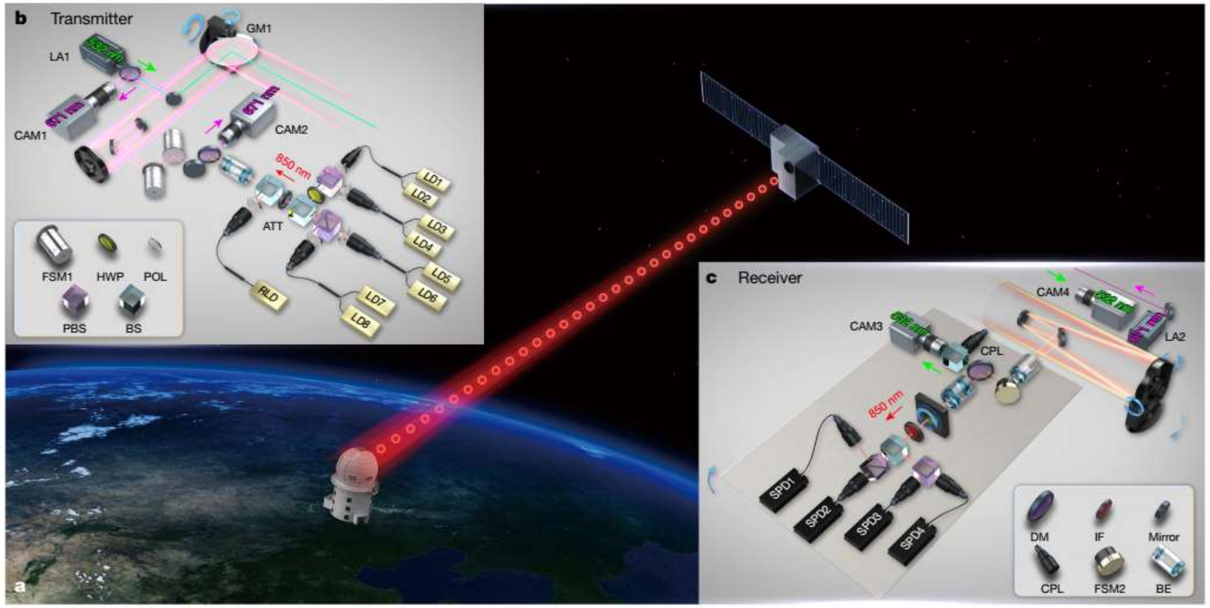
- Problem of classical communication: security (especially if/when quantum computers will become reality). Possible solution: data encryption via quantum keys



- Bits (**qubits**) of key encoded, e.g., in the polarization state of a photon
- Any attempt of Eve to measure the key will perturb the result (wavefunction collapse), which can be detected by Bob and Alice
- For long distance communication, photon losses become critical → Amplifiers (A) for classical channel. But qubits cannot be copied and amplified. Quantum repeaters (QR) needed, which - in turn - require **indistinguishable photons** and **entanglement resources**.

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

SATELLITE-BASED QUANTUM COMMUNICATION



Quantum key distribution (QKD) over 1200 km

Nature 549, 43 (2017)

Entanglement distribution over 1200 km
Science 356, 1140 (2017)

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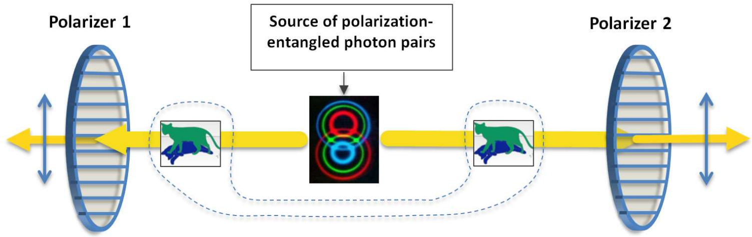
ENTANGLED PARTICLES

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

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

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

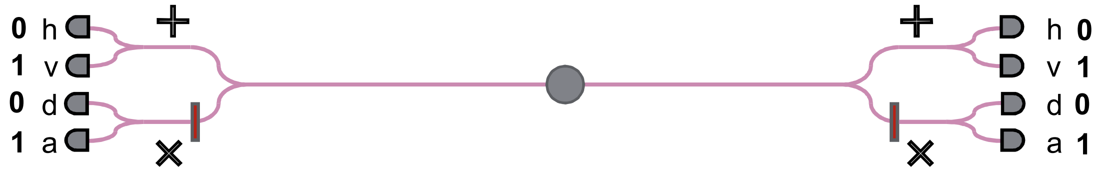
$$= \frac{1}{\sqrt{2}}(|R\rangle_1|L\rangle_2 + |L\rangle_1|R\rangle_2)$$



- Counterintuitive phenomenon, „Spooky action at a distance“ – Einstein
- Resource for quantum technologies (enables establishing correlations among remote quantum objects)

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

USE OF ENTANGLED PHOTON PAIRS FOR QKD – THE BB92 PROTOCOL

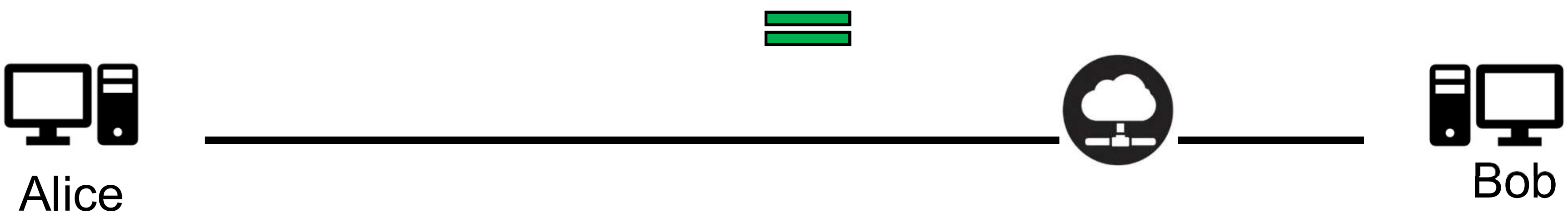


Value	1	0	1	1	0	0	0	1	0	1
Basis	+	x	x	+	x	+	x	x	x	+
	x	+	x	x	x	+	x	x	+	+
Key			1		0	0	0	1		1

Basis & Time ←

Time →

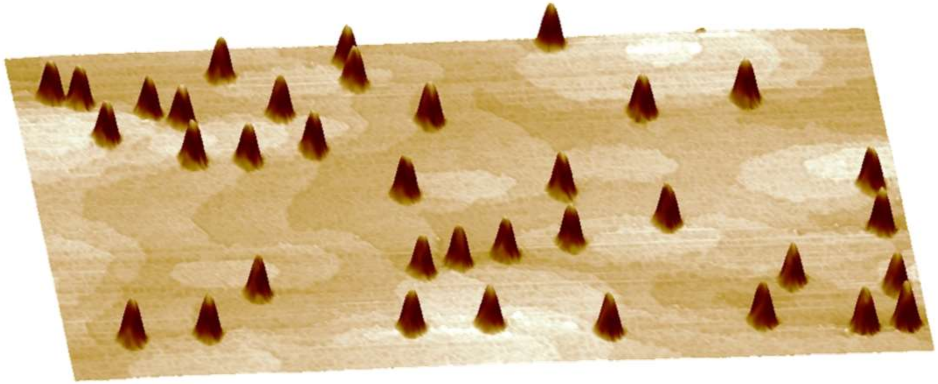
0	0	1	1	0	0	0	1	1	1
x	+	x	x	x	+	x	x	+	+
		1		0	0	0	1		1



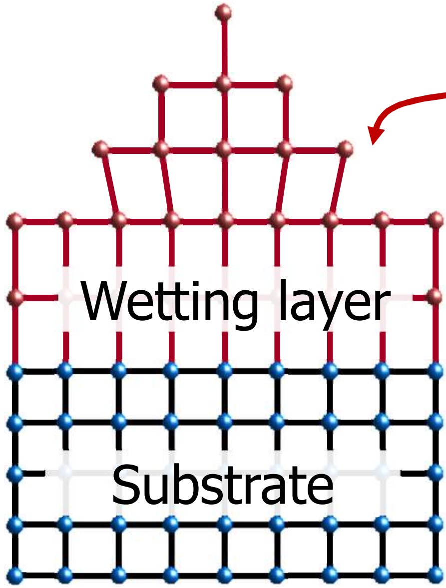
Bennet, C., Brassard, G., Mermin, N., Phys. Rev. Lett., 68 (1992)

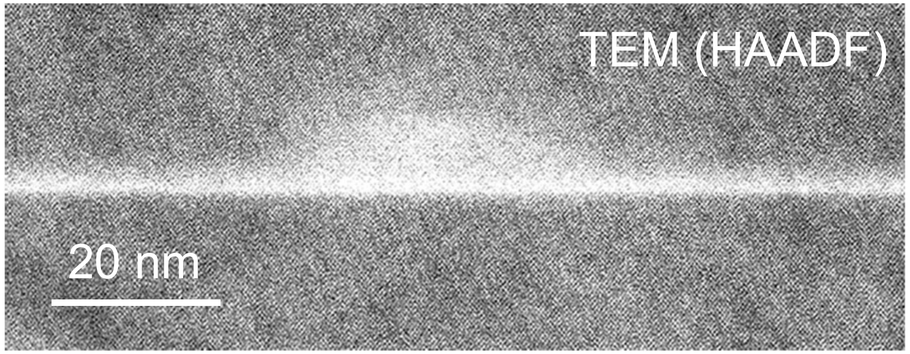
Need reliable and scalable sources of quantum light!

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“
- Easy to integrate in optoelectronic devices
- Practical sources of quantum light „on demand“?

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

P. Michler (ed.), Single Semiconductor Quantum Dots, Springer 2009, 2017

VOLUME 64, NUMBER 16 PHYSICAL REVIEW LETTERS 16 APRIL 1990

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Dislocation-Free Stranski-Krastanow Growth of Ge on Si(100)

D. J. Eaglesham and M. Cerullo

AT&T Bell Laboratories, 600 Mountain Avenue, Murray Hill, New Jersey 07974

(Received 27 December 1989)

We show that the islands formed in Stranski-Krastanow (SK) growth of Ge on Si(100) are initially *dislocation-free*. Island formation in true SK growth should be driven by strain relaxation in large, dislocated islands. Coherent SK growth is explained in terms of *elastic* deformation around the islands, which partially accommodates mismatch. The limiting critical thickness, h_c, of coherent SK islands is shown to be higher than that for 2D growth. We demonstrate growth of dislocation-free Ge islands on Si to a thickness of $\approx$ 500 Å, 50× higher than h_c for 2D Ge/Si epitaxy.

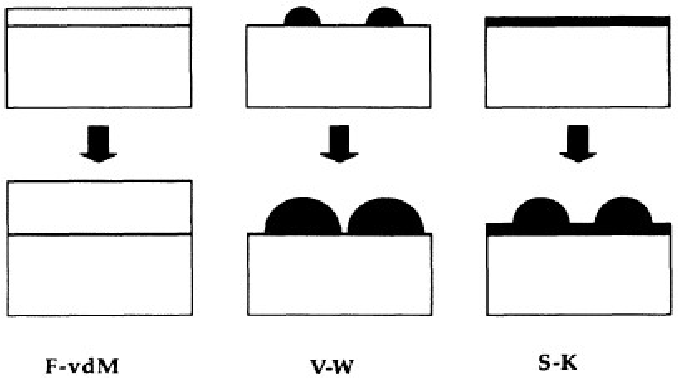


FIG. 1. Schematic diagram of the three possible growth modes: Frank–van der Merwe, Volmer-Weber, and Stranski-Krastinov. Where interface energy alone is sufficient to cause island formation, VW growth will occur; SK growth is uniquely confined to systems where the island strain energy is lowered by misfit dislocations underneath the islands.

500°C, 3 ML Ge

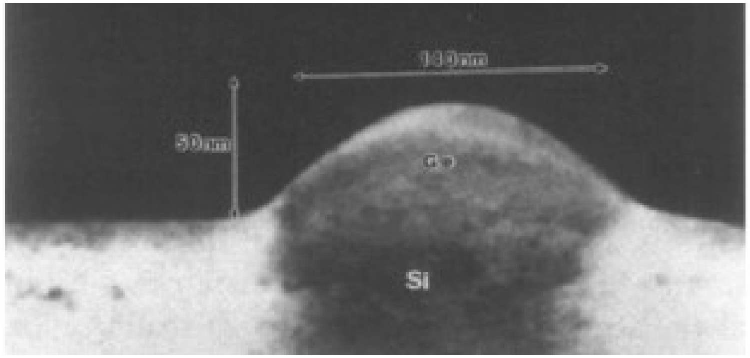
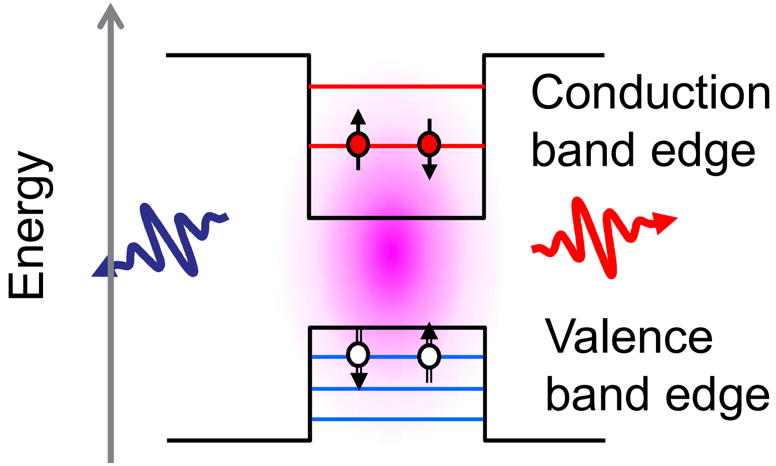
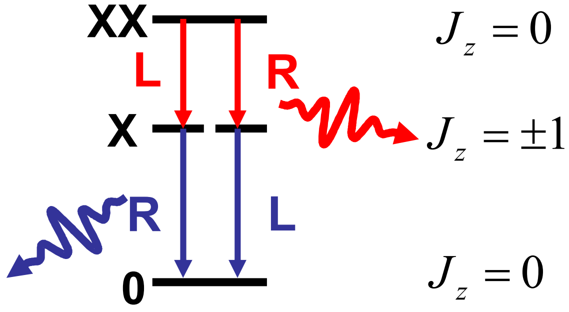


FIG. 4. Plan-view and cross-section TEM images of large coherent SK islands close to their maximum size prior to dislocation introduction. (a) Bright-field image near the {202} Bragg position showing characteristic "bend-contour" contrast due to dome-shaped deformation of the substrate around the island. (b) (400) dark-field image; note strong strain contrast around island.

QDs as sources of single and polarization entangled photons: typically used levels



Biexciton XX – Exciton X cascade



XX – X – 0 cascade
Two decay paths possible

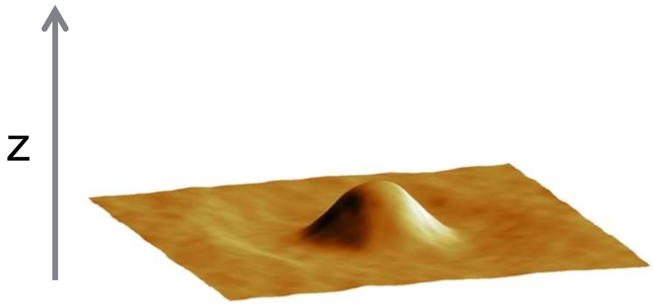
First left, then right polarized photon $\left|\psi^{(1)}\right\rangle = \left|L\right\rangle_{XX}\left|R\right\rangle_{X}$

viceversa $\left|\psi^{(2)}\right\rangle = \left|R\right\rangle_{XX}\left|L\right\rangle_{X}$

If paths are indistinguishable

$$\left|\psi\right\rangle = \frac{1}{\sqrt{2}}\left(\left|R\right\rangle_{XX}\left|L\right\rangle_{X} + \left|L\right\rangle_{XX}\left|R\right\rangle_{X}\right)$$

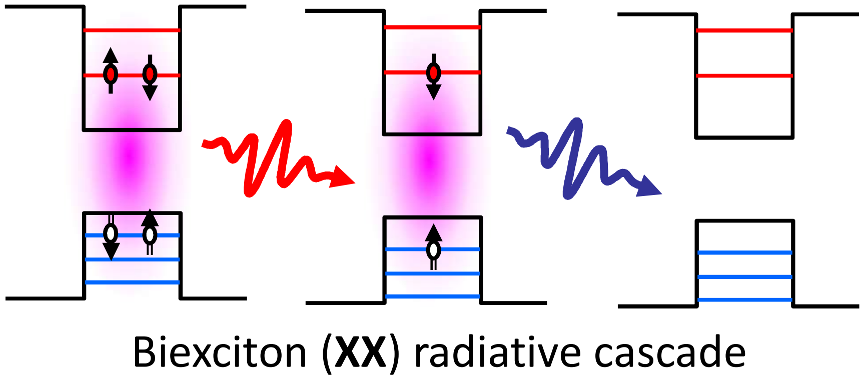
Entangled state!

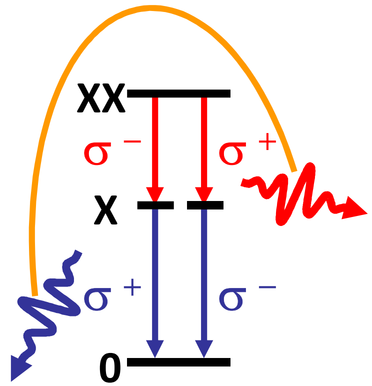


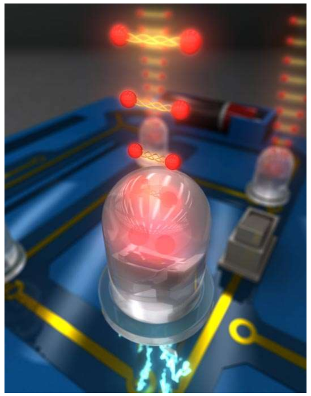
Flat QD: height/width~0.1-0.2

Reviews: D. Huber et al. Journal of Optics 20, 073002 (2018)
A. Orieux et al. Rep. Prog. Phys. 80, 076001 (2017)

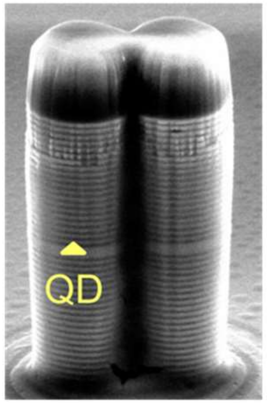
QDs as sources of polarization entangled photons



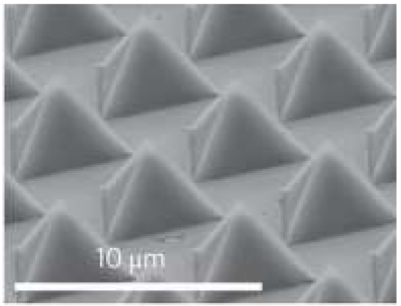




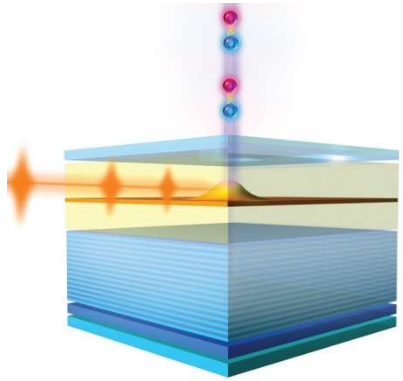
Nature **465**, 594 (2010)



Nature **466**, 217 (2010)



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



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

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

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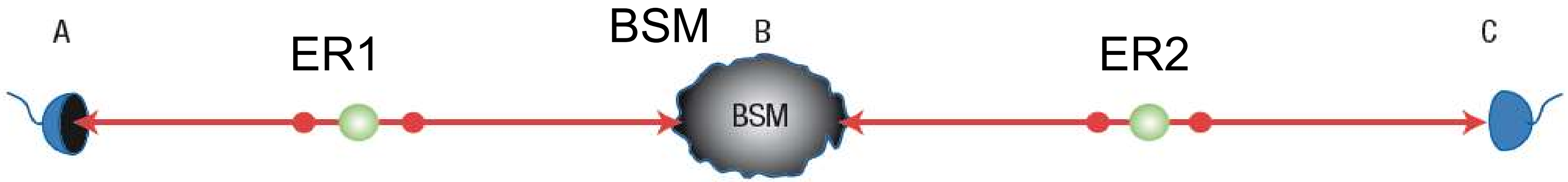
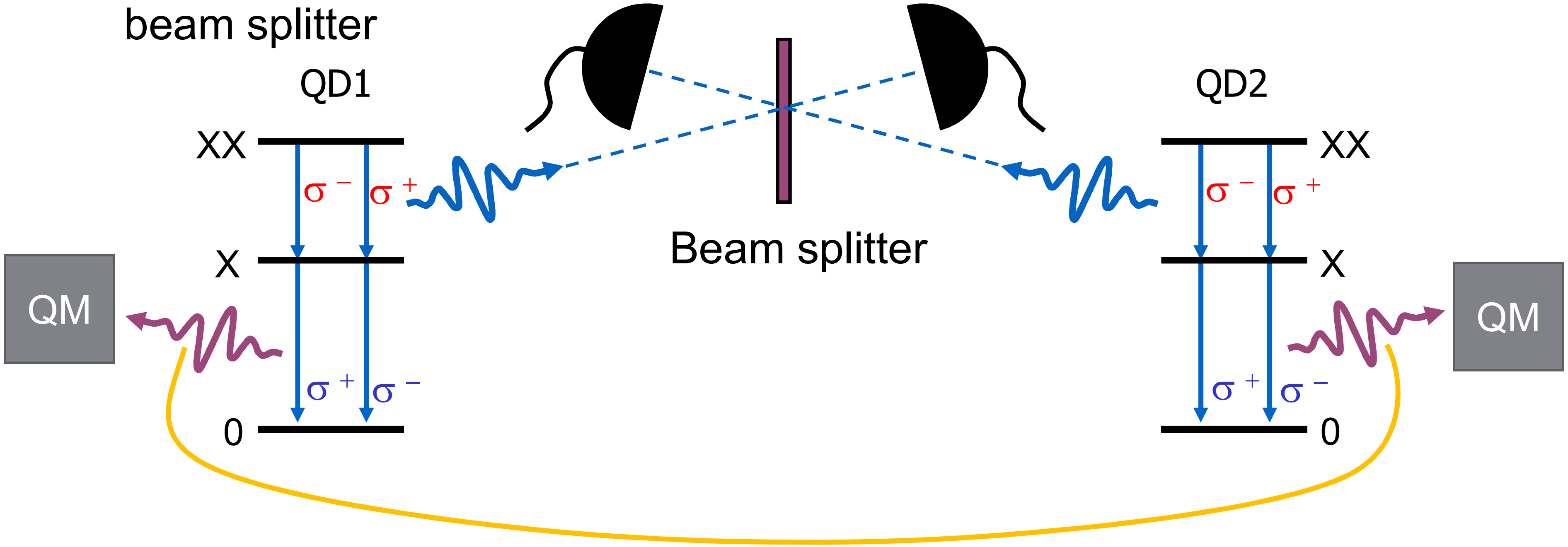
Problem: fidelity to maximally entangled state still limited to ~0.8

A quantum relay with QD photons?

N. Gisin, R. Thew, Nature Photon. 1, 165 (2007)



- Entanglement resource (ER): XX→X→0 cascade in QD
- BSM (partial): two-photon Hong-Ou-Mandel (HOM) interference at a beam splitter



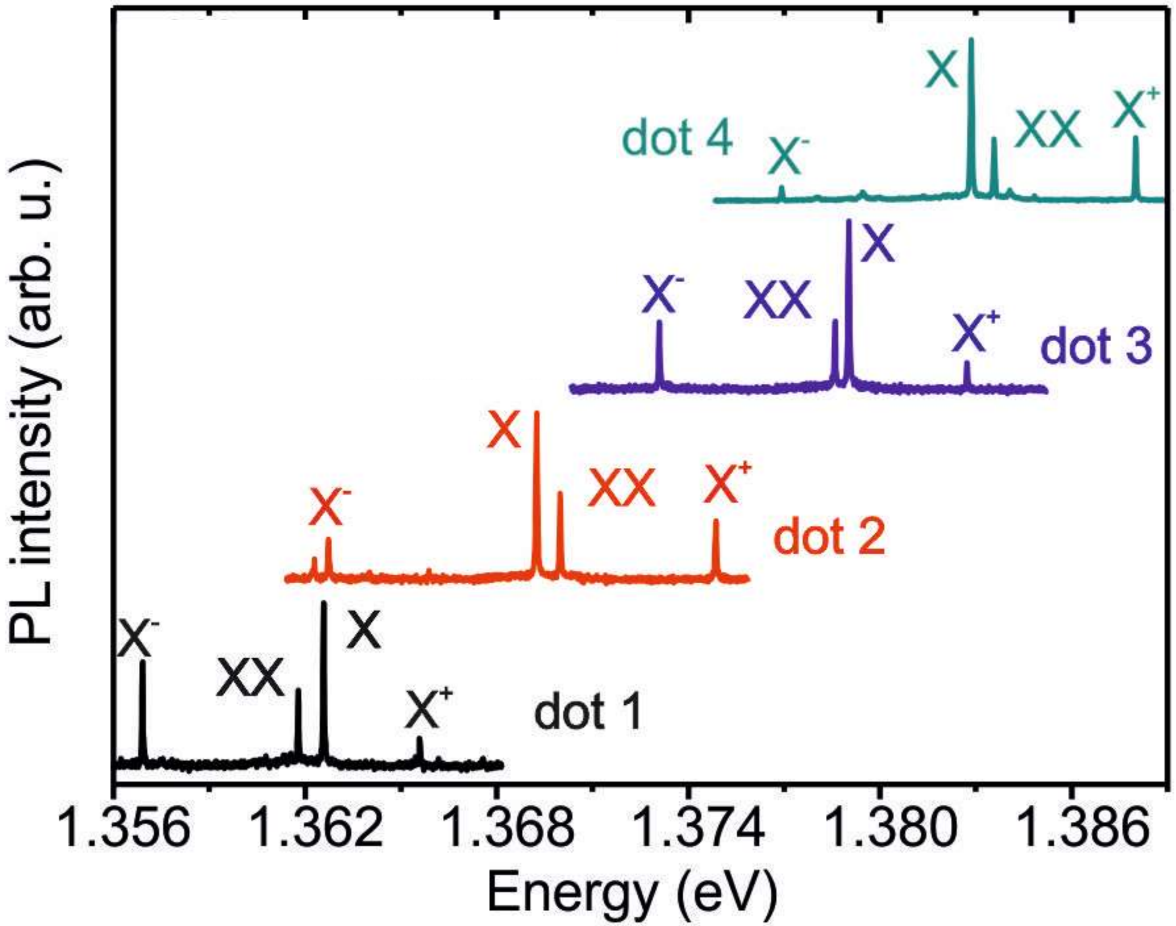
J.-W. Pan, *et al*., Phys. Rev. Lett. **80**, 3891 (1998)
R. Trotta et al. Phys. Rev. Lett. 114, 150502 (2015) and refs. therein

IDEAL PROPERTIES OF QD SOURCES

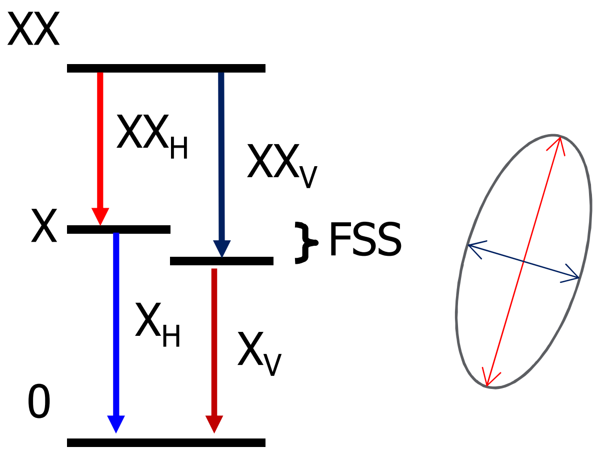
- **“Purity”**: not more than one photon (or photon pair) per excitation pulse
- **Short radiative decay times** to allow GHz operation
- **Entanglement:** generation of maximally entangled photon pairs
- **Brightness:** not (much) less than one photon (or photon pair) in desired optical mode per excitation pulse
- **Indistinguishability**: all photons emitted by the same source are identical to achieve perfect HOM interference (indispensable for photonic-based quantum computing and for long-distance quantum communication)
- **“Right” wavelength** depending on application
- **Scalability:** multiple sources emit mutually indistinguishable photons (requires ~Fourier-limited emission and matching of emission energies and decay times of relevant transitions)

See also: P. Senellart et al. *Nat. Nanotechnol*. **12,** 1026 (2017)
C.-Y. Lu & J.-W. Pan, *Nat. Photonics* **8**, 174 (2014)

PROBLEM: SPREAD IN QD EMISSION PROPERTIES



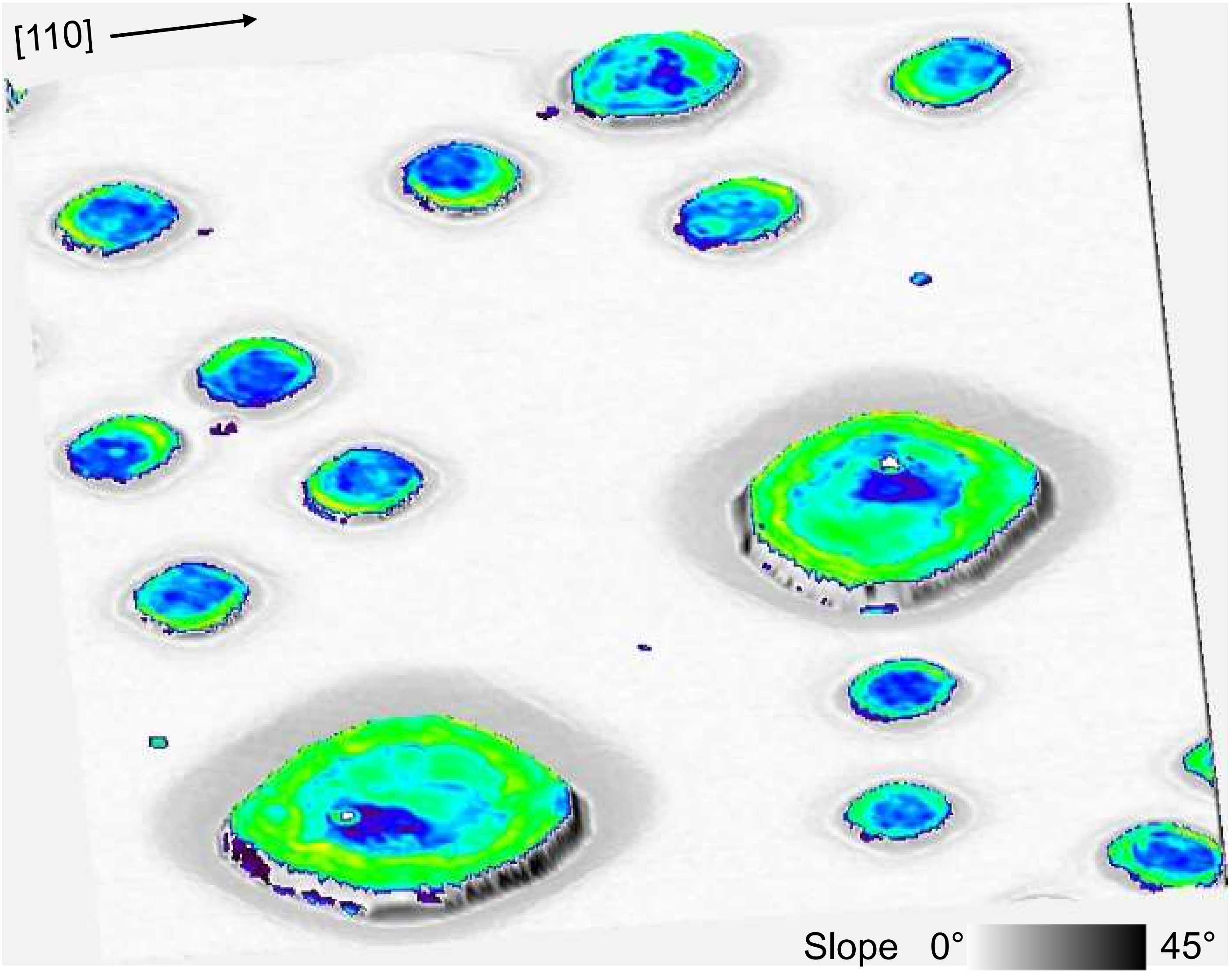
- QD potential varies from QD to QD



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

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

REASON – SPREAD IN STRUCTURAL PROPERTIES IN STRANSKI-KRASTANOW QDs



3D composition profiles of SiGe SK-dots obtained by AFM combined with selective etching.

Similar trends for InGaAs QDs

Horizontal slices spaced 3 nm in vertical direction

Local Ge fraction x

0.3 0.43

AFM Scale:
1670 x 2150 x 107 nm^3

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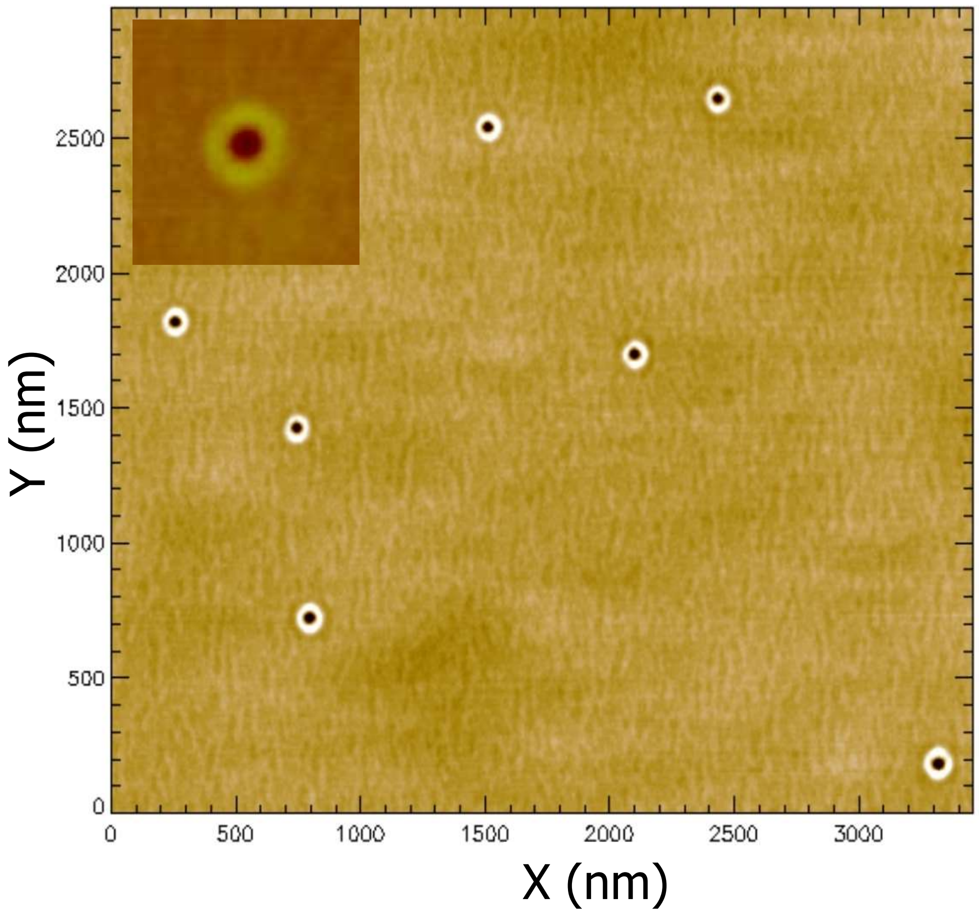
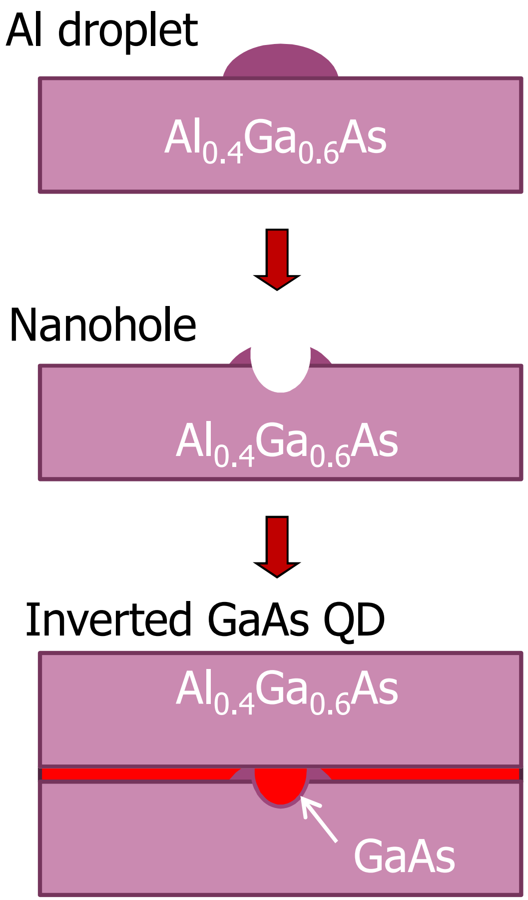
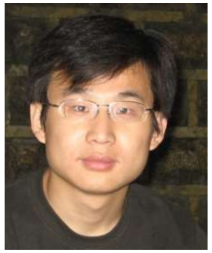
A. Rastelli, M. Stoffel *et al.* Nano Lett. 8, 1404 (2008)

ALTERNATIVE MATERIAL SYSTEM: GaAs QDs IN AlGaAs MATRIX





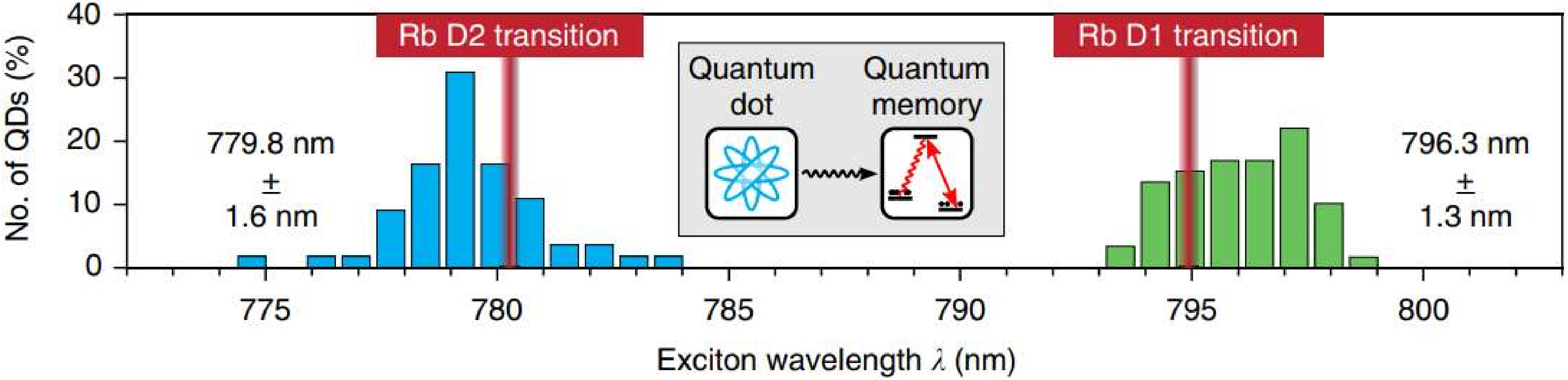


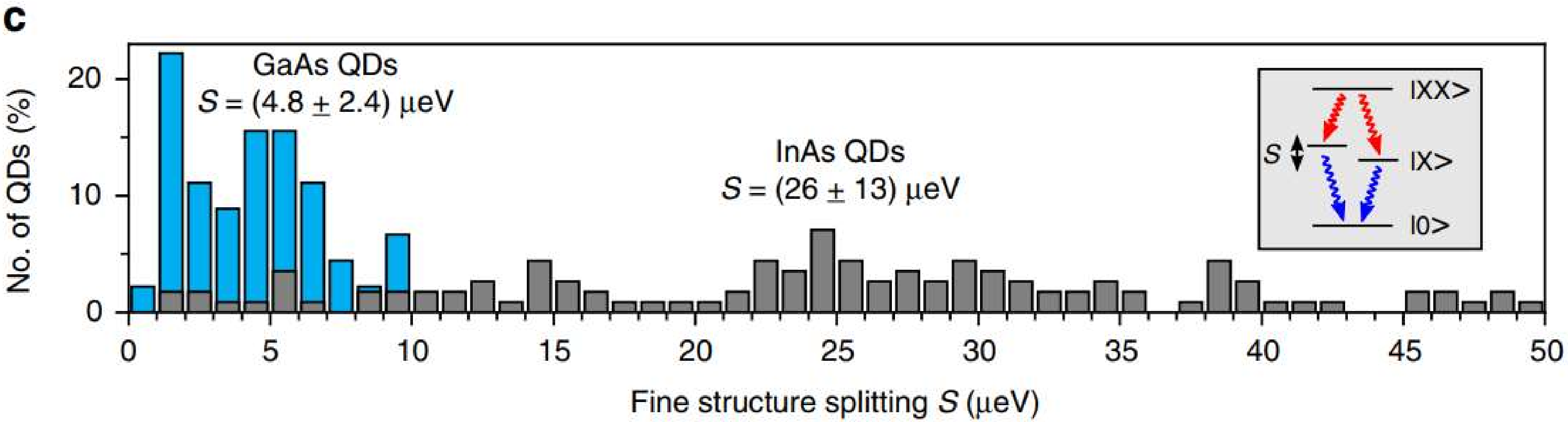
- Highly symmetric shape, limited intermixing with barrier, tunable size and wavelength, low density for single-QD devices

A. Rastelli *et al.* Phys. Rev. Lett. 92, 166104 (2004)

Y. Huo, A. Rastelli, O. G. Schmidt, APL 102, 152105 (2013)
Ch. Heyn et al. Appl. Phys. Lett. 94, 183113 (2009)

GaAs QDs in AlGaAs matrix by local droplet etching



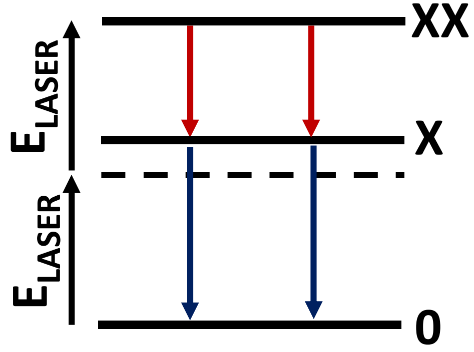


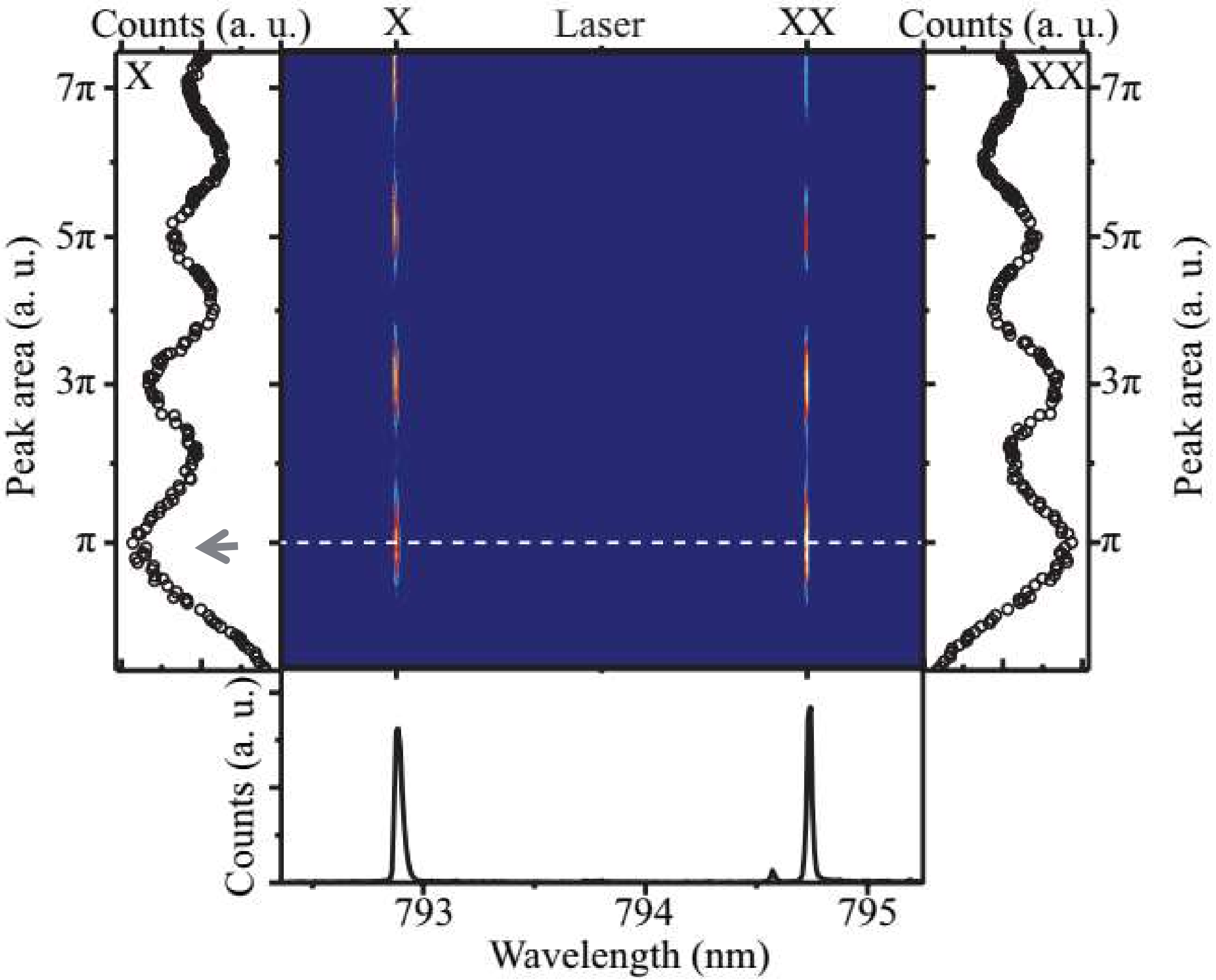
- Improved ensemble homogeneity and symmetry over InGaAs QDs

R. Keil et al. *Nature Comm.* **8**, 15501 (2017)
See also: Y. Huo, A. Rastelli, O. G. Schmidt, APL 102, 152105 (2013)
Review: M. Gurioli et al. *Nature Mater.* ***18,*** *799* (2019)

CREATION OF BIEXCITON IN GaAs QDs WITH TWO-PHOTON EXCITATION

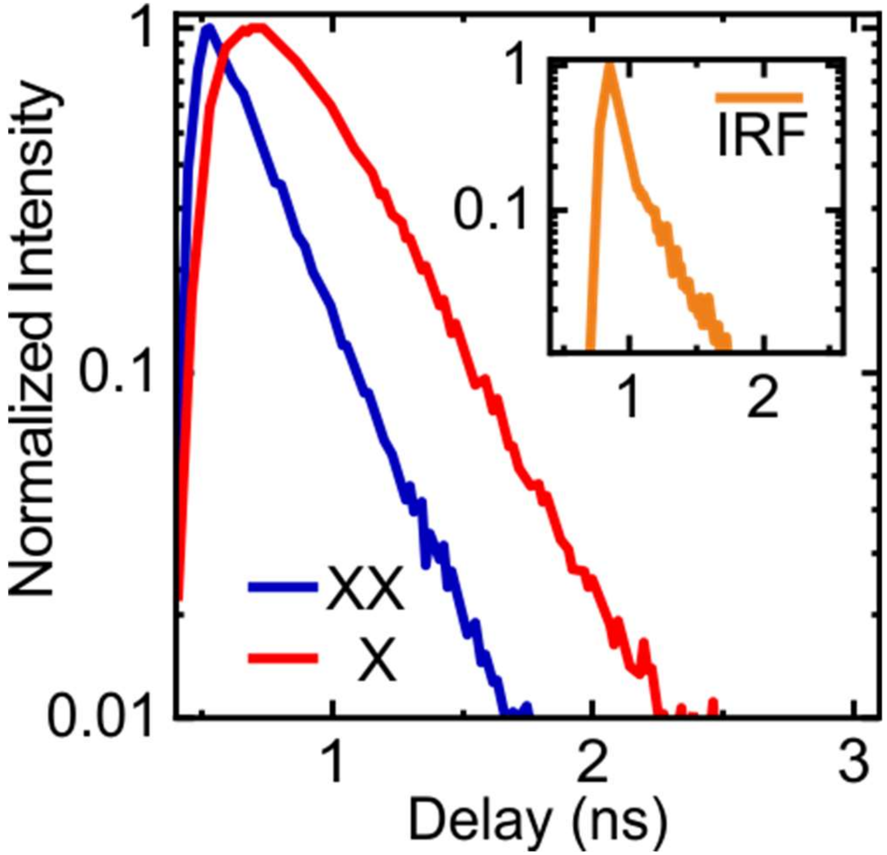
- ~Deterministic preparation of XX state via resonant two-photon excitation (fidelity ~90%)

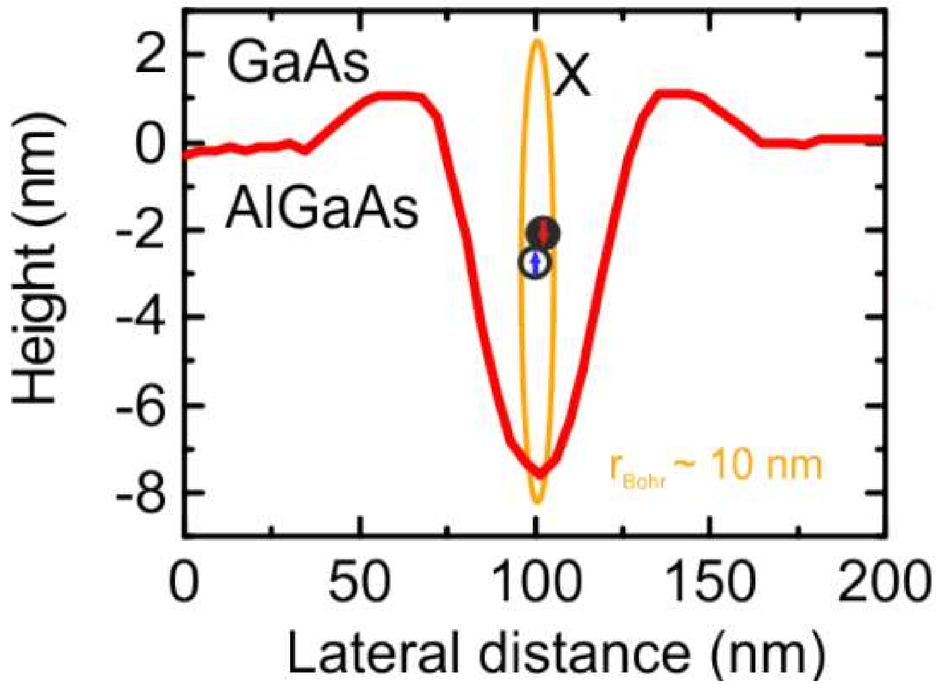




D. Huber *et al*, Nature Comm. **8** 15506 (2017)
L. Schweickert *et al.*, Appl. Phys. Lett. **112,** 093106 (2018)

DECAY DYNAMICS UNDER TPE (EVIDENCE OF "WEAK CONFINEMENT")



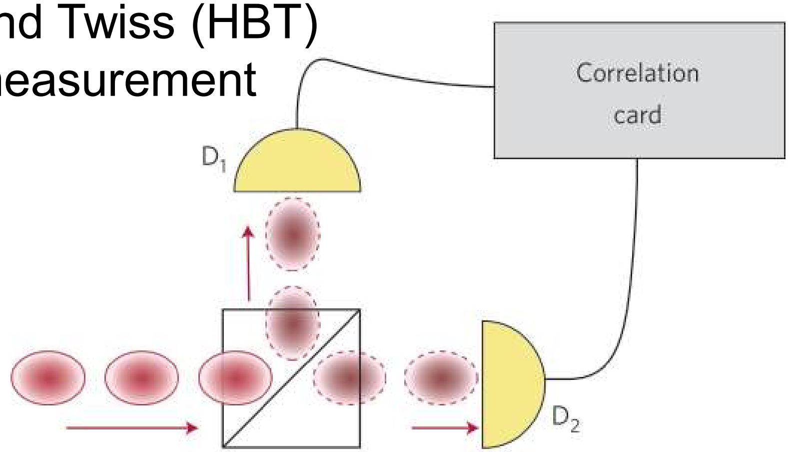


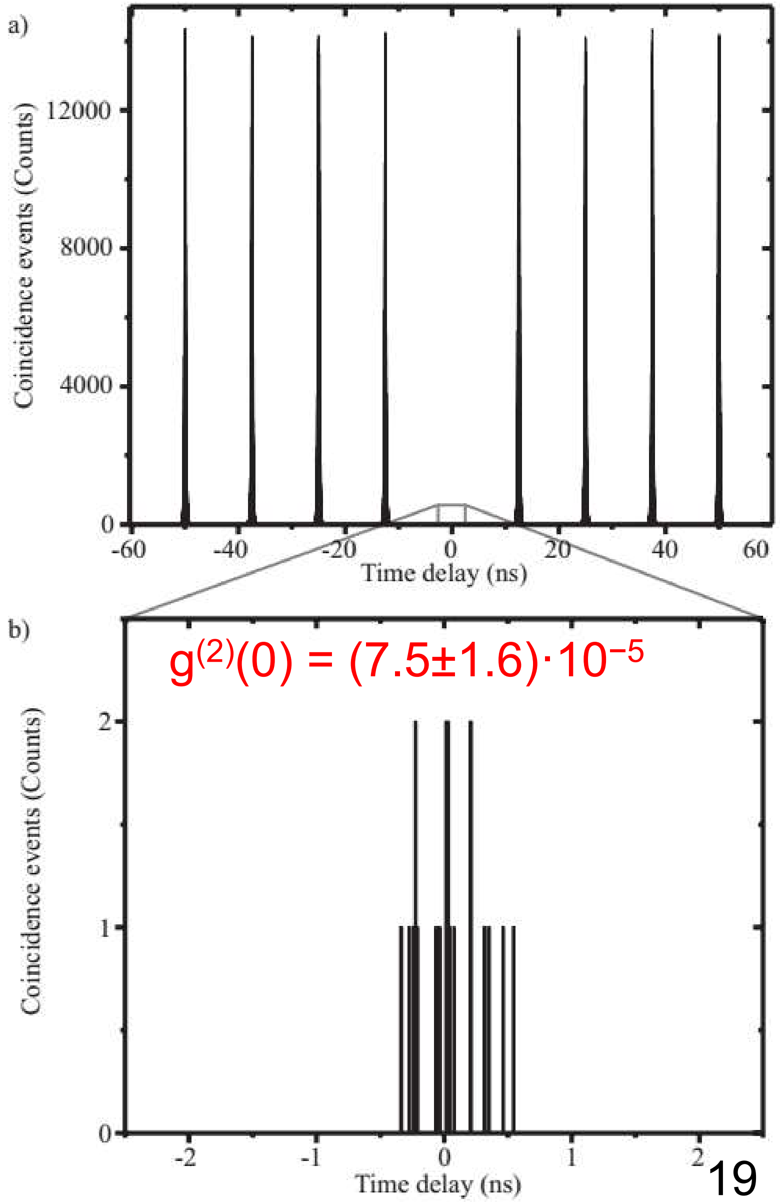
Lifetimes: ~125 ps (250 ps) for XX (X) → GHz operation possible
[For strong confinement, X lifetime > 480 ps → indication of weak confinement]

See S. Stobbe et al. Phys. Rev. B 86, 085304 (2012), L.C. Andreani et al. Phys. Rev. B 60, 13276 (1999)

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

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)
Former record: g(2)(0) = $(3 \pm 1.5) \cdot 10^{-4}$
D.B. Higgingbottom et al. New J. Phys. 18, 093038 (2016)

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)

IDEAL PROPERTIES OF QD SOURCES

- **Purity**: not more than one photon (or photon pair) per excitation pulse
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See also: P. Senellart et al. *Nat. Nanotechnol*. **12,** 1026 (2017)
C.-Y. Lu & J.-W. Pan, *Nat. Photonics* **8**, 174 (2014)

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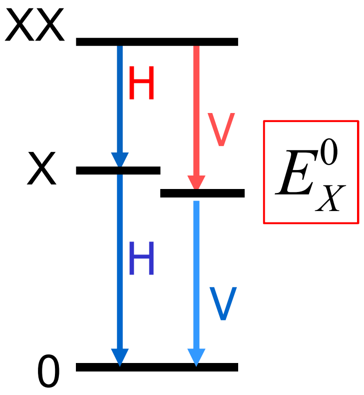
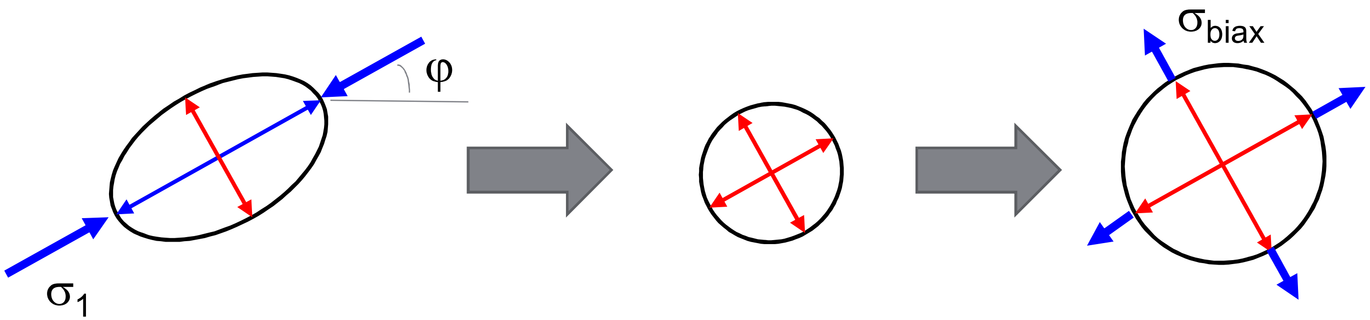
C.-Y. Lu & J.-W. Pan, *Nat. Photonics* **8**, 174 (2014)

ENERGY TUNABLE SOURCE OF ENTANGLED PHOTONS VIA POST-GROWTH STRAIN ENGINEERING



We need 1 "knob" to control E_X^0 and 2 for FSS (the two bright-exciton levels are coherently coupled) → 3 "tuning knobs"

- Intuitive view:



- 3 Knobs? In-plane stress components!

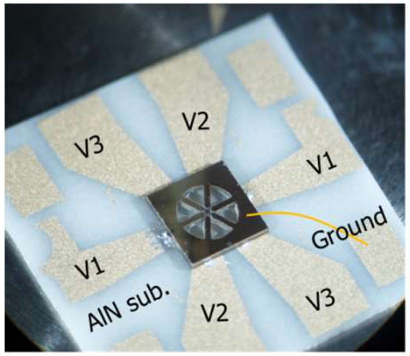
$$\overleftrightarrow{\boldsymbol{\sigma}} = \begin{pmatrix} \sigma_{xx} & \sigma_{xy} & \sigma_{xz} \\ \sigma_{xy} & \sigma_{yy} & \sigma_{yz} \\ \sigma_{xz} & \sigma_{yz} & \sigma_{zz} \end{pmatrix}$$

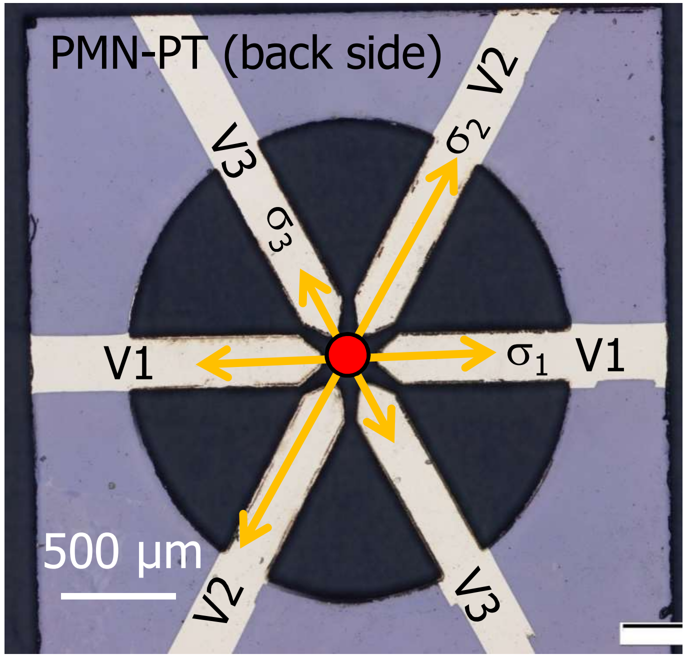
R. Trotta, J. Martín-Sánchez, I. Daruka, C. Ortix, A. Rastelli, PRL 114,150502 (2015) and refs

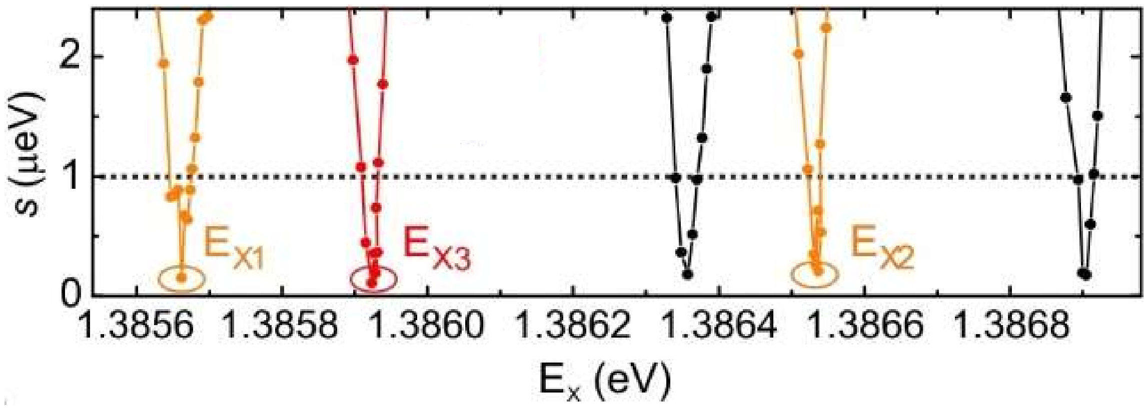
WAVELENGTH-TUNABLE SOURCE OF ENTANGLED PHOTONS

- Full control of in-plane stress tensor via three independent uniaxial stresses at 60°

$$\begin{cases} \sigma_{xx} = \sigma_1 + \frac{1}{4}(\sigma_2 + \sigma_3) \\ \sigma_{yy} = \frac{3}{4}(\sigma_2 + \sigma_3) \\ \sigma_{xy} = \frac{\sqrt{3}}{4}(\sigma_2 - \sigma_3) \end{cases}$$





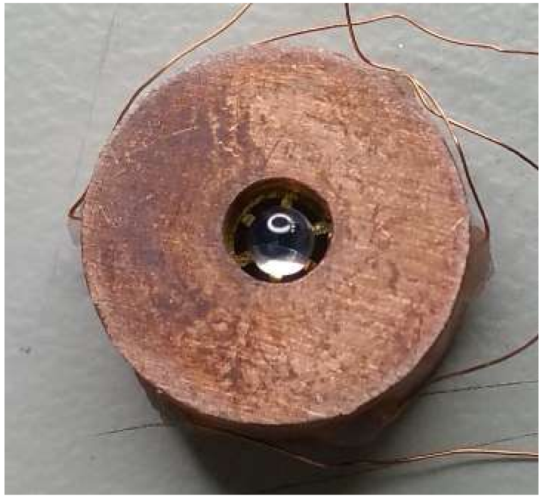


Entanglement fidelity preserved within tuning range

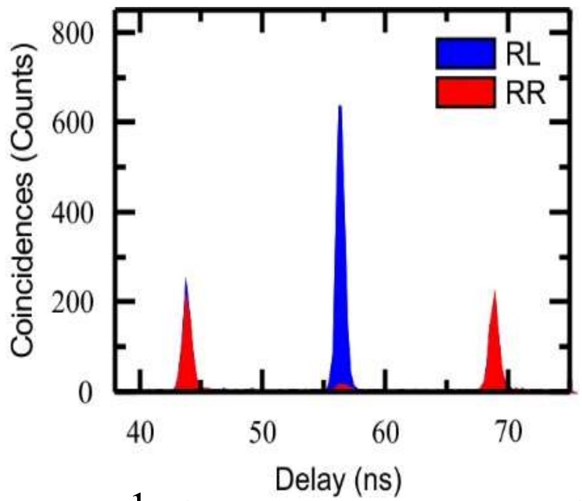
R. Trotta, J. Martín-Sánchez et al. Nature Comm. 7, 10375 (2016)

A. Rastelli, I. Daruka, R. Trotta, **EP3077328B1**
J. Martín-Sánchez *et al*. Adv. Opt. Mat. 4, 682 (2016)

NEARLY MAXIMALLY ENTANGLED PHOTONS FROM GAAS QDS



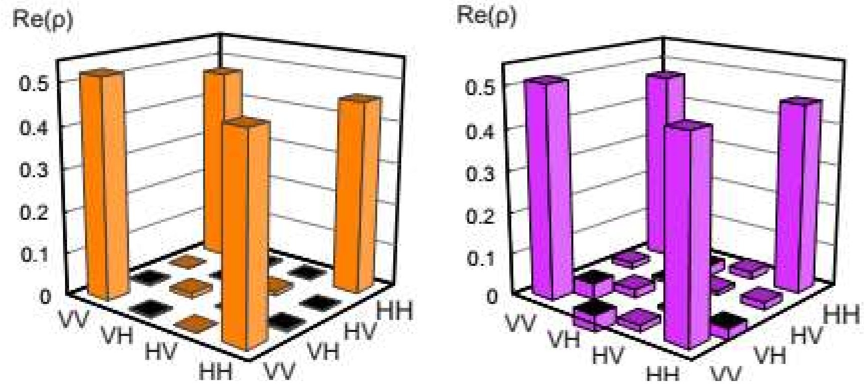
- GaAs QDs in cavity integrated on micromachined actuator for FSS tuning to 0

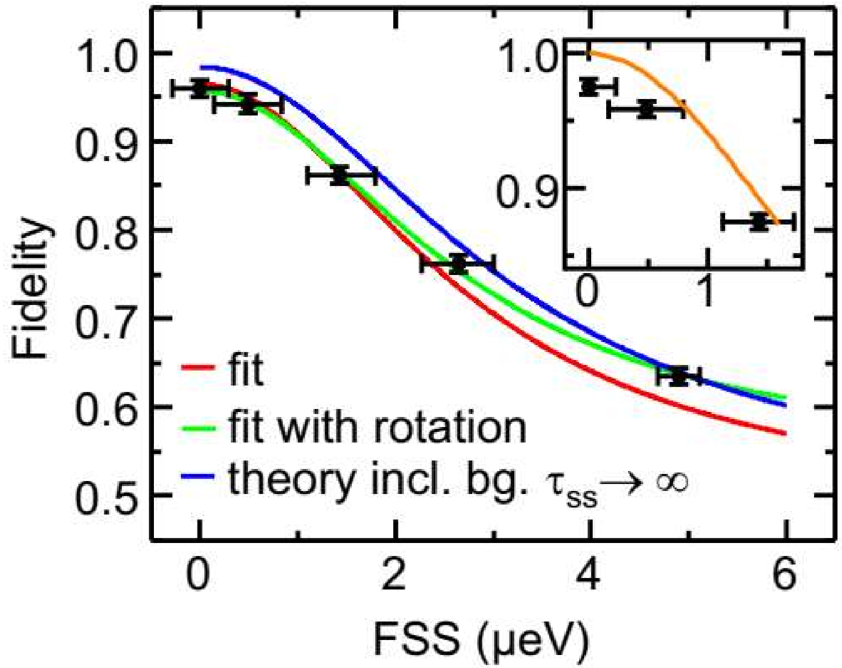


$$|\psi\rangle = \frac{1}{\sqrt{2}}\left(|R\rangle_{XX}|L\rangle_{X} + |L\rangle_{XX}|R\rangle_{X}\right)$$

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)%

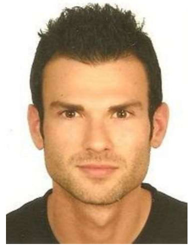
Highest reported so far for QD sources with no temporal nor spectral filtering. Reasons:

- ☐ Short X lifetime (250 ps)
- ☐ Full control of FSS
- ☐ Suppressed re-excitation
- ☐ Lower nuclear spin of Ga compared to In (?)

- Residual imperfection attributed to exciton spin scattering
- >99% fidelity achievable with moderate Purcell enhancement

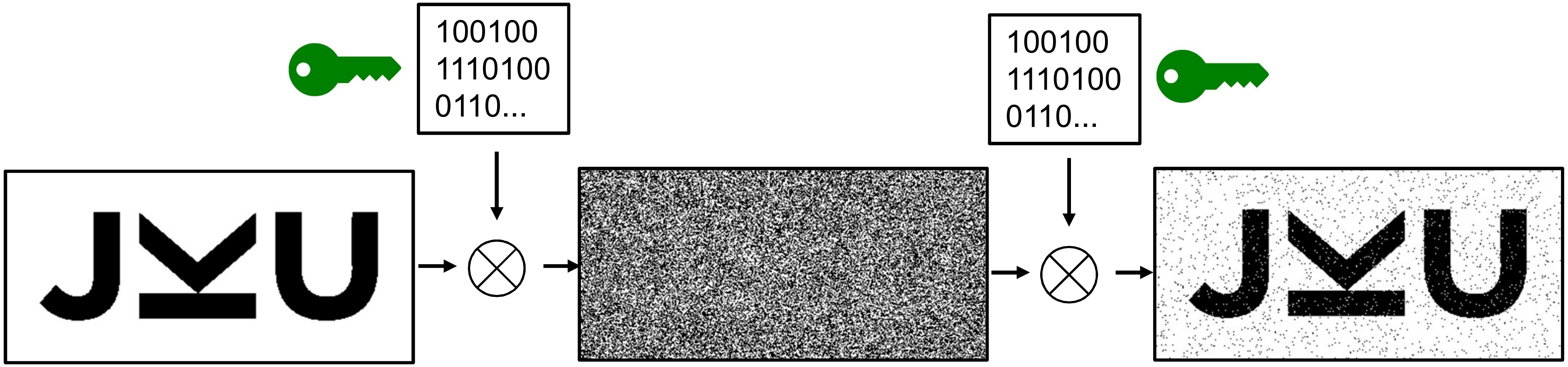
D. Huber, et al. Phys. Rev. Lett. 121, 033902 (2018)

QKD WITH ENTANGLED PHOTON PAIRS FROM A QD



Raw key rate = **646 bits/s**

QBER = **2.6%**

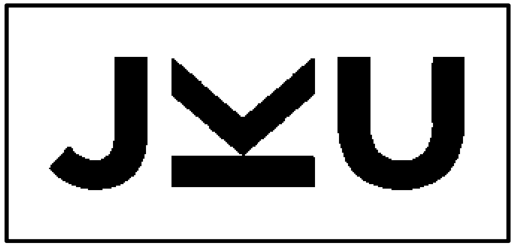


Original Message

Encrypted Message

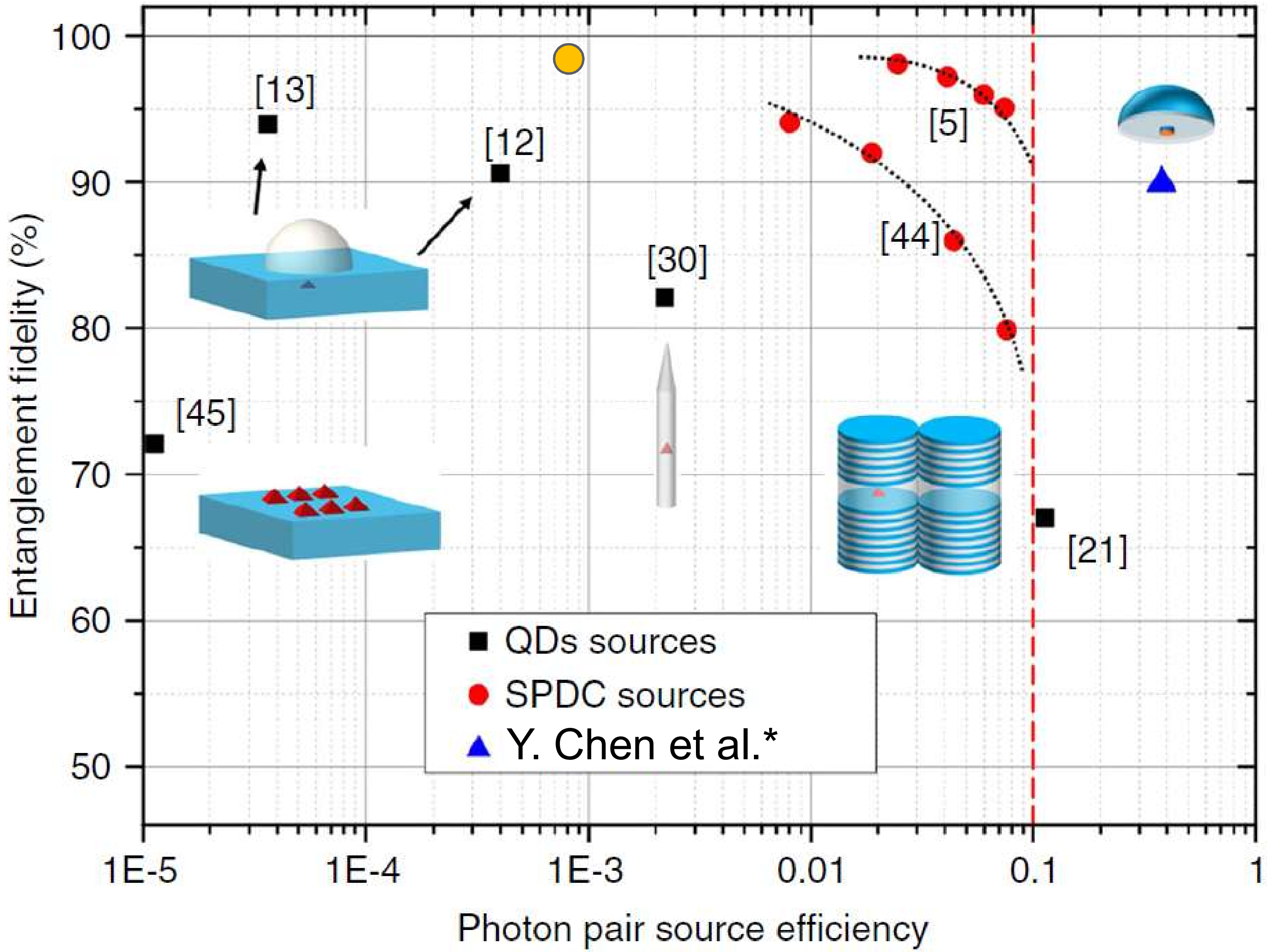
Decrypted Message

Error-corrected key rate = **415 bits/s**



Decrypted

ENTANGLED PHOTON SOURCES: STATE-OF-THE-ART



- D. Huber, et al. Phys. Rev. Lett. 121, 033902 (2018)
- *Y. Chen et al. *Nature Communications* **9**, 2994 (2018)

IDEAL PROPERTIES OF QD SOURCES

- **Purity**: not more than one photon (or photon pair) per excitation pulse
- **Short radiative decay times** to allow GHz operation
- **Entanglement:** generation of maximally entangled photon pairs
- **Brightness:** not much less than one photon (or photon pair) in desired optical mode per excitation pulse
- **Indistinguishability**: all photons emitted by the same source are identical to achieve perfect HOM interference (indispensable for photonic-based quantum computing and for long-distance quantum communication)
- **“Right” wavelength** depending on application
- **Scalability:** multiple sources emit mutually indistinguishable photons

See also: P. Senellart et al. *Nat. Nanotechnol*. **12,** 1026 (2017)
C.-Y. Lu & J.-W. Pan, *Nat. Photonics* **8**, 174 (2014)

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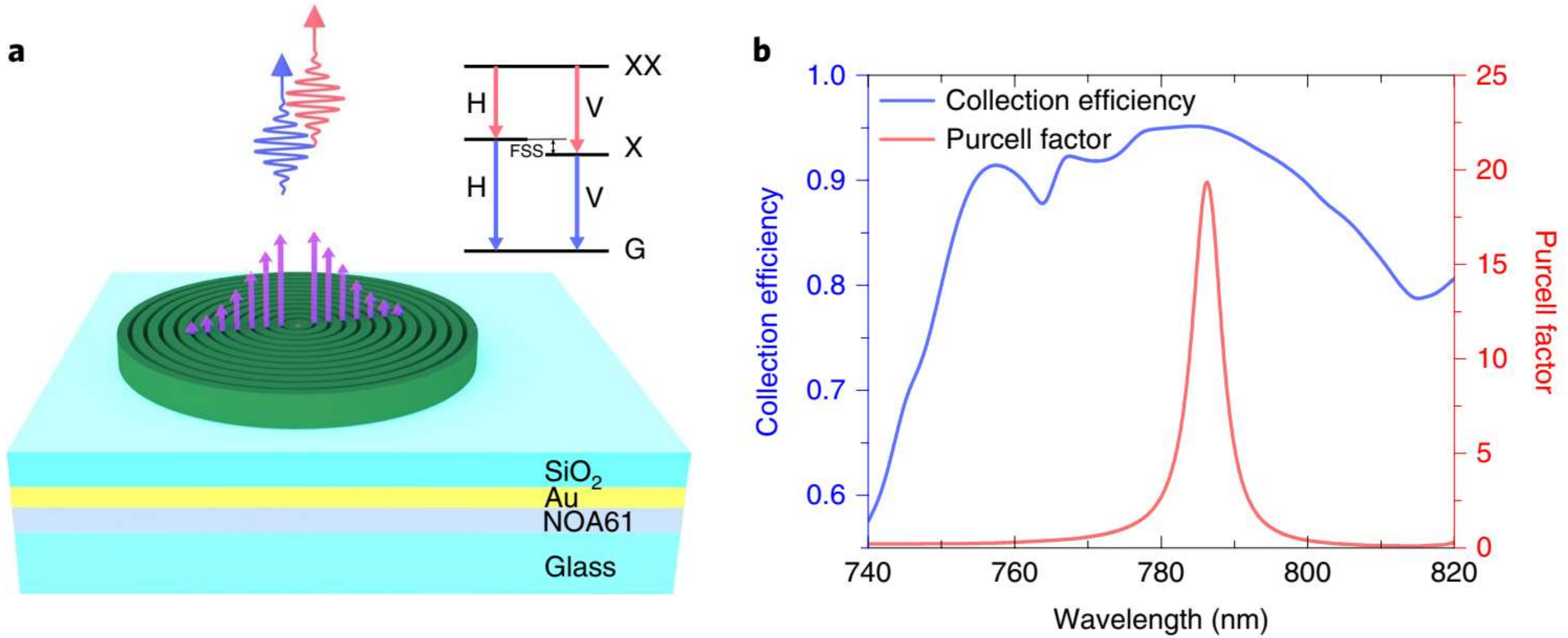
BOOSTING BRIGHTNESS AND RADIATIVE RATES THROUGH CIRCULAR BRAGG GRATINGS

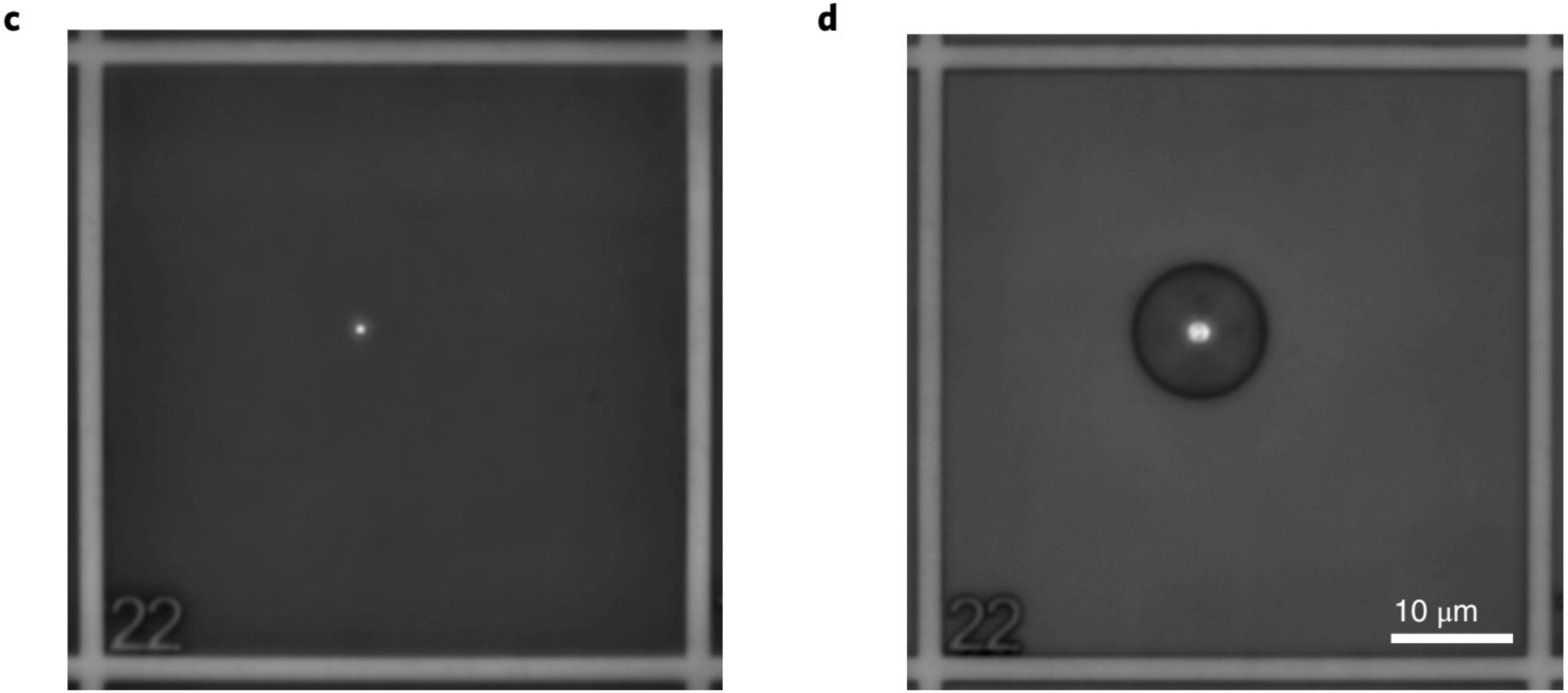


Key features:

- Broadband enhancement of collection efficiency → tolerant to wavelength mismatch
- Broadband Purcell enhancement suitable for non-degenerate entangled-photons

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

BOOSTING BRIGHTNESS AND RADIATIVE RATES THROUGH CIRCULAR BRAGG GRATINGS

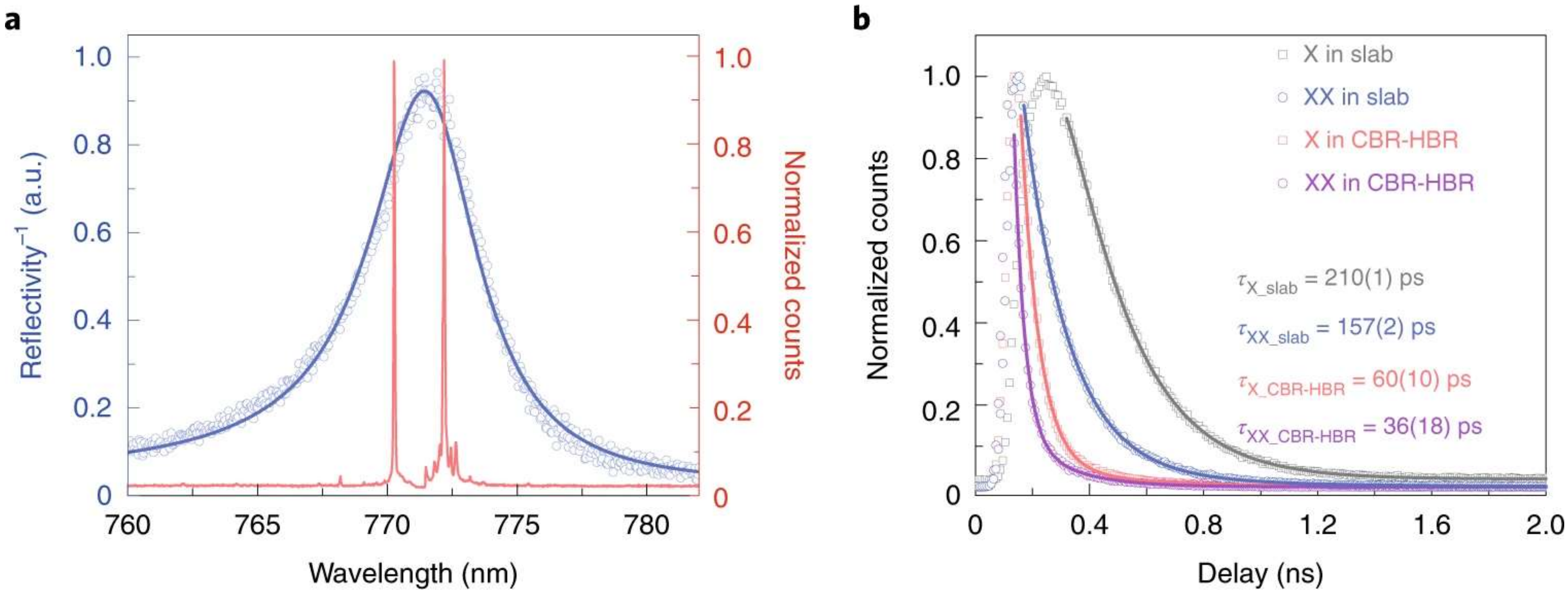


Deterministic fabrication of device around preselected QD

- Membrane fabrication on back-reflector
- Precise location of QD position via PL imaging of QD emission + reflectivity of metal markers (~10 nm accuracy)
- E-beam + etching

J. Liu et al. Rev. Sci. Instruments **88**, 023116 (2017)
J. Liu et al. Nature Nanotech. 14, 586 (2019)

BOOSTING BRIGHTNESS AND RADIATIVE RATES THROUGH CIRCULAR BRAGG GRATINGS

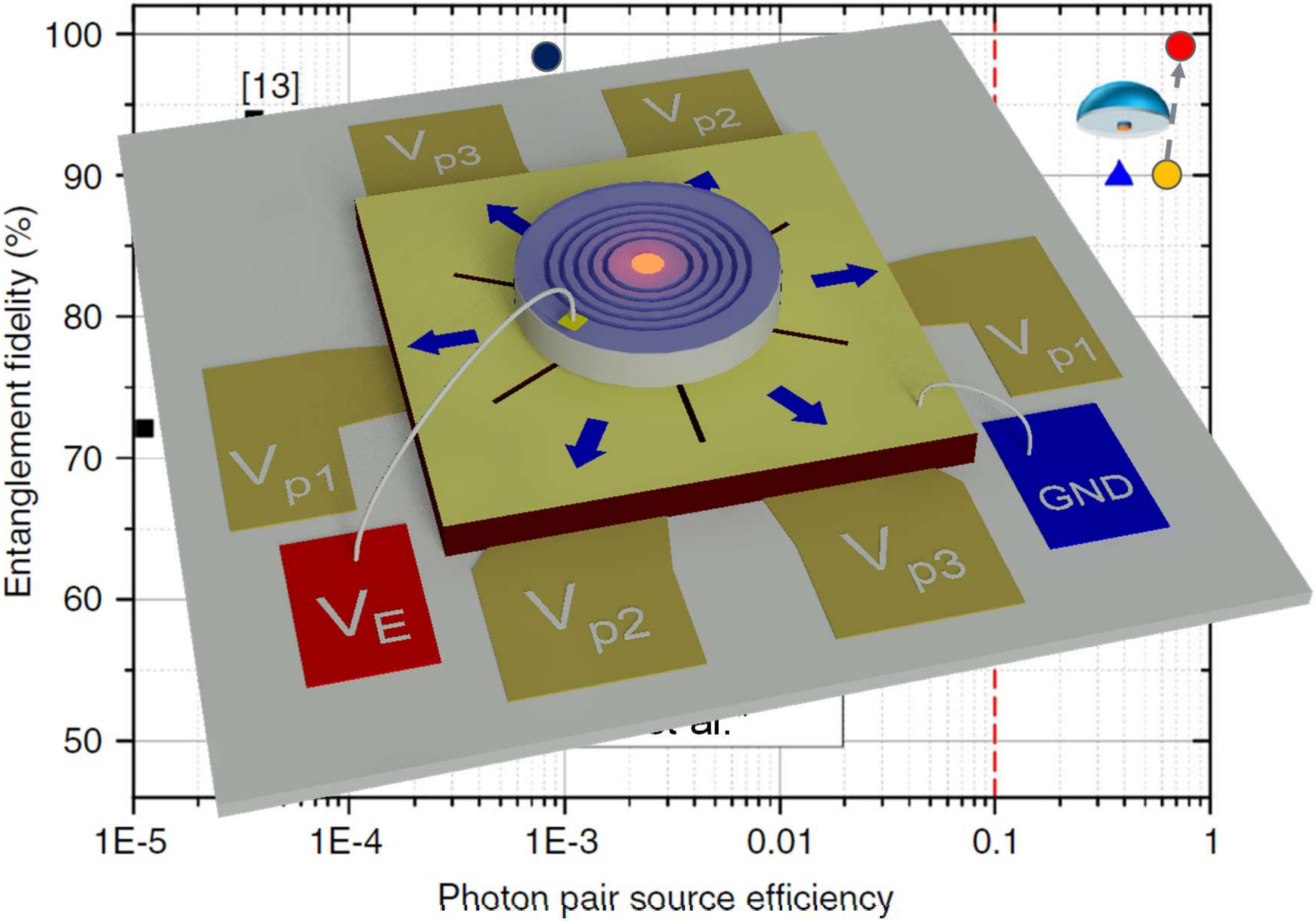


Experimental performance:

- Purcell enhancement: ~4 → X radiative rate >10 GHz
- Pair collection efficiency ~0.65
- Entangled fidelity ~0.88 (limited by FSS)

J. Liu et al. Nature Nanotech. 14, 586 (2019)
See also H. Wang, Phys. Rev. Lett. 11, 113602 (2019)

ENTANGLED PHOTON SOURCES: STATE-OF-THE-ART



- D. Huber, et al. Phys. Rev. Lett. 121, 033902 (2018)
- J. Liu et al., Nature Nanotech. 14, 586 (2019)

*Y. Chen et al. *Nature Communications* **9**, 2994 (2018)

JKU

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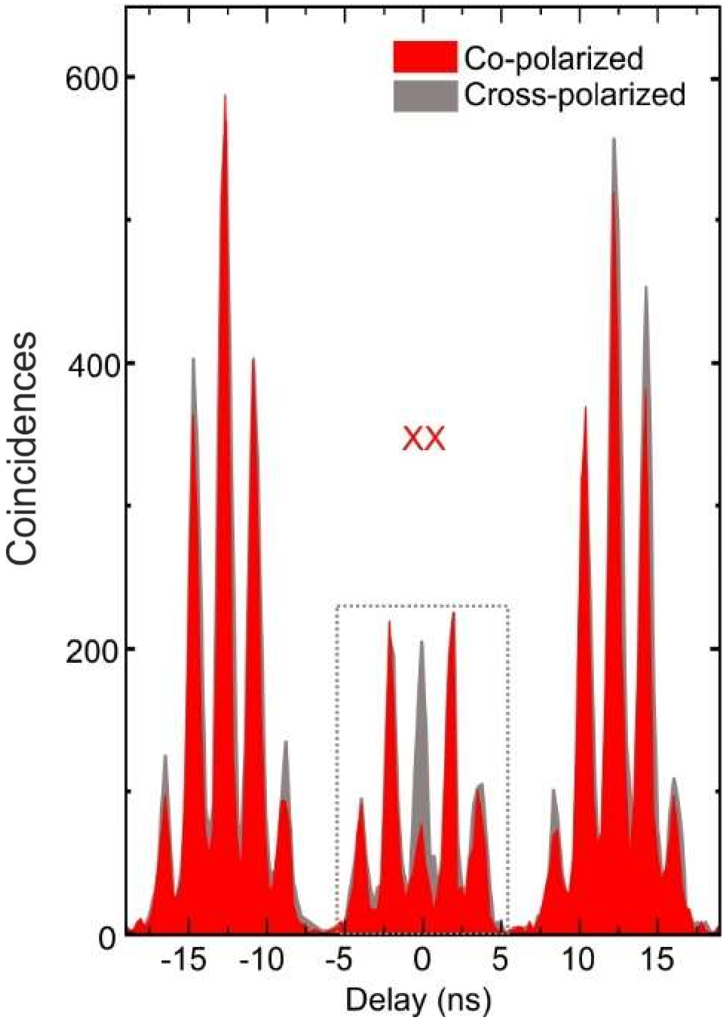
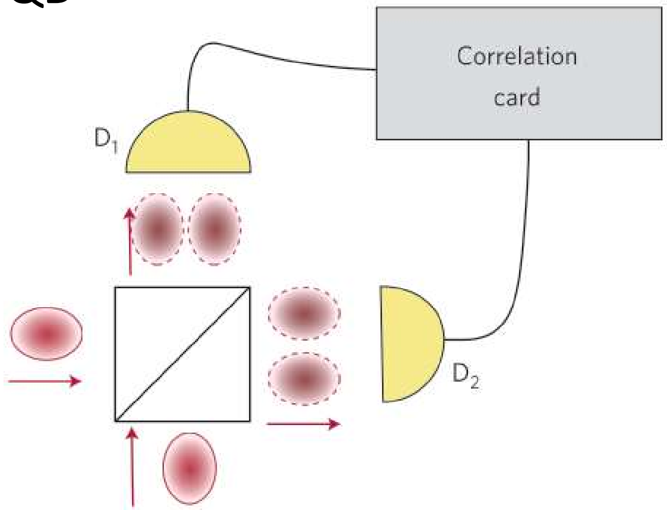
C.-Y. Lu & J.-W. Pan, *Nat. Photonics* **8**, 174 (2014)

PHOTON INDISTINGUISHABILITY OF GAAS QDS UNDER TPE

Hong-Ou-Mandel (HOM) type interference for consecutive photons (2 ns delay) emitted by the same QD





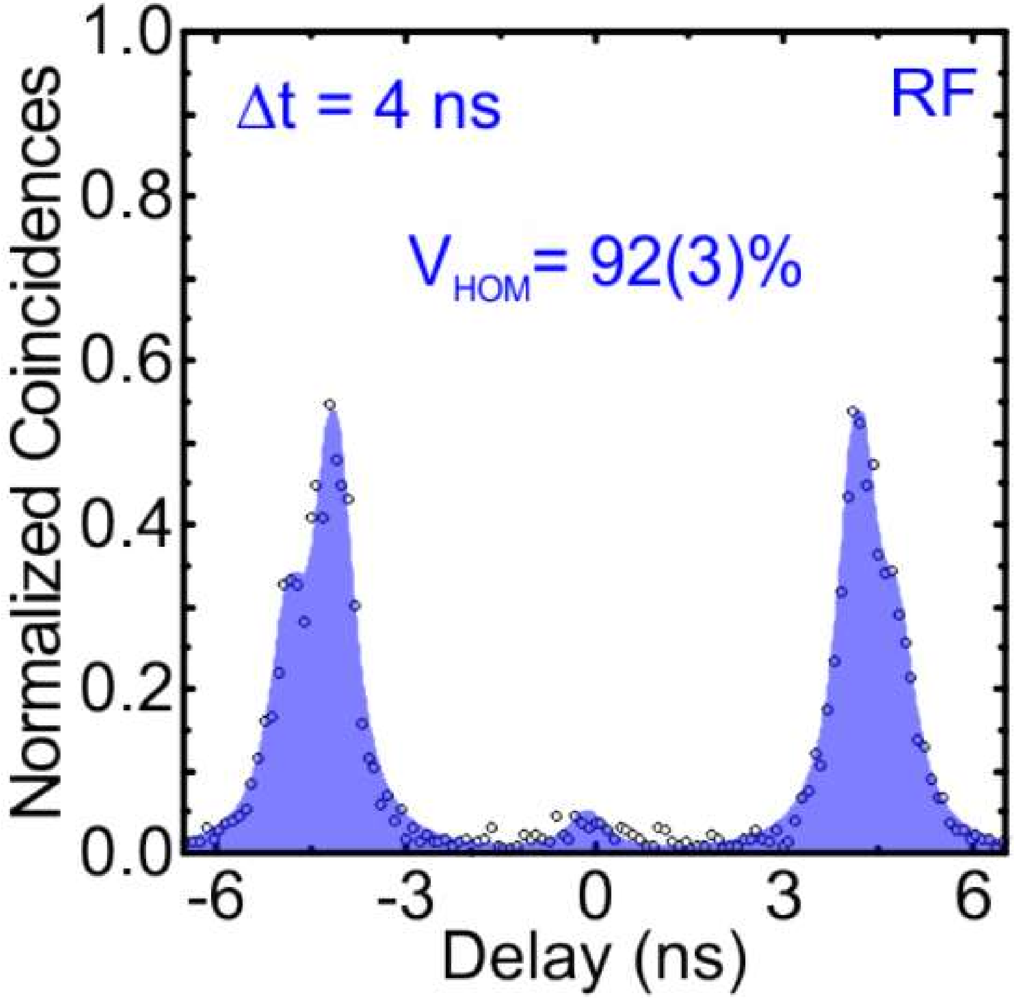
Visibility for different QDs under TPE: **70 – 80 %** with no filtering, Purcell enhancement, background subtraction

Limitations:

- Phonon interactions
- Time and energy correlations introduced by cascade

D. Huber *et al*, Nature Comm. **8** 15506 (2017)
T. Huber et al. Opt. Express **21,** 9890 (2013)
See also M. Müller et al, Nature Photon **8**, 224 (2014)

PHOTON INDISTINGUISHABILITY FOR GaAs QDs UNDER STRICTLY RESONANT EXCITATION



- Resonant fluorescence (RF) obtained by suppressing laser stray light via crossed-polarization
- State of the art value in absence of Purcell enhancement and spectral filtering (for InGaAs dots see Y.M. He et al. *Nat Nano 8*, 213 (2013))

Data by J. Weber, S. Portalupi, P. Michler (Univ. Stuttgart)

M. Reindl et al., Phys. Rev. B 100 (15), 155420
See also: E. Schöll et al., Nano Lett. 19, 2404 (2019)

IDEAL PROPERTIES OF QD SOURCES

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- **Short radiative decay times** to allow GHz operation
- **Entanglement:** generation of maximally entangled photon pairs
- **Brightness:** not much less than one photon (or photon pair) in desired optical mode per excitation pulse
- **Indistinguishability**: all photons emitted by the same source are identical to achieve perfect HOM interference (indispensable for photonic-based quantum computing and for long-distance quantum communication). Indistinguishability of photons from cascade to be improved.
- **"Right" wavelength** depending on application
- **Scalability:** multiple sources emit mutually indistinguishable photons

See also: P. Senellart et al. *Nat. Nanotechnol*. **12,** 1026 (2017)
C.-Y. Lu & J.-W. Pan, *Nat. Photonics* **8**, 174 (2014)

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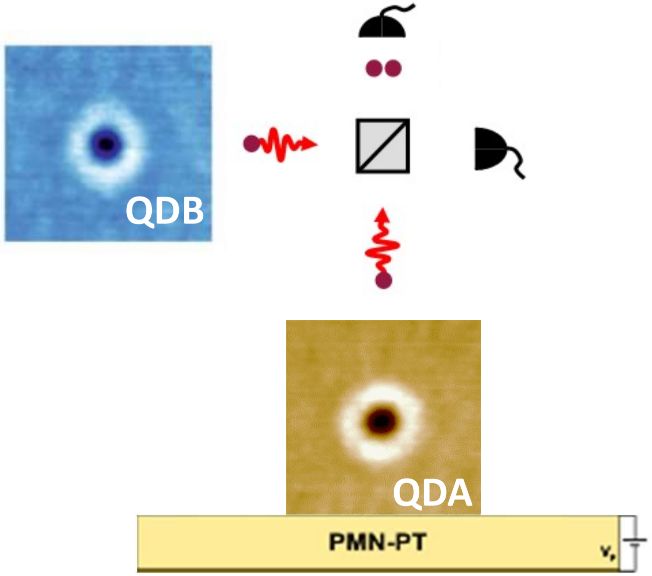
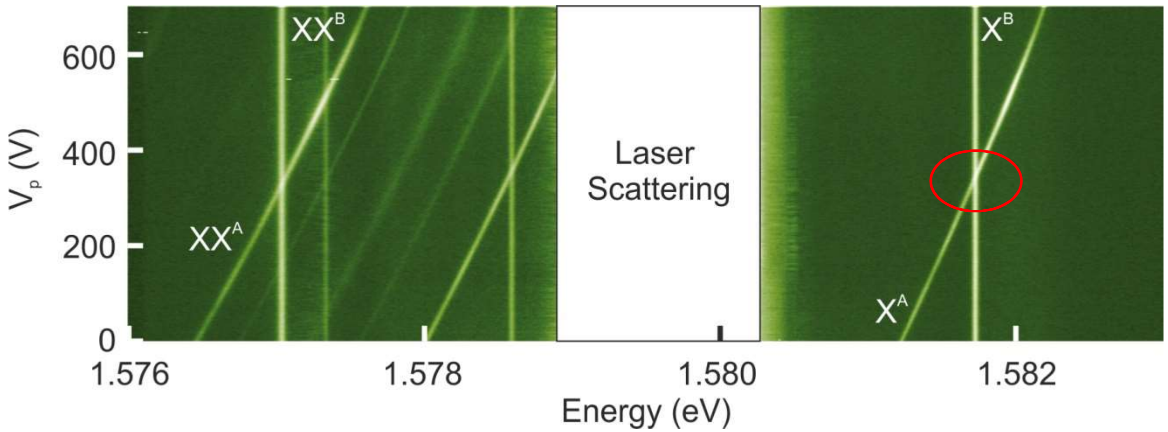
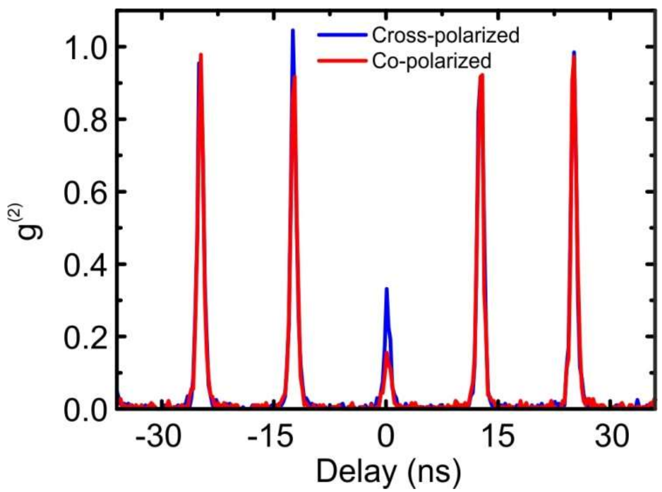
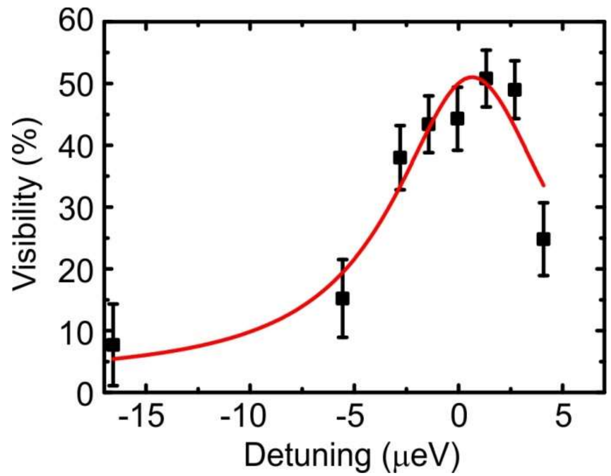
HOM INTERFERENCE BETWEEN PHOTONS FORM REMOTE GaAs QDS





Strain tuning to control relative energy

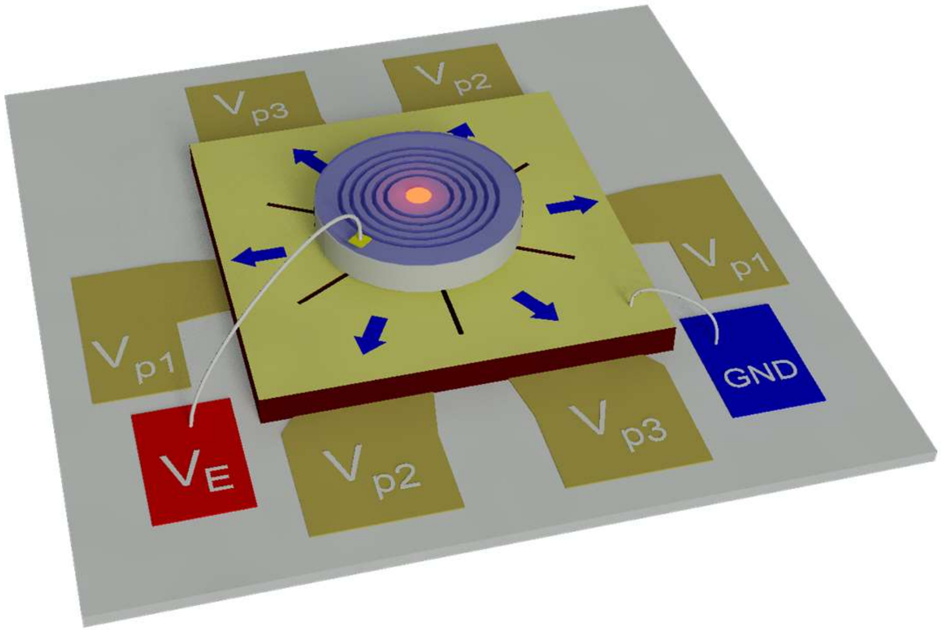


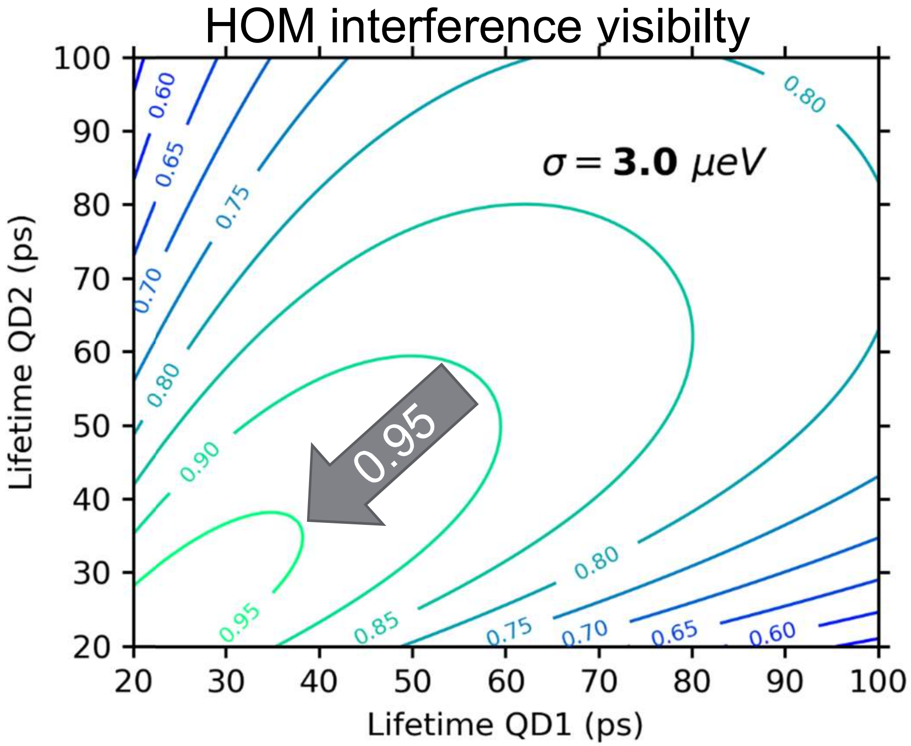


Visibility ~50% (with no spectral filtering and no Purcell effect)

M. Reindl, et al. Nano Letters 17, 4090 (2017)

FUTURE: CBR INTEGRATED ON MICROMACHINED ACTUATORS AS ROUTE TO SCALABLE ENTANGLEMENT SOURCES





- Actuator: Control of FSS and emission wavelength of remote sources
- QDs in weak confinement regime → Intrinsically high radiative rates
- CBR: Brightness + Purcell enhancement (→ overcome charge-noise and dephasing and enable high HOM visibility for remote sources; boost rates to >10 GHz)
- Move to telecom wavelength (also to stay far from free surfaces)