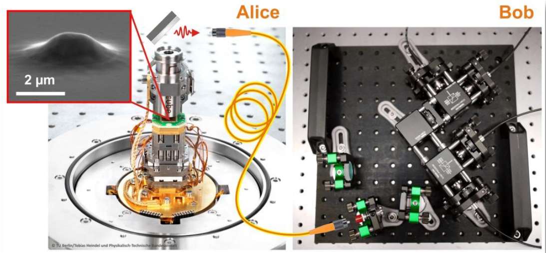

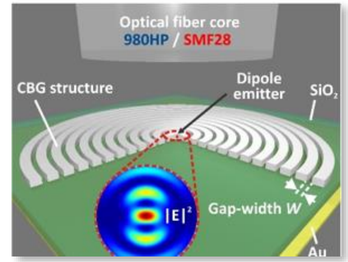

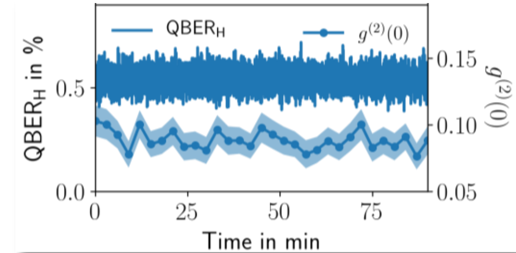

Quantum Communication

Towards Quantum Networks using Engineered Solid-State Quantum-Light Sources

Tobias Heindel

Head of Group
Quantum Communication Systems

Institute of Solid State Physics
Technische Universität Berlin
Germany

QuSecure

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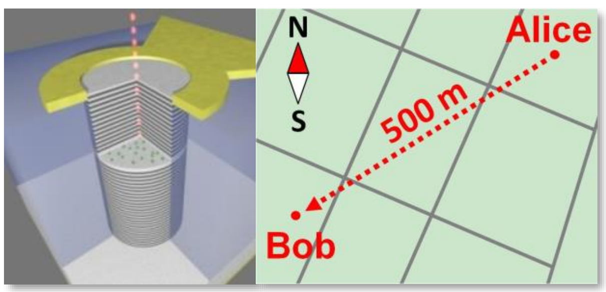
VCQ
Vienna Center for Quantum Science and Technology

Overall Outline

Part I: *Intro & Basics*

Basics

- About Us
- Quantum Key Distribution (QKD)
- Single-Photon Generation in the Solid-State
- Review on Single-Photon QKD



Part II: *Early Work*

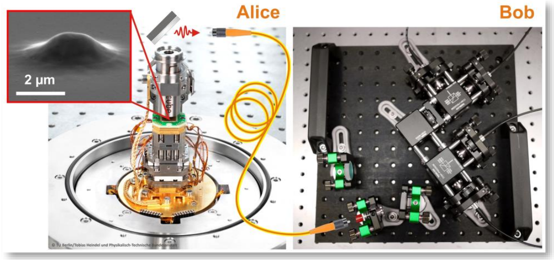
PhD + Postdoc

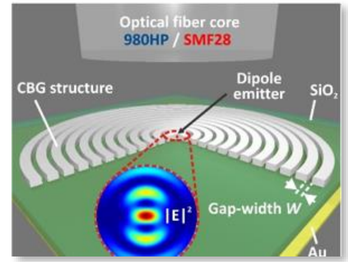
- Efficient Single-Photon LEDs
- Free-space QKD in-lab and in Munich City
- Deterministic Device Technology
- Quantum Optics & Spin-Photon Interfaces

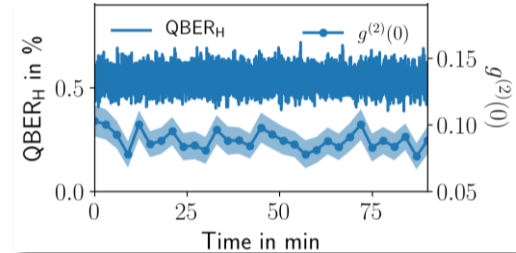
Part III: *Towards Quantum Networks*

Own Group

- Tools for Optimization and Certification
- Plug'n'Play Quantum Light Sources
- Benchtop QKD Testbeds
- Emerging Materials
- Berlin Quantum Network Activities







Quantum Communication
Part I: Intro & Basics

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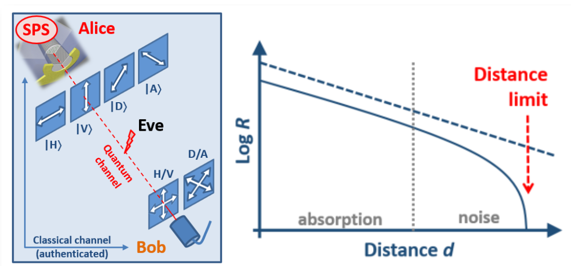
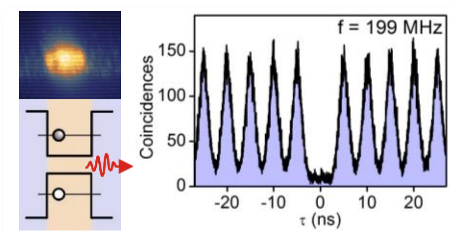
Outline – Part I

About Us
- ○ QuCom Group @ Berlin
- ○ Research & Vision



Quantum Communication Intro
- ○ Point-to-Point QKD Protocols (BB84, E91, …)
- ○ Advanced Protocols (MDI-QKD, QuRepeater)
- ○ Beyond QKD



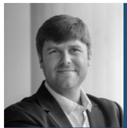
Single-Photon Generation in the Solid-State
Quantum Dots and the Purcell Effect


REVIEW
ADVANCED QUANTUM TECHNOLOGIES
www.advquantumtech.com
Quantum Communication Using Semiconductor Quantum Dots

Single-Photon QKD
A Brief Review

The Team

Group Website



Group
Quantum Communication Systems

Follow us on Twitter... @HeindelTobias

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PhD Student

Daniel Vajner
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Fenja Drauschke
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MSc Student

Rodrigo Lomas
BSc Student

Lukas Otto Markmann
BSc Student

Mareike Lach
MSc Student

Lena Maria Hansen
(+ U Vienna)
MSc Student

Philipp Schroth
BSc Student

You?

QuSecure
tubLAN Q.0
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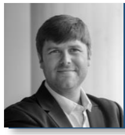
Einstein Research Unit "Quantum Devices"
Berlin University Alliance
EINSTEIN Foundation.de

Collaborators



Group Website

Group
Quantum Communication Systems

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TU Dortmund

Falk Eilenberger
U Jena

David Gershoni
Technion, Haifa, Israel

Gregor Weihs
U Innsbruck

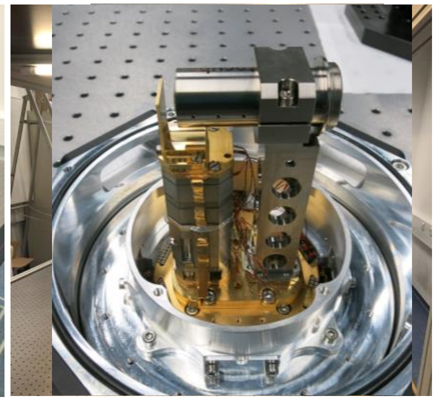
Armando Rastelli
JKU Linz

You?

Equipment

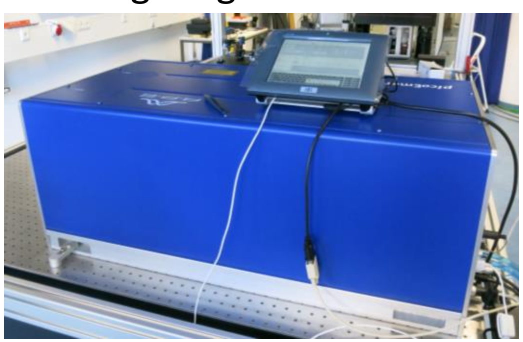
attoDry800 cryo-optical table

- World‘s first (attoDRY800)^2 incl. 2x closed-cycle cryos



Hands-free ps-OPO-Lasersystem + 2x Pulse Shaper

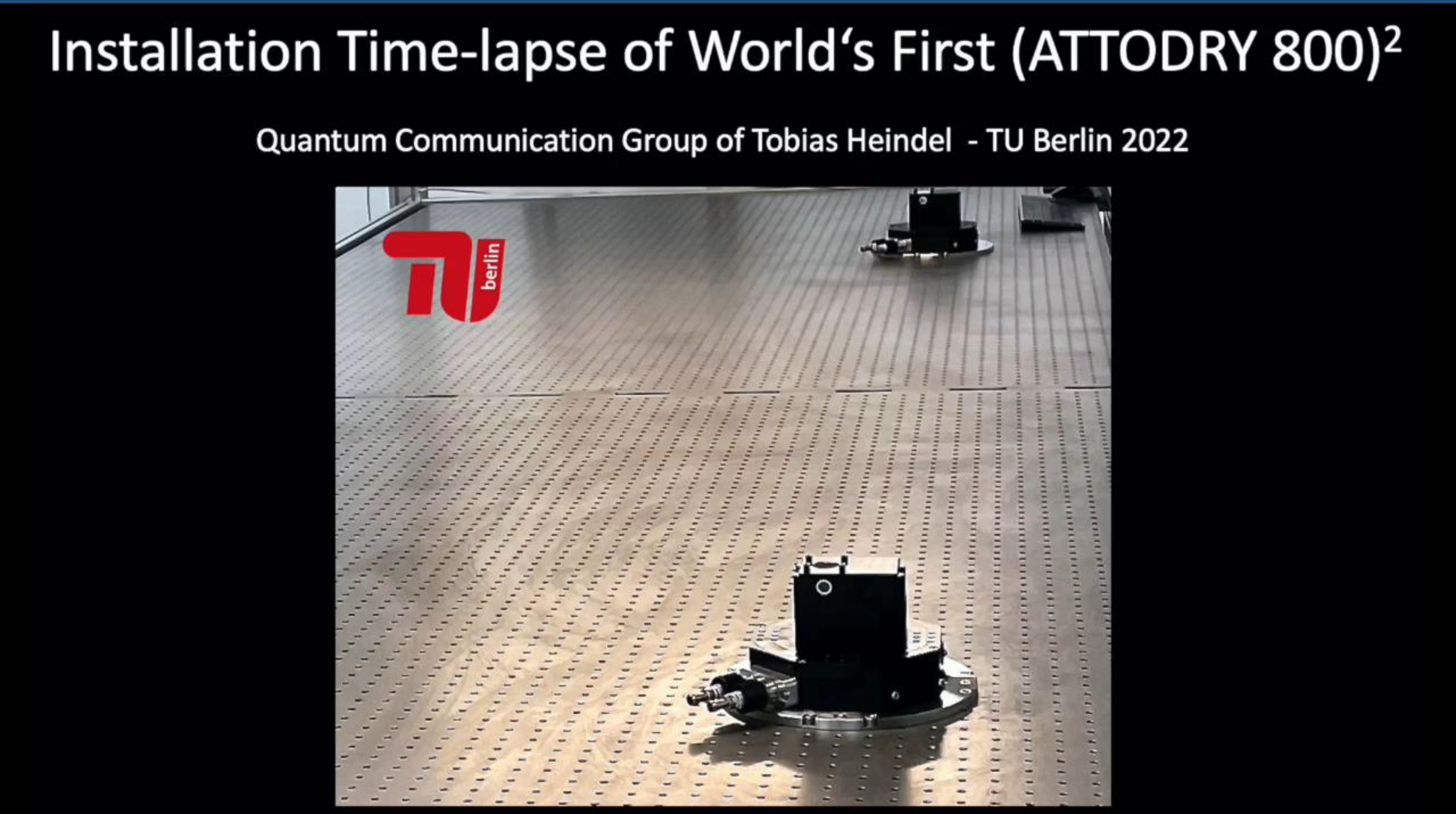
- Tuning range: 700 – 1900 nm, 2 ps, 80 MHz



12-Channel SNSPD System

- 4 Chs @ 780 nm
- 4 Chs @ 900 nm
- 4 Chs @ 1.3/1.5 µm

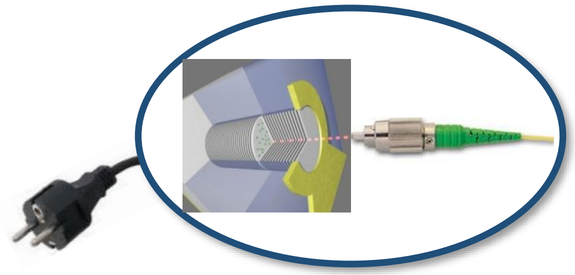
Setting-up World‘s 1st (attoDRY800)^2



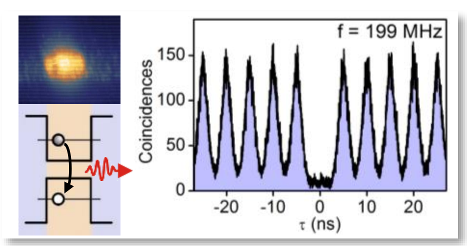
Research & Vision

Global Secure Communication

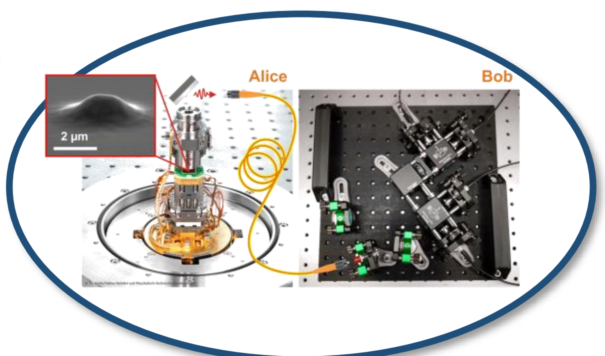
Beyond QKD



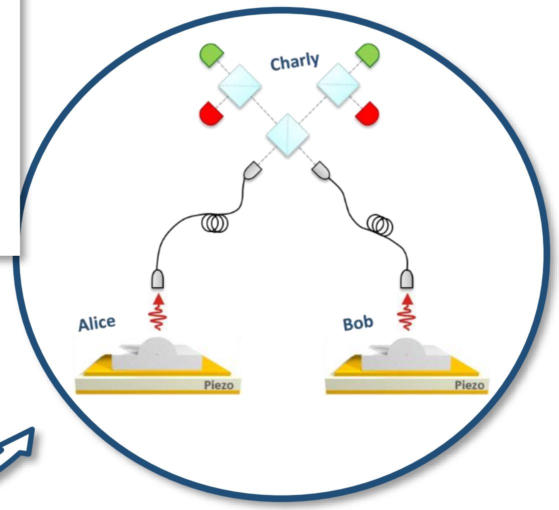
Plug'n'Play Quantum Lights Sources



Quantum Dots (QDs) [1]



BB84-type QKD

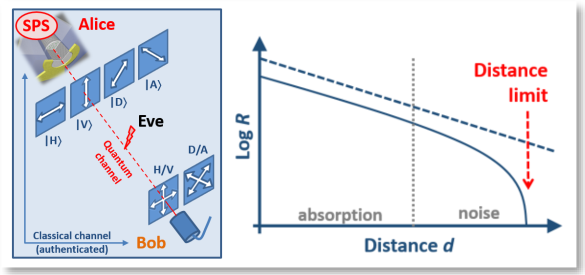


Device-independent QKD

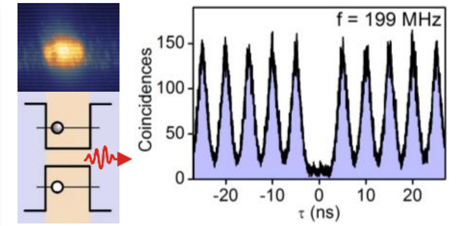
[1] P. Michler et al., *Science* **290**, 2282 (2000)

Outline – Part I

About Us
- QuCom Group @ Berlin
- Research & Vision



Quantum Communication Intro
- Point-to-Point QKD Protocols (BB84, E91, …)
- Advanced Protocols (MDI-QKD, QuRepeater)
- Beyond QKD



Single-Photon Generation in the Solid-State
Quantum Dots and the Purcell Effect


REVIEW

ADVANCED QUANTUM TECHNOLOGIES

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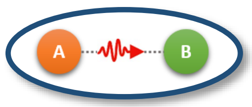
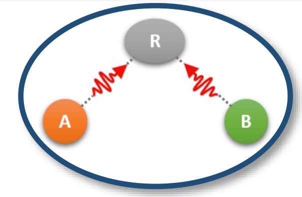
Single-Photon QKD
A Brief Review

Notions & Topology

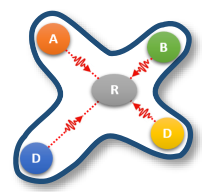
Direct Point-to-Point QKD
(BB84, E91, …)



Advanced Protocols
(MDI-QKD, Entanglement Swapping, …)

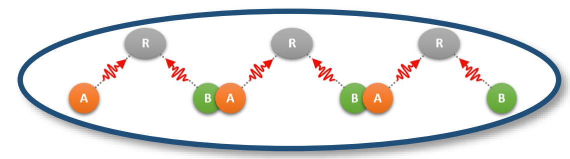


MDI-QKD



Star-like Topology
→ City Networks

Quantum Repeater



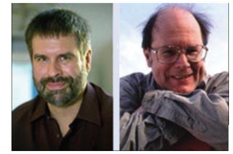
Chaining
→ Long-distance Links

Global Quantum Communication Networks

The BB84 Protocol

One-Time Pad

- The only information theoretically secure encryption
  → **Symmetric, random, and secret key for one-time use**

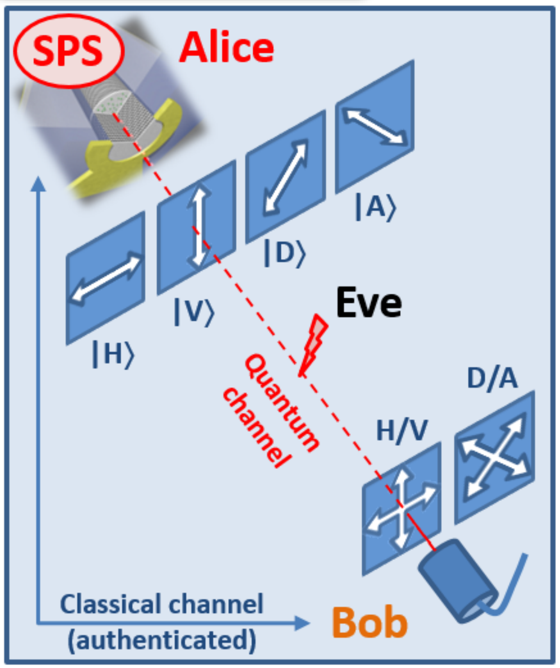


QUANTUM CRYPTOGRAPHY: PUBLIC KEY DISTRIBUTION AND COIN TOSSING

Charles H. Bennett (IBM Research, Yorktown Heights NY 10598 USA)
Gilles Brassard (dept. IRO, Univ. de Montreal, H3C 3J7 Canada)

International Conference on Computers, Systems & Signal Processing Bangalore, India December 10-12, 1984

BB84 – Scheme [1]



- Sending and receiving single photons in randomly chosen polarization
  → **Raw Key**
- Keep only bits measured in same polarization basis (otherwise delete bit)
  → **Sifted Key = ½ Raw Key** - Should be perfectly correlated (ideal hardware)
- Spy „Eve“ introduces errors in **Sifted Key**
  → Determine quantum bit error ratio (QBER) from subsets of the sifted key
  → Secret key distillation possible if QBER < ~ 12%
- Error correction and privacy amplification
  → **Secure Key**

[1] C. H. Bennett und G. Brassard, *Proc. of IEEE International Conference on Computers, Systems and Signal Processing*, Bangalore, India S. 175–179 (1984)

The BB84 Protocol

BB84 - Example [1]

Sifting (50%)

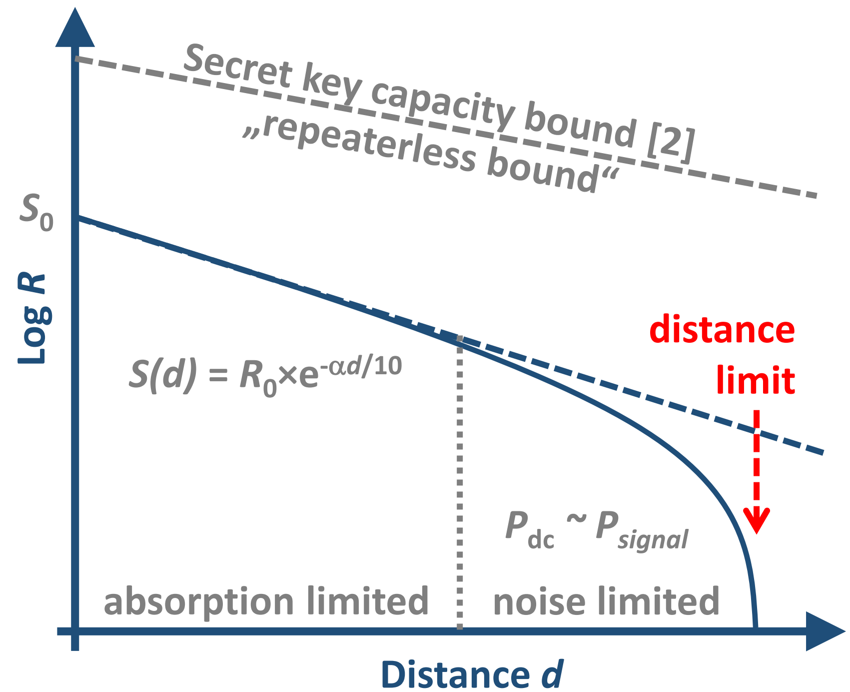
Error (25%) for „intercept-resend"

	BB84 Protocol	1	2	3	4	5	6	7	8	9	10	11	12	...
Alice	Bit	~~1~~	0	0	~~0~~	~~0~~	1	0	~~0~~	1	1	~~0~~	0	...
	Basis	×	×	×	+	×	×	×	×	+	+	×	+	...
	Polarisation	|↘⟩	|↗⟩	|↗⟩	|↔⟩	|↗⟩	|↘⟩	|↗⟩	|↗⟩	|↕⟩	|↕⟩	|↗⟩	|↔⟩	...
Eve	Basis	×	×	×	×	+	+	+	×	×	+	×	+	...
	Bit	1	0	0	1	0	0	0	0	0	1	0	0	...
	Polarisation	|↘⟩	|↗⟩	|↗⟩	|↘⟩	|↔⟩	|↔⟩	|↔⟩	|↗⟩	|↗⟩	|↕⟩	|↗⟩	|↔⟩	...
Bob	Basis	+	×	×	×	+	×	×	+	+	+	×	×	...
	Bit	~~1~~	0	0	~~1~~	~~0~~	1	0	~~1~~	0	1	~~0~~	0	...

[1] C. H. Bennett und G. Brassard, *Proc. of IEEE International Conference on Computers, Systems and Signal Processing*, Bangalore, India S. 175–179 (1984)

How far can we go?

Rate vs. Loss [1,2]

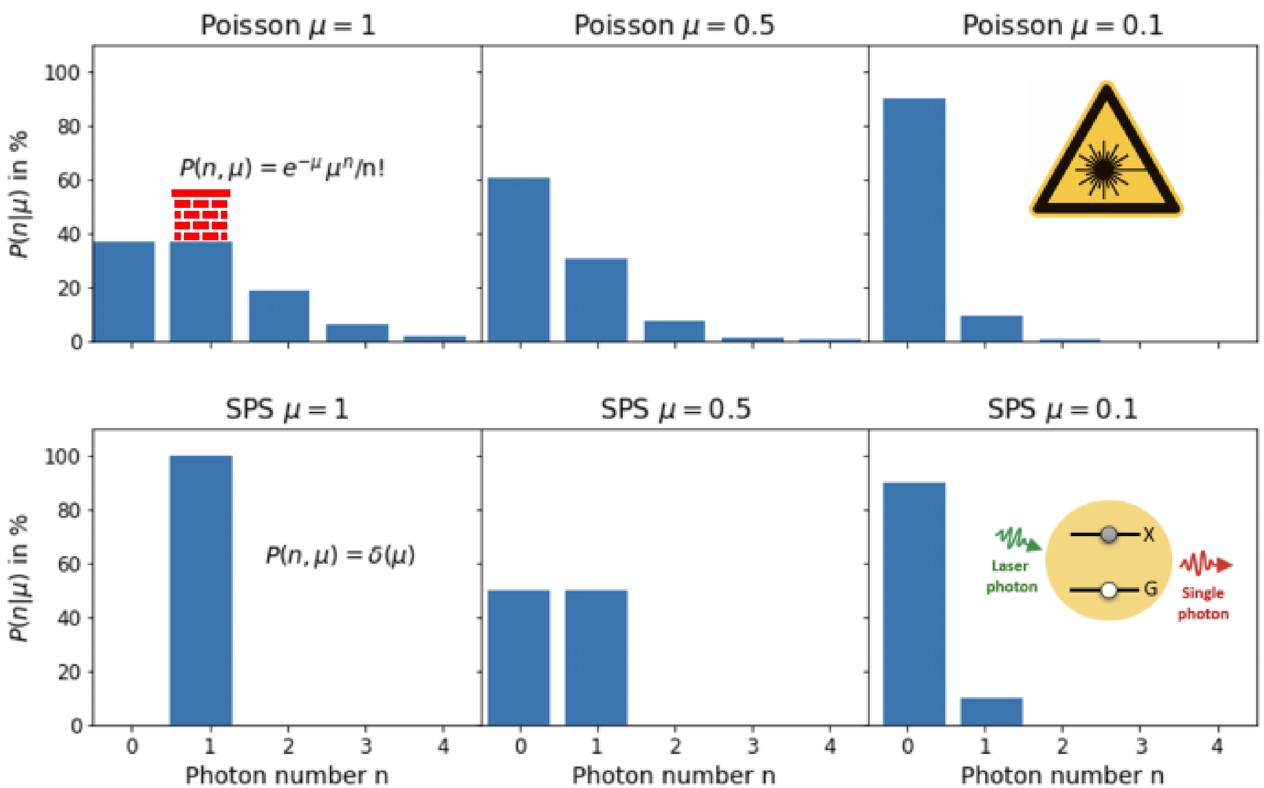


- Absorption-limited linear regime
  → **Channel attenuation (0.2 dB/km @ 1.55 µm)**
- Noise-limited multi-exponential regime
  → **Detector dark counts**
- Current record using attenuated lasers (WCPs)
  → **421 km communication distance [3]**
- **Secret key capacity bound [2]**
  → Limit for direct point-to-point QKD
  → Advanced schemes required (e.g. qua-repeaters)

[1] R. Alléaume et al., *New J. Phys.* **11**, 075002 (2009)
[2] S. Pirandola et al., *Nat. Commun.* **8**, 15043 (2017)
[3] A. Boaron et al., *Phys. Rev. Lett.* **121**, 190502 (2018)

Classical vs. Quantum Light Sources

Multi Photons and Pair Generation



$$P_{1,\mathrm{WCP}} \leq 0.37$$

$$P_{2,\mathrm{WCP}} = \frac{e^{-\mu}\mu^2}{2}$$

WCPs require protocol "add-on"
→ Decoy States [1,2]

$$P_{1,\mathrm{SPS}} \leq 1$$

$$P_{2,\mathrm{SPS}} \leq \frac{1}{2}\mu^2 g^{(2)}(0)$$

[1] W.-Y. Hwang, Phys. Rev. Lett. 91, 057901 (2003)
[2] X.-B. Wang, Phys. Rev. Lett. 94, 230503 (2005)

Calculating Secret Key Rates

QKD Performance (point to point)

Asymptotic Secret Key after GLLP [1,2] *...infinitely long bit strings!*

$$S_\infty = S_{\text{sift}} \left[A \left(1 - h\left(\frac{e}{A}\right)\right) - f_{\text{EC}} h(e) \right]$$

Single-Photon Yield: $A = 1 - \frac{p_{\text{m}}}{p_{\text{click}}}$

Error Correction Efficieny: $f_{\text{EC}} \approx 1.1$ ... 1.3

Binary Shannon Entropy $h(x) = -x\log_2(x) - (1-x)\log_2(1-x)$

QBER: $e = \frac{N_{\text{false}}}{N_{\text{false}} + N_{\text{correct}}}$

Noise

Sifted Key Rate $p_{\text{sifted}} = \frac{p_{\text{click}}}{2}$

Efficiency

Multi Photon Probability $p_{\text{m}} \leq \frac{\mu^2 g^{(2)}(0)}{2}$

Purity

[1] D. Gottesman, H.-K. Lo, N. Lütkenhaus, and J. Preskill, Quant. Inf. Comput. 5, 325-360 (2004)
[2] P. Chaiwongkhot, S. Sajeed, L. Lydersen, and V. Makarov, Quantum Science and Technology 2, 044003 (2017)

Calculating Secret Key Rates

QKD Performance (point to point)

Secret Key including *Finite-Size-Effects* [1] ***… bit string of finite length N = n + m***

key generation (n) · parameter estimation (m)

$$S_{\text{finite}}(N,\epsilon) = nA\left[1 - h\left(\frac{\tilde{e}}{A}\right)\right] - n f_{\text{EC}} h(e) - \Delta(n)$$

Overall Security Parameter: ϵ

Modified QBER: $\tilde{e} = e + \delta(m,\epsilon)$

Additional Corrections: $-\Delta(n,\epsilon)$

The protocol is ϵ-secure if:

$$\left(1 - P^{\text{abort}}\right) \cdot \frac{1}{2}\left\|\rho^{\text{pass}}_{A,B,E} - \rho_{U,U} \otimes \rho_E\right\|_1 \leq \epsilon$$

Different sub-steps can fail:

$$\epsilon = \epsilon_{\text{EC}} + \tilde{\epsilon} + \epsilon_{\text{PE}} + \epsilon_{\text{PA}}$$

Typically: $\epsilon \approx 10^{-9}$

Like a decomposition of technical failures:

protocol is ε-secure

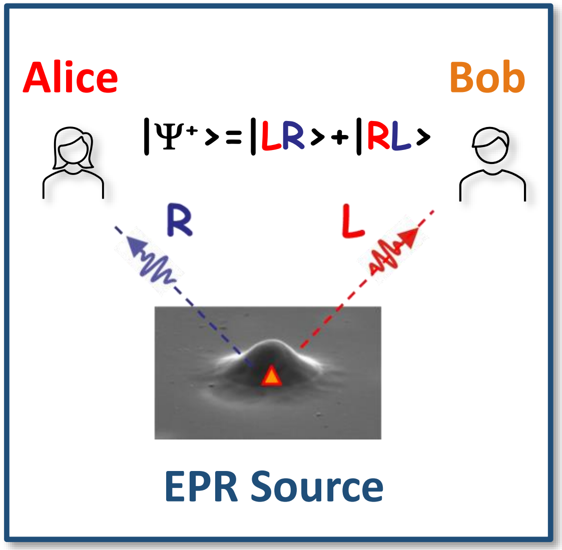
$\Leftrightarrow$ prob. of failure $\leq \varepsilon$

$$\epsilon_{plane} = \epsilon_{wings} + \epsilon_{motor} + \epsilon_{fuel} + \dots$$

[1] R. Y. Q. Cai and V. Scarani, New Journal of Physics 11, 045024 (2009)

The E91 Protocol

E91 – Scheme [1]



Artur Ekert

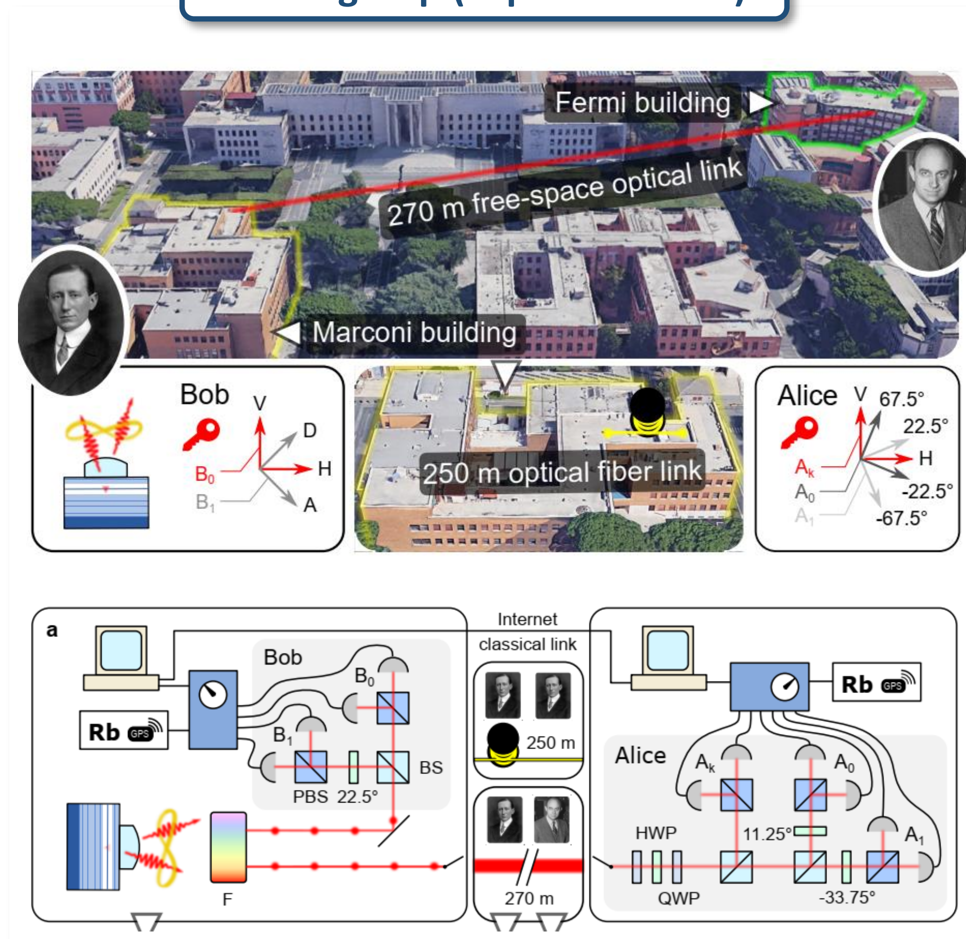
- Alice and Bob receive photons from an EPR source emitting polarization entangled photon pairs
- Alice and Bob measure their part of the 2-photon state randomly and independently in 3 different polarization bases (e.g. HV, DA, RL)
  → **Raw Key**
- Bits measured in **same bases → Sifted Key**
- Bits measured in **different bases → Monitor *S* via CHSH inequality**
  → Deviations in *S* (potentially introduced by „Eve“) quantify the information leakage and determine the amount of privacy amplification
  → **Secure Key**

[1] **Proposal**: A. Ekert, Phys. Rev. Lett. 67, 661 (1991)
[2] **1st experiment**: T. Jennewein et al., Phys. Rev. Lett. 84, 4729 (2000)

The E91 Protocol - Recent Progress [1]

Rastelli group (JKU Linz)

Trotta group (Sapienza Rome)

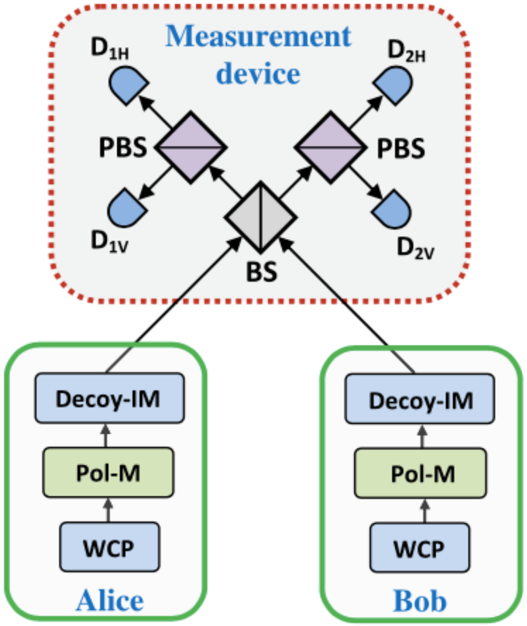


C. Schimpf et al., Sci. Adv. 7, 16 (2021) and F. Basso Basset et al., Sci. Adv. 7, 12 (2021)

MDI-QKD

Measurement-Device-Independent (MDI) QKD – Scheme [1]

= time-reversed E91 protocol!



- Alice **and** Bob both prepare single photons with randomly chosen BB84 states and send them to a common relay station ‚Charly'

- Charly performs a partial Bell-state measurement (BSM) on both photons:
  → Projection in Ψ^- → Click at D_{1H} and D_{2V} or D_{1V} and D_{2H}
  → Projection in Ψ^+ -> Click at D_{1H} and D_{1V} or D_{2V} and D_{2H}

- Charly announces successful BSMs (clicks in orthogonal polarization) and resepctive results

- Alice and Bob sift their keys:
  → Keep entries which resulted in a succesfull BSM
  → Keep entries with same basis choice (for sending)

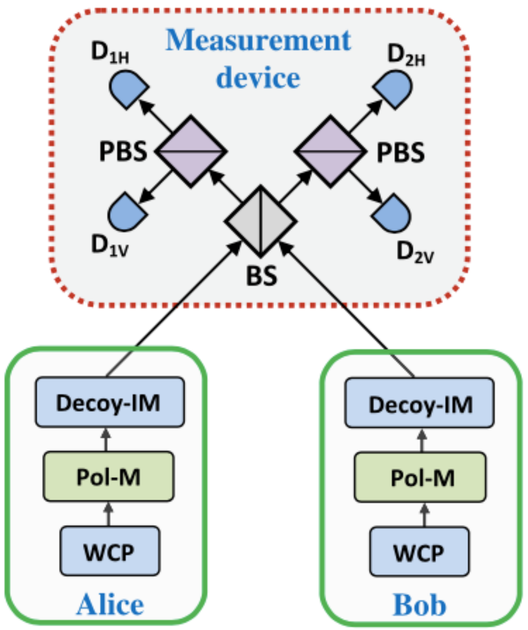
- Alice (or Bob) performs a bit flip on all entries except when both send in the diagonal basis resulting in a successfull BSM:

Alice & Bob	Relay output $\vert\psi^-\rangle$	Relay output $\vert\psi^+\rangle$
Rectilinear basis	Bit flip	Bit flip
Diagonal basis	Bit flip	No bit flip

[1] H. K. Lo, M. Curty, and B. Qi, PRL 108, 130503 (2012) and S. L. Braunstein and S. Pirandola, PRL 108, 130502 (2012)

MDI-QKD

MDI-QKD – Motivation [1]



- Hard to avoid security loopholes in practical applications
  → Device-independent (DI) schemes very attractive but challenging!

- Many attacks target the detector [2]:

Attack	*Target component*	*Tested system*
Time-shift [76–79]	Detector	Commercial system
Time-information [80]	Detector	Research system
Detector-control [81–83]	Detector	Commercial system
Detector-control [84]	Detector	Research system
Detector dead-time [85]	Detector	Research system
Channel calibration [86]	Detector	Commercial system
Phase-remapping [87]	Phase modulator	Commercial system
Faraday-mirror [88]	Faraday mirror	Theory
Wavelength [89]	Beam-splitter	Theory
Phase information [90]	Source	Research system
Device calibration [91]	Local oscillator	Research system

→ MDI-QKD interesting alternative to full DI schemes for some applications

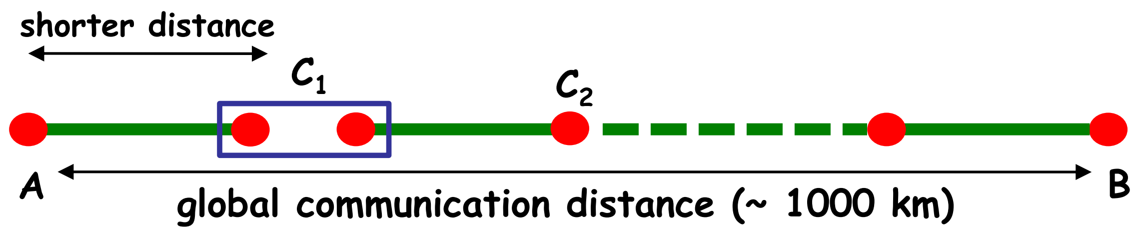
⇨ **MDI-QKD important step towards multi-user neteworks and quantum repearters**

[1] H. K. Lo, M. Curty, and B. Qi, PRL 108, 130503 (2012) and S. L. Braunstein and S. Pirandola, PRL 108, 130502 (2012)
[2] H. K. Lo, M. Curty, and K. Tamaki, Nature Photonics 8, 595-604 (2014)

Quantum Repeater

Working Principle

- Quantum repeater [1] extend achievable communication distance



[1] 1st Theory: H.-J. Briegel et al., Phys. Rev. Lett 81, 5932 (1998)

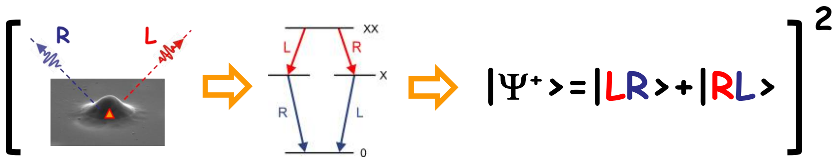
Resources Required [2]

- Entanglement Swapping
- Entanglement Purification
- Quantum Memories

[2] N. Gisin & R. Thew, Nat. Photon. 1, 165 (2007)

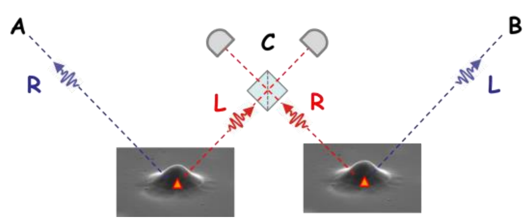
Entanglement Swapping

1. Generate entangled photon-pairs from remote quantum emitters



2. Perform Bell-state measurement of XX-photons at C:

$$|\Psi^+\rangle_C = |LR\rangle + |RL\rangle$$



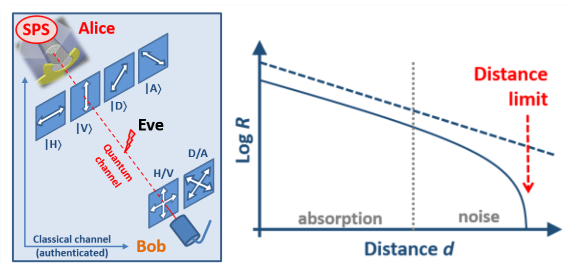
3. Verify entanglement of photon-pairs A-B: $|\Psi^+\rangle = |RL\rangle + |LR\rangle$

Note: Experimental progress by groups Trotta, Rastelli, and Schmidt using quantum dots

Outline – Part I

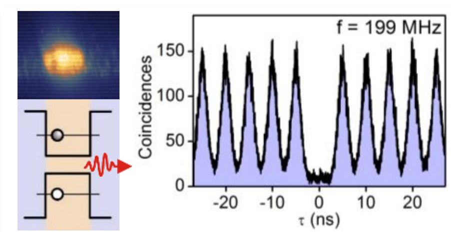
About Us

- QuCom Group @ Berlin
- Research & Vision



Quantum Communication Intro

- Point-to-Point QKD Protocols (BB84, E91, …)
- Advanced Protocols (MDI-QKD, QuRepeater)
- Beyond QKD



Single-Photon Generation in the Solid-State

Quantum Dots and the Purcell Effect


REVIEW

ADVANCED QUANTUM TECHNOLOGIES

www.advquantumtech.com

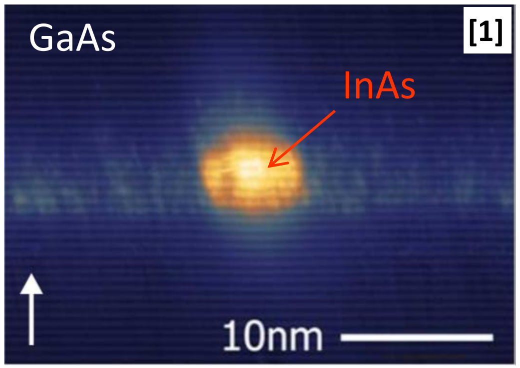
Quantum Communication Using Semiconductor Quantum Dots

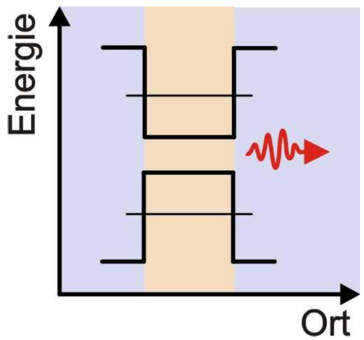
Single-Photon QKD

A Brief Review

How to Single Photon

Quantum dot (QD) – "artificial atom" ⇨ **Excitonic multiparticle-states [2]**





[1] Keizer et al., *APL* **101**, 243113 (2012)

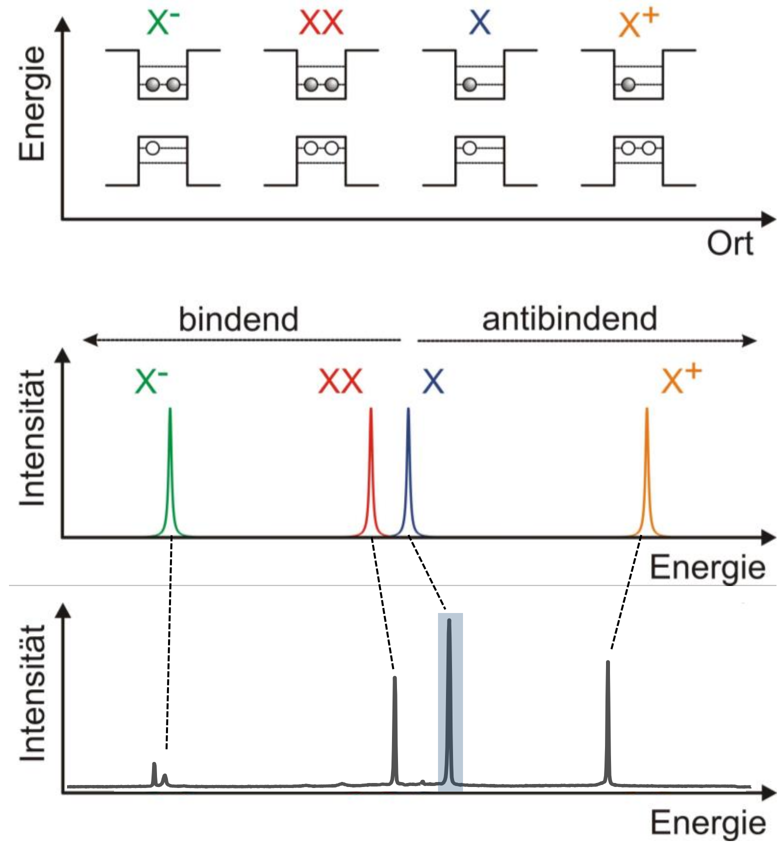
3D confinement of charge carriers ≤ λ_{db}

→ Descrete energy levels

→ Bound electron-hole pairs: excitons (X)

→ Radiative recombination

→ **Emission of single photons**

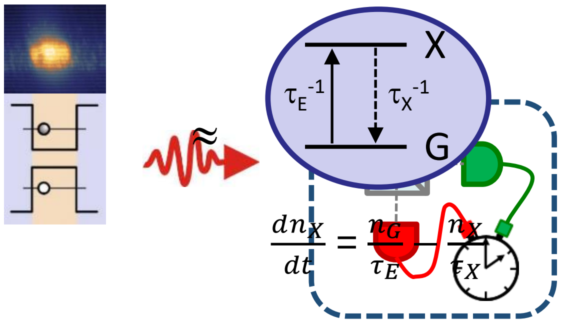


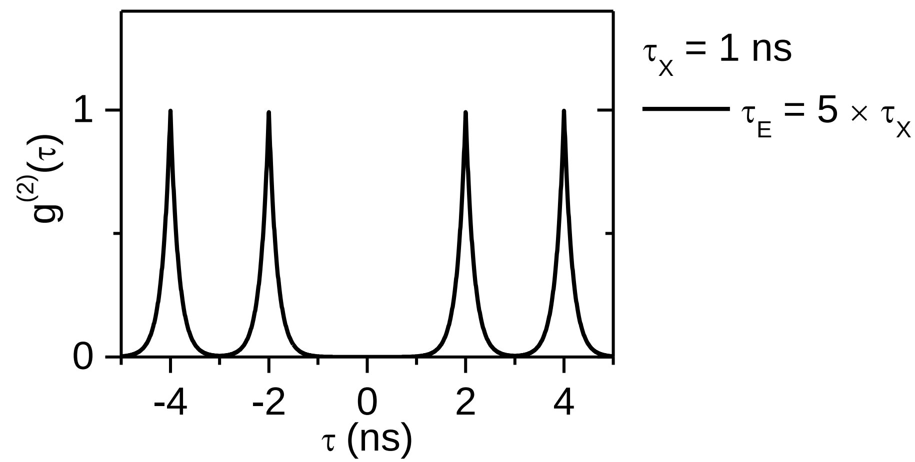
[2] S. Rodt et al., *Phy. Rev. B* 71, 155325 (2005)

How to Single Photon

Quantum dot (QD) ≈ 2-Level System [1]

[1] P. Michler et al., *Nature* **406**, 968 (2000)





Hanbury-Brown and Twiss (HBT) setup

[1] HBT, *Nature* **177**, 4497 (1956)

Autocorrelation function:

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

thermal light: $g^{(2)}(0) > g^{(2)}(\tau)$ (bunching)

coherent light: $g^{(2)}(0) = g^{(2)}(\tau)$ (Poissonian)

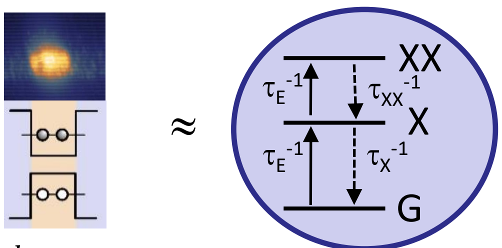
non-classical light: $g^{(2)}(0) < g^{(2)}(\tau)$ (antibunching)

How to Entangle Photons

Entanglement!

Quantum dot (QD) ≈ 3-Level System [2,3]

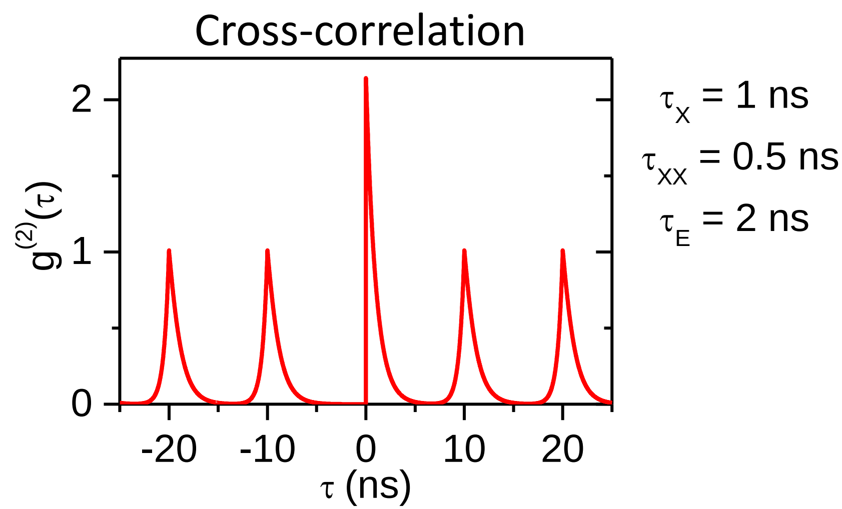
[2] E. Moreau et al., *Phys. Rev. Lett.* **87**, 183601 (2001)
[3] T. Aichele, *PhD Thesis*, Humboldt-Universität zu Berlin, (2005)



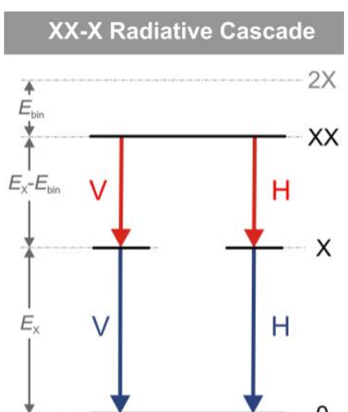
$$\frac{dn_G}{dt} = -\frac{n_G}{\tau_E} + \frac{n_X}{\tau_X}$$

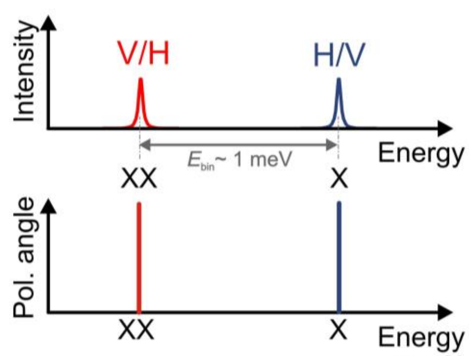
$$\frac{dn_X}{dt} = \frac{n_G}{\tau_E} - \left(\frac{1}{\tau_X} + \frac{1}{\tau_E}\right) \cdot n_X + \frac{n_{XX}}{\tau_{XX}}$$

$$\frac{dn_{XX}}{dt} = \frac{n_X}{\tau_E} - \frac{n_{XX}}{\tau_{XX}}$$



[4] T. Kuroda et al., *Phys. Rev. B* **79**, 035330 (2009)





$|\Psi^+\rangle = |LR\rangle + |RL\rangle$

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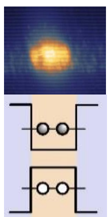
[3] T. Aichele, *PhD Thesis*, Humboldt-Universität zu Berlin, (2005)



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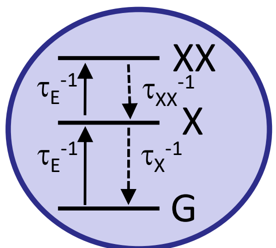

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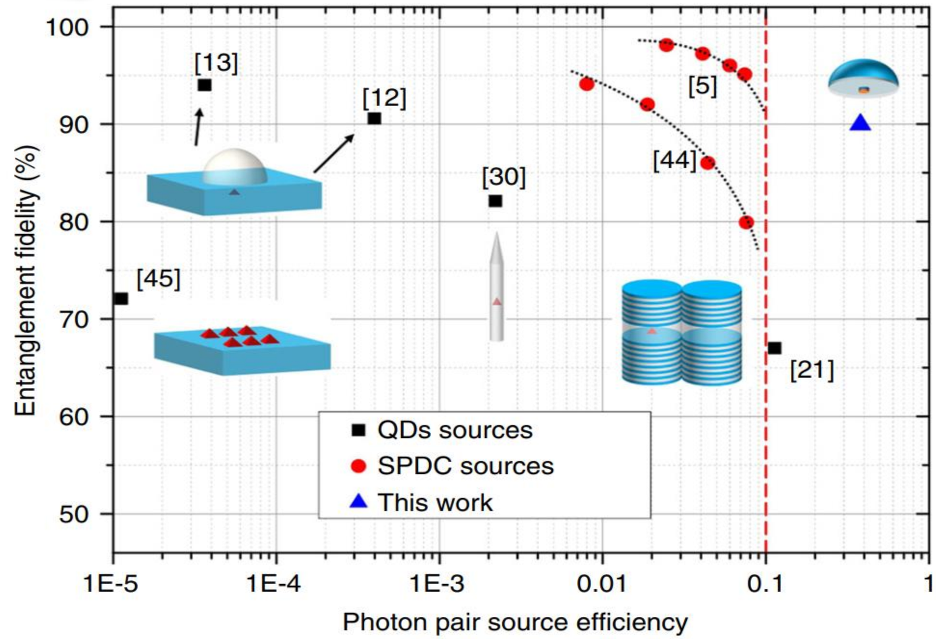
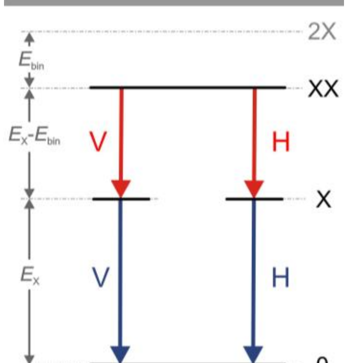
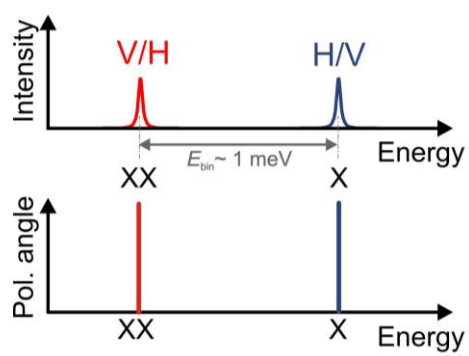
$$\frac{dn_{XX}}{dt} = \frac{n_X}{\tau_E} - \frac{n_{XX}}{\tau_{XX}}$$

Y. Chen et al.., Nat. Commun. 9, 2994 (2018)



XX-X Radiative Cascade





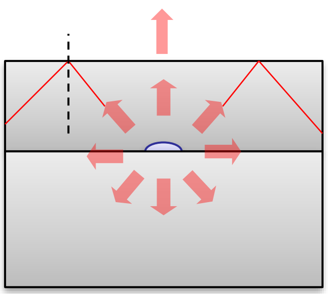
|Ψ⁺> = |LR> + |RL>

Photon Extraction Strategies

Quantum Dot in Bulk ⇔ **Quantum Dot in Microcavity**

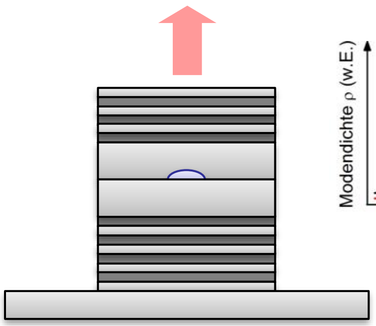
⇨ Single photon emitter

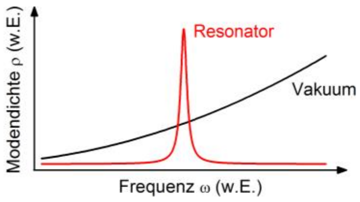
But: Efficiency $\eta_{ext} < 3$ %



⇨ Exploit Purcell Effect [1]

→ Efficient SPSs $\eta_{ext} \sim 1$





Fermis Golden Rule

$$\frac{1}{\tau} = \frac{4\pi}{\hbar}\rho(\omega_0)|\langle \vec{d} \cdot \vec{f}(r_0)\rangle|^2$$

+ Op. Mode density $\rho(\omega)$ in microcavity

⇨ Modification of spontaneous emission lifetime [1]

Purcell factor: $$F_P = \underbrace{\frac{3Q(\lambda_C/n)^3}{4\pi^2 V_M}}_{F_P^{max}} \cdot \underbrace{\frac{\gamma_C^2}{4\Delta^2 + \gamma_C^2}}_{\text{spektral}}$$ [2]

$F_P = \tau_{3D} / \tau_{Res}$

[1] E. M. Purcell, *Proc of the APS* **69**, 681 (1946)
[2] B. Gayral et al., *Phys. Rev. Lett.* **90,** 229701 (2003)
[3] K. J. Vahala, *Nature* **424**, 839-846 (2003)

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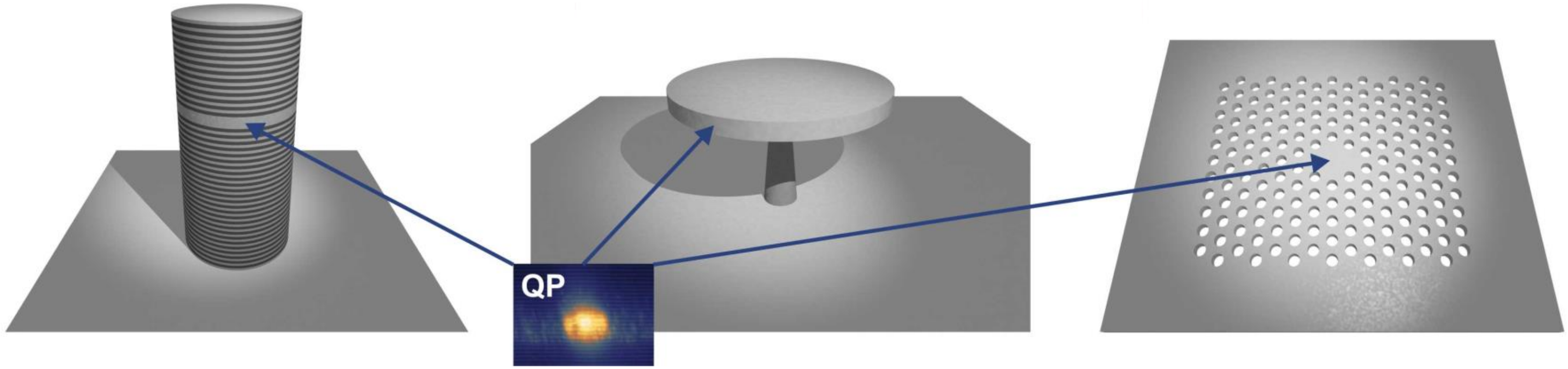

Micro-Pillar

Micro-Disc

Photonic Crystall

[3] K. J. Vahala, *Nature* **424**, 839-846 (2003)

Outline – Part I

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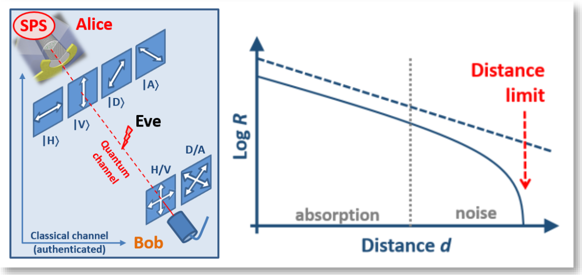

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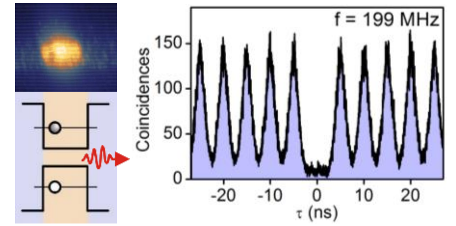


Single-Photon Generation in the Solid-State

Quantum Dots and the Purcell Effect

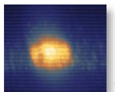
Single-Photon QKD

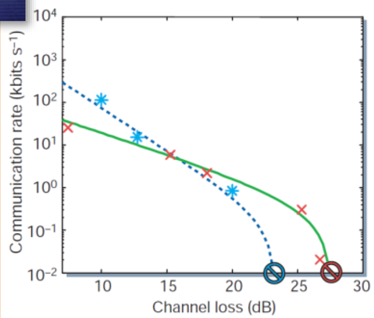
A Brief Review

Single-photon QKD

Early Work ... more recent: Jennewein/Reimer (arXiv) and Rastelli/Trotta (entanglement QKD)

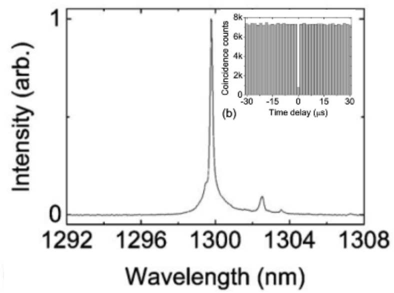
Yamamoto Group





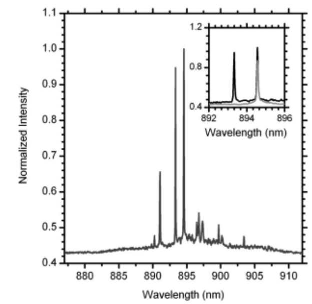
E. Waks et al.:
Nature 420, 762 (2002)

Shields Group



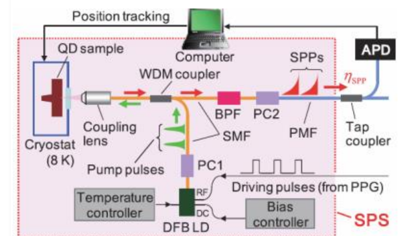
P. M. Intallura et al.:
APL 91, 161103 (2007)

Skolnick Group



P. J. Collins et al.:
JAP 107, 073102 (2010)

Arakawa Group

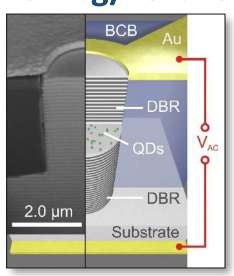


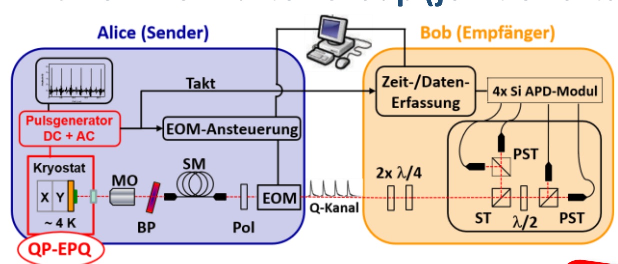
K. Takemoto et al.:
AP Express 3, 092802 (2010)

Benson Group

M. Leifgen et al.:
NJP 16, 023021 (2014)

Höfling/Forchel-Michler-Weinfurter Group (joint efforts)





T. Heindel et al.: *New J. Phys.* 14, 083001 (2012)
M. Rau, T. Heindel et al.: *New. J. Phys.* 16, 03003 (2014)

In-Lab + 500 m Link

Single-photon QKD

D. Vajner et al., *Adv. Qauntum Technol.* 2100116 (2022)

Paper Link

REVIEW

ADVANCED QUANTUM TECHNOLOGIES
www.advquantumtech.com

Quantum Communication Using Semiconductor Quantum Dots

*Daniel A. Vajner, Lucas Rickert, Timm Gao, Koray Kaymazlar, and Tobias Heindel**

Worldwide, enormous efforts are directed toward the development of the so-called quantum internet. Turning this long-sought-after dream into reality is a great challenge that will require breakthroughs in quantum communication and computing. To establish a global, quantum-secured communication infrastructure, photonic quantum technologies will doubtlessly play a major role, by providing and interfacing essential quantum

well as the strategies of breaking them, have been employed over time (see Singh for a historic overview[1]), most current security standards rely on the computational complexity of so-called one-way functions.[2] However, considering the steady increase in computat not stay

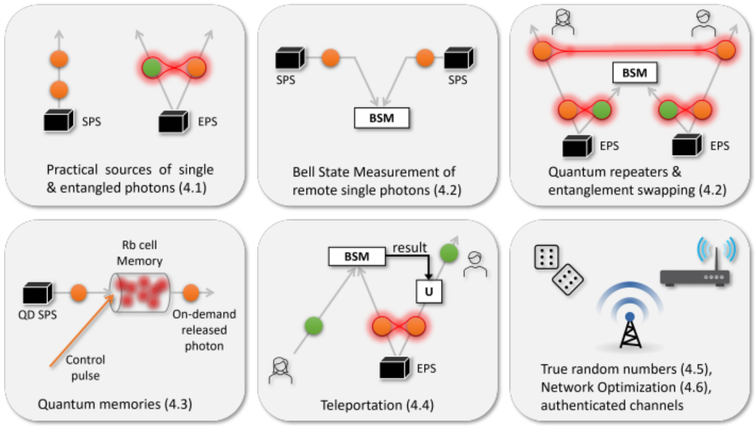
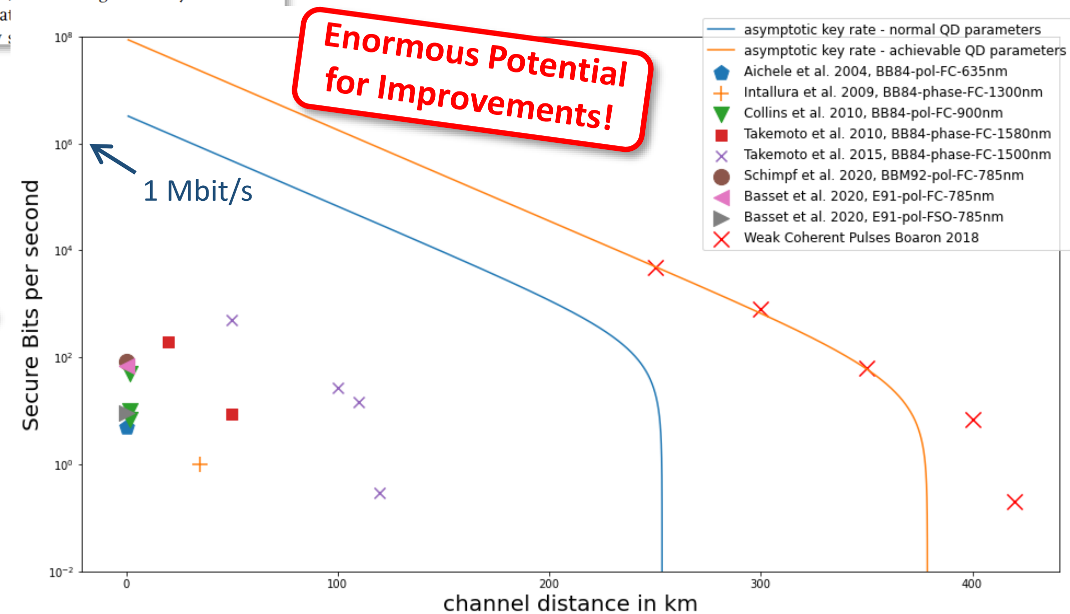
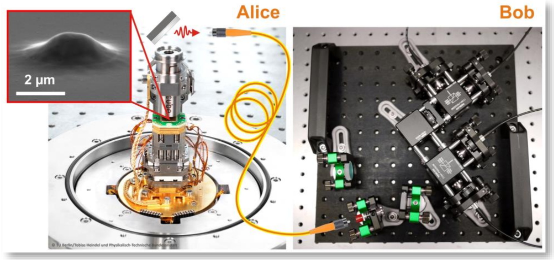
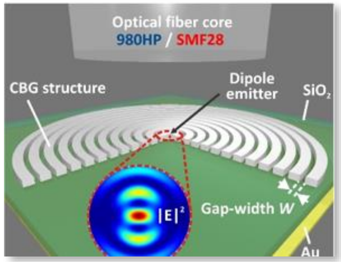


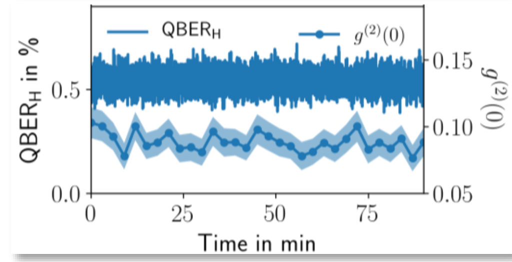
Table 1: Summary of QKD implementations employing QD-based quantum light sources (abbreviations: polarization (Pol), single-photon source (SPS), entangled photon-pair source (EPS), free space optical (FSO), fiber-coupled (FC))

Protocol	Coding	Source/ Pump	Clock-rate [MHz]	λ [nm]	Max Sifted Key Rate	Max Secure Key Rate	QBER [%]	FSO/ FC	Max distance	Ref.
BB84	Pol	SPS / optic.	76	880	-	25 kbps	2.5	FSO	In-Lab	[130]
BB84	Pol	SPS / optic.	0.01	635	15 bps	5 bps	6.8	FSO	In-Lab	[161]
BB84	Phase	SPS / optic.	1	1300	10 bps	1 bps	5.9	FC	35 km	[131]
BB84	Pol	SPS / optic.	40	895	-	8-600 bps	1.2-21.9	FC	2 km	[165]
BB84	Phase	SPS / optic.	20	1580	15-386 bps	3-9 bps	3.4-6	FC	50 km	[141]
BB84	Pol	SPS / elect.	182.6	898	8-35 kbps	-	3.8-6.7	FSO	In-Lab	[135]
BB84 a)	Pol	SPS / elect.	200	653	9-117 kbps	-	4.1-6.0	FSO	In-Lab	[135]
BB84	Pol	SPS / elect.	125	910	5-17 kbps	-	6-9	FSO	500 m	[170]
BB84	Phase	SPS / optic.	62.5	1500	34 bps	0.307 bps	2-9	FC	120 km	[168]
E91	Pol	EPS / elect.	50 b)	885	0.2 bps	0.1 bps	-	FC	In-Lab	[140]
E91 c)	Pol	EPS / optic.	320	785	243 bps	69 d)	3.4	FC	250 m	[142]
E91	Pol	EPS Optic.	320	785	30 bps	9 bps	4.0	FSO	270 m	[142]
BBM92	Pol	EPS / optic.	80	785	135 bps	86 bps	1.9	FC	350 m	[143]









Quantum Communication
Part II: *Early Work*

Tobias Heindel

Head of Group
Quantum Communication Systems

Institute of Solid State Physics
Technische Universität Berlin
Germany

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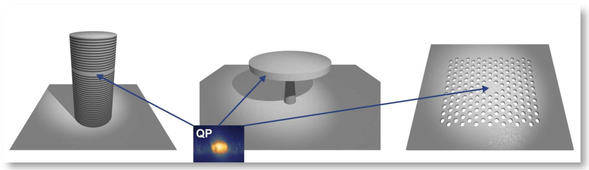
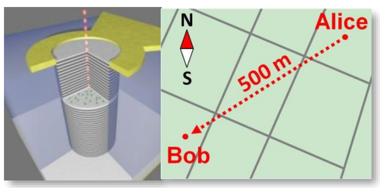
Outline – Part II

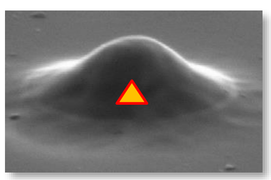


Recap
- Photon Extraction Efficiencies

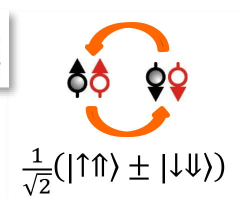
Early Work



- Electrically Triggered Single-Photon Sources
- Quantum Communication using Single-Photon LEDs



- Deterministic 3D In-Situ Electron Beam Lithography
- Fundamental Quantum Optics Experiments



Spin-Photon Interfaces

All-optically Accessing the Dark Exciton Spin-Qubit

Photon Extraction Strategies

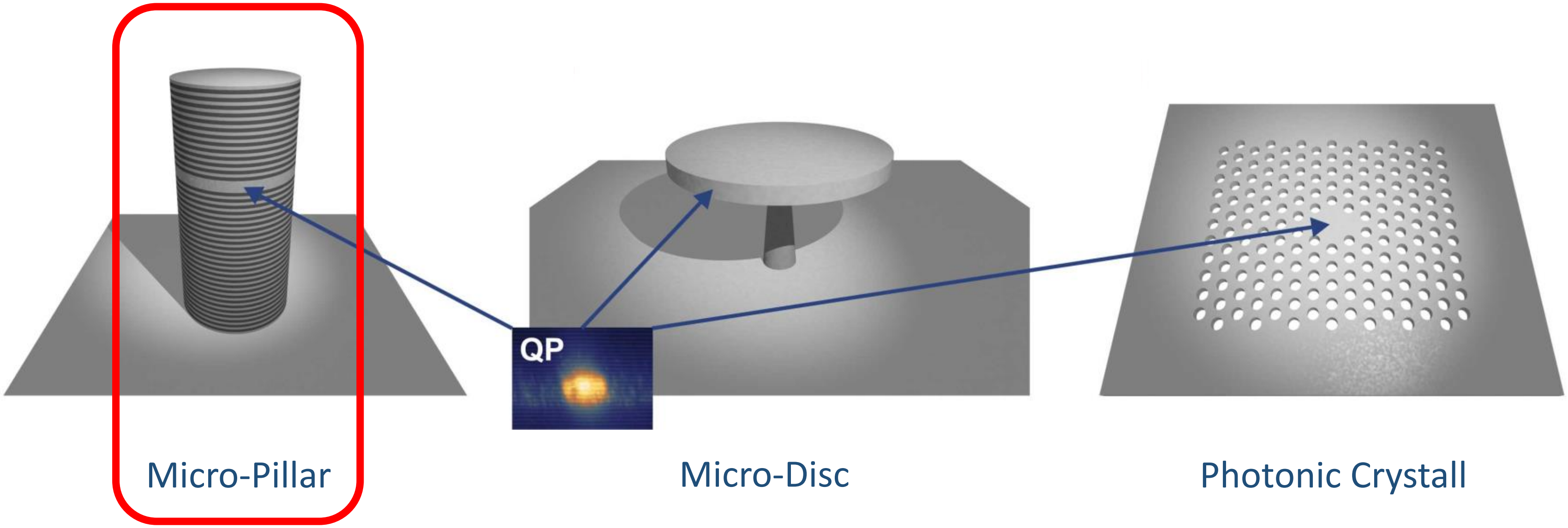
Quantum Dot in Bulk ⇔ Quantum Dot in Microcavity

⇨ Single photon emitter

But: Efficiency $\eta_{ext} < 3$ %

⇨ Exploit Purcell Effect [1]

→ Efficient SPSs $\eta_{ext} \sim 1$



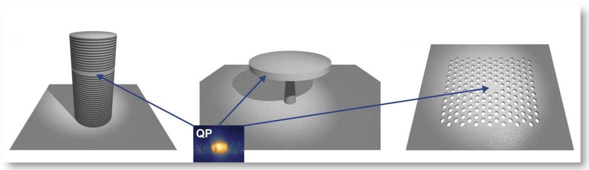
Micro-Pillar

Micro-Disc

Photonic Crystall

[3] K. J. Vahala, *Nature* **424**, 839-846 (2003)

Outline – Part II



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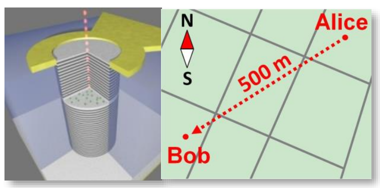

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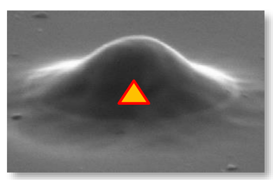
- Quantum Communication using Single-Photon LEDs



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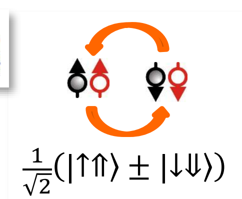


Spin-Photon Interfaces

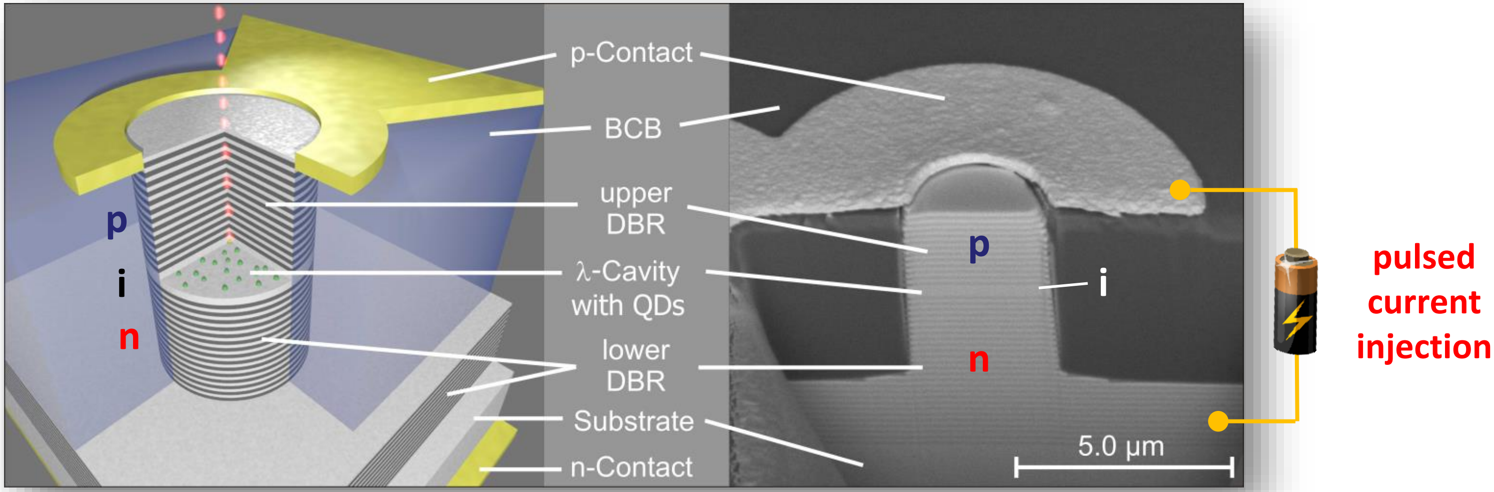
All-optically Accessing the Dark Exciton Spin-Qubit

Single-Photon Light Emitting Diode

→ T. Heindel et al., *Appl. Phys. Lett.* 96, 011107 (2010)

Quantum Dot Micropillar single-photon source

- Optimized Design
- Efficient light extraction



- Upper DBR: 13 λ/4 GaAs/AlAs, p-doping
- Active region: InAs QDs in an intrinsic λ-cavity
- Lower DBR: 26 λ/4 GaAs/AlAs, n-doping

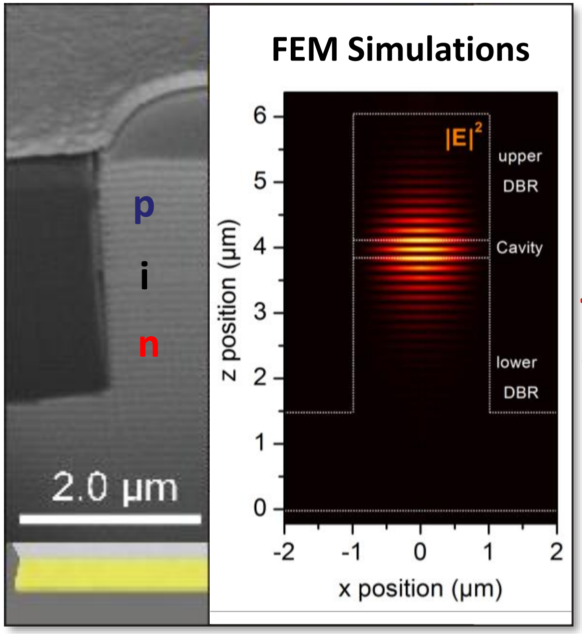
⇨ **Exploit Purcell-effect for efficient photon extraction**

Device Technology

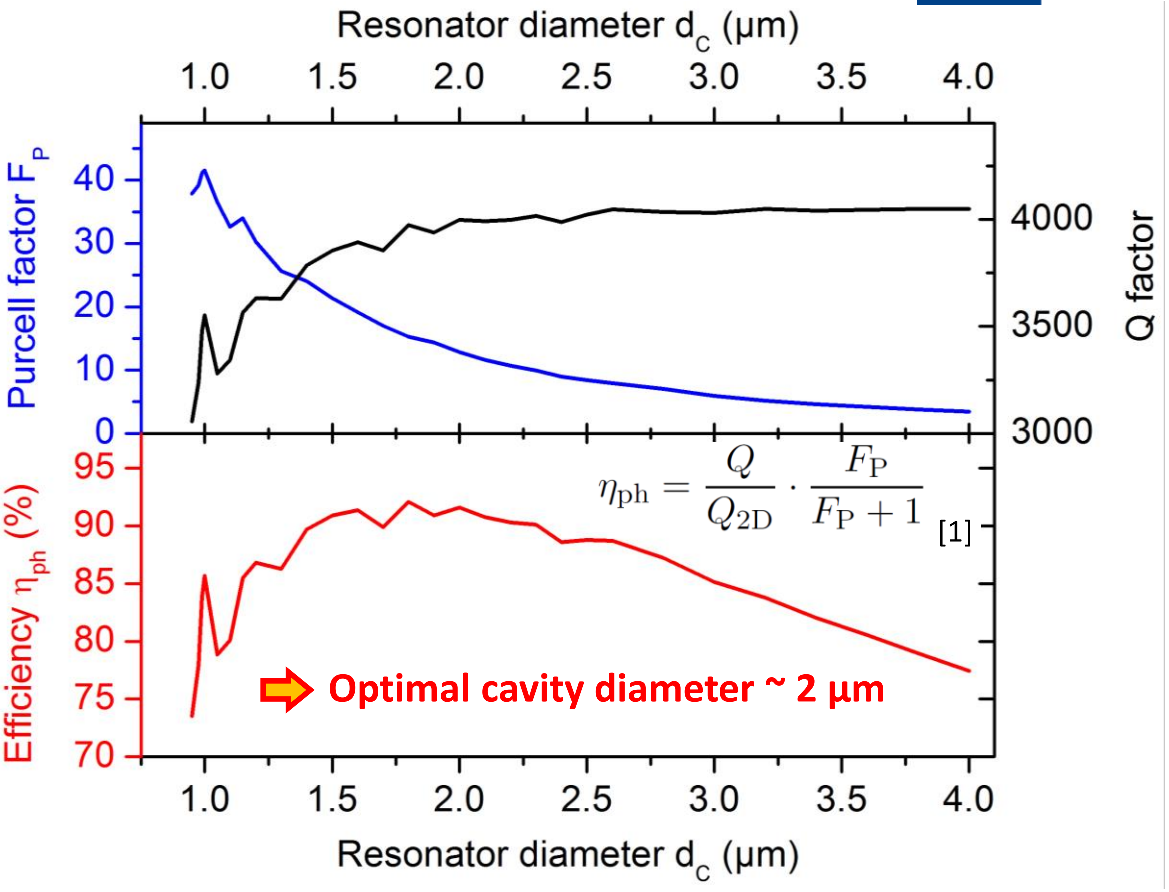
→ T. Heindel et al., *Appl. Phys. Lett.* 96, 011107 (2010)

Quantum Dot Micropillar single-photon source

- Optimized Design
- Efficient light extraction



JCMwave
Supported by Sven Burger

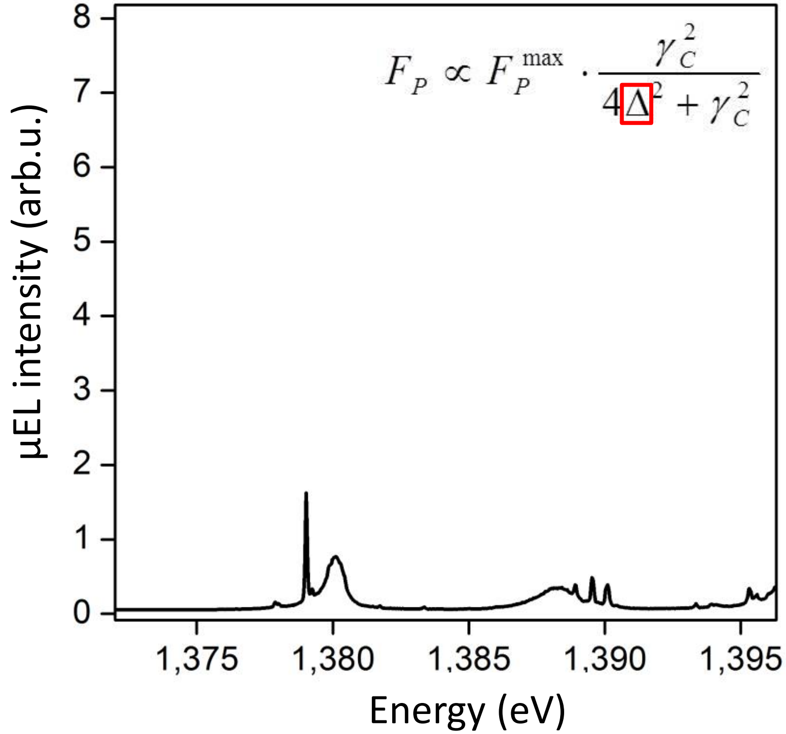


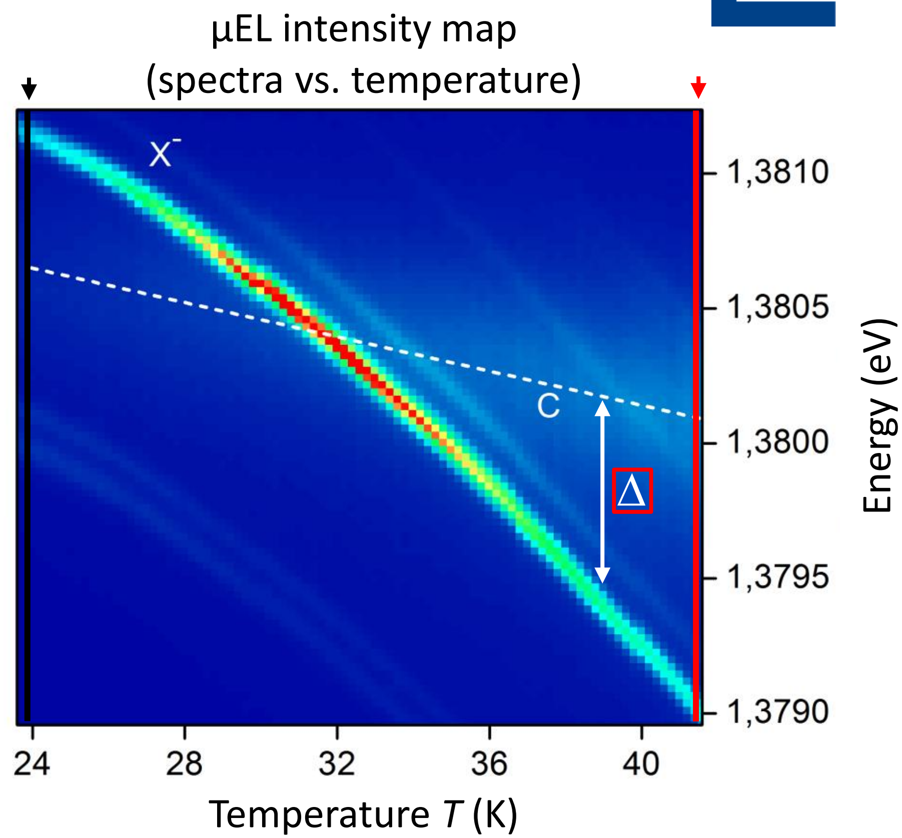
[1] W. L. Barnes et al., *Eur. Phys. J. D* **18**, 197 (2002)

Purcell Enhancement

→ T. Heindel et al., *Appl. Phys. Lett.* 96, 011107 (2010)

Observation of Purcell-enhancement:





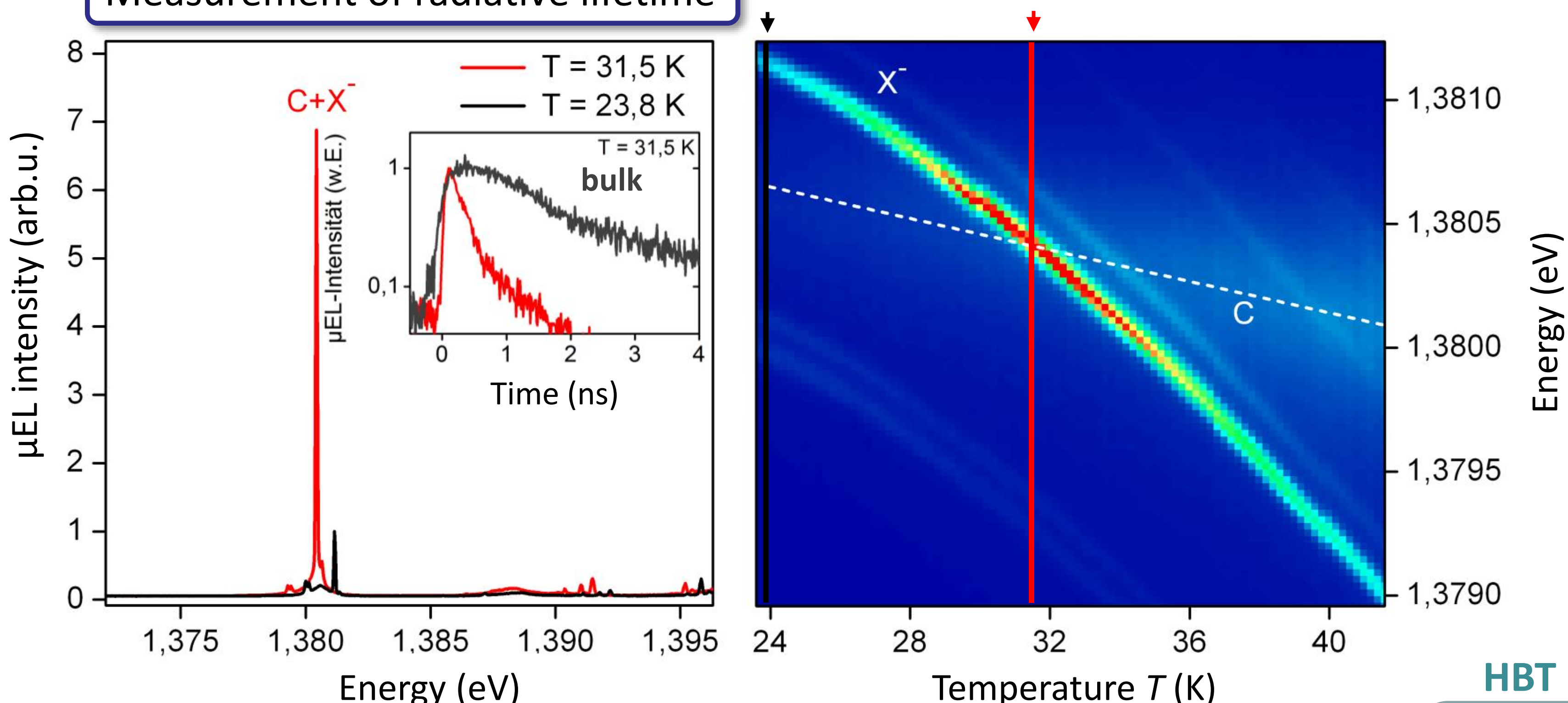
- Temperature-induced spectral tuning of QD emission

Purcell Enhancement

→ T. Heindel et al., *Appl. Phys. Lett.* 96, 011107 (2010)

Observation of Purcell-enhancement:

Measurement of radiative lifetime



Lifetime at spectral resonance: 300 ps (↔ 1.2 ns in bulk)
→ enables GHz modulation speed

Purcell-Factor $F_P = 4$

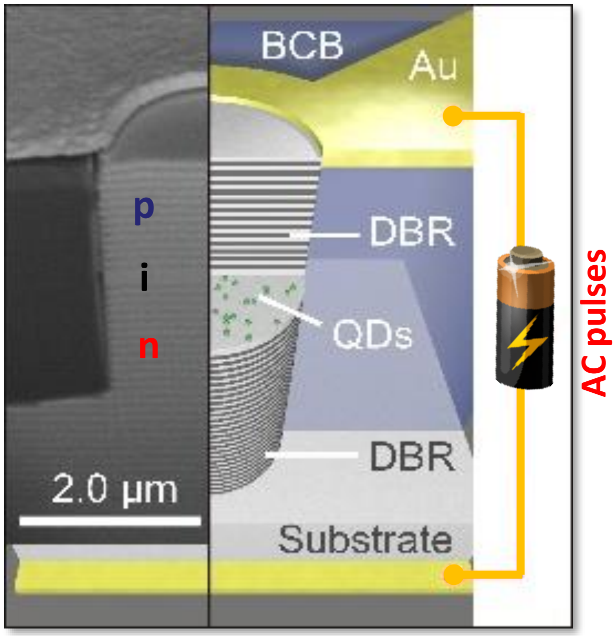
HBT

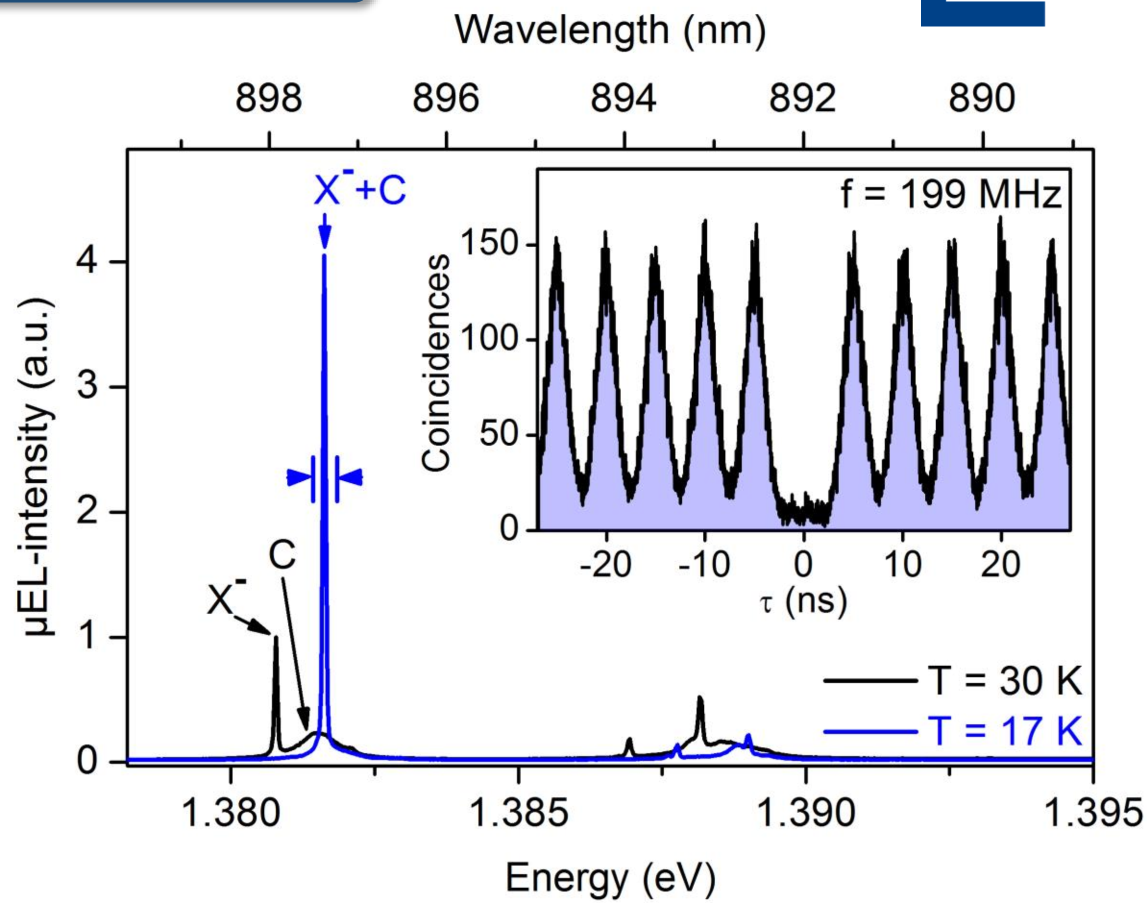
Purcell-enhanced SPS

→ T. Heindel et al., *Appl. Phys. Lett.* 96, 011107 (2010)

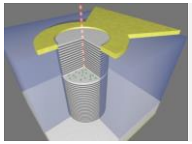
Quantum Dot Micropillar single-photon source

- Optimized Design
- Efficient light extraction





Single-Photon QKD



Electrically triggered Single-Photon Source

T. Heindel et al., *Appl. Phys. Lett.* 96, 011107 (2010)

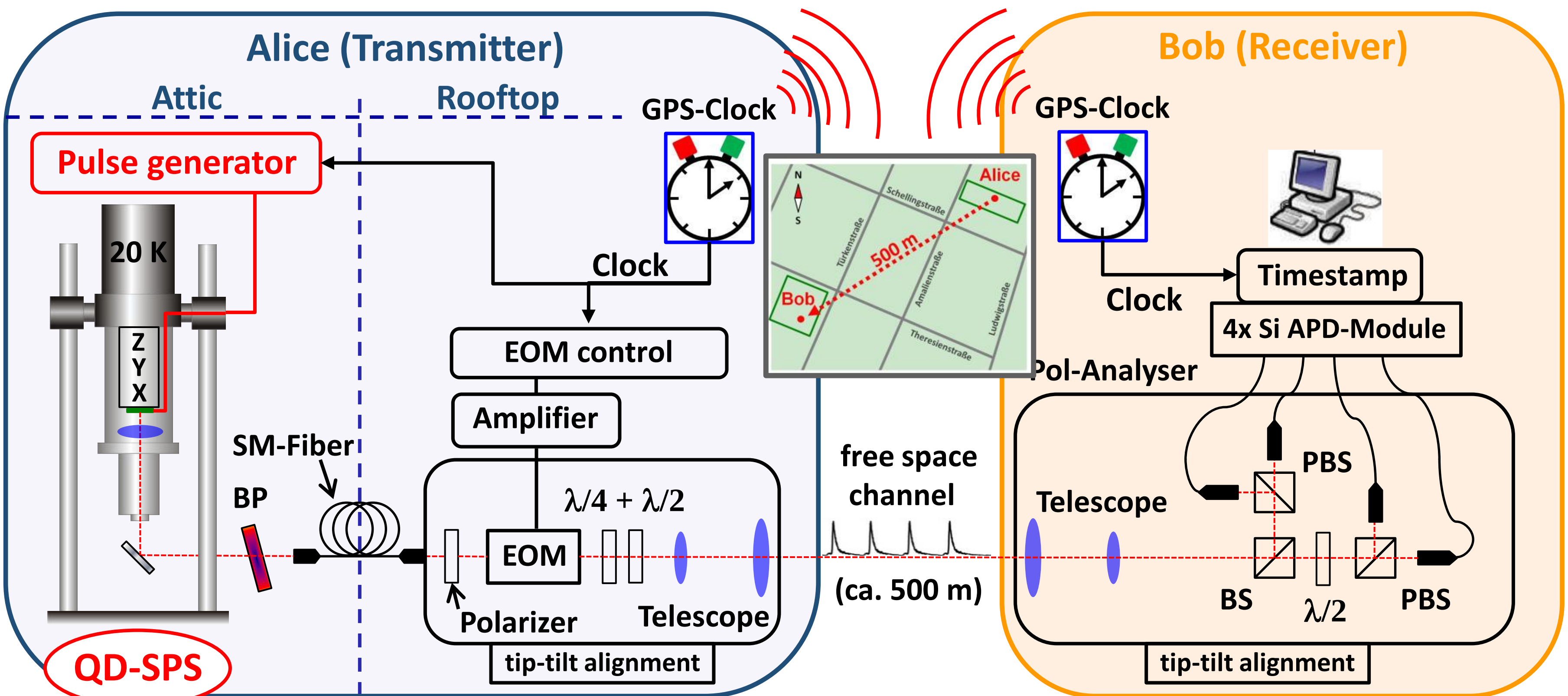
⇨

Lab-scale QKD experiment

Key rate: 35.4 kbit/s, QBER: 3.8%

T. Heindel et al., *New J. Phys.* 14, 083001 (2012)

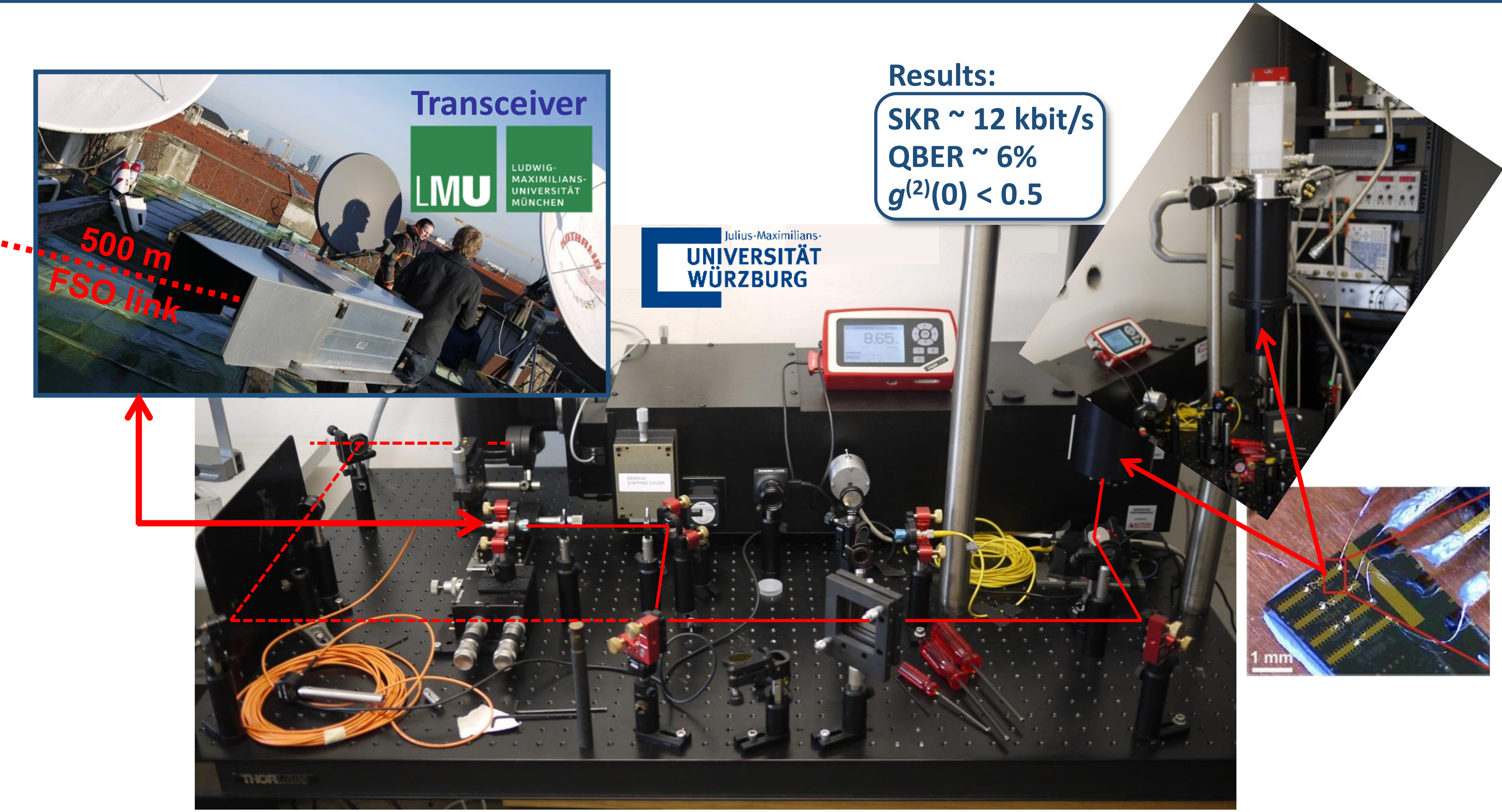
⇩ **Free space optical QKD-link in downtown Munich** ⇩



H → +45° → V → -45°

500 m QKD – Experimental setting

→ M. Rau, T. Heindel et al., *New. J. Phys.* 16, 03003 (2014)



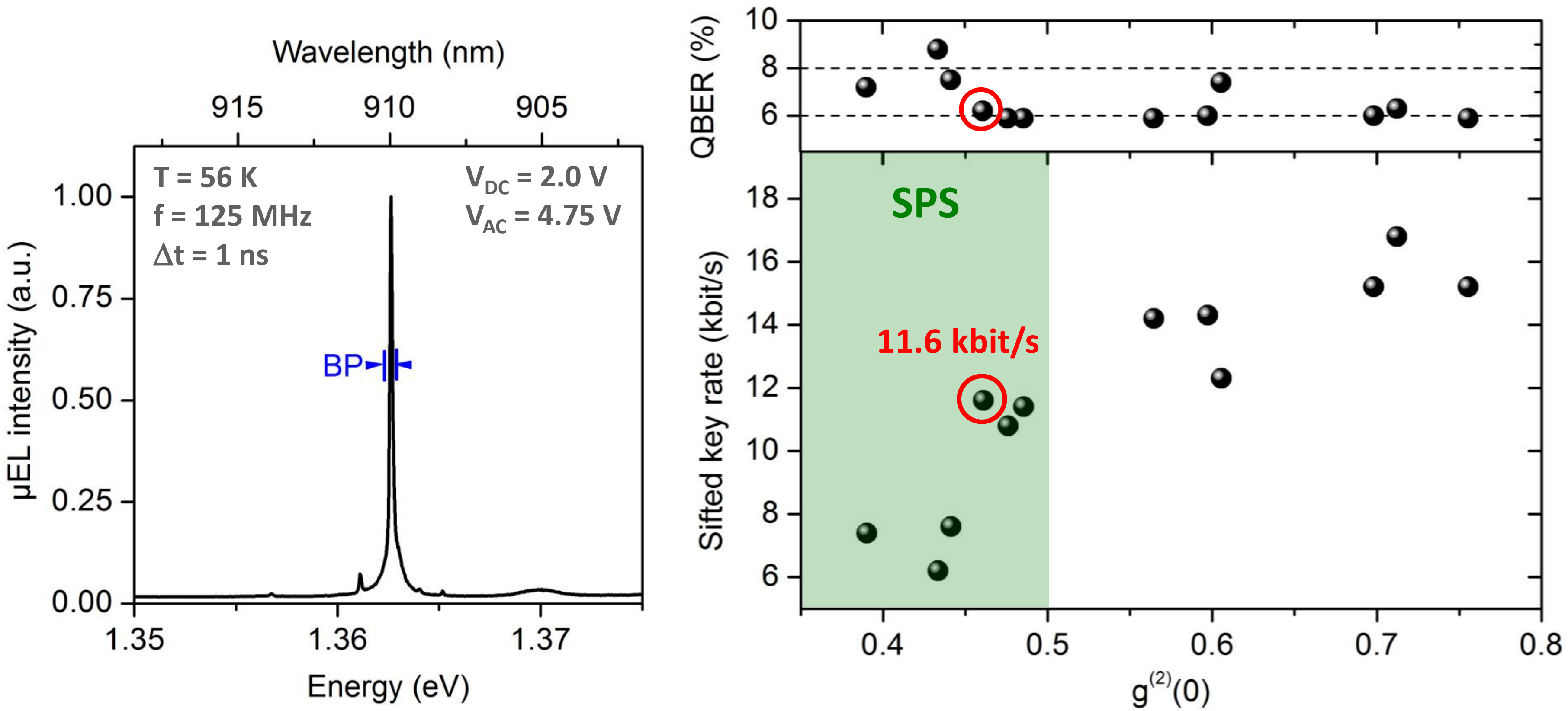
Results:

- SKR ~ 12 kbit/s
- QBER ~ 6%
- $g^{(2)}(0) < 0.5$

500 m QKD – Results

→ M. Rau, T. Heindel et al., *New. J. Phys.* 16, 03003 (2014)

New Journal of Physics
The open access journal at the forefront of physics



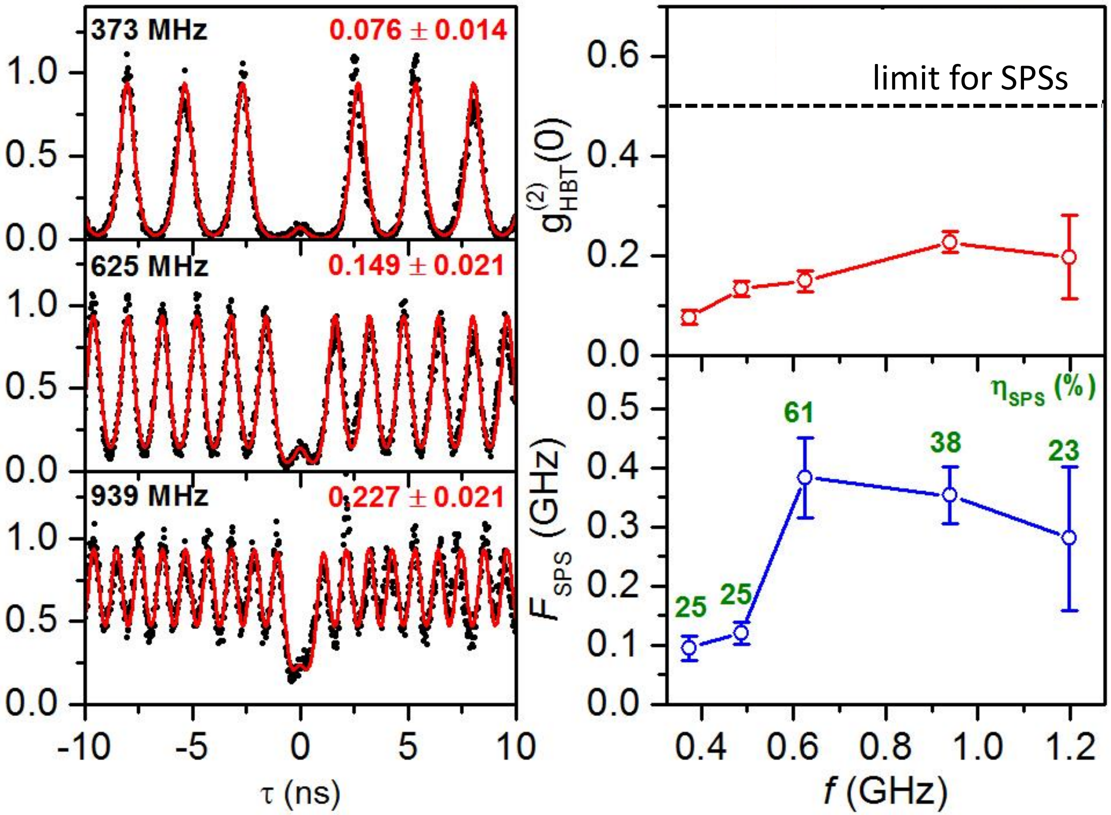
First proof-of-concept QKD field-experiments using elctrically operated SPSs

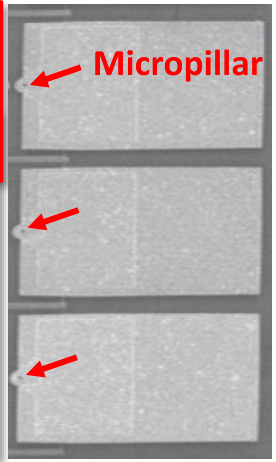
- **Exploiting full potential of SPSs → ~10-100 Mbit/s possible**
- **Enhanced security considering advanced attacks**

QuSecure

High-speed Single-Photon LED

→ A. Schlehahn, TH et al., *APL Photonics* 1, 011301 (2016)





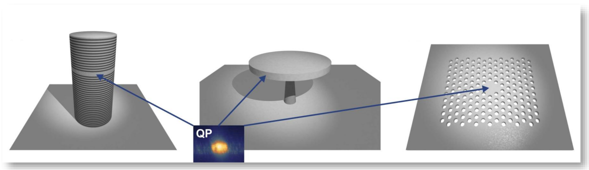
World Record!

⇨ Single-photon emission rate: 383 MHz @ 625 MHz → 61 % overall efficiency

[1] J. Claudon et al., *Nat. Photonics* **4**, 174 (2010) → 55 MHz (optically, QD in nanowire)
[2] K. G. Lee et al., *Nat. Photonics* **5**, 166 (2011) → 50 MHz detected (optically, molecule)
[3] O. Gazzano et al., *Nat. Commun.* **4**, 1425 (2013) → 65 MHz (optically, micropillar cavity)
[4] Schlehahn, TH et al., *Appl. Phys. Lett.* 107, 041105 (2015) → 143 MHz (optically, microlens)

Early work:
F. Hargart et al.,
Appl. Phys. Lett. **102**, 011126 (2013)
→ QD-LED @ 2 GHz rep. rate

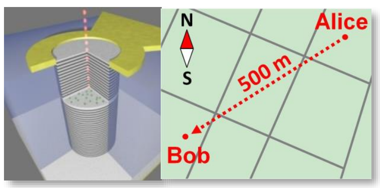
Outline – Part II



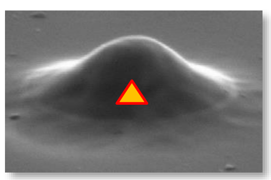
Recap

- Photon Extraction Efficiencies

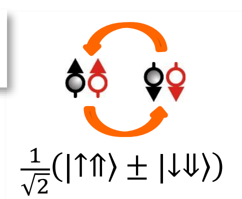
Early Work



- Electrically Triggered Single-Photon Sources
- Quantum Communication using Single-Photon LEDs



- Deterministic 3D In-Situ Electron Beam Lithography
- Fundamental Quantum Optics Experiments

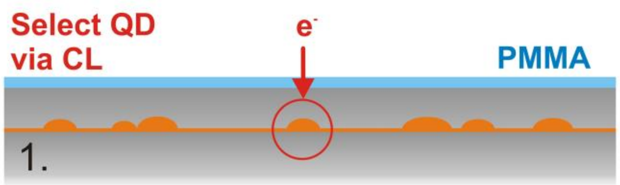


Spin-Photon Interfaces

All-optically Accessing the Dark Exciton Spin-Qubit

Deterministic Device Technology

Deterministic device concept



3D in-situ
E-beam lithography[1,2]

- Selection of suitable QDs
- Spatially deterministic processing

→ **High device yield & quality**

Journal of Physics: Condensed Matter 32, 153003 (2020)

TOPICAL REVIEW

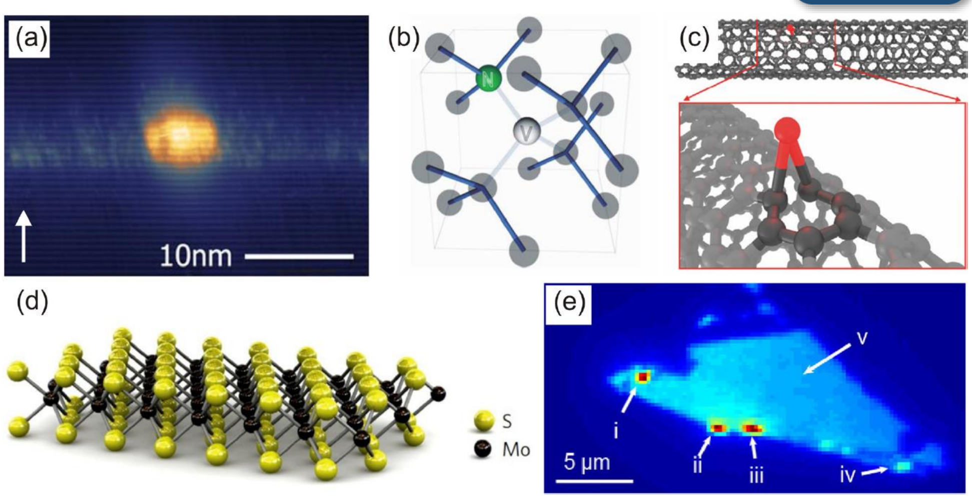
Deterministically fabricated solid-state quantum-light sources

Sven Rodt, Stephan Reitzenstein and Tobias Heindel

Published 14 January 2020 • © 2020 IOP Publishing Ltd

Journal of Physics: Condensed Matter, Volume 32, Number 15

Paper Link

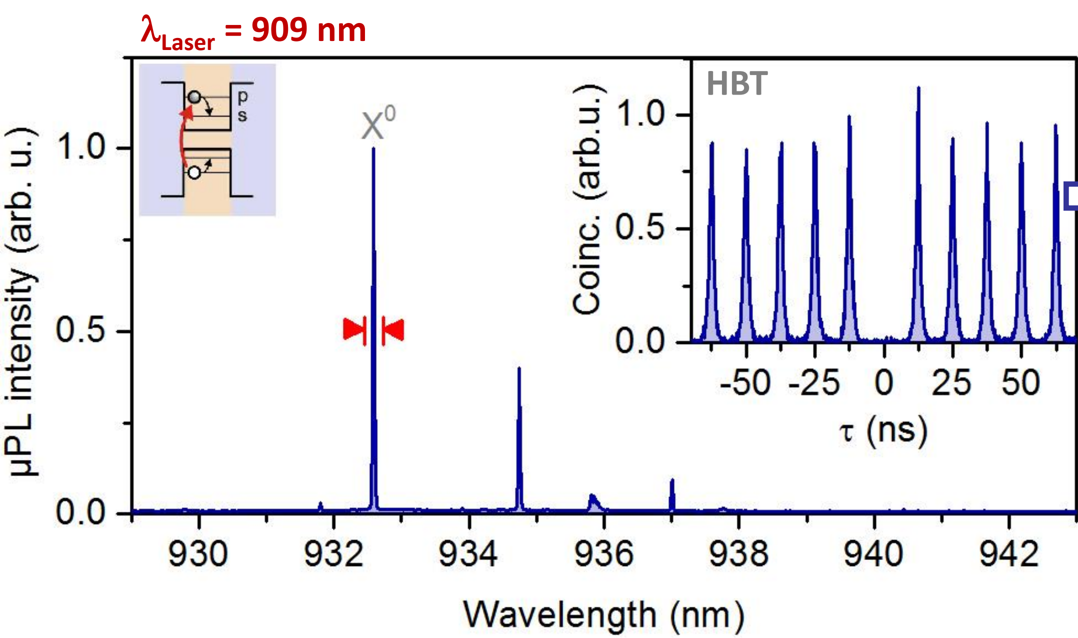


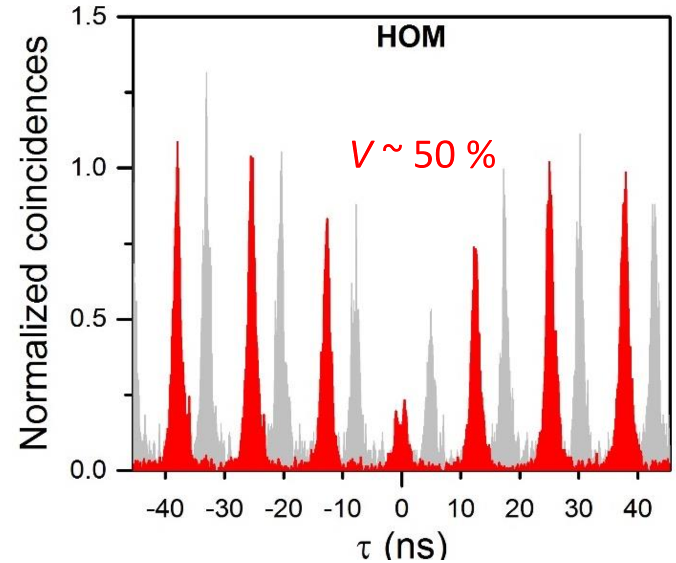
[1] M. Gschrey, T.H. et al., *APL* 102, 251113 (2013)
[2] M. Gschrey, T.H. et al., *Nat. Commun.* 6, 7662 (2015)
[3] A. Schlehahn, T.H. et al., *APL* 107, 041105 (2015)

Quantum Optics Experiments

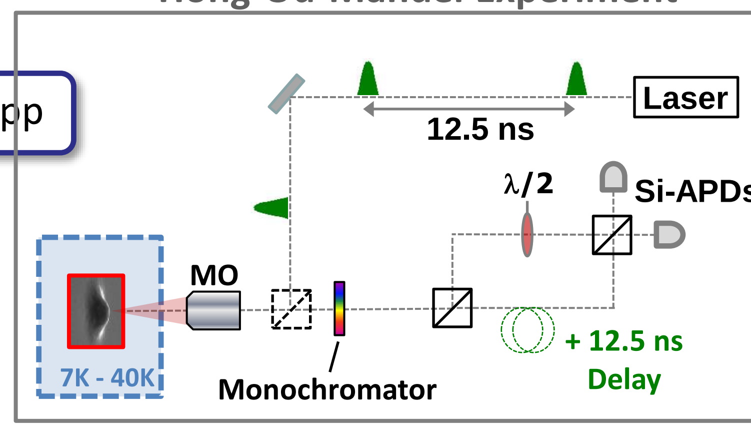
→ A. Thoma et al., *Phys. Rev. Lett.* 116, 033601 (2016)

What limits the Visibility?



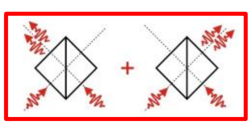


Hong-Ou-Mandel Experiment



Probe photon-indistinguishability = mean wavepacket overlapp

⇨ Crucial for advanced QKD scenarios beyond the BB84

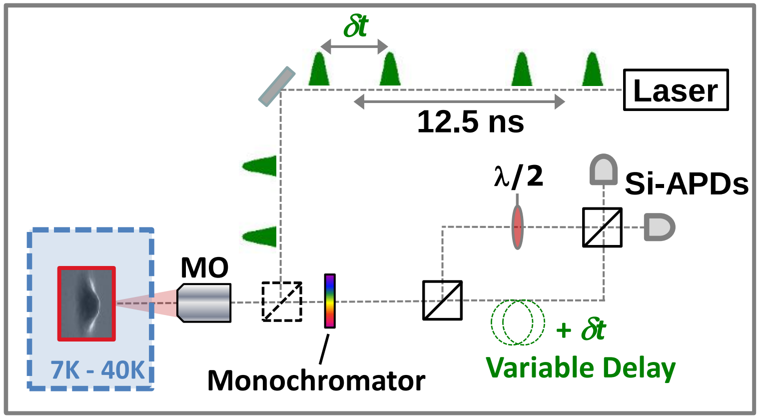


$$(|2_3 0_4\rangle - |0_3 2_4\rangle)/\sqrt{2}$$

Quantum Optics Experiments

→ A. Thoma et al., *Phys. Rev. Lett.* 116, 033601 (2016)

Hong-Ou-Mandel Experiment

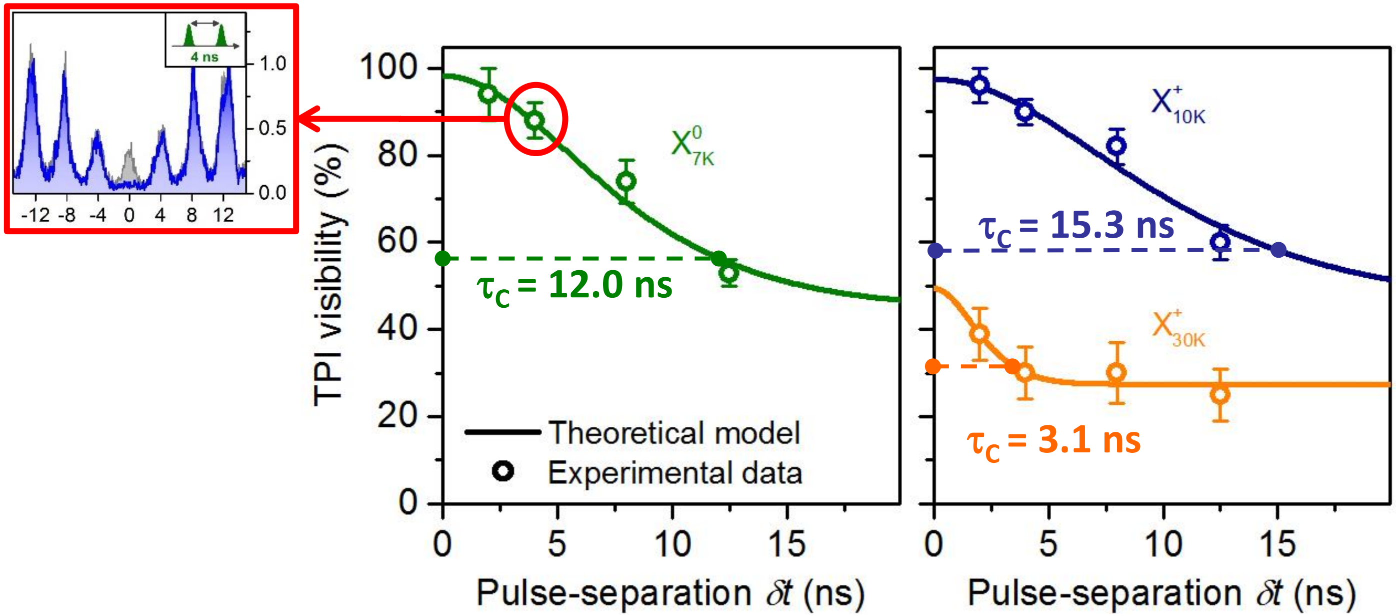


⇨ Probe photon-indistinguishability as a function of the time δt elapsed between consecutive emission events

Quantum Optics Experiments

→ A. Thoma et al., *Phys. Rev. Lett.* 116, 033601 (2016)

Up to (94 ± 4) % wavepacket overlapp



Interference of remote emitter?

Nature **419**, 594 (2002); *New J. Phys.* **6**, 89 (2004); *Phys. Rev. B* **89**, 035313 (2014); *Opt. Express* **13**, 7772 (2005);

Explanation

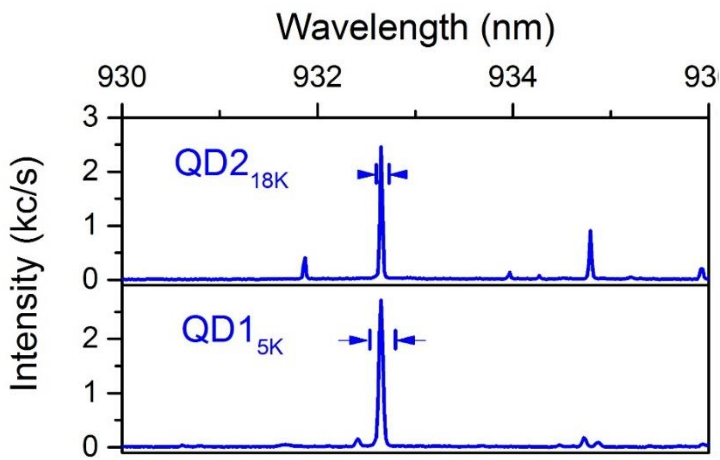
$$\frac{\Gamma}{\Gamma_0'(1-e^{-(\delta t/\tau_c)^2})+\gamma(T)+\Gamma}$$

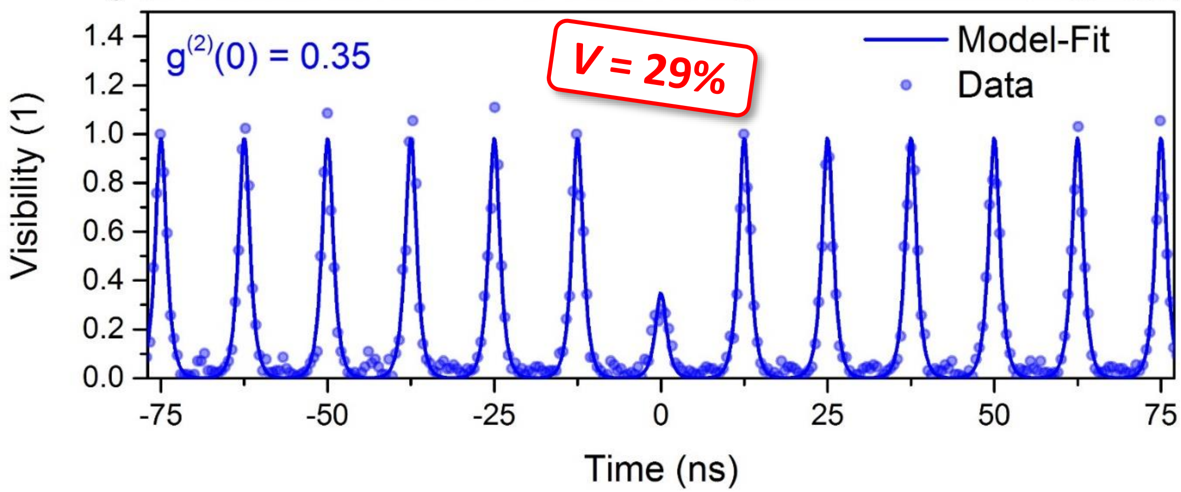
- Plateau-like behavior of TPI visibility with decreasing pulse-separation δt
- Similiar for different excitonic states of same QD (at given *T*)
- *V*(δt) reduces and τ_C shortens with increasing *T*

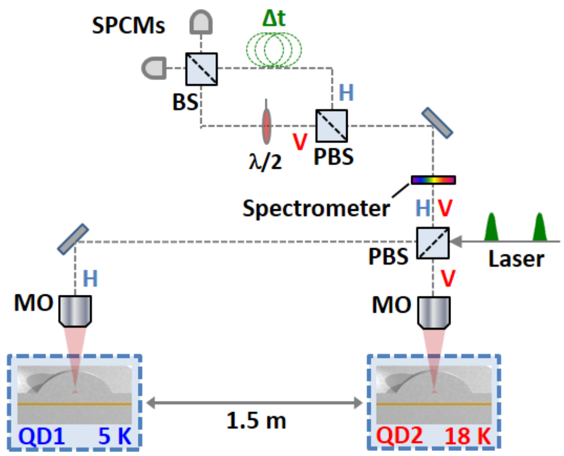
⇨ Theory: Non-Markovian noise due to spectral diffusion ↔ charge fluctuations

Quantum Optics Experiments

→ A. Thoma et al., *Appl. Phys. Lett. 110, 011104 (2017)*

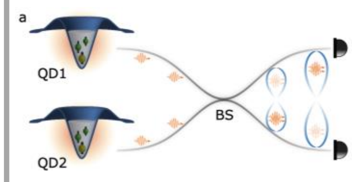


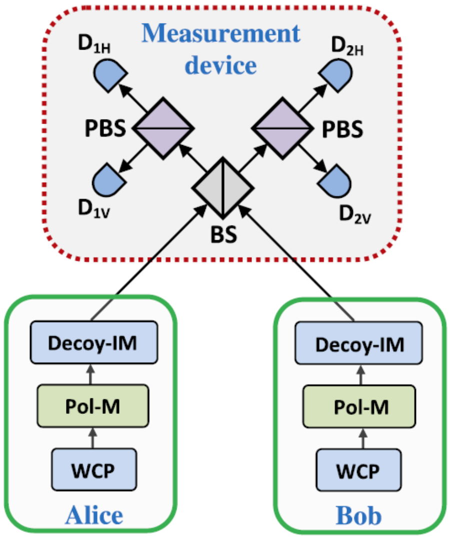




State of the art:

L. Zhai et al.
Warburton Group (2021)
93% Visibility



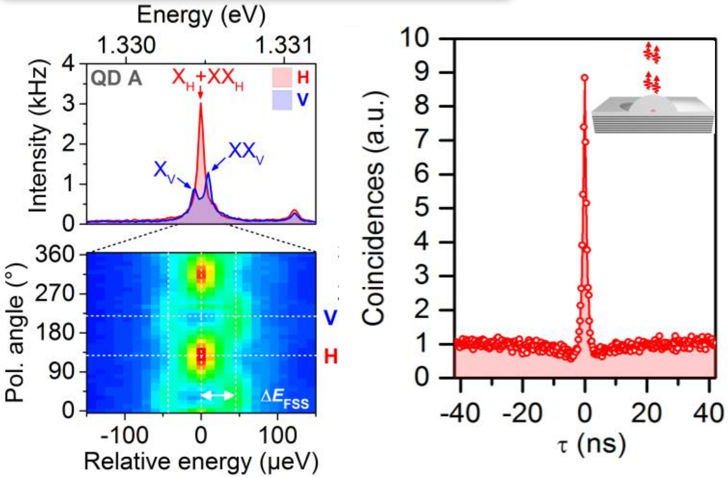


⇨ Measurement-Device-Independent (MDI) QKD

Other Exciting Experiments

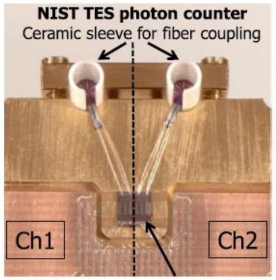
Twin-Photon Generation

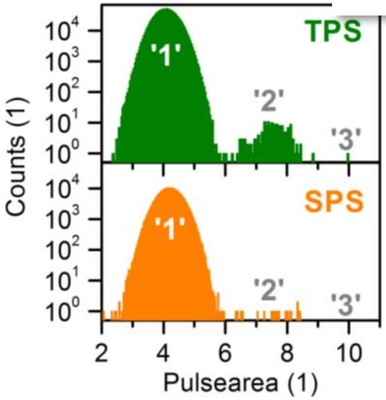
T. Heindel et al., *Nat. Commun.* 8, 14870 (2017)



J. Beyer

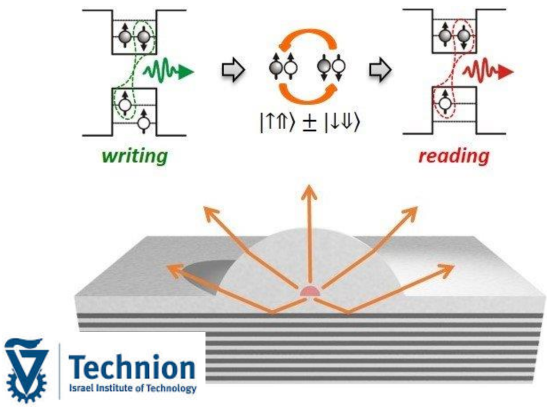
S. W. Nam

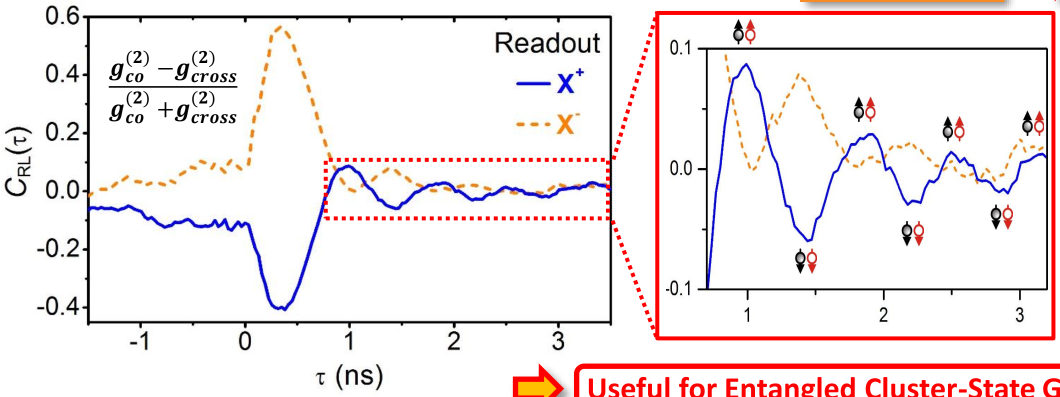




Accessing the Dark Exciton Spin

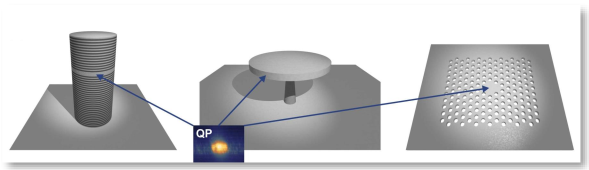
T. Heindel et al., *APL Photonics* 2, 121303 (2017)





Useful for Entangled Cluster-State Generation

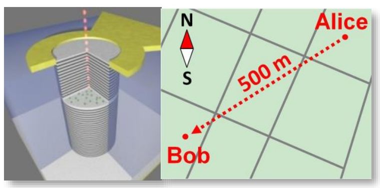
Outline – Part II



Recap

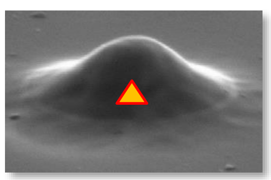
○ Photon Extraction Efficiencies

Early Work



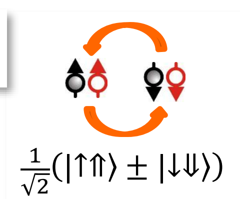
○ Electrically Triggered Single-Photon Sources

○ Quantum Communication using Single-Photon LEDs



○ Deterministic 3D In-Situ Electron Beam Lithography

○ Fundamental Quantum Optics Experiments



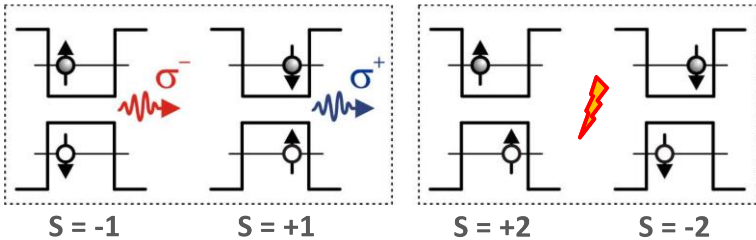
Spin-Photon Interfaces

All-optically Accessing the Dark Exciton Spin-Qubit

Dark Exciton Spin-Qubits

Dark Excitons (DE)

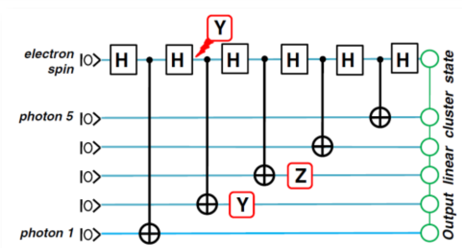
"Bright Excitons" (BE) **"Dark Excitons"**



→ DE = e-h with parallel spin orientation

Radiative recombination dipo-verbidden
→ Long-lived 2-level system
→ Quantum Information Processing!

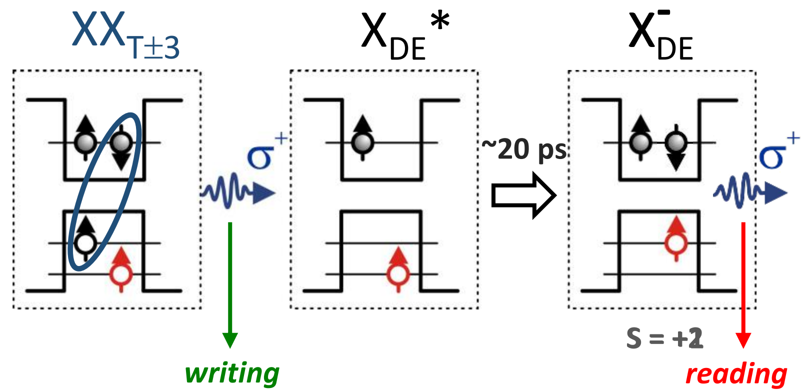
Photonic cluster-state generation [2,3]



[1] Theory: N. H. Lindner and T. Rudolph, *PRL* **103**, 113602 (2009)
[2] Experiment: I. Schwartz et al., *Science* **354**, 434-437 (2016)

How to optically access the DE?

Solution [1]: Use excited XX-state
→ Spinblockaded Biexciton



- ***Writing*** = detection of heralding photon
- ***Reading*** = charging + photon detection

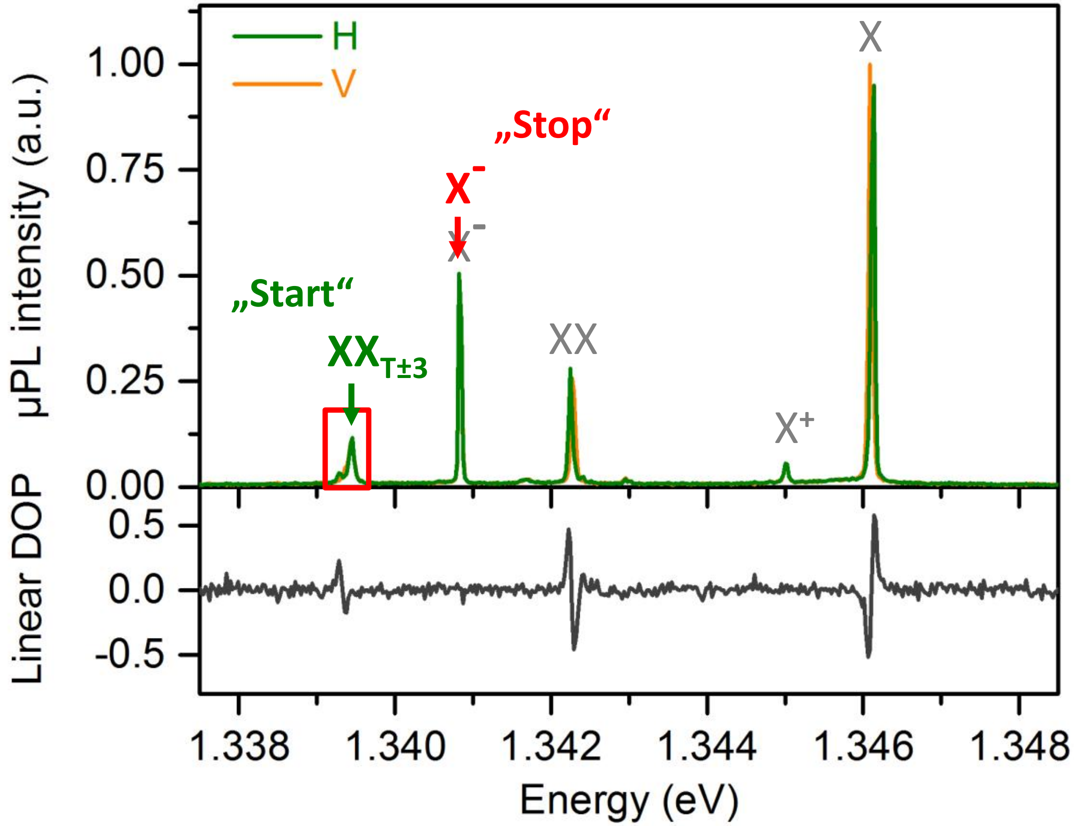
[1] E. Poem et al., *Nature Physics* **6**, 993 (2010)

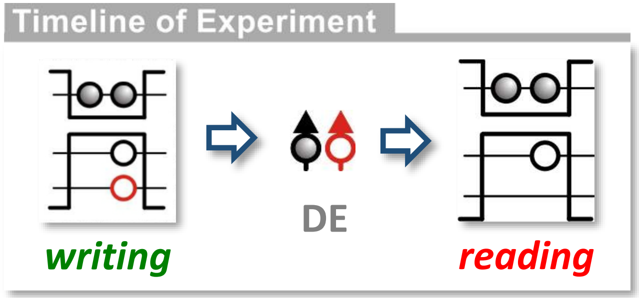
Photonic Cluster States for Fault Tolerant Quantum Computing[2,3]

The Experiment

→ T. Heindel et al., *APL Photonics* 2, 121303 (2017)

Technion Israel Institute of Technology

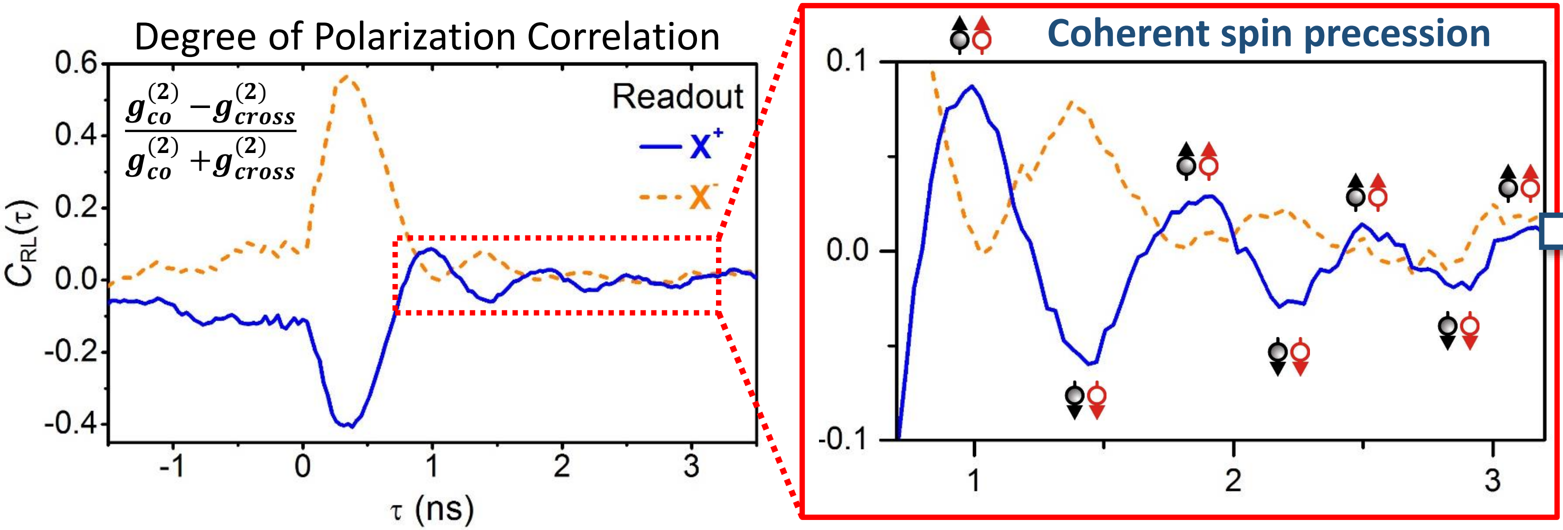




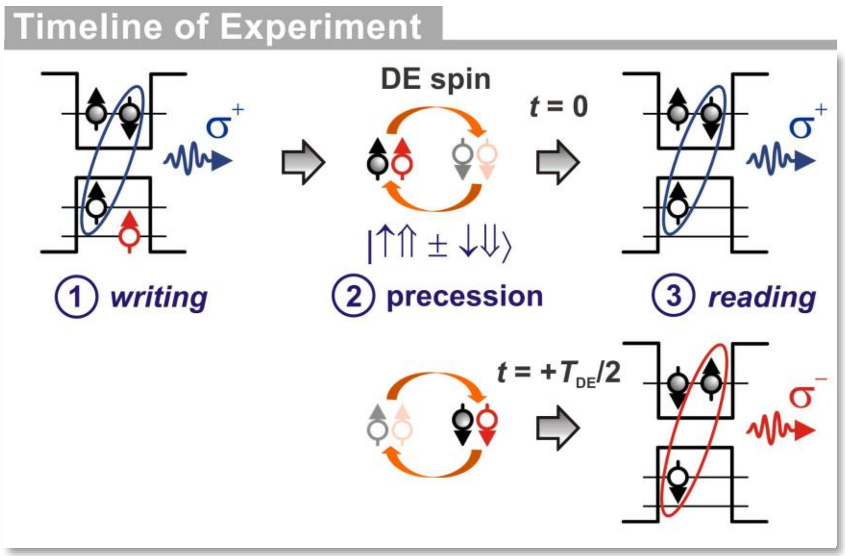
Spin-Precession

→ T. Heindel et al., *APL Photonics* 2, 121303 (2017)

Thank You! Questions?



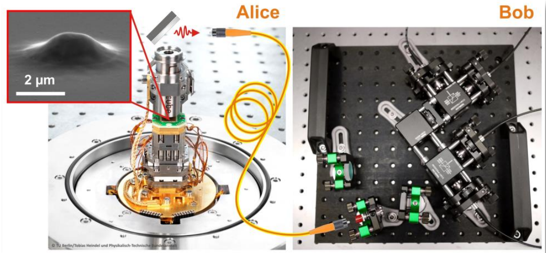
$T_{DE} = h/\Delta E_{FSS,DE}$
$= 0.82$ ns
$\Delta E_{FSS,DE} = 5.0\ \mu eV$

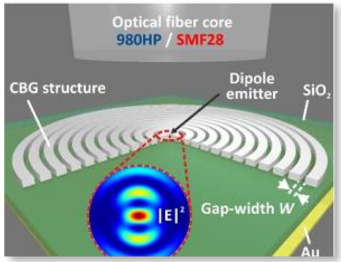


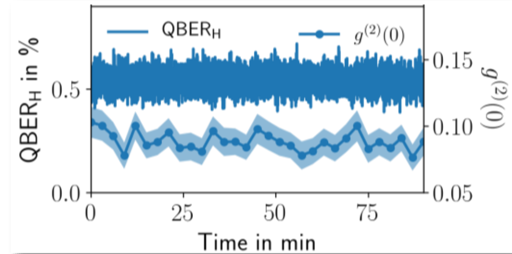
DE spin-qubit optically addressed

First-time demonstration with deterministic technology!

[1] N. H. Lindner and T. Rudolph, *PRL* **103**, 113602 (2009)
[2] I. Schwartz et al., *Science* **354**, 434-437 (2016)







Quantum Communication
Part III: *Towards Quantum Networks*

Tobias Heindel

Head of Group
Quantum Communication Systems

Institute of Solid State Physics
Technische Universität Berlin
Germany

QuSecure

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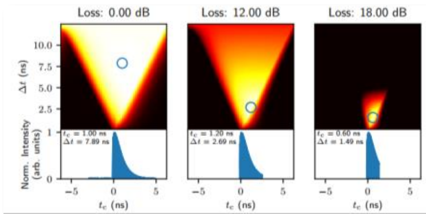
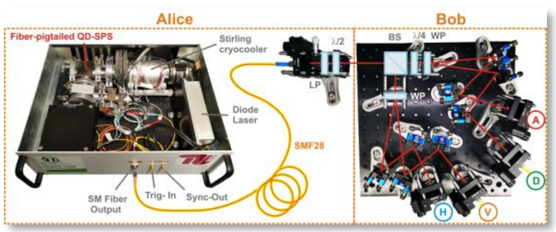
Vienna Center for Quantum Science and Technology

Outline – Part III

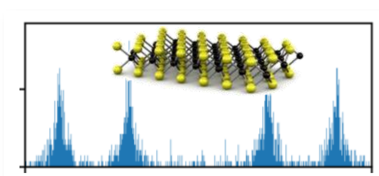
Recap
- BB84 & Rate vs. Loss Diagramm



Optimization & Certification
- About How Bob Should Measure
- …and Other Usefull Tools



Developing Practical Single-Photon QKD Systems
- Plug'n'Play Quantum Light Sources
- Benchtop QKD Testbeds



Emerging Materials

Atomically-Thin Single-Photon Sources for QuCom

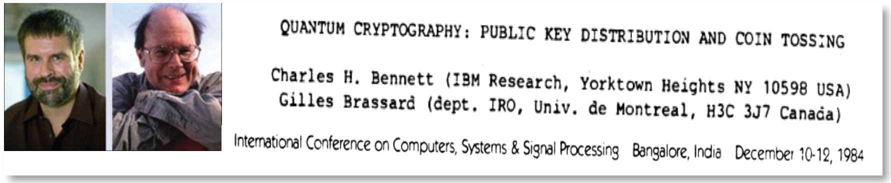
QuSecure

Group Website

Summary & Outlook

Towards Quantum Communication Networks

Outline



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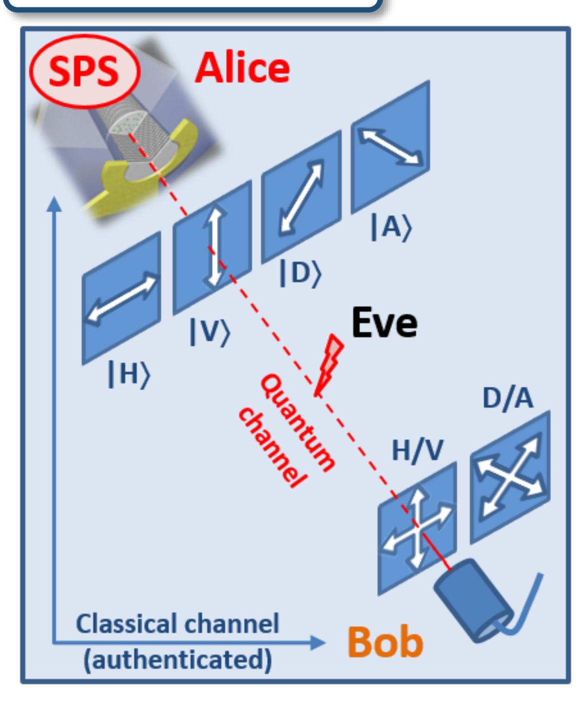
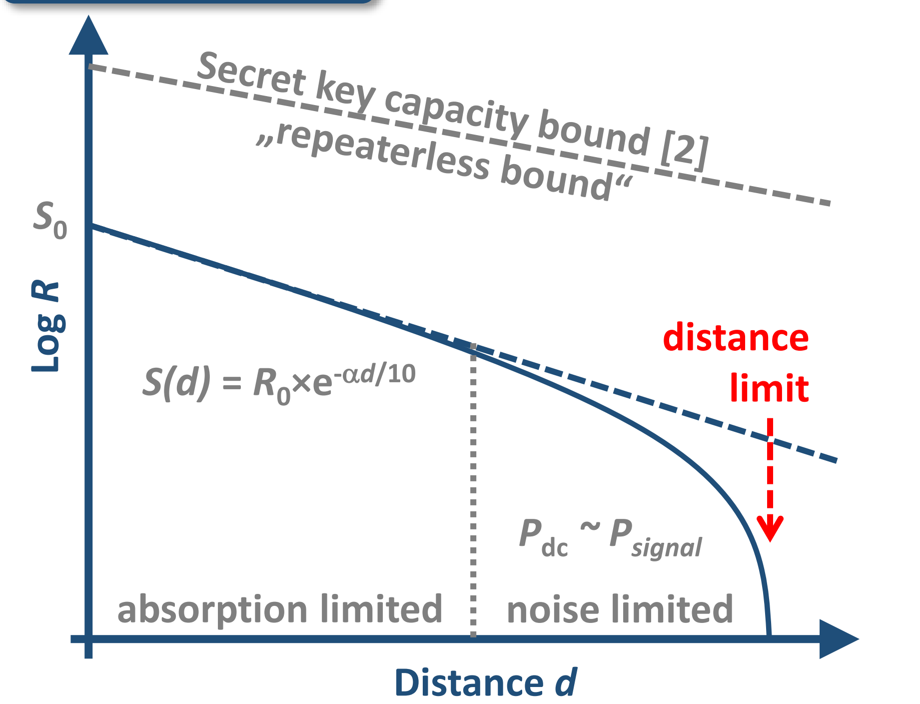
Charles H. Bennett (IBM Research, Yorktown Heights NY 10598 USA)
Gilles Brassard (dept. IRO, Univ. de Montreal, H3C 3J7 Canada)

International Conference on Computers, Systems & Signal Processing Bangalore, India December 10-12, 1984

BB84 – Scheme [1]



Rate vs. Loss [2,3]



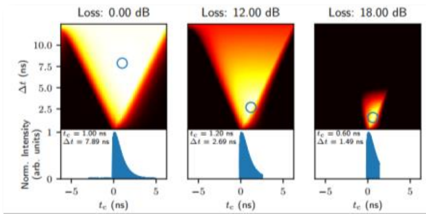
[1] C. H. Bennett und G. Brassard, *Proc. of IEEE International Conference on Computers, Systems and Signal Processing*, Bangalore, India S. 175–179 (1984)

[2] R. Alléaume et al., *New J. Phys.* **11**, 075002 (2009)

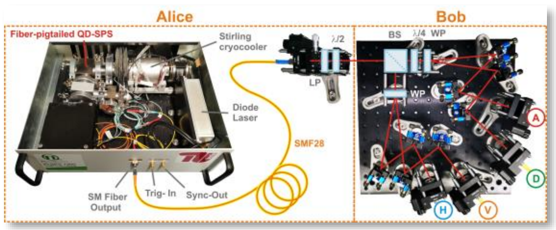
[3] S. Pirandola et al., *Nat. Commun.* **8**, 15043 (2017)

Outline – Part III

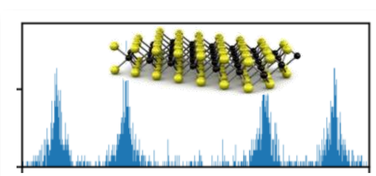
Recap
- BB84 & Rate vs. Loss Diagramm



Optimization & Certification
- About How Bob Should Measure
- …and Other Usefull Tools



Developing Practical Single-Photon QKD Systems
- Plug'n'Play Quantum Light Sources
- Benchtop QKD Testbeds



Emerging Materials

Atomically-Thin Single-Photon Sources for QuCom

QuSecure

Group Website

Summary & Outlook

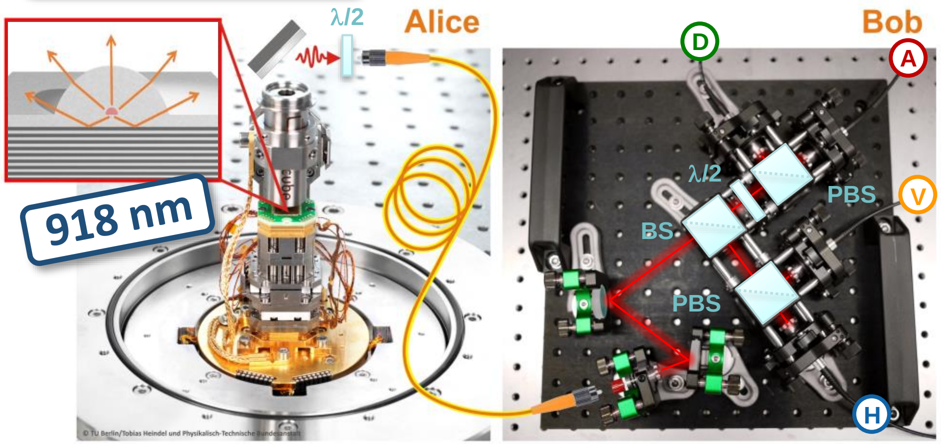
Towards Quantum Communication Networks

How Bob Should Measure?

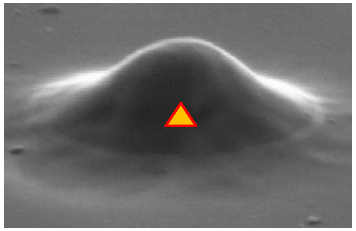
→ T. Kupko et al., npj Quantum Information (2020)

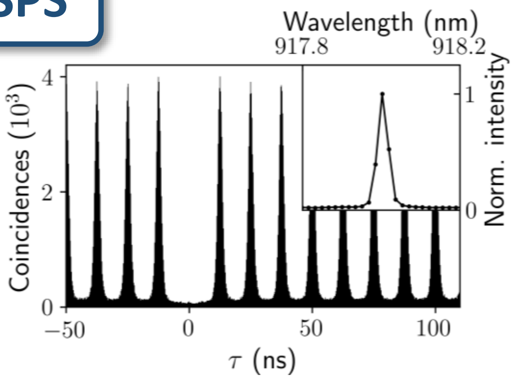
QKD Testbed

Paper Link

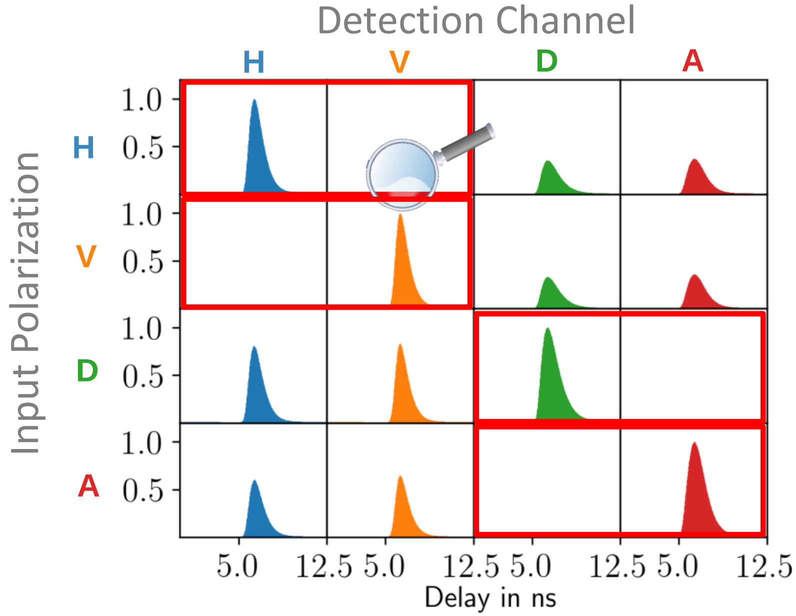


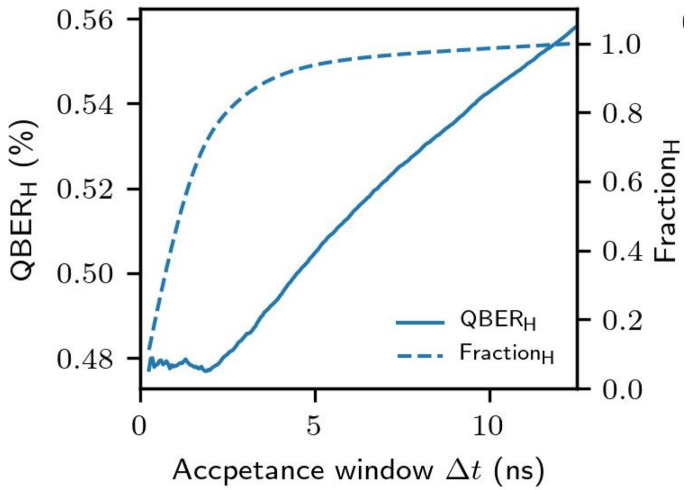
Microlens QD-SPS





Reitzenstein Group: 3D in-situ e-beam lithography
[M. Gschrey, TH et al., *Nat. Com.* 6, 7662 (2015)]





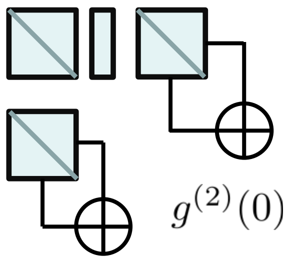
Photon Statistics – Live „On-Air“

→ T. Kupko et al., *npj Quantum Information* (2020)

Paper Link

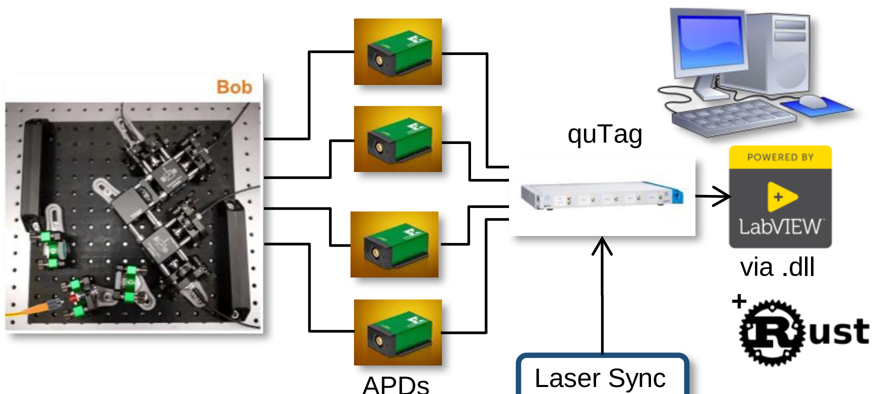
4-Channel ‘Hanbury Brown and Twiss’

…by directly correlating Bob’s filtered time-tags



⇨ $g^{(2)}(\tau)$

$$p_{\mathrm{m}} \leq \frac{\mu^2 g^{(2)}(0)}{2} \quad [1]$$

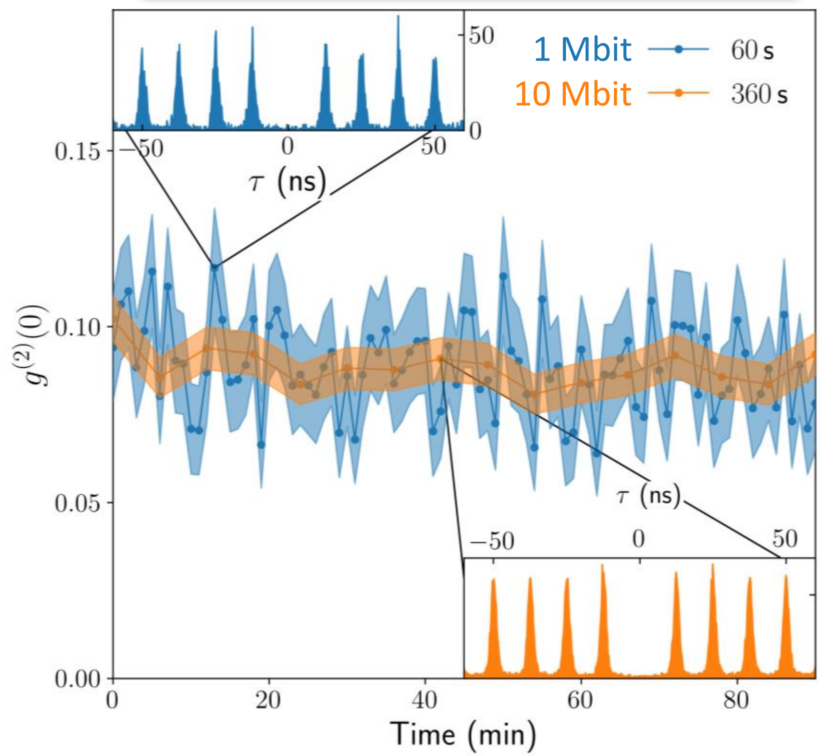


[1] E. Waks et al., Phys. Rev. A 66, 042315 (2002)

⇨

Parameter monitoring

Real-time Security Assessment

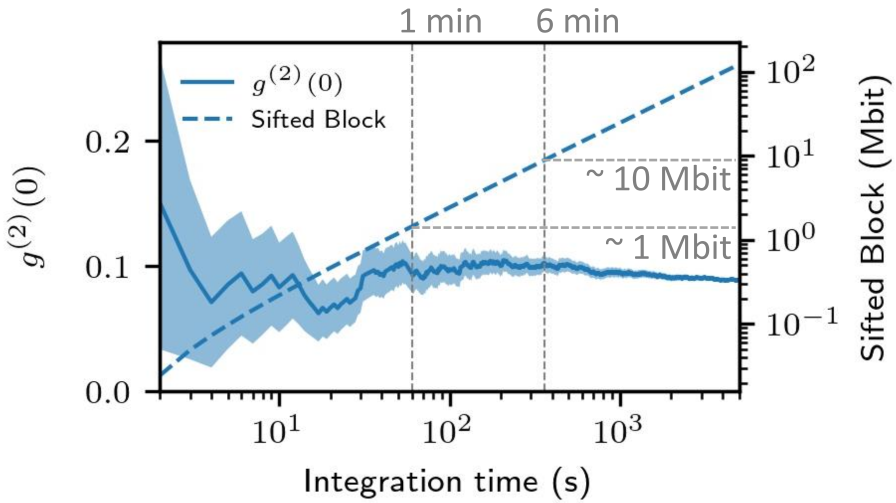


Photon Statistics – Live „On-Air“

→ T. Kupko et al., *npj Quantum Information* (2020)

$g^{(2)}(0)$ and sifted block size vs. int. time

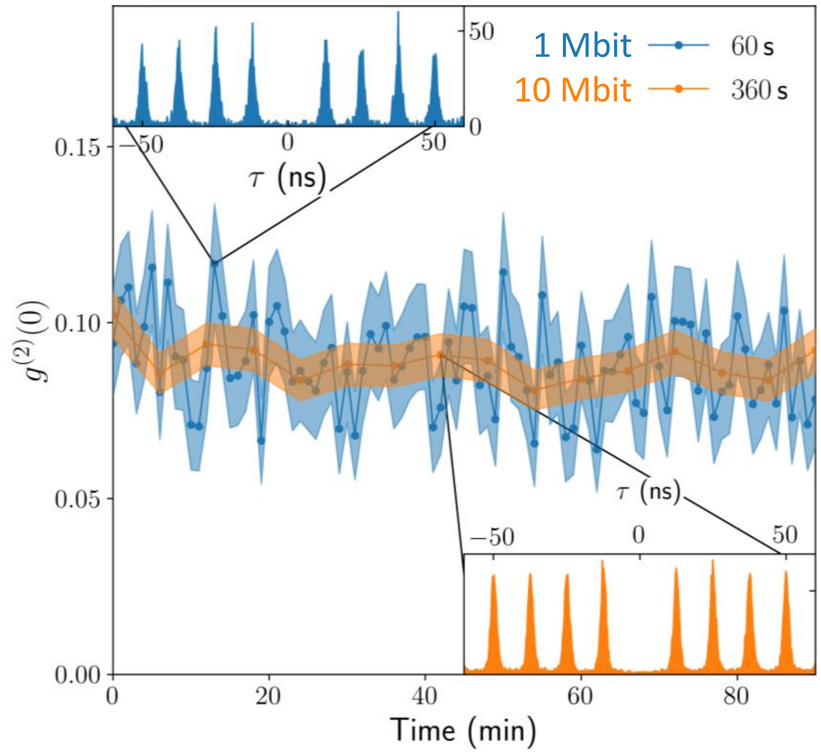
…how long to choose the accumulation time?



- **~ 1 Mbit block size @ 60 s**
  - → Relative error: 16 %
  - → Sufficient if finite-size effects are considered
- **~ 10 Mbit block size @ 6 min**
  - → Relative error: 6 %
  - → Sufficient for neglecting finite-size effects

Parameter monitoring

Real-time Security Assessment

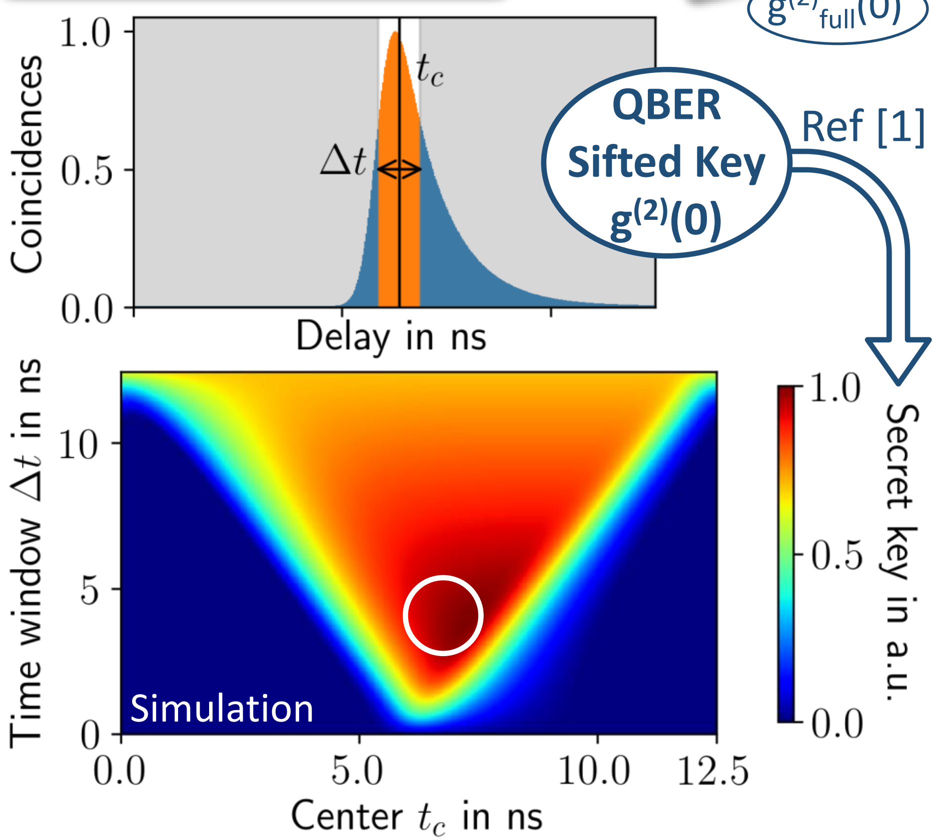


Key-Rate Optimization

→ T. Kupko et al., npj Quantum Information (2020)

2D Temporal Filtering

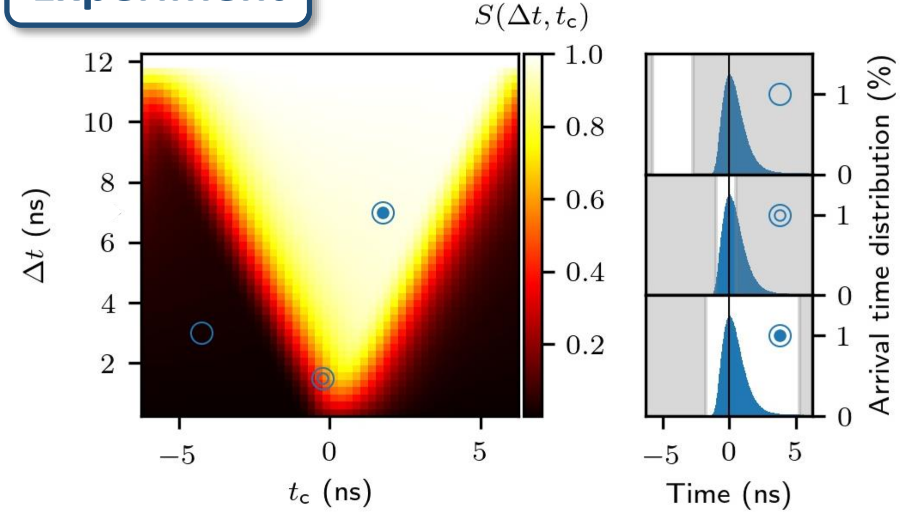
Important! $g^{(2)}_{full}(0)$

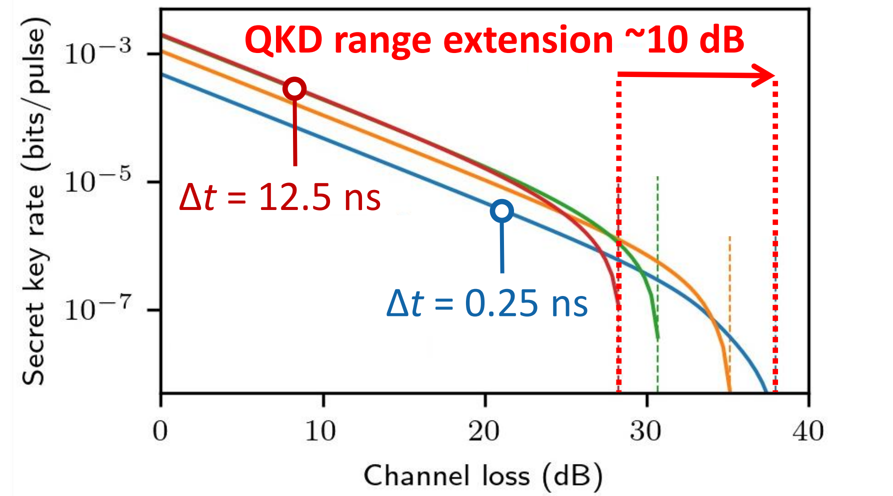


⇨ **Key Rate Optimization Possible**

[1] E. Waks et al., Phys. Rev. A 66, 042315 (2002)

Experiment

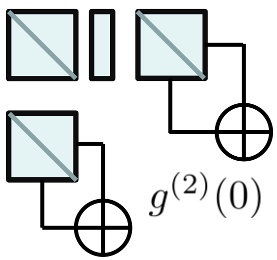




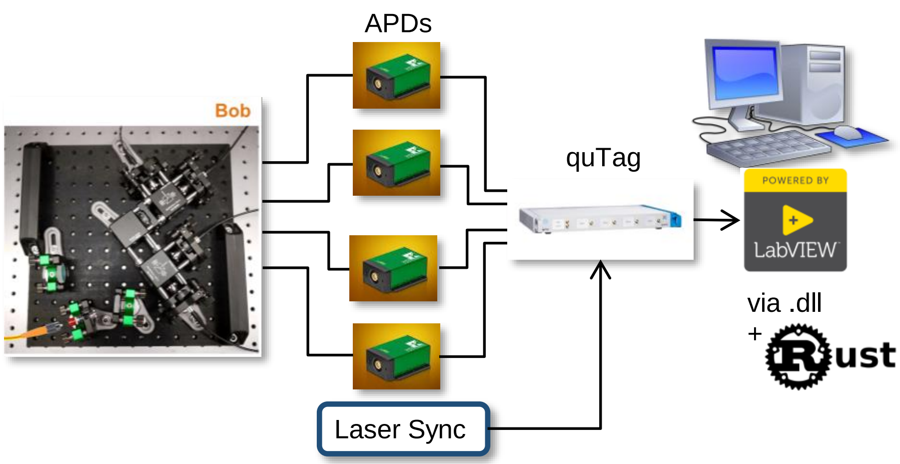
* Important to note Note *

4-Channel 'Hanbury Brown and Twiss'

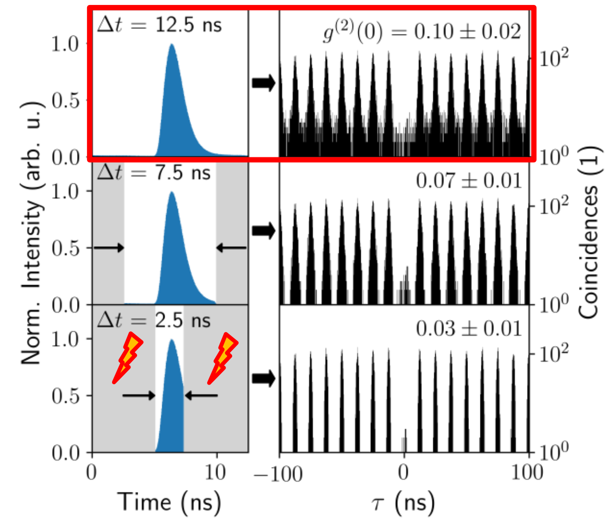
…by directly correlating Bob's filtered time-tags

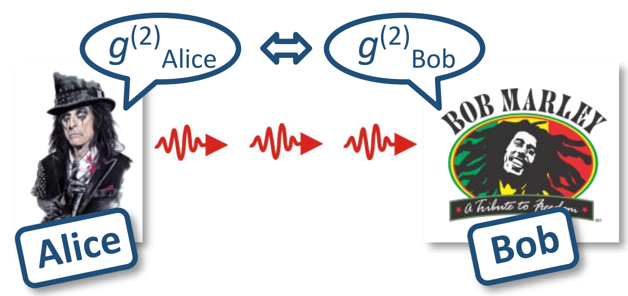


⇨ $g^{(2)}(\tau)$



Temporally filtered $g^{(2)}(\tau)$-Histograms

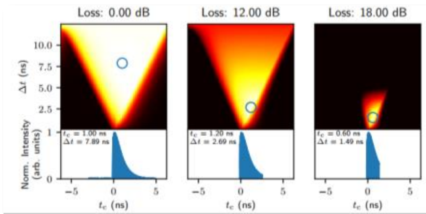




Outline – Part III

Recap

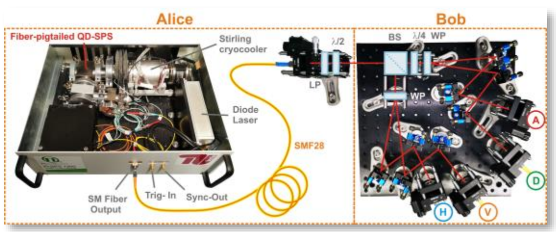
○ BB84 & Rate vs. Loss Diagramm



Optimization & Certification

○ About How Bob Should Measure

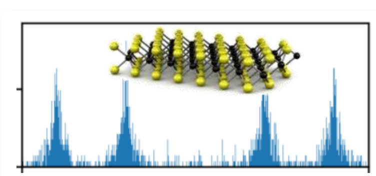
○ …and Other Usefull Tools



Developing Practical Single-Photon QKD Systems

○ Plug'n'Play Quantum Light Sources

○ Benchtop QKD Testbeds



Emerging Materials

Atomically-Thin Single-Photon Sources for QuCom

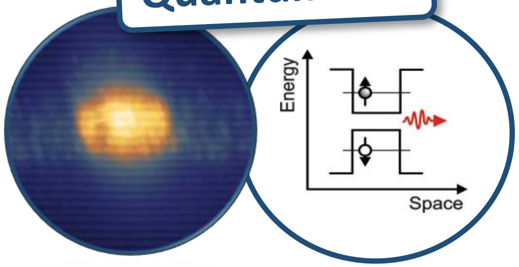
Summary & Outlook

Towards Quantum Communication Networks

Single-Photons Plug‘n‘Play?

Single photon generation outside shielded lab environment

Quantum Dot



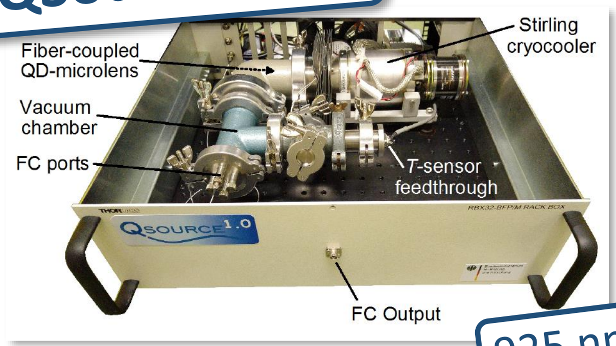
+

Stirling Cryocooler [1]

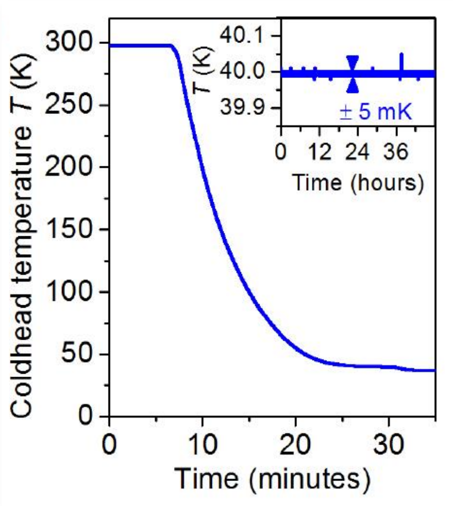
+

=

QSource$^{1.0}$ [2]



925 nm



[1] Schlehahn, TH et al., *Rev. Scient. Instrum.* 86, 013113 (2015)

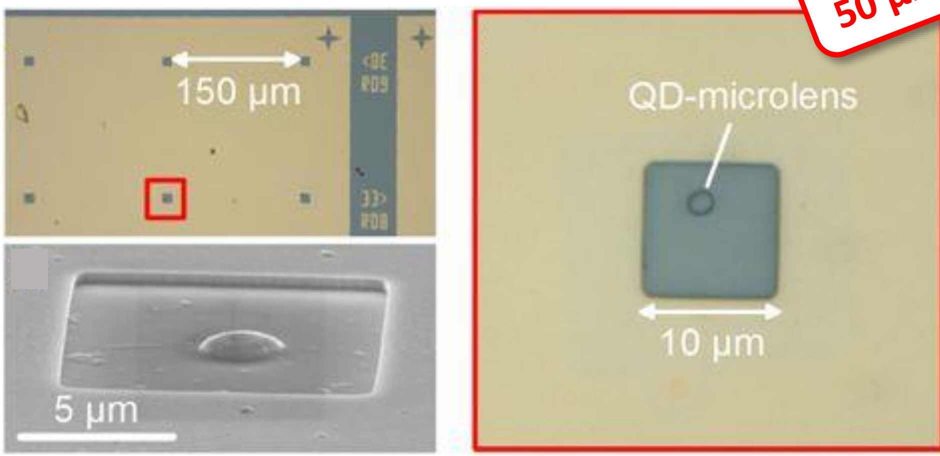
[2] A. Schlehahn, TH et al., Scientific Reports 8, 1340 (2018)

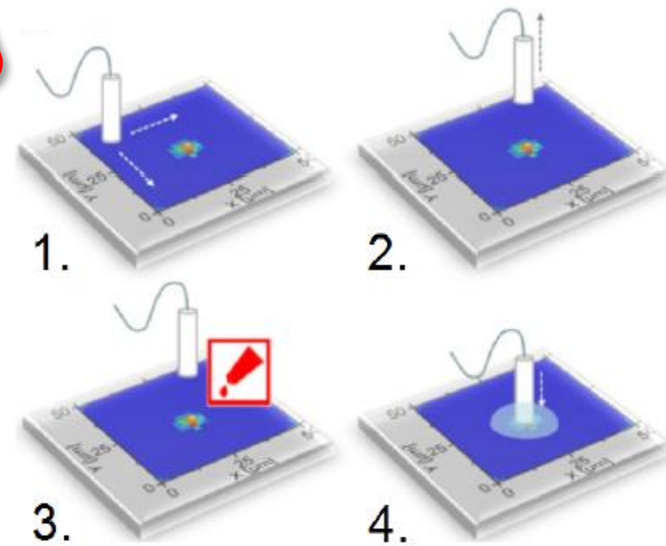
Stand Alone Single-Photon Source

→ A. Schlehahn, TH et al., Scientific Reports 8, 1340 (2018)

Direct fiber-coupling of QD microlens:

MM-fiber
50 µm core





- Au metal mask
- Apertures (10x10 µm²)
- Deterministic fab of QD microlens inside aperture

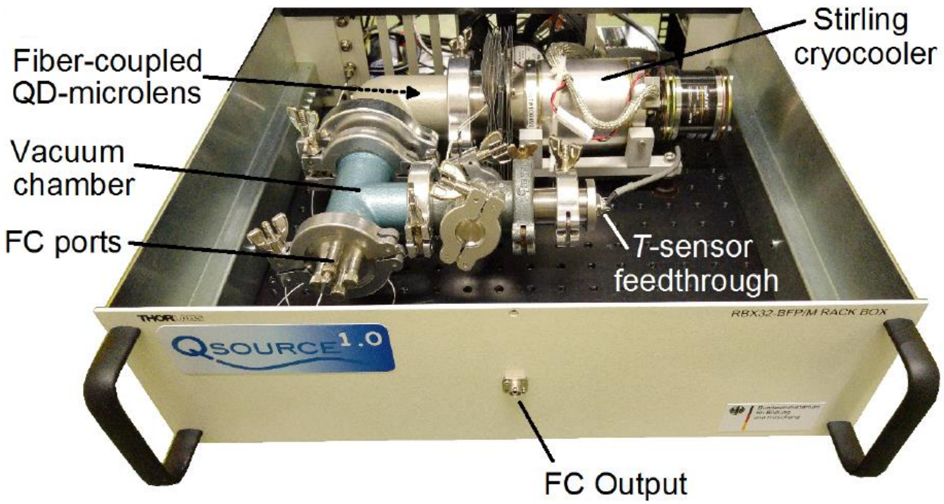
- Scanning MM fiber across sample
- Localizing Aperture region
- Gluing fiber ferrule above QD-microlens using epoxide adhesive

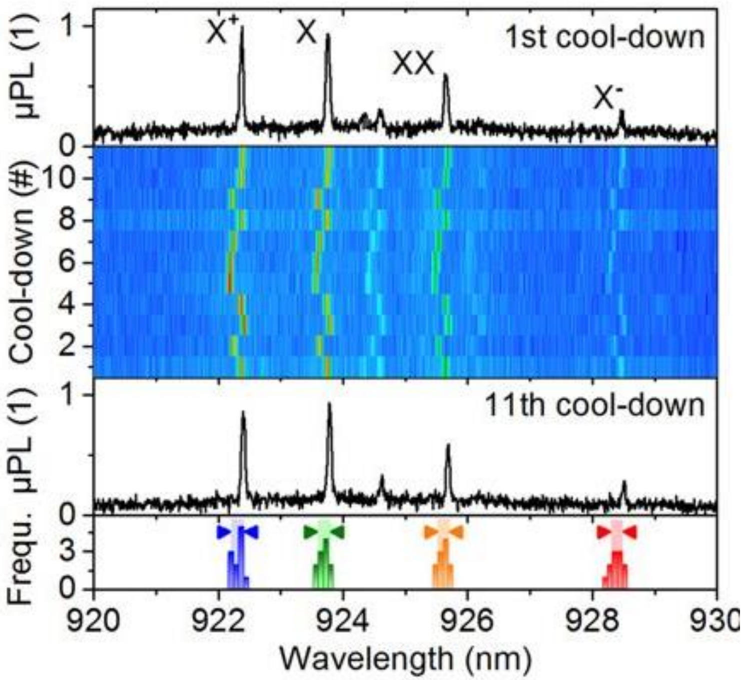
[1] M. Gschrey, TH et al., *APL* 102, 251113 (2013)
[2] M. Gschrey, TH et al., *Nat. Commun.* 6, 7662 (2015)

Stand Alone Single-Photon Source

→ A. Schlehahn, TH et al., Scientific Reports 8, 1340 (2018)

Integration into compact Stirling cryocooler:





⇩

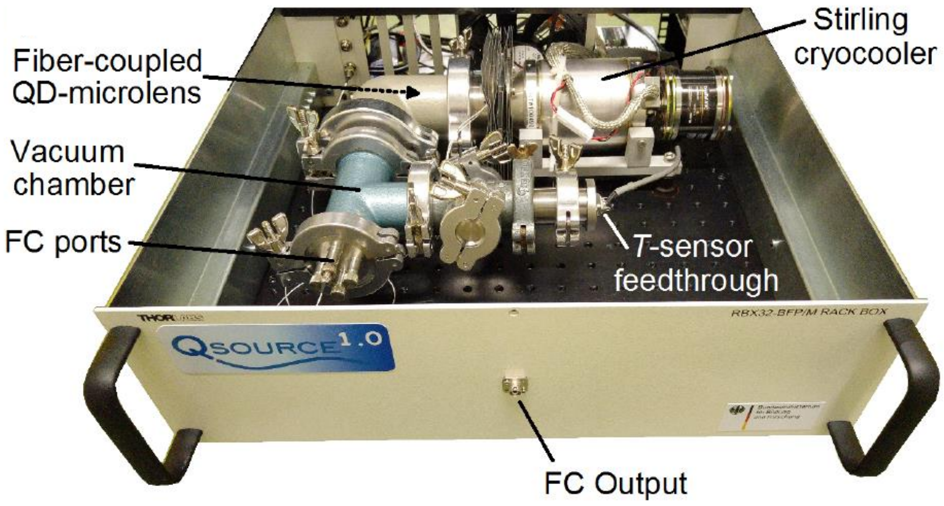
Durable Fiber Coupling

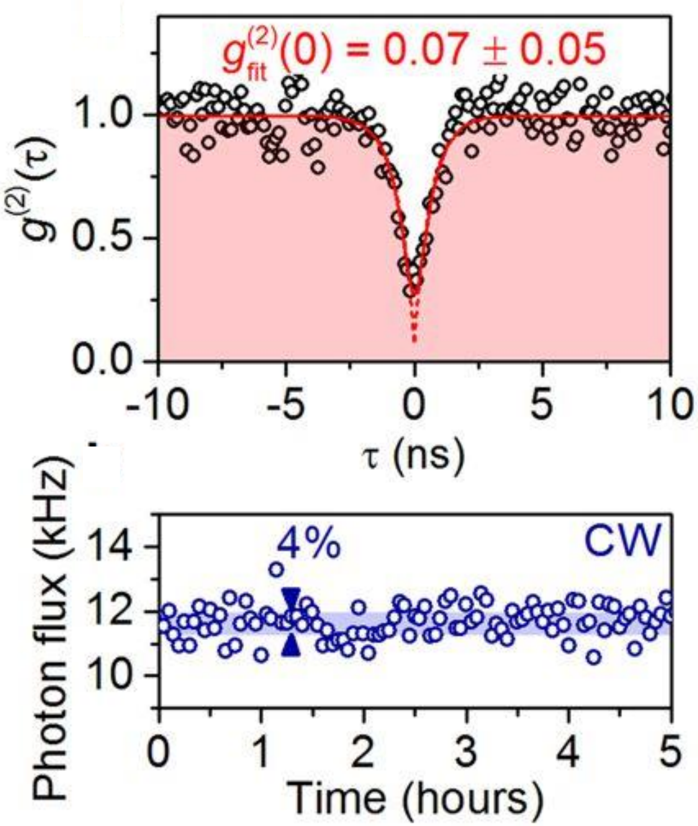
Single-Photon Emission?

Stand Alone Single-Photon Source

→ A. Schlehahn, TH et al., Scientific Reports 8, 1340 (2018)

Integration into compact Stirling cryocooler:



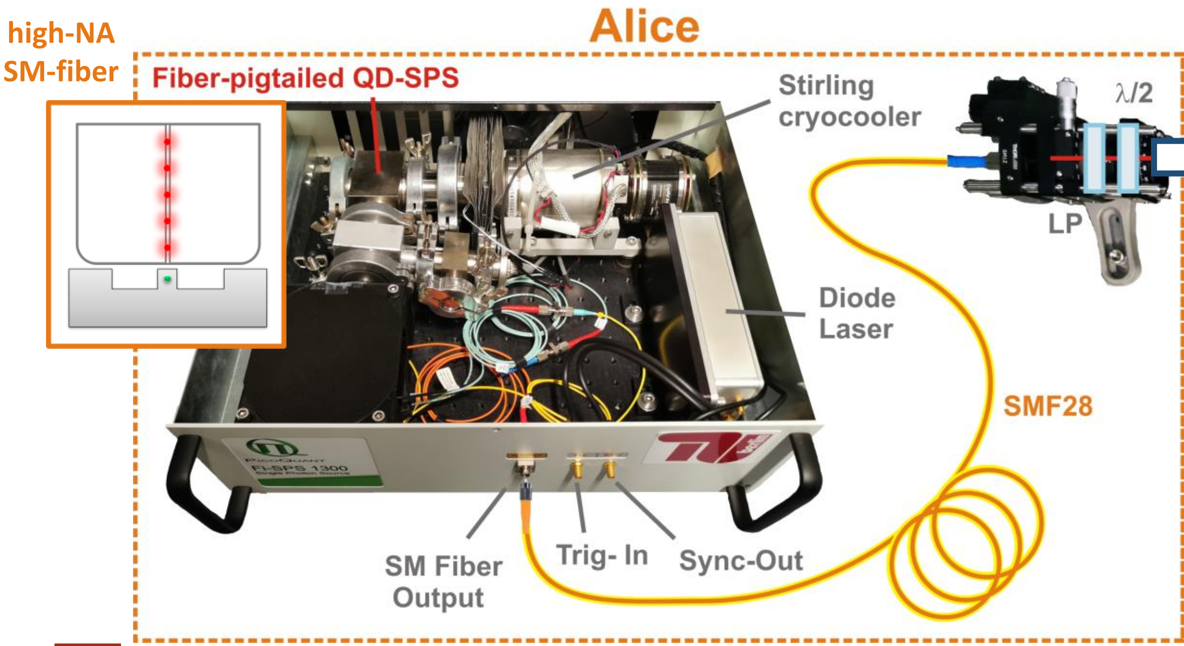


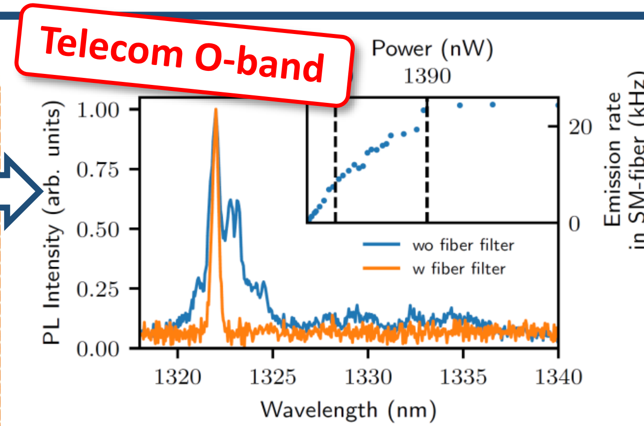
SM fibers?
Telecom window?

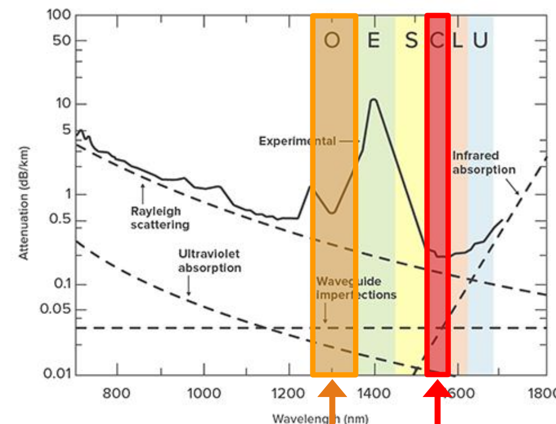
Single-Photon Emission!

Telecom-Wavelength QKD-Testbed

→ T. Gao, L. Rickert et al., Applied Physics Reviews 9, 011412 (2022)







Quantum Traffic

Classical Traffic

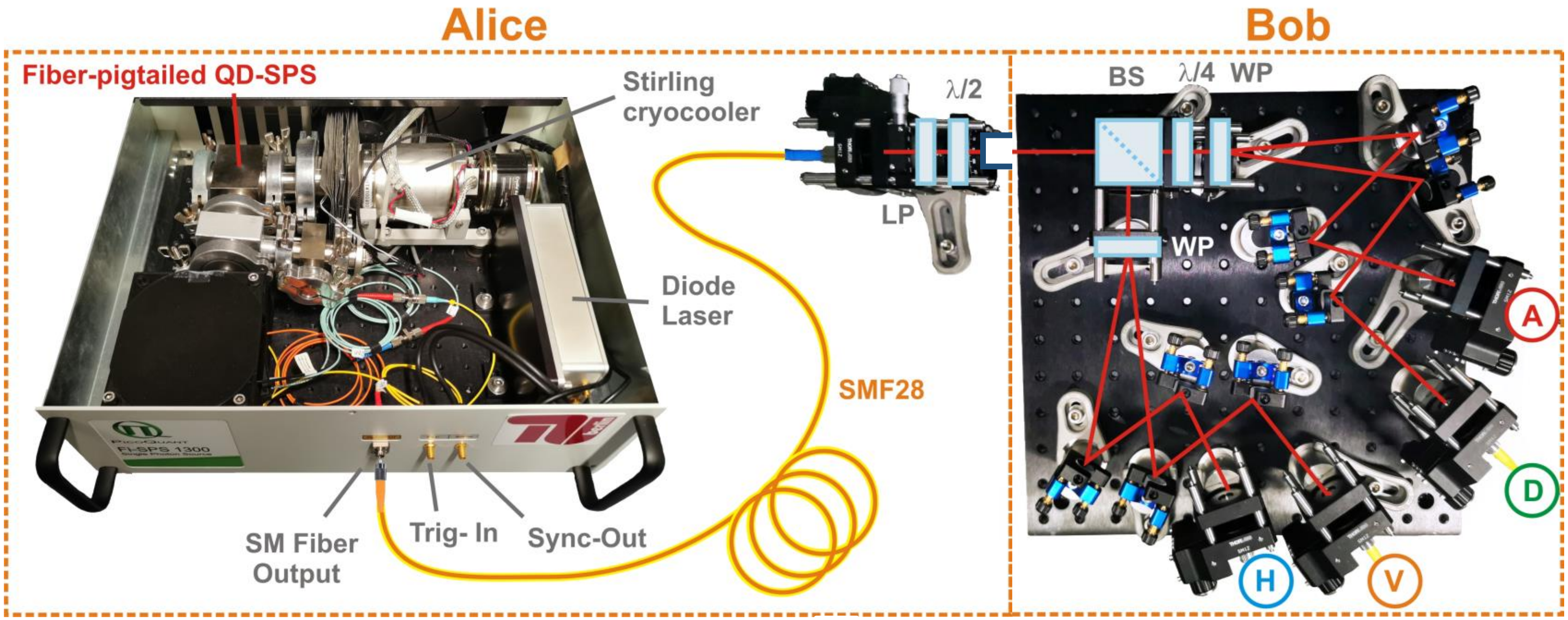
λ-multiplexing
→ existing infrastructure

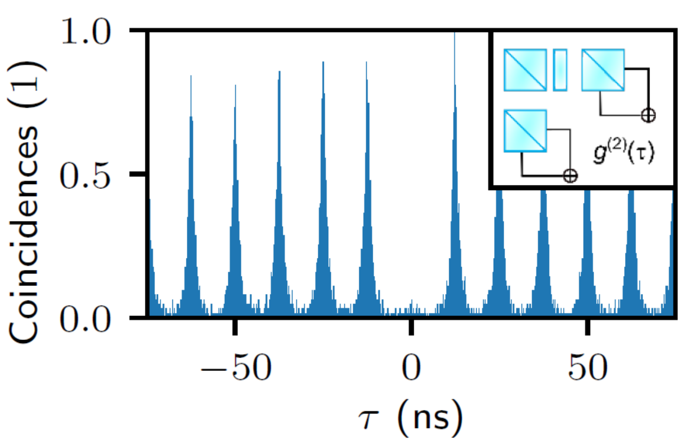
FIBRAIN UMCS ZIB

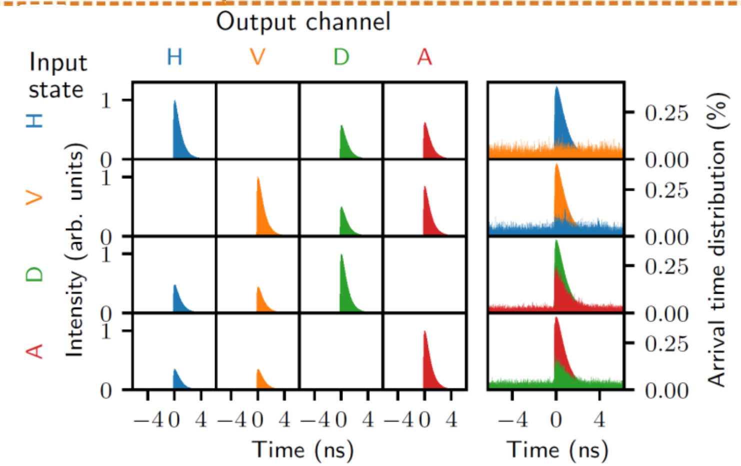
Details on FC-QD: Zolnac et al., *Opt. Express* 27, 26772 (2019)
First O-band QD in Stirling:
Musiał et al., Adv. Qu. Technol. 10.1002/qute.202000018 (2020)
Project Fi-Secure: Reitenstein, Sęk, et al.

Telecom-Wavelength QKD-Testbed

→ T. Gao, L. Rickert et al., Applied Physics Reviews 9, 011412 (2022)



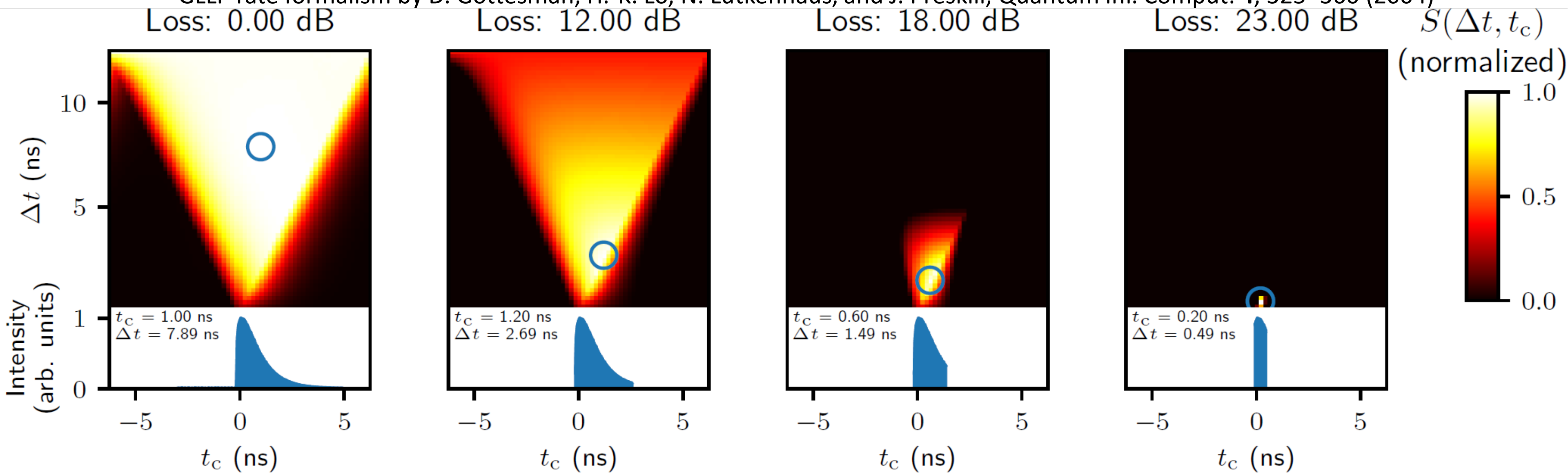


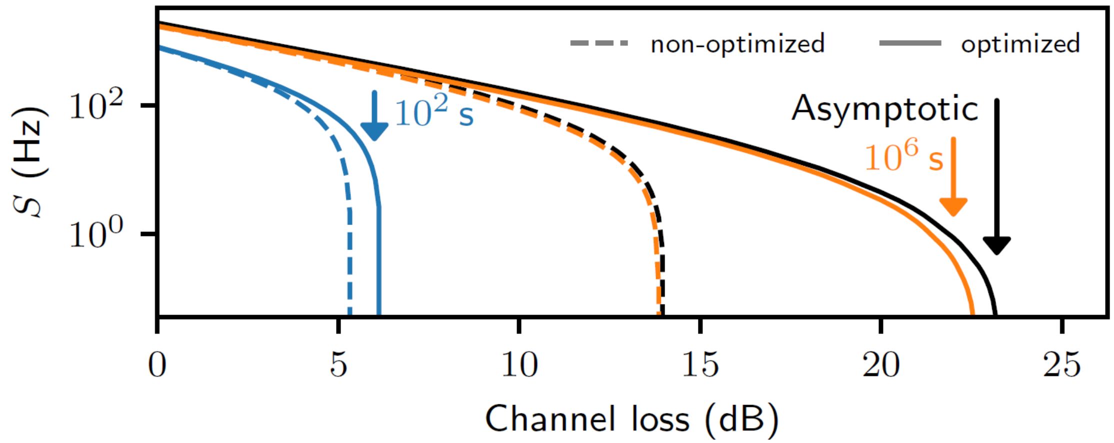


Telecom-Wavelength QKD-Testbed

→ T. Gao, L. Rickert et al., Applied Physics Reviews 9, 011412 (2022)

GLLP rate formalism by D. Gottesman, H.-K. Lo, N. Lütkenhaus, and J. Preskill, Quantum Inf. Comput. **4**, 325–360 (2004)





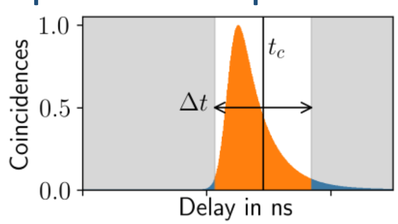
Accounting for finite key-size effects: R. Y. Q. Cai and V. Scarani, New Journal of Physics 11, 045024 (2009)

Telecom-Wavelength QKD-Testbed

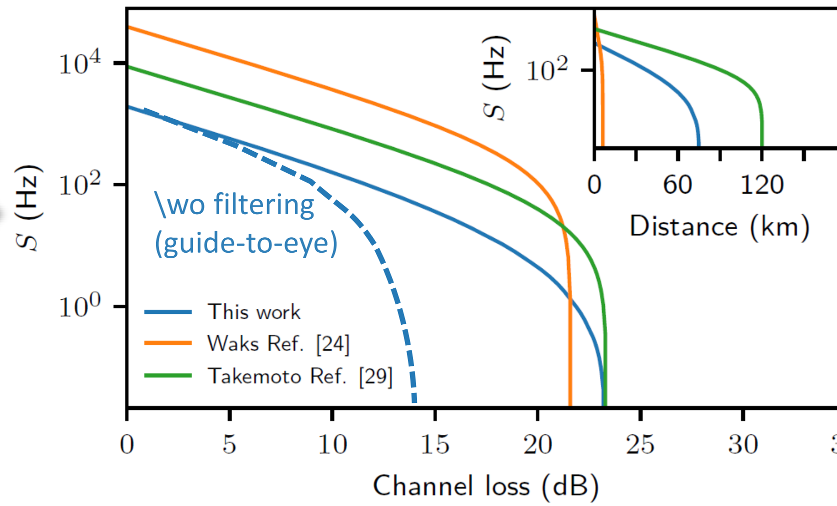
→ T. Gao, L. Rickert et al., Applied Physics Reviews 9, 011412 (2022)

	Ref.[24]	Ref.[29]	This Work
λ (nm)	877	1580.5	1321
μ	0.007	0.009	0.0002
p_{dc}	$10.5 \cdot 10^{-7}$	$3 \cdot 10^{-7}$	$5.25 \cdot 10^{-7}$
$e_{detector}$	0.025	0.023	0.010
η_{Bob}	0.24	0.048	0.3
$g^{(2)}(0)$	0.14	0.0051	0.10

Optimized 2D temporal filtering



T. Kupko et al., *npj Quantum Inf.* 6, 29 (2020)



[24] E. Waks et al., Nature 420, 762 (2002)
[29] K. Takemoto et al., Sci. Rep. 5, 14383 (2015)

Telecom-Wavelength QKD-Testbed

→ T. Gao, L. Rickert et al., Applied Physics Reviews 9, 011412 (2022)

Home > Applied Physics Reviews > Volume 9, Issue 1 > 10.1063/5.0070966

Free · Submitted: 10 September 2021 · Accepted: 05 January 2022 · Published Online: 26 January 2022

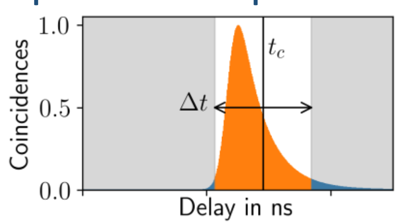
A quantum key distribution testbed using a plug&play telecom-wavelength single-photon source

Editor's Pick + Scilight

Paper Link

Applied Physics Reviews **9**, 011412 (2022); https://doi.org/10.1063/5.0070966

Timm Gao[1], Lucas Rickert[1], Felix Urban[1], Jan Große[1], Nicole Srocka[1], Sven Rodt[1], Anna Musiał[2], Kinga Żołnacz[3], Paweł Mergo[4], Kamil Dybka[5], Wacław Urbańczyk[3], Grzegorz Sęk[2], Sven Burger[6], Stephan Reitzenstein[1], *and* Tobias Heindel[1,a)]



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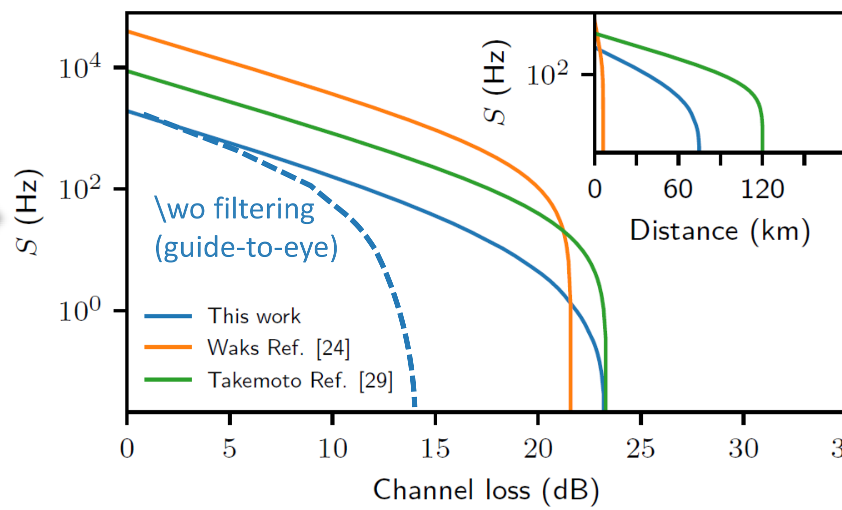


[24] E. Waks et al., Nature 420, 762 (2002)

[29] K. Takemoto et al., Sci. Rep. 5, 14383 (2015)

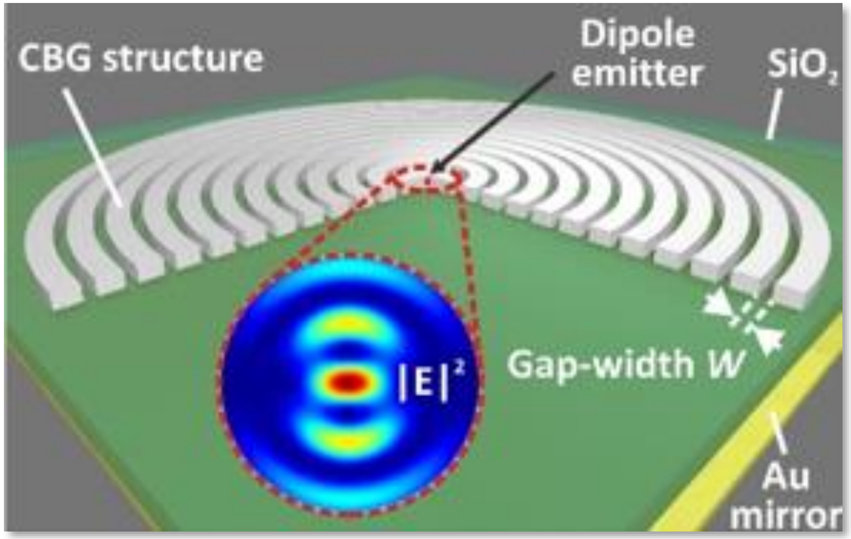
Towards Telecom FC-SPS

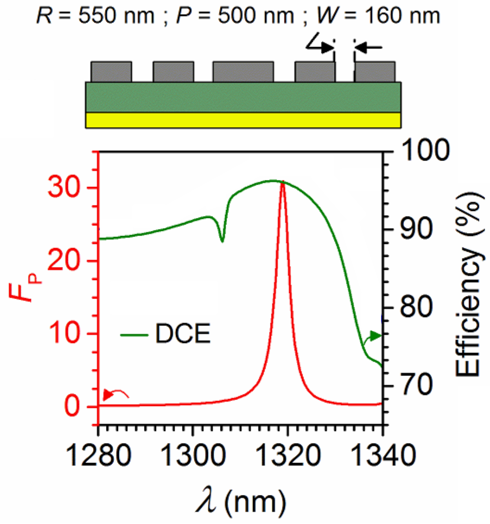
→ L. Rickert et al., Optics Express (2019)

Hybrid circular Bragg grating

Design Optimization via FEM Simulations

- Parameter study on R, W, P, t_{GaAs}, t_{SiO2}





$$\eta_{DCE} = \frac{P_{NA=0.8}}{P_{Dipole}}$$

Designed for telecom O-band

Mode forming in central disc

- Collection efficiencies of >95%
- F_P of up to 30
- Collimated far-field

[1] J. Liu et al., Nat. Nanotechnol. 14, 586 (2019)
[2] H. Wang et al., Phys. Rev. Lett. 122, 113602 (2019)

JCMwave
Support by Philipp-Immanuel Schneider and Sven Burger greatfully acknowledged

Towards Telecom FC-SPS

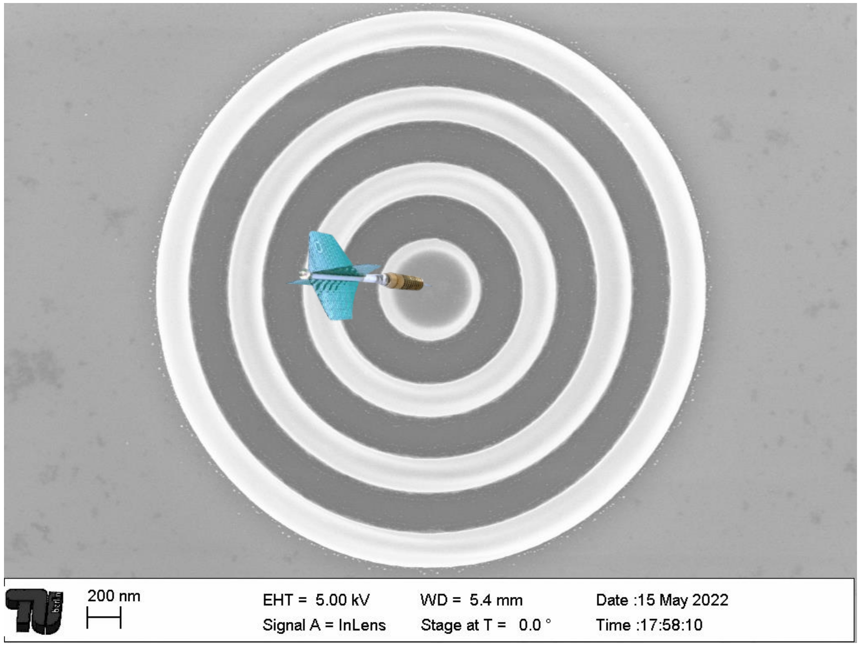
→ L. Rickert et al., Optics Express (2019)

Hybrid circular Bragg grating

Fiber-couplin

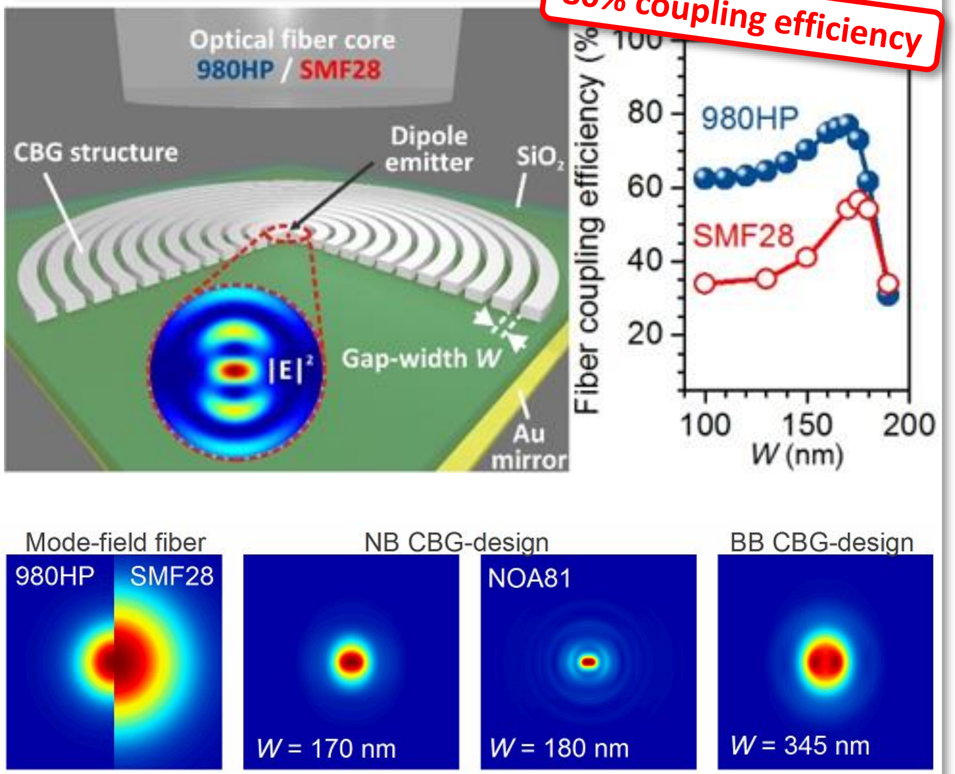
Design Optimization via FEM Simulations

- Bandwidth engineering



Efficient direct fiber-coupling

80% coupling efficiency

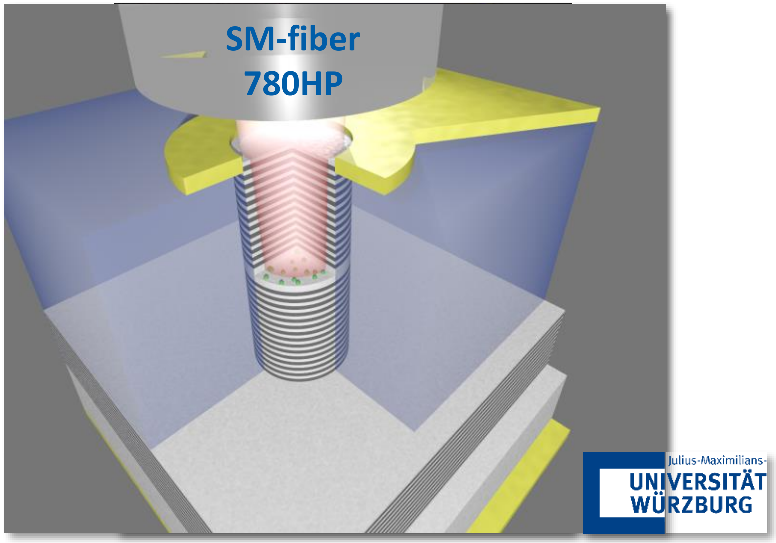


⇨ **Blueprint for Telecom-Wavelength Quantum Light Sources**

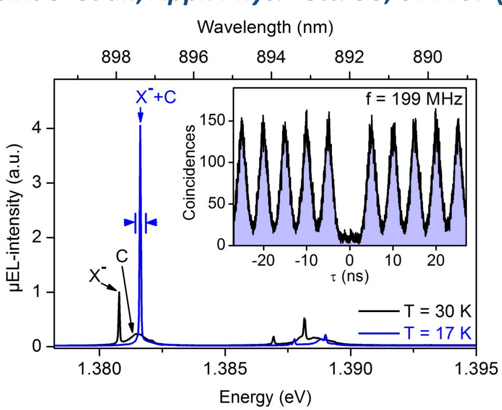
Fiber-pigtailing Microcavity-LEDs

→ L. Rickert et al., Appl. Phys. Lett. 119, 131104 (2021)

Micropillar-SPS



T. Heindel et al., *Appl. Phys. Lett.* 96, 011107 (2010)

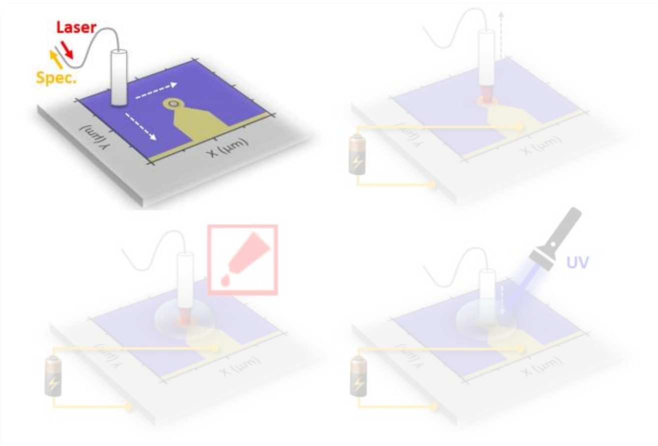


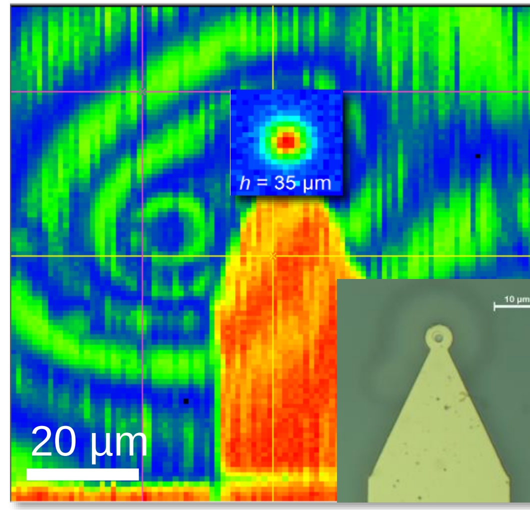
Paper Link

Fiber-pigtailing Microcavity-LEDs

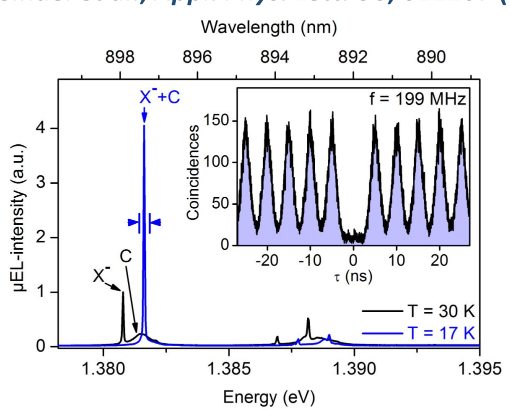
→ L. Rickert et al., Appl. Phys. Lett. 119, 131104 (2021)

Micropillar-SPS + SM-Fiber





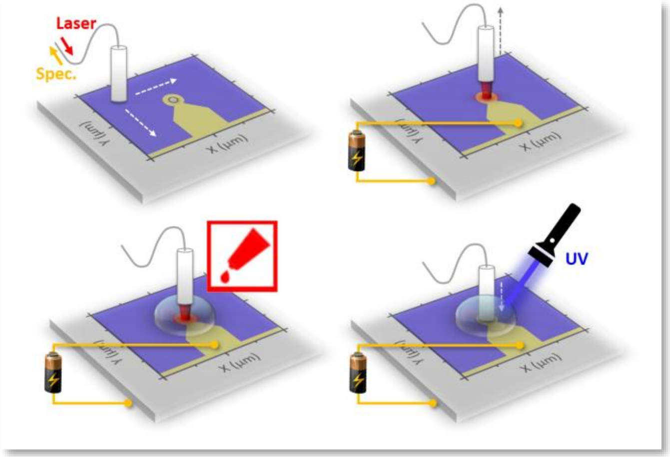
T. Heindel et al., *Appl. Phys. Lett.* 96, 011107 (2010)

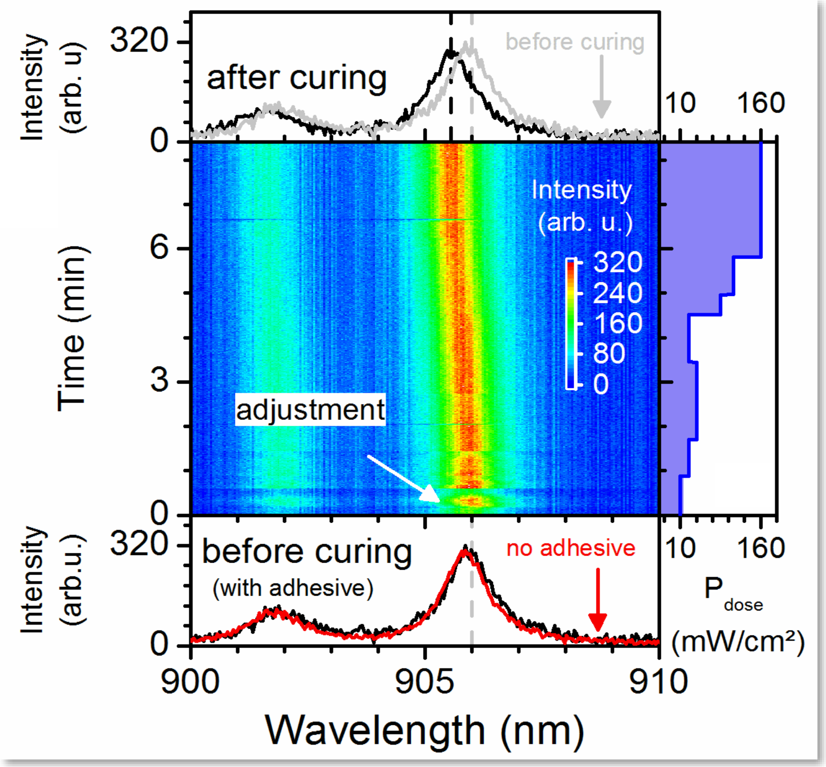


Fiber-pigtailing Microcavity-LEDs

→ L. Rickert et al., Appl. Phys. Lett. 119, 131104 (2021)

Micropillar-SPS ✚ SM-Fiber





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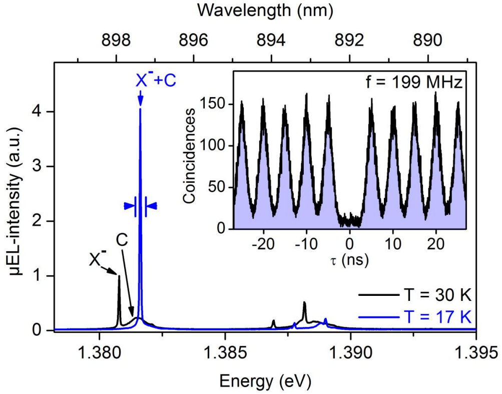

Paper Link

Fiber-pigtailing Microcavity-LEDs

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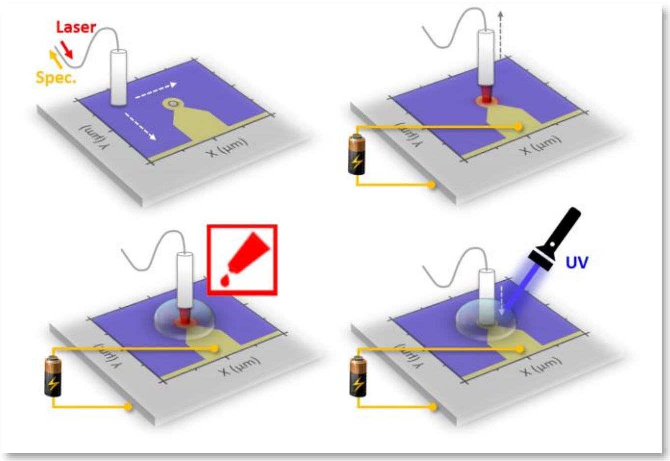

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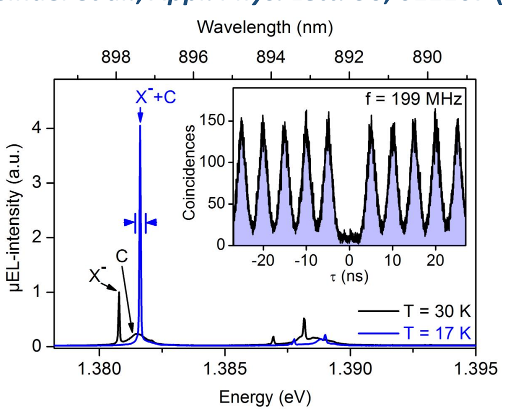
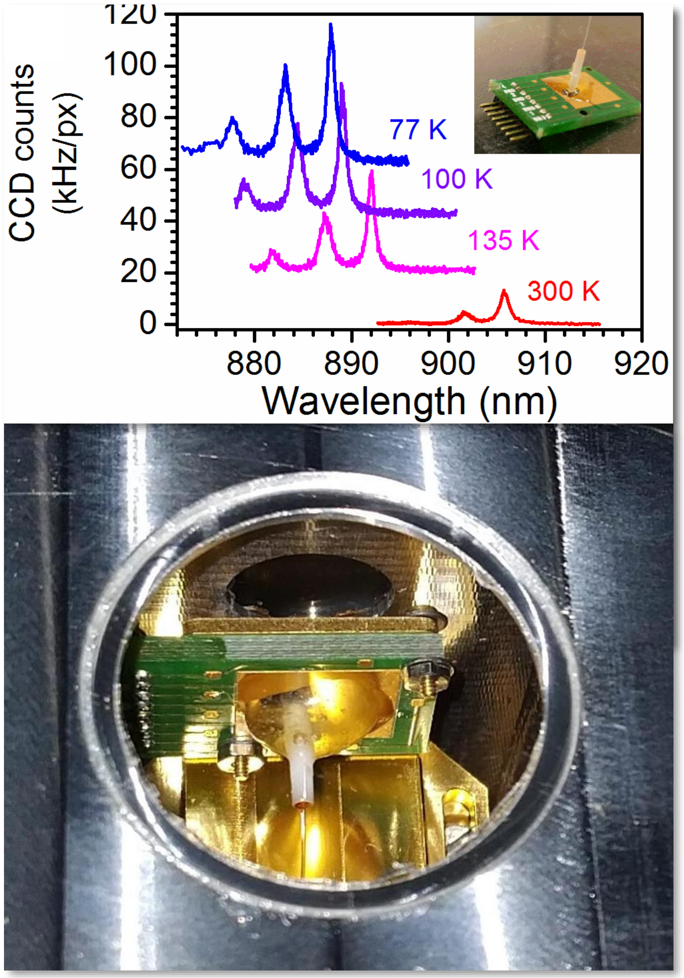
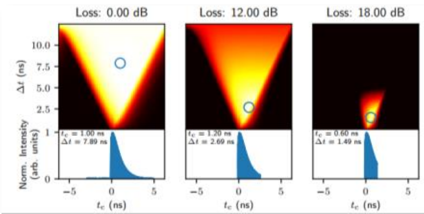




Outline – Part III

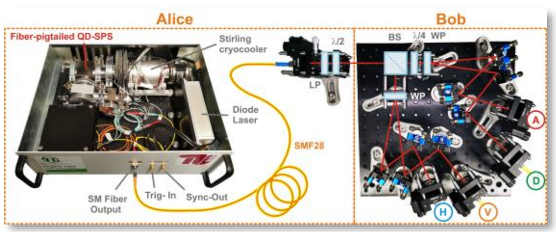
Recap

- BB84 & Rate vs. Loss Diagramm



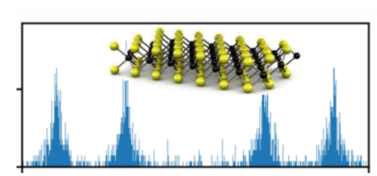
Optimization & Certification

- About How Bob Should Measure
- …and Other Usefull Tools



Developing Practical Single-Photon QKD Systems

- Plug‘n‘Play Quantum Light Sources
- Benchtop QKD Testbeds



Emerging Materials

Atomically-Thin Single-Photon Sources for QuCom

QuSecure

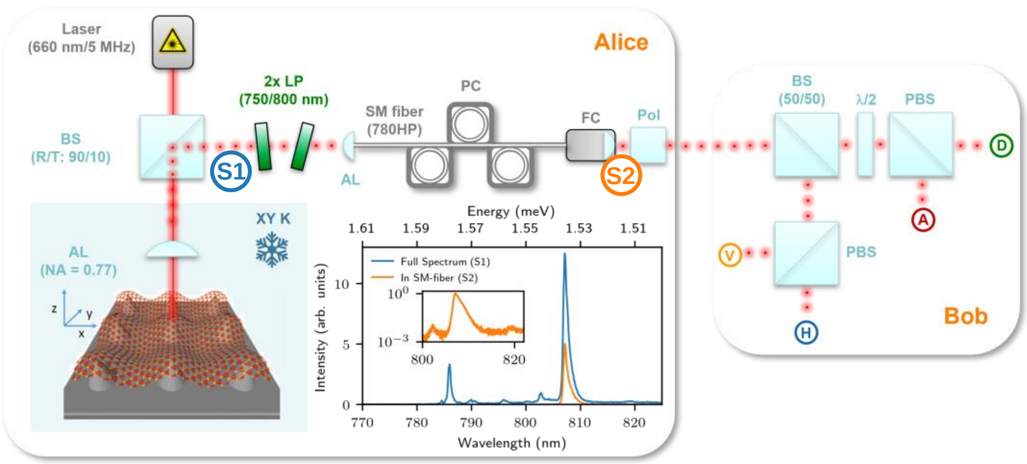
Group Website

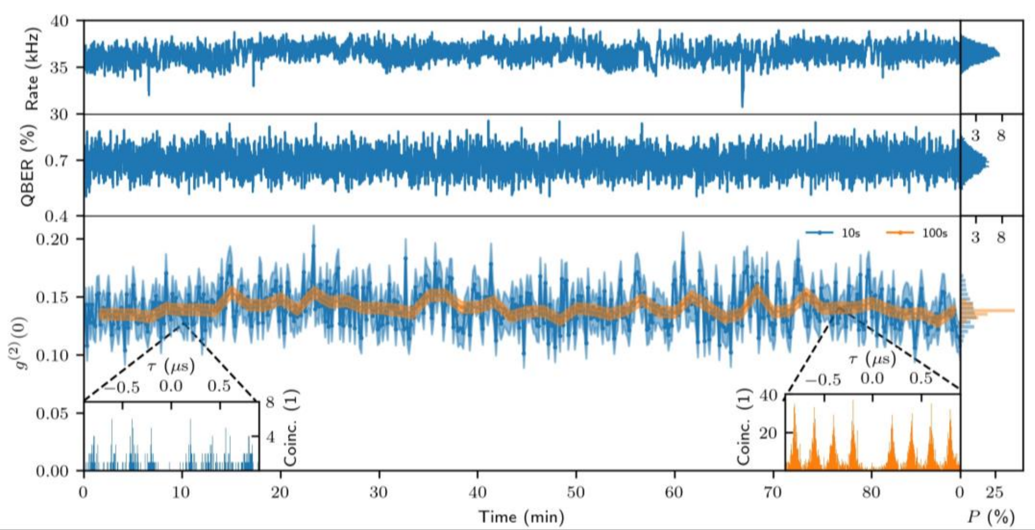
Summary & Outlook

Towards Quantum Communication Networks

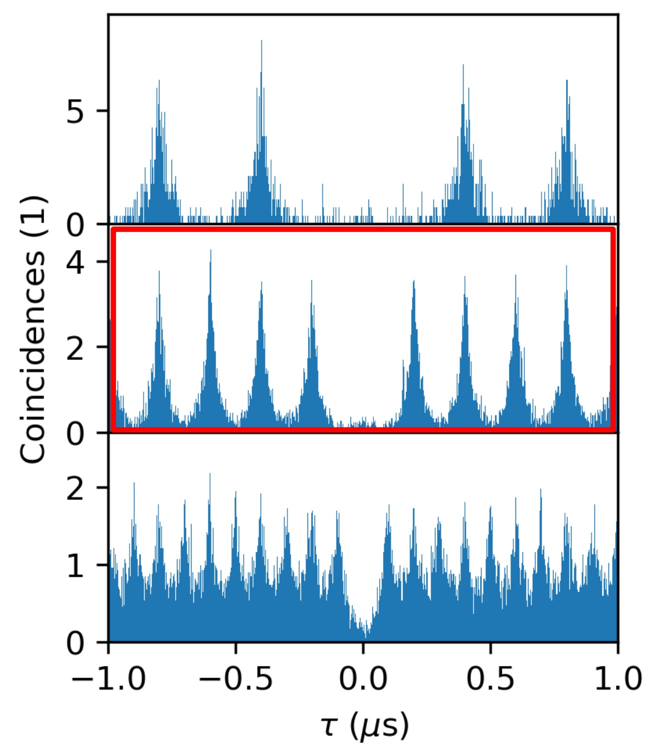
QKD using 2D-TMDCs?

T. Gao, M. von Helversen, C. Anton-Solanas, C. Schneider, and T. Heindel, arXiv.2204.06427 (2022)

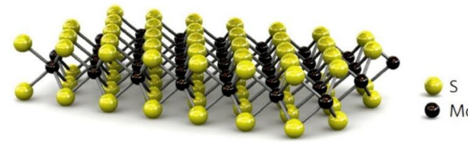




- ○ WSe_2 monolayer on structured surface (Silver nanoparticles)
- → Nanoparticles result in strain centers
  - → Single confined quantum emitters
- ○ Up to 0.5 MHz click-rate (CW)
- ○ $g^{(2)}(0)$ down to 0.034 ± 0.002 (pulsed)



QKD using



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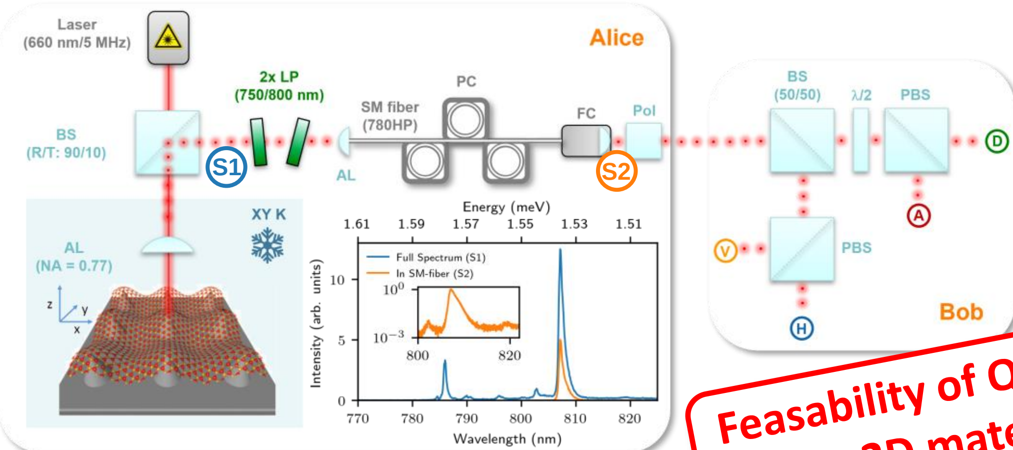
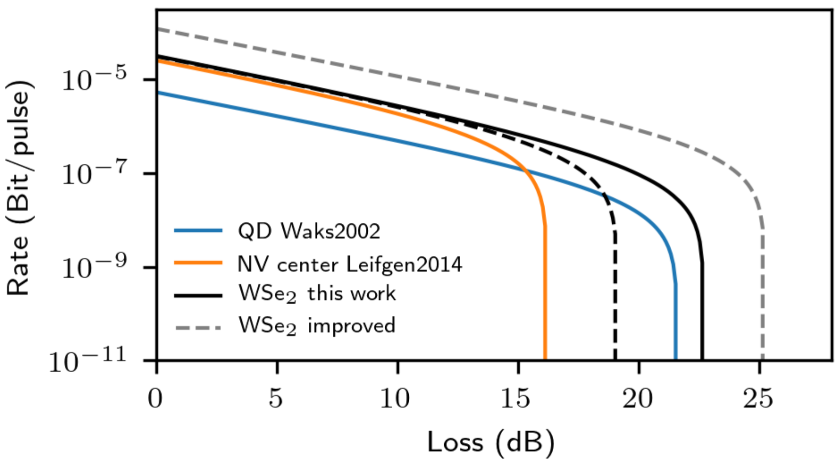


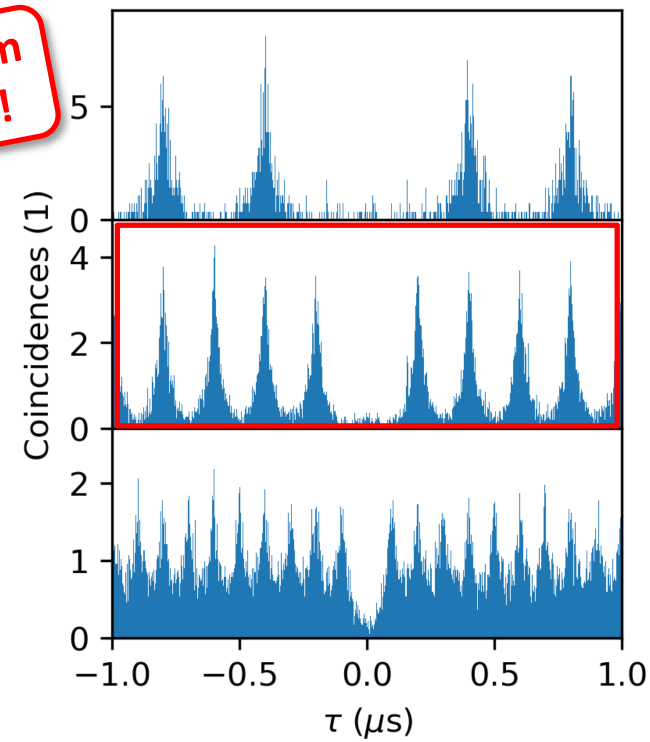
- WSe$_2$ monolayer on structured surface (Silver nanoparticles)

→ Nanoparticles result in strain centers
→ Single confined quantum emitters

- Up to 0.5 MHz click-rate (CW)
- $g^{(2)}(0)$ down to 0.034 ± 0.002 (pulsed)

Feasability of QuCom using 2D materials!





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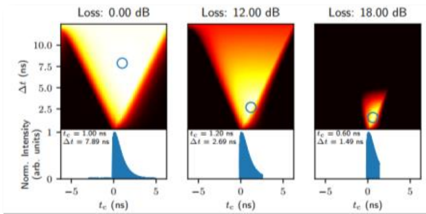

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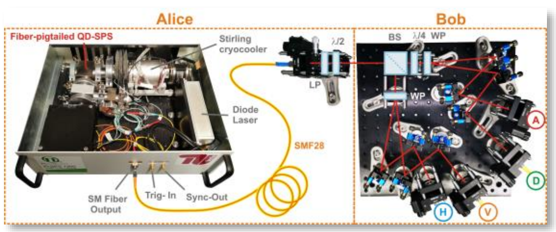

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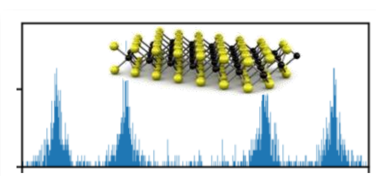


Emerging Materials

Atomically-Thin Single-Photon Sources for QuCom

Group Website

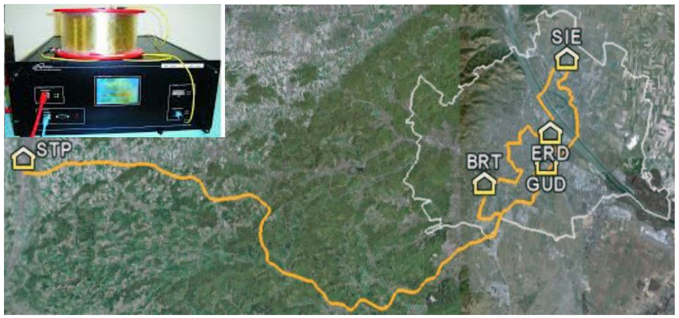
Summary & Outlook

Towards Quantum Communication Networks

Metropolitan Area QKD Networks

Carrying owls to athens… ;-)

SECOQC – Vienna/Austria

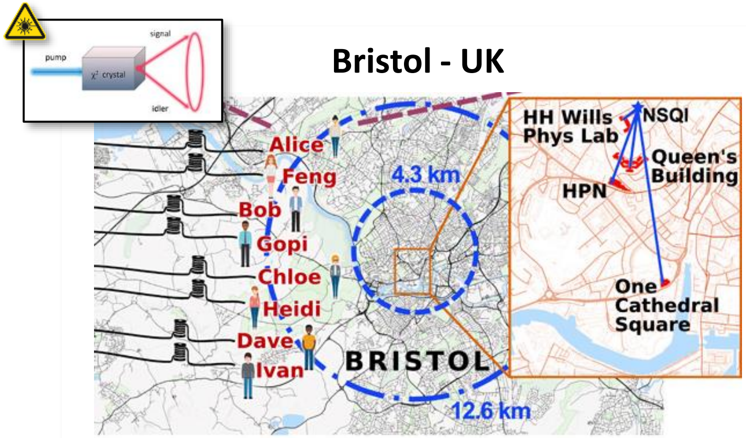


M. Peev et al., New J. Phys. 11, 075001 (2009)

Cambridge - UK

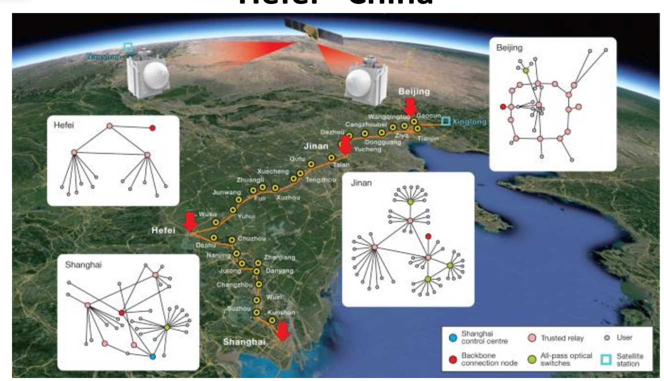
J. F. Dynes et al., *npj Quantum Inf.* 5, 101 (2019)

Bristol - UK



S. K. Joshi et al., *Science Adv.* 6, eaba0959 (2020)

Hefei - China



Y.-A. Chen et al., *Nature* 589, 214 (2021)

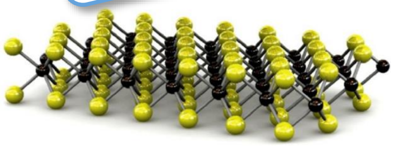
Towards a Berlin Quantum Network

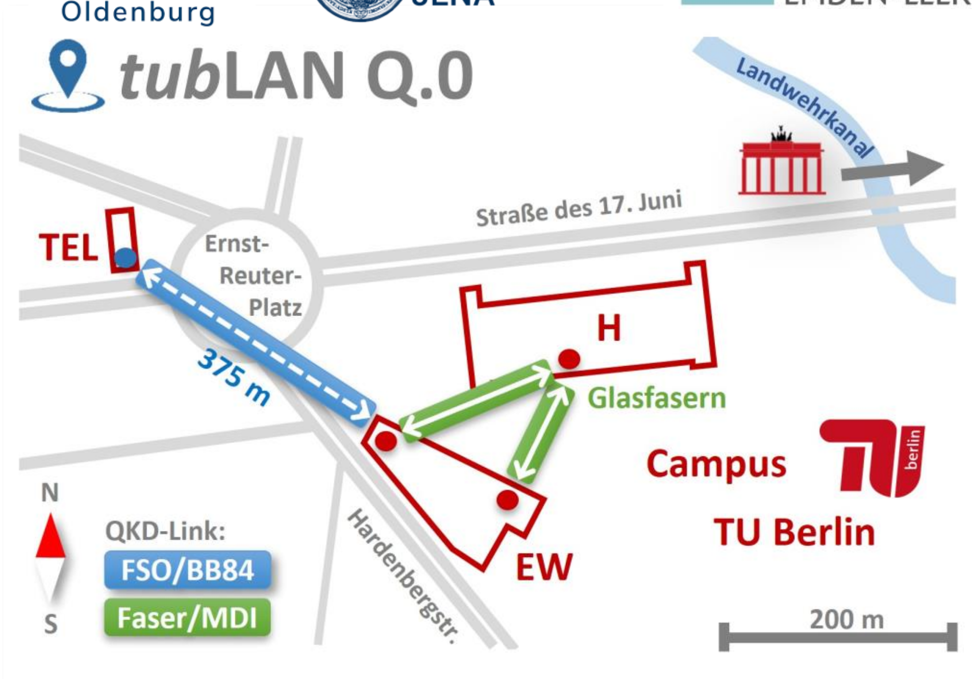
Carl von Ossietzky Universität Oldenburg

FRIEDRICH-SCHILLER-UNIVERSITÄT JENA

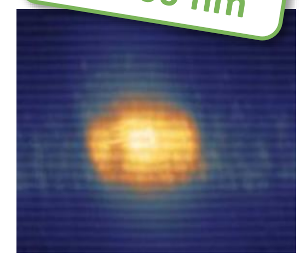
University of Applied Sciences HOCHSCHULE EMDEN·LEER

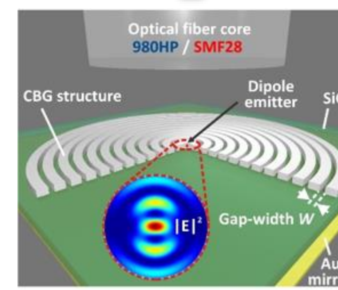
FSO-QKD at 800 nm

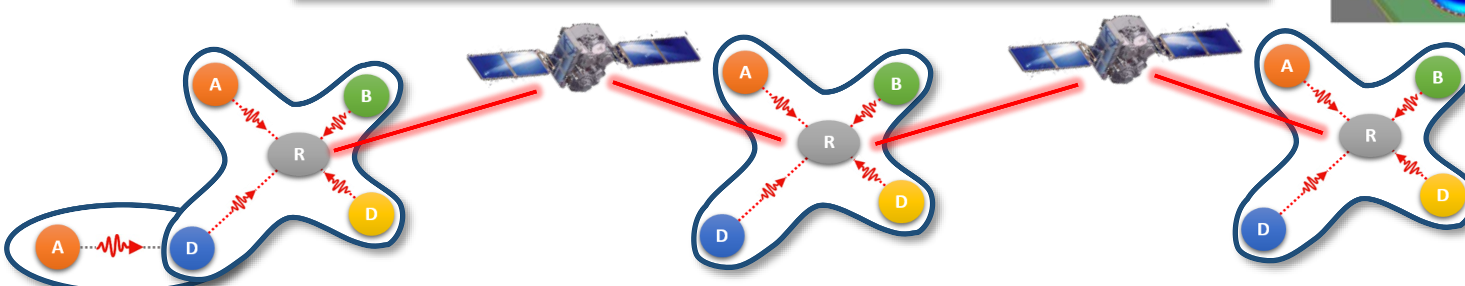




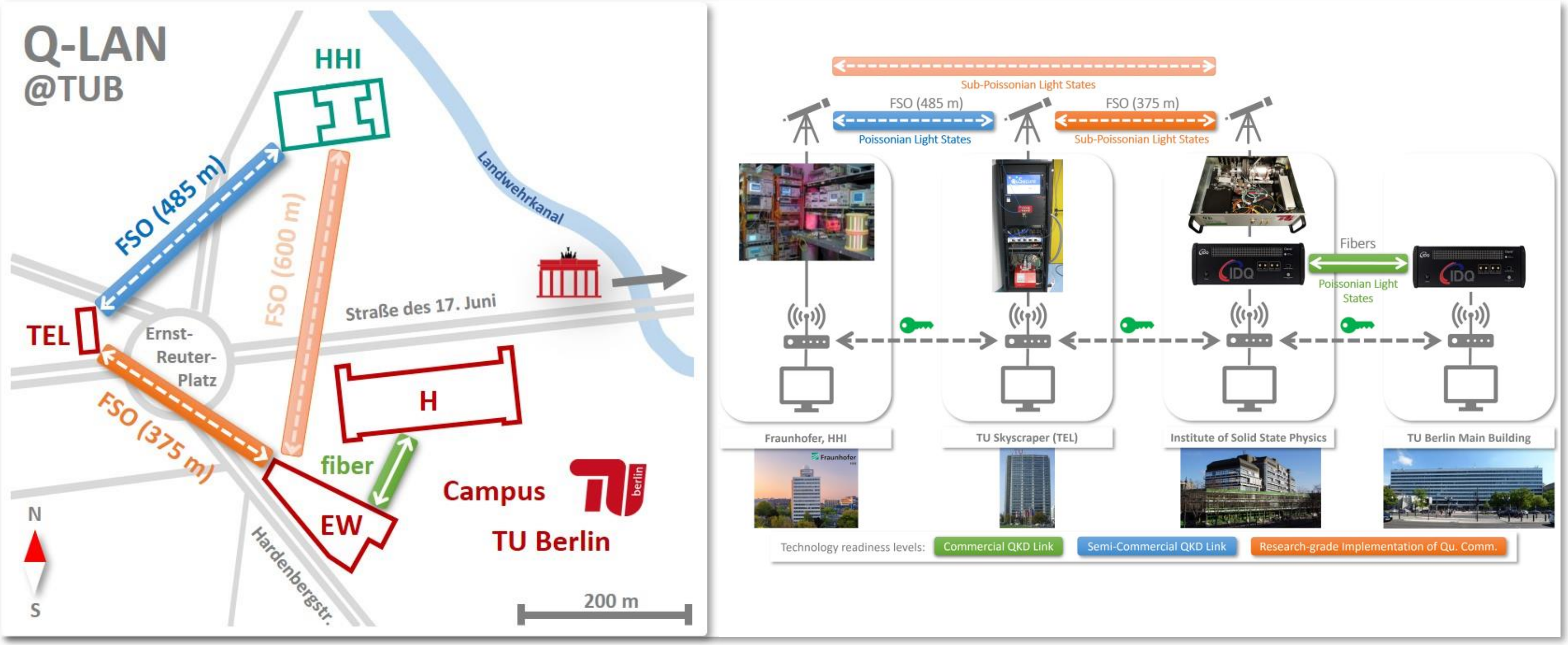
MDI-QKD at 1300 nm

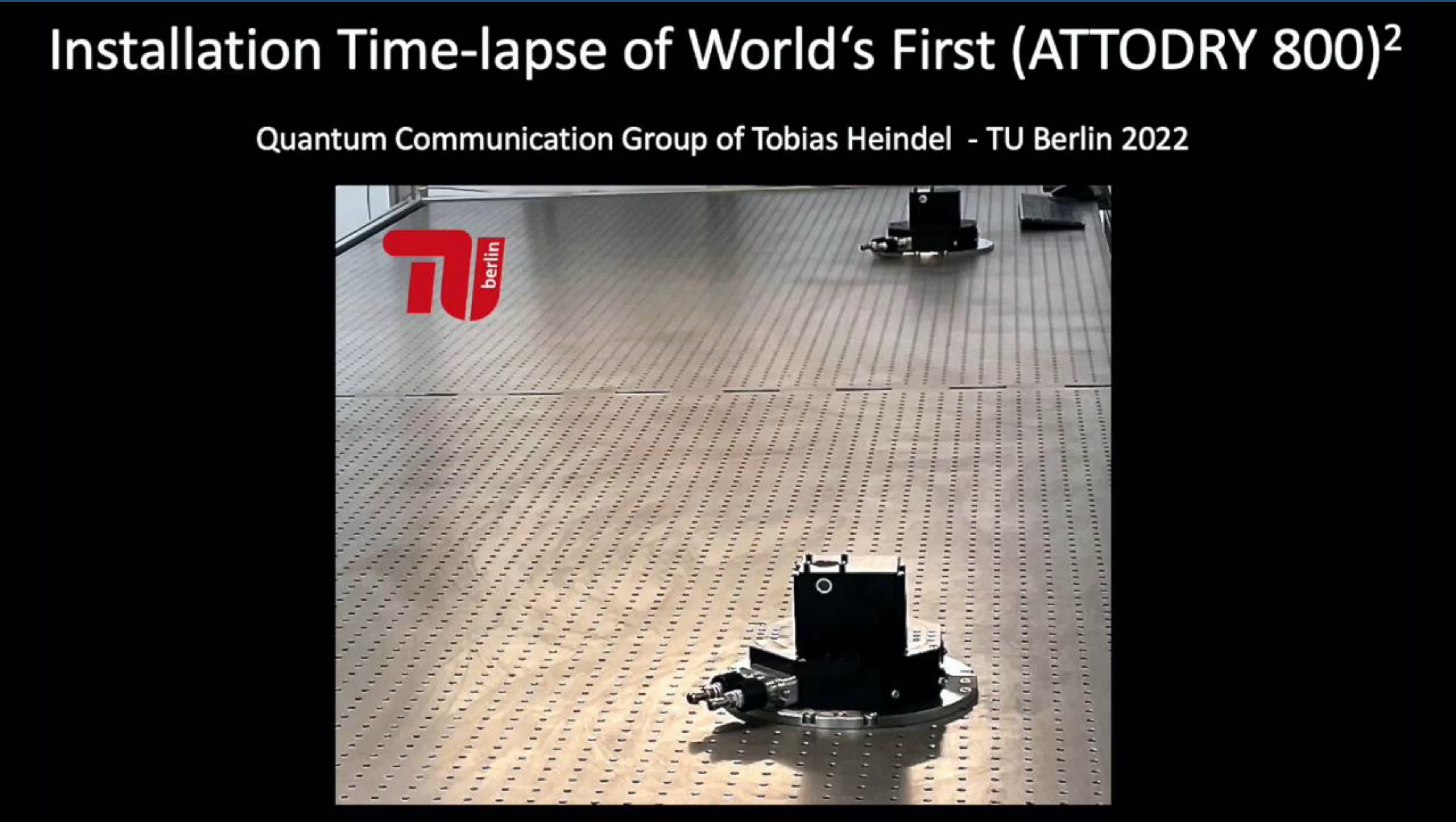






Towards a Berlin Quantum Network





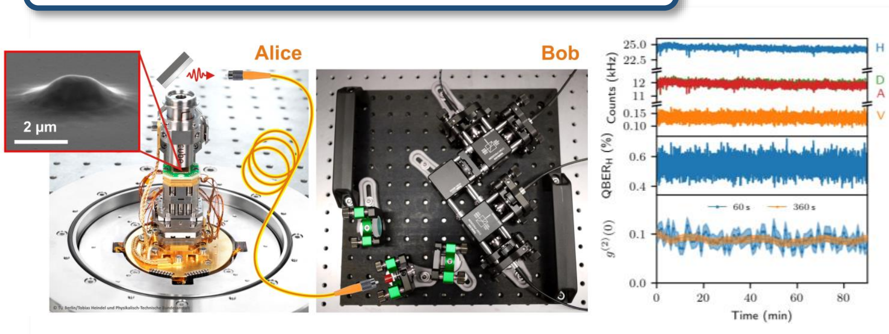
Installation Time-lapse of World‘s First (ATTODRY 800)^2
Quantum Communication Group of Tobias Heindel - TU Berlin 2022

QuCom group

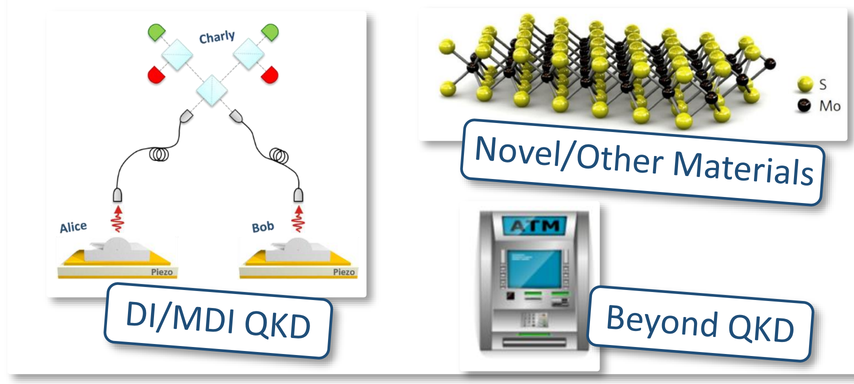
Group Website

Summary & Outlook

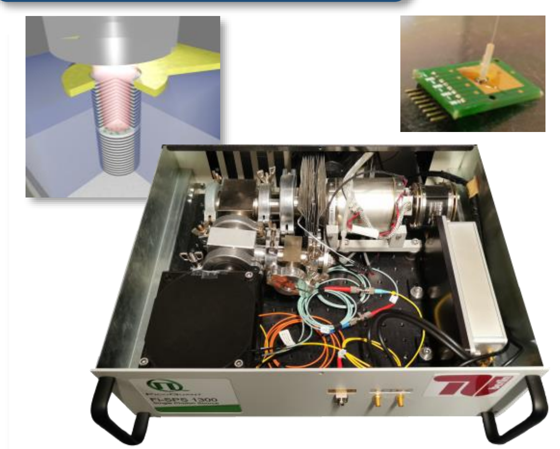
Advances in Single-Photon QKD

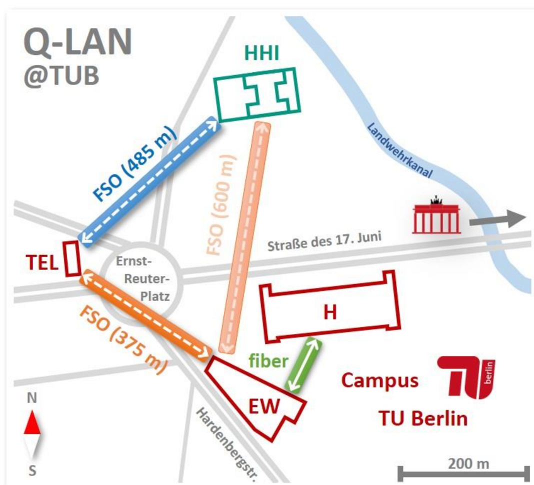


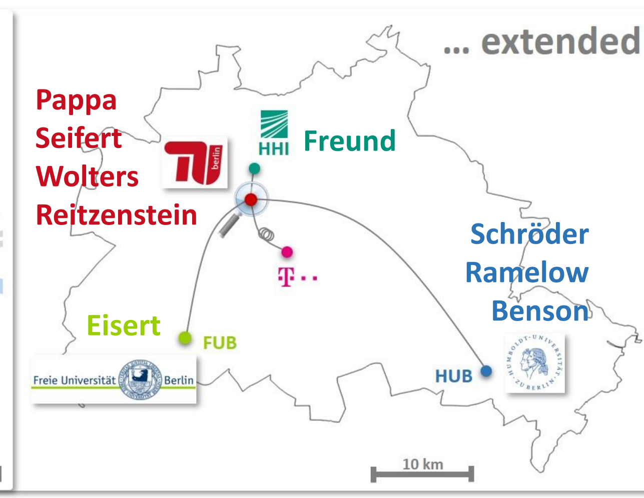
Advanced Implementations & Materials



Plug‘n‘Play Devices







International Quantum Year 2025

→ https://quantum2025.org/

INTERNATIONAL YEAR OF
Quantum Science
and Technology