

# Grand Challenge der Quantenkommunikation

Joint presentation of the funded projects:

**DIQTOK**

**HybridQToken**

**NEQSIS**

**Q-ToRX**

**QPIS**

**QuaMToMe**

and theoretical supporting project

**Q-TOK**

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und Forschung



Authentification hacked!

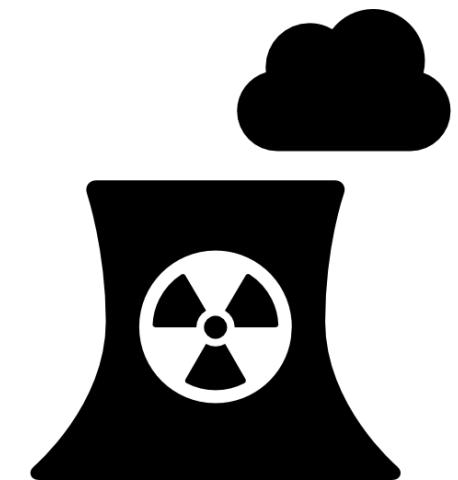
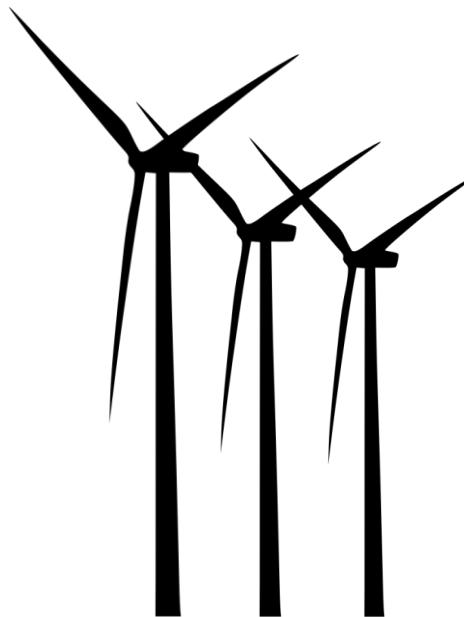
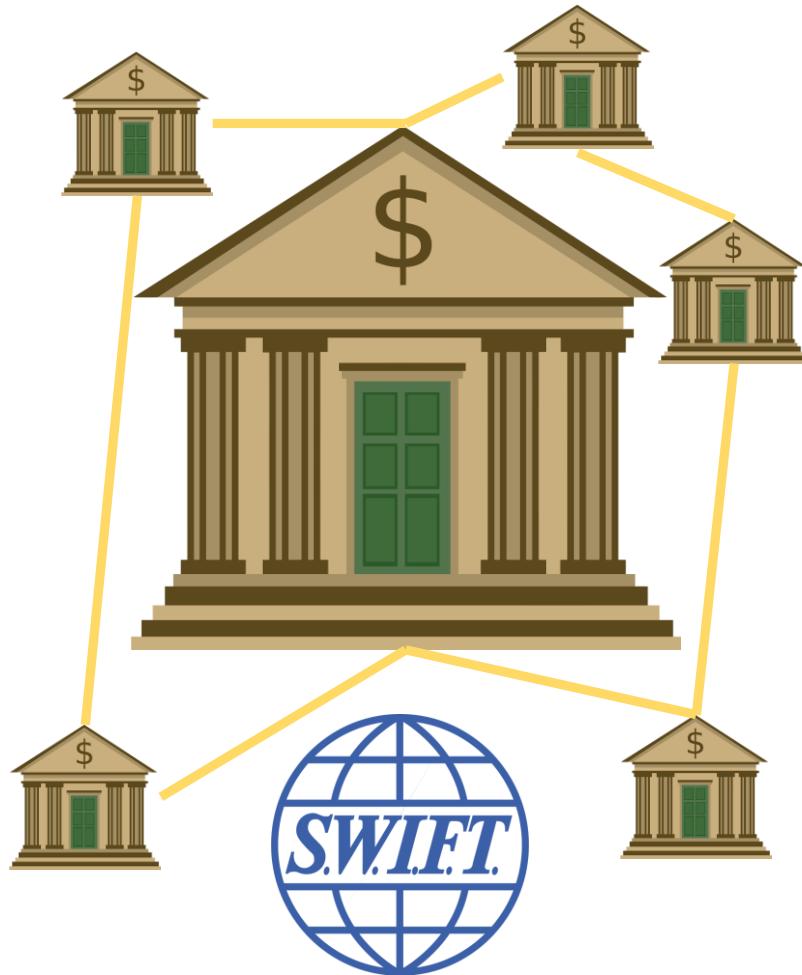
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# Grand Challenge DER QUANTENKOMMUNIKATION



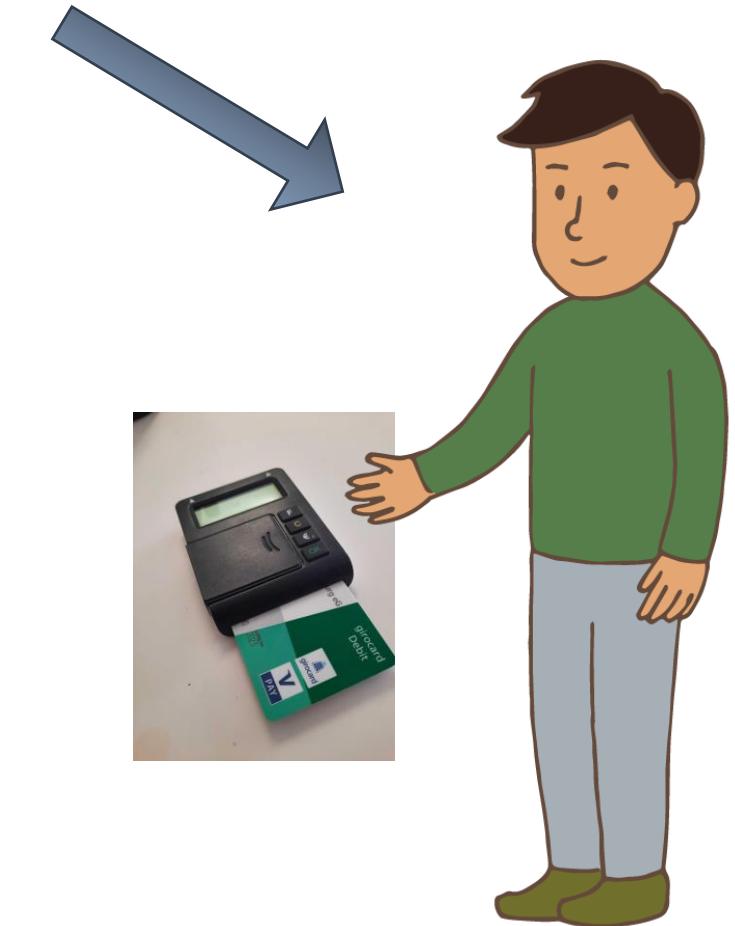
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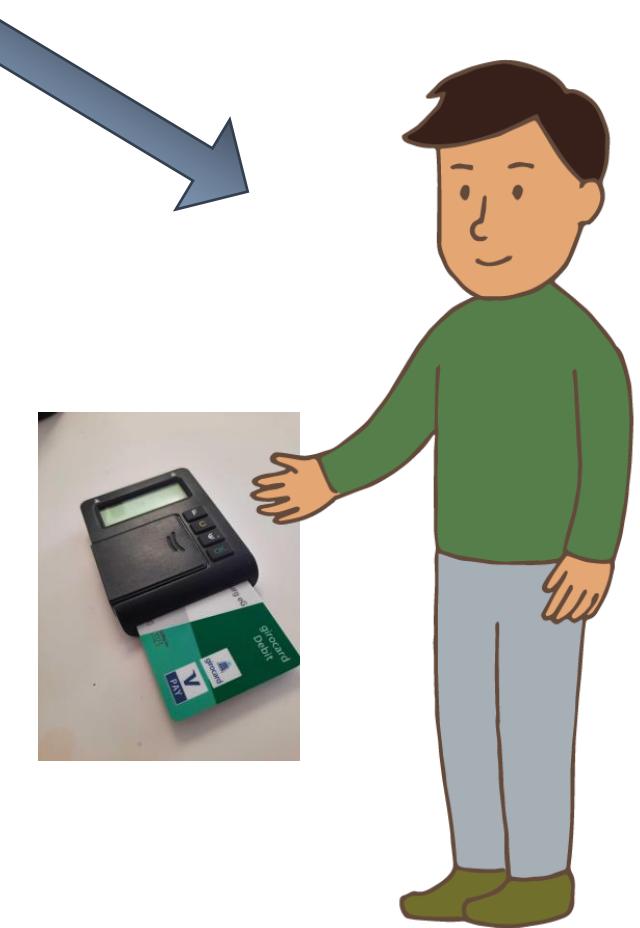


Classical token  
for online shopping



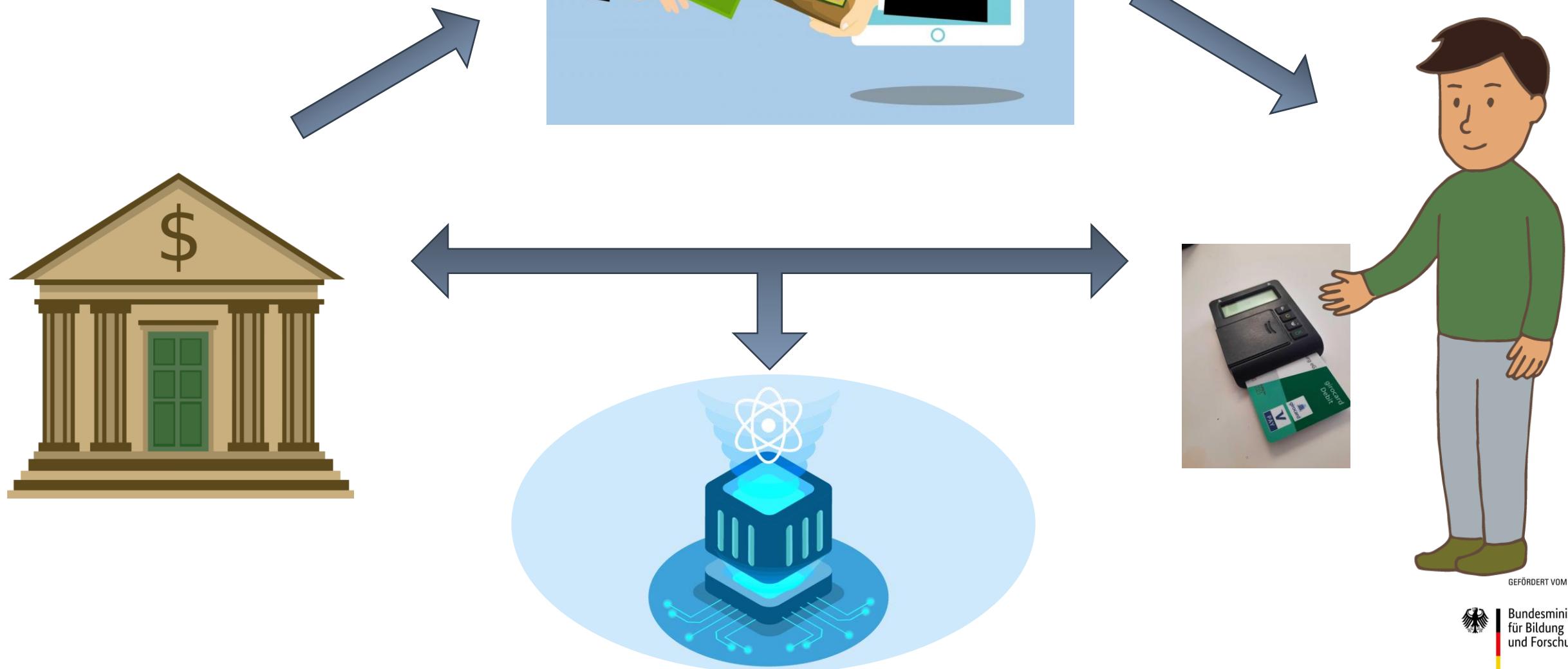
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# Classical token for online shopping



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Classical token  
for online shopping

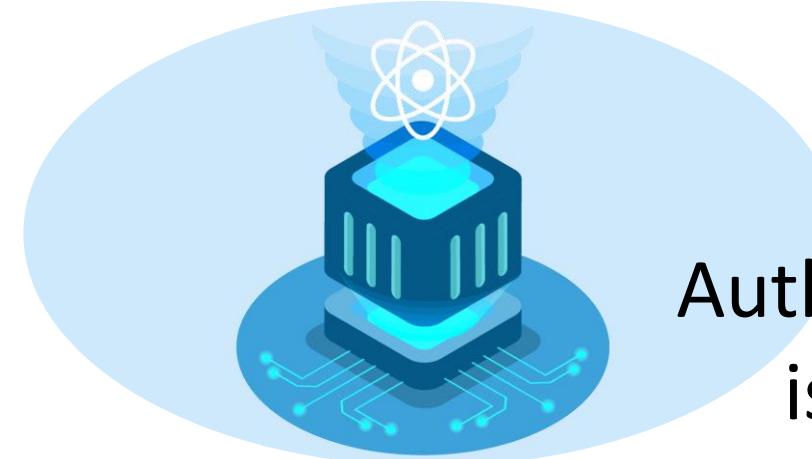
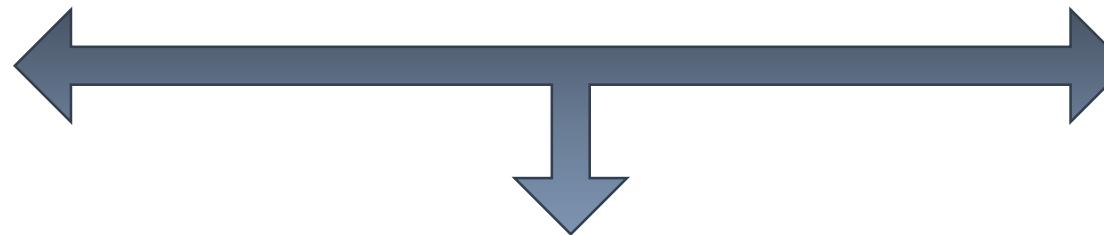
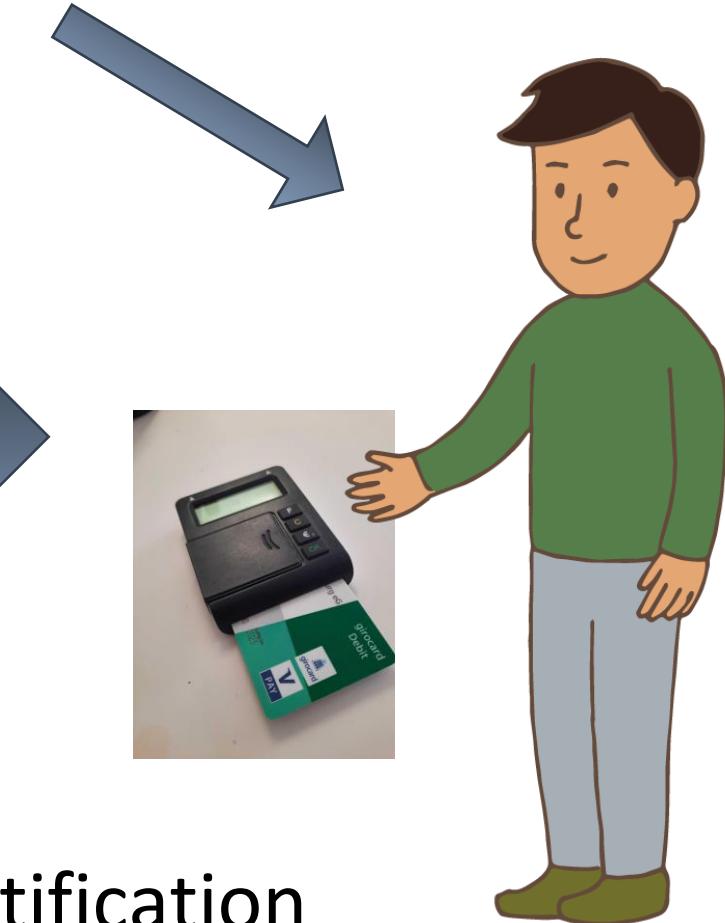


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Classical token  
for online shopping

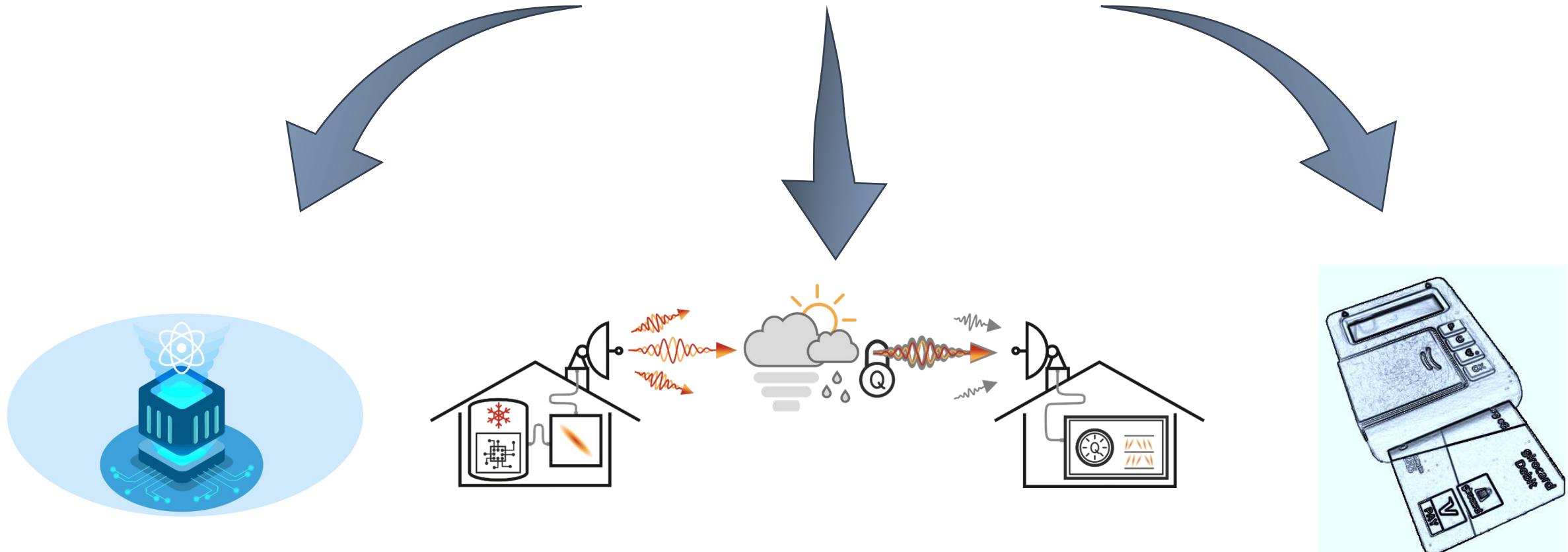


Authentification  
is hacked!

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# QUANTUM TOKEN

Identification at... computing, generation, transfer, storage, reading, ...



Quantum computing

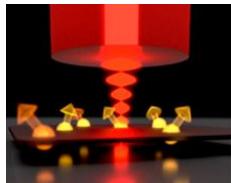
Quantum communication

Quantum storage

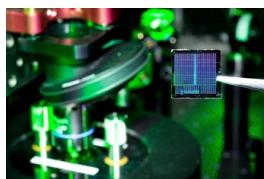
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Integration with network



Integration in  
microchip technology

**|DIQTOK⟩**

Mobility

NEQSIS

Q-ToRX

HybridQToken

**Q-TOK**  
Theory  
Project

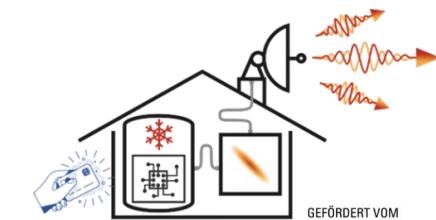
QPIS

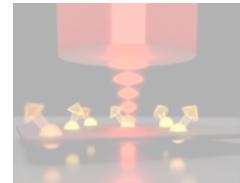
DIQTOK

QuaMToMe

QPIS

Quantum key for 5G





Integration with network

NEQSIS

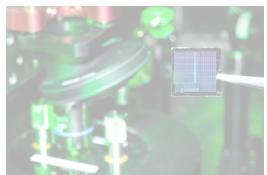
Q-ToRX

Ultralong storage time

**Q-ToRX**



Integration in  
microchip technology



HybridQToken

**Q-TOK**  
Theory  
Project

QPIS

Efficient writing and reading



QPIS

Mobility

DIQTOK

QuaMToMe

Quantum key for 5G

**|DIQTOK>**



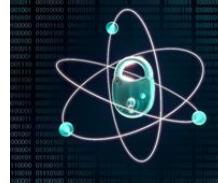
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# Quantentoken für sichere Authentifizierung

Provable Security and Simulation Accuracy

Resilience, Security, Low Latency – by Design



Protocols for authentication  
and secure data storage based on **Quantum Token**.

## Goals:

- Quantum token-based application scenarios in the sense of **Post Shannon Theory**  
e.g. secure identification
- Applications for storage and processing of data
- Alternative Use Cases  
→

Matching of Theory with Experiment  
and System Design

## Systematic Development of Software and Simulations

- Modular Software Development
- Simulative Evaluation of Hardware-Plattforms  
via  
Key Performance Indicators

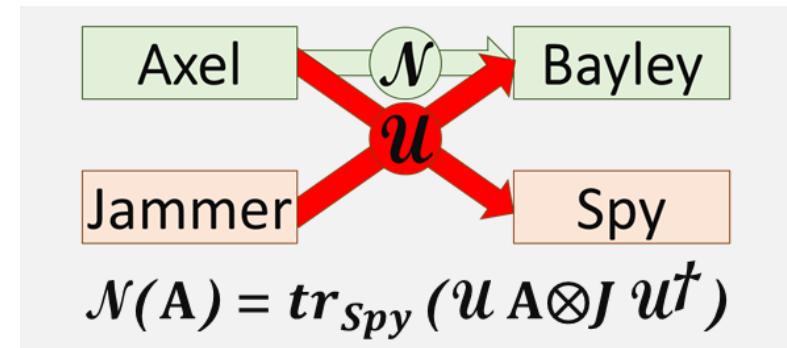
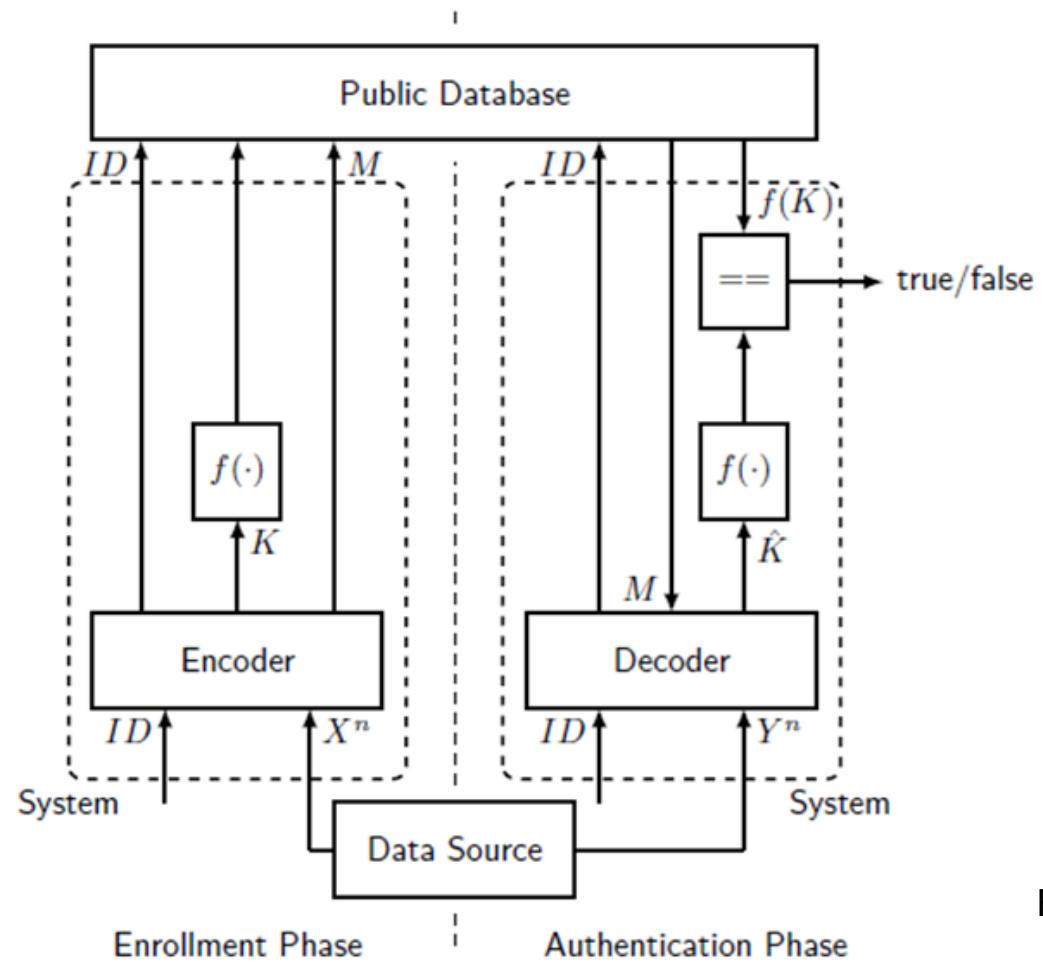
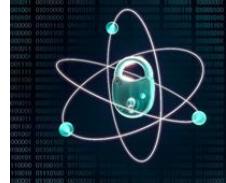
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# Quantum token for secure authentification

## Provable Security and Simulation Accuracy



$$G(S) = \text{tr}_E(U S \otimes G_{E_1} \otimes G_{E_2} U^\dagger)$$

$$G(S) = \text{tr}_E(U S \otimes G_{E_1} \otimes U^\dagger)$$

First theoretic models for quantum PUF have been obtained

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## Partners in consortium



**Holger Boche**

Post-Shannon Information theory and protocols for applications, as well as new approaches in information theory. Automated approaches for security proofs and stability under denial-of-service attacks. Certification and standardisation.



**Christian Deppe**

Hardware agnostic base protocols for quantum token-based authentication and secure storage.



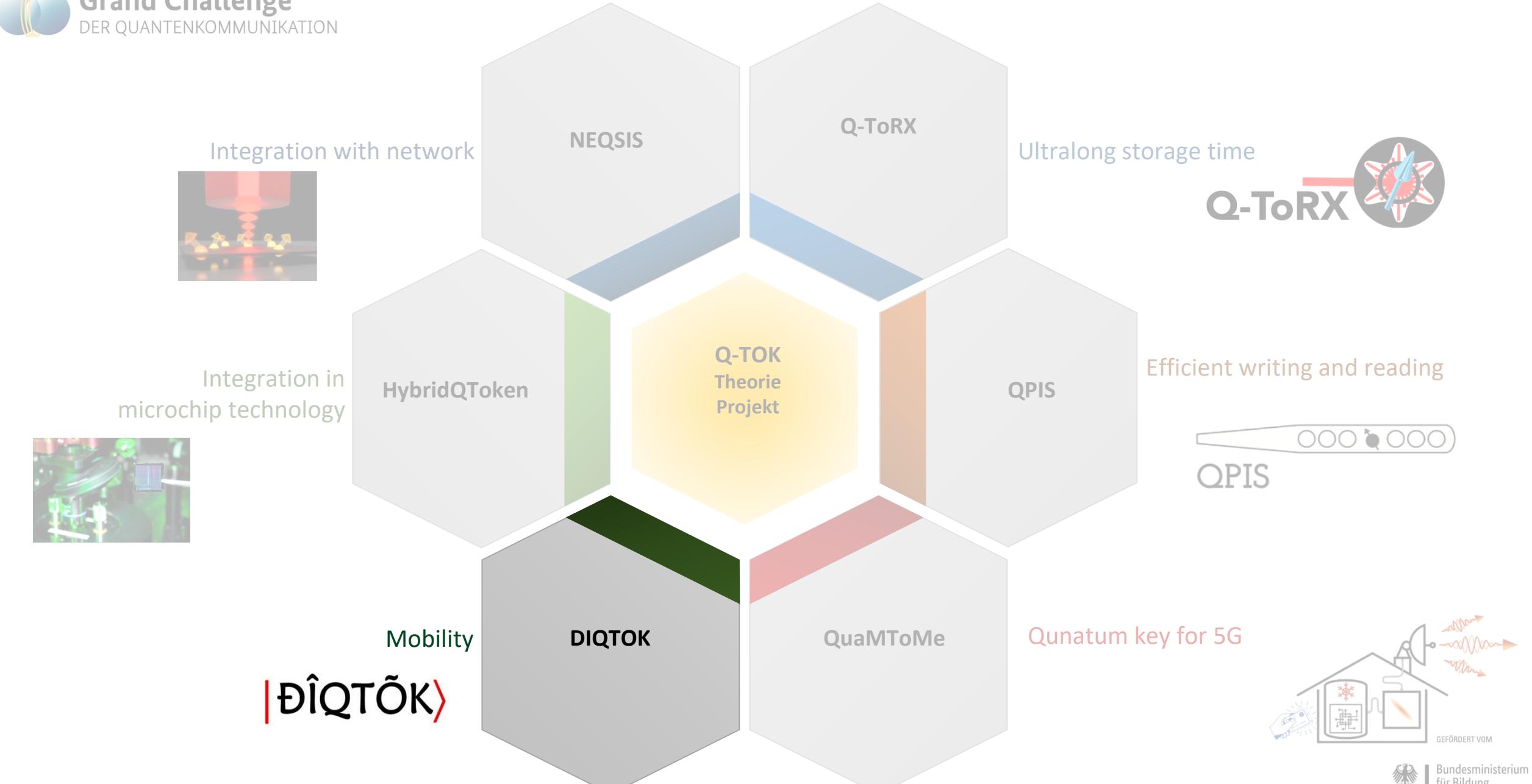
**Janis Nötzel**

Information-theoretic modelling, base protocols, preparation of performance evaluation for hardware platforms via software.

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## Diamond-based quantum token

Kilian Singer

*Light-matter interaction*

**Cyril Popov**

*Diamond nanotechnology*

**UNIKASSEL**  
**VERSITÄT**

**Martin Garcia**

*Theoretical solid state and  
ultrafast physics*

**CINSaT** Center for  
Interdisciplinary Nanostructure  
Science and Technology

**Boris Naydenov**

*Spins in energy conversion and  
quantum information*

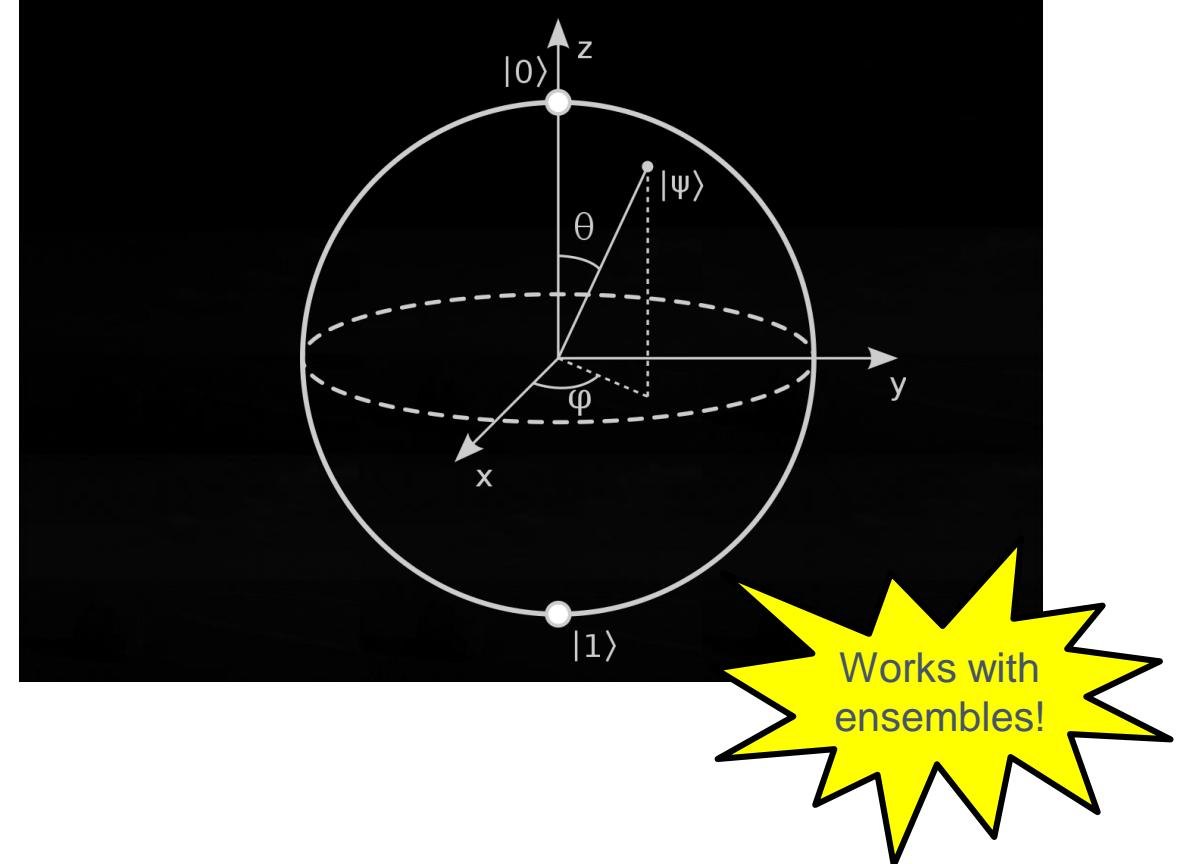
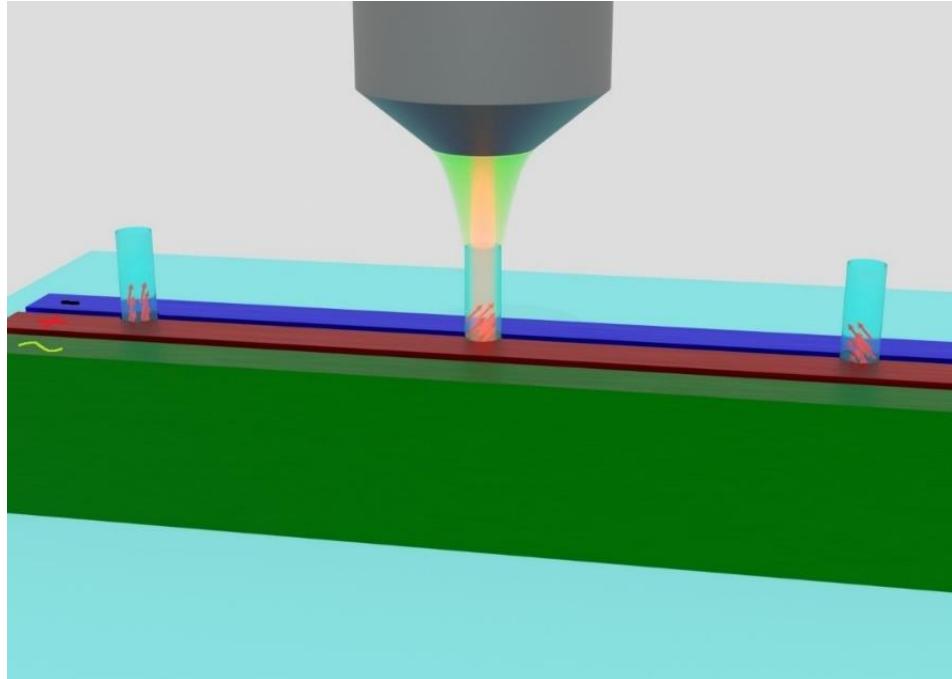
**HZB** Helmholtz  
Zentrum Berlin

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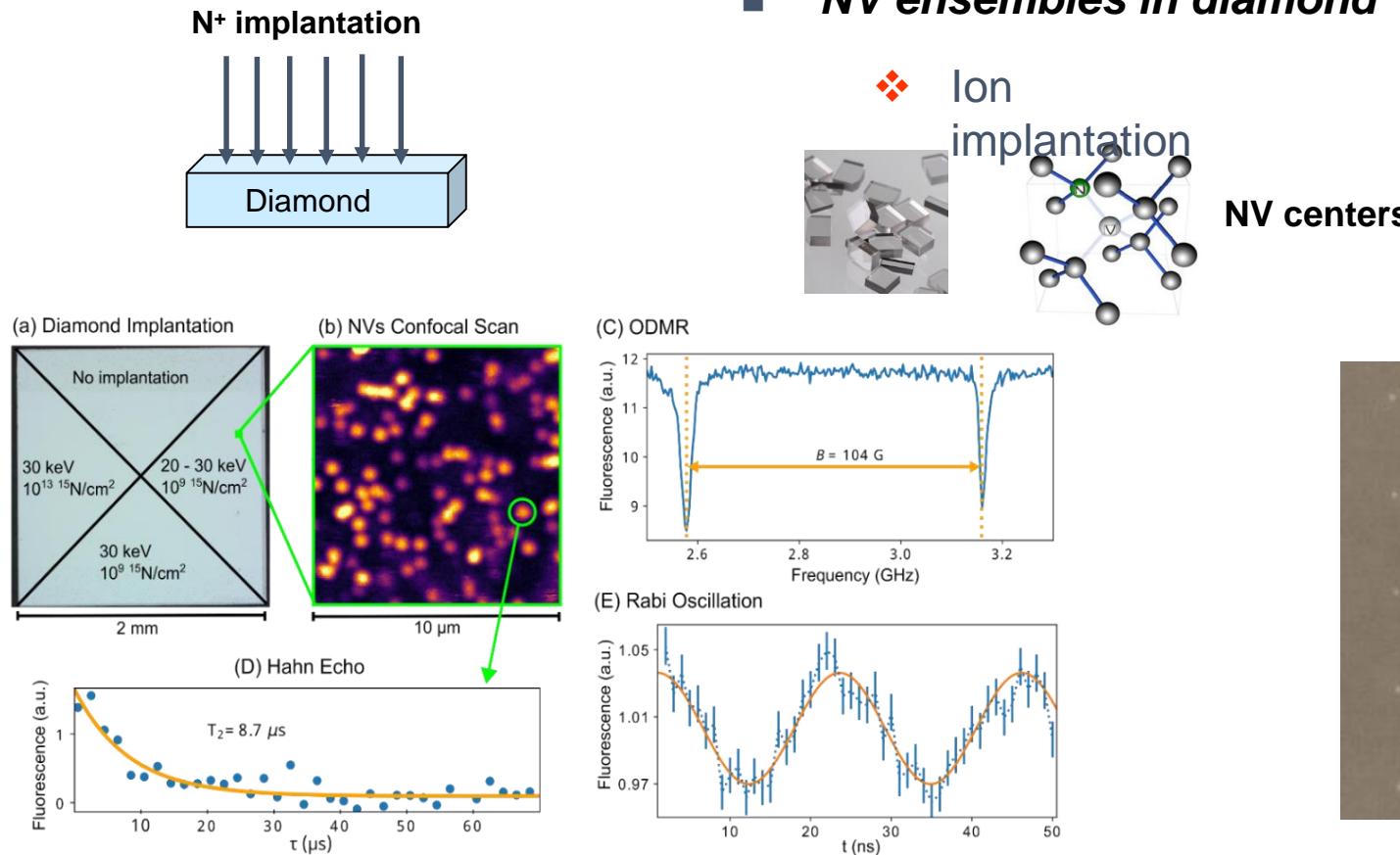
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## Goal: Robust mobile quantum tokens based on ensembles of NV color centers in diamond



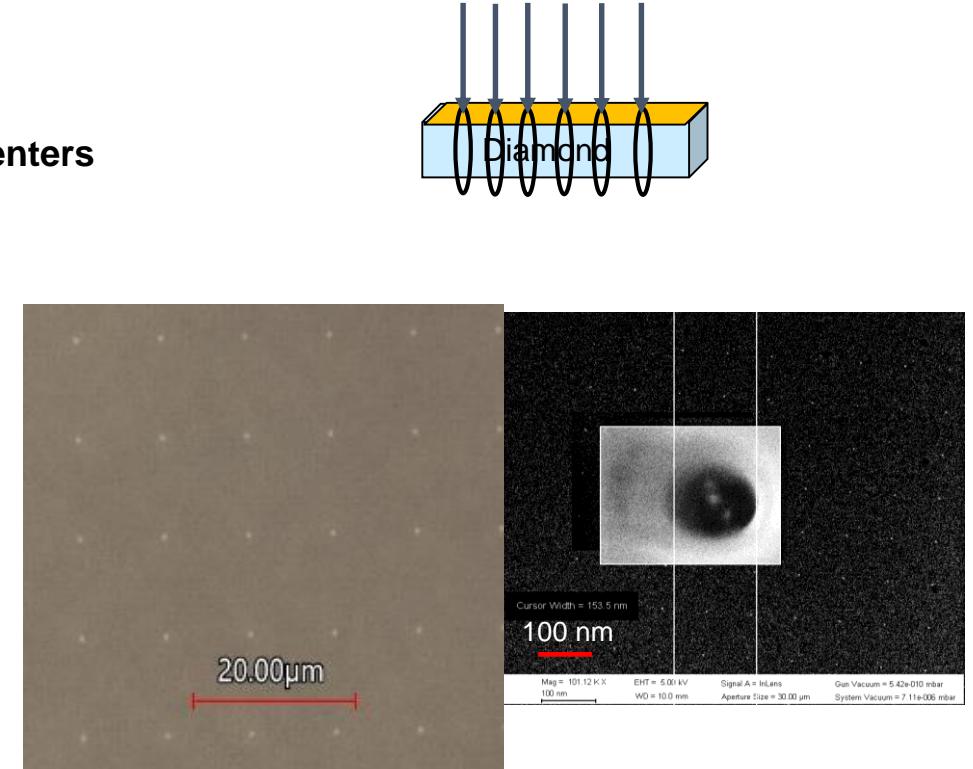
# Material optimization

## ■ NV ensembles in diamond



NV centers created by N ion implantation in diamond

## N<sup>+</sup> implantation through a mask



PMMA masks for deterministic implantation

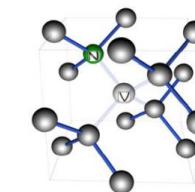
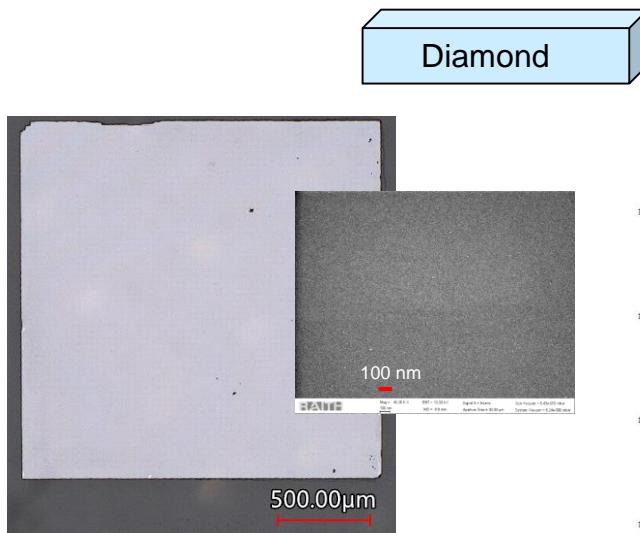


# Material optimization

## ■ NV ensembles in diamond

- ❖ Chemical vapor deposition – homoepitaxial overgrowth of diamond with short introduction of nitrogen

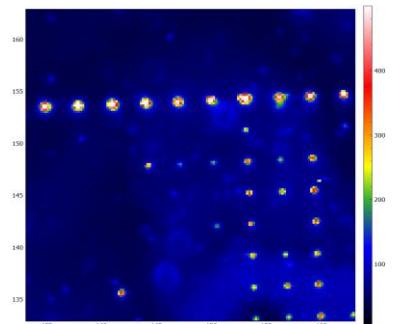
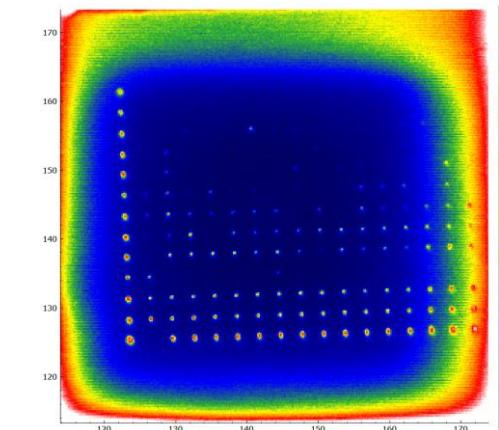
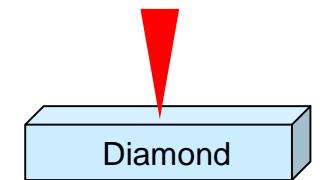
CVD



NV centers

- ❖ fs-laser irradiation – a seed pulse for creation of vacancies followed by a pulse train with lower energy for deterministic annealing

fs-laser



Uniform overgrown layer with incorporated NV centers

NV centers prepared with different laser fluences

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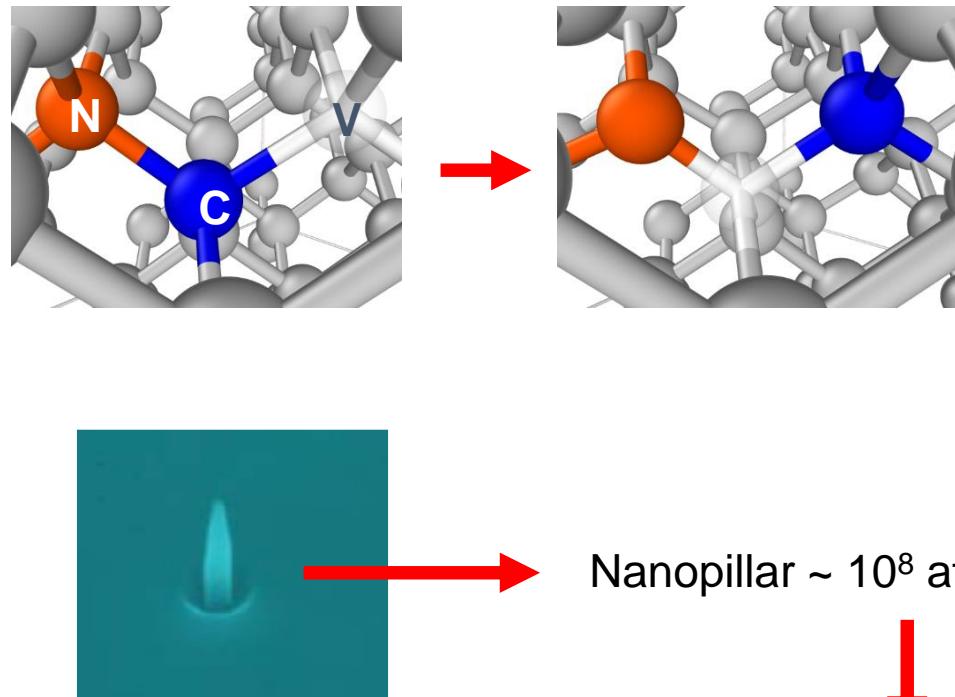
Y.C. Chen, P. Salter, S. Knauer, et al. Laser writing of coherent colour centres in diamond, *Nature Photon.* 11, 77 (2017)



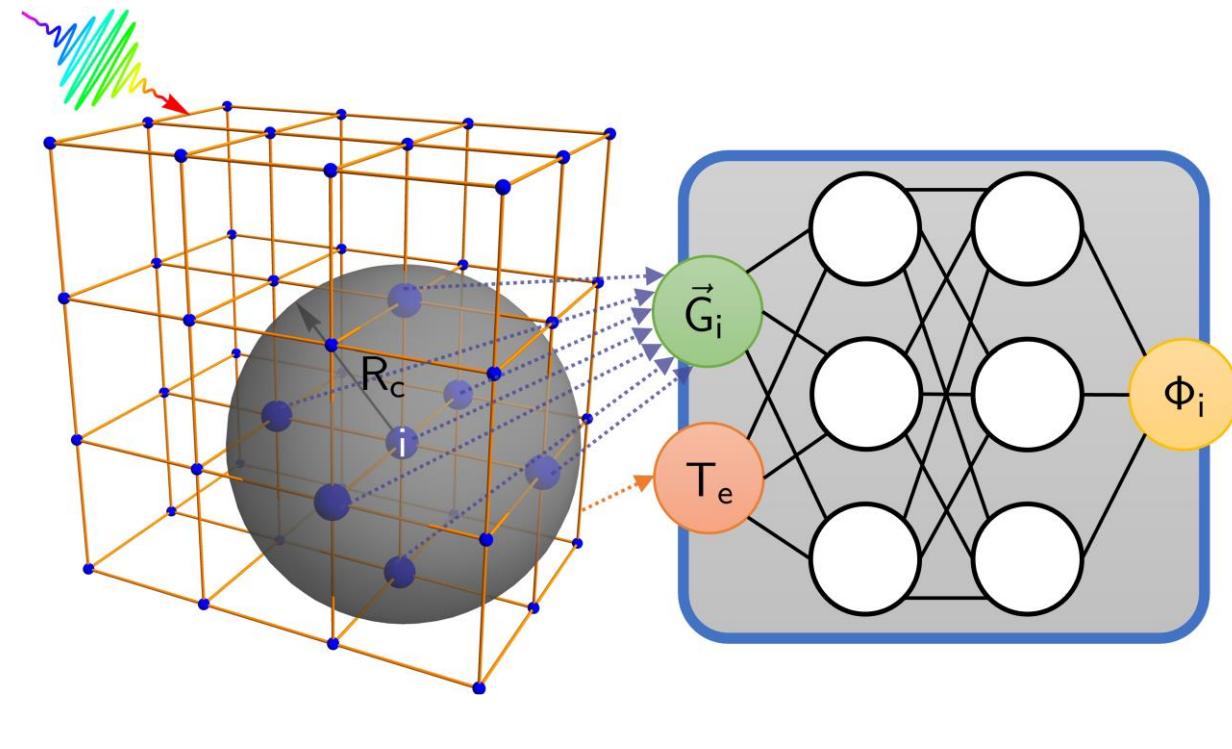
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## Material modelling

- **Ab-initio simulations of fs-laser excitation**



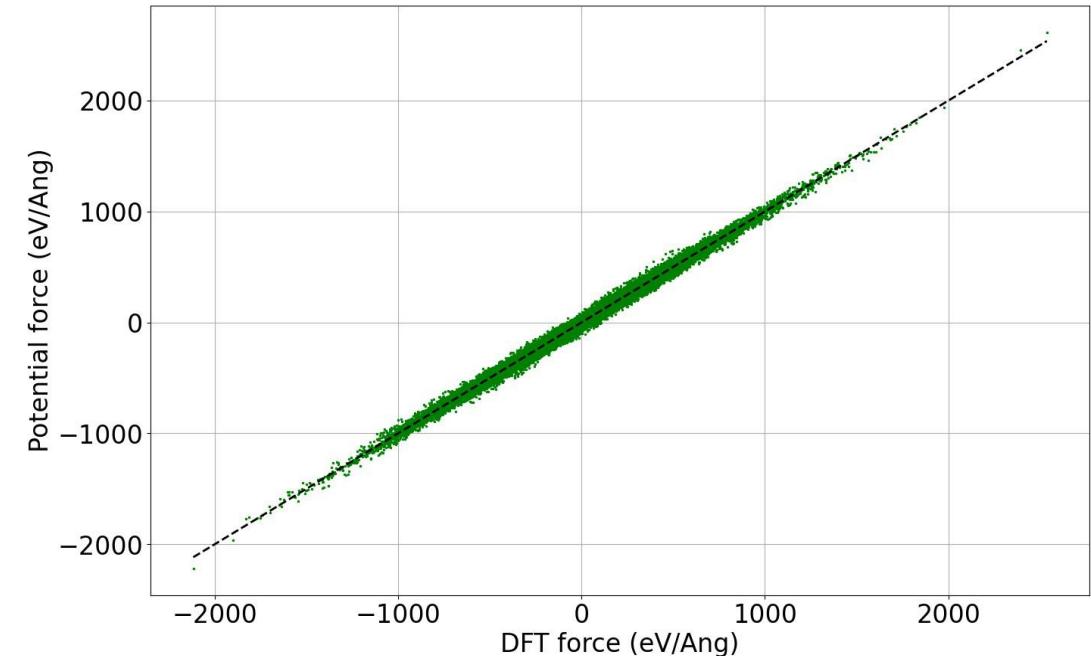
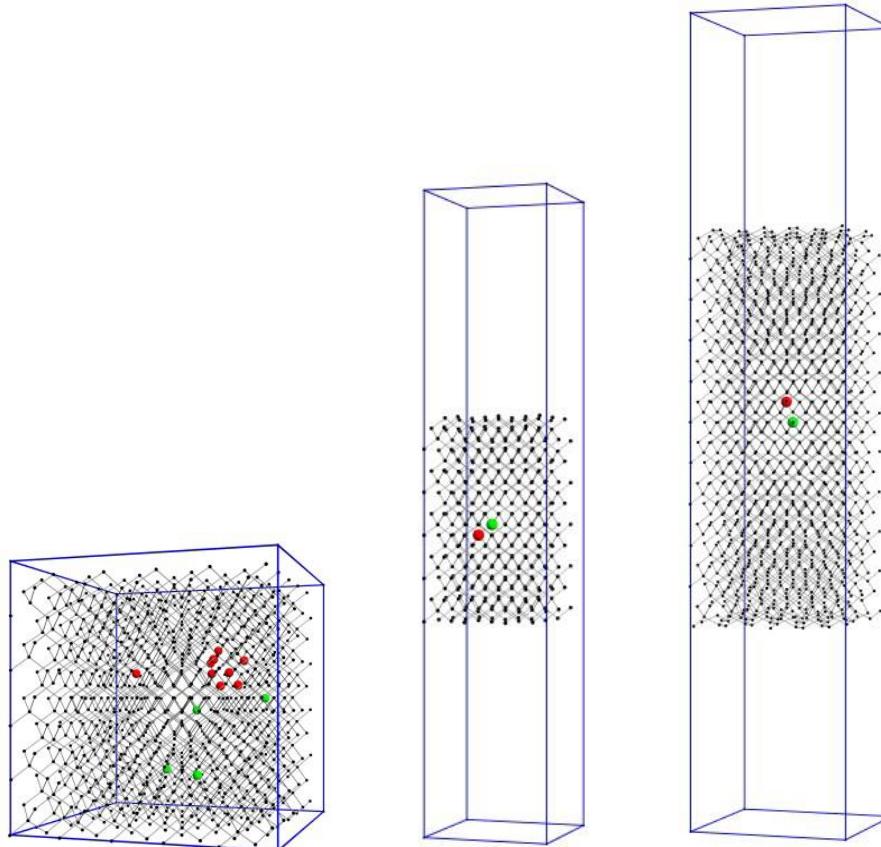
- **Development of interatomic potential**



Simulation only with interatomic potential

## Material modelling

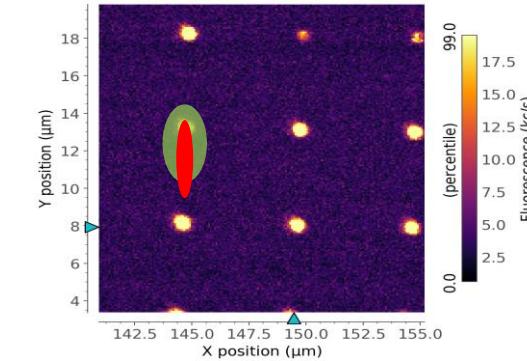
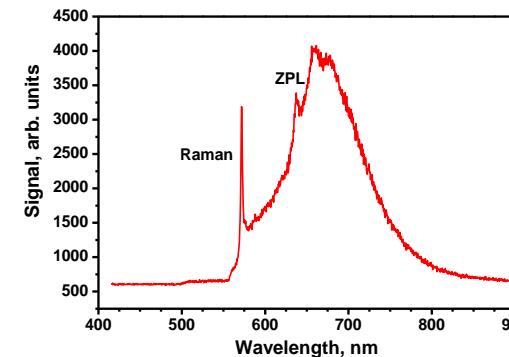
- Large data set of *ab-initio* simulations of NV
- Interatomic potential for C-C interaction (performance)



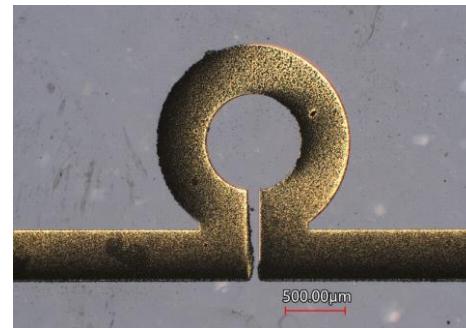


## Diamond nanotechnology

- *Incorporation of NV ensembles in nanopillars for enhanced photon emission yield and increased collection efficiency of emitted photons*



- *Microwave antennas for control of the spin state*



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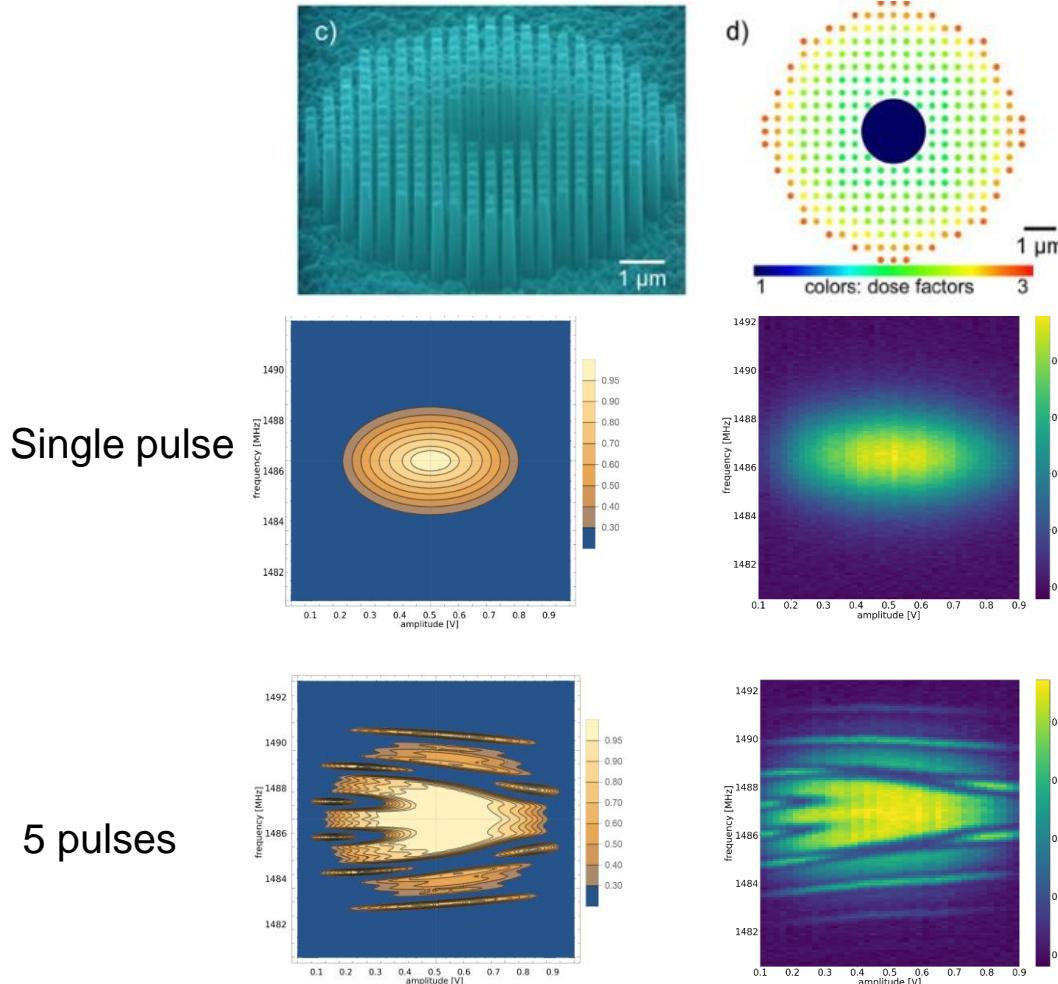
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# Composite pulses for robust ensemble manipulation



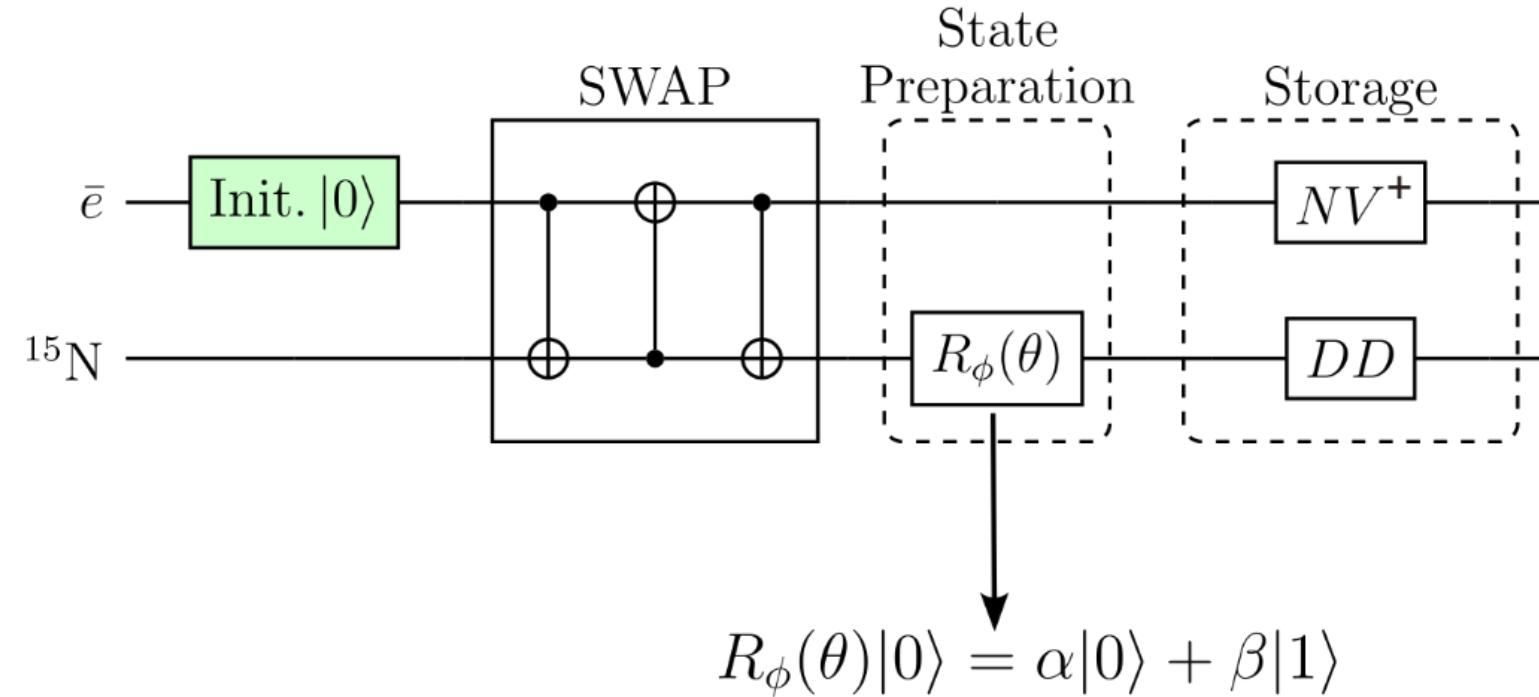
- Robust excitation needed for ensembles
- Usage of Rosen-Zener-model for analytical solution of the unitary  $\hat{U}$  with coefficients

$$U_{1,1} = \frac{\Gamma(1/2 + i\delta)^2}{\Gamma(1/2 + i\delta + \alpha) \cdot \Gamma(1/2 + i\delta - \alpha)}, U_{2,1} = -i \frac{\sin(\pi\alpha)}{\cosh(\pi\delta)}$$

- Finding excitation profile of a train of  $2n+1$  pulses

$$\hat{U}(\delta, \phi_1) \dots \hat{U}(\delta, \phi_{n-1}) \cdot \hat{U}(\delta, \phi_n) \cdot \hat{U}(\delta, \phi_{n-1}) \dots \hat{U}(\delta, \phi_1)$$

## Quantum token preparation and storage



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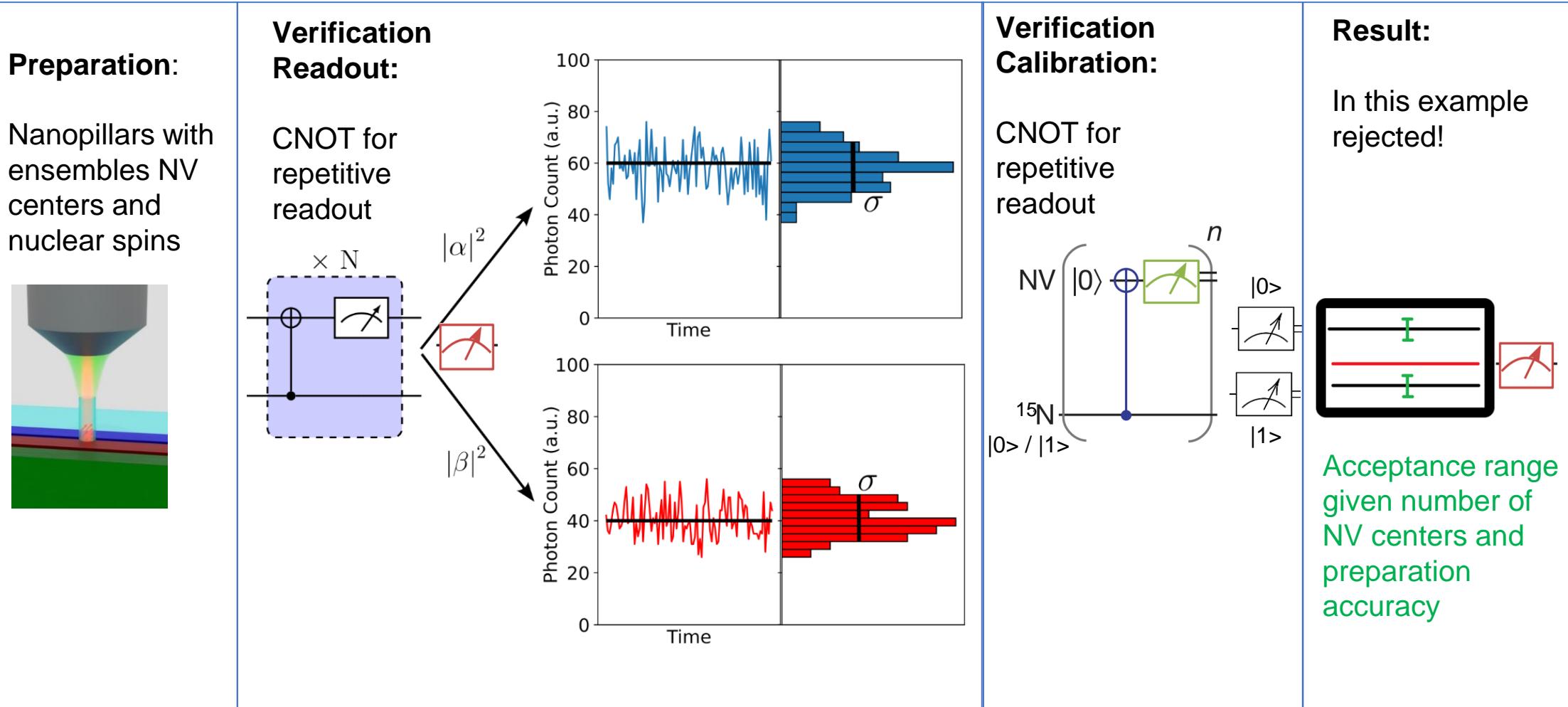
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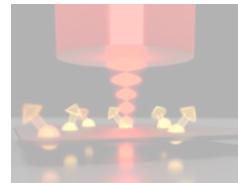


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# Experimental realization of ensemble-based quantum token protocol





Integration with network

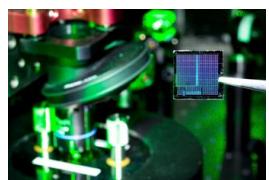
NEQSIS

Q-ToRX

Ultralong storage time



Integration in  
microchip technology



HybridQToken

Q-TOK  
Theorie  
Projekt

QPIS

Efficient writing and reading



QPIS

Mobility

| $\hat{D}\hat{I}Q\hat{T}\hat{O}\hat{K}$

DIQTOK

QuaMToMe

Quantum key for 5G



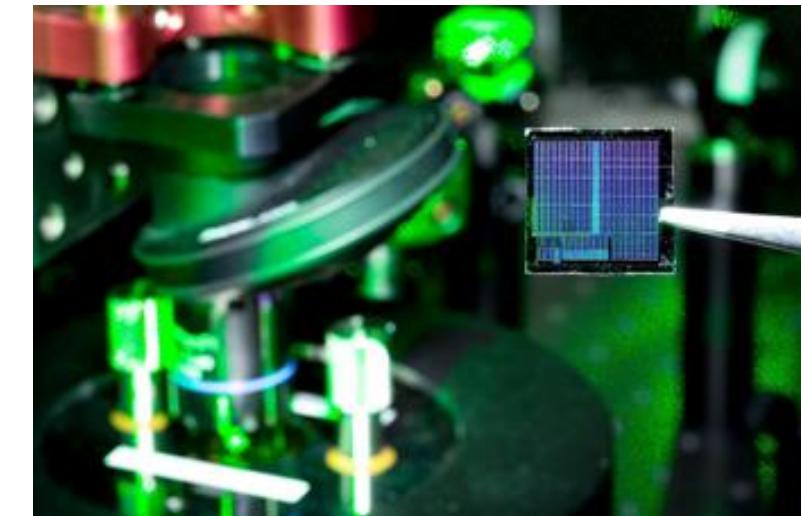
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## Quantenspeicher integriert auf industrie relevanter Chiptechnologie

### Anforderungen:

- Getrennte Optimierung des Quantensystems und der Photonik
- Optimierte Speicherzeiten in integrierbarer Festkörper Matrix
- Auf Industriestandards basierende Photonik
- Skalierbare und benutzerfreundliche Quanten Plattform

HybridQToken: Chipbasierte Quantentechnologie



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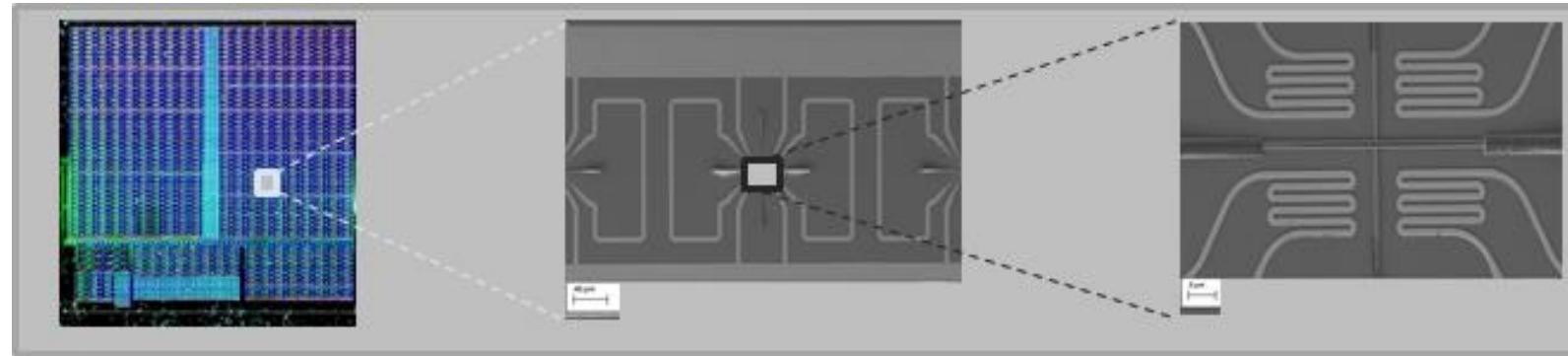
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## Vorteile einer hybriden Quantentechnologie

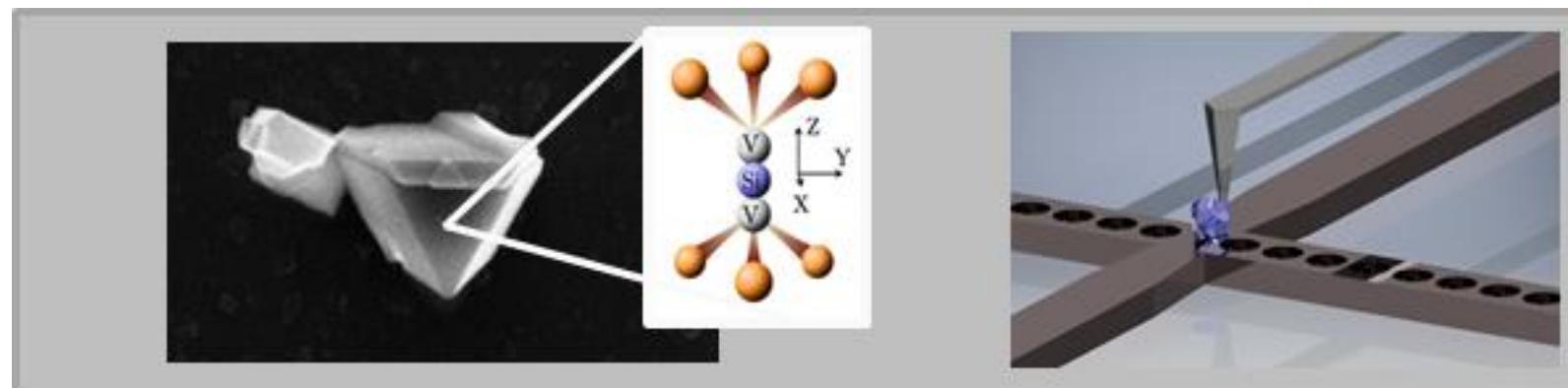
### Auf Industriestandards basierende Photonik:

- Hoher Durchsatz
- Hohe Qualität
- Skalierbar
- Schreiben/Auslesen/Kontrolle auf integrierter Plattform



### Integrierbares Quantensystem:

- Optimale Quanteneigenschaften
- Individuell optimierbar
- Flexibel einsetzbar
- Hochpräzise Integration über Nanomanipulation



## Partner:innen im Konsortium

### U-Ulm



Prof. Dr.  
Alexander Kubanek  
Universität Ulm

- Hybride Quantenphotonik
- Festkörperbasierte Quantensysteme kleinster Abmessungen
- Optische Resonatoren
- Kohärente Spinkontrolle
- Spin-Photon Schnittstellen
- Farbzentren in Diamant
- 2-dimensionale Materialien

### U-Heidelberg



Prof. Dr.  
Wolfram Pernice  
Universität Heidelberg

- Neuromorphic Quantumphotonics

### U-Münster



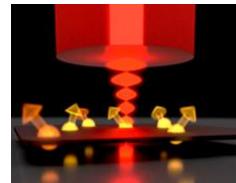
Dr.  
Anna Ovyan  
Universität Münster

- Nanophotonics

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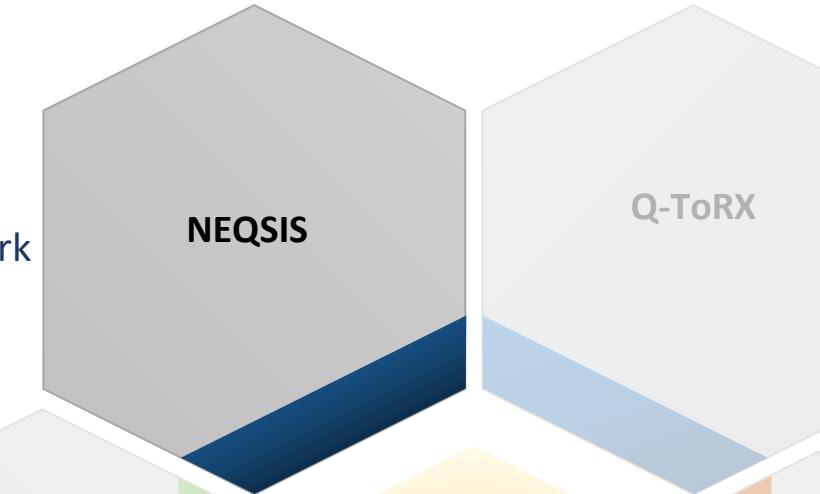
Integration with network



Integration in  
microchip technology

$|\tilde{\text{D}\text{I}\text{Q}\text{T}\tilde{\text{O}}\text{K}\rangle}$

Mobility



Q-ToRX

Ultralong storage time



Efficient writing and reading



QPIS

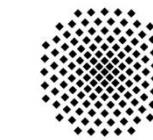
Quantum key for 5G



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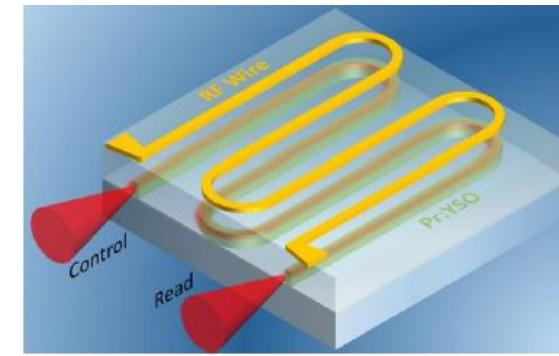
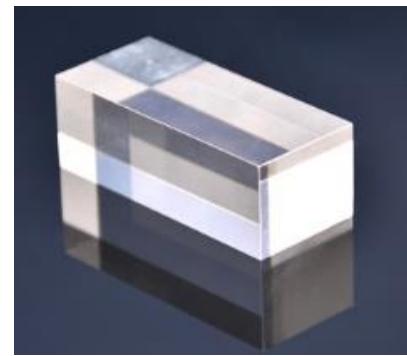
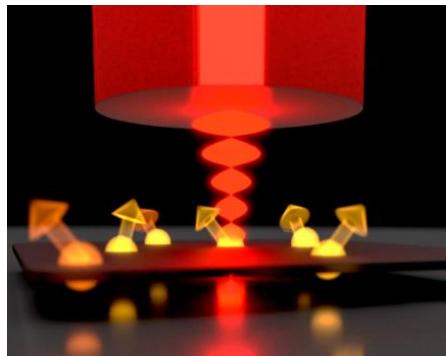


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## Netzwerkfähige Quantenspeicher mit Seltenerdionen NEQSIS

**David Hunger (KIT)**  
**Thomas Halfmann (TU Darmstadt)**  
**Roman Kolesov (Universität Stuttgart)**



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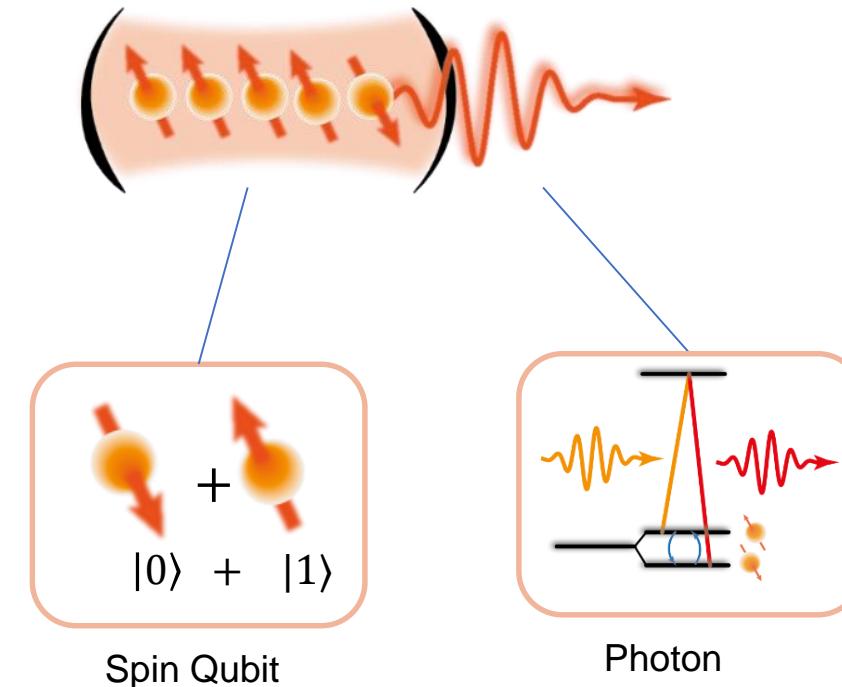


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# Quantenspeicher für Quantentoken

## Leistungskennwerte

- Kohärenz- / Speicherzeit
- Schreib / Lese Fidelität
- Schreib / Lese Effizienz
- Qubitanzahl
- Photonische Integration
- Ankopplung an Netzwerke



# Seltenerdionen

- Herausragende Quantenkohärenz  
( $\text{Eu}^{3+}$ : 2ms optisch, 6h hyperfein)

Zhong et al., Nature 517, 177 (2015)

- Langlebige und effiziente  
Quantenspeicher
  - 1h AFC Speicher

Ma et al., Nature Commun. 12, 2381 (2021)

- 69% Speichereffizienz

Hedges et al., Nature 465, 1052 (2010)

- Multiplexing (130 Moden)

Seri et al. PRL 123, 080502 (2019)

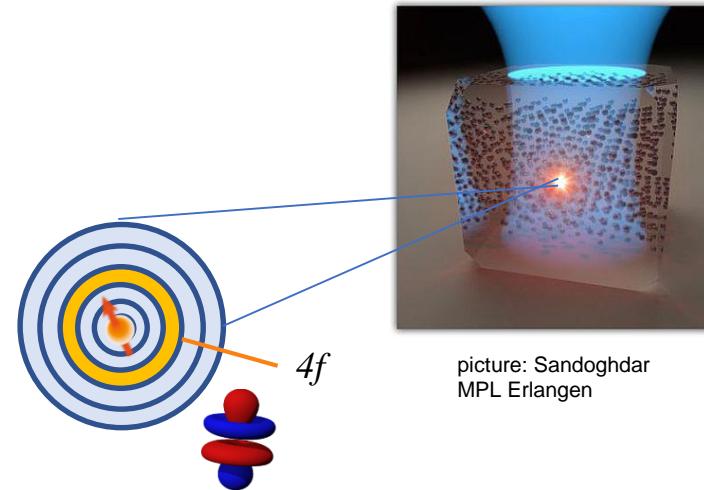
- spektrale Einzelionenselektion  
 $\rightarrow \sim 10^3$  Qubit Register

Kolesov et al., Nature Commun 3, 1029 (2012)

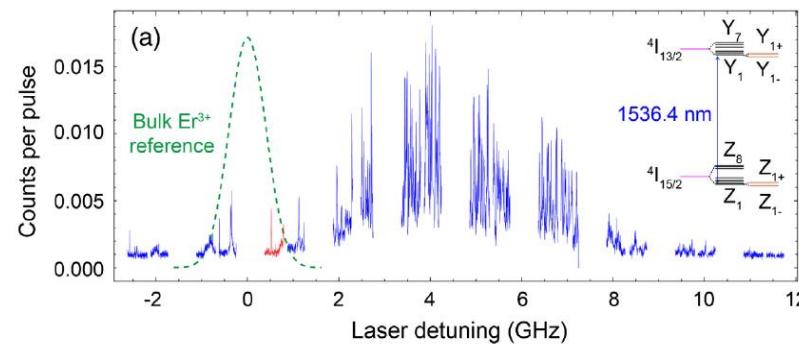
Utikal et al., Nature Commun 5, 3627(2014)

Dibos et al., PRL 120,243601 (2018)

Zhong et al.,PRL 121 183603 (2018)



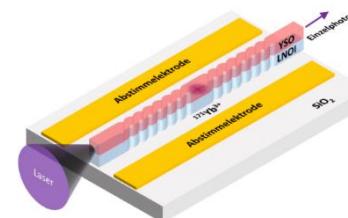
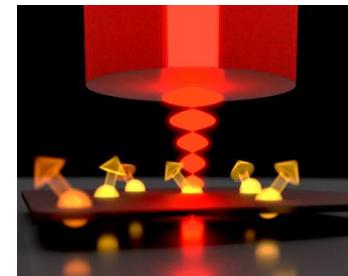
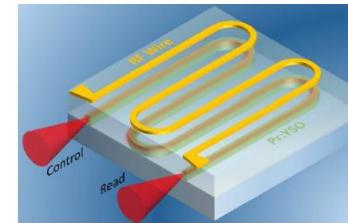
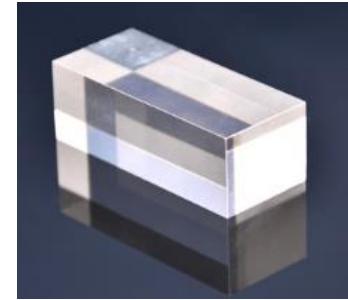
picture: Sandoghdar  
MPL Erlangen



$$\gamma_{inh} > 10^5 \gamma_h$$

# Ziele von NEQSIS

- Einzelphoton Speicherung bis zu 1 sec
- Chip-integrierte Speicher
- Speicherung in einzelnen Ionen
- Multiplexen mit bis zu 4 Speicherionen
- Schaltbare Einzelphotonerzeugung



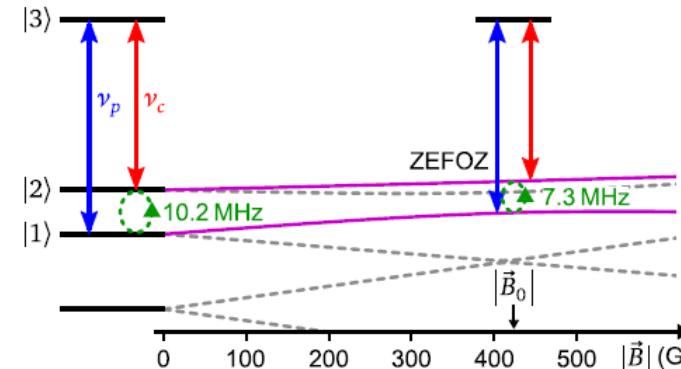
# ZEFOZ & DD zur Kohärenzverlängerung



TECHNISCHE  
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## Zero first-order Zeeman shift (ZEFOZ)

bis zu  $\sim 10^3$  x Kohärenzverlängerung

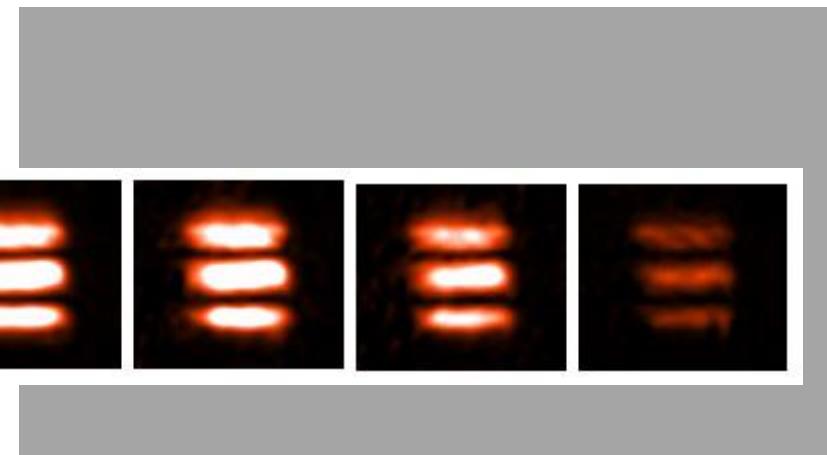


## Rephasierung & dynamical decoupling (DD)

bis zu  $\sim 10^3$  x Kohärenzverlängerung

## TUDA Vorarbeiten

- 1 Min. Speicherung starker Lichtpulse
- 1 Sec. Speicherung von  $\langle n \rangle = 7$



Hain et al., New J. Phys. 24, 1367 (2022)

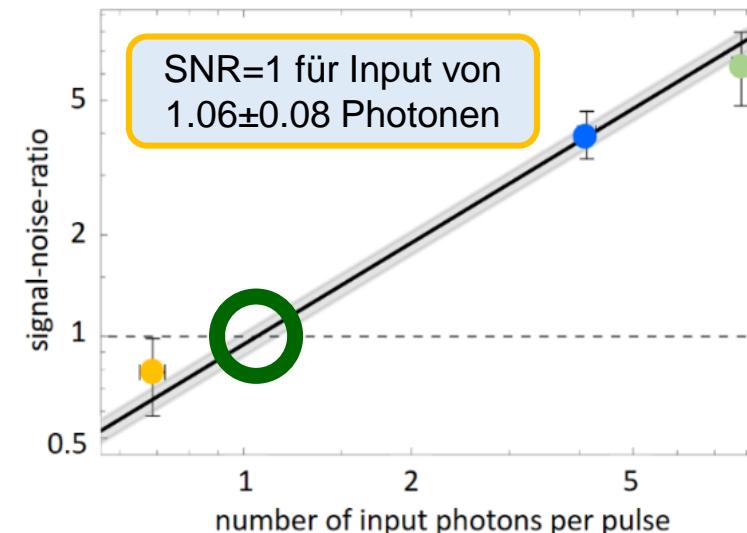
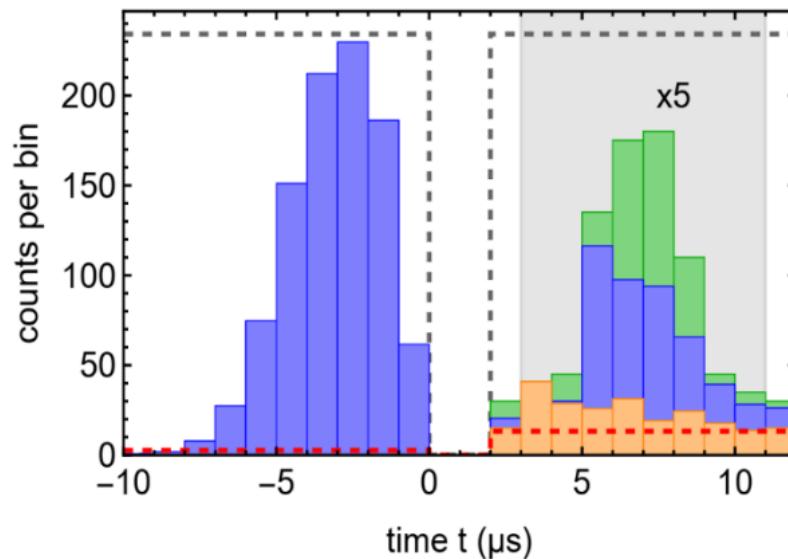
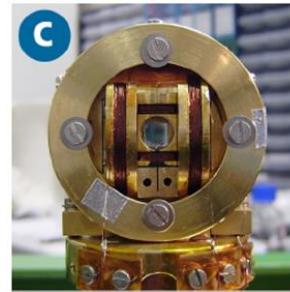
Heinze et al., Phys. Rev. Lett. 111, 33601 (2013)

# Zwischenergebnis # 1

## Einzelphotonspeicherung



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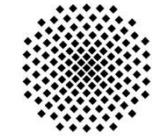


@ZEFOZ aber  
bisher ohne DD



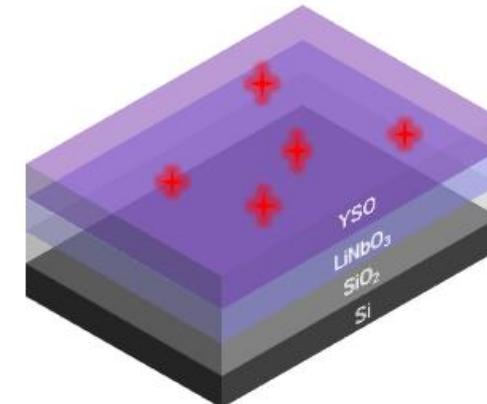
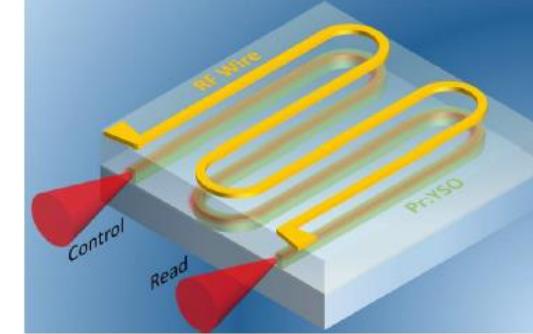
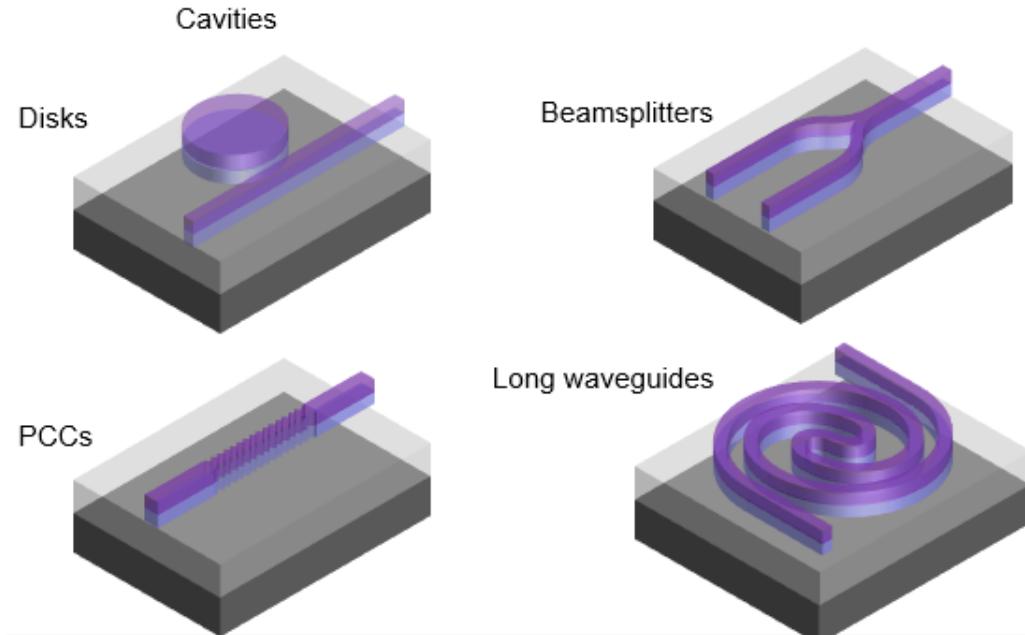
10 x Verbesserung  
während NEQSIS

# Höhere Effizienz: photonisch integrierte Speicher



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- Pr:YSO Wellenleiter & Membranen
- LiNbO<sub>3</sub> für elektro-optische Durchstimmung
- YSO als ruhiger REI Wirtskristall
- → hybrider LN/YSO Sandwich
- Nanofabrikation photonischer Elemente

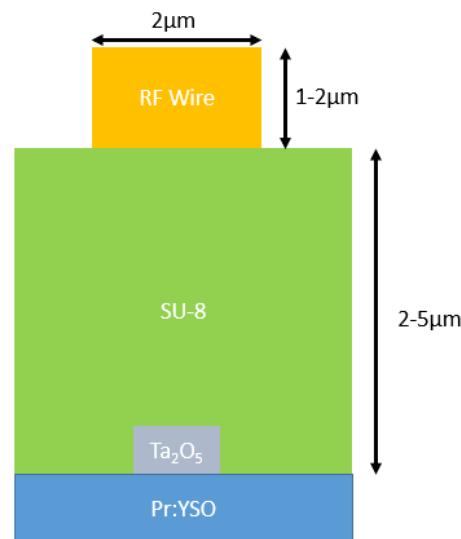
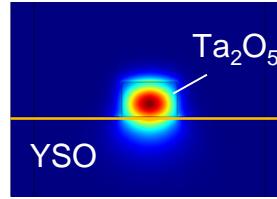
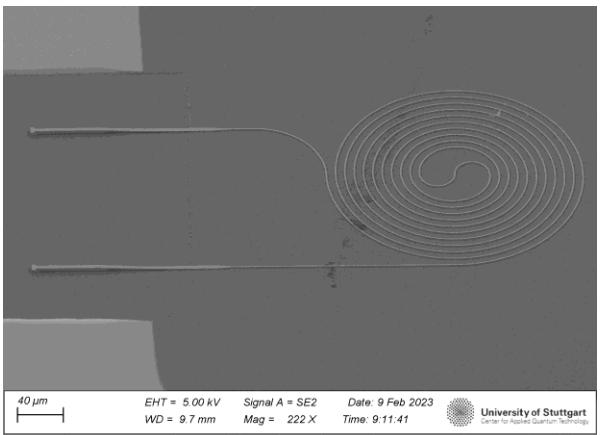


# Zwischenergebnis # 2

## Wellenleiter

### Wellenleiter in $\text{Ta}_2\text{O}_5$

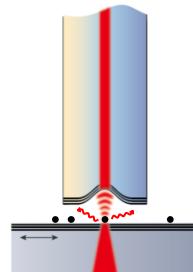
- Hohe Effizienz für Länge  $\sim 3\text{cm}$
- Dämpfung derzeit  $0.6\text{dB/cm}$
- Alternative:  $\text{Si}_3\text{N}_4$



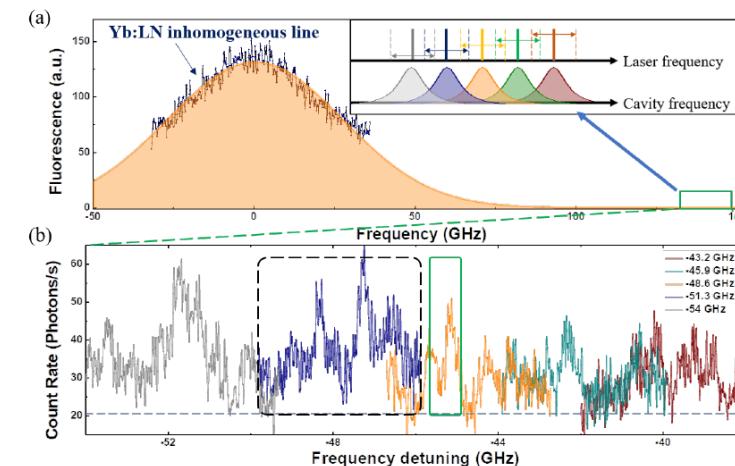
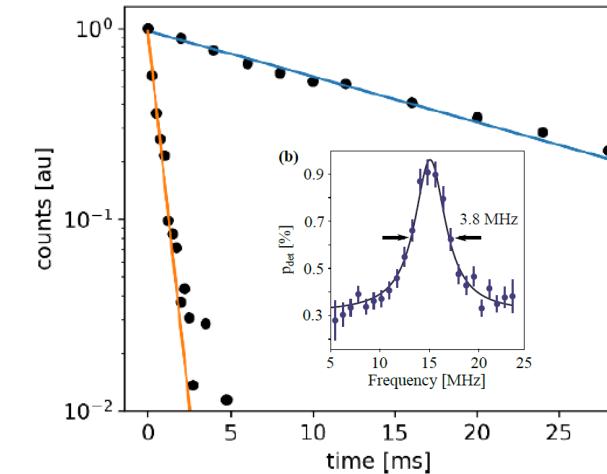
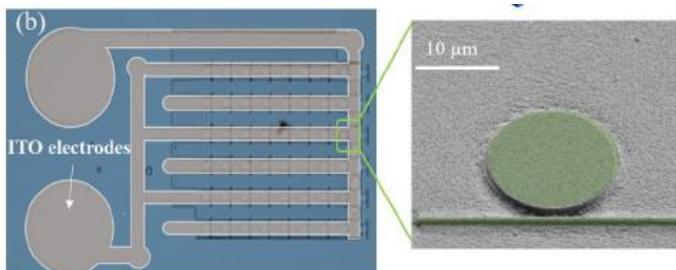
# Einzelionenauslese

- Emissionsverstärkung durch Purcell Effekt

$$C = \frac{3}{4\pi^2} \frac{Q}{V} \left( \frac{\lambda}{n} \right)^3$$

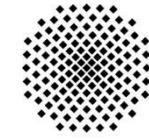


- durchstimmbare Mikroresonatoren

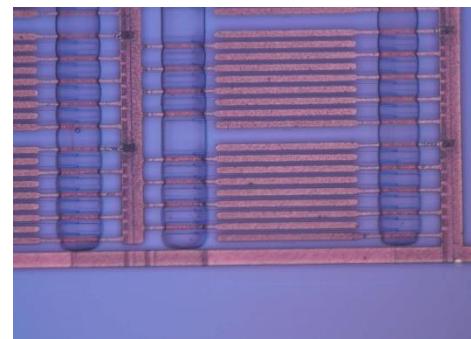
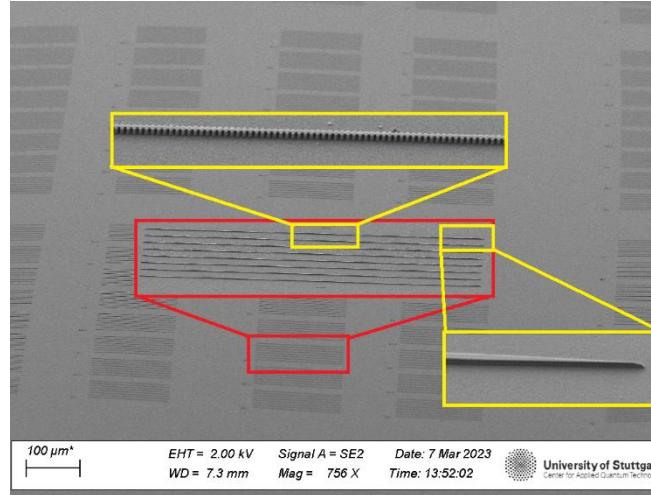
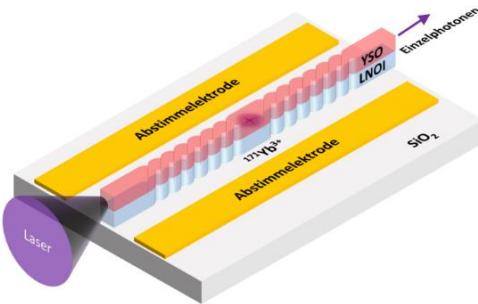


# Zwischenergebnis # 2

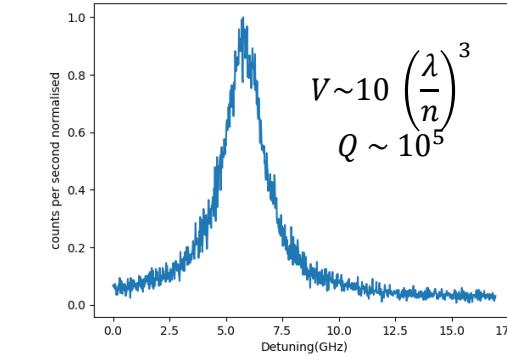
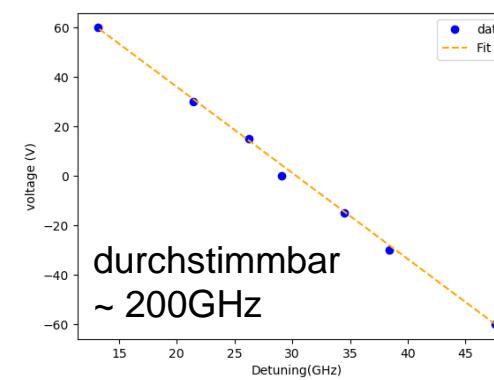
## Nanoresonatoren in LNOI



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Nanoresonatoren mit Elektroden



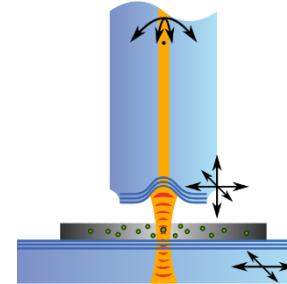
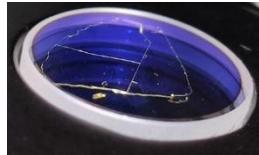
# Zwischenergebnis # 3

## Fasercavity Plattform mit integrierter Membran



### YSO Membranen

- Dicke  $< 10\mu\text{m}$ ; Rauhigkeit 0.2 nm



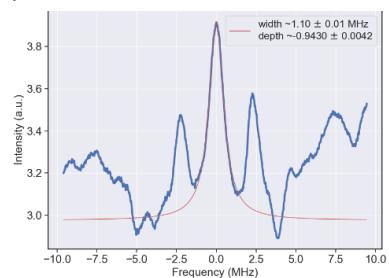
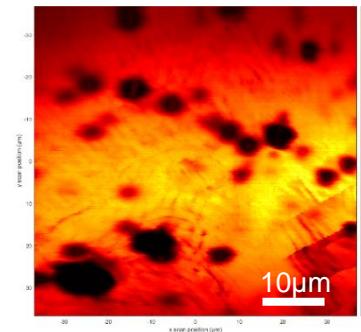
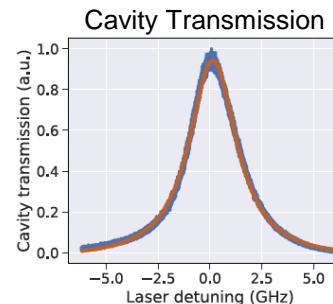
### Cavity mit integrierter Membran

$$F = 3800, \quad w_0 = 1.8\mu\text{m}$$

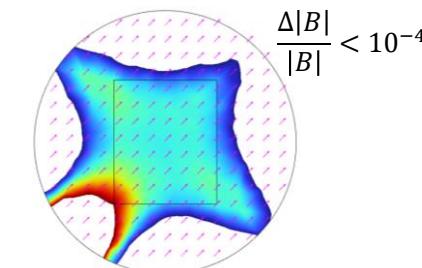
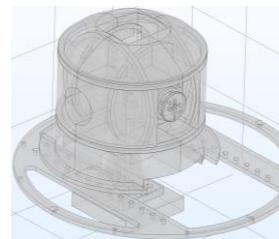
$$Q = 3 \times 10^5, \quad V_m \sim 50 \lambda^3$$

- Scanning Cavity Mikroskopie der Membran

Körber et al., arxiv:2210.05514



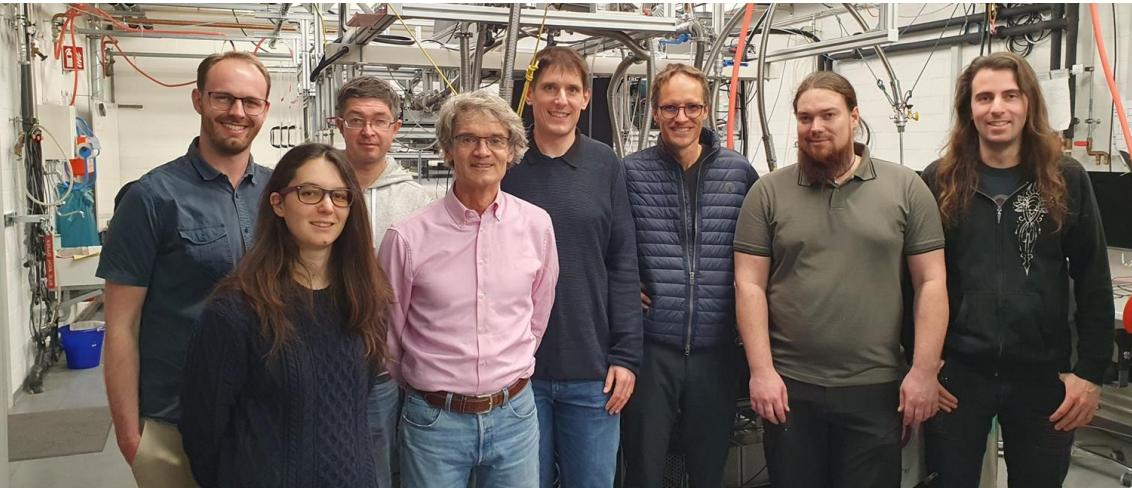
- Kombination mit Vektormagnet



# Thank you



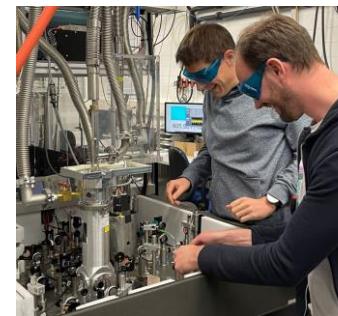
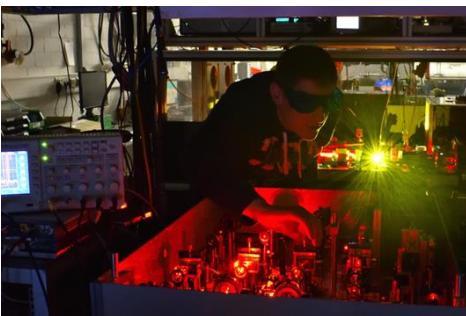
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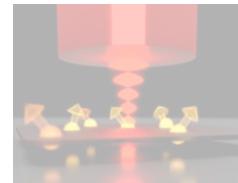


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Integration with network

NEQSIS

**Q-ToRX**

Ultralong storage time



Integration in  
microchip technology

HybridQToken

**Q-TOK**  
Theorie  
Projekt

QPIS

Efficient writing and reading



QPIS

Mobility

DIQTOK

QuaMToMe

Quantum key for 5G

**|DIQTOK>**



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PTB

111  
102  
100:4

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# Quantum Tokens based on Alkalines and Xenon

Ilja Gerhardt | Wolfgang Kilian | Jens Voigt | Janik Wolters

Q-ToRX





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## Q-ToRX vision: Quantum memory with ultralong storage time

### Requirements:

- **Storage time up to hours**
- **Room temperature**
- **Optical interface to single photons**
- **Mobile and robust**



classical memory

...1001100...



QToRX quantum token

$|0\rangle + |1\rangle$

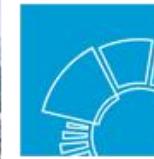


Q-ToRX Memory: (almost) as easy as classical memories

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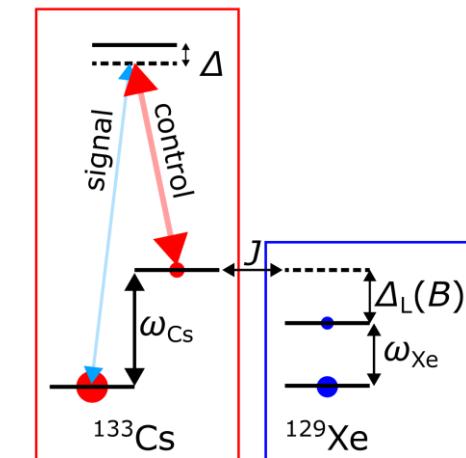
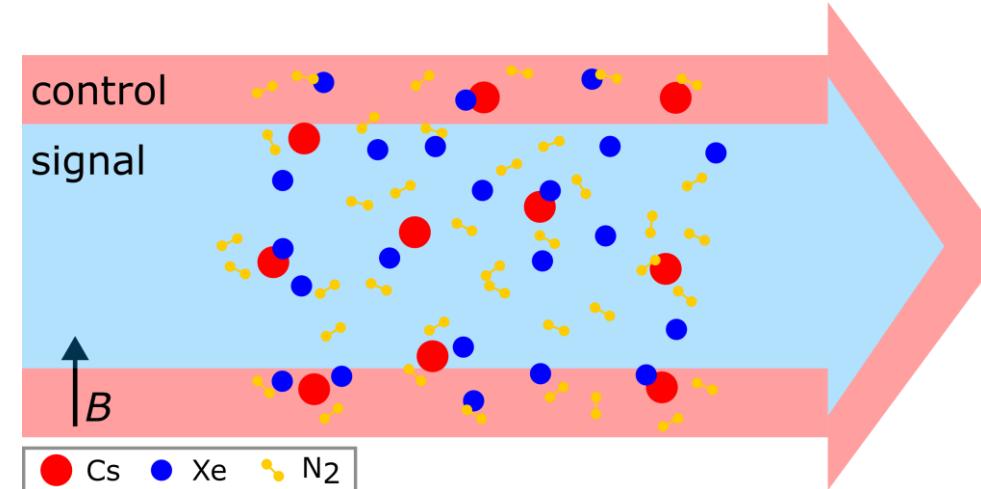
## Q-ToRX ansatz: Combine advantages of different elements

### Alkalines:

- Room temperature
- **Good optical interface**
- Short coherence time

### Nobel gases:

- **Long coherence time**
- Room temperature
- No optical Interface

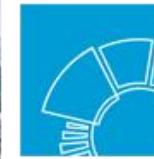


Working principle of a spin-exchange quantum memory

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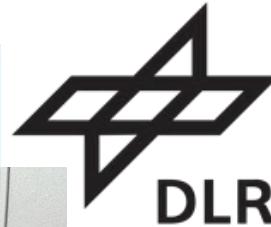


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## Q-ToRX Project overview

- **AP1:** Manufacturing and characterisation of suitable gas cells (LUH).
- **AP2:** Storage of optical signals in alkalines (DLR).
- **AP3:** Coherent control of noble gas spins (PTB).
- **AP4:** Demonstrator (all)
  - (a) towards long-lived superposition states in mobile setup
  - (b) towards principle of a spin-exchange quantum memory



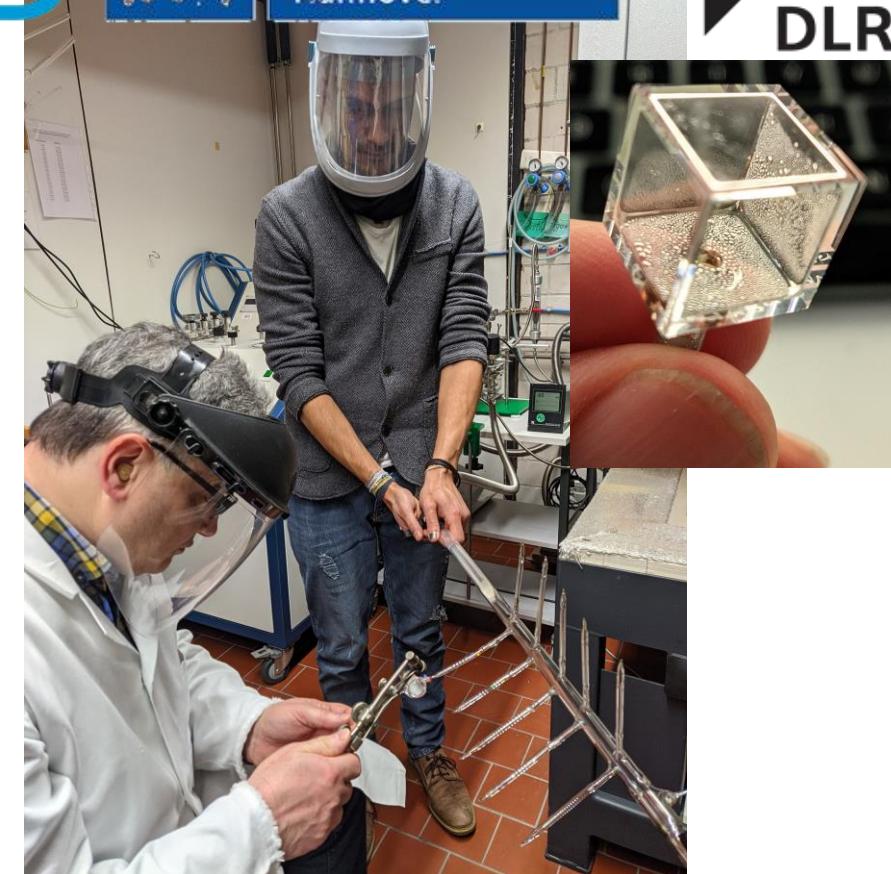
## AP1: Manufacturing and characterisation of suitable gas cells

### Creation of technical possibilities

- Procurement of devices
- Setup of gas mixing device and gas cleansing

### Optimised process steps:

- Cleansing of cells via gas discharge
- Calculation of the partial pressures for optimal partitions of buffer gases (15 mbar N<sub>2</sub>, 35 mbar <sup>129</sup>Xe)



*Manufacturing of Rubidium cells with <sup>129</sup>Xe and N<sub>2</sub> buffer gases.*



## AP2: Storage of optical signals in alkalines

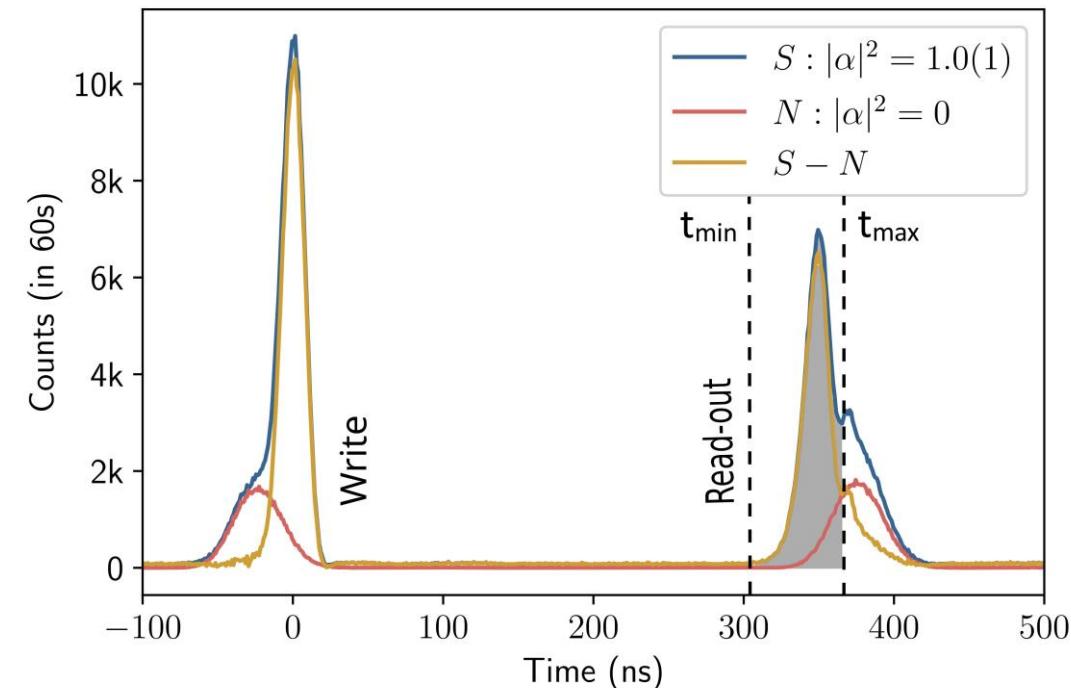
### Reached performance (Cesium-133, 60°C)

- Efficiency:  $\eta_{\text{end-to-end}} = 13\%$ ,  $\eta_{\text{memory}} = 33\%$
- Storage at single photon level:  $\text{SNR} = 14$
- Storage time (possible):  $T_{\text{storage}} \sim 10 \mu\text{s}$

### Planned improvements for 100 ms storage time:

- Beam geometry (larger beam diameter)
- Higher buffer gas pressure
- Exploitation of spin-orientation degrees of freedom (Zeeman-narrowing)

Esguerra et al., PRA 107, 042607, 2023



*Histogram of a typical Storage experiment*

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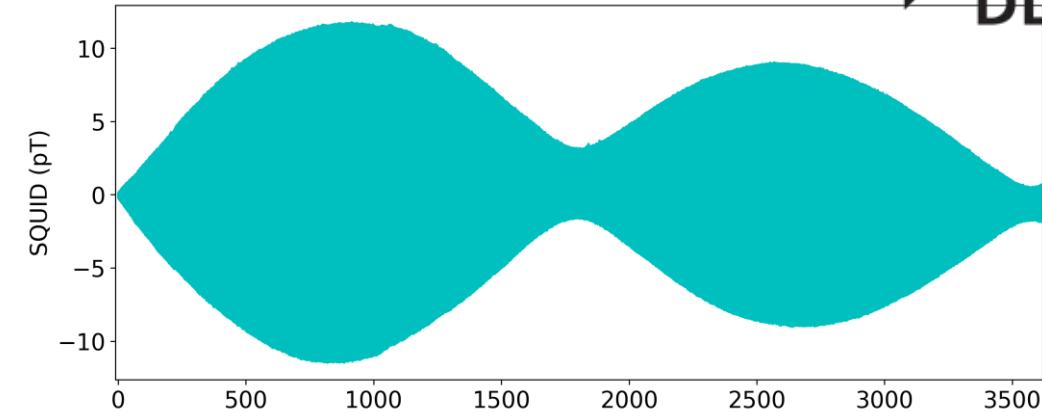
## AP3: Coherent control of noble gas spins

### Coherent control of $^{129}\text{Xe}$ in BMSR-2.1

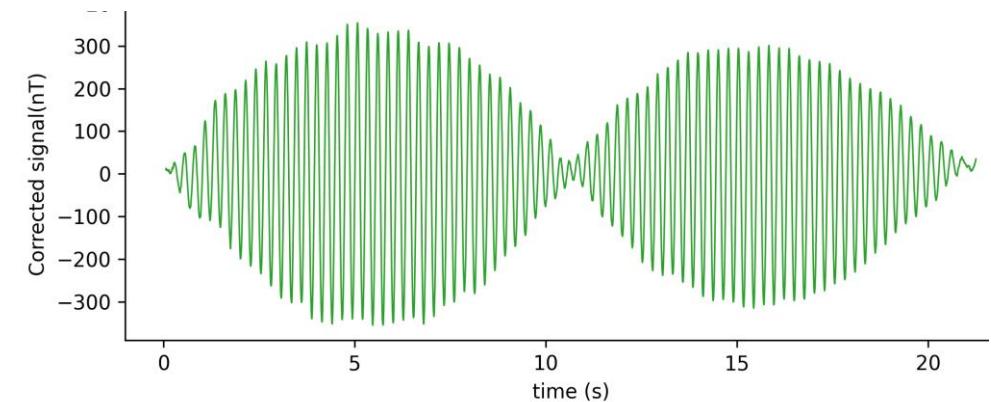
- Coherent Rabi nutation for 60 min
- Repeated coherent excitation over  $> 2$  h
- Theoretical understanding of systematic effects

### Preparation of experiments in lab scale

- Mobile noble-gas spin-precession setup
- Optical readout of  $^{129}\text{Xe}$  spin precession
- 60 s Rabi nutation in lab shield with Rb-Xe cell



SQUID detection of 60 min.  $^{129}\text{Xe}$  Rabi cycle



Optical readout of  $^{129}\text{Xe}$  Rabi cycle



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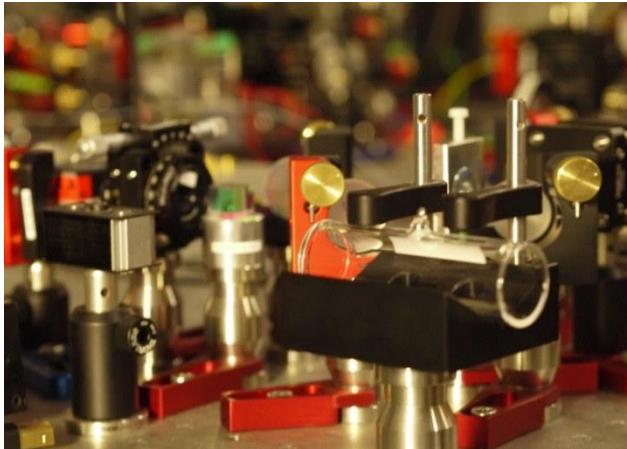


## Intermediate results:

### Experimentally measured Q-ToRX storage / coherence times:

Alkaline memory

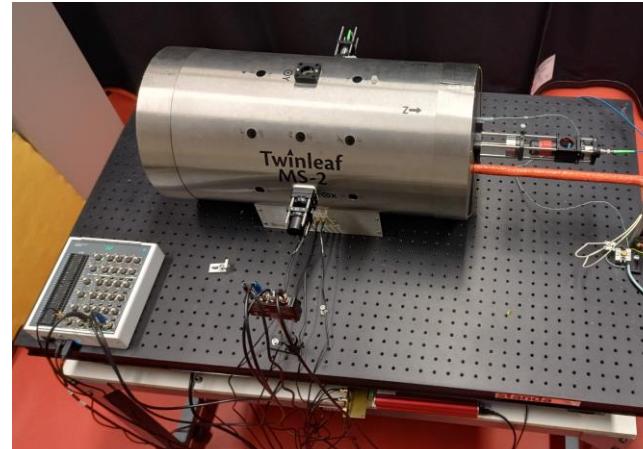
10  $\mu$ s



100 ms

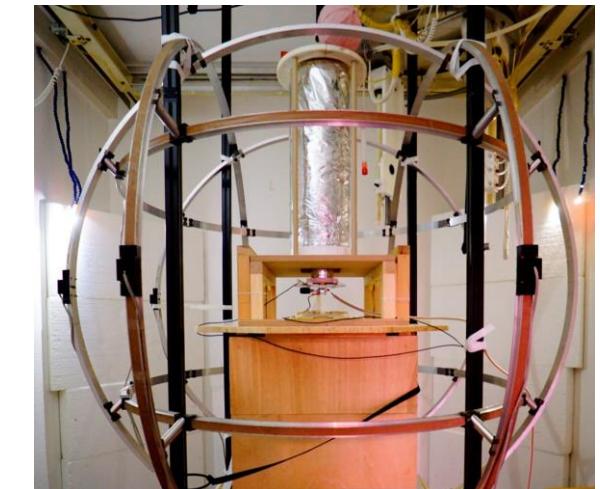
Rb-<sup>129</sup>Xe mobile setup

1 min



<sup>129</sup>Xe in BMSR 2.1

1 h





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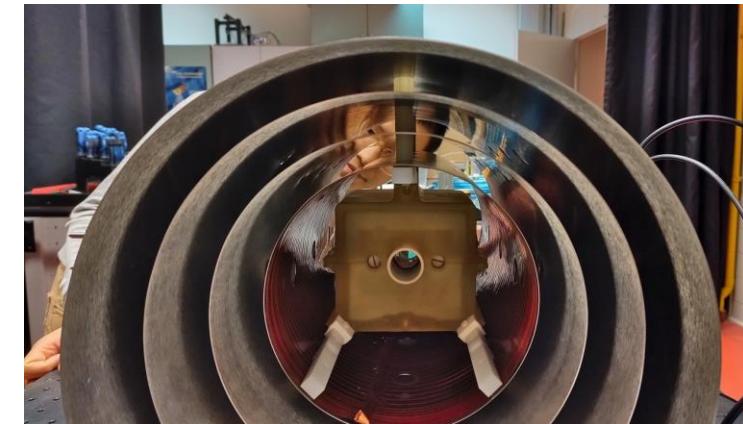
## Goals and perspectives:

### Next intermediate steps

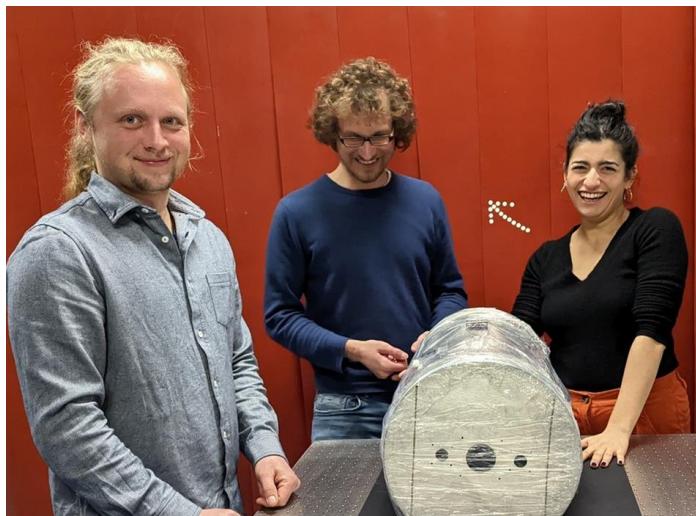
- Improved cell manufacturing & incl. in-situ characterisation
- Storage in spin-projection d.o.f. (alkalines)  
→ 100 ms storage time
- Long spin coherence times and manipulation in lab scale
- Demonstration: alkaline token, how can this be achieved?

### Perspectives

- Transport of token with superposition (noble gas) > 1 km
- Demonstration of working principle of spin-exchange memory
- Wafer scale cell fabrication



N.V. Ewald, J. Wolters, L. Esguerra: Photonenspeicherung

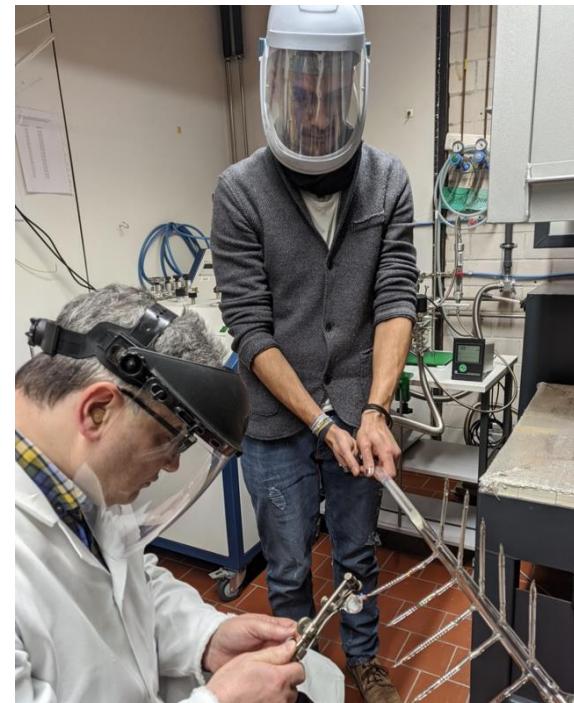


AG Physikalische Grundlagen der  
IT Sicherheit  
**Alkalimetall Quantenspeicher**

## Q-ToRX Team @ work:



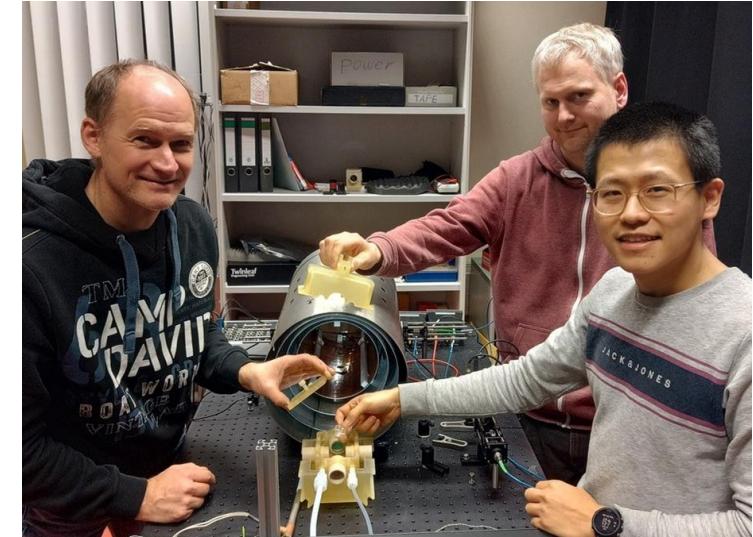
**AG Light & Matter**  
**Atomspektroskopie bei**  
**Raumtemperatur**



I. Gerhardt und D. Uhland: Herstellung  
der Rb-Xe-Zellen



W. Kilian, J. Voigt, T. Liu:  
mobiler Aufbau für die Rb-Xe-Zelle

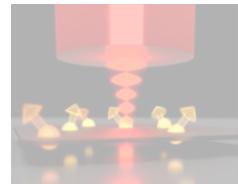


Fachbereich 8.2 Biosignale  
**Kohärenten Kontrolle von**  
**Edelgasspins**

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Integration with network

NEQSIS

Q-ToRX

Ultralong storage time



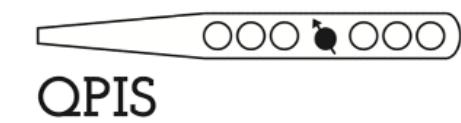
Integration in  
microchip technology

HybridQToken

Q-TOK  
Theorie  
Projekt

QPIS

Efficient writing and reading



Mobility

$|\tilde{\text{D}}\tilde{\text{I}}\text{QT}\tilde{\text{O}}\text{K}\rangle$

DIQTOK

QuaMToMe

Quantum key for 5G



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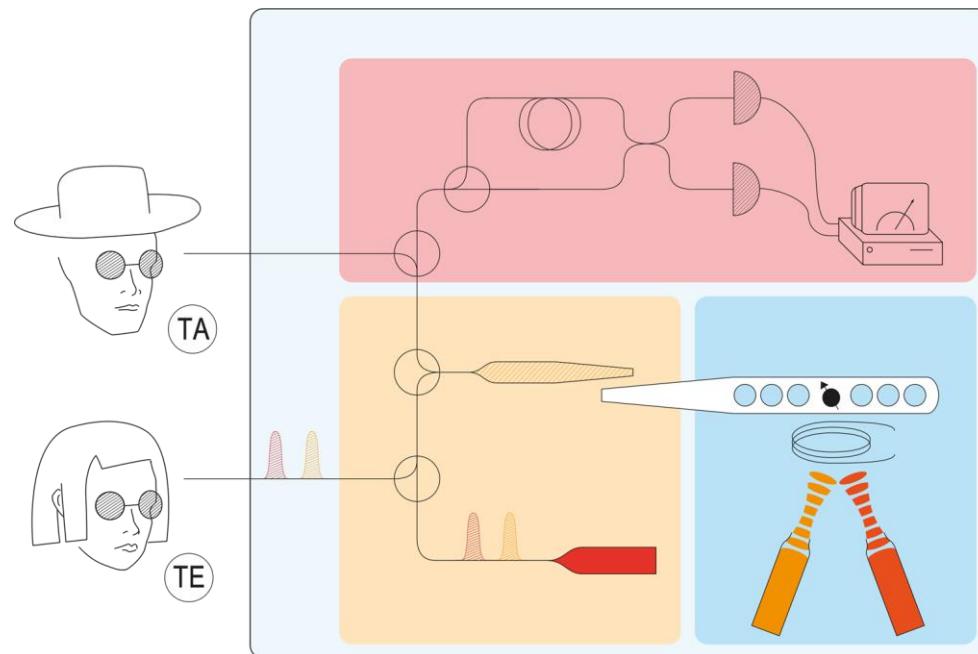


Conventional token



Quantumtoken

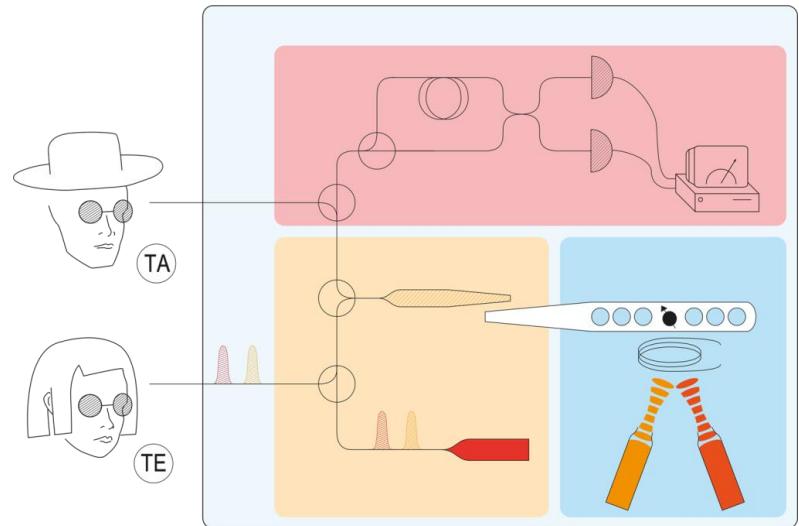
Quantum-Photonic Integrated Scalable Memory (QPIS)



Goal: Diamond based quantum memory

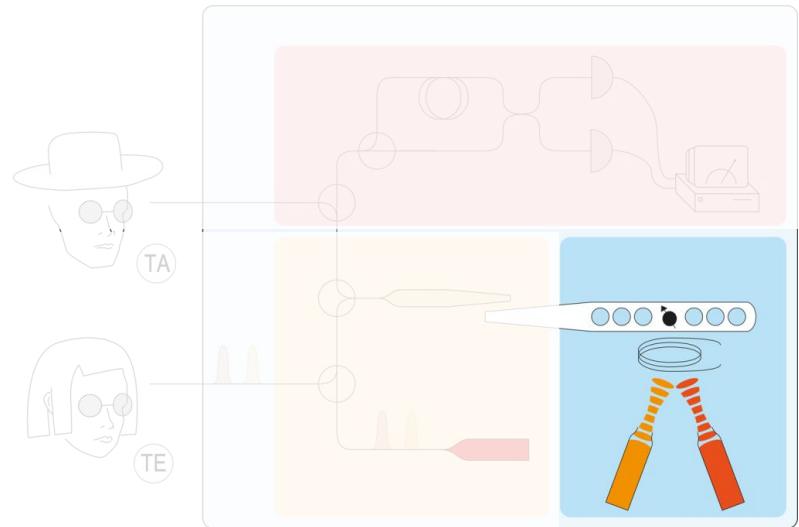
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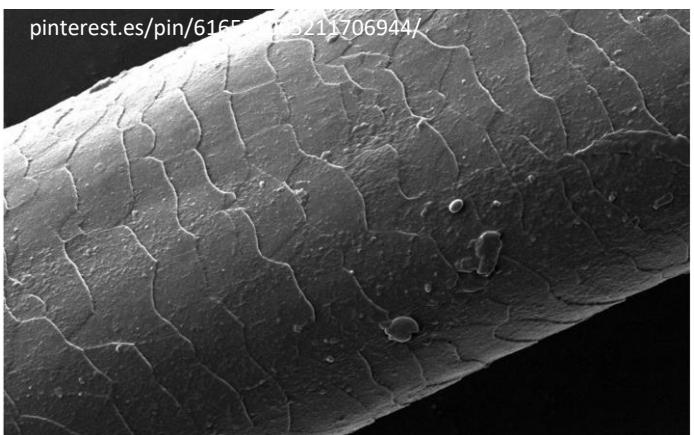
## Quantum memory

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Quantum memory

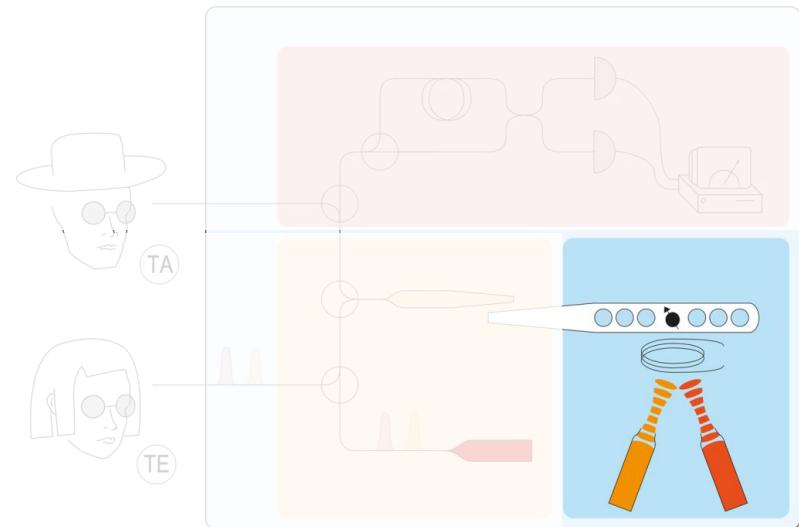
Human hair



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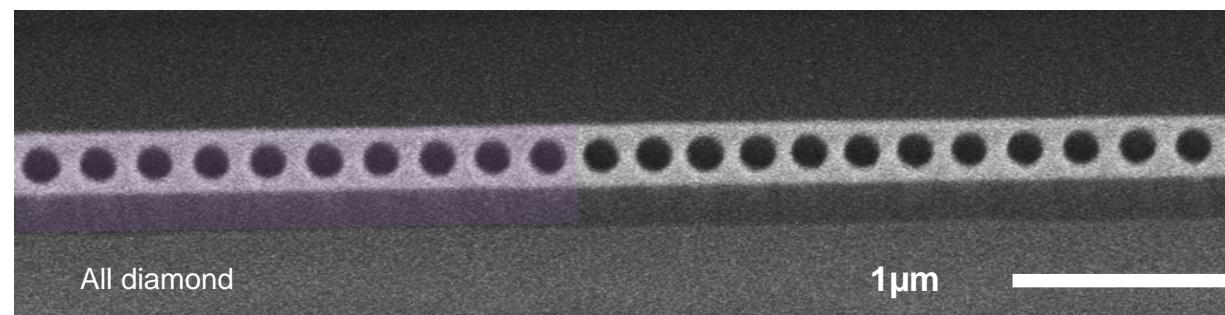
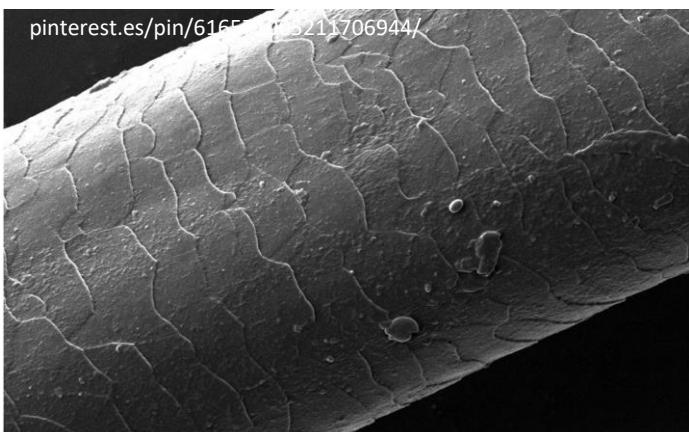
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Quantum memory

Optical resonator in diamond

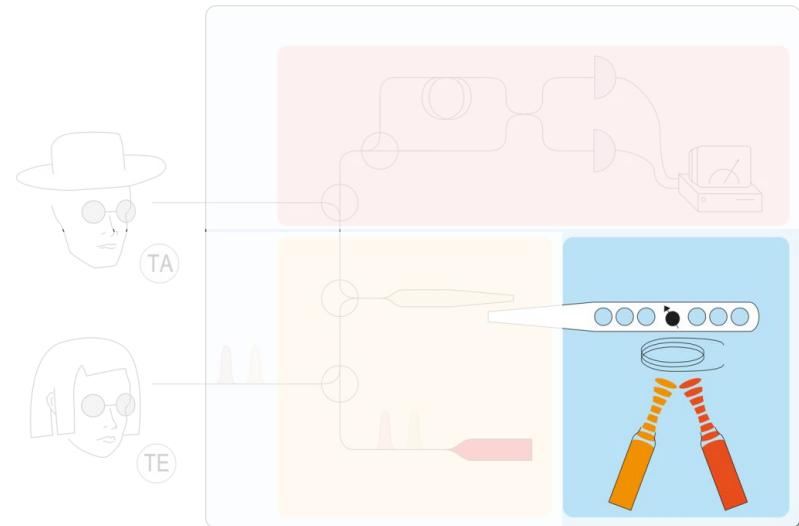
Human hair



1.000x smaller

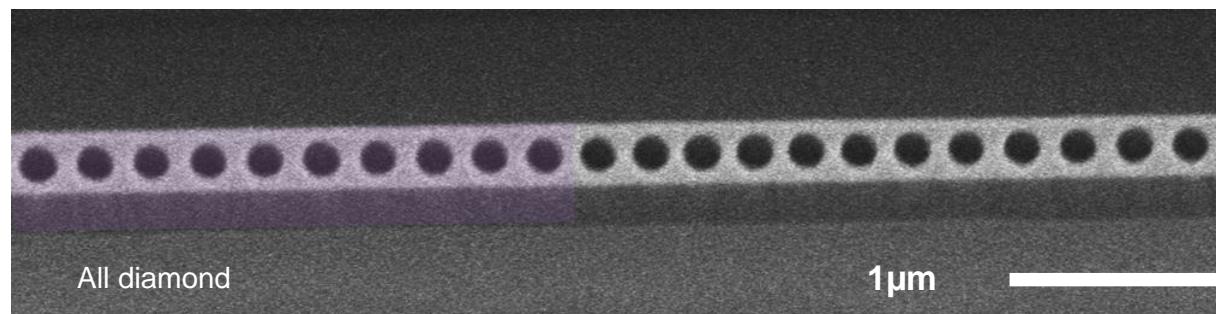
GEFÖRDERT VOM



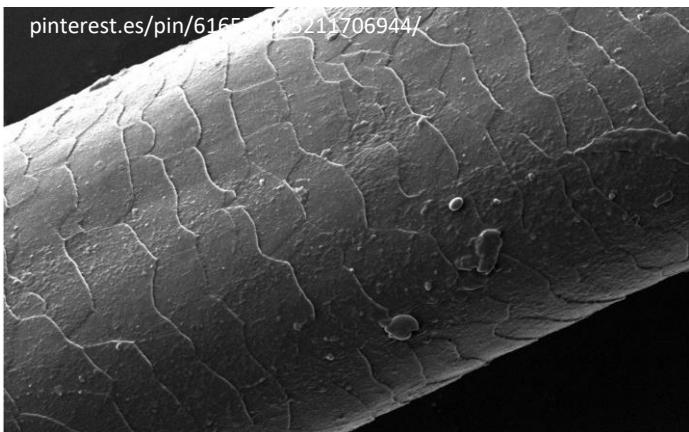


Quantum memory

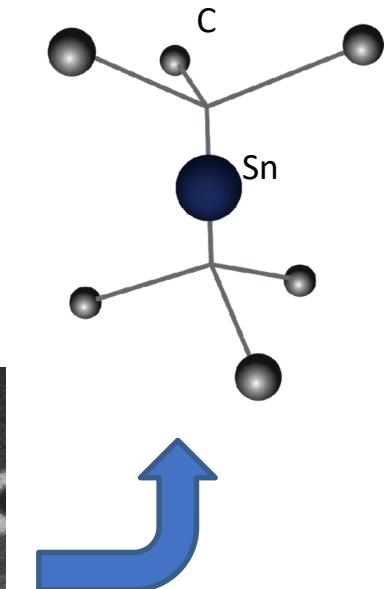
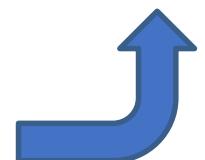
optical resonator in diamond



1.000x smaller



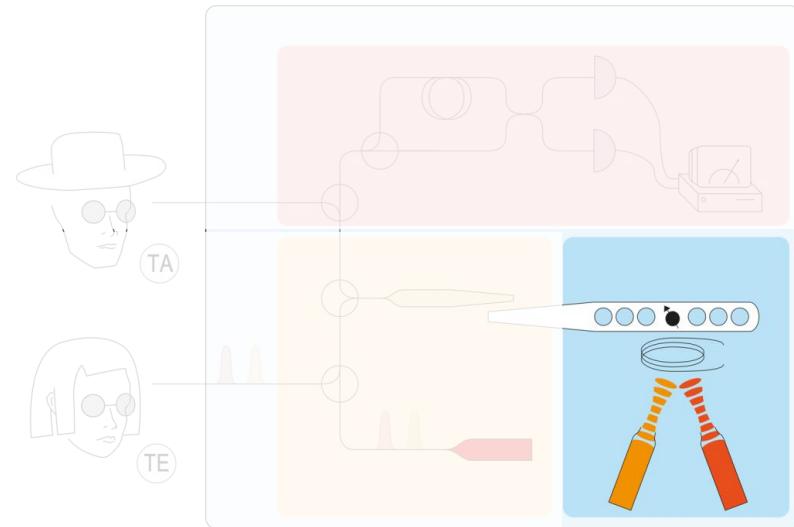
Human hair



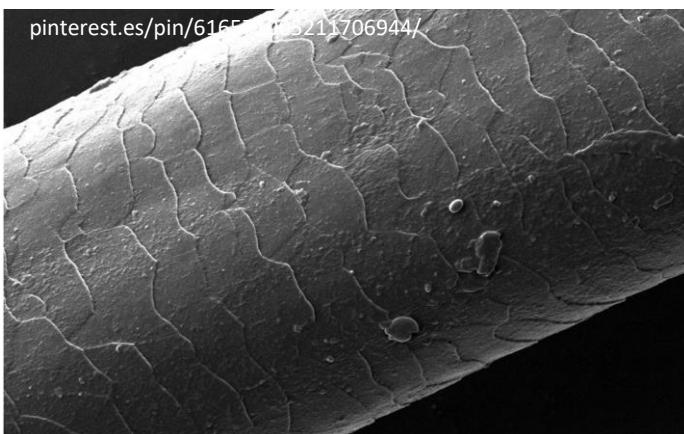
Quantum memory

GEFÖRDERT VOM



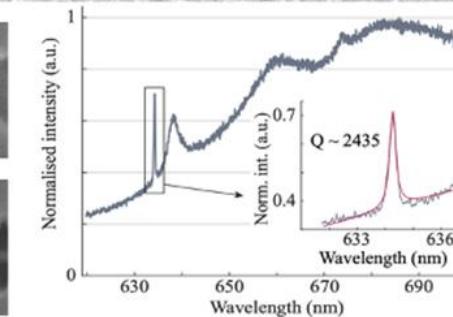
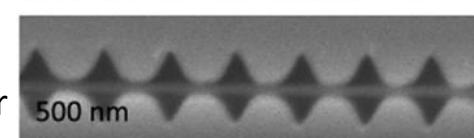
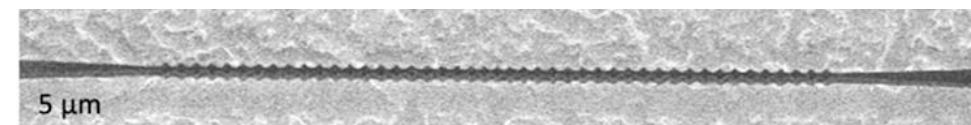
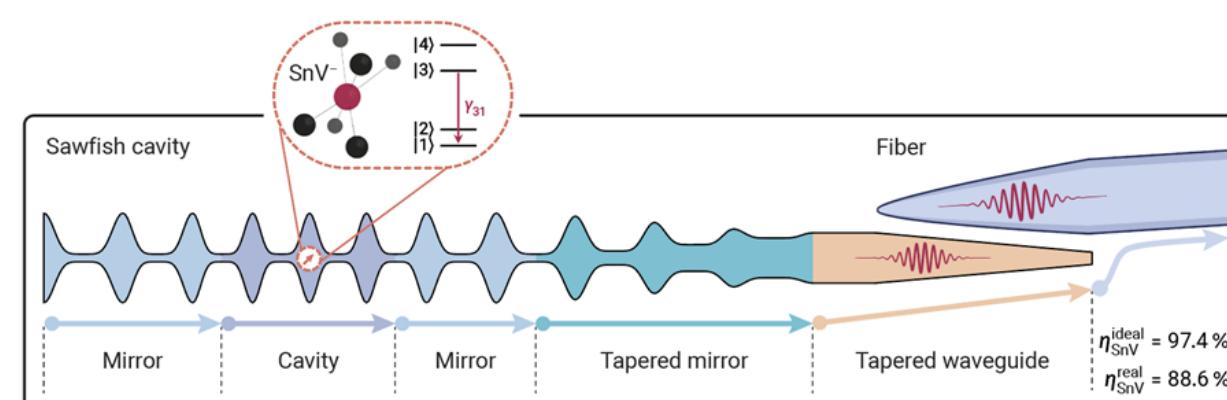


Human hair

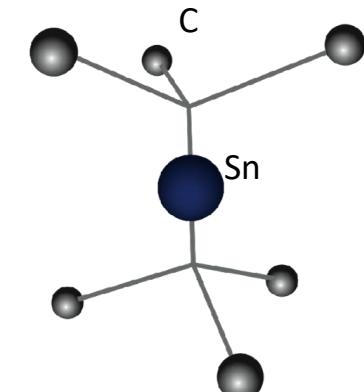


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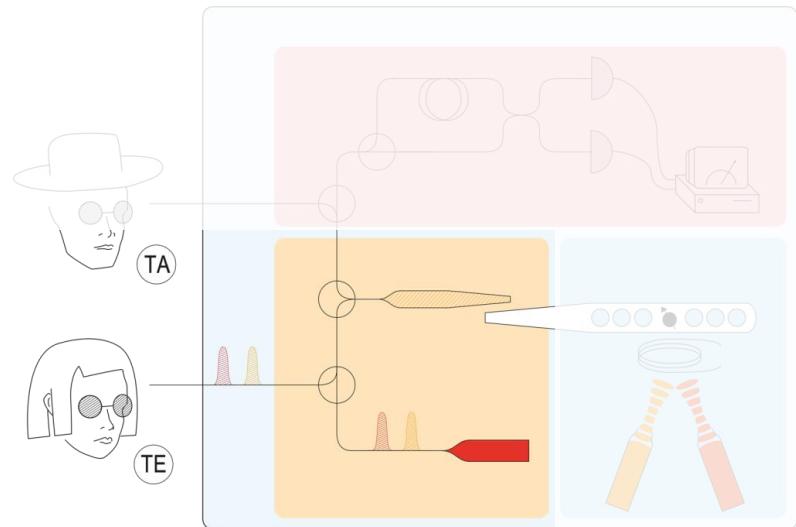
Quantum memory



Quantum memory



100x smaller



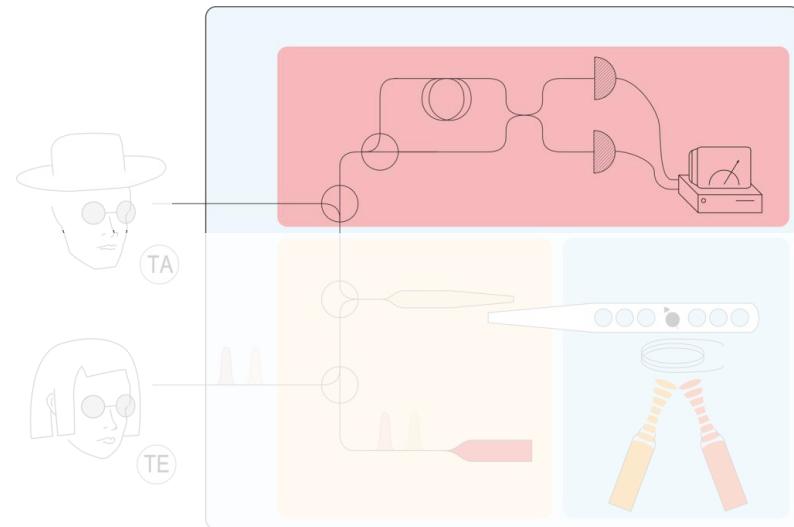
Quantum-lightsource in diamond



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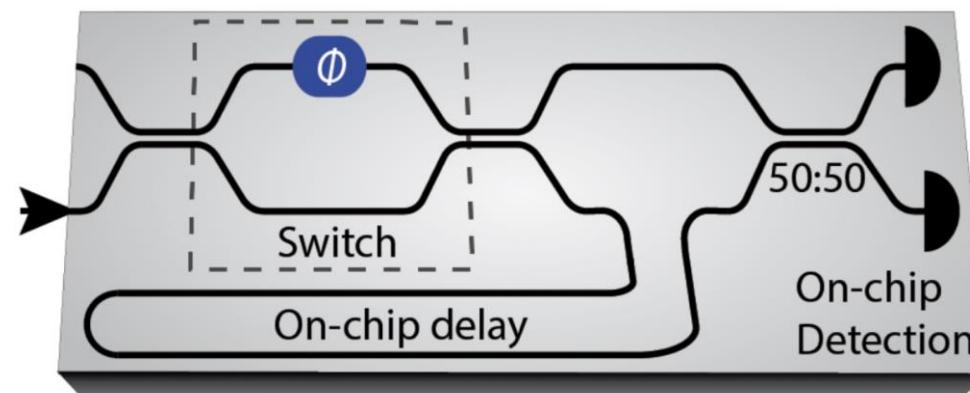
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für Bildung  
und Forschung



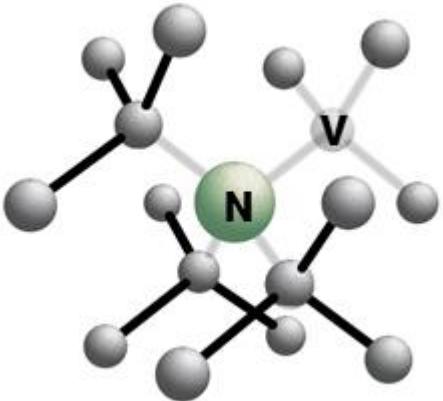
Optical detectors with >95% efficiency



Photonic integrated circuit for read-out



## Nitrogen Vacancy in Diamond (NV)



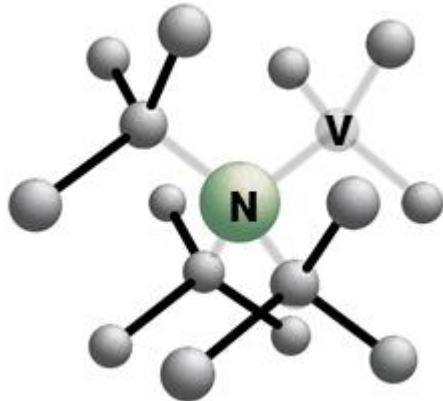
- Well understood optically active spin defect
- Long spin coherence > 3s
- Very low coherent optical efficiency ca. 3%
- Integration into nanostructures possible [1] but challenging due to **spectral diffusion** [2]

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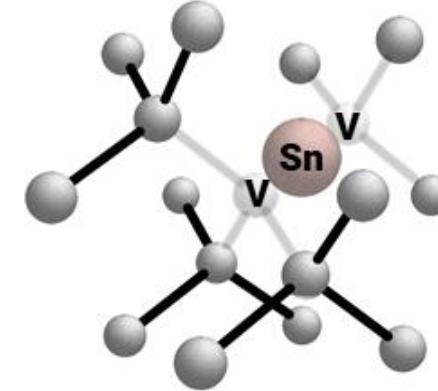
[1] Cem G.Torun, et al., (2021). *Applied Physics Letters*, 118(23), 234002.

[2] LauraOrphal-Kobin, ..., Gregor Pieplow, and Tim Schröder *Physical Review X*, 13(1), (2023): 011042

## Nitrogen Vacancy in Diamond (NV)



## Tin Vacancy in Diamond (SnV)



- Well understood optically active spin defect
- Long spin coherence  $> 3\text{s}$
- Very low coherent optical efficiency ca. 3%
- Integration into nanostructures possible [1] but challenging due to **spectral diffusion** [2]

- New platform
- Long spin coherence (0.3ms)
- Very high coherent optical efficiency 60% ( $> 3\%$ )
- Integration: due to higher symmetry less affected by spectral diffusion

[1] Cem G.Torun, et al., (2021). *Applied Physics Letters*, 118(23), 234002.

[2] LauraOrphal-Kobin, ..., Gregor Pieplow, and Tim Schröder *Physical Review X*, 13(1), (2023): 011042

## The QPIS Team

Tim Schröder  
Humboldt-Universität zu Berlin

- Experimental quantum control
- Photonic integration diamond

Kai Müller  
Technische Universität München

- Engineering superconducting detectors
- Integrated quantum photonics

Gregor Pieplow  
Humboldt-Universität zu Berlin

- Dynamics of open quantum systems
- Modelling, developing concepts, analysis of integrated circuits

GEFÖRDERT VOM

# The QPIS Team

Tim Schröder  
Humboldt-Universität zu Berlin

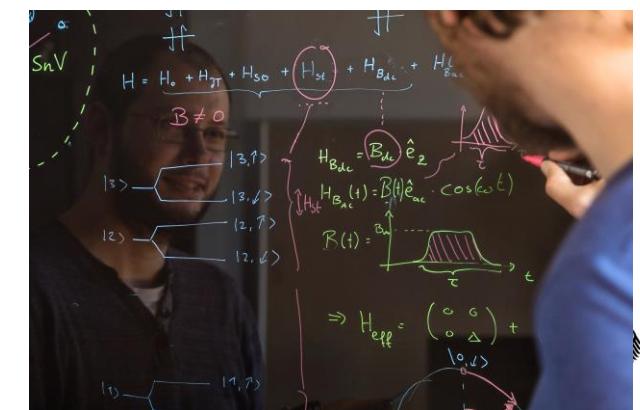
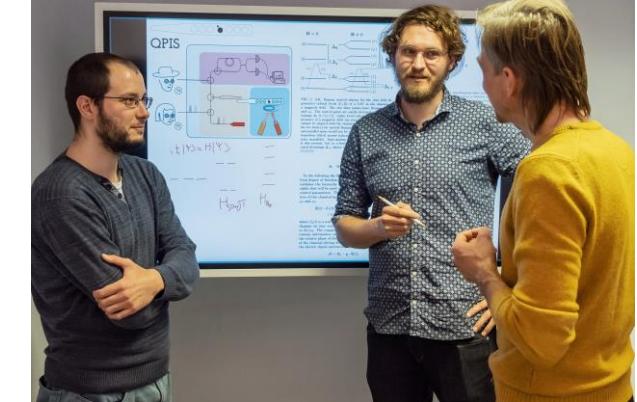
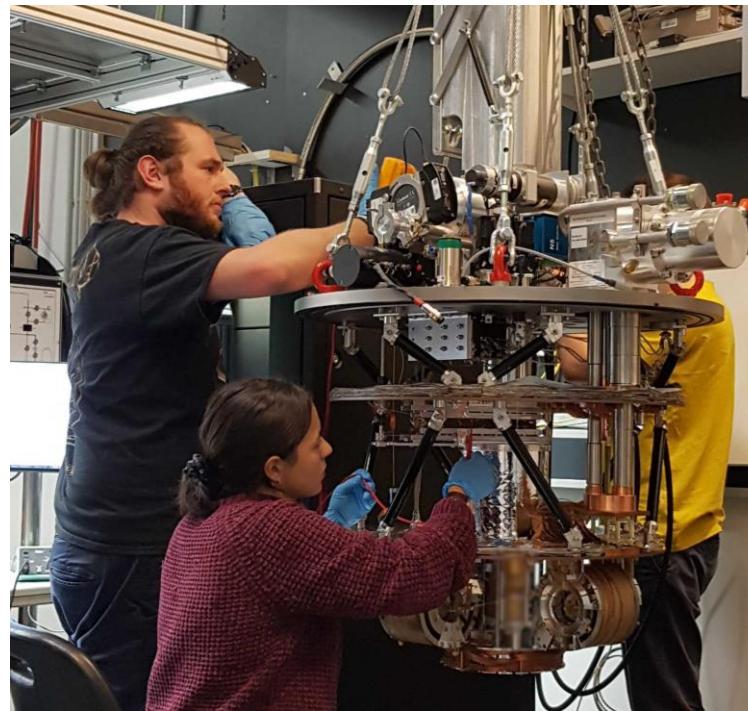
- Experimental quantum control
- Photonic integration diamond

Kai Müller  
Technische Universität München

- Engineering superconducting detectors
- Integrated quantum photonics

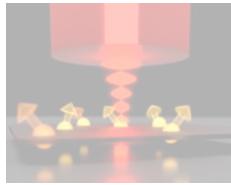
Gregor Pieplow  
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- Modelling, developing concepts, analysis of integrated circuits



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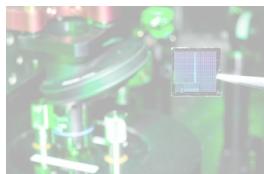


Integration with network

NEQSIS

Q-ToRX

Ultralong storage time



Integration in  
microchip technology

HybridQToken

Q-TOK  
Theorie  
Projekt

QPIS

Efficient writing and reading



QPIS

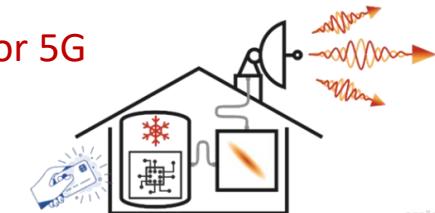
Mobility

$|\text{D}\hat{\text{I}}\text{Q}\text{T}\tilde{\text{O}}\text{K}\rangle$

DIQTOK

QuaMToMe

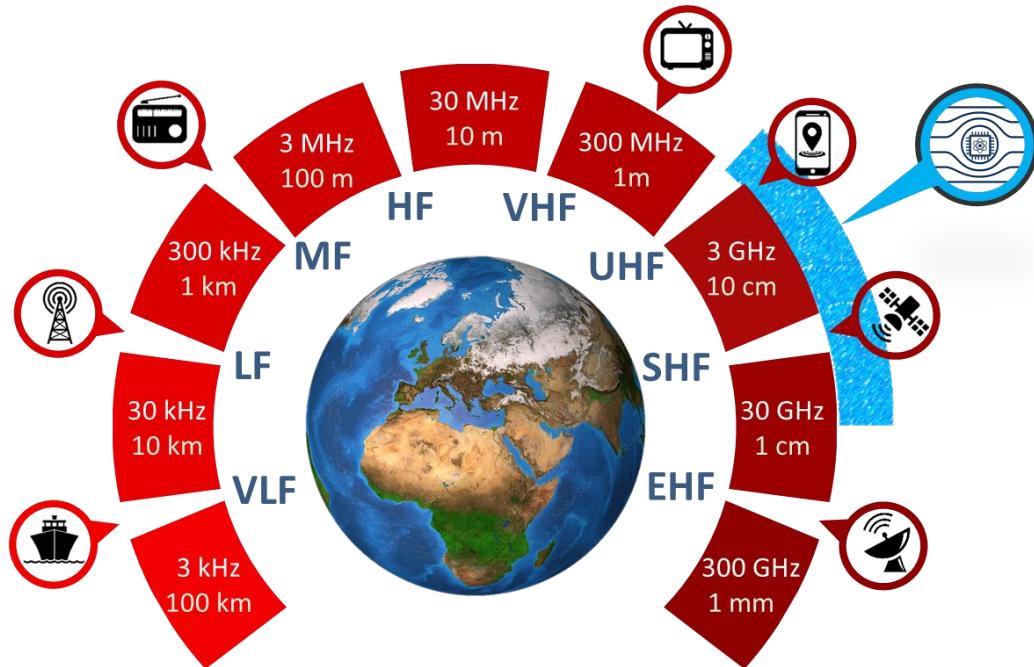
Quantum key for 5G



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## Microwave quantum token

compatible with

superconducting quantum technologies,



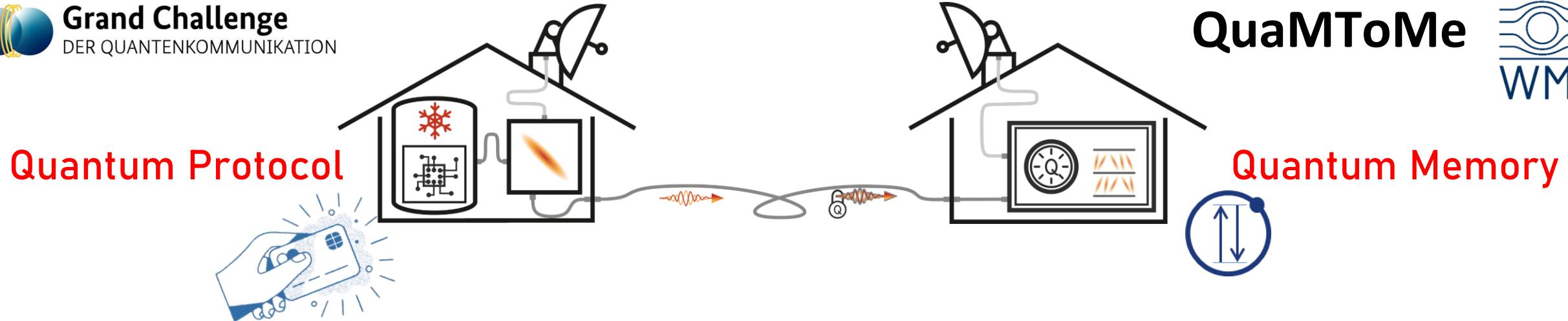
s. a. superconducting quantum computers (1 GHz – 12 GHz),

and



short distance wireless communication (up to 200 m)

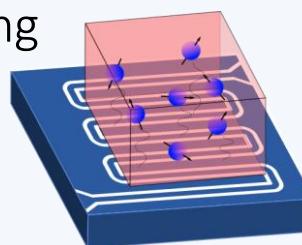
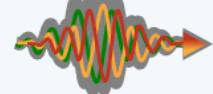
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Generation and decoding of  
the microwave quantum key  
Using superconducting quantum technologies

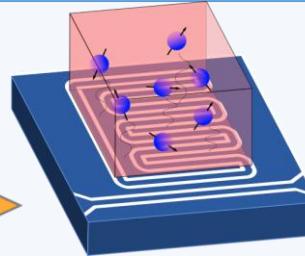
Storage and retrieval of the microwave quantum key  
Using spin ensembles with long lifetimes of quantum  
states

Frequency domain multiplexing  
(FDM)

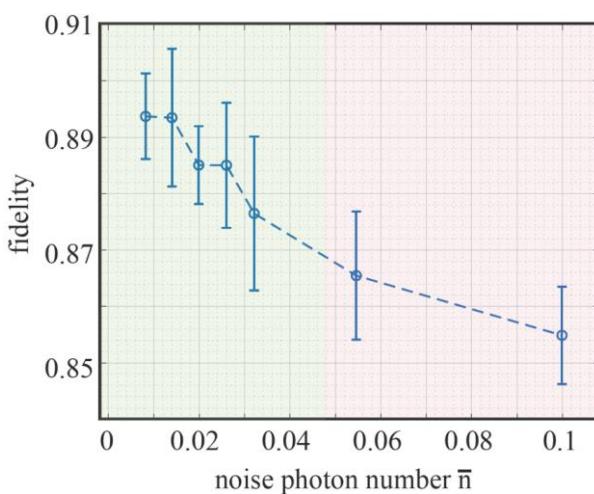
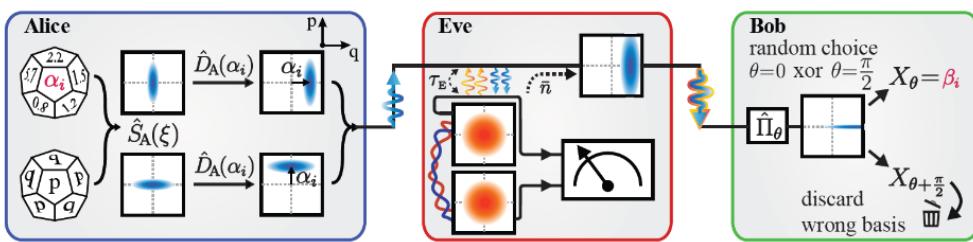
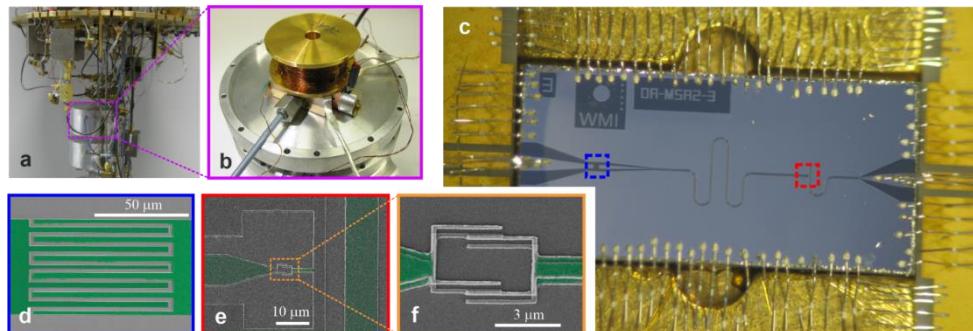


Rare earth spin ensembles  
coupled to a transmission line

Time domain multiplexing  
(TDM)



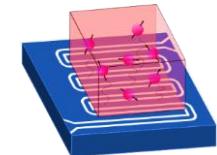
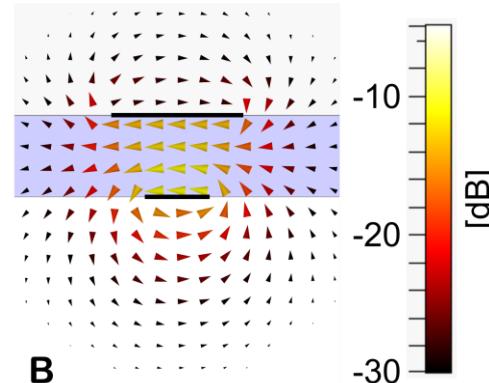
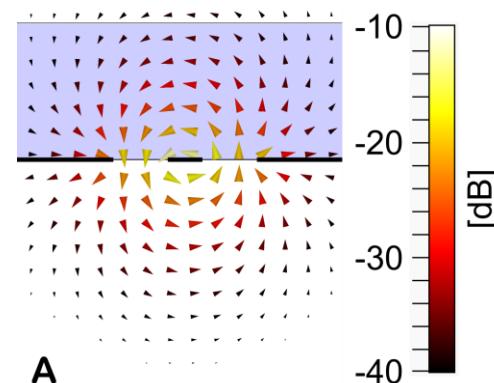
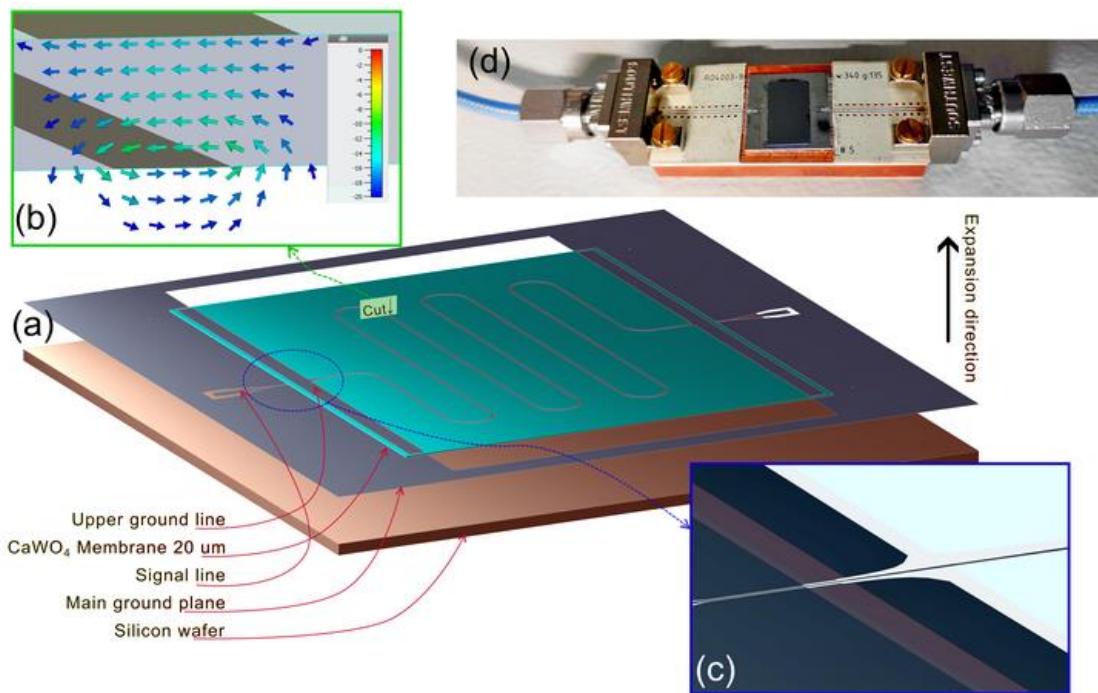
Spin ensembles of donors in  
Silicon coupled to a resonator



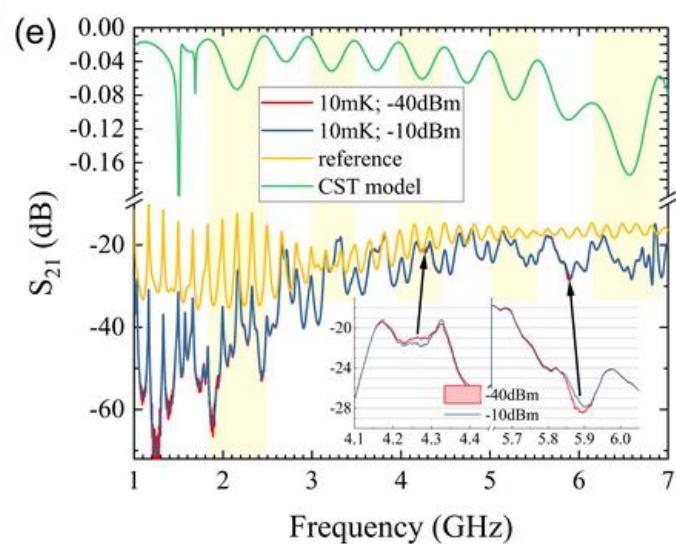
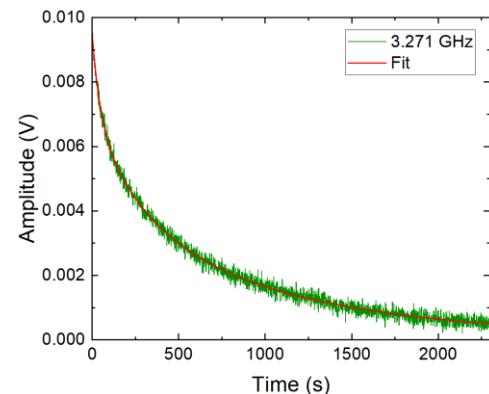
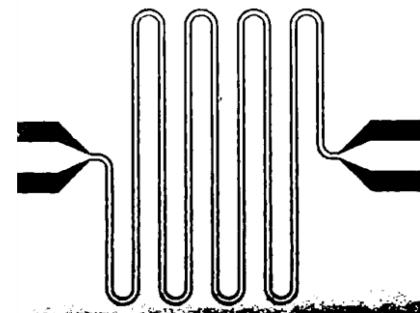
- Quantum token (QT) states can be interpreted as elementary units of the CV-QKD protocol [Phys. Rev. A **63**, 052311 (2001)]
- Experimental verification of the QT security is based on the entangling cloner attack from a potential eavesdropper (Eve) and projective quadrature measurements (Bob) [F. Fesquet, et al., arXiv:2203.05530 (2022)]
- Positive secret key rates measured for microwave QT states with the squeezing level  $S \simeq 3.5$  dB
- Unconditional security of the quantum token demonstrated vs. variable coupled photon noise  $\bar{n}$
- Finite-size effects considered for multi-key QT states with up to  $N = 1.6 \times 10^4$  of elements

# Quantum Memory

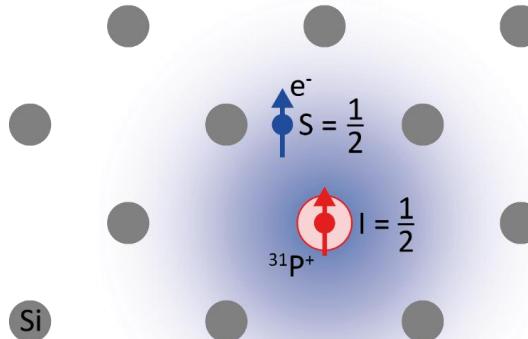
- Addressing spin ensembles via coplanar transmission line
- $^{167}\text{Er}$ ;  $^7\text{LiYF}_4$  and  $\text{CaWO}_4$
- $B = B_{\text{earth}} \cdot 10^{-3}$
- $B_{\text{tuned}} = 0 \dots 100 \text{ mT}$



# QuaMToMe



# Quantum Memory



$$H = \underbrace{g\mu_B BS}_{\text{Zeeman interaction}} + \underbrace{\text{ASI}}_{\substack{\text{Hyperfine interaction} \\ \text{nuclear spin} \\ I=1/2}}$$

- atomistic system of  $^{31}\text{P}$  in Si and  $^{28}\text{Si}$
- long coherence times reported for isotopically engineered  $^{28}\text{Si}$   
 $T_{2e} \approx$  seconds  
 $T_{2n} \approx 180$  min
- zero field splitting 117 MHz

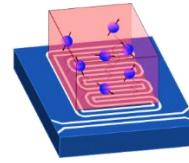
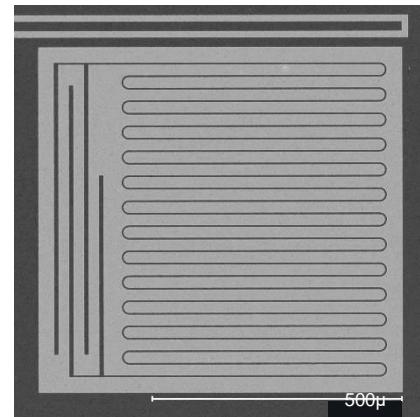
G. Feher et al., *Phys. Rev.* **100**, 1784 (1955).

M. Steger et al. *Science* **336**, 1280 (2012),

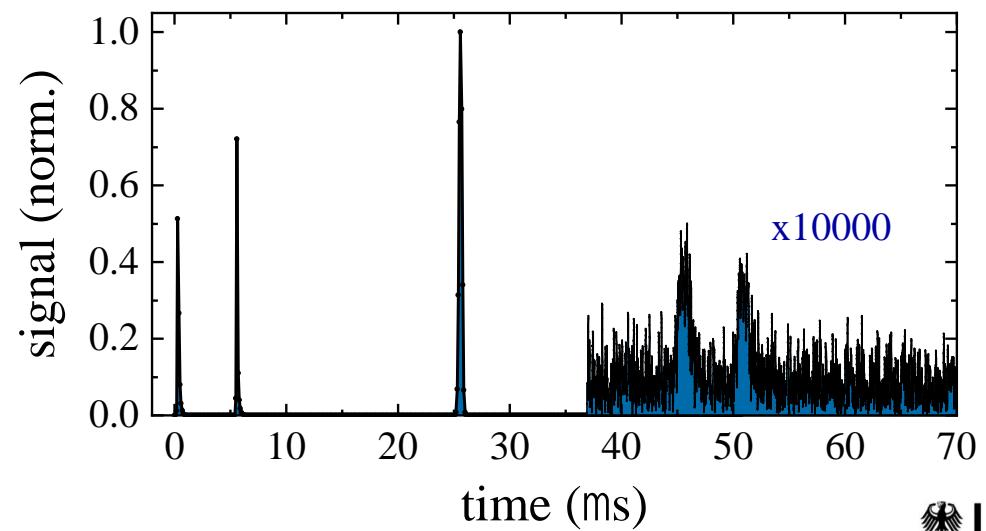
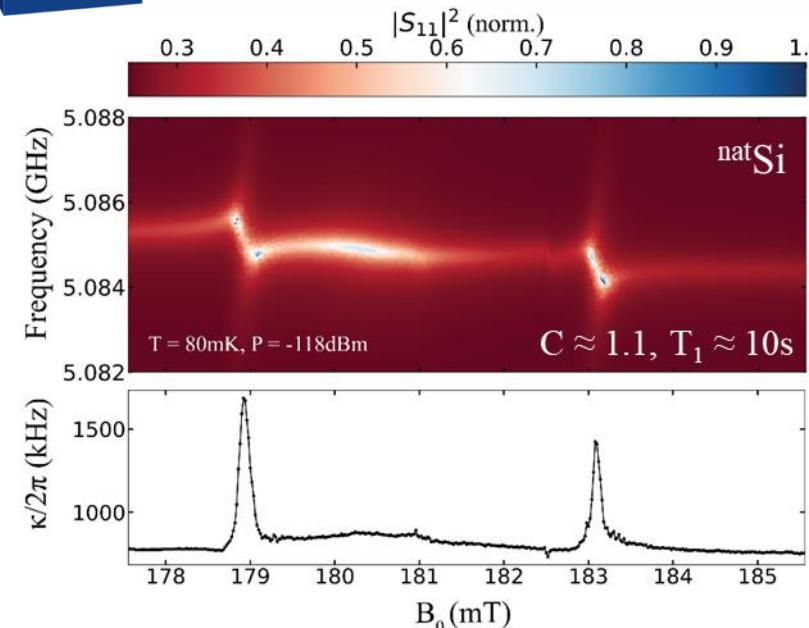
A. Tyryshkin et al., *Nat. Mat.* **11**, 143 (2012),

K. Saeedi et al., *Science* **342**, 833 (2013)

J. T. Muhonen et al., *Nature Nanotechnology* **9**, 986 (2014)



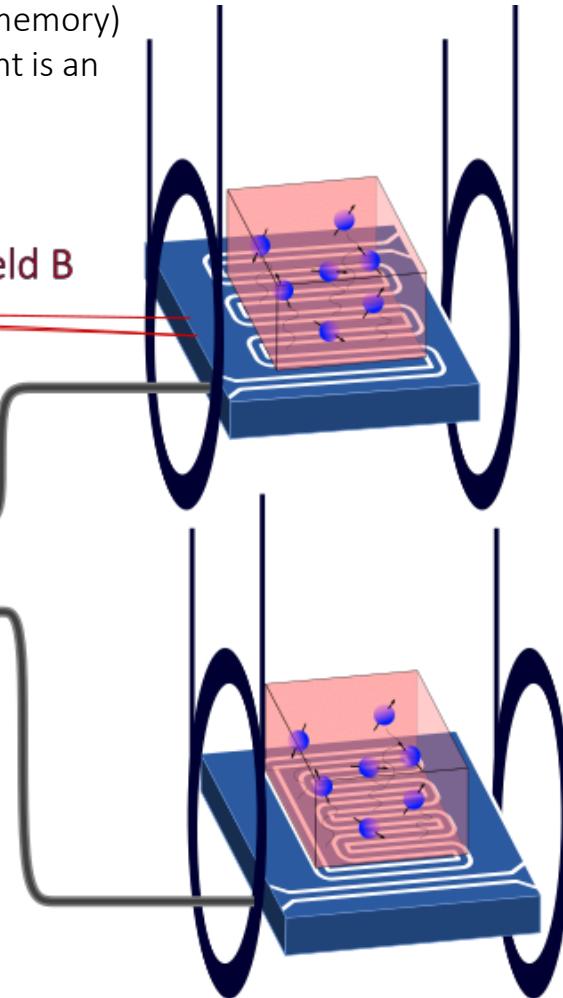
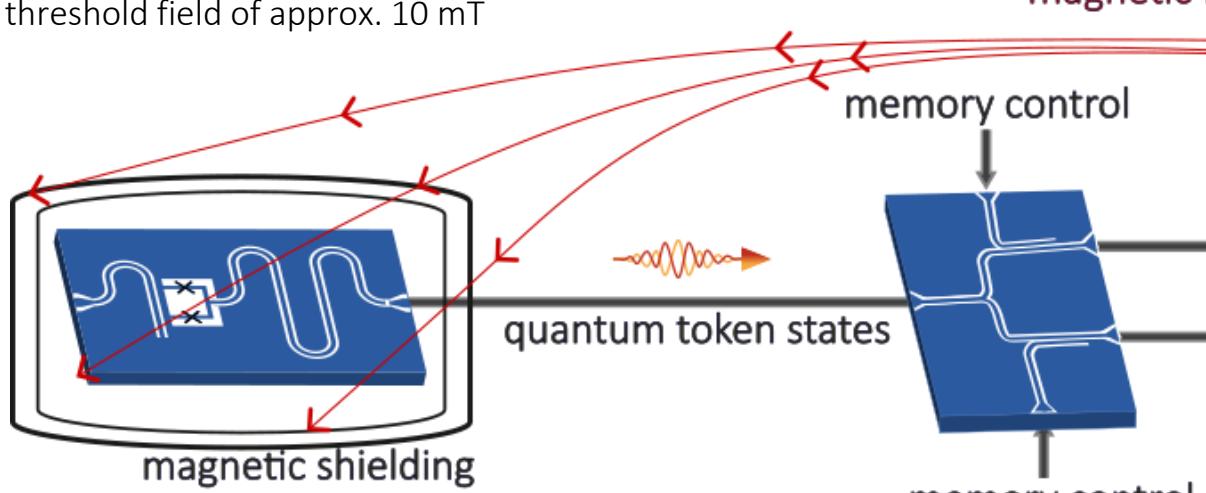
# QuaMToMe



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Superconducting magnetic shielding has low threshold field of approx. 10 mT



JPA are sensitive to external magnetic field, which generate vortices in superconducting film

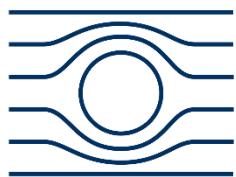
Magnetic field is an essential tool to tune spin transitions to desired frequencies:

- To ZEFOZ transitions
- To resonator frequency

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und Forschung



Walther  
Meißner  
Institut



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**Dr. Kirill G. Fedorov**

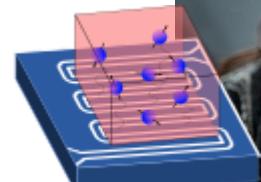
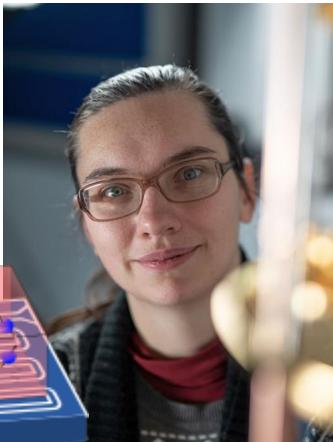
Quantum communication and  
superconducting quantum  
circuits, propagating  
microwaves



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**Dr. Nadezhda Kukharchyk (coordinator)**

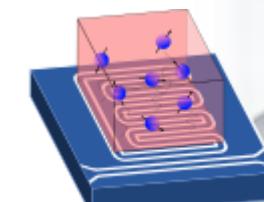
Rare-earth spin ensembles, optical  
and microwave quantum memory,  
resonator free quantum memory



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**PD Dr. habil. Hans-Gregor Huebl**

Spin ensembles of donors in silicon,  
microwave quantum memory,  
quantum memory coupled with  
superconducting resonators



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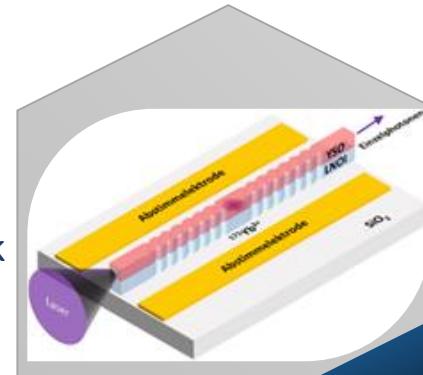


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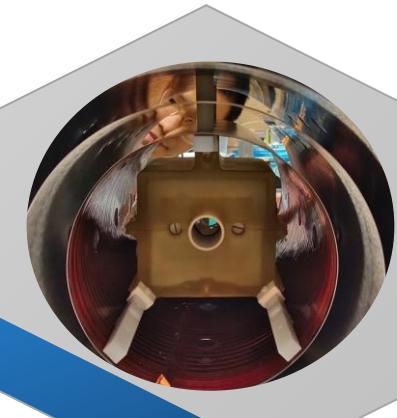
**NEQSIS**

Integration with network



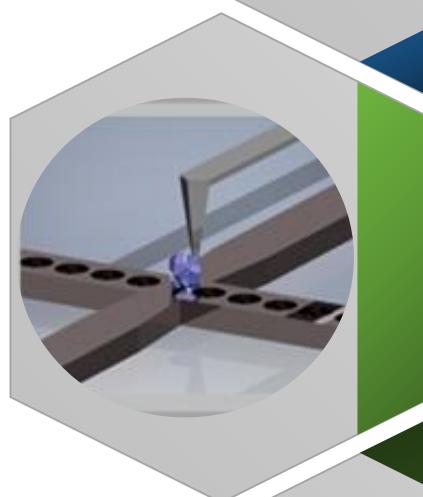
**Q-ToRX**

Ultralong storage time



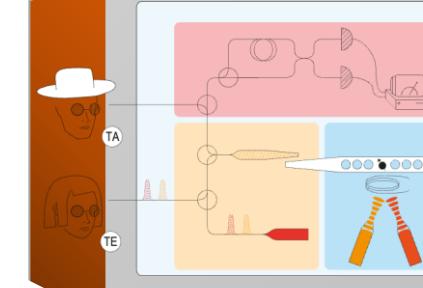
**HybridQToken**

Integration in  
microchip technology



**Q-TOK**

$$N(A) = \text{tr}_{S^2} (\mathcal{U} A \otimes J \mathcal{U})$$

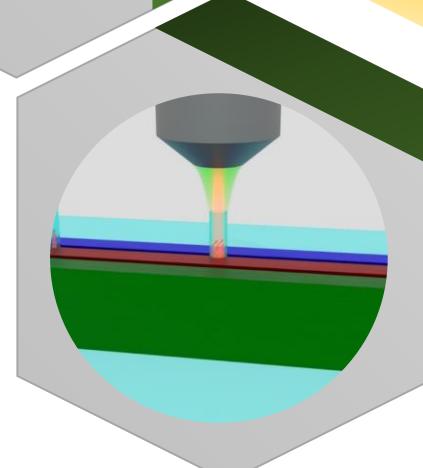


**QPIS**

Efficient writing and reading

**DIQTOK**

Mobilität



**QuaMToMe**

Quantum key for 5G

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und Forschung



Autherntification NOT hacked!

GEFÖRDERT VOM



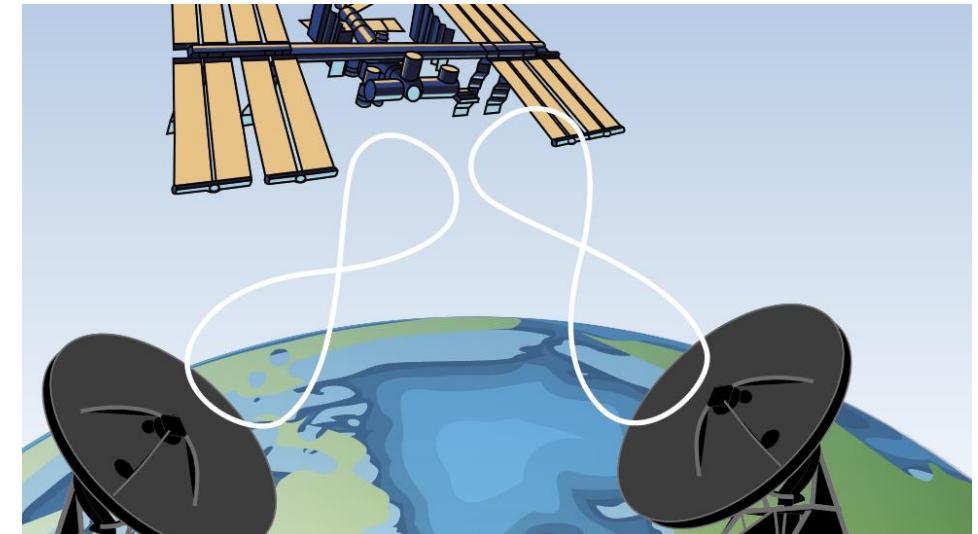
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## Quantum token



→ Reliable authentication

## Quantum communication



→ Secure communication