ML4Q

MATTER AND LIGHT FOR QUANTUM COMPUTING

ML4Q CLUSTER OF EXCELLENCE

ANNUAL REPORT 2022

UNIVERSITY OF COLOGNE

RWTH AACHEN UNIVERSITY

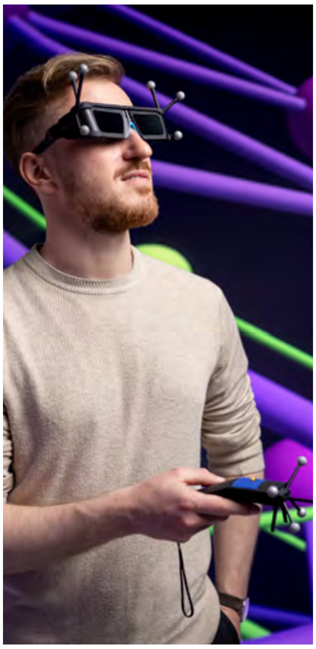
UNIVERSITÄT BONN

JÜLICH Forschungszentrum

ANNUAL REPORT 2022

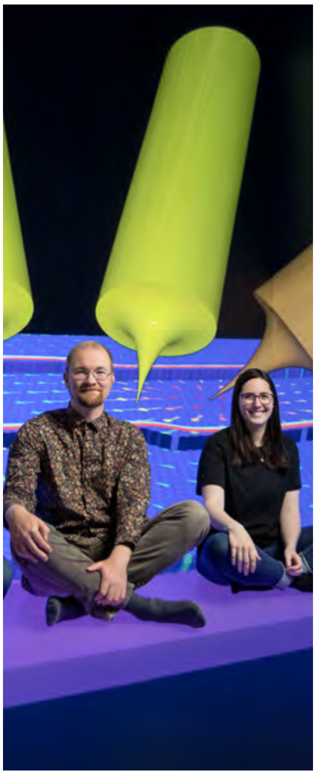
CONTENT

01 ML4Q AT A GLANCE



02 ML4Q RESEARCH

03 ML4Q LIFE



ML4Q
ANNUAL REPORT 2022

Our Cluster of Excellence "Matter and Light for Quantum Computing" (ML4Q) has already seen the fourth year of its 7-year funding period, and I am glad to present our latest developments in this annual report 2022.

ML4Q was established in 2019 in the context of the German Excellence Strategy with the aim of installing a new research infrastructure to foster the fundamental research on future quantum information technologies in the state of Nordrhein-Westfalen, with focus on the developments of new concepts and devices for scalable quantum computing and quantum communications. It encompasses the universities of Cologne, Bonn, and Aachen as well as the Forschungszentrum Jülich (with additional participation of the universities of Düsseldorf and Bochum, Fraunhofer ILT and Fraunhofer FHR).

The biggest event for ML4Q in 2022 was the self-organized midterm review, which was planned in the proposal stage in view of the rapidly changing research landscape in the field of quantum information science. All the projects within ML4Q were asked to submit a short research proposal for the remaining period which was evaluated internally with the help of the international science advisory board. (I thank the board members who kindly took the time and efforts for this important event!) This made it possible to update the project structure to adjust to the current situation and to better prepare ourselves for the possible second funding period. Although there were some strains associated with such a procedure, we were able to redirect our precious resources to incorporate new ideas, thereby addressing the fundamental challenges in the quantum information science.

This midterm review was our first step towards the conception of the cluster proposal for the second funding period. The new/updated ideas that were sharpened in the midterm review have helped us to define the new goals and the research structure of the future ML4Q. By the time you will be reading these lines, the concrete planning of "ML4Q-2" will be already going on.

Another important development is the hiring of ML4Q professors. To strategically strengthen the research and education potential of quantum information science at the partner universities, seven new professorships (all tenure-track) were created by using the ML4Q budget, and as of this writing, six of them have been filled by splendid young researchers. (In addition, there were four professor hires associated with ML4Q using the university budget.) I am proud to announce that two of the six ML4Q professors so far hired are females, which contributes to fostering equal opportunities in physics and motivates female students to become professors by presenting role models. In fact, we view the improvements of equal opportunities in physics as an important mission of ML4Q and we promised in the proposal that at least two of the seven ML4Q professors will be females. Other measures include giving generous incentives to the PIs who hire female postdocs, which actually has had positive outcomes.

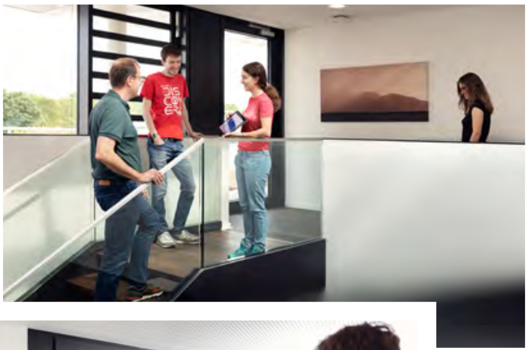
Besides promoting female scientists, ML4Q considers the support of young researchers at the early stage of their independence to be crucial for building a vibrant research community. In this regard, the midterm review offered a perfect opportunity to identify promising young researchers who want to pursue their own ideas. The steering board has hand-picked six candidates and offered them the "ML4Q Young Investigator Award", which provides financial support and a special status within the cluster community.

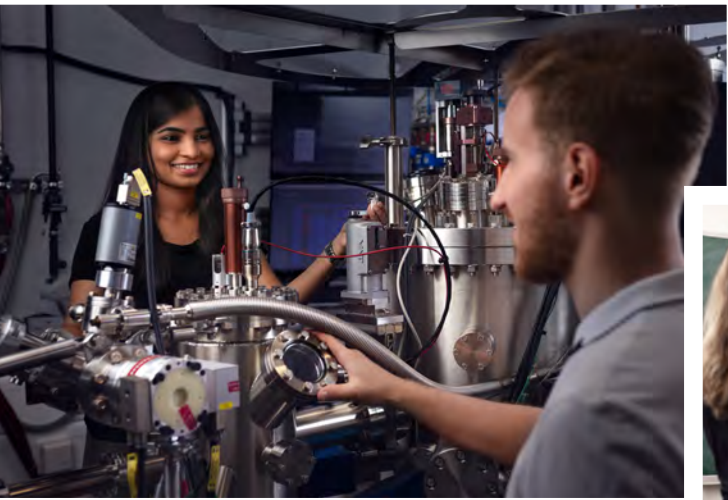
Finally, I would like to thank you for your continuing support to ML4Q. With the optimized project structure and the new hires, we are sure that we can make wider and deeper contributions to quantum information science in the remaining funding period. You can see some of our highlight results in this annual report, but if you are interested in the latest developments, please check out our News section on ml4q.de/news. You will not be disappointed!

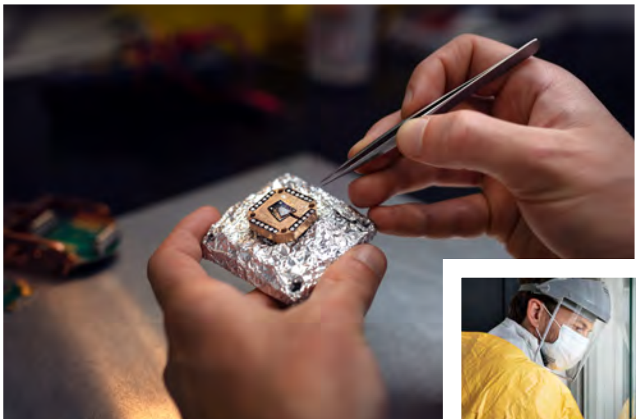
Yoichi Ando

4 SITES – 4 YEARS

A photo gallery from previous reports

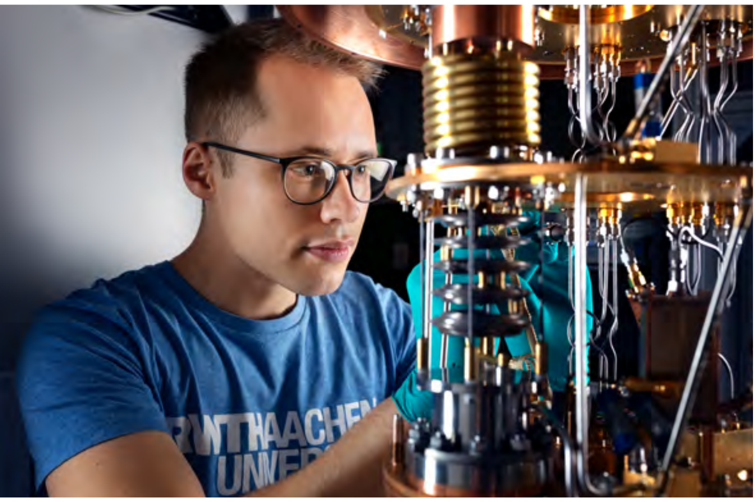


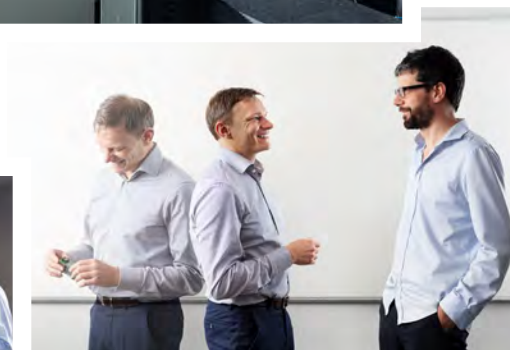




2019

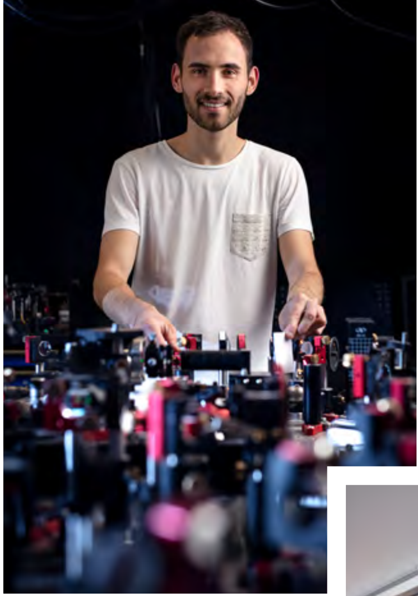
ML4Q set off in 2019 for a long collaborative journey. The cluster involved in its first year of funding over 150 members and associated members, a number which continued to grow in the following years. First communication and networking measures were established to enhance cross-site collaborations. The images selected for the first annual report showcase several Cologne research groups working both in experiment and theory to contribute to the project's overall success.

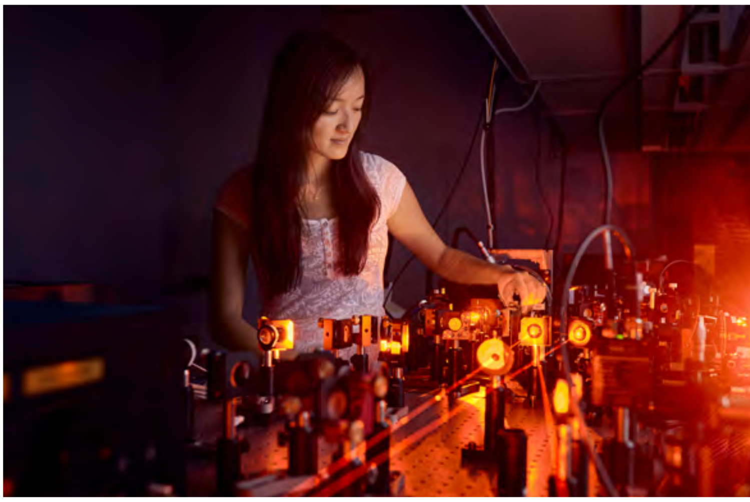


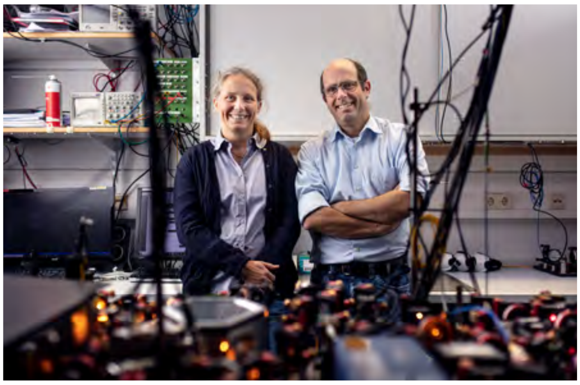


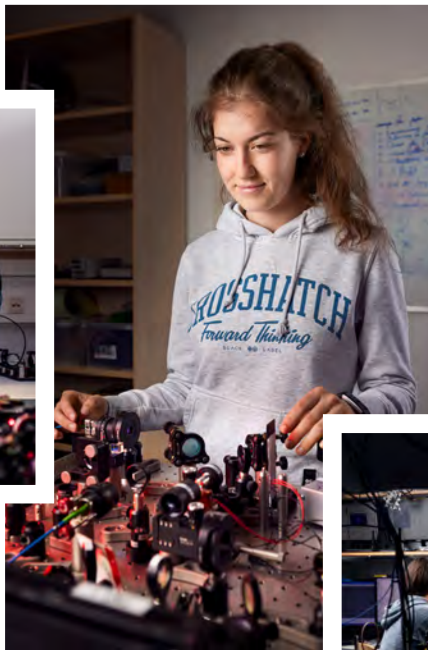
2020

Our journey continues as the cluster grows to involve almost 200 members and associated members. Despite – or rather because of the shift to video-conferencing – cross-group collaborations intensified and brought forth more than 20 joint publications, some of which were highlighted in the second annual report of the cluster's activities. The images selected for this report featured research groups from RWTH Aachen University.



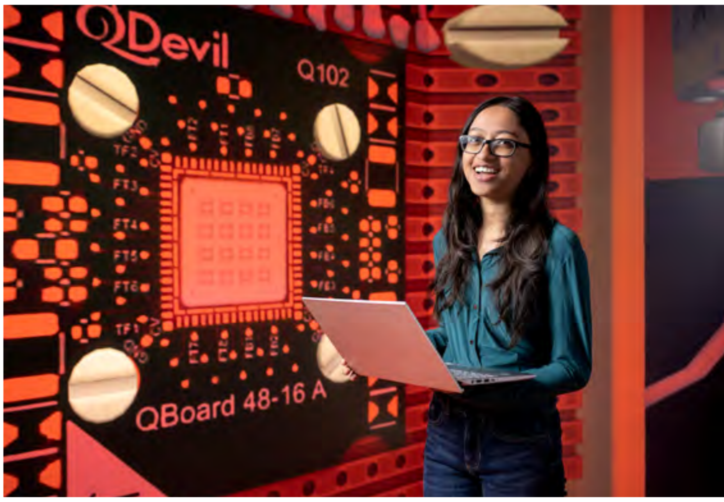


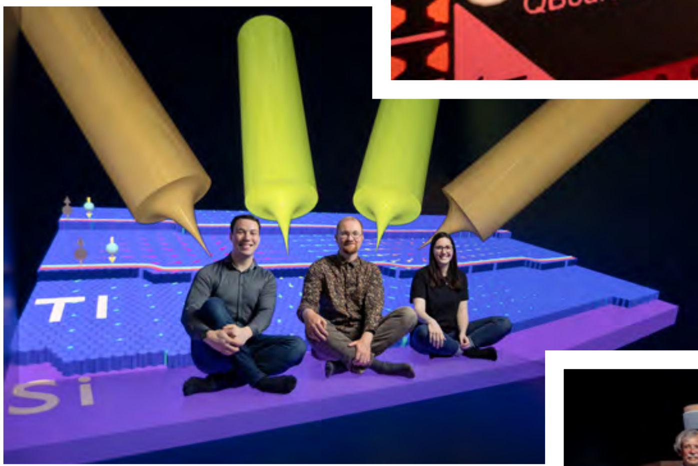


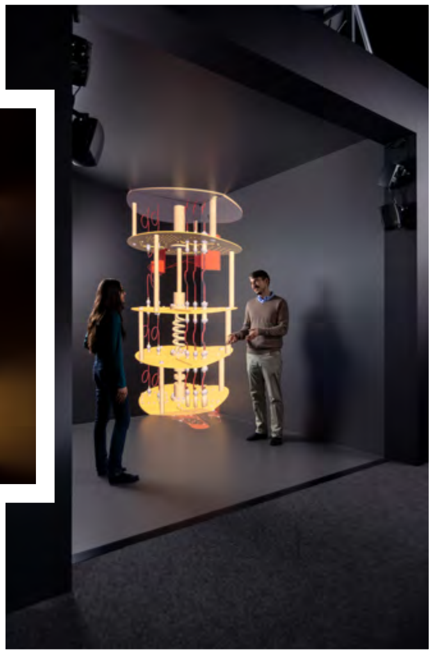


2021

The cluster – meanwhile comprising almost 250 members and associated members – is successful in recruiting excellent young scientists, thus establishing several professorships at all sites, who were portrayed in the third annual report. The report is visually enriched by captivating images showcasing the research groups affiliated with the University of Bonn.

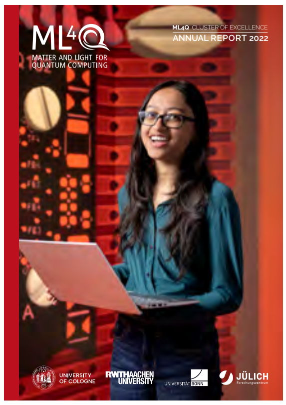






2022

To ensure optimal project alignment and progress, the cluster underwent in 2022 a comprehensive midterm evaluation. This evaluation provided a valuable opportunity to assess the program's direction, make necessary adjustments, and strategically reallocate resources for enhanced outcomes in the remaining funding period. The outcome of the midterm evaluation is shown in more detail on pages 18-21. The images chosen to illustrate the report depict cluster members from Forschungszentrum Jülich alongside the objects of their research, beautifully capturing the dynamic interplay between their work and its tangible results.



01

ML4Q
AT A GLANCE

ML4Q
AT A GLANCE

ML4Q stands for Matter and Light for Quantum Computing. The Cluster of Excellence set off in 2019 for a long collaborative journey in order to develop new computing and networking architectures using new findings in the fundamental research in solid-state physics, quantum optics, and quantum information science.

THE CLUSTER'S MISSION

Using the principles of quantum mechanics, it is the long-term goal of ML4Q to develop new computing and networking architectures with a power beyond anything classically imaginable. Quantum computers could be powerful tools in key areas such as materials design, pharmaceutics, or artificial intelligence. Quantum communication could be made effectively secure. ML4Q builds on the complementary expertise in the three key research fields of solid-state physics, quantum optics, and quantum information science to develop the best hardware platform for quantum information technology, and provide comprehensive blueprints for a functional quantum information network.

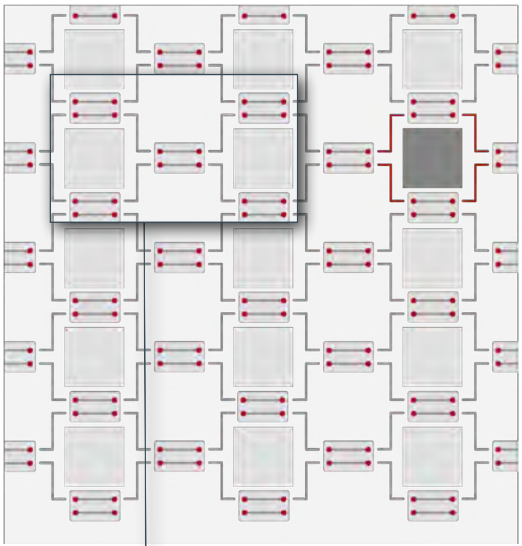
The long-term goal of the cluster is to realize network and processing architectures protected by error correction protocols and eventually connected to a quantum version of the internet. This goal defines a hierarchy of challenges, both in fundamental science and in technology, which must be overcome at early and intermediate stages.

qubits
for information storage

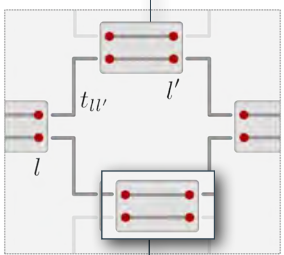
processing
quantum information

connectivity
through quantum links

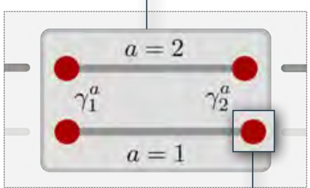
THE VISION



The processor units of a network comprise arrays of qubits whose implementation requires scalable designs. We envision to realize these units by the end of the second funding period.



The ML4Q core projects are dedicated to the development of both spin qubit platforms as well as topologically protected Majorana qubits as an alternative platform with the prospect of superior performance in the long term.



As Majorana-based quantum information hardware is still in its infancy, major intermediate challenges need to be overcome. These include the actual engineering of Majorana qubits.

On an even more fundamental level, first significant achievements in the realization and optimization of quantum materials harboring Majorana states are subject of the running research in Focus Area 1 and 2.

THE SCIENTIFIC APPROACH

The scientific structure of ML4Q spans four Focus Areas, each addressing a specific set of problems relevant to the cluster's mission. All Focus Areas include theoretical as well as experimental components and transcend the boundaries of disciplines and institutions.

- **Focus Area 1** aims to identify and explore novel topological hardware platforms for quantum information processing, including hybrid structures of topological insulators and superconductors as well as the ways to realize parafermions.
- **Focus Area 2** aims to realize Majorana qubits as a promising alternative to superconducting qubits or spin qubits. In parallel, protocols for readout, manipulation, and error correction are designed.
- **Focus Area 3** designs novel schemes of quantum control, error correction and mitigation. It investigates the operation of quantum devices under realistic noisy environmental conditions and explores topological and computational quantum matter subject to external driving.
- **Focus Area 4** focuses on the linkage of quantum processing units. Specifically, it takes steps towards realizing integrated atomic/optical and solid-state platforms and implementing quantum links between heterogeneous qubit setups.

Following the midterm review in June 2022, the scientific program of ML4Q was restructured to span three Focus Areas, each addressing a specific set of problems relevant to the cluster's mission (**A**: Majorana devices and topological matter | **B**: NISQ and error-aware quantum computing | **C**: Quantum networks and interconnects). As part of the new structure, projects funded from 2023 onwards include research on NISQ computing and novel 2D materials.

OPPORTUNITIES FOR YOUNG SCIENTISTS

Attracting and retaining the best young talents in the field by offering competitive career opportunities is a top priority for ML4Q. Current offers include:

- Undergraduate grants
- Undergraduate research internship
- Independence grants for postdoctoral researchers
- New tenure-track professorships
- ML4Q Research School with cluster-specific courses, e.g. "Platforms for Quantum Technologies" for Master students
- Master program for Quantum Technology in Aachen as well as specialized lectures on quantum technologies in Bonn and Cologne

PARTICIPATING INSTITUTIONS

ML4Q is a cooperation by the University of Cologne, University of Bonn, RWTH Aachen University as well as the Forschungszentrum Jülich. Partner institutions are the Heinrich Heine University Düsseldorf, the Fraunhofer Institute for Laser Technology ILT and the Fraunhofer Institute for High Frequency Physics and Radar Techniques FHR.

FUNDING

ML4Q is funded since January 2019 within the Excellence Strategy of the German federal and state governments. The first funding period ends in 2025.

ML4Q **IN NUMBERS**

267
MEMBERS AND ASSOCIATES

52
PROFESSORS

89
INTERNATIONAL SCIENTISTS

116
PHD STUDENTS

50
FEMALE SCIENTISTS

49
ADMINISTRATIVE & TECHNICAL STAFF

4
NEW HIRED ML4Q PROFESSORS

122
PUBLICATIONS* IN 2022

48
POSTDOCS

8
OPEN CALL PROJECTS AND INDEPENDENCE GRANTS

32
PUBLICATIONS* IN 2022
WITH TWO OR MORE ML4Q GROUPS INVOLVED
(10 CROSS-SITE PUBLICATIONS)

*including preprints

MIRA SHARMA

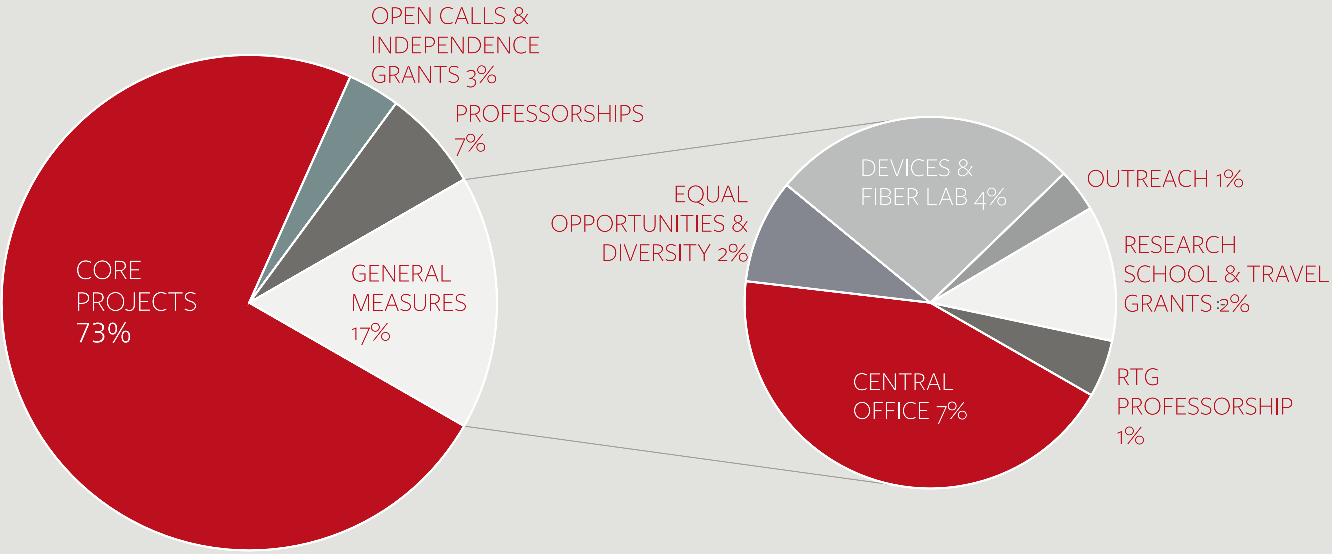
“

Through my research journey, I have come to discover that dreams are realities present in another plane, just waiting to be realized. Today, I am thankful for the opportunity to transform one of my cherished dreams into reality through my PhD studies here in Aachen.

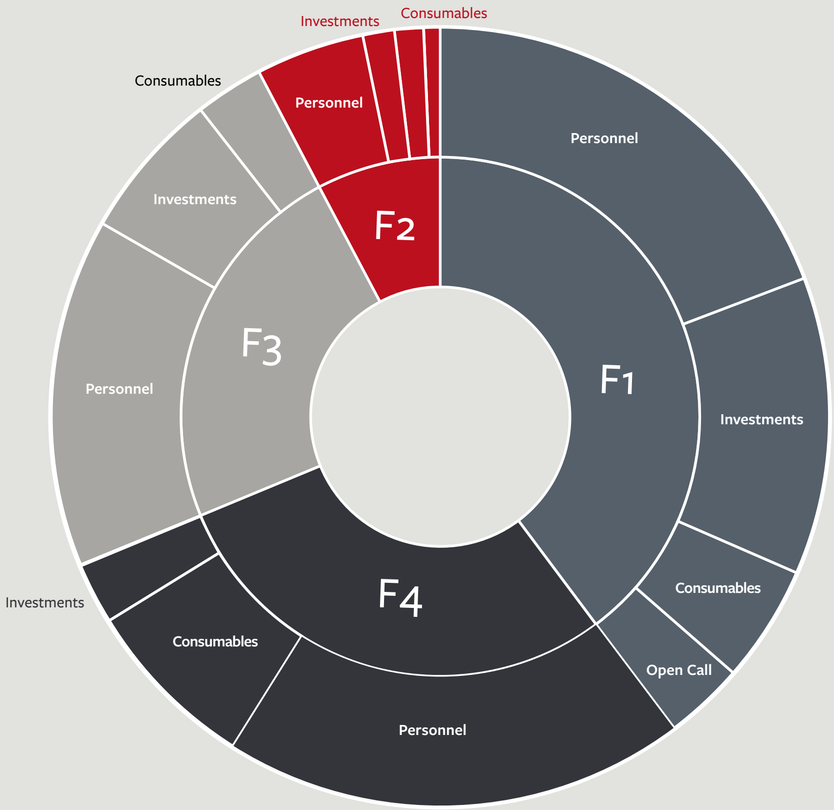
Mira Sharma completed her Master's degree in Physics from Aix-Marseille University in France and has embarked on her PhD journey in 2021.
She is currently a member of David DiVincenzo's group in Aachen, where her research primarily focuses on the theoretical aspects of Silicon-Germanium qubit technologies.

ML4Q **IN NUMBERS**

CORE PROJECTS & CENTRAL MEASURES

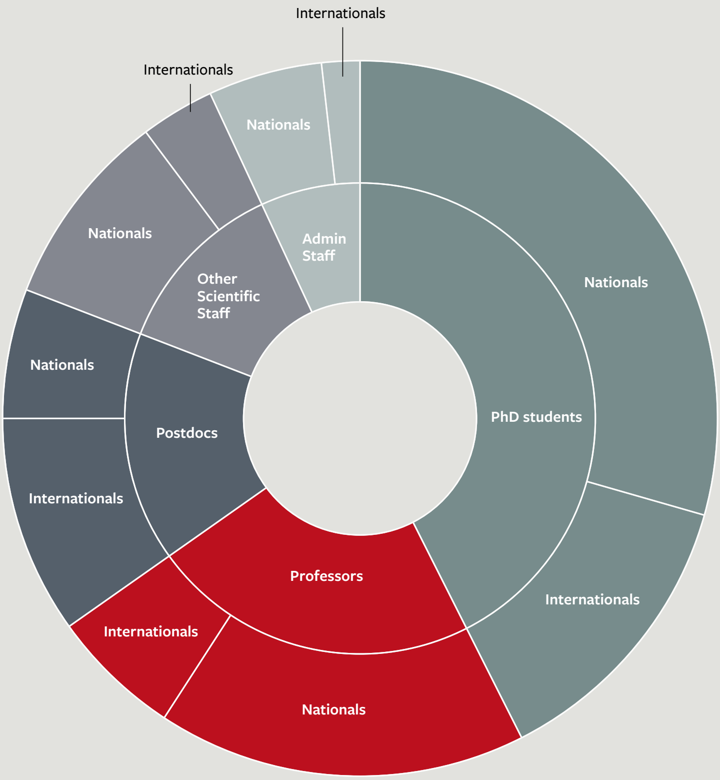


In 2022, almost three quarters of the expenses were dedicated to personnel, instrumentation and consumables in the core projects. Several Open Call projects had their last funding year in 2022. With 3 ML4Q faculty hirings starting in 2021/2022, 7% of the annual budget was dedicated to professorships. Compared to the previous years, expenses for supporting measures (research school, equal opportunities, workshops and outreach) as well as the ML4Q Fiber Lab, ML4Q Devices and the central office increased to make up one sixth of the annual budget.



All Focus Areas include theoretical as well as experimental components bringing different needs for personnel, consumables and instrumentation. Here is an overview of the allocation of core project funds in 2022 broken down by Focus Area and type of fund. The start of new ML4Q professors in 2022 was supported by an increase in investments.

INTERNATIONALIZATION



All academic groups continued to grow in 2022, with a relatively high increase in postdoctoral fellows. 33% of ML4Q members and associated members are international scientists coming from 25 countries (see map below). As in previous years, postdoctoral scientists still show the highest level of internationalization (58%) while the internationalization in other academic groups is roughly half as high.

AUSTRIA
BELGIUM
BOSNIA & HERZEGOVINA
BRAZIL
BULGARIA
CHINA
FRANCE
GEORGIA
GREECE
INDIA
IRAN
ISRAEL
ITALY
JAPAN
LIECHTENSTEIN
NETHERLANDS
POLAND
RUSSIA
SPAIN
SWEDEN
SWITZERLAND
TAIWAN
UKRAINE
USA
UNITED KINGDOM

NEW DEVELOPMENTS IN 2022

June 2022 meant halftime for our seven-year cluster funding period. As promised in our proposal, we held a comprehensive three-day midterm evaluation to ensure optimal project alignment and progress. This evaluation provided a valuable opportunity to assess the program's direction, make necessary adjustments, and strategically reallocate resources for enhanced outcomes in the remaining funding period of 2023-2025.

All existing ML4Q projects as well as new projects were invited to apply for funding starting in January 2023. The submitted proposals – with an average of three to five partners, hence strengthening inter- and intra-site collaborations – were each reviewed by two internal experts and afterwards presented at the Maritim Hotel in Cologne to all cluster members and the scientific advisory board. The final funding decisions were made by the ML4Q Steering Board with advice by the international scientific advisory board and resulted in a funding rate of 67%.

Following the midterm review, ten new colleagues were integrated into the cluster, among them several early-career researchers as well as the ML4Q professors. 12 out of 18 new projects are inter-site collaborations between two or more cluster sites. Additionally, the scientific program of ML4Q was restructured to span three Focus Areas, each addressing a specific set of problems relevant to the cluster's mission. As part of the new structure, projects funded from 2023 onwards include research on NISQ computing and novel 2D materials.

Focus Area A

Majorana devices and topological matter

Area representative: **Thomas Schäpers**
Deputy representative: **Fabian Hassler**

A1	Materials, fabrications, and physics basis for topological-insulator Majorana devices
A2	Quantum anomalous Hall insulator devices
A3	Exploring Majorana modes in van der Waals heterostructures
A4	Ab-initio Bogoliubov-de Gennes investigation of superconducting interfaces for Majorana materials platforms
A5	Atomistic investigations of structure, chemistry and electronic properties in 3D TIs and at TI/SC interfaces
A6	Four-tip scanning tunneling microscope operating at 100 mK
A7	Majorana States and Parafermions in Ultracold Atom Systems


Yoichi Ando


Daniel Rosenbach


Erwann Bocquillon


Christian Dickel


Matteo Rizzi


Achim Rosch

A


Reinhold
Egger


Corinna
Kollath


Martin
Weitz


Michael
Köhl


**Thomas
Schäpers**


Stefan
Blügel


Detlev
Grützmacher


Joachim
Mayer


Gregor
Mussler


Markus
Schmitt


Peter
Schüffelgen


**Fabian
Hassler**


Timofey
Balashov


Markus
Morgenstern


Christoph
Stampfer

- Aachen
- Cologne
- Bonn
- Jülich
- Düsseldorf
- Open Call

Focus Area B

NISQ and error-aware quantum computing

Area representative: **David DiVincenzo**
Deputy representative: **Markus Müller**

B1	Commissioning a NISQ platform: Enhancements and supremacy certification
B2	Disorder in quantum technology devices
B3	Fault-Tolerant Quantum Error Correction (QEC)
B4	Measurement induced phase transitions on Rydberg NISQ devices
B5	Quantum Software for the Near and Mid-Term
B6	Robustness and controllability of driven open few and many-qubit ensembles


Christian Gogolin


Frank Wilhelm-Mauch


Sebastian Hofferberth


Michael Köhl


Dagmar Bruss


Corinna Kollath


David Luitz


Alexander Altland


Michael Buchhold


Markus Müller


Dante Kennes


Tommaso Calarco


Sebastian Diehl


Mario Berta


Manuel Rispler


David Gross


Simon Trebst


David DiVincenzo

- Aachen
- Cologne
- Bonn
- Jülich
- Düsseldorf
- Covestro
- Open Call

Focus Area C

Quantum networks and interconnects

Area representative: **Michael Köhl**
Deputy representative: **Andrea Bergschneider**

C1	Telecom-ready optical interface to qubits in gate-defined quantum dots with high coupling efficiency
C2	Optical coupling of qubits in 2D materials
C3	Multipartite quantum networks
C4	A quantum link between a solid-state emitter and an atomic qubit
C5	Electron shuttling for scalable semiconductor quantum computing


Andrea Bergschneider


Michael Köhl


Hans Kroha


Stefan Linden


Julian Schmitt


Simon Stellmer


Martin Weitz


Hendrik Bluhm


David DiVincenzo


Beata Kardynal


Alexander Pawlis


Dante Kennes


Annika Kurzmann


Gláucia Murta


Andreas Wieck


Silvia Viola Kusminskiy


Lars Schreiber

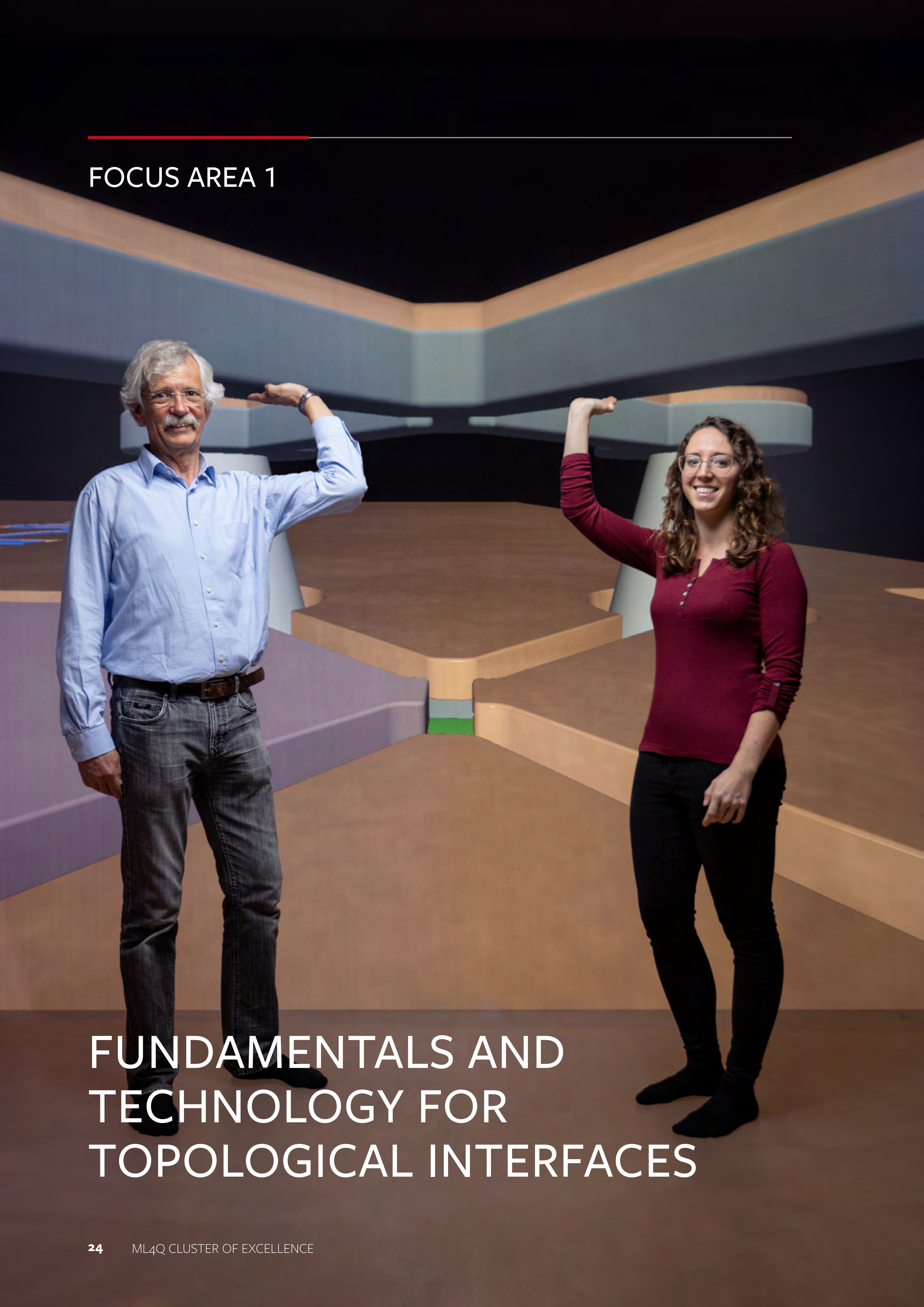

Christoph Stampfer


Jeremy Witzens

- Aachen
- Cologne
- Bonn
- Jülich
- Düsseldorf
- Bochum
- Open Call

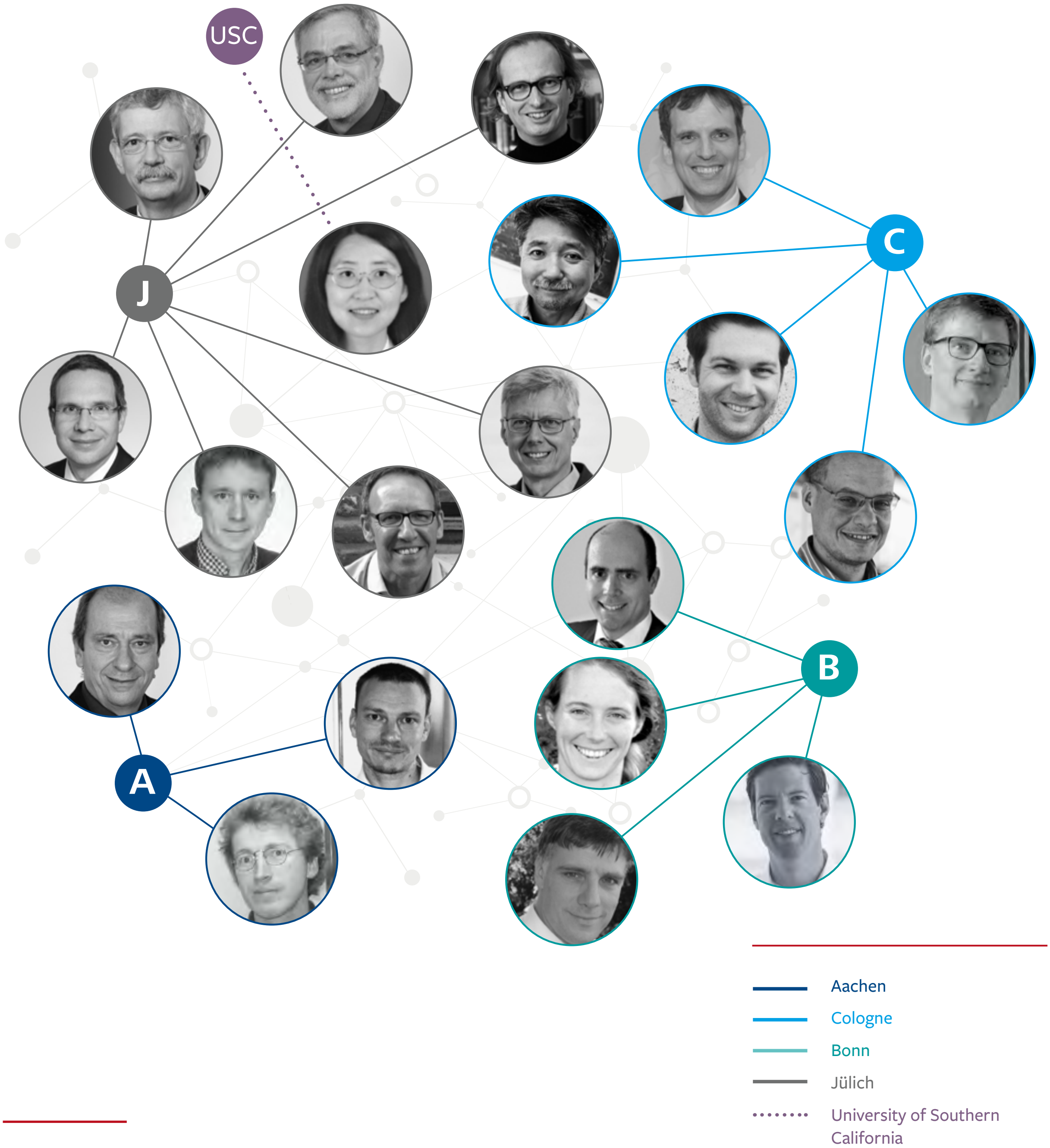
ML4Q
RESEARCH

02



FOCUS AREA 1

FUNDAMENTALS AND TECHNOLOGY FOR TOPOLOGICAL INTERFACES



Focus Area 1 comprises four projects on materials and hybrid structures hosting topological edge modes such as Majorana states and explores how such edge states can be optimized for their use as building blocks of quantum information technologies. More than 15 research groups are collaborating in order to investigate hybrid structures based on topological insulators and superconductors and use ultracold atoms to realize Majorana states and parafermions controlled by light.

A central goal of *Focus Area 1* is to explore the stability of topological edge states determined by their interaction with thermal quasiparticles and impurity states in all these systems. In order to prepare ultraclean interfaces and devices, new fabrication methods in ultra-high vacuum are being developed. This is complemented by novel ab-initio approaches able to predict quantitatively how superconductors can penetrate into spin-orbit coupled matter via the proximity effect.

FOCUS AREA 1

FUNDAMENTALS AND TECHNOLOGY FOR TOPOLOGICAL INTERFACES

1
FOCUS AREA

Focus Area 1 *tackles fundamentals and technology of topological interfaces. The focus is on interfaces between bulk insulating topological insulators (TIs) or quantum anomalous Hall (QAH) systems with superconductors (SCs) towards the implementation of Majorana qubits. We also employ ultracold atoms as model systems to realize Majorana and parafermion states by light. A central event in 2022 was the midterm review that led to a restructuring of the Focus Areas. Namely, the former two Focus Areas 1 and 2 were united in the new Focus Area A "Majorana devices and topological matter" starting 2023. The described results have been achieved within the old Focus Area 1, but are partly already focused towards the new Focus Areas.*

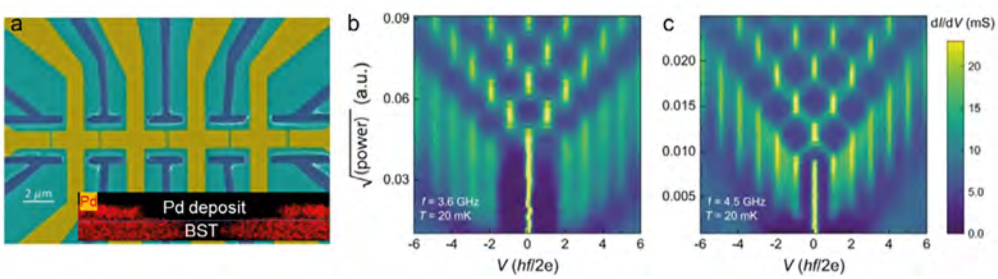
ACHIEVEMENTS

The Grützmacher group has optimized the selective area growth (SAG) of $Bi_xSb_{2-x}Te_3$ for various areal SAG shapes [1] including sapphire substrates for bulk insulating $Bi_xSb_{2-x}Te_3$. The Voigtländer group probed the edge state conductivity of thin $Bi_xSb_{2-x}Te_3$ films by 4-tip STM (scanning tunneling microscopy) [2]. Josephson junctions using Al with diffusion barriers revealed strongly temperature dependent Andreev reflections attributed to the interplay of bulk states and topological surface states [3]. Magnetic doping during SAG by V or Cr is under development. The TI/SC Josephson junction was integrated into a transmon qubit for later readout of the Majorana mode manipulation (actual T_2^*= 30 ns) [4; see paper highlight on pages 30/31].

The groups of Mayer and Ando have published their results on intrinsic SC proximity by Pd diffusion into Bi_2Te_3 highlighting the importance of flexoelectricity for the diffusion [5; see figure a]. Patterned Josephson junctions exhibit a missing first Shapiro step at low frequency [5; see figure b and c]. Tunnel probes at the $Pd_xBi_{2-x}Te_3$/Bi_2Te_3 interface for further characterizing the presumable Majorana modes are underway. The Ando group has also improved the fabrication of Nb/$Bi_xSb_{2-x}Te_3$ nanowire Josephson junctions with bulk insulating properties revealing gate tunable 1D band occupation and a missing first Shapiro step (below 2.5 GHz) [6]. Current correlation measurements (noise) for identifying the Majorana modes are developed in the Bocquillon group. The Ando group has applied STM to study the proximity effect of $Bi_{2-x}Sb_xTe_3$ on top of Nb or $PdTe_2$ and the absence of surface superconductivity in Sr-doped Bi_2Te_3 [7].

For characterizing SC/TI interfaces theoretically, the Blügel group applied its novel ab-initio Bogliubov-de Gennes code [8] to Nb/Bi_2Te_3 heterostructures revealing a characteristic broadening of the coherence peaks via state hybridization at the interface [9]. The code is currently extended to include disorder/intermixing at the interface. The Rosch group developed numerical codes for studying Coulomb disorder in proximitized TI nanowires self-consistently including band bending effects.

Pure TI properties have been studied for their later combination with SCs. The Ando group found that the breakdown of the QAH effect in V-doped $Bi_{2-x}Sb_xTe_3$ is caused by the electric field across the sample implying coupling of the opposing edge states via charge puddles [10]. The Plucinski group was involved in identifying a new weak TI exhibiting edge states, namely $Bi_{12}Rh_3Cu_2I_5$ [11]. Close to a



False color SEM image (a) of $Bi_xSb_{2-x}Te_3$ (green) with Pd on top (yellow). Inset: Cross sectional EDX (energy dispersive x-ray spectroscopy) image of Pd distribution obtained by STEM (scanning transmission electron microscopy) showing the Pd diffusion into the $Bi_xSb_{2-x}Te_3$ (BST) layer at the bottom. (b), (c) Shapiro steps across the junction displayed in (a), as a function of microwave power at two frequencies as indicated [5].

Participants:

Yoichi Ando
Stefan Blügel
Sebastian Diehl
Alexander Grüneis
Detlev Grützmacher
Michael Köhl
Corinna Kollath
Grace Lu
Joachim Mayer
Markus Morgenstern
Gregor Mussler
Lukasz Plucinski
Achim Rosch
Thomas Schäpers
Christoph Stampfer
Stefan Tautz
Bert Voigtländer
Martin Weitz

Open Call PIs:

Erwann Bocquillon

topological quantum phase transition, the groups of Rosch and Ando identified a record-large magnetochiral anisotropy (MCA) for $ZrTe_5$ attributed to a torus-shaped Fermi surface with spin texture [12]. The system additionally exhibits a non-linear I(V) characteristic for both magnetic field and current along the same crystallographic axis due to the nodal lines of the material within disorder [13]. For proximitized $Bi_{2-x}Sb_xTe_3$ nanowires, the large MCA of the topological 1D subbands [14] can be used for tuning the nanowire into the Majorana regime.

Towards Majorana modes in proximitized edge states of graphene, the Morgenstern group used STM to map the edge states in the quantum Hall regime [15]. Edge states of quantum Hall systems are also realized for cold Er atoms by the Weitz group [16]. The Stampfer group further developed the stacking process of 2D materials using an automated search procedure for adequate flakes. As an important ingredient for topological tuning, proximity induced spin-orbit coupling into graphene by WSe_2 is verified by a huge spin relaxation anisotropy (factor 80). Towards the new Focus Area B, the group also summarized the potential of 2D materials for quantum computing [17], achieved spin relaxation times in graphene quantum dots of 200 μs [18] and coherent charge oscillations in double quantum dots with $T_2^* = 0.5$ ns [19].

For creating Majorana modes in cold atom systems, the Köhl group pursues the bilayer Hubbard model, recently implementing an additional superlattice for creating the required ladder, layer-distinct chemical potentials and tunable tunneling between the two layers. The groups of Diehl and Rizzi theoretically invented a method to suppress detrimental single particle hopping between the two ladders by Aharonov-Bohm caging [20]. The Kollath group studied the enhancement of the desired pair tunneling via Floquet engineering [21], the stability of Majorana modes in the 1D ladder configuration [22], and probing options of the resulting Majorana modes by radio frequency driving [23].

Addressing the novel Focus Area B, the Weitz group realized quantum Rabi dynamics mapping a cold atom system to fluxonium qubits [24], while the Rosch group studied the efficient preparation of interacting many-particle ground states by noisy intermediate scale quantum computers applying ideas from adiabatic demagnetization [25].

REFERENCES

[1] A R Jalil, P Schüffelgen, H Valencia, M Schleenvoigt, C Ringkamp, G Mussler, M Luysberg, J Mayer, and D Grützmacher, Selective Area Epitaxy of Quasi-1-Dimensional Topological Nanostructures and Networks, Nanomater. 13, 354 (2023)

[2] A Leis, M Schleenvoigt, K Moors, H Soltner, V Cherepanov, P Schüffelgen, G Mussler, D Grützmacher, B Voigtländer, F Lüpke, and F S Tautz, Probing Edge State Conductance in Ultra-Thin Topological Insulator Films, Adv. Quantum Technol. 2200043 (2022)

[3] T W Schmitt, B Frohn, W Wittl, A R Jalil, M Schleenvoigt, E Zimmermann, A Schmidt, T Schäpers, J C Cuevas, A Brinkman, D Grützmacher, and P Schüffelgen, Anomalous temperature dependence of multiple Andreev reflections in a topological insulator Josephson junction, Supercond. Sci. Technol. 36 024002 (2023; published 21 Dec 2022)

[4] T W Schmitt, M R Connolly, M Schleenvoigt, C Liu, O Kennedy, J M Chávez-Garcia, A R Jalil, B Bennemann, S Trellenkamp, F Lentz, E Neumann, T Lindström, S E de Graaf, E Berenschot, N Tas, G Mussler, K D Petersson, D Grützmacher, and P Schüffelgen, Integration of Topological Insulator Josephson Junctions in Superconducting Qubit Circuits, Nano Lett. 22, 2595 (2022)

[5] M Bai, X-K Wei, J Feng, M Luysberg, A Bliesener, G Lippertz, A Uday, AA Taskin, J Mayer, and Y Ando, Novel realization of superconducting topological-insulator nanowires, Commun. Mater. 3, 20 (2022)

[6] M Rößler, D Fan, F Münning, H F Legg, A Bliesener, G Lippertz, A Uday, R Yazdanpanah, J Feng, A A Taskin, and Yoichi Ando, Top-down fabrication of bulk-insulating topological insulator nanowires for quantum devices, arXiv:2302.01209 (2023)

[7] M Bagchi, J Brede, and Y Ando, Observability of superconductivity in Sr-doped Bi_2Se_3 at the surface using scanning tunneling microscope, Phys. Rev. Mat. 6, 034201 (2022, Editors' Suggestion)

[8] P Rüßmann and S Blügel, Density functional Bogoliubov-de Gennes analysis of superconducting Nb and Nb(110) surfaces. PRB 105, 125143 (2022)

[9] P Rüßmann and S Blügel, Proximity induced superconductivity in a topological Insulator, arXiv:2208.14289 (2022)

[10] G Lippertz, A Bliesener, A Uday, L M C Pereira, A A Taskin, and Yoichi Ando, Current-induced breakdown of the quantum anomalous Hall effect, Phys. Rev. B 106, 045419 (2022)

[11] E Carrillo-Aravena, K Finzel, R Ray, M Richter, T Heider, I Cojocariu, D Baranowski, V Feyer, L Plucinski, M Gruschwitz, C Tegenkamp, and M Ruck, $Bi_{12}Rh_3Cu_2I_5$: A 3D Weak Topological Insulator with Monolayer Spacers and Independent Transport Channels, Phys. Status Solidi B 259, 2100447 (2022)

1
FOCUS AREA

[12] Y Wang, H F Legg, T Bömerich, J Park, S Biesenkamp, A A Taskin, M Braden, A Rosch, and Y Ando, Gigantic Magnetochiral Anisotropy in the Topological Semimetal $ZrTe_5$, Phys. Rev. Lett. 128, 176602 (2022)

[13] Y Wang, T Bömerich, J Park, H F Legg, A A Taskin, A Rosch, and Y Ando, Nonlinear transport due to magnetic-field-induced flat bands in the nodal-line semimetal $ZrTe_5$, arXiv:2208.10314 (2022)

[14] H F Legg, M Rößler, F Münning, D Fan, O Breunig, A Bliesener, G Lippertz, A Uday, A A Taskin, D Loss, J Klinovaja, and Y Ando, Giant magnetochiral anisotropy from quantum confined surface states of topological insulator nanowires, Nat. Nanotechnol. 17, 696 (2022)

[15] T Johnsen, C Schattauer, S Samaddar, A Weston, M Hamer, R Gorbachev, F Libisch, and M Morgenstern, Mapping quantum Hall edge states in graphene by scanning tunneling microscopy, Phys. Rev. B 107, 115426 (2023, Editors suggestion), first made public as arXiv:2210.01831

[16] R Röll, A Laskar, F Huybrechts, and M Weitz, Chiral edge dynamics of cold erbium atoms in the lowest Landau level of a synthetic quantum Hall system, Phys. Rev. A 107, 043302 (2023), first made public as arXiv:2210.09874

[17] M C Lemme, D Akinwande, C Huyghebaert, and C Stampfer, 2D Materials for Future Heterogeneous Electronics, Nat. Commun. 13, 1392 (2022)

[18] L Banszerus, K Hecker, S Möller, E Icking, K Watanabe, T Taniguchi, C Volk, and C Stampfer, Spin relaxation in a single-electron graphene quantum dot, Nat. Commun. 13, 3637 (2022)

[19] K Hecker, L Banszerus, A Schäpers, S Möller, A Peters, E Icking, K Watanabe, T Taniguchi, C Volk, and C Stampfer, Coherent Charge Oscillations in a Bilayer Graphene Double Quantum Dot, arXiv:2303.10119 (2023)

[20] N Tausendpfund, S Diehl, and M Rizzi, Majorana zero modes in fermionic wires coupled by Aharonov-Bohm cages, Phys. Rev. B 107, 035124 (2023), first made public as arXiv:2208.09382

[21] F Hübner, C Dauer, S Eggert, C Kollath, and A Sheikhan, Floquet-engineered pair and single particle filter in the Fermi Hubbard model, Phys. Rev. A 106, 043303 (2022)

[22] F T Lisandrini and C Kollath, Majorana edge-modes in a spinful particle conserving model, Phys. Rev. B 106, 245121 (2022)

[23] J Kombe, M Köhl, C Kollath, and J-S Bernier, Radiofrequency driving of an attractive Fermi gas in a one-dimensional optical lattice, Phys. Rev. A 105, 023330 (2022)

[24] J Koch, G Hunanyan, T Ockenfels, E Rico, E Solano, and M Weitz, Quantum Rabi dynamics of trapped atoms far in the deep strong coupling regime, Nat. Commun. 14, 954 (2023), first made public as arXiv:2112.12488

[25] A Matthies, M Rudner, A Rosch, and Erez Berg, Programmable adiabatic demagnetization for systems with trivial and topological excitations, arXiv:2210.17256 (2022)

INTEGRATION OF TOPOLOGICAL INSULATOR JOSEPHSON JUNCTIONS IN SUPERCONDUCTING QUBIT CIRCUITS

BY T W SCHMITT, M R CONNOLLY, M SCHLEENVOIGT, C LIU, O KENNEDY, J M CHÁVEZ-GARCIA, A R JALIL, B BENNEMANN, S TRELLENKAMP, F LENTZ, E NEUMANN, T LINDSTRÖM, S E DE GRAAF, E BERENSCHOT, N TAS, G MUSSLER, K D PETERSSON, D GRÜTZMACHER, AND P SCHÜFFELGEN
NANO LETT. 22, 2595 (2022)

1
FOCUS AREA

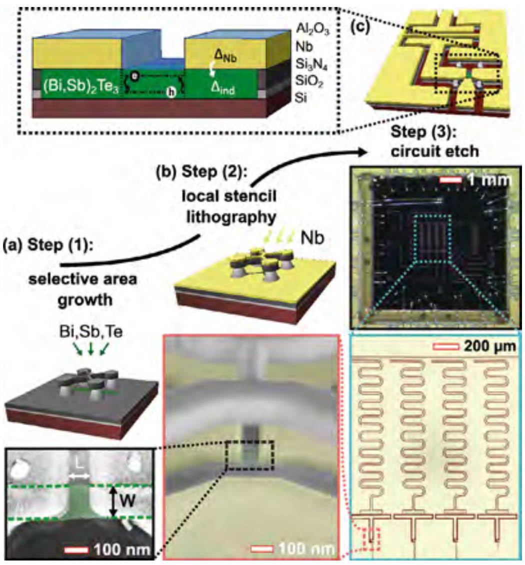
In this publication, we successfully integrated a topological insulator nanoribbon into a conventional superconducting transmon qubit. In our experiment, the topological insulator acts as the weak-link that connects the transmon island to the ground plane. Due to the sensitivity of $(Bi,Sb)_2Te_3$ topological insulators to air exposure, the integration of these materials into superconducting quantum circuits has been a challenge.

We overcame this obstacle by fabricating parts of the qubit in ultra-high vacuum and protecting the topological insulator with an *in situ* capping layer before exposure to ambient conditions. In this process, topological, superconductive and dielectric materials were deposited via molecular beam epitaxy. This technique is known for the growth of highly crystalline planar thin films. In our study, however, we used different hard masks for selective area epitaxy and stencil lithography, which allowed us to structure the different materials already in the ultra-high vacuum into devices.

On the resulting quantum chip, we showed for the first time qubit control and temporal coherence of such a topological-insulator-based transmon qubit. The demonstrated compatibility of topological insulators with superconducting qubits and circuits paves the way for integrating more complex networks of topological materials into arbitrary qubit architectures. These architectures offer the potential to realize novel types of qubits, including highly sought-after topological qubits.

Additionally, hybrid devices, as the one demonstrated, provide new experimental platforms for testing topological materials in sensitive quantum circuits and for searching for signatures of elusive topological quasiparticles.

> **For the first time, we integrated a topological insulator into a superconducting qubit. The integration was performed under ultra-high vacuum conditions, to account for the sensitivity of $(Bi,Sb)_2Te_3$ topological insulators to air exposure.**
>
> PETER SCHÜFFELGEN



The figure shows the technique to integrate a topological insulator (TI) Josephson junction into a superconducting quantum circuit without exposing the delicate TI surface to air by using two different hard masks. Step (1): A thin global mask with a narrow trench allows to grow a $(Bi,Sb)_2Te_3$ TI nanoribbon selectively in the defined trench under ultra-high vacuum conditions. Step (2): The second mask, which is located right above the narrow trenches, shadows a part of the $(Bi,Sb)_2Te_3$ nanoribbon during a subsequent deposition of superconductive Nb. It thus allows to form a S-TI-S Josephson junction without breaking the vacuum. After passivating the sample with a thin Al_2O_3 layer, all sensitive surfaces are protected, and the chip can be exposed to ambient conditions. Step (3): Finally, the microwave circuitry for the qubits is patterned around the junction with conventional fabrication techniques.

On pages 22 and 23, members of the author team are featured in front of a 3D model of the S-TI-S Josephson junction described above.

TRIVIA

10

PIXEL LINES

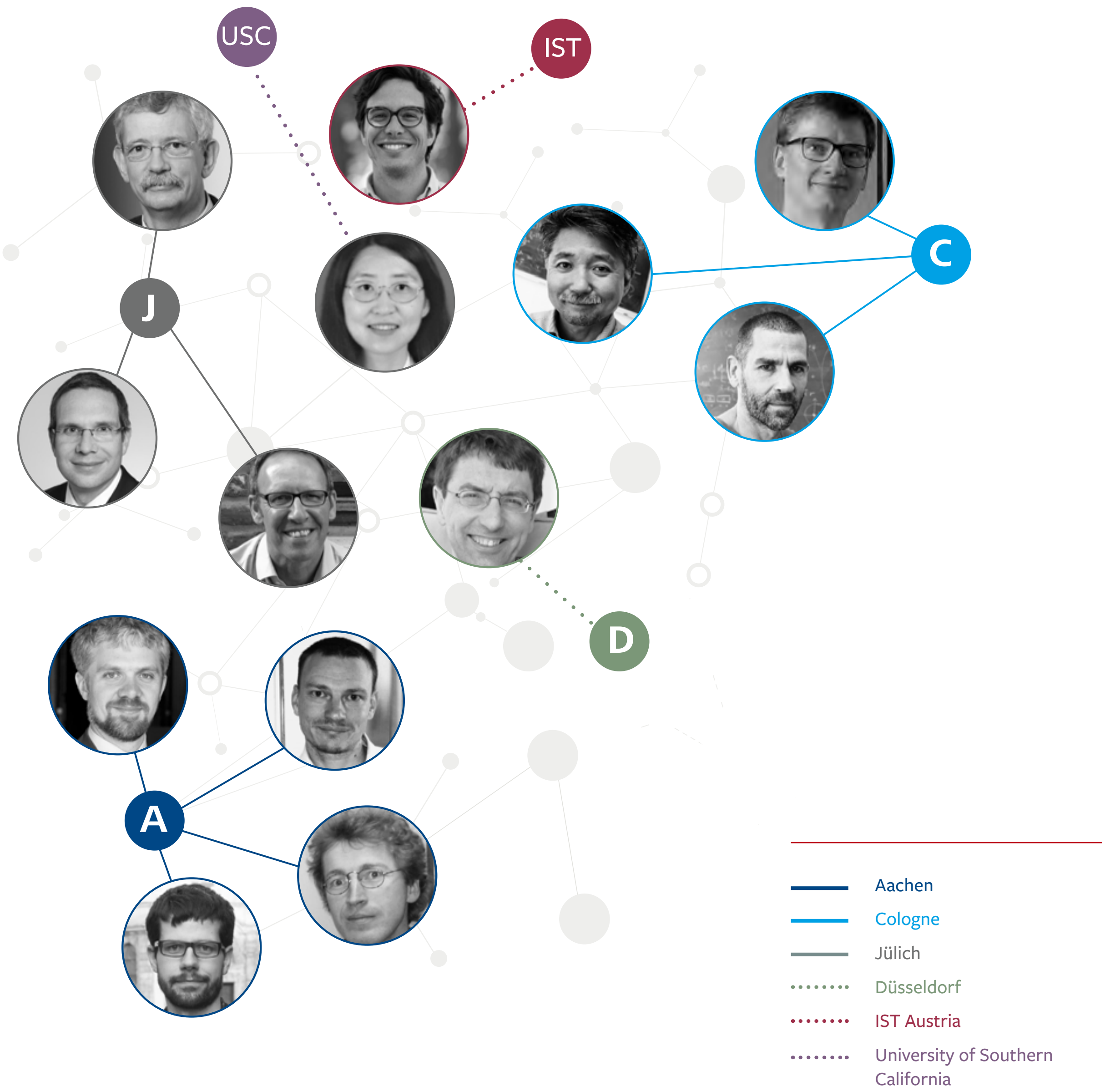
Number of pixel lines in a large color-coded measurement plot that led the researchers to the observation of Rabi oscillations of the topological insulator based transmon qubit.

IN THE SPOTLIGHT

Benjamin Bennemann is a highly engaged technician at PGI-9. He led the construction of the Nanocluster and has kept it operational and in very good shape ever since. In our study, he deposited the superconducting and dielectric materials. By steadily moving the substrate holder (by hand!) throughout the entire deposition of superconductors, he decreased the length of the Josephson junctions on purpose and thereby placed the qubit right into the transmon regime @ 6.3 GHz.

FOCUS AREA 2

MAJORANA QUBITS



In *Focus Area 2*, 15 groups including collaborating teams at HHU Düsseldorf, IST Austria and University of Southern California are joining efforts to explore viable ways to utilize Majorana states as carriers of quantum information. Employing the materials basis developed in *Focus Area 1*, this area aims at building Majorana qubits and devising concepts for implementing error-correcting codes, mainly using topological insulators. Prime objectives include the development of the necessary hardware for Majorana qubits, the initialization and readout of the fermion parity, and the verification of the qubit functionality.

Advanced error-correcting designs on a specific Majorana qubit setting will be theoretically explored and experimentally tested, which bridges topological qubits to *Focus Area 3*. The developed Majorana qubits will later be used in *Focus Area 4* for establishing strong coupling to microwave photons, which can subsequently be used for various quantum connections.

FOCUS AREA 2

MAJORANA QUBITS

2
FOCUS AREA

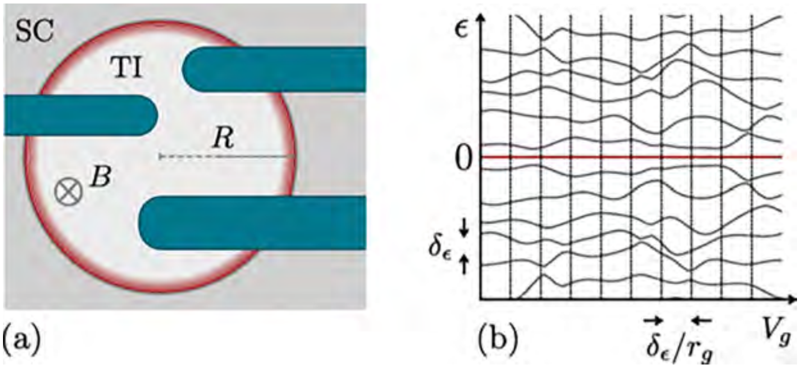
ACHIEVEMENTS

The groups of Egger [1-7] and Hassler [9-11] have theoretically investigated signatures of Majorana zero modes that are relatively easy to measure and provide a high level of confidence. They studied the heat transport through a Majorana island where different Majorana states were contacted by different lead electrodes held at unequal temperatures. The researchers found a universal violation of the Wiedemann-Franz law caused by the presence of Majorana states [1,2]. These heat transport experiments can provide better evidence for Majoranas than simple zero-bias peaks in transport spectroscopy. Additionally, they proposed detection schemes for parafermions and showed that their exotic properties (as compared to Majoranas) could already be detected in simple transport experiments [5].

Furthermore, in collaboration with the Altland group, they have outlined a statistical detection protocol that could provide unambiguous evidence for Majorana bound states from sequences of conventional tunnel spectroscopy data [8]. The protocol can be applied to any Majorana platform. Tunnel spectroscopy data for detecting Majorana states is often criticized for its susceptibility to misinterpretation of genuine Majorana states with low-lying Andreev bound states. To address this issue, the researchers suggested a protocol that extends single-shot measurements to sequences performed at varying system parameters, which requires only moderate effort for current experimental platforms [see figure]. They demonstrated how such sampling resolves the statistics of Andreev side lobes, providing compelling evidence for the presence or absence of a Majorana center peak. The Schäpers group extended their studies of topological-insulator-nanoribbon networks under applied magnetic fields and gate controls. Such a system will be an essential ingredient of future Majorana-based quantum computers and the understanding of its normal-state magnetotransport properties forms a basis for manipulating Majorana zero modes. By measuring the magnetoconductance under magnetic-field rotation and changing gate voltages, they were able to identify the roles of topological surface states [12].

In the Ando group, following the successful demonstration of magnetic-field resilience of aluminum-based 3D transmon qubits [13; see paper highlight on pages 36/37], they went on to measure the parity life-time of such transmons in magnetic fields. By doing so, they established the protocol to detect the charge parity in a transmon qubit, which is a crucial technology for the read out of a transmon-based Majorana qubit. Using this protocol, they were able to measure the magnetic-field dependence of the parity life-time. As a byproduct of these efforts, the Ando group discovered a significant deviation of the qubit-level spectrum from the standard transmon model, which points to the importance of higher harmonics in the Josephson current-phase relation. Together with other leading groups in the field of superconducting qubits, a joint paper to compare various high-performance transmons to demonstrate the ubiquitous prominence of the higher harmonics was written (arXiv:2302.09192).

To realize Majorana zero modes in a non-nanowire platform, the Ando group is working on topological-insulator-based Josephson junction devices with tunnel probes made on the junction area. By controlling the phase bias across the junction, they were able to detect a gap closing phenomenon as a function of phase, which can be interpreted to signify the appearance of Majorana bound states. In collaboration with the Hassler group, theoretical understanding of this system is being developed.



Statistical spectroscopy setup. Left: A vortex is defined by a TI coated with an s-wave superconductor (SC) except for a region of radius *R* which is threaded by ν magnetic flux quanta. Electrostatic finger gates effectively change the disorder configuration. Red lines indicate spatial support of a Majorana edge mode. Right: In-gap spectrum vs gate voltage V_g obtained by simulating the setup in (a). By varying V_g, Andreev state energy levels change on a scale set by the level spacing δ_ε . Sequences of independent disorder realizations are separated by $\delta V_g \approx \delta_\varepsilon / r_g$ as marked by the vertical lines.

Participants:

Alexander Altland
Yoichi Ando
Hendrik Bluhm
Reinhold Egger
Johannes Fink
Detlev Grützmacher
Fabian Hassler
Grace Lu
Markus Morgenstern
Gregor Mussler
Thomas Schäpers
Christoph Stampfer

REFERENCES

[1] D Giuliano, A Nava, R Egger, P Sodano, and F Buccheri, Multi-particle scattering and breakdown of the Wiedemann-Franz law at a junction of N interacting quantum wires, Phys. Rev. B 105, 035419 (2022)

[2] F Buccheri, A Nava, R Egger, P Sodano, and D Giuliano, Violation of the Wiedemann-Franz law in the topological Kondo model, Phys. Rev. B 105, L081403 (2022)

[3] F Buccheri, A De Martino, R G Pereira, P W Brouwer, and R Egger, Phonon-limited transport and Fermi arc lifetime in Weyl semimetals, Phys. Rev. B 105, 085410 (2022)

[4] F Buccheri, R Egger, and A De Martino, Transport, refraction, and interface arcs in junctions of Weyl semimetals, Phys. Rev. B 106, 045413 (2022)

[5] I B Nielsen, K Flensberg, R Egger, and M Burrello, Readout of parafermionic states by transport measurements, Phys. Rev. Lett. 129, 037703 (2022)

[6] N Ackermann, A Zazunov, S Park, R Egger, and A L Yeyati, Dynamical parity selection in superconducting weak links, preprint arXiv:2207.05782

[7] T Bauer, L R D Freitas, R G Pereira, and R Egger, Tunneling spectroscopy of Majorana zero modes in a Kitaev spin liquid, Phys. Rev. B 107, 054432 (2023, Editors' Suggestion), first made public as arXiv:2209.12930

[8] A Ziesen, A Altland, R Egger, and F Hassler, Statistical Majorana bound state spectroscopy, Phys. Rev. Lett. 130, 106001 (2023), first made public as arXiv:2211.15296

[9] J Wouters, F Hassler, H Katsura, and D Schuricht, Phase diagram of an extended parafermion chain, SciPost Phys. Core 5, 008 (2022)

[10] S Franca, F Hassler, and I C Fulga, Topological reflection matrix, Phys. Rev. B 105, 155121 (2022)

[11] S Franca, V Könye, F Hassler, J van den Brink, and I C Fulga, Non-Hermitian physics without gain or loss: the skin effect of reflected waves, Phys. Rev. Lett. 129, 086601 (2022)

[12] D Rosenbach, K Moors, A R Jalil, J Kölzer, E Zimmermann, J Schubert, S Karimzadah, G Mussler, P Schüffelgen, D Grützmacher, H Lüth, T Schäpers, Gate-induced decoupling of surface and bulk state properties in selectively-deposited Bi2Te3 nanoribbons, SciPost Phys. Core, 5, 17 (2022)

[13] J Krause, C Dickel, E Vaal, M Vielmetter, J Feng, R Bounds, G Catelani, J M Fink, and Y Ando, Magnetic field resilience of 3D transmons with thin-film Al/AlO_x/Al Josephson junctions approaching 1 T, Phys. Rev. Applied 17 (2022) 034032

REAPPEARANCE OF FIRST SHAPIRO STEP IN NARROW TOPOLOGICAL JOSEPHSON JUNCTIONS

BY J KRAUSE, C DICKEL, E VAAL, M VIELMETTER, J FENG, R BOUNDS, G CATELANI, J M FINK, AND Y ANDO,
MAGNETIC FIELD RESILIENCE OF 3D TRANSMONS WITH THIN-FILM AL/ALO$_x$/AL JOSEPHSON JUNCTIONS APPROACHING 1 T
PHYS. REV. APPLIED 17 (2022) 034032

2
FOCUS AREA

Superconducting circuits are a leading platform for quantum computing, but they can also be highly sensitive quantum sensors: they can resolve on-chip flux noise as well as the dynamics of single electrons in the system. Making them resilient to large magnetic fields adds an additional experimental control knob to study the field dependence of flux noise and quasiparticle dynamics. Additionally, it enables hybrid quantum computing architectures involving spin or topological qubits and electromechanical elements.

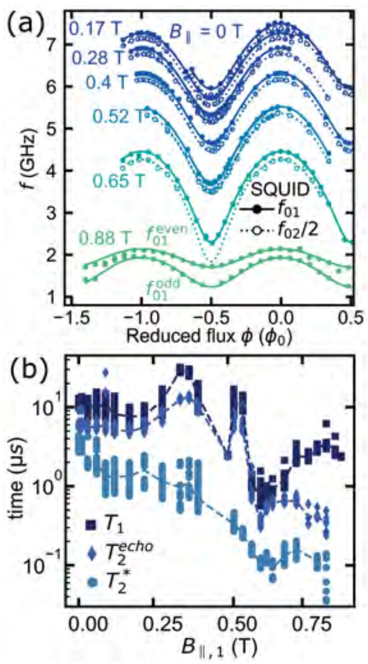
The workhorse building block of superconducting circuits are Josephson junctions formed by a sandwich structure of two superconducting aluminum layers, separated by an insulating aluminum-oxide layer. In its superconducting state, the junction acts like a non-linear inductance with very low dissipation. However, in bulk aluminum superconductivity already breaks in small magnetic fields of around 10 mT. Yet, by reducing the aluminum layer thicknesses to 10 and 18 nm, we were able to operate transmon qubits – a circuit made of a junction shunted by a capacitor – in parallel magnetic fields up to 1 T.

The transmons are placed in a 3D copper cavity resonator, which acts as a readout circuit of the transmon state and is unaffected by the magnetic fields. We investigate the effect of the magnetic field on the spectrum and coherence times of two transmons. The transmon frequencies decrease with increasing field, due to suppression of the superconducting gap and a geometric Fraunhofer-like contribution. Nevertheless, the thin-film transmons show strong magnetic field resilience: both transmons display microsecond coherence up to at least 0.65 T, and the qubit lifetime T1 remains above 1 µs over the entire measurable range.

We conclude that thin-film aluminum Josephson junctions are suitable hardware for superconducting circuits in the high-magnetic-field regime.

“Previously, the operation of aluminum transmon circuits was considered to be incompatible with magnetic fields. In our work, we show that with simple design choices conventional aluminum transmons are in effect very resilient even to large magnetic fields, outperforming alternative devices involving semiconductor nanowires or graphene.

JONAS KRAUSE



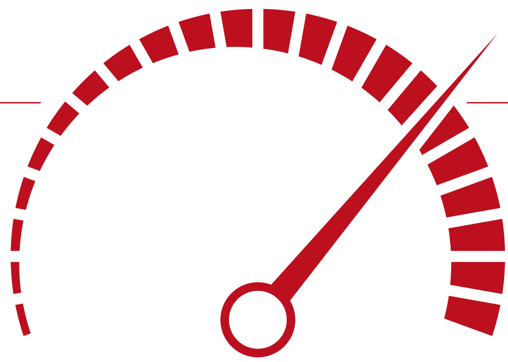
(a) Transmon qubit frequency as a function of flux through the SQUID loop at different in-plane magnetic fields. The qubit frequency is reduced by the in-plane magnetic field because of a combination of the suppression of the superconducting gap and a Fraunhofer suppression of the critical current. For the highest field, the qubit frequency is so low that the splitting due to quasiparticle parity is visible on this scale.

(b) Maximum qubit coherence extracted at each magnetic field. Generally, the coherence can strongly fluctuate with the magnetic field; millitesla out-of-plane fields can strongly suppress T1. We have used our vector magnet to find the optimum at each in-plane field. In the missing region roughly between 0.4mT and 0.5mT the SQUID flux is very jumpy and the qubit coherence is suppressed for reasons we do not yet understand.

TRIVIA

12023

MEASUREMENTS



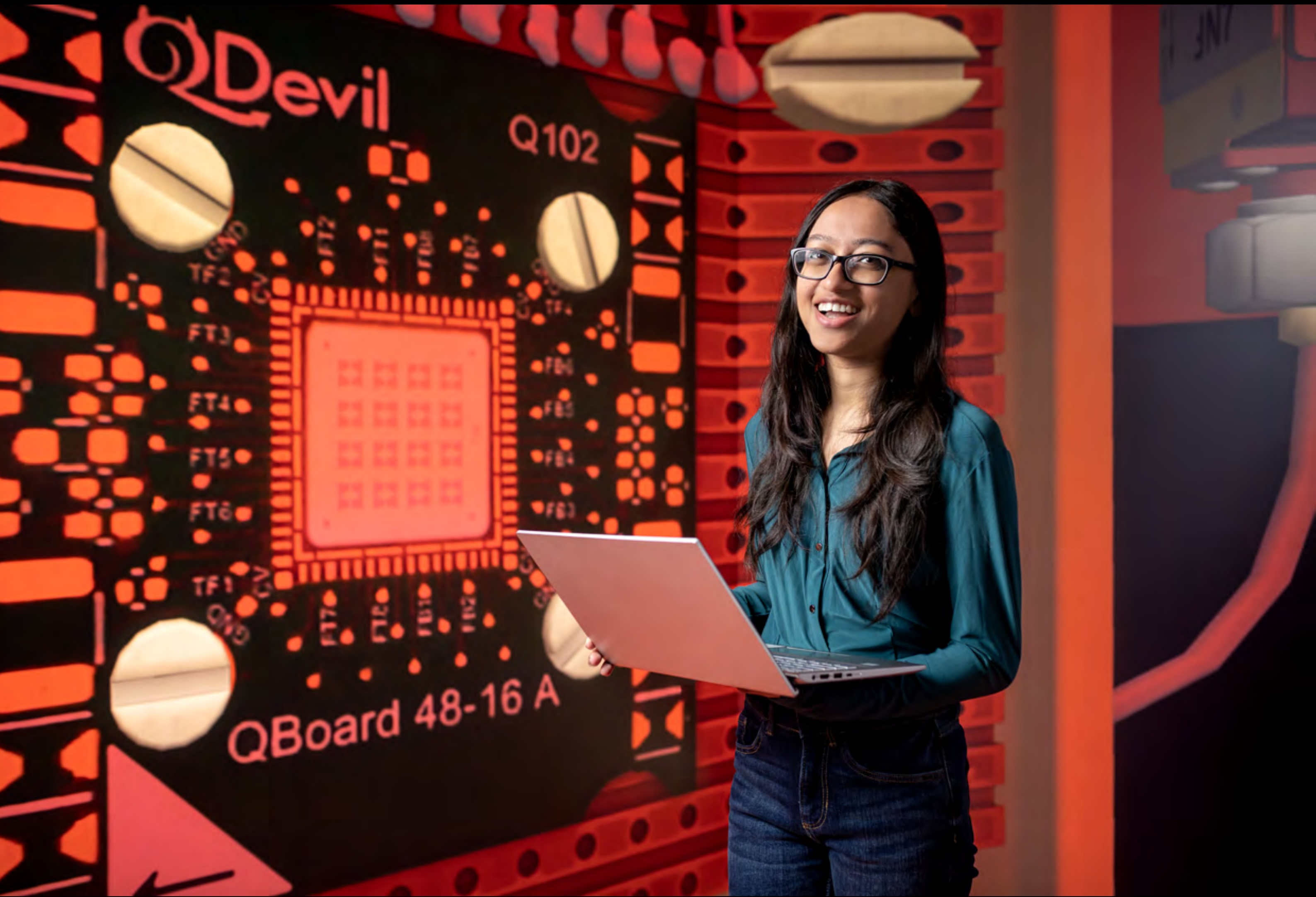
Number of T1 measurements we took in the course of the measurements for the paper. They were taken at different in-plane and out-of-plane magnetic fields for the two transmons.

THE TEAM

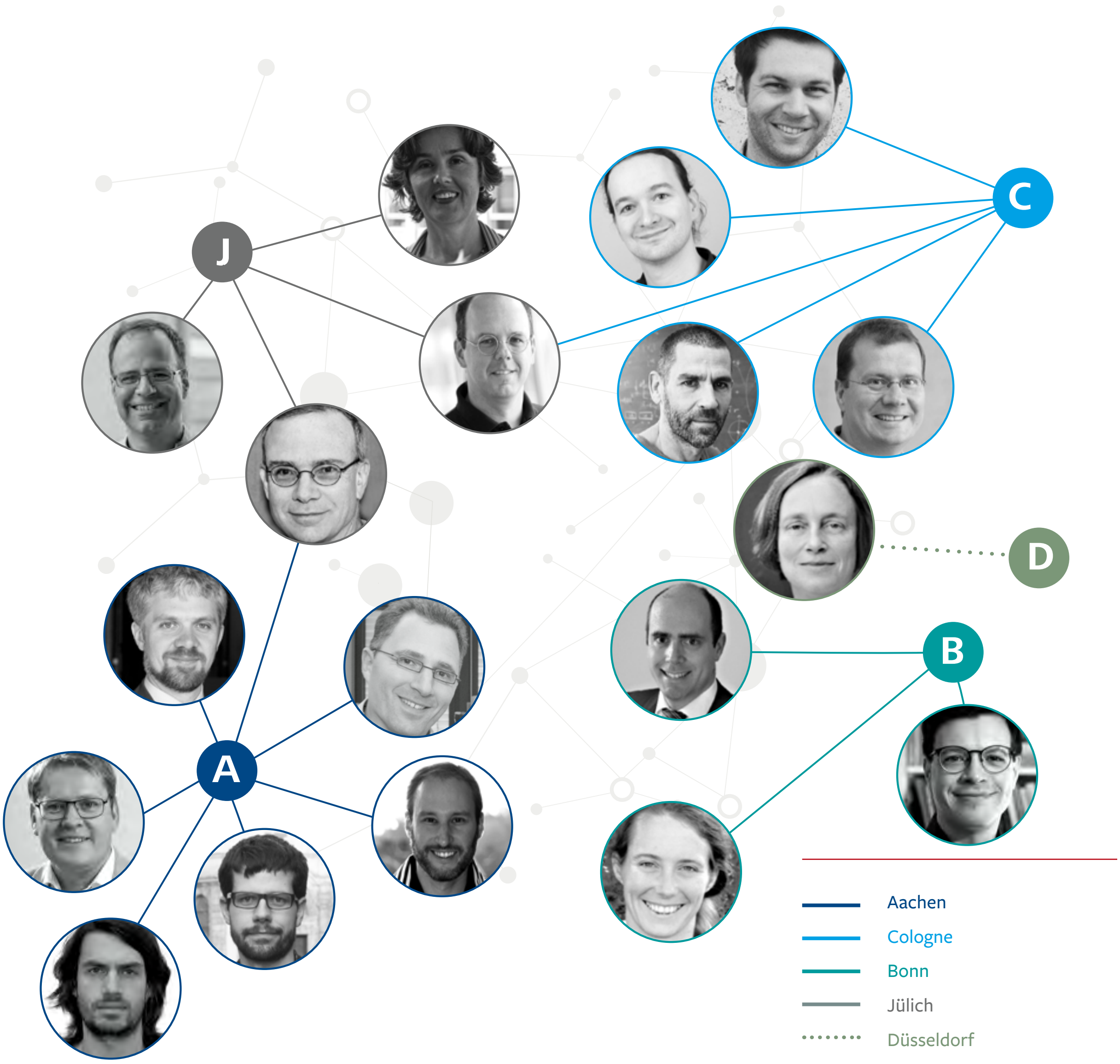
Coming from superconducting labs at TU Delft and ETH Zürich, **Christian Dickel** and **Jonas Krause** largely started the circuit quantum electrodynamics experiments in the Ando lab together. This involved ordering new equipment, wiring dilution refrigerators and setting up a code base for performing qubit experiments.

The goal is to eventually use methods from conventional superconducting qubits to show a more peculiar topological qubit based on Majorana zero modes. You can find both not only on the arXiv but also on Spotify – Chris with the ML4Q&A podcast and Jonas with his band Rasga Rasga.

FOCUS AREA 3



DECOHERENCE, MEASUREMENTS, AND ERROR CORRECTION



Fully characterizing quantum decoherence and combatting it with the techniques of quantum error correction are essential for quantum technologies and for constructing a quantum computer.

In *Focus Area 3*, 18 groups are teaming up in three different projects to tackle these partially understood phenomena by harnessing topological matter and quantum devices under real-world noise conditions and using suitably engineered dissipative processes and extended error correction schemes to control them.

Carefully chosen experiments will put the theories developed here to the test. In particular, the Focus Area explores the dissipative preparation of topological states of ultracold atomic fermions and implements electron shuttling in spin-qubit arrays to ultimately construct a minimal realization of a topological surface code. Developed theories shall also be applied to the physical platforms designed in the other Focus Areas.

FOCUS AREA 3

DECOHERENCE, MEASUREMENTS, AND ERROR CORRECTION

3
FOCUS AREA

ACHIEVEMENTS

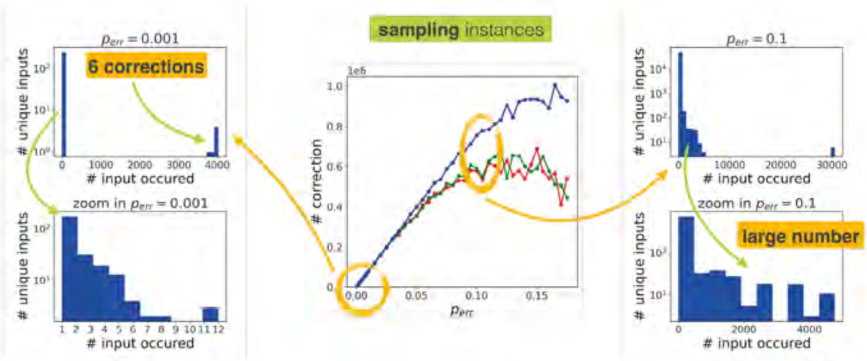
A Cologne-Aachen-Düsseldorf collaboration has theoretically analyzed the statistical properties of Andreev bound states in disordered Majorana quantum devices. Focusing on the TI vortex platform as a paradigmatic example, it is demonstrated that the statistical distribution of these states for different device configurations (realized, e.g. by variation of side gates) contains compelling evidence for the presence or absence of Majorana bound states [1].

The Diehl group has also addressed measurement induced phase transitions. In [2] measurement induced phase transitions in fermion systems are studied with long-range hopping, revealing analytically and numerically a new phase with subalgebraic entanglement scaling. In [3], the measurement induced phase transition is studied under the powerful assumption of chaoticity of the Hamilton dynamics. Kollath has continued work in collaboration with Rosch on the strong quantum-light quantum matter couplings as this is an important building block for quantum technological devices [4]. Current work extends these studies to fermionic atoms coupled to optical cavities. In order to apply the method previously proposed in a work with the Rosch group, it is studied whether the ionic Hubbard model is integrable or chaotic [5]. The new group of Luitz has used a novel Quantum Monte Carlo technique, showing that an ohmic bath coupled to a spin chain can induce long range order, which is not possible without the bath due to the Mermin-Wagner theorem [6].

Significant progress has also been achieved in the area of error correction and related control problems for quantum computation. The Trebst group has reached an important milestone in further analyzing the performance of our previously introduced machine learning-assisted decoder, which delivers on (i) fast real-life decoding times already for small error rates, (ii) improved error thresholds (by resolving correlated errors), and (iii) algorithmic scaling to tens of thousands of qubits. A much better understanding is now achieved of how to assign different error regimes to different level of our hierarchical decoder layout [see figure; unpublished]. Rotated surface code geometries with open boundary conditions are explored as they are implemented in actual device geometries (as opposed to periodic boundary conditions as assumed in initial, more conceptually driven work).

The Gross and Bluhm groups have a new result on calibration of gate sets [7]. The work is part of the first author's (Yaiza Aragonés-Soria) PhD thesis, which has since been successfully defended. On NISQ algorithms, Gross has developed [8] a new method that speeds up the optimization in variational quantum eigensolvers by using symmetry-adapted circuits. The Bruss group has shown that, if one is only interested in information about the channel that is actually relevant for quantum error correction, estimation from syndrome data is possible under weak conditions [9]. Essentially, estimation from syndrome data is possible if error correction itself is possible. The Müller group continued in the area of fault-tolerant quantum error correction (QEC). Currently, efforts are worldwide underway to operate the first low-distance logical qubits in the regime of beneficial QEC. In collaboration with experimental colleagues at the University of Innsbruck, Austria, it was demonstrated for the first time [10] a fault-tolerant universal set of gates on two logical qubits in a trapped-ion quantum computer, using the recently introduced paradigm of flag fault tolerance.

In experimental work on error-corrected archi-tectures, the Aachen groups have collaborated on different approaches to reduce the effect of band tailing with an



Error regimes and hierarchical decoding. The middle panel shows the number of different error corrections applied to 10,000 randomly generated error instances for a given error rate. The number of disctinct error corrections varies strongly, with only six corrections being routinely applied for error rate p_{err} = 0.001 (left panels), while a few thousand distinct correction moves are applied for an error rate p_{err} = 0.1 (right panels).

interface engineering ansatz, strongly improving the switching behavior of the transistors with record steep inverse subthreshold slopes of ~2mV/dec [11]. The Bluhm/Schreiber group have extended the previous distance for single electron shuttling by two orders of magnitude from 720 nm to 20 μm distance [12; see paper highlight on pages 42/43]. For this demonstration, the 10 μm long QuBus was used, and shuttling occurred in our developed conveyor mode a single charge across the full device and back. At all shuttle distances, the shuttling fidelity was at least 99 %.

Participants:

Alexander Altland
Mario Berta
Hendrik Bluhm
Dagmar Bruss
Tommaso Calarco
Sebastian Diehl
David DiVincenzo
David Gross
Fabian Hassler
Joachim Knoch
Michael Köhl
Corinna Kollath
David Luitz
Lars Schreiber
Barbara Terhal
Simon Trebst

Open Call PIs:

Markus Müller

REFERENCES

[1] A Ziesen, A Altland, R Egger, and F Hassler, Statistical Majorana bound state spectroscopy, arXiv:2211.15296

[2] T Müller, S Diehl, and M Buchhold, Measurement-induced dark state phase transitions in long-ranged fermion systems, Phys. Rev. Lett. 128, 010605 (2022, Editors' Suggestion, featured in Physics)

[3] A Altland, [...] and T Micklitz, Dynamics of measured many-body quantum chaotic systems, Phys. Rev. Research 4, L022066 (2022)

[4] C-M Halati, A Sheikhan, and C Kollath, Breaking strong symmetries in dissipative quantum systems: the (non-)interacting bosonic chain coupled to a cavity, Phys. Rev. Research 4, L012015 (2022)

[5] J De Marco, L Tolle, C-M Halati, A Sheikhan, A M Läuchli, and C Kollath, Level statistics of the one-dimensional ionic Hubbard model, Phys. Rev. Research 4, 033119 (2022)

[6] M Weber, D J Luitz, and F F Assaad, Dissipation-Induced Order: The $S=1/2$ Quantum Spin Chain Coupled to an Ohmic Bath, Physical Review Letters 129, 056402 (2022)

[7] Y Aragonés-Soria, R Otten, T Hangleiter, P Cerfontaine, and David Gross, Minimising statistical errors in calibration of quantum-gate sets, arXiv:2206.03417 (2022)

[8] T Hubregtsen, D Wierichs, E Gil-Fuster, P-J H S Derks, P K Faehrmann, and J J Meyer, Training Quantum Embedding Kernels on Near-Term Quantum Computers, Phys. Rev. A 106, 042431 (2022)

[9] T Wagner, [...] and M Kliesch, Learning logical quantum noise in quantum error correction , arXiv:2209.09267 (2022)

[10] L Postler, S Heussen, I Pogorelov, M Rispler, T Feldker, M Meth, C D Marciniak, R Stricker, M Ringbauer, R Blatt, P Schindler, M Müller, and T Monz, Demonstration of fault-tolerant universal quantum gate operations, Nature 605, pages 675-680 (2022)

[11] B Richstein, Y Han, Q Zhao, L Hellmich, J Klos, S Scholz, L R Schreiber, and J Knoch, Interface Engineering for Steep Slope Cryogenic MOSFETs, IEEE Electron Device Letters 43, 2149 (2022)

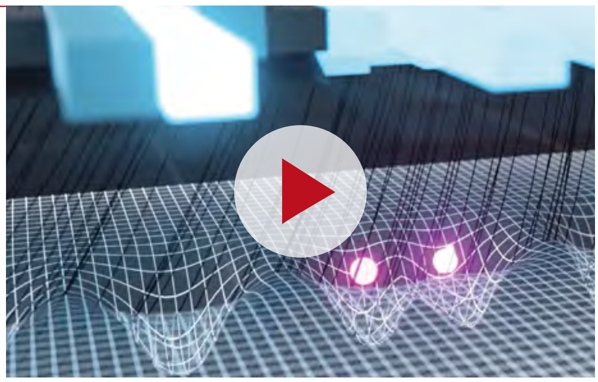
[12] I Seidler, T Struck, R Xue, N Focke, S Trellenkamp, H Bluhm, L R Schreiber, Conveyor-mode single-electron shuttling in Si/SiGe for a scalable quantum computing architecture, npj quantum information 8 :100 (2022)

CONVEYOR-MODE SINGLE-ELECTRON SHUTTLING IN Si/SiGe FOR A SCALABLE QUANTUM COMPUTING ARCHITECTURE

I SEIDLER, T STRUCK, R XUE, N FOCKE, S TRELLENKAMP, H BLUHM, L R SCHREIBER
NPJ QUANTUM INFORMATION 8 :100 (2022)

A key challenge in the scale-up of semiconductor spin qubits is how to get all the connections and electronics to the qubits. This is particularly relevant for semiconductor spin qubits since these qubits are quite dense, an advantage in general, but results in the problem of how to rout the connections. For this, a medium range (order of 10μm) interconnect is needed. This would couple qubits over some distance, resulting in more space for connections and electronics in between. Our proposal for this interconnect is based on creating a sinusoidal potential along a 1D channel. By changing voltages on the metallic gates that create this potential, we can create a moving potential that the electron can 'ride' in, being moved a bit as if in a conveyor, which is why we call it conveyor mode shuttling. In our research, we demonstrate first work towards this interconnect which we call the Quantum Bus or QuBus. In particular, we shuttle an electron over a distance of 420 nm in a device similar to the longer range interconnect.

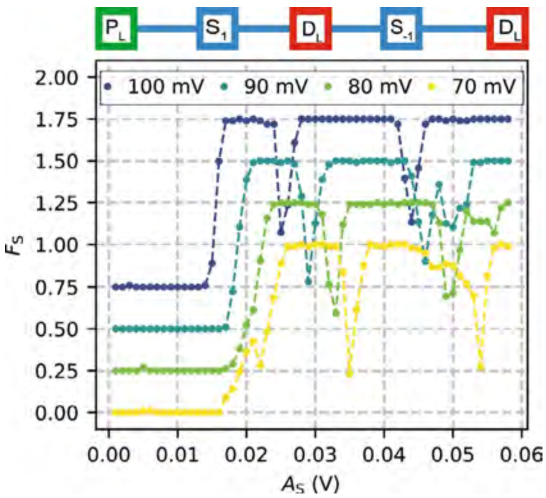
Watch the Quantera Si-QuBus Video



"

Through our proof-of-principle, we've pioneered a path to scalable quantum computation, demonstrating high-fidelity, efficient electron charge shuttling in a Si/SiGe quantum-channel.

TOM STRUCK



This figure shows how accurately we can move an electron between two points using different control settings. We adjust the strength of the movement (shuttling amplitude) and the difference in voltage between the two control gates. The schematic on the top shows the sequence of operations. We prepare an electron on the left, move the electron from the left side to the right, detect if an electron is close to the left detector, shuttle the electron back again and check if it was successfully transported by detecting again if an electron is close to the left sensor. The success rate of this movement is shown for various control settings. A successful movement is when the electron isn't detected in the middle, but only when it returns to the start.

TRIVIA

23659

NUMBER OF DATA FILES CAPTURED

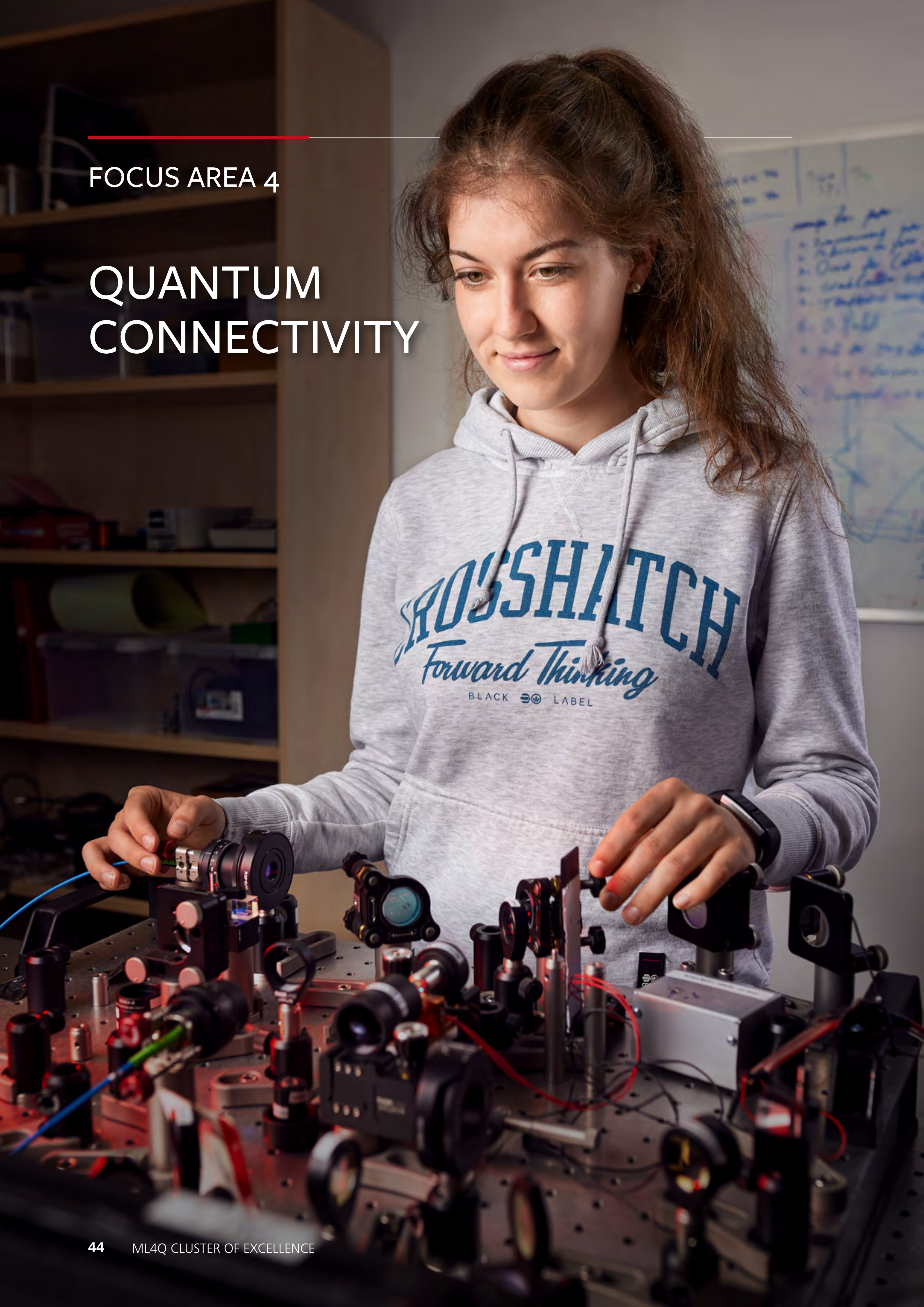
THE TEAM

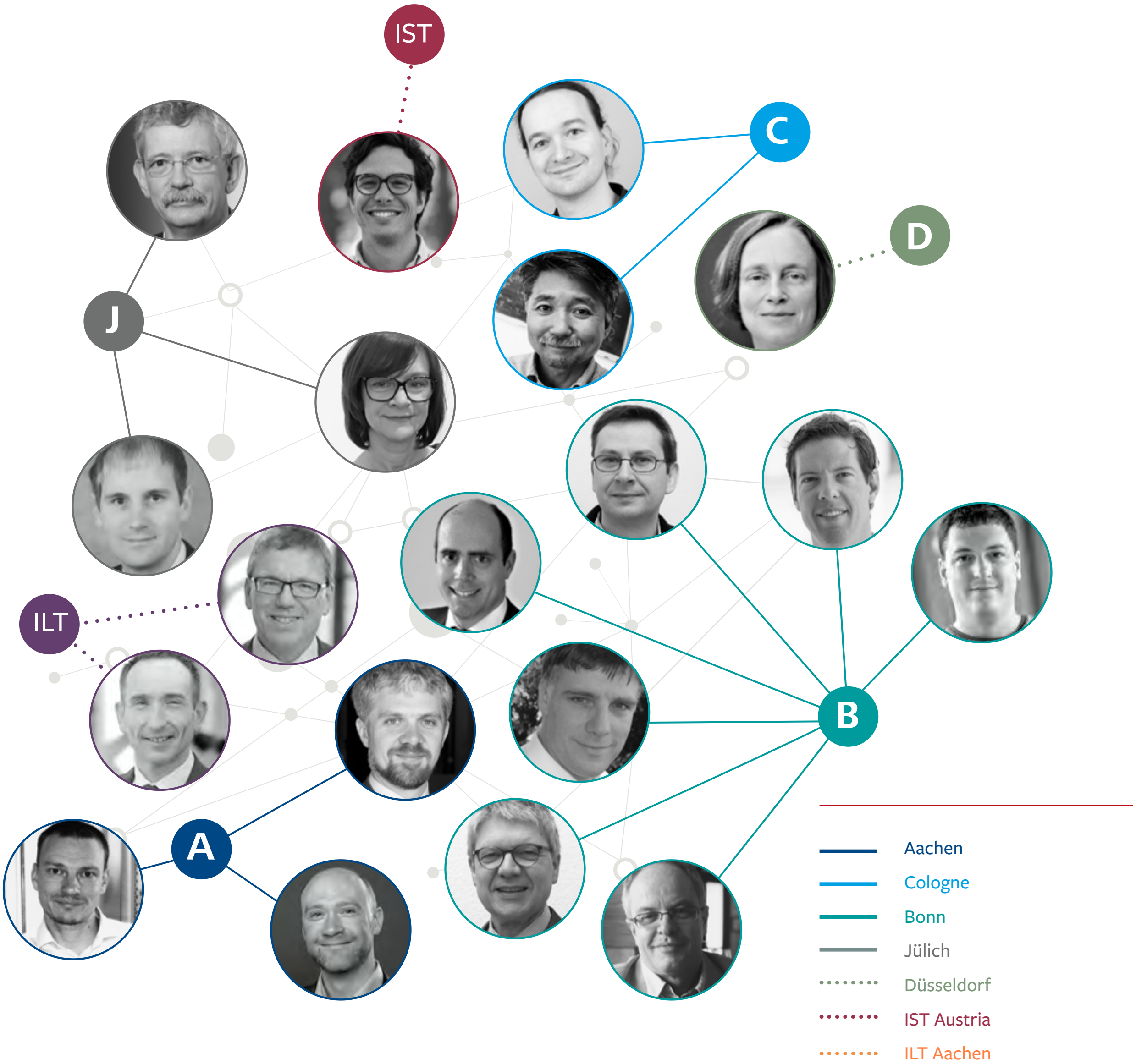
Inga Seidler is PhD researcher in her 5th year at the time. The focus of her research was the developement of fabrication processes for the QuBus device, including the one measured for this work. She performed the measurements and analysis together with Tom Struck.

Tom Struck was in the 4th year of his PhD project at the time of publishing. The focus of his research is on the operation of quantum devices, including qubit operation and electron shuttling. He performed the measurements and analysis together with Inga Seidler and contributed to the hardware and software setup.

FOCUS AREA 4

QUANTUM CONNECTIVITY





Connectivity between quantum processing units arises at many layers of an envisaged quantum computing infrastructure. Small ensembles of qubits should connect with each other in quantum networks. Such quantum networks will not only provide information transfer between nodes but, by realizing (generalized) quantum repeaters, these networks can also be used to reduce error rates in transmission over large distances. These architectures are addressed both theoretically and experimentally in *Focus Area 4*.

Furthermore, scalable quantum computers will benefit from interfaces that can distribute entangled states over macroscopic distances of meters or even kilometers and link to quantum memories. We will demonstrate such interfaces and develop a small hybrid quantum network. We will also take a first step to networking Majorana qubits by coherently coupling them to single microwave photons.

Collaborating groups in this *Focus Area* combine solid-state qubits available in Aachen and Jülich with atomic qubits in Bonn, and Majorana qubits developed in Cologne, in order to demonstrate quantum connectivity. This endeavor is only possible through the extensive experience with electrically controlled state preparation and readout available at Aachen and Jülich as well as the expertise of the Bonn groups in light-matter interfaces and the Cologne and Düsseldorf groups in quantum network theory.

FOCUS AREA 4

QUANTUM CONNECTIVITY

4
FOCUS AREA

ACHIEVEMENTS

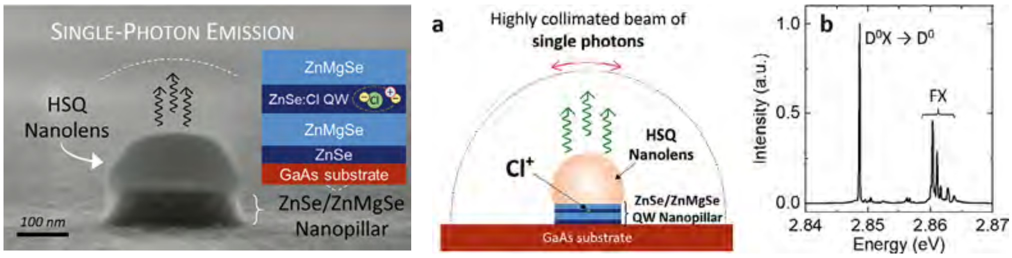
One of the central objectives of this Focus Area is to use a ring of open, photonic microcavities coupled to a reservoir of dye molecules to produce highly entangled multi-photon states as a resource, for example for multipartite quantum key distribution. Experimentally, a dye-filled optical microcavity apparatus realizing a potential with four minima subject to tunnel coupling was realized in the Weitz and Schmitt groups to work towards this goal, and the formation of a Bose-Einstein-condensate of photons in the symmetric ground state of the coupled four-site system was observed [1].

An essential ingredient to realize the targeted highly entangled states based on such a device is a strong nonlinearity. Since for the previously considered reservoir-induced photon-photon interactions, the required strength is difficult to achieve, theory work involving three different ML4Q groups (Bruss, Kroha and Weitz) focused on the large, imaginary nonlinearity induced by the dissipative molecule reservoir on the level of a photon gas or a photon BEC, for use in continuous-variable quantum computing. Building on this concept, ML4Q researchers identified the multipartite continuous variable protocol that is most promising to match the experimental platform and proposed multipartite entanglement witnesses that may be suitable to demonstrate entanglement in the experimental setup. The required parameters for the experimental implementation are currently under evaluation. On a further note, a protocol on anonymous conference key agreement [2] developed earlier within the ML4Q theory effort was demonstrated experimentally in cooperation with the group of Alessandro Fedrizzi in Edinburgh.

The second main thrust of the Focus Area is to optically interface quantum dot and trapped ion qubits as a foundation for heterogeneous quantum networking with nodes that have significant quantum computing capabilities. After good progress with quantum state transfer between photons and individual ionic qubits, work in the Köhl group with ions concentrated on developing an innovative trap design which supports the simultaneous confinement of two (or more) ions within an optical cavity that provides efficient single-photon coupling. This has required the design of a new electrode geometry in order to minimize the radio-frequency induced micromotion along a line inside the ion trap (rather than only at a point as used so far). To account for the resulting high sensitivity of misalignment, ML4Q researchers invented a new fabrication technique to ensure mechanical alignment of the millimeter-sized electrodes to a few micrometers precision without movable parts.

On the quantum dot side, mostly technological efforts in the Kardynal group have been complemented by the exploration of droplet GaAs quantum dots as optically active center, whose growth is more compatible with high quality two dimensional electron gases (2DEGs) for electrically controlled qubits [3]. Electrostatic simulations underpin the feasibility of device operation and guided the design of wafers that allow coupling of droplet dots with gated quantum dots. First measurements of the transport properties of 2DEGs near droplet quantum dots showed a high mobility and a reasonable gate response.

These device developments are complemented by the pursuit of several approaches to improve the photon extraction efficiency, which will be crucial for good experimental performance and technological exploitation. To this end, a cryogenic scanning fiber microcavity previously tested at room temperature was designed in cooperation between the Kardynal and Linden groups and is now being fabricated. The approach to efficiently couple to electrically defined exciton traps in GaAs membranes containing a 2DEG via photonic crystal cavities was extended theoretically (Witzens) to accommodate the electrical connectivity needs for these devices by adjusting the cavity design. On the experimental side (Bluhm),



Schematic illustration of a Cl-doped ZnSe/ZnMgSe QW NP with spherical-shaped HSQ nanolens on top that helps to collect the emitted photons [6]. Panel b shows a typical PL spectrum measured for a ZnSe/ZnMgSe NP (ZnSe QW width of approximately 2.71 nm) with a spherical-shaped lens at a temperature of 5 K and with 5 μW pulsed laser excitation. The spectrum reveals a single-photon emission line at 2.848 eV that originates from the recombination of donor-bound excitons (D^{0}X → D^0). The FX-labeled group of peaks corresponds to the recombination of heavy-hole free excitons.

measurements of the optical property of photonic crystal cavity test samples show good agreement with 3D-FDTD simulations, thus validating the cavity design [4].

In a further collaboration, an enhancement of the extraction efficiency of the newly developed ZnSe:Cl spin qubit [5,6] was improved by roughly a factor ten using a self-aligned nano-sized immersion lens on top of the nanopillar accommodating the qubit (see figure). To bridge between the optical frequencies of the different qubit platforms, ML4Q is pursuing optical wavelength conversion for a range of wavelength combinations. In 2022, photon conversion from 850 nm (InGaAs quantum dot) to the 1550 nm telecom band with the preservation of the single photon characteristics was demonstrated. The setup used for an earlier demonstration between 850 nm and 370 nm (Yb+ Ion) [7; see paper highlight on pages 48/49] has been upgraded to improve efficiency and to preserve entanglement. As a novel approach that circumvents many of the limitations and troubles with crystal-based approaches, ML4Q in addition developed frequency conversion in high-pressure hydrogen. The conversion of laser light from 434 nm (emission wavelength of fluorine donors in ZnSe) to 370 nm (Yb+ ions) has been shown [8]. The setup is currently altered to convert 850-nm photons to the telecom band.

Participants:
Yoichi Ando
Hendrik Bluhm
Dagmar Bruss
Johannes Fink
David Gross
Detlev Grützmacher
Beata Kardynal
Michael Köhl
Johann Kroha
Stefan Linden
Dieter Meschede
Alexander Pawlis
Christoph Stampfer
Simon Stellmer
Martin Weitz

Open Call PIs:
Sebastian Hofferberth
Jeremy Witzens

REFERENCES

[1] E Busley, LE Miranda, A Redmann, C Kurtscheid, K Karkihalli Umesh, F Vewinger, M Weitz, and J Schmitt, Compressibility and the equation of state of an optical quantum gas in a box, Science 375, 6587 (2022)

[2] F Grasselli, G Murta, J de Jong, F Hahn, D Bruss, H Kampermann, and A Pappa, Secure Anonymous Conferencing in Quantum Networks, PRX Quantum 3, 040306 (2022)

[3] D H Fricker, [...] and B E Kardynał, Effect of surface gallium termination on the formation and emission energy of an InGaAs wetting layer during the growth of InGaAs quantum dots by droplet epitaxy, Nanotechnology 34, 145601 (2022)

[4] K Wu, T Descamps, B Marzban, JC Müller, S Kindel, M Künne, F Merget, H Bluhm, and J Witzens, Highly efficient spin qubit to photon interface assisted by a photonic crystal cavity, Proc. SPIE Int. Soc. Opt. Eng. 11995 (2022) 40-48

[5] A Karasahin, RM Pettit, N von den Driesch, MM Jansen, A Pawlis, and E Waks, Single quantum emitters with spin ground states based on Cl bound excitons in ZnSe, Phys. Rev. A 106, L030402 (2022)

[6] Y Kutovyi, MM Jansen, [...] and D Grützmacher, and A Pawlis, Efficient Single-Photon Sources Based on Chlorine-Doped ZnSe Nanopillars with Growth Controlled Emission Energy, ACS Nano 16, 14582 (2022)

[7] A Hamer, D Fricker, M Hohn, P Atkinson, M Lepsa, S Linden, F Vewinger, B Kardynal, and S Stellmer, Converting single photons from an InAs/GaAs quantum dot into the ultraviolet: preservation of second-order correlations, Optics Letters, 47(7), 1778-1781 (2022)

[8] A Aghababaei, C Biesek, F Vewinger, and S Stellmer, Frequency conversion in pressurized hydrogen, Optics Letters 48, 45 (2023; first made public as arXiv:2209.07298)

CONVERTING SINGLE PHOTONS FROM AN InAs/GaAs QUANTUM DOT INTO THE ULTRAVIOLET: PRESERVATION OF SECOND-ORDER CORRELATIONS

ANICA HAMER, DAVID FRICKER, MARCEL HOHN, PAOLA ATKINSON, MIHAIL LEPSA, STEFAN LINDEN, FRANK VEWINGER, BEATA KARDYNAL, AND SIMON STELLMER

OPTICS LETTERS, 47(7), 1778-1781 (2022)

4
FOCUS AREA

Quantum networks, as envisioned for quantum computation and quantum communication applications, are often based on a hybrid architecture. Such a layout may include solid-state emitters, network nodes based on single or few atoms or ions, and photons as so-called flying qubits. This approach requires an efficient and entanglement-preserving exchange of photons between the individual components. These components have their own resonance frequencies, and quantum frequency conversion of the photons is required to link the various components.

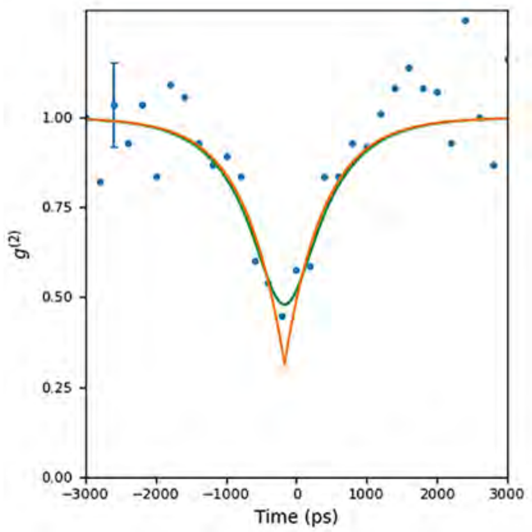
Specifically, we aim to interface a solid-state platform with an atomic qubit. In this work, we prepare for the transfer of a spin state from a self-assembled quantum dot in indium arsenide/gallium arsenide to a trapped ytterbium ion. While the quantum dots are fabricated and operated in Jülich, the trapped-ion expertise is located in Bonn. We present a frequency conversion module that can take single photons at 853 nm, as emitted from the quantum dot, and convert them all the way across the visible spectrum into the ultraviolet. The photons emerge at 370 nm, which is the resonance wavelength of the ytterbium ions. The obtained signal-to-background allows us to measure, for the first time, the correlation function of the converted UV photons. We find that the single-photon property of the source is preserved throughout the conversion process. In future work, we will increase the conversion efficiency even further.

This work constitutes a step towards the coherent coupling of solid-state emitters and ions, and brings us closer to the realization of a quantum network utilizing different components.

“

ANICA HAMER

This was already the third measurement campaign in which we drove two vans full of lasers, optics, and related equipment from Bonn to Jülich. Next time, we'll ship the samples from Jülich to Bonn.

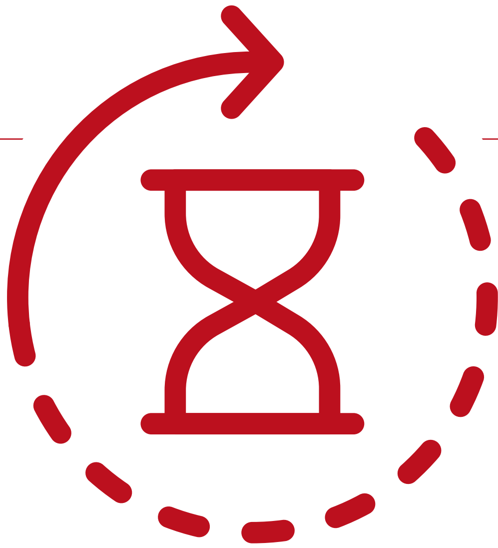


Quantum dots are sources of single photons: they emit photons only one-by-one, and never more than one at the same time. This behavior is quantified by the so-called correlation function, which measures the probability of two photons being emitted at the same time. For a good single-photon source, the function drops to zero. In our work, we changed the color of the photons from infrared to ultraviolet and measured the correlation function of the converted photons. We find that their one-by-one property remains preserved even though their color has changed entirely!

TRIVIA

220

NUMBER OF HOURS REQUIRED TO PRODUCE THE DATA SHOWN IN THE FIGURE ABOVE

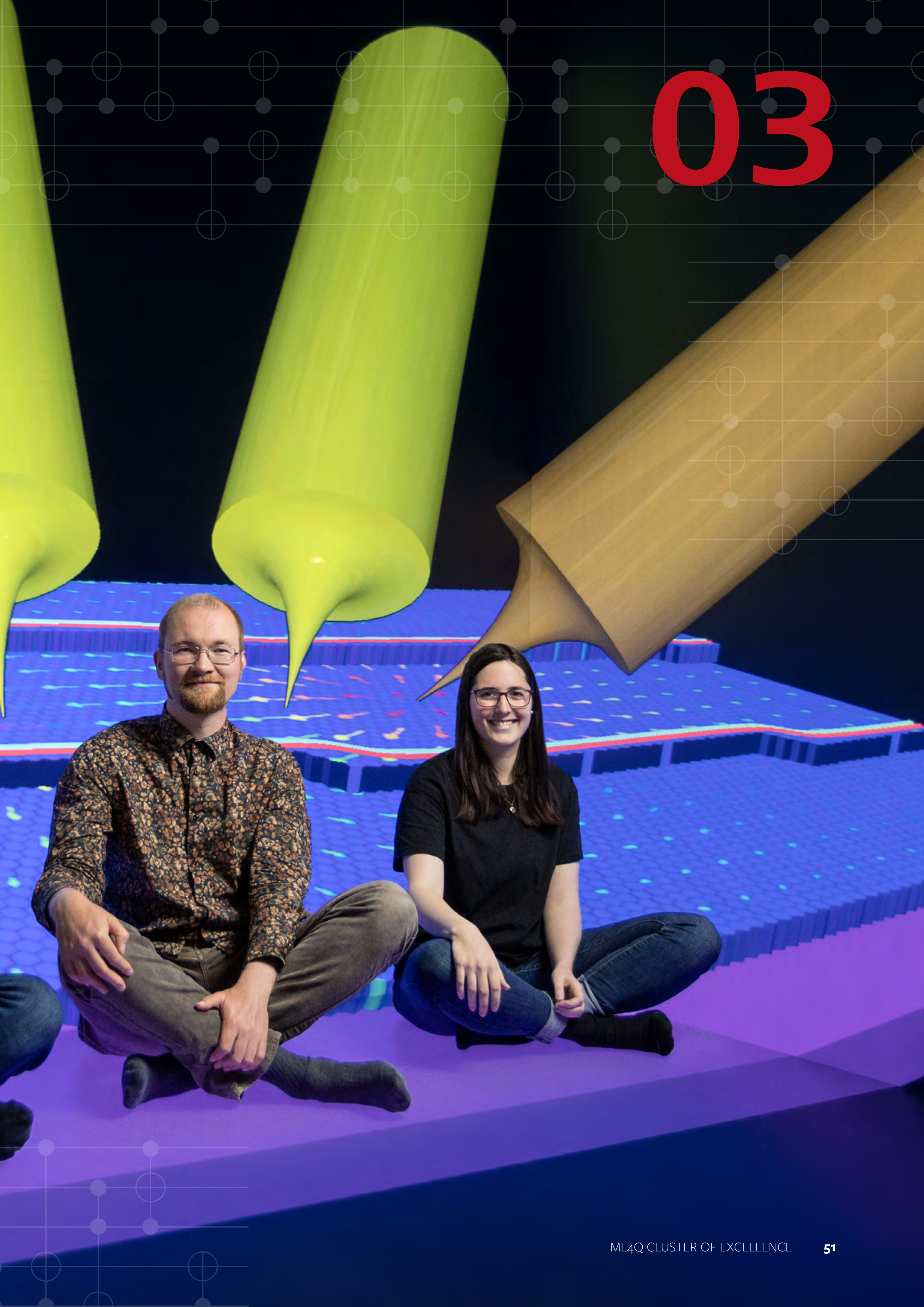


THE TEAM

Anica Hamer Master student in the Stellmer group (Bonn) at the time. The focus of her research was the frequency conversion part.

David Fricker PhD student in the Kardynal group (Jülich) at the time. The focus of his research was the fabrication of the quantum dots.

ML4Q
LIFE



03

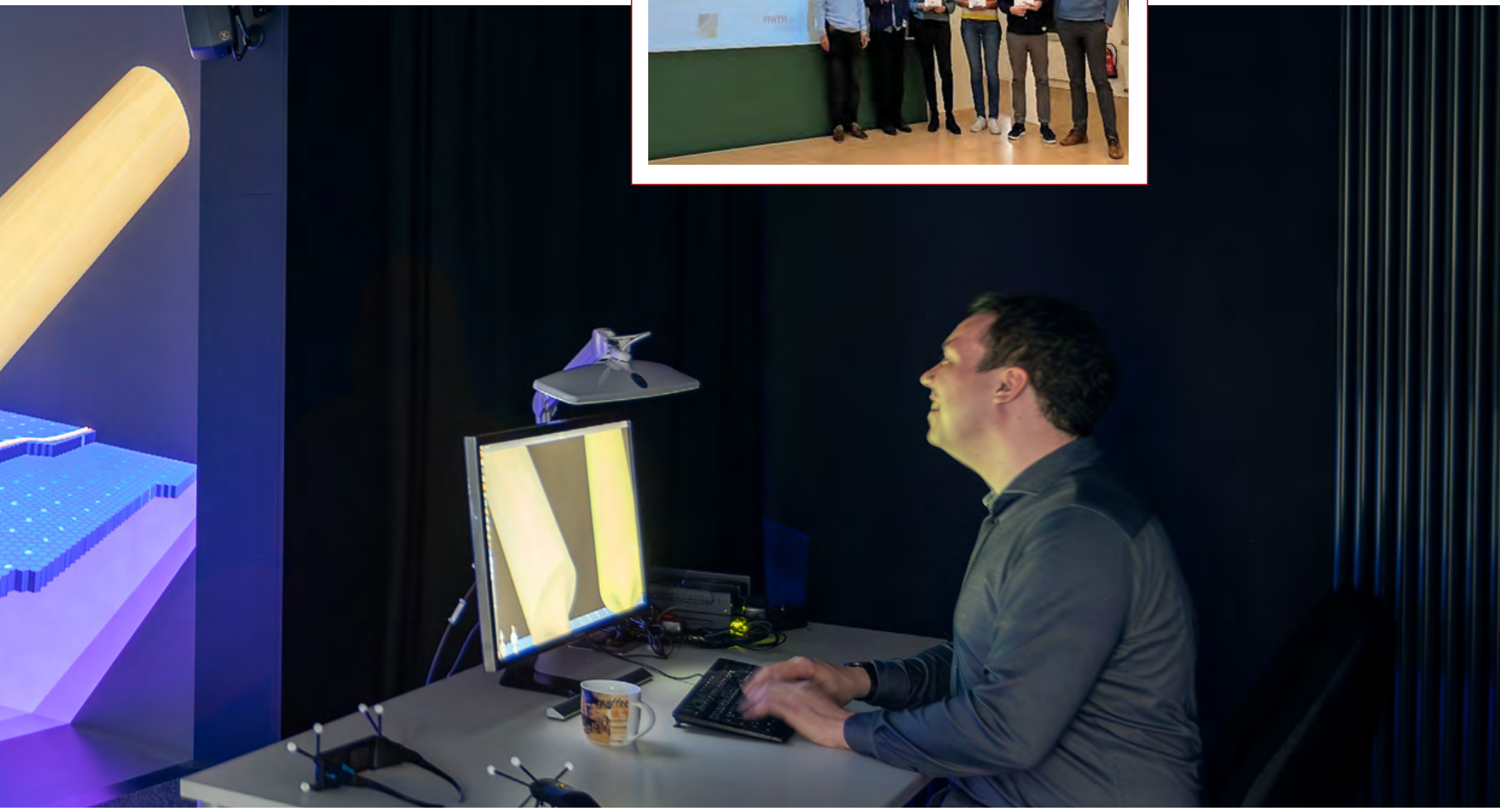
INTRO

[1]

2022 started like 2021 ended: After uncertainties concerning the safety of participants and Corona regulations, our annual ML4Q conference planned for February 2022 had to be cancelled and was converted into a successful but online-only PI meeting. However, we were all the happier that after two years, we were able to finally have the whole cluster come together at the **ML4Q Annual Conference** in August. With 125 participants, 41 posters, 4 top-class keynote speakers, cluster-internal talks from all four Focus Areas and additional sessions focusing, for example, on EIN Quantum NRW and the career development of postdocs, the three days in the beautiful Westerwald were vital for scientific exchange and strengthening the sense of community in our cluster after two years of only seeing each other on screen.

The conference was also the starting point for the preparation of the **renewal of ML4Q into a second funding period**. During the conference, the **ML4Q2 Concept Group** was founded, which conducted its first brainstorming session on site. It met regularly in the following months to sharpen the scientific and strategic goals for ML4Q2. Initial ideas were presented to the rectorate and an external advisory board in Aachen in November 2022 and to the external scientific advisory board of the University of Cologne in December 2022.

Another highlight of 2022 was the **visit to New York** [1] of ML4Q members Prof. Tommaso Calarco and Prof. Alexander Altland who gladly joined a delegation of the University of Cologne led by rector Prof. Axel Freimuth to celebrate the 10th anniversary of the University of Cologne's North America Office. They took part in a panel discussion on "Transatlantic Perspectives on Quantum Science and Technologies". The delegation of the University of Cologne also visited Washington D.C. where it initiated a dialogue between the scientific community and the funding agencies of both countries, the German



[2]

Research Foundation (DFG) and the National Science Foundation (NSF). Another highlight was a high-level meeting with the German Ambassador to the United States and University of Cologne alumna Dr. Emily Haber at her residence, where the delegation discussed Future Technologies with, among others, representatives of the Department of Energy, the Department of State, and the White House Office of Science and Technology Policy.

To support our early career researchers, we have awarded three **Independence Grants** in 2022 to Felix Lüpke (Jülich), Renu Rani (Jülich) and Manuel Rispler (Aachen). Additionally, a new funding format was introduced in late 2022: the **ML4Q Young Investigators Award** [2]. This grant was awarded to six relatively independent young researchers to support them on their career path and increase their visibility. Three pairs were selected to strengthen the collaborations between the sites and in addition, value was placed on diversity in the teams: **Andrea Bergschneider (Bonn) and Annika Kurzmann (Aachen), Gláucia Murta (Düsseldorf) and Julian Schmitt (Bonn), as well as Christian Dickel (Cologne) and Peter Schüffelgen (Jülich)**.

In 2022, we also continued our successful established event series, most notably the MSc course on Platforms for Quantum Technologies and our **ML4Q Concepts seminar** with four talks on quantum communication - this time organized by Anne Matthies, a PhD student at the University of Cologne. In addition, our monthly **cleanroom meeting**, during which students, postdocs, and technicians from all cluster sites discuss current issues that they have encountered during their work in the cleanrooms and exchange best-practice tips, continued with great success.

ML4Q RESEARCH SCHOOL AND EARLY-CAREER SUPPORT

The ML4Q Research School builds on the wide collaborative network that the various cluster sites provide. Hence, it brings along a multifaceted and rich training environment for early-career scientists. In addition to bundling existing offers at the different sites, new formats are also being developed. An even more important role which goes beyond training offers is to optimize the cross-site and cross-topic communication among young scientists. Thus, all Research School activities serve as a platform to enhance interactions between young researchers at different sites and career stages.

In 2022, the Research School succeeded to extend these interactions to include external students. After a delayed start caused by the pandemic, the **ML4Q Undergraduate Research Internship** program hosted seven international undergraduate students in the summer of 2022 who were selected out of 80 excellent applicants. The interns spent 9 to 12 weeks in five cluster groups in Aachen, Bonn, Cologne and Jülich. The main focus of their internship was to gather hands-on experience in the research done in the cluster. But interactions with our students, postdocs and more senior scientists were also of great importance.

Our guests joined the **ML4Q Students and Postdoc Retreat** as well as the ML4Q Conference. During these events, interns and local participants had a chance to meet, discuss science during talks and poster sessions and profit from the cluster expertise during the workshops offered by postdocs. A highlight was a very entertaining Science Slam – a new format at the retreat that we plan to keep for the future. Also the networking part did not come too short and it became very clear that there is a strong need for more regular events bringing students and postdocs together. The first attempt of such a meeting was the **Networking Event 2022** in Cologne. On a Friday afternoon, students and postdocs from all cluster sites met to learn something about cosmology from the guest speaker, Dr. Sandra Unruh.

In addition to cluster internal interactions, our students had a chance to participate in the **Quantum Alliance PhD Conference** which was organised by students' representatives from all Clusters of Excellence in the field of quantum science. There, young scientists had a chance to present their research during talks and poster sessions and discuss it with students from different fields of quantum. As the conference took place next to the World of QUANTUM trade fair in Munich, participants could also visit the fair – an excellent opportunity to learn more about the international quantum technology field.

All these activities were complemented by existing formats for training and career development support. As in the previous years, the very well attended **ML4Q master course on Platforms for Quantum Technologies** was held. This three- week course covers all major topics represented in the cluster research program and its Focus Areas starting by the introduction of basics of quantum information processing, spanning over the AMO (atomic, molecular, optical), solid-state, and topological platforms and concluding with lectures on quantum error correction and topological codes. Building on the multi-site character of the cluster, the course is taught by lecturers from all sites and is open (and recognized) for students from all three partner universities. In 2022, we could offer additional on-site days, which included lectures and exercises as well as lab tours at all sites.

The broad offer of transferable skills training available at all partner institutions was enriched by a workshop on **Project Management** with an adjusted curriculum to meet the needs of ML4Q students. For the future, we plan to develop more courses with such individually tailored content.

In addition to providing our students and postdocs with soft skills tools, we continued to organise seminars relevant for career development. For those who are undecided about their next steps, the **ML4Q Alumni Career Talks series** gave a great opportunity to get in touch with former cluster members and learn more about various positions and options in academia and beyond. Those interested in continuing their career in academia were introduced to funding possibilities and support available for various grants and fellowship applicants. Participants also profited from cluster members who shared their experience in acquiring prestigious fellowships providing practical advice for increasing the success chances of funding proposals.

Ricardo Escobar Gavilanez

***Ecuador**, Master student in the Erasmus Mundus program in Applied Physics, intern in the Hofferberth lab, Bonn*

I participated in the ML4Q internship at the University of Bonn working on Waveguide-QED with Rydberg superatoms and it was an incredibly enriching experience. Not only did I have the opportunity to meet and work with some of the brightest minds in the field, but I was also able to immerse myself in a new culture and feel part of the group from the first day.

During my stay, I was involved in different research and outreach projects, also I had the chance to attend a number of seminars and workshops. I am more than grateful for all the support and guidance provided by my supervisors, not only with my questions in the lab, but also everything related to my stay in Bonn.

Overall, I feel that my internship was a valuable and rewarding experience, and I am grateful for the opportunity to have been a part of such a dynamic and stimulating academic community.

Arthur Wohlfahrt

***Germany**, BSc in Physics, Minor in Computer Science, student at Leibniz University Hannover, intern in the Rizzi group, Cologne*

The internship was a great opportunity for me to focus on an interesting topic, spend time with a research group and take a lot of skills back home.

Overwhelmed with the new topics at first, I quickly gained confidence thanks to the very supportive atmosphere in the group of Prof. Matteo Rizzi. They took the time to explain everything in my pace, but never forgot to provide some challenges for me to solve on my own.

I enjoyed developing ideas together on the blackboard and learning to program with the Julia language, which I´m still using today.

The internship motivated me to take courses in advanced solid state theory and computer physics for my master studies and I´m really grateful for the time in Cologne.

Sandra Simard

***Canada**, Combined Honors in Chemistry and Physics with Minor in Programming at McGill University, Montreal, intern in the Bocquillon lab, Cologne*

During my first days at the institute, I got the chance to meet my professor, but also many students and other professors in the department. I was introduced to many topics in condensed matter, but also to a team of passionate people. As my group was small at the beginning, I was taught a lot by PhD students and I think that was the most enriching part of my experience. I got to understand why they chose to do graduate studies in physics, specifically at the University of Cologne in Condensed Matter Physics, and what were the advantages and challenges of such a choice. As an undergraduate student, decisions for graduate school are upcoming and I think that this experience is one of the most formative that I could have had in my undergraduate journey.

Yonatan Gideoni

***Israel**, B.Sc. Expanded Physics Track with Computer Science Minor, Hebrew University of Jerusalem, intern in the Rosati group, PGI-12, Jülich*

I interned at Forschungszentrum Jülich over 9 weeks in the summer, working on optimising simple pulses in overparameterized systems. This was a fascinating experience that allowed me to learn more about the field and interact with expert researchers. Over the course of my time there I saw a real quantum computer, went to two conferences, and managed to find an innovative solution to our problem. I am still in touch with my advisor, chatting about our research and the work I did there, which we hope to publish soon. My time at Jülich was lovely, allowing me to invest myself in a new academic culture and work on some state of the art problems. The ML4Q team helped make my time there as nice as possible, being responsive and as accommodating as possible. I hope future interns can enjoy and utilize this experience to its fullest!

03

ML4Q LIFE

EQUAL OPPORTUNITIES & DIVERSITY

We at ML4Q are convinced that the lack of diversity in physics – and essentially in any research area – is not only a problem of inequality, but also affects the way research is conducted and applied. Therefore, we strive to improve diversity within the cluster through various measures that take into account aspects such as gender, work-life balance, internationalization, socio-economic background, and disabilities. Only if we recognise the individual stories and identities of our cluster members and associated members and respect that they have different needs, we as a cluster can achieve our goal of not only providing excellent research but also having created an appreciative environment that makes this excellent research possible at all. One factor that we have focused on first is **increasing the visibility of female scientists in physics**. We are aware of the importance of visible role models who can help motivate and inspire underrepresented groups to consider academic careers in STEM. Therefore, ML4Q encourages female members and associate members of various academic career stages to participate in some of its outreach activities.

In 2022, ML4Q participated in the **Girls'Day** for the first time. Annika Kurzmann and Corinne Steiner (RWTH Aachen), Ella Nikodem [1] (University of Cologne) and Gláucia Murta (HHU Düsseldorf) presented the exciting world of quantum physics and technologies to female high school students. We made use of the rising popularity of online events among Girls'Day participants and offered virtual lab tours at different cluster sites within the 3-hour workshop. The event started with interactive lab tours in Aachen and Cologne. Annika and Corinne had a live demonstration of how they prepare their bilayer graphene samples for measurements and how low the temperatures really are at which they perform their experiments. Ella showed an entire building dedicated to quantum technology and explained the development of a sample from the growth of the material over the patterning of the sample in the cleanroom to the final measurement of the chip. The Girls'Day ended with a code-breaking exercise explained by Gláucia, where the girls had to encode and decode a secret message. Due to the enthusiasm and interest of the attending girls, it was decided to support the concept of the Girls'Day again with an event in 2023 and to give teenage girls insights into the life of a female physicist.

As part of the **DPG Summer School on Quantum Computing**, held at the Physikzentrum Bad Honnef in August 2022 on the theory of quantum computing, a dedicated **networking event** organized by ML4Q gave female participants the opportunity to network with each other and with established female scientists from various academic/industry backgrounds and career stages. ML4Q members Barbara Terhal (TU Delft & QuTech) and Gláucia Murta (HHU Düsseldorf), as well as Christa Zoufal (IBM Zurich) and Inés de Vega (IQM, Munich), spent an evening with the students, sharing their own stories but also answering many questions from the students in lively discussions ranging from career tips, to advice on balancing work and family, to sharing experiences and anecdotes as a woman in STEM.

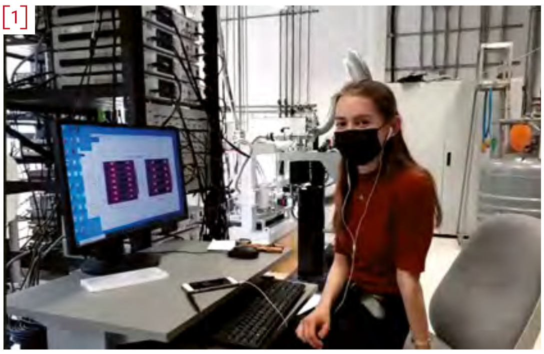
One story from 2022 we are happy to tell is that of our associated member, **Mariami Gachechiladze**, who joined the cluster in the first year and worked in the group of David Gross in Cologne. Mariami has taken the next step on her personal career path and started a **professorship for Quantum Computing** at TU Darmstadt as of February 1, 2022. During her time in the cluster she has taken great efforts in empowering women who want to pursue a career in Mathematics, Computer Science or related topics, e.g. by contributing to Q-Turn 2020 – a unique international quantum information workshop series which fosters an inclusive community and highlights outstanding research that may be under-appreciated in other high-impact venues due to systemic biases. As part of our alumni talks, Mariami already shared her first experiences as a junior professor.

Further outreach activities included Anne Matthies joining **Soapbox Science** in Bonn. Anne – who is doing her PhD project in Theoretical Physics at the University of Cologne in the group of Achim Rosch – presented the quantum computer where she kept Schrödinger's cat hidden. She let her audience guess whether the cat is still alive when she opens the box. Based on the thought experiment of Schrödinger, Anne introduced her audience to quantum mechanical principles and explained how such principles and phenomena are used in the quantum technology research in order to enhance existing computing capabilities. Thanks to the sun, many visitors stopped by to listen to some science in exciting nutshells presented by scientists from different departments.

Also noteworthy is the participation of several excellent female scientists in the **ML4Q&A podcast**. In May, **Beata Kardynal** [2] was the interview partner. She spoke about her career and her training in electronic devices for the coupling of single photons. Furthermore, she revealed her favourite materials and how she didn't see a strong distinction between physics and engineering from the start. In August, **Annika Kurzmann** [3] gave exciting insights into her work on optical quantum dots during her PhD and bilayer graphene quantum dots in her postdoc and how she is now bringing this together to detect single electron dots in graphene. Glimpses of starting a lab during the pandemic were also part of the conversation. Early in 2022, a podcast episode featured Kathrin Dorn, PhD student in the Egger group at the time.

In addition to its focus on promoting female scientists and helping them to gain more visibility, ML4Q remains strongly committed in creating a family-friendly environment. In order to support members with children in balancing care work and responsibilities in the cluster, ML4Q reserved places for children at local day care providers of the Froebel Group – a service which is gladly received by many of the associated members of the cluster.

[1]



[2]

Listen to the ML4Q&A-Podcast with Beata Kardynal

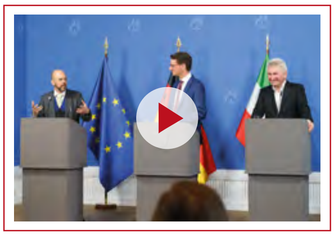
[3]

Listen to the ML4Q&A-Podcast with Annika Kurzmann

Silicon wafer with hundreds of industry-grade quantum computing units utilizing ARQUEs technology. Chip manufacturing done by Infineon Dresden. Photo taken by R. Otten, ARQUE Systems.

Through the establishment of **EIN Quantum NRW**, North Rhine-Westphalia joined forces to create a hub for quantum science and technologies in the region. In a press conference in March 2022, Minister President Hendrik Wüst, Minister of Science Isabel Pfeiffer-Poensgen and Minister of Economics Prof. Dr. Andreas Pinkwart announced the three goals of the new quantum computing network: Education, Innovation, Networking. EIN Quantum NRW bundles the expertise of universities, non-university institutions and aims to improve the networking of excellent basic research with large companies and quantum spin-offs in the state.

> **The state government's support comes at the right time, because regional ecosystems of quantum technology are currently being established throughout Germany and Europe. The extraordinarily high density of quantum expertise in science and industry in our state can multiply its impact through this bundling.**
>
> TOMMASO CALARCO



Watch Press conference on the Quantum Computing Competence Network with Tommaso Calarco, Minister President Wüst and Minister Pinkwart

As in 2021, the cluster partnered with **QT.NMWP.NRW** to bring together ML4Q's early-career scientists with experts from the corporate world on the **ML4Q Technology Day 2022**. In 2022, the event was all about knowledge transfer and entrepreneurship. We started with a sparking introductory keynote by ML4Q member, Tommaso Calarco, who spoke about the launching of his **tech-based startup, Qruise**. The engaging talk was followed by a panel discussion with several transfer experts from our cluster sites. Benefiting from the company network of QT.NMWP.NRW, scientist entrepreneurs from NRW (Michael Johanning/ EleQtron, Dennis Michaelis/Gemesys and Nicolai Walter/Pixel Photonics) talked about their lessons learned and gave best practice entrepreneurial insights.

ARQUE Systems - a new spin-off is born

Driving and succeeding in technology transfer from academia to industry can be argued to be a major challenge, and hence is rarely seen, especially within the hardware sector.

However, **ARQUE Systems**, a dynamic startup and a spin-off from RWTH Aachen University and the Forschungszentrum Jülich, defied the odds and embarked on their journey in 2022 to build fully scalable quantum computers using electron spins in silicon, leveraging a unique shuttling-based quantum computing unit.

Their story begins with ML4Q core project P3.3 [see also section on Focus Area 3 on pages 38-43], where they laid the foundation for innovation. With relentless determination, they successfully transferred the cutting-edge technology of electron spin shuttling with the help of the BMBF-project QUASAR to industrial semiconductor production lines at Infineon Dresden, effectively bridging the gap between academia and industry. Establishing a complete supply chain, ARQUE Systems now works with industry-grade quantum processing units, setting new standards in semiconductor quantum computing.

At the heart of ARQUE's technology lies the concept of electron spin shuttling, a revolutionary approach that enables qubits with a mere 100 nm footprint to be transferred coherently across the entire quantum chip architecture on the micrometer scale [see also paper highlight on pages 42/43]. The increased space between neighboring qubits facilitates the integration of control electronics directly on the quantum chip, significantly reducing signal cross-talk and ensuring higher qubit fidelities, thus unlocking the true potential of quantum computing. With this approach, a quantum chip with the size of 1 cm² can host 1 million qubits without compromising their operation fidelities.

ARQUE Systems' journey is guided by a team of dedicated experts, with Prof. Hendrik Bluhm and Dr. Lars Schreiber as scientific directors, Dr. Jan Klos as the director of technology, and two more founding partners, Dr. Markus Beckers and Dr. Wolf Meissner as managing directors overseeing the operative and strategic developments. Their collective expertise has been instrumental in steering ARQUE's progress from its early stages to where it stands today.

OUTREACH

[1]

[2]

Based on the communication and outreach strategy which identifies fundamental research as the cluster's core value – thus differentiating it from other funding structures which place more emphasis on application and technological aspects – we continued the outreach efforts which were established in previous years setting a focus on school and general public outreach in 2022. All outreach activities made sure to communicate ML4Q's core competency, spotlighting different nuances (the physics, the people behind the physics, etc.) and using different and complementary types of media (video, blog post, podcast, live slam, etc.).

Targeting the young scientific community

In order to address students within our multiple sites as well as the international student quantum community in Germany and beyond, more content on the cluster's blog, **ML4Q Stories**, and the cluster's podcast, **ML4Q&A** [1], was released in 2022. Four more podcast episodes with guests from Aachen and Jülich were published featuring some of the experimental work done in the cluster and offering a nice mix of junior and more established male and female cluster members. The episodes spanned from semiconducting qubits with Rami Barends and semiconductor quantum photonics with Beata Kardynal to 2D materials with Annika Kurzmann and quantum dot spin qubits with Jan Klos. As the popularity of the podcast is growing, we were able to achieve more than 1500 downloads since the launch of the podcast until the first quarter of 2023.

ML4Q was also present in several **career fairs as part of the Quantum Alliance**. By appearing together at career fairs and meetings of the quantum community, our cluster, alongside the Quantum Alliance, can effectively provide scientists interested in research opportunities in Germany with a comprehensive overview of all clusters in the country. This approach proved quite impactful and efficient in previous years and was therefore pursued in 2022 as well.

While the MIT Career Fair (February) and the fair organized by DAAD's Research in Germany campaign (June) were held virtually, the German Academic

[3]

[5]

[4]

International Network (GAIN) career fair took place for the first time in Germany in September 2022. These fairs offer information on academic career paths in Germany, the German research landscape as well as funding and admission procedures for PhD studies in German universities and the events targeted scientists working in the STEM field and who are mainly located in the US. ML4Q – once again together with the Quantum Alliance – was also present in the exhibition areas of the **APS March Meeting**, the **World of Quantum** taking place for the first time in Munich (April) as well as the **DPG Meeting for Condensed Matter Physics (SKM)** in Regensburg [2] (September).

School outreach

A highlight in 2022 was the **Quanteen Day** [3] which was conceived by associated members of the cluster who are involved in the school labs at Cologne, Bonn, Aachen and Jülich. This four-hour virtual event attracted over 280 school pupils from more that 70 schools in the Rhineland and beyond. One-third of the participants comprised students from 5th to 8th grade (Mittelstufe) – a target group favored by many teachers we involved in our conceptual phase of this event as this group was introduced to fascinating physical phenomena, thus encouraging or confirming their wish to major in physics during high school years.

Building on the bundled expertise in theoretical physics and quantum information in **Cologne**, we established connections to the **Junior- and Kinderuni** [4 & 5] with whom we developed age-appropriate workshops on quantum computing and quantum algorithms to be included in their program for 2022.

Furthermore, we were able to transfer the expertise with quantum experiments with school classes in the Physikwerkstatt Rheinland Bonn to the **SciPhyLab in Aachen** by putting together the **ML4Q Education Package** which was acquired through Open Call funds. Demonstrations of wave-particle-duality and the Hong-Ou-Mandel effect were included in the programs of the **Schüleruni** in June, the **HOT Ferienprogramm** in July as well as in the **Wissenschaftsnacht "5 vor 12"** in November.

[6]

[7]

MATTER AND LIGHT FOR QUANTUM COMPUTING

Public outreach

To address the broad public, we included a German subpage on the cluster's homepage – **ML4Q auf Deutsch** – which offers a variety of information, videos, interviews and published articles on quantum computing. The episode in **Exzellent Erklärt** [6] – the podcast of all German Clusters of Excellence – and the high quality **explanatory film on quantum computing** which was produced in a cooperation with the Konrad Adenauer Foundation (KAS) enable a popular introduction into the topic including expert statements from the cluster's members. In addition, the German section includes the new video series **ML4you – unsere Forschung im Dialog** [7] in which PhD students and early postdocs try to explain their work first to a (high) school student, then to a bachelor student and dig deeper in a conversation with a master or PhD student. Finally, they discuss their work with their supervisor and relate their work to the bigger picture of the cluster's mission. In 2022, three videos were produced to cover the topics of quantum optics, quantum simulation and quantum cryptography with students from Bonn and Düsseldorf.

In a **special publication in the Frankfurter Allgemeine Sonntagszeitung** and Welt am Sonntag (30 January 2022), ML4Q experts joined scientists from North Rhine-Westphalian universities in Bochum, Dortmund, Münster, Paderborn and Siegen, the DLR Cologne as well as several research institutes of the Fraunhofer Society (ILT, FHR, IAIS, SCAI) in an impressive presentation of the bundled and dynamically growing expertise in basic and applied quantum sciences and technologies in the region.

On a further note, **Pint of Science Germany** [8] came back to the pubs again in 2022 and ML4Q was represented in the Ehrenfeld pub Bumann&SOHN by Christoph Berke (PhD student in the Trebst group) who showed the fundamental difference between classical and quantum computers and emphasized the complexity of these systems. In the second talk, Chris Dickel (postdoc in the Ando lab in Cologne) took the audience into the complex world of matter and its physical peculiarities. Even though he showed phenomena that are relevant to the engineering of quantum devices, he took up the

[8]

[10]

[9]

cudgels for "crazy academic questions" – questions about fundamental research which is the strength of performing science at a university. Questions that are at the heart of exploratory projects and investigate materials that could potentially revolutionize today's computing processes.

Together with colleagues from the Clusters of Excellence of the University of Bonn, ML4Q participated in the **Bonn Excellence Slam** [9], attended by 600 viewers who listened to Andreas Redmann (PhD student in the Weitz group) who offered a tour through his lab showing the often so cluttered optical table. By presenting his experimental setup using mini mirror-mazes for light, he explained his work on quantum communication and how he is investigating the ways by which the photons can be entangled in order to use them one day to transmit encrypted information.

Finally, in a collaborative effort with the PGI Science Office at Forschungszentrum Jülich, ML4Q joined the one-week exhibition at the physics science festival in Germany – the **Highlights der Physik** [10] – which was attended by over 40,000 visitors in Regensburg in September. A miniature model of a superconducting quantum computer was used to demonstrate the idea behind running research projects. Other computing platforms – including those pursued in the cluster's program – were introduced at the booth entitled **Wie funktioniert ein Quantencomputer?** and explained by Friederike Butt (back then Master student in the Müller group at RWTH Aachen) as well as Jan Timper and Daniel Zeuch from the PGI Science Office at Forschungszentrum Jülich.

In all our efforts to explain to the public the potential of quantum computation for future technologies, we always make sure to comment on the current media hype around quantum computing and elaborate on how much work in fundamental research is still needed in order to pave the way for high quality quantum computers and provide the theoretical fundaments for societally relevant applications.

MISCELLANEOUS

NEW MEMBERS

13 NEW MEMBERS ELECTED IN THE ML4Q MEMBERS' ASSEMBLY 2022

Thirteen new members were elected in the Members' Assembly that took place during the Ml4Q Annual Conference in August. The elected members included new principal investigators of projects that received funding in the midterm review. These are: **Timofey Balashov, Silvia Viola Kusminskiy** and **Annika Kurzmann** from RWTH Aachen University, **Andrea Bergschneider, Johannes Gooth** and **Julian Schmitt** from the University of Bonn, **Michael Buchhold** and **Matteo Rizzi** from the University of Cologne, **Martin Kliesch** and **Gláucia Murta** from the HHU University Düsseldorf and **Rami Barends**, **Vincent Mourik** and **Peter Schüffelgen** from Forschungszentrum Jülich.

POLITICAL DEVELOPMENT

A NEW HUB FOR QUANTUM SCIENCE AND TECHNOLOGY IN NRW

Education, Innovation, Networking in quantum science and technology – these are the goals of the new quantum computing network **EIN Quantum NRW**, which bundles the expertise of universities, non-university institutions as well as industrial partners in North Rhine-Westphalia. Minister President Hendrik Wüst announced the establishment of the state's hub for quantum science and technology in a press conference in March 2022. ML4Q member, Tommaso Calarco, contributed substantially to the conception and development of this crucial hub which enhances the visibility and competitiveness of the region in the high dynamic field of quantum science and technology research.

NEW ML4Q PROFESSORS

DAVID LUITZ AND MARIO BERTA JOIN ML4Q

ML4Q welcomed two new professors in 2022. While David Luitz was appointed by the University of Bonn to start his ML4Q professorship as of January 2022, Mario Berta started his new position at RWTH Aachen University in November.

David Luitz is moving to Bonn after having spent 4 years as head of the Computational Quantum Many-body Physics group at the Max-Planck-Institute for the Physics of Complex Systems in Dresden, Germany. He will be leading the research group Theoretical Quantum Many-Body Physics focusing on condensed matter theory at the University of Bonn.

Mario Berta will lead a research group on mathematical questions in quantum information science, focusing on quantum communication theory and the theory of quantum algorithms. Mario is moving from London from his former academic position as a UK Reader in Quantum Information Theory at the Department of Computing Imperial College London. Mario also worked in industry as a Senior Research Scientist at the Amazon Web Services Center for Quantum Computing.

CASA
Cyber Security in the Age of Large-Scale Adversaries

ML4Q
MATTER AND LIGHT FOR QUANTUM COMPUTING

SUMMER SCHOOL

PHYSICS MEETS COMPUTER SCIENCE

In a joint effort between computer scientists (CASA Cluster of Excellence Bochum and University of Latvia) and physicists (David Gross from ML4Q), a comprehensive summer school program has been put together to introduce interested master students, PhDs and prospective postdocs to the field of quantum computing during a summer school at the Physikzentrum Bad Honnef from August 14-19, 2022. The organizing committee reflected the growing collaboration between the fields of quantum physics and computer science to tackle future challenges in the field of quantum computing.

GRANTS & AWARDS
JULIAN SCHMITT RECEIVES ERC STARTING GRANT

In July 2022, **Julian Schmitt** received an ERC starting grant for his project TopoGrand. Julian is a project leader and junior principal investigator at the Institute of Applied Physics at the University of Bonn and has been part of our cluster since 2020, when he was awarded an ML4Q Independence Grant. During the midterm evaluation, he was granted funds as a new PI on the ML4Q project 'Multipartite quantum networks'. In TopoGrand he will investigate new ways of generating and controlling topological states in open systems by using Bose-Einstein condensates of photons in coupled optical cavities.

GRANTS & AWARDS
ML4Q MEMBERS ACQUIRE FUNDING FOR SEVERAL LARGE CONSORTIA

Stefan Tautz and **Sebastian Hofferberth** received ERC Synergy grants for the consortial projects Orbital Cinema and SuperWave, respectively. **Simon Stellmer** successfully competed within the European QuantERA program with **QuantumGuide** – a collaborative project aiming to guide laser-cooled atoms through hollow-core photonic crystal fibers in order to incorporate them into quantum sensors and quantum computers. Two consortial projects which involve ML4Q members started as of January 2022 within the Federal Government Framework Program "Quantum technologies – from basic research to market". **Quantum computer in the solid state – QSolid** which is coordinated by **Frank Wilhelm-Mauch**. **David Gross** is one of the partners of **Quantum Methods and Benchmarking for Resource Allocation – QuBRA** which is a collaborative effort between research and industry. Within a related Call of the German Federal Ministry of Economics and Climate Protection entitled "Quantum Computing – Applications for Industry", **David Gross** became part of the **ProvideQ** project consortium.

PRIZES & AWARDS
VINCENT MOURIK JOINS THE JUNGES KOLLEG

For his outstanding academic achievements, **Vincent Mourik** – newly elected member of ML4Q – has been elected to join the Junges Kolleg of the North Rhine-Westphalian Academy of Sciences, Humanities and the Arts. Fellows receive an annual stipend of 10,000 euros for a period of up to four years. Besides financial support, fellows are given the opportunity to exchange ideas and network with other researchers and artists from a wide range of disciplines at the same career stage. Vincent joined Forschungszentrum Jülich and the JARA-Institute for Quantum Information (PGI-11) late in 2021 where he has been establishing his new lab as a Junior Group Leader. He moved from Australia from his former academic position as a postdoctoral researcher in the group of Andrea Morello at the University of New South Wales. During his PhD studies at Delft University of Technology he worked on the engineering and detection of Majorana zero modes in nanowire devices.

IN THE SPOTLIGHT
NINA STIESDAL PORTRAYED IN PHYSIKERIN DER WOCHE

Nina Stiesdal, postdoc in the Hofferberth group at the University of Bonn, was featured by the German Physical Society (DPG) in May 2022 in "Physikerin der Woche". Since January 2018, the working group on equal opportunities of the DPG highlights weekly women in physics in Germany or German women in physics abroad. Nina successfully defended her PhD project in May 2022 in which she worked on Rydberg superatoms, which are many atoms acting together as single two-level systems.

IMPRINT

ML4Q
MATTER AND LIGHT FOR
QUANTUM COMPUTING

EDITOR
Cluster of Excellence ML4Q
Matter and Light for Quantum Computing
University of Cologne, Pohligstraße 3, 50969 Cologne, Germany

The editing process involved members of the ML4Q office, the ML4Q Executive Board as well as the cluster members responsible for outreach, Alexander Altland, Michael Köhl and Markus Morgenstern.

ML4Q EXECUTIVE BOARD
Yoichi Ando
Hendrik Bluhm
David Gross
Detlev Grützmacher
Simon Stellmer

ML4Q OFFICE
Magda Baer Radermacher
Marian Barsoum (text layout)
Andrea Bliesener
Eva Kanis
Beate Saal
Konstantinia Schäfer
Philipp Wilking

COVER IMAGE
Mira Sharma (DiVincenzo group)
The background image is a 3D visualization of the QC model, courtesy of the PGI Science Office (https://apps.fz-juelich.de/qcmodel/).

GRAPHIC DESIGN
University of Cologne
Department 82 Marketing
Alexander Jahn
Martina Markus

PHOTOGRAPHY
Simon Wegener Fotografie
www.simonwegener.com

IMAGE CREDITS
All image credits go to Simon Wegener unless specified below:
Alexander Altland (p.12, vision image)
Nathalie Schueller (p. 52, NY event)
Andrea Bliesener (p.53, Young Investigators Award)
René Otten/ ARQUE (p.58)
Alex Jahn (p.60, Illustration ML4Q&A Podcast)
Andrea Bliesener (p.60, DPG Meeting)
Marian Barsoum (p.61, Junior- and KinderUni)
Katharina Link (p.63, Pint of Science)
Jan Timper (p.63, Highlights der Physik)
Volker Lannert/Uni Bonn (p.63, Bonn Excellence Slam)

Photographs of ML4Q members, associated members as well as authors of highlighted papers that appear on pages 18, 19, 20, 21, 25, 31, 33, 35, 39, 41, 45, 47, 64 and 65 were provided individually by the principal investigators and authors, respectively.

PRINT
Köllen Druck- und Verlagsgesellschaft mbH
Ernst-Robert-Curtius-Straße 14
53117 Bonn

ANNUAL REPORT 2022

MATTER AND LIGHT FOR
QUANTUM COMPUTING