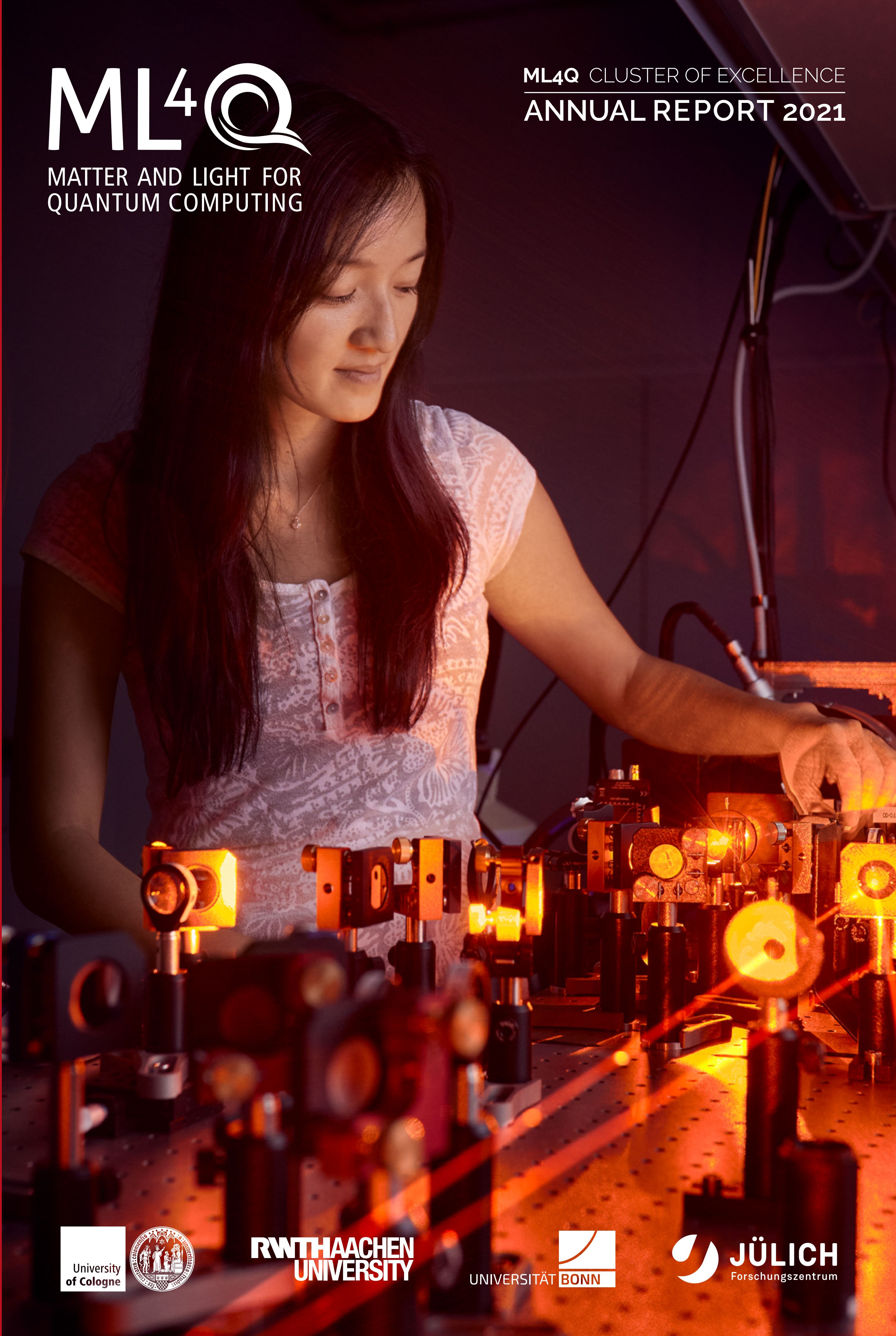


ML4Q

MATTER AND LIGHT FOR QUANTUM COMPUTING

ML4Q CLUSTER OF EXCELLENCE

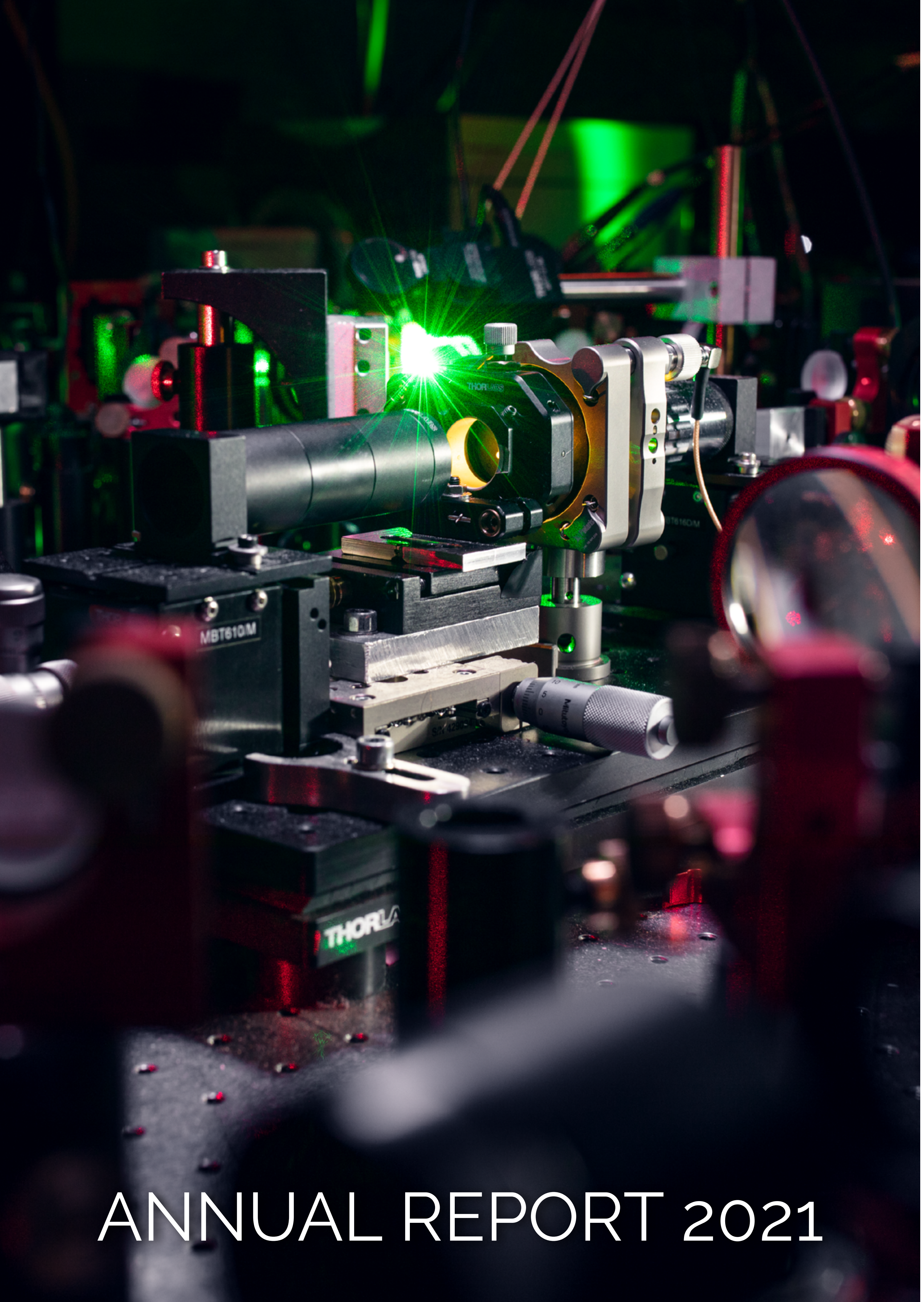
ANNUAL REPORT 2021

University of Cologne

RWTH AACHEN UNIVERSITY

UNIVERSITÄT BONN

JÜLICH Forschungszentrum



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02 ML4Q RESEARCH

03 ML4Q LIFE

ML4Q
ANNUAL REPORT 2021

In this third annual report of our Cluster of Excellence "Matter and Light for Quantum Computing" (ML4Q), you will see how far we have come in the middle of the 7-year funding period. ML4Q was established in 2019 in the context of the German Excellence Strategy with the aim of installing a new research infrastructure encompassing the universities of Cologne, Bonn, and Aachen as well as the Forschungszentrum Jülich (with additional participation of the University of Düsseldorf, Fraunhofer ILT and Fraunhofer FHR) to foster the fundamental research on future quantum information technologies, with focus on the developments of new concepts and devices for scalable quantum computing and quantum communication. I am glad to report that we are steadily making high-quality scientific outputs while strengthening the regional collaborations, as you will see in the following pages.

As the developments of cutting-edge science and technologies are difficult to foresee even in the time scale of a few years, already at the start of ML4Q, we planned to make a major restructuring of the internal projects in 2022 in the form of a mid-term review, so that the available resources are most efficiently used to maximize our scientific output. This will also help maximize the chance of extending ML4Q into the 2nd funding period beyond 2025. There were a lot of preparations in 2021 for the mid-term review, which just took place at the time of this writing (June 2022). As a part of the preparation, we undertook a relatively large-scale Open Call funding in 2021 with the total sum of 1.7 M€, which was used to incorporate new groups and new research directions as well as to purchase new pieces of equipment for important experiments. Many new ideas involving new groups received bridge-funding in the Open Call in 2021, and they were developed into new Core Projects of collaborative nature to be funded in the mid-term review.

An important recent development in ML4Q is that 6 new professors have been hired at Cologne, Bonn, Aachen and Düsseldorf (they are individually introduced later in this report). Their research areas include mesoscopic devices, cold atoms, quantum information, and many-body physics. They are actively creating new collaborative projects and contributing greatly to energizing ML4Q. With further hires that will be made soon, ML4Q is in a good position to dynamically adopt new exciting directions.

There is currently strong tailwind blowing for quantum computing. One of the consequences of the tailwind is the BMBF-funded project QSolid (76.3 M€ for 5 years), which will build a solid-state-based quantum computer made in Germany; the spokesperson of QSolid (Frank Wilhelm-Mauch) is a Strategy Board member of ML4Q and the agenda of QSolid is strongly complementary to that of ML4Q. Another consequence of the tailwind was the installment of the state-funded "EIN Quantum NRW", which will strengthen the education in quantum technologies in NRW and enhance the innovation potential in the quantum computing area in particular; for this initiative, members of ML4Q played leading roles.

It is prudent to mention that in contrast to the tailwind for quantum computing in general, "topological" quantum computing is facing headwind, due to a couple of problematic papers on Majorana zero modes published in the past. However, the problem lies in the instability of the semiconductor-based Majorana platform against disorder; ML4Q continues to work on proving the promise of the topological-insulator-based Majorana platform, which is inherently more stable against disorder.

Finally, I should mention that the growing communication and outreach platforms offered in ML4Q (such as the ML4Q Concepts seminar series, cleanroom and subgroup meetings as well as the ML4Q&A podcast, the cluster's blog, etc.) played important roles in fostering new perspectives and collaborations for the mid-term review and incorporating new groups into the ML4Q community. Many of the contents of our communication platforms are also useful to the quantum community in general as well as to the public, so please take time to explore some of our interesting online contents after you have gone through this annual report.

I wish you a productive year after the Corona pandemic and I am looking forward to reporting further positive developments in ML4Q in the next annual report!

ML4Q
AT A GLANCE

01

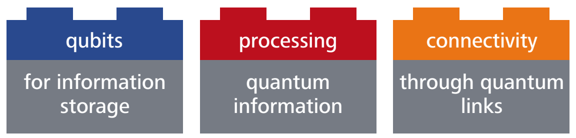
ML4Q
AT A GLANCE

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.

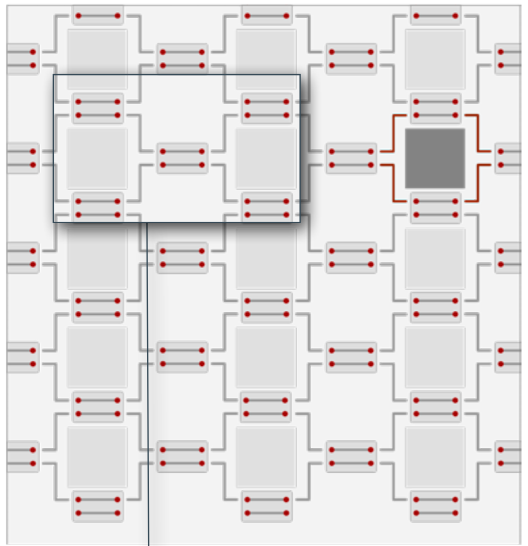
THE CLUSTER'S MISSION

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.

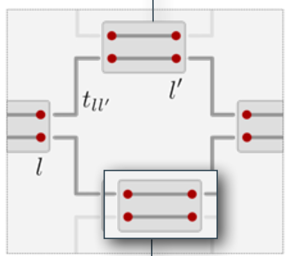
The long-term goal of the cluster is to realize network and processing architectures protected by error-correction protocols and eventually connected to a quantum version of the internet.
This goal defines a hierarchy of challenges, both in fundamental science and in technology, which must be overcome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



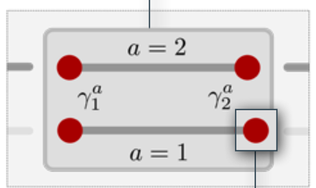
THE VISION



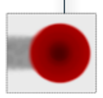
The processor units of a network comprise arrays of qubits whose implementation requires scalable designs. We envision to realize these units by the end of the second funding period.



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.

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 has been funded within the Excellence Strategy by the German Research Foundation (DFG) since January 2019. The first funding period ends in 2025.

ML4Q **IN NUMBERS**

237 MEMBERS AND ASSOCIATES

53 PROFESSORS

90 INTERNATIONAL SCIENTISTS

100 PHD STUDENTS

36 FEMALE SCIENTISTS

45 ADMINISTRATIVE & TECHNICAL STAFF

37 POSTDOCS

7 RESEARCH INSTITUTIONS

117 PUBLICATIONS* IN 2021

19 OPEN CALL PROJECTS AND INDEPENDENCE GRANTS

27 PUBLICATIONS* IN 2021 WITH TWO OR MORE ML4Q GROUPS INVOLVED (10 CROSS-SITE PUBLICATIONS)

*including preprints

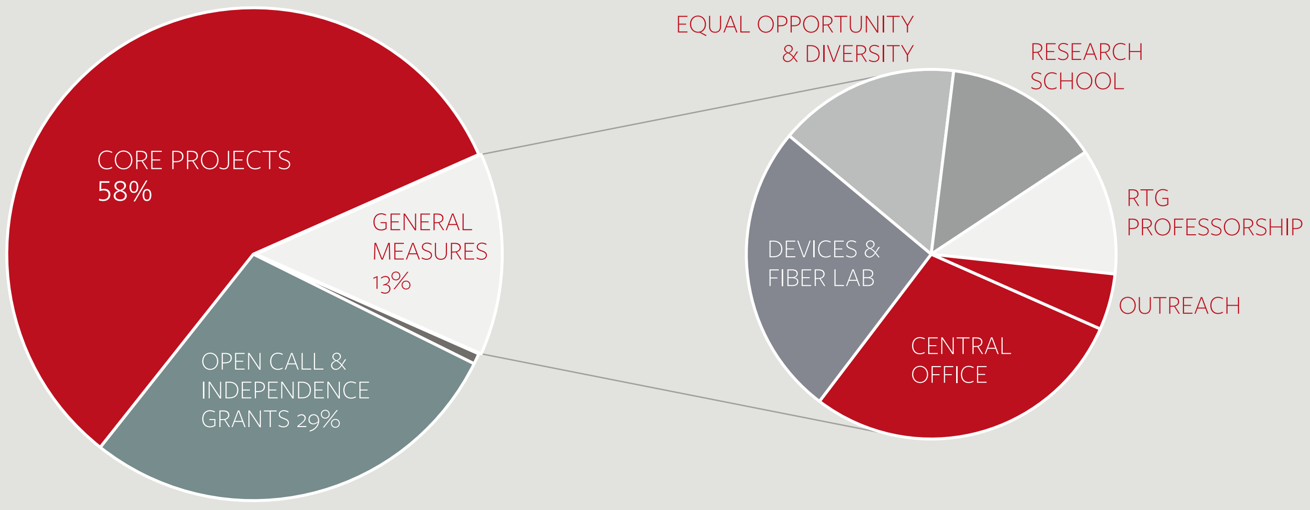
ANICA HAMER

“Whether you're constantly tidying up the lab like me or working in the chaos, the mood of a laser or other fickle devices is unpredictable.

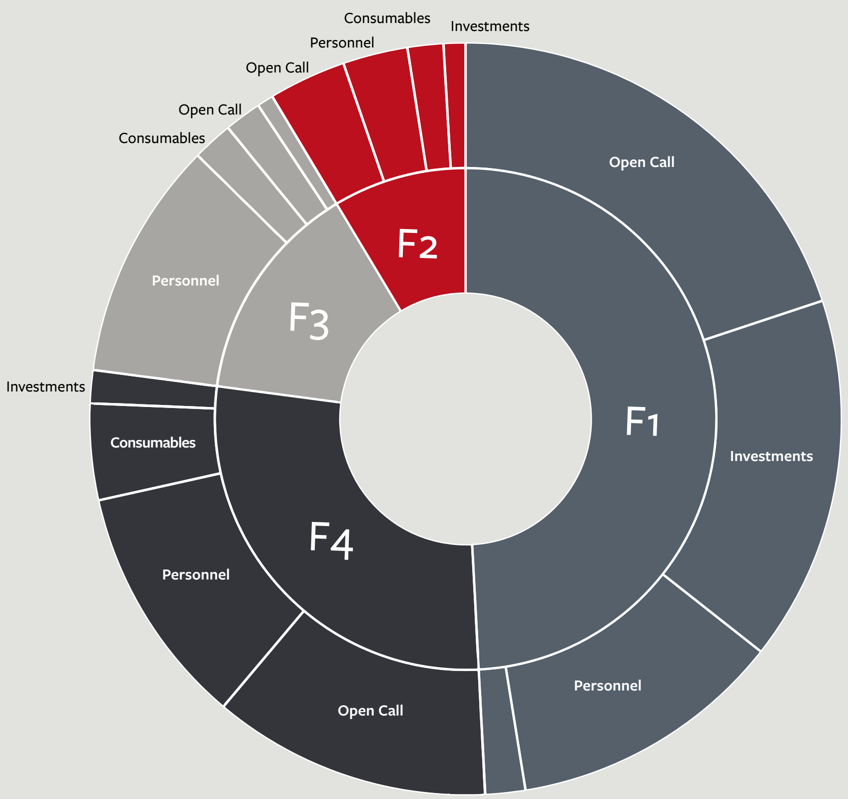
Anica started her master thesis in 2021 in the Quantum Metrology group in Bonn under the supervision of Simon Stellmer. In her project, she studied single-photon frequency conversion in a collaboration with Beata Kardynał's lab at Forschungszentrum Jülich. Her paper was accepted early 2022 to appear in Quantum Letters (see Focus Area 4 report on pages 38/39).

ML4Q **IN NUMBERS**

CORE PROJECTS & CENTRAL MEASURES



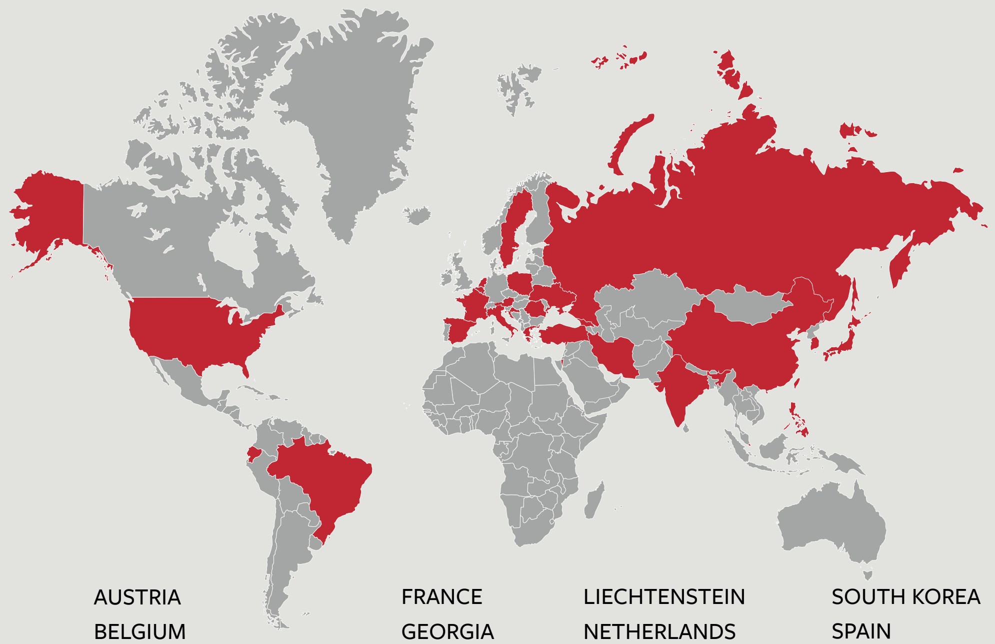
In 2021, 58% of the expenses were dedicated to personnel, instrumentation and consumables in the core projects. While funds allocated to Open Call projects made up only 2% of the expenses in 2019 and 16% in 2020, 19 Open Call projects and Independence Grants were granted almost one third of the total expenses in 2021. As in the previous years, expenses for supporting measures (research school, equal opportunity, workshops and outreach) as well as the Fiber Lab, ML4Q Devices and the central office made up about one tenth 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 2021 broken down by Focus Area and type of fund. All Focus Areas experienced additional growth in 2020 through the Open Call projects.

INTERNATIONALIZATION

All academic groups experienced growth in 2021 on both a national and an international level. 38% of ML4Q members and associated members are international scientists coming from 30 countries (see map below). As in the previous years, postdoctoral scientists still show the highest level of internationalization (62%) while the internationalization in other academic groups is about half as high.



AUSTRIA
BELGIUM
BOSNIA & HERZEGOVINA
BRAZIL
CANADA
CHINA
ECUADOR
EGYPT
FRANCE
GEORGIA
GREECE
INDIA
IRAN
ISRAEL
ITALY
JAPAN
LIECHTENSTEIN
NETHERLANDS
PHILIPPINES
POLAND
ROMANIA
RUSSIA
SINGAPORE
SOUTH KOREA
SPAIN
SWEDEN
TAIWAN
TURKEY
UKRAINE
USA

NEW DEVELOPMENTS IN 2021

As research on quantum science and technology is experiencing a boost in state as well as industrial funding, the academic landscape has been triggered accordingly – leading to the recruitment of excellent young scientists and the establishment of several professorships in our partner institutions.

In 2021, the first ML4Q professorship was offered to **Erwann Bocquillon** who joined the University of Cologne in October to work on Topological Quantum Computing Architectures. In addition, the University of Bonn appointed **David Luitz** to start his ML4Q professorship in Theoretical Quantum Many-Body Physics as of January 1st, 2022. A bit slowed down by the pandemic, **Sebastian Hofferberth** finally established his new lab at the Institute for Applied Physics at the University of Bonn heading the Nonlinear Quantum Optics group. **Martin Kliesch** joined the Heinrich Heine University Düsseldorf as junior professor and Emmy Noether fellow leading working on the Quantum Technology group and working Quantum Computing Theory. A great brain gain was accomplished by the RWTH Aachen and Forschungszentrum Jülich by successfully recruiting **Silvia Viola Kusminskiy** and **Rami Barends** who bring in their expertise in the Theory of Quantum Hybrid Systems and Functional Quantum Computing from their previous work at the Max Planck Institute for the Science of Light and the Google Quantum A.I. Lab, respectively.

ERWANN BOCQUILLON

CURRENT POSITION Professor for Experimental Physics, University of Cologne

PREVIOUS POSITION CNRS Researcher (« Chargé de recherche »), Laboratoire de Physique de l'ENS, Paris

FIELD OF EXPERTISE Quantum transport, quantum electronics, topological insulators

WHY COLOGNE? To contribute to an ambitious research program in an excellent environment, but also to find better work and life conditions and a better work-life balance.

CONTRIBUTION TO ML4Q Hopefully the realization of flying Majorana excitations in quantum anomalous Hall insulators.

BIGGEST CHALLENGE Besides scientific challenges, (rapidly) building a new lab, an efficient team and a positive and inclusive atmosphere requires energy and dedication on a daily basis!

FUNDAMENTAL OR APPLIED RESEARCH? I love to tackle fundamental questions but I can also be nerdy about technological aspects. I see this rather as a complementary approach rather than a contradiction. One of my mentors (Teun Klapwijk) referred to the Pasteur's quadrant (following a classification by D.E. Stokes) as Pasteur bridged the gap between basic and applied research unlike Edison or Bohr who were bright minds but focused exclusively either on applied or basic research.

FAVORITE SCIENTIST No particular name comes to my mind, but as explained above, I am impressed by people having a broad range of knowledge from fundamental to applied aspects, or in different fields.

DISCOVERY YOU WISH YOU WERE PART OF The fabrication of one of the most sensitive experiments ever, and involving quantum physics at the kg and kW scale: the gravitational wave interferometers LIGO and Virgo.

MOST SCIENCE-UNRELATED HOBBY YOU EVER HAD Trail running. Though I did thoroughly monitor my pace and heart rate as an experimental physicist!

MARTIN KLIESCH

CURRENT POSITION Junior-professorship and Emmy-Noether group leader

PREVIOUS POSITION POLONEZ fellow (Marie-Curie Cofund)

FIELD OF EXPERTISE Quantum computing, characterization of quantum computing components

WHY DÜSSELDORF? The area is very attractive for researchers interested in quantum computing with many potential collaborators.

CONTRIBUTION TO ML4Q Identify experimentally feasible quantum computing settings that allow for a practically relevant quantum advantage. Promising and relevant computational problems come from the areas of quantum chemistry and condensed matter physics.

BIGGEST CHALLENGE Managing at the same time a scientific career and raising children in a modern way.

FUNDAMENTAL OR APPLIED RESEARCH? Both! However, at the moment fundamental research on rigorous quantum algorithms, especially in the area of the characterization of quantum devices, is more important. Currently, a lot of funding is available for applied industry-related research. In order to increase chances for lasting progress, this effort urgently requires a backing of foundational research for many reasons.

FAVORITE SCIENTIST There are many scientists who I admire and I find it difficult to highlight a particular one. What I find important, in particular in current times, is that scientists focus on actually doing science. Most of us get distracted by science politics, science management, science marketing, science communication etc., so that the actual scientific work becomes increasingly superficial.

DISCOVERY YOU WISH YOU WILL BE PART OF The demonstration of the first useful real-world quantum advantage. Ideally, this would come along with both, mathematically rigorous guarantees and industry-relevant applications.

MOST SCIENCE-UNRELATED HOBBY YOU EVER HAD Having kids, I guess. I also love rock climbing but this hobby has many parallels to doing research.

SEBASTIAN HOFFERBERTH

CURRENT POSITION Professor in the Institute for Applied Physics at the University of Bonn – head of the Nonlinear Quantum Optics group

PREVIOUS POSITION Professor at the University of Southern Denmark and head of the Nonlinear Quantum Optics group

FIELD OF EXPERTISE Quantum optics, ultracold atoms, Rydberg physics, quantum technology

WHY BONN? Bonn is a "hot place" for quantum optics in general and light-matter interaction at the quantum level in particular. Our work fits very well into this area and continues this "tradition" in Bonn.

CONTRIBUTION TO ML4Q We work on Rydberg-based quantum technology in the areas of quantum computing and quantum interconnects.

BIGGEST CHALLENGE Moving a research group and a family from abroad in Covid times.

FUNDAMENTAL OR APPLIED RESEARCH? We explore photon-atom interactions at the most fundamental quantum level - both to investigate core concepts of quantum mechanics - but also to turn this basic research into new concepts for applications in quantum computing and communication.

FAVORITE SCIENTIST If this is about "famous" physicists, I cannot say. I don't really know enough about any of them to consider them favorites. On a more spontaneous level, I usually jump multiple times per day between students and colleagues I consider as super-cool, because they just did something brilliant and showed it to me.

DISCOVERY YOU WISH YOU WERE PART OF So many to choose from - somewhat random: the first observation of lasing. Seeing the red ruby light must have been really cool.

MOST SCIENCE-UNRELATED HOBBY YOU EVER HAD I play drums (if and when I have time) - but that's actually not so science-unrelated, music is quite scientific.

NEW DEVELOPMENTS IN 2021

SILVIA VIOLA KUSMINSKIY

CURRENT POSITION Professor of Physics at the Institute for Theoretical Condensed Matter in RWTH Aachen University and Max Planck Research Group Leader at the Max Planck Institute for the Science of Light in Erlangen (until the end of 2022)

PREVIOUS POSITION Max Planck Research Group Leader at the Max Planck Institute for the Science of Light in Erlangen

FIELD OF EXPERTISE Theoretical physics at the intersection between Condensed Matter Theory and Quantum Optics, light-matter interaction in mesoscopic systems.

WHY AACHEN? The region presents excellent opportunities for collaborations in my area of expertise both with theoretical and experimental groups, in particular considering the groups participating in the ML4Q cluster.

CONTRIBUTION TO ML4Q To apply theoretical methods of light-matter interaction specifically tailored for the experimental platforms in the cluster, in particular cavity-enhanced methods for control and readout of qubits in 2D materials and more generally solid-state qubits.

BIGGEST CHALLENGE To find a good balance in my schedule to devote enough time for regular scientific discussions with the members of my group.

FUNDAMENTAL OR APPLIED RESEARCH? We do fundamental research but with a keen eye on possible applications in quantum technologies.

FAVORITE SCIENTIST Here I guess I have to be boring: Albert Einstein

DISCOVERY YOU WISH YOU WERE PART OF General Relativity! This is my favorite theory due to its mathematical elegance and the profound implications it had in the way we think about space and time.

MOST SCIENCE-UNRELATED HOBBY YOU EVER HAD I wanted to be a lifeguard when I finished high-school. The university schedule was not really compatible with spending four months at the beach during summer...

RAMI BARENDS

CURRENT POSITION Director of the Peter Grünberg Institute for Functional Quantum Systems (PGI-13) at Forschungszentrum Jülich and Professor in RWTH Aachen University

PREVIOUS POSITION Research scientist at Google Quantum AI as part of the Martinis Group at the University of California in Santa Barbara

FIELD OF EXPERTISE Qubit design and device architecture in the superconducting platform, development of validation tools in small- and large-scale systems, cryogenic engineering

WHY JÜLICH? Jülich has a densely interwoven ecosystem of researchers from different fields which makes it a great location for competitive research.

CONTRIBUTION TO ML4Q In my new team, I want to construct an architecture and develop a methodology that can enable useful quantum computing. There are many aspects to this challenge. In particular research into algorithms and fundamental materials properties can overlap synergetically with ML4Q.

BIGGEST CHALLENGE To go back to the core and figure out what we can actually build, in other words to lay the scientific and technological foundations to build a system that can be something on the path towards usefulness.

FUNDAMENTAL OR APPLIED RESEARCH? In application-driven research, for example in enabling useful quantum computing, you can end up doing a lot of fundamental research, for example to understand fundamental physical limitations. So in my mind there's no clear border between fundamental and applied research, we'll be doing both.

FAVORITE SCIENTIST There are many! I admire Niels Bohr and his fundamental work on quantum mechanics. But I also like the problem- or application-driven spirit of Louis Pasteur who ended up doing really fundamental science, however with a specific application in mind.

DAVID LUITZ

CURRENT POSITION Professor at the University of Bonn

PREVIOUS POSITION Group Leader at the Max Planck Institute for the Physics of Complex Systems in Dresden

FIELD OF EXPERTISE Quantum Many-Body Physics, Nonequilibrium Quantum Mechanics, Entanglement and Quantum Information

WHY BONN? Bonn is an excellent place for my research. As a University of Excellence, it hosts many outstanding research groups I enjoy interacting with and the embedding in the regional environment (in particular the other ML4Q sites) is a unique opportunity for generating new ideas.

CONTRIBUTION TO ML4Q I would like to push forward on the one hand a true many-body understanding of quantum computers, and in particular their noise processes, which are a major roadblock for general purpose quantum computing. On the other hand, I am very much interested in the application of quantum computers available in the near term for fundamental research, in particular for studying quantum many-body physics relevant for example in condensed matter physics, light-matter systems and quantum chemistry. Performing so-called digital quantum simulations is a paradigm shift within computational physics, which we aim to achieve in the future.

BIGGEST CHALLENGE Starting a faculty position after many years of pure research is exciting and certainly a true challenge. Essentially, one has to learn to deal with three jobs, and keeping all balls in the air isn't easy, but I find the experience also highly rewarding.

FUNDAMENTAL OR APPLIED RESEARCH? Our research is of purely fundamental nature. We are interested in fundamental mechanisms and phenomena in nature, and view quantum computing platforms as a tool to further our understanding.

FAVORITE SCIENTIST Carl Friedrich Gauß - one of the giants who set the stage for today's research.

DISCOVERY YOU WISH YOU WERE PART OF Oh, there are many! Certainly one of the recent discoveries which fascinated me most was the first observation of a binary black hole merger through gravitational waves. I remember reading the PRL paper with great excitement, like many of us -- the journal server was temporarily not available to download the pdf.

MOST SCIENCE-UNRELATED HOBBY YOU EVER HAD I enjoy singing in a choir very much. Unfortunately, the many moves in the past years have completely disrupted this practice and due to the general lack of time it will probably take a while before I can pick this up again.

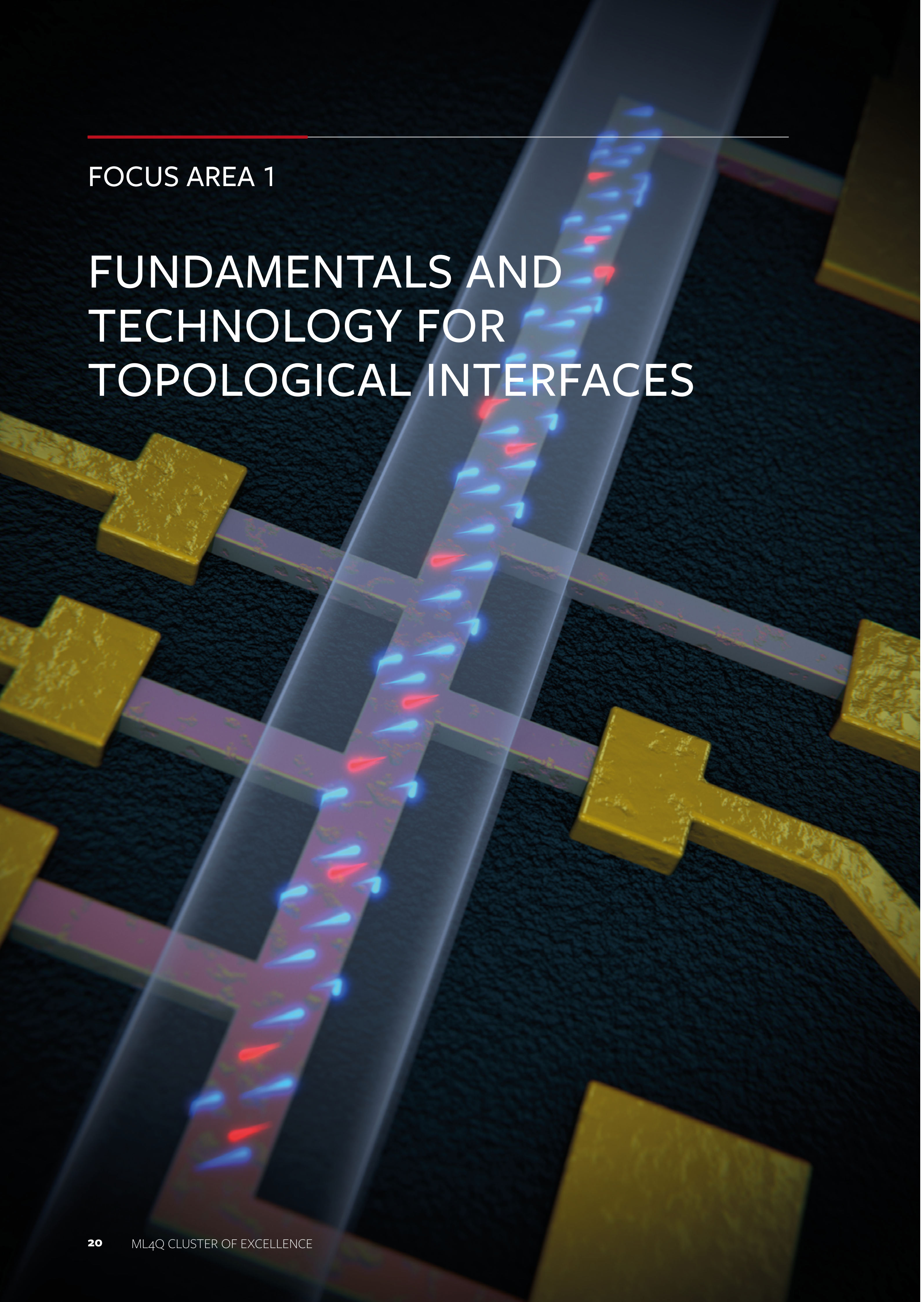
“

The region presents excellent opportunities for collaborations in my area of expertise both with theoretical and experimental groups, in particular considering the groups participating in the ML4Q cluster.

SILVIA VIOLA KUSMINSKIY

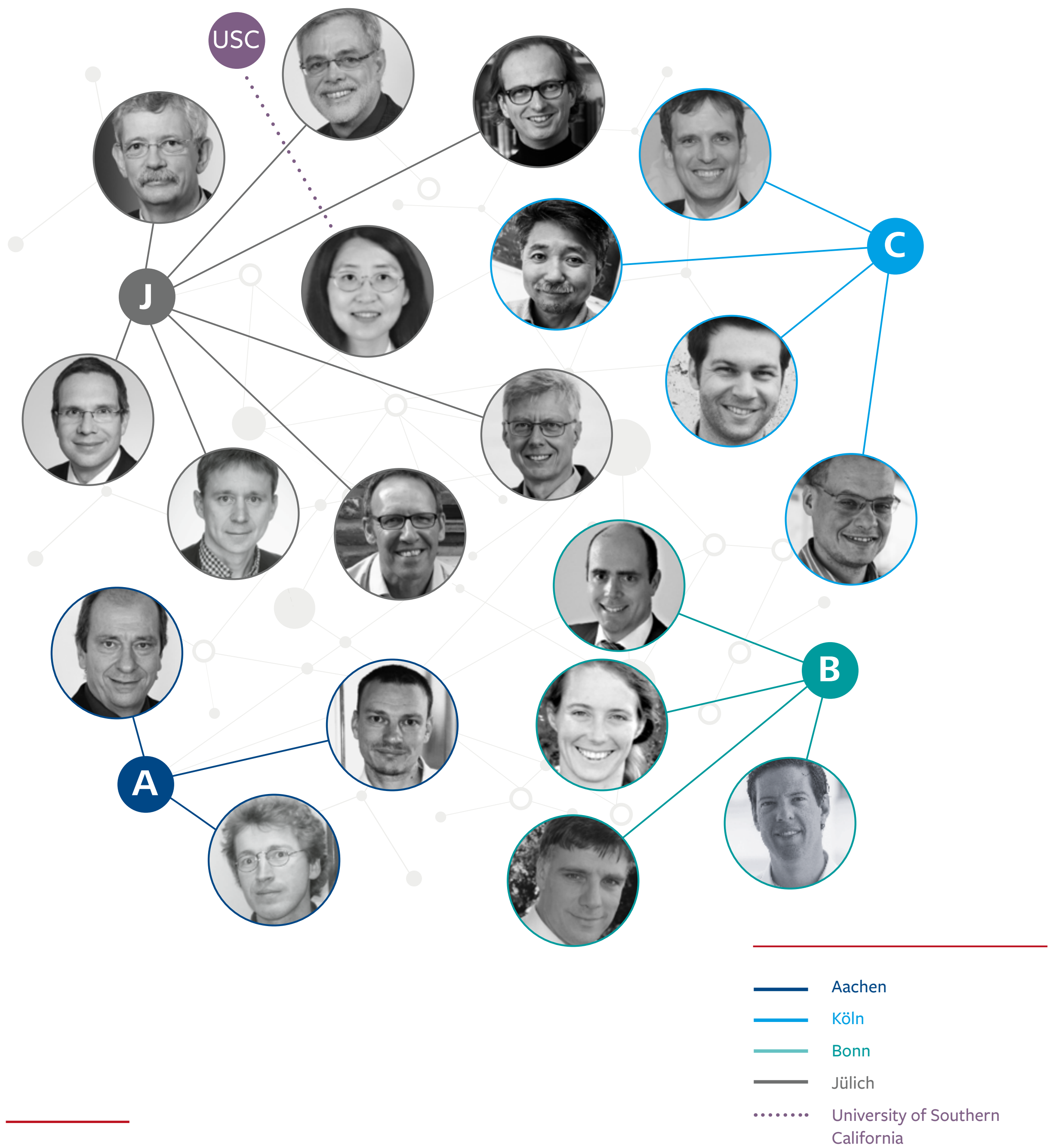
02

ML4Q
RESEARCH



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

Focus Area 1 tackles fundamentals and technology of topological interfaces. The focus are 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 states by light.

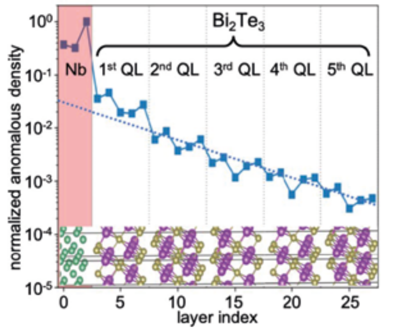
1 FOCUS AREA

ACHIEVEMENTS

One goal of Focus Area 1 is to realize nanowires from topological insulators (TIs), whose surface states become superconducting (SC) due to the superconducting proximity effect. Such wires will host robust Majorana zero modes in the presence of small magnetic fields. This program poses several challenges on the materials' side: The nanowires have to be bulk insulating and interfaces should be highly transparent to allow for a robust and efficient proximity effect. There should be rough match of work functions of SC and TI to suppress excessive doping and to avoid large potential differences of parts of the nanowires covered and not covered by the SC. Finally, even tiny densities of charged defects on the ppm level may induce large potential fluctuations, inducing uncontrolled and undesirable Majorana states. Substantial progress was achieved both in theory and experiment in these directions. On the theory side, a new ab-initio code was developed [1] by the Blügel group and implemented into the JuKKR code to make it available to the community. This code allows to calculate reliably and optimize proximity effects and workfunctions (see figure). Similarly, simulations of the formation of electron-hole puddles due to charged impurities (as performed by the Rosch group) allowed to quantiatively address their effect on device operation. Experimentally, several new SC-TI interfaces have been explored. Following our discovery of the self-formation of $PdTe_2$ superconductor in Pd-deposited $Bi_{2-x}Sb_xTe_3$ (BST) thin films, the groups of Ando and Mayer have developed a novel route to realize superconducting TI nanowires by using the Pd diffusion into BST thin films [2]. The Grüneis group explored a new TI/SC interface, combining the organic SC Rb_3C_{60} with the TI Bi_4Te_3. For the selective-area growth of nanowires and the fabrication of TI/SC Josephson junctions, the Grützmacher and Mussler groups found that sapphire substrates have major advantages compared to, e.g., silicon substrates. They accomplished the bulk and selective-area growth of (Bi,Sb)(Te,Se)-based TI films on sapphire substrates with the focus of reducing the bulk carrier concentration [3]. Transport experiments show substantially higher mobilities of these samples with respect to comparable TI films grown on Si substrates. In addition, they have successfully employed the shadow mask technique to realize in-situ grown TI/superconductor Josephson junctions grown on sapphire substrates. Transport experiments on these samples are currently being performed. An alternative preparation technique is the van-der-Waals stacking, allowing to combine flexibly 2D SCs, transition metal dichalcogenites with, e.g., bilayer graphene where high-quality spin-valley qubits have been achieved [4].

A key to understanding and controlling sample quality and inhomogeneity is the characterization of materials, especially using methods with a high space resolution. Scanning tunnelling microscopy (STM) as performed in the Morgenstern and Ando groups allows to explore directly the proximity effect [5,6,7] using, e.g., nanostructured $Nb/(Bi,Sb)_2Te_3$ samples and to map fluctuations induced by inhomogeneity in the materials quantitatively [5]. A new low-temperature four-tip magnetic STM will extend the capabilities in this direction considerably. In addition, electron microscopy as performed in the Mayer group tracks the quality of nanowires and epitaxial interfaces [2] and ARPES is used by the Grüneis and Plucinski groups to measure the opening of gaps. The Ando group found record-high electric breakthrough currents – despite the presence of electron-hole puddles – in their magnetic TI samples showing the quantum anomalous Hall effect [8]. Another discovery, a giant magnetochiral anisotropy in TI nanowires – many orders of magnitude larger than in other materials – can be used as a fingerprint of the gate-control of TI surface states [9; see paper highlight on pages 24/25].

Towards the goal to create Majorana and parafermion modes in cold atom systems, the Weitz group succeeded to observe Erbium atoms in the lowest Landau level of a "synthetic" quantum Hall system in a two-dimensional state space spanned by internal degrees of freedom and real space. A theory-experiment collaboration between the Kollath, Rizzi, Diehl and Köhl groups continues to work towards a realization of Majorana fermions in Hubbard ladders. Here, a key to is to suppress single-particle tunnelling while enhancing pair tunnelling which can be achieved using oscillating fields [10].



Exponential decay of the proximity effect in a SC/TI heterostructure (courtesy by S Blügel, unpublished).

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GIANT MAGNETOCHIRAL ANISOTROPY FROM QUANTUM-CONFINED SURFACE STATES OF TOPOLOGICAL INSULATOR NANOWIRES

BY HENRY F LEGG, MATTHIAS RÖSSLER, FELIX MÜNNING, DINGXUN FAN, OLIVER BREUNIG, ANDREA BLIESENER, GERTJAN LIPPERTZ, ANJANA UDAY, ALEXEY A TASKIN, DANIEL LOSS, JELENA KLINOVAJA & YOICHI ANDO

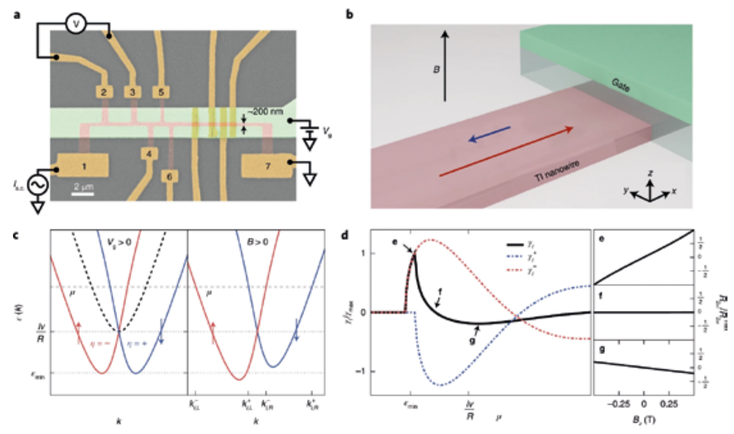
NATURE NANOTECHNOLOGY (2022) doi.org/10.1038/S41565-022-01124-1

In a collaboration with the group of Daniel Loss and Jelena Klinovaja at the University of Basel, the Ando lab succeeded to demonstrate that wires more than 100 times thinner than a human hair can act like a quantum one-way street for electrons when made of a peculiar material known as a topological insulator. The discovery opens the pathway for new technological applications of devices made from topological insulators and demonstrates a significant step on the road to achieving so-called topological qubits, which could help to robustly encode information for a quantum computer.

Topological insulators are materials in which a combination of quantum mechanics and the mathematical concept of topology produce conductive surfaces and insulating interiors. In this work, the researchers were able to show that, under the right circumstances, electric currents can flow more easily in one direction compared to the other, a process known as rectification. Rectification offers a wide range of applications and forms the basis of most wireless technologies.

The rectification effect discovered in topological insulator nanowires arises as a result of quantum mechanics and is extremely controllable. The high degree of control allowed the team of researchers to achieve a truly gigantic rectification effect compared to what had previously been observed, paving the way to create topological qubits. Thus, the study does not only discover a unique and very large quantum effect, but it also shows that all the key properties of topological insulators are there to move forward on the path to making topological qubits.

> “Usually, quantum rectification effects arise as a result of something known as spin-orbit coupling, which is actually a mix of quantum mechanics and Einstein’s theory of relativity. That strange mix normally results in tiny rectification effects. What is great about the topological insulator nanowires is that we can artificially produce essentially the same physics but with a much larger magnitude. This leads to a rectification effect that is really huge compared to other materials. It is also one of the aspects that makes topological insulators so exciting for applications in quantum computing.
>
> HENRY LEGG



In thin wires, smaller than a typical bacterium, made of a topological insulator (red) (Fig. 1a), applying a magnetic field as well as an electrostatic field via a gate-electrode (green) in a specific direction (Fig. 1b) results in a characteristic splitting of the energy bands which electrons can access (Fig. 1c). This behaviour caused by an interplay of quantum mechanical and relativistic effects allows electric currents to flow more easily in one direction compared to the other when sent through the device via its contacts (yellow). This process, known as rectification, is predicted by theory to be exceptionally large in such wires and to show a characteristic sign change (Fig.1d), both observed in experiments.

TRIVIA

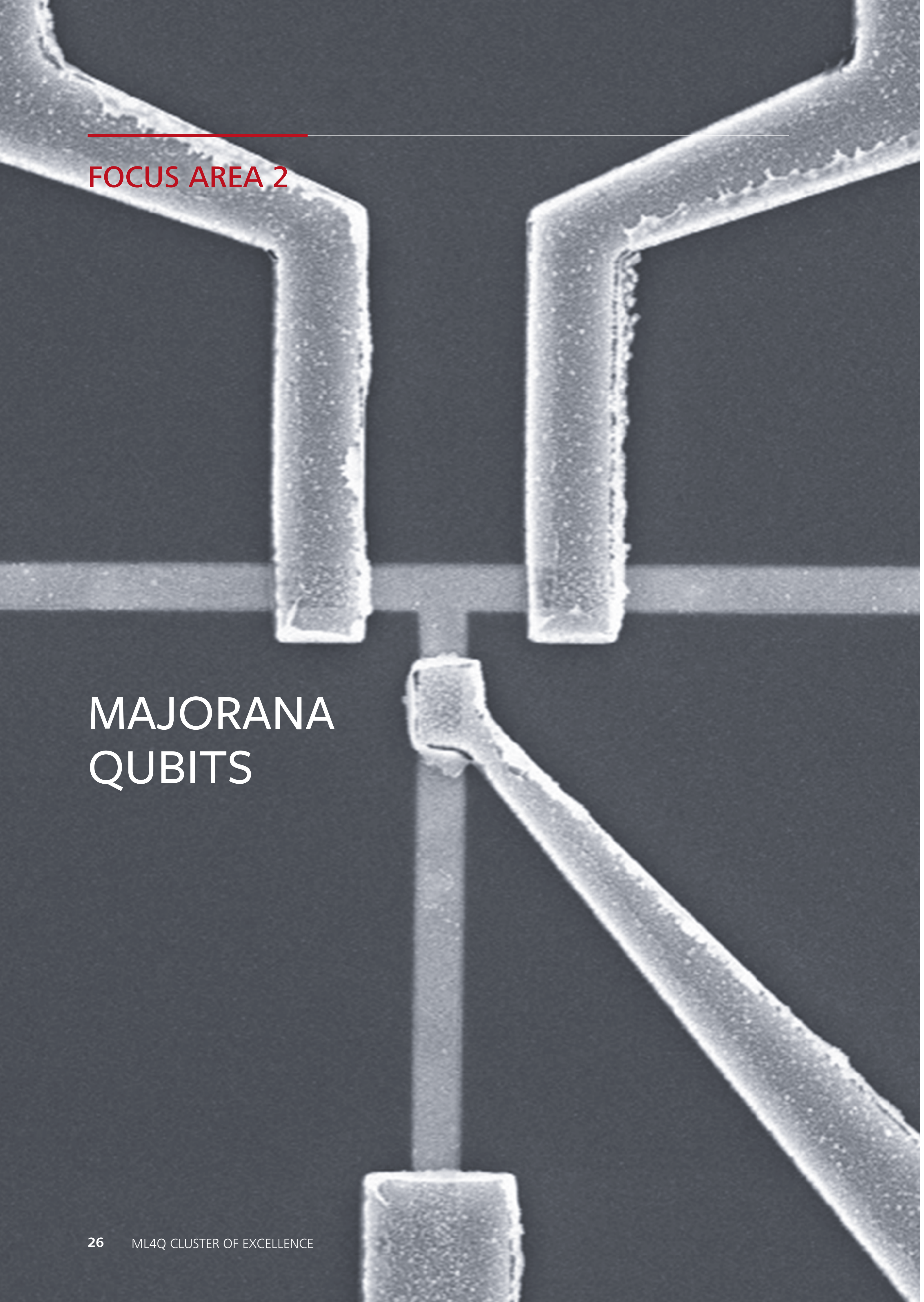
100

TIMES THINNER

TOPOLOGICAL INSULATOR NANOWIRES ARE MORE THAN 100 TIMES THINNER THAN A HUMAN HAIR.

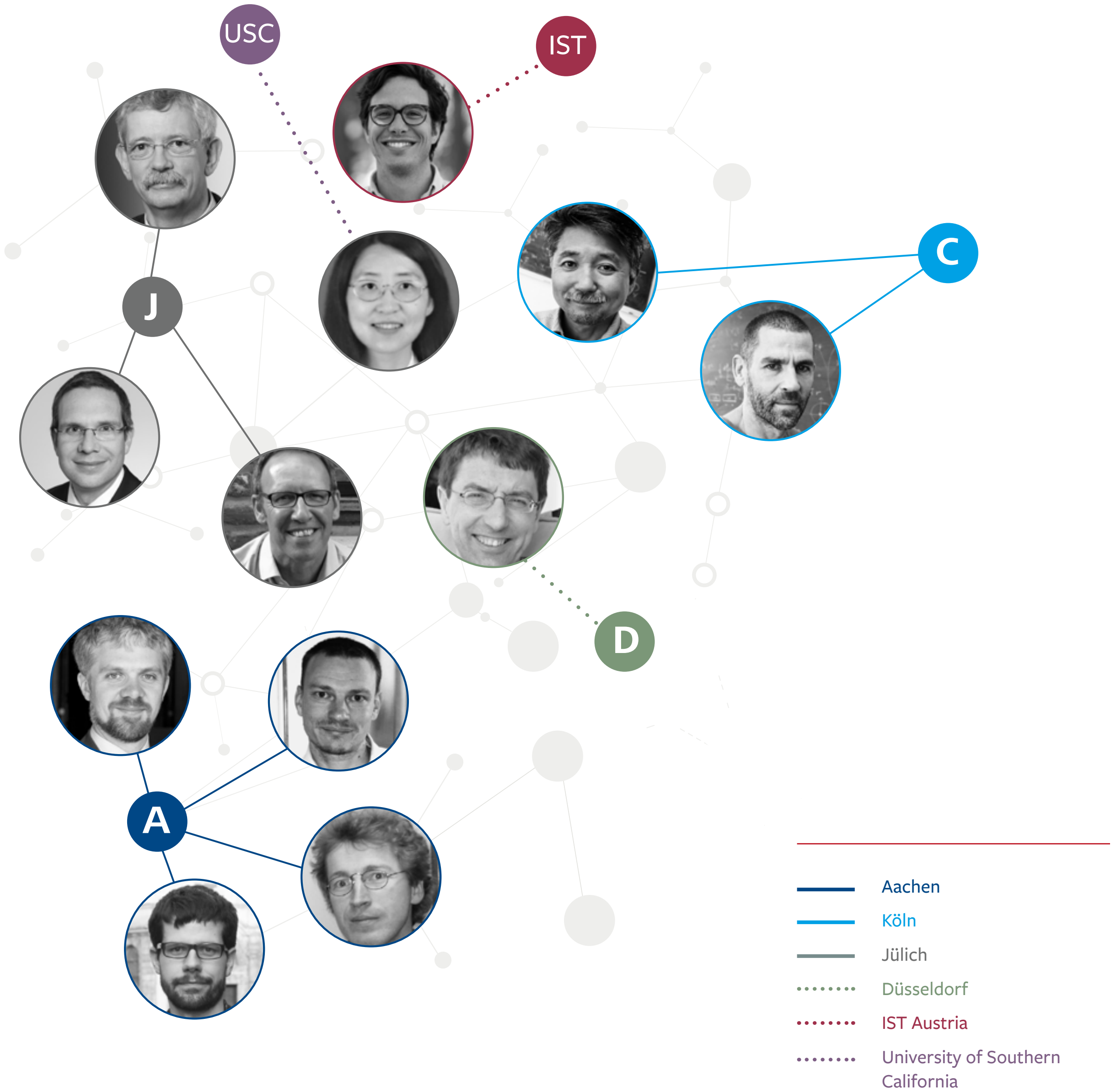
THE TEAM

Henry Legg and Matthias Rößler have worked together in Cologne on topological insulator nanowires for several years including long discussions, arguments and, of course, lots of beer. After Henry’s move to Basel for his postdoc in 2020, Zoom kept the discussion running and even increased its pace, resulting in an unpreceded understanding of the system.



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

Following the successful installation of the capability to perform superconducting qubit experiments in the Ando group in Cologne, the magnetic-field resilience of aluminum-based 3D transmon qubits was studied. By making the constituting aluminum to be thinner than 20 nm, a microsecond coherence in magnetic fields approaching 1 T has been achieved [1, see figure]. This demonstrates the feasibility of applying the advanced Al/Al_2O_3-based transmon technology to Majorana qubits, which requires quantum coherent measurements in high magnetic fields.

The AC Josephson effect in Nb-$(Bi_{0.06}Sb_{0.94})_2Te_3$ (BST) junctions with varying width was studied in the Schäpers group in Jülich and it was found that the missing first Shapiro step, which points to the existence of Majorana modes, is observed only in wide junctions. This suggests the opening of a topological gap due to the quantization of transverse momentum sub-bands [2; see paper highlight on pages 31/32]. In the studies of topological insulator nanoribbon networks – as a step towards Majorana quantum processors –, in-situ prepared 3-terminal Josephson junctions were investigated in the presence of in-plane magnetic fields and an interesting symmetry breaking effect was observed [3].

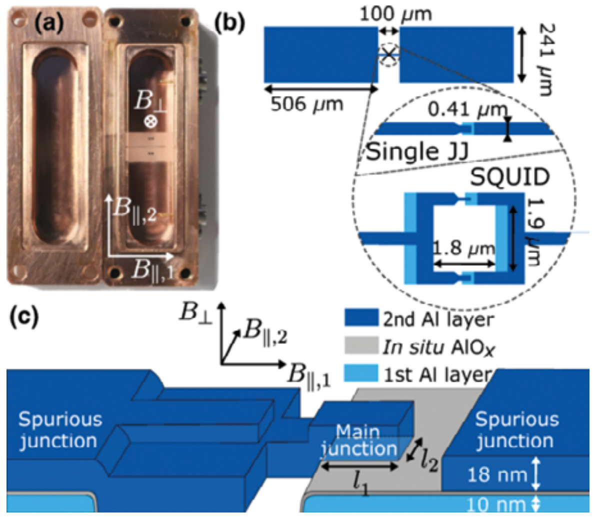
In this Focus Area, the Majorana bound state formed in a superconductor anti-dot made on the surface of a topological insulator is pursued as a potential building block for Majorana qubits. Experiments are being performed in the Ando lab in Cologne, in which tunnel junctions are fabricated on the topological-insulator surface in such anti-dots, and the gate-voltage dependencies of the spectra are measured with/without a trapped flux.

The theoretical analysis of this set-up was performed by the Hassler group in Aachen who could show that, to increase the topological protection, it is important to tune the chemical potential close to the Dirac point and minimize the vortex radius [4].

Theoretical contribution of the Egger group in Düsseldorf focused on the analysis of the heat transport through a Majorana island and found a universal violation of the Wiedemann-Franz law due to the presence of Majorana states [5, 6]. This points to the possibility that heat transport experiments could provide Majorana evidence superior to simple zero-bias peaks in transport spectroscopy.

In theoretical studies of the topological states of matter that arise in open systems which connects to Focus Area 3, a novel method to engineer driven-dissipative topological systems without the need of external driving was figured out [7], providing an alternative way to realize topologically non-trivial driven-dissipative systems. This method can also be used for engineering higher-order topological states and crystalline topological insulators [8]. In the analysis of a chain of parafermions that might be realized in Focus Area 1, its stability with respect to interactions was confirmed [9], thus pointing out that such a system can be a viable platform to realize topological qubits beyond the Majorana paradigm.

A new Open Call project to apply optimal control theory to the future topological qubits has started, in which the initial efforts are focused on improving the quasiparticle-parity readout of a Transmon or a Cooper-pair box, by implementing new theoretical ideas in actual experiments.



3D copper cavity with two transmons, referred to as the single-Josephson-junction transmon and the SQUID transmon. (b) Top view of the transmons, with enlargement of the junction region for both the single-JJ and the SQUID device. (c) Sketch of a Dolan-bridge JJ, relating the magnetic field coordinate system $(B_{\parallel,1}, B_{\parallel,2}, B_\perp)$ to the JJ geometry [1].

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REAPPEARANCE OF FIRST SHAPIRO STEP IN NARROW TOPOLOGICAL JOSEPHSON JUNCTIONS

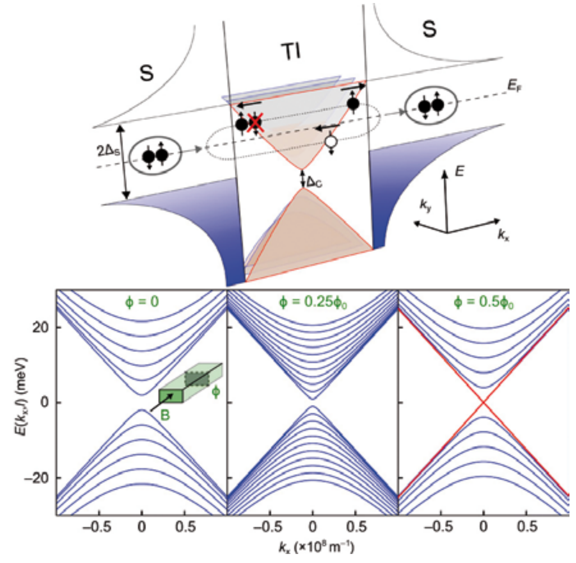
BY DANIEL ROSENBACH, TOBIAS W. SCHMITT, PETER SCHÜFFELGEN, MARTIN P. STEHNO, CHUAN LI, MICHAEL SCHLEENVOIGT, ABDUR R. JALIL, GREGOR MUSSLER, ELMAR NEUMANN, STEFAN TRELLENKAMP, ALEXANDER A. GOLUBOV, ALEXANDER BRINKMAN, DETLEV GRÜTZMACHER & THOMAS SCHÄPERS

SCIENCE ADVANCES 2021; 7 : EABF1854

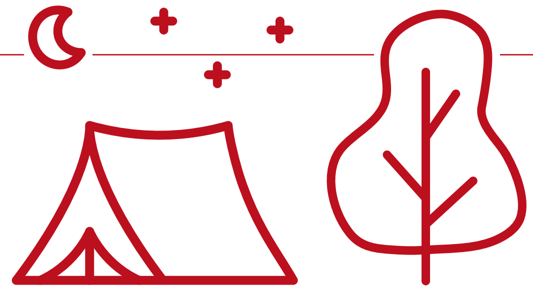
The state of a topological quantum bit is defined by the arrangement of two Majorana zero modes in space and time. In condensed matter, these quasiparticles that constitute their own anti-particles can be identified at zero energy within a superconducting condensate. Within the electron-hole bound state spectrum of Josephson junctions – comprised of two superconducting leads interrupted by a short topological insulator weak link – Majorana bound states are established with a zero-energy solution. These gapless Majorana bound states establish ultimately due to the helical spin dispersion of topological insulators as it prohibits direct backscattering, which leads to a unity probability of quasiparticles at the topological insulator to superconductor interface to undergo an Andreev reflection. Compared to Andreev bound states, the gapless Majorana bound states have a doubled periodicity with respect to the phase difference in between the two superconducting leads. This is identified by a doubling of the voltage standard of Shapiro steps, when the junction is irradiated by a radio-frequency signal. In order to realize locally confined Majorana zero modes, the dimensionality of the topological insulator needs to be reduced from two-dimensional surfaces to a one-dimensional nanowire or nanoribbon. We defined Josephson junctions on topological insulator nanoribbons, which for scalability reasons have been deposited selectively in a pre-defined silicon nitride mask. The confinement of coherent states on the perimeter of the nanoribbon initially gaps the topological surface states and furthermore lifts the spin degeneracy of surface states. Therefore, quasiparticles at the nanoribbon to superconductor interface can be retro-reflected as a state of opposite momentum within the nanoribbon is available. The finite probability to be reflected will result in gapped bound states and a conventional Shapiro step response. In future experiments this can be overcome by applying an in-plane magnetic field, that restores the helical spin dispersion of the topological insulator nanoribbon surface states.

> **It is the spin-momentum locking of topological surface charges that triggers Majorana bound states in Josephson junctions, but also what makes it technically so much more difficult for the same observation in confined nanoribbons of topological insulator materials.**
>
> DANIEL ROSENBACH

Due to the interaction of spin and momentum of topological surface charges the otherwise spin non-degenerate surface states become doubly spin degenerate within confined topological insulator nanoribbons. Due to the spin degeneracy, the probability of quasiparticles at the interface of a topological insulator towards a superconductor to reflect becomes finite. As not every quasiparticle is being Andreev reflected, the bound state dispersion in topological insulator Josephson junctions is gapped and 2p-periodic with respect to the phase difference of the two superconducting leads of the junction.



TRIVIA



5
DAYS

5 DAYS WERE SPENT ON THE CAMPING GROUNDS IN ENSCHEDE WHILE RUNNING EXPERIMENTS AT THE UNIVERSITY OF TWENTE.

THE TEAM

Abdur Rehman Jalil Postdoctoral researcher at the PGI-10 of the FZJ and father of 3, focusing on the growth of high quality topological thin-films and nanostructures via the technique of selective area epitaxy.

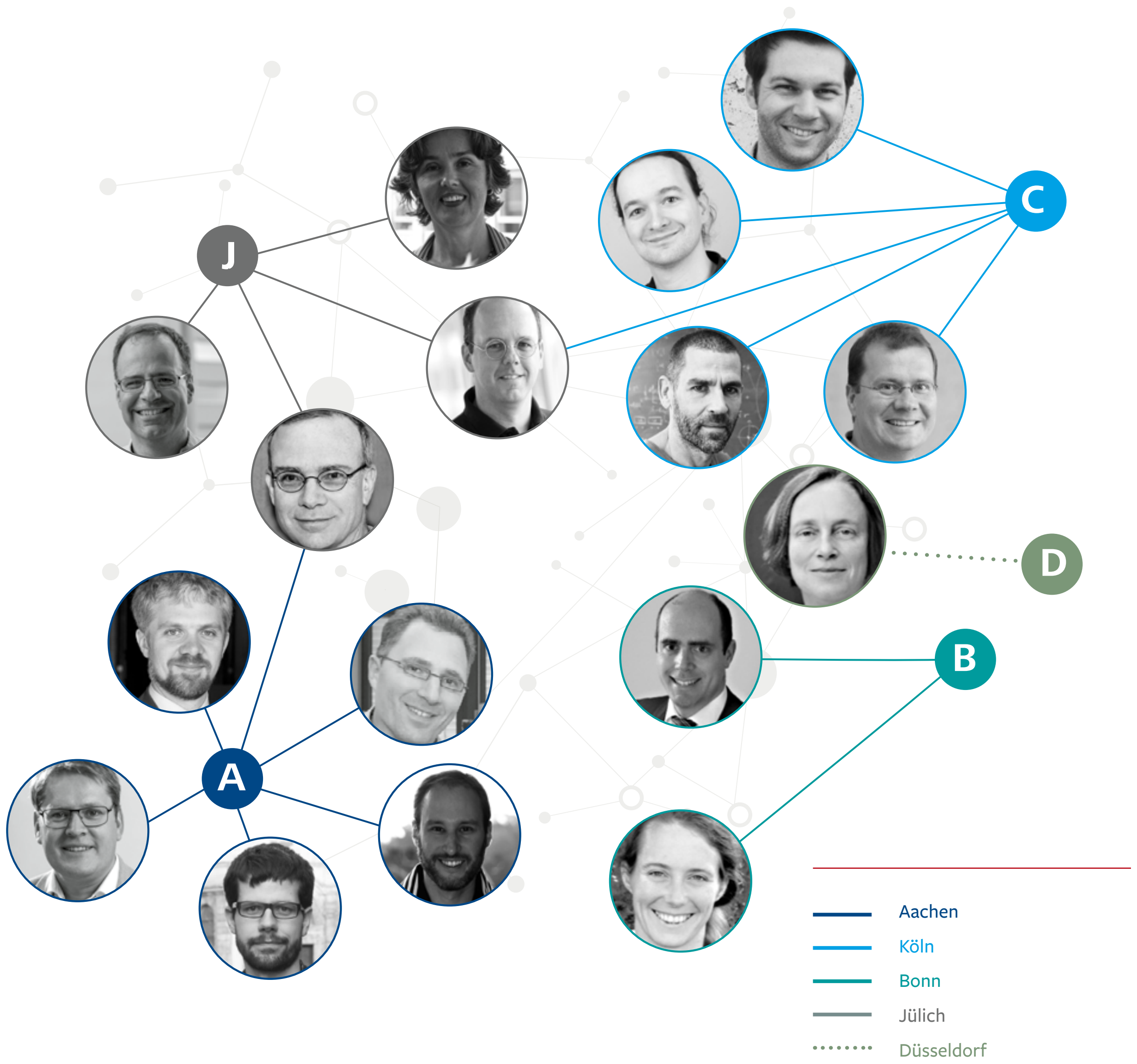
Chuan Li did her PhD in Orsay (south of Paris) on Dirac semimetal-based Josephson devices. Now she is an assistant professor at the University of Twente (The Netherlands), working on topological superconducting devices.

Tobias Werner Schmitt started his master's project on the investigation of Josephson junctions based on topological insulator nanoribbons. As a PhD student, he continued his research on the induced superconductivity in these systems.

Daniel Rosenbach After doing his PhD within the PGI-9 of the FZJ, Daniel Rosenbach continued his topological insulator based research at the University of Twente. He will soon join the ML4Q cluster again as postdoctoral researcher at the University of Cologne.

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*, 15 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

Focus Area 3 continues to work on fully characterizing quantum decoherence, and combatting it with the techniques of quantum error correction, for the achievement of quantum technologies and the quantum computer. The projects of this Focus Area are largely theoretical, with carefully chosen experiments designed to put the theories to the test. Here we highlight the top achievements in 2021.

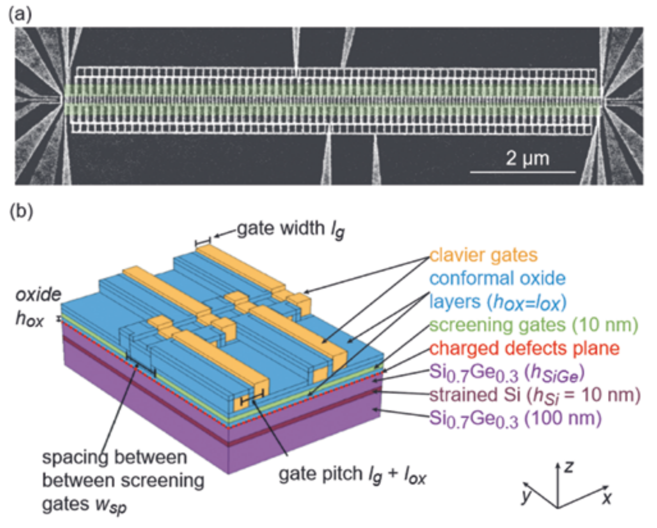
ACHIEVEMENTS

TOPOLOGY IN AND OUT OF EQUILIBRIUM

The Kollath and Rosch groups continue their fruitful collaboration, developing a theory of interacting many-particle systems strongly coupled to the light of a lossy cavity [1]. Fluctuations completely change the nature of the steady state, and lead to universal properties of emerging self-organized states. The Diehl and Müller groups have launched a new collaboration showing that along wave function trajectories, the competition between coherent unitary dynamics and stochastic measurements, performed by the environment, give rise to transitions in entanglement scaling [2]. By examination of the single-particle unitary dynamics, they find that the system undergoes an entanglement transition from a logarithmic growth with system size to an area law when the competition ratio between the unitary evolution and the nonunitary dynamics increases. Diehl also continues his work with the Altland group on measurement-induced phase transitions that are marked by a qualitative change of the behavior of the entanglement entropy [3; see paper highlight on pages 36/37]. They consider a system of free Dirac fermions and show that, by observation alone, the Dirac fermions are made to behave like strongly interacting electrons or planar magnets—they undergo what is known as a Berezinskii-Kosterlitz-Thouless quantum phase transition.

THEORY OF ERROR CHARACTERIZATION, MITIGATION, AND CORRECTION

Deriving effective Hamiltonian models plays an essential role in quantum theory, with particular emphasis in recent years on control and engineering problems. Work of the Calarco group presents two symbolic methods for computing effective Hamiltonian models: the Non-perturbative Analytical Diagonalization (NPAD) and the Recursive Schrieffer-Wolff Transformation (RSWT) [4]. Both NPAD and RSWT have made successful predictions about effective ZZ interaction strengths in superconducting qubit systems. The Gross group continues to develop mathematical tools for resource theory of error mitigation and correction. In one work [5], important steps are taken in determining the properties of "stabilizer extent", a key element of basic tool of quantum error correction. In another [6], the Schur-Weyl duality is extended to the elements of the Clifford group, an essential element in the theory of quantum fault tolerance.



Realistic Si/SiGe Spin Qubit Shuttling (SQuS) device: (a) Scanning electron micrograph of 10 µm long SQuS showing three gate layers: on top of a screening gate layer (colored in green), two clavier gate layers connected to four gate sets for CV mode. Gates at the ends of the SQuS are for the formation of single electron transistors. (b) COMSOL model of the SQuS device from panel a showing two SQuS unit cells and thus eight clavier gates. The typical thickness of layers is given in brackets [7].

ELECTRON SHUTTLING FOR SPIN-QUBIT SURFACE CODE WITH THEORISTS

Painstaking progress continues to be made in the fabrication and testing of the complex structures needed to establish the possibility of spin-coherent shuttling of electrons between quantum structures separated at micron scale. The Bluhm and DiVincenzo groups continue to work together on these questions. Members of their groups, with other European collaborations, have now completed a comprehensive modeling analysis of the shuttling problem [7; see figure], exhaustively analyzing all sources of error in the devices that are being constructed. The important conclusion is that by using surprisingly low magnetic field (around 20 mT), and with materials engineering directed towards achieving the highest possible valley splitting, prospects for the successful operation of the shuttle remain quite optimistic.

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EFFECTIVE THEORY FOR THE MEASUREMENT-INDUCED PHASE TRANSITION OF DIRAC FERMIONS

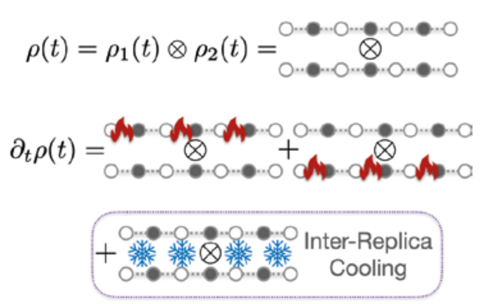
BY MICHAEL BUCHHOLD, YURI MINOGUCHI, ALEXANDER ALTLAND & SEBASTIAN DIEHL

PHYS. REV. X 041004 (2021)

The recent discovery of a novel type of phase transition—driven by the competition between a quantum system's internal evolution and its external observation—has sparked significant research into its nature and origin. Induced by measurements, the transition is marked by a qualitative change of the behavior of the entanglement entropy. Here, we provide the missing bridge from micro- to macrophysics by developing a new theory that describes the transition from the perspective of nonequilibrium quantum statistical mechanics.

The decisive step in understanding the change from microscopic simplicity to macroscopic complexity lies in the identification of the relevant degrees of freedom. Our work takes that step for this novel class of measurement-induced phase transitions. Such transitions then appear as a natural consequence of an underlying quantum field theory, distilling the quantum physics of the monitored many-body wave function from the noisy background that is caused by the random measurement outcomes. To make this more concrete, we consider a system of free Dirac fermions and show that, by observation alone, the Dirac fermions are made to behave like strongly interacting electrons or planar magnets—they undergo what is known as a Berezinskii-Kosterlitz-Thouless quantum phase transition.

Our approach connects the novel class of measurement-induced transitions more firmly to quantum phase transitions. We demonstrate that measurement-induced transitions reflect profound changes in many-body wave functions due to observation. In this picture, the newly discovered entanglement signatures just represent the tip of the iceberg for quantum correlations in monitored many-body wave functions.



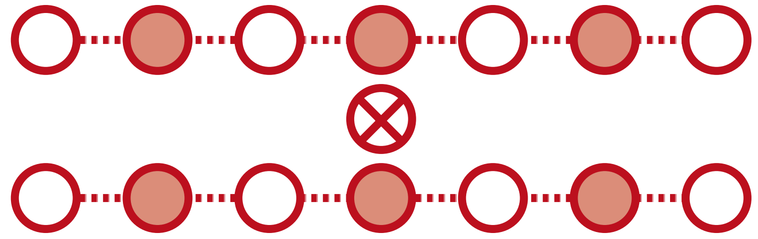
The outcomes of quantum measurements are commonly unpredictable and random. An ensemble of measured wave functions therefore appears to be structureless just as a series of randomly chosen numbers. A non-random structure, and non-trivial quantum correlations are, however, revealed when one inspects two or more identical copies of wave functions, so called replicas. Quantum measurements build out correlations between different replicas in a very similar way as one would observe it by cooling a system into a ground state. The inter-replica correlations are the key to understanding the hidden entanglement in an ensemble of monitored wave functions.

“

MICHAEL BUCHHOLD

Monitoring a quantum-many body system can induce unanticipated quantum correlations, and quantum phase transitions. Compared to ground states, however, the correlations tend to hide themselves within seemingly random wave functions and are revealed only through particularly well-chosen observables.

TRIVIA



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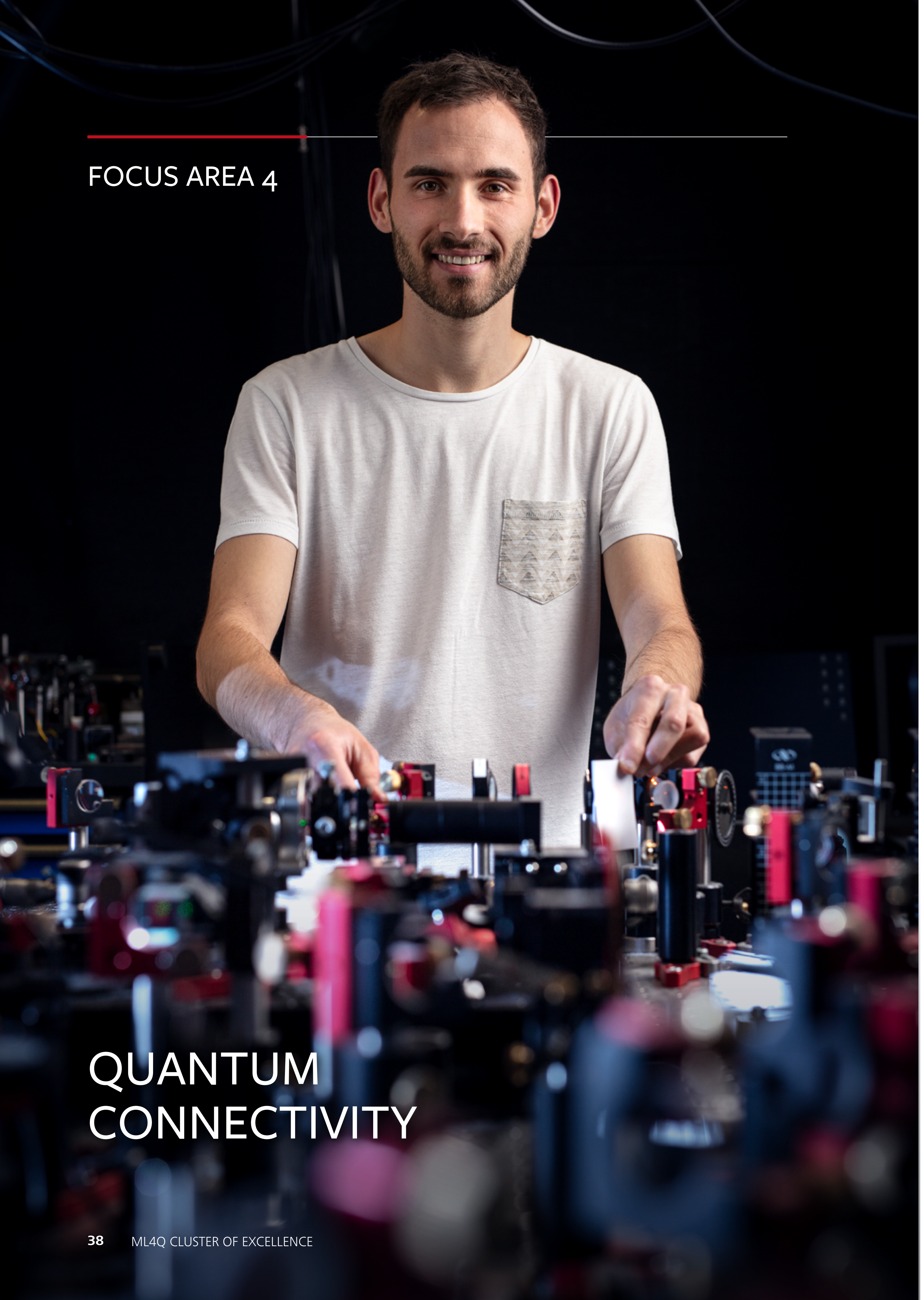
REPLICA

1 REPLICA MAKES THE DIFFERENCE BETWEEN A TRIVIAL RESULT AND OUR PAPER.

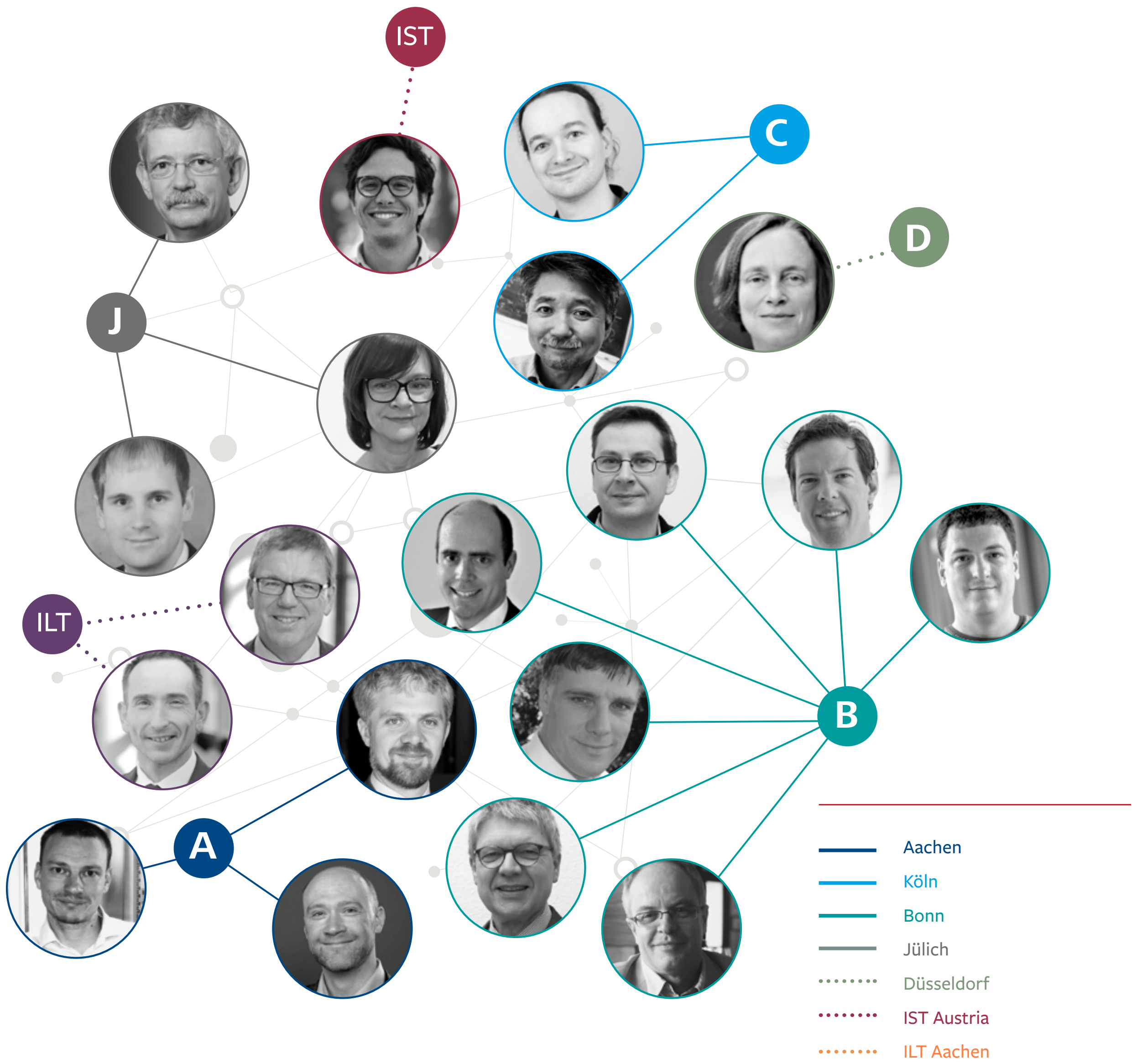
THE AUTHOR

Michael Buchhold has been a senior postdoc at the Institute for Theoretical Physics (ITP) Cologne since 2020, working on quantum dynamics out of equilibrium. Michael did his PhD at TU Dresden and before joining the ITP was a Feodor Lynen Fellow at the California Institute of Technology.



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

Focus Area 4 tackles quantum connectivity by exploring ways to interlink elementary quantum processors and the properties of the resulting quantum networks.

ACHIEVEMENTS

THEORY Our theoretical work continued to analyze the utility of future quantum networks with a focus on anonymous conference key agreement. A key result is the formulation of rigorous security definitions for the described task and the design of a robust and efficient protocol. This led to the striking insight that the performance gain due to multi-partite entanglement is substantially larger when taking anonymity requirements into account compared to what was previously known for other figures of merit [1; see figure]. Furthermore, protocols that provide security independent of assumptions on the devices used were improved [2]. Another paper succeeded for the first time in showing completeness of a systematic method for characterizing quantum correlations in networks [3]. More experiment-oriented theoretical work has provided important guidance for the photon condensate platform pursued experimentally by comparing the merits of different quantum encodings and using detailed simulations to identify ways to achieve the desired high degree of nonlinearity [4,5].

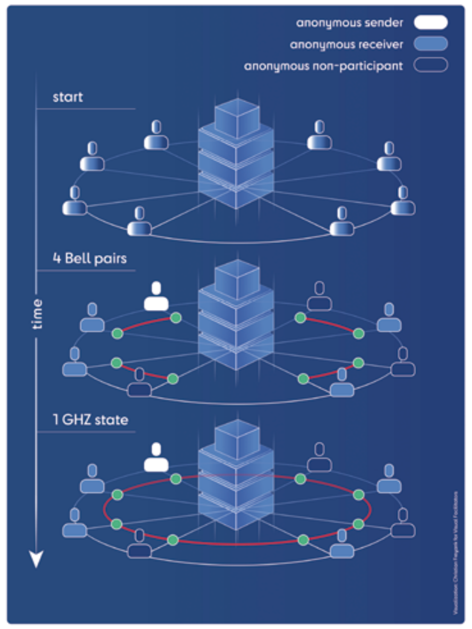
PHOTON BOSE-EINSTEIN CONDENSATES This experimental platform aims to use engineered interaction between a photonic Bose-Einstein condensate and matter to generate useful quantum states. A key step of the year was to extend an earlier breakthrough result [Kurtscheid et al., Science 894, 366 (2019)] to optical lattices with multiple sites, thus realizing a threefold-split photon wave package. The observation of a non-Hermitian phase transition in a photon Bose-Einstein condensate [6] may provide an alternative route to engineer the required effective photon-photon interaction.

SEMICONDUCTOR QUANTUM DOTS Another platform aims to realize a photonic interface to matter qubits defined in electrostatically defined quantum dots, which are broadly similar to transistor-devices and thus compatible with semiconductor processing. An important step ahead in 2021 was the demonstration that the fundamental requirements regarding device quality can be met for one of the two approaches pursued. We identified promising concrete device designs for the optical interface based on simulations and our unique home-built setup allowing optical experiments at temperatures well below 1 K was improved and qualified. For the second approach considered, we demonstrated the crucial technological requirement to align patterned electrostatic gates relative to the randomly placed self-assembled quantum dots used as optically active center with 40 nm precision. Finally, we started to investigate the possibility of using quantum dots and emitters in novel 2D materials, thus adding a very promising and "hot" platform to the cluster's portfolio.

TRAPPED IONS Trapped ions represent the third major platform pursued for realizing a light matter interface. Here, we have demonstrated an actual quantum networking protocol, namely quantum key distribution using our entangled ion-photon setup in which the photon carries the secure key and the trapped ion is a quantum memory. The integrated quantum memory of this setup makes it compatible with future quantum repeaters that would allow long-distance quantum-secured communication and represent one of the most promising applications of quantum network nodes as targeted by ML4Q.

QUANTUM FREQUENCY CONVERSION Since different platforms for light-matter interfaces emit at different wavelengths, which in most cases are not suitable for long distance fiber transmission, converting photonic quantum states between different wavelengths is indispensable. Collaborative work within ML4Q demonstrated a photon conversion from 850 nm (InGa/GaAs quantum dots) into 370 nm (Yb+ ion) [7] and from 850 nm to 1550 nm (best for telecom fiber transmission), both while preserving the single photon characteristics. The first result is particularly noteworthy as the UV domain involved is challenging and new territory.

HIGH EFFICIENCY OPTICAL COUPLING The performance of matter-light quantum interfaces crucially depends on the ability to extract and inject photons with high efficiency, which requires specially engineered structures tailored to each platform. As a near-term approach for semiconductor devices, we use printed micro-lenses. First tests showed a significant enhancement (approximately by a factor of 2-5) of the collection efficiency. We also developed an alignment procedure allowing us to position micro-lenses sufficient accuracy. As a more involved solution, we are exploring to embed optically active quantum dots in photonic crystal cavities that are specially designed to also accommodate the electrostatic gates. Latest simulations indicate an extraction efficiency of up to 60 %. A first test sample has been fabricated.



Anonymous conference key agreement: The anonymous protocols are implemented on a quantum network consisting of n parties (n = 8 in the picture) linked to a central quantum server. The roles of the parties are not predetermined and are instead assigned during the protocol's execution. The quantum server provides the necessary entangled resources by distributing –in each network use– either Bell pairs between distinct pairs of parties (e.g. four pairs when n = 8) or one GHZ state shared between all parties. The figure of merit to compare the performance of the protocols is the number of secret conference key bits generated per network use [1].

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[3] L Ligthart, M Gachechiladze, and D Gross, A convergent inflation hierarchy for quantum causal structures, arXiv:2110.14659

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[7] A Hamer, D Fricker, ..., 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)

ENTROPY BOUNDS FOR MULTIPARTY DEVICE-INDEPENDENT CRYPTOGRAPHY

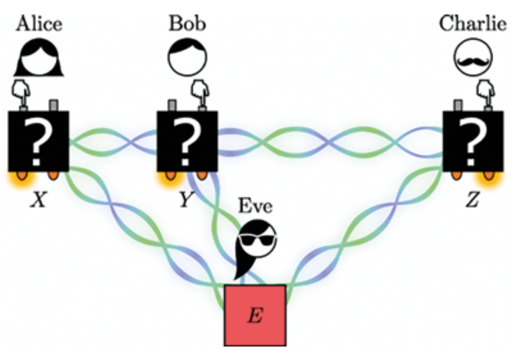
BY FEDERICO GRASSELLI, GLÁUCIA MURTA, HERMANN KAMPERMANN & DAGMAR BRUSS
PRX QUANTUM 2, 010308 (2021)

It is now widely accepted that properties of quantum systems can be truly random while being highly correlated with the properties of other distant systems. Such correlations are said to be non-local. They defy our intuition for which measuring a property of a system merely reveals a local pre-existing value.

Remarkably, when non-locality is observed in the outcomes of a set of parties measuring their quantum systems, one can infer that a party's outcome is secret to some extent. Secret randomness is a crucial cryptographic primitive and non-locality allows its certification regardless of the details of the physical implementation, namely in a device-independent manner. The challenge is to quantify the amount of secret randomness generated given the observed non-local correlations. Our paper provides the tools to certify the secret randomness generated by three or more parties (e.g. in a quantum network) when their measurement outcomes are non-locally correlated.

The non-locality of correlations is quantified by the violation of a given correlation inequality, called Bell inequality, involving the outcomes of each collaborating party. We certify the fraction of secret bits in a single party's outcome and in two parties' outcomes by appropriate conditional entropies. In particular, we derive analytical expressions for the entropies that solely depend on the Bell inequality violation.

The derived conditional entropies play a fundamental role in the security proof of multiparty device-independent quantum cryptographic protocols. Indeed, they determine the length of the secret bitstrings generated by randomness expansion and key agreement protocols.



Three parties hold unknown quantum devices, which can share arbitrary correlations with each other and with the system E of an eavesdropper. Each device has two inputs and produces one of two outputs when an input is selected. The parties' goal is to certify that their outcomes, X,Y and Z, are truly random and secret, that is, unknown to the eavesdropper. To this aim, they test for a violation of a multipartite correlation inequality, called MABK inequality. In our work, we quantify the eavesdropper's ignorance about the outcomes X and (X,Y) through analytical formulas which depend on the magnitude of the MABK inequality violation.

"

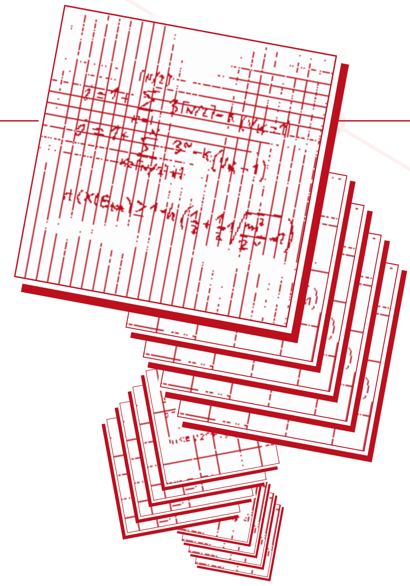
F. GRASSELLI

Certifying secret randomness in a device-independent manner guarantees the ultimate level of security for the quantum networks of tomorrow.

TRIVIA

93

A TOTAL OF 93 EQUATION LINES WERE NEEDED TO PROVE THE SECOND THEOREM IN THE PAPER.



THE TEAM

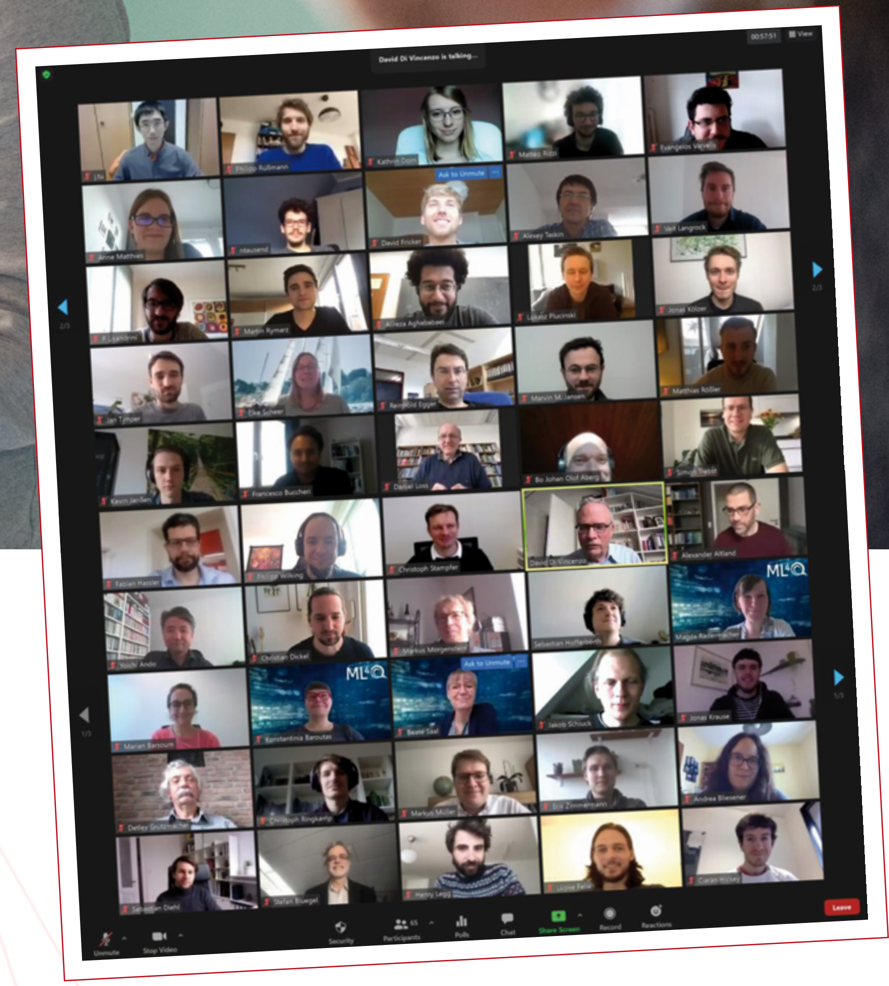
Gláucia Murta Obtained her PhD in Brazil (UFMG) and has been subsequently worked as postdoc at QuTech-TU Delft in the Netherlands. Since 2019, she is a postdoc researcher at HHU Düsseldorf and part of ML4Q. Her research focuses on the design of new quantum cryptographic protocols, with special focus on network tasks.

Federico Grasselli Studied physics in Italy (Perugia and Milano) before moving to Düsseldorf for his PhD in the Bruß group. There, he tackled quantum cryptography and contributed to generalizing it to the multiparty scenario. He is now a postdoc at the same institute in Düsseldorf.

03

ML4Q LIFE

INTRO



Life in ML4Q continued in 2021 as it ended in 2020 – in full-on online mode. Since improving cluster-internal communication was one of the main goals of our newly established Strategy Board, the ongoing Corona pandemic posed a particular challenge, which was met with a set of **online communication measures**: On top of a revamp of our cluster-internal Slack, the internal cluster website was fully relaunched and turned into a first point-of-interest for our members and associates to find any cluster-related information. Most prominently, it now features a who-is-who of researchers within ML4Q (searchable by scientific and methodological keywords to help in particular new members find potential collaborators), databases of posters and talk recordings, fabrication maps of the (solid-state) lab facilities at the cluster sites, and more.

The question of what kind of (and how many) regular scientific meetings are most efficient is difficult to answer in any larger collaborative research endeavor, but of course particularly challenging for a project of the scope of a Cluster of Excellence with four major sites (and additional participating institutions). Following discussions at our annual conference, we established a new meeting structure within ML4Q, namely regular workshops of three **topical subgroups**, which serve as a platform for scientific exchange.

In 2021, we also continued our successful established event series, most notably the MSc course on **Platforms for Quantum Technologies** and our **ML4Q Concepts seminars**, which, based on feedback by the participating students, sparked three new series of talks on near-term quantum algorithms and applications; quantum gravity, holography, and error correction; as well as driven-dissipative quantum systems.

In addition to these mostly theory-focused seminars, a new meeting point for the experimentalists within our cluster was established: in our (roughly monthly) **cleanroom seminar**, 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.

ML4Q RESEARCH SCHOOL AND EARLY-CAREER SUPPORT

- Students and Postdocs Retreat
- Undergraduate Research Internship Program
- BCGS-ML4Q - Scientific Integrity Workshop

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.

The true highlight of 2021 was in this regard the **ML4Q Students and Postdoc Retreat**. During these days, the participants had a chance to finally meet in person, discuss science during talks and poster sessions and profit from the cluster expertise during the workshops offered by postdocs. 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 – not only virtually.

In 2021, career development support shaped many of the Research School activities. Successful research group leaders from the cluster gave seminars for postdocs, where they shared their experience in acquiring prestigious fellowships and gave practical advice for increasing the success chances. We plan to complement this offer with more individual mentoring for those who plan to apply for fellowships and grants to enable scientific independence. For those who are undecided about the next career steps, we started a new series of **ML4Q Alumni Career Talks**, where students can get in touch with former cluster members and learn more about various positions and options in academia and beyond.

Another highlight in 2021 was the **ML4Q Undergraduate Research Internship** program. Within this new initiative, excellent international students can apply for a 9-12 week internship in one of the cluster's groups and/or laboratories. The 6 outstanding students selected in the first application round in fall 2020 were unfortunately not able to join us due to the pandemic. However, in October 2021 we could open a new call for projects. We received 80 excellent applications and eventually offered seven internships in five ML4Q groups located at four sites. The internships are planned to take place during the summer semester 2022.

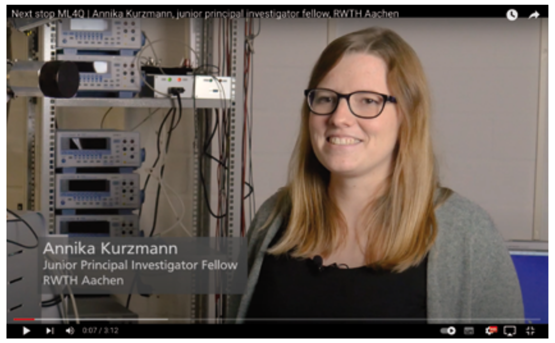
All these activities were complemented by further developments in the training offer. In 2021, we held an improved version of the **master course on Platforms for Quantum Technologies**. This three-week course covers all major topics represented in the cluster research program and its Focus Areas starting with an 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. The course was taught by lecturers from all cluster sites and was attended by roughly 40 participants from all three partner universities. This rather broad course was complemented by the more focused **ML4Q Intensive Week** on 'Security proofs on Quantum Key Distribution'. This new format was very well received and the online classes allowed the participation of external students and postdocs.

We also make sure that our students and postdocs have an opportunity to improve their transferable skills. As a joint event of ML4Q and the Bonn-Cologne Graduate School of Physics and Astronomy (BCGS), we developed a new **Scientific Integrity Workshop** and offer it on a regular basis to PhD students. In the future we consider including it also in the master program curriculum. Building on a very productive **collaboration with the Career Development Department at RWTH Aachen**, we offered courses on scientific presentation, teaching and supervision as well as time management. Course offerings are continually being adjusted to better meet the needs of young researchers, with the nice side-effect that all our members – regardless their own affiliation – can profit from a wide range of courses offered at the partner universities.

03

ML4Q LIFE

EQUAL OPPORTUNITY & DIVERSITY



Watch Annika as she describes her journey in science and how she succeeded in combining both solid-state physics and quantum optics in her new lab at RWTH Aachen!

We are convinced that the lack of diversity in physics – and basically any field of research – is not only an issue of inequality, but that it in fact affects how research is conducted and applied. Hence, we are dedicated to **enhance diversity** within the cluster by different measures addressing aspects of gender, work-life-balance, internationalization as well as disabilities.

As for promoting gender equality, we are aware of the leaky pipeline and therefore put a lot of effort to hire female postdocs. In spite of the global pandemic situation the lab of Christoph Stampfer at RWTH Aachen succeeded in **recruiting Dr. Annika Kurzmann**, an outstanding expert on quantum dots in bilayer graphene. Annika successfully acquired a Junior Principal Investigator Fellowship of RWTH Aachen University where she is hosted by the Stampfer group. She started building up her lab in January 2021 and participated successfully in the first ML4Q Open Call early in the year, thus acquiring additional funds to establish resonant optical measurements in her lab. The goal of her project is to investigate the potential of single photon emitters and quantum dots in 2D materials for applications in quantum information processing.

Knowing how important it is to identify role models who can motivate underrepresented groups to consider a career in academia, the cluster encourages female members and associated members of different academic ages to participate in its outreach activities.

In its newly launched podcast ML4Q&A, the cluster featured some of its **female theoretical physicist**. In one episode, Kathrin Dorn, a PhD student in the group of Reinhold Egger at HHU Düsseldorf, interviewed ML4Q member, Dagmar Bruss, who talked about her passion about quantum information theory, how a coffee break in Oxford changed her research focus to quantum key distribution, and her experience with the imposter phenomenon. In another episode, Kathrin herself was guest on the show and talked about her PhD project and how she started off to combine math, physics and arts in her studies and ended up in analyzing theoretical aspects of topological insulators.

Kathrin Dorn was also invited by the **Konrad Adenauer Foundation** to take part in an interview on Instagram Live to answer questions about quantum computers, how they are supposed to work and why they promise an advantage over classical computers. The interview was part of a social media campaign of the Foundation's thematic focus #KAS4Innovation. To that end, it seeks to strengthen competitiveness in Germany through digitalization and examines the economic and socio-political effects of relevant technologies and draws up action recommendations for politics.

Further outreach formats included the yearly science festival, **Pint of Science**, where Anne Matthies and Andrea Bliesener slammed about their PhD projects which they are doing in theoretical and experimental physics in Cologne, respectively. Another science festival which took place in the summer in downtown Cologne was **Soapbox Science** which features women in science. Once again, Kathrin Dorn shared insights of her life as a theoretical physicist in the middle of Cologne Rudolfplatz and many visitors were intrigued by Schrödinger's gedankenexperiment.

Furthermore, Anne Matthies was featured by the German Physical Society (DPG) in September 2021 within the "**Physikerin der Woche**" initiative. 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.

As for promoting a family-friendly work environment, ML4Q reserved places for children of cluster members at local day care providers of the Froebel Group – a service which is gladly received by many of the associated members of the cluster.

In order to intensify the cluster's efforts by conceiving new and sustainable diversity measures that are customized to the current situation in the field of physics, a **new coordinator position** with focus on equal-opportunity and diversity measures was advertised in 2021 and we are glad that we were able to win Andrea Bliesener for this task, who after finishing her PhD in the group of Yoichi Ando decided to build on her experience in academia and empower underrepresented groups to consider a scientific career in quantum science and technology. Andrea joined the cluster office in December 2021.

PHYSICS IS NOT ONLY A “BOY THING”

How ML4Q member and APS fellow Corinna Kollath is trying to overcome gender stereotypes as early as kindergarden.

Corinna, it’s almost 10 years now that you became professor for Theoretical Quantum Physics at the University of Bonn. How has it been? *I hardly notice that it is almost 10 years, since it has been very busy: I contributed to setup two collaborative research centers (SFBs) and the Cluster of Excellence ML4Q. However, it has taken more time and efforts to balance different interests than I had expected.*

In January 2021, you were nominated by the APS Division of Atomic, Molecular & Optical Physics to become an APS fellow. What does this achievement mean to you? *It is of course a great honor and thus, I was very happy receiving the message to be chosen as an APS fellow. I feel that my research on non-equilibrium quantum systems received additional recognition.*

When you think of promoting equal opportunities and diversity in the scientific and academic community. Which measures do you regard most important and effective? Are there any current development that you are sceptic about? *This is a very complex subject which cannot be dealt with in a short answer. In my opinion, two of the most important measures are to support talented persons at an individual level and to offer early chances on permanent positions as the tenure track positions. However, this alone is not enough and it is an interplay of many points which need to be changed. One main obstacle is the unconscious bias of many persons which is hard to change and at the end only this would allow for more equal opportunities and diversity in the scientific community.*

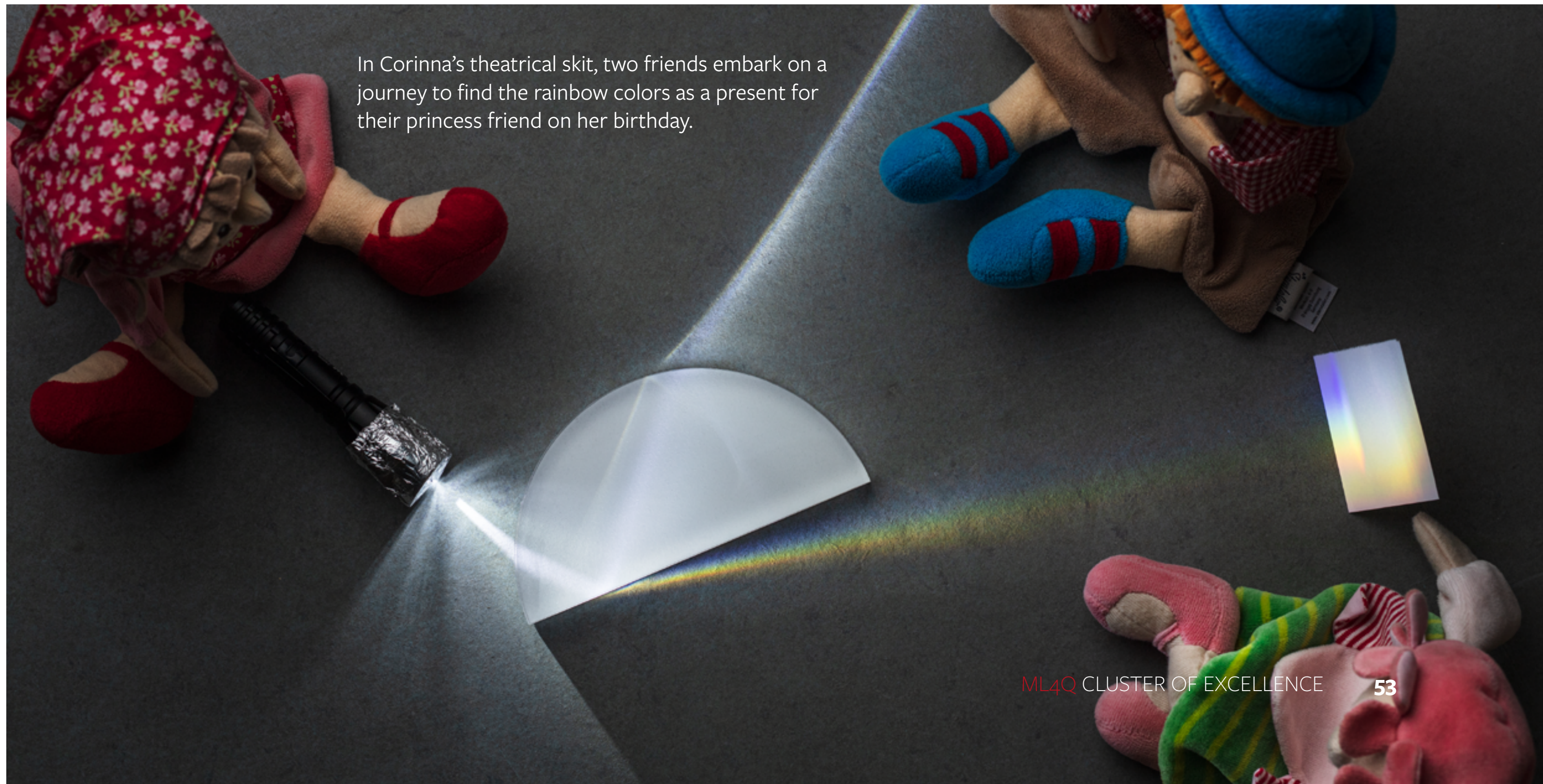
You started a little theater project for Kindergarden children. What motivated you and how is going? *Our Kindergarden project was conceived to create interest of the young kids and in particular young girls for physics. To do this, we are mixing physics experiments into stories which are interesting to all kids. We started the project, since we saw that already very early on the kids are biased from outside in their interests by comments as ‘this is a boy/girl thing’. We would like to show to the kids and in particular to the girls that physics is fascinating and that it is not only a “boy thing”.*

What part of your work do you enjoy most and how much of your time can you dedicate for it at the moment? *I enjoy most working with the students on research, teaching students and performing outreach activities like for the Kindergarden kids. However, since I am working part time, the time I can dedicate to this is sadly very limited due to all the other tasks which come along with a professor position.*

CORINNA KOLLATH

In January 2021, Corinna Kollath was nominated by the APS Division of Atomic, Molecular & Optical Physics to become an APS fellow. The APS Fellowship Program is a distinct honor signifying recognition by one’s professional peers for outstanding original research and publication, or innovative contributions in the application of physics to science and technology. Corinna was honored for her studies of low dimensional correlated systems, in particular out of equilibrium, using a combination of analytic and novel numerical approaches.

Corinna was born in Stirling (UK). She studied physics in Cologne and got her BSc Honours in Physics and Mathematics from the University of Glasgow. Her diploma thesis on “Quasiparticles in p-wave superconductors” was supervised by Martin Zirnbauer (University of Cologne). After getting her PhD degree from RWTH Aachen she worked as a postdoctoral fellow at University of Geneva and the École Polytechnique. In 2013, she became professor of Theoretical Quantum Physics at the University of Bonn. Corinna’s work was recognized by several prizes: her outstanding PhD thesis got her the “Borchers Plakette” of RWTH Aachen, the German Physical Society honored her with the “Hertha Sponer Prize”, and the “Akademie der Wissenschaften zu Goettingen” chose her for the Prize for Physics in 2010.



In Corinna’s theatrical skit, two friends embark on a journey to find the rainbow colors as a present for their princess friend on her birthday.

RESEARCH DATA MANAGEMENT

RESEARCH DATA MANAGEMENT, RDM in short, refers to the organization, storage and preservation of all data created in research projects. This includes raw data from experiments, simulations, processed data and results but also used and developed source code and publications and its figures. RDM aims to have all this data structured, equipped with metadata, easily accessible and usable for future researchers and colleagues.

From an RDM perspective, the gold standard are the FAIR principles, according to which data should be (F)indable, (A)ccessible, (I)nteroperable, and (R)eusable. If all research data would met these principles, there would be no more lost data, lying on some research computer in a forgotten directory, new colleagues could easily reuse previously created data and base their research on it and published results could be verified and checked by others. Obviously, not all data meets the FAIR principles. Some fields are way ahead of others in this regard and physics is mostly and unfortunately not one of those fields, which leaves us with lots of development opportunities and just a few standards across the field.

Structuring and managing research data is an expensive and time demanding process, that requires the support from everyone in the research process. From the data manager through the researchers to the PIs, RDM has to be considered and applied before, during, and after the whole project. The transition to this takes time and has to be done in steps. Questions, concerns and fears have to be addressed. Is the additional cost worth it? Who would benefit from our raw data? Are we allowed to publish data, which could fall under confidentiality agreements? Do we even need our data to be FAIR? How is research and research data assessed?

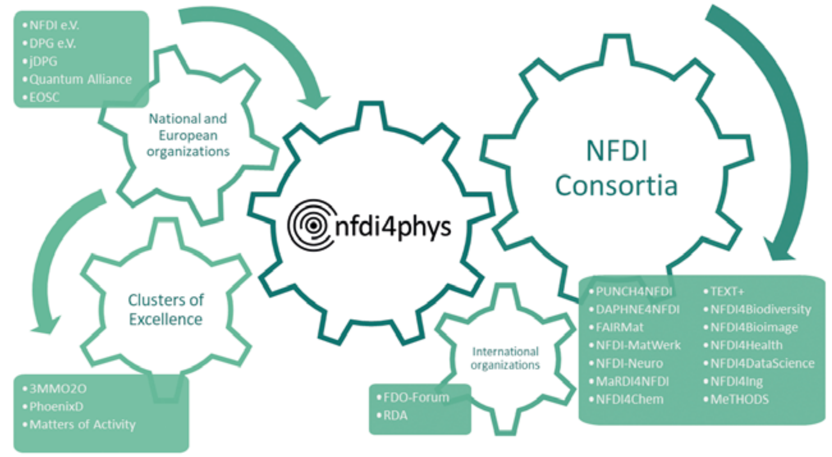
RDM IN ML4Q Nevertheless, the transition has already started and is constantly moving forward. Already in its proposal, the cluster included plans for tackling the data management challenge and in February 2021, Daniel Grothe joined the cluster as research data manager based at RWTH Aachen.

According to the planned measures for data management, all cluster publications should be made fully reproducible, using arXiv's data storage and GitHub/GitLab, whenever appropriate. Currently, if a data availability statement is present in a publication, it often states, that data is available on request. This could very well be replaced by a unique identifier to the already published data, thus removing barriers to accessing the data.

On top of our own ambitions, the DFG has recently published new application guidelines with special focus on RDM. These guidelines lead towards even stronger integration of data management in future research projects. This includes a cluster-wide data management policy and the adoption of a data management plan, which documents research data and those responsible for every research project.

With the creation of the Nationale Forschungsdateninfrastruktur (NFDI), a nation-wide infrastructure of field-specific consortia has been funded to move RDM forward and coordinate various initiatives. Communication and participation with and in the NFDI consortia is currently done in the cluster from several members.

Further communication is done through a loose German network of data stewards in Collaborative Research Centers and Clusters of Excellence. This ExIni-Network meets irregularly to discuss existing software solutions, RDM strategies and more.



NFDI4Phys is engaged in a large number of mutual collaboration within and external to the NFDI. ML4Q interacts with NFDI4Phys as part of the Quantum Alliance. (Source: https://nfdi4phys.de/interfaces/)

SOFTWARE PROJECTS As important the addition of metadata to raw measurement data is, it creates administrative overhead for the researcher. To minimize this overhead as much as possible, a measurement framework paired with a metadata database, **qtools** is currently being developed by Daniel Grotehe and Till Huckemann for the use with **QCoDeS**. This framework collects most of the metadata about the performed measurements automatically and loads them to the database. Qtools also tries to abstract the measurement routines from the used measurement instruments to simplify the reuse of measurement routines with different instruments.

Apart from the active development of qtools, we are currently thinking about how to improve the structure of the research data and metadata through the use of Electronic Lab Notebooks (ELN) or Scientific Data Management Systems (SDMS).

qtools

QCoDeS

ML4Q DATA MANAGER, Daniel Grothe, joined the cluster early in 2021 and is based at RWTH Aachen. He is always available for discussions and inquiries regarding RDM, data management plans and open data or specific software solutions.

Contact: grothe@physik.rwth-aachen.de

03

KNOWLEDGE TRANSFER

- ML4Q Technology Day
- Industry Talk with Dieter Meschede
- Joint PhD projects with Covestro
- Midel Photonics – the success story continues

Quantum technologies are attracting substantial interest from industry and private capital. However, with many press releases overemphasizing success, ML4Q recognizes its competence to provide an unbiased expert opinion for decision makers in order to obtain a balanced picture of realistic future scenarios.

In January 2021, ML4Q member Dieter Meschede was invited by the Industrie-Club Bremen to give the opening talk of the **Bremen Industry Talks** entitled "*Quantentechnologie – Kuriosität oder technologische Revolution?*" [Quantum technologies – curiosity or technological revolution?]. Meschede discussed the roots of quantum technology and assessed opportunities and challenges quantum technology could offer for science and society. His talk received a huge interest: Over 250 participants from the general public as well as members of the German Physical Society (DPG) registered for the online talk and engaged in a lively Q&A session. The Industry Talks, a regional series of events organized by the DPG's Arbeitskreis Industrie und Wirtschaft (AIW), are initially aimed at all physicists working in industry outside universities and research institutions, but are also popular with the general public.

In 2019, ML4Q joined a growing network coordinated by **QT.NMWP.NRW** which is dedicated to bring quantum technology scientists and industry in NRW together and foster know-how transfer in the region. In 2020, several ML4Q members and their research were portrayed in the NMWP.NRW cluster magazine issue on Quantum Technologies. This year, Frank Wilhelm-Mauch was invited to join the online event "A Quantum Christmas". In his talk, Wilhelm-Mauch gave a brief overview on the quantum advantage in computing processes and touched upon current challenges in developing the needed hardware platforms. He also presented some use cases for the industry including using quantum computing for the optimization of machining processes.

In a new effort, 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 2021**. Company representatives from Elmos, Eleqtron, Fraunhofer ILT, IDQ, E.ON, Pasqal, Rigetti and Parity QC presented current R&D projects and discussed with ML4Q associates about career and development opportunities for scientists coming from academia. The presentations were complemented by mingling and networking sessions with virtual coffee and beer.

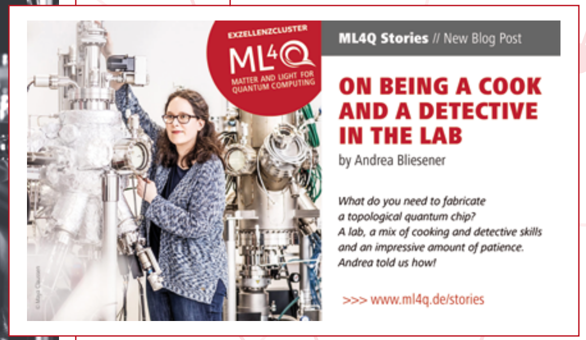
Together with researchers from **Covestro**, we are working on quantum algorithms for chemistry problems, in particular with an eye on near-term "noisy intermediate-scale quantum computers" (NISQ). This work is conducted as a joint PhD project (with David Wierichs) within the core project P3.2 and resulted in 2020 in a publication in Physical Review Research. In 2021 the quantum computing team at Covestro has grown further and at the end of the year encompassed three PhD students. Work with David Wierichs continued and has led to another publication in the New Journal of Physics with contributions from the University of Cologne on "Local, expressive, quantum-number-preserving VQE ansätze for fermionic systems". Another paper on "General parameter-shift rules for quantum gradients" was published in early 2022 on Quantum, the open journal for quantum science, as a result of an internship which David completed at Xanadu Quantum Technologies.

Building on ideas from core project P3.3, the JARA Institute for Quantum Information is coordinating a BMBF project on the realization of a shuttling-based scalable architecture. A key element of the project is to transfer the device fabrication concepts developed by the institute within ML4Q to industrial semiconductor technology at **Infineon Dresden GmbH**, **Leibniz institute IHP** and **Fraunhofer IPMS**. In 2021. the project has started successfully and is in full swing. The design of the architecture has been fully elaborated by now and measurements have been performed on the first test structures manufactured by Infineon. New samples are continuously provided for iterative optimization. Ideally, these will be the world's first industrially produced Si/SiGe quantum dots, and subsequently qubits.

In our 2020 report, we presented the success story of the spin-off **Midel Photonics** which started with an Open Call project and evolved in 2020 following a ten-week incubation program into a mature business plan, winning the third prize at the HIGH-TECH.NRW Demo Day 2020.

In 2021, the entrepreneurial team consisting of David Dung, Frederik Wolf, Christopher Grossert and Christian Wahl was selected for the "EXIST Research Transfer" funding program of the German Federal Ministry for Economic Affairs and Energy and the European Social Fund. The funding of around 750,000,- € is intended to help the entrepreneurs take their promising approach from research to industrial application.

OUTREACH



In 2020, a communication and outreach strategy was conceived 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. Hence, we made sure to communicate this core competency in every outreach format we developed. By 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.) we aim at promoting a coherent image of ML4Q's competencies catering to as many recipient tastes as possible.

TARGETING THE YOUNG SCIENTIFIC COMMUNITY

In 2021, we continued the outreach efforts which were established in 2020, all of which are in English in order to address students within our multiple sites as well as the international student quantum community in Germany and beyond. The cluster's blog, **ML4Q Stories**, grew to include stories about science management, working in fabrication facilities in Jülich and Cologne, publishing the first paper, and doing research in times of Covid.

The first episode of the cluster's podcast, **ML4Q&A**, was launched in early 2021 and throughout the year, four episodes were published which featured theoretical scientists from the cluster offering a mix of junior and more established female and male scientists. Four more episodes were recorded in the end of 2021 which will be published in 2022 and highlight the work of experimentalists. Future seasons are planned to include new professors, partners within the German quantum community as well as industrial partners.

ML4Q also participated as part of the Quantum Alliance in a virtual career fair organized by DAAD's Research in Germany campaign in June. 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. The event in 2021 targeted scientists working in the STEM field and are mainly located in the US. Research in Germany also invited the Quantum Alliance to join the APS March Meeting and provide detailed information on the German physics research landscape and about career and funding opportunities for scientists of all career stages. On behalf of ML4Q, Felix Motzoi (Jülich) participated in the online workshop "Doing Physics in Germany" where he shared his experience with the German research system after relocating from Canada to Jülich.

SCHOOL AND PUBLIC OUTREACH In 2021, more effort was put into participating in and developing outreach activities in German for schools and the public. We started by approaching teachers from the region who are in contact with our school labs in Cologne, Bonn, Aachen and Jülich. With their feedback and input, we were able to organize the **Quanteen Day** 2022 – a virtual half-day event for secondary and high school students on quantum computing. We also established connections to the Junior- and Kinderuni in Cologne with whom we developed age-appropriate workshops on quantum computing 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.

To address the broad public we became part of **Exzellent Erklärt** – the podcast of all German Clusters of Excellence which was launched in September 2021. The episode featuring ML4Q was recorded in December with ML4Q members Michael Köhl (Bonn) and Sebastian Diehl (Cologne) and is scheduled go online in March 2022. Furthermore, Alex Altland and Tommaso Calarco were guests in **WDR5 Quarks – Wissenschaft und mehr** on March 30, where they explained the principles of quantum computers and elaborated on current challenges in research and development. In a quite straight-forward statement, Calarco emphasized the importance of striking the balance between convincing the public of the importance of ongoing research in such a future technology and avoiding making empty promises for future applications.

On a further note, ML4Q took part in **Pint of Science Germany** 2021 with more than 70 guests who joined our "Quantenrevolution" session. David Dung (Bonn) talked about transferring ideas from the lab to the industry and how a world trip after his PhD had an impact on his choice to turn into an entrepreneurial scientist. Anne Matthies (Cologne) was finally able to tell her family what she is really doing and made them all understand what topology is and how this can be used to store and process information. Andrea Bliesener (Cologne) revealed the secret why growing her films needed wrapping the whole MBE system in aluminum foil. And Jonas Krause (Cologne) showed his audience how he uses cool temperatures and magnetic fields to realize Majorana qubits – a work that will make him busy for at least a couple of years.

This year, we also had a very productive cooperation with the Konrad Adenauer Foundation (KAS) which resulted in a high-quality **explanatory film on quantum computing** in German and a publication on the topic featuring ML4Q member David DiVincenzo.

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 foundations for societally relevant applications.

MISCELLANEOUS

EARLY-CAREER SCIENTISTS

PASCAL CERFONTAINE ELECTED FIRST WINNER OF THE QUANTUM FUTUR AWARD 2021

While the PhD and postdoc retreat was taking place, **Pascal Cerfontaine** – who got backed up by a substantial amount of crossed fingers in the Eifel – convinced the jury to award him the first prize for best PhD project which is endowed with 6000 Euro and granted by the BMBF. His PhD thesis which he accomplished in 2019 in the group of Hendrik Bluhm at RWTH Aachen is entitled: “High-Fidelity Single- and Two-Qubit Gates for Two-Electron Spin Qubits”.

PRIZES & AWARDS

ALEXANDER ALTLAND RECEIVES THE ALBERTUS MAGNUS TEACHING AWARD

In acknowledgement of his special commitment to teaching, **Alexander Altland** has been rewarded the Albertus Magnus Lehrpreis for the Department of Physics at the University of Cologne in the winter semester 20/21. Both the high professional quality and the engaging way of communicating with the students, especially in online and distant learning mode, qualified him for the award. Alex talked to the **Kölner Universitätsmagazin** about the lessons he learned while teaching during the lockdown and under pandemic conditions.

PRIZES & AWARDS

CHRISTOPH STAMPFER RECEIVES THE ARS LEGENDI FACULTY AWARD FOR MATHEMATICS AND NATURAL SCIENCES

Together with **Sebastian Staacks** and **Heidrun Heinke**, **Christoph Stampfer** was awarded the Ars Legendi Faculty Award of the Stifterverband and the German Physical Society. The award recognizes scientists who distinguish themselves through outstanding, innovative and exemplary achievements in teaching, advising and mentoring. The award has been presented since 2014 in the categories of biology, chemistry, mathematics and physics and is endowed with 5000,- € each. Among other achievements, the development of the app **phyphox** is one of the stand-alone projects that was conceived by the awardees. You can read more about the making-of this app in the cluster’s blog, **ML4Q Stories**.

> “I was an absolute chalk fanatic and didn't care about that digital stuff. This changed! It makes much more sense to film the content once and to invest the time gained into more interaction with the students!
>
> ALEXANDER ALTLAND

PRIZES & AWARDS

SIMON STELLMER RECEIVES THE FULBRIGHT-COTTRELL AWARD

In acknowledgement of his scientific community on both sides of the Atlantic for the quality and innovation of his research and his academic leadership skills, **Simon Stellmer** was awarded the Fulbright-Cottrell Award 2021. The award is granted by the German-American Fulbright Commission in Berlin to junior faculty in the fields of chemistry, physics and astronomy and offers funding for a three-year project that combines pioneering research and creative teaching. The U.S.-based Cottrell Scholar Award was initiated in 1994 to tackle the challenge that high performance in teaching lacks both prestige and funding in the more research-centered and publication oriented scientific community. The award recognizes outstanding young university “teacher-scholars” – scientists who strive to integrate their research and teaching activities, regarding them as interdependent.

RESEARCH TRANSFER

TOMMASO CALARCO ELECTED TO ACATECH

Tommaso Calarco, Director at the Peter Grünberg Institute for Quantum Control (PGI-8), and Professor for Theoretical Physics at the University of Cologne is now full member of acatech – the German Academy of Science and Engineering. He was elected, together with other scientists from engineering, natural sciences, humanities and social sciences, at the Academy’s General Assembly. With this election, acatech recognizes the relevant scientific work of the experts and invites them to contribute their expertise to advising policy and decision makers on issues related to the future of science and technology. acatech members also support the transfer of knowledge between science and industry and promote the next generation of technology scientists.

NEW MEMBERS

4 NEW MEMBERS ELECTED IN THE ML4Q MEMBERS’ ASSEMBLY 2021

Four new members were elected in the Member’s Assembly that took place during the ML4Q Annual Conference in February: Markus Müller, Jeremy Witzens, Frank Wilhelm-Mauch and Sebastian Hofferberth.

Markus Müller joined RWTH Aachen and Forschungszentrum Jülich in 2019 as head of the Theoretical Quantum Technology Group at RWTH Aachen and FZJ. Within Focus Area 3, Markus has been leading an Open Call project entitled “Towards Fault-Tolerant Spin-Qubit-Based Logical Qubits” since 2020.

Jeremy Witzens joined RWTH Aachen in 2011 where he is heading the Integrated Photonics Laboratory. Through the Open Call for projects in 2020, Jeremy joined ML4Q through a Focus Area 4 related project entitled “Electrically gated multi-qubit to fiber interface”.

Frank Wilhelm-Mauch joined FZJ in 2020 as the Director of the Institute for Quantum Computing Analytics. He joined ML4Q from the start as a member of the Scientific Advisory Board. Since his new appointment at FZJ, he became a member of the Strategy Board which was established in 2020.

Sebastian Hofferberth joined the Institute for Applied Physics at the University of Bonn in 2020 as head of the Nonlinear Quantum Optics group. Together with Simon Stellmer, Sebastian is leading in 2021 a pilot study on the “Quantum transduction of entangled photons from microwave to optical”.

IMPRINT

ML4Q
MATTER AND LIGHT FOR
QUANTUM COMPUTING

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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.

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Timo Heepenstrick (p.56; image of the Midel Photonics founders)
David Dung (p.56; image of the beam shaper)
Maya Claussen (p.58; right image)
Alexander Jahn (p.59; left image)

Photographs of ML4Q members, new professors as well as authors of highlighted papers that appear on pages 14-17, 21, 25, 27, 31, 33, 37, 39, 43, 55 and 60-61 were provided individually by the principal investigators and authors, respectively.

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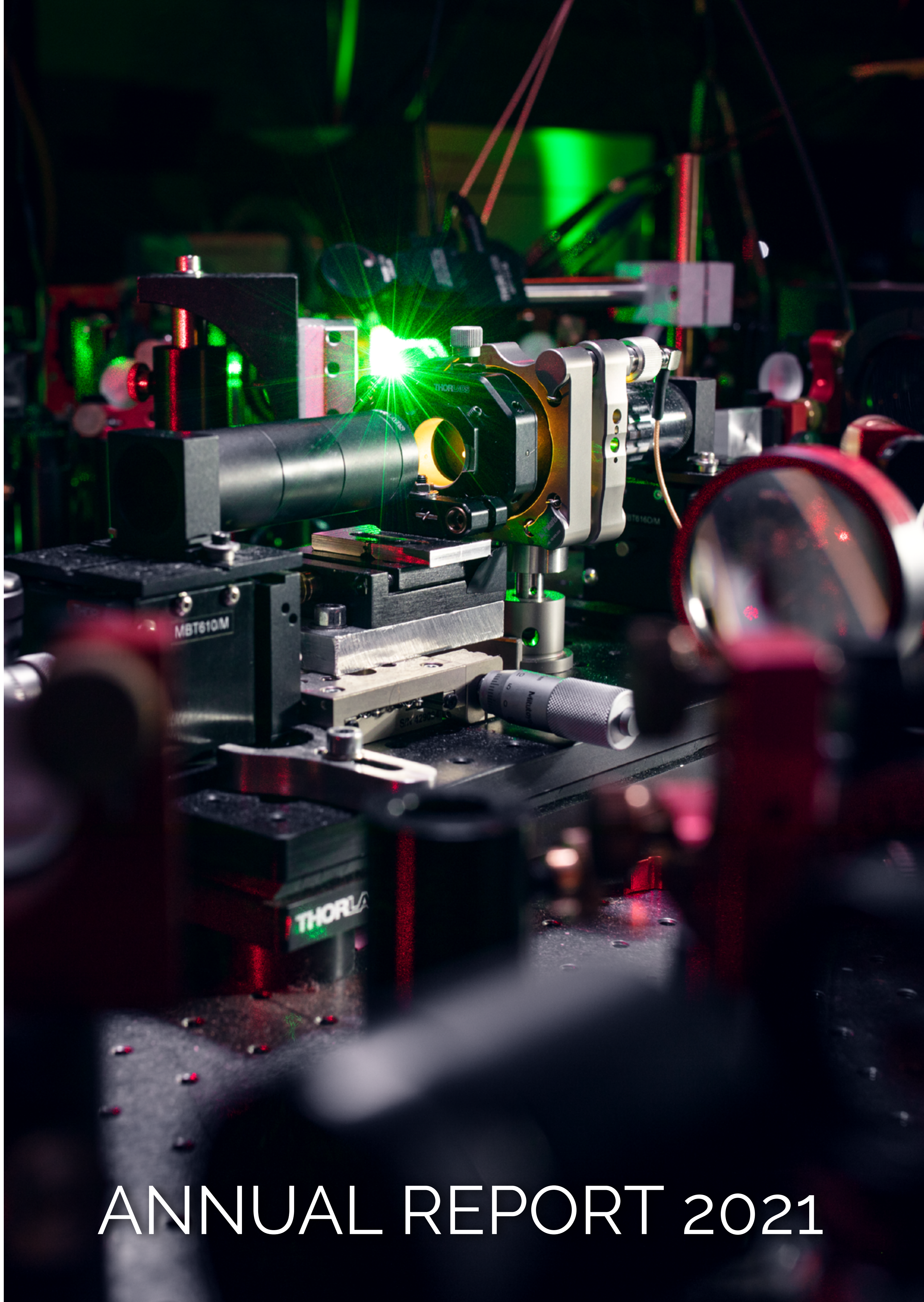

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