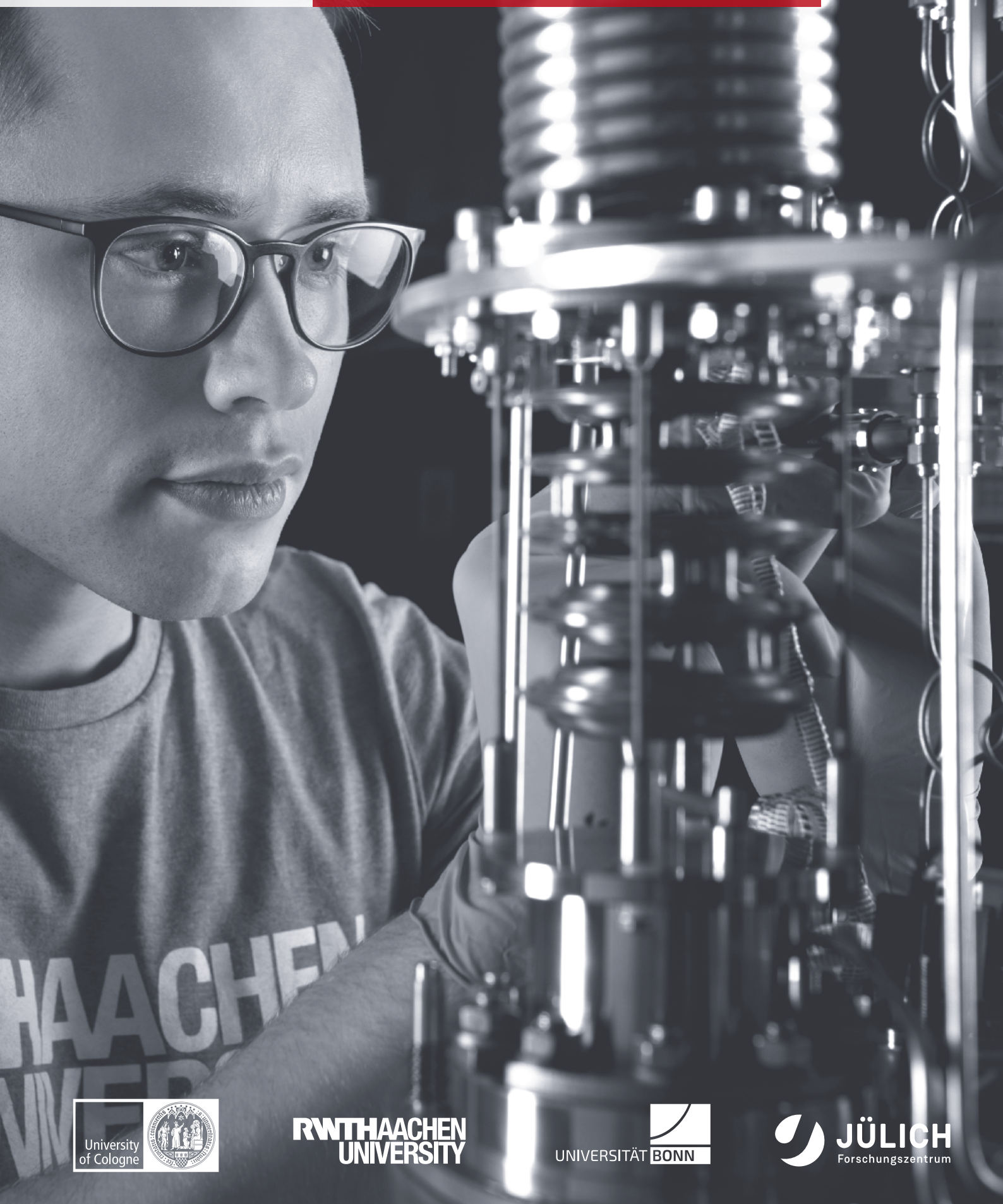
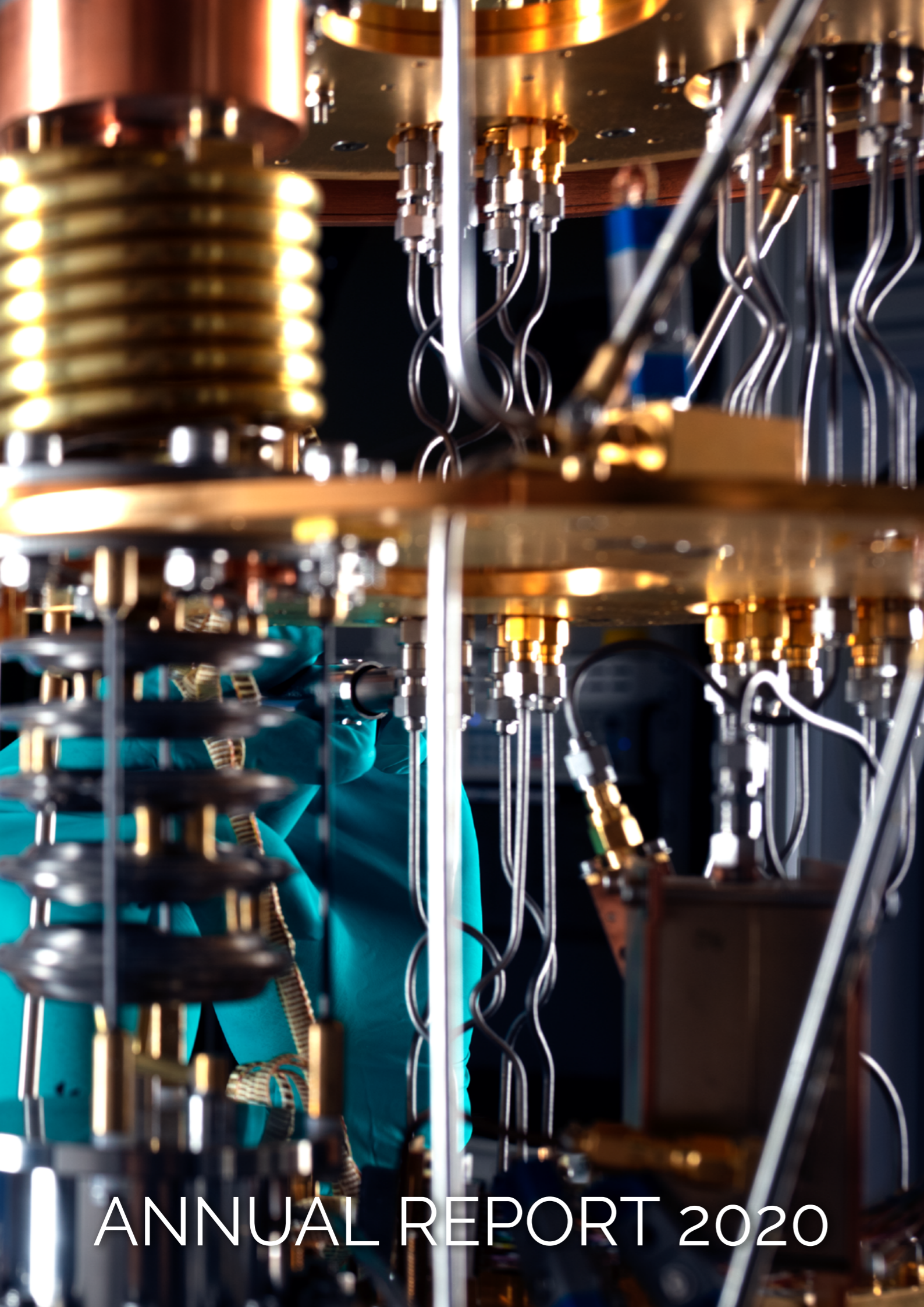


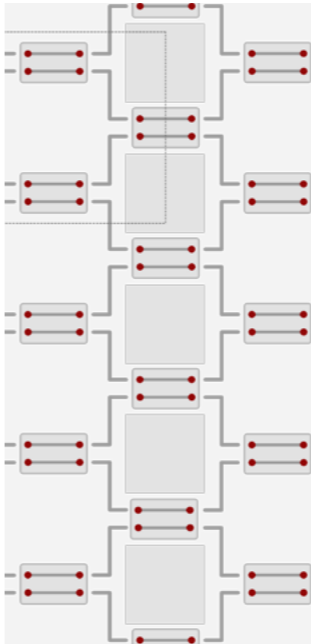
ANNUAL REPORT 2020





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ML4Q

ANNUAL REPORT 2020

PREFACE YOICHI ANDO

The year 2020 was the second year of our Cluster of Excellence “Matter and Light for Quantum Computing” (ML4Q) since its establishment in the context of the German Excellence Strategy. The aim of ML4Q is to install 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. Our vision is to make fundamental discoveries that will enable scalable quantum computing and quantum communication, the combination of which will open the door to the “quantum internet” with almost unimaginable potential. I am glad to bring you this second annual report, which gives you a glimpse on the current activities of ML4Q and shows you how we are progressing towards our goals.

The COVID-19 pandemic has affected everybody in 2020 and, needless to say, our research activities had a lot of difficulties. Nevertheless, during the pandemic we all became accustomed to online meetings, which actually helped improve the communications within ML4Q encompassing several different sites. We are now regularly organizing seminar series, journal clubs, topical research meetings etc. via Zoom with a lot of participants from multiple sites, which has largely solved the communication problem we experienced in 2019. Another unexpected outcome of the pandemic was the boost of the funding for quantum computing: The federal government has announced the “Konjunkturpaket” (stimulus package for the economy), which includes a total funding volume of 2 billion Euro for quantum computers, with a strong focus on actually building them. In this regard, ML4Q is not building a quantum computer based on current technologies – rather, we try to discover and demonstrate new principles to enable future, fault-tolerant quantum computers. Hence, the stimulus package is not directly relevant to us, but nevertheless, we are positively involved in this national development.

One of the new principles we would like to realize in ML4Q are topological qubits based on Majorana zero-modes. Recently, there was an interesting development regarding this topic: a 2018 Nature paper from a group in the Netherlands claiming the detection of Majorana zero-modes has been retracted, and a new theoretical analysis showed that the semiconductor platform used for such experiments needs to be orders of magnitude cleaner than what is currently available to support robust Majorana zero-modes. ML4Q is working on a different materials platform, topological insulators, which are expected to be more promising in view of unavoidable disorder. Hence, the recent development is encouraging, rather than discouraging, for ML4Q to further our efforts on topological Majorana qubits. As an example of our Majorana efforts where theory and experiment tightly collaborate, a recent paper by ML4Q theorists proposes a practical protocol to identify Majorana zero-modes (see paper highlight on pages 28-29).

As you will see in this annual report, ML4Q is growing in terms of the number of people – currently we have 194 members and associates, with 46 professors among them. Last year, these numbers were 151 and 39. This rapid growth, in combination with the rapid change in the research environment, prompted us to think strategically about our research focus and diversity as well as our positioning in the research community. As a result, as described on page 14, a new Strategy Board has been installed and it is very actively doing its job; the measures it has taken are already creating positive effects.

Finally, I thank you very much for your direct and indirect support to ML4Q and I hope that we can make steady progress towards our goals despite the restrictions caused by the pandemic.



01

ML4Q AT A GLANCE

ML4Q AT A GLANCE

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

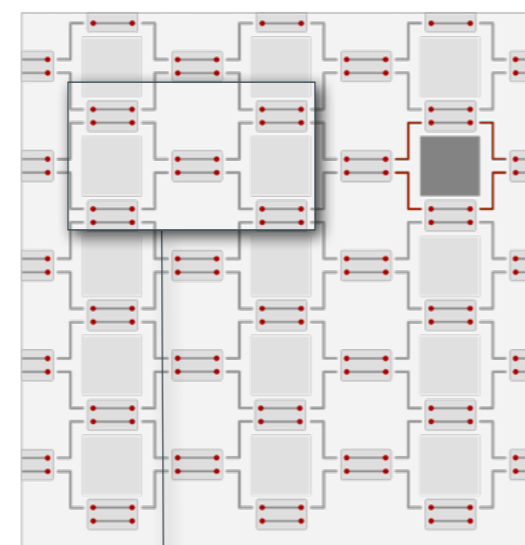
THE CLUSTER'S MISSION

Using the principles of quantum mechanics, it is the long-term goal of ML4Q to develop new computing and networking architectures with a power beyond anything classically imaginable. Quantum computers could be powerful tools in key areas such as materials design, pharmaceuticals, 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.

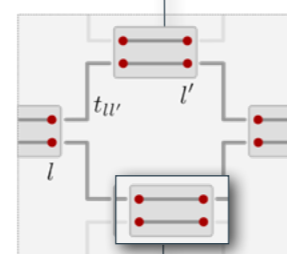
The long-term goal of the cluster is to realize network and processing architectures protected by error-correction protocols and eventually connected to a quantum version of the internet. This goal defines a hierarchy of challenges, both in fundamental science and in technology, which must be overcome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



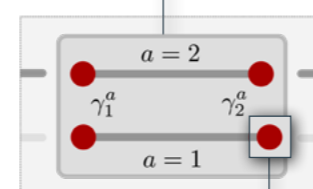
THE VISION



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 were subject of the first two years of the running period (see Focus Area 1 and Focus Area 2 reports).

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
- 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



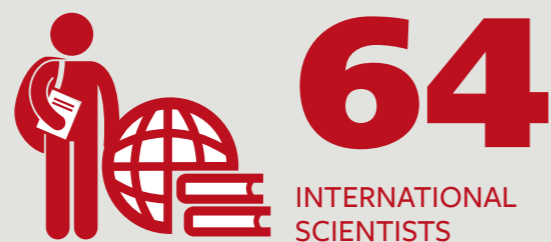
PROFESSORS



PHD STUDENTS



POSTDOCS



FEMALE SCIENTISTS



RESEARCH INSTITUTIONS



OPEN CALL PROJECTS AND
INDEPENDENCE GRANTS



ADMINISTRATIVE &
TECHNICAL STAFF



PUBLICATIONS IN 2020



PUBLICATIONS IN 2020
WITH TWO OR MORE ML4Q
GROUPS INVOLVED
(13 CROSS-SITE PUBLICATIONS)

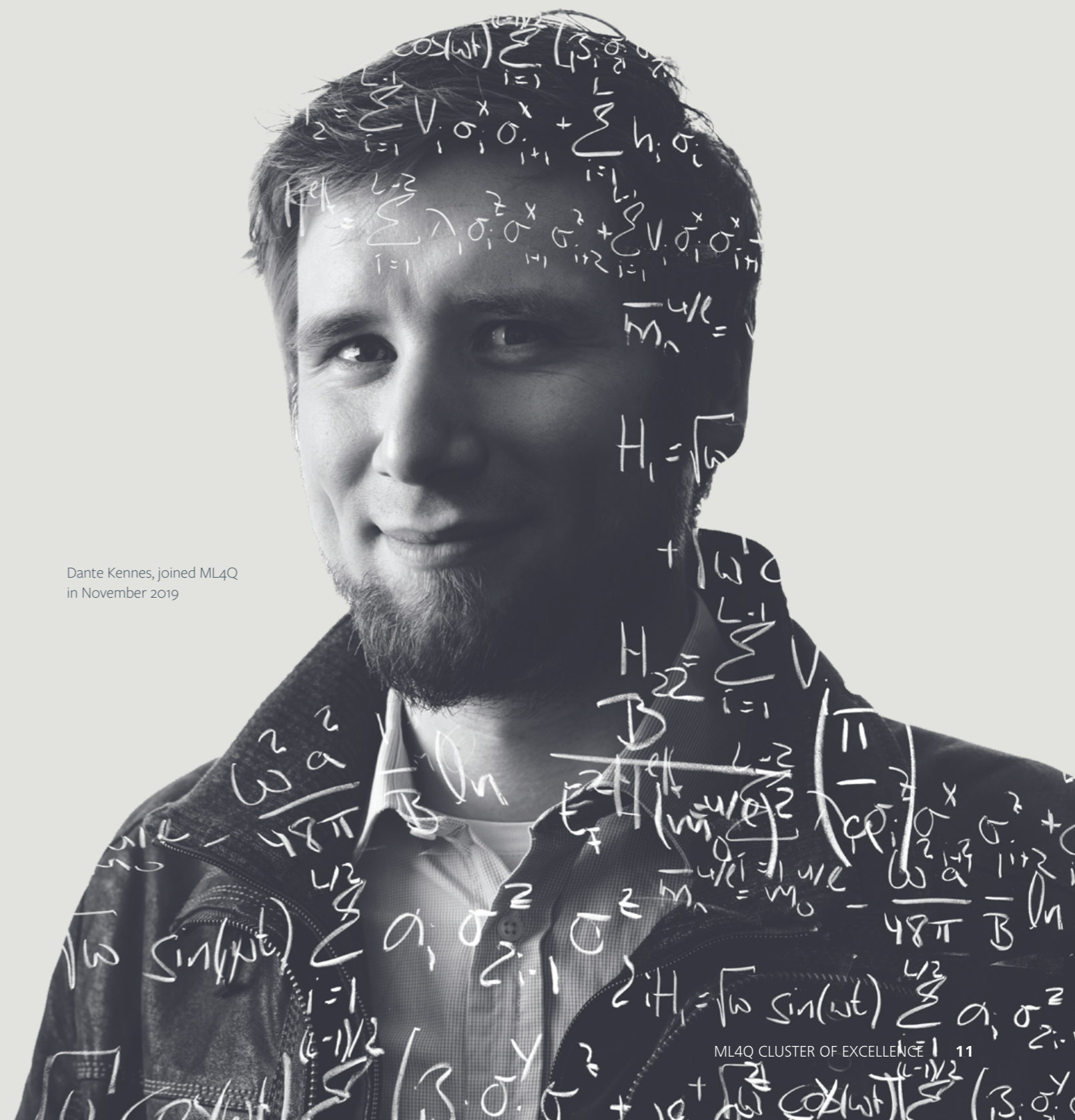
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DANTE KENNES

The vibrant scientific environment within ML4Q as well as critical efforts being spent on connecting different geographic and scientific communities within the cluster allow younger scientists to enter the field of quantum computing with ease.

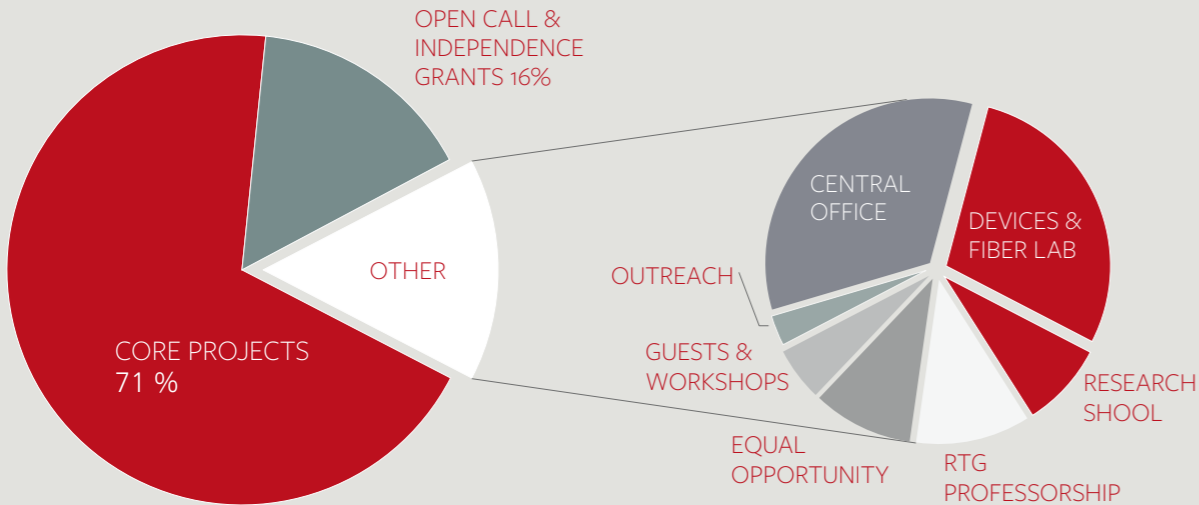
01

ML4Q AT A GLANCE

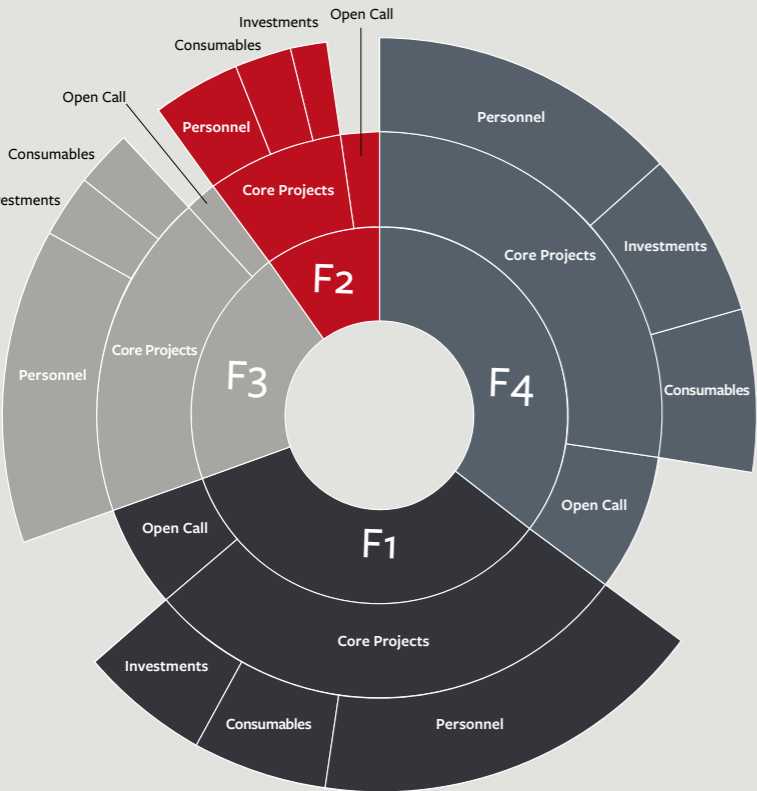


Dante Kennes, joined ML4Q
in November 2019

CORE PROJECTS & CENTRAL MEASURES



In 2020, 71% 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, two calls in 2020 led to the allocation of 16% of the expenses to Open Call projects as well as Independence Grants. 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 2020 broken down by Focus Area and type of funding. Most Focus Areas experienced additional growth in 2020 through the Open Call projects.

INTERNATIONALIZATION



All academic groups experienced growth in 2020 on both a national and an international level. 32% of ML4Q members are international scientists coming from over 20 countries (see map below). As in 2019, postdoctoral scientists still show the highest level of internationalization.



NEW DEVELOPMENTS IN 2020

2020 was a year of significant developments for the whole field of quantum technologies, which of course triggered new activities and strategic changes within our cluster as well. In June, the Konjunkturpaket (stimulus package) by the federal government, which aimed at stabilizing and stimulating Germany's economy following the impact of the global Covid-19 pandemic, was all over the news. The announcement of a dedicated funding program for quantum technologies (with a particular focus on quantum computing and a total funding volume of 2 billion Euro) was welcomed not only by ML4Q, but by the scientific community in the field as a whole, as expressed in a joint press release by the Quantum Alliance, the consortium of the German Clusters of Excellence and research centers working in quantum science and technology.

It became clear that positioning ML4Q in the rapidly developing "quantum landscape" would be a major task for the months and years to come, which was the impetus for the creation of the ML4Q Strategy Board in autumn 2020.

The Strategy Board will play a major part in driving the strategic development of ML4Q. A second major task will be improving cluster-internal communication and in particular cohesion between the cluster sites, which is an obvious day-to-day challenge in a large research project spanning five locations (and an ever-growing number of external partners).

In December 2020, the first ML4Q Concepts seminar series kicked off. It focused on Majorana fermions and was a huge success in bringing together students, postdocs and senior researchers from all cluster sites – you can read more about events and other activities in the ML4Q Life section.

Similarly to the first year of the cluster, our Open Call funding line proved to be a major instrument for integrating new research lines and members into the cluster. In the two calls (one in June and one towards the end of the year), a total of 14 new projects were funded, and several new PIs from various institutions joined the cluster. Overall, ML4Q has grown significantly over its second year, with a total of 194 members and associated members.

“

TOMMASO CALARCO

Quantum technologies will decisively shape the 21st century and trigger a revolution in information technologies. A joint effort by science and industry can succeed in making Germany a world-leading innovation driver for this future technology and thus generate jobs and prosperity in the very long term.

STRATEGY BOARD



Yoichi Ando (Cologne) has become a pioneer in the fields of topological insulators and topological superconductors. He is determined to realize topological quantum devices within the mission of ML4Q. Having deep insight in the strengths and challenges of Majorana-based qubits, he navigates the cluster adapting its research focus to developments in this fast growing field.



Markus Morgenstern (Aachen) is an expert in scanning tunneling microscopy (STM). He works on nanoelectronic devices and topological systems at low temperature. In ML4Q, he develops different STM techniques to characterize and understand superconductor-topological insulator interfaces. His understanding of the dynamics at interfaces – on a much larger scale that is – makes him contribute significantly to the communication culture in ML4Q's multi-site complex structure.



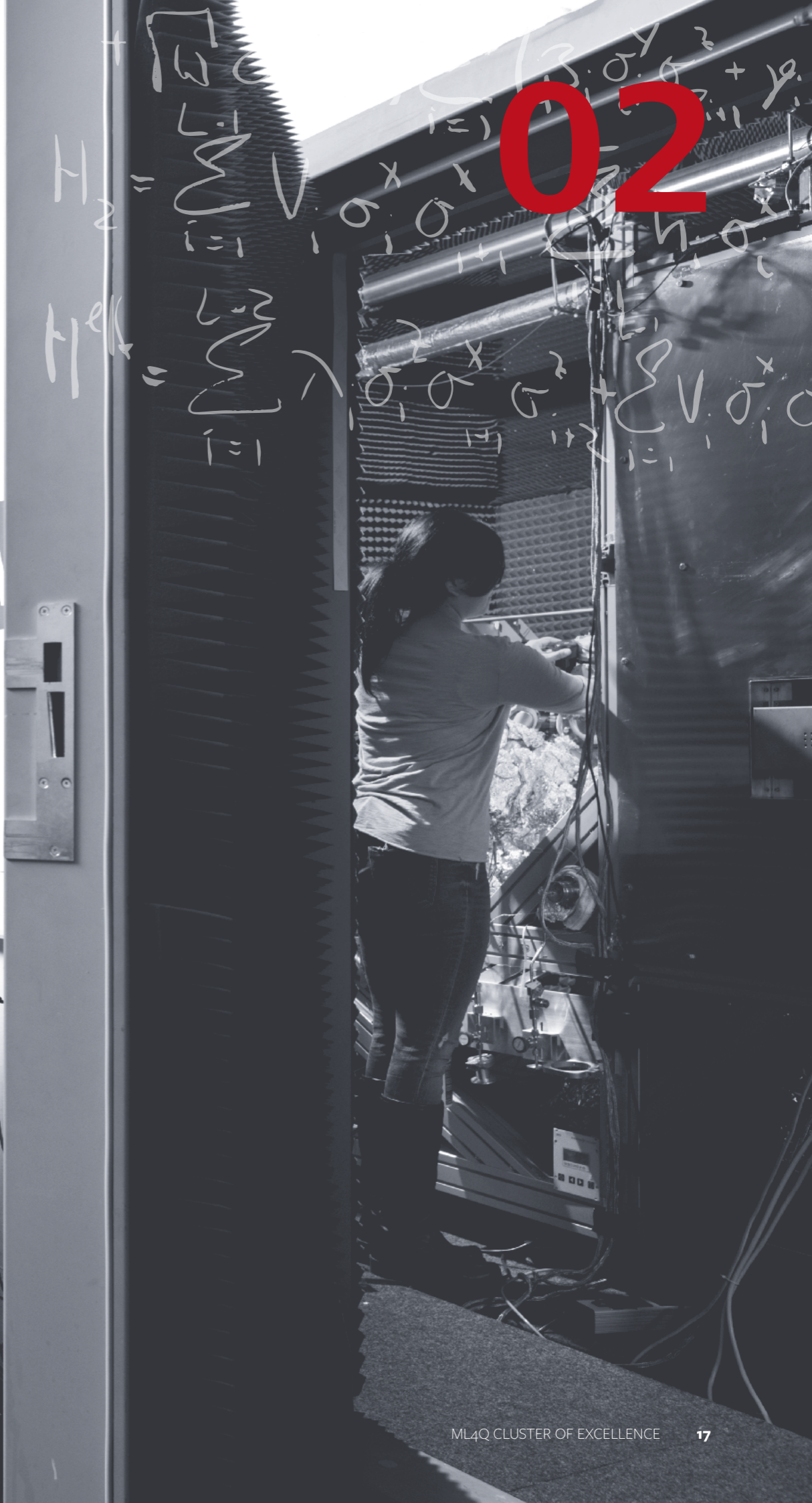
Simon Stellmer (Bonn) started his new position in Bonn a few months before ML4Q got started. He is an expert in novel optical clocks, degenerate quantum gases, and quantum simulation. Within the mission of ML4Q, he works on compact optical frequency references, optical network synchronization, and wavelength conversion. With an eye on young scientists and a heart for a vibrant working environment, he makes sure that ML4Q keeps and constantly increases its attractiveness as an employer.



Frank Wilhelm-Mauch (Jülich/Saarbrücken) joined ML4Q first as a member of the Advisory Board and since his appointment at Forschungszentrum Jülich in July 2020 as a member of the Strategy Board. Since October 2018, he has been coordinating the construction of the first freely programmable European quantum computer in Jülich as part of the European Flagship project OpenSuperQ. He accompanies ML4Q as it positions itself in the coming years in the rapidly changing quantum computing research landscape.

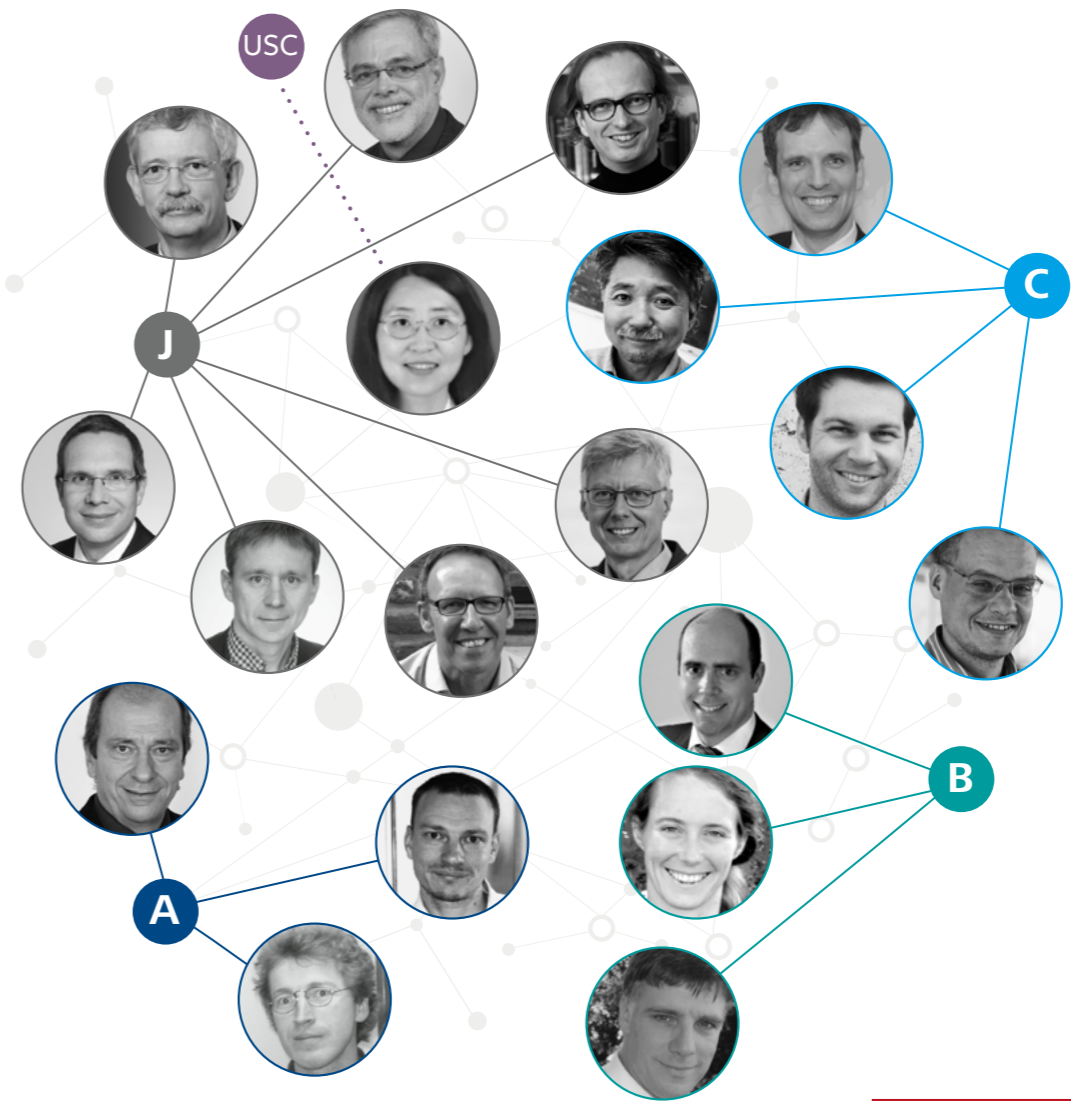


ML4Q RESEARCH



FOCUS AREA 1

FUNDAMENTALS AND
TECHNOLOGY FOR
TOPOLOGICAL INTERFACES



- Aachen
- Köln
- Bonn
- Jülich
- University of Southern California

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.

ACHIEVEMENTS

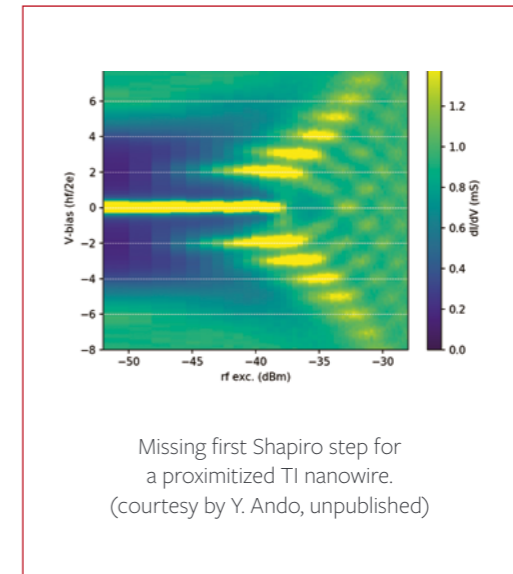
TI/SC INTERFACES The Ando group made significant progress in coupling various superconductors (Nb, Ti/Al, Ti/V) to bulk insulating $\text{Bi}_{2-x}\text{Sb}_x\text{Te}_3$ films after in-situ capping by Al_2O_3 . Moreover, in collaboration with the Mayer group they invented that sputter-deposited Pd on $\text{Bi}_{2-x}\text{Sb}_x\text{Te}_3$ induces PdTe_2 layers in the surface region [1] such that a quasi-monolithic lateral interface between SC and TI results. The Mayer group also investigated other deposits (M=Pd, Ti, Nb) on $\text{Bi}_{2-x}\text{Sb}_x\text{Te}_3$ indicating that the formation of MTe_2 layers as well as the formation of Bi bilayers is a common feature at such interfaces. The Blügel group developed an ab-initio BdG method towards description of the proximity effect in TIs enabling now an ab-initio based calculation of the SC band gap of Nb that favorably compares with scanning tunneling spectroscopy results. Moreover, high throughput ab-initio calculations have been pursued calculating properties of thousands of impurity configurations within TIs [2]. The Grüneis group explored the possibility to interface

the TI Bi_4Te_3 with the SC Rb_3C_{60} . The Stampfer group proximitized graphene with the SC MoRe and observed Andreev bound states [3]. Within an Open Call project, work conducted by Vaal, Dickel and Catelani combined SC resonator structures with TIs aiming at microwave readout of Majorana states.

QAH SYSTEMS The Plucinski group was involved in a study revealing that electron bombardment turns Mn-doped Bi_2Te_3 bulk insulating such that the QAH effect appears below the Curie temperature $T_c \approx 10$ K [4]. The Morgenstern group established that $\text{Mn}_{1+x}\text{Sb}_{2-x}\text{Te}_4$ has a pronounced magnetic gap of 15 meV within the topological surface state persisting up to $T_c \approx 50$ K [5]. The Ando group accomplished MBE growth of V-doped $\text{Bi}_{2-x}\text{Sb}_x\text{Te}_3$ used to investigate the QAH effect breakdown. The Voigtländer group probed spin transport properties of TI surface states in-situ by 4-tip STM [6].

NANOWIRES The groups of Ando and Rosch identified quantized surface modes on $\text{Bi}_{2-x}\text{Sb}_x\text{Te}_3$ nanowires via gate dependent resistivity measurements [7]. The Ando group could contact bulk-insulating TI nanowires with Nb again revealing a missing 1st Shapiro step (see figure). The groups of Schäpers and Mayer realized SC proximity in Sb_2Te_3 nanoribbons [8]. The Mussler group prepared T-shaped TI nanowires as triple junctions in-situ via the selective area growth studying their magnetotransport properties [9]. The Rosch group studied the influence of charge puddles and the large dielectric surface mismatch on the properties of TI nanowires.

Cold atoms The Köhl group achieved control on the crossover between interlayer and intralayer quantum magnetism as key prerequisite for realizing 1D ladders featuring Majorana end states [10; see paper highlight on page 22/23]. The groups of Kollath and Diehl found that particle losses in such systems can lead to a novel dissipative metastable state [11,12]. Both groups (collaborating with the Rizzi group) developed methods to implement Majorana states in such systems, either by Aharonov-Bohm caging or by Floquet-type driven pair tunneling. First important ingredients of these methods are currently implemented in the experiments. The Weitz group demonstrated ultrastrong coupling of motional degrees of freedom for Rb atoms in an optical lattice.



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Martin Weitz

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COMPETING MAGNETIC ORDERS IN THE BILAYER HUBBARD MODEL WITH ULTRACOLD ATOMS

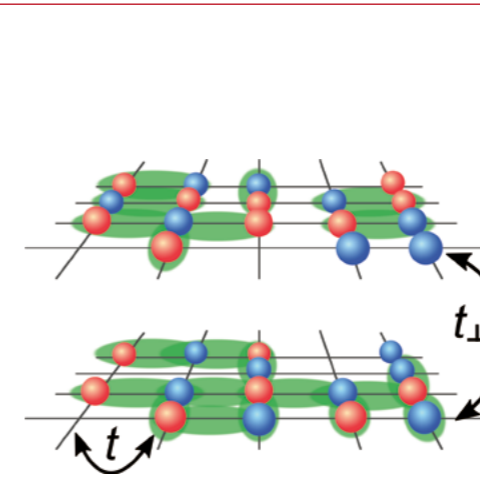
BY MARCELL GALL, NICOLA WURZ, JENS SAMLAND, CHUN CHAN & MICHAEL KÖHL
NATURE 589, 40–43 (2021)

They are as thin as a hair, only a hundred thousand times thinner—so-called two-dimensional materials, consisting of a single layer of atoms, have been booming in research for years. They became known to a wider audience when two Russian-British scientists were awarded the Nobel Prize in Physics in 2010 for the discovery of graphene, a building block of graphite. The special feature of such materials is that they possess novel properties that can only be explained with the help of the laws of quantum mechanics and that may be relevant for enhanced technologies. However, how unusual quantum phenomena arise is still far from being fully understood.

To shed light on this, we are using so-called quantum simulators, which mimic the interaction of several quantum particles something that cannot be done with conventional simulation methods. Even state-of-the-art

computer models cannot calculate complex processes such as magnetism and electricity down to the last detail. The quantum simulator consists of ultracold atoms — ultracold because their temperature is only a millionth of a degree above absolute zero in order to make very precise observations. Within the quantum simulator, we have, for the first time, succeeded in measuring the magnetic correlations of exactly two coupled layers of a crystal lattice. By controlling the strength of this coupling, we were able to rotate the direction in which magnetism forms by 90 degrees — without changing the material in any other way.

The new results make it possible to better understand magnetism in complex materials at the microscopic level. In the future, the findings will help to make predictions about material properties and achieve new functionalities of solids, among other things.



In solid-state materials, the atomic nuclei form a lattice structure (illustrated by the grid lines) and the electrons (symbolized by red and blue balls) hop between the lattice sites. Here, the color refers to either of the two possible orientations of the electron spin. An anti-ferromagnet is a material in which all electrons on neighboring sites have the opposite spin – just like a checkerboard pattern. Moreover, quantum entanglement (indicated by the green shades) emerges between the electrons, which makes this material very difficult to understand. In our work, we perform an experimental quantum simulation of a solid-state material with ultracold atoms in an optical lattice consisting of precisely two coupled layers. The additional degree of freedom of two coupled layers allows us to explore and control the way how magnetism emerges. Our experimental data reveal a crossover at nano-Kelvin temperatures between two distinct magnetic phases, where magnetic correlations form either within or between the two-dimensional layers.

TRIVIA

0

ZOOM MEETINGS



THIS WORK WAS PERFORMED WITHOUT A SINGLE VIDEO CALL.
INCREDIBLE UNDER TODAY'S CONDITIONS!

“

MICHAEL KÖHL

The direction of magnetic order, i.e. the mutual alignment of the atomic magnetic moments in a solid, can be controlled at the quantum level. The magnetic order between strongly coupled layers competes with the original magnetic order within a single layer.

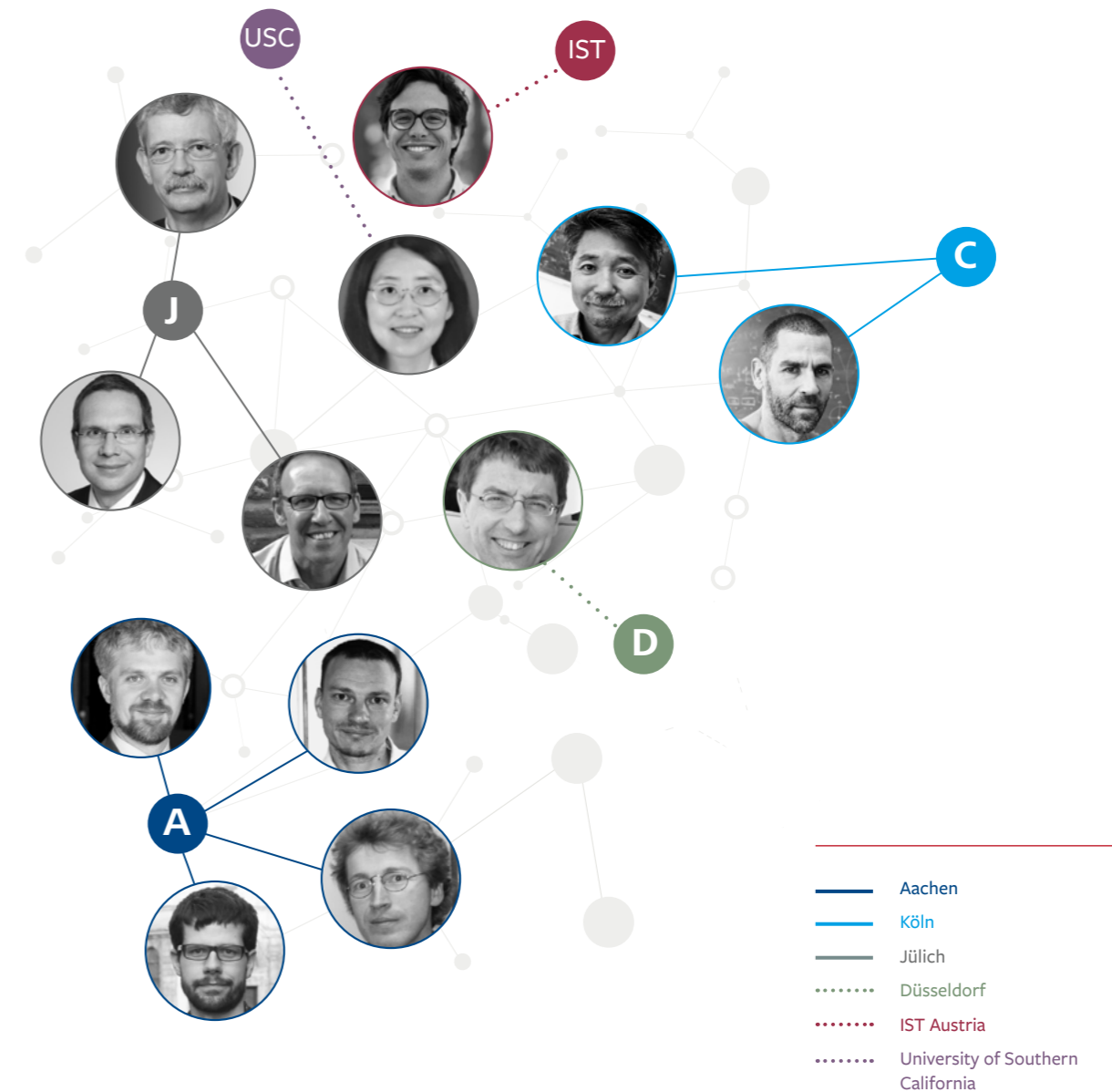
THE TEAM



Nicola, Marcell and Jeffrey have worked together on this project for several years. After upgrading the experimental setup and developing the measurement protocols, they have analyzed the data in several intense discussions and are now very happy to share their results on magnetic correlations in a bilayer 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

ACHIEVEMENTS

Our ultimate objective is to realize Majorana qubits based on topological insulators and to perform braiding. Based on the successful installation of the capability to perform superconducting qubit experiments in 2019, we have further advanced the qubit fabrication technology as well as the qubit control technology. As a result, we realized an aluminum-based transmon qubit showing competitive coherence properties in relatively high magnetic fields, which is a requirement for future topological insulator-based Majorana qubits. Moreover, tunnel-junction devices have been realized in order to investigate the Majorana states in Abrikosov vortices deterministically-created in a proximitized topological insulator surface.

For future quantum processors based on Majorana zero modes, networks of topological insulator nanoribbons are a prime platform. In a first stage, we have addressed the transport properties of $(\text{Bi,Sb})_2\text{Te}_3$ nanoribbons and investigated the distribution of phase-coherent loops formed in the topological surface channels. As a next step, nanoribbons were equipped with superconducting electrodes. Here, we succeeded in observing a Josephson supercurrent in junctions based on Sb_2Te_3 and GeTe nanoribbons. Special attention was devoted to the junction behavior in magnetic fields, since future Majorana qubit circuits need to be biased by an in-plane magnetic field.

Theoretically, a weak measurement protocol for the unambiguous identification of a Majorana qubit via probing the underlying Pauli operator algebra in quantum shot noise has been devised [1; see paper highlight on pages 28/29]. Such a protocol may serve to experimentally rule out topologically trivial zero energy states that may compete with topological Majorana states. This idea applies to arbitrary Majorana platforms and therefore is expected to guide the experimental efforts in implementing Majorana qubits.

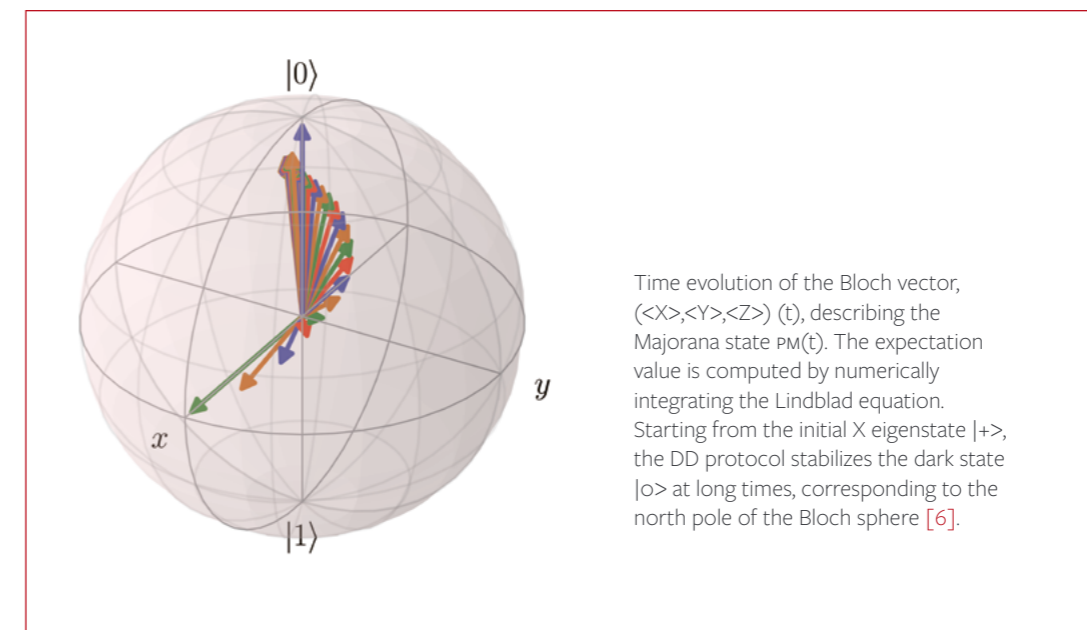
The measurement process of reading out a selected Majorana parity via a tunnel-coupled quantum dot represents an intricate and rich physical problem [2]. In general, the quantum feedback by the measurement apparatus plays a crucial role, which is especially nontrivial for the topological Majorana qubits studied in ML4Q. In this respect, we have constructed a theoretical model on a master equation that is tailored for experiments under realistic conditions.

As an alternative platform for Majorana qubits, the braiding based on flying non-Abelian anyons in the form of chiral edge vortices has been considered. Experimentally, such a system can be realized by the edge mode of a chiral topological superconductor engineered by proximitizing a quantum anomalous Hall insulator. In [3], it

was shown that the non-Abelian braiding can be detected via the charge signal when fusing the non-Abelian anyons after braiding.

Driven-dissipative systems, an alternative route for operating Majorana qubits, have been studied in [4,5]. We have studied how the future Majorana qubits are connected to quantum dots which

in turn are connected by driven tunnel links. In such a setup, it is possible to exploit the interplay between driving and the dissipative effects of the electromagnetic environment in such a way that arbitrary target states and even degenerate manifolds of automatically stabilized target states could be created. Such a setup is effective in protecting the fragile quantum memory and abolishes the need for quantum error correction.



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WEAK MEASUREMENT PROTOCOLS FOR MAJORANA BOUND STATE IDENTIFICATION

BY JAN MANOUSAKIS, CAROLIN WILLE, ALEXANDER ALTLAND, REINHOLD EGGER, KARSTEN FLENSBERG, AND FABIAN HASSLER
PHYS. REV. LETT. 124, 096801 (2020), EDITORS' SUGGESTION

In a quantum computer the processing of information takes place entirely in the quantum realm. This is the source of its widely proclaimed computational powers and, at the same time, the reason why building a quantum computer is hard. Quantum information in its very nature is fragile. To overcome this fundamental obstacle, it is of key importance to identify the physical systems optimally suited as minimal units, the so called quantum bits.

Qubits which rely on a particular unconventional electronic state, the so called Majorana bound state (MBS), are advantageous in that they store information in a non-local fashion which makes them intrinsically more robust against noise. However, the existence of

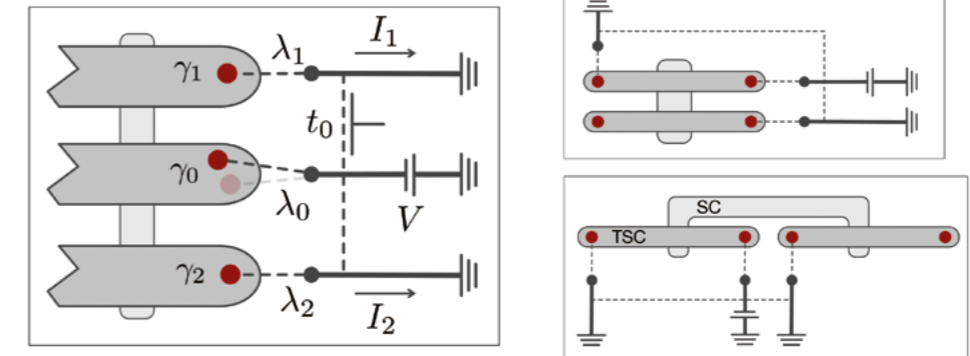
MBS itself is still under debate as experimental evidence allows for alternative explanations of the observed phenomena. The lack of clear experimental evidence is unsettling not only for prospective applications in quantum computation, but also from a perspective of fundamental research.

This is where the work by Manousakis et al. comes in. The researchers propose an experiment which directly addresses the defining property of an MBS-qubit – the fact that information is stored non-locally. This allows to unambiguously identify MBS. In particular the proposed experiment is able to distinguish MBS from so called Andreev bound states (ABS), a different (and arguably less useful) electronic state which can easily be mistaken for MBS in experiments that rely only on local probes.



CAROLIN WILLE

Majorana bound states (MBSs) could be the qubits of the future. However, researchers are not sure to have actually observed them. We believe, that this experiment would yield a definite fingerprint.



The proposed experiment is performed on a system of topological nanowires coupled to a superconductor. The electronic states to be probed are located at the ends of the wires. A voltage is applied to one wire and the current shot noise cross correlations between the other two wires is recorded. The experiment is repeated with an additional short-cut (t_0) between the first and the second wire. If the shot noise is drastically suppressed by the presence of the short-cut, this indicates MBS, while ABS are insensitive to the additional short-cut.

TRIVIA

3
4
5

SUB-DISCIPLINES OF PHYSICS

TRYING TO TACKLE THE QUESTION OF HOW MANY SUB-DISCIPLINES OF PHYSICS NEED TO COME TOGETHER TO DETECT A MAJORANA QUBIT IN A SIGNAL THAT IS PURE NOISE, WE STOPPED COUNTING AT FOUR!

THE TEAM

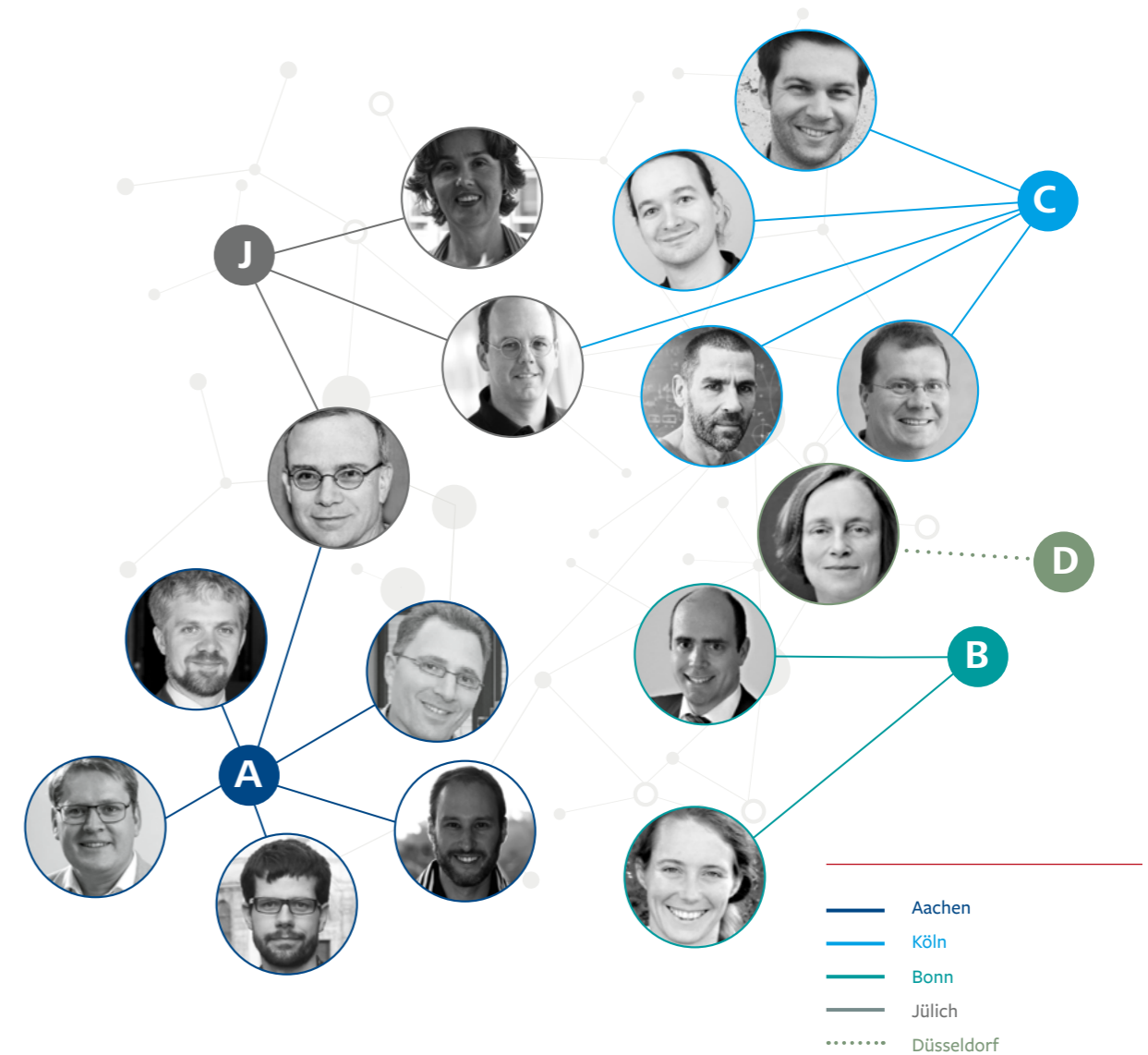
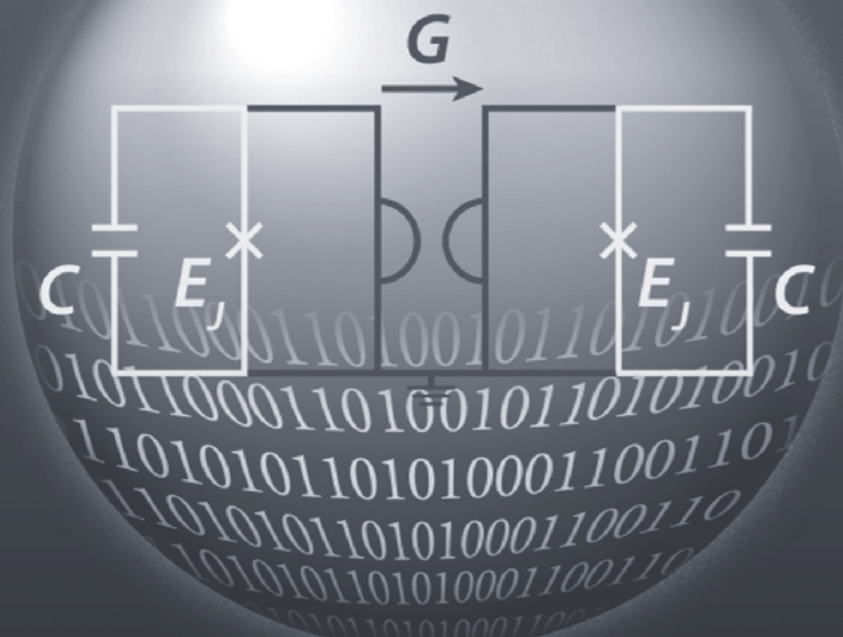


Jan Manousakis received his PhD in Theoretical Physics in 2020 after conducting research in Cologne and Copenhagen on the topic of Majorana qubits. Since then he has been working as a consultant.



Carolin Wille did her PhD in Berlin on topological quantum matter and is now a Postdoc in Cologne. Her contribution to the highlighted project was to discuss with Jan about conceptual points and technical details of the derivations and to double check all calculations.

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

The charter of Focus Area 3 continues to be to fully characterize quantum decoherence, and combat 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 2020.

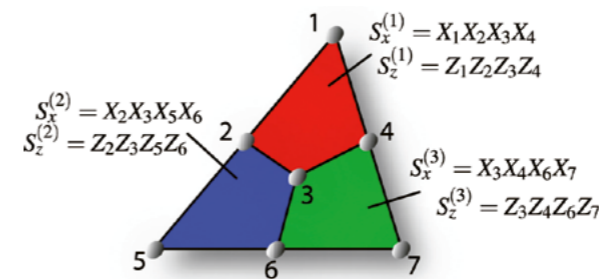
ACHIEVEMENTS

TOPOLOGY IN AND OUT OF EQUILIBRIUM

The Diehl group, in a collaboration with Altland, has established a complete symmetry classification of arbitrary interacting open quantum systems based on a first principles approach operating in fermionic Fock space. The classification works irrespective to the system being in pure or mixed states [1]. The Kollath and Rosch groups have collaborated on the paradigmatic system of strong quantum-light and quantum-matter coupling for ultra-cold atoms coupled to an optical cavity. Such strong quantum-light quantum matter couplings are important building blocks for quantum technological devices. They developed new theoretical techniques in order to treat these very complex systems and by this solved long standing questions on the nature of the arising non-equilibrium transitions [2].

THEORY OF ERROR CHARACTERIZATION,
MITIGATION, AND CORRECTION

In a remarkably productive Cologne-Jülich collaboration, Altland, DiVincenzo and Trebst have analyzed the general feasibility of superconducting transmon arrays as platform for quantum computing devices. In particular, they have been exploring the question how one can balance intentional disorder (to protect qubits) and non-linear resonator couplings (to couple qubits) without driving the system into a chaotic regime. This project stands out for its relevance in designing future transmon computing architectures, as well as its truly interdisciplinary nature where we brought statistical tools such as the Kullback-Leibler divergence to the many-body localization/chaos transition along with quantum information measures such as Walsh transforms [3; see paper highlight on pages 34/35]. Bruss has progressed on the objective of high-speed decoders in her machine learning approach for efficient decoding and post-correction of surface codes (O2), in particular for the toric surface code with two logical qubits. They showed how symmetries of the toric code can be exploited to reduce the amount of training data that is required to obtain good decoding results [4]. The Open Call project of Müller, “Towards Fault-Tolerant Spin-Qubit-Based Logical Qubits” spans this and the next core project. Müller and his group developed and tested an adaptive subset-sampling algorithm [5]. This simulation tool allows for highly-efficient stabiliser simulations of quantum error correction protocols.



Steane code or seven-qubit colour code: a structure composed of seven qubits is used for encoding one logical qubit. The code is defined by six stabiliser generators $S_x^{(j)}$ and $S_z^{(j)}$ for $j=1, 2, 3$ associated with each of the four-qubit plaquettes. The code space is defined as the simultaneous +1 eigenspace of these stabilisers [5].

ELECTRON SHUTTLING FOR SPIN-QUBIT
SURFACE CODE WITH THEORISTS

Calarco and DiVincenzo, the Aachen/Jülich experimental team aims to establish connectivity between spin qubits via spin-coherent electron shuttling [6], with ultimate achievement of topological error correction. Concerning the previously reported 280 gate-array device fabricated with metal lift-off technique, this process can now produce one sample batch per month. Charge sensors are working, and we use

these to detect loading and unloading electrons into/from the conveyor and developing the corresponding tuning techniques at 20 mK as the next steps towards shuttling. Electrostatic simulations show that the gate layout used can readily be extended to realize T-Junctions for branching. As the reliability of the process used for the above devices was considered likely to be insufficient to reach our long term goals, a more advanced process is developed in cooperation with the Knoch group.

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TRANSMON PLATFORM FOR QUANTUM COMPUTING CHALLENGED BY CHAOTIC FLUCTUATIONS

BY CHRISTOPH BERKE, EVANGELOS VARVELIS, SIMON TREBST,
ALEXANDER ALTLAND AND DAVID DIVINCENZO
ARXIV:2012.05923

Military units crossing bridges avoid marching in step to prevent the formation of resonances destabilizing the construction. Perhaps counterintuitively, the superconducting transmon qubit processor – the technologically most advanced platform for quantum computing pursued by IBM, Google and other consortia – relies on the same stability principle: individual transmon qubits are (quantum) oscillators, and random frequency detuning is intentionally introduced to block the formation of resonant chaotic fluctuations destabilizing the multi-qubit processor. In this paper, we ask just how reliable this “stability by randomness” principle is in practice. Applying state of the art diagnostics of the theory of disordered systems, we find that at least some of the industrially pursued system architectures are operating at the verge of chaotic meltdown.

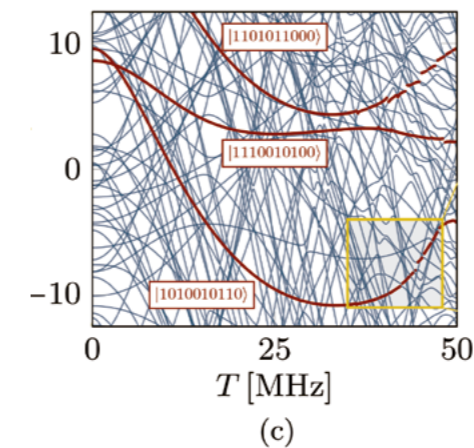
From the point of view of the many-body physicists, a transmon processor is operated in a regime where substantial randomness preserves the integrity of many-qubit states in the presence of the finite inter-qubit coupling required for device functionality. Recent progress has led to the development of sensitive numerical tools diagnosing early indicators of quantum chaotic fluctuations destabilizing such “many body localized” phases. Applying this methodology to a realistic modeling of Google and IBM chips, we find that in the latter qubit states are coupled to a degree that may jeopardize controlled gate operations.

Our study demonstrates that the combination of state of the art methodology of quantum randomness and realistic device modeling must become a routine part of qubit processor design in the superconducting platform.

“

DAVID DIVINCENZO

Arrays of coupled superconducting (transmon) qubits define the most advanced quantum computing platform to date. Perhaps counterintuitively, the transmon chip not only tolerates but actually requires effectively random qubit-to-qubit device imperfections.



Energy states of a 10-transmon quantum computer, as a function of how strongly the transmons are coupled (T). The actual data-carrying states (red) live in a sea of other quantum states that are invalid states for computation. Usually they cross right through each other and don't see one another, but for large T sometimes they start to melt together. We call these our “spaghetti” diagrams, with uncooked spaghetti on the left and cooked spaghetti on the right.

TRIVIA

3

ML4Q PARTNER INSTITUTIONS CONTRIBUTING TO THE PAPER



THE TEAM



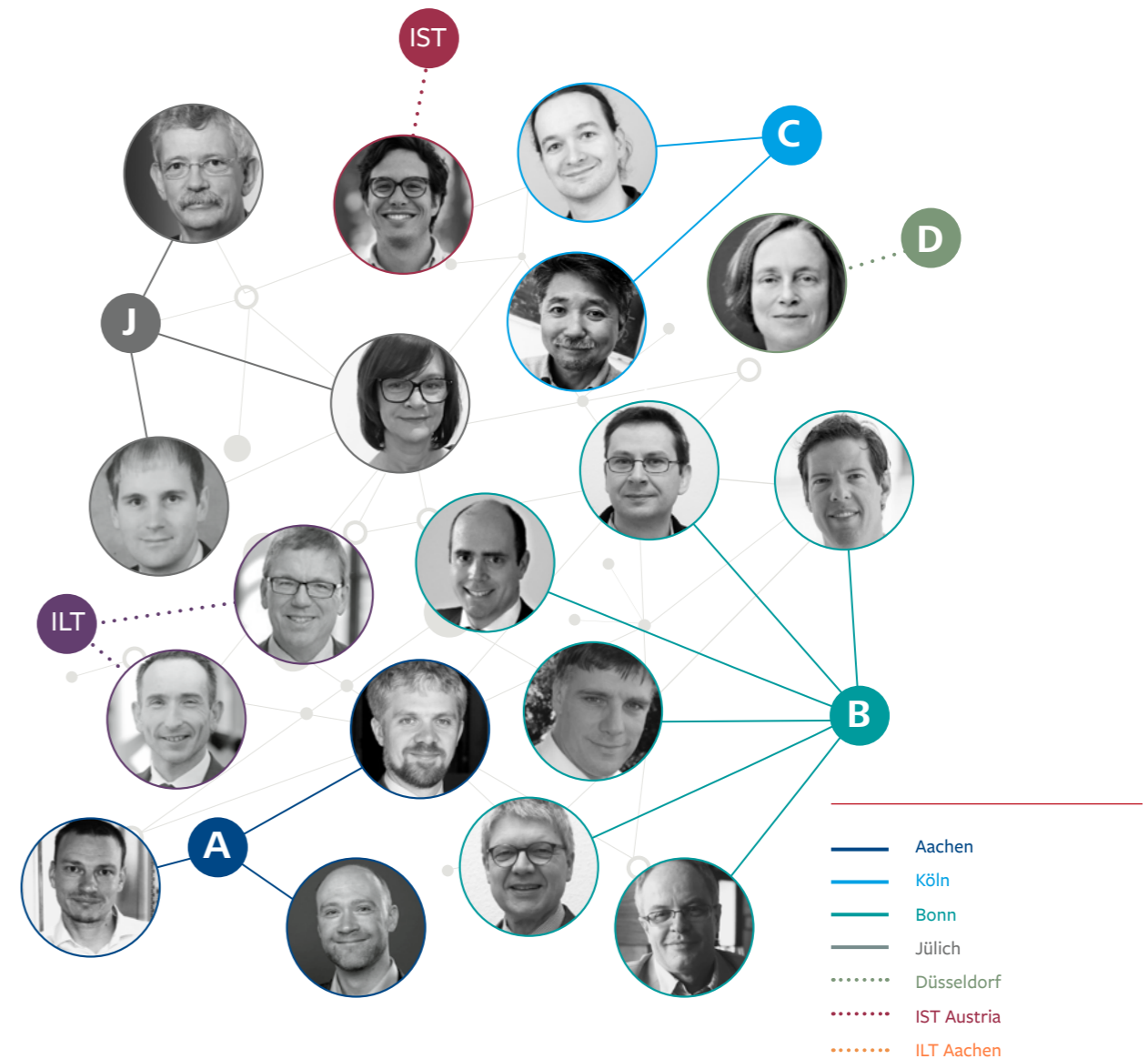
Alexander Altland All-around solid state physicist, controversialist, and wordsmith

David DiVincenzo Never likes disorder, even more of a wordsmith

Christoph Berke Father of two with penchant for beautiful figures

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 Majoranas 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, i.e., the processing of quantum information in elementary quantum processors and the distribution of quantum information in networks. The research work spans several experimental platforms, such as correlated photons, semiconductor quantum dots, trapped ions, and nanoplasmonics, as well as theory.

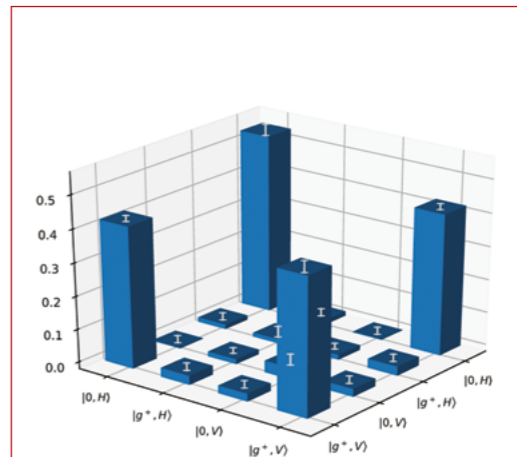
researchers David Dung and Christian Wahl studies surface-structured mirrors that can be used for the creation of precision potentials for highly-entangled quantum states in a dye-filled optical microcavity and successfully reached sub-Angström accuracy [6].

SEMICONDUCTOR QUANTUM DOTS The Kardynal and Bluhm groups have focused on growth optimization in GaAs, in order to achieve the required mobility of the two-dimensional electron gases and the gate performance of the heterostructures that is needed for high-quality spin qubits. Recent wafers have demonstrated promising mobility and the preparation of spin-photon interface devices is underway. Quantum dots were optimized for the required wavelength and incorporated into heterostructures designed for photon extraction tests. In order to enhance the photon extraction efficiency from the semiconductor material, the Linden group has simulated, built and tested microoptical elements on a semiconductor wafer from Jülich and the Witzens and Linden groups have designed and theoretically analyzed photonic crystal structures etched into the (Al)GaAs membrane [7]. The characterization of the enhanced extraction is ongoing in the Linden group. On an alternative semiconductor platform, Alexander Pawlis has established the fabrication technique of photonic crystal cavities from ZnMgSe/ZnSe:Cl/ZnMgSe quantum well structures and a novel growth procedure has been developed to implement nanowire based single photon sources [8, 9].

FREQUENCY CONVERSION The frequency conversion projects at Fraunhofer ILT and in the Stellmer group have gained momentum and set up large parts of their equipment. Fraunhofer ILT has been investigating a

polarization-independent converter to convert photons from a qubit system in collaboration with Beata Kardynal, and the Stellmer group explores both conventional conversion in waveguides and pressure-cell enhanced conversion for collaboration with the Pawlis, Kardynal and Köhl groups.

TRAPPED IONS The Köhl group has demonstrated the creation of entanglement between a trapped ion and a single photon in a fiber cavity. We have observed a fidelity of > 90% and a detected rate of entangled states of > 60 Hz (corresponding to 25 kHz entanglement creation rate). This result compares extremely well to other approaches world-wide and our entanglement success rate is among the highest ever reported. Furthermore, we have conducted a full quantum state tomography of the entangled state showing that they indeed create a maximally entangled state [10].



Quantum state tomography of the entangled state between a spin of trapped ion and the polarization of the emitted photon [10].

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ACHIEVEMENTS

THEORY A major research task addressed by all three theory groups (Bruss, Gross and Kroha) is quantum conference key agreement, both in the device-dependent and device-independent scenarios [1-4]. The work has spanned both fundamental aspects and the development of new protocols as well as the connection to the correlated photon states experimentally to be produced in the Weitz group. The strong experiment/theory link aims at understanding driven, nonlinear optical resonators from a microscopic perspective to produce GHZ states of photons.

PHOTON BOSE-EINSTEIN CONDENSATES The work in the Weitz group on photon Bose-Einstein condensates has studied complex geometries of the dye microcavity apparatus, as required to realize N-photon entanglement. Specifically, three-, four-, and six-site structures were realized and tunneling of photons has been observed in coupled three-site dye microcavity arrays. Collaborating with the Bonn theory Kroha group, we have in a separate experimental setup demonstrated a non-Hermitian phase transition in an optical quantum gas [5, see paper highlight on page 40/41]. An Open-Call project by junior

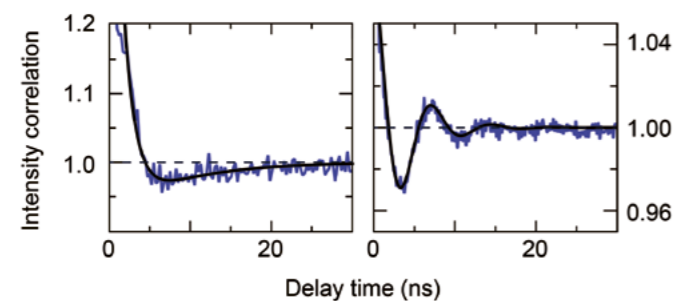
OBSERVATION OF A NON-HERMITIAN PHASE TRANSITION IN AN OPTICAL QUANTUM GAS

BY FAHRI EMRE ÖZTÜRK, TIM LAPPE, GÖRAN HELLMANN, JULIAN SCHMITT, JAN KLAERS, FRANK VEWINGER, JOHANN KROHA AND MARTIN WEITZ
SCIENCE, VOL. 372, ISSUE 6537, PP. 88-91 (2021)

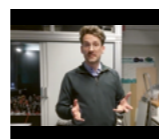
Researchers at Bonn University have discovered a previously unknown dissipative phase transition to a so-called overdamped phase in a Bose-Einstein condensate of light particles.

Bose-Einstein condensation is an effect where a large fraction of particles of a gas condenses into a single quantum state, forming a macroscopic wave. Usually, Bose-Einstein condensates are only observed at very low temperatures, but with photons, the quantized particles of light, Bose-Einstein condensates can be observed at room temperature. The experiments are performed in microscopic cavities made of two closely spaced mirrors with liquid dye solution filled in between. The newly observed phase transition occurs in such a Bose-Einstein

condensate of light particles and is due to small losses of the system, as present from e.g. the finite transmission of cavity mirrors, along with the photo-excitable dye molecules constituting a reservoir for the condensate particles. For large losses an oscillating condensate phase occurs, while when losses become smaller a phase transition to an overdamped phase is observed, the latter constituting a new state of the light field. While usually Bose-Einstein condensates are smoothly linked to the effect of lasing, the overdamped phase separates both phenomena by a sharply defined transition. For the future, the observed effects can allow for highly entangled ground states in coupled condensates arising from the openness of the system, offering prospects for efficient multi-site quantum connectivity.



The images show the measured intensity correlation of the emission of the dye-solution filled microscopic resonator versus delay time, for average photon numbers of 2300 (left) and 14000 (right). For the first case, with a smaller photon number, the Bose-Einstein condensate of light is in the overdamped phase, in the second case in the oscillating phase. Tuning between the two condensate phases was here accomplished by varying the average number of light particles (photons) contained in the resonator.



Watch co-author Julian Schmitt explains the main findings and speaks about exciting future directions to the team of uni-bonn.tv.



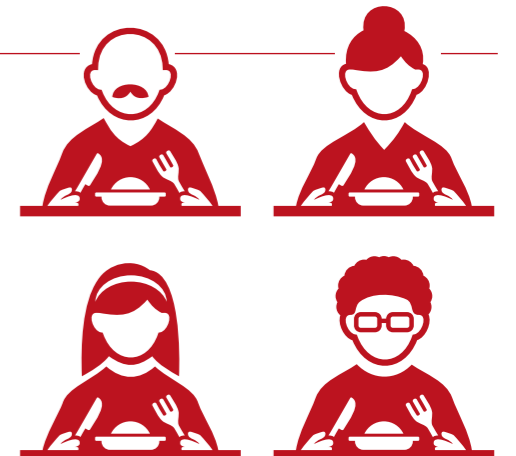
MARTIN WEITZ

ML4Q physicists have observed a phase transition to a new dissipative state of the light field. The work was enabled by a collaboration between theorists and experimentalists of the cluster.

TRIVIA

~50

JOINT INTERGROUP LUNCHES
BETWEEN PHD STUDENTS



THE TEAM



Fahri Öztürk studied engineering physics in Ankara and completed his M.Sc. studies in nanotechnology, where he worked on artificial noses using infrared fibers. In Bonn as a PhD student in the Weitz group, he studies fluctuation properties of photon BEC and took the experimental data on the observed transition.



Tim Bode (né Lappe) studied physics at ETH Zürich and joined the Kroha group as a PhD student to develop theory methods for photon BEC and work out the existence of the exceptional point at which the observed transition takes place. After his Ph.D. he joined the quantum computing group at the German Aerospace Center (DLR).



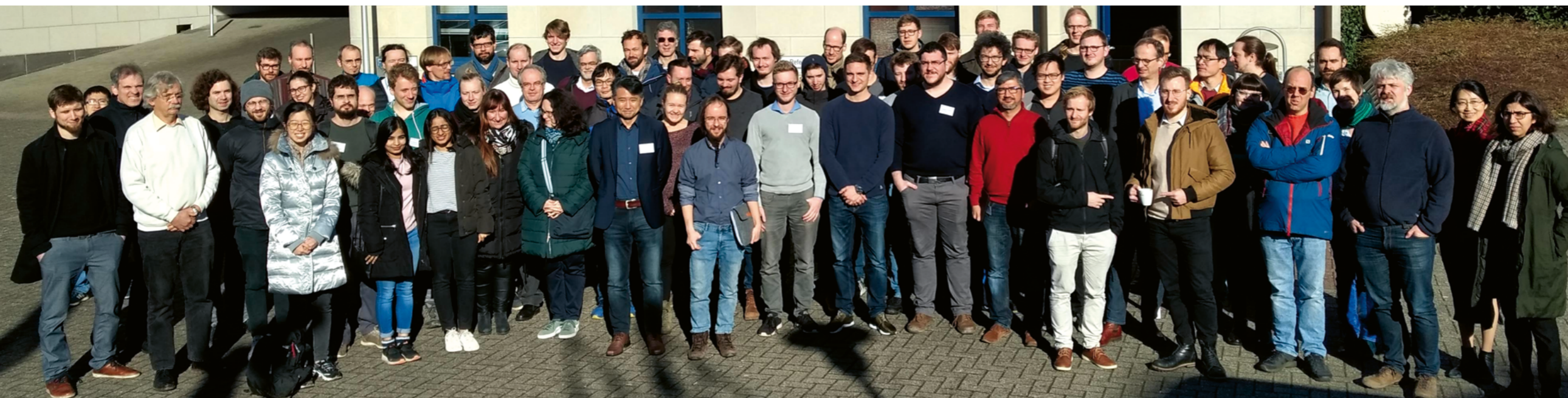
Dr. Julian Schmitt is a Junior Principal Investigator and ML4Q Independence Grant Fellow. In his PhD project he for the first time realized and observed grand canonical statistical conditions in photon BEC. As a postdoctoral researcher at the University of Cambridge, he studied the emergence of topologically induced superfluidity in two-dimensional atomic gases.



$$H_2 = \sum_{i=1}^L V_i \sigma_i^x \sigma_{i+1}^x + \sum_{i=1}^L h_i \sigma_i^x$$
$$H^{eff} = \sum_{i=1}^{L-2} \lambda_i \sigma_i^z \sigma_{i+1}^x \sigma_{i+2}^x + \sum_{i=1}^L V_i \sigma_i^x \sigma_{i+1}^x + \sum_{i=1}^L h_i \sigma_i^x$$

03

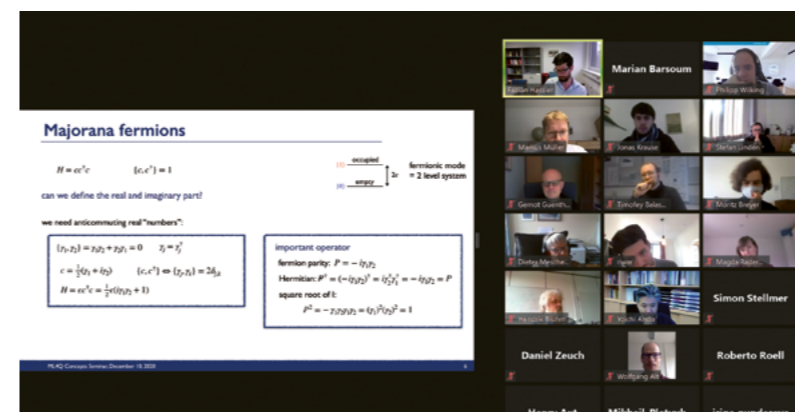
ML4Q LIFE



One highlight of our cluster life in 2020 was the **first annual ML4Q Conference** in February. With 120 participants, 40 posters, 4 high-profile keynote speakers, and about 20 cluster-internal talks and discussion sessions over the course of three days, it was pivotal for scientific exchange and strengthening the sense of community in our cluster. The active participation of several members of our Scientific Advisory Board provided valuable input for the Boards in evaluating the start of the cluster and steering it towards the future. Of course, the scenic setting in the Eifel and the social evenings (including a cozy torch hike warmed by mulled wine) strongly contributed to the success of the conference.

A month later, the **Corona** pandemic hit, and all life shifted to online mode. The transition was certainly eased by the fact that videoconferencing had been an important tool within our cluster since the proposal-writing days (for example, Board meetings with participants from four sites have practically always been held online) – but of course, the pandemic situation nonetheless proved to be a major challenge, in particular for the experimentalists in the cluster who had to deal with lab closures and delays in experiments.

In mid-March 2020, we took our first deep plunge into online teaching, when the new **Master course on Platforms for Quantum Technologies** was switched to online mode on very short notice – nonetheless, the block course (held jointly by lecturers from all cluster sites) was a huge success (read more in the Research School section).



Curiously, the necessity of online events even proved beneficial in some cases – without the need for time-consuming travel, the threshold to organize and attend multi-site networking events might actually have lowered: For example, our joint **community event for PhD students of all Quantum Alliance partners** in November proved that personal interactions and fruitful exchange with peers from all over Germany can be just a click away.



Towards the end of the year, the first **ML4Q Concepts seminar series** on Majorana fermions took place in online mode as well and attracted a regular audience of >50 researchers (mostly students and postdocs), despite the temptation of readily-available talk recordings after the seminar. The seminars were met with positive feedback, and topic suggestions in particular by the PhD students within the cluster immediately sparked a number of follow-up seminar series.

ML4Q RESEARCH SCHOOL AND EARLY-CAREER SUPPORT

The ML4Q Research School builds on the wide collaborative network that the various cluster sites provide. Hence, it brings along a multifaceted and rich training environment for early-career scientists. In order to optimize the cross-site communication among young scientists and to exploit possibilities for synergies within the cluster universities and research institutions, Magdalena Baer Radermacher joined the ML4Q office in December 2019 taking over the Research School coordination.

In 2020, the Research School continued putting together an attractive training program for Master and PhD students as well as for postdocs in various sub-disciplines of physics that are relevant to quantum science and technology. All Research School activities serve as a platform to enhance interactions between young researchers at different sites and career stages.

ML4Q succeeded in opening the well-established Bonn-Cologne Graduate School of Physics and Astronomy (BCGS) to cluster groups at RWTH Aachen. Starting from winter term 2020/21, full two-year Master scholarships per year will be awarded to two outstanding students at RWTH Aachen in the framework of ML4Q as well as the new Master track on Quantum Technologies at RWTH Aachen which started in the winter semester 2019/2020. In addition, Master students enrolled in Cologne and Bonn have the possibility to benefit from courses offered within the Master track in Aachen. On a more general note, students from all locations gained access to and made use of available cross-site courses in quantum technologies as well as training in transferable skills.

Not only do we benefit from existing training structures, but we have also developed new offers. One of the highlights was a new Master course on Platforms for Quantum Technologies in March 2020. This two-week course covers all major topics represented in the cluster research program and its focus areas starting by the introduction of basics of quantum information processing, spanning over the AMO (atomic, molecular, optical), solid-state, and topological platforms and concluding with lectures on quantum error correction and topological codes. The course is taught by lecturers from all cluster sites and was attended by roughly 50 participants from all three partner universities in its first instalment in 2020. Since the first course was very well received by students, we have since offered it again in the winter term 2020/21 where it was complemented by the first ML4Q Intensive Week on 'Security proofs on Quantum Key Distribution'.

Another highlight in 2020 was the start of 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. In the first application round, 4 ML4Q principal investigators offered internships in their groups and 6 outstanding students were selected from over 100 applicants who showed immediate interest in the program. The internships are planned to take place during the summer semester 2021, assuming that international travel and on-site internships will be possible again in the light of the global pandemic situation.

- Bonn-Cologne Graduate School extended to include cluster groups at RWTH
- Master study track on Quantum Technology at RWTH
- New Master course on Platforms for Quantum Technologies
- Undergraduate Research Internship Program



As for courses and trainings in transferable skills, our students and postdocs could profit from various offers organised in collaboration with the Career Development Department at RWTH Aachen. These included workshops on scientific writing, good scientific practice and research data management. Plans to expand the workshop offer in 2021 to include courses on scientific presentation, teaching or career planning as well as scientific integrity are in development.

While the offers and programs mentioned above focus on undergraduate as well as Master and PhD students, ideas for networking activities were developed in

2020 in order to support young postdocs in their career development. In a series of Alumni Career Talks, successful research group leaders from the cluster will talk about their experience in acquiring prestigious fellowships to enable their scientific independence. Also a Students' & Postdocs' Retreat was conceived in 2020 as a self-organised event to enhance cross-group interactions and spark ideas for new projects that are developed among the young scientists, thus strengthening their capabilities for independent project management. Both networking activities will take place on a regular basis starting from 2021 on.

EQUAL OPPORTUNITY & DIVERSITY



We are convinced that the lack of diversity in physics 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 effect” 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. As a postdoc in Klaus Ensslin’s group at ETH Zurich, Annika acquired expertise in quantum transport measurements that provide the basis for the fabrication and characterization of nanodevices based on 2D materials. In addition, she also masters high-resolution optical spectroscopy techniques, which have been key ingredients of her PhD work on self-assembled quantum dots in the group of Axel Lorke at the University of Duisburg-Essen. Annika will start her independent research in Aachen in January 2021. 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.

On a further note, ML4Q welcomed and gladly co-funded Q-Turn 2020 – a unique international quantum information workshop series which is dedicated to foster an inclusive community and highlight outstanding research that may be under-appreciated in other high-impact venues due to systemic biases. Q-Turn’s awareness program promotes diversity, equity, inclusion, intersectionality, responsible research, workers’ rights, as well as physical and mental health in quantum science and technology. Q-Turn’s quantum science program highlights top-quality experimental and theoretical work on quantum information technology and foundations. Two ML4Q associates contributed to the event organization as members of the organizing committee (Gláucia Murta, ML4Q Independent Grant Fellow at HHU Düsseldorf) as well as the program committee (Mariami Gachechiladze, postdoctoral fellow in the Gross group at University of Cologne).

To promote a family-friendly work environment, ML4Q reserved places for children of cluster members at local day care providers of the Froebel Group and a few of the cluster associated members made use of this service. Other associated members received support in their labs through student assistants in order to tackle the challenges of homeschooling during the lockdown periods in 2020. In Cologne, a parent-child-room was fully equipped to make it easier for parent scientists to bring their children along to work.

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 has been proposed and greenlit by the Steering Board and will be filled in 2021.



Watch the ML4Q short trailer on Q-Turn 2020!



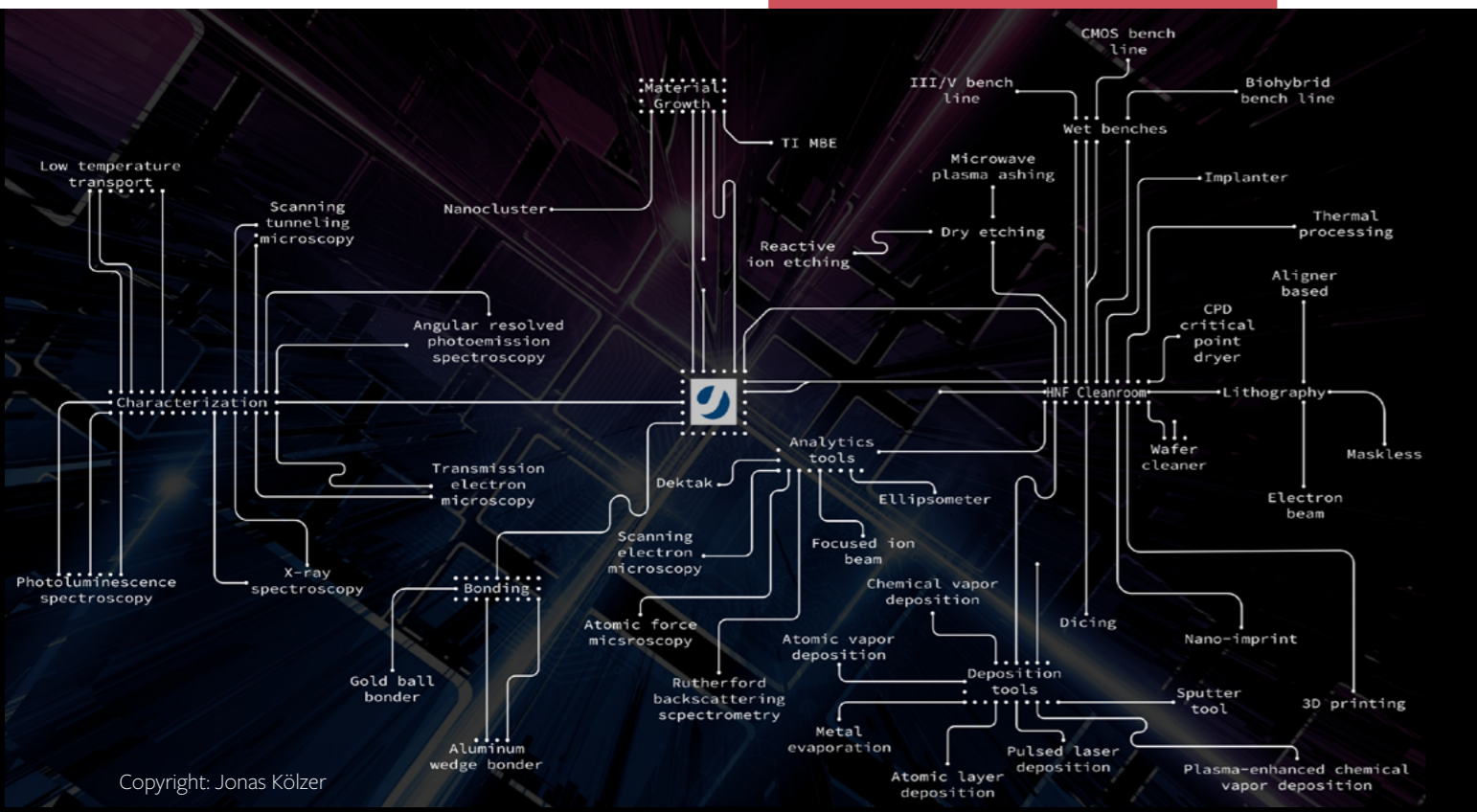
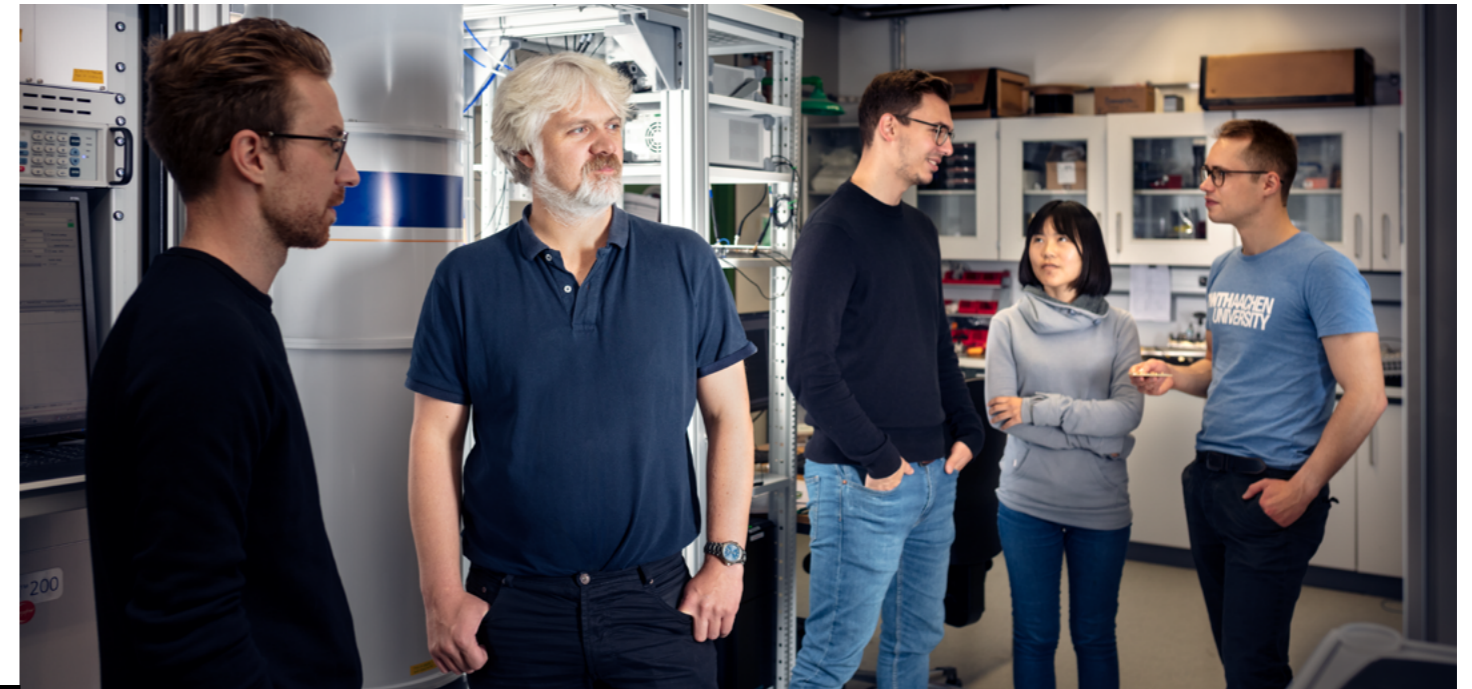
Find out about Mariami and her challenges as a female scientist coming from a third-world country!



Watch Gláucia as she speaks about growing up in a country where young people of different ethnicities and economical status experience inequalities in access to higher education!

As in the first year of our cluster, a significant fraction of 2020's ML4Q budget was dedicated to equipment (see the budget pie charts in the "ML4Q in numbers" section). Experimental efforts remain a cornerstone of ML4Q's research, both in the labs of the individual research groups and in the central facilities, i.e. the nanofabrication facility ML4Q Devices (linked to the Helmholtz Nano Facility at FZJ) and the ML4Q Fiber Lab in Bonn.

- 1/4 of the expenditures dedicated to acquiring equipment
- 100 keV electron-beam lithography tool at the Helmholtz Nano Facility in Jülich
- Fabrication of micro-optical elements in the Fiber Lab in Bonn
- Fabrication maps for Aachen, Cologne and FZJ
- New global network of US, Japanese and European nanofabrication and quantum technology platforms



Building on the added value of having a multi-site cluster, the idea of creating a hub for available infrastructure within the ML4Q framework emerged early on in the project, and students/postdocs in our cluster have started building interactive maps of the fabrication facilities at the cluster sites.

As a strong link to the international nanofabrication community, ML4Q is a part of Global Quantum Leap (GQL), a recently launched "network of networks" (funded via the National Science Foundation and led by the University of Minnesota) that aims to link nanofabrication technologies with quantum information sciences. ML4Q students and researchers will benefit from exchange programs, workshops, etc. with the various international partners within GQL.



The Global Quantum Leap (GQL) brings together key nodes within the NSF-funded National Nanotechnology Coordinated Infrastructure (NNCI) and complementary networks in the US such as the University of Chicago, Chicago Quantum Exchange, Cornell University and Georgia Tech. The "network of networks" which is led by the University of Minnesota includes European partners from OpenSuperQ, ML4Q and the EuroNanoLab as well as the Nanotechnology Platform Japan.



www.globalquantumleap.org

KNOWLEDGE TRANSFER



- Innovation2go with Tommaso Calaraco
- Joint PhD project with Covestro
- Shuttling-based scalable architecture design with Infineon Dresden GmbH, Leibniz institut IHP and Fraunhofer IPMS
- Midel Photonics – a new start-up emerging in Bonn

Quantum technologies are attracting substantial interest from industry and private capital. However, with many press releases overemphasizing success, ML4Q recognizes its competency to provide an unbiased expert opinion for decision makers in order to obtain a balanced picture of realistic future scenarios. The need for this competency became even clearer facing the media coverage of Google's quantum supremacy demonstration in September 2019.

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. Tommaso Calarco was invited to give a talk in the **Innovation2go series**. His talk focused on the second quantum revolution providing an overview on different industrial sectors that can profit from this technology and political efforts on the European level in order to invest into this key technology.

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 within the core project P3.2** and resulted in 2020 in a publication in Physical Review Research entitled "Avoiding local minima in variational quantum eigensolvers with the natural gradient optimizer".

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 a remarkably effective Open Call project, David Dung, Frederik Wolf and Christian Wahl were successful in spinning-off methods used within Focus Area 4 to produce laser beam-forming components for industrial purposes. The entrepreneurial team of **Midel Photonics** which combines scientific as well as business expertise was selected among 12 start-ups to take part in the High-Tech.NRW Start-Up Business Accelerator program offered by the Cluster NanoMikroWerkstoffe Photonik.NRW (NMWP).

After a ten-week incubation program which included networking with other start-ups, training in customer acquisition as well as support in developing the business plan for attracting investors, David Dung presented a business pitch introducing Midel Photonics at the HIGH-TECH.NRW Demo Day 2020. The expert jury awarded Midel Photonics the third prize for the business pitch presentation.

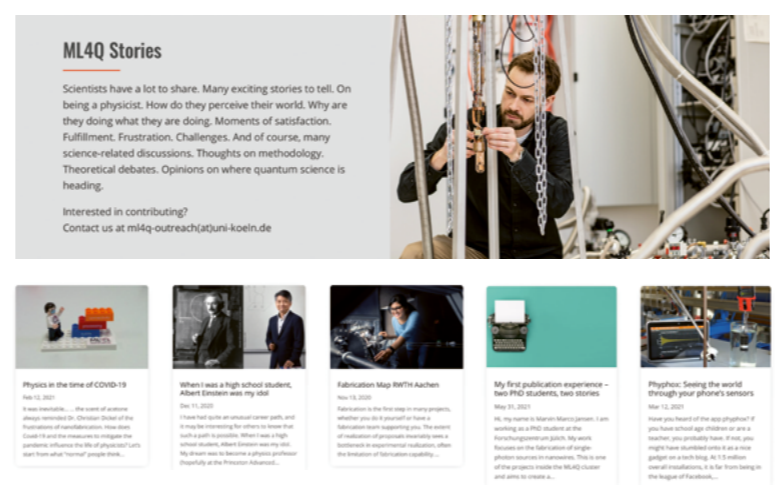
Midel Photonics is now working on generating prototypes. Standardized as well as customized beam-shaping elements will comprise the product portfolio of the company which will be founded in 2021/2022.

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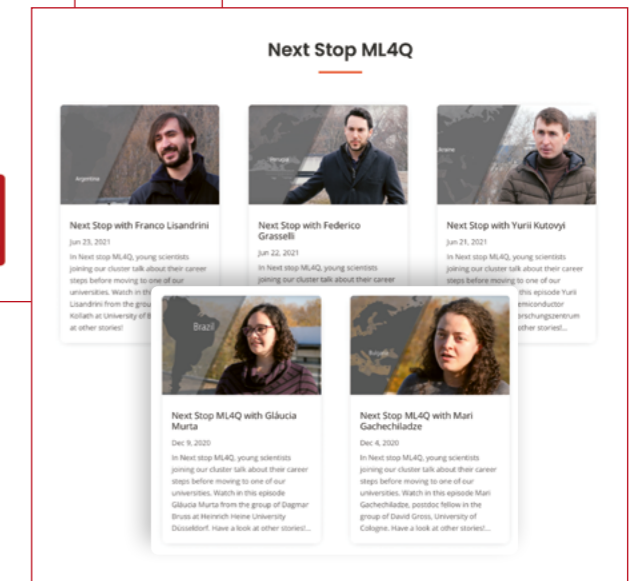
DAVID DUNG

The great thing is that our technology works simultaneously in research and in practice. Any progress we make in development is directly used for basic research in the laboratory next door.

OUTREACH



MATTER AND LIGHT FOR
QUANTUM COMPUTING



Conceiving ideas for outreach measures on a research group or institute level usually focuses on communicating science to a more general public – on the one hand showing the world out there how exciting one's own research is and on the other hand acknowledging the indirect, yet essential, contribution of the German taxpayer in publicly funded research. Conceiving ideas for outreach measures for a Cluster of Excellence, however, faces the additional challenge that comes with the complex structure of the project, which in our case spans over 4 universities and 3 non-university institutions. Hence, it was both the duties of both internal as well as external communication that Marian Barsoum took over when she joined the ML4Q office in April 2020.

First efforts were dedicated to cluster and community-wide communication, e.g. a **News section** on the cluster homepage, monthly newsletters etc., in order to bridge the gap between all cluster sites especially among the young researchers who are often not as well networked as their established group leaders. Not only did the **Annual Report 2019** help introduce the cluster's structure and mission to our young associates, but it also helped us reach out to the Quantum Alliance partners and provide them with more details on our scientific program.

When asking the cluster associates about ideas on outreach measures, a small group of dedicated early-

career scientists from Cologne (Chris Dickel), Aachen (Priya Bhaskar) and Jülich (Jonas Kölzer) suggested to start a blog and soon formed an editor team for **ML4Q Stories** where scientific as well as career- and academia-related topics are reflected upon.

Next stop ML4Q is a short video series which was released in November featuring newly recruited postdocs who talk about their journey in science and why they chose ML4Q for their next career step.

Another communication measure that was developed by Jonas Kölzer from our blog editor team was **ML4Q&A** – a podcast that hosts researchers from and close to the cluster and gives them the opportunity to explain their research activities to the scientific community and the scientifically interested public. In the podcast, our guests talk about specific projects, but also about their view on how the field of quantum technology is evolving and what it's like to be part of this rapidly growing field.

ML4Q also participated as part of the Quantum Alliance in two **virtual career fairs** organized by DAAD's Research in Germany campaign in July and November 2020. The virtual fairs which offered information on academic career paths in Germany, the German research landscape as well as funding and admission procedures for PhD studies in German universities were organized with different geographical and thematic scopes.

Owing to the pandemic, many science events for the public had to be postponed to 2021. However, shortly before the first lockdown, RWTH Aachen invited talented high-school students to dive into the world of physics for a whole week. The **Physikwoche 2020** took place from 20.-24.01.2020 and focused on light and related phenomena. In his lecture "Computing à la Star Trek", Hendrik Bluhm presented past and current developments in quantum computing technology and explained why we still have to overcome grand challenges before quantum computing and quantum communication become a reality.

The first week of November was an exciting week for the quantum community. Parallel to the Berlin Science Week, the European Quantum Flagship organized in collaboration with the European Commission the **European Quantum Week** as an online multi-modular event. The program included outreach activities for the general public, specialized talks and presentations for the quantum community as well as European policy-making and institutional visions for the future of Europe within the field of Quantum Technologies. ML4Q members and associated members were involved in the multi-faceted program. While Tommaso Calarco was part of the round table discussion organized on the first day of the event, Frank Wilhelm-Mauch led an educational session targeted to high-school classes introducing the broad topic of quantum technologies.

In December, David Gross gave a lecture on quantum computers at the **Karl Rahner Akademie** in Cologne. In continuation of the Jesuite's efforts to foster the dialogue between Theology and Natural Sciences, the academy offers a wide range of cultural, political, interreligious, philosophical and scientific talks and debates for the public. In his talk, David took his audience on a journey starting from classical mechanics to the birth of quantum mechanics shedding some light on its complicated philosophical implications. His introduction of making use of quantum mechanical theories for quantum information was interspersed by enjoyable anecdotes about David Deutsch, Hugh Everett and other influential scientists. The talk was concluded by an explanation of the basic principles of quantum computers, challenges in current research and feasible application fields for quantum computation.

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 fundamentals for socially relevant applications.



OBITUARY TRAGIC LOSS OF A GIFTED PHD STUDENT

Federico Tonielli was a PhD student at the Institute for Theoretical Physics in the group of Sebastian Diehl. Born in Naples, he graduated 2010 from the Liceo Scientifico Enrico Fermi and studied physics at the University of Pisa before he joined the Diehl group in Cologne to pursue his PhD studies. He passed away suddenly and unexpectedly in June 2020 at the age of 27. In his honor, the Federico Tonielli Award will be offered in 2021 for the first time in cooperation with his family. It includes a travel stipend of €1,500 to enable scientific travel of a talented PhD student in the Faculty of Mathematics and Natural Sciences. Faculty of the University of Cologne and is to be awarded at a ceremony in June 2021.



PERSONALIA ACHIM ROSCH RECEIVES THE MAX DELBRÜCK FUTURE PRIZE 2020

In acknowledgement of his excellent research in the last 6 years, **Achim Rosch** has been awarded the Max-Delbrück-Zukunftspreis 2020. With this award, the University of Cologne supports outstanding faculty members in Natural Sciences. In this video, Achim Rosch speaks about his research, his work on skyrmions and what he mostly likes about his work.



PERSONALIA MICHAEL KASTORYANO IS NOW SENIOR RESEARCH SCIENTIST AT AMAZON WEB SERVICES (AWS)

Michael Kastoryano – ML4Q PI in Focus Area 3 – will start his new appointment as Senior Research Scientist at Amazon Web Services (AWS) in March. He joined the Institute for Theoretical Physics of the University of Cologne as an Assistant Professor in 2017. His research lies at the intersection of quantum information theory, condensed matter physics and mathematical physics. More on Michael's research interests and publications are available on his website. (www.mkastoryano.com)



PERSONALIA FRANK WILHELM-MAUCH APPOINTED DIRECTOR OF THE PETER GRÜNBERG INSTITUTE PGI-12 AT FORSCHUNGSZENTRUM JÜLICH

Frank Wilhelm-Mauch who has been a member of the cluster's Scientific Advisory Board has now accepted a joint appointment of the Saarland University and the Forschungszentrum Jülich. In his new role as Director of the Peter Grünberg Institute, Quantum Computing Analytics (PGI-12), he will continue his research which lies at the intersection of solid state physics and quantum information. Frank Wilhelm-Mauch is coordinator of the OpenSuperQ project which is dedicated to the establishment of a working prototype of a high-performance quantum computing system at the Forschungszentrum Jülich.



PRIZES & AWARDS YOICHI ANDO AMONG THE HIGHLY CITED RESEARCHERS 2020 IN PHYSICS

Professor Yoichi Ando, has been named on the annual Highly Cited Researchers™ 2020 list from Clarivate. The highly anticipated annual list identifies researchers who demonstrated significant influence in their chosen field or fields through the publication of multiple highly cited papers during the last decade. Their names are drawn from the publications that rank in the top 1% by citations for field and publication year in the Web of Science™ citation index. Yoichi Ando has been selected together with around 180 researchers in Physics. He has published 330 papers that have been cited almost 20,000 times in total. His Invited Review Paper on Topological Insulator Materials in the Journal of the Physical Society of Japan earned more than 850 citations since 2013. His work published in Nature Physics showing the experimental realization of a topological crystalline insulator in SnTe was cited more than 500 times since 2012.



It's a great honor to be recognized as a highly cited researcher. This recognition owes to the hard work of my lab members, and I cannot thank them more. I am also glad to see that there are 7 highly cited researchers from our university, which is the highest number so far and shows that we are on the uptrend!

YOICHI ANDO



MILESTONE PUBLICATIONS TWO PAPERS BY DAVID DIVINCENZO TO BE INCLUDED IN THE 50TH ANNIVERSARY MILESTONE COLLECTION OF PHYSICAL REVIEW A

As part of the celebrations of Physical Review A's 50th anniversary, the journal highlighted in 2020 a collection of milestone papers that have made important contributions to atomic, molecular, and optical physics and quantum information by announcing significant discoveries or by initiating new areas of research. Many of them have had a far-reaching impact on other subjects of the physical sciences. The papers in this collection span all decades of the journal's existence and all subject areas covered by the journal. The collection included two papers by **David DiVincenzo** published in 1995 and 1998. In the first paper "Quantum computation with quantum dots" (Physical Review A 57, 120 (1998)) DiVincenzo and Loss laid out a proposal for quantum computation based on quantum dots. A detailed implementation of a universal set of one- and two-quantum-bit gates using the spin states of coupled single-electron quantum dots is presented. Following the proposal, significant theoretical and experimental achievements have made quantum dots another candidate platform for quantum computation. In the second paper "Elementary gates for quantum computation" (Physical Review A 52, 3457 (1995)), Barenco and collaborators showed that the combination of classical two-bit gate with quantum one-bit gates are universal, and derived bounds on the number of elementary gates required to construct several two- and three-bit quantum gates.

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