# Recent Progress in Quantum Computing

## WE-Heraeus-Symposium

**November 3, 2022**
**Berlin Brandenburgische**
**Akademie der Wissenschaften (BBAW)**
**Berlin**

WILHELM UND ELSE
HERAEUS-STIFTUNG

[redacted]

## Aims and scope of the WE-Heraeus-Symposium

Recent years have seen significant scientific and technological advance concerning efficiency and scalability in very different physical quantum computing platforms. Considering existing activities, projects, and commercial actors, the goal of this one-day symposium to discuss recent advances and novel ideas that could solve important concrete real-world problems.

The symposium is part of the Berlin Science week and will be held as in-person format to enable an intensive and fruitful interaction with internationally renowned speakers from academic and industrial research

## Scientific Organizers:

| | |
|---|---|
| Prof. Dr. Oliver Benson | Humboldt-Universität zu Berlin, Germany<br>E-mail: oliver.benson@physik.hu-berlin.de |
| Prof. Dr. Rainer Blatt | Universität Innsbruck, Austria<br>E-mail: rainer.blatt@uibk.ac.at |
| Prof. Dr. Walter Riess | IBM Research - Zurich, Switzerland<br>E-mail: wri@zurich.ibm.com |

## Administrative Organization:

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|---|---|---|
| 08:00 | ***REGISTRATION / WELCOME COFFEE*** | |
| 09:00 | Oliver Benson,<br>Rainer Blatt,<br>Walter Riess | **Welcome and introduction** |
| | Stefan Jorda,<br>WE-Heraeus-Stiftung | **Welcome address** |
| 09:15 | Jörg Wrachtrup | **Quantum Technology with spin networks** |
| 09:45 | Christopher Eichler | **Towards Error-Corrected Quantum Computing with Superconducting Circuits** |
| 10:15 | Markus Müller | **Fault-Tolerant Quantum Computing: From Concepts to Experiments** |
| 10:45 | *COFFEE BREAK* | |
| 11:15 | Ferdinand Schmidt-Kaler | **Trapped ions as a platform for quantum information processing** |
| 11:45 | Christian Ospelkaus | **Towards a fully-integrated trapped-ion QCCD processor** |
| 12:15 | Martin Ringbauer | **Quantum computing beyond physical qubits** |
| 12:45 | *LUNCH* | |
| 14:00 | Heike Riel | **IBM Quantum Computing Roadmap** |
| 14:30 | Frank Wilhelm-Mauch | **Superconducting quantum computers: Opportunities and bottlenecks** |
| 15:00 | Guido Burkard | **Towards high-fidelity quantum computing with spins in semiconductor nanostructures** |
| 15:30 | *COFFEE BREAK* | |
| 16:15 | Jens Eisert | **Can quantum computers learn better than classical computers?** |
| 16:45 | Christine Silberhorn | **Scaling photonics systems for quantum information processing** |
| 17:15 | Immanuel Bloch | **Quantum Simulations & Quantum Computing with Neutral Atoms** |
| 17:45 | *SHORT BREAK* | |
| 18:00 | **Final Reception & Exhibition Roman Lipski** | |
| 19:00 | End | |

# Quantum Technology with spin networks

J. Wrachtrup,[1]

[1]*Centre for Applied Quantum Technologies and IQST, University of Stuttgart, Germany*

Spin defects in wide band gap semiconductors are leading contenders in various areas of quantum technology. Early forerunners in the field, like the NV center in diamond have shown impressive progress for sensing, communication and quantum computing [1]. Single NV electron spin qubits e.g. have matured into a new tool for material science [2]. Multiple interacting spins in a spin network enable quantum algorithms for signal analysis, e.g. via a quantum Fourier transformation of AC signals. Depending on the specific use case there is an intense search for new spin systems. Defects in 2D materials offer new opportunities in quantum simulations [4]. 3D materials like silicon carbide seem to be particularly suited as spin photon interface as they show both excellent spin coherence times and very good optical properties [5]. In my talk I will discuss these systems and analyze their use in quantum information processing.

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[1] M. Atatüre et al. Nature Rev. Mat. 3, 38 (2018)
[2] T. Son et al. Science 374, 1140 (2021)
[3] V. Vorobyov et al. njp Quantum Information 7, 124 (2021)
[4] N. Chejanovsky et al. Nature Mat. 20, 1079 (2021)
[5] C. Babin et al. Nature Mat. 21, 67 (2022)

# Towards Error-Corrected Quantum Computing with Superconducting Circuits

Christopher Eichler

Universität Erlangen-Nürnberg, Physik, Erlangen, Germany

The ability to perform logical quantum operations fault-tolerantly by correcting unavoidable errors induced by control inaccuracies and decoherence, will be essential for building and operating large-scale quantum computers. In my talk, I present our recent demonstration of repeated quantum error correction using a surface code [1], which is known for it exceptionally high error threshold and its compatibility with planar qubit architectures featuring nearest-neighbor coupling. The code implemented in our experiments uses 17 physical qubits, nine of of which encode the logical information and eight of which perform repeated measurements of error syndromes. By decoding the syndrome data in post-processing we preserve initialized logical states with a low error probability of 3% per cycle. The demonstration of repeated, fast and high-performance quantum error correction supports our understanding that fault-tolerant quantum computation will eventually be realizable. I will discuss challenges on the path towards this goal in the context of superconducting circuits.

[1] S. Krinner, N. Lacroix, A. Remm, A. Di Paolo, E. Genois, C. Leroux, C. Hellings, S. Lazar, F. Swiadek, J. Herrmann, G. J. Norris, C K. Andersen, M. Müller, A. Blais, C. Eichler, and A. Wallraff, Nature 605, 669–674 (2022)

# Fault-Tolerant Quantum Computing: From Concepts to Experiments

**Markus Müller**

[1]*Institute for Quantum Information, RWTH Aachen University*
[2] *Peter Grünberg Institute 2, Forschungszentrum Jülich, Germany*

To date, the construction of a scalable fault-tolerant quantum computer remains a fundamental scientific and technological challenge, due to the influence of unavoidable noise. Harnessing the full power of large-scale quantum computers for practical applications will require the incorporation of quantum error correction routines. Quantum error correction codes allow one to protect quantum information during storage and processing by redundant encoding of information in logical qubits formed of multiple physical qubits. When manipulating logical quantum states, errors caused by imperfect operations must be prevented from spreading uncontrollably through the quantum register, requiring so-called fault-tolerant quantum circuit designs. I will discuss concepts and theory work, perspectives for scalability, as well as recent collaborative experimental breakthroughs towards fault-tolerant quantum error correction. This includes the implementation of fault-tolerant circuit building blocks [1] and the first demonstration of a universal and fault-tolerant logical quantum gate set [2], realised with trapped ions.

## References

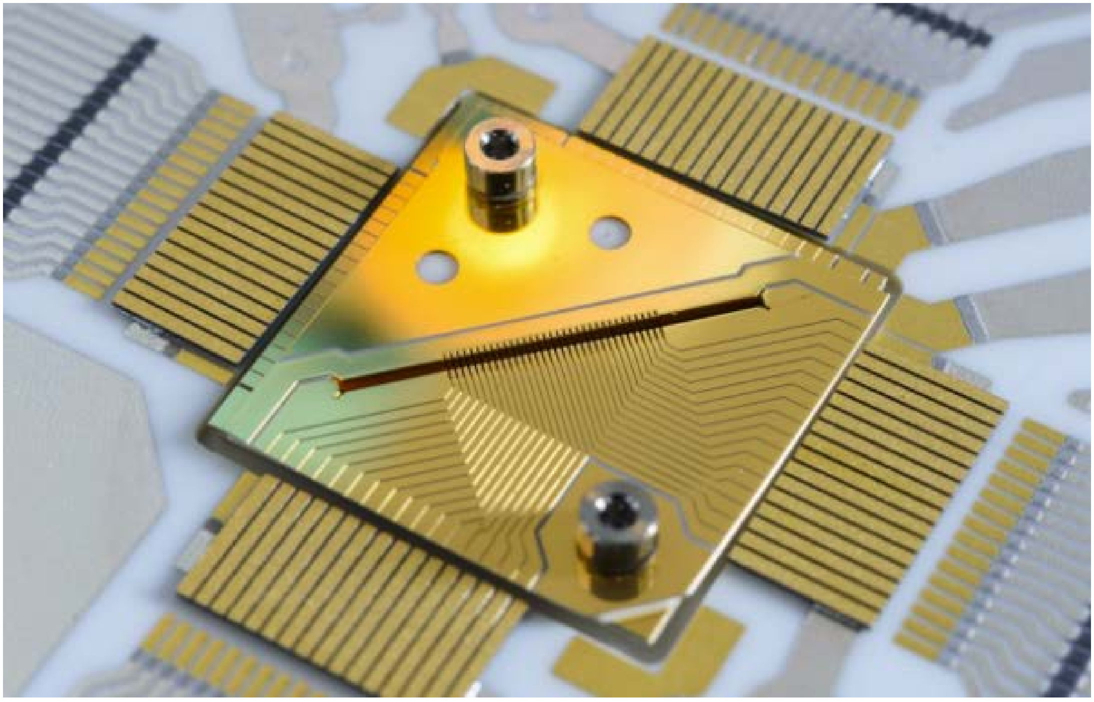
[1] J. Hilder *et al.*, Fault-tolerant parity readout on a shuttling-based trapped-ion quantum computer, Physical Review X 12, 011032 (2022)
[2] L. Postler *et al.,* Demonstration of fault-tolerant universal quantum gate operations, Nature 605, 675 (2022)

## Trapped ions as a platform for quantum information processing

Ferdinand Schmidt-Kaler, QUANTUM, Univ. Mainz

Quantum computing is addressing hybrid computing e.g. for quantum chemical simulations. We employ modern segmented ion traps and reach gate fidelities of 99.995% (single bit) and 99.85% (two bit). We are implementing these gates in a reconfigurable qubit register and have realized multi-qubit entanglement, more recently fault-tolerant syndrome readout [2] in view for topological quantum error correction [3]. I am describing architectures, which combine individual addressing of ion qubits with qubit transports and reordering within the segments of one trap [4], and sketch the required trap technologies and fabrication methods, qubit control, circuit compilation [5] and user interface. In the IQuAn architecture [6] we plan to execute the qubit register reconfiguration operations in parallel with quantum gate operation and connect this quantum processor to the MOGON-II HPC. Ion transport between traps [7] may allow for further scalability.

[2] Hilder, et al., Phys. Rev. X.12.011032 (2022)
[3] Bermudez, et al., Phys. Rev. X 7, 041061 (2017)
[4] Kaustal et al., AVS Quantum Sci. 2, 014101 (2020)
[5] Kreppel et al., arXiv:2207.01964
[6] https://iquan.physik.uni-mainz.de/
[7] Stopp et al., Quantum Sci. Technol. 7 034002 (2022)



QUANTUM Mainz segmented trap

# Towards a fully-integrated trapped-ion QCCD processor

**C. Ospelkaus[1,2]**

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[2] *Physikalisch-Technische Bundesanstalt, Bundesallee 100, 38116 Braunschweig*

Microfabricated planar ion traps offer the potential of leveraging scaling techniques developed over the past few decades for the implementation of quantum computing with trapped ions [1]. A fully integrated device would incorporate as much as possible of the infrastructure for cooling and detection of ions as well as for quantum gates into a scalable structure.

We present recent advances on an integrated gate mechanism which implements quantum gates using chip-embedded microwave conductors [2]. We discuss amplitude shaping as a means of obtaining gates that are insensitive to key experimental perturbations. We show how universal operations can be implemented in a two-qubit computation register and show preliminary data on cycle benchmarking for the computation register.

Further scaling can be achieved by implementing qubit shuttling operations between dedicated registers [3]. We discuss the design of a processor based on two storage zones, a computation register, and a readout / preparation register, interconnected using a surface-electrode X-junction.

Two experimental setups are currently under construction to demonstrate this approach experimentally – one based on $^{9}\mathrm{Be}^{+}$ qubits cooled by $^{40}\mathrm{Ca}^{+}$ ions, and a second apparatus based on $^{43}\mathrm{Ca}^{+}$ qubits cooled by $^{88}\mathrm{Sr}^{+}$ ions. The latter will be suitable for the integration of chip-integrated waveguide-based light delivery for cooling and detection, such that the delivery of all qubit control signals is integrated at the chip level. We present the design of the cryogenic apparatus into which these processors will be integrated.

We acknowledge funding from the QVLS-Q1 project of MWK Lower Saxony and from the BMBF MIQRO and ATIQ projects.

## References

[1] J. Chiaverini *et al.*, Quant. Inf. Comp. 5, **419** (2005)
[2] C. Ospelkaus *et al.*, Nature **476**, 181 (2011)
[3] D. J. Wineland *et al.*, J Res NIST 103, 259 (1998) ; D. Kielpinski *et al.*, Nature **417**, 709 (2002)

# Quantum computing beyond physical qubits

**Martin Ringbauer**[1]

[1]*Institute for Experimental Physics, University of Innsbruck, Innsbruck, Austria*

Trapped-ion quantum computing has developed rapidly over recent years with devices now operating routinely with tens of qubits [1] and quantum operations [2]. As we scale quantum computers further, fault-tolerant operation and quantum error correction will be of central importance. While quantum error correction remains one of the main challenges in the field, several key ingredients have already been achieved in the trapped-ion platform, including encoding of a logical qubit in a topological error correcting code [3], and a universal fault-tolerant set of operations [2]. Yet, the work is long not done. Going beyond the basis routines, I will discuss recent achievements, including the correction of qubit loss errors [4] and how to tailor the error correcting code to our needs via lattice surgery [5]. Finally, I will conclude with an outlook on how departing from the long tradition of binary information processing allows us to make even better use of the available quantum hardware [6].

## References

[1] I. Pogorelov, et al., PRX Quantum **2**, 020343 (2021)
[2] L. Postler, et al., Nature **605**, 675-680 (2022)
[3] D. Nigg et al., Science **345**, 302-305 (2014)
[4] R. Stricker, et al., Nature **585**, 207-210 (2020)
[5] A. Erhard, et al., Nature **589**, 220-224 (2021)
[6] M. Ringbauer, et al., Nature Physics (2022)

# IBM Quantum Computing Roadmap

**H. Riel**

*IBM Research, Rüschlikon, Switzerland*

Despite the continued advances of digital computing, there are still many important and relevant mathematical problems that are intractable for classical computers but could be solved by Quantum Computers. Quantum systems have advanced significantly over the recent years, still we are only at the beginning. These systems are developed and built from the bottom up comprising the entire stack from the qubit and quantum processor technology, control electronics, control software, algorithms, to quantum computing applications that address relevant problems in science and business. Advancing the state of the art as quickly as possible requires pursuing in parallel improvements in the scale (number of qubits), quality (coherence, gate fidelities, and quantum volume), and speed (circuit level operations per second) of quantum systems. Integrating new technologies such as superconducting vias and multi-layer wiring enabled scaling of superconducting quantum processors to 127-qubits so far and soon beyond. Combined with increases in quality and speed this has driven significant improvements in the performance of quantum computations. Moreover, the computational capabilities of today's quantum hardware can be extended by tight integration of quantum and classical resources using techniques like circuit knitting to accelerate reaching quantum advantage. In our technology portfolio we also develop approaches to connect individual quantum processors in various ways such as the use of quantum transduction from microwave to optical for long distance quantum links and we also explore other solid-state qubits that may tie into the same quantum computing stack further in the future.

# Superconducting quantum computers: Opportunities and bottlenecks

**Frank K. Wilhelm**[1]

*[1] Institute for Quantum Computing Analytics (PGI-12), Forschungszentrum Jülich,*
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Quantum computers based on superconducting integrated circuits are a promising platform for scalable quantum computing that are developed in both commercial companies and public laboratories. I will highlight their appeal in being a system with strong design flexibility and a clear engineering roadmap originating from their remarkable simplicity. These come with the flip side of challenges related to further improving coherence and overall consistency and systems engineering. I will highlight the role of critical enabling technologies such as calibration and optimal control for improving coherence of given hardware and discuss the opportunities to taylor processor designs to specific applications.

## References

[1] F. Author, Journal **volume**, page (year)
[2] S. Author, Journal **100**, 101101 (2009)

# Towards high-fidelity quantum computing with spins in semiconductor nanostructures

**G. Burkard**

*Department of Physics, University of Konstanz, D-78457 Konstanz, Germany*

Spin-based quantum bits in semiconductor devices allow for high-fidelity quantum gates and long-range interconnects via on-chip superconducting resonators, while their nanoscale dimensions offer various routes to scale-up [1]. This talk will describe recent progress towards high-fidelity quantum operations, as illustrated in Figure 1, the implementation of small-scale quantum algorithms, as well as some of the remaining obstacles and challenges. We discuss the importance of spin-charge hybridization for spin-qubit control and measurement. Electric on-chip spin control with synthetic spin-orbit coupling provided by magnetic field gradients in combination with the exchange coupling has allowed for one- and two-qubit in silicon quantum dots. In this context, we also discuss the valley degeneracy in the conduction band of silicon and other semiconductors which offers both challenges and opportunities. Recently, the use of hole spins in germanium has attracted great interest because it avoids both the valley degeneracy and the need for magnetic field gradients. Finally, we briefly overview alternative approaches to all-electric control of spin qubits with the help of multi-electron qubits, such as the singlet-triplet, exchange-only, and quadrupolar qubits.

## References

[1] G. Burkard, T. D. Ladd, J. M. Nichol, A. Pan, and J. R. Petta, *Semiconductor Spin Qubits*, to appear in Rev. Mod. Phys., https://arxiv.org/abs/2112.08863

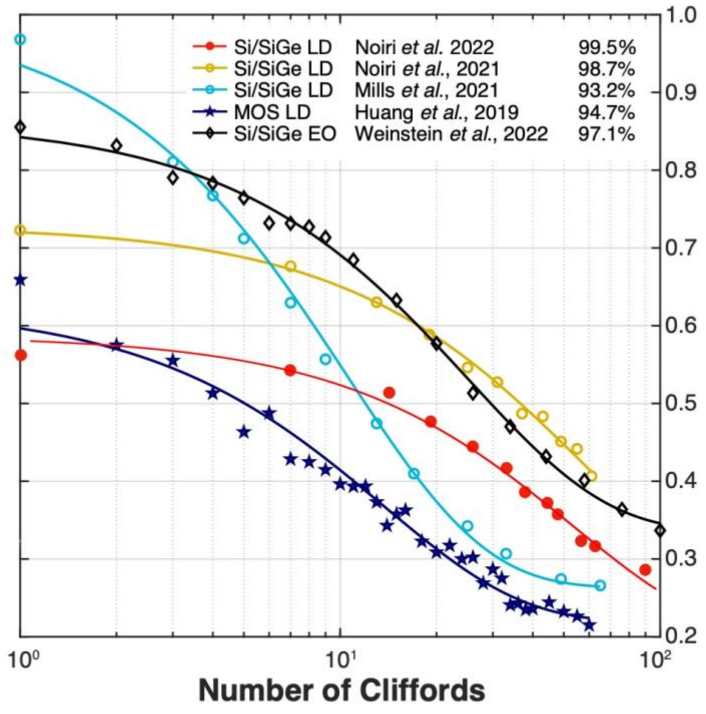


**Figure 1**: Fidelity of two-qubit gates in silicon quantum dots as evaluated by randomized benchmarking (RB). Here, the initial-state return probability is plotted as a function of the number of random Clifford gates N. Data is shown from different initialization, readout, and Clifford implementations giving rise to offsets. However, in all cases a least-squares fit to an exponential decay with N provides a fidelity benchmark (adapted from [1]).

# Can quantum computers learn better than classical computers?

**M. Hinsche, M. Ioannou, A. Nietner, J. Haferkamp, Y. Quek, D. Hangleiter, J.-P. Seifert, R. Sweke, J. Eisert**
*Dahlem Center for Complex Quantum Systems, Freie Universität Berlin*

There has been substantial excitement recently in identifying tasks for which quantum devices could possibly outperform classical devices. Recent experimental implementations on random circuit sampling have provided strong evidence that quantum devices can outperform classical computers on paradigmatic tasks [1]. Also, quantum simulators seem to reach regimes out of scope for classical computers. These developments invite further studies to see what further applications of quantum devices could be found. Notions of quantum-assisted machine learning are seen as candidates for this. In this talk, we will have a look at such notions of quantum-assisted machine learning, driven by the hope that quantum algorithms could fare better than classical ones in instances of learning tasks. These advantages could refer to computational speedups, but also to better generalization and other figures of merit. We will discuss the comparative power of classical and quantum learners for generative modelling within the probably approximately correct framework, for which we prove a separation between the quantum and classical settings [2,3]. In the light of new findings on the PAC learnability of the output distributions of local quantum circuits, we will discuss how much structure is actually expected to be required to hope for quantum advantages in quantum-assisted machine learning [4]. We prove that the injection of a single T-gate into Clifford circuits renders the task of learning evaluators from samples infeasible in polynomial time. This is in stark contrast to the case of Clifford circuits for which we provide an efficient learning algorithm based on Gaussian elimination [5]. This work will provide a roadmap of what next steps are to be taken for work in quantum machine learning, and will flesh out the potential and limitations of quantum probabilistic modelling.

## References

1. Computational advantage of quantum random sampling,
   D. Hangleiter, J. Eisert, review for Rev. Mod. Phys., arXiv:2206.04079 (2022).
2. On the quantum versus classical learnability of discrete distributions,
   R. Sweke, J.-P. Seifert, D. Hangleiter, J. Eisert, Quantum 5, 417 (2021).
3. A super-polynomial quantum-classical separation for density modelling,
   N. Pirnay, R. Sweke, J. Eisert, and J.-P. Seifert, in preparation (2022).
4. Learnability of the output distributions of local quantum circuits,
   M. Hinsche, M. Ioannou, A. Nietner, J. Haferkamp, Y. Quek, D. Hangleiter, J.-P. Seifert, J. Eisert, R. Sweke, arXiv:2110.05517 (2021).
5. A single T-gate makes distribution learning hard,
   M. Hinsche, M. Ioannou, A. Nietner, J. Haferkamp, Y. Quek, D. Hangleiter, J.-P. Seifert, J. Eisert, R. Sweke, arXiv:2207.03140 (2022).

# Scaling photonic systems for quantum information processing

**Ch. Silberhorn**
*Paderborn University, Integrated Quantum Optics, Department Physics, Institute for Photonic Quantum Systems (PhoQS), 33098 Paderborn, Germany*

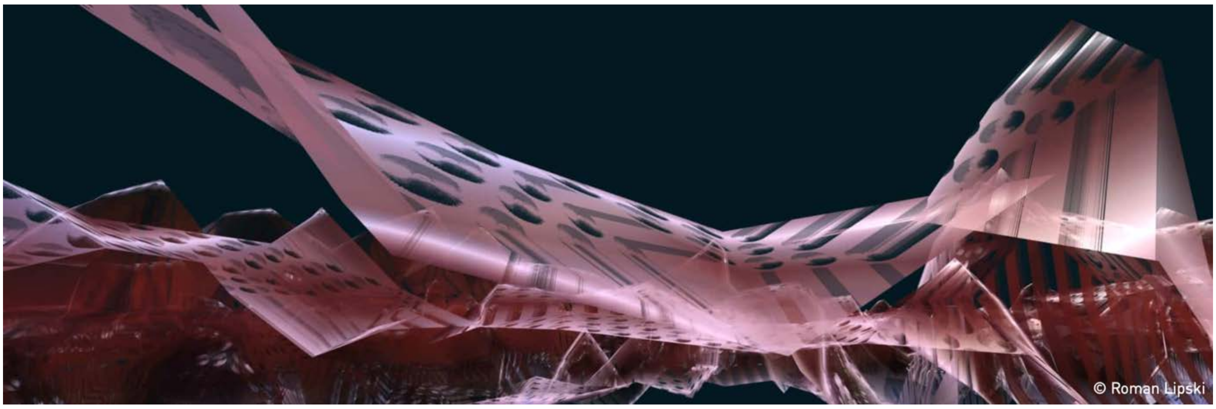
Photonic quantum simulations and computations requires an efficient scaling of photonic quantum systems, which comprise many controllable modes and input states with many photons. However, the implementation of such systems including many operations with high control still poses a considerable challenge. Here we present our approaches for the experimental implementation of future multi-dimensional photonic quantum systems.

# Quantum Simulations & Quantum Computing with Neutral Atoms

**Immanuel Bloch**

Max-Planck-Institut für Quantenoptik, Garching, Germany

40 years ago, Richard Feynman outlined his vision of a quantum simulator for carrying out complex calculations of physical problems. Today, his dream has become a reality and a highly active field of resarch across different platforms ranging from ultracold atoms and ions, to superconducting qubits and photons. In my talk, I will outline how ultracold atoms in optical lattices played a vital contribution in starting this vibrant and interdisciplinary research field 20 years ago and now allow probing and controlling of quantum phases in- and out-of-equilibrium with fundamentally new tools and single particle resolution. Novel (hidden) order parameters, entanglement properties, full counting statistics or topological features can now be measured routinely and provide deep new insight into the world of correlated quantum matter. I will introduce measurement and control techniques and discuss a few highlight applications from the field of 1) strongly correlated quantum systems, 2) topological quantum matter and 3) out-of equilibrium dynamics in quantum many-body systems and provide an outlook for challenges and opportunities in this system. Finally, I will show how we aim to expand these techniques towards quantum computing platforms with neutral atoms.



# QUANTUM PHYSICS MEETS CONTEMPORARY ARTISTIC PRACTICE

HUMBOLDT-UNIVERSITÄT ZU BERLIN | ROMAN LIPSKI

**Art meets Quantum Physics**
The open studio and art exhibition will bring together the scientists' and artists' perspectives on phenomena in quantum physics. On the one hand, there is the real application of such phenomena in quantum technology, on the other hand, there is the seemingly incomprehensible and vague essence of quantumness.

**Exhibition during Symposium / Nov 03 / 9 AM – 9 PM**
The exhibition is embedded in the WE-Heraeus symposium on "Recent Progress in Quantum Computing", on November 3rd, in the Berlin-Brandenburgische Akademie der Wissenschaften.

**Step Inside the artist Roman Lipski's Studio / Nov 04 / 5 PM – 8 PM**
Have you considered how the developments in quantum computing are being adopted and represented in the arts? Would you like a personal peek into the work of a practising artist who is collaborating with quantum scientists? Come and visit Studio Roman Lipski for wine, small bites and conversation with the artist and his team.

If you would like to visit, please register here: **It is a guestlist only** event with limited capacity. If you have booked a spot but are unable to attend, please take a moment to cancel. If you would like to visit, please register here

**More information about Roman Lipski**: