

A Research Fab to Enable and Scale Quantum Computing

Research Fab Microelectronics Germany with Extension Module
for Quantum and Neuromorphic Computing (FMD-QNC)

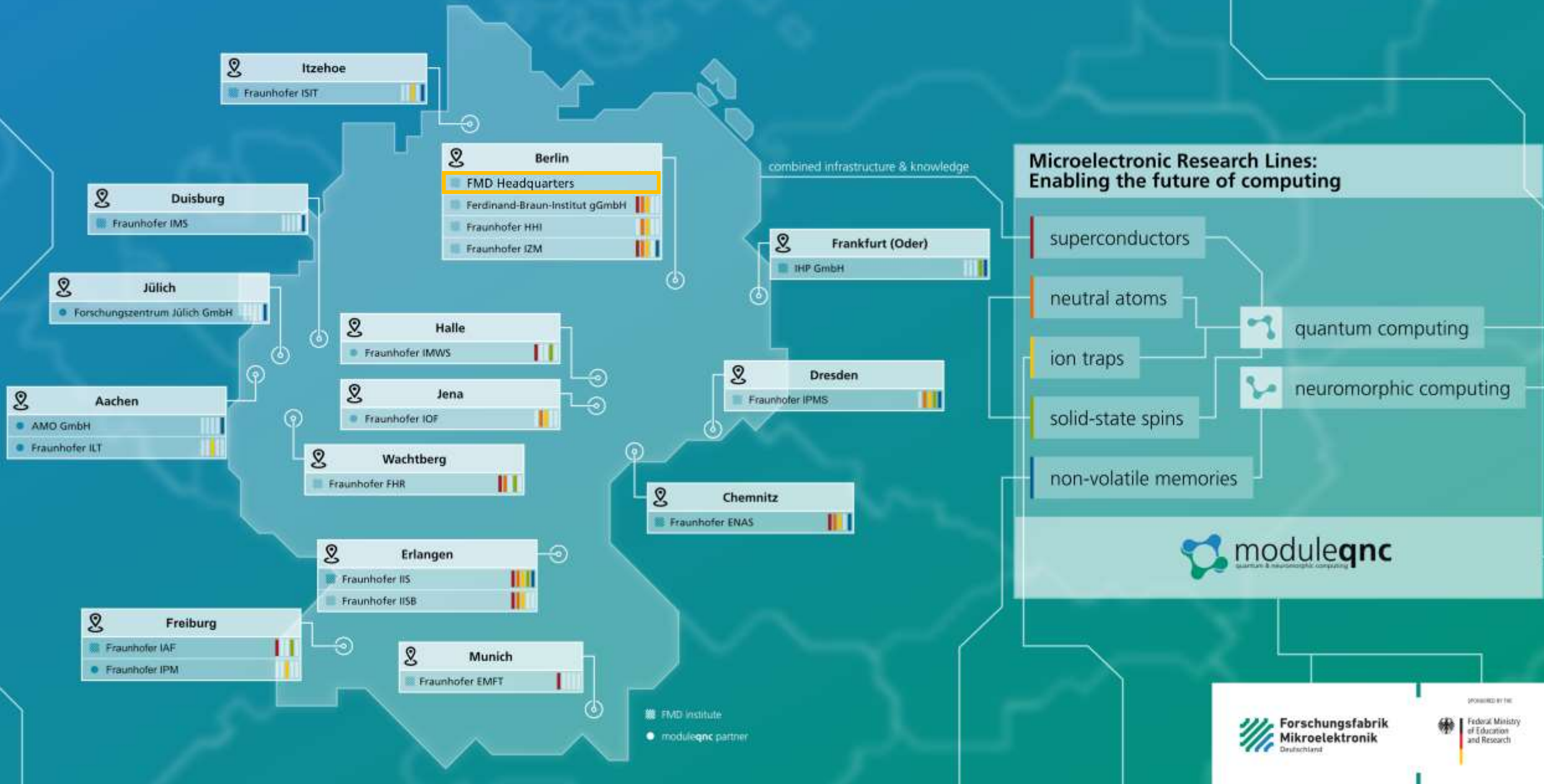
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We support research groups, start-ups and industry in the development of quantum & neuromorphic computing hardware with customised solutions from microelectronics, nanotechnology, optics and photonics.



Tailored Solutions for Next Generation Computing

Supporting hardware developments based on different platform technologies



superconducting qubits

neutral atoms

ion traps

solid-state spin qubits

photonic qubits

analogue and neuromorphic computing architectures

diverse memristor technologies

Enabling Technologies & Services Across the Entire Value Chain

Providing solutions for system scale-up and smooth transition to industrial production



Components, Circuits , Modules [digital, analog, quantum]

Process Technology, Assembly, Pilot Production

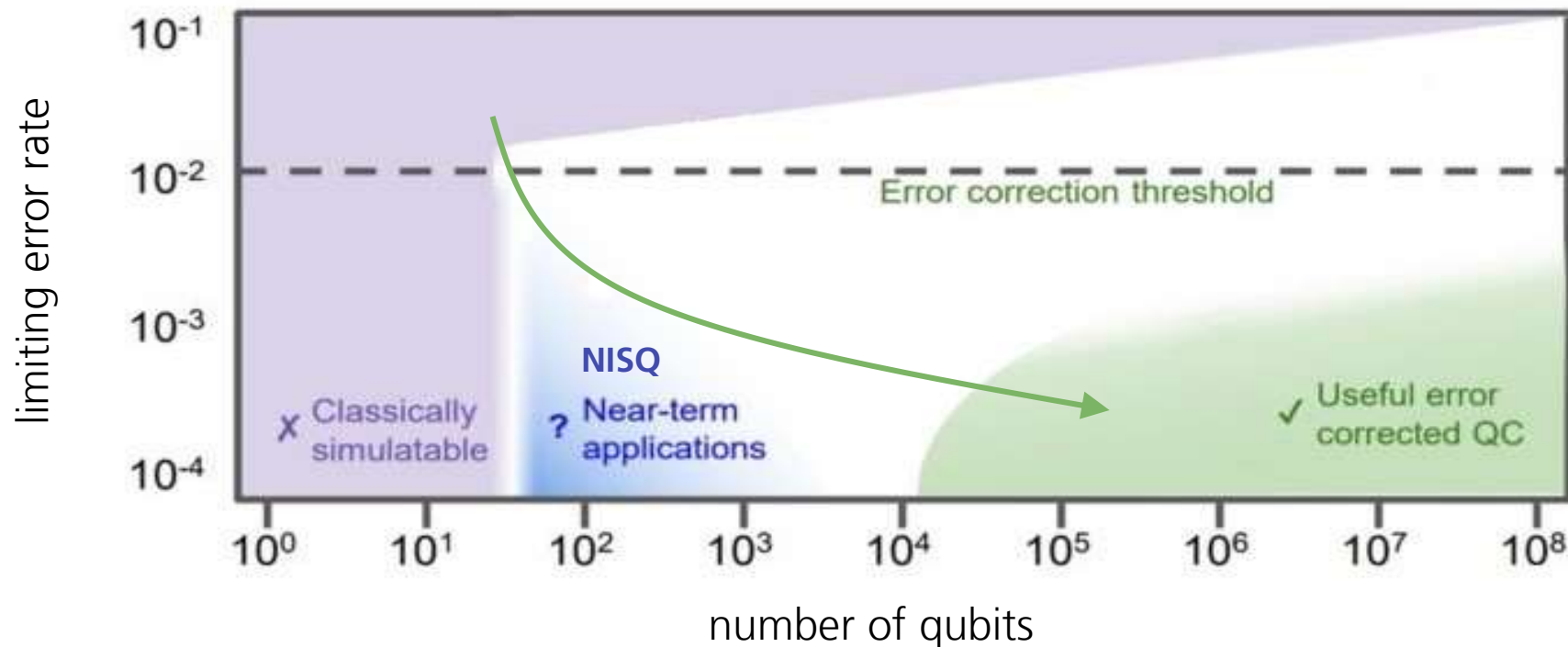
Test, Characterization, Validation

Design, Simulation, Architectures

Scaling quantum computer hardware

The path to fault-tolerant QC

increasing quantity and quality!



Current qubit technologies

and their maturity levels according to McKinsey Monitor 2022

Preliminary

Technology						
	Superconducting circuits	Trapped ions	Spin qubits	Photonic networks	Neutral atoms	Majorana fermions
Qubit description	Difference in Cooper pairs between two islands of a Josephson tunnel junction	Internal energy levels of ions trapped by electromagnetic fields	Electron spin of one electron localized in a semiconductor quantum dot or insulator defect (eg, NV centers in diamond)	Occupation of a photonic waveguide	Internal energy levels of highly excited atoms trapped by laser fields	Two Majorana modes at superconductor/semiconductor interfaces
Maturity						

McKinsey Quantum Technology Monitor, June 2022

The full-stack QC

System architecture of the full-stack quantum computer

Layer model for universal and fault-tolerant quantum computer

Quantum Algorithms

High-Level Programming Language

Compiler, Runtime

Quantum Instruction Set Architecture (QISA)

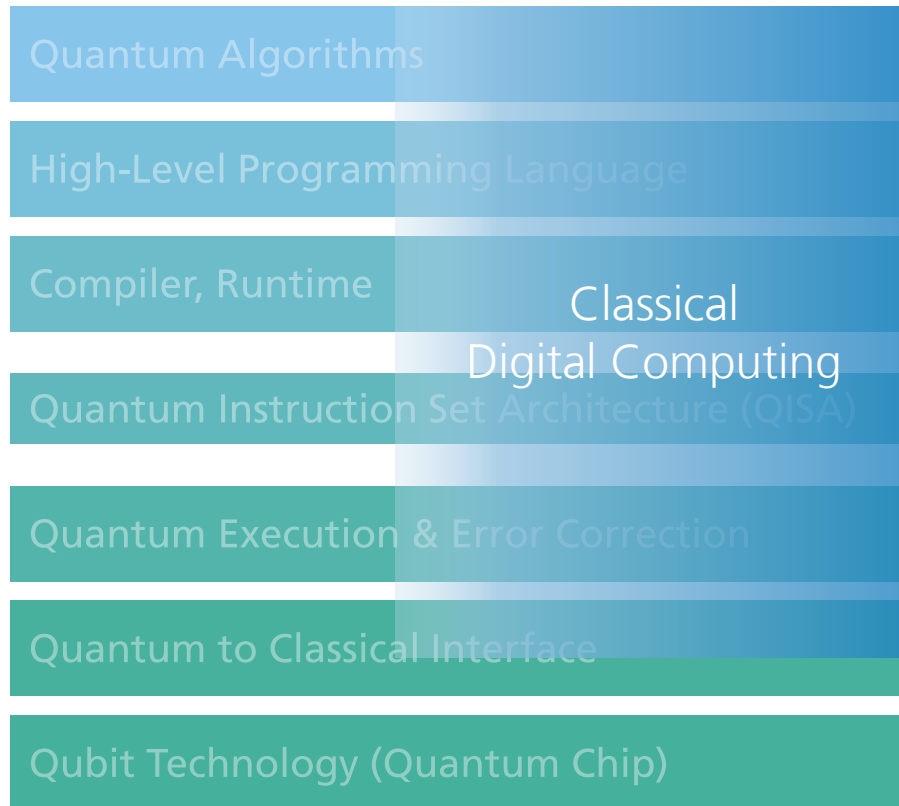
Quantum Execution & Error Correction

Quantum to Classical Interface

Qubit Technology (Quantum Chip)

Synergies with classical computer architectures

Hybrid systems



Quantum computing stack



Connection to classical supercomputers (HPC)

Jülich Wizard for European Leadership Science (JUWELS)

A close interweaving of scientific and technological challenges

requires interdisciplinary cooperation among all levels

Quantum Algorithms

High-Level Programming Language

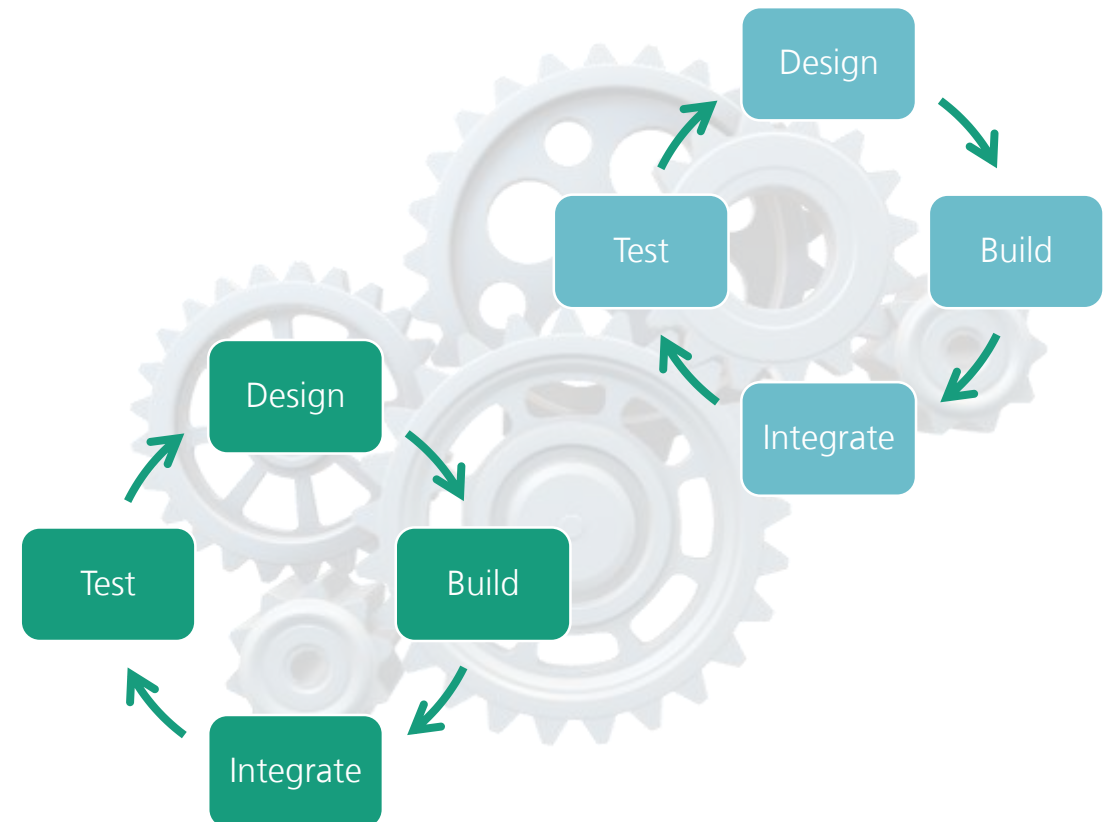
Compiler, Runtime

Quantum Instruction Set Architecture (QISA)

Quantum Execution & Error Correction

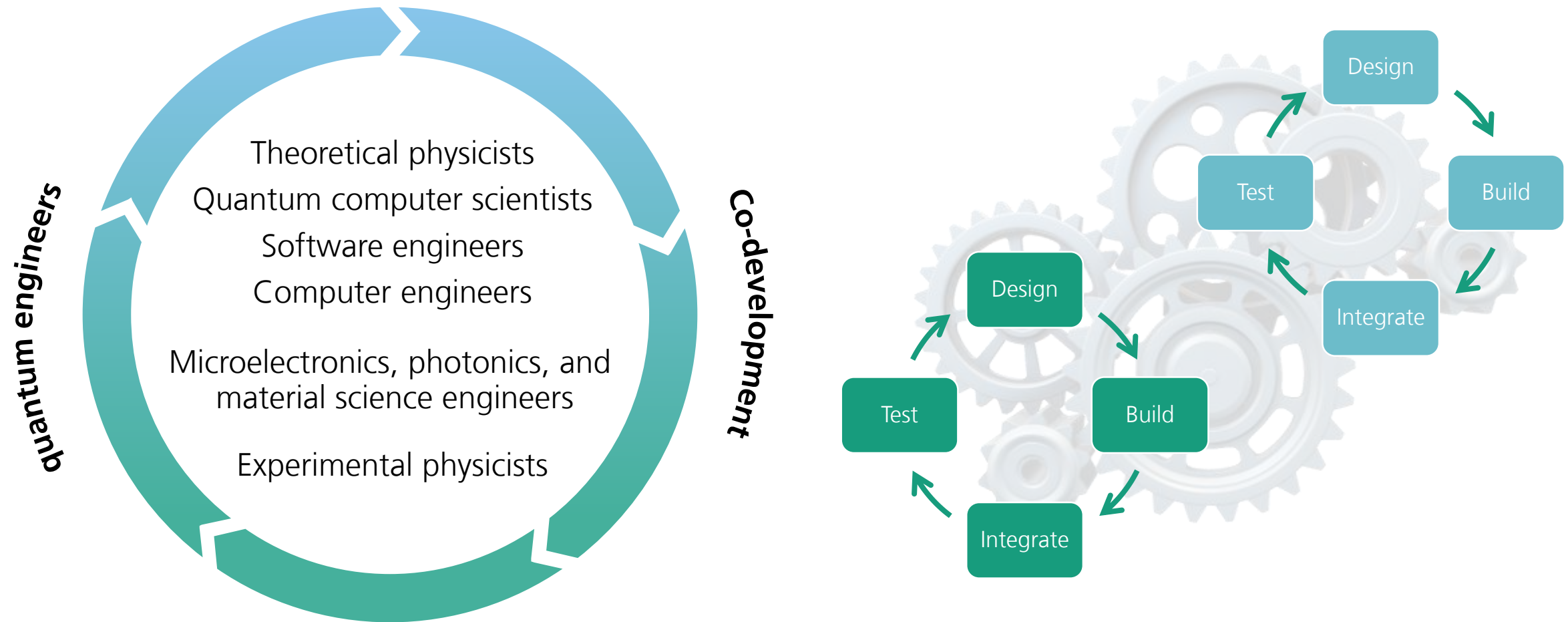
Quantum to Classical Interface

Qubit Technology (Quantum Chip)



A close interweaving of scientific and technological challenges

requires interdisciplinary cooperation among all levels



Scaling in quantity and quality: From NISQ to fault-tolerant quantum computing



Isolating a quantum particle from the universe is hard,
and error sneaks in from everywhere.

– IonQ Inc.

The dilemma of quantum computers

Perfect isolation from the environment



Image: IBM Research, IBM cools down world's largest quantum-ready cryostat

The dilemma of quantum computers

Perfect isolation from the environment and yet perfect control from outside

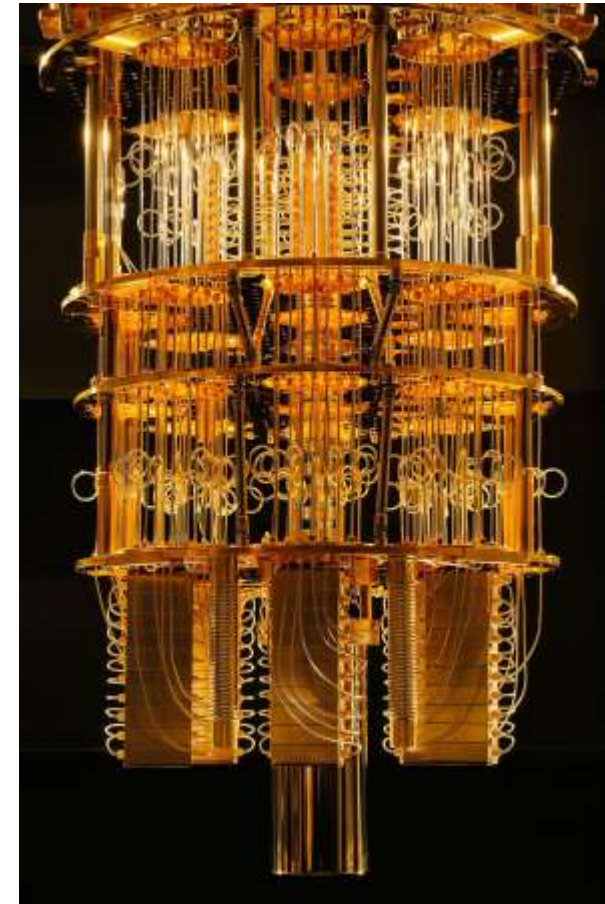


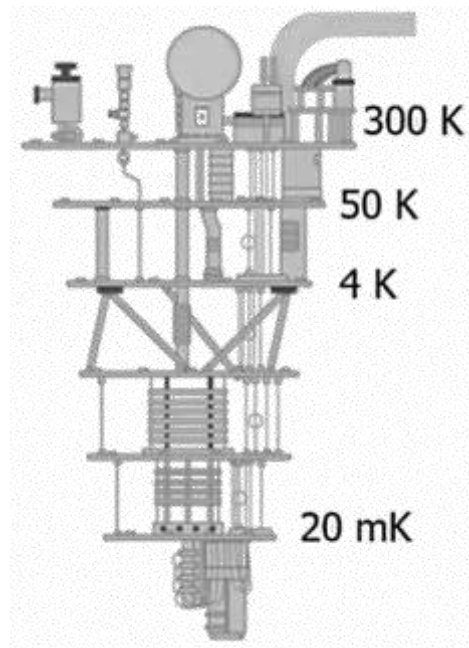
Image: IBM Research, IBM cools down world's largest quantum-ready cryostat

IBM Research 2019

The Quantum-Classical-Interface for Cryogenic Qubits

Challenges with the Q-to-Classical interface for cryogenic qubits

Scaling control and readout units while minimizing external heat and noise input

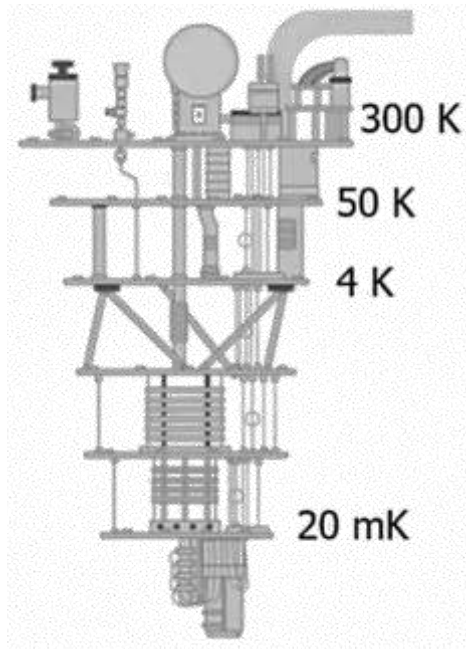


Quantum Chip

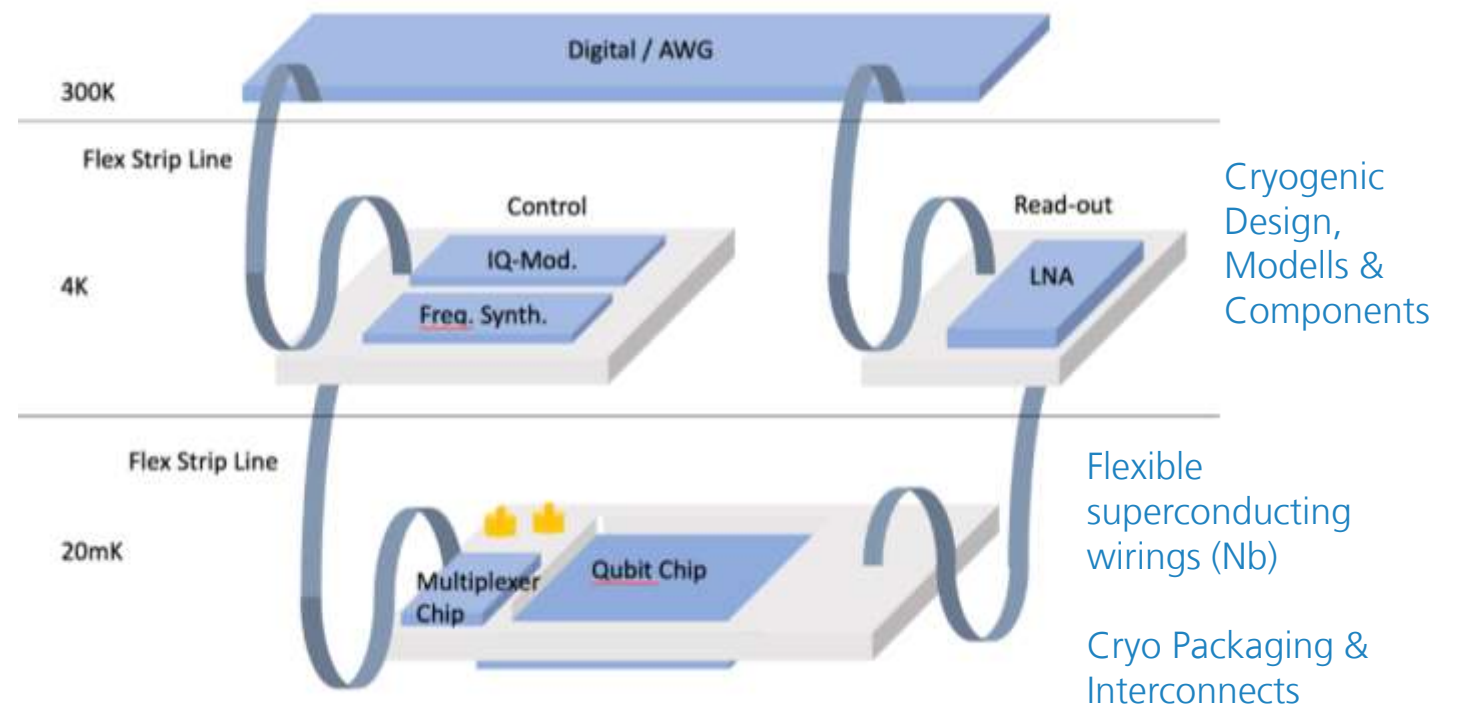


Challenges with the Q-to-Classical interface for cryogenic qubits

Scaling control and readout units while minimizing external heat and noise input



Quantum Chip

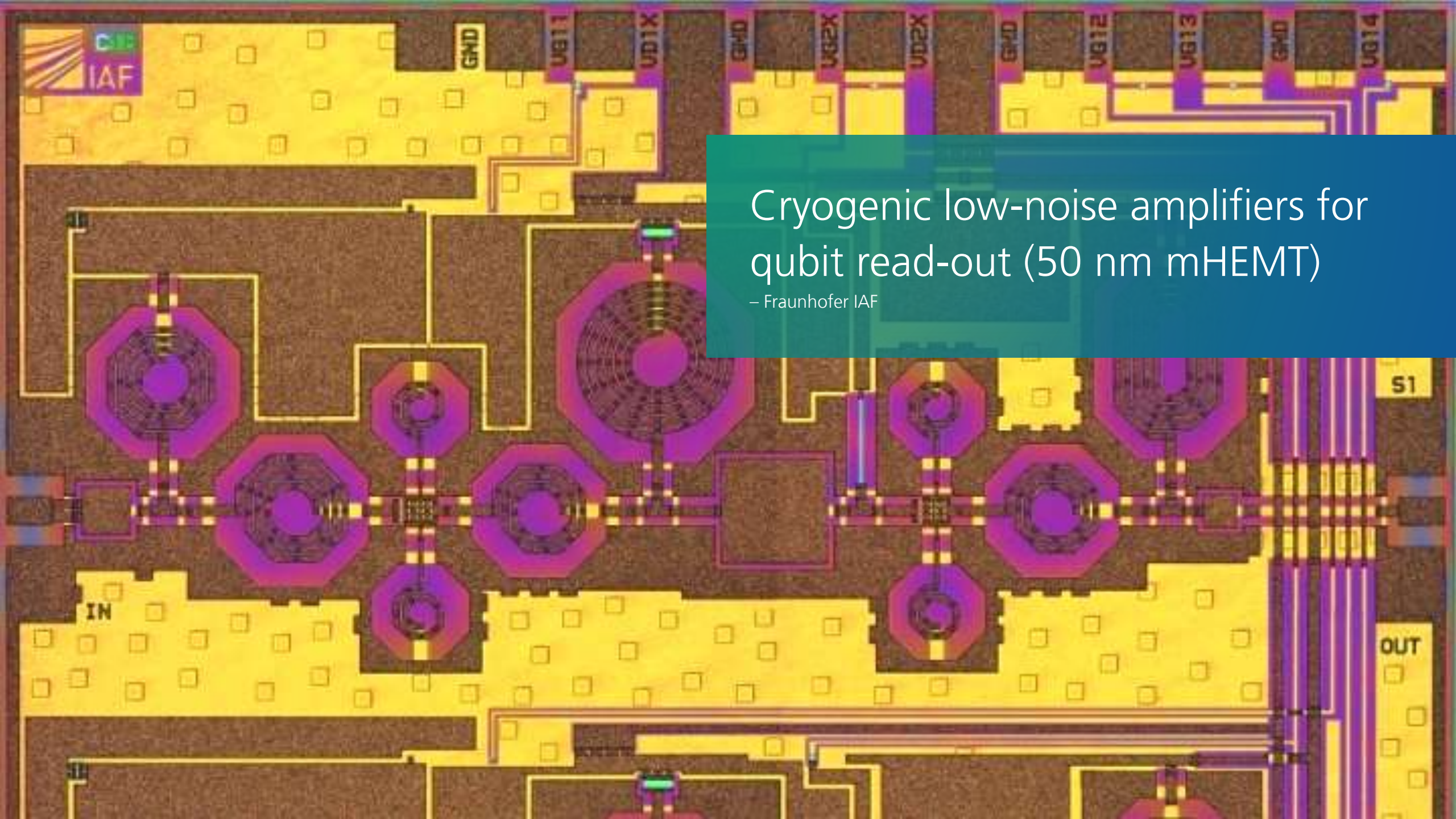


Munich Quantum Valley, Fraunhofer IIS & EMFT

Flexible, shielded and high density superconducting wiring for qubits

– Fraunhofer EMFT





Cryogenic low-noise amplifiers for qubit read-out (50 nm mHEMT)

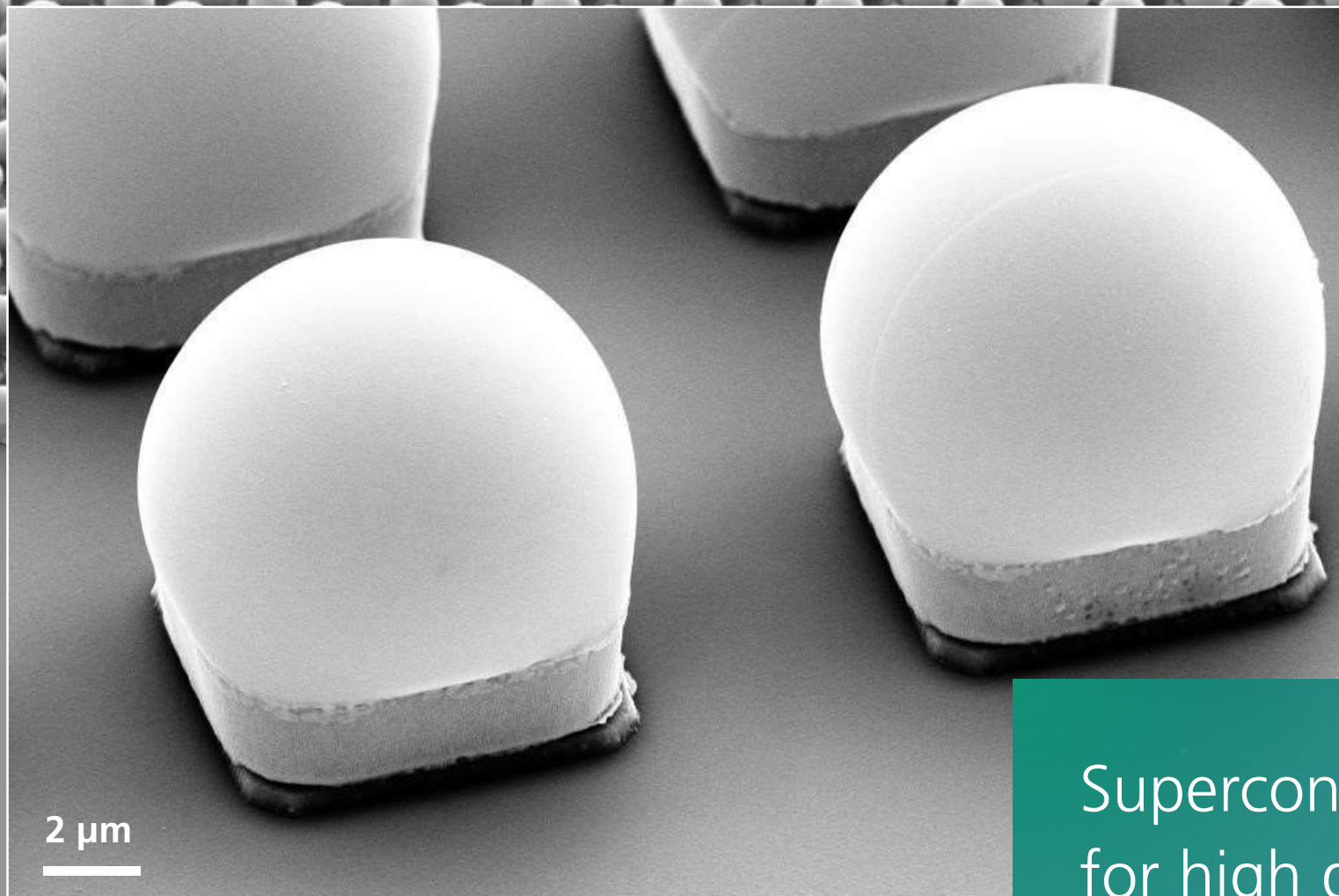
– Fraunhofer IAF



96 channels, 16 bit, up to 80 GHz,
programmable delays 4ns and 1°

Coherent multi-signal sources for cryogenic qubit control

– Fraunhofer FHR



Superconducting micro bumps (In) for high density integration

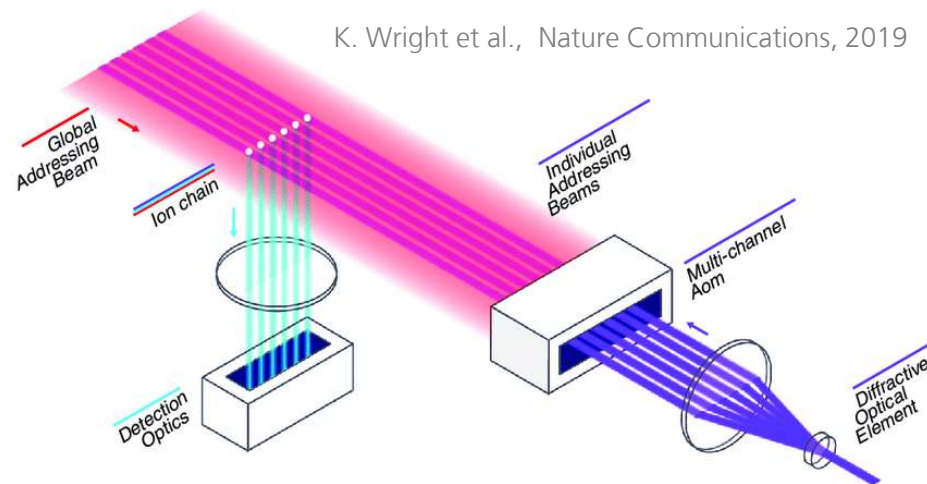
– Fraunhofer IZM

The Optical Quantum-Classical-Interface

Challenges with the optical Quantum-to-Classical interface

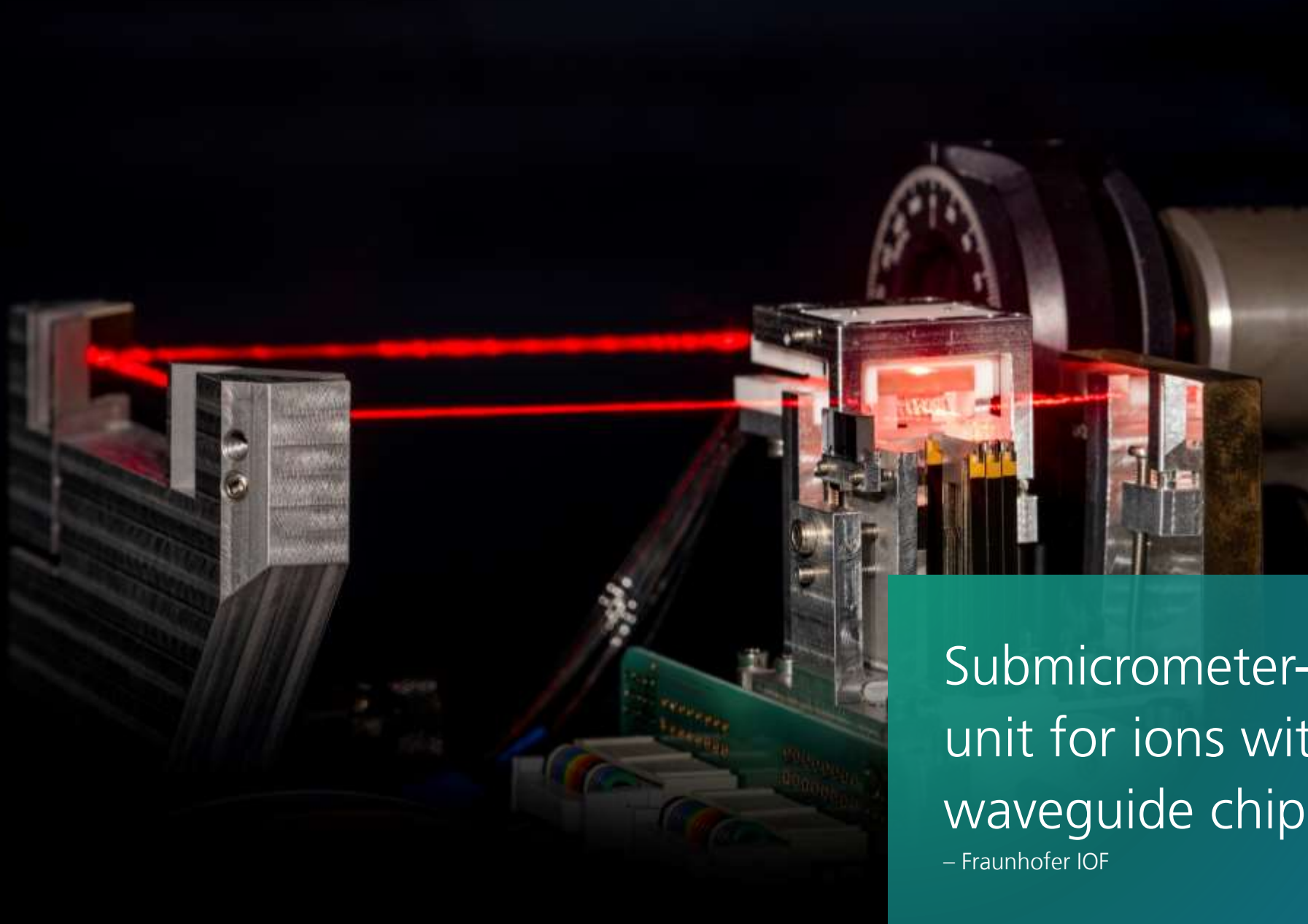
Scaling of control and readout units

- High-power, stable, and narrowband **laser sources** (up to visible and UV)
- Fast, highly parallelized, and integrated (**PIC**) optical **modulators** for temporal laser pulse shaping (NIR to UV)
- Fast **addressing** of the individual qubits with **high spatial resolution** (for minimal crosstalk)
- High-resolution imaging or **efficient** fluorescence **detection** (SPAD)



Example: Addressing and detection of ion qubits



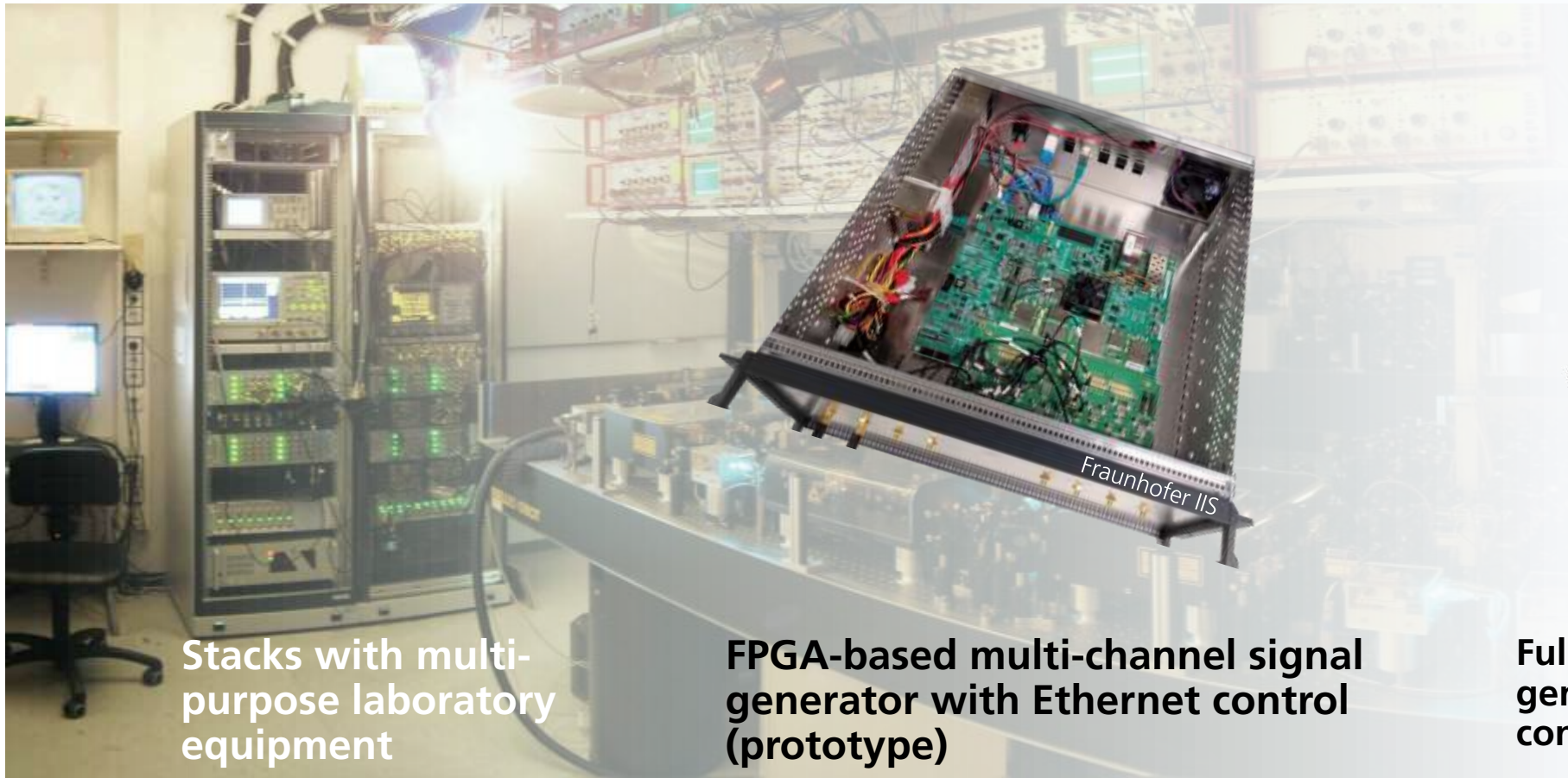


Submicrometer-precise addressing unit for ions with fibre coupled waveguide chip and micro-optics

– Fraunhofer IOF

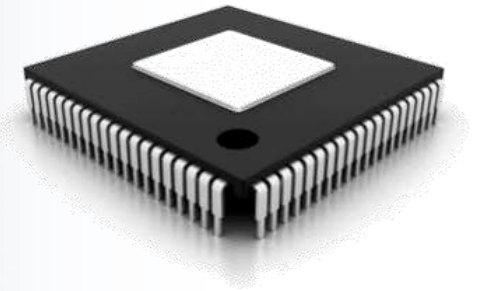
From electronic laboratory equipment to application-specific ICs

Research and enabling technologies need to go hand in hand



Stacks with multi-purpose laboratory equipment

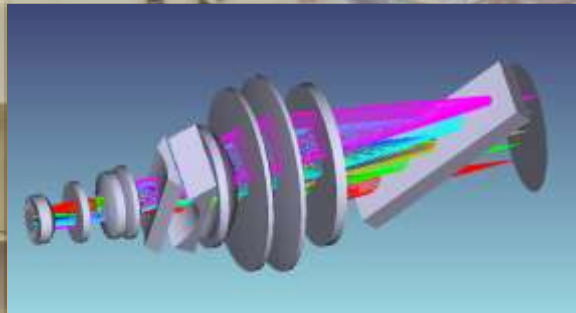
FPGA-based multi-channel signal generator with Ethernet control (prototype)



Fully integrated signal generator with active loop control on ASIC

From optics via micro-optics to integrated photonics

Research and enabling technologies need to go hand in hand



Fraunhofer ILT

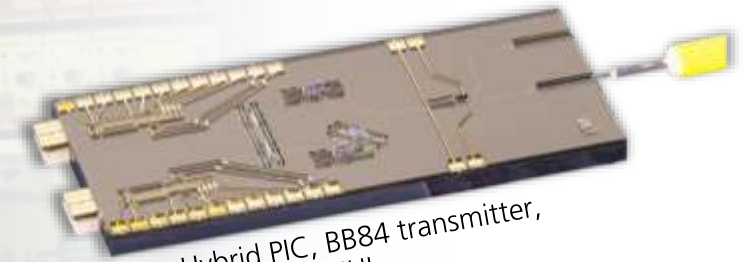
**High-resolution
optical systems**

Atomic spectroscopy module, Leibniz FBH

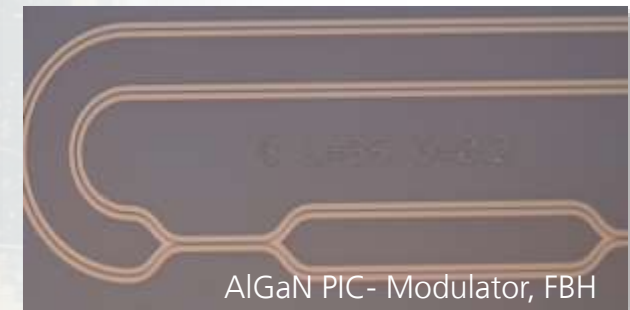


DFB-MOPA laser with
electrical interface, FBH

**Hybrid microintegration to
robust micro-optical modules**

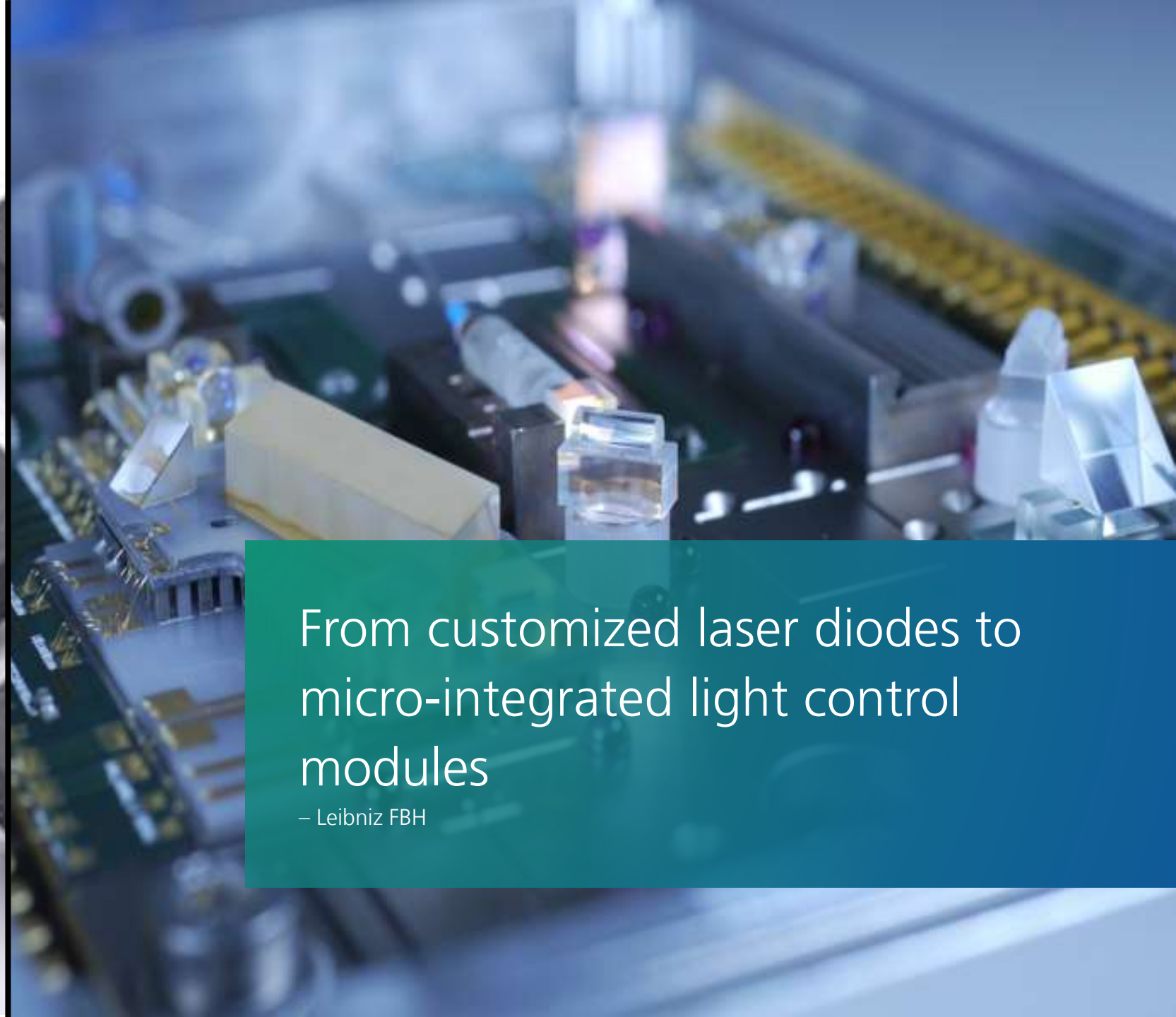


Hybrid PIC, BB84 transmitter,
Fraunhofer HHI



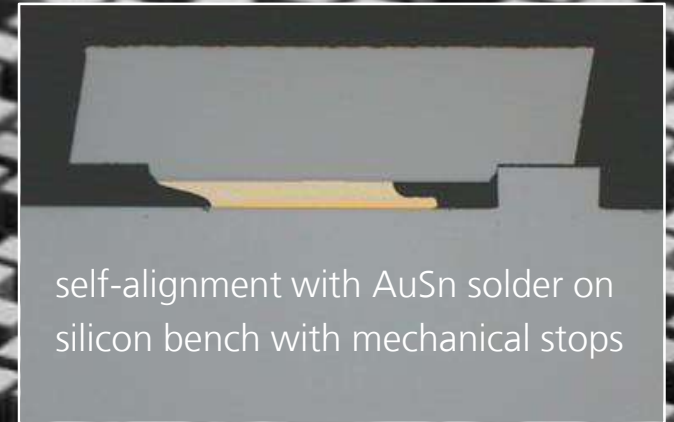
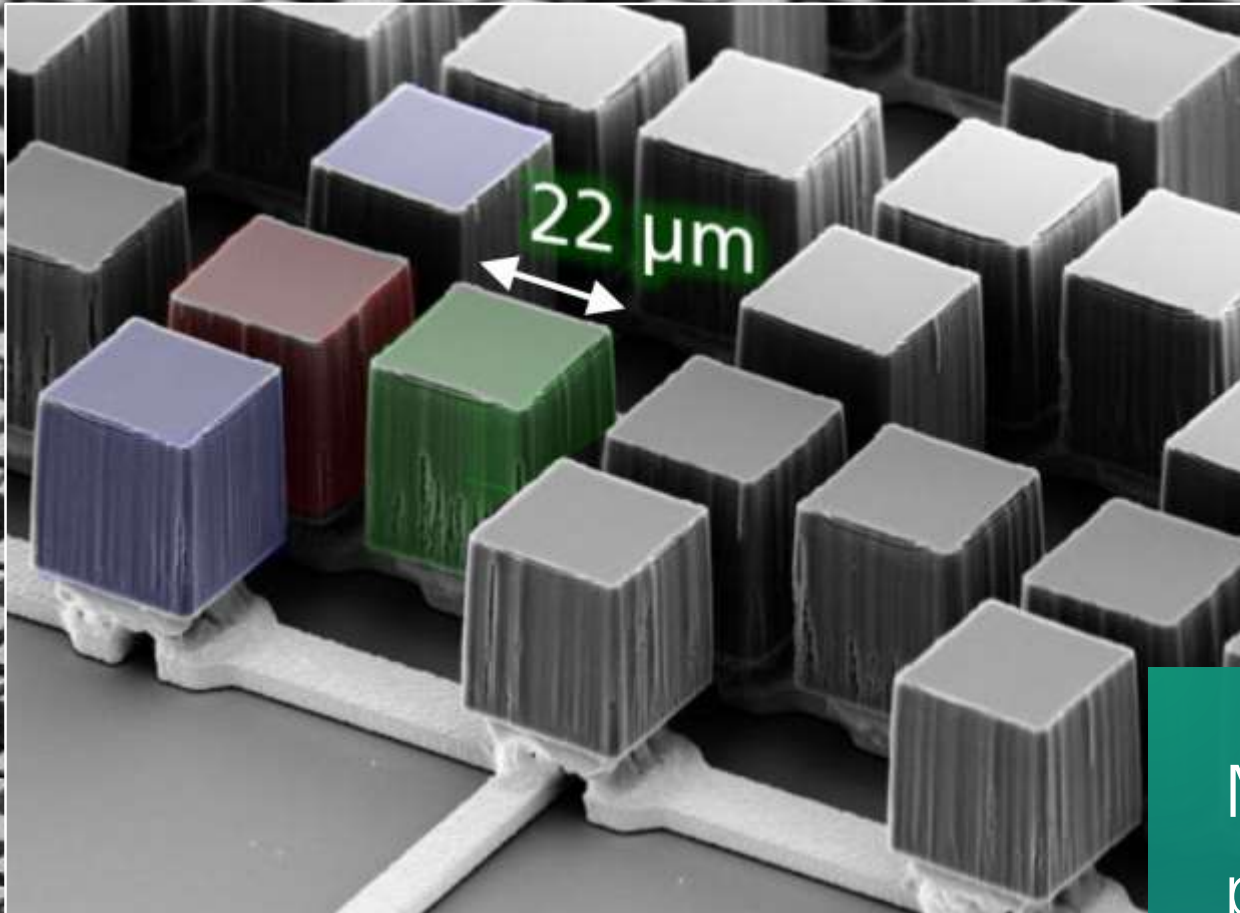
AlGaN PIC- Modulator, FBH

Photonic Integrated Circuits (PIC)



From customized laser diodes to micro-integrated light control modules

– Leibniz FBH



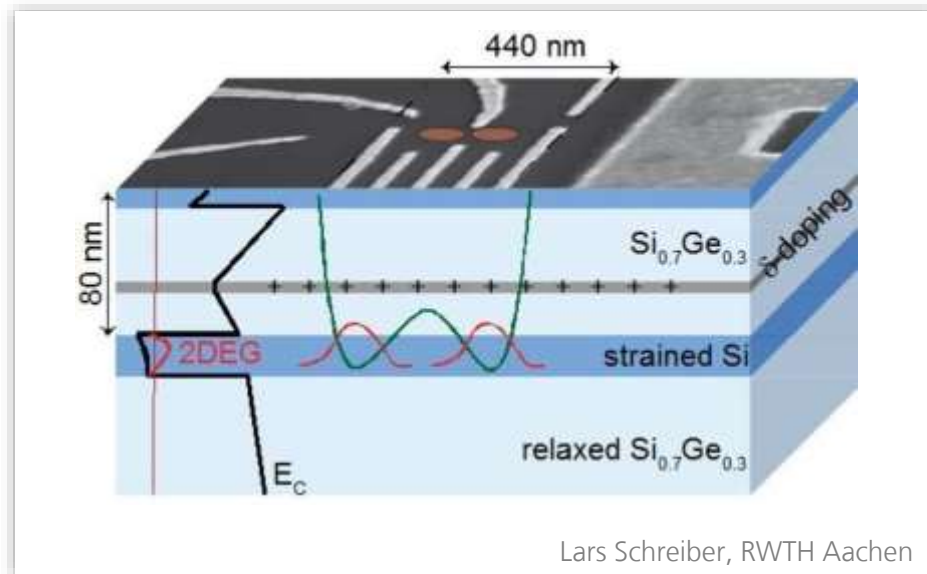
Massive parallel assembly of
photonic devices via micro-transfer
bonding with precise self-alignment

– Fraunhofer IZM

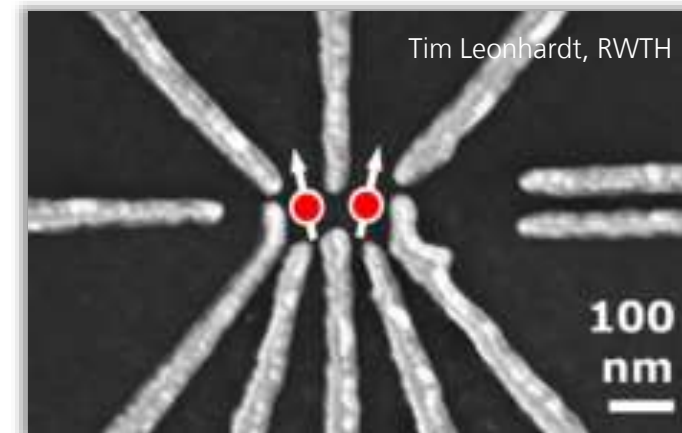
Qubit Technology - The Quantum Chip

Spins qubits in electrostatically defined quantum dots

The basics of implementation

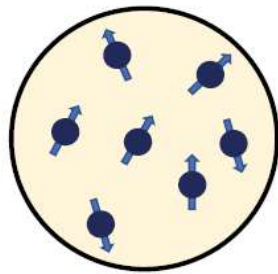


- The qubit is represented by a **single electron (spin 1/2)** confined in a quantum dot induced by a **set of electrostatic gates**.
- **Microwaves** and electro/magnetic fields are utilized for addressing the spin qubits.
- By controlling the **exchange interaction** spin qubits in neighbouring quantum dots are entangled.

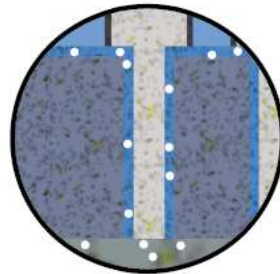


Spins qubits in quantum dots

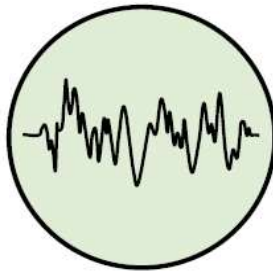
Challenges in material and nanostructure properties



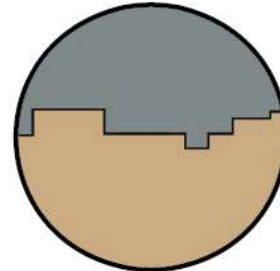
Nuclear spins



Charge traps
interface spins



Potential
fluctuation



Interface
inhomogeneity

Requirements:

- **Isotopically enriched ^{28}Si** for suppression of decoherence due to nuclear spins fluctuations
- **Avoidance of lattice defects and oxygen impurities** (that reduce necessary valley-splitting)
- **Good oxide interfaces** to minimise charge noise
- **Homogeneity in the material and reproducibility in the structures** are required for a high qubit "yield" and for simplifying their calibration and addressing.

"Materials challenges and opportunities for quantum computing hardware",
Nathalie P. de Leon et al., Science 2021

Industrially manufactured quantum dots

by QuTech (Delft, NL) and Intel (Oregon, USA)



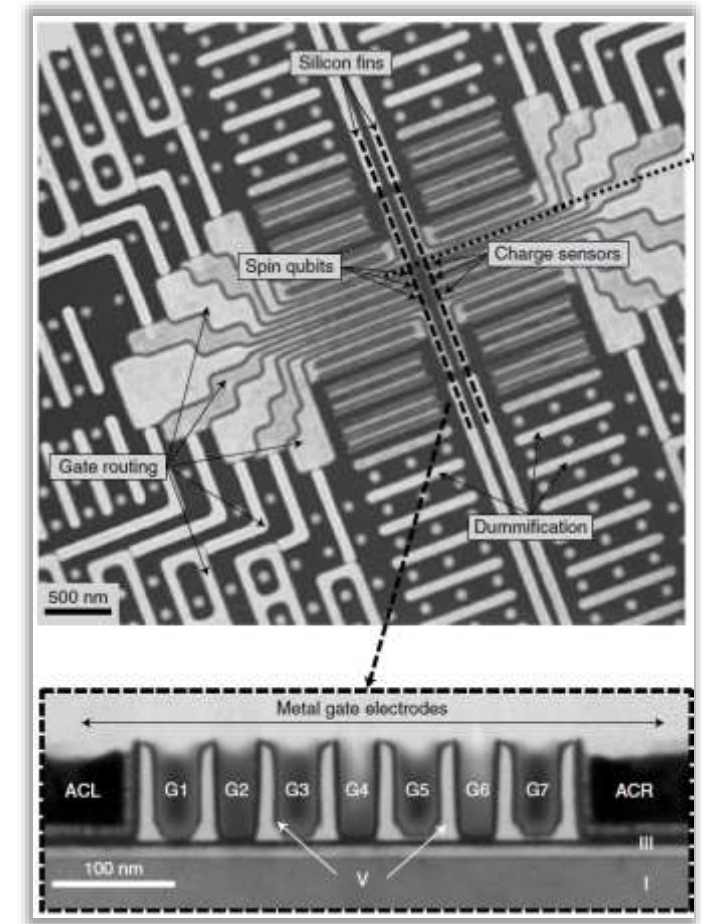
- fabricated in a **300mm semiconductor fab** (CMOS technology)
- **High quality and yield**
- **crucial for** the future fabrication of **millions of qubits**

R&D flexibility and rapid prototyping can be a **challenge in an industrial fab?**

Scaling will pose enormous challenges in terms of the necessary wirings.

“wiring apocalypse”

“Qubits made by advanced semiconductor manufacturing”,
A. M. J. Zwerger, Nature Electronics 2022



Spins qubits in quantum dots

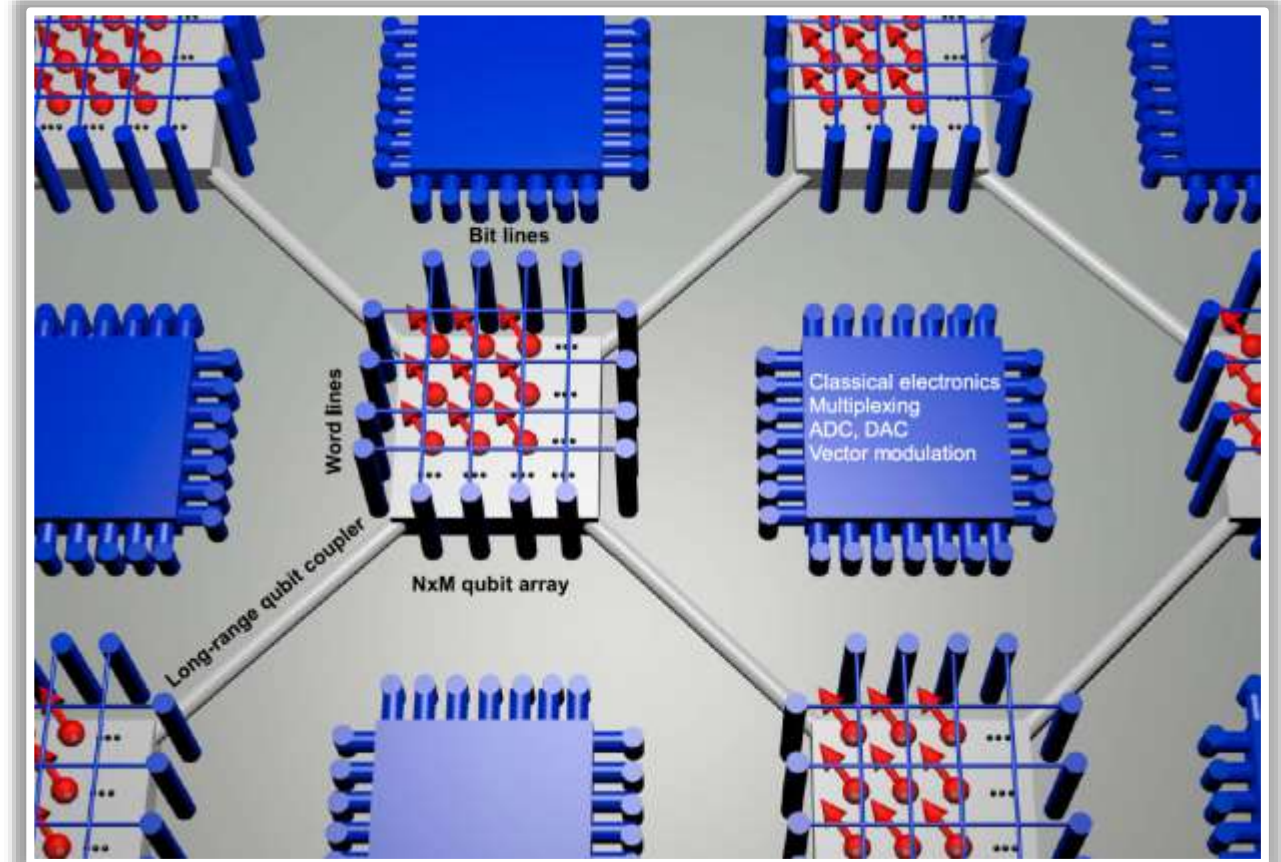
Concepts for scaling the quantum circuit

Challenges

- Spatially dense qubits (gate pitches $< 70\text{nm}$)
- Require extremely high wiring & interconnect density
- at temperatures $T < 100\text{ mK}$ (potentially at 1-4K)

Solution I: Sparse qubit array

“Quantum bus” connections create space for local control and readout electronics, thus minimising the control lines to the outside.



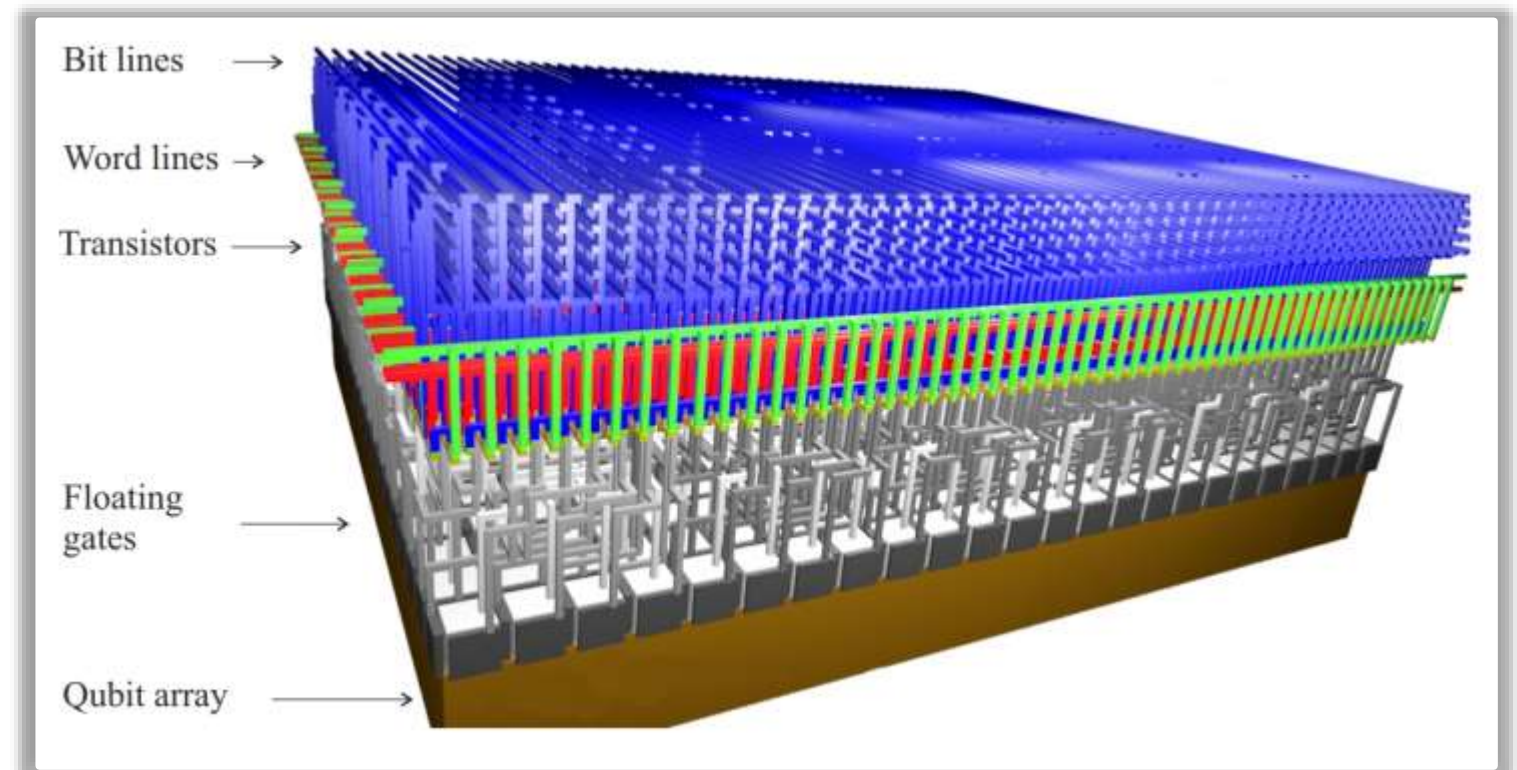
„Interfacing spin qubits in quantum dots and donors — hot, dense, and coherent”,
L. M. K. Vandersypen, H. Bluhm, M. Veldhorst et al., npj Quantum Information 2017

Spins qubits in quantum dots

Concepts for scaling the quantum circuit

Solution II:

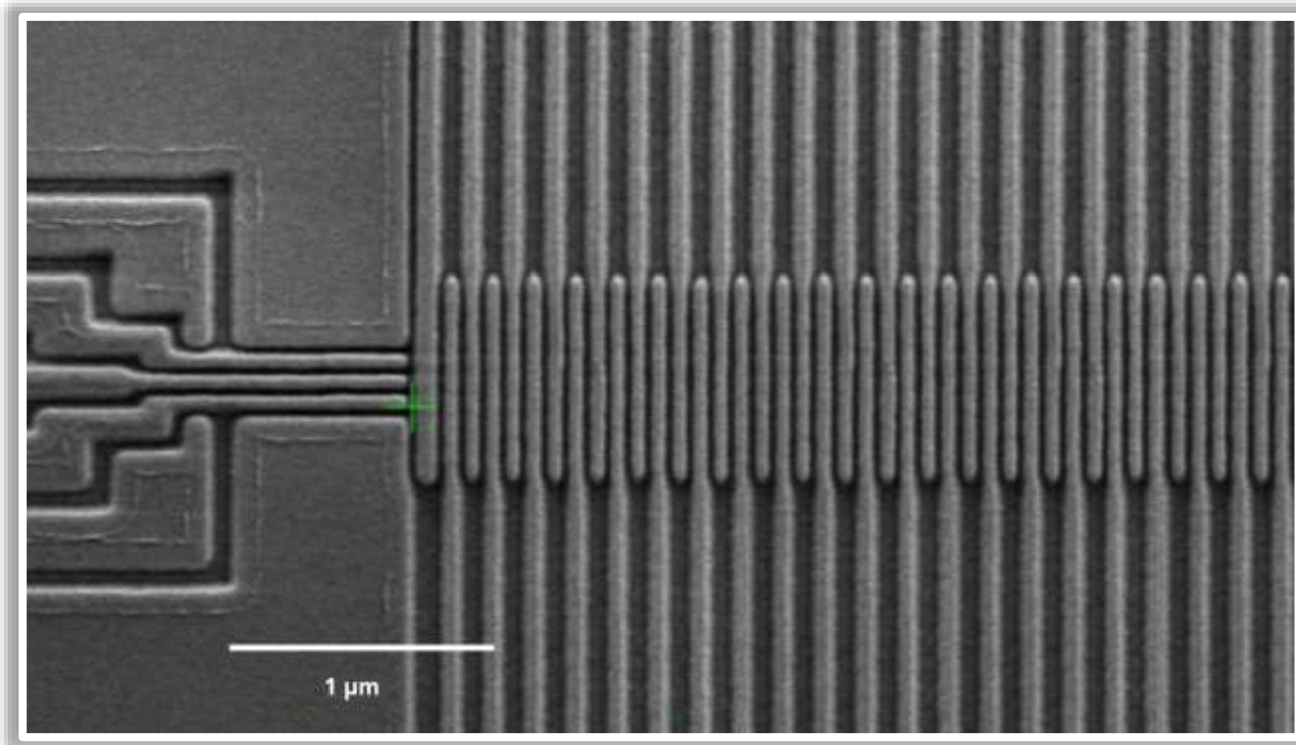
Large 2D qubit array
controlled by floating memory gates
(similar to non-volatile memories).



„Silicon CMOS architecture for a spin-based quantum computer“,
M. Veldhorst et al., Nature Communications, 2017

Quantum bus for spin qubits in silicon

Goal: Connecting spatially separated sparse qubit arrays



Concept and design: RWTH Aachen
Electrode fabrication: Fraunhofer IPMS

Quantum Bus gate structure

Pulsating gate voltages guide a quantum dot with a single electron through an electrostatically formed one-dimensional channel.

Research and pilot lines for qubits and enabling technologies

Flexibility and customization for rapid innovation

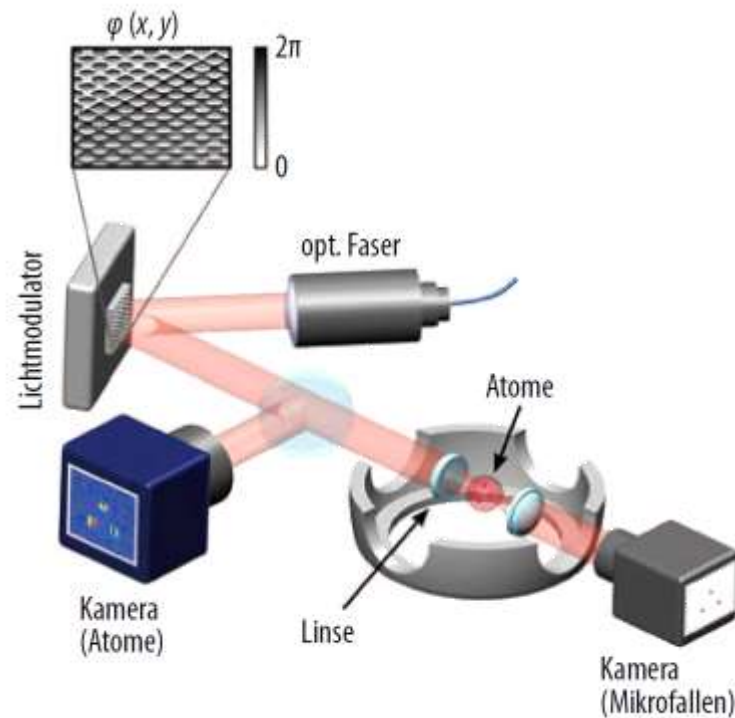
- **State-of-the-art infrastructure** and CMOS compatible process lines (up to 300 mm wafer size)
- **Low volume** and **high-quality manufacturing**
- Cleanrooms infrastructure **throughout Germany**, with collaborative wafer handling capabilities
- **Fast development cycles** for research and optimization (high tool availability)
- **High throughput characterization** of “exotic” materials (new superconductors)
- **Strict IP management**, no data to third parties
- Preparing technology transfer to industry



Neutral Atoms - The Quantum Chip?

Neutral atoms

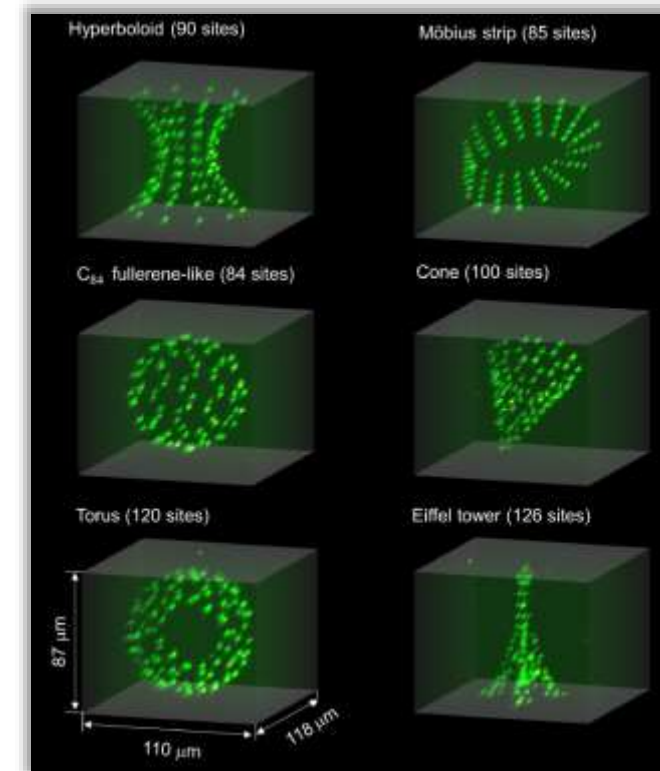
in holographically generated "optical tweezers"



Setup for atoms trapped in optical tweezers.

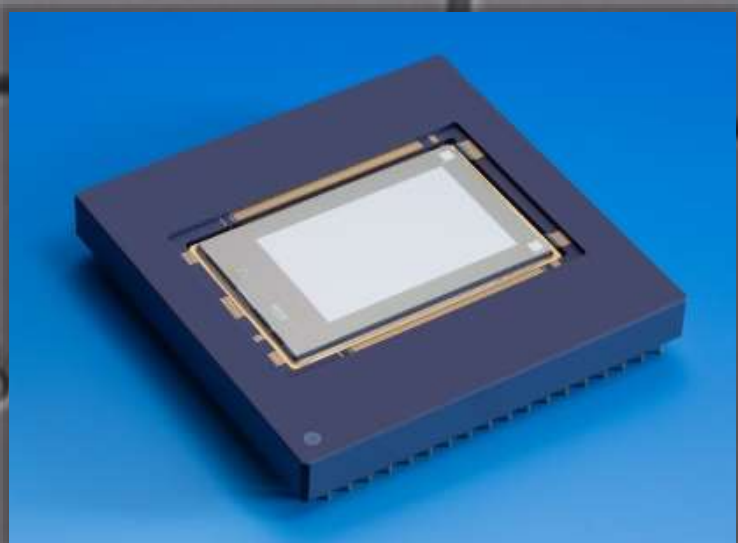
Almost arbitrary 3D arrays can be generated through spatial light modulators (SLMs).

„Hoch angeregt und kontrolliert“, S. Hofferberth und C. Groß, Physik Journal 2019



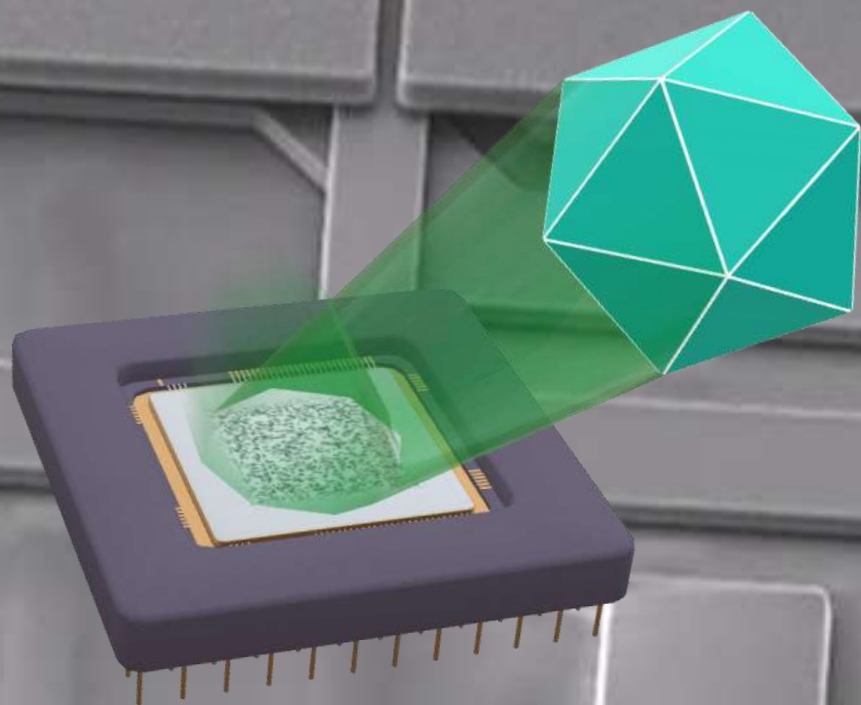
Fluorescence image of single atoms in different tweezer arrangements.

“Synthetic three-dimensional atomic structures assembled atom by atom”, D. Barredo, A. Browaeys et al., Nature 2018



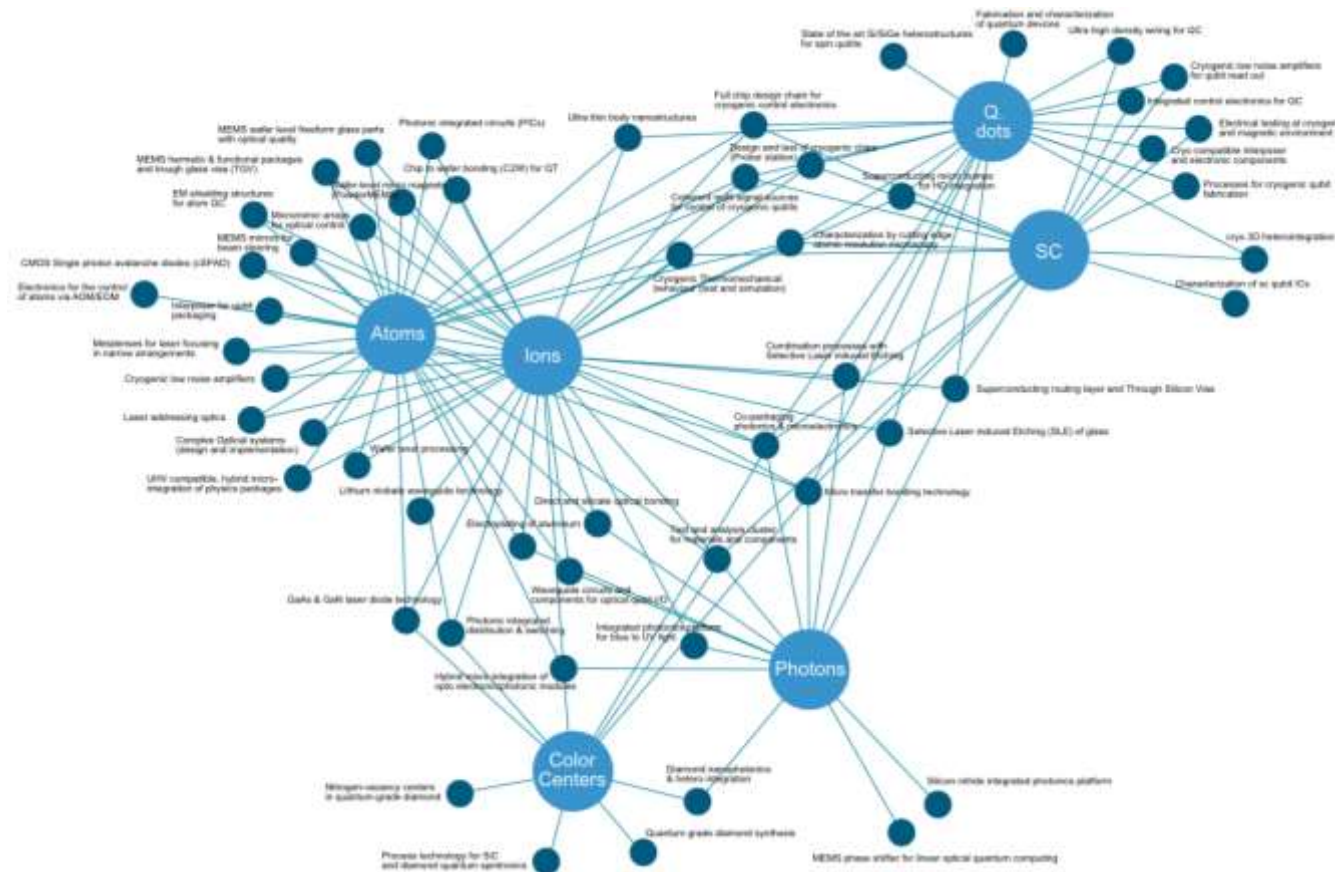
MEMS Micromirror array for holographic shaping of light fields

– Fraunhofer IPMS



Synergies of a multidimensional portfolio

Quantum enabling technologies and services along the entire value chain



Components, Circuits , Modules
[digital, analog, quantum]

Process Technology, Assembly, Pilot Production

Test, Characterization, Validation

Design, Simulation, Architectures

We offer solutions at the quantum limit

Tell us about your current challenges!

- **Quality** is paramount in **scaling** up qubit systems.
- A research fab can provide **solutions tailored** to the needs of the computing **system**.
- **Agile collaboration** between **quantum scientists and engineers** will lead to flourishing developments.
- Quantum technologies are converging towards **wafer technologies**.
- **Let's discover** where state-of-the-art microelectronics and its processes **can already boost QC today!**

Get in Touch

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accelerator »QNC Space«
to get your process ideas
off the ground*



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