4021131: Solid State Quantum Technologies ECTS: 4

Mi 14:00-14:30 hybrid

4021132: Übungen ECTS: 4

Mi 8:00-9:30, Seminarraum 3.01

Prof. Wolfgang Wernsdorfer, Dr. Tino Cubaynes,

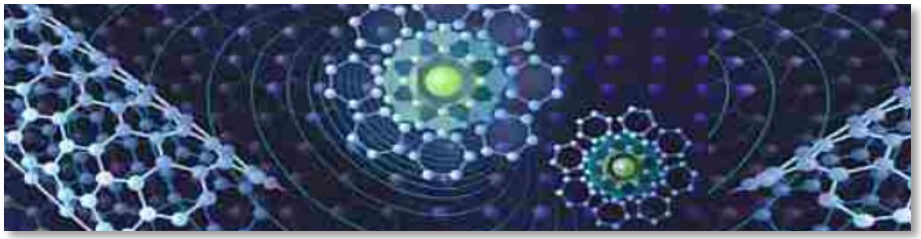
Course content:

Solid State Quantum Technologies

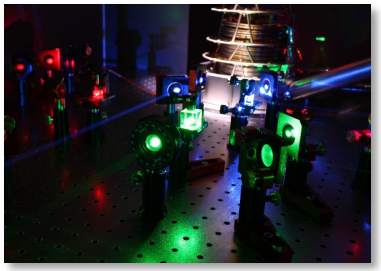
- The second quantum revolution and its applications

Quantum Communication

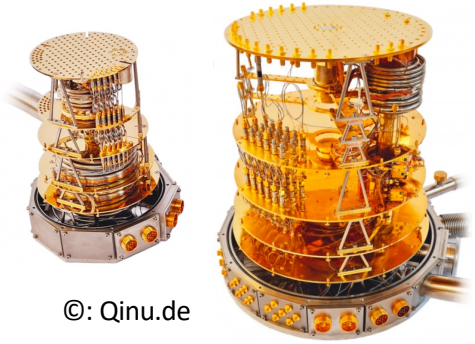
Quantum Materials Fundamental Research



Quantum Sensing



Infrastructure



©: Qinu.de

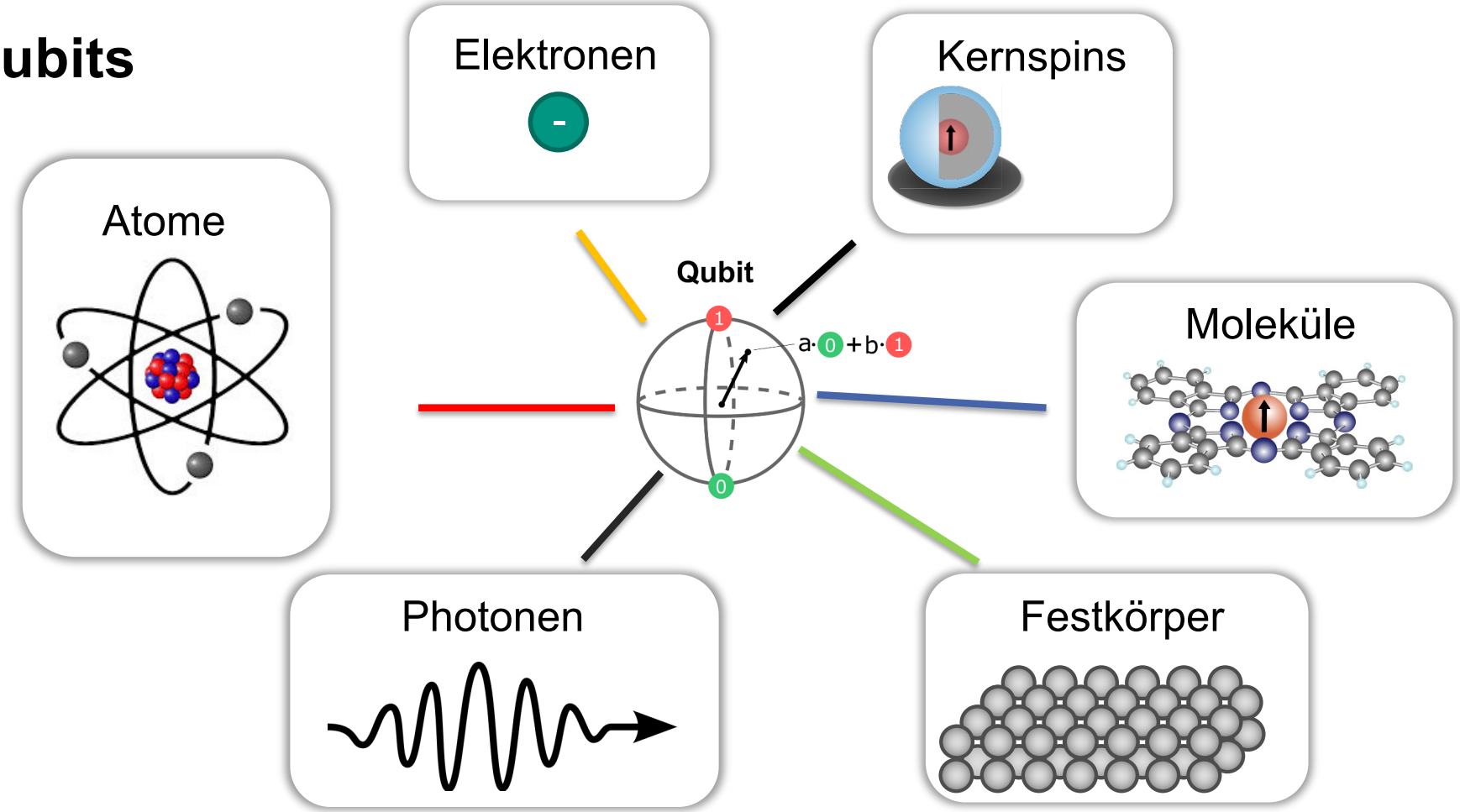
Quantum Computing

Quantum Simulation

©: FZJ / Ralf-Uwe Limbach

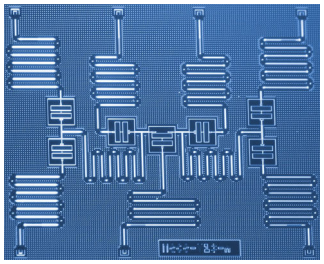
2

Qubits


Elektronen
-
Kernspins
Atome
Qubit
1
0
a·0+b·1
Moleküle
Photonen
Festkörper

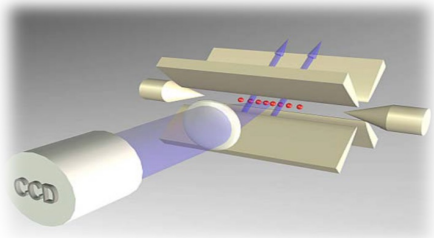
Different architectures

- **Superconducting Quantum Circuits**



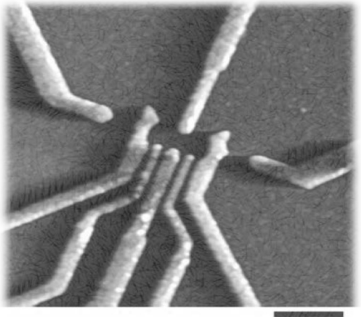
IBM, Google

- Trapped Ions

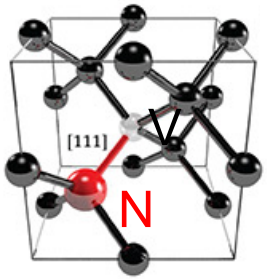


Quantinium, IonQ

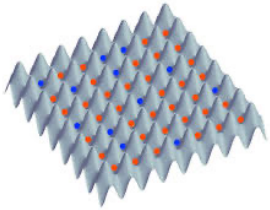
- **Semiconductor Quantum Dots: Silicon Spins**



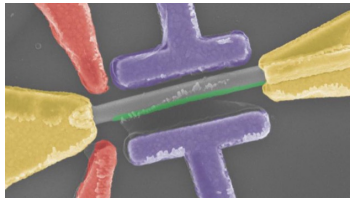
Intel



- **Colour Centers in Crystals**



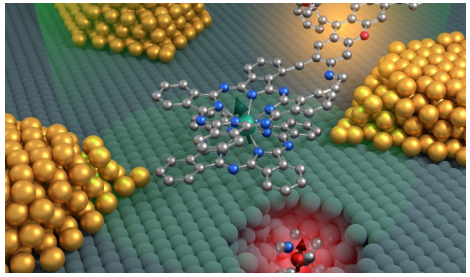
- Neutral Atoms/ Rydberg Atoms



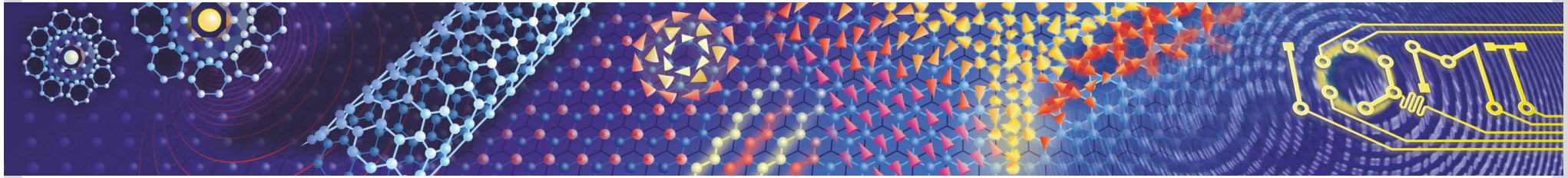
- Topological Qubits

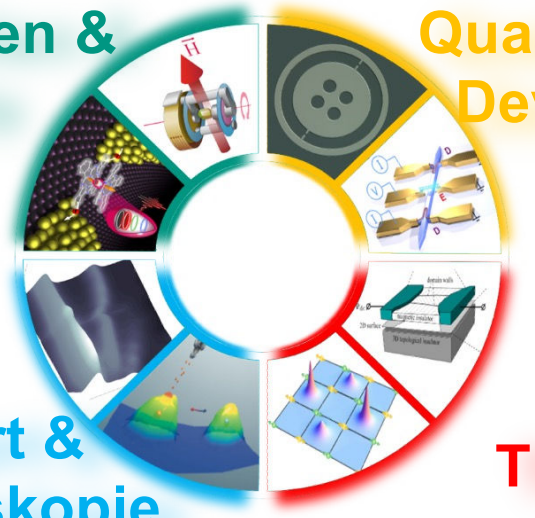
Microsoft

- **Molecules**



Institut für QuantenMaterialien und –Technologien (IQMT)





- Gründung 01/2020 HELMHOLTZ QUANTUM
- Entwicklung neuer Quantenmaterialien
- Funktionalisierung
- Bausteine für Quantentechnologien und Quantencomputer
- 8 Abteilungen, 17 Professoren

  ca. 110 Mitarbeiter (45 Dauerstelle)

  Personalbudget ca. 7M€/a

  (80% HGF, 20% Drittmittel)

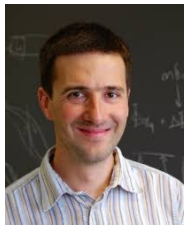
IQMT unfolded

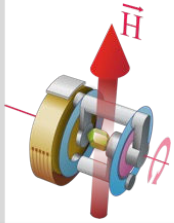
Karlsruher Institut für Technologie

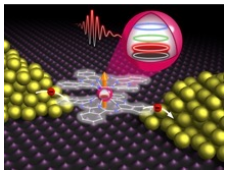
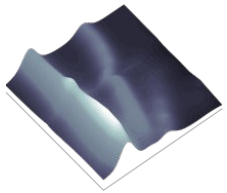
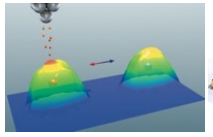
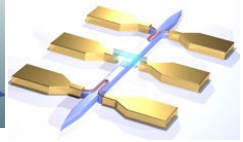


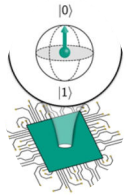


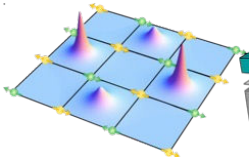
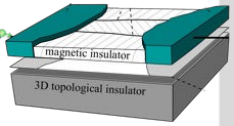






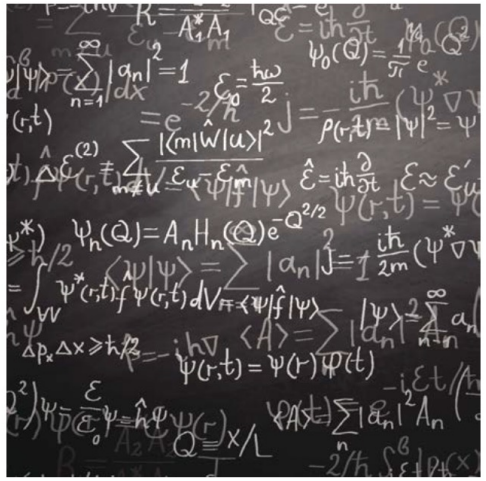


New Quantum Materials	Molecular Quantum Systems	Quantum Materials Spectroscopy	Quantum Transport	Quantum Optical Devices	Quantum Circuits	Quantum Computing	Theory of Quantum Materials	Theory of Mesoscopic Quantum Systems
C. Meingast	**M. Ruben**	**M. Le Tacon**	**W. Wulfhekel**	**D. Hunger**	**W. Wernsdorfer**	**I. Pop**	**J. Schmalian**	**A. Mirlin**
AG Meingast	AG Ruben	AG Le Tacon	AG Beckmann	AG Krupke	AG Ustinov	AG Pop	AG Garst	AG Gornyi
AG Schneider	AG Powell	AG Schuppler	AG Gerhard	AG Hunger	AG Wernsdorfer	AG Schäffer	AG Schmalian	AG Mirlin
		AG Weber		AG Kappes				AG Metelmann
								AG Shnirman

Recommended requirements for this course:

- Quantum mechanics I
- Modern Physics II (Physik V, Solid-state physics)

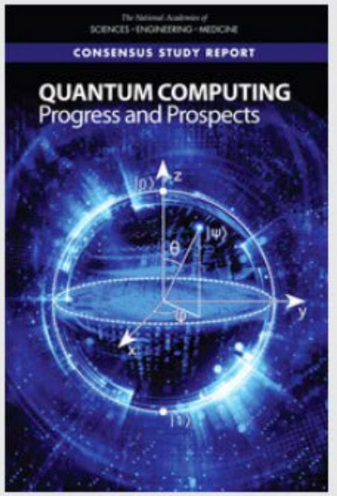


Possible parallel lecture:

4013114 – Hauptseminar:
Aktuelle Experimente in der Quantenphysik
Thursdays 14:00-15:30
Seminarraum 3.1

Literature

- M. A. Nielsen and I. L. Chuang, *Quantum computation and quantum information,* 2000
- A. M. Zagoskin, *Quantum Engineering*, 2011
- Additional reading material will be provided throughout the lecture on the ILIAS web page:
  - *Quantum Computing: Progress and Prospects*, Washington, DC: The National Academies Press, https://doi.org/10.17226/25196 (2019)
  - P. Kranz, et al. *A quantum engineer's guide to superconducting qubits*, Appl. Phys. Rev. **6**, 021318 (2019)



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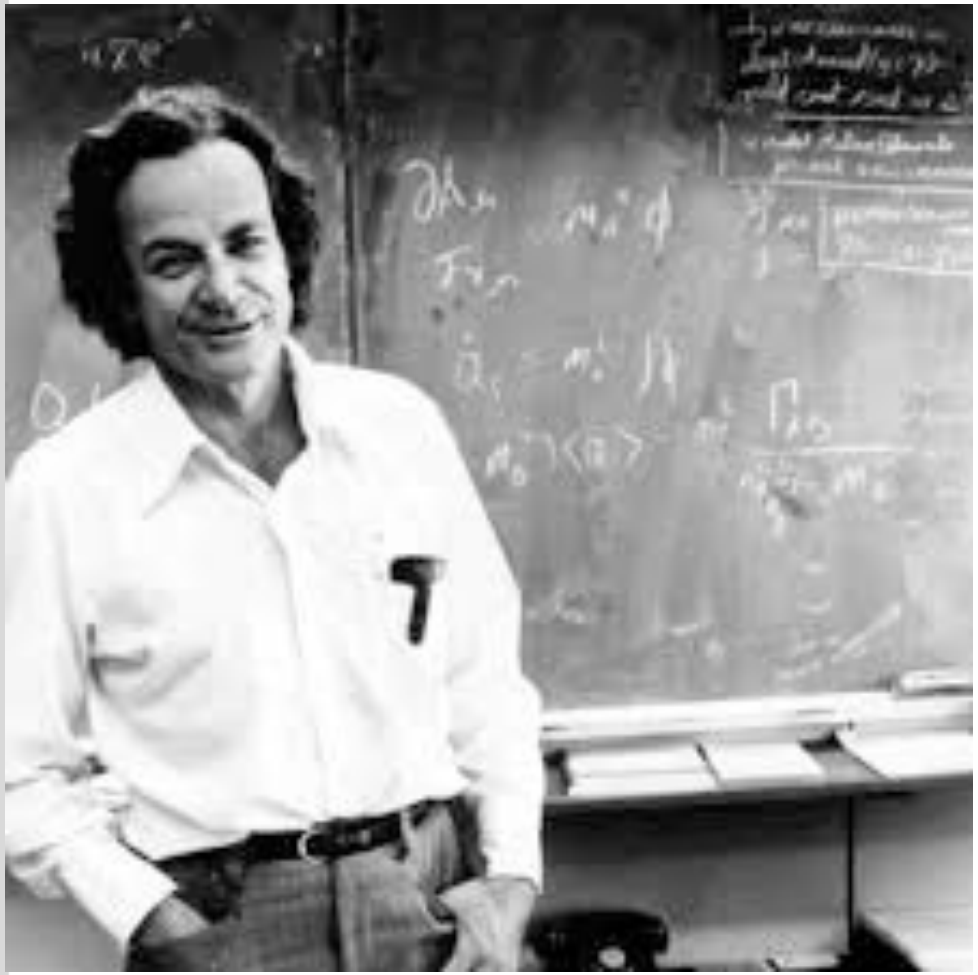
Ask questions !!!
Give comments !

The whole world is quantum

Is it possible to build computers that use the laws of quantum mechanics to compute?



Richard Feynman

“Nature isn't classical, dammit, and if you want to make a simulation of nature, you'd better make it quantum mechanical, and by golly it's a wonderful problem, because it doesn't look so easy.”

Simulating physics with computers,
R. Feynman,
Int. J. Theor. Phys., 21, 467 (1982)

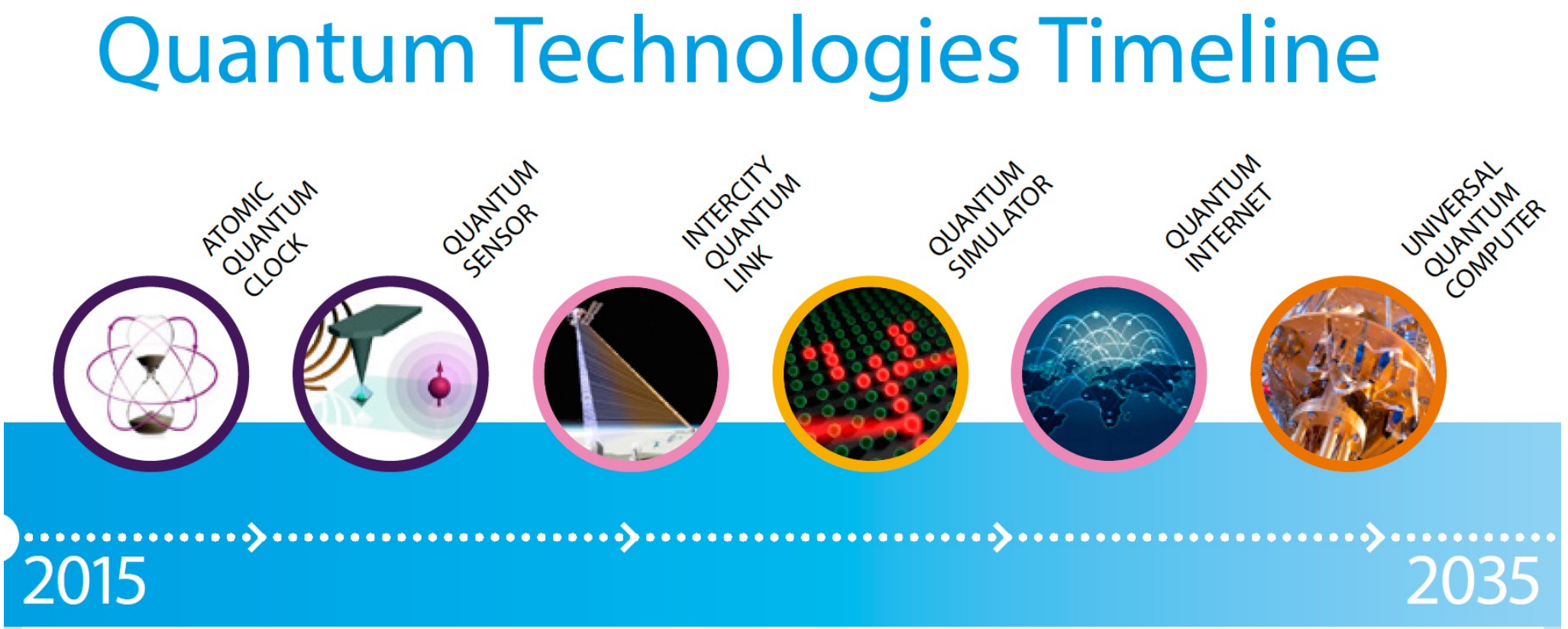
Quantum Manifesto

A New Era of Technology

May 2016

http://qurope.eu/

European initiative in quantum technologies



http://qurope.eu/

International public investment (2021)

UK: 330 M€ over five years for all quantum technologies

EU Flagship: 2 B€ over ten years.

China: Reports on 10 B$ for national center for Quantum Information Science

Germany: 2 B€ over four years for all quantum technologies

Do we really need different computers ?

abacus

Foundations of modern computers

Alan Turing

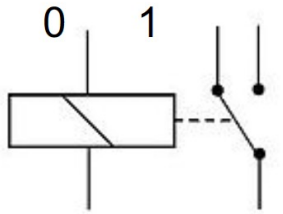
1936
published his seminal work
"On computable numbers, with an application to the Entscheidungsproblem"

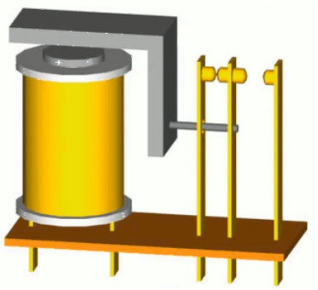
Konrad Zuse

1941
the world's first programmable computer
1943
the first high-level programming language
“Plankalkül”

John von Neumann

1945
formulated basic operation principles and components of modern computers



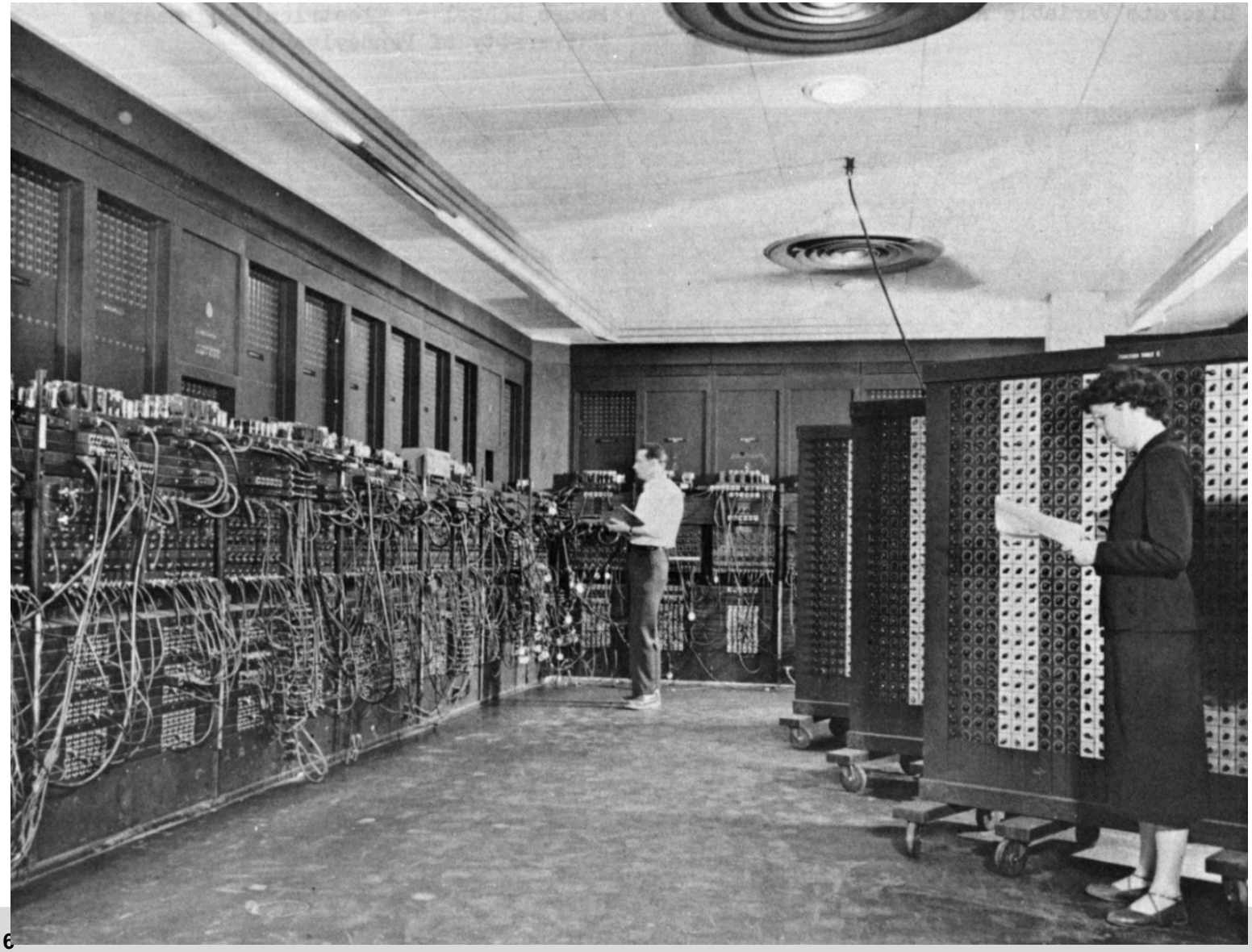


relay

vacuum tube

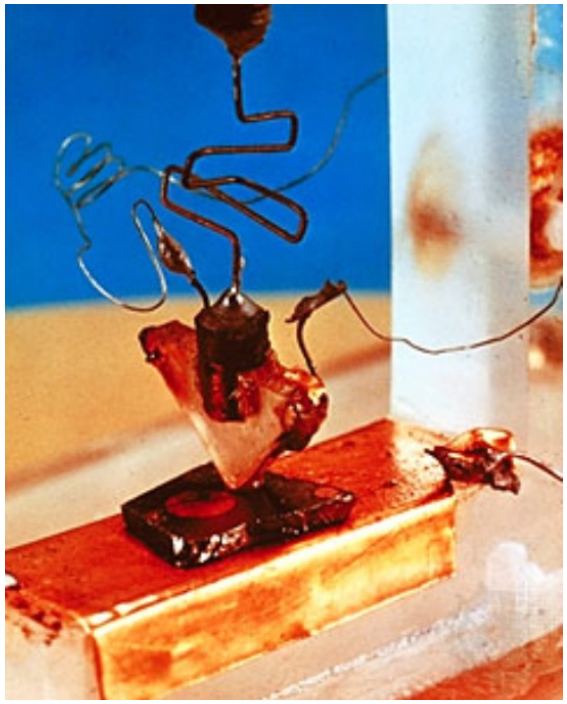
The first powerful digital computer

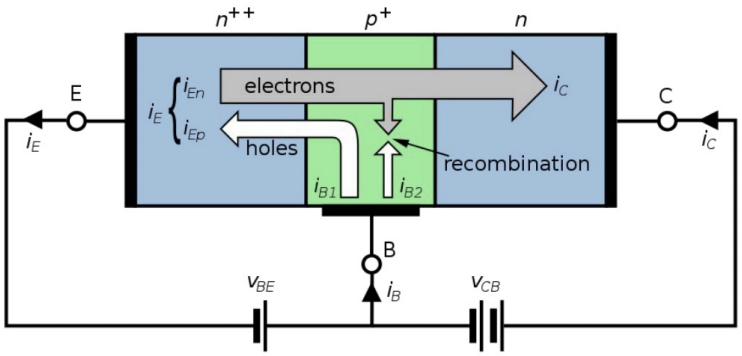
1946 John Mauchly and J. Presper Eckert designed ENIAC



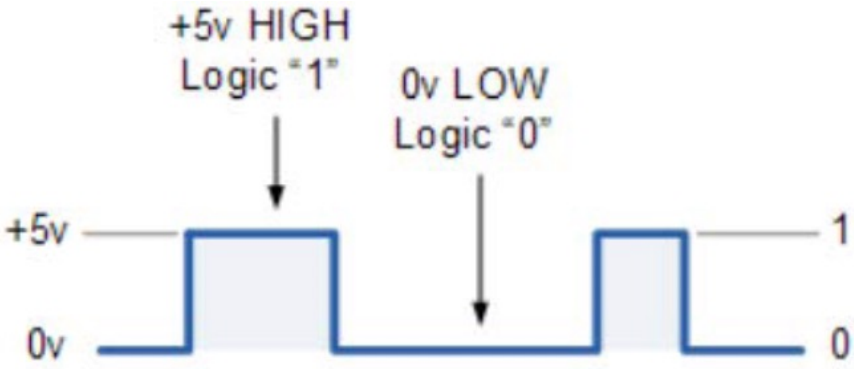
The first transistor

1947 John Bardeen, Walter Brattain, William Shockley





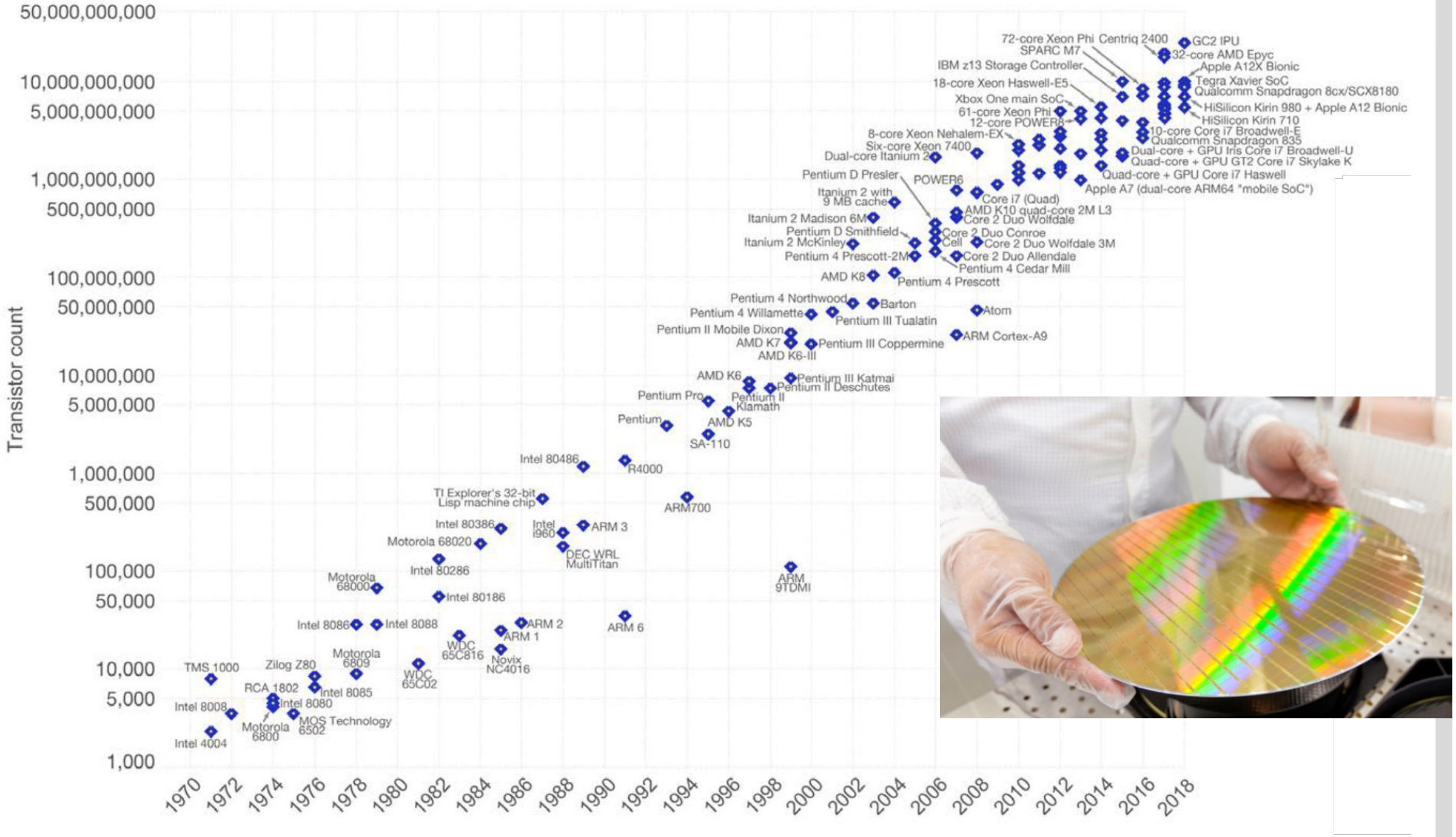
Transistor-bassed processors




```
1111111110110
1110111111101100
1001111111111001
0111111111110000
1111111111110011
0000111111110011
0001111111110010
```

Moore's Law – The number of transistors on integrated circuit chips (1971-2018)

Moore's law describes the empirical regularity that the number of transistors on integrated circuits doubles approximately every two years. This advancement is important as other aspects of technological progress – such as processing speed or the price of electronic products – are linked to Moore's law.



Data source: Wikipedia (https://en.wikipedia.org/wiki/Transistor_count)

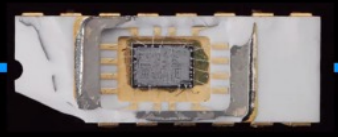
The data visualization is available at OurWorldinData.org. There you find more visualizations and research on this topic.

Why Quantum Computing? Why now?

1958

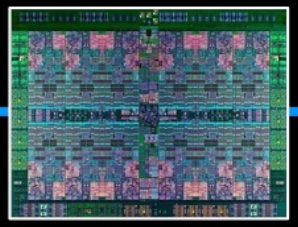
First integrated circuit
Size ~1cm²
2 Transistors

1971

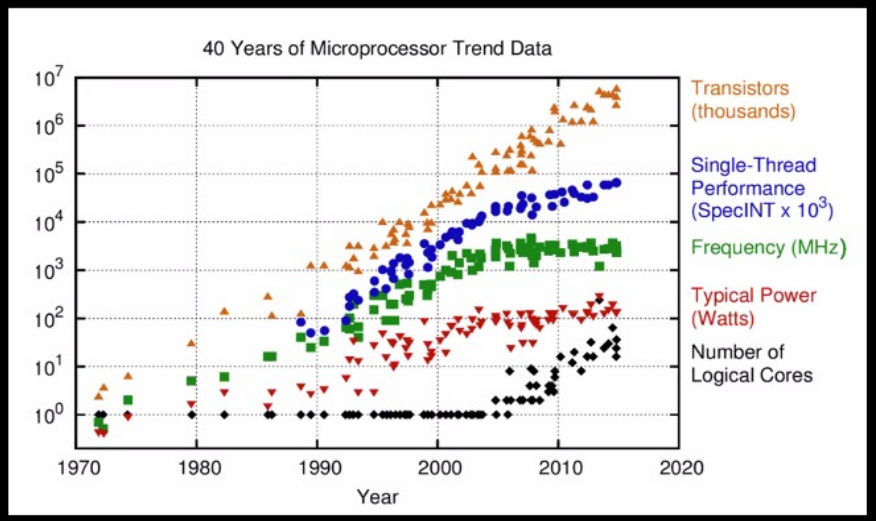


Moore's Law is Born
Intel 4004
2,300 transistors

2014



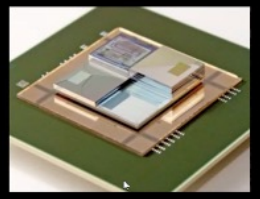
IBM P8 Processor ~ 650 mm²
22 nm feature size, 16 cores
> 4.2 Billion Transistors



Stefan Filipp, WMI, München

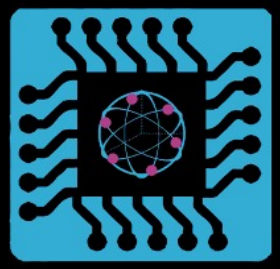
Alternative (co-existing) architectures:

next generation systems (e.g. 3D)



neuromorphic (cognitive)

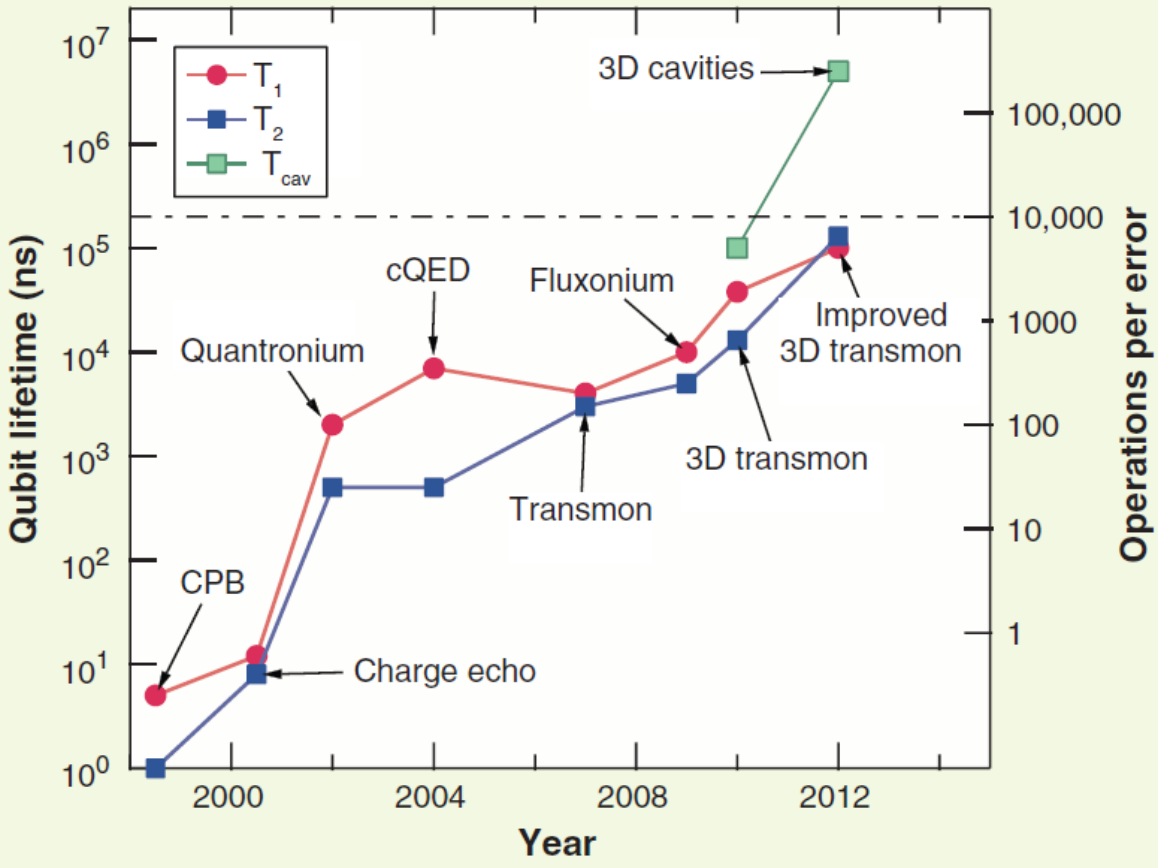
quantum computing



Quantum Moore‘s Law

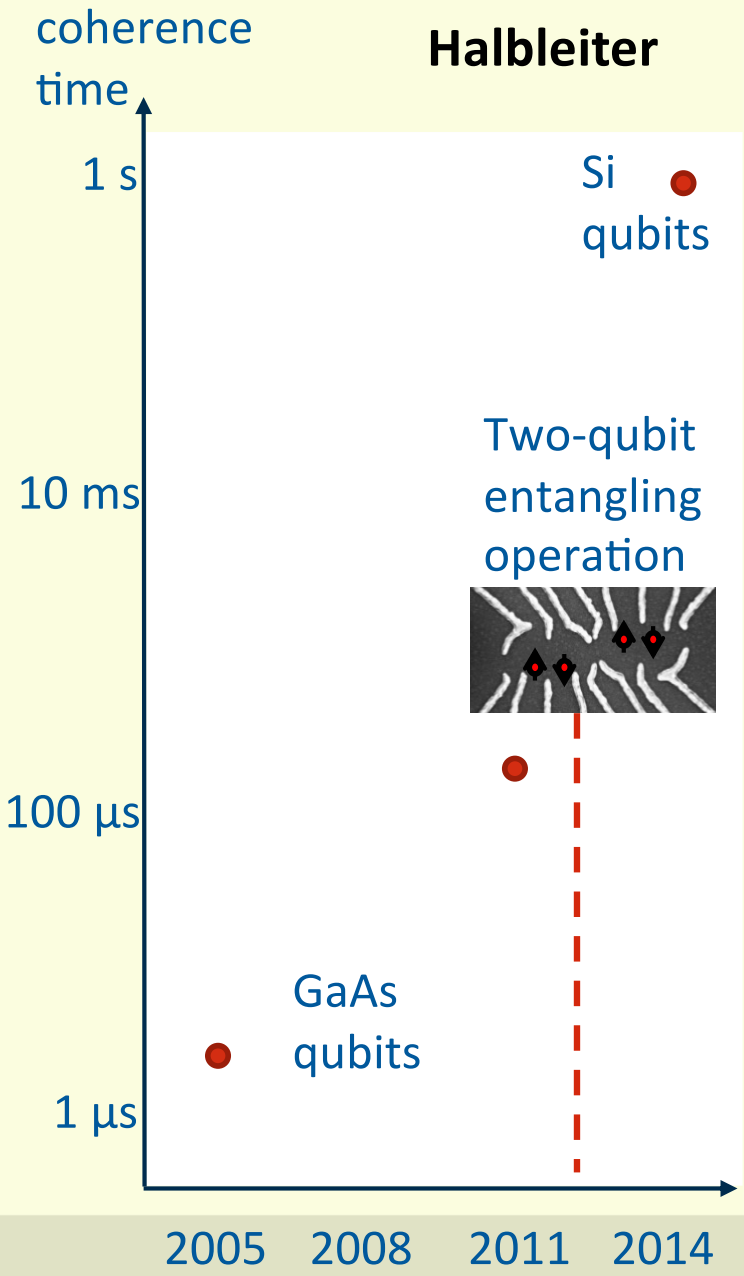
– Exponentieller Anstieg der Lebenszeit von Quantenzuständen.

Supraleitend



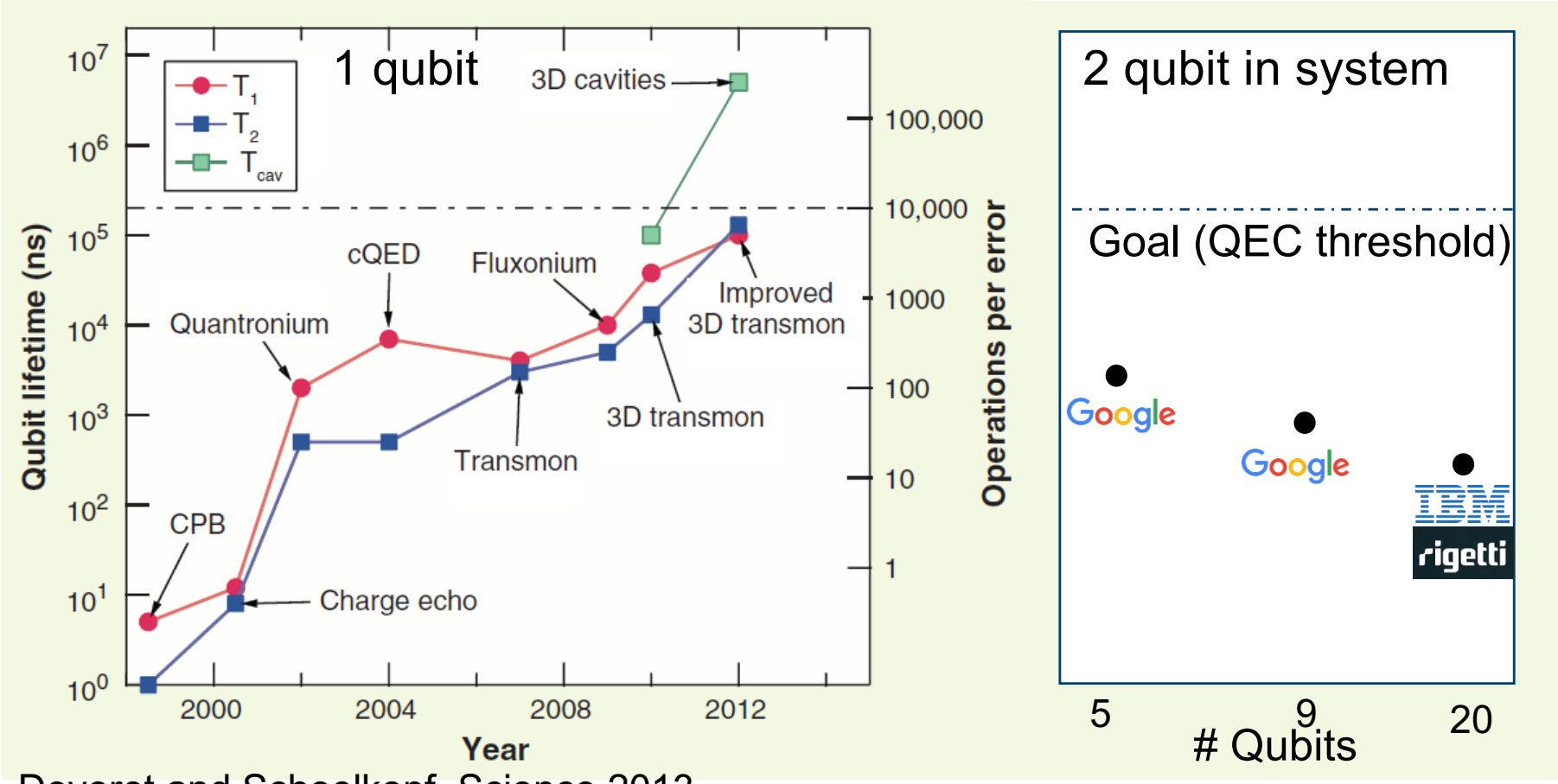
(M. H. Devoret and R. J. Schoelkopf, Science 2013)

Halbleiter



Acknowledgement: H. Bluhm

Maintaining performance when up-scaling

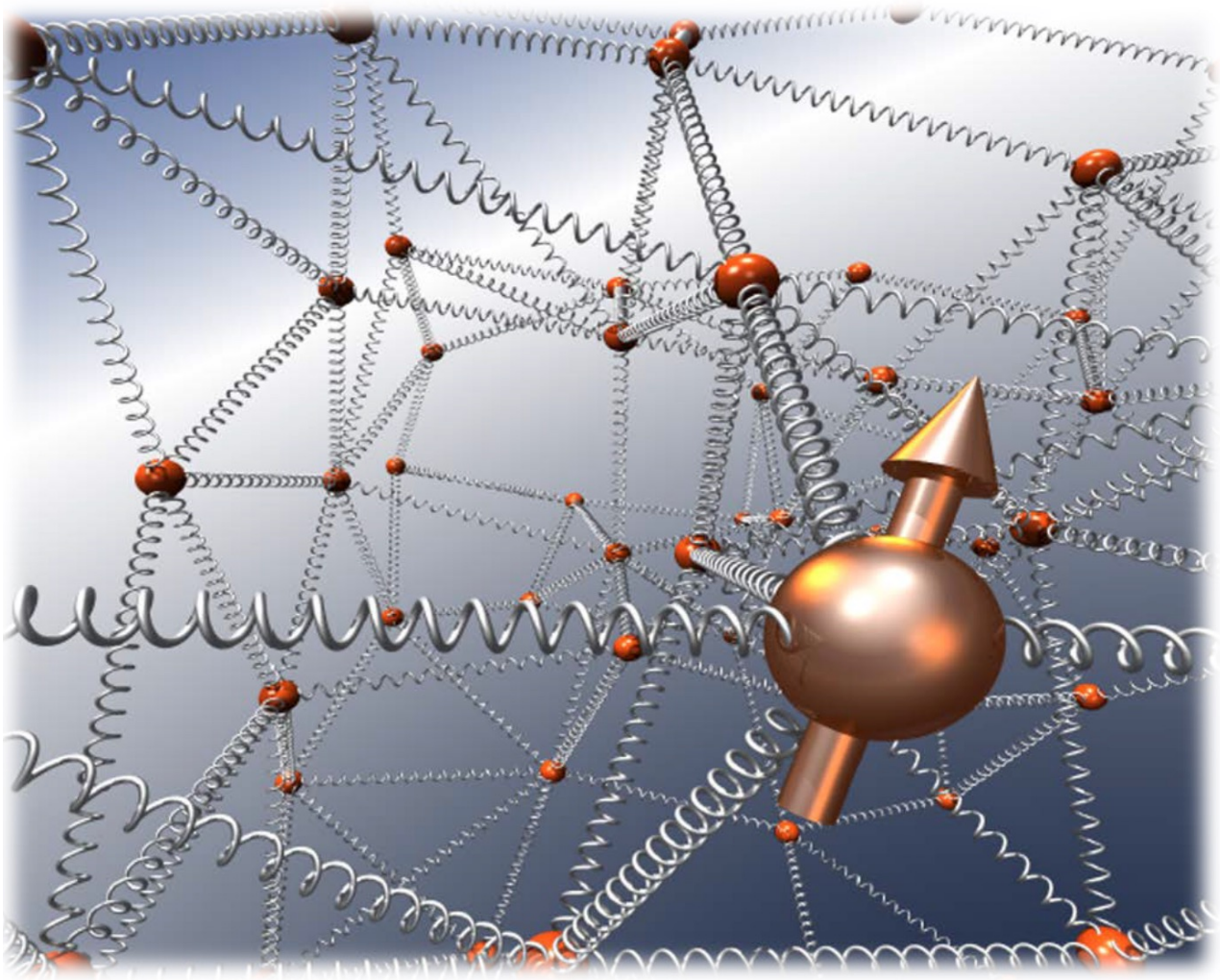


Devoret and Schoelkopf, Science 2013

- Exponential development explains „boundless optimism“
- Two-qubit operations and maintaining performance in systems not trivial. Problems: crosstalk, undesired coupling, variability, frequency crowding, …

Acknowledgement: H. Bluhm

Why is it so difficult?



"life" time of quantum states is limited

↓

decoherence

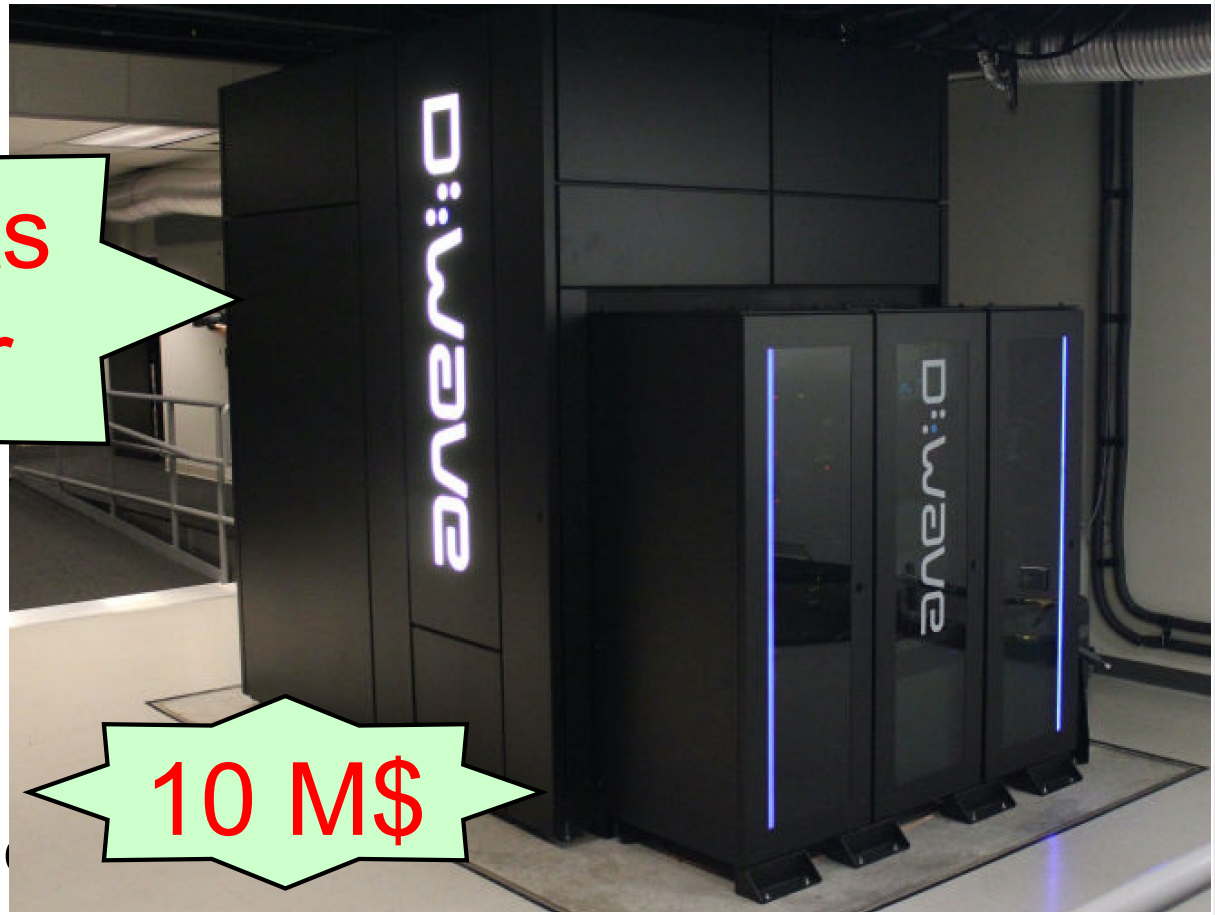
↓

unavoidable errors

D-Wave Systems

World's first quantum computing company (1999)

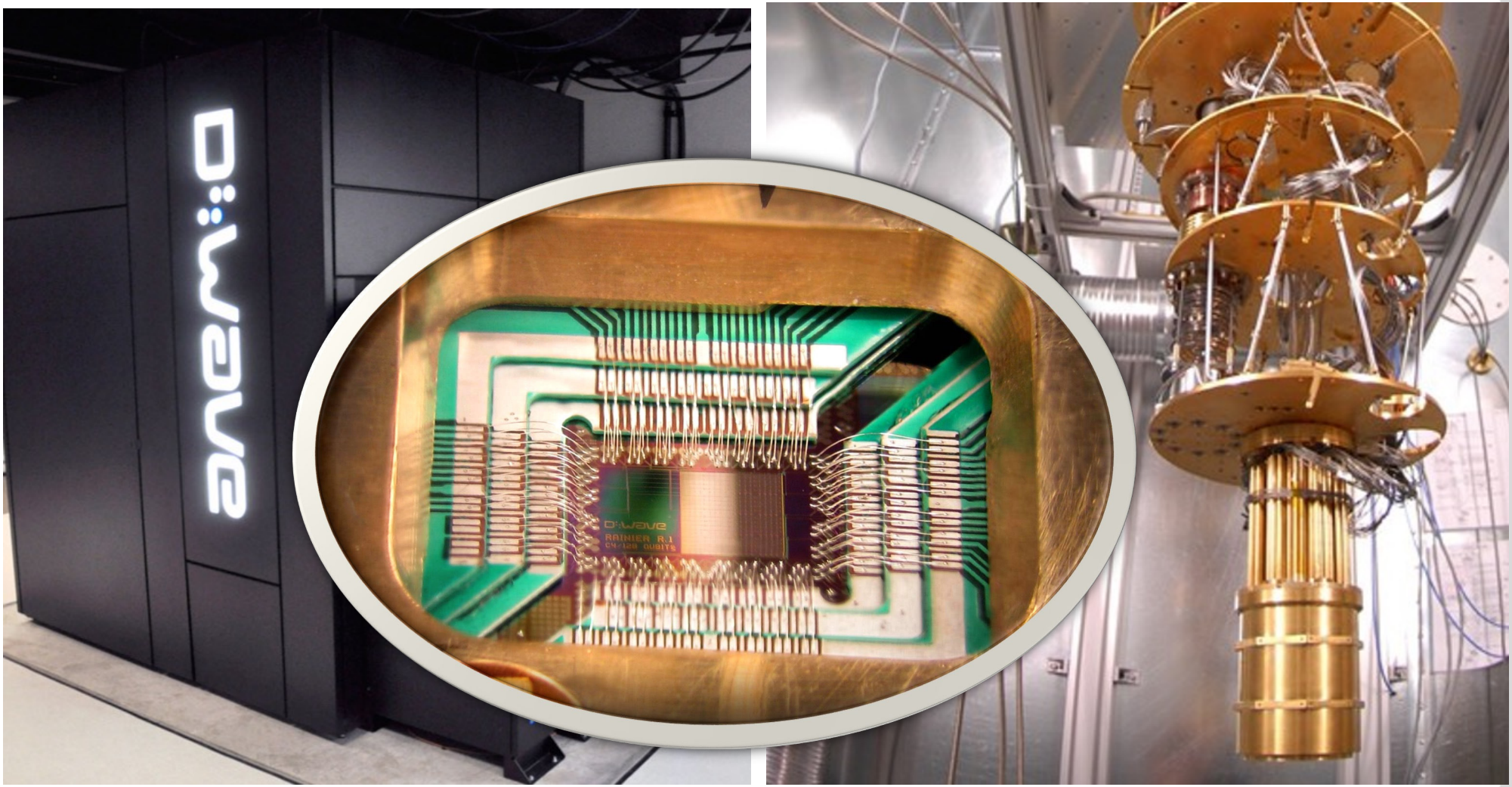
5000 qubits processor



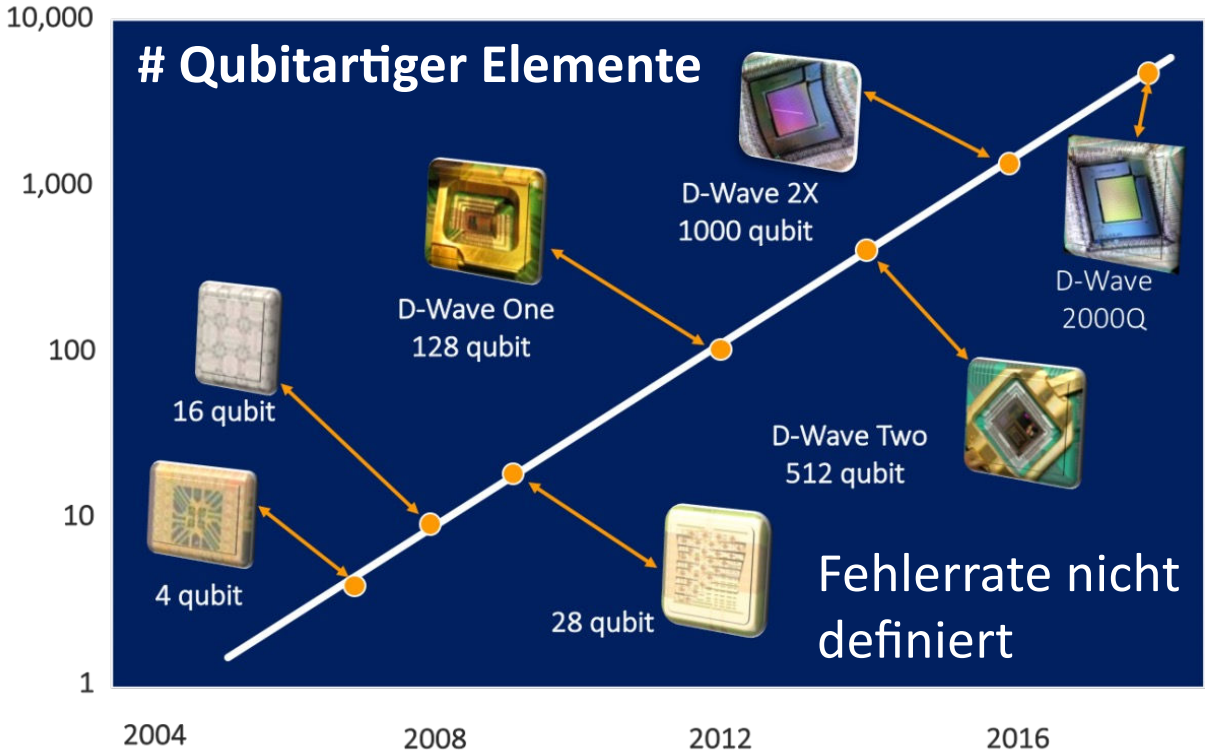
10 M$

First customers:
Lockheed Martin,
Google, NASA,
USC, USRA
Los Alamos National Lab

D-Wave Systems



“Quantum” Annealer - D-Wave



2019: > 5000 Qubits
Höhere Konnektivität

- Technisch beeindruckend
- Quanten-speedup unklar
- Anwendungsmöglichkeiten intensiv untersuch
- Mit derzeitiger Hardware noch nicht wirtschaftlich relevant, aber Vorteil gegenüber konventionellem HPC mit nächsten Versionen denkbar
- Als Modellsystem für Anwendungsentwicklung interessant
- Grundprinzipien ähnlich zu prominenten analogen Quantenalgorithmen

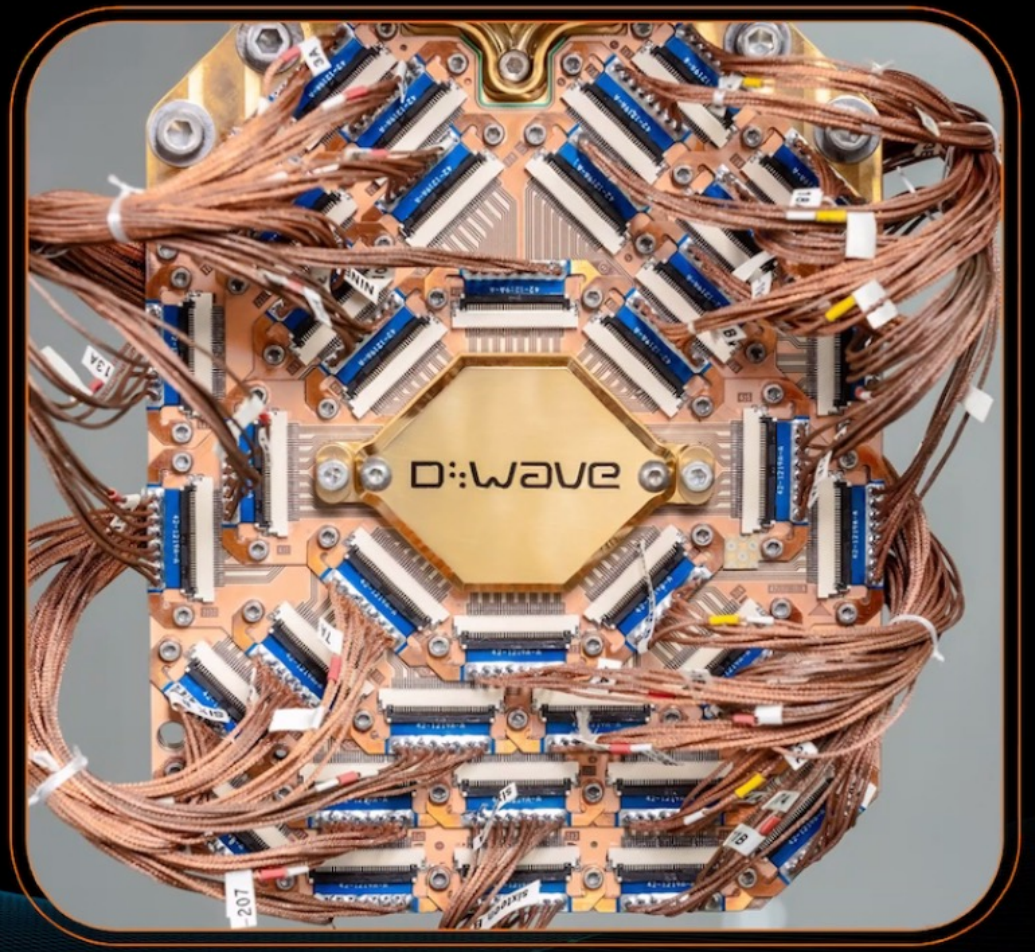
Acknowledgement: H. Bluhm

Beyond Classical: The Significance of This Achievement

D-Wave is the first and only in the world to demonstrate **quantum supremacy** on a useful, real-world magnetic materials simulation problem

These problems **cannot** be solved by classical computers

What took D-Wave's system minutes would take a classical supercomputer nearly **1 million years** and more than the world's annual electricity consumption to solve



D:Wave

Digital pioneering work: Volkswagen uses quantum computers

Wolfsburg, 2017-03-13

- Cooperation with D-Wave Systems

  - **Traffic flow optimization**

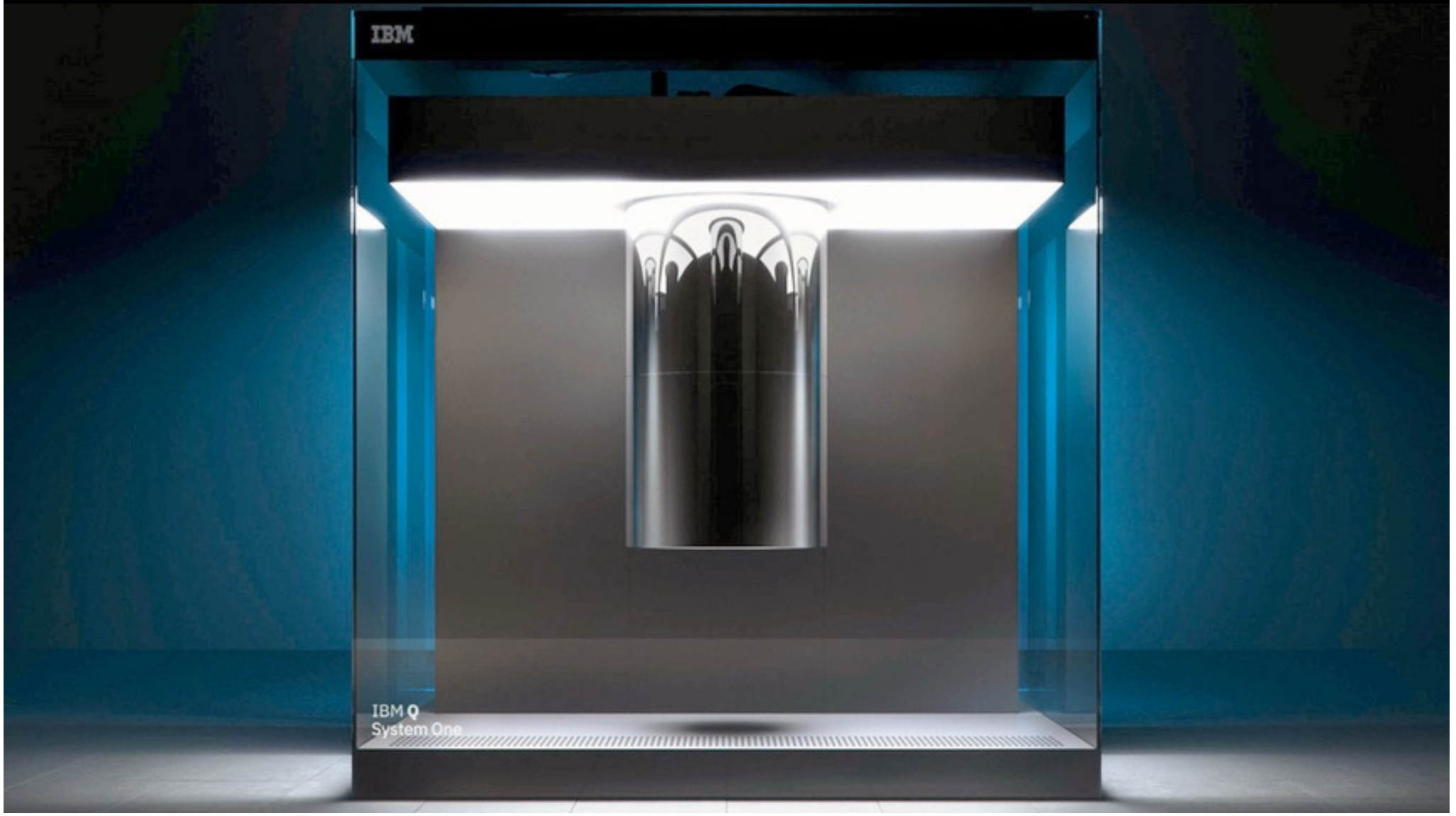
IBM Building First Universal Quantum Computers for Business and Science

Karlsruher Institut für Technologie

On March 6th 2017, IBM announced the company's initiative to build the first universal quantum computing system for commercial use in New York. The so-called "IBM Q" quantum system and service will be delivered via the IBM Cloud platform. While technologies that currently run on classical computers, such as Watson, can help to find patterns and insights buried in vast amounts of existing data, quantum computers will deliver solutions to important problems where patterns cannot be detected because data doesn't exist. In this case, possibilities are too enormous to ever be processed by classical computers.

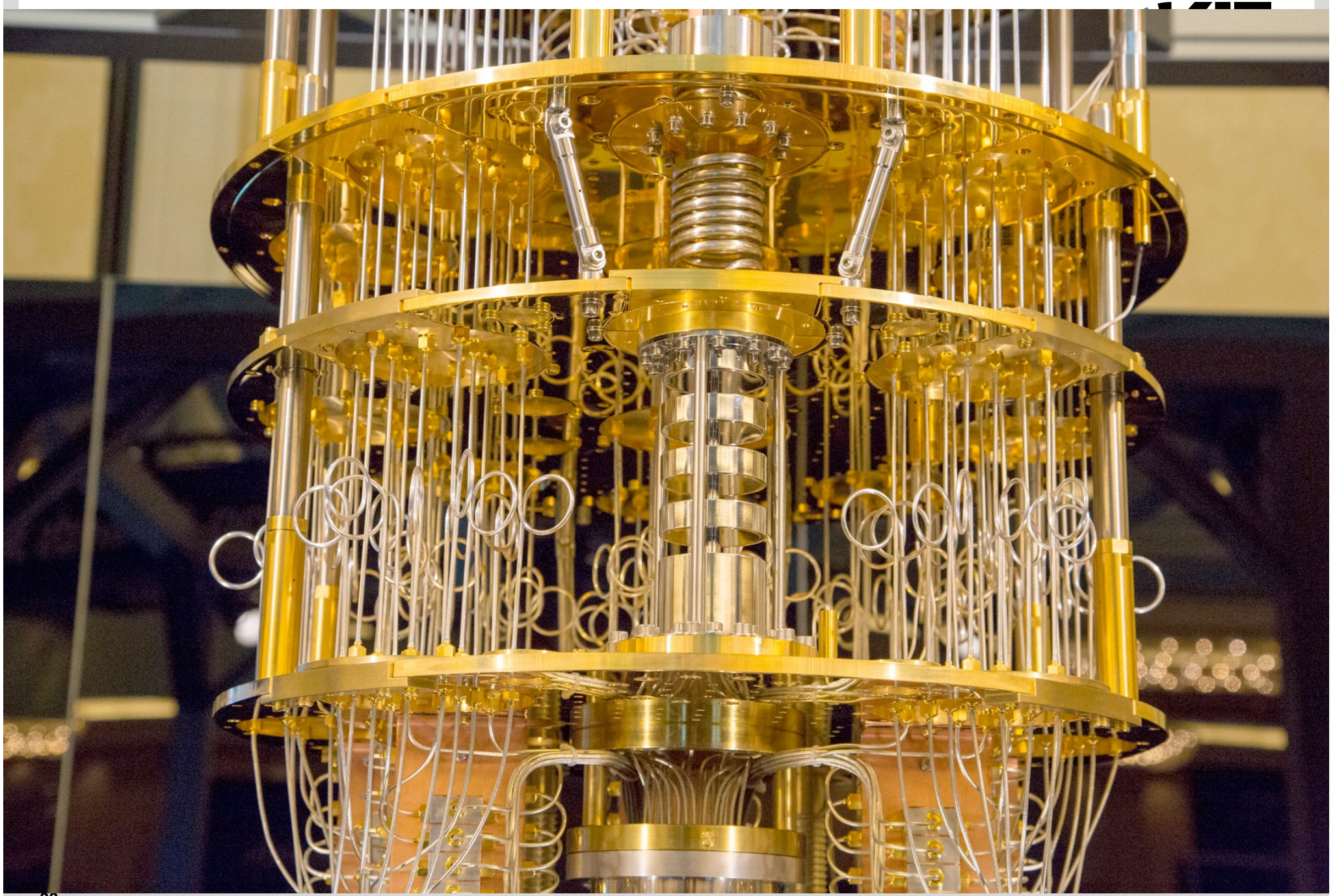
IBM Q System One

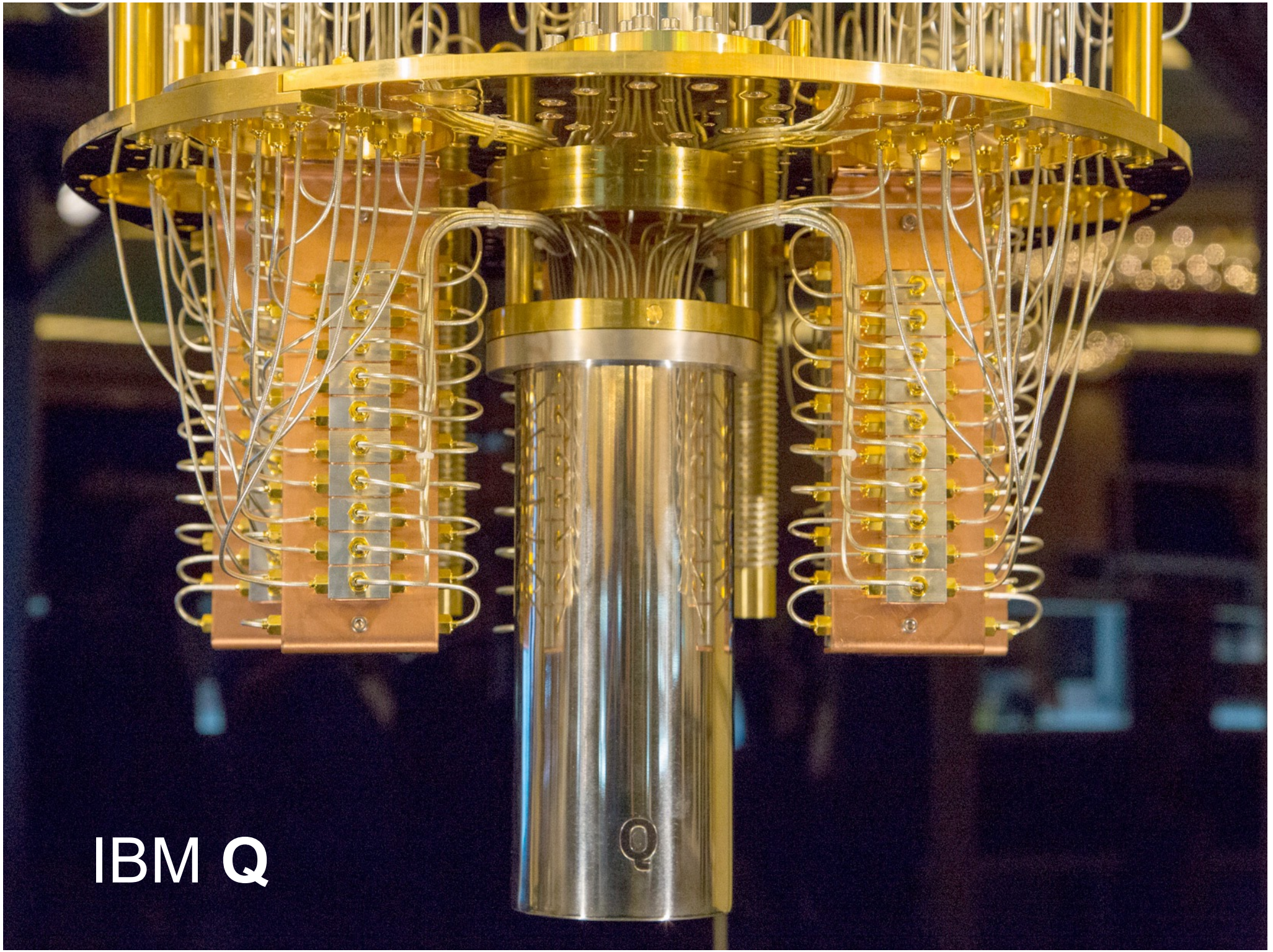
The system is the first universal approximate superconducting quantum computer to operate outside the research lab



Come and take a look at IBM's Quantum Computer

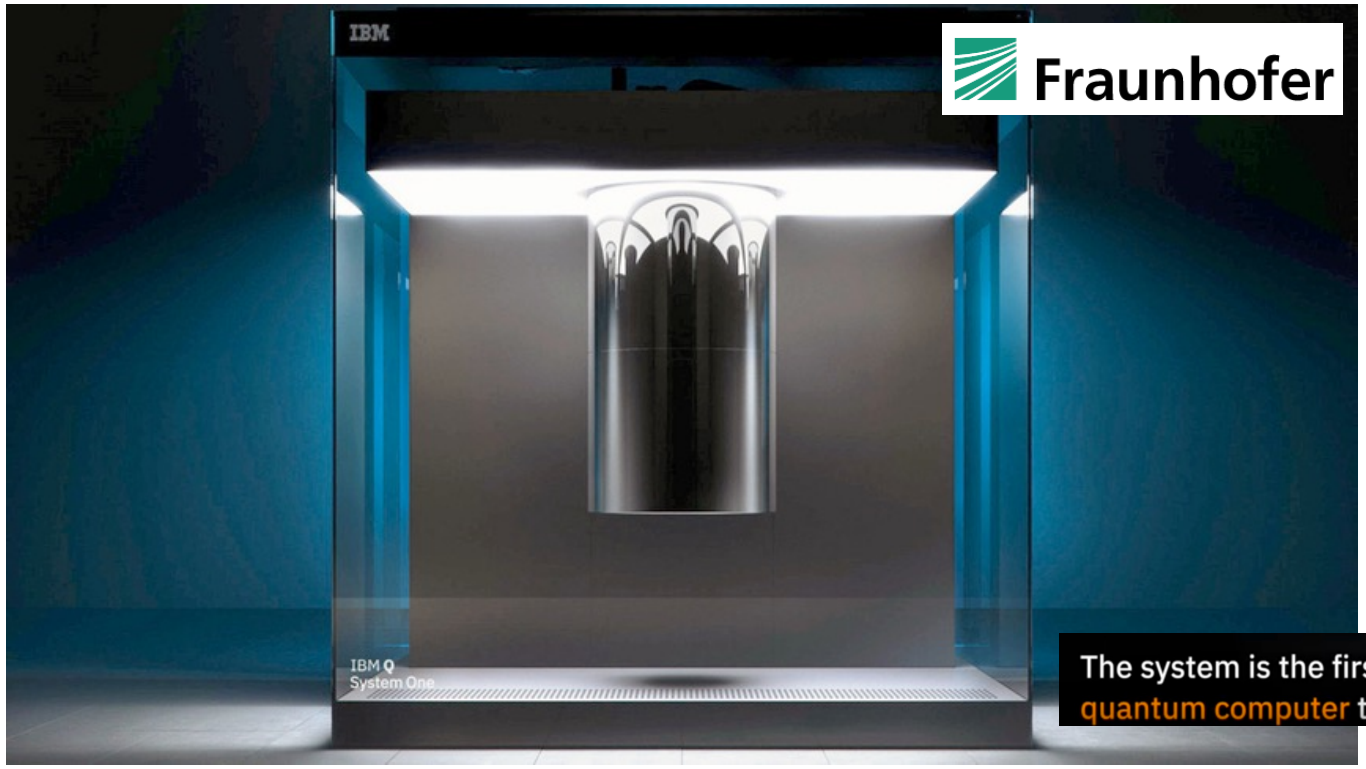

Q
IBM Q

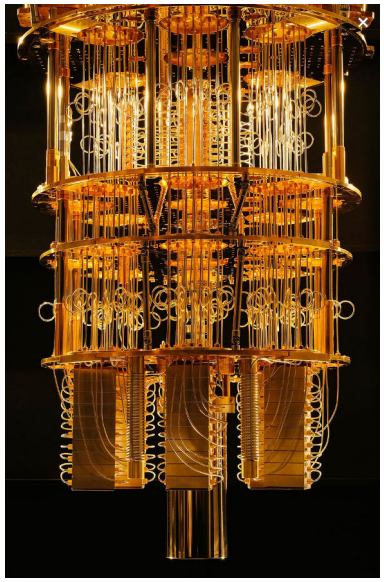



IBM Q

Einweihung der Forschungsplattform für Quantencomputer

Das erste IBM Quantum System One in Europa, in Ehningen bei Stuttgart (15. Juni 2021)





The system is the first universal approximate superconducting quantum computer to operate outside the research lab

Online QC systems - IBM

Name	Qubits	QV	Status	Total pending jobs	Processor type	Features
ibmq_casablanca	7	32	Online	377	Pigeon r1	
ibmq_bogota	5	32	Online	623	Canary r3	
ibmq_santiago	5	32	Online	57	Canary r3	-
ibmq_rome	5	32	Online	43	Canary r3	
ibmq_athens	5	32	Online	70	Canary r3	-
ibmq_16_melbourne	15	8	Online	9583	-	-
ibmq_5_yorktown	5	8	Online	4368	-	-
ibmq_armonk	1	-	Online	0	Emu r1	
ibmq_qasm_simulator	32	-	Online	1	-	-

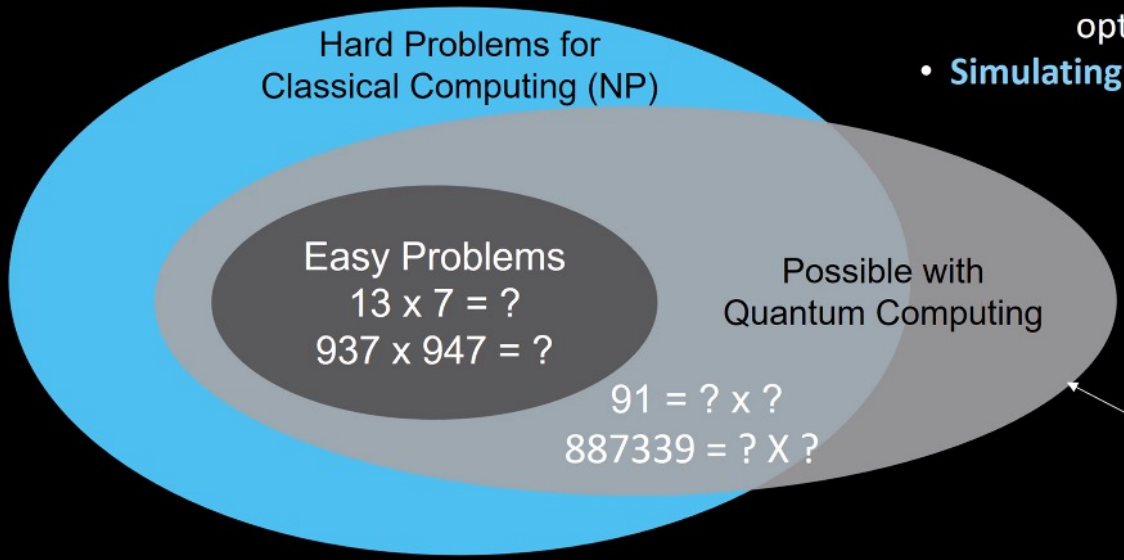
Quantum Computing as a path to solve intractable problems

Many problems in business and science are too complex for classical computing systems

"hard" / intractable problems:

(exponentially increasing resources with problem size)

- **Algebraic algorithms** (e.g. factoring, systems of equations) for machine learning, cryptography,…
- **Combinatorial optimization** (traveling salesman, optimizing business processes, risk analysis,…)
- **Simulating quantum mechanics** (chemistry, material science,…)



Material, Chemistry | Machine Learning | Optimization

Stefan Filipp, WMI, München

The Quantum Advantage – Storing quantum states

How much memory is needed to store a quantum state?

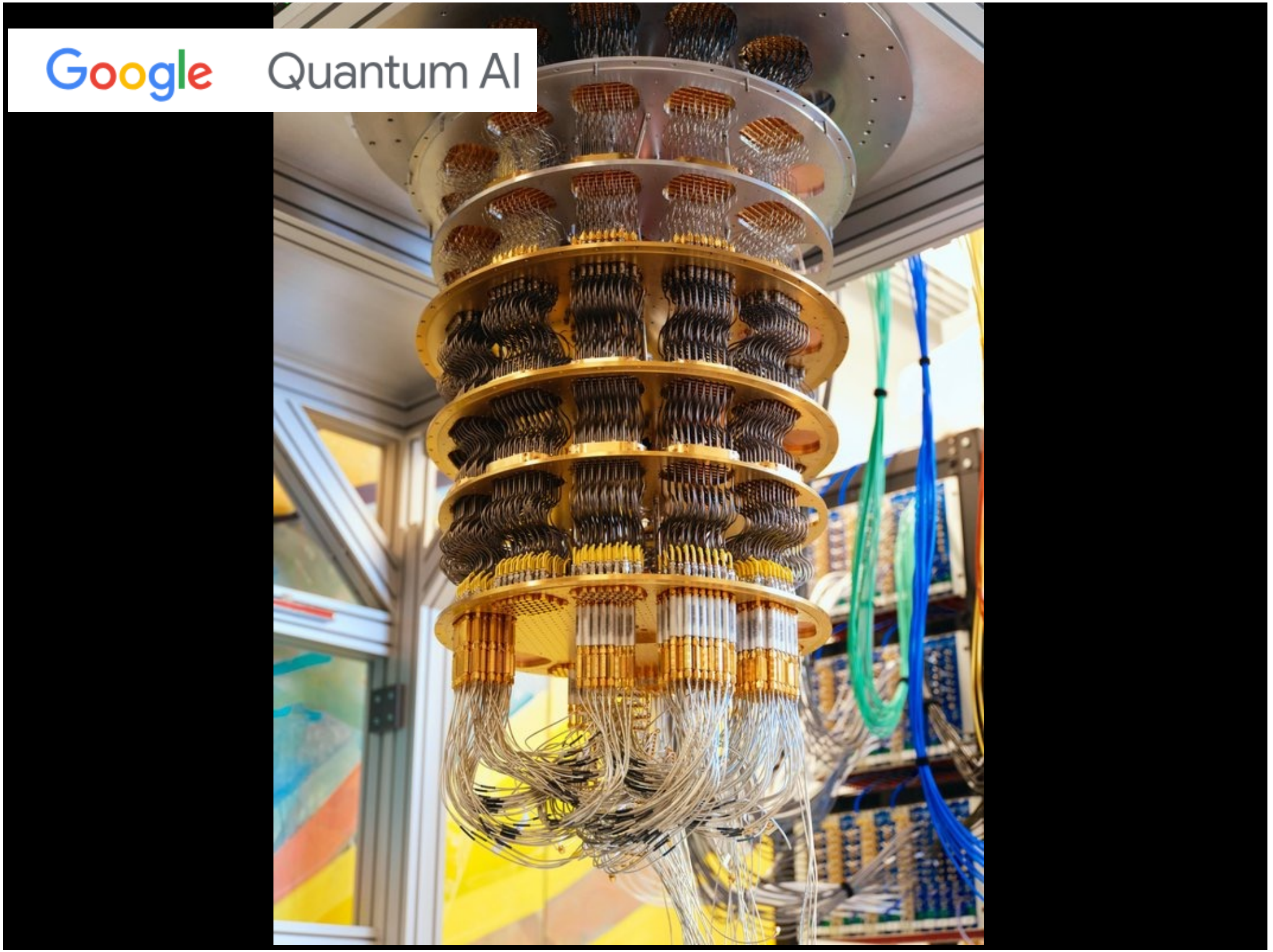
# qubits/	quantum state	coefficients	# bytes
1	$a\|0\rangle + b\|1\rangle$	$2^1 = 2$	16 Bytes
2	$a\|00\rangle + b\|01\rangle + c\|10\rangle + d\|11\rangle$	$2^2 = 4$	32 Bytes
8		$2^8 = 256$	2kB
16	…	$2^{16} = 65'536$	512 kB
32	…	~4 billion	32 GB
64	…	~ information in internet	128 EB (134 million GB)
256	…	~ # of atoms in universe	…

Development Roadmap | Executed by IBM ✓ On target

IBM **Quantum**

	2019 ✓	2020 ✓	2021 ✓	2022	2023	2024	2025	Beyond 2026
	Run quantum circuits on the IBM cloud	Demonstrate and prototype quantum algorithms and applications	Run quantum programs 100x faster with Qiskit Runtime	Bring dynamic circuits to Qiskit Runtime to unlock more computations	Enhancing applications with elastic computing and parallelization of Qiskit Runtime	Improve accuracy of Qiskit Runtime with scalable error mitigation	Scale quantum applications with circuit knitting toolbox controlling Qiskit Runtime	Increase accuracy and speed of quantum workflows with integration of error correction into Qiskit Runtime
Model Developers					Prototype quantum software applications →		Quantum software applications Machine learning | Natural science | Optimization	
Algorithm Developers		Quantum algorithm and application modules ✓ Machine learning | Natural science | Optimization			Quantum Serverless		Intelligent orchestration Circuit Knitting Toolbox Circuit libraries	
Kernel Developers	Circuits ✓	Qiskit R… ✓		Dyn…ic circuits	Threaded primitives	Error suppression a…d mitigation		Error correction
System Modularity	Falcon ✓ 27 qubits	Hummingbird ✓ 65 qubits	Eagle ✓ 127 qu…s	Osp…ey 433 …ubits	Condor 1,121 qubits Heron 133 qubits x p	Flamingo 1,386+ qubits Crossbill 408 qubits	Kookaburra 4,158+ qubits	Scaling to 10K-100K qubits with classical and quantum communication

https://research.ibm.com/blog/ibm-quantum-roadmap-2025

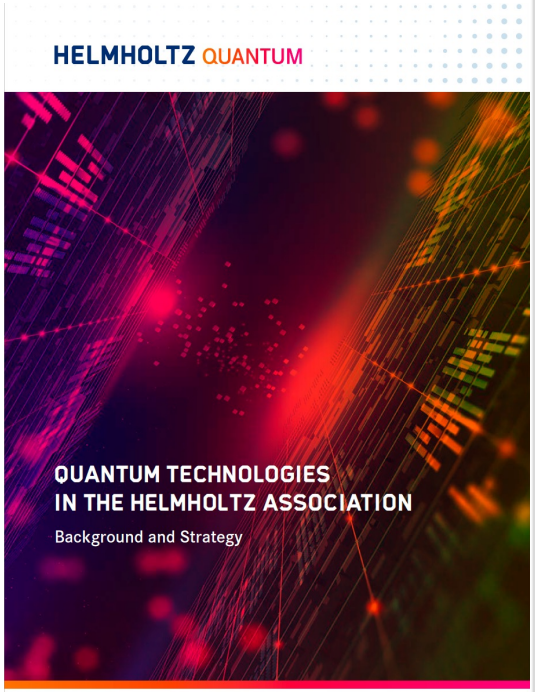

Google
Quantum AI


https://www.helmholtz.de/forschung/quantentechnologie/computing/
RESEARCHING THE SECOND QUANTUM REVOLUTION
Quantum technologies in the Helmholtz Association

Umsetzung der PoF IV am KIT

P2 NACIP – Quantum

- Strong participation to the Helmholtz Roadmap for Quantum Technologies
- Intensive response to the many BMBF quantum calls (next slide)
- NFDI project DAPHNE
- Approval of the new GradUP “KIT Graduate School on Quantum Matter” (Coord. Prof. M. Garst)
- New Nanomat Focus Group (exchange platform with industry) „Quantum Materials and Technologies“



https://www.helmholtz.de/forschung/quantentechnologie/computing/

Karlsruher Institut für Technologie

Bundesministerium für Bildung und Forschung

quanten technologien

BMBF Call	Project	Partners	Budget (Total)	Budget (KIT)	Status
Schluesselkomponenten für QT	PtQube (2020-2023)	KIT, TransMIT GmbH Entropy GmbH	1.4M€	0.9k€	Started
Quantenprozessoren und Technologien für QC	GeQCOS (2021-2025)	WMI, IAF, Infineon, KIT, FAU, FZJ	16.1M€	3.2M€	Started
Selbstbestimmt in der digitalen Welt	QR.X (2021-2024)	KIT + ca. 30 weitere deutsche Partner	35M€	1.2M€	Started (1.8.21)
Quantum Computing Demonstrators	Spining	KIT + ca. 30 German Partners	36.5M€	1M€	Expected (10-20% cut) 1.1.22
	Qsolid	KIT + ca. 40 German Partners	~70M€	5.7 M€	Final decision exp. 12/21
Grand Challenge der Quantenkommunikation	NEQSIS	PIs: Hunger + 2 German Partners	1.05M€	350 k€	Begin exp. 1.11.21
Enabling Technologies für die QT	qBriqs	KIT, IAF, PTB + Rosenberger, Stahl	1.9 M€	450 k€	Begin exp. 1.11.21
Nachwuchswettbewerb Quantum Futur Runde 2	DiamondNanoNMR	KIT	3.9 M€	3.9 M€	Step 2 in preparation

P2 NACIP - Quantum

- Pending recruitments:
  - T1/T2: New UB professorships get affiliation with IQMT and positions
    - W3 Quantum Computing (Fiebiger Professorship)
    - W3 Quantum Optics (NF Kalt)
    - W3 Quantum Circuits (professorship in Stuttgart)
    - W1 TT-Prof. for Quantum control of spins on surfaces

- YigPrepPro:
- 2021 Dr. Mehdi Frachet (T1)

  Holistic investigation of quantum materials under uniaxial strain
- 2021 Dr. Eider Berganza (T1)

  Artificial Spin Ice systems

Fraunhofer IAF

https://www.iaf.fraunhofer.de/de/netzwerker/KQC.html

Karlsruher Institut für Technologie

Baden-Württemberg
MINISTERIUM FÜR WISSENSCHAFT, FORSCHUNG UND K

Karlsruher Institut für Technologie

Ministerium für Wirtschaft, Arbeit und Tourismus Baden-Württemberg

Suchbegriff eingeben

Gebärdensprache Leichte Sprache

Ministerium Wirtschaft Innovation Arbeit Tourismus Service

Beteiligungsportal

Sie sind hier: Startseite > Service > Förderprogramme und Aufrufe > *Verbundforschungsprojekte im Rahmen des Kompetenzzentrums Quantencomputing Baden-Württemberg*

Teilen

Drucken

Als PDF speichern

FÖRDERPROGRAMM

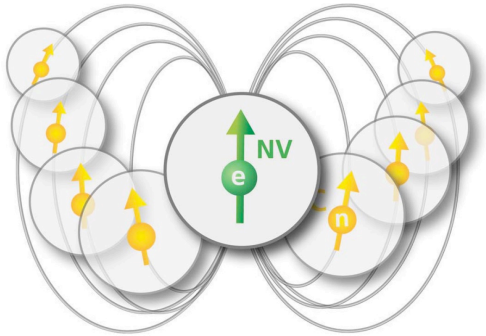
Text vorlesen

Verbundforschungsprojekte im Rahmen des Kompetenzzentrums Quantencomputing Baden-Württemberg

https://wm.baden-wuerttemberg.de/de/service/foerderprogramme-und-aufrufe/liste-foerderprogramme/verbundforschungsprojekte-im-rahmen-des-kompetenzzentrums-quantencomputing-baden-wuerttemberg/

QC-4-BW

Entwicklung und Benchmarking eines Diamant-basierten, spintronischen Quantenregisters für einen aufskalierbaren Quantenprozessor



Fraunhofer IAF — FHI für Angewandte Festkörperphysik

Fraunhofer ICT — FHI für Chemische Technologie

Universität Stuttgart

Universität Ulm

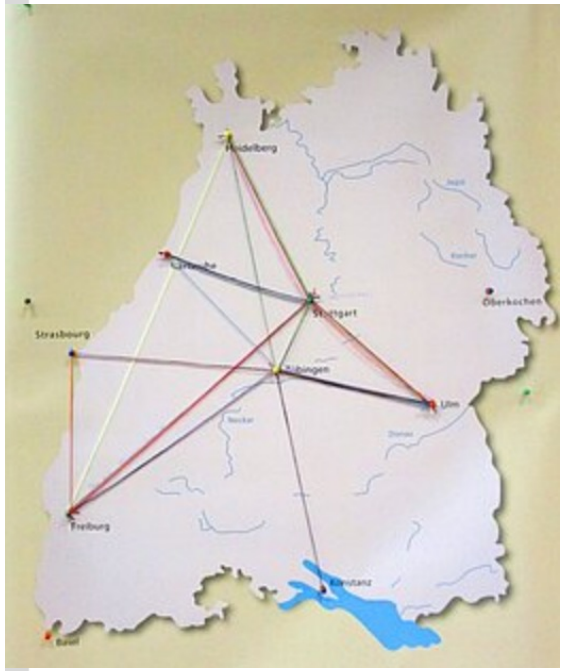
Karlsruher Institut für Technologie

Universität Konstanz

Assoziierte Partner: BASF, Merck, IBM, HQS, Bosch, Q,Ant, SVA, Evatec, attocube, Cynora, Diehl, Quantum Brilliance

Competence Network Quantum Technology in BW | QTBW.net

https://iqst.org/initiatives/qtbwnet.html



Partner Institution	Contact	Institute
University of Konstanz	Guido Burkard	Condensed Matter Theory and Quantum Information
University of Freiburg	Tobias Schaetz	Experimental Atomic, Molecular, and Optical Physics
University of Tuebingen	Daniel Braun	Theoretical Quantum Optics
University of Karlsruhe	Wolfgang Wernsdorfer	Experimental Solid State Physics
University of Stuttgart	Sebastian Loth	Institute for Functional Matter and Quantum Technologies | co-ordinator QTBW.net
University of Heidelberg	Philipp Preiss	Institute for Physics and Center for Quantum Dynamics
Ulm University	Joachim Ankerhold	Institute for Complex Quantum Systems | co-ordinator QTBW.net
Max Planck Institute for Solid State Research, Stuttgart	Christian Ast	Nanoscale Science
Fraunhofer Institute for Applied Solid State Physics (IAF), Freiburg	Oliver Ambacher	

Baden-Württemberg Stiftung
WIR STIFTEN ZUKUNFT

Baden-Württemberg
MINISTERIUM FÜR WISSENSCHAFT, FORSCHUNG UND KUNST

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QUSTEC COFUND

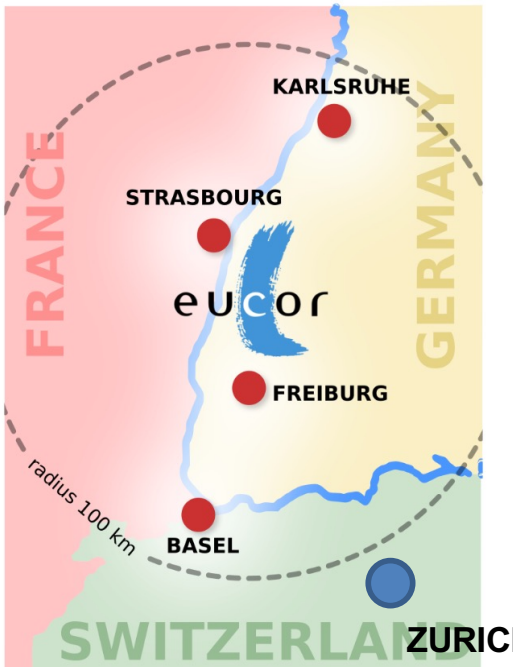
A first-of-its-kind, international PhD program in quantum science and technology (QST)

for **39 doctoral researchers** across 3 countries 2020-2024

→ Strong QST Player in the Upper-Rhine Region

→ Educating the Quantum Engineer at

- **University of Basel**
- **University of Freiburg**
- **Karlsruhe Institute of Technology**
- **University of Strasbourg**
- **Industry: IBM Zurich**



First H2020 project to be approved to a European Grouping of Territorial Cooperation (EUCOR)

- ✓ Theory / experiments
- ✓ Solid state / Quantum optics
- ✓ Quantum dynamics
- ✓ Quantum technologies
- ✓ Quantum computing

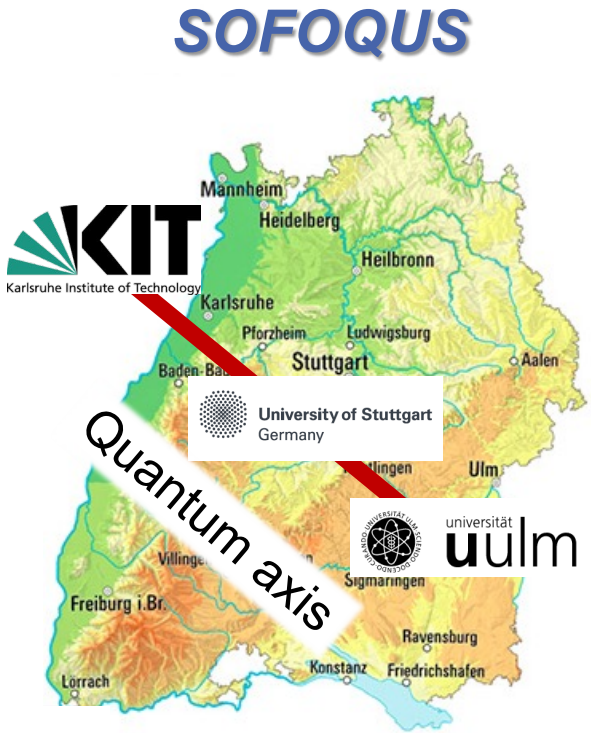
DFG Cluster of Excellence proposal: Self-organized functional quantum systems

Joint effort with Stuttgart and Ulm

- large number of joint QT projects ongoing
- previous interaction on SFB
- strong & complementary thematic fit

Central idea: Bottom up, self-organized quantum systems for quantum technologies

- **Area 1**: Self-organized quantum materials (molecules, color centers, ultra-cold atoms)
- **Area 2**: Engineered quantum properties (novel functionalities with integration in devices)
- **Area 3**: Application of emerging quantum functionalities (building blocks for quantum networks, distributed computing, sensing, simulation)



Looking for HiWis and more

Qinu

Enabling Cryo-Quantum Technologies

- Founded in early 2021 in Karlsruhe

Task:

"[…] development, production, worldwide distribution, and consulting of solutions in the field of cryogenics and quantum technologies."

https://qinu.de/

Vision:

„Paving the way for everday quantum technologies"

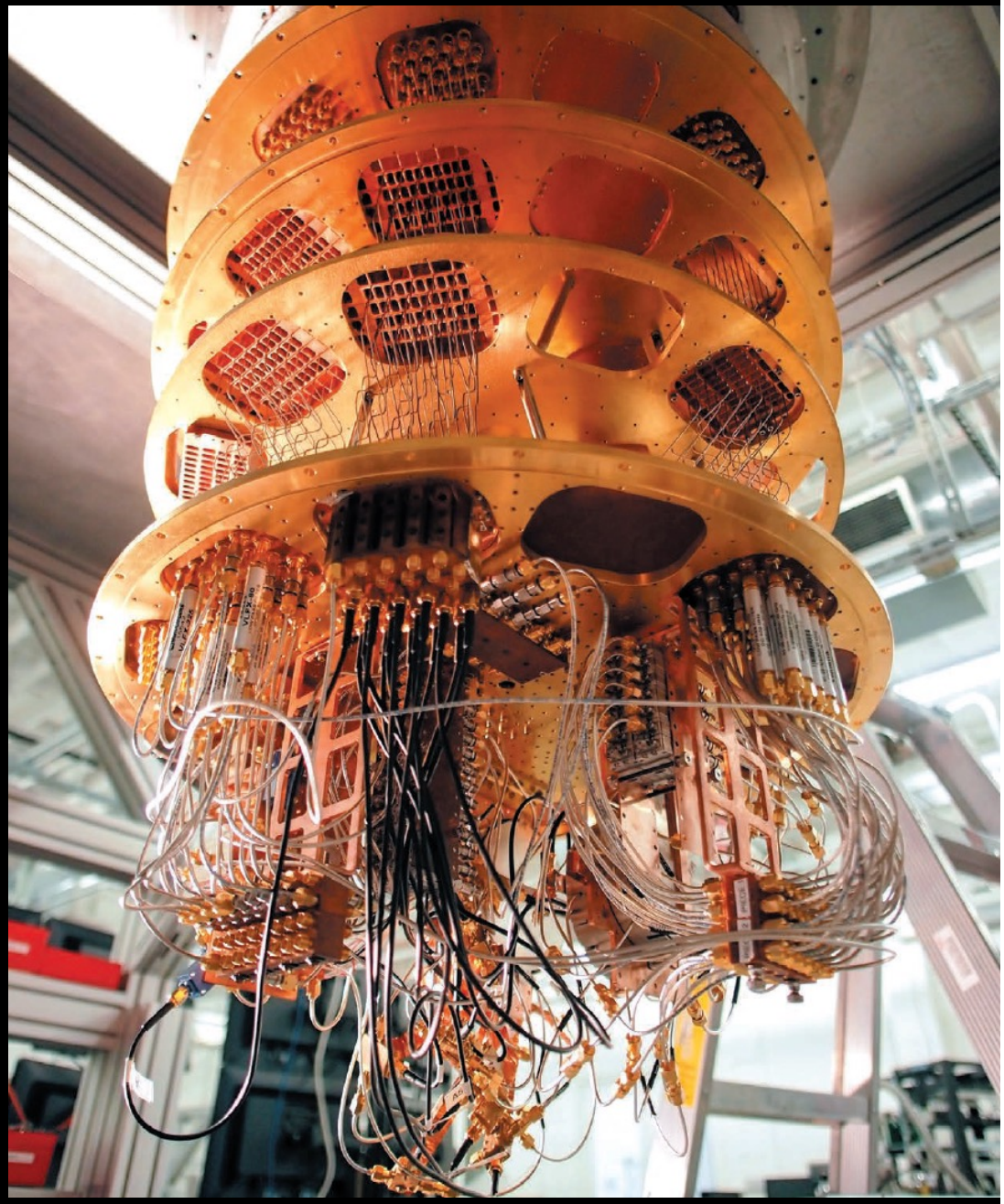
Google Quantum Artificial Intelligence Laboratory

May 26, 2017

Google

M. Mohseni, P. Read,
H. Neven, S. Boixo,
V. Denchev, R. Babbush,
A. Fowler, V. Smelyanskiy,
J. Martinis

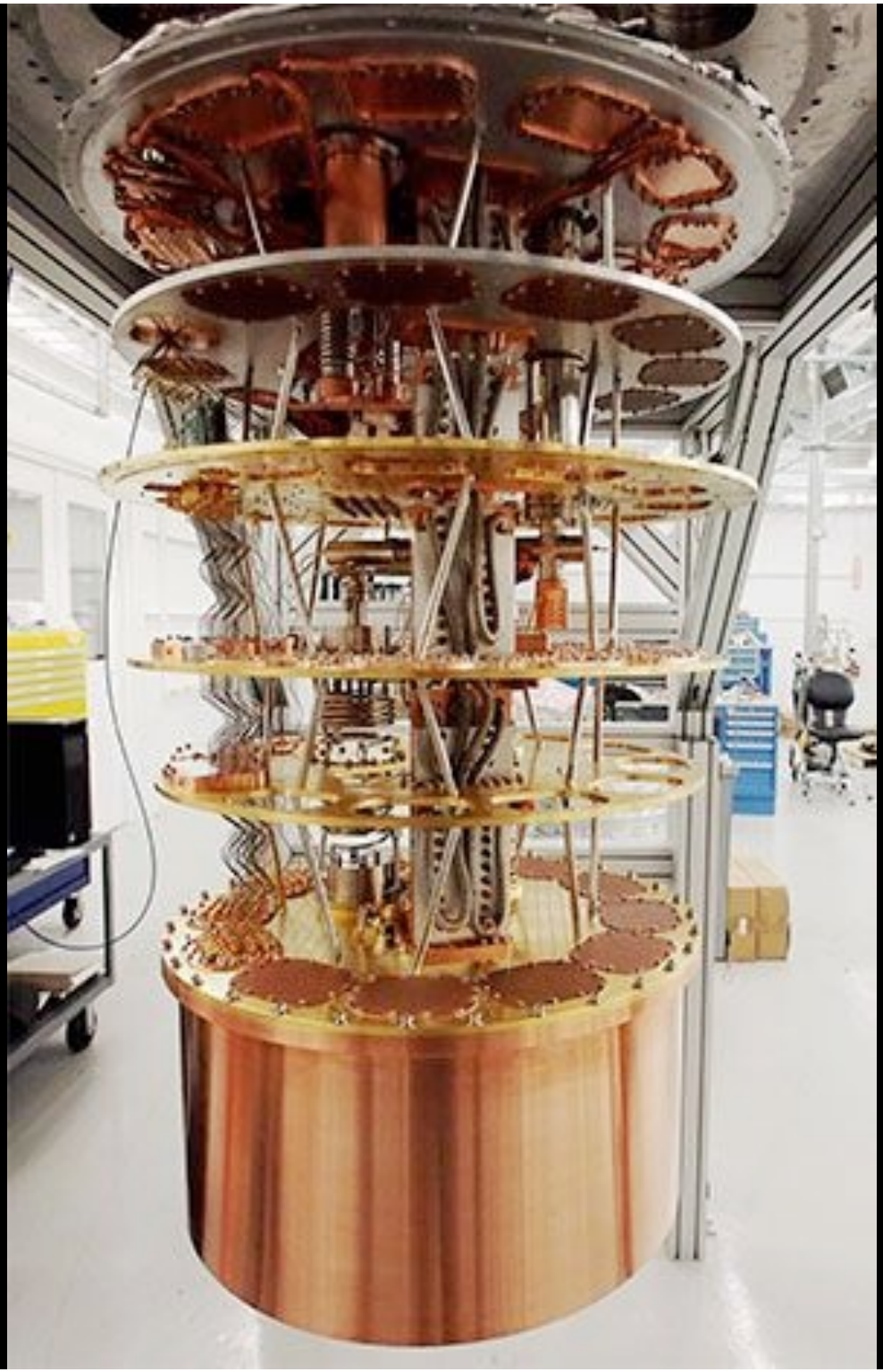
Quantum supremacy



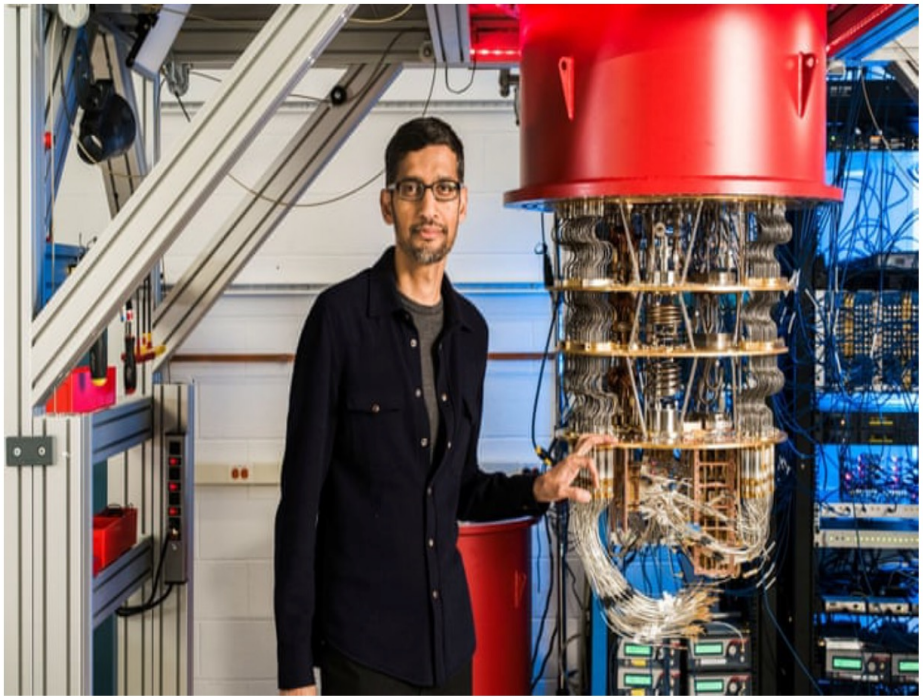
Google

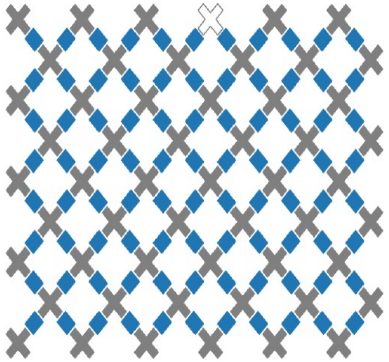
12 Apr 2018

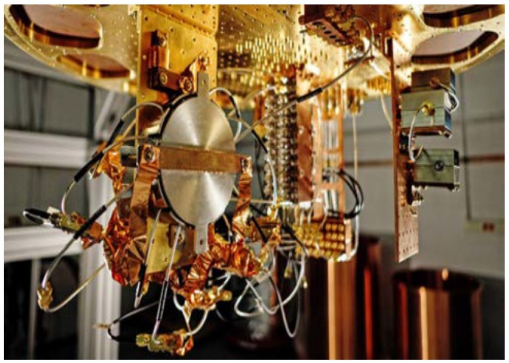
Things are getting real for researchers in the UC Santa Barbara John Martinis/Google group. They are making good on their intentions to claim **supremacy** in a tight global race to build the first quantum machine to outperform the world's best classical supercomputers.



Google: Demonstration of Quantum Supremacy







- October 2019: *Nature* article
  - 54-qubit Sycamore chip
  - 53 qubits working
  - claim:

    Sycamore supercomputer

    200 seconds = 10,000 years
  - IBM argues:

    Sycamore supercomputer

    200 seconds = 2.5 days
- Application
  - quantum random number generation