FAPESP WEEK GERMANY
March 25-26th, 2025

FAPESP SÃO PAULO RESEARCH FOUNDATION

DFG Deutsche Forschungsgemeinschaft

Walther-Meißner-Institut
DER BAYERISCHEN AKADEMIE DER WISSENSCHAFTEN

State-of-the-Art Superconducting Quantum Hardware

FAPESP Week Germany 25.03.2025-26.03.2025
Berlin
26.03.2025

Christian Schneider

Technical University of Munich, TUM School of Natural Sciences, Physics Department
Walther-Meißner-Institut, Bayerische Akademie der Wissenschaften

Christian.Schneider@wmi.badw.de

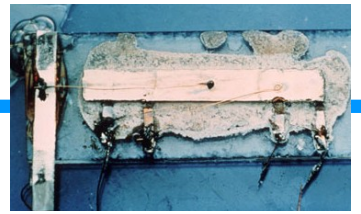
BAdW BAYERISCHE AKADEMIE DER WISSENSCHAFTEN

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The Future of Computing

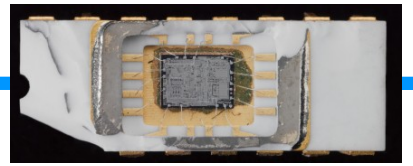
FAPESP SÃO PAULO RESEARCH FOUNDATION
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1958



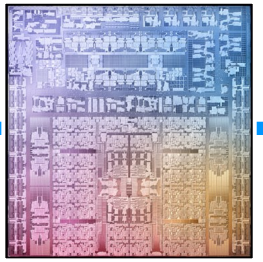
First integrated circuit Size 1 cm²
2 Transistors

1971



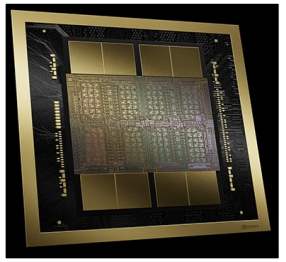
Moore's Law is Born
Intel 4004
2,300 transistors

2023

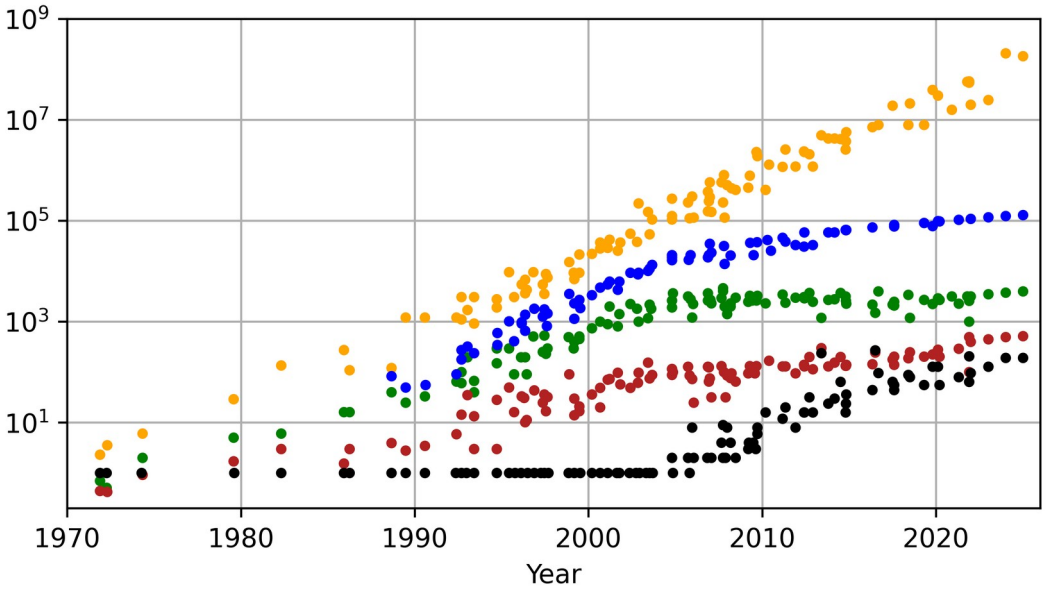


Apple M3 Ultra
4 nm technology, 32 cores
184 Billion Transistors

2024



NVIDIA Blackwell B100
4 nm technology
208 Billion Transistors



Transistors (thousands)

Single-Thread Performance (SpecINT)

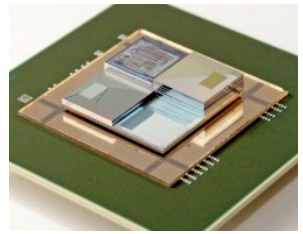
Frequency (MHz)

Typical Power (Watts)

Number of Logical Cores

Original data up to year 2010 collected and plotted by M. Horrowitz, F. Labonte, O. Shacham, K. Olukotun, L. Hammond, C. Batten
Data from 2010 to 2020 by K. Rupp: github.com/karlrupp/microprocessor-trend-data
Data from 2020 to 2025 collected by OpenAI ChatGPT

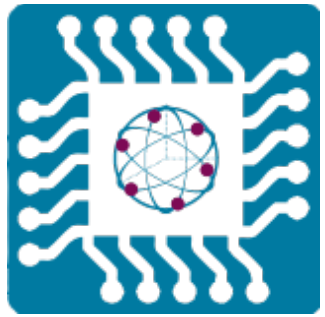
next generation systems ('More than Moore')



neuromorphic (cognitive)

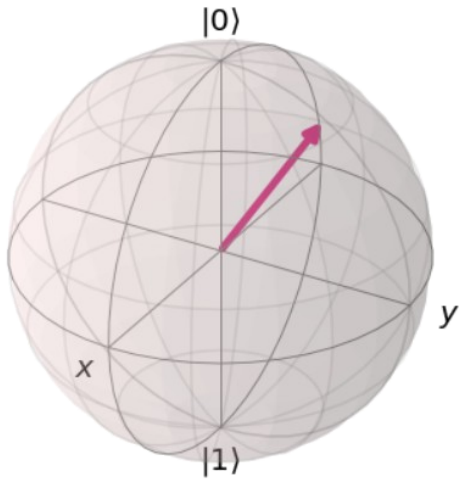


quantum computing



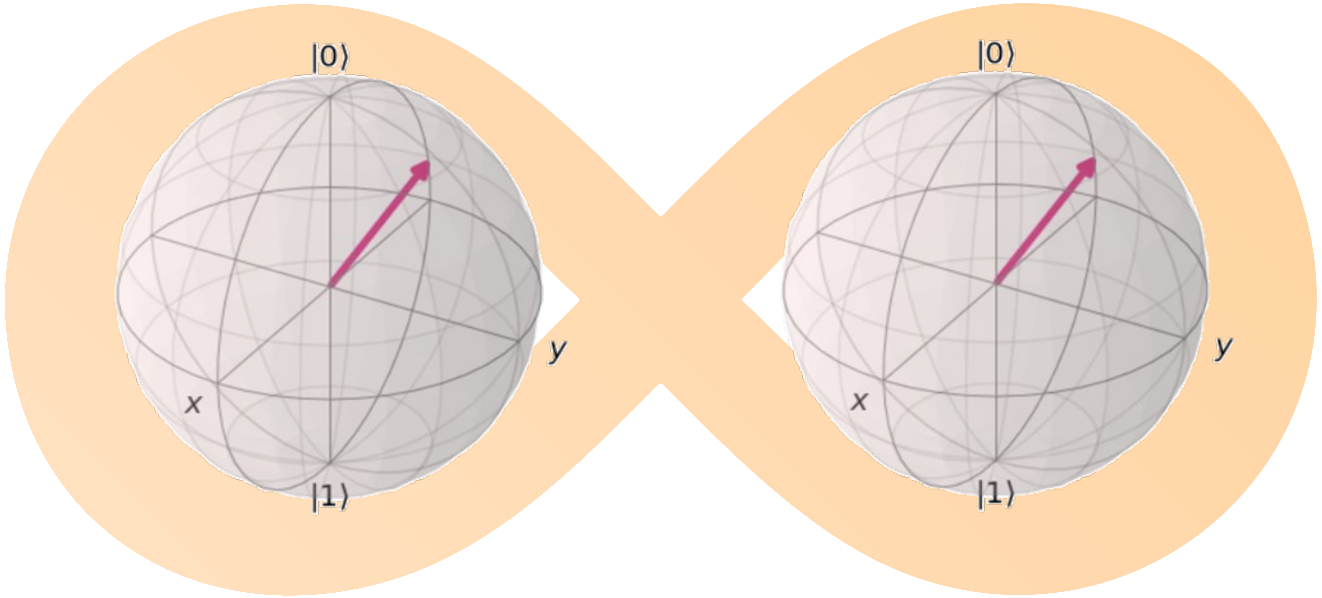
Quantum advantage

Superposition $a|0\rangle+b\vee1\rangle a,b\in\mathbb{C}$



Entanglement $a|00\rangle+b|01\rangle+c|10\rangle+d|11\rangle$

$a,b,c,d\in\mathbb{C}$



3 Qubits: coefficients,

N Qubits: coefficients

This leads to an **exponentially** growing available state space!

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Applications

1. Quantum Simulations

Use: Simulation of quantum systems (e.g. molecules, proteins, materials, high-Tc superconductors)
Advantage: Simulate quantum interactions avoiding exponential overheads on classical computers

2. Cryptography

Use: Breaking classical encryption (e.g. RSA) and enabling secure communication(Quantum Key Distribution, QKD)
Advantage: Shor's algorithm enables exponential speedup for integer factorization and discrete logarithms.

3. Optimization Problems

Use: Solving combinatorial problems (e.g. portfolio management, logistics, scheduling)
Advantage: Minimize hard optimization landscapes exploiting the high dimensionality of entangled quantum systems

4. Machine learning and linear equation solving

Use: Improve learning, solving sparse linear equations
Advantage: Potential polynomial or exponential speedups in specific subroutines (subject to data access and noise constraints

Challenges

A. **Algorithmic Limitations:** Only a handful of algorithms known with speed-up compared to classical algorithms
(Shor, Harrow–Hassidim–Lloyd, Grover, …)
B. **Hardware Requirements**: Realization depends on fault-tolerant quantum computers with many high-fidelity qubits and low-error operations.

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Quantum Bits

Classical Bits



Relais



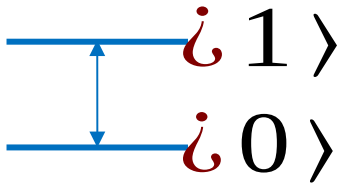
Vacuum Tube



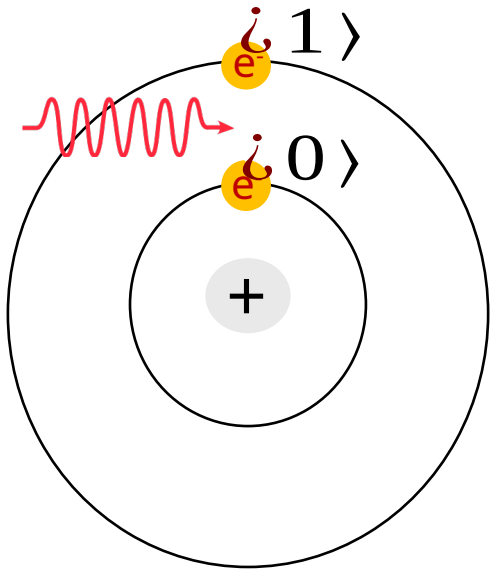
Transistor

Quantum Bits

Two-Level Systems



Example:
Atom orbitals with different energetic levels

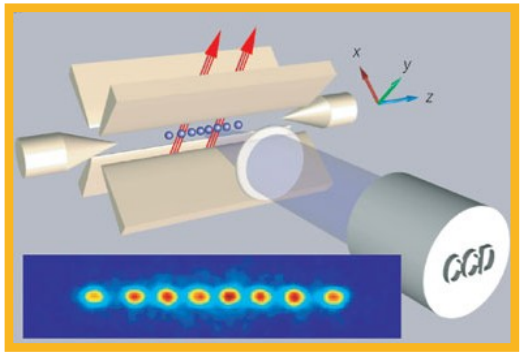


Neutral Atoms



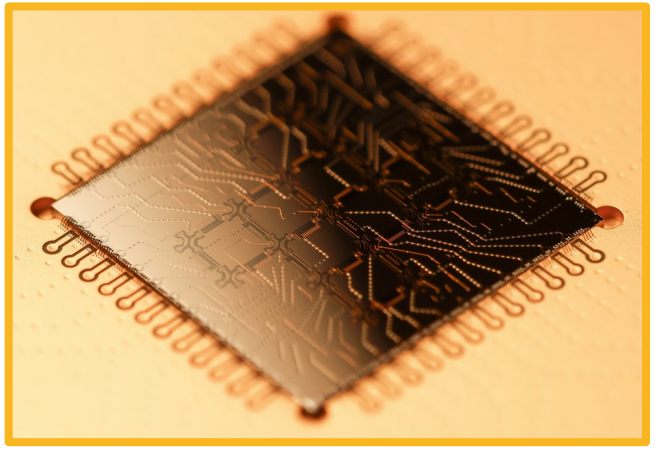
© JQI

Ion Traps



© Blatt & Wineland

Superconducting Circuits

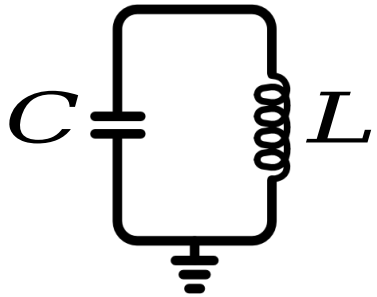


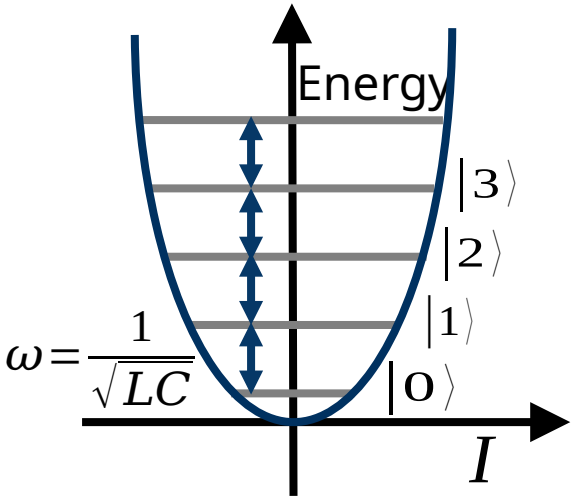
Walther-Meissner-Insitute

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Superconducting Quantum Circuits

LC Circuit/Resonator

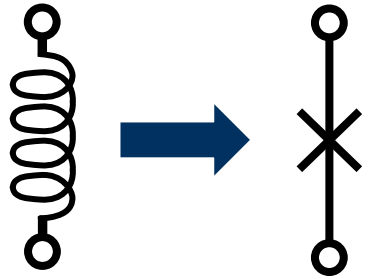


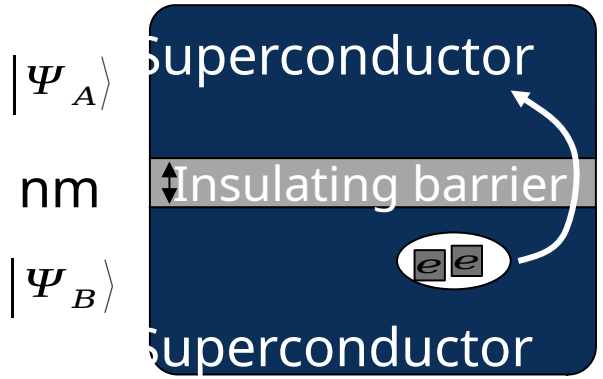


$$\hat{H} = \frac{\hat{Q}^2}{2C} + \frac{\hat{\Phi}^2}{2L}$$

Josephson Junction

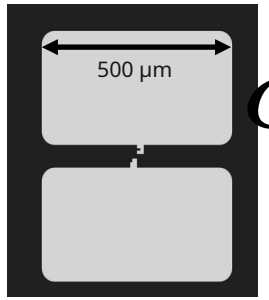
$$V_L = L\dot{I} \qquad V_{JJ} = L_J(I)\dot{I}$$

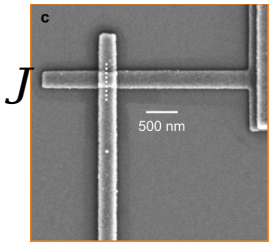




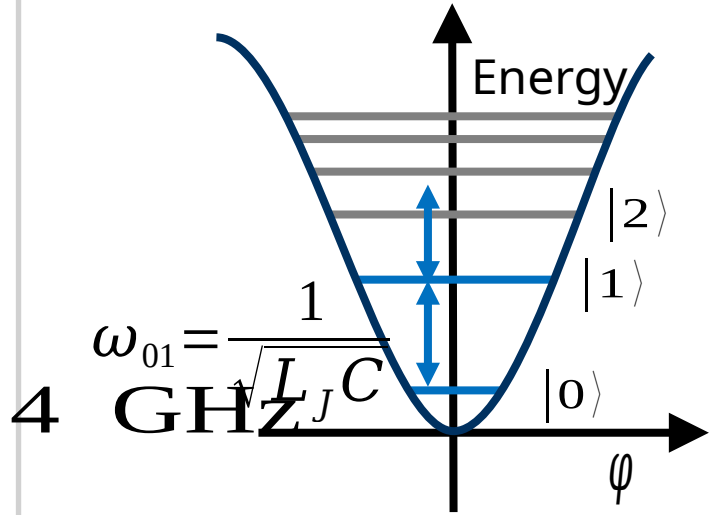
Huge success for theory: First predicted by Brian Josephson during his PhD (1962)
Experimentally verified in the same year at Bell Labs
(J. Rowell and P. W. Anderson)

Nonlinear LC Circuit: Transmon





F. Wang *et al.*, arXiv: 2405.05481 (2024)

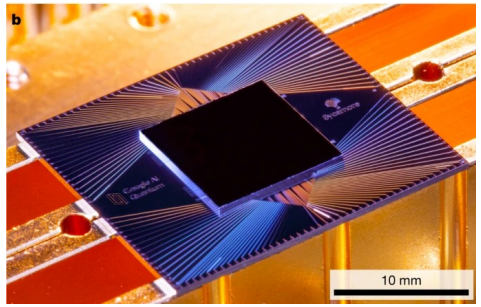


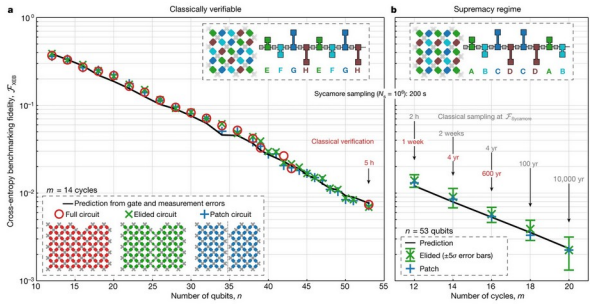
$$\hat{H} = 4E_C\hat{n}^2 - E_J\cos\hat{\varphi}$$

State of the art

Quantum Supremacy

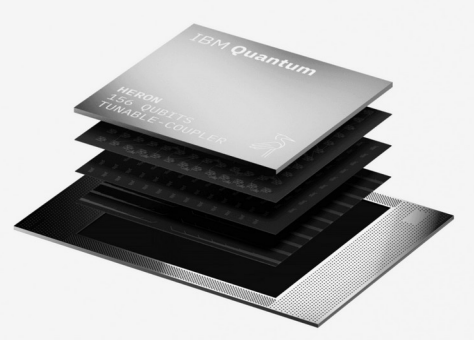
Google Quantum AI, Nature 574, 505-510 (2019)
53 Qubits
(median)
% | %

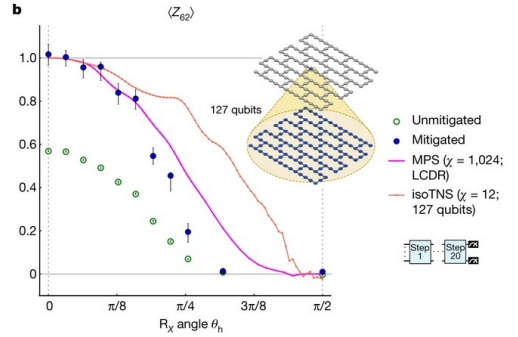




Quantum Utility

IBM, Nature 618, 500-505 (2023)
127 Qubits
| s (median)
% | Fidelity %

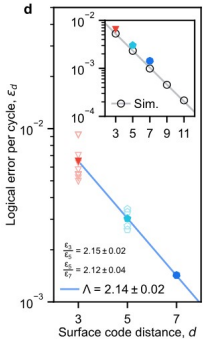


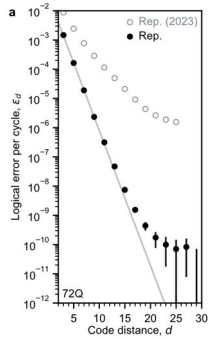


Quantum Error Correction

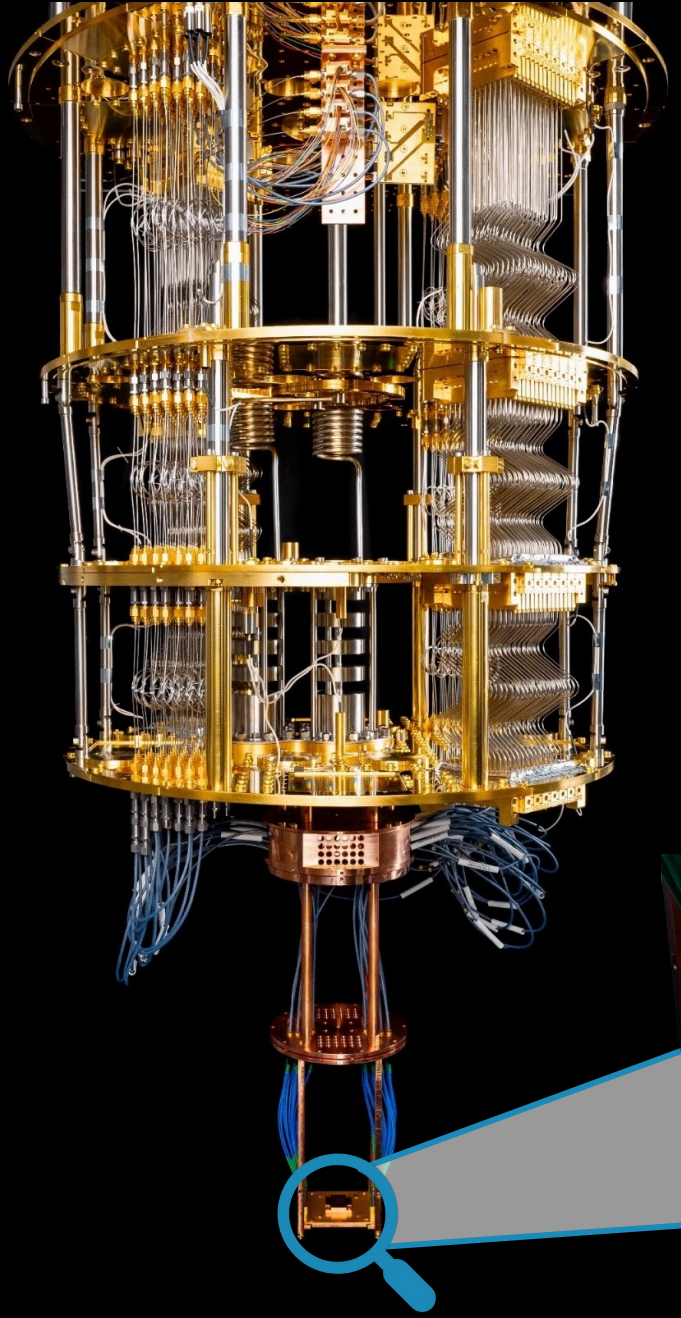
ETH Zürich, Nature 605, 669–674 (2022)
Google Quantum AI, Nature 614, 676-681 (2023)
Google Quantum AI, Nature 638, 920-926 (2025)
105 Qubits
| s (median)
% | %







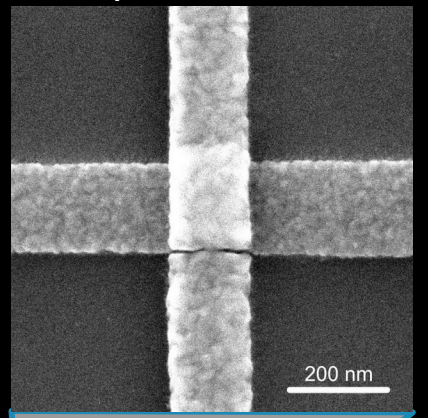
Many more to come: IBM 100x100 challenge, Google Logical 2Qubit gates, Dynamic codes, ...

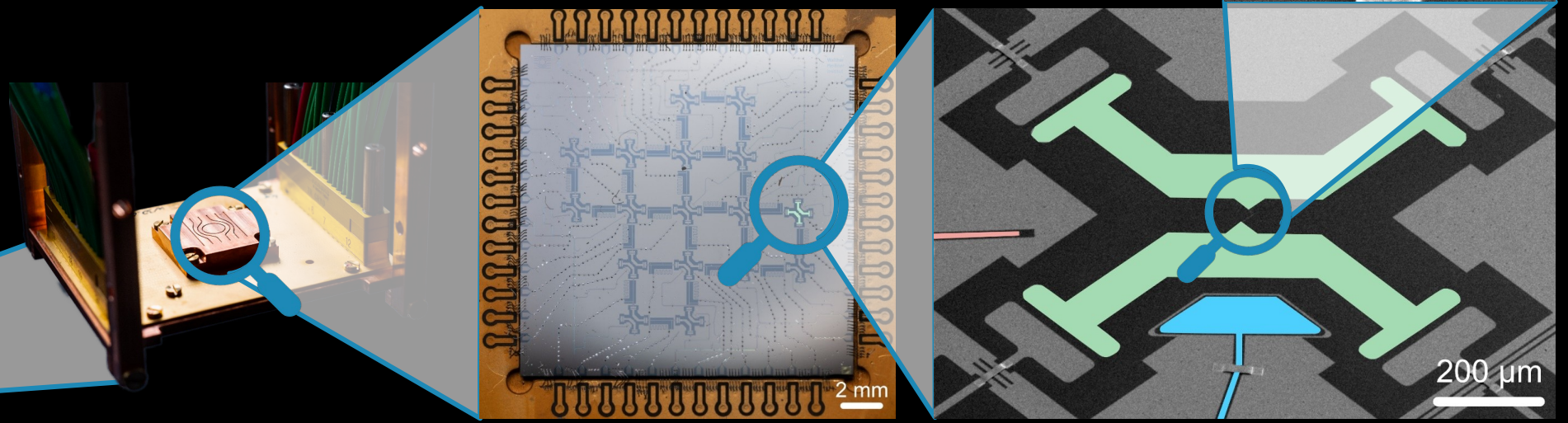


Features of Superconducting Quantum Processors

- Quantized non-linear superconducting LC circuits
- Typical frequencies: GHz (microwave range)
- Fast operations (gates) on 10 ns timescales
- High fidelity gate operations (2-Qubit gates)
- Scalable nanofabrication technology
- Requires cryogenic environment (< 100 mK, < -273 °C)

Josephson Junction





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A superconduting QPU made in Germany

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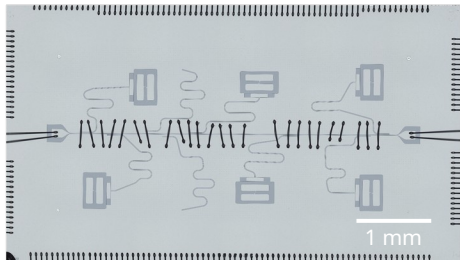
DFG Deutsche Forschungsgemeinschaft

1



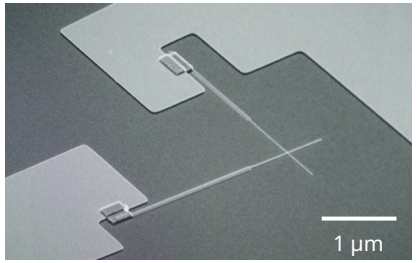
Setting up **reliable** nanofabrication with **superconductor deposition** and **patterning** using electron beam lithography and etching

2



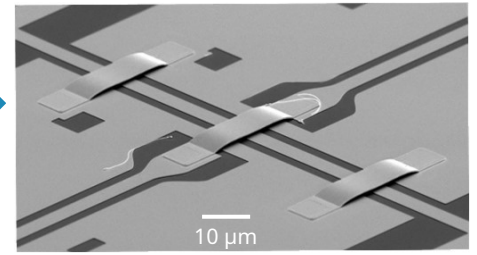
Resonator & single qubit **design** and **fabrication** optimization

3



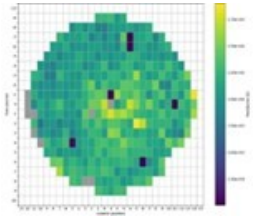
High quality **Josephson junctions**

4



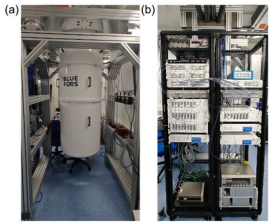
Multi-layer routing technology

5



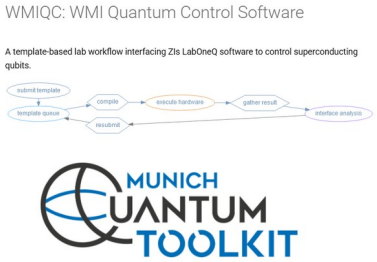
Waferscale fabrication

6



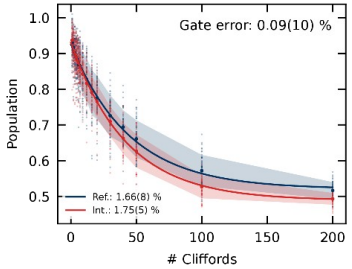
Scalable **cryogenic environment** and **control electronics**

7



Full software stack including remote user access

8



Tune-up and **2-qubit gate optimization**

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A superconduting QPU made in Germany

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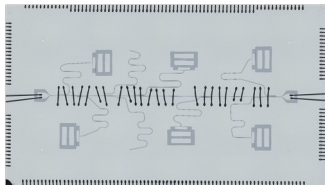
DFG Deutsche Forschungsgemeinschaft

1



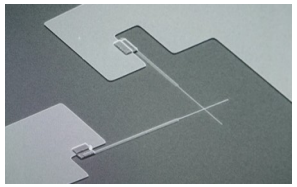
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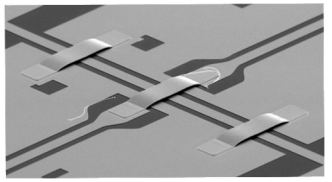
Resonator & single qubit **design** and **fabrication** optimization

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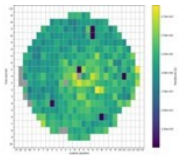
High quality **Josephson junctions**

4



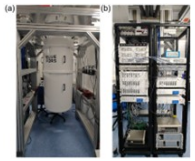
Multi-layer routing technology

5



Waferscale fabrication

6



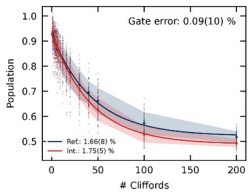
Scalable **cryogenic environment** and **control electronics**

7



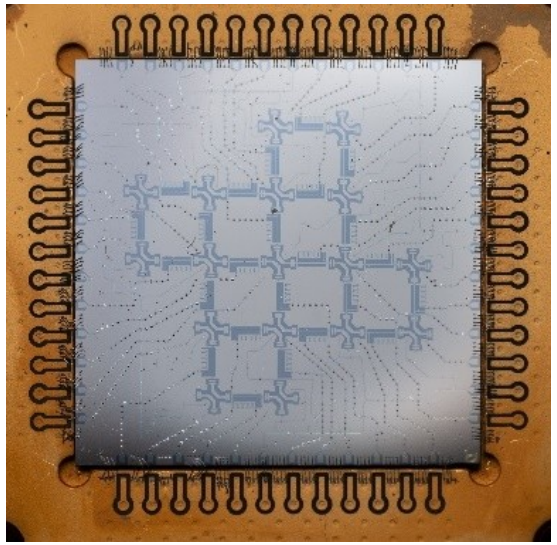
Full software stack including remote user access

8



Tune-up and **2-qubit gate optimization**

Walther-Meissner-Institute 17 transmon qubit QPU



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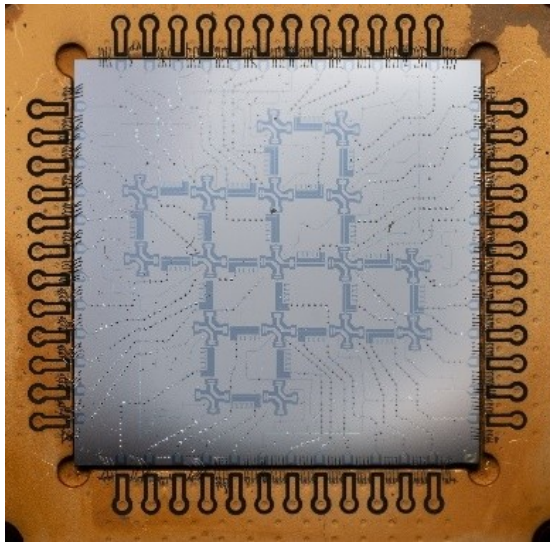
Key performance Indicators of 17 qubit chip

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KPI	Current Status	
	17-Q QPU	Dedicated QPU
# Qubits	17	
Connectivity	c≥2	
Gate Set	SU(2) + CZ + iSWAP	
1|2-Qu. Gate fid. (%)	| 90^{+3}_{-7}	> 99.9 | **99.9**
Readout fid. (%)		**99**
times (µs)	|	**420 | 437**
T_2/t_{gate}	**93**	**1170**
Qubit Reprod.	**5.2 %**	
Crosstalk	< 3 % avg	
# Parallel Ops	**5-6**	
Cycle time	**3 µs (active reset)**	
Uptime (h/day)	>20	

Walther-Meissner-Institute
17 transmon qubit QPU



Research & Innovation

Ongoing research at the Walther Meißner Institut

- Multi-mode qubits [F. Pfeiffer, et al., Phys. Rev. X 14, 041007 (2024), P. Garcia-Azorin, et al., arXiv2407.18895 (2024)]
- Parity dependent state transfer [F. Roy, J. Romeiro, et al., Nature Comm. 16, 2660 (2025)]
- Fluxonium qubits and protected control [J. Schirk, F. Wallner, *et al.*, arXiv:2410.00495 (2024)]
- Parametric control [G. Huber, et al., arXiv:2403.02203 (2024)]
- Optimal control [N. Glaser, et al., arXiv:2412.17454 (2024)]
- Fabrication technology [N. Bruckmoser, L. Koch, et al., arXiv:2503.12076 (2025)]
- Material improvements
- Quantum simulations (Thouless pumping, Lattice Gauge Field simulations, …)
- Noise analysis and benchmarking
-
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-

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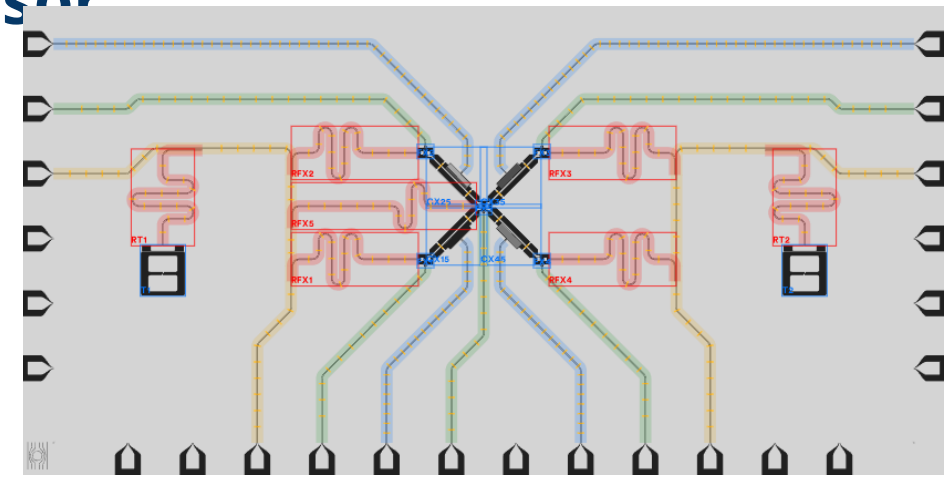
SC Hardware in the Munich Quantum Valley

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Building an Alternative Qubit Quantum Processor

- **Transfer** the knowledge and tools developed for **scaling transmons**
- Optimize Fluxonium as a **reliable** building block
- Develop a **scalable architecture** (using **couplers**)
- Going towards small scale Fluxonium QPU demonstrators



Roadmap

	2022	2023	2024	2025	2026
transmon		6(+6) qubits	9(+12) qubits	17(+24) qubits	35(+54) qubits
fluxonium		1 qubit	2 qubits	5 qubits	
P-mon		1 qubit	2 qubits		
Dual-rail			1 qubit		

Towards applications!

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Walther-Meißner-Institut
DER BAYERISCHEN AKADEMIE DER WISSENSCHAFTEN

Thank you for your attention!



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Lukas Vetter
Rui Wang
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MUNIQC-SC
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Munich Quantum Valley

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Backup

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Potential Quantum Processors

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https://en.wikipedia.org/wiki/Qubit

Physical support	Name	Information support		
Photon	Polarization encoding	Polarization of light	Horizontal	Vertical
	Number of photons	Fock state	Vacuum	Single photon state
	Time-bin encoding	Time of arrival	Early	Late
Coherent state of light	Squeezed light	Quadrature	Amplitude-squeezed state	Phase-squeezed state
Electrons	Electronic spin	Spin	Up	Down
	Electron number	Charge	No electron	Two electron
Nucleus	Nuclear spin addressed through NMR	Spin	Up	Down
Neutral atom	Atomic energy level	Spin	Up	Down
Trapped ion	Atomic energy level	Spin	Up	Down
Josephson junction	Superconducting charge qubit	Charge	Uncharged superconducting island (Q=0)	Charged superconducting island (Q=2e, one extra Cooper pair)
	Superconducting flux qubit	Current	Clockwise current	Counterclockwise current
	Superconducting phase qubit	Energy	Ground state	First excited state
Singly charged quantum dot pair	Electron localization	Charge	Electron on left dot	Electron on right dot
Quantum dot	Dot spin	Spin	Down	Up
Gapped topological system	Non-abelian anyons	Braiding of Excitations	Depends on specific	Depends on specific

17 Qubit tune-up

One-Time: 28 hours

Daily-weekly: 6.8 hours

Reset, parallelization -> 1/100

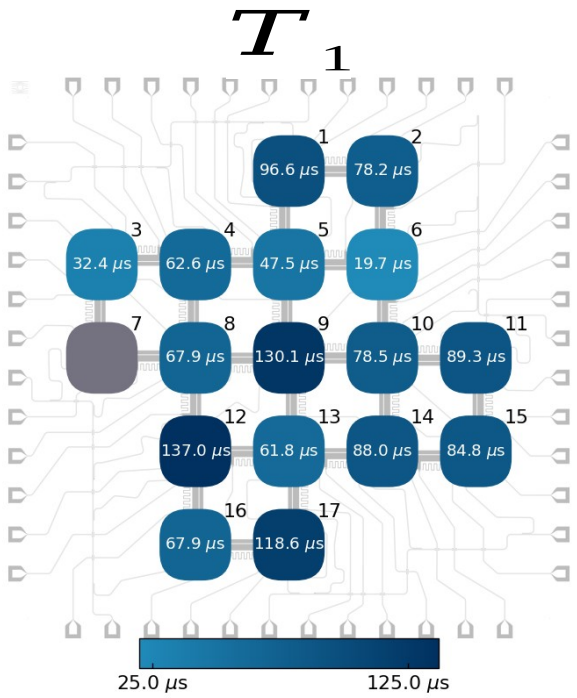
Worldwide QPUs available

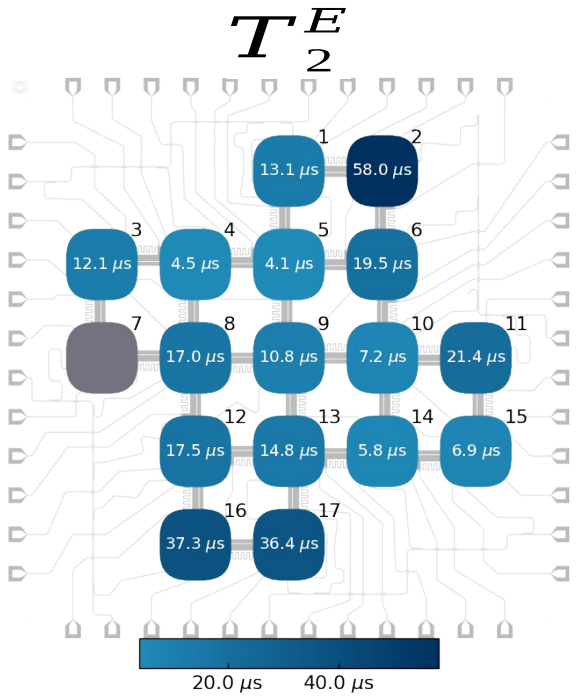
Commercial

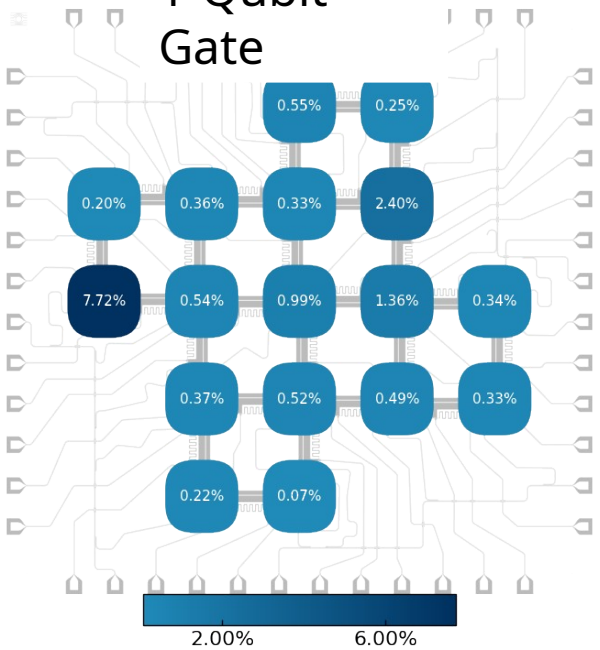
- Google (USA)
- IBM (USA)
- Rigetti (USA)
- AWS (USA)
- Oxford Quantum Circuits (EU)
- IQM (EU)
- Quantware (EU)
- RIKEN (Japan)

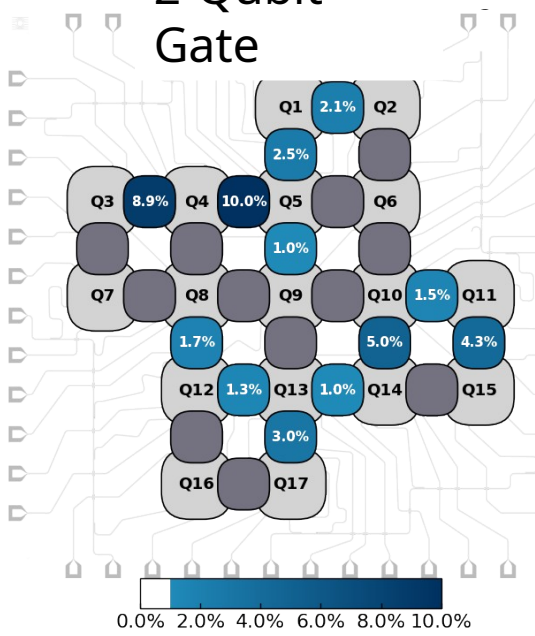
Academic

- China: Heifei, Jian Wei Pan
- USA: MIT, Caltech
- Japan: RIKEN
- Sweden: Chalmers
- Netherlands: TU Delft
- Switzerland: ETH Zürich
- Germany: WMI, FZ Jülich
-


T_1
1 96.6 μs
2 78.2 μs
3 32.4 μs
4 62.6 μs
5 47.5 μs
6 19.7 μs
7
8 67.9 μs
9 130.1 μs
10 78.5 μs
11 89.3 μs
12 137.0 μs
13 61.8 μs
14 88.0 μs
15 84.8 μs
16 67.9 μs
17 118.6 μs
25.0 μs
125.0 μs


T_2^E
1 13.1 μs
2 58.0 μs
3 12.1 μs
4 4.5 μs
5 4.1 μs
6 19.5 μs
7
8 17.0 μs
9 10.8 μs
10 7.2 μs
11 21.4 μs
12 17.5 μs
13 14.8 μs
14 5.8 μs
15 6.9 μs
16 37.3 μs
17 36.4 μs
20.0 μs
40.0 μs


1-Qubit Gate
0.55%
0.25%
0.20%
0.36%
0.33%
2.40%
7.72%
0.54%
0.99%
1.36%
0.34%
0.37%
0.52%
0.49%
0.33%
0.22%
0.07%
2.00%
6.00%


2-Qubit Gate
Q1 2.1% Q2
2.5%
Q3 8.9% Q4 10.0% Q5 Q6
1.0%
Q7 Q8 Q9 Q10 1.5% Q11
1.7% 5.0% 4.3%
Q12 1.3% Q13 1.0% Q14 Q15
3.0%
Q16 Q17
0.0% 2.0% 4.0% 6.0% 8.0% 10.0%