Walther
Meißner
Institut

Quantum Computing with Superconducting Qubits

TCG CREST CQuERE
International Conference on Quantum Information Science and Technology (ICQIST)
09.12.2025 - 13.12.2025
Kolkata, India

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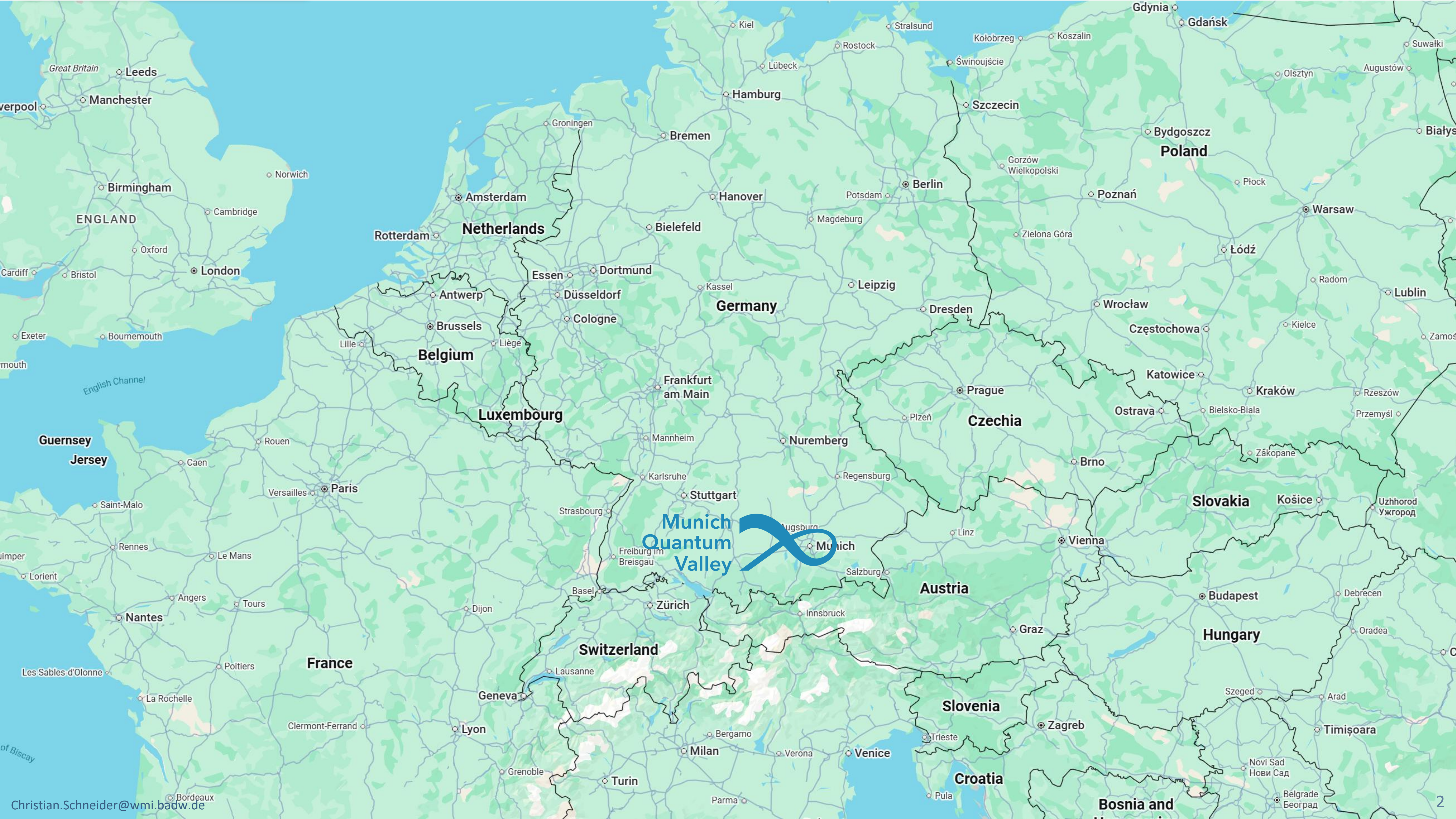
BAdW BAYERISCHE AKADEMIE DER WISSENSCHAFTEN

Munich Quantum Valley



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Munich Quantum Valley

Walther-Meißner-Institut
DER BAYERISCHEN AKADEMIE DER WISSENSCHAFTEN

MAX PLANCK INSTITUTE
OF QUANTUM OPTICS

MUNIQC-SC
Quantum Computing Demonstrator
Superconducting Qubits
Munich Quantum Valley

MUNIQC-Atoms
Neutral Atom based
Quantum Computing Demonstrator
Munich Quantum Valley

Develop and operate Quantum Computers

Peak Quantum

planqc

TUM LMU LUDWIG-MAXIMILIANS-UNIVERSITÄT MÜNCHEN FAU Fraunhofer

infineon Zurich Instruments lrz

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Quantum Computing: Applications and challenges

1. Quantum Simulations

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

2. Cryptography

Breaking classical encryption (e.g. RSA)
Advantage: Shor's algorithm enables **exponential** speedup for integer factorization and discrete logarithms.

3. Optimization Problems

Solving combinatorial problems (e.g. portfolio management, logistics, scheduling)
Advantage**:** Minimize hard optimization landscapes exploiting entangled quantum systems in high dimensional Hilbert spaces

4. Linear equation solving and machine learning

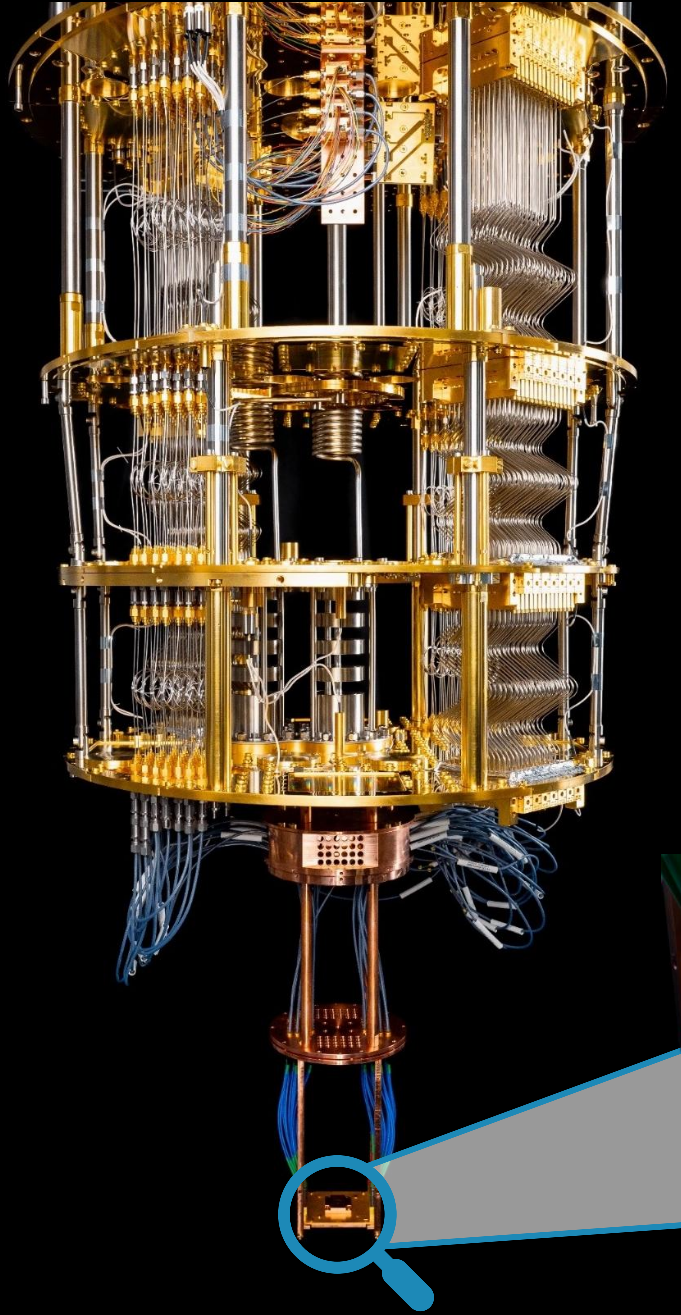
Improve learning, solving sparse linear equations
Advantage: Potential **polynomial** or **exponential** speedups in specific subroutines (subject to data access and noise constraints

Challenges

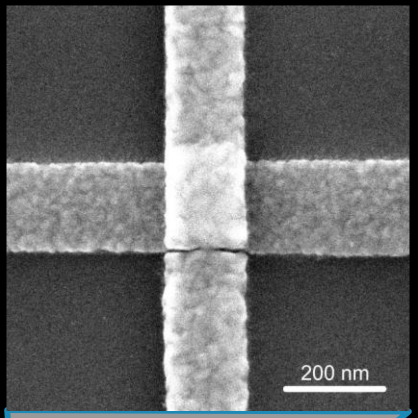
A. **Algorithmic Limitations:** Only a handful of algorithms known with speed-up compared to classical algorithms (Shor, Harrow–Hassidim–Lloyd, Grover, ….)
B. **Hardware Requirements**: Realization depends on fault-tolerant quantum computers with many high-fidelity qubits and low-error operations.

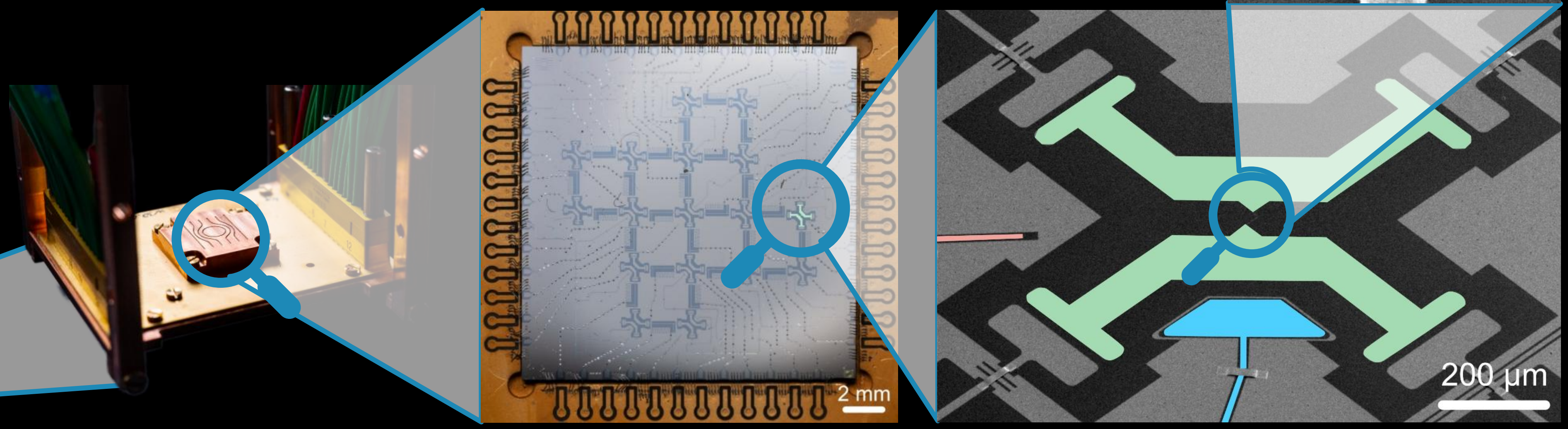
Superconducting Quantum Processors

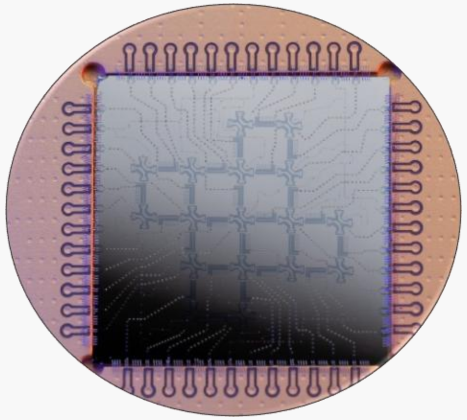
- Quantized non-linear superconducting LC circuits
- Typical frequencies: $0.05 - 10$ GHz (microwave range)
- Fast operations (gates) on 10 ns timescales
- High fidelity gate operations ($> 99.9\%$ 2-Qubit gates)
- Scalable nanofabrication technology
- Requires cryogenic environment (< 100 mK)



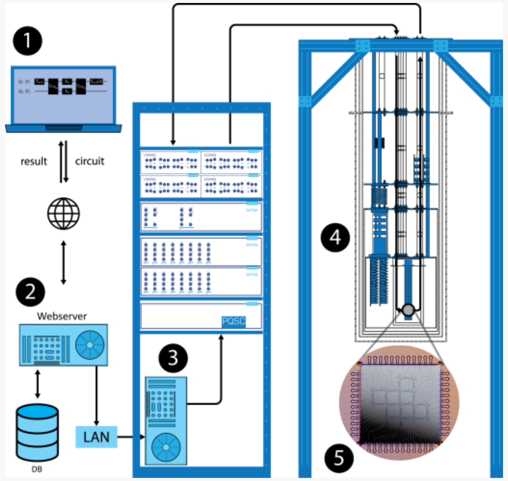
Josephson Junction



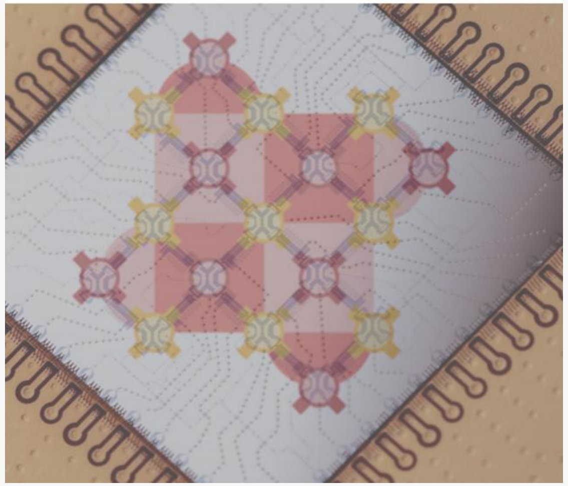




How to
get qubits



How to
program qubits



How to
use qubits

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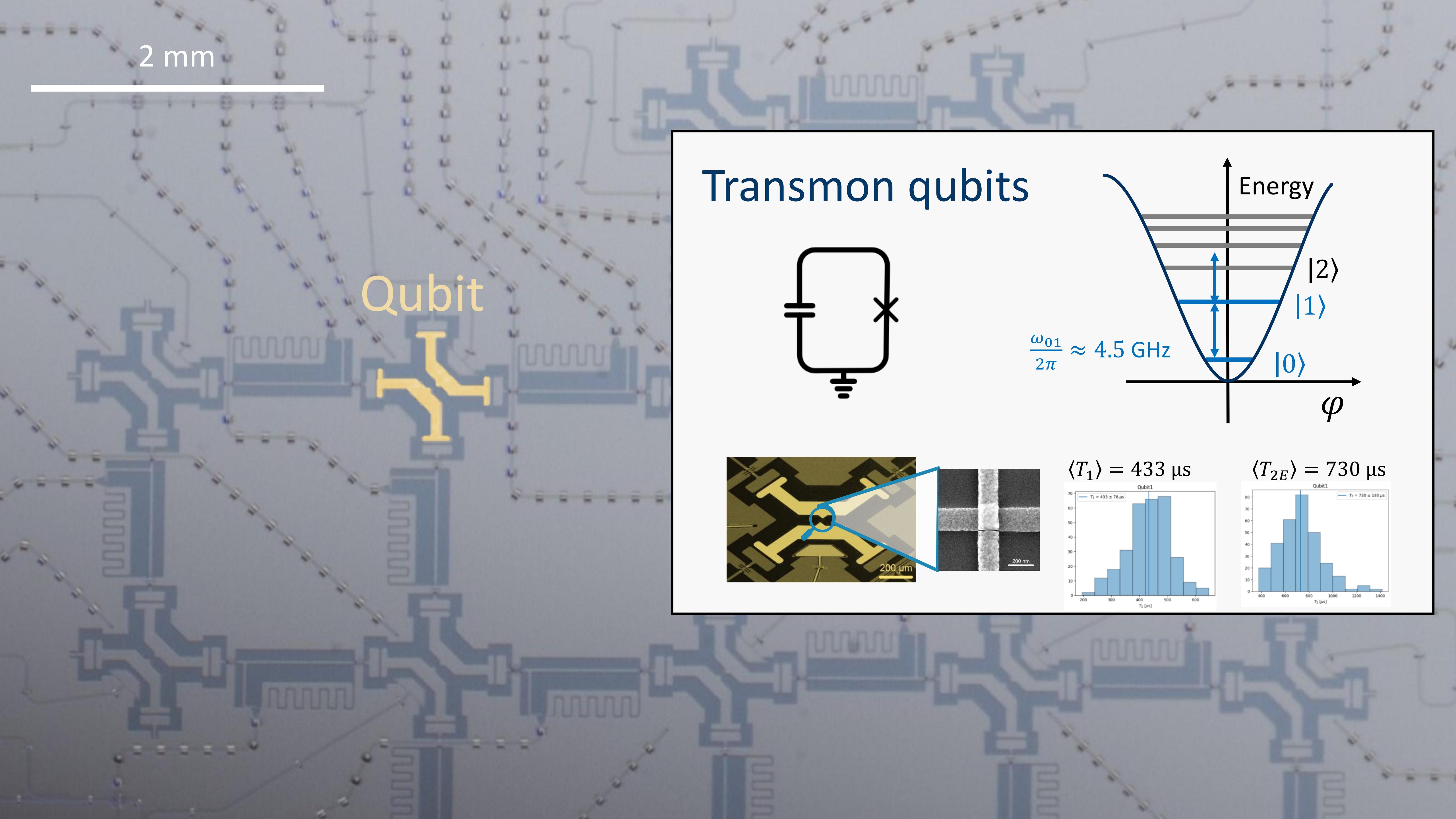
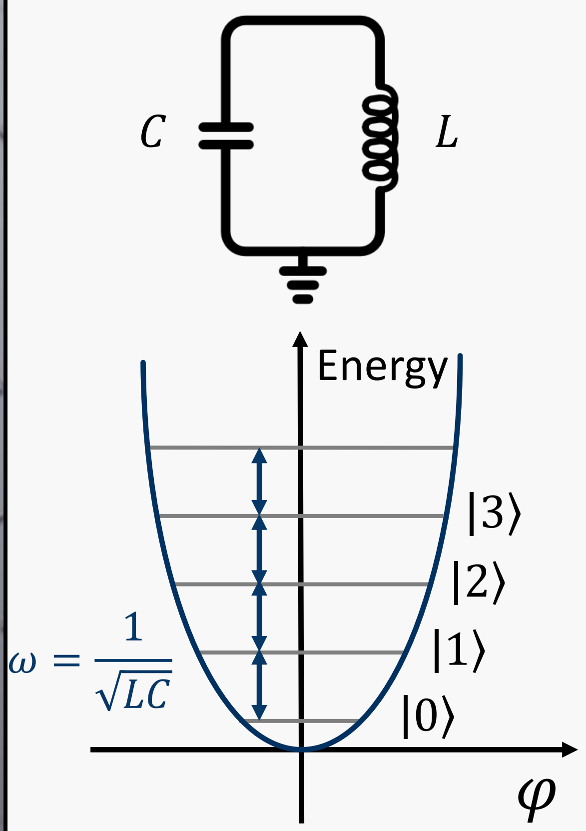

2 mm
Qubit
Transmon qubits
Energy
$|2\rangle$
$|1\rangle$
$|0\rangle$
$\frac{\omega_{01}}{2\pi} \approx 4.5$ GHz
φ
200 µm
200 nm
$\langle T_1 \rangle = 433$ µs
$\langle T_{2E} \rangle = 730$ µs
Qubit1
Qubit1

Transmon qubits

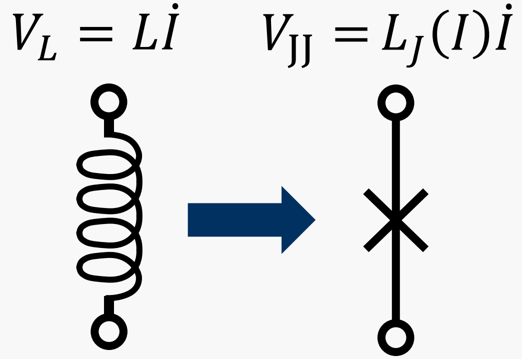
LC Circuit/Resonator

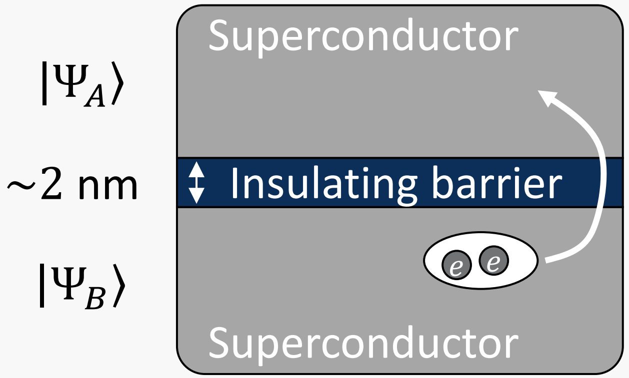


$$\hat{H} = 4E_C\hat{n}^2 + E_L\hat{\varphi}^2$$

Charge and flux

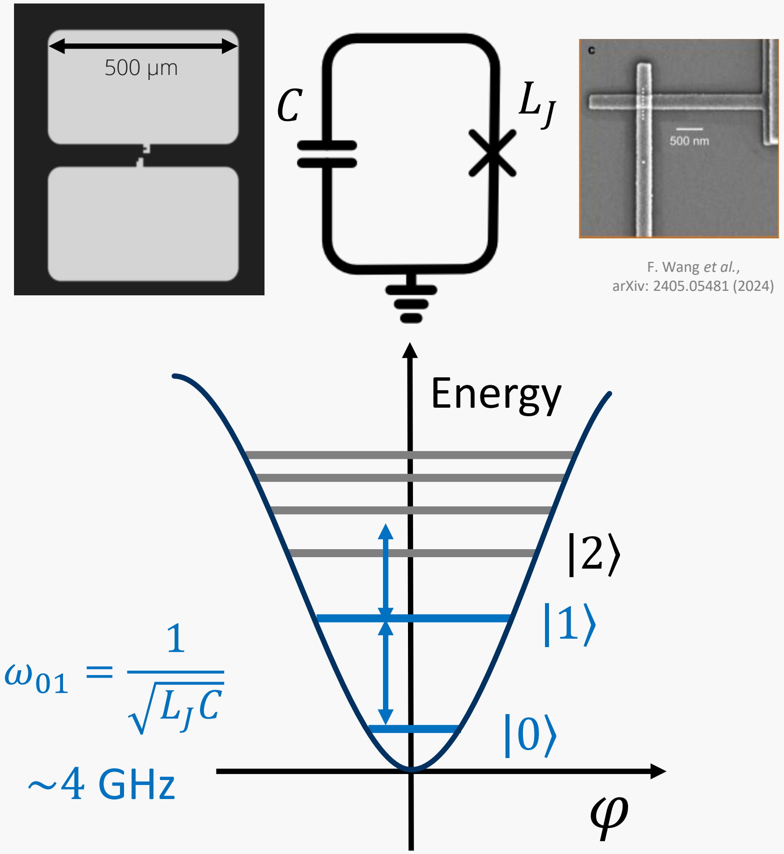
Josephson Junction





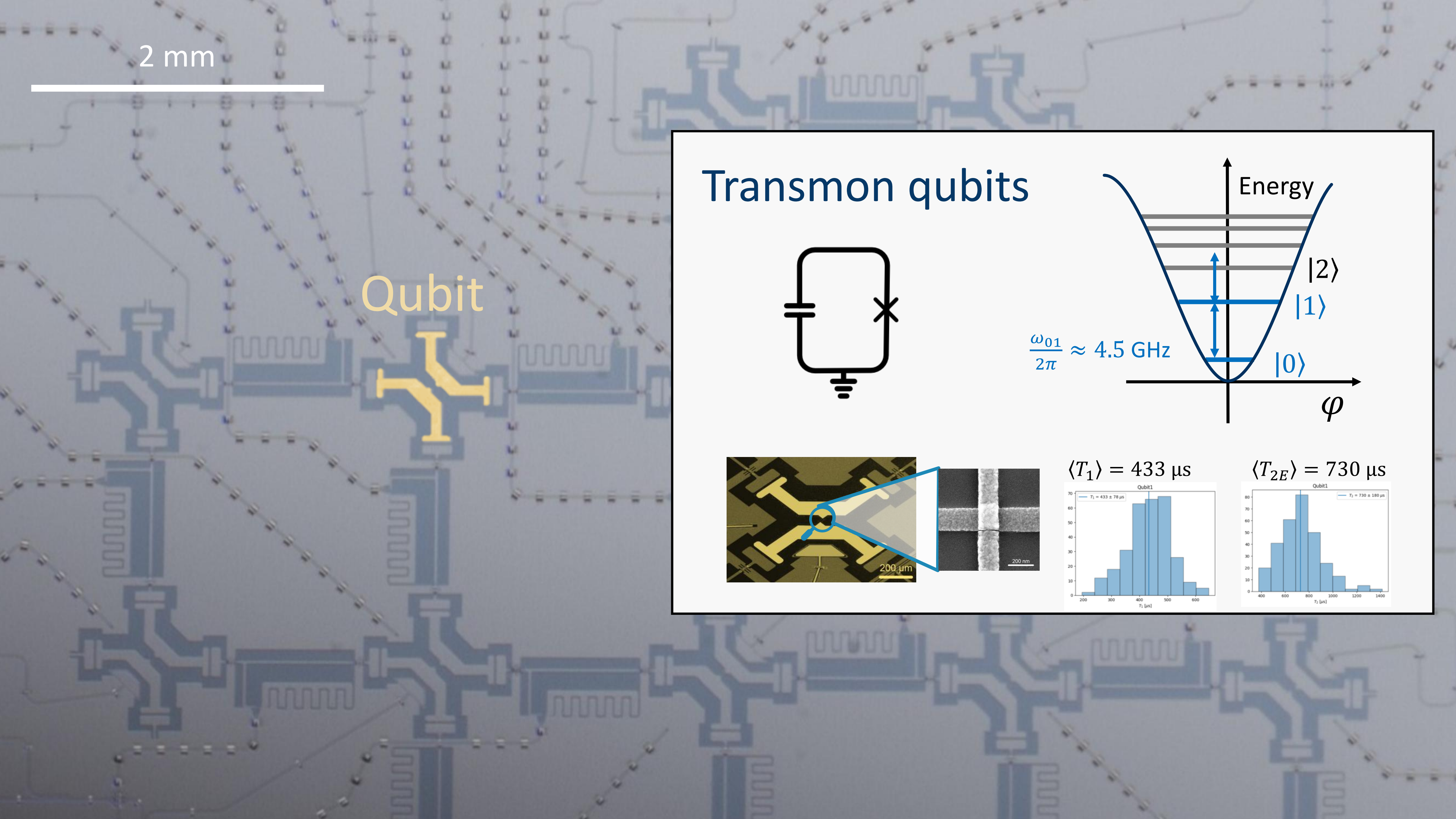
Huge success for theory: Predicted by **Brian Josephson** during his PhD (1962) -> **Nobel prize**
Experimentally verified in the same year at Bell Labs (J. Rowell and P. W. Anderson)

Nonlinear LC Circuit: Transmon

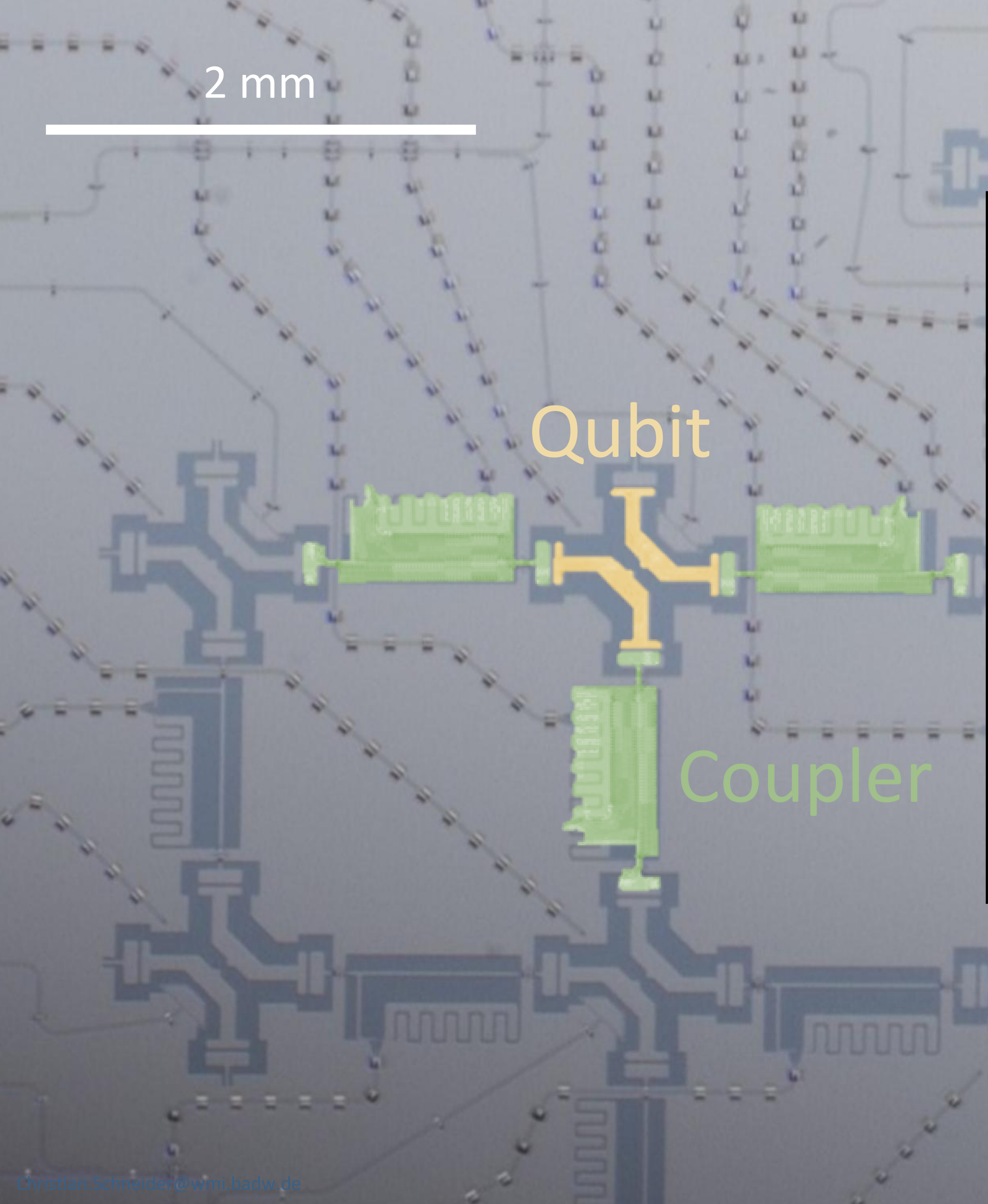


F. Wang *et al.*, arXiv: 2405.05481 (2024)

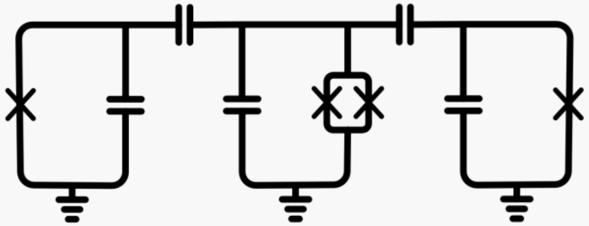
$$\hat{H} = 4E_C\hat{n}^2 - E_J\cos\hat{\varphi}$$

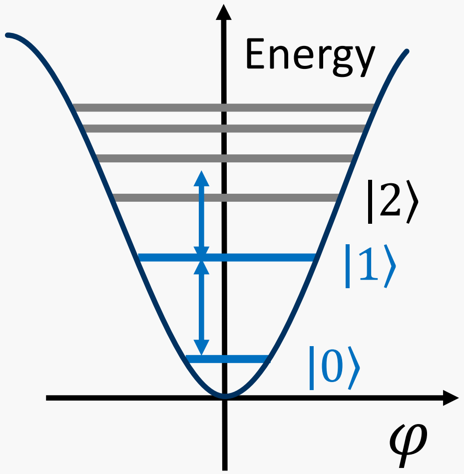


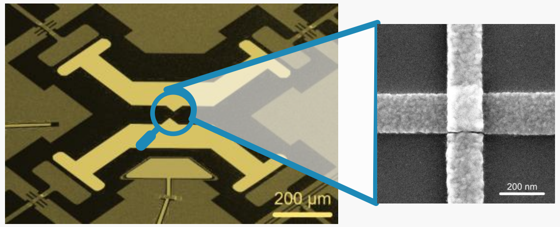
2 mm
Qubit
Transmon qubits
Energy
|2⟩
|1⟩
|0⟩
$\frac{\omega_{01}}{2\pi} \approx 4.5$ GHz
φ
200 µm
200 nm
$\langle T_1 \rangle = 433$ µs
Qubit1
T_1 = 433 ± 78 µs
T_1 [µs]
$\langle T_{2E} \rangle = 730$ µs
Qubit1
T_2 = 730 ± 180 µs
T_2 [µs]



Coupled Transmons

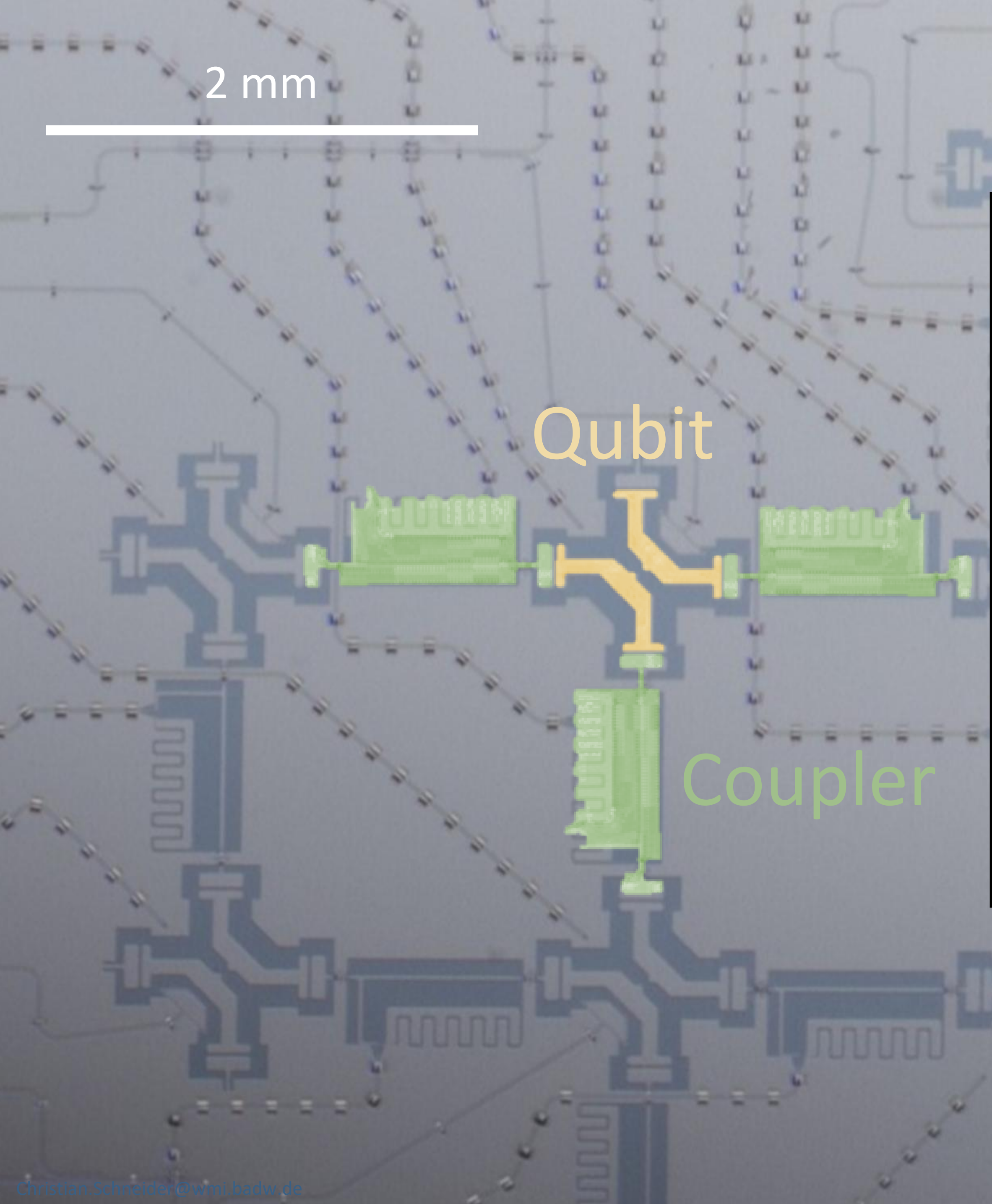




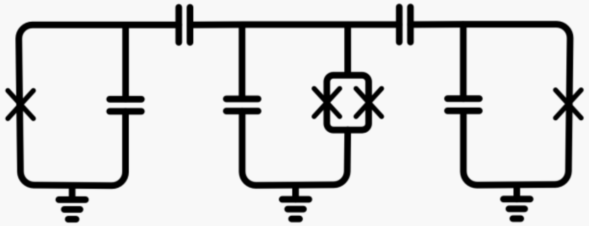


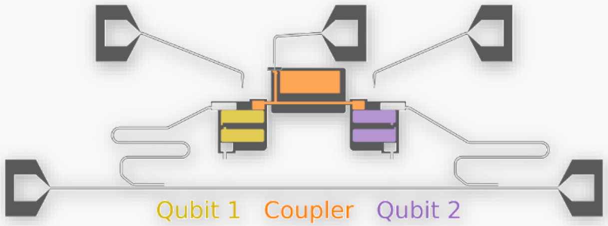
$\langle T_1 \rangle = 102\ \mu s$

$\langle T_{2E} \rangle = 157\ \mu s$

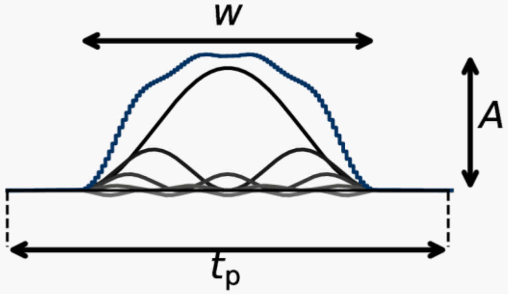


Coupled Transmons





- **60 ns operations with 99.9 % Fidelity**
- Re-calibration in ≈ 80 minutes
- Calibration speed expected to reduce further



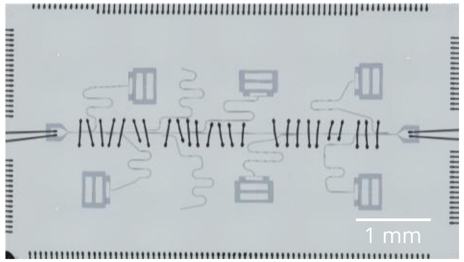
N. Glaser et al, PR Applied **24,** 024048 (2025)

A superconducting QPU made in Munich

1

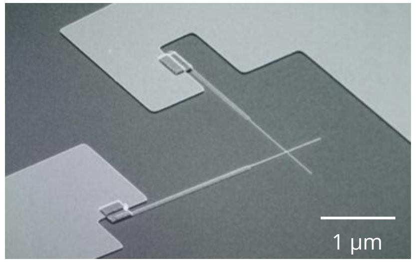
Setting up reliable nanofabrication with superconductor deposition and patterning using electron beam lithography and etching

2



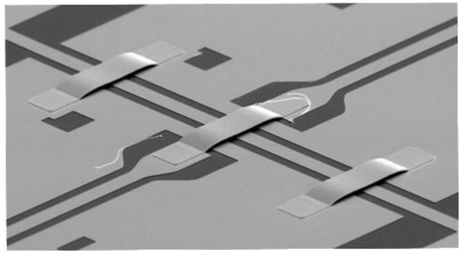
Resonator & single qubit design and fabrication optimization

3



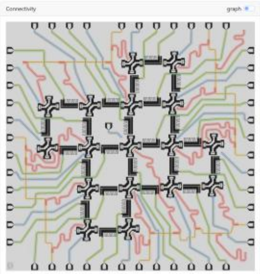
High quality Josephson junctions

4



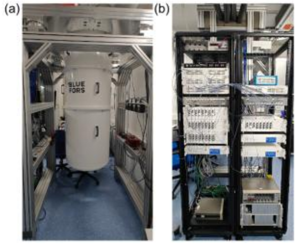
Multi-layer routing technology

5



Scalable architecture and design suite

6

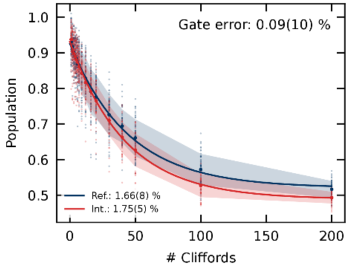


Scalable and tested cryogenic environment and control electronics

7

Scalable software stack including remote user access

8



Automated tune-up routines and 2-qubit gate optimization

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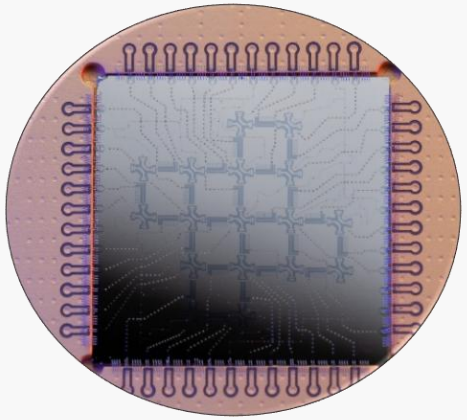
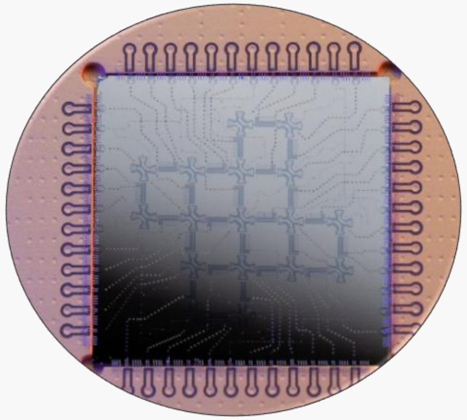
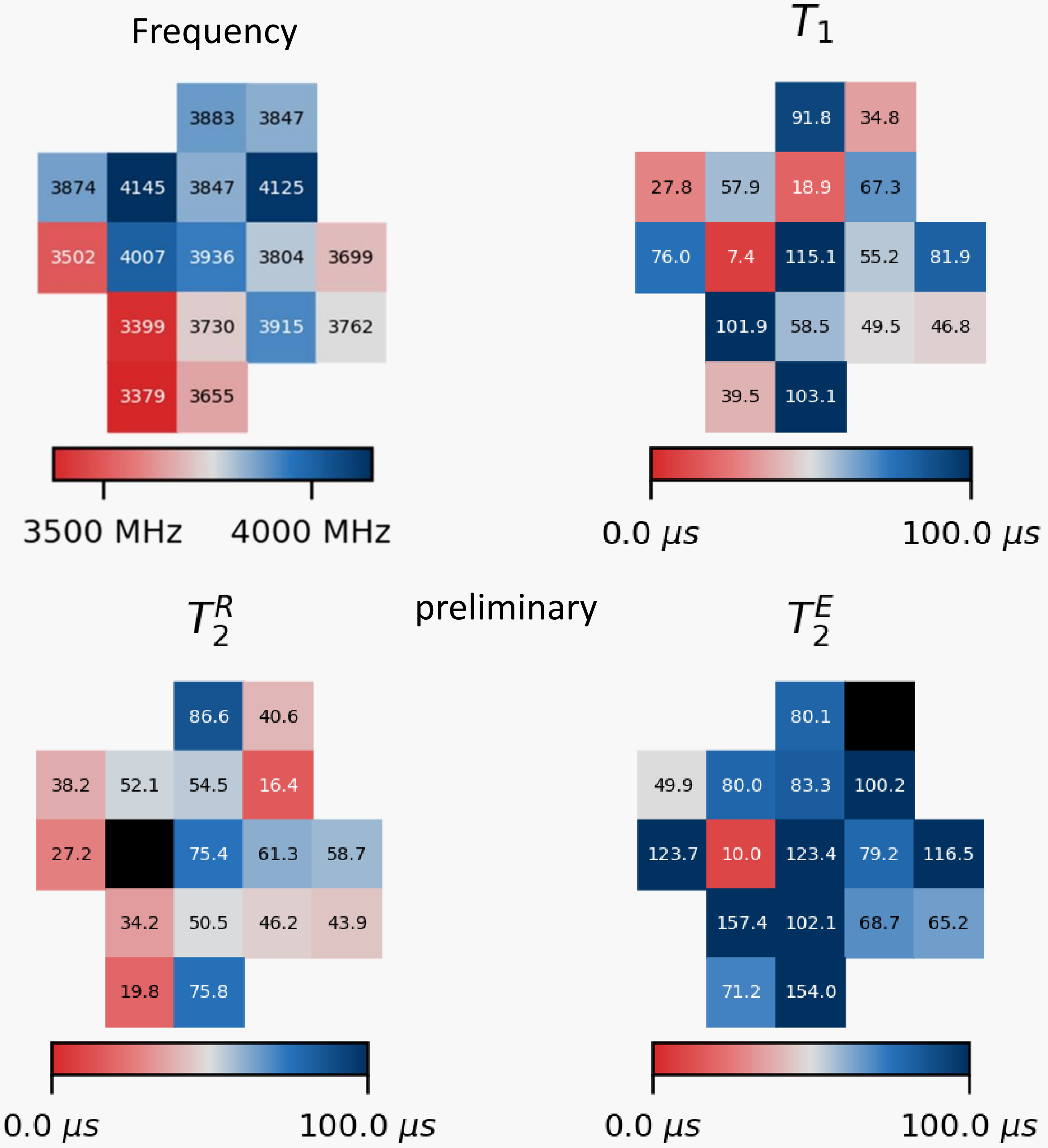


WMI's
17 Qubit QPU

Key Performance Indicator	Current Status
# Qubits	17
Avg. connectivity	$c = 3.0$
Gate Set	SU(2) + CZ + iSWAP
1|2-Qu. Gate fid. (%)	$99.5^{+0.2}_{-0.6}$ | $97.7^{+0.8}_{-2.2}$
Readout fid. (%)	90^{+3}_{-7}
T_1| T_2 times (µs)	$\mathbf{54^{+23}_{-15}}$ | $\mathbf{82^{+36}_{-12}}$
T_2/t_{gate}	328
Qubit Reprod.	5.2 %



WMI’s 17 Qubit QPU



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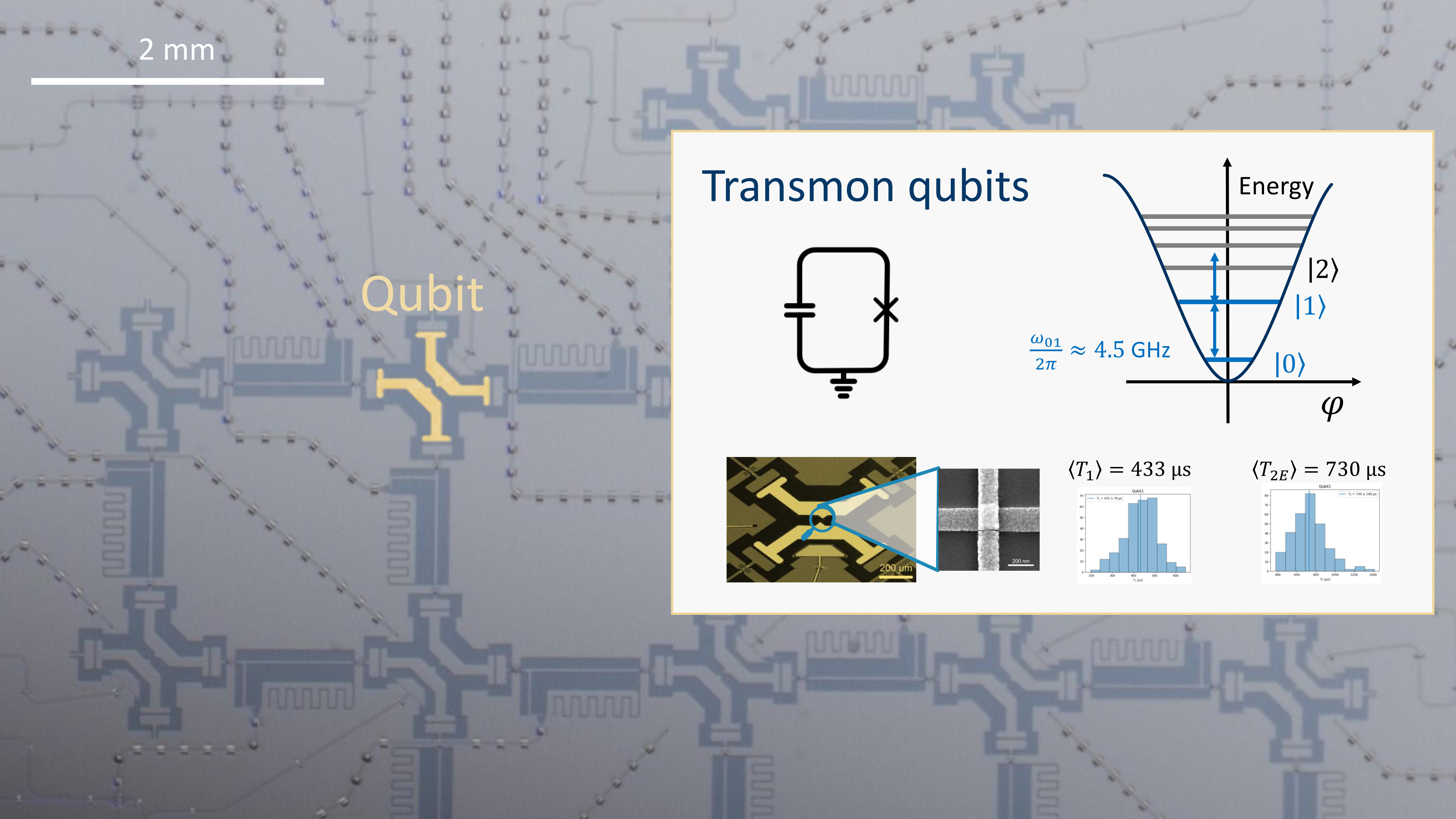
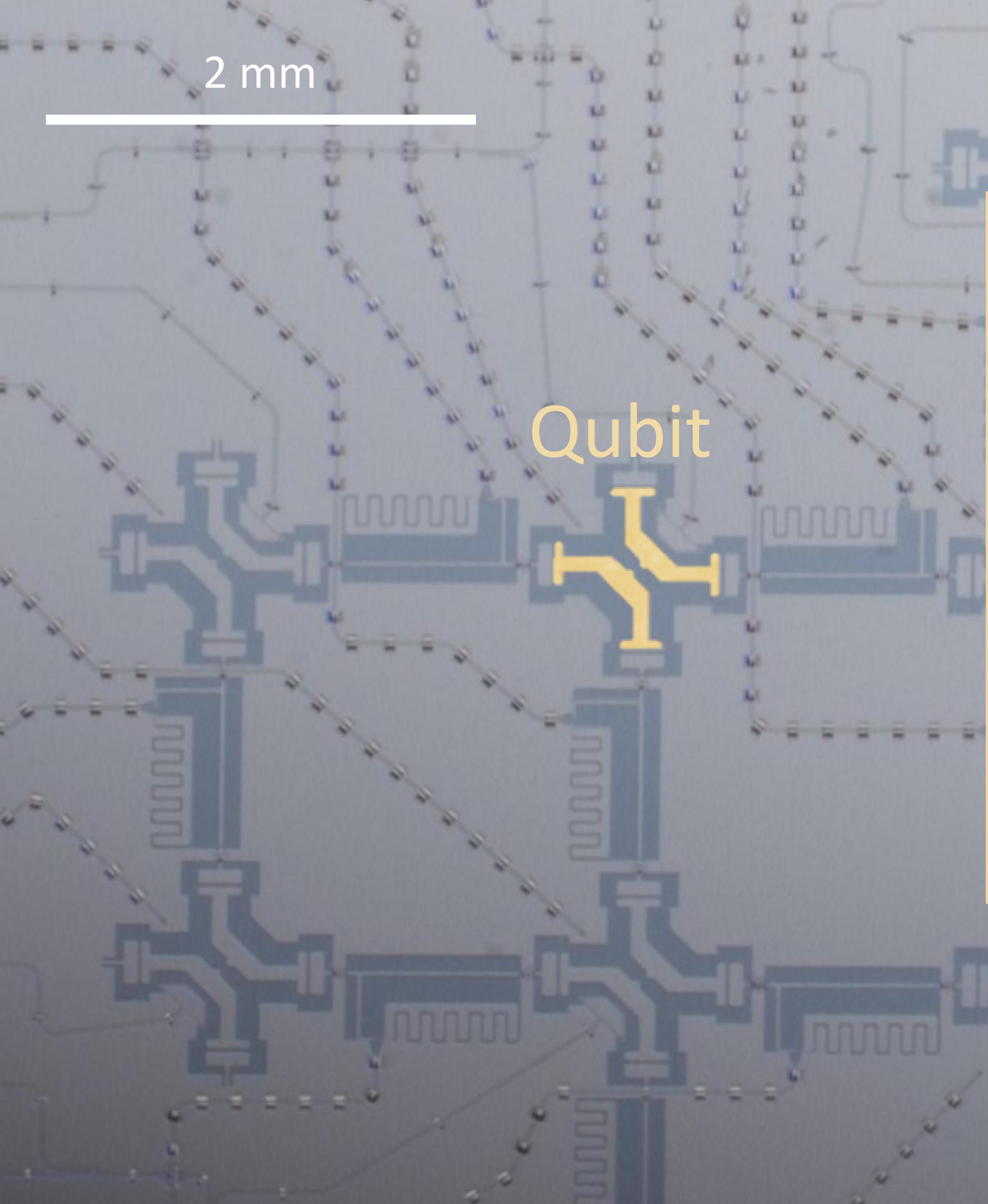
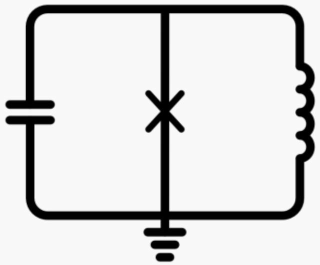
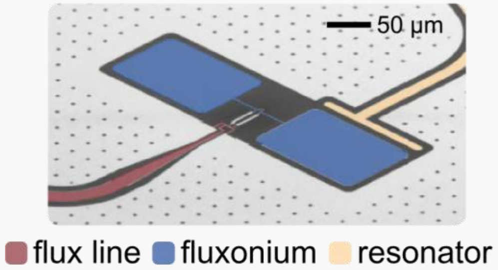
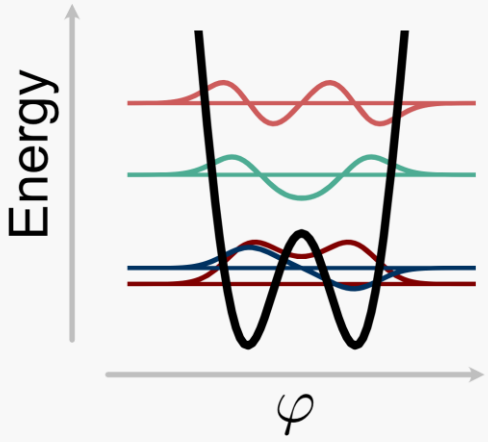

2 mm
Qubit
Transmon qubits
Energy
|2⟩
|1⟩
|0⟩
ω01/2π ≈ 4.5 GHz
φ
200 µm
200 nm
⟨T1⟩ = 433 µs
⟨T2E⟩ = 730 µs
Qubit1
Qubit1



Fluxonium qubits

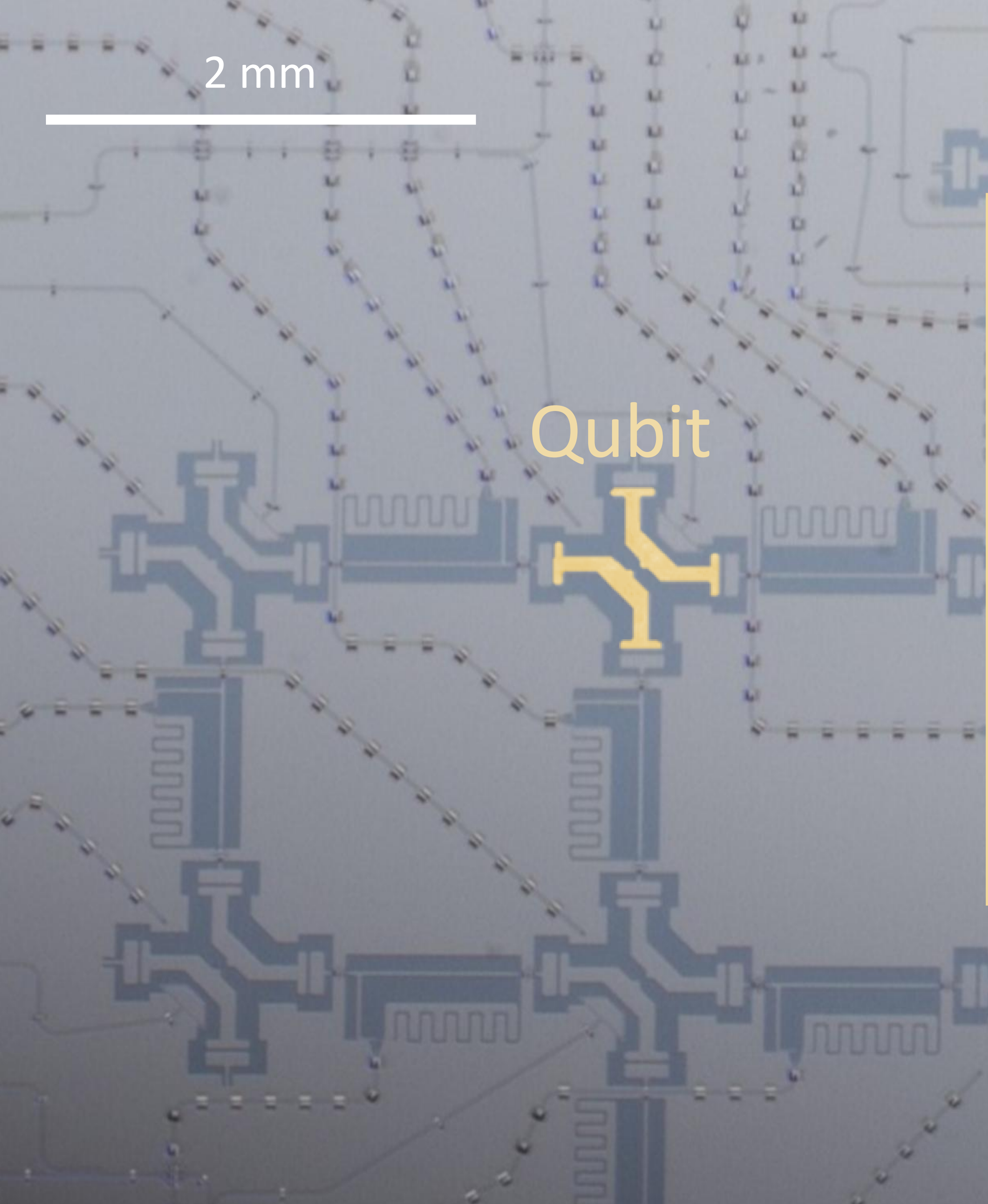




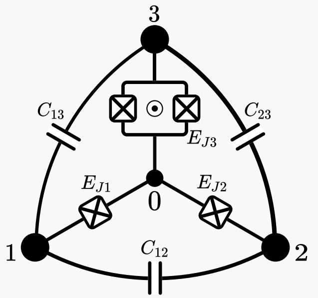


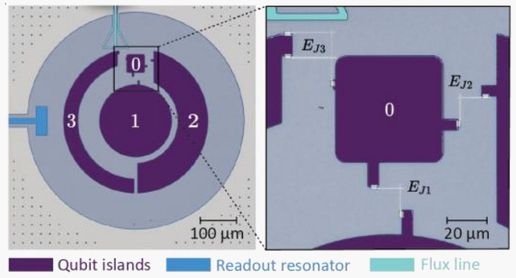
$\langle T_1 \rangle \approx 183\ \mu s \quad \langle T_{2E} \rangle \approx 171\ \mu s$

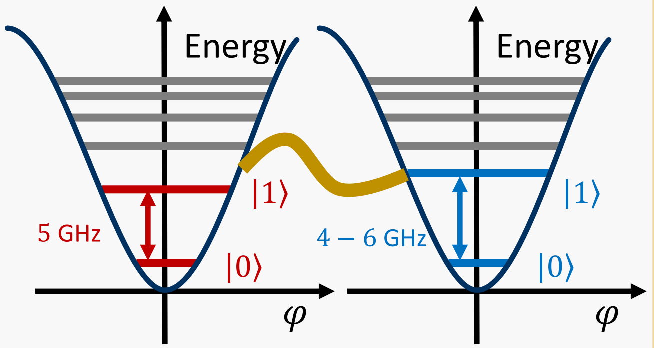
J. Schirk *et al.*, PRX Quantum **6**, 030315 (2025)



Protected mode qubits



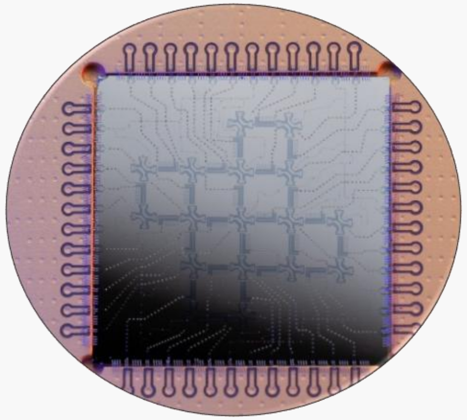


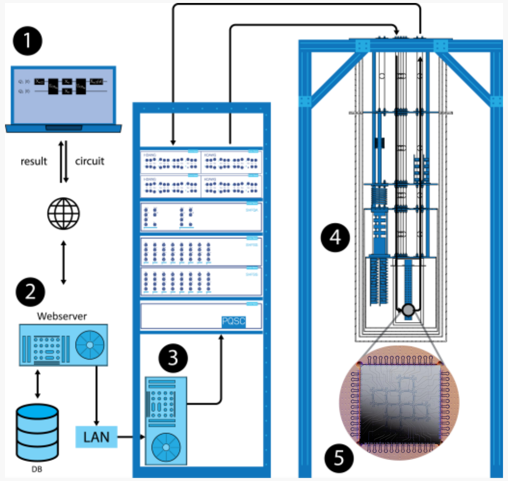


$\langle T_1 \rangle \approx 105\ \mu s$ $\quad \langle T_{2E} \rangle \approx 60\ \mu s$

F. Pfeiffer *et al.*, PRX **14**, 041007 (2024)

More in exploration

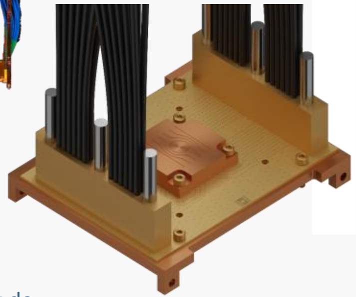


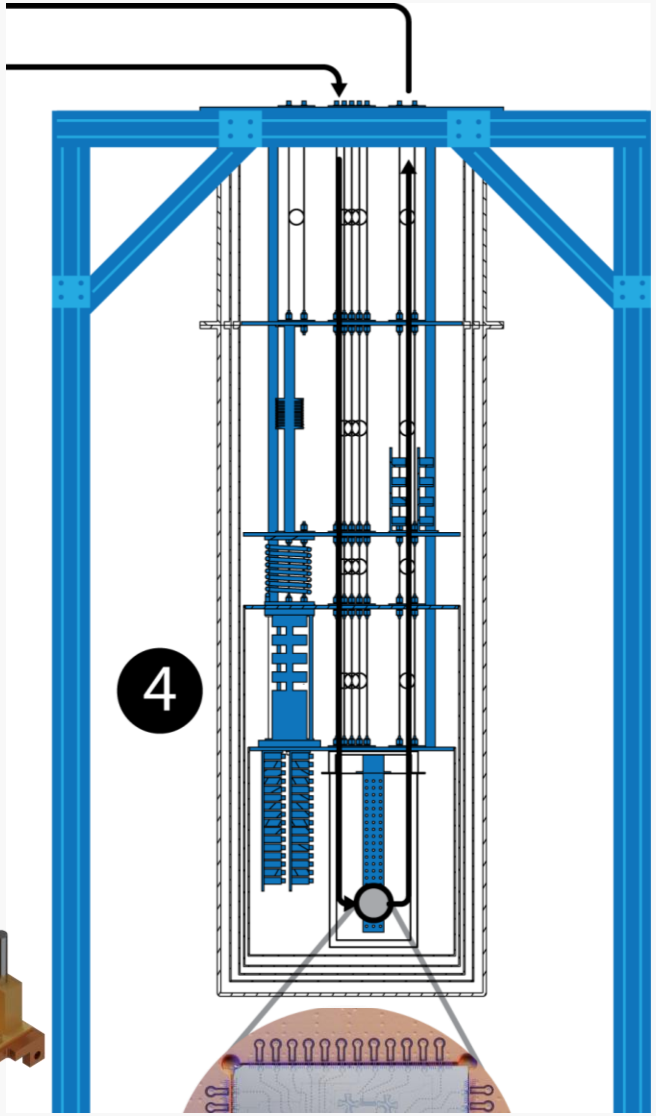


How to
get qubits

How to
program qubits

Cryogenic environment





Cryostat environment

- Base temperatures around **10 mK**
- Each **qubit** requires **one coaxial cable**
- Each **coupler** requires **one coaxial cable**
- Each cable **takes cooling capacity**
- Current setup: **400 cables**
- **Packages** supporting up to **96 Ports** (120 and 350 ports in progress)
- Engineering efforts: flex cabling, heatload optimization, increased cooling power, packaging, filter optimization, ….

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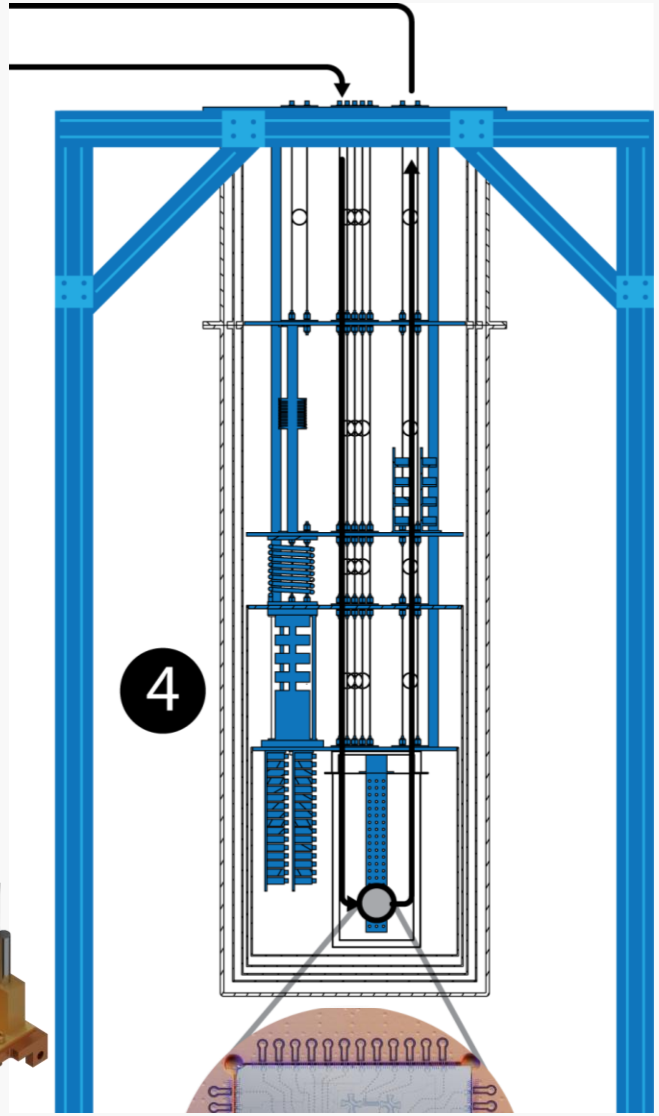
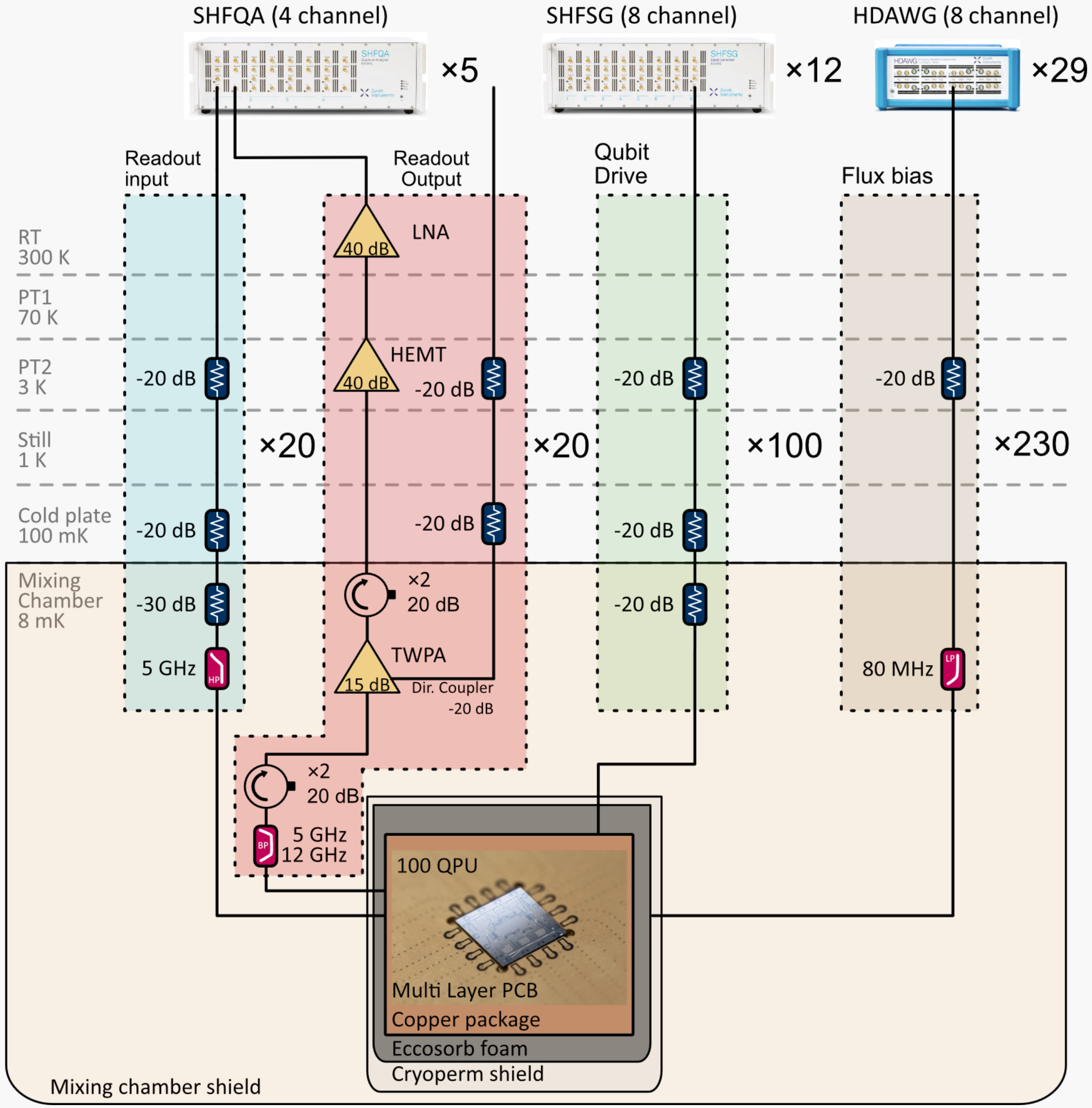
Cryogenic environment





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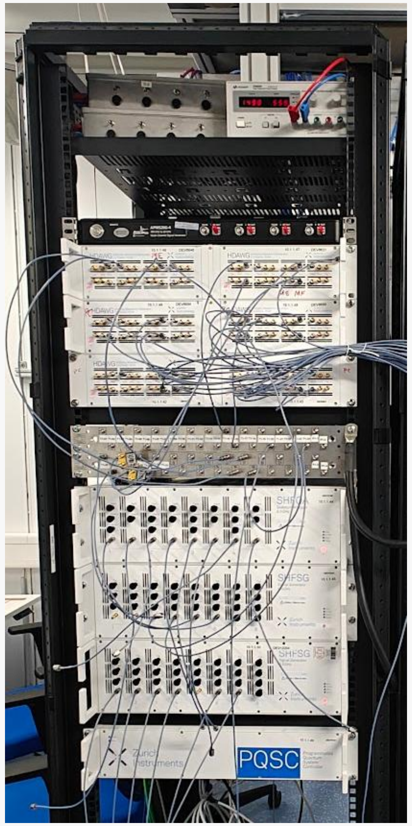
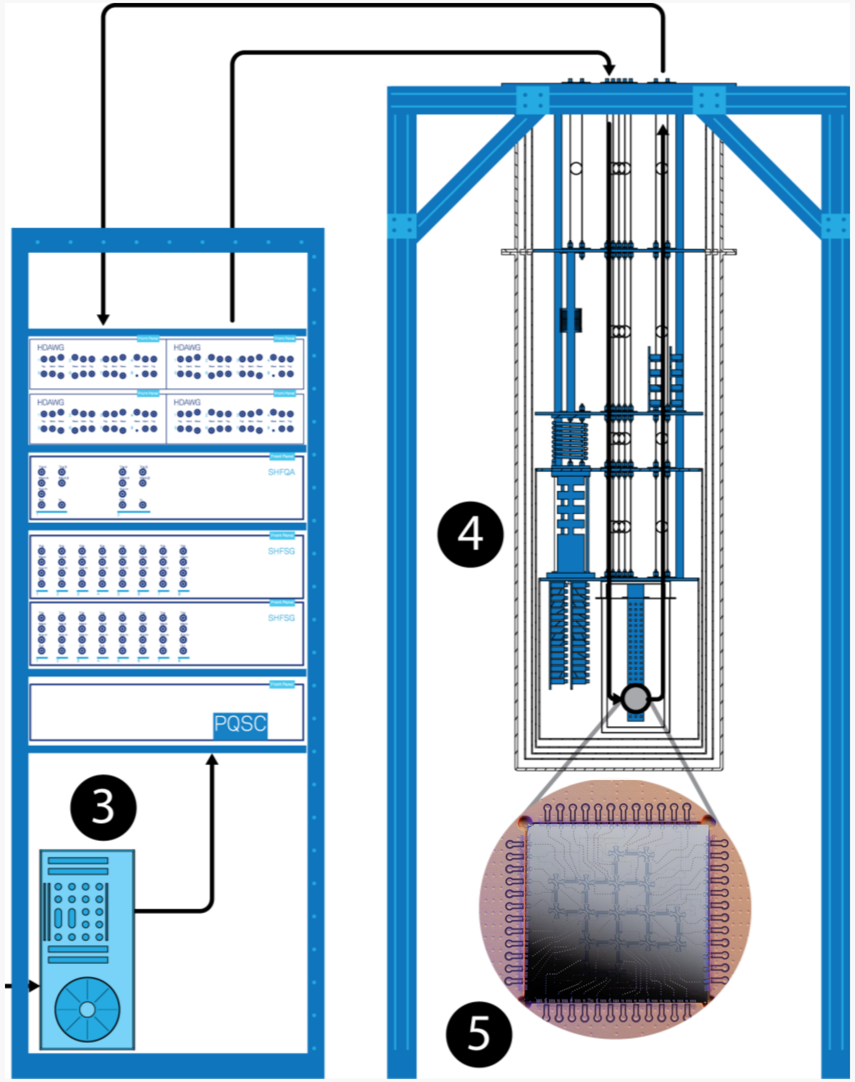
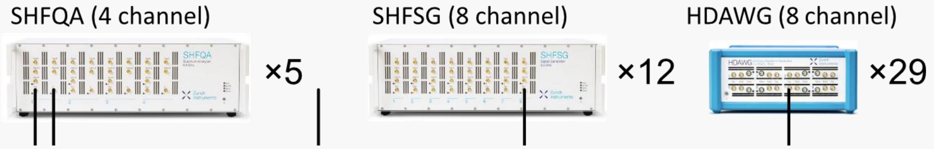
Control electronics

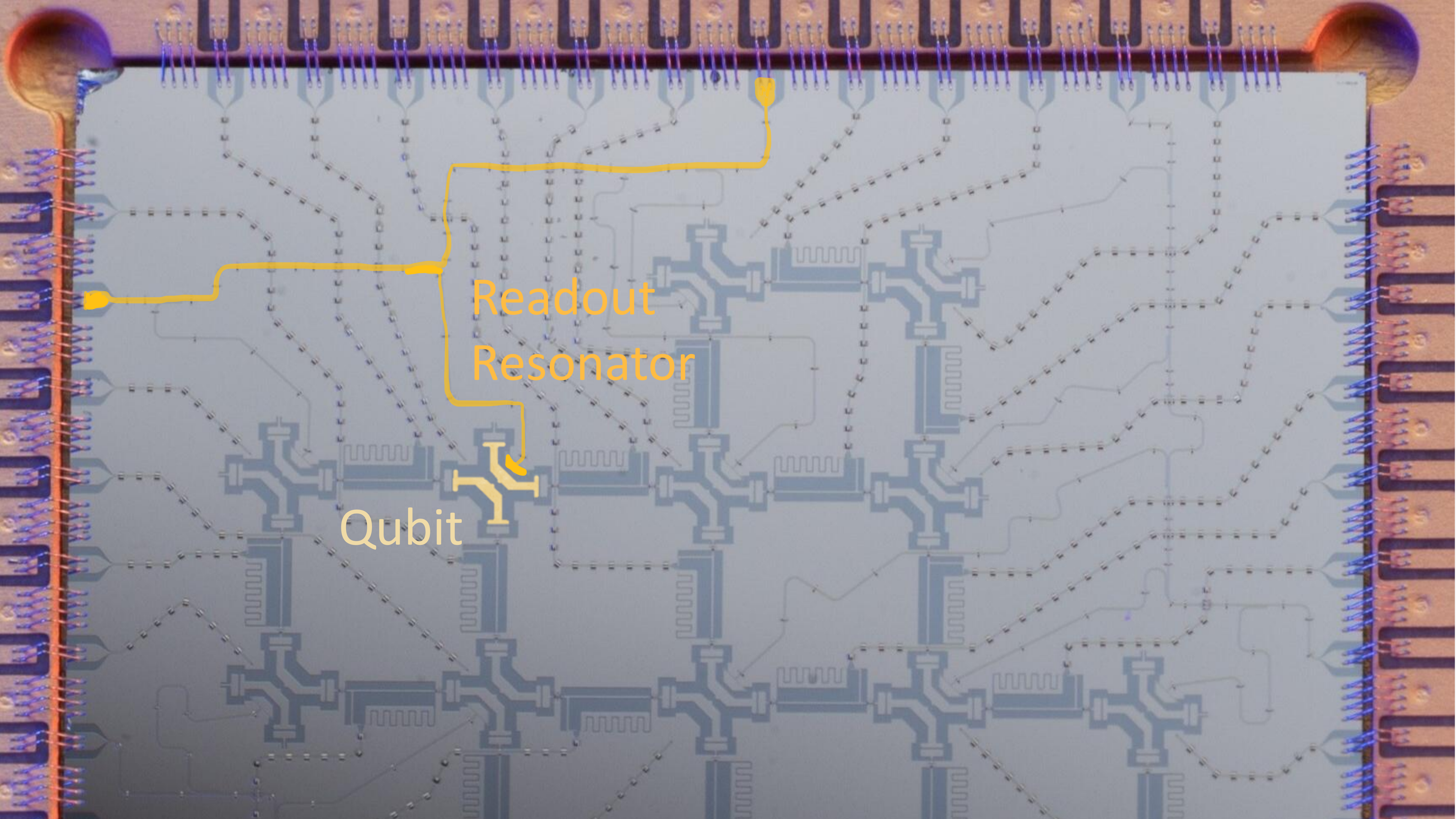




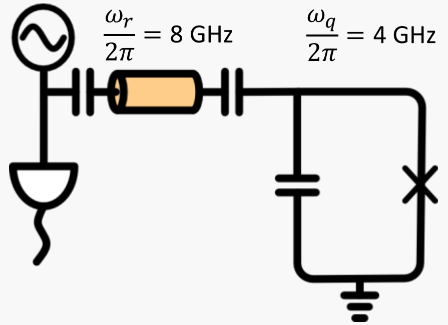


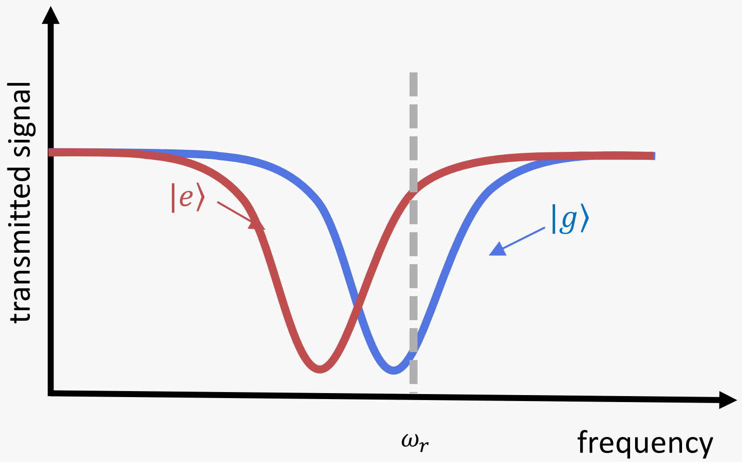
Microwave pulses

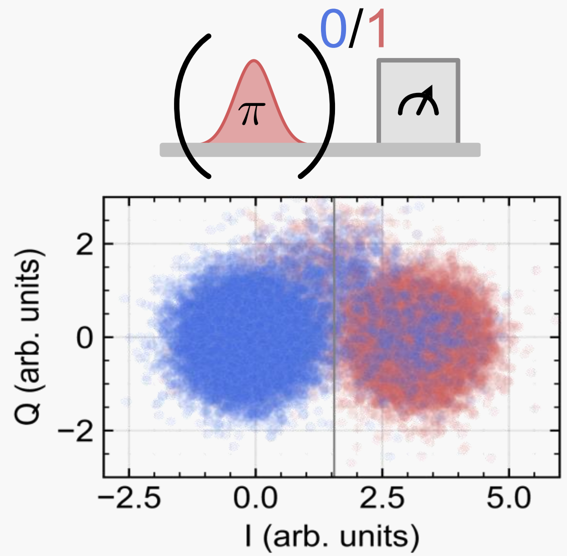
- **Microwave pulses** for **control and readout**
- **Electronics** now commercially available
- Each qubit requires one **AWG/local oscillator**
- Engineering efforts: miniaturization, scaling, multiplexing, feedback

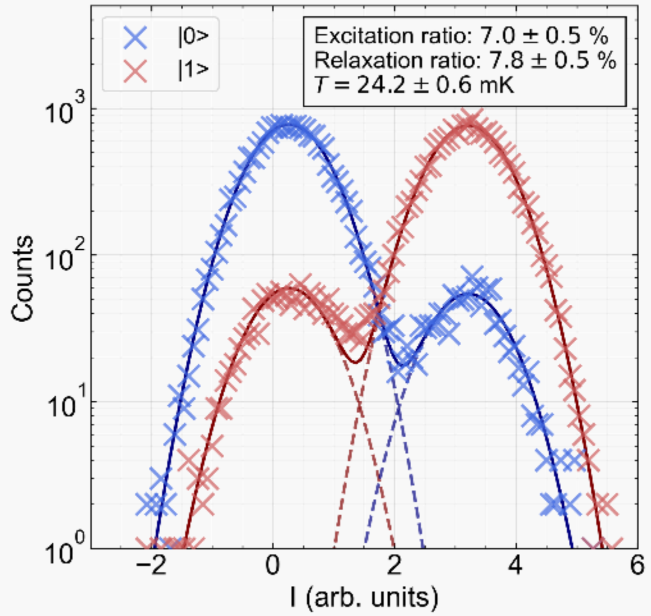

Readout
Resonator
Qubit

Qubit Readout





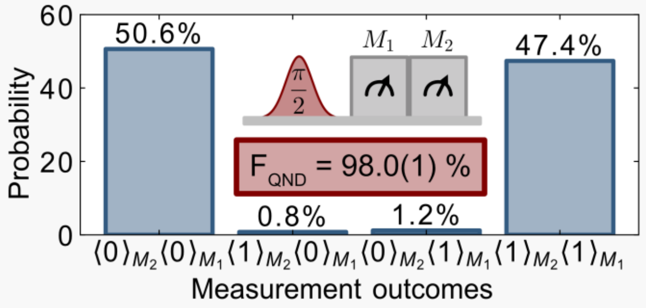




Measurement efficiency

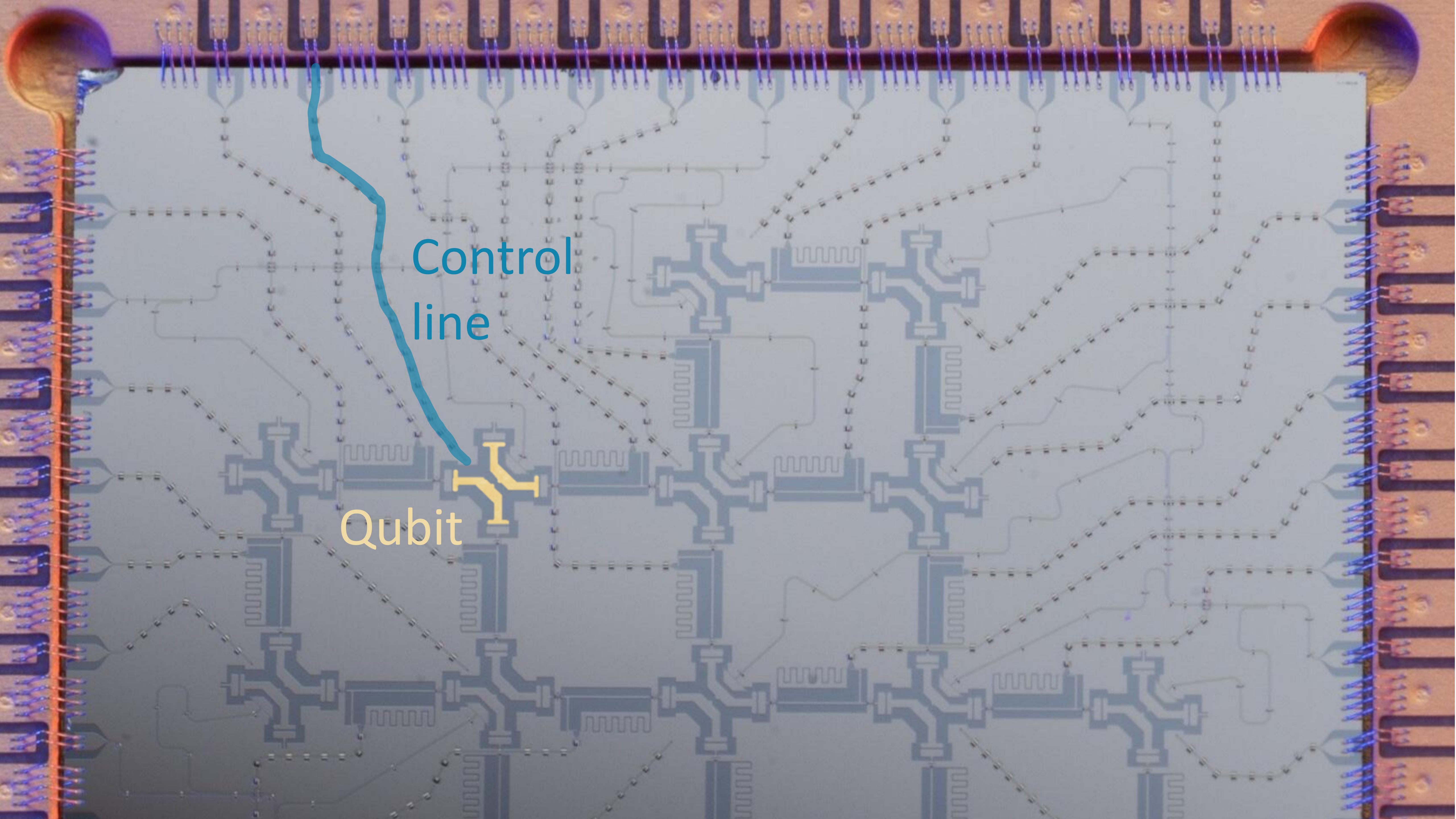
$2\eta = 18.8\ \%$

Readout time: 600 ns

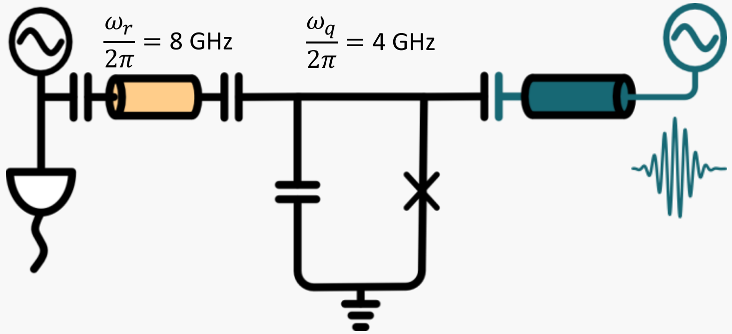


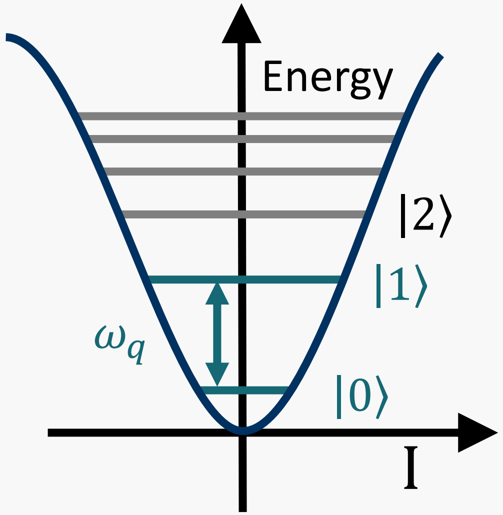
Typical values

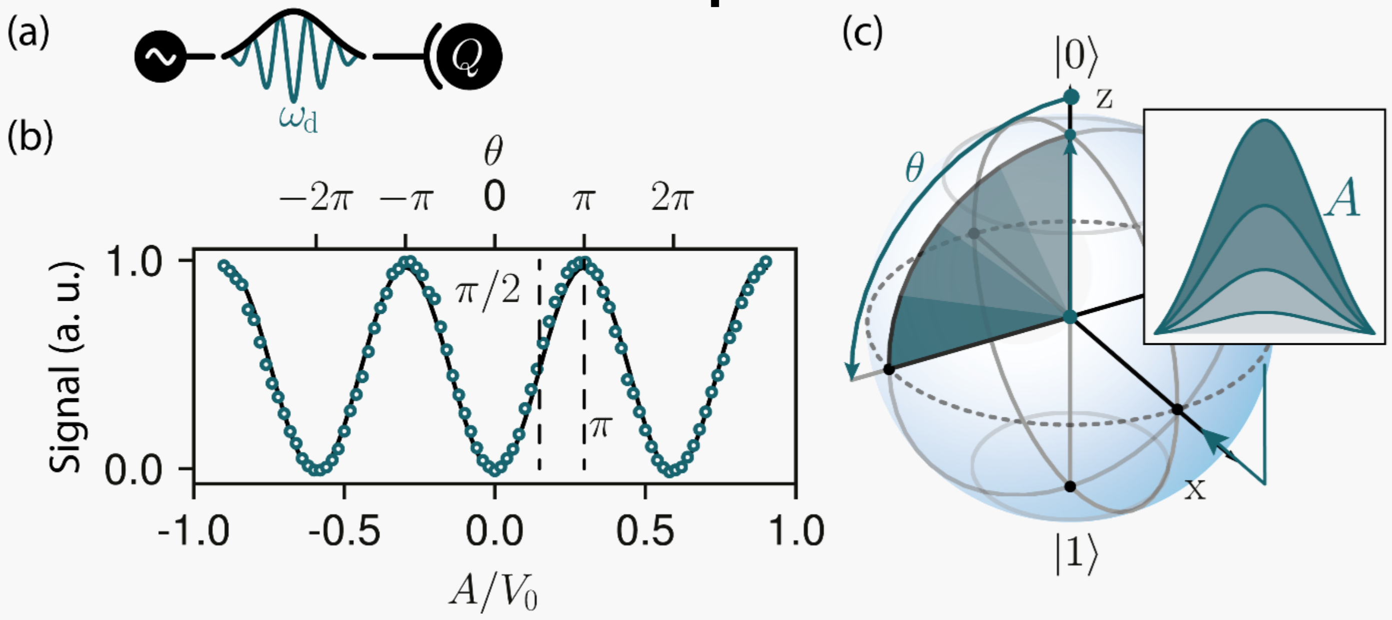
- Readout times: 0.1 to 2 μs
- Readout fidelities: 90 – 99 %


Control
line
Qubit

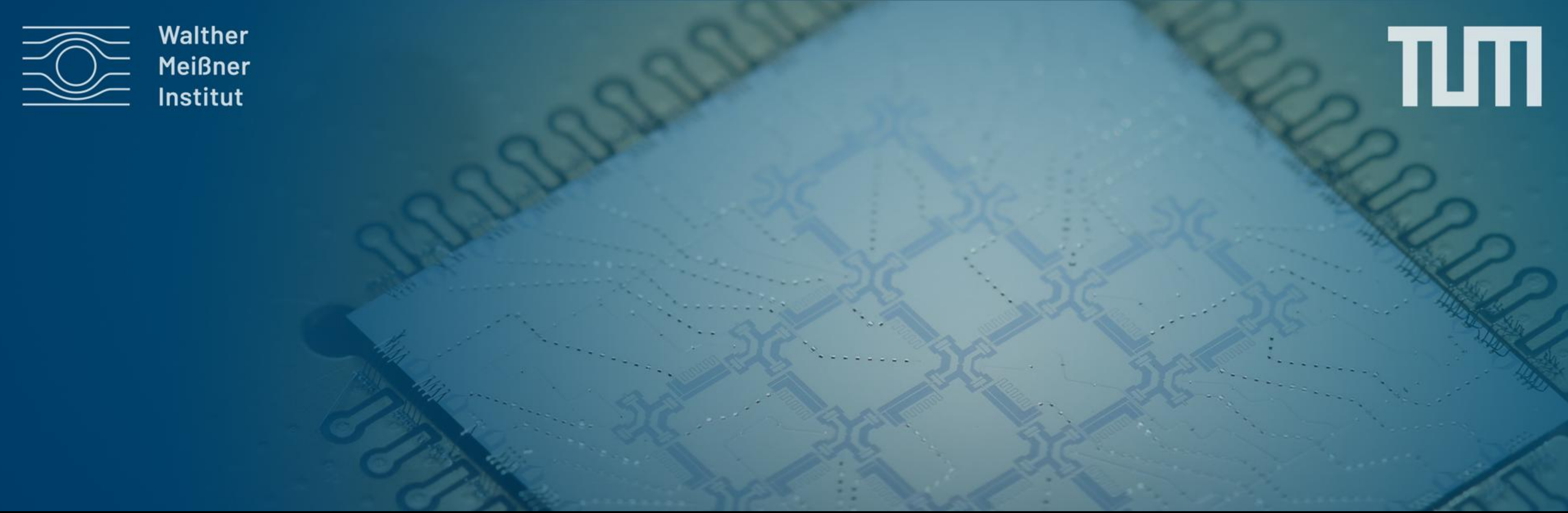
Qubit control







- Control channel for fast & high fidelity control pulses
- Gate times down to 10 ns
- Gate errors < 10^{-3}



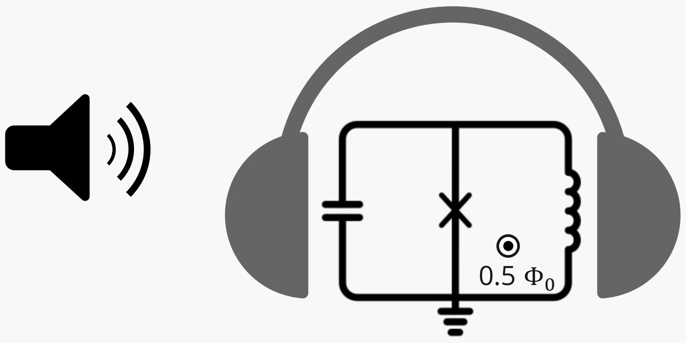
Recent highlight:
Purcell-Protected Fluxonium Control with Sub-Harmonic Driving

What if we have a perfect qubit?

J. Schirk *et al.*, PRX Quantum **6**, 030315 (2025)

Protected Qubit Control

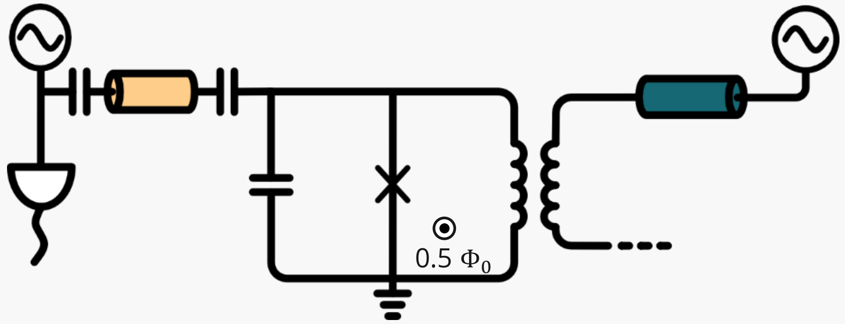
Long coherence



- Requires **decoupling** from the environment
- Achieved through **advances in fabrication** and **design** of superconducting qubits

A. Somoroff *et al.*, PRL **130**, 267001 (2023)

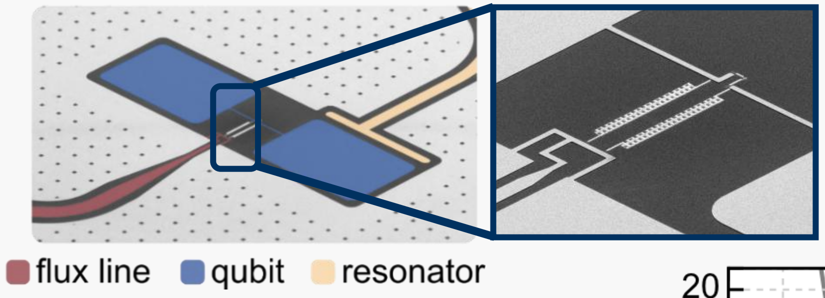
Fast control and readout

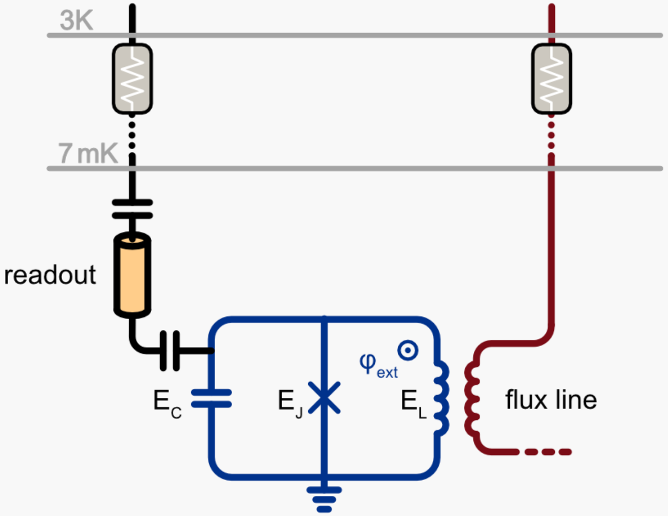


- **Couplings** with the readout and control **environment** are necessary
- **Challenge:** prevent decoherence through engineered coupling channels

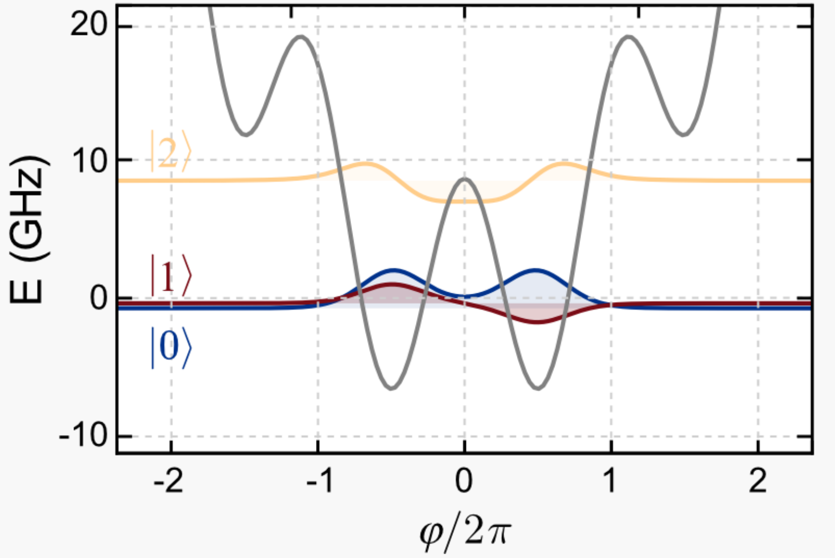
Fluxonium Qubits

V. E. Manucharyan *et al.*, Science **326**, 113 (2009)
L. B. Nguyen *et al.*, PRX Quant. **3**, 037001 (2022)

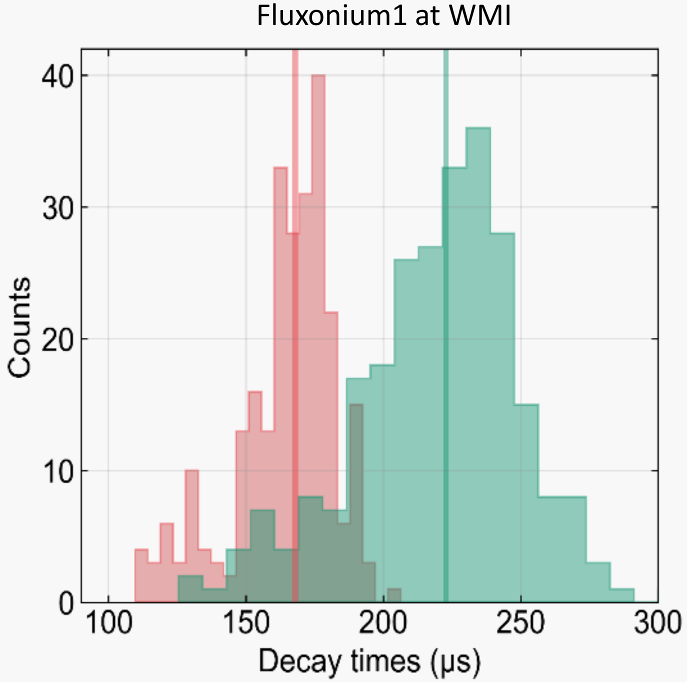




$E_J = 1.69$ GHz
$E_c = 0.68$ GHz
$E_L = 1.07$ GHz
$\boldsymbol{\omega_q} = \mathbf{1.32}$ **GHz**



$$\hat{H} = 4E_C\hat{n}^2 - E_J\cos(\hat{\varphi}) + \frac{1}{2}E_L(\hat{\varphi} - \varphi_{ext})^2$$



$\boldsymbol{T_1 = 167 \pm 19}$ **μs**

$\boldsymbol{T_2^E = 223 \pm 30}$ **μs**

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Fluxonium Qubits

V. E. Manucharyan *et al.*, Science **326**, 113 (2009)
L. B. Nguyen *et al.*, PRX Quant. **3**, 037001 (2022)

Pro

- Record 1-qubit and 2-qubit **gate fidelities**

$$F_{1QB} > 0.9999$$

$$F_{2QB} > 0.999$$

A. Somoroff *et al.*, PRL **130**, 267001 (2023)
L. Ding *et al.*, Phys. Rev. X **13**, 031035 (2023)
H. Zhang *et al.*, arXiv:2309.05720 (2023)
I. N. Moskalenko *et al.*, npj Qu.Inf. **8**, 130 (2022)

- Record **coherence** times

$$T_1 \approx T_2^* \approx 1\ \mathrm{ms}$$

A. Somoroff *et al.*, PRL **130**, 267001 (2023)
F. Wang, *et al.*, arXiv:2405.05481

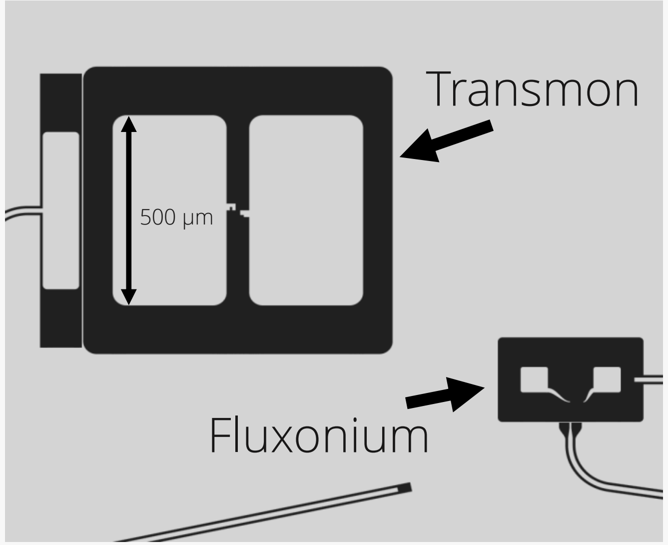
- Tunable noise protection

T. Stefanski, C.K. Anderson arXiv:2309.17286

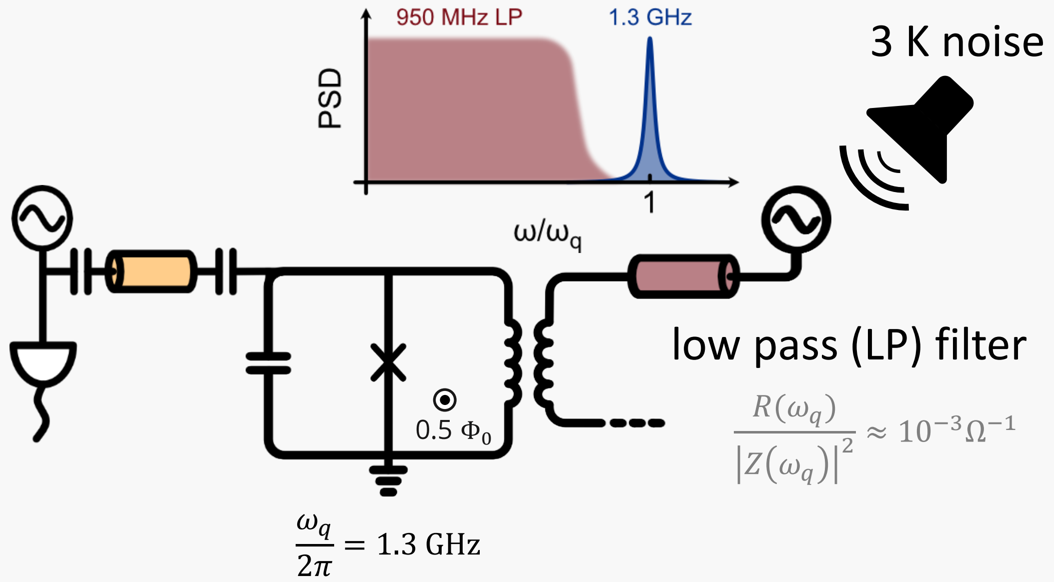
- **Lower crosstalk** due to lower frequencies
- **Less leakage**
- Lower footprint
- Compatible with existing readout chain & control

Con

- More demanding for fabrication:
  $\sim$100 Josephson junctions for a single qubit
- Added noise channel: sensitive to magnetic flux
- No one has demonstrated a scalable architecture



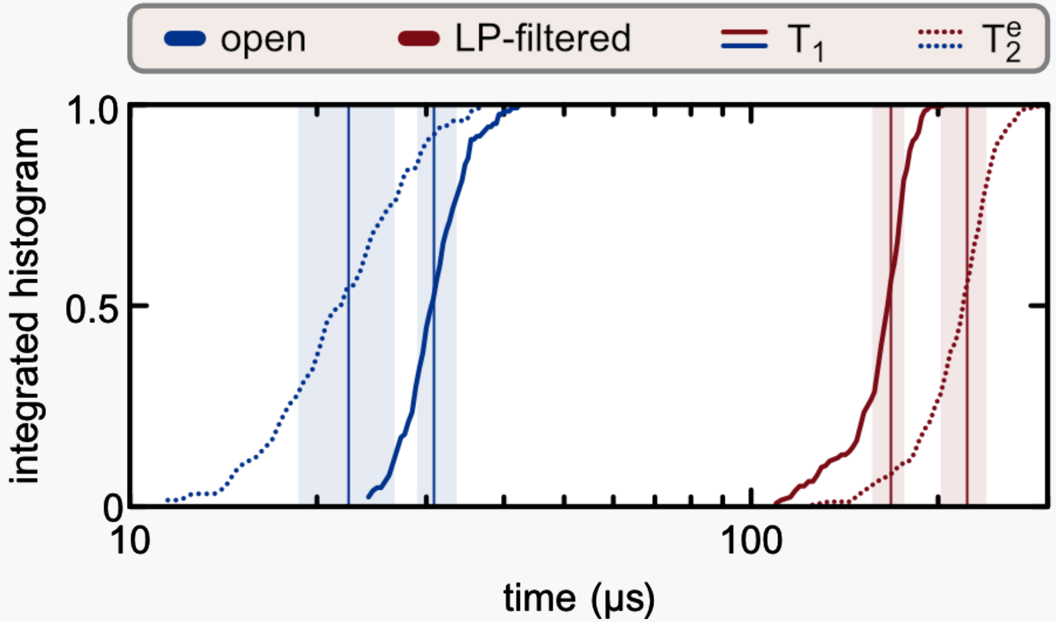
Protecting the Qubit through an Engineered Environment



Fermi's golden rule: $\Gamma = \frac{1}{\hbar^2}\left|\langle 0|\hat{A}|1\rangle\right|^2 S(\omega_\mathrm{q})$

$$S(\omega) = \hbar\omega \frac{R(\omega)}{|Z(\omega)|^2}\left[1 + \coth\left(\frac{\hbar\omega}{2k_BT}\right)\right]$$

Mode density in environment | Spontaneous emission | Stimulated emission



	Un-filtered	LP-filtered	Improvement
T_1	31(5) µs	168(20) µs	$\times$ 5.4
T_2^e	22(8) µs	223(37) µs	$\times$ 10.1
T_eff	245(25) mK	28 (1) mK	$\times$ 8.8

Protection against control environment!

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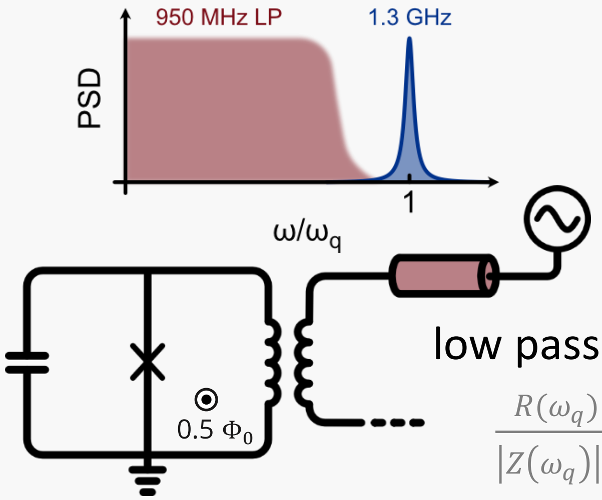
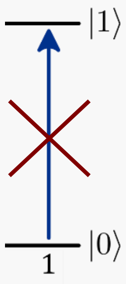
Qubit Control through the Engineered Environment



low pass (LP) filter

$$\frac{R(\omega_q)}{|Z(\omega_q)|^2} \approx 10^{-3}\Omega^{-1}$$

No direct qubit excitation possible!



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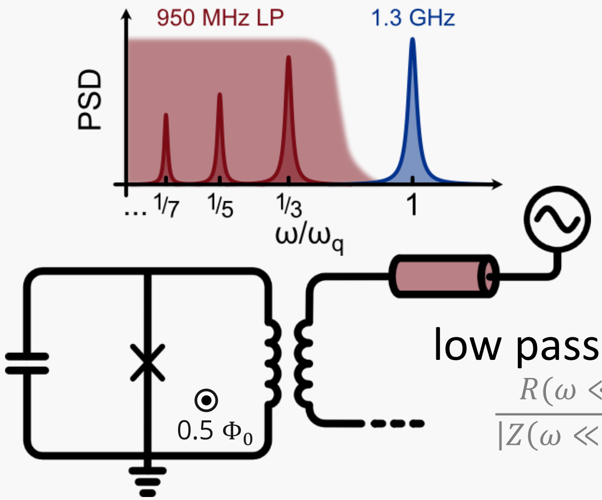
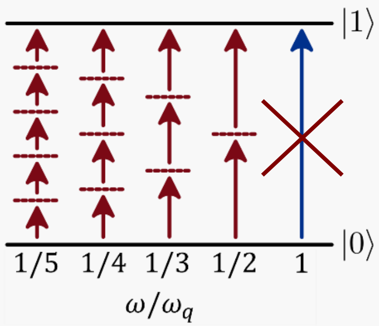
Qubit Control through the Engineered Environment



low pass (LP) filter

$$\frac{R(\omega \ll \omega_{LP})}{|Z(\omega \ll \omega_{LP})|^2} \approx \frac{1}{50\ \Omega}$$

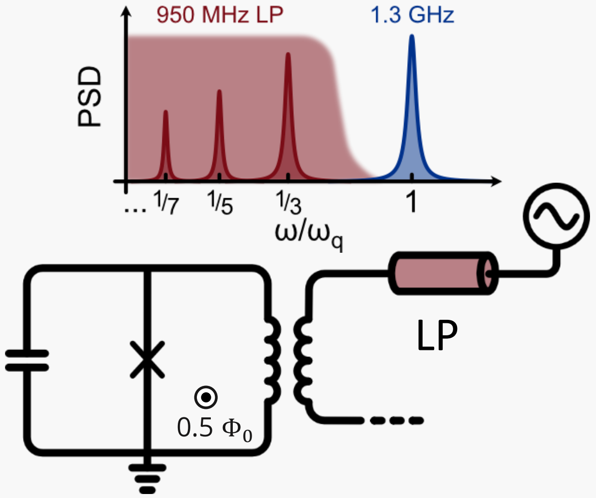
No direct qubit excitation possible!

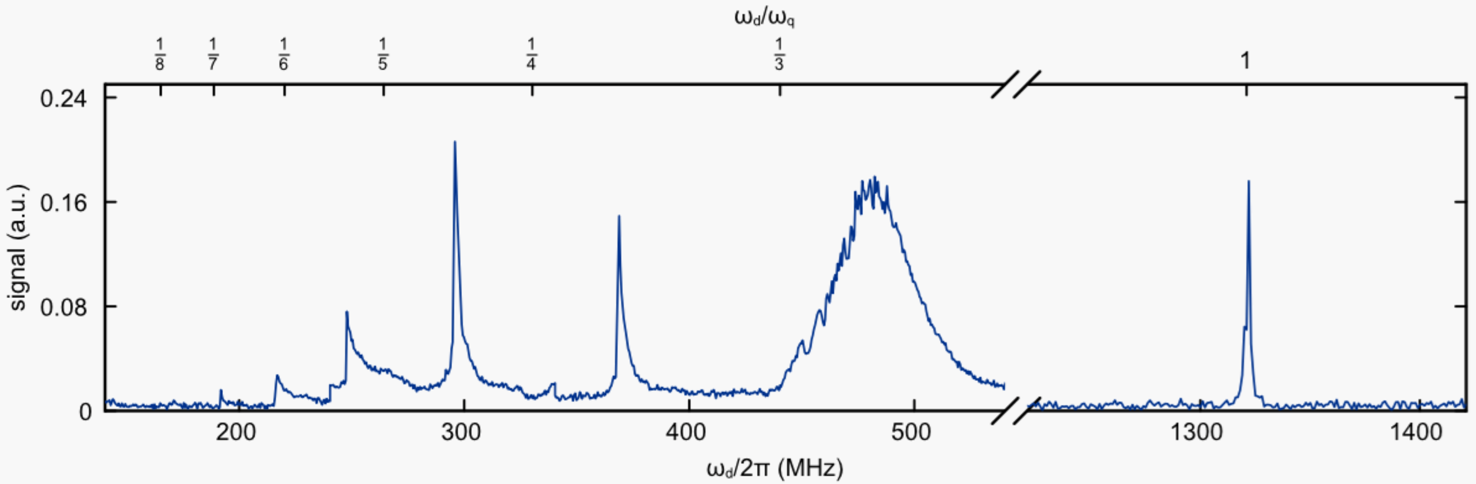


→ Use parametric sub-harmonic multi-photon processes through the flux line

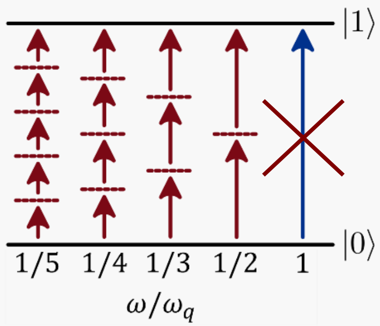
Y. Nakamura, *et al.*, Phys. Rev. Lett. **87**, 246601 (2001)
A. Wallraff, *et al.,* Phys. Rev. Lett. **90**, 037003 (2003)
S. Saito, *et al.,* Phys. Rev. Lett. **93**, 037001 (2004)
C. Liu, *et al.*, PRX Quantum **4**, 030310 (2023)
M. Xia, *et al.*, arXiv:2306.10162 (2023)

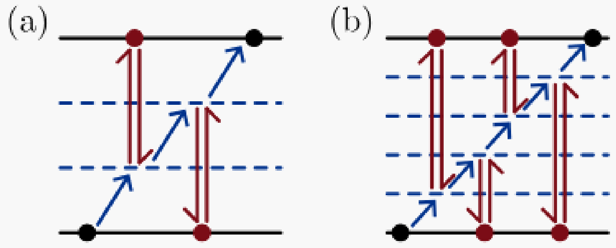
Qubit Control through the Engineered Environment

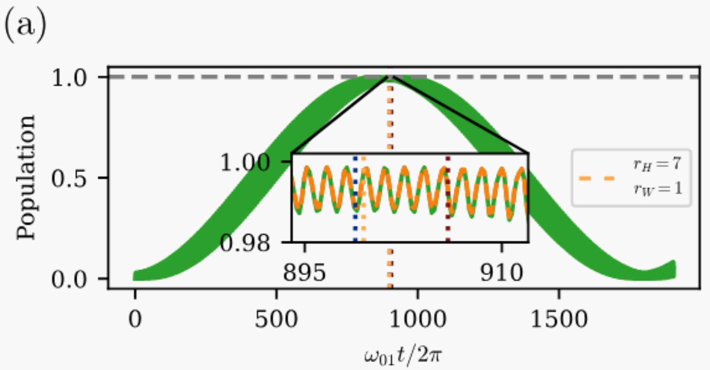




No direct qubit excitation possible!







L. Huang, et al., arXiv:2509.16074

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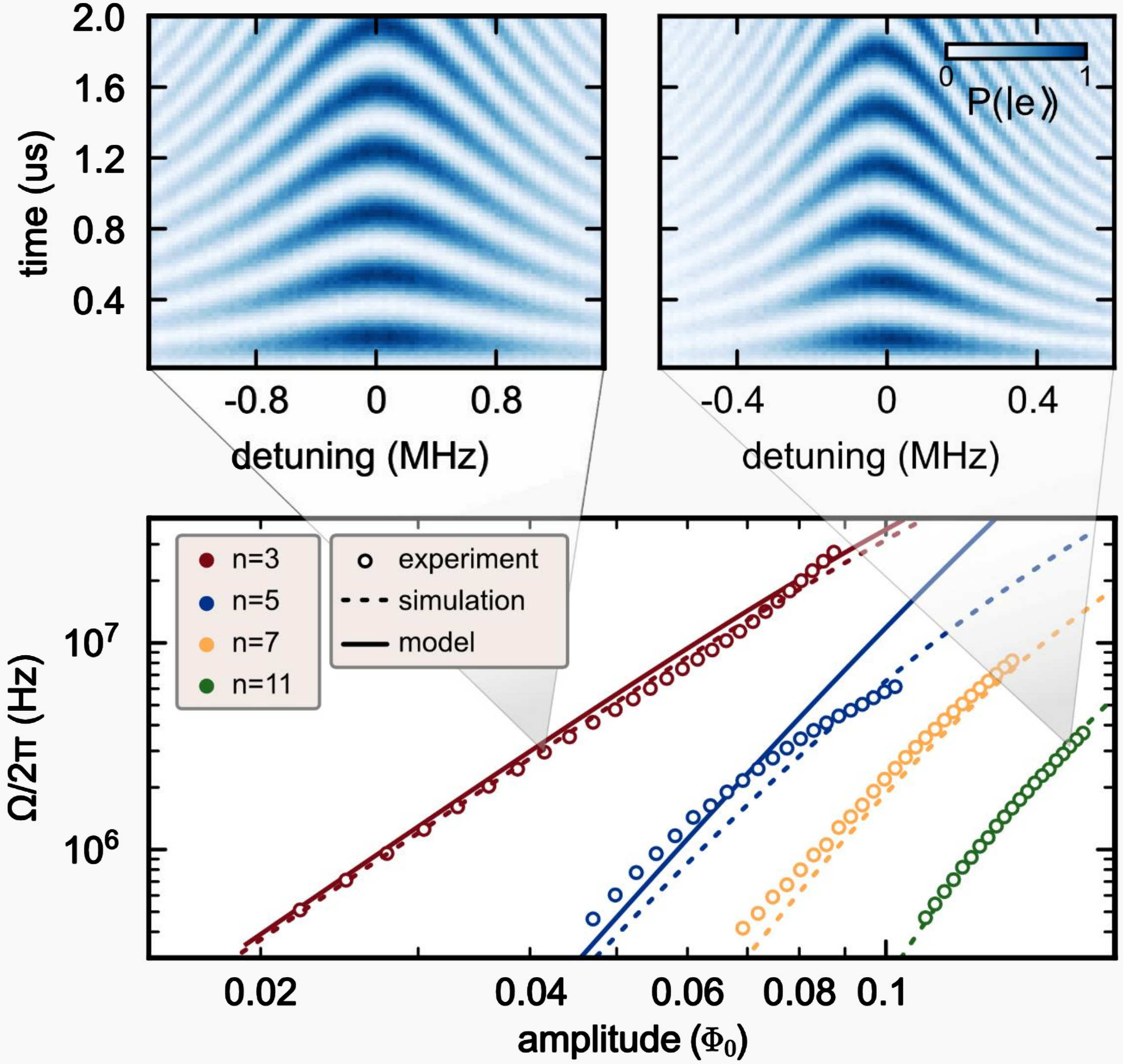
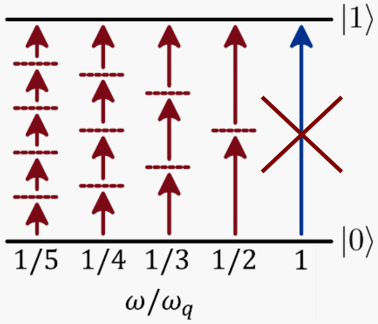
S. Saito, *et al.,* Phys. Rev. Lett. **93**, 037001 (2004)
C. Liu, *et al.*, PRX Quantum **4**, 030310 (2023)
M. Xia, *et al.*, arXiv:2306.10162 (2023)

Coherent Control - Rabi Oscillations

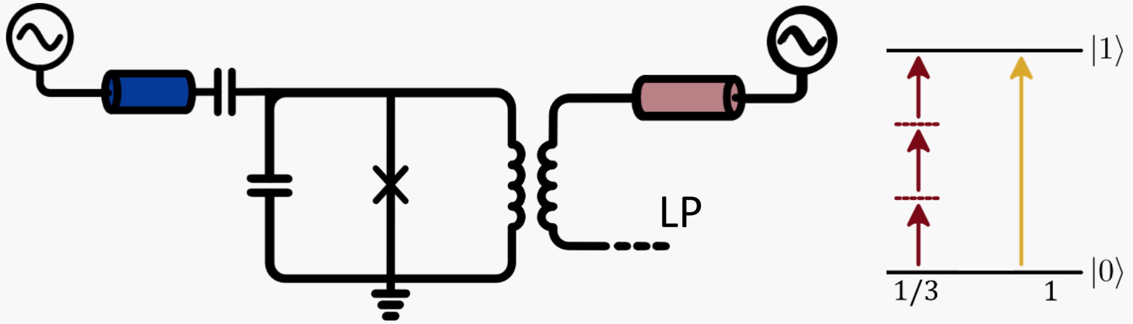


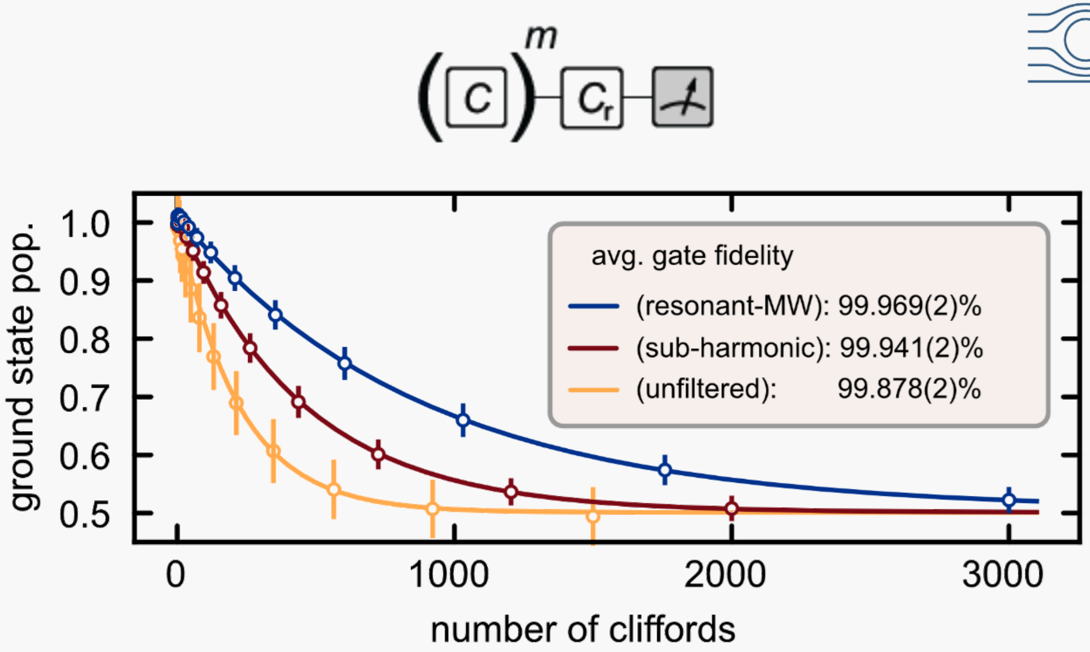


Rabi frequency $\boldsymbol{\Omega_{1/\mathrm{n}} \propto \bar{\phi}^k}$

k = 2.82(3) for 1/3 order
k = 3.25(9) for 1/5 order
k = 4.36(3) for 1/7 order
k = 5.02(6) for 1/11 order

Randomized Benchmarking



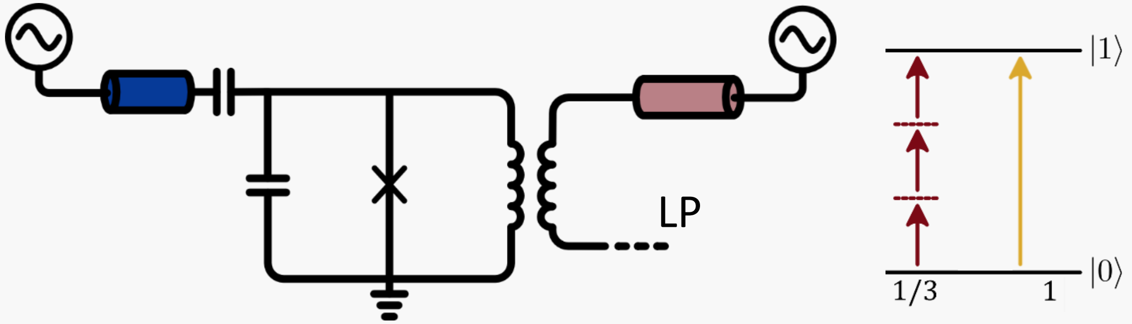


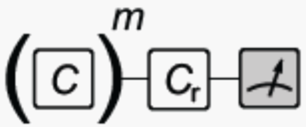
3rd sub-harmonic parametric gate

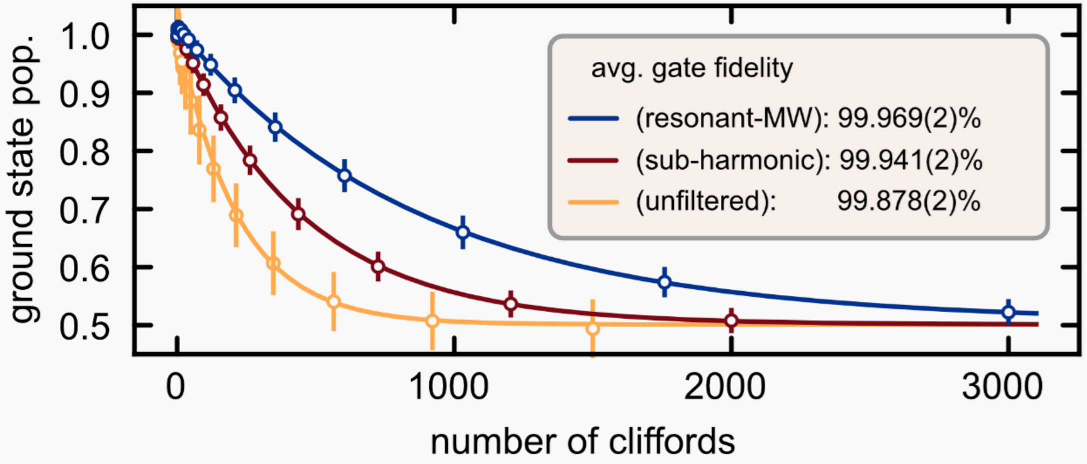
Resonant gates are coherence limited

Sub-harmonic gates getting close to resonant gate performance!

Randomized Benchmarking



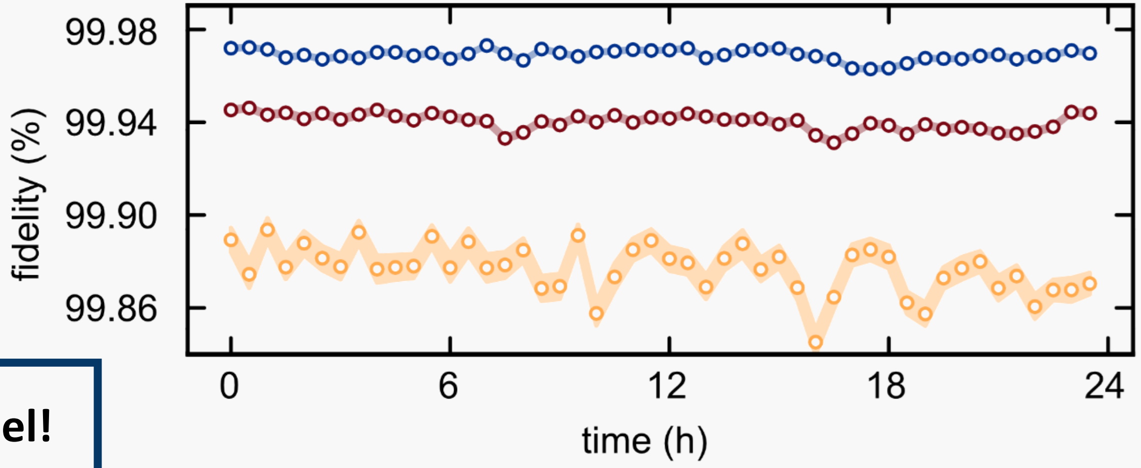




3rd sub-harmonic parametric gate

Resonant gates are coherence limited

Sub-harmonic gates getting close to resonant gate performance!



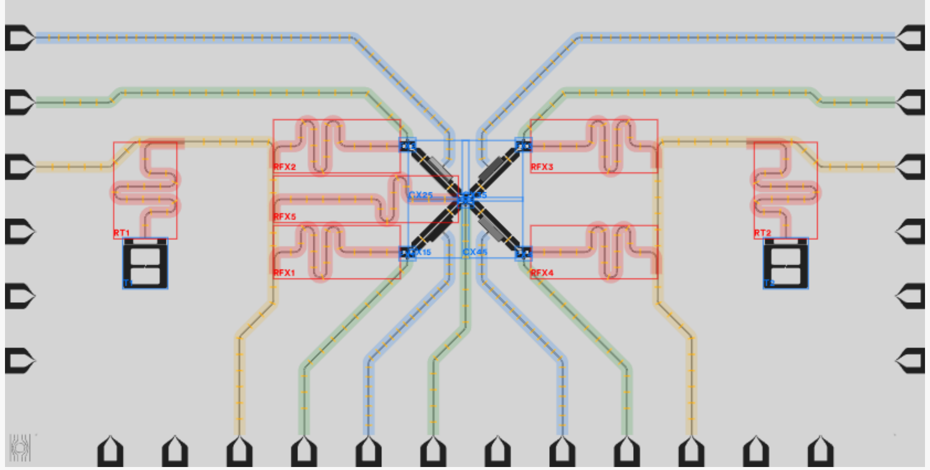
High fidelity qubit control through a protected control channel!

J. Schirk *et al.*, PRX Quantum **6**, 030315 (2025)

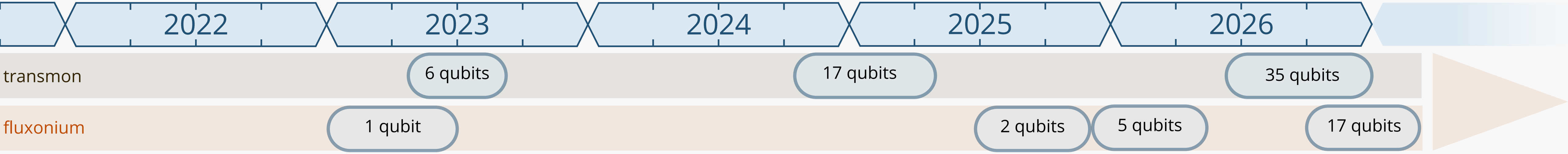
Fluxonium Qubits at WMI

Building a Fluxonium Quantum Processor

- **Transfer** the knowledge and tools developed for **scaling transmons**
- Optimize Fluxonium as a **reliable** building block
- Develop a **scalable architecture** (using **coupling elements)**



Roadmap



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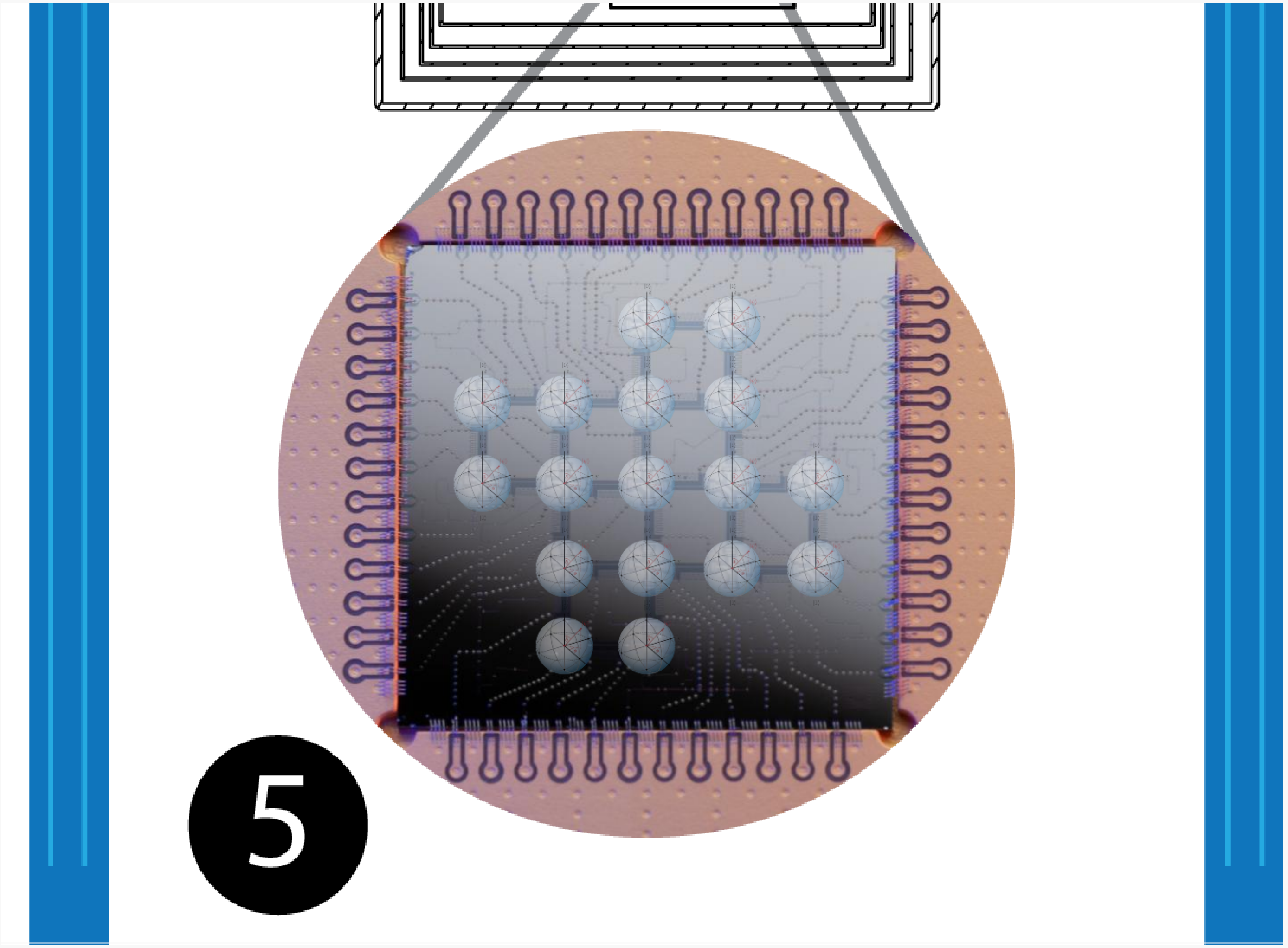
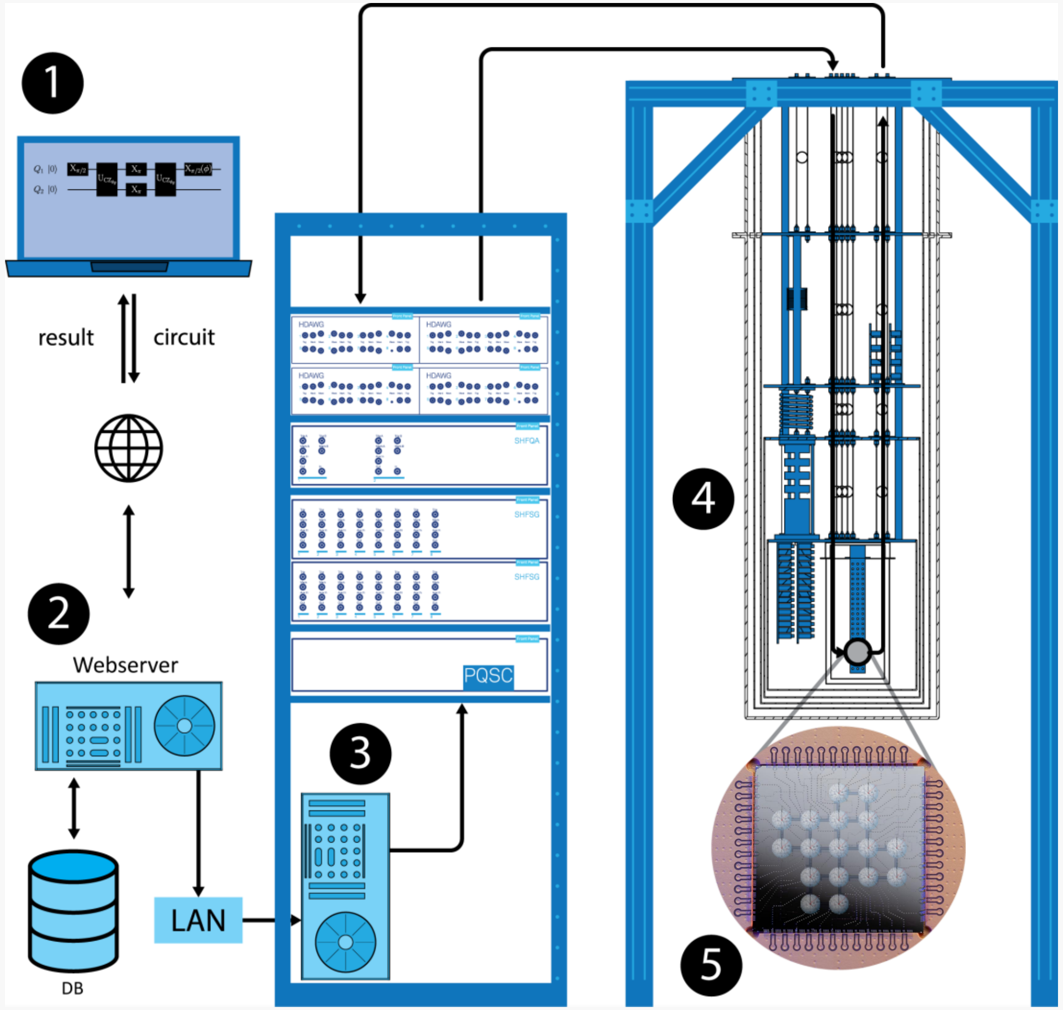
Putting it together → Programmable qubits



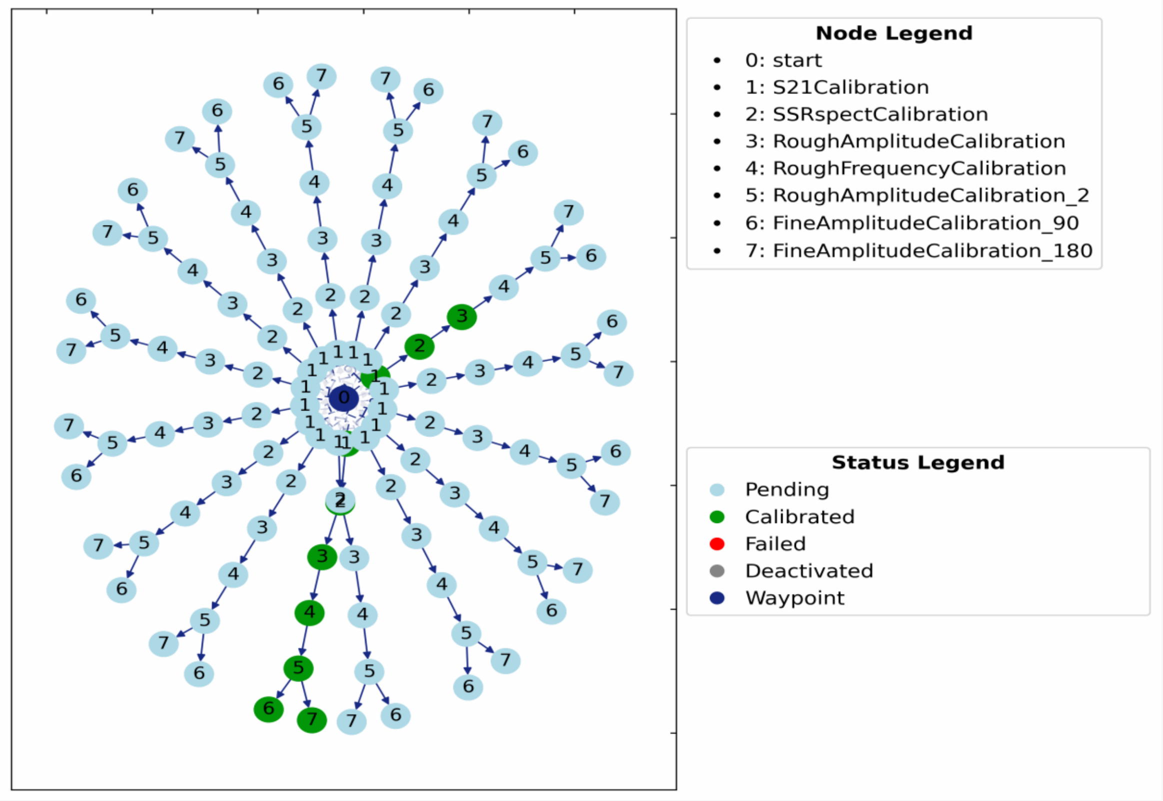
Automatized control and tune-up



Automatize everything:

Tune-up and recalibration of qubits

(in collaboration with Zürich Instruments)



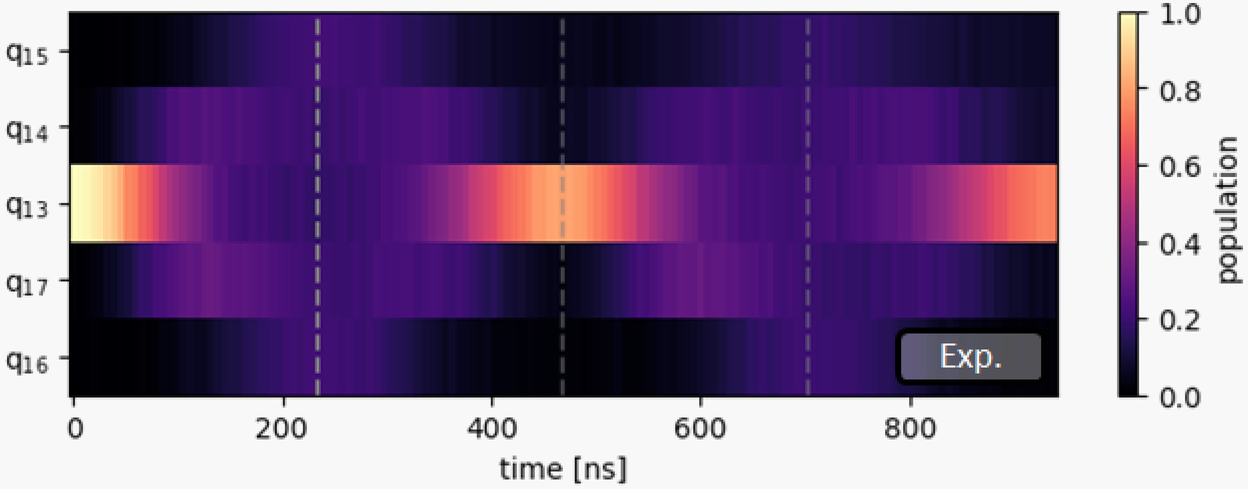
Automatized control and tune-up

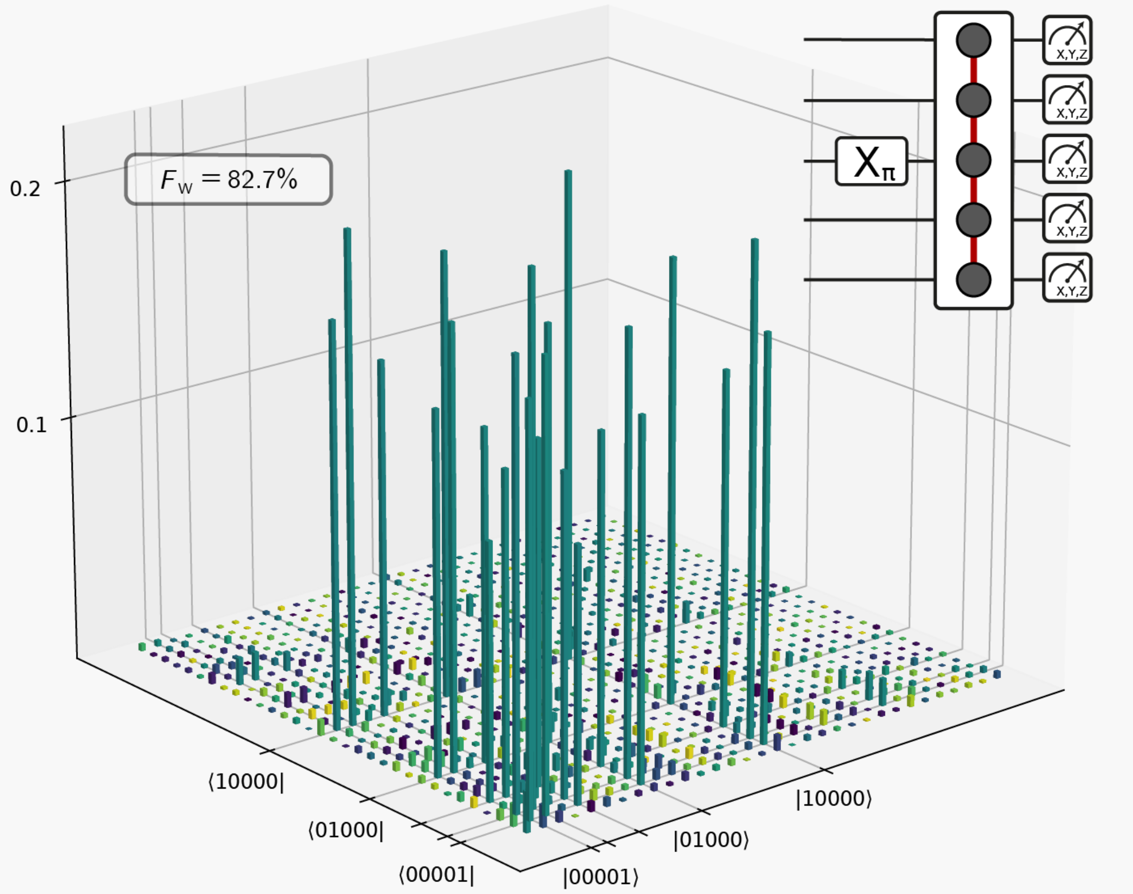
Calibration Workflow

Getting entangled

Preliminary!

- Simultaneous operation of couplers in a qubit chain or lattice to efficiently generate **fully-entangled** W states.
- **Demonstrated** on chains of up to 5 qubits with $F_W = 82.7\%$
- 5-qubit operation takes **240ns**.





- To be implemented in larger chains and higher **connectivies**.

J.H. Romeiro, *et al.,* in preparation (2026)
F. Roy, J.H Romeiro, *et al.,* Nat. Comm. **16**, 2660 (2025)

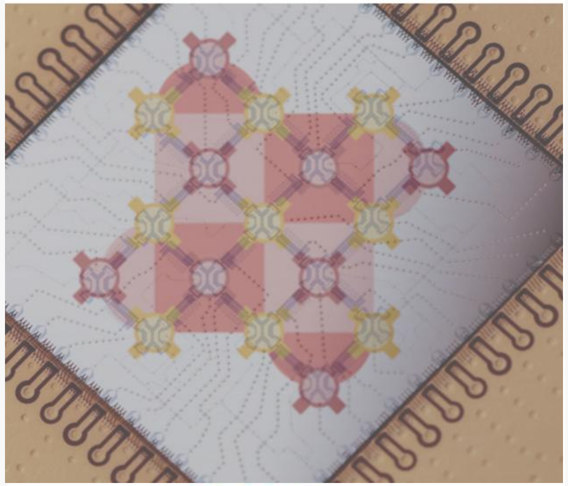
Quantum Error Correction

$$p_L \propto \left(\frac{p_{\mathrm{phys}}}{p_{\mathrm{thresh}}}\right)^{d+1/2}$$

Surface code: $p_{\mathrm{thresh}} \approx 1\,\%$

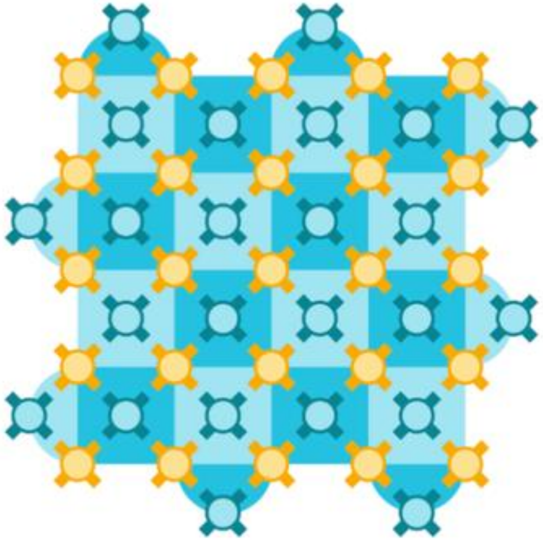
1 Logical Qubit encoded in

[[9,1,3]]



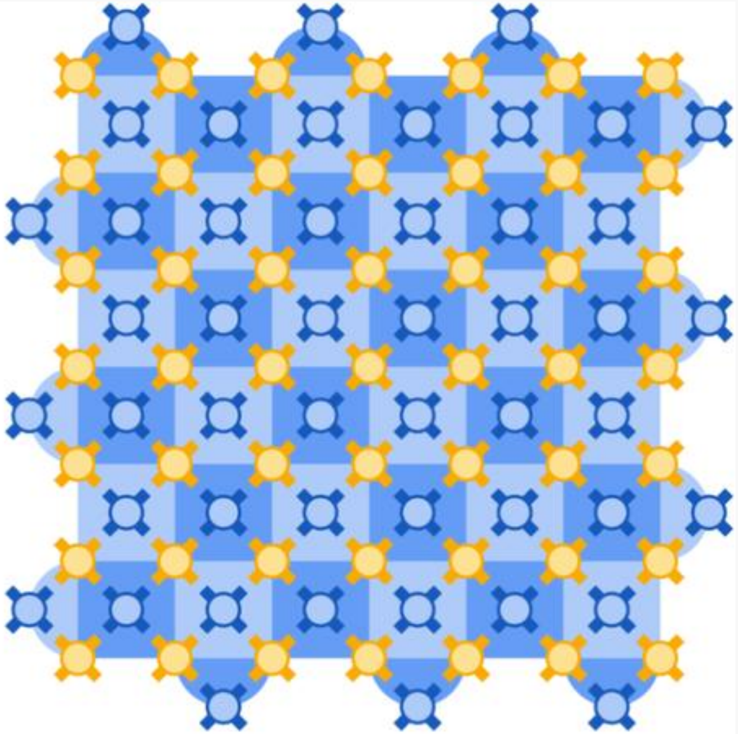
“1 error at a time”
17 qubits

[[25,1,5]]



5x5
“2 errors at a time”
49 qubits

[[49,1,7]]



7x7
“3 errors at a time”
97 qubits

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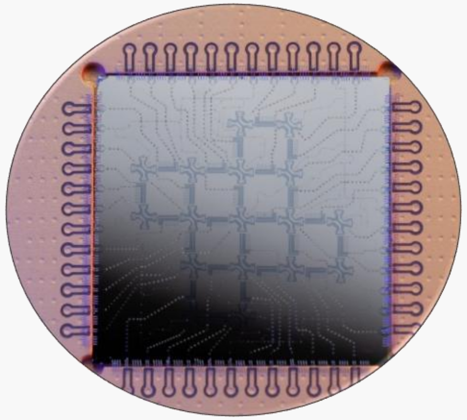
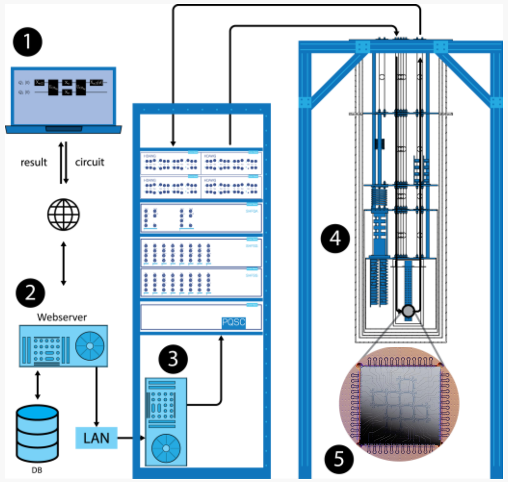
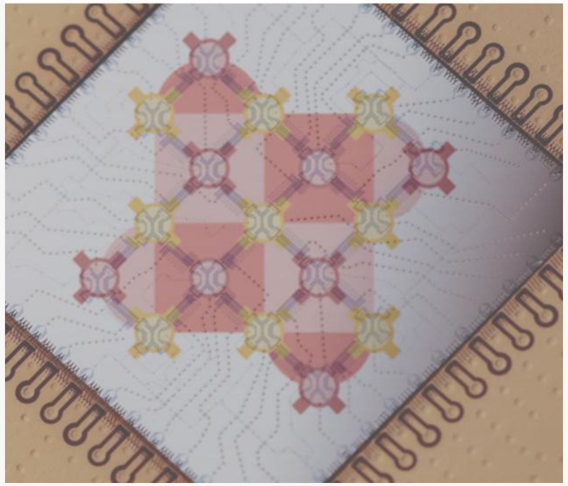
Google Quantum AI, Nature 638, 920-926 (2025)







How to get qubits

17 Transmon chip @ WMI

Development of drop-in replacements: fluxoniums, p-mon, ….

How to program qubits

Readout and control infrastructure to support 100 qubits

Automated tune-up, purcell-protected control scheme

How to use qubits

Entangling Qubits

Towards Error Correction

2022 2023 2024 2025 2026

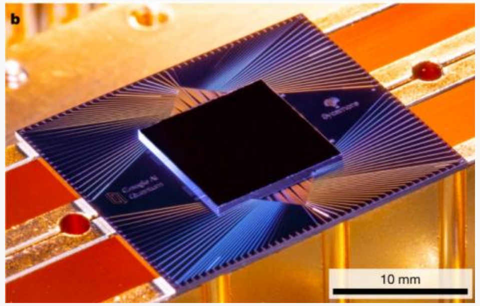
transmon: 6 qubits (2023), 17 qubits (2024–2025), 35 qubits (2026)

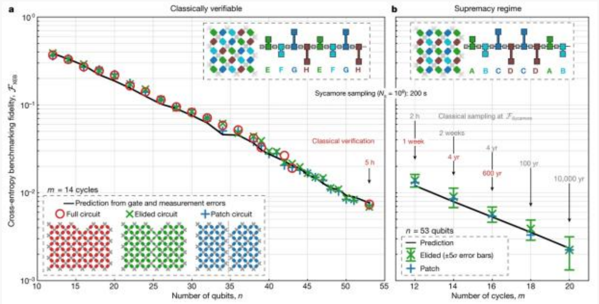
fluxonium: 1 qubit (2022–2023), 2 qubits (2025), 5 qubits (2025–2026), 17 qubits (2026)

State of the art

Quantum Supremacy

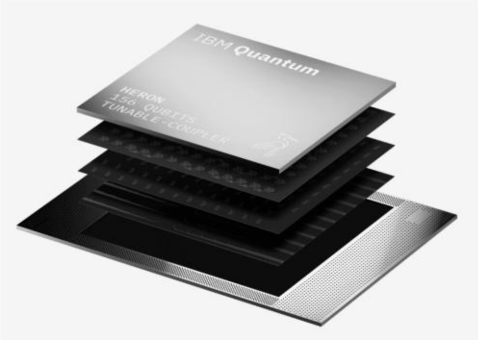
Google Quantum AI, Nature **574**, 505-510 (2019)
Hefei's Zuchongzhi 3.0, PRL **134**, 090601 (2025)
53 Qubits
$T_1 = 15.5\ \mu s$ (median)
$F_{1Q} = 99.81\ \%$ | $F_{2Q} = 99.7\ \%$

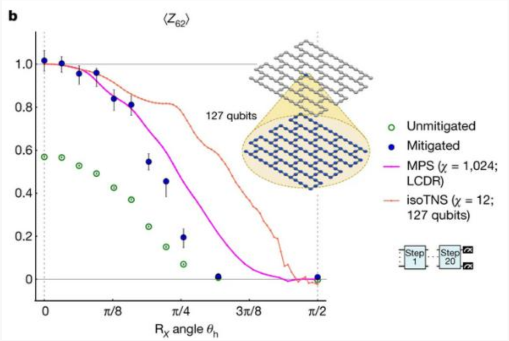




Quantum Utility

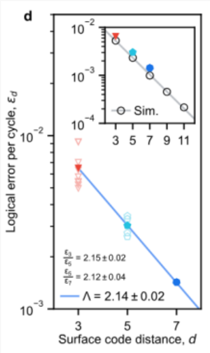
IBM, Nature **618**, 500-505 (2023)
127 Qubits
$T_1 = 287\ \mu s$ | $T_2 = 127\ \mu s$ (median)
$F_{1Q} = 99.96\ \%$ | Fidelity $F_{2Q} = 99\ \%$

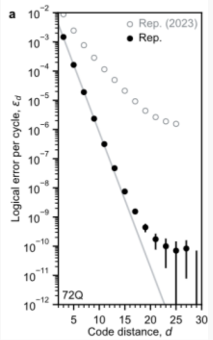




Quantum Error Correction

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
$T_1 = 68\ \mu s$ | $T_2 = 87\ \mu s$ (median)
$F_{1Q} = 99.93\ \%$ | $F_{2Q} = 99.7\ \%$





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

Walther Meißner Institut

Thank you for your attention

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Max Werninghaus

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Gerhard Huber
Kevin Kiener
Martin Knudsen
Leon Koch
Frederik Pfeiffer
Lea Richard
Joao Romeiro
Johannes Schirk
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Lukas Vetter
Matthias Zetzl

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