Walther-Meißner-Institut
DER BAYERISCHEN AKADEMIE DER WISSENSCHAFTEN

Quantum information processing with superconducting circuits

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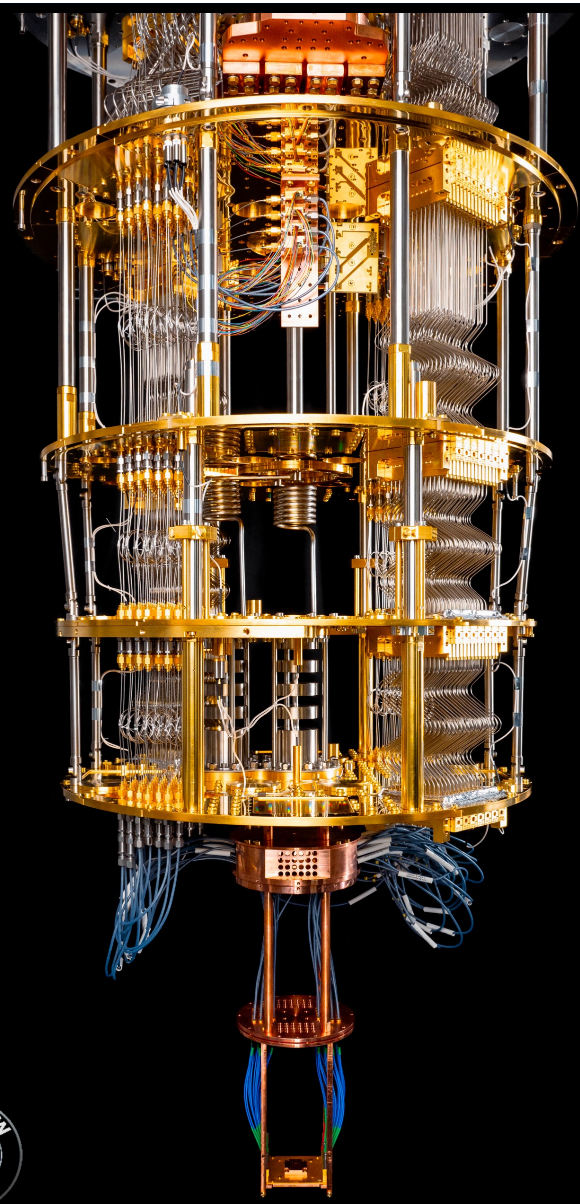
HLL Opening Symposium, Garching – Oct 8, 2024



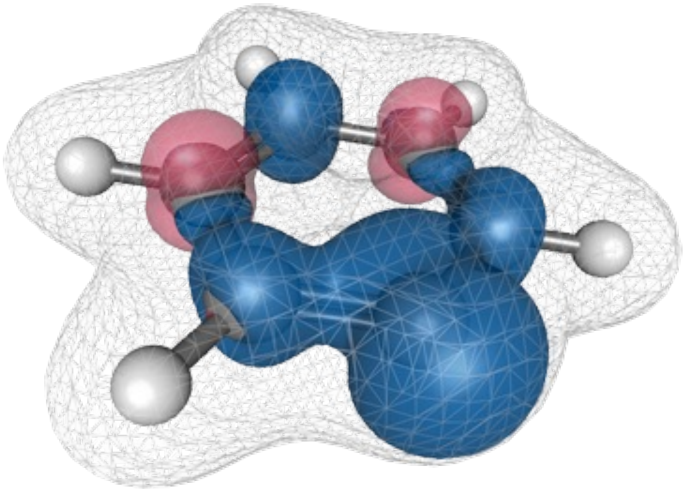
Quantum Computing to solve intractable problems

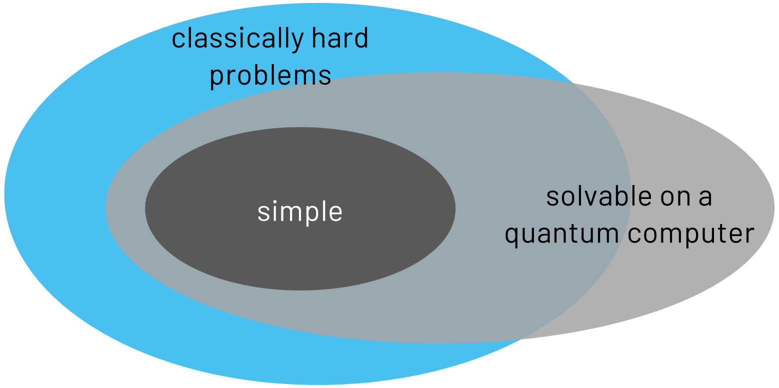
Many problems in science and business are too complex for classical computing systems!

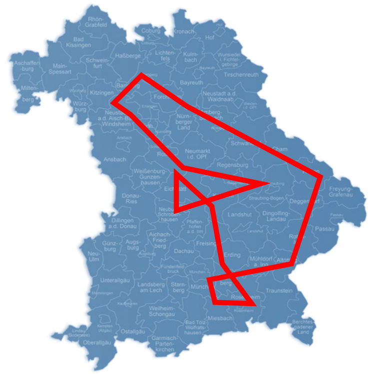
Simulation of quantum-mechanical systems:
Chemistry, material science,...

Algebraic algorithms:
Machine learning, cryptography, ...

Optimization problems:
Travelling salesman, logistics, portfolio optimization







Challenge:

Realization of a quantum computer with many (1.000.000+) **good qubits** and **high-fidelity gate operations**

Factoring Numbers (Shor's Algorithm)

The problem of multiplication vs factoring:

3 x 5 = 15
29 x 47 = 1363
→ easy!

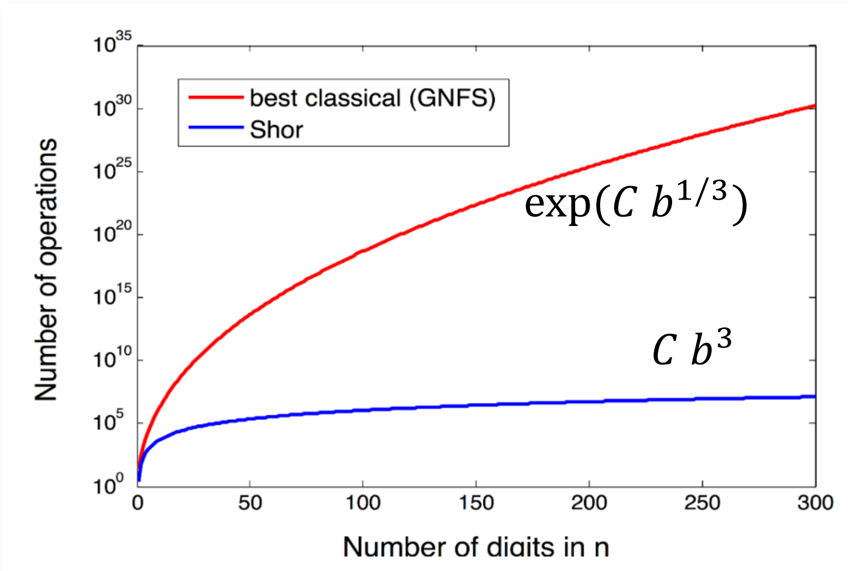
Vs.

35 = 5 x 7
1711 = 29 x 59
→ hard!

1024 bit – number:
6840125346266703910299476456048009922209314
9989331030295165931443599135301801722012147060
5413209954499422279093750218860993825228288
5928598498460373901639820978437936108085233 5
6222568724634919656824685012711832466570372 81
2969247294818566930469719541057172136556101 20
393542415375408830748739559265912349073090

= p × q

→ just short of impossible



Exponential speed-up:
A task taking 300 years (2^{33} seconds) on a classical computer might take a minute (~ 30 seconds) on a quantum computer

Shor's algorithm jumpstarted interest in quantum computing!

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Optimization

TUM

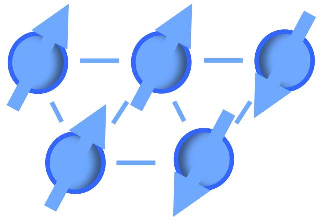
Traveling Salesman Problem (NP hard):

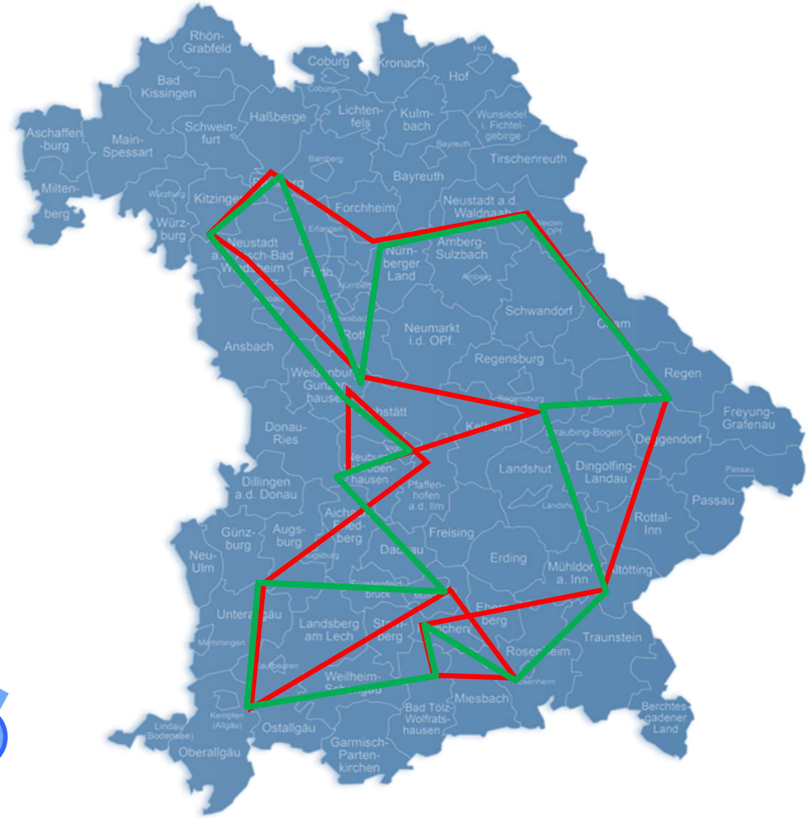
- visit all cities just once
- choose the shortest path
- come back to starting point

17 x … x 5 x 4 x 3 x 2 x 1 = 17! =
355’687’428’096’000 possible paths

can be encoded into a quantum physics problem:
find the ground-state of a spin (qubit) system,
which encodes the optimal path

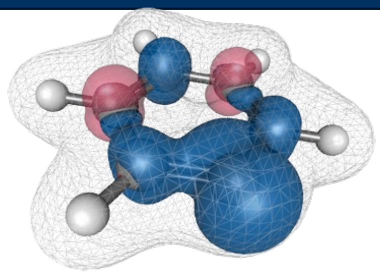
(at least) quadratic speedup expected



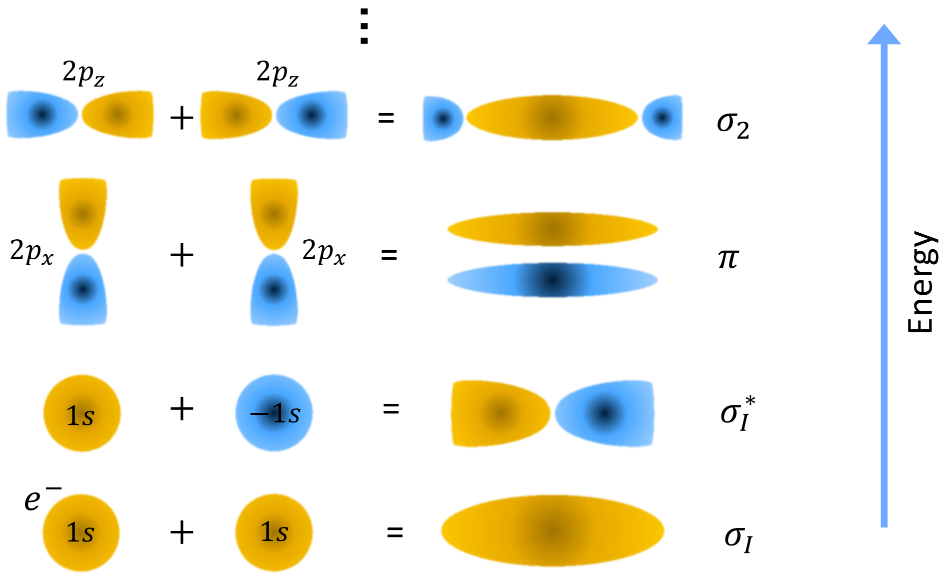


18 locations in Bavaria

Quantum chemistry – Why is it a challenge?



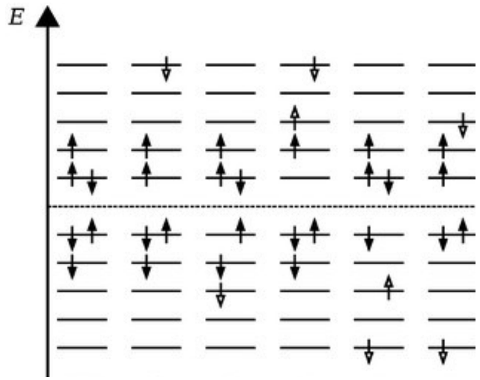
Electrons can occupy different orbitals in many possible combinations (e.g. in hydrogen H_2)



$$\frac{M!}{(M-N)!\,N!}$$

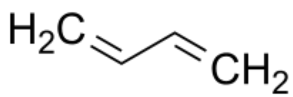
M: # orbitals

N: # electrons



$\approx 2^{65}$ possibilities

for M=82,N=22



(Butadien)

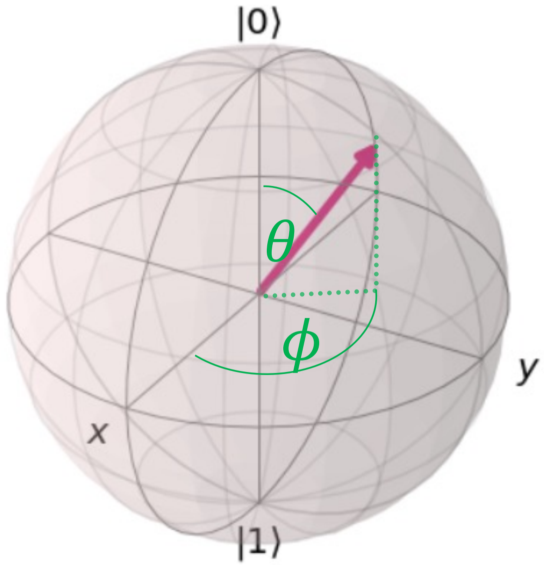
Exponential quantum advantage when electron wavefunction is stored directly in a quantum system

What are the basic units of information?

Classical Bit

0 or 1

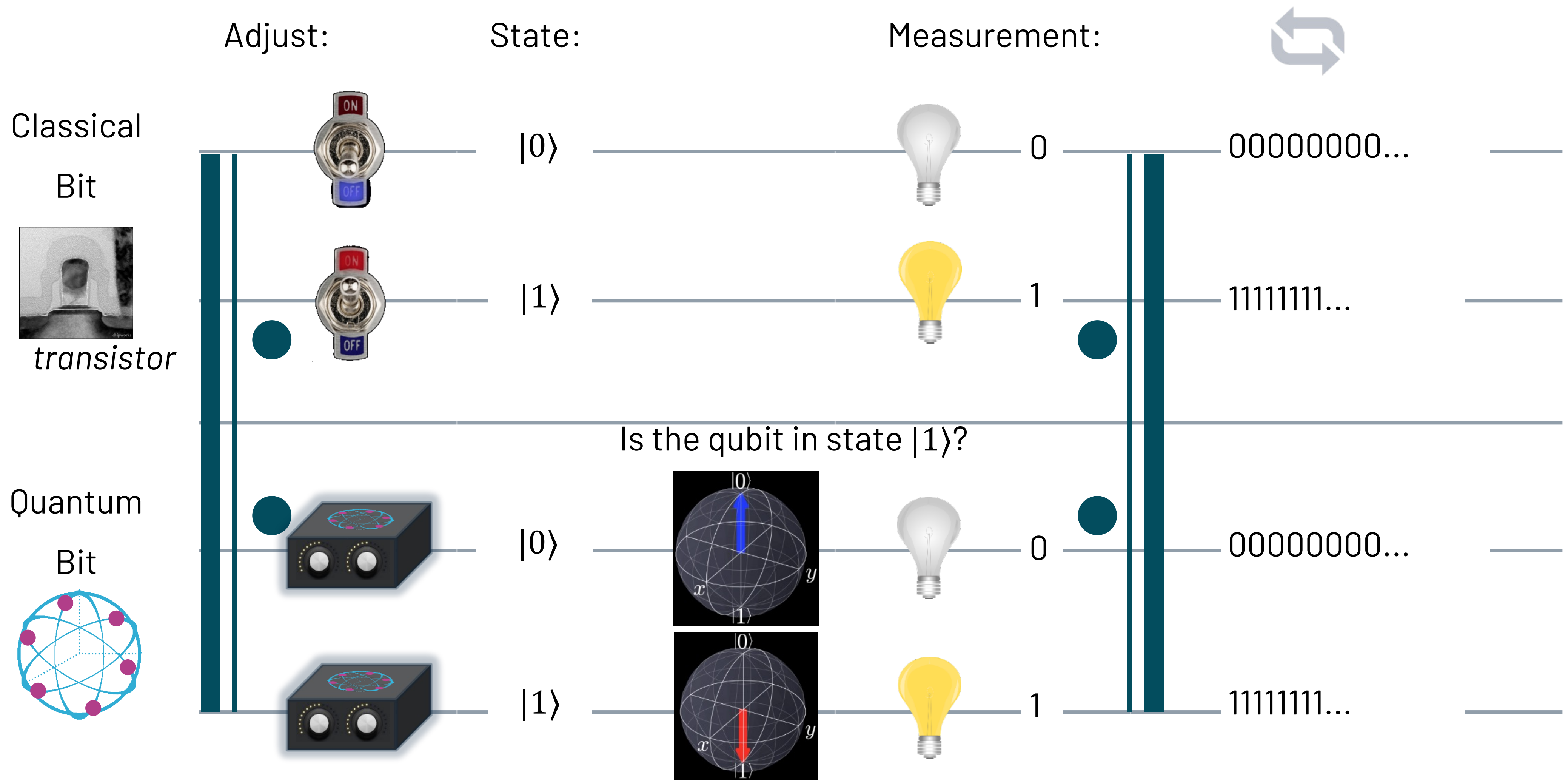
Quantum Bit (Qubit)



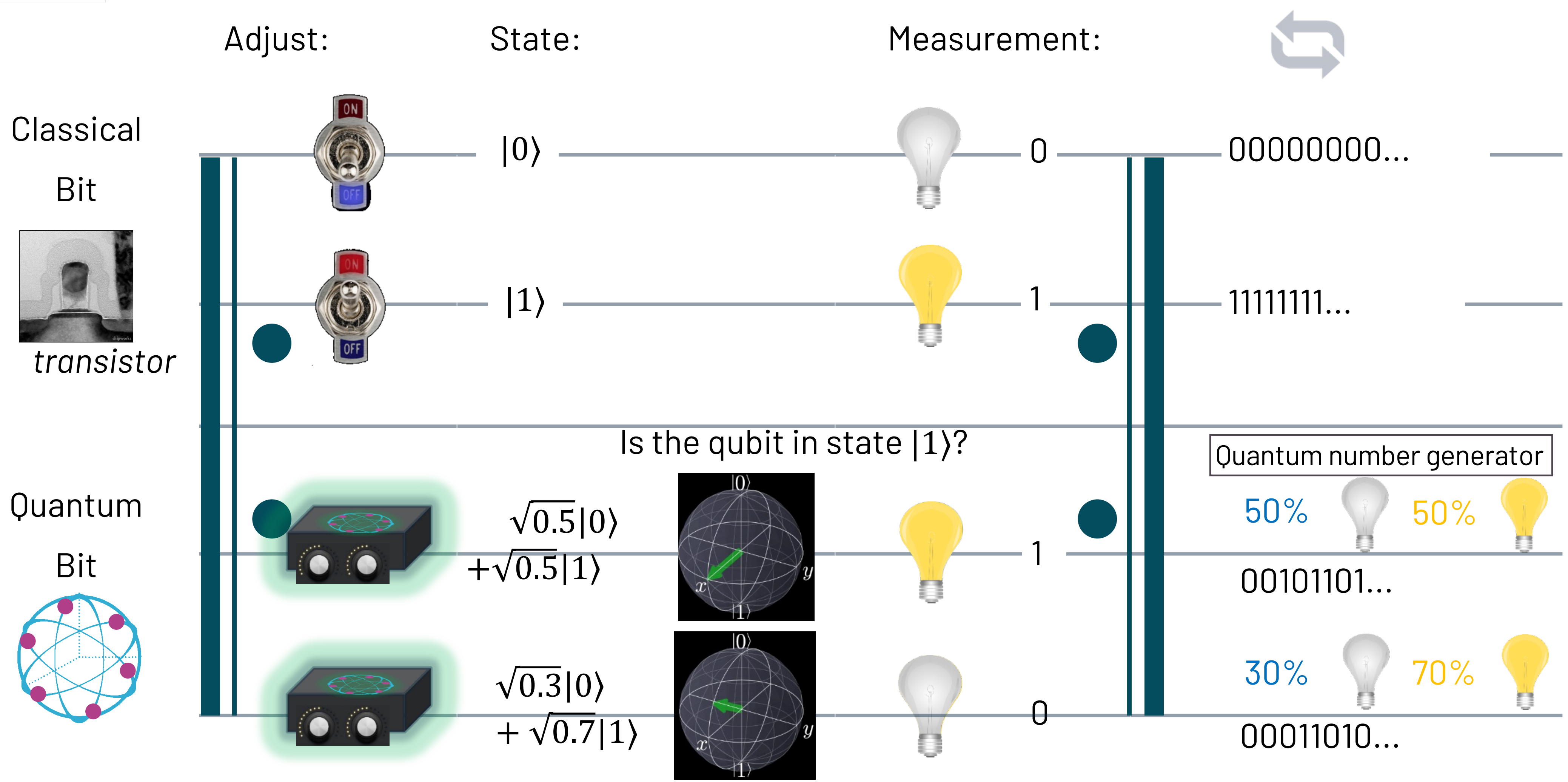
0 and 1, at the same time
represented by point on (Bloch-)Sphere

'superposition'

Bits and Qubits



Bits and Qubits



Bits and Qubits

Adjust: State: Measurement:

Classical Bit

transistor

$|0\rangle$

0

00000000...

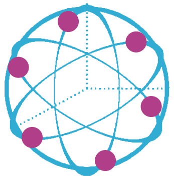
$|1\rangle$

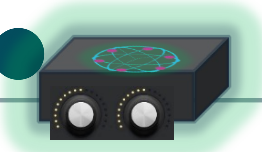
1

11111111...

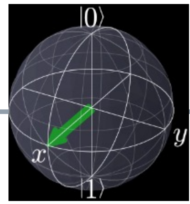
Is the qubit in state $\frac{(|0\rangle+|1\rangle)}{\sqrt{2}}$?

Quantum Bit





$\sqrt{0.5}|0\rangle + \sqrt{0.5}|1\rangle$



1

0%  100% 

11111111...

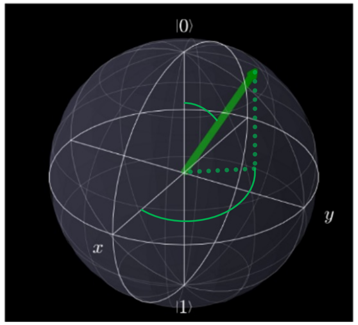
What are the basic units of information?

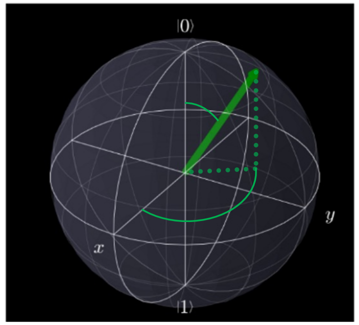
2 Classical Bits

00, 01, 10, or 11

2 Quantum Bits (Qubits)

$$\alpha|00\rangle+\beta|01\rangle+\gamma|10\rangle+\delta|11\rangle$$





00, 01, 10 and 11 at the same time

with probability $|\alpha|^2$, $|\beta|^2$, $|\gamma|^2$ and $|\delta|^2$

Superposition + Entanglement

Exponential Growth

1 qubit – 2 basis states

α|0> + β|1>

$$2^1$$

Exponential Growth

1 qubit – 2 basis states

$\alpha|0\rangle + \beta|1\rangle$

2 qubits – 4 basis states

$\alpha|00\rangle + \beta|01\rangle + \gamma|10\rangle + \delta|11\rangle$

2^2

WMI

Exponential Growth

1 qubit – 2 basis states

$$\alpha|0> + \beta|1>$$

2 qubits – 4 basis states

$$\alpha|00> + \beta|01> + \gamma|10> + \delta|11>$$

3 qubits – 8 basis states

$$\alpha|000> + \beta|001| + \gamma|010> + \delta|011> +$$
$$\epsilon|100> + \zeta|101| + \eta|110> + \theta|011>$$

$$2^3$$

Exponential Growth

n qubits – 2^n basis states

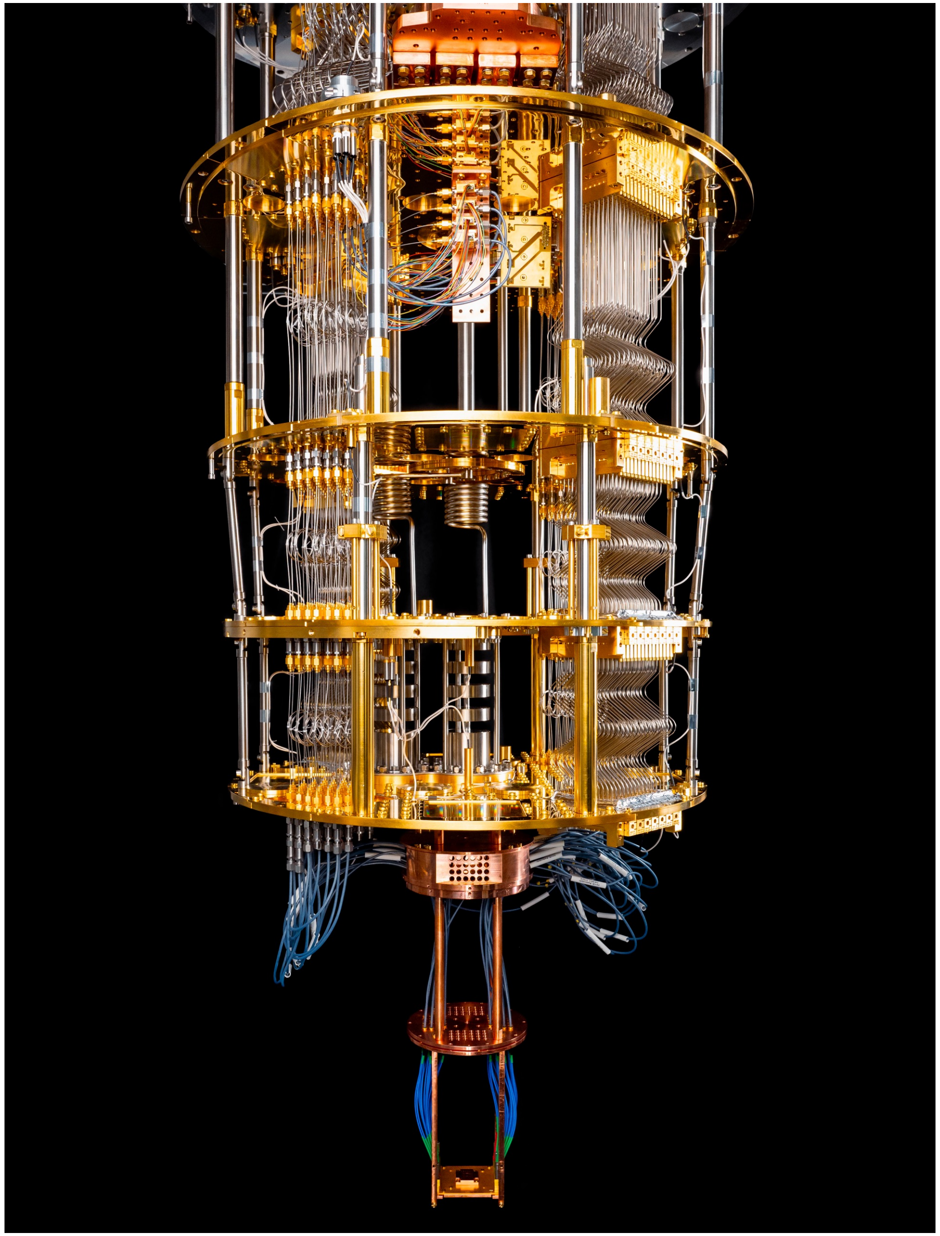
$$2^n$$

2^{50}~8EB

(8 million GB)

Basis states of a 50 qubit system:

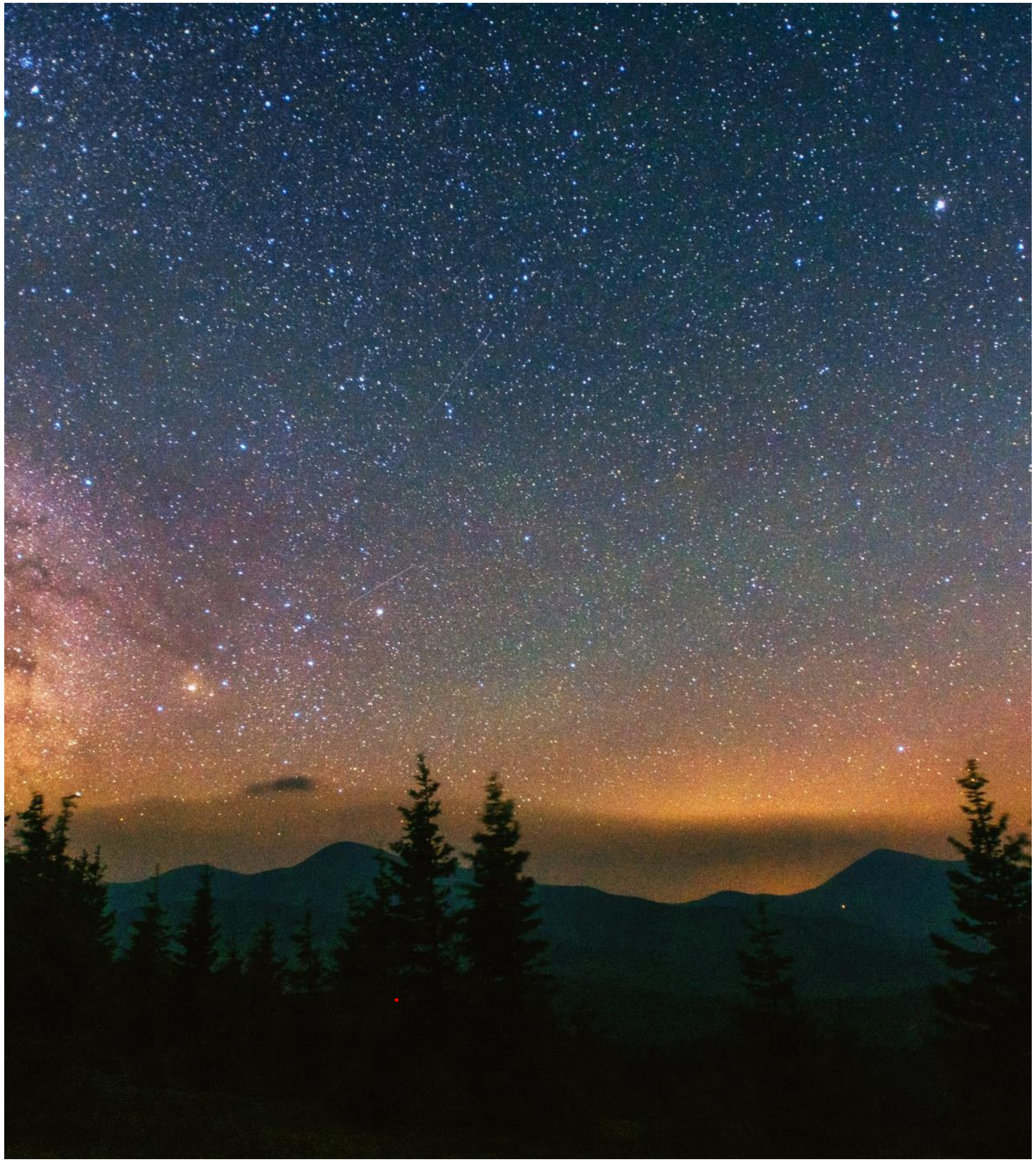
1125899906842624



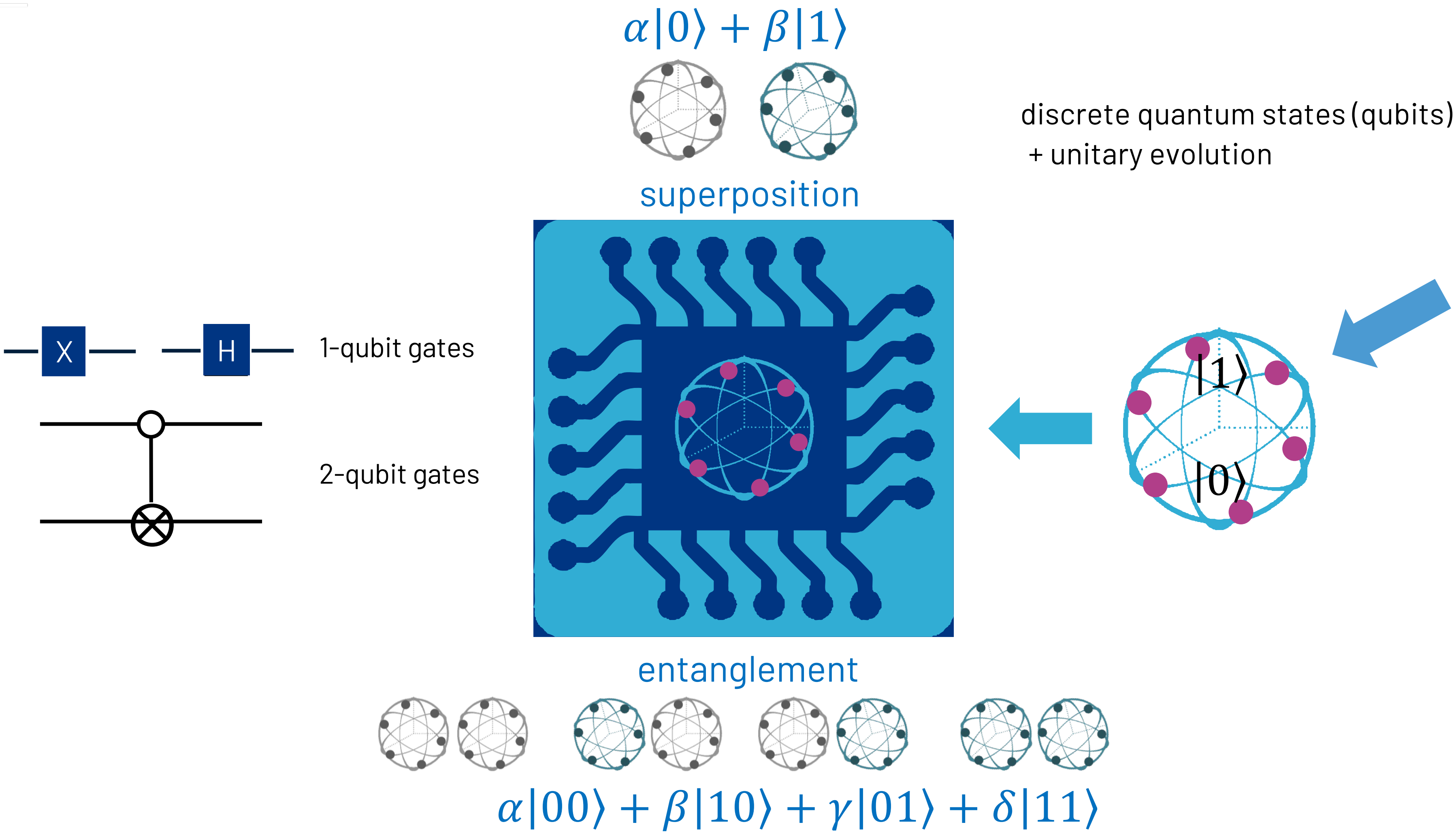
2^{275}

More basis states than there are atoms in the observable universe

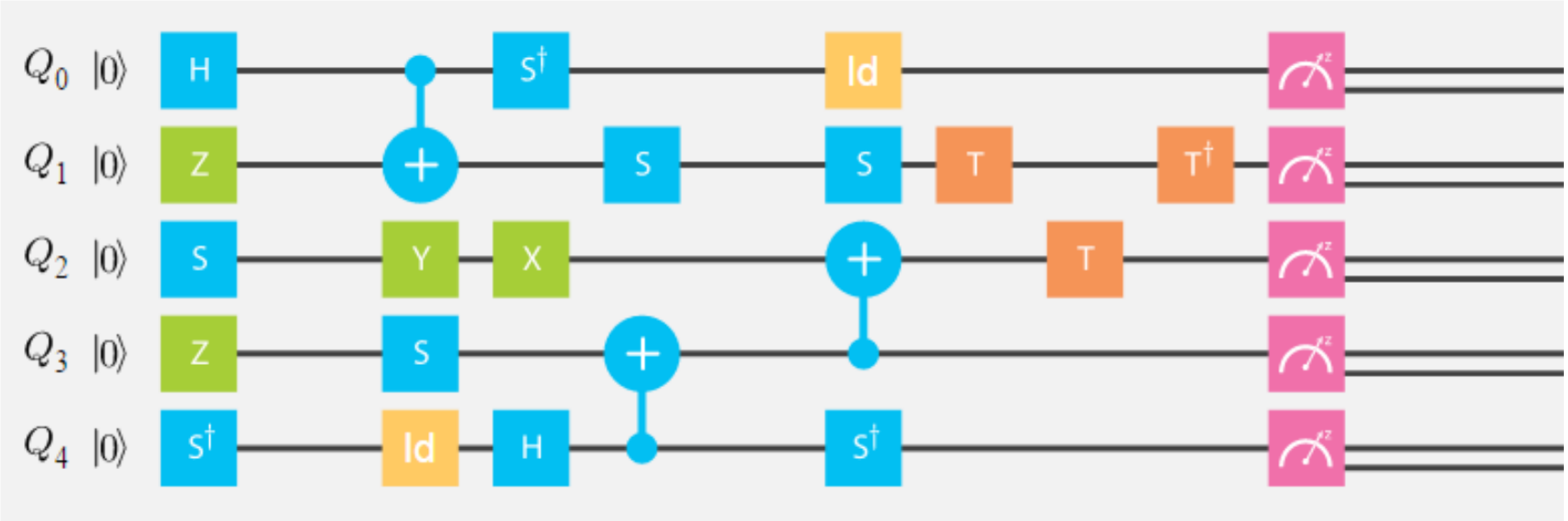
6070840288205403346623318458823
4965832575213720379360039119137 8
04340758912662765568



Quantum computation



Quantenalgorithmus

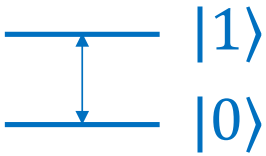


1. Initialisierung des Qubitregisters Q_i (z.B. in Grundzustand $|0\rangle$)
2. Einzel- und Zwei-Qubit Quantengatter
3. Messung des Qubitregisters

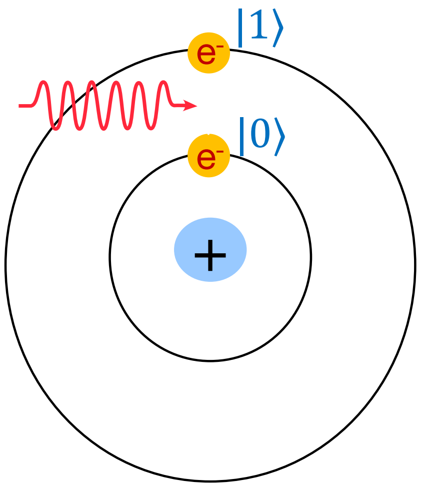
What is a qubit?

Quantum Bits:

Two-Level Systems



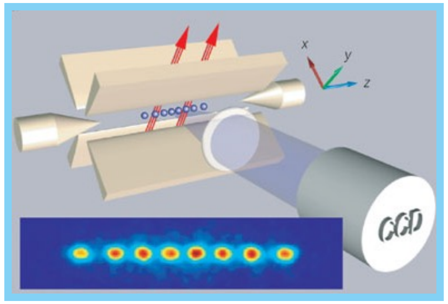
Example:
Atom orbitals with different energetic levels



Neutral Atoms

© JQI

Ion Traps



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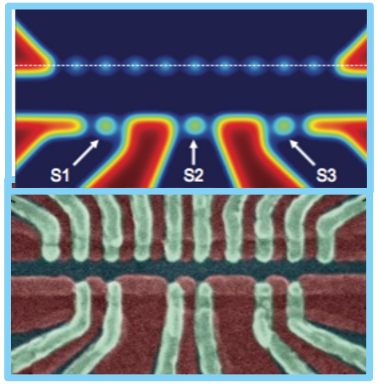
Quantum Dots



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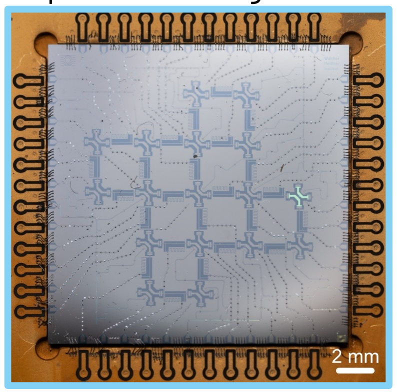
Superconducting Circuits



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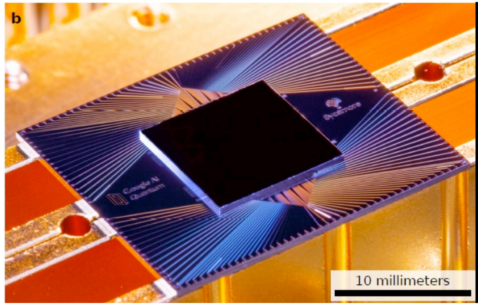
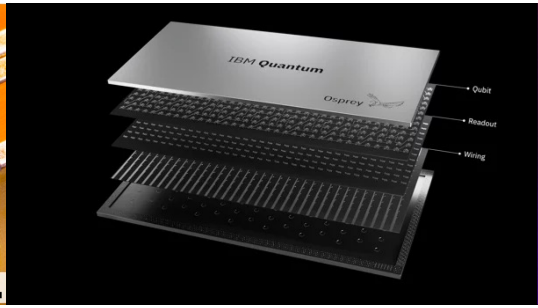
State of the art Quantum Computation

1st quantum computer prototypes are ‘on the market’ (>100 qubits)

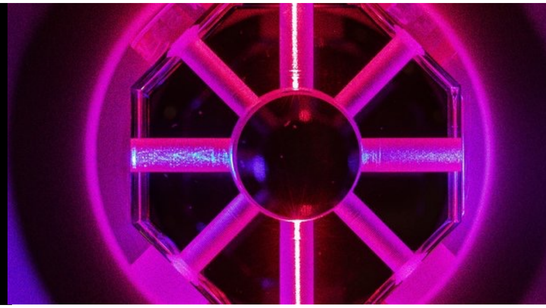
Google AI



IBM



PlanQC



AQT

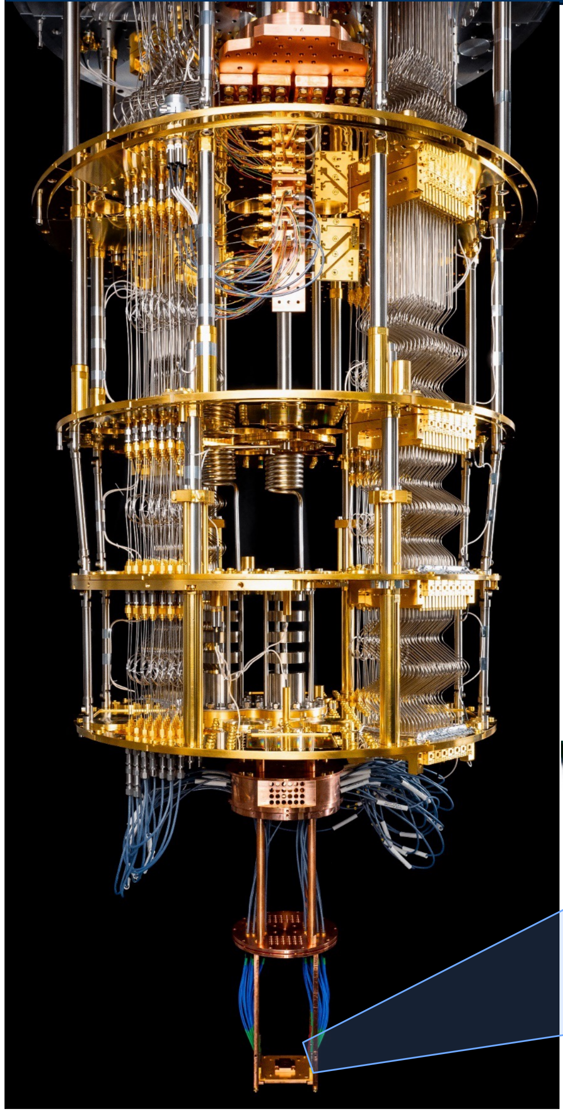
or in development (OpenSuperQ GeQCoS MUNIQC-SC SOLID ...)
on different platforms (solid state systems, photons, ...)

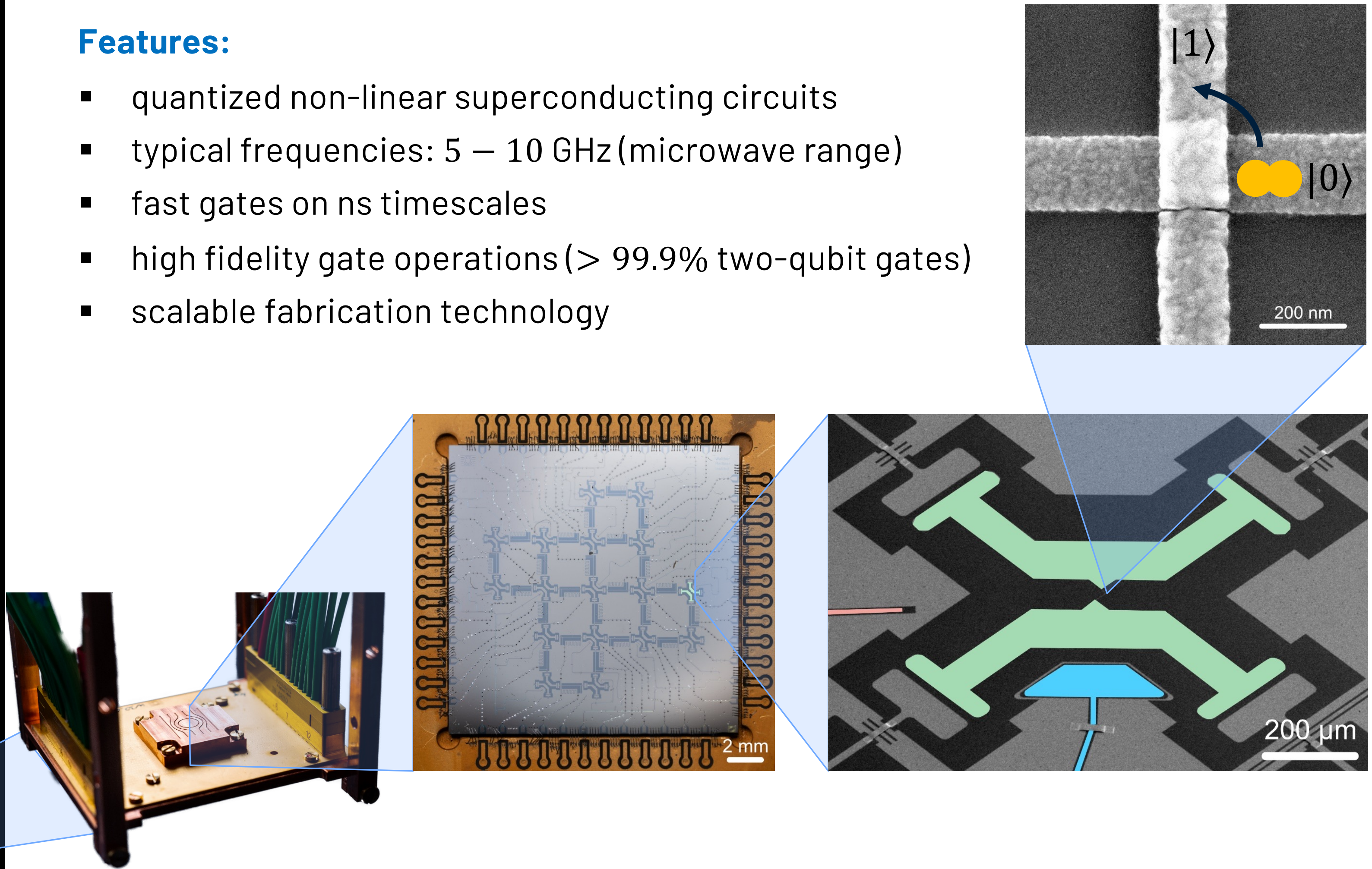
→ next milestones: practical quantum algorithm, logical qubits
→ many challenges ahead (scaling, coherence, control & readout, system integration)

Superconducting Qubits

Features:

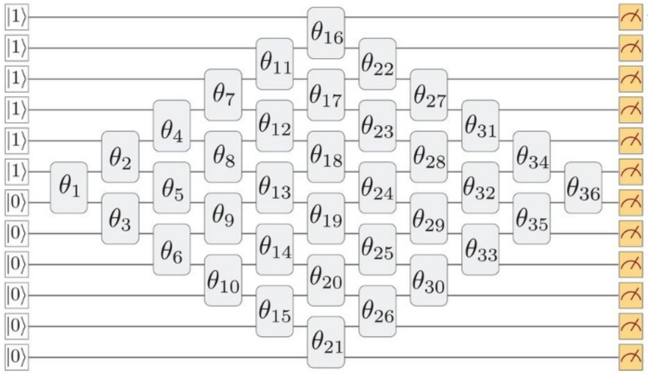
- quantized non-linear superconducting circuits
- typical frequencies: 5 – 10 GHz (microwave range)
- fast gates on ns timescales
- high fidelity gate operations (> 99.9% two-qubit gates)
- scalable fabrication technology

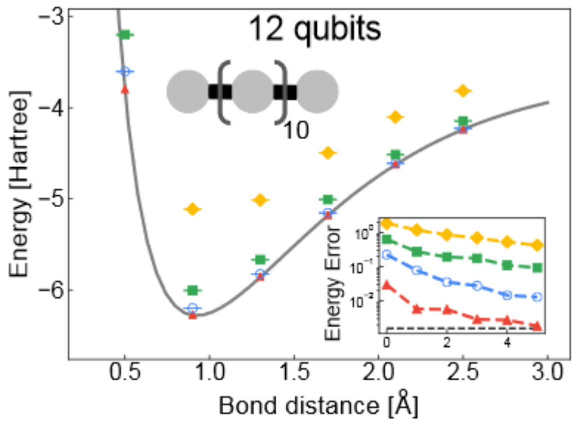




NISQ applications

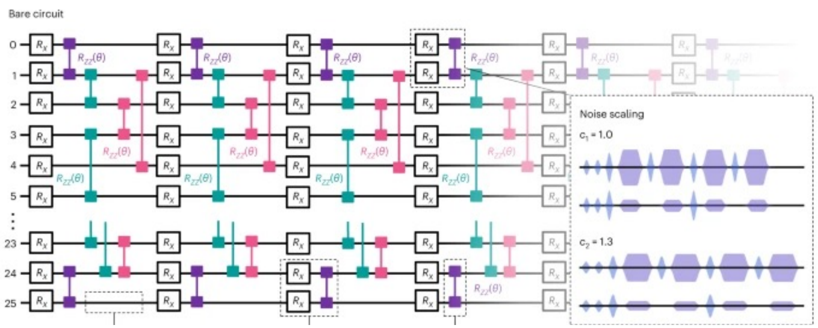
Quantum chemistry: calculate ground state of simple molecules (hydrogen chain)

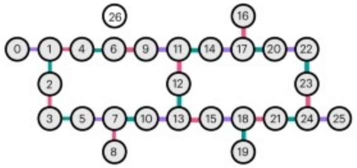


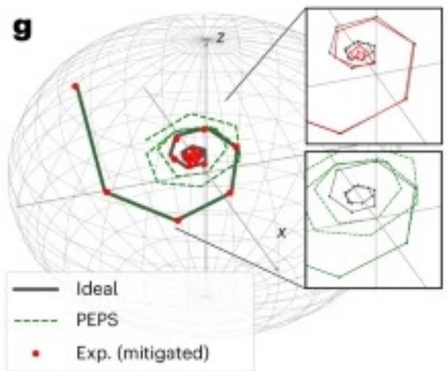


F. Arute, Science 369, 2020;
A. Kandala, Nature 549 (2017); Nature 567 (2019)]

Material science: dynamics of spin systems (with up to 127 qubits)

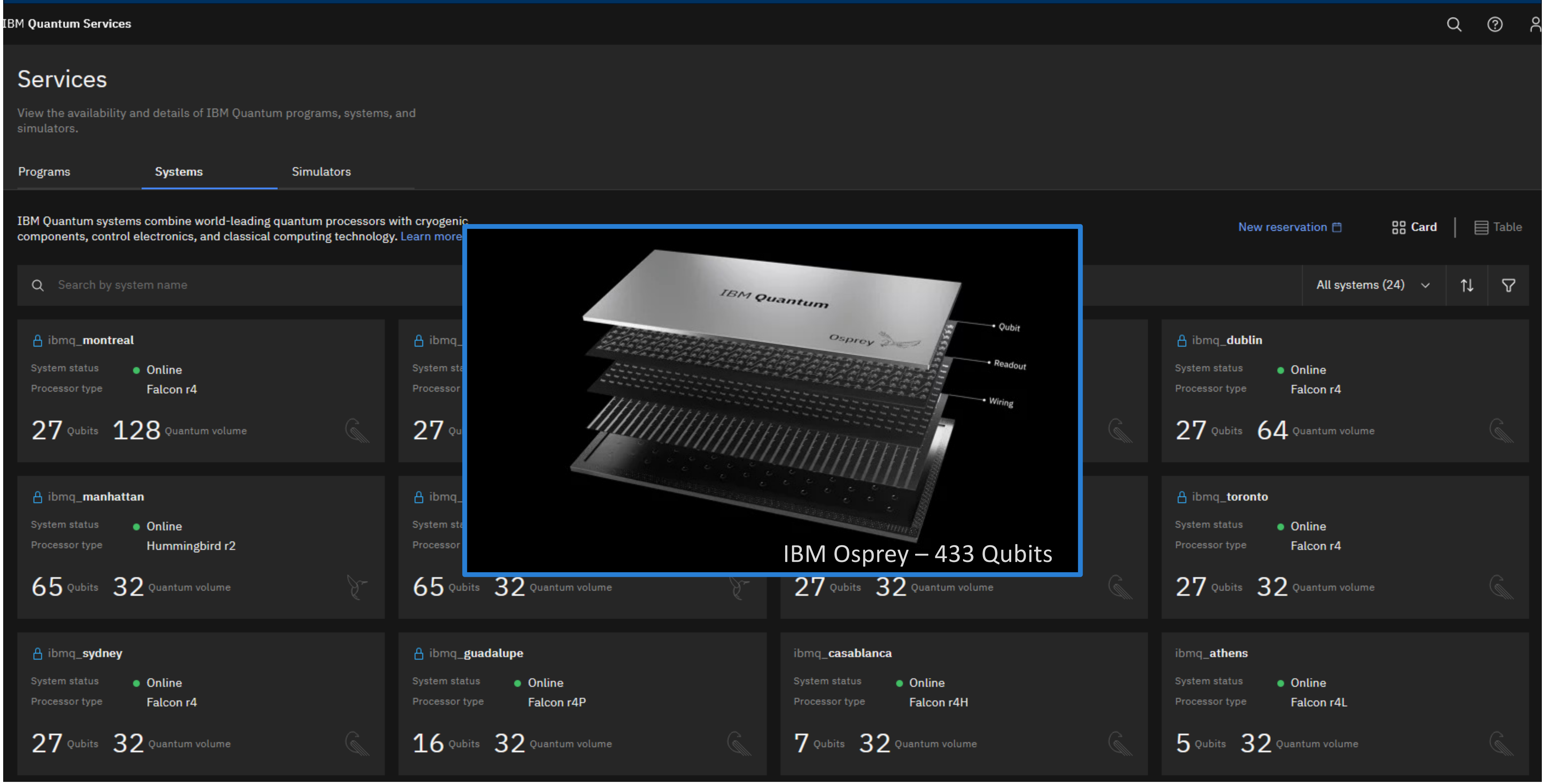




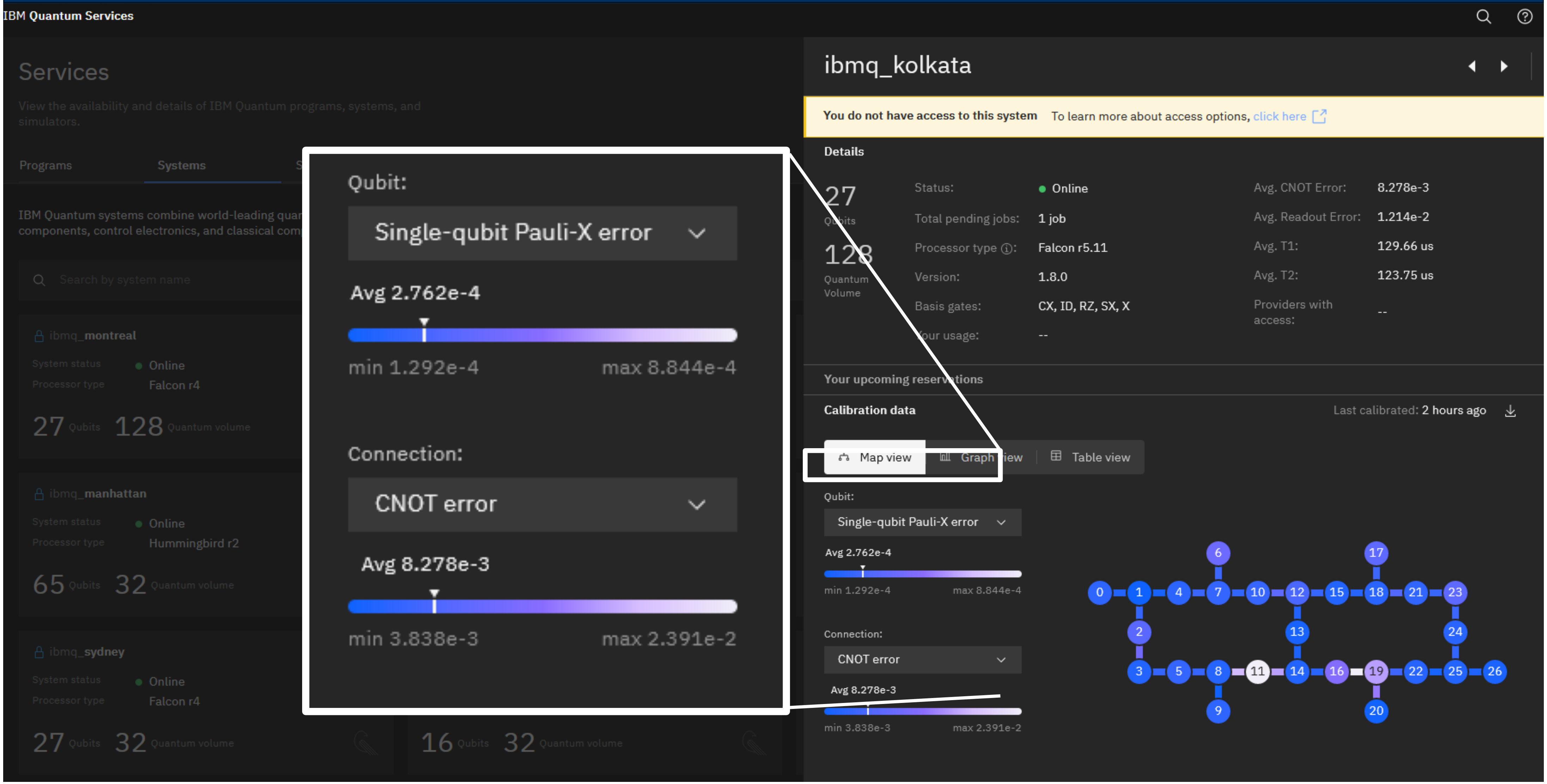


Y. Kim et al. (IBM), Nat. Phys 1 (2023); Nature (2023)

IBM Q Experience



IBM Q Experience



The Universal Quantum Computing System

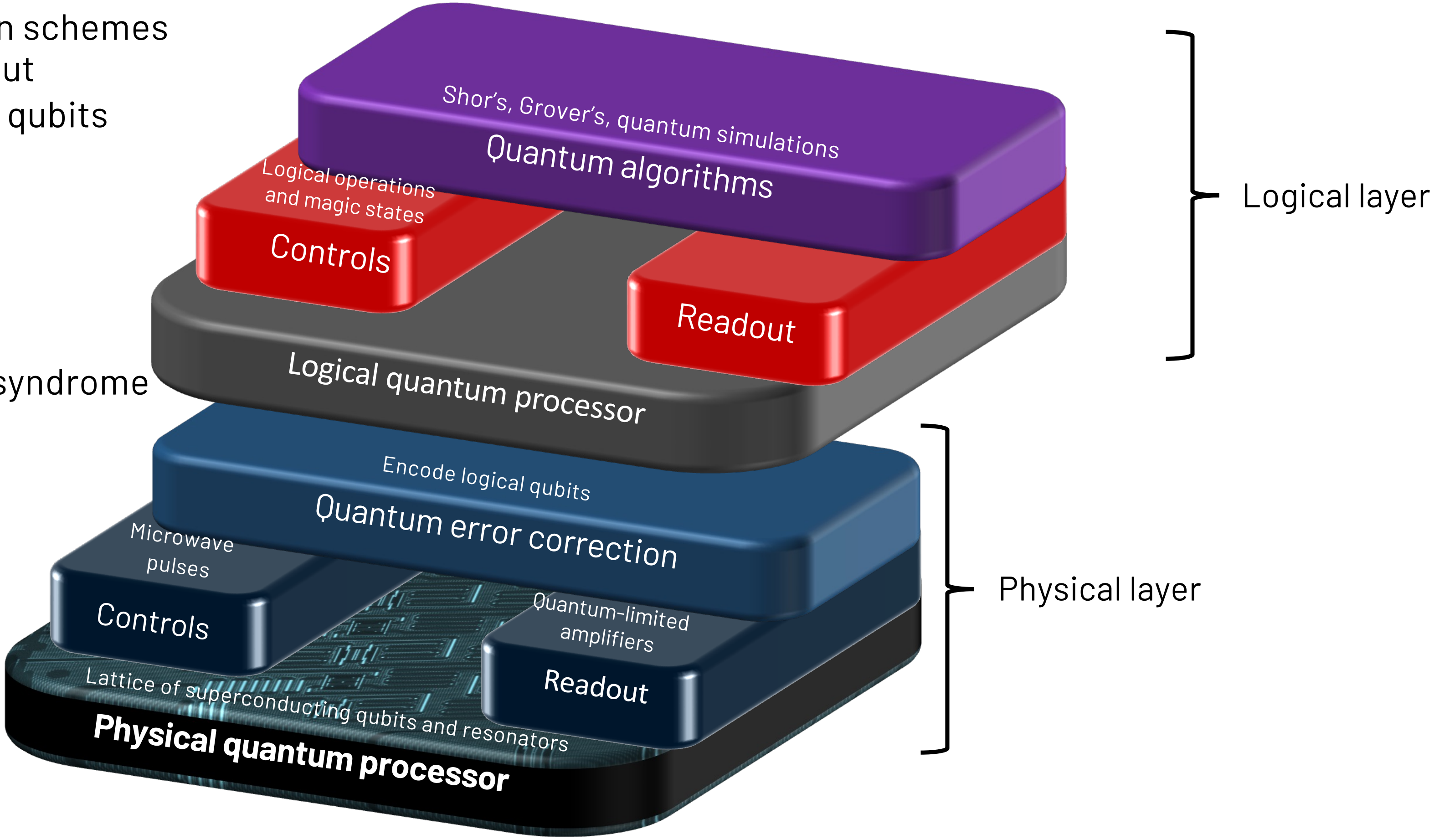
Idea: use error correction schemes to make a 'logical' qubit out of several 'good' physical qubits

$$|0\rangle \rightarrow |00 \ldots 0\rangle$$

$$|1\rangle \rightarrow |11 \ldots 1\rangle$$

100-1000 x

measure parity as error syndrome

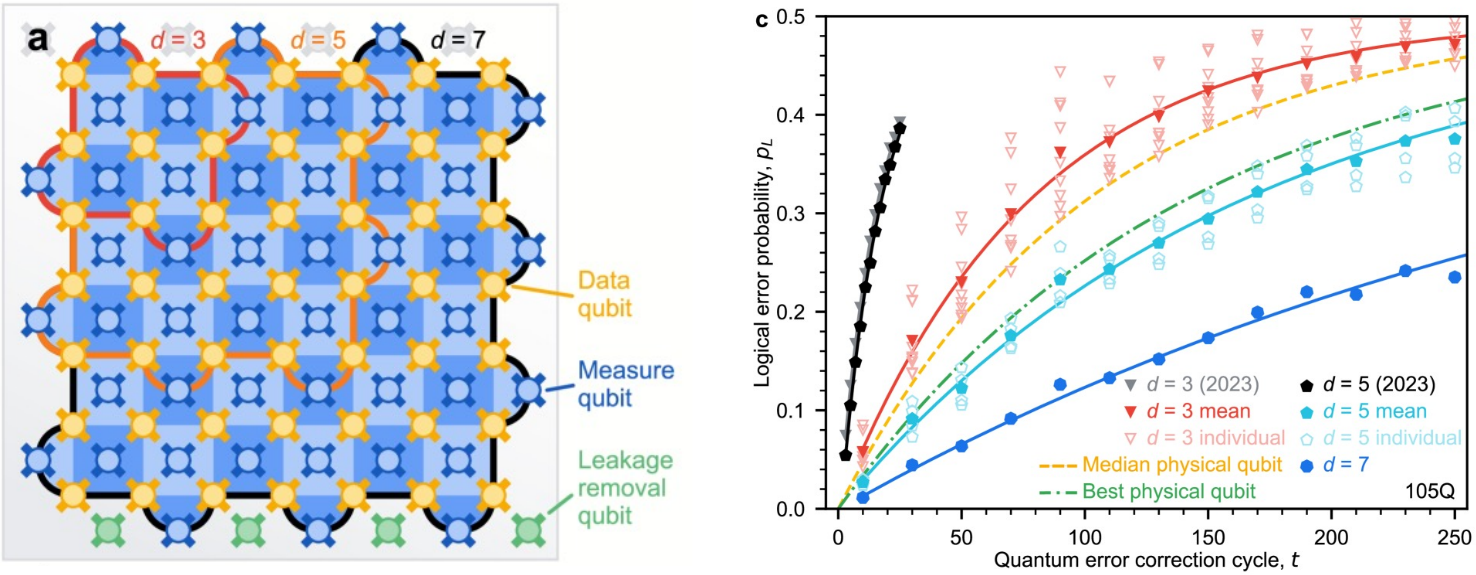


[Gambetta, Chow, Steffen, npj Quantum Information 3, 2 (2017)]

QEC – lowering logical error rates

Surface Code error threshold:

Logical error should decrease for increasing number of physical qubits per logical qubit



[R. Acharya et al., Nature (2023); Google AI, Nature (2024)]

→ Stabilization of logical qubit below error threshold (distance 7 code)

→ still much larger codes needed (1000's of qubits)

Challenges ahead (hardware centric)

Scaling: *guarantee performance at scale*

cross-coupling and cross-talk, uniformity & reproducibility, scalable control, I/O, size of qubits, thermal budget

System: *guarantee stable operation conditions*

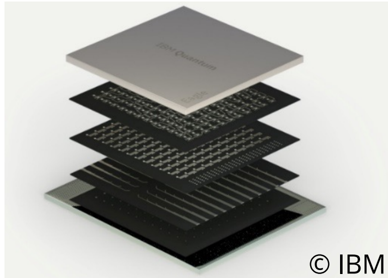
automated calibration & bring-up, run-time environment, characterization & verification, quantum/classical integration, (cryogenic) electronics,...

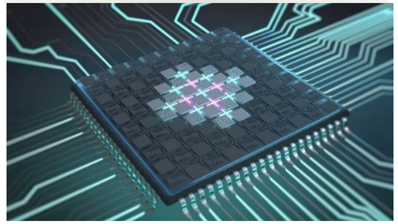
Coherence: maximize lifetime of quantum states

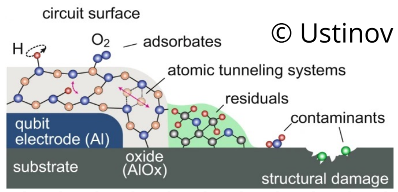
identification of loss channels and noise sources (two-level fluctuators, quasi-particles,B-field fluctuations), mitigation (by design, by choice of materials, by fabrication)

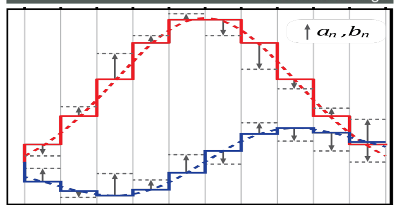
Control & readout: coherence-limited high-fidelity gates

pulse optimization, benchmarking sequences, multi-qubit operations & extended gate sets,...



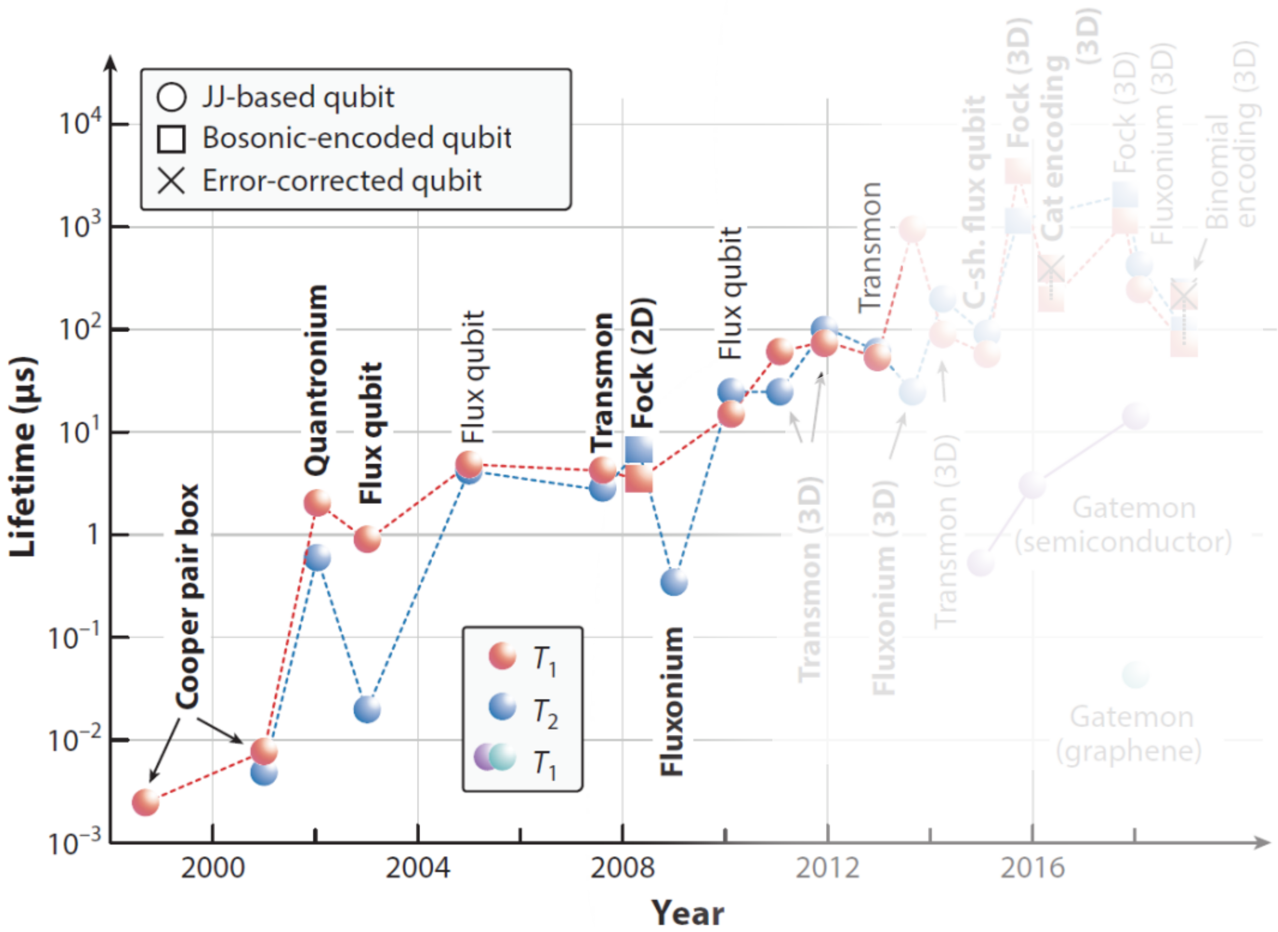




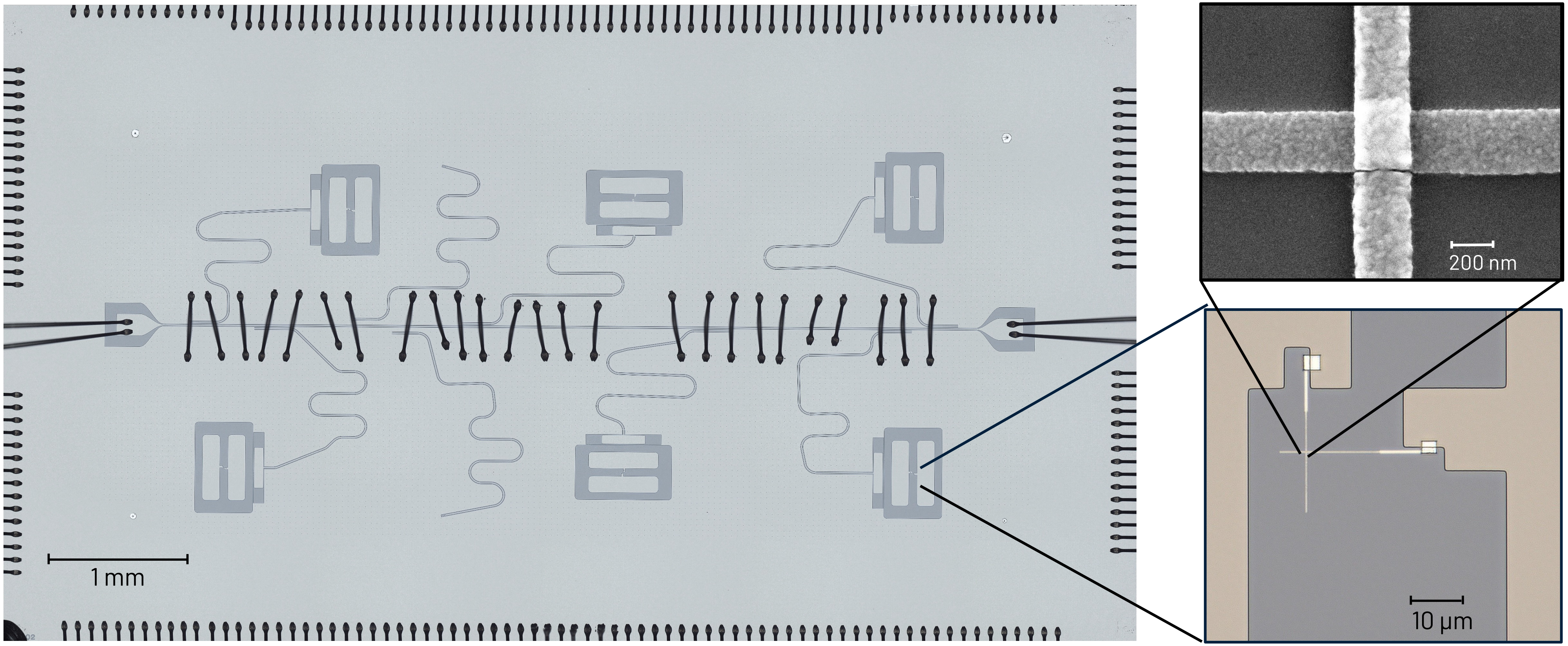


Superconducting qubits – trend of coherence times

Kjaergaard et al. Ann. Rev. Cond. Mat Phys 11 (2020);



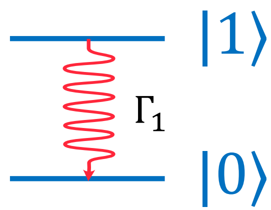
Microscope image of qubit chip

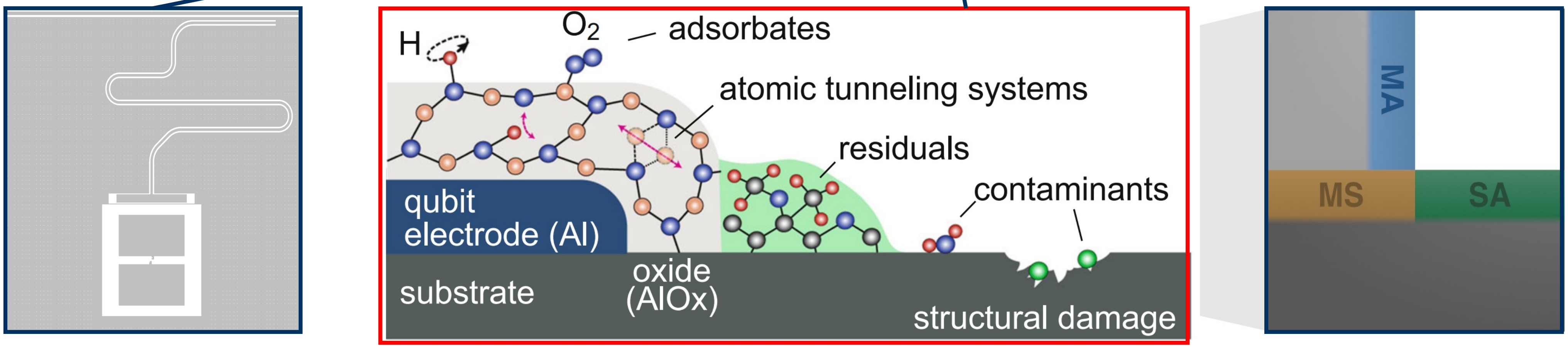


Fermi‘s golden rule

Fermis golden rule describes the decay rate from an excited state Ψ_1 to ground state Ψ_0

$$\Gamma_1 \propto |\langle 0|H_c|1\rangle|^2 \rho_{env}(\omega_{01})$$



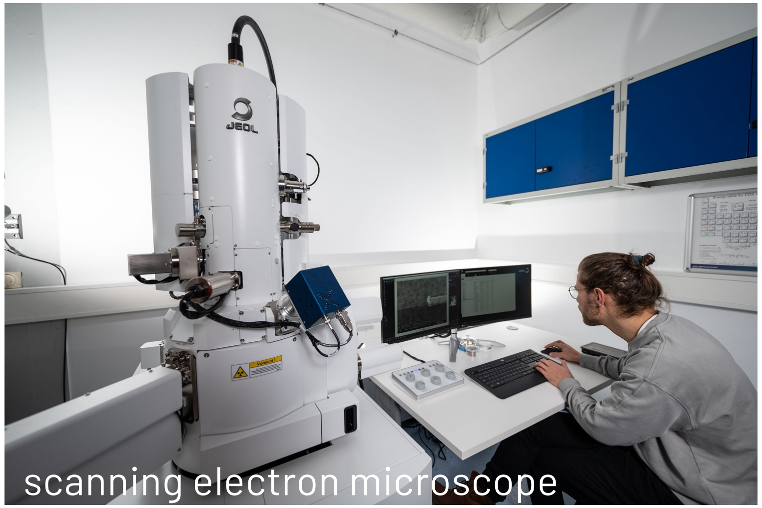


J. Lisenfeld *et al.*, npj Quantum Inf **5,** 105 (2019); C. Müller et al. Rep. Prog. Phys. **82** (2019)

- Transition matrix element from perturbation (environment, TLSs, flux noise,…), can be modified in design
- density of states of the environment (TLSs,…) at transition frequency; one of the main challenges in fabrication

Fabrication impressions

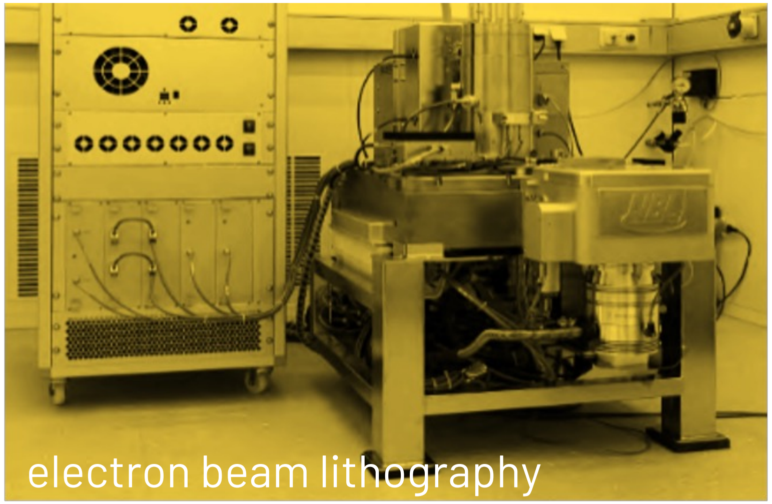
reactive ion etcher



scanning electron microscope

wafer with qubits

optical lithography



electron beam lithography

wafer saw/dicer

Clean Interfaces

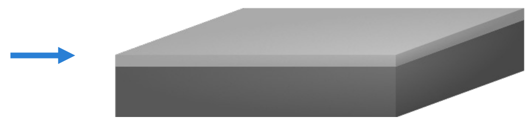
Surface clean (piranha, BOE)

→ dissolves organic contaminations

→ removes native SiO_x layer

Sputter deposition of Nb

→ 150nm Nb thin-film at optimized temperature



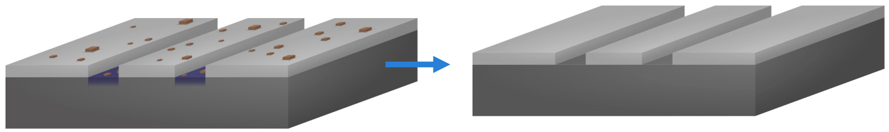
Pattern transfer via reactive ion etching

→ steep side walls, low line edge roughness, low damage and roughness of substrate surface

→ via SF_6 based ICP RIE process

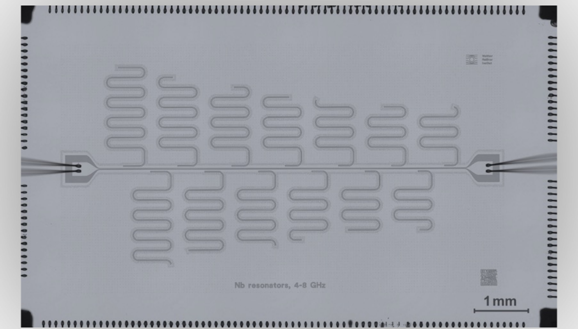
Post-lithography cleaning

→ remove SiO_x layer in trenches and NbO_x layer



Internal quality factors of CPW resonators (single photon limit)

Niobium coplanar waveguide resonators
(4-8 GHz; 6 μm gap; 10 μm center width)



measured **directly** after post process cleaning

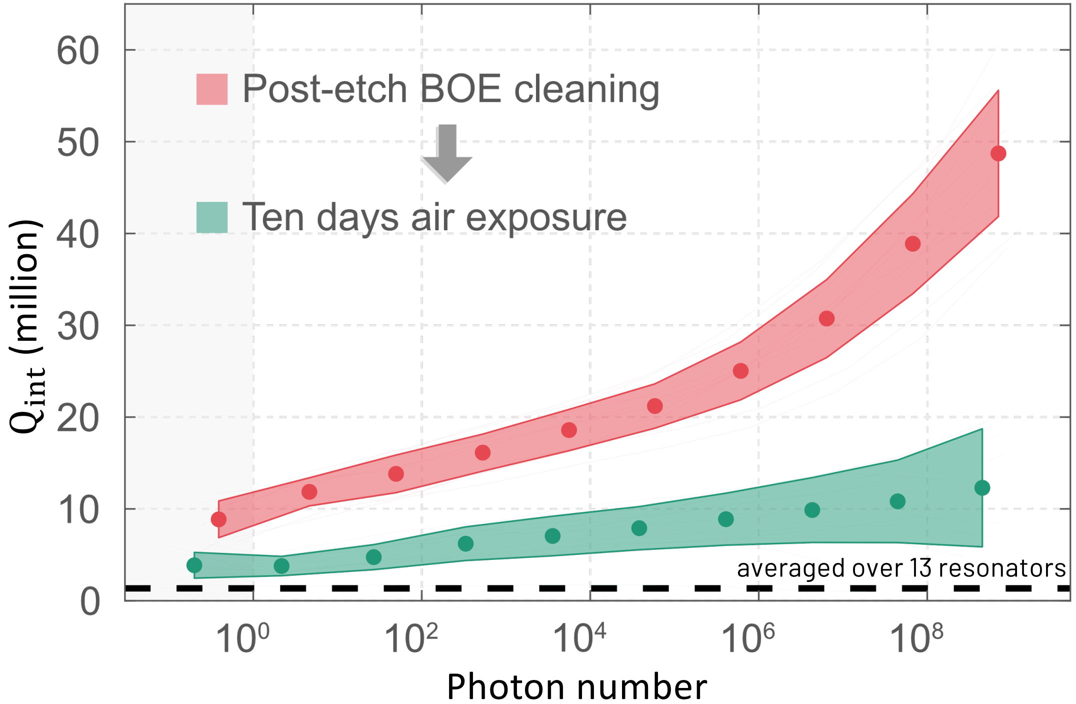
$$Q_{int,avg} = 8.8 \pm 2.2 \times 10^6$$
$$Q_{int,max} = 11.7 \pm 0.4 \times 10^6$$

fully **oxidised** after ten days at atmosphere:

$$Q_{int,avg} = 3.8 \pm 1.4 \times 10^6$$
$$Q_{int,max} = 6.2 \pm 1.0 \times 10^6$$

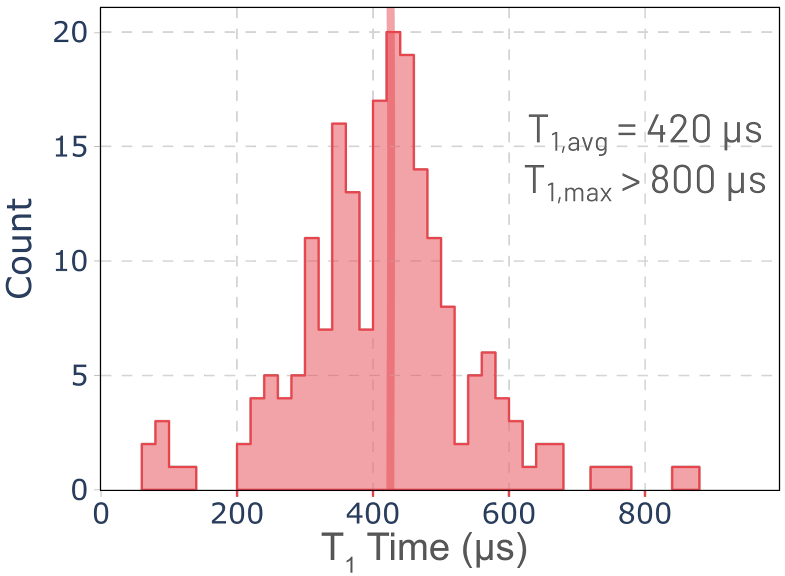
without post process surface cleaning:

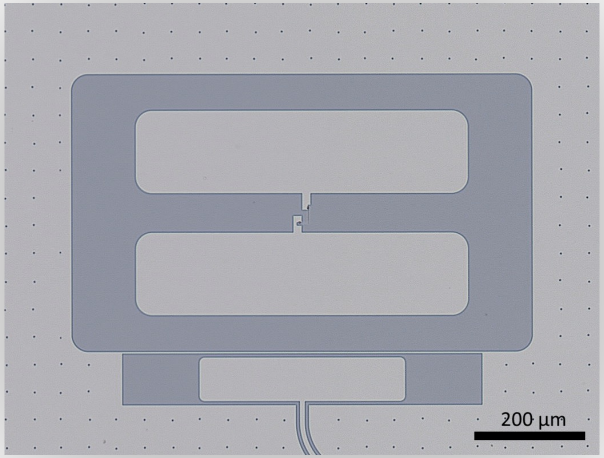
$$Q_{int,avg} = 1.0 \times 10^6$$

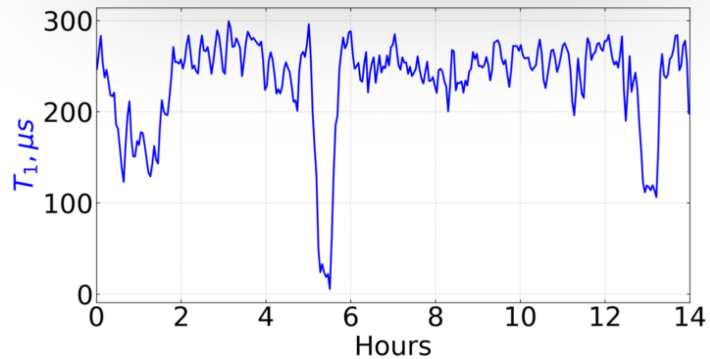


Qubit coherence

- Fixed-frequency single transmon qubits (frequency around 4.4 GHz
- $Al/AlO_x/Al$ Josephson junctions with Niobium ground plane



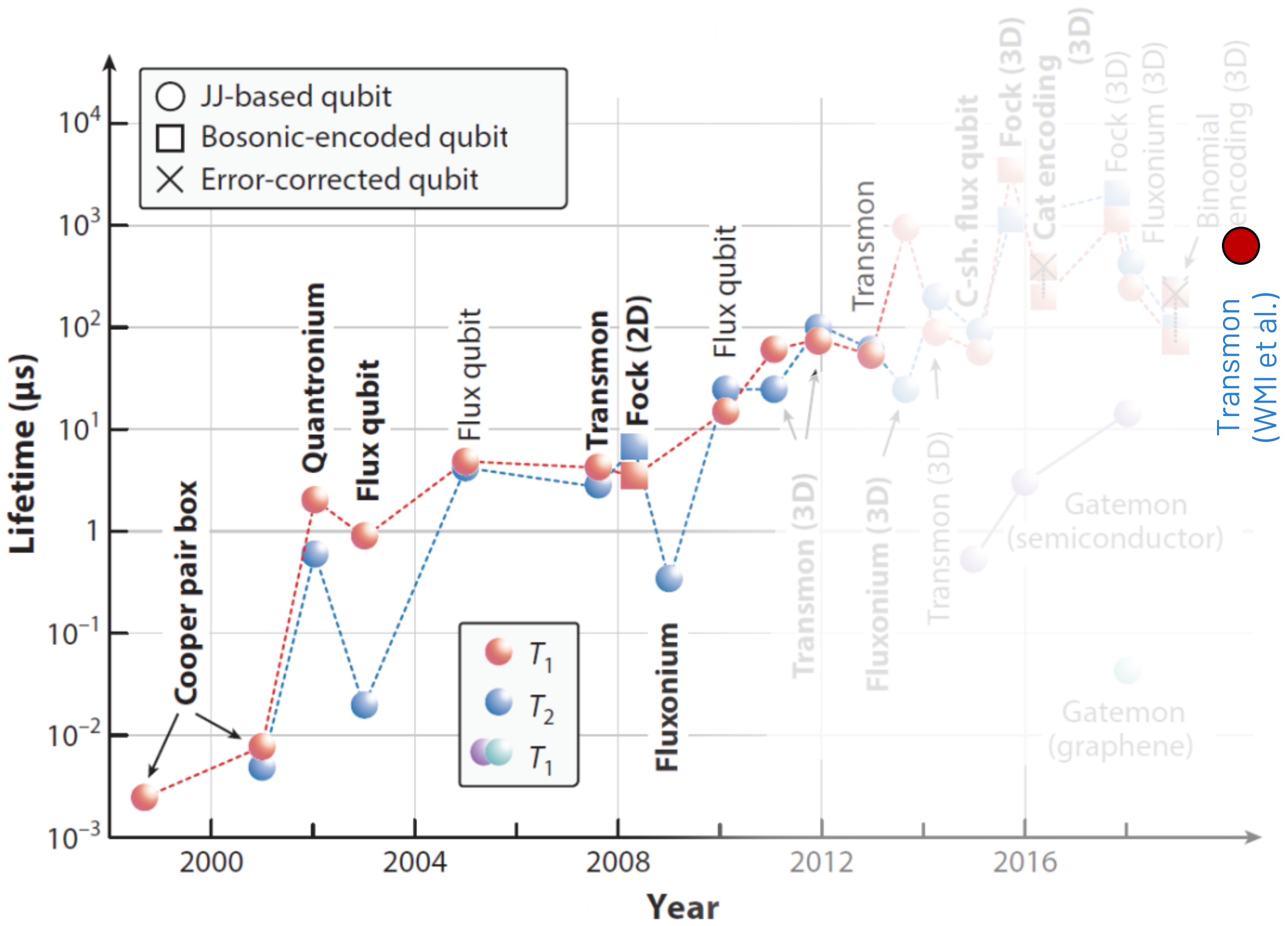




→ fluctuating environment (TLSs)

Superconducting qubits – trend of coherence times

Kjaergaard et al. Ann. Rev. Cond. Mat Phys 11 (2020);



Challenges ahead (hardware centric)

Scaling: *guarantee performance at scale*
cross-coupling and cross-talk, uniformity & reproducibility, scalable control, I/O, size of qubits, thermal budget

System: *guarantee stable operation conditions*
automated calibration & bring-up, run-time environment, characterization & verification, quantum/classical integration, (cryogenic) electronics,...

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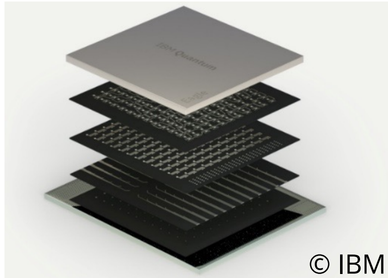
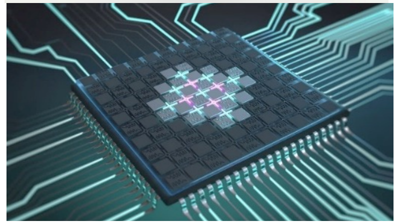
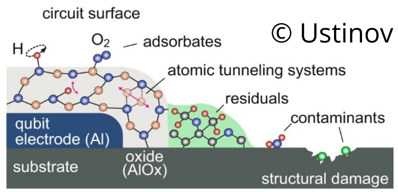
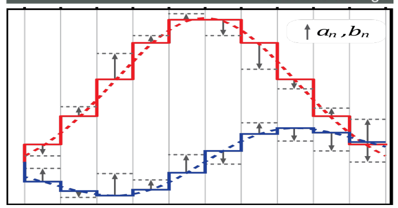
Control & readout: coherence-limited high-fidelity gates
pulse optimization, benchmarking sequences, multi-qubit operations & extended gate sets,...



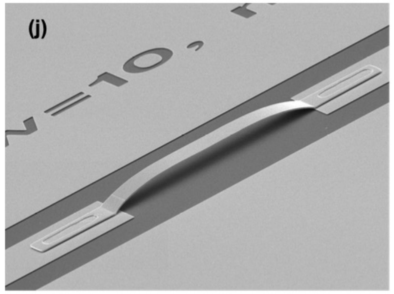


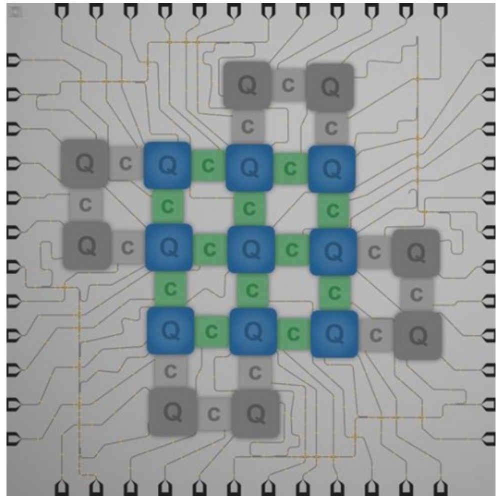




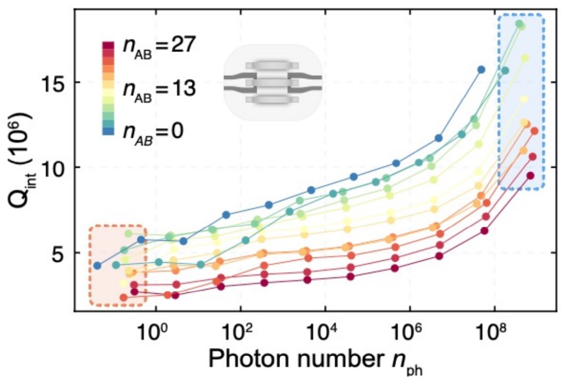
3D/2.5D integrated devices

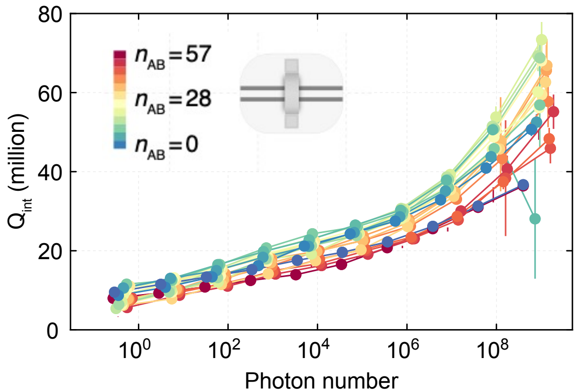
Scalability challenge 1:
Can one retain the coherence & controllability for larger devices?
E.g. How to address all qubits and cross over signal lines?





→ **Air-bridge technology** for routing of signals & for connecting ground planes

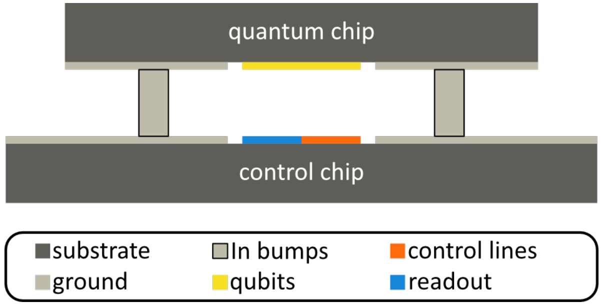




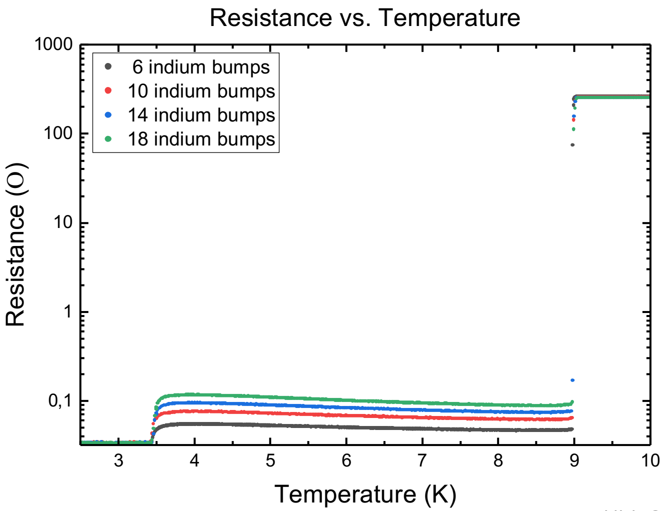
[N. Bruckmoser, L. Koch et al., in preparation (2024)]

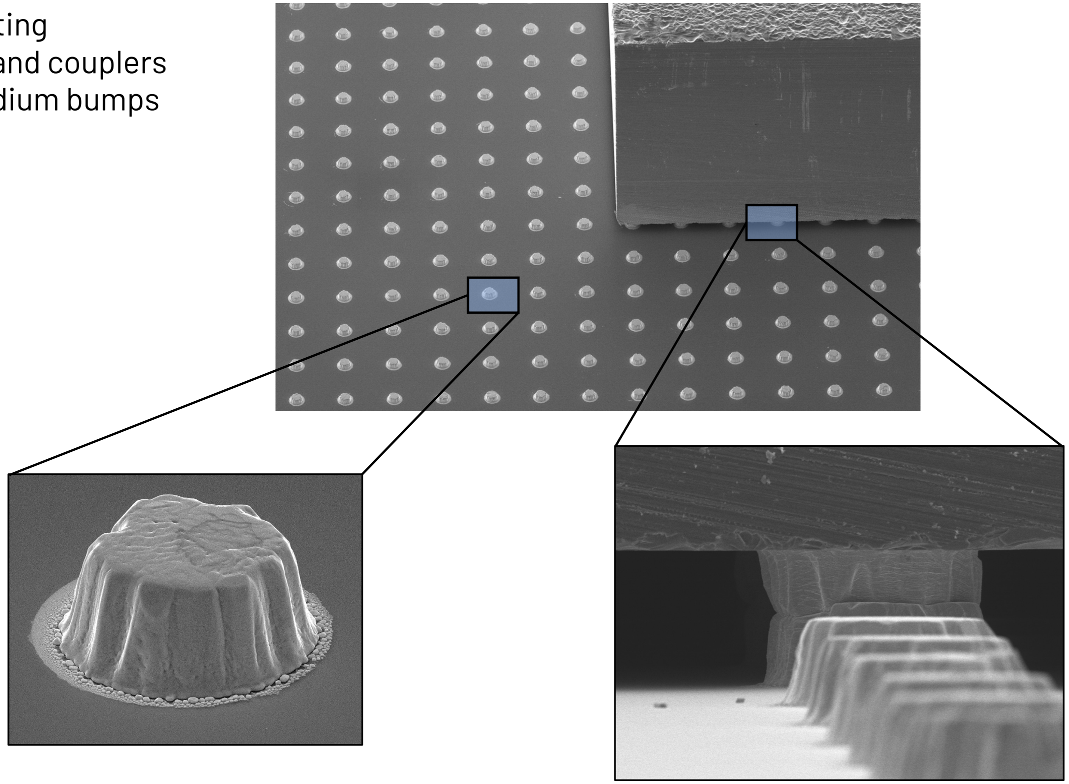
Flip chip bonding

→ **Indium bump bonds** to separate qubit/coupler layer from signal routing layer

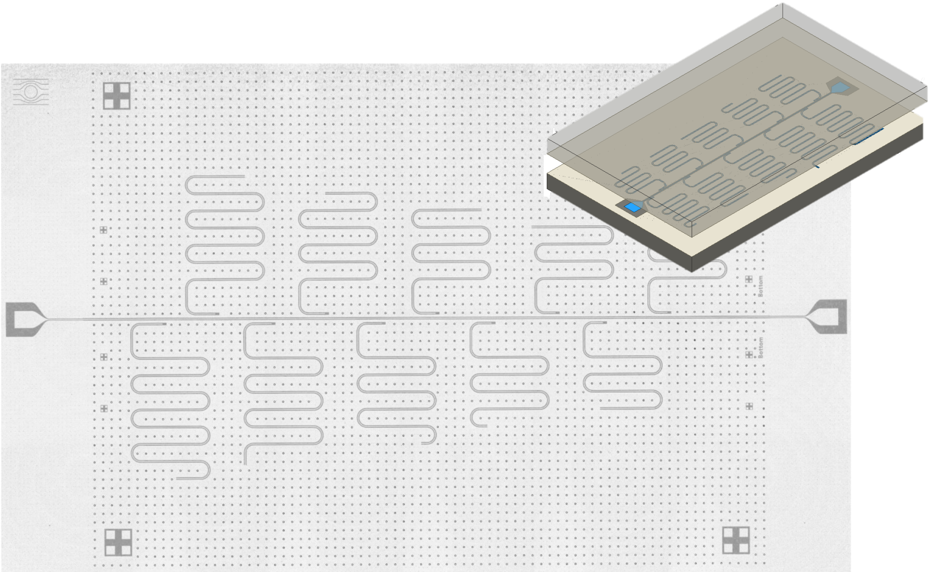


- Bottom chip : routing
- Top chip : qubits and couplers
- Connection via indium bumps

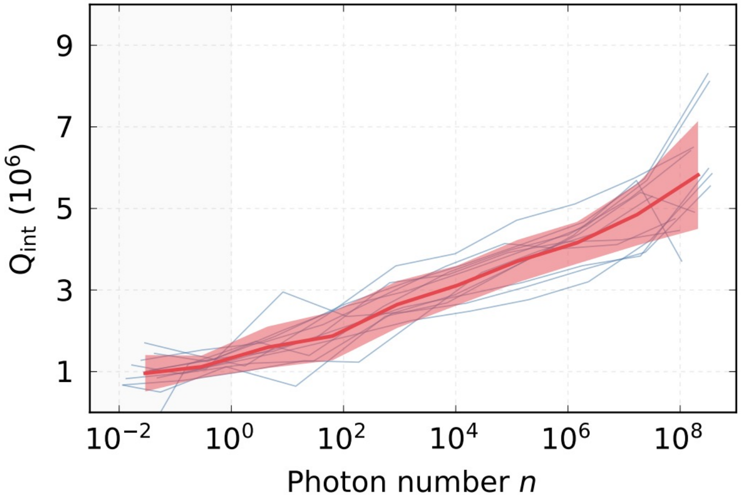




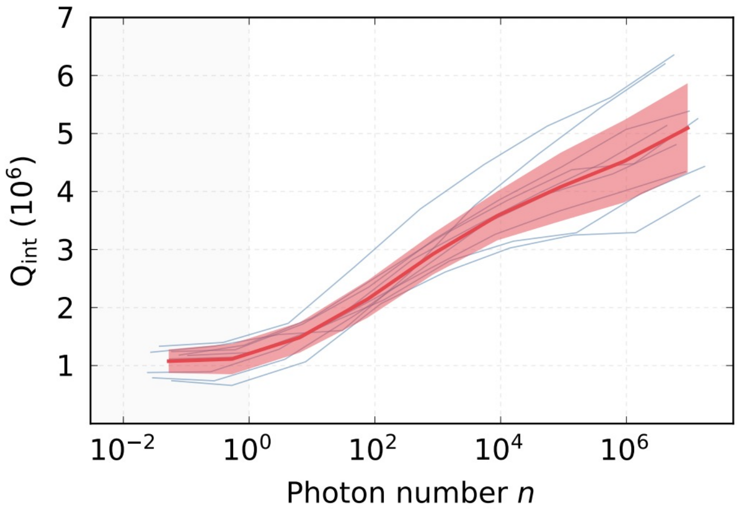
Resonators in 3D architecture



2D resonator :
(fabricated on wafer with 3D resonators)



3D resonator :



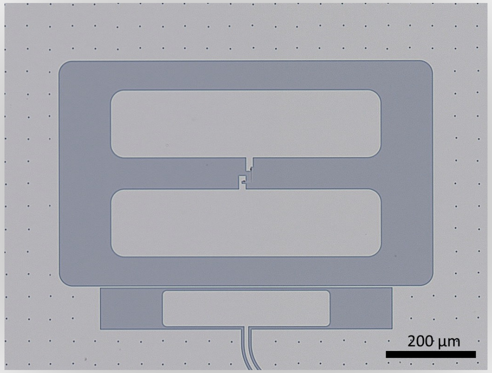
average Q_i above 1 M in single photon limit
(without post-processing)

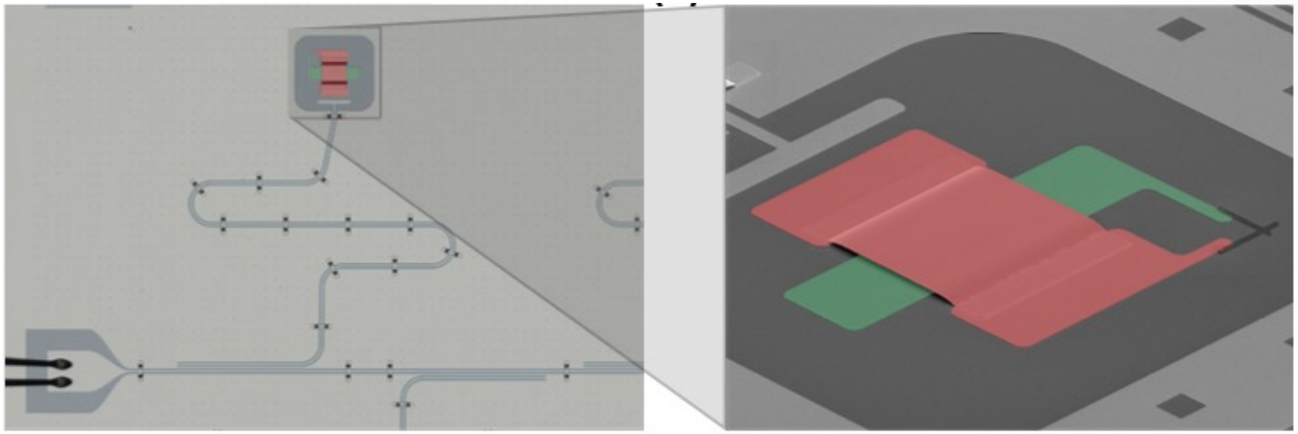
→ 3D geometry does not limit Q factors

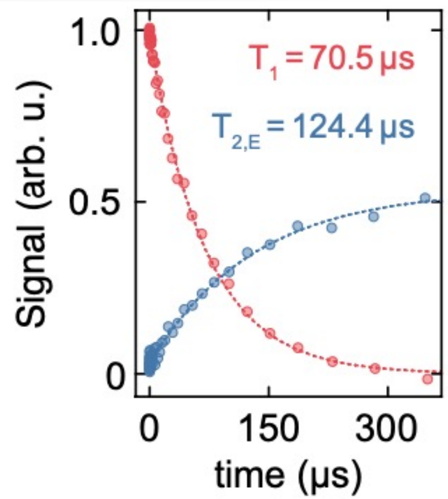
3D/2.5D integrated devices

Scalability challenge 2:
Can one reduce the footprint of qubits/couplers?

→ **Air-gap capacitors** for smaller qubits
(with decent coherence times)







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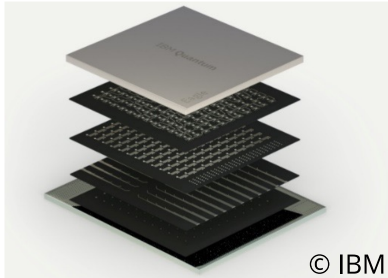
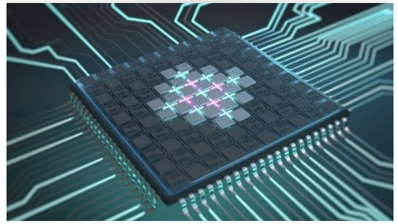
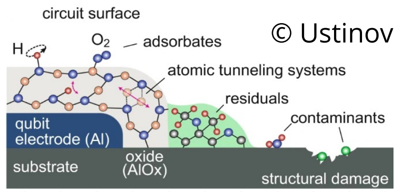
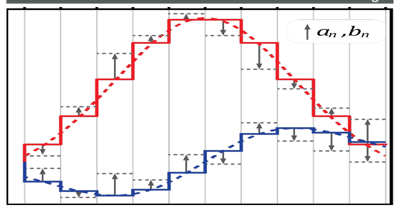








Simultaneous multi-qubit operations

Quantum processors increase in size

↓

low connectivity and local operations lead to large gate overhead

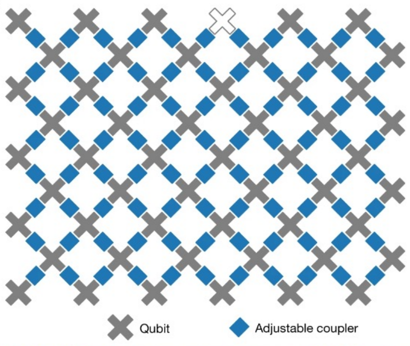
↓

control multiple local interactions simultaneously

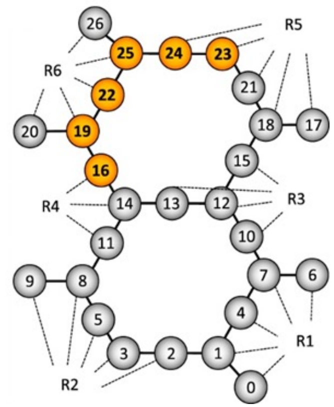
↓

multi-qubit and non-local operations

Arute et al., Nature 574 (2019)



Petar et al., QS&T 6 (2021)



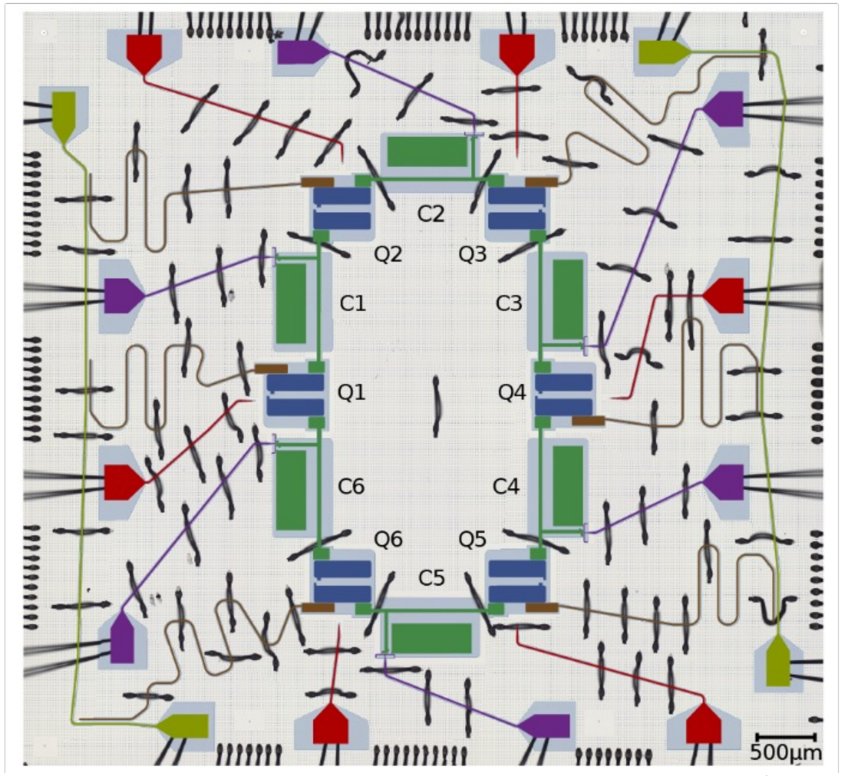
efficient state transfer along chains

Gu et al., PRX Quantum 2 (2021)
Burkhart et al., PRX Quantum 2 (2021)
Zhang et al., PRL 128 (2022)
Warren et al., arXiv 2207.02938 (2022)

Glaser et al., PR Applied 19 (2023)
Kim et al., Nature Physics 1 (2022)
Baker et al., Appl PL 120 (2022)
Lu et al., PRX Quantum 3 (2022)

Christandl et al., PRL 92 (2004)
Li et al., PRApplied 10 (2018)
Genest et al., Annals of Physics 371 (2016)
Lemay et al., JPA 49 (2016)
Nägele et al., PR Research 4 (2022)

6-qubit ring



- 6 fixed-frequency **transmons**, individual **drive lines**.
- 6 **resonators**, 2 **feedlines**.
- 6 **tunable-couplers**, individual **flux lines**.

Perfect state transfer (PST) of single excitations

Spin chain Hamiltonian

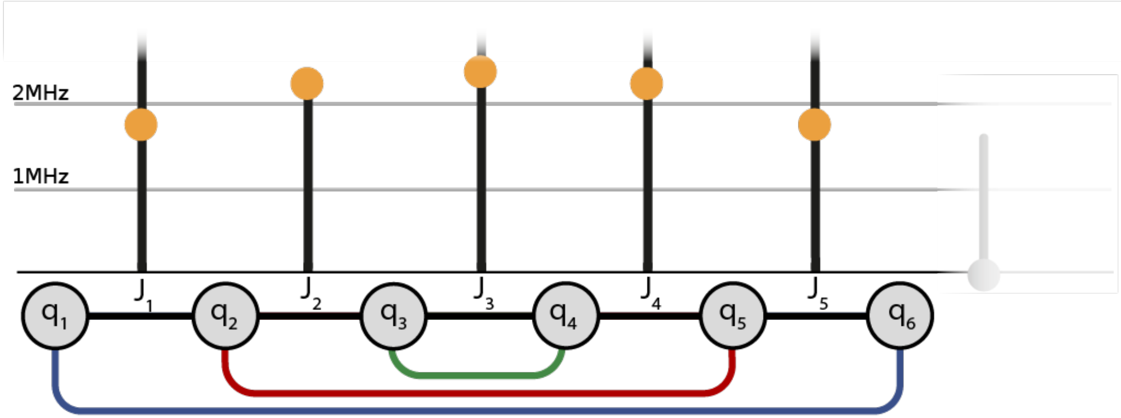
$$H_{\text{chain}} = \sum_{n=1}^{N-1} J_n(\hat{\sigma}_n^- \hat{\sigma}_{n+1}^+ + \hat{\sigma}_n^+ \hat{\sigma}_{n+1}^-)$$

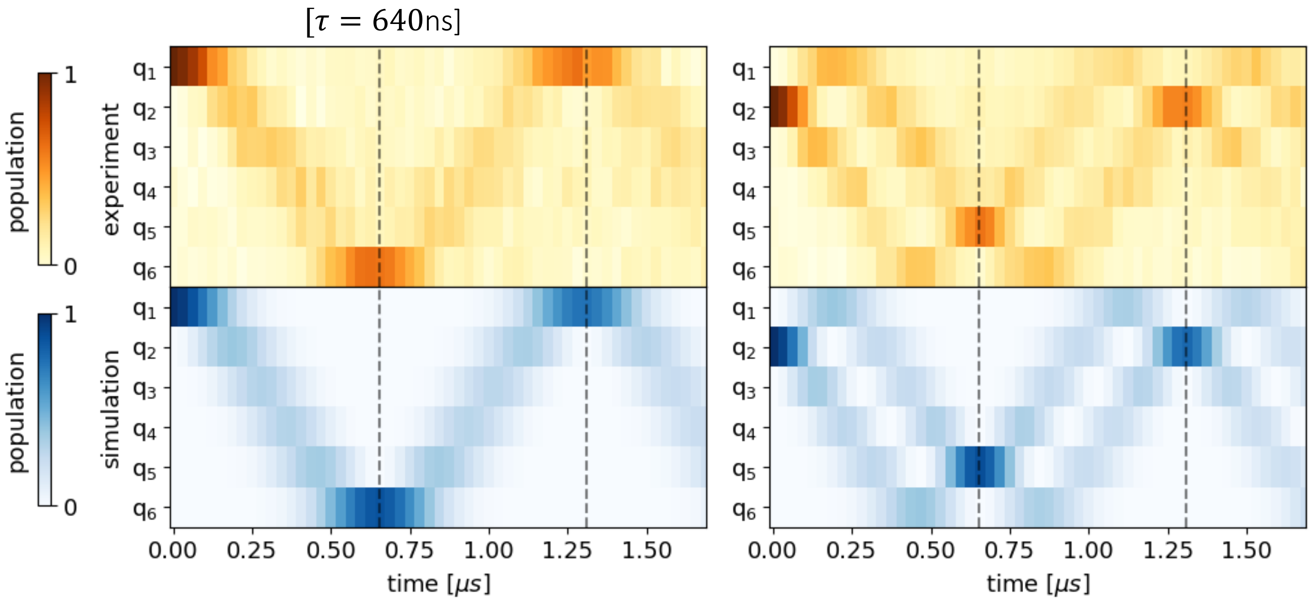
Given $J_n = \pi\sqrt{n(N-n)}/2\tau$

For a **transfer time τ**

$$H_{PST} = \sum_{n=1}^{\lfloor N/2 \rfloor} \frac{\pi}{2\tau}(\hat{\sigma}_n^- \hat{\sigma}_{N+1-n}^+ + \hat{\sigma}_n^+ \hat{\sigma}_{N+1-n}^-)$$

Effective PST Hamiltonian (single excitation)

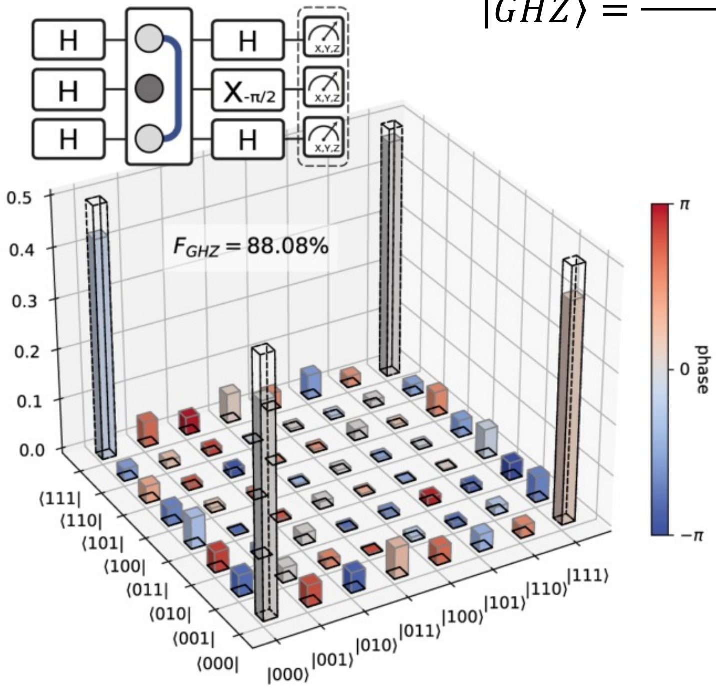




GHZ state preparation

GHZ-state preparation: based on single multi-qubit unitary transformation

$$|GHZ\rangle = \frac{|0\rangle^{\otimes N} + |1\rangle^{\otimes N}}{\sqrt{2}}$$

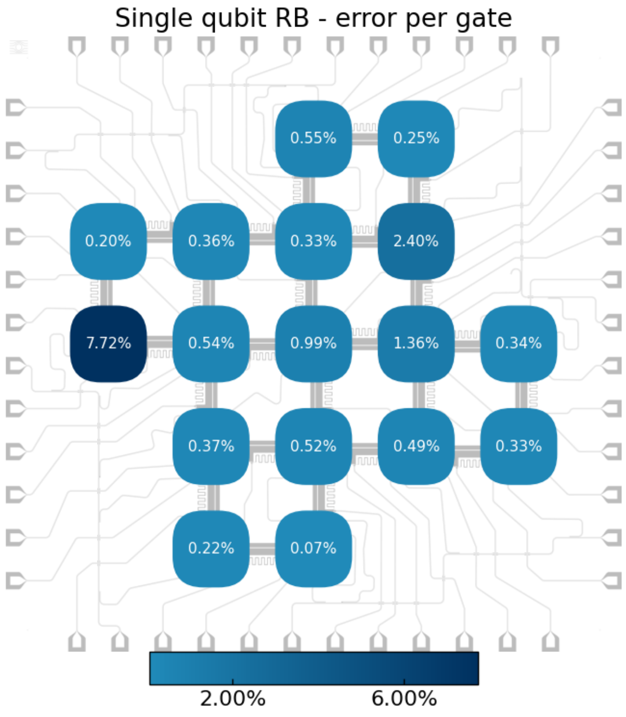


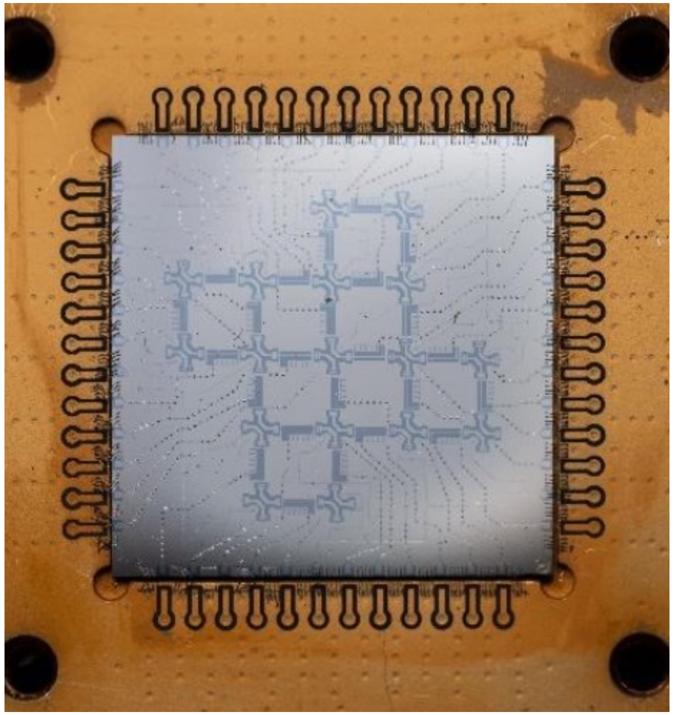
→ reduction of gate overhead
→ parity-check codes
→ quantum simulation of fermionic many-body systems
→ generation of different classes of graph states

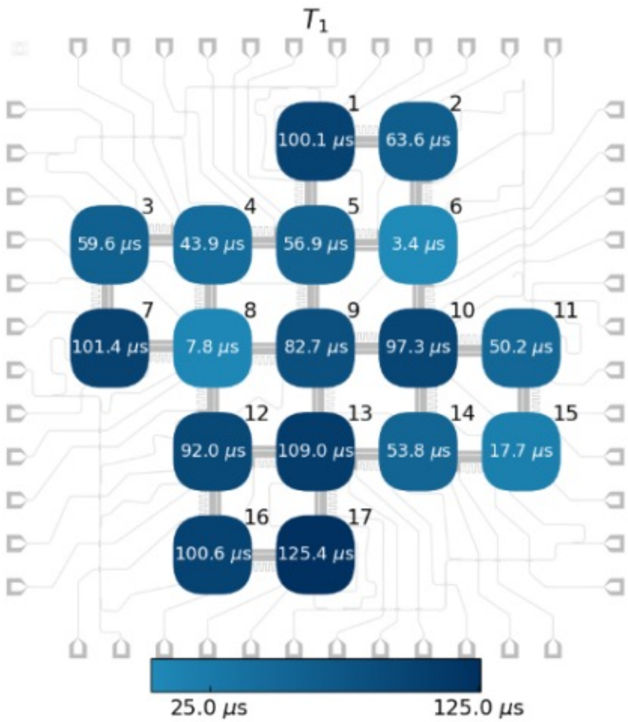
[F. Roy, J. Romeiro et al. arXiv:2405.19408 (2024)]

Outlook: a new playground with 17 qubits

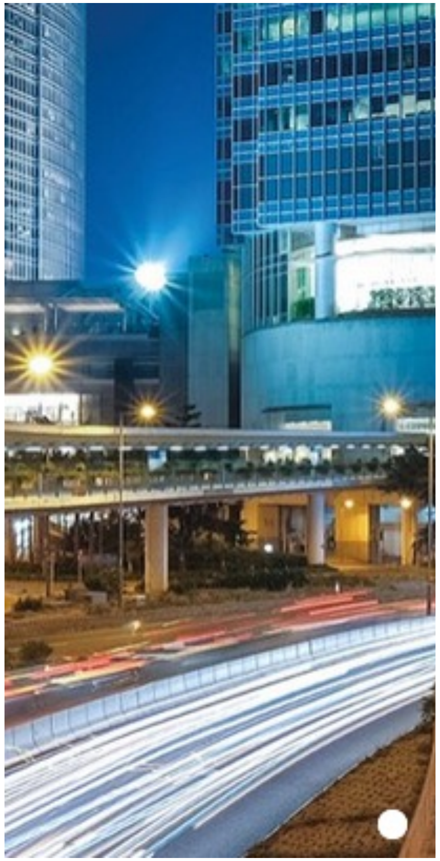
Operation of a 17 qubit processor (transmon-based)

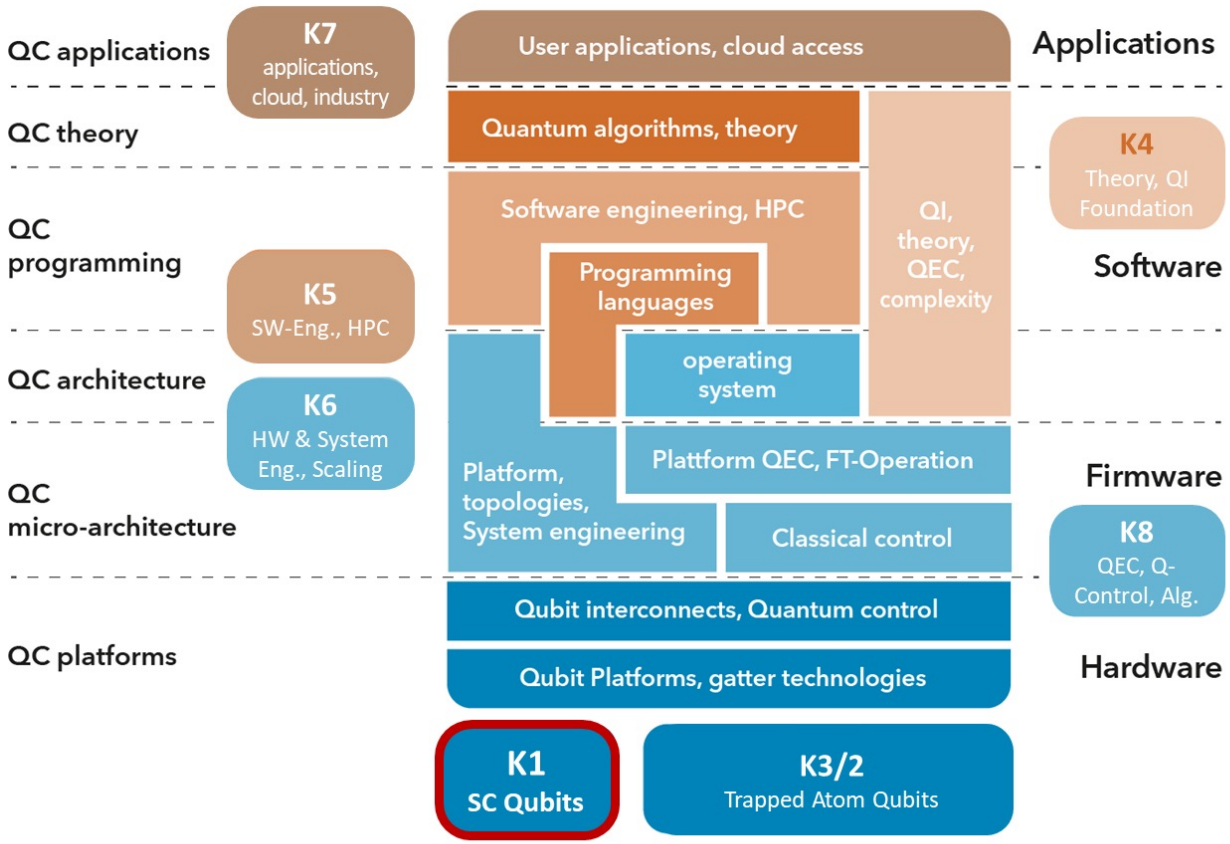






Munich Quantum Valley / MUNIQC-SC





Fraunhofer · FAU Friedrich-Alexander Universität Erlangen-Nürnberg · Technische Universität München · Max Planck Gesellschaft · BAdW Bayerische Akademie der Wissenschaften · LMU Ludwig-Maximilians-Universität München · DLR

Strategy for the Bavarian Quantum Roadmap

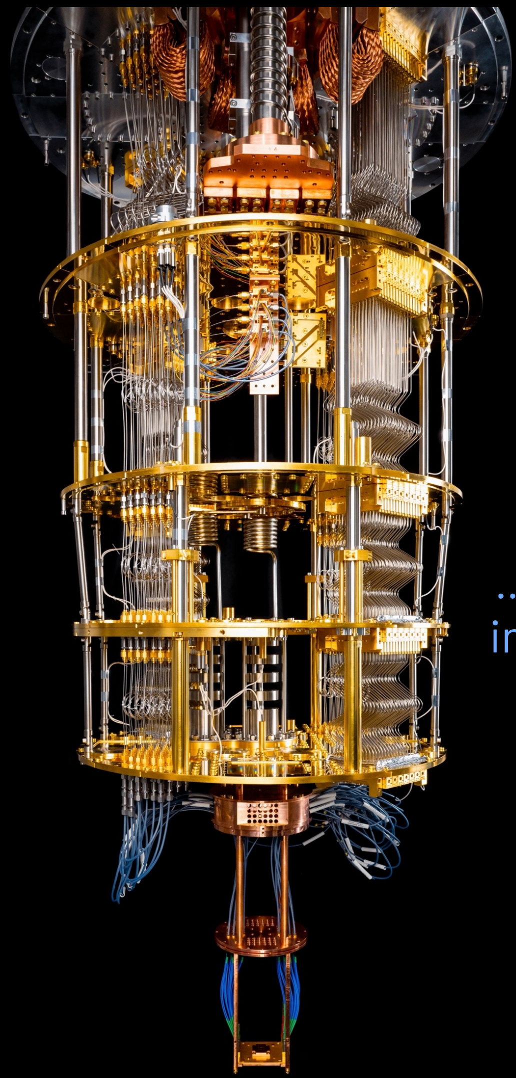
1. Center for Q-computing & technologies
   - Funding of flagship projects
   - Developing quantum computers

2. Q-technology park
   - Deep-tech infrastructure
   - Open for universities, start-ups, companies,…
   - Connected to Fraunhofer EMTF & Max Planck Semiconductor Labs

3. Q-workforce
   - Education
   - Recruiting
   - Outreach

Grand Challenge: Quantum Computing

Overcome the challenges in controlling large scale quantum systems…



… to solve problems that are otherwise intractable and to explore new physics!

Munich Quantum Valley