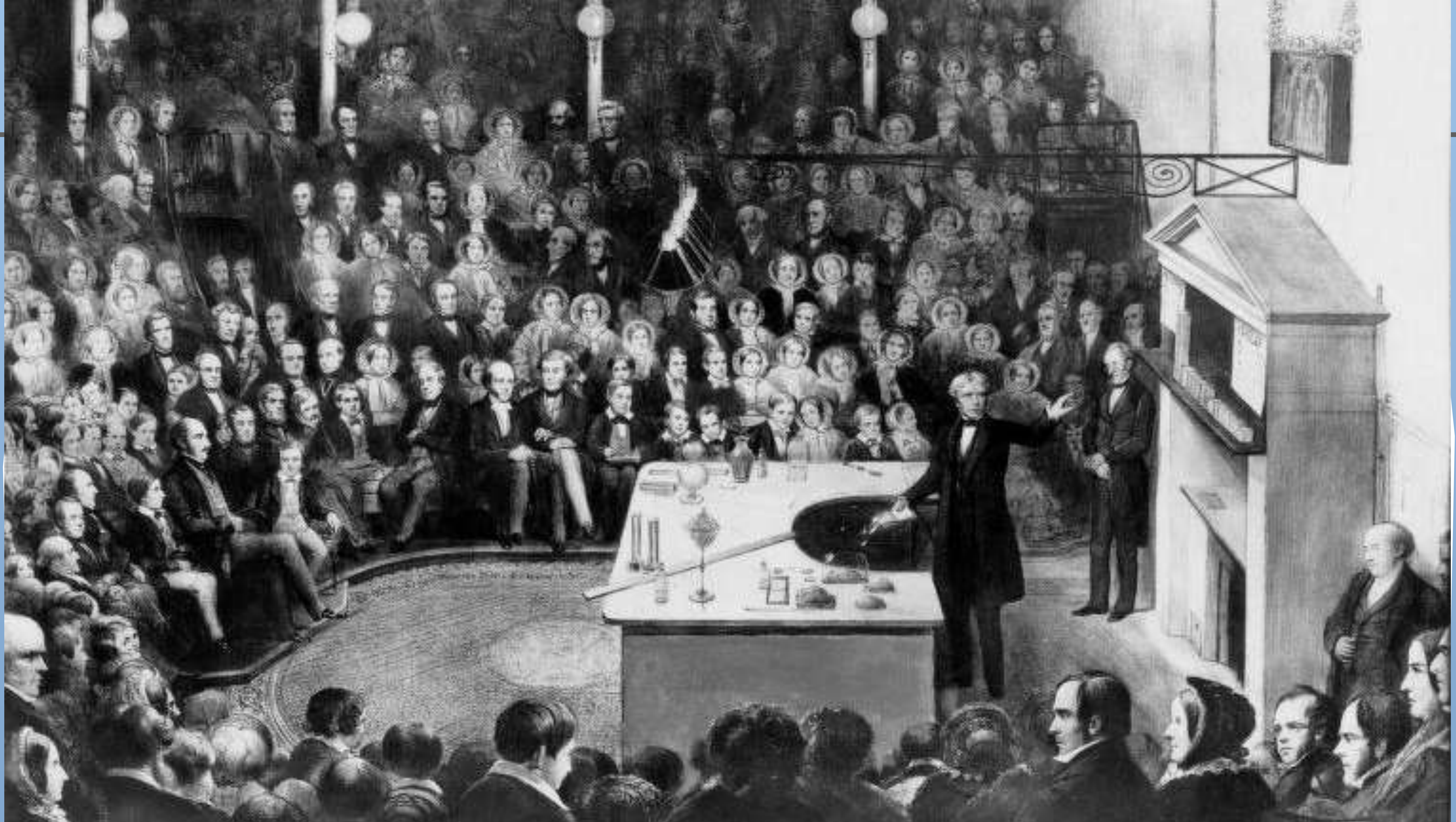


ENGINEERING THE QUANTUM COMPUTER

HPCQC Conference, Cineca

14.12.2023 | DAVID DIVINCENZO

Back in 1959…

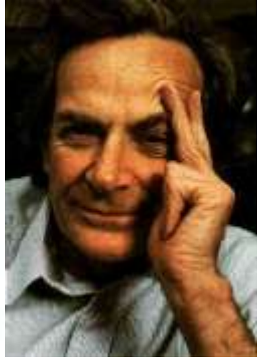
…When we get to the very, very small world---say circuits of seven atoms---we have a lot of new things that would happen that represent completely new opportunities for design. Atoms on a small scale behave like *nothing* on a large scale, for they satisfy the laws of quantum mechanics. So, as we go down and fiddle around with the atoms down there, we are working with different laws, and we can expect to do different things. We can manufacture in different ways. We can use, not just circuits, but some system involving the quantized energy levels, or the interactions of quantized spins, etc.

From "There's Plenty of Room at the Bottom",
Lecture by Richard Feynman at
American Physical Society meeting in 1959.

International Journal of Theoretical Physics, Vol. 21, Nos. 6/7, 1982

Simulating Physics with Computers

Richard P. Feynman



There are two ways that we can go about it. We can give up on our rule about what the computer was, we can say: Let the computer itself be built of quantum mechanical elements which obey quantum mechanical laws. Or we can turn the other way and say: Let the computer still be the same kind that we thought of before—a logical, universal automaton; can we imitate this situation? And I'm going to separate my talk here, for it branches into two parts.

4. QUANTUM COMPUTERS—UNIVERSAL QUANTUM SIMULATORS

The first branch, one you might call a side-remark, is, Can you do it with a new kind of computer—a quantum computer? (I'll come back to the other branch in a moment.) Now it turns out, as far as I can tell, that you can simulate this with a quantum system, with quantum computer elements. It's not a Turing machine, but a machine of a different kind. If we disregard

Rolf Landauer, IBM, c. 1960
“Information is Physical”

модели репликации, при разворачивании спирали часть хромосомы должна вращаться со скоростью, не меньшей 125 оборотов в секунду. Параллельно должна происходить сложная сеть безошибочных биохимических превращений.

Возможно, для прогресса в понимании таких явлений нам недостает математической теории квантовых автоматов. Такие объекты могли бы показать нам математические модели детерминированных процессов с совершенно непривычными свойствами. Одна из причин этого в том, что квантовое пространство состояний обладает гораздо большей емкостью, чем классическое: там, где в классике имеется N
дискретных состояний, в квантовой теори
зицию, имеется c^N планковских ячеек. П
систем их числа состояний N_1 и N_2 пе
варианте получается $c^{N_1 N_2}$.

Эти грубые подсчеты показывают гора
сложность квантового поведения системы
ческой имитацией. В частности, из-за
деления системы на элементы состояние
рассматриваться многими способами ка
ных виртуальных классических автомато
тельным подсчетом в конце работы [17].
расчета молекулы метана требуется про
сеток в 10^{42} точках. Если считать, что в
нить всего 10 элементарных операций,
числения производятся при сверхнизкой
то и при этом расчет молекулы метана п
гию, производимую на Земле примерно

Первая трудность при проведении этой программы состоит в выборе правильного баланса между математическими и физическими принципами. Квантовый автомат должен быть абстрактным: его математическая модель должна использовать лишь самые общие квантовые принципы, не предрешая физических реализаций. Тогда модель эволюции есть унитарное вращение в конечномерном гильбертовом пространстве, а модель виртуального разделения на подсистемы отвечает разложению пространства в тензорное произведение. Где-то в этой картине должно найти место взаимодействие, описываемое по традиции эрмитовыми операторами и вероятностями.

Y. Manin, c. 1980
“Computable & Uncomputable”, mentions quantum computer

A. Holevo, c. 1975: quantum channels

Outline

- **The nature of qubits**/quantum algorithms
- **Materials and devices for a quantum computer**
  - ***(Solid state perspective)***
- **Error correction and fault tolerance**
- **Strategies for 2D layouts for qubits**
- **Measurement, Isolation, Amplification**
- **The full system view**

POPULAR SCIENCE

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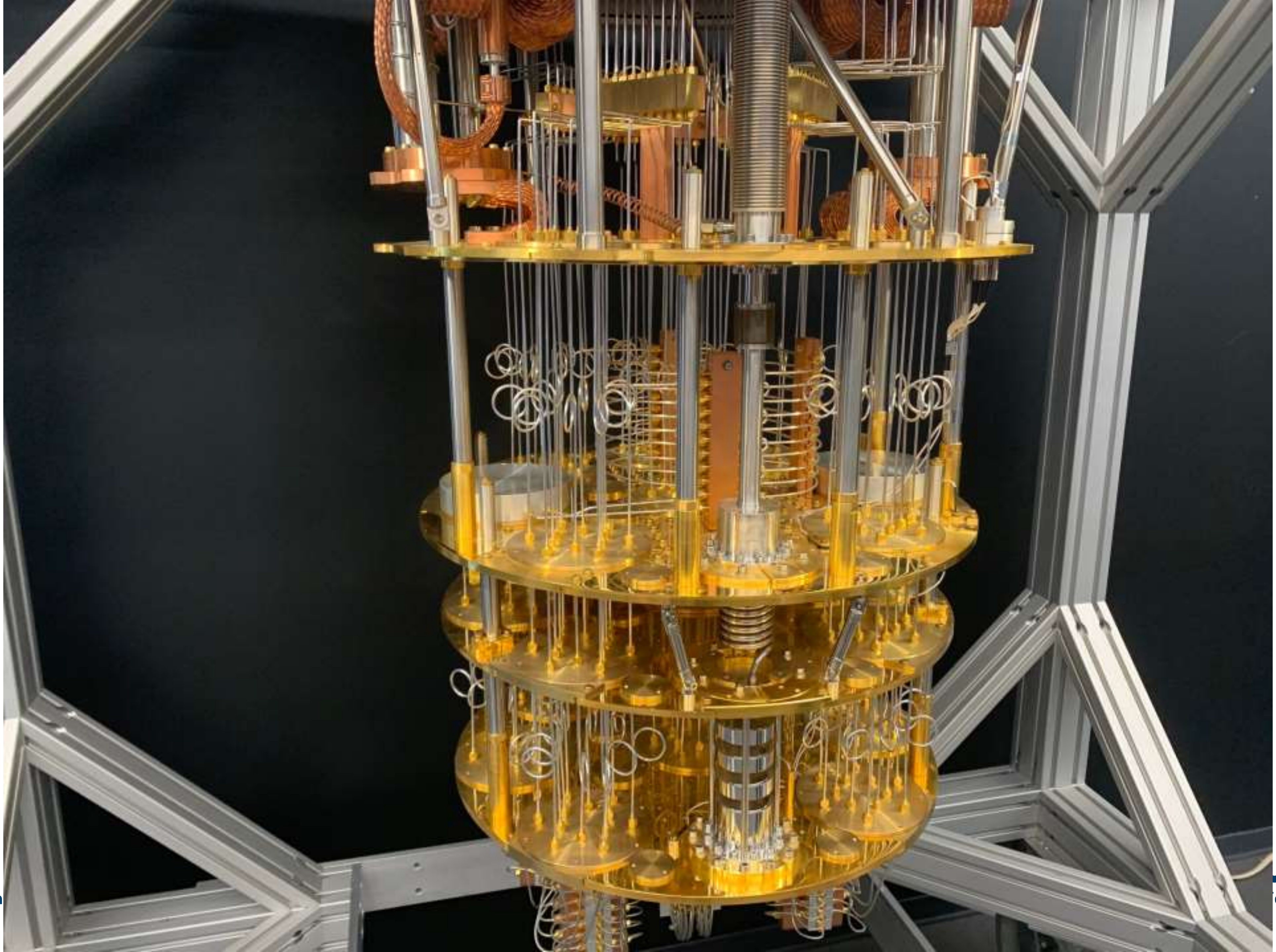
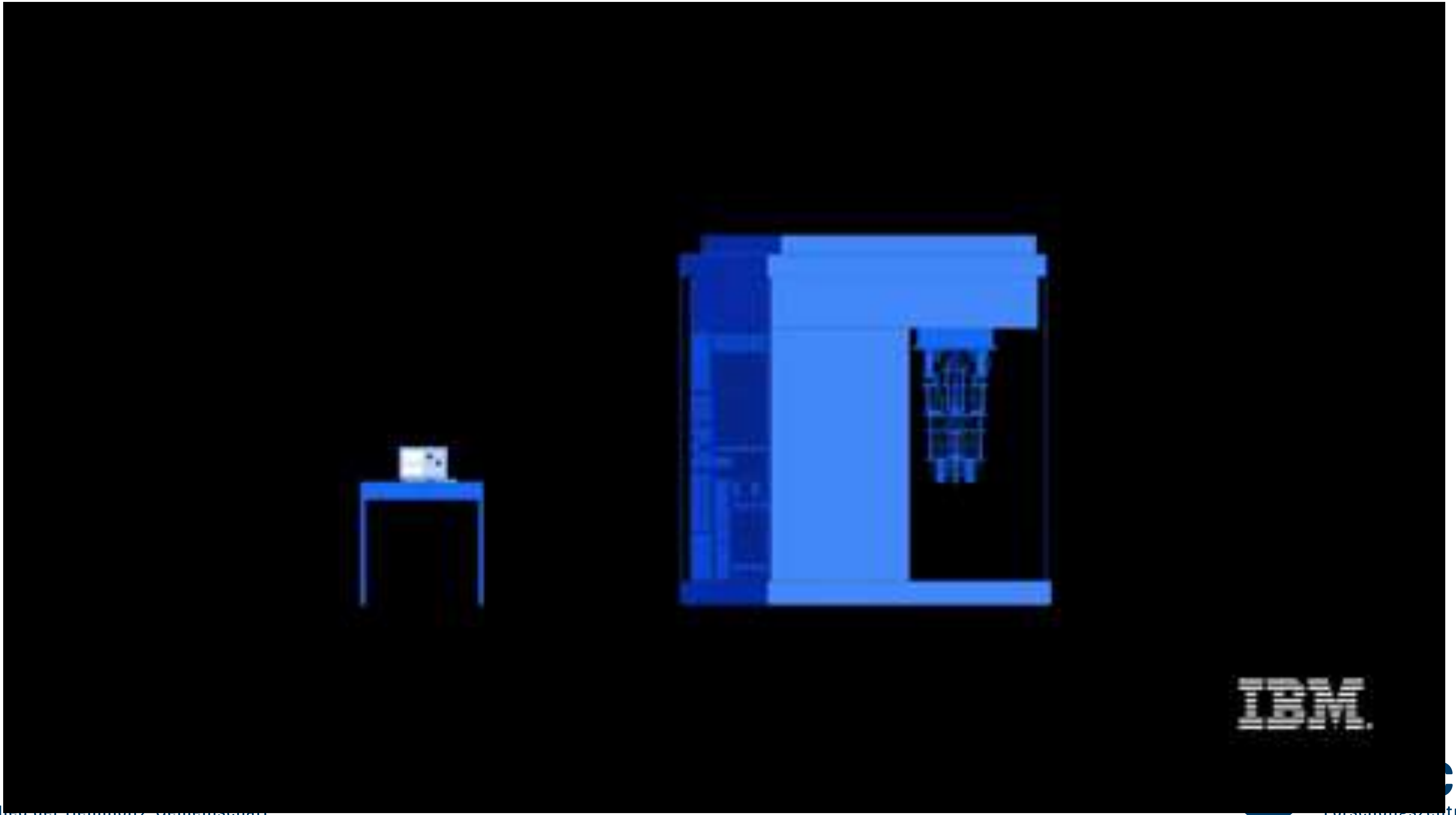
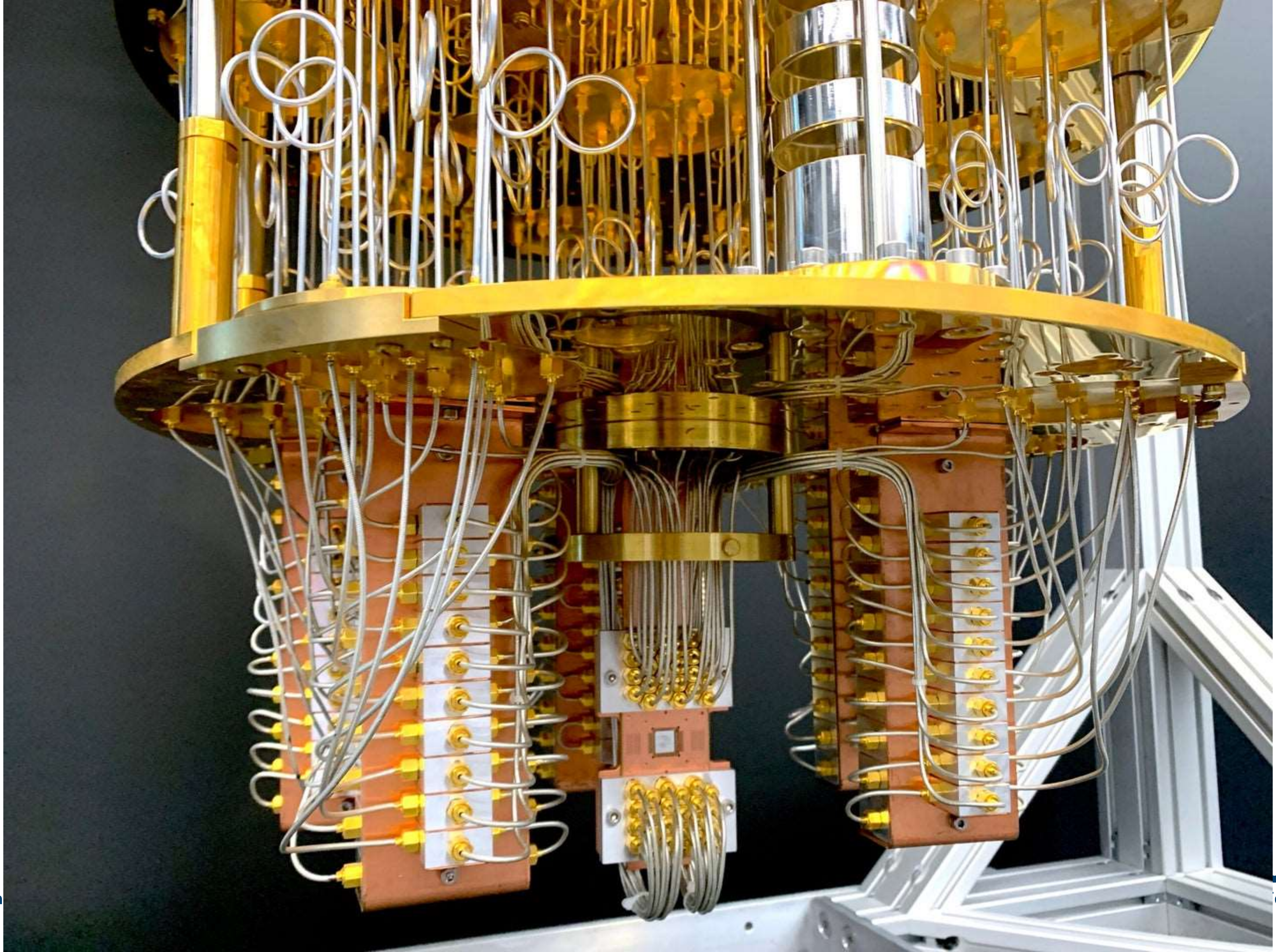
In photos: Journey to the center of a quantum computer

A fantastic voyage into the cold inner workings of a mystical modern machine.

BY CHARLOTTE HU | PUBLISHED SEP 7, 2022 9:30 AM EDT




IBM

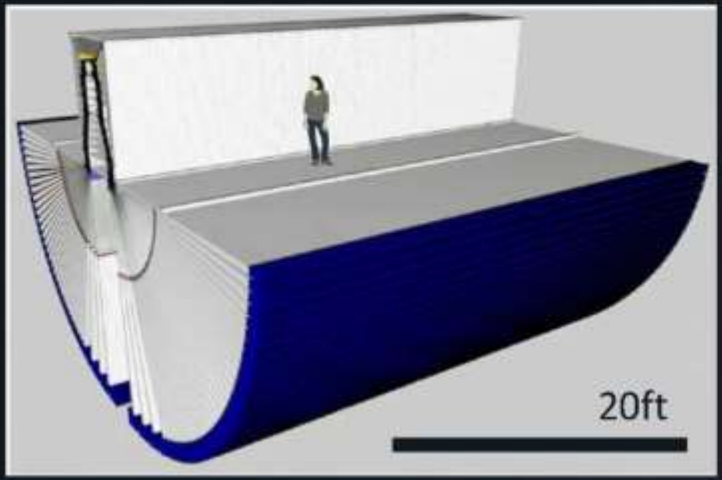


Scaling will require SWAP-C (size/weight/power/cost)

IBM

An IBM engineer working on the custom-built dilution refrigerator casing for a single QPU

Google



Google rendering of a planned million-physical-qubit system

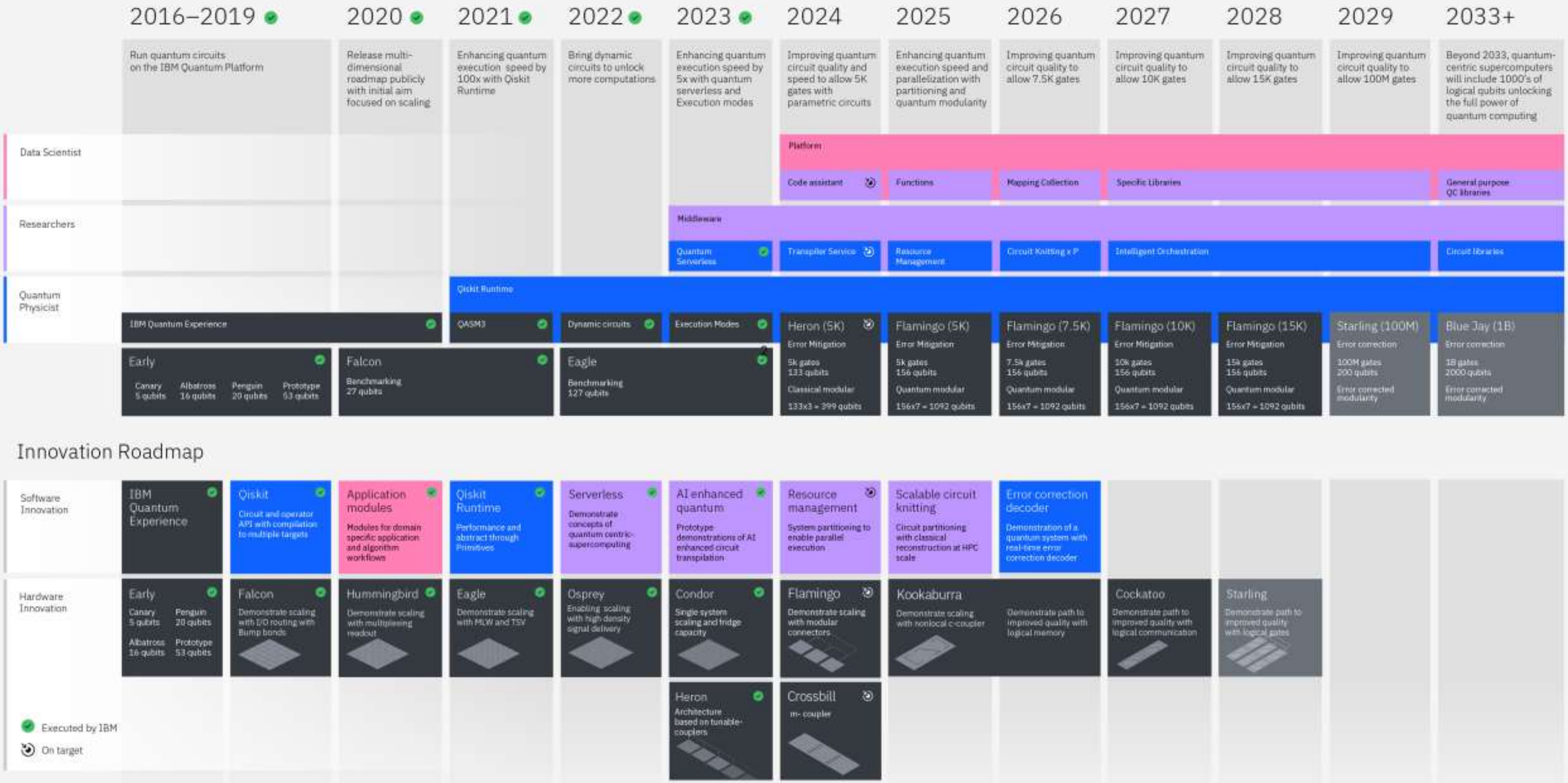
IONQ

IonQ ion trap and vacuum chamber in a single, minuscule package.

Superconductor Error Correction overhead:
1,000 – 100,000

Ion Trap Error Correction overhead:
10 – 100

Development Roadmap



nature
https://doi.org/10.1038/s41586-023-06927-3

Accelerated Article Preview

Logical quantum processor based on reconfigurable atom arrays

Received: 21 October 2023

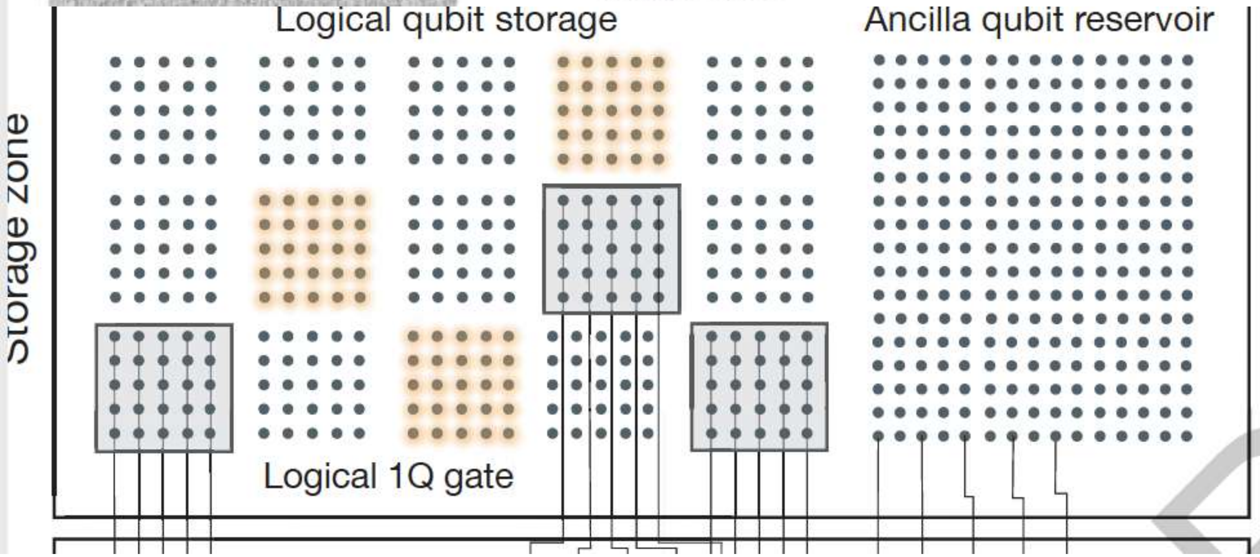
Accepted: 1 December 2023

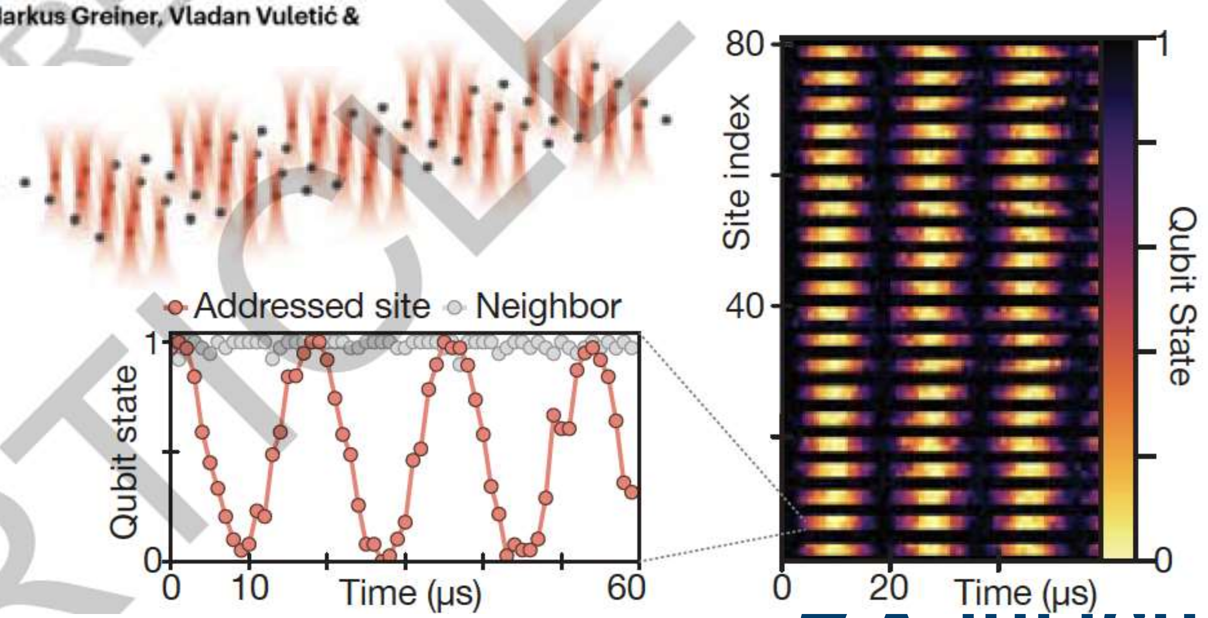
Accelerated Article Preview

Dolev Bluvstein, Simon J. Evered, Alexandra A. Geim, Sophie H. Li, Hengyun Zhou, Tom Manovitz, Sepehr Ebadi, Madelyn Cain, Marcin Kalinowski, Dominik Hangleiter, J. Pablo Bonilla Ataides, Nishad Maskara, Iris Cong, Xun Gao, Pedro Sales Rodriguez, Thomas Karolyshyn, Giulia Semeghini, Michael J. Gullans, Markus Greiner, Vladan Vuletić & Mikhail D. Lukin

A new, strong contender:
280-qubit Rb atom device,
Harvard University

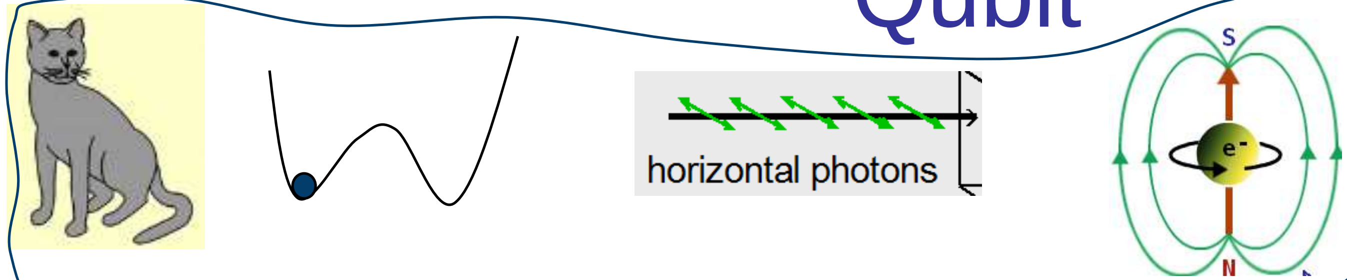
Good at parallel gate operations



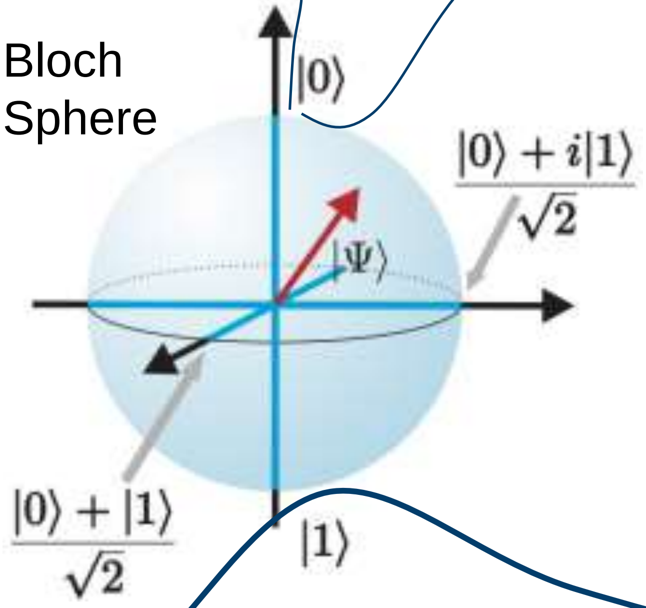


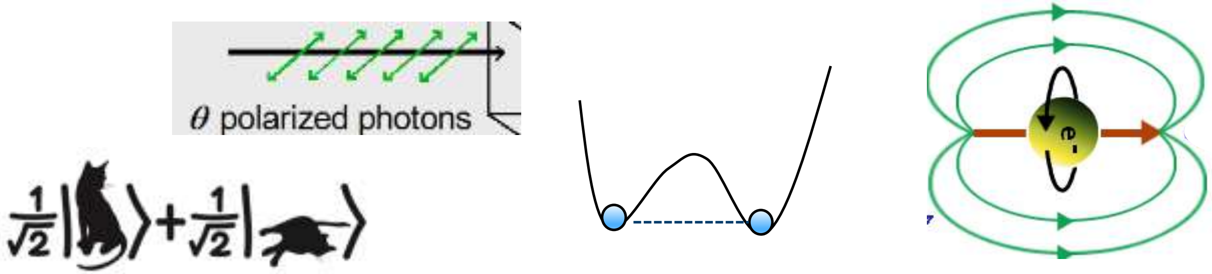
Qubit

Definite state “0”



Bloch Sphere





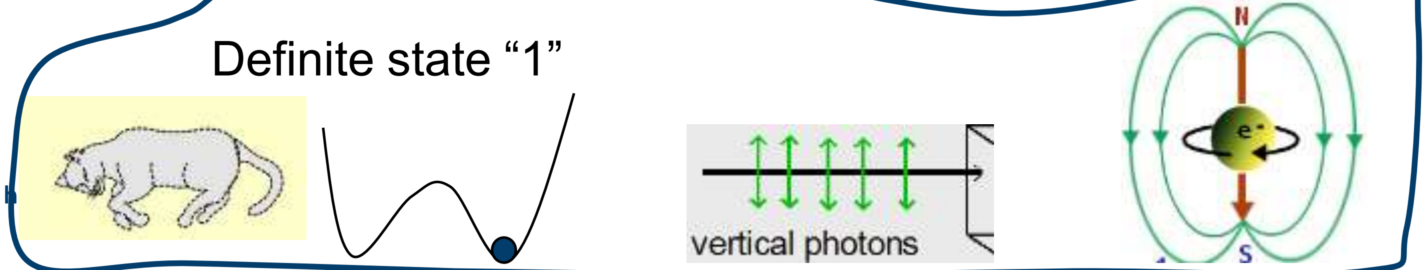
Superposition states (“halfway” shown)

-- sometimes has a clear classical meaning, usually not

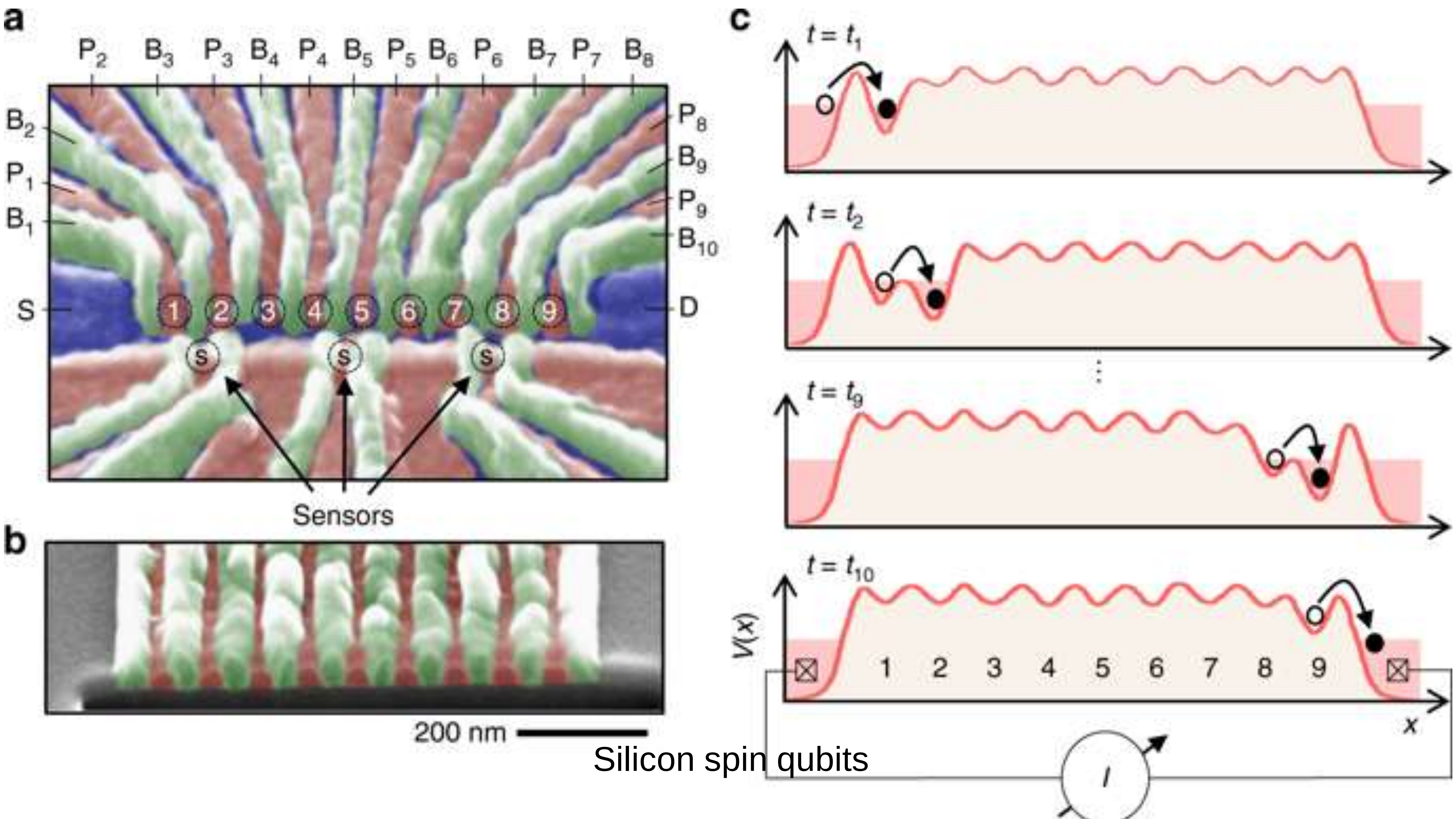
-- must be isolated from environment to exist

-- can couple to other qubits, then **entangled** states are formed, e.g $\frac{1}{\sqrt{2}}(|000\rangle + |111\rangle)$

Definite state “1”

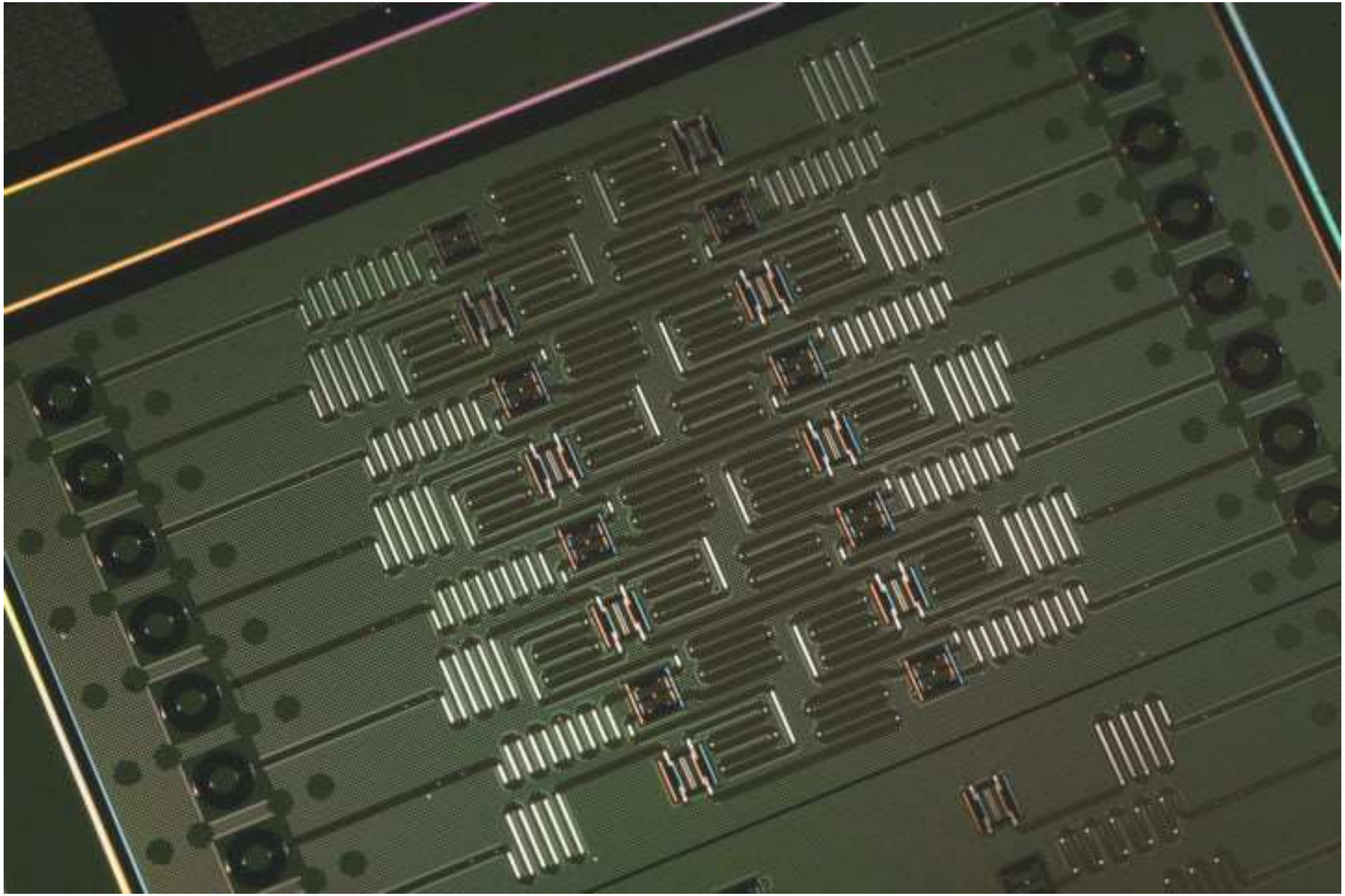


Single-spin quantum dots:
Also a route to a scaleable processor?



Silicon spin qubits

Scale up has begun! 16-qubit IBM cloud quantum computer



Metalized structure on Si chip

(all resemblance to normal chips ends there.)

Qubit possibilities are
- superconducting/SQUID type
- single electron type

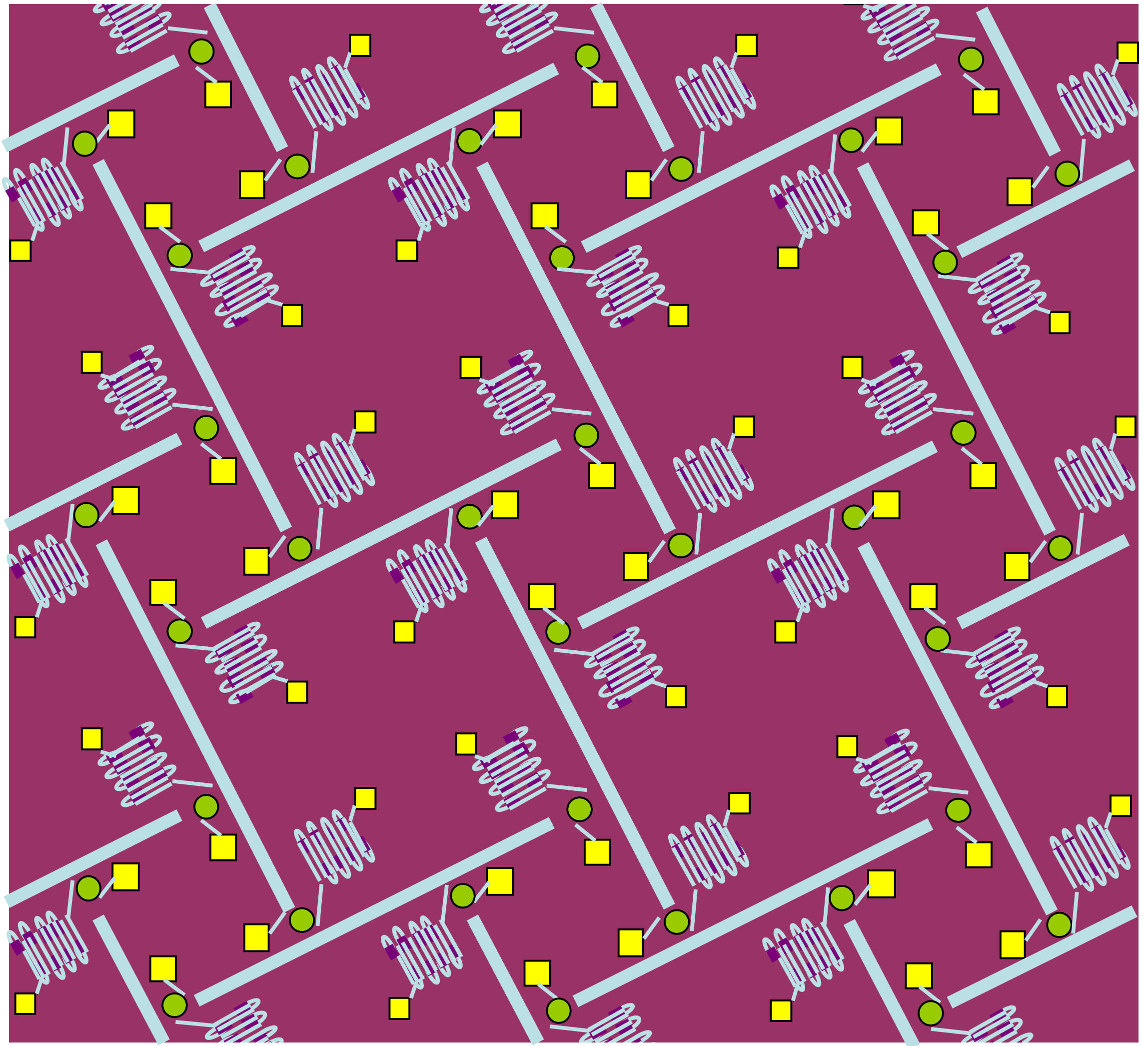
c. IBM

1 mm

T=0.02 K

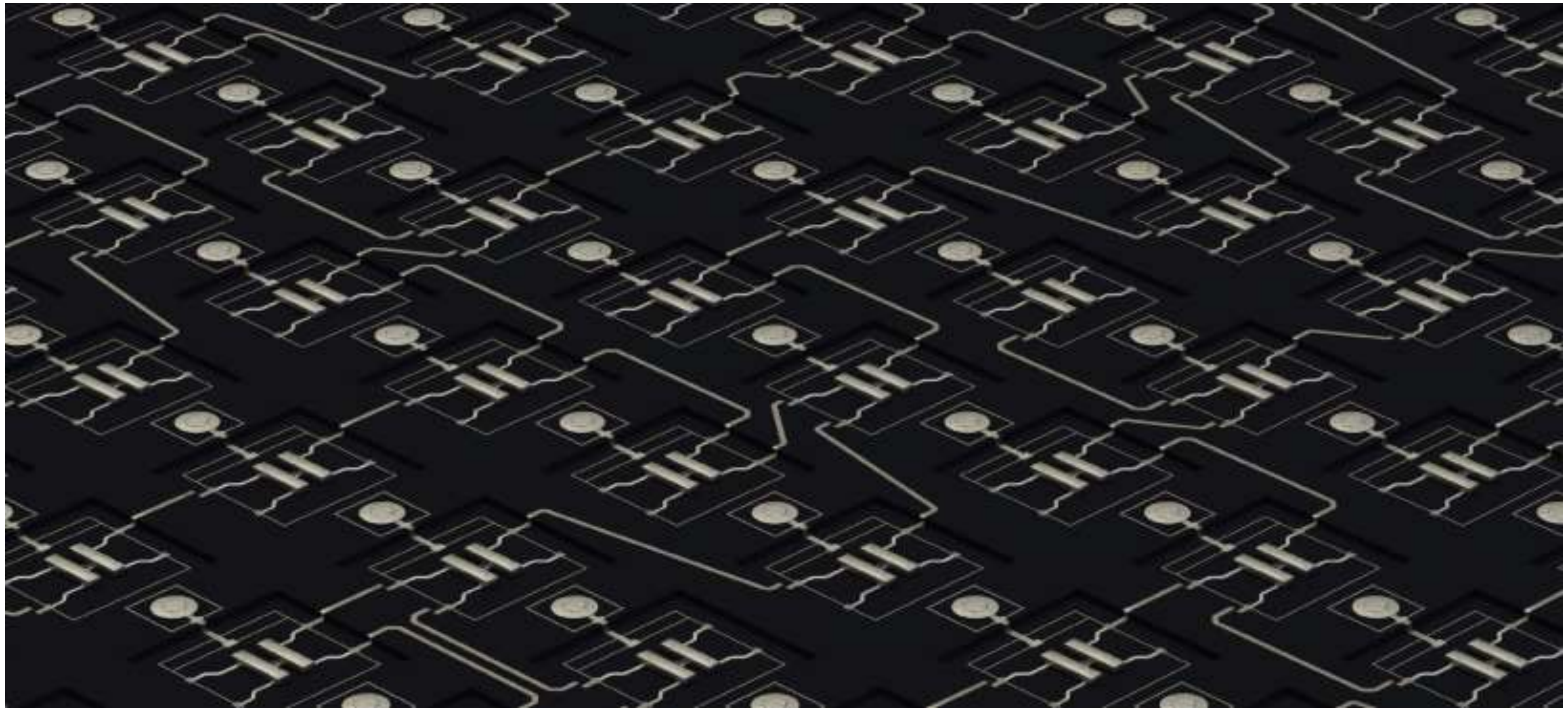
“Standard” scheme for multi-qubit/resonator layout

- Qubits (green) coupled via high-Q superconducting bus resonators (straight gray) –
- Each qubit coupled to readout resonator (meander gray)
- Sufficient connectivity for **error correction code scheme**
- Every qubit has a number of controller and sensor lines to be connected to the outside world **(gold pads)**

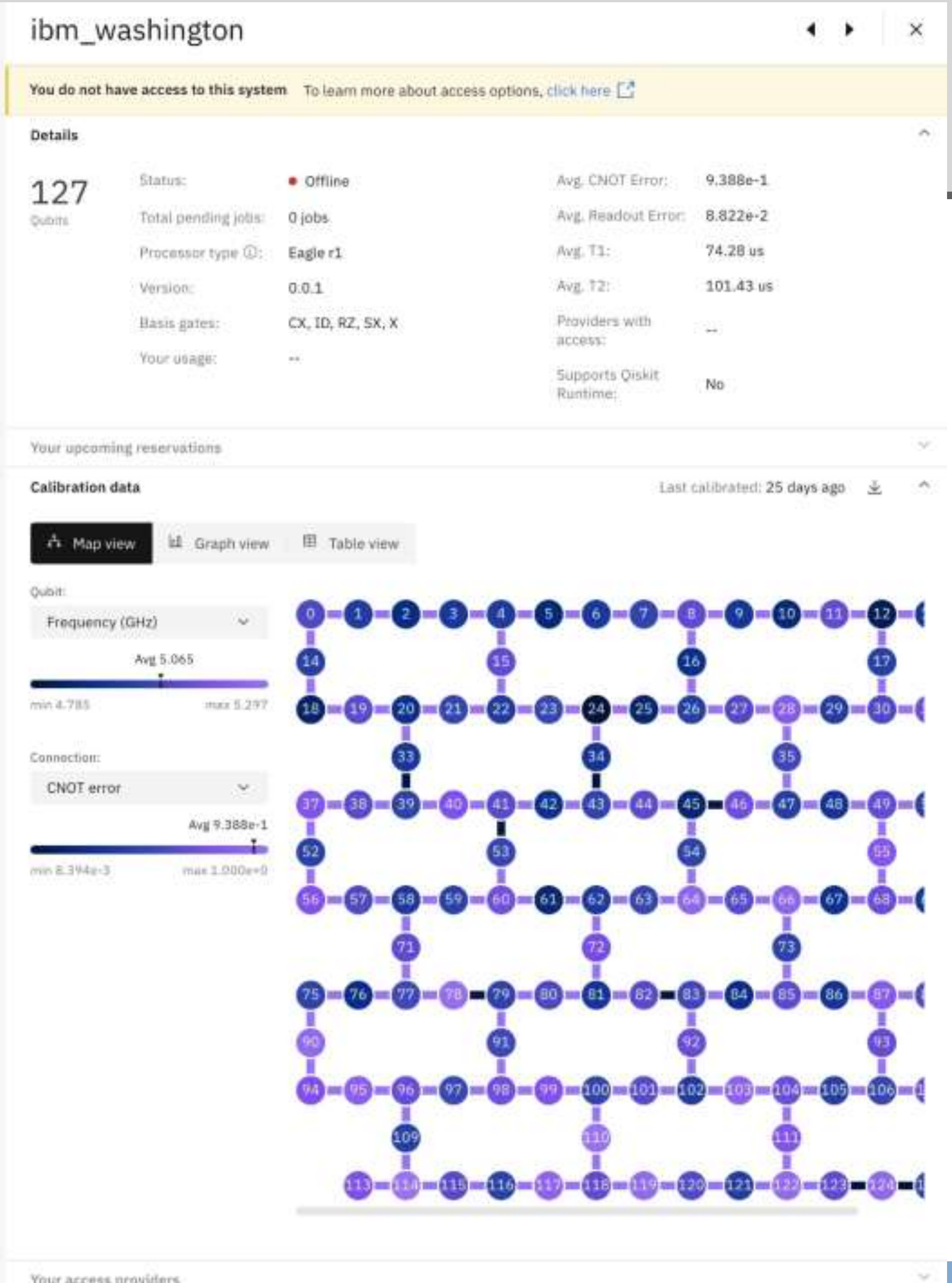


D. DiVincenzo, “Fault tolerant architectures for superconducting qubits,” Phys. Scr. T **137** (2009) 014020.

A recent IBM qubit chip

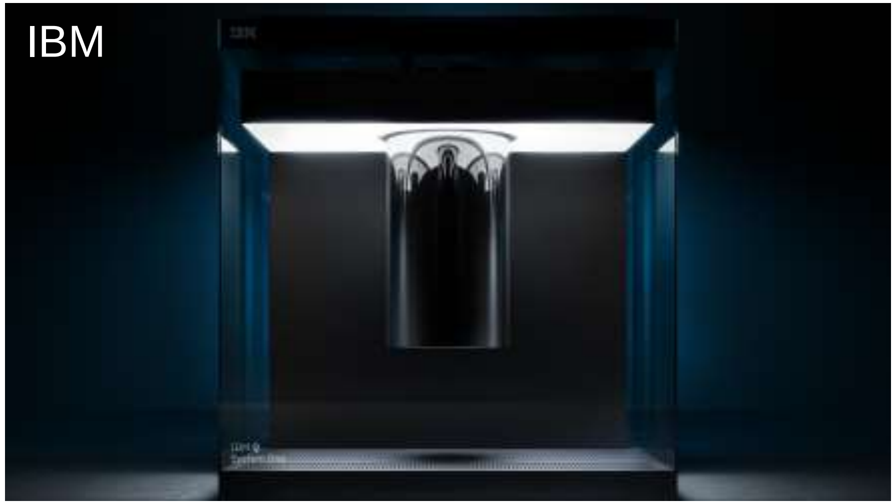


QUANTUM COMPUTING



Noisy intermediate scale quantum devices

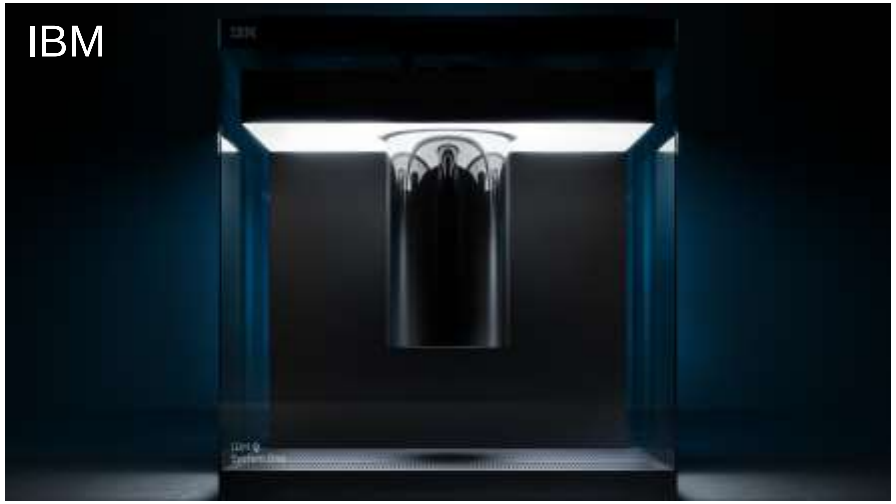
A experimental pivot from of a **few pristine qubi**
of **50-100 qubits** but tolerating a significant level

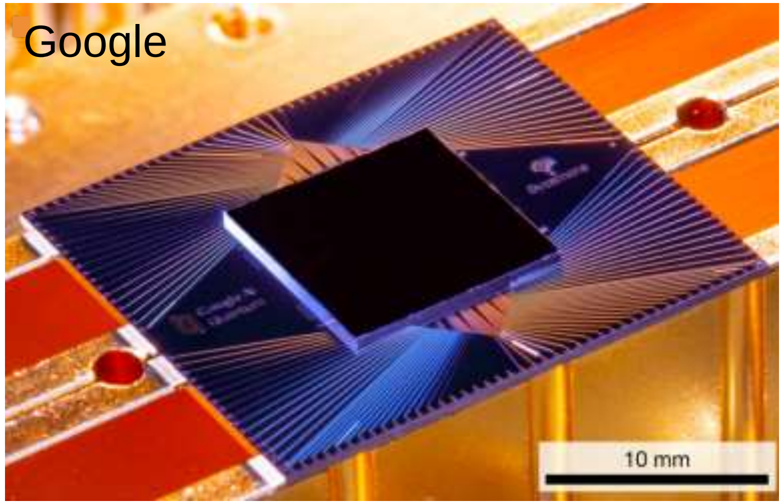


Quantum Computing in the NISQ era

Noisy intermediate scale quantum devices

A experimental pivot from of a **few pristine qubits** to the realization of circuit architectures of **50-100 qubits** but tolerating a significant level of **imperfections.**





IBM, Google, CAS, …, use superconducting charge qubits: the transmon

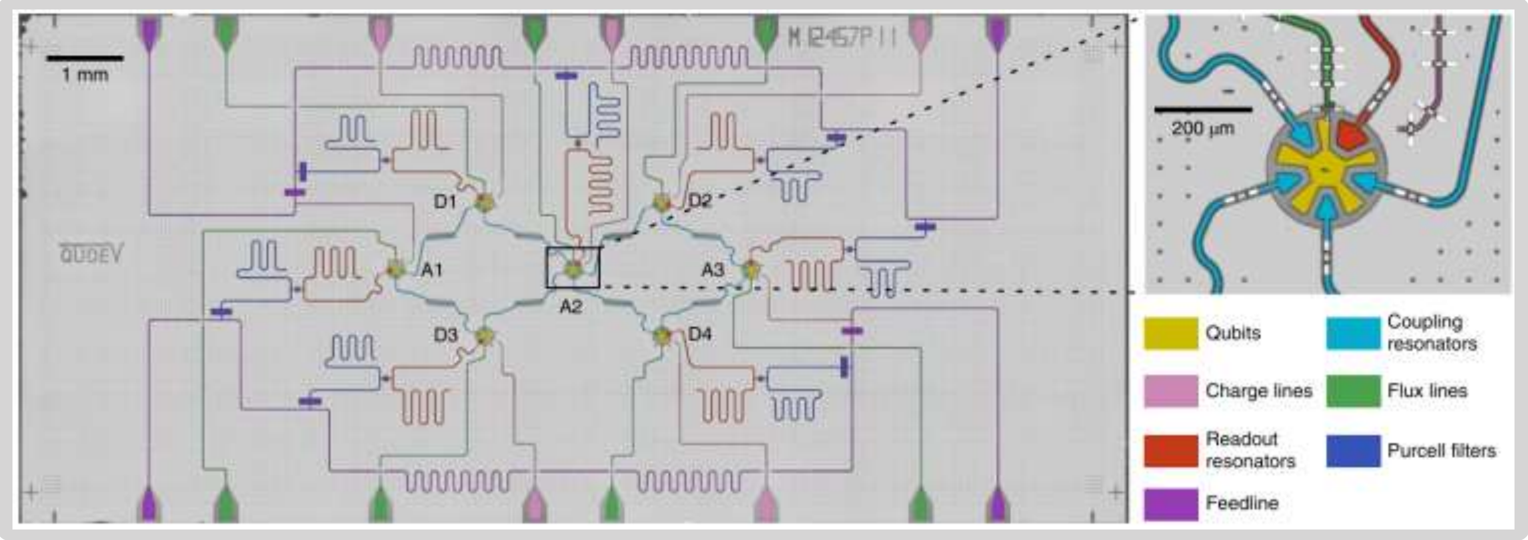
What's on the menu for today: A taste for the potential dangers and limits in this approach.

What’s really on the chip?

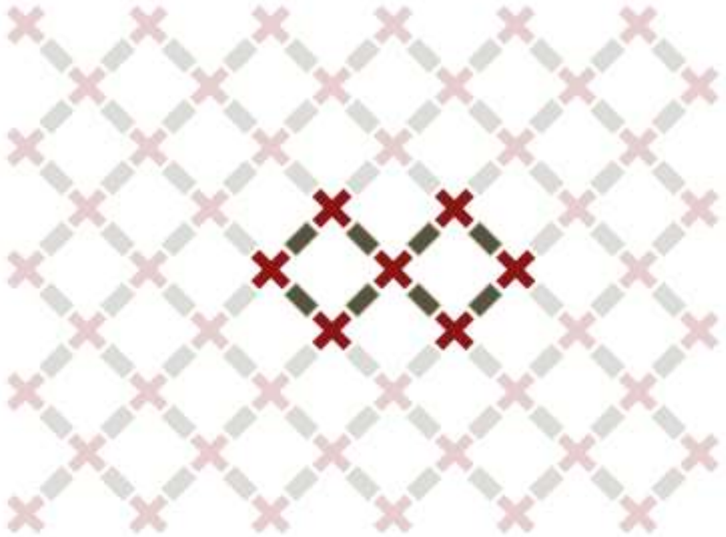
Workers at ETH and TU Delft do high-precision work on fragments of the square grids:

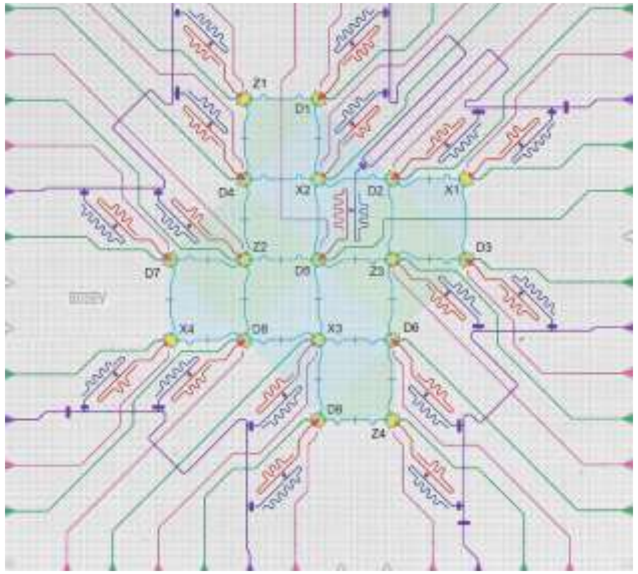
Google’s sycamore processor

surface 7 (demonstrates quantum error correction)



C. Andersen et al., Nature Physics (2020)

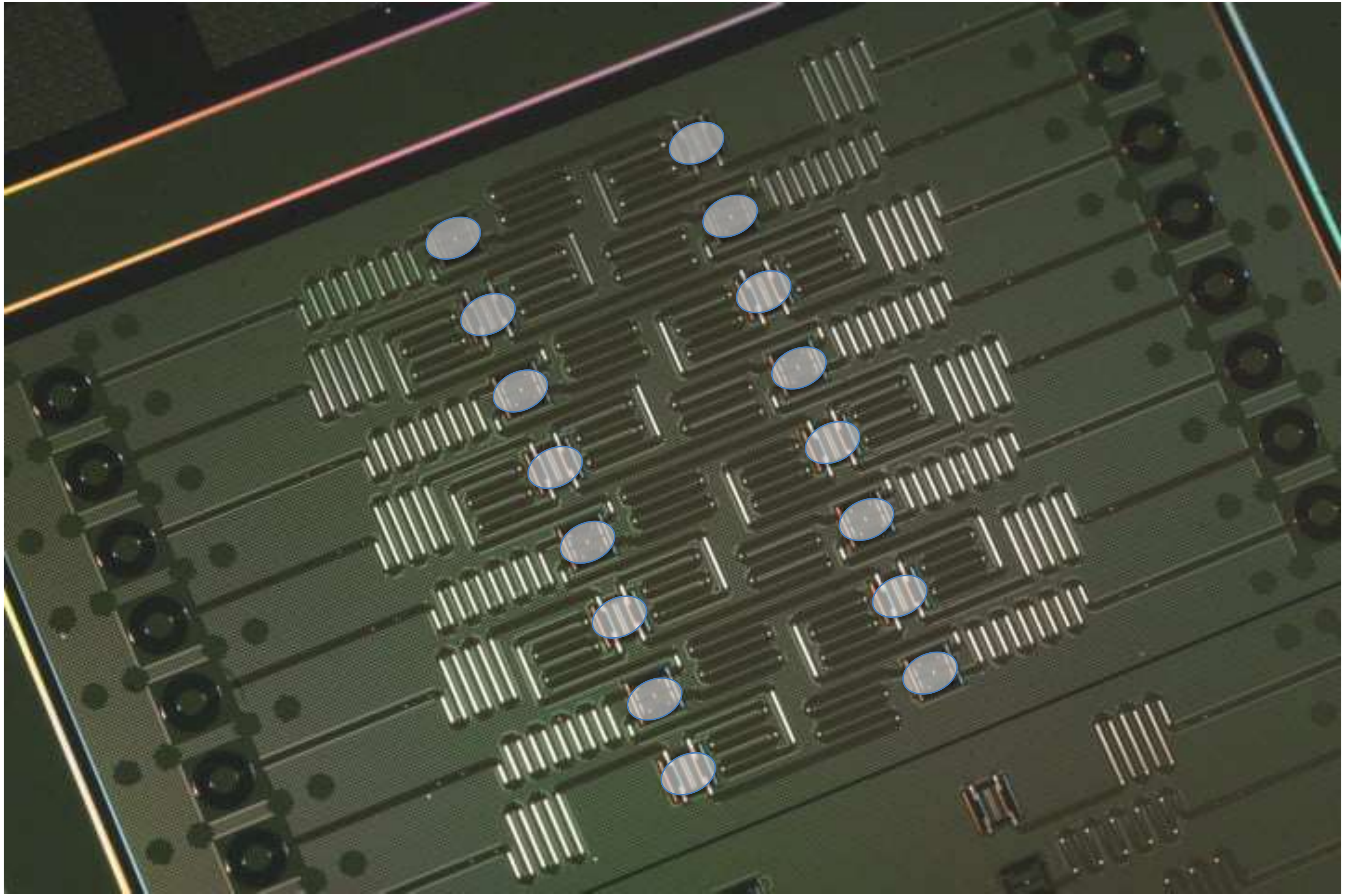




Now: surface 17

Work at ETH group

Situation with scale-up. 16-qubit IBM cloud quantum computer



c. IBM 1 mm T=0.02 K

Metalized structure on Si chip

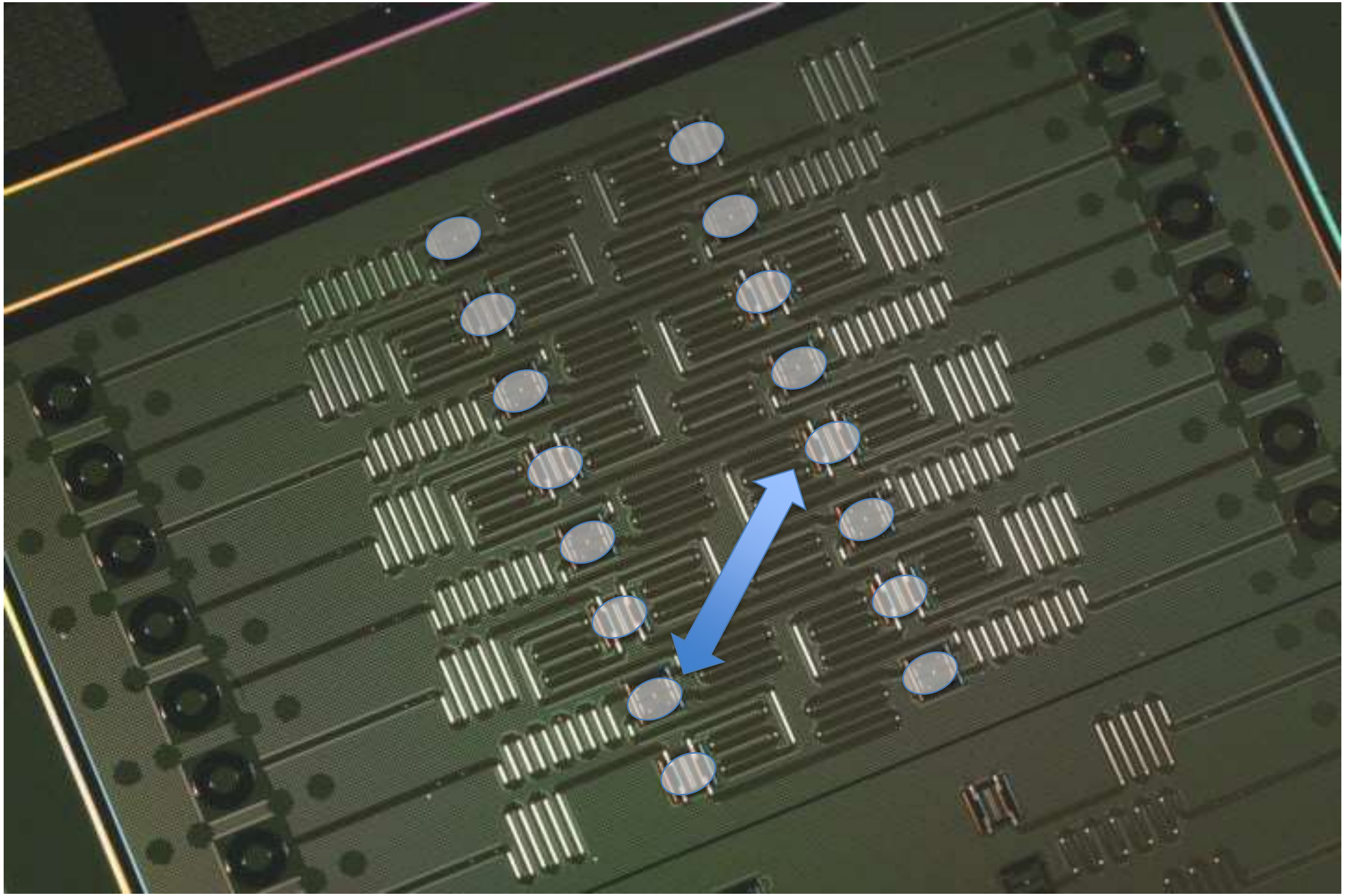
(all resemblance to normal chips ends there.)

Qubit possibilities are
- superconducting/SQUID type
- single electron type

16 qubits (highlighted white)
active part is nanometer scale

Massive additional structures are resonant couplers, sections of coplanar waveguides

Example of problematic situation: 16-qubit IBM chip



Qubits indicated are not supposed to have any direct entangling interaction

Nevertheless there is one, at the 1 MHz level

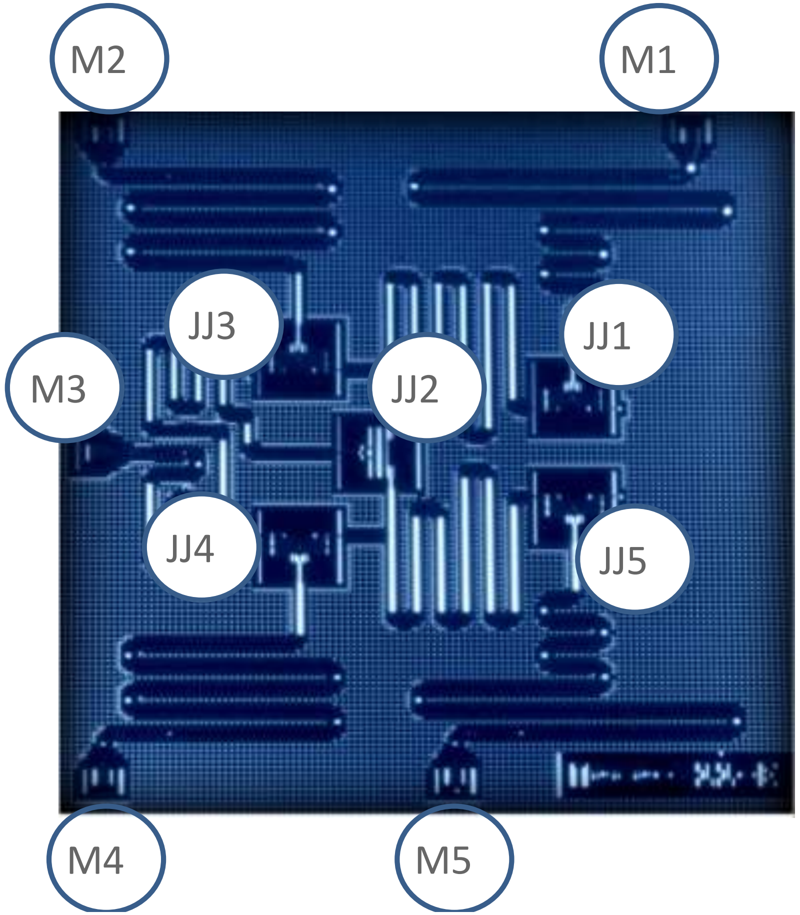
Not very big, but 10^4 linewidths!

c. IBM

1 mm

T=0.02 K

Black-box modeling methodology



Work with Solgun, Gambetta (IBM)

Black box modeling formulas:

Solgun, DiVincenzo, Gambetta, "Simple Impedance Response Formulas for the Dispersive Interaction Rates in the Effective Hamiltonians of Low Anharmonicity Superconducting Qubits," IEEE Trans. Micro. Theory and Techn., **67** (3), 928-948 (2019).

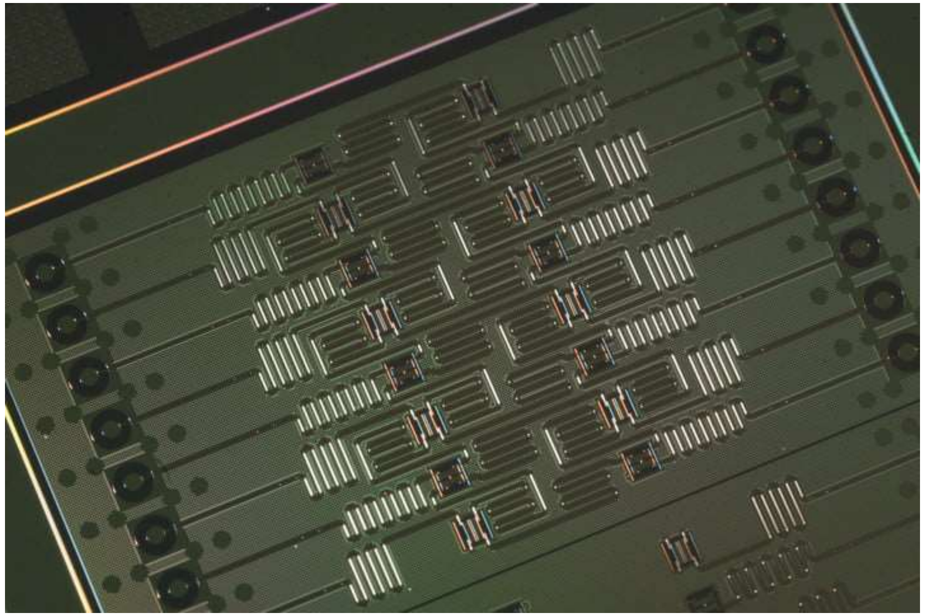
- Introduces new formulas for qubit J couplings, drive crosstalk, and other quantities, in terms of multiport impedance
- The 7-port "gray-box", or the 10-port IBM device on the right can be accurately simulated with HFSS, given the full impedance matrix
- E.g., J-coupling formula:

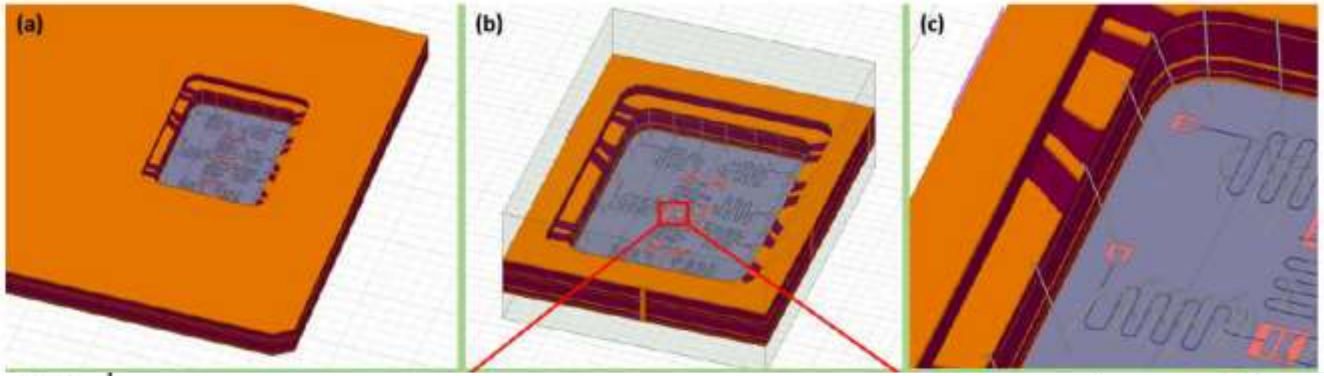
$$J_{ij} = -\frac{1}{4}\sqrt{\frac{\omega_i\omega_j}{L_iL_j}}\mathrm{Im}\left[\frac{Z_{ij}(\omega_i)}{\omega_i} + \frac{Z_{ij}(\omega_j)}{\omega_j}\right]$$

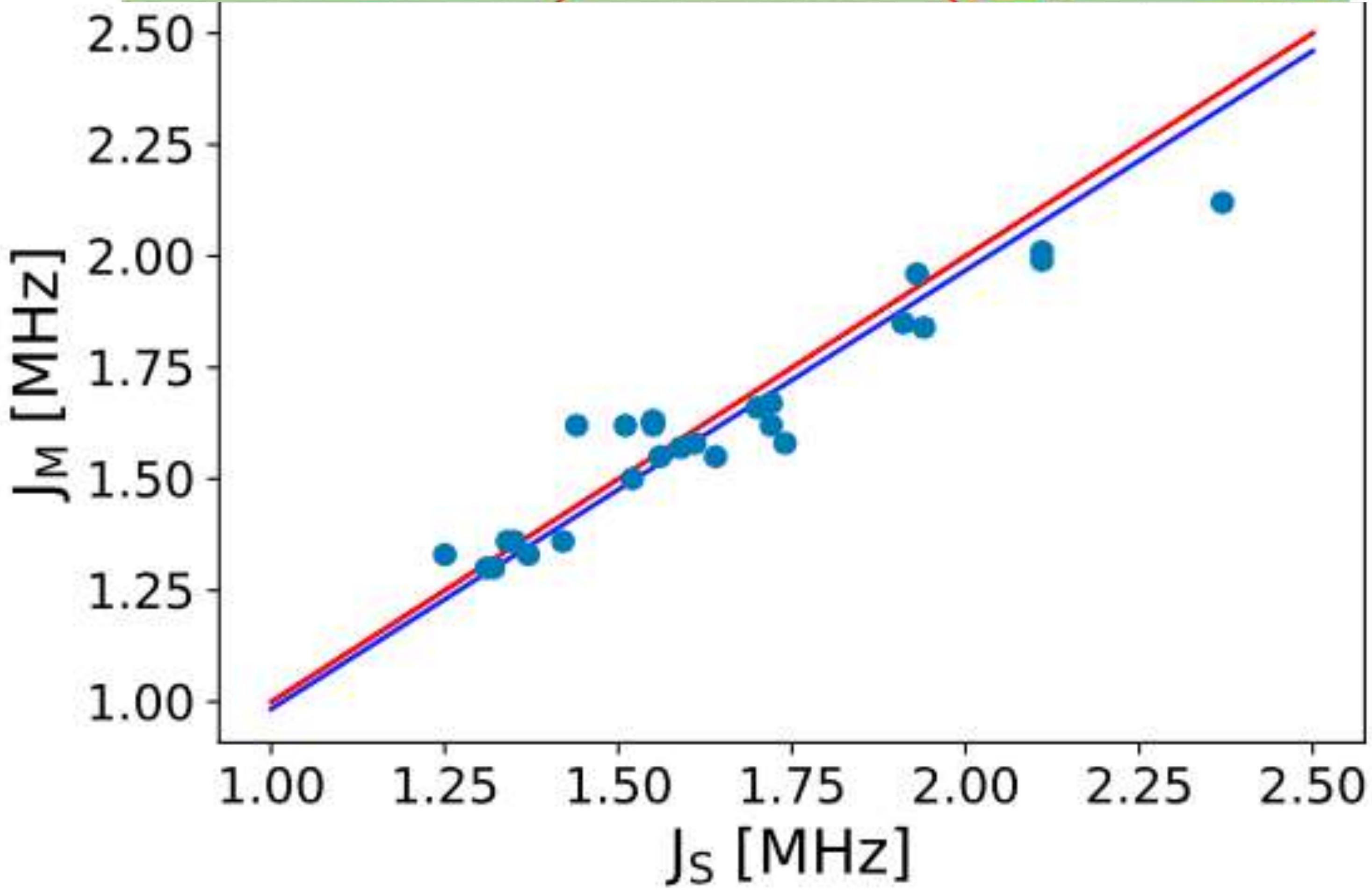
$$H = J_{ij}(X_iX_j + Y_iY_j) + \ldots$$

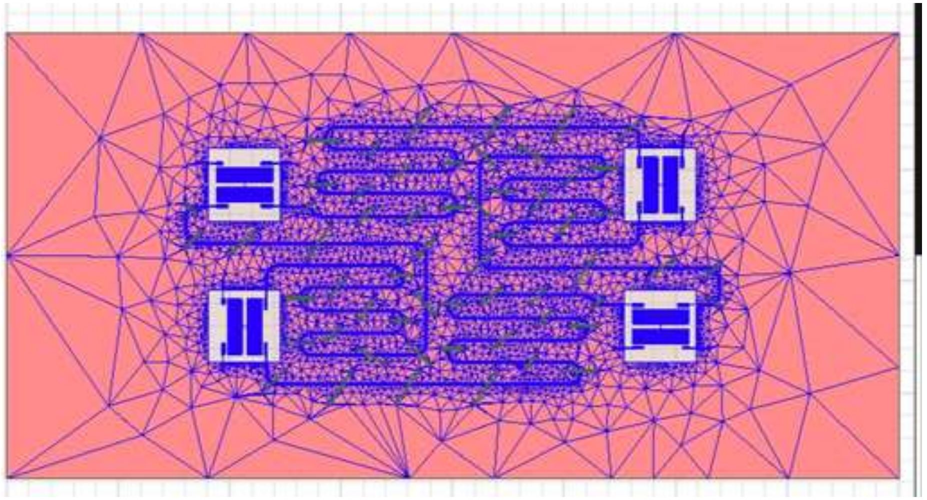
JÜLICH FORSCHUNGSZENTRUM

Very good theory-experiment correspondence for J couplings



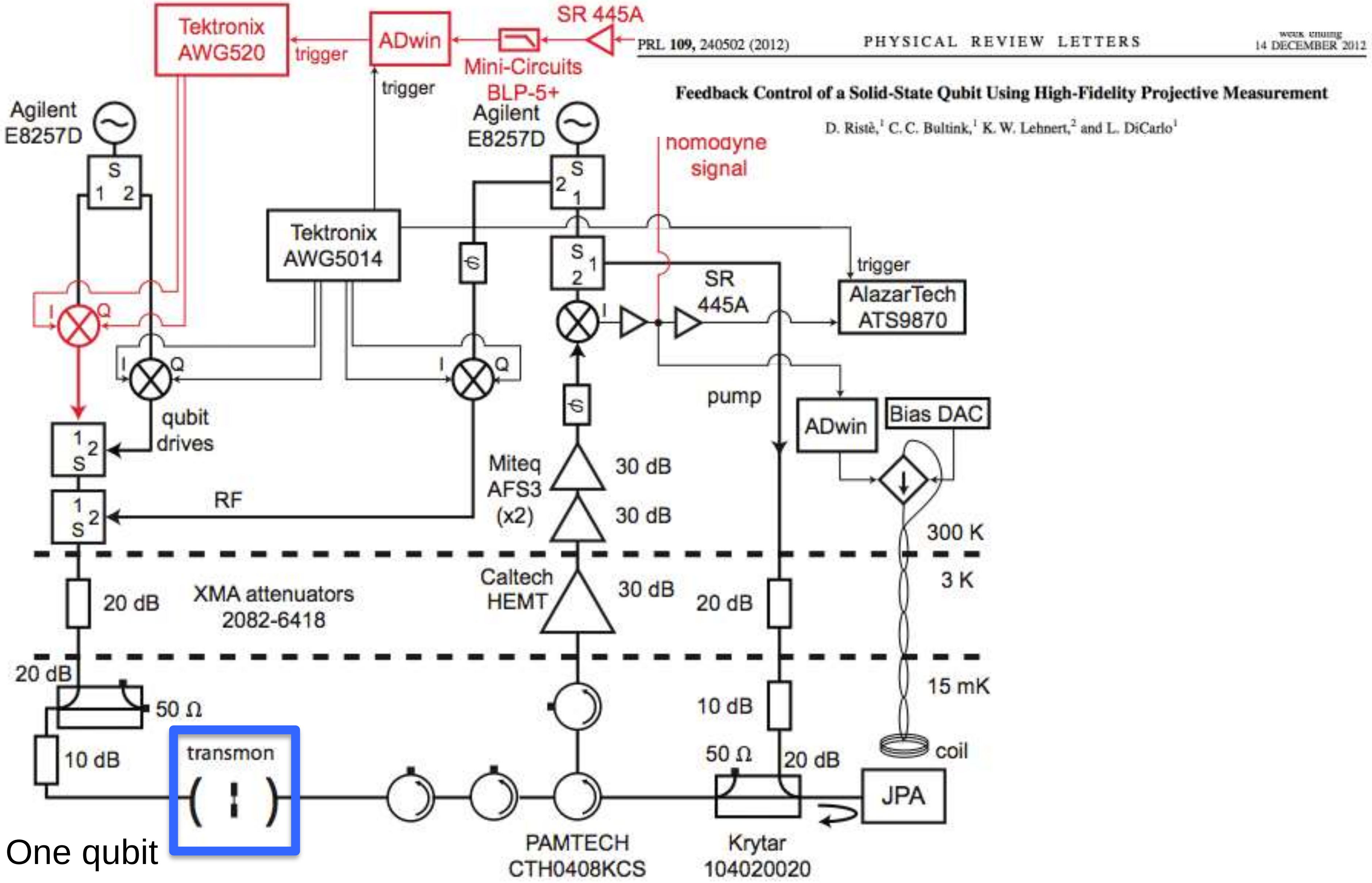






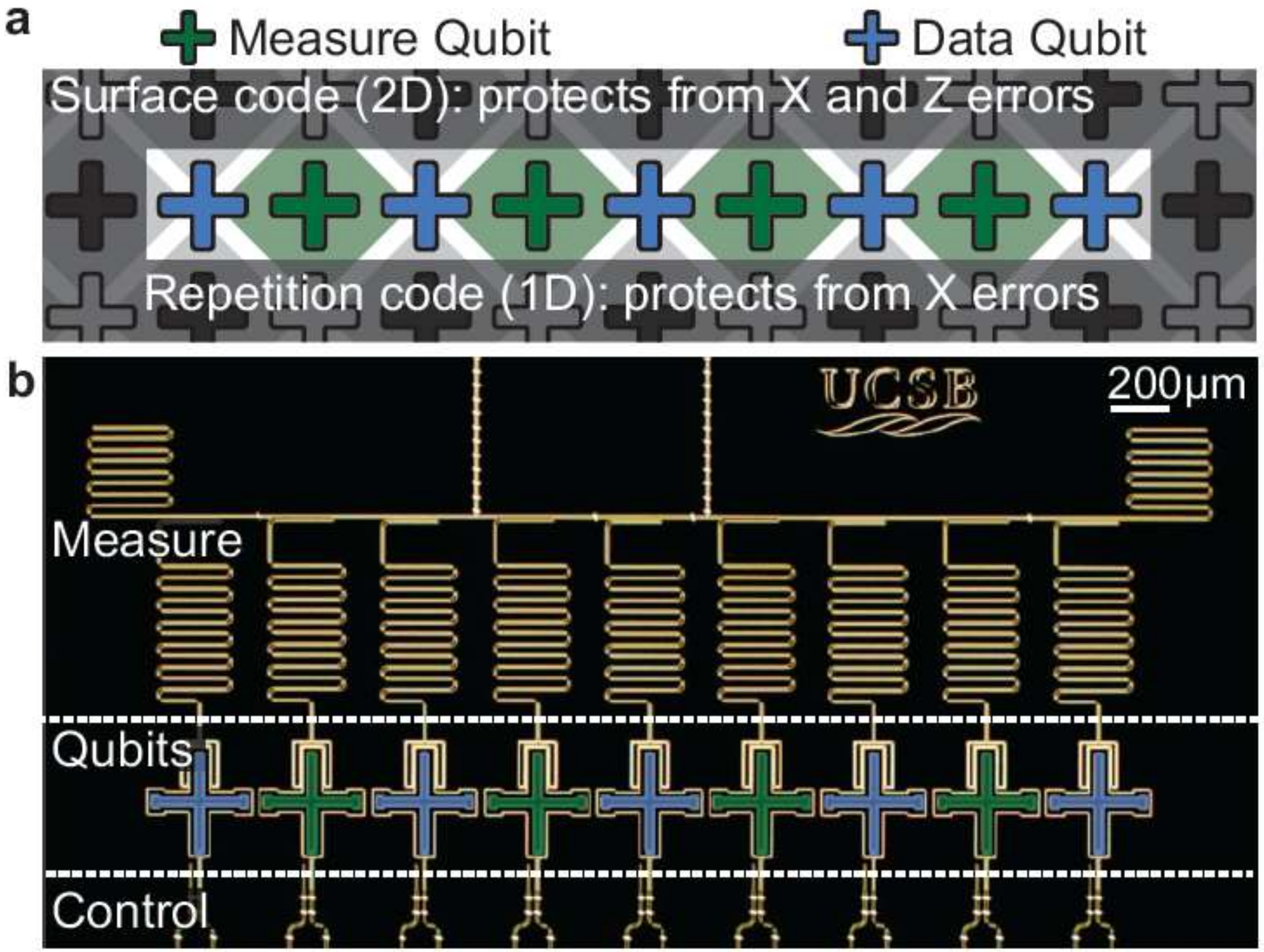
An impression of the meshing needed in the microwave simulation

Real instrumentation for qubit protection, manipulation, and measurement



One qubit

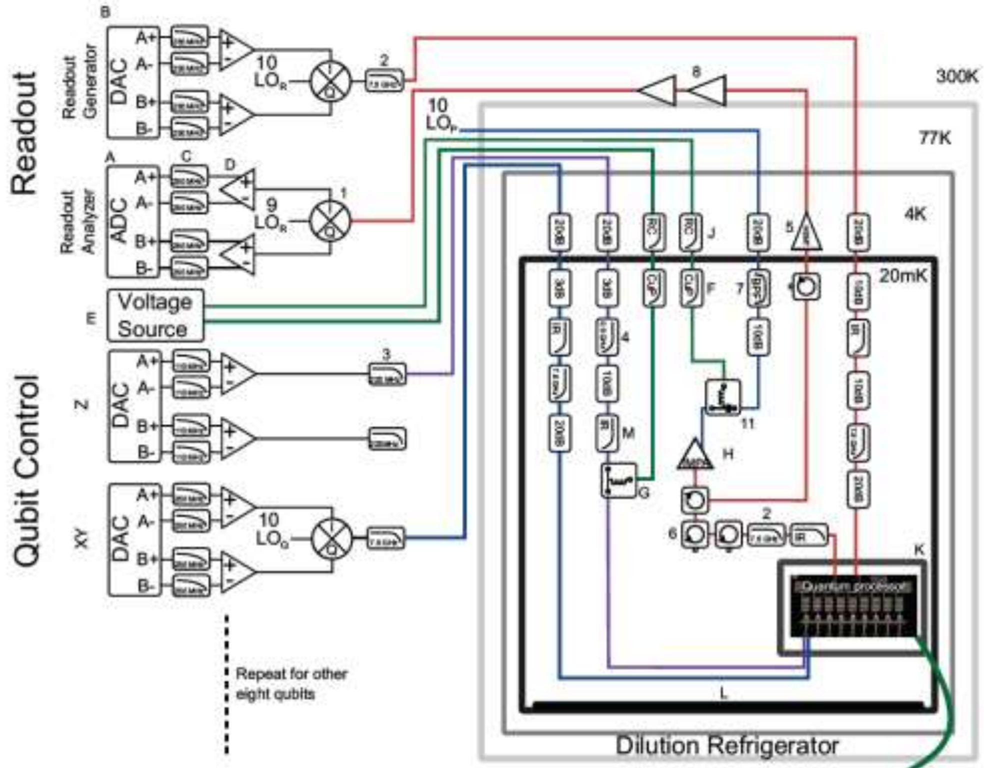
State of the art (2015):
Fully controlled 9-qubit device (UCSB/Google)



J. Kelly et al., State preservation by repetitive error detection in a superconducting quantum circuit, Nature 519, 66–69 (05 March 2015).

UCSB/Google

Classical control: 23 control wires for the 9 qubits!



Commercial

1	Marki IQ-0307
2	Marki FLP-0750
3	Mini Circuits VLFX-225
4	Mini Circuits VLFX-500
5	Low Noise Factory LNC4_8A
6	QuinStar CTH1392KS
7	Marki FB-1310
8	Miteq AFS3-00100200-22-10P-4
9	Hittite HMC-T2100
10	Anritsu MG3692C
11	Signatek SB11D2

Custom

A	Analog to Digital Converter (ADC)
B	Digital to Analog Converter (DAC)
C	Gaussian Filter
D	Differential Amplifier
E	Voltage source ("Fastbias Card")
F	Copper powder & light tight LPF
G	DC Bias T
H	Parametric Amplifier (IMPA)
J	1.5k cold resistor
K	Magnetic Shield
L	"IR-black" coating
M	Light tight LPF

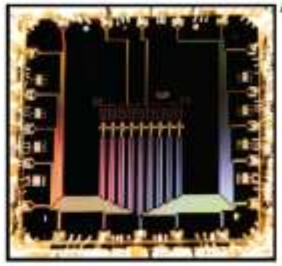


FIG. S29. **Electronics and Control Wiring.** Diagram detailing all of the control electronics, control wiring, and filtering for the experimental

Waveforms of classical signals going to the dilution refrigerator

10 kW power consumption

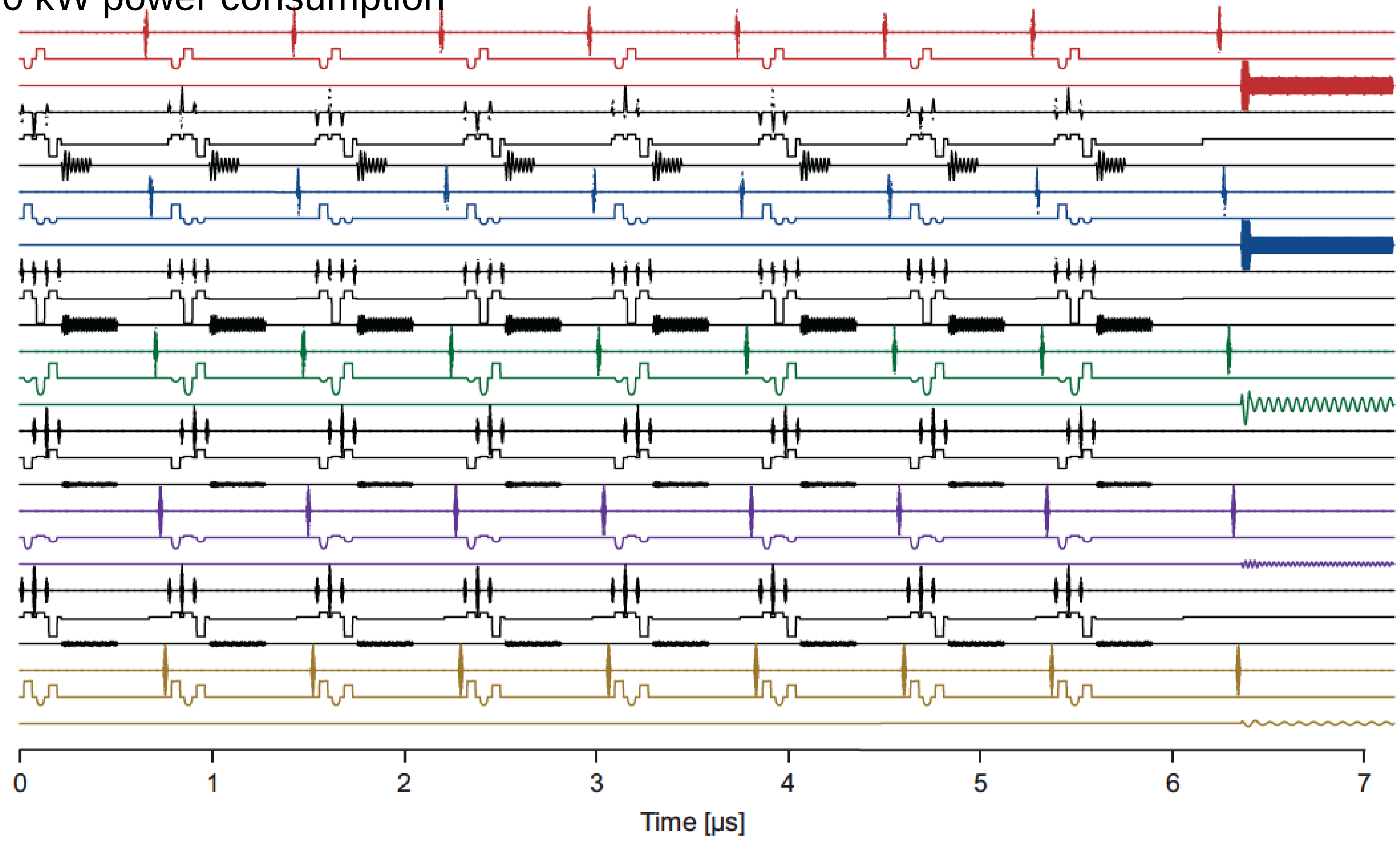
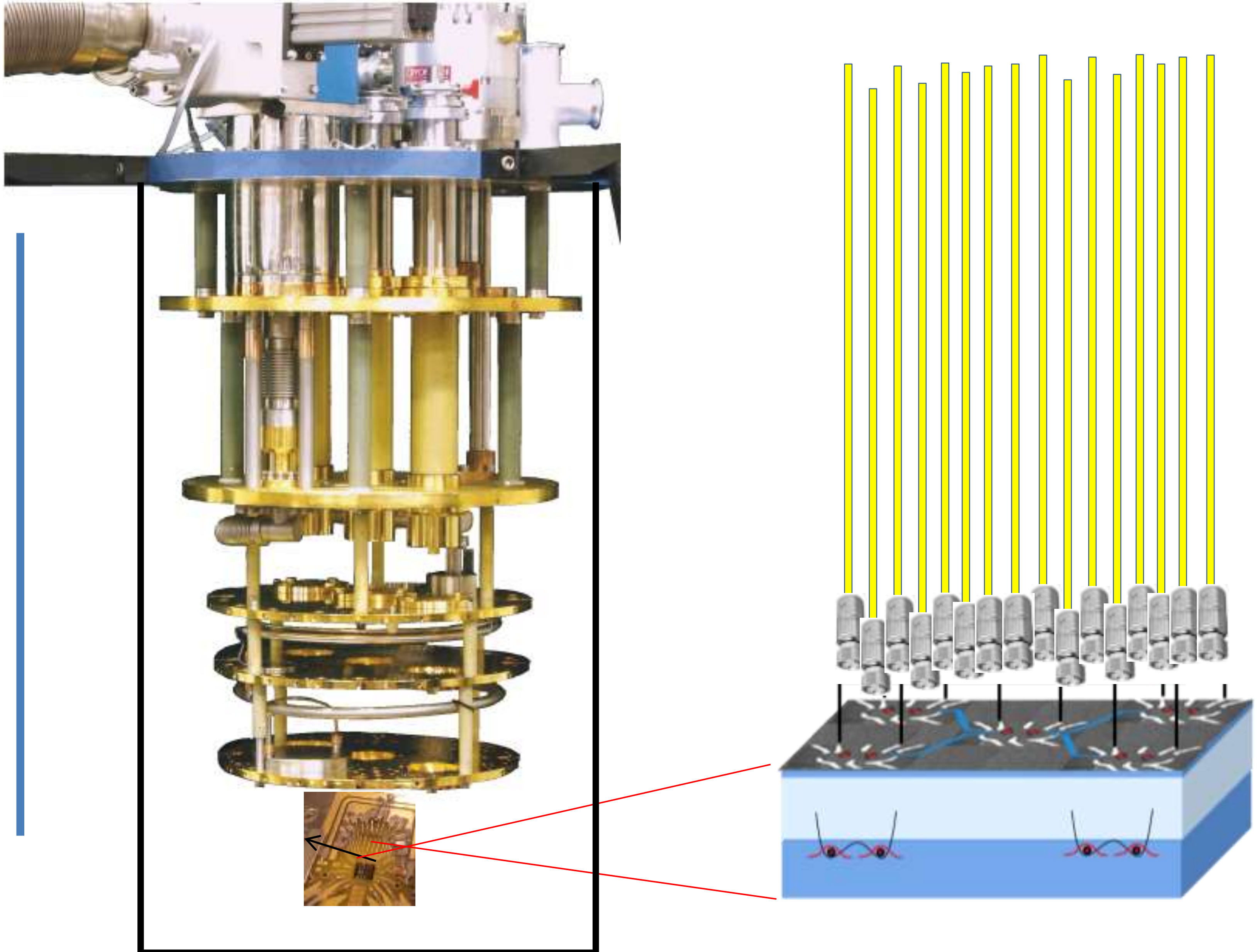


FIG. S27. Waveform data for eight cycles of the nine qubit repetition code.

The ugly part of the architecture – meter-long cable runs to control-room instrumentation

Workhorse
„dilution“
refrigerator

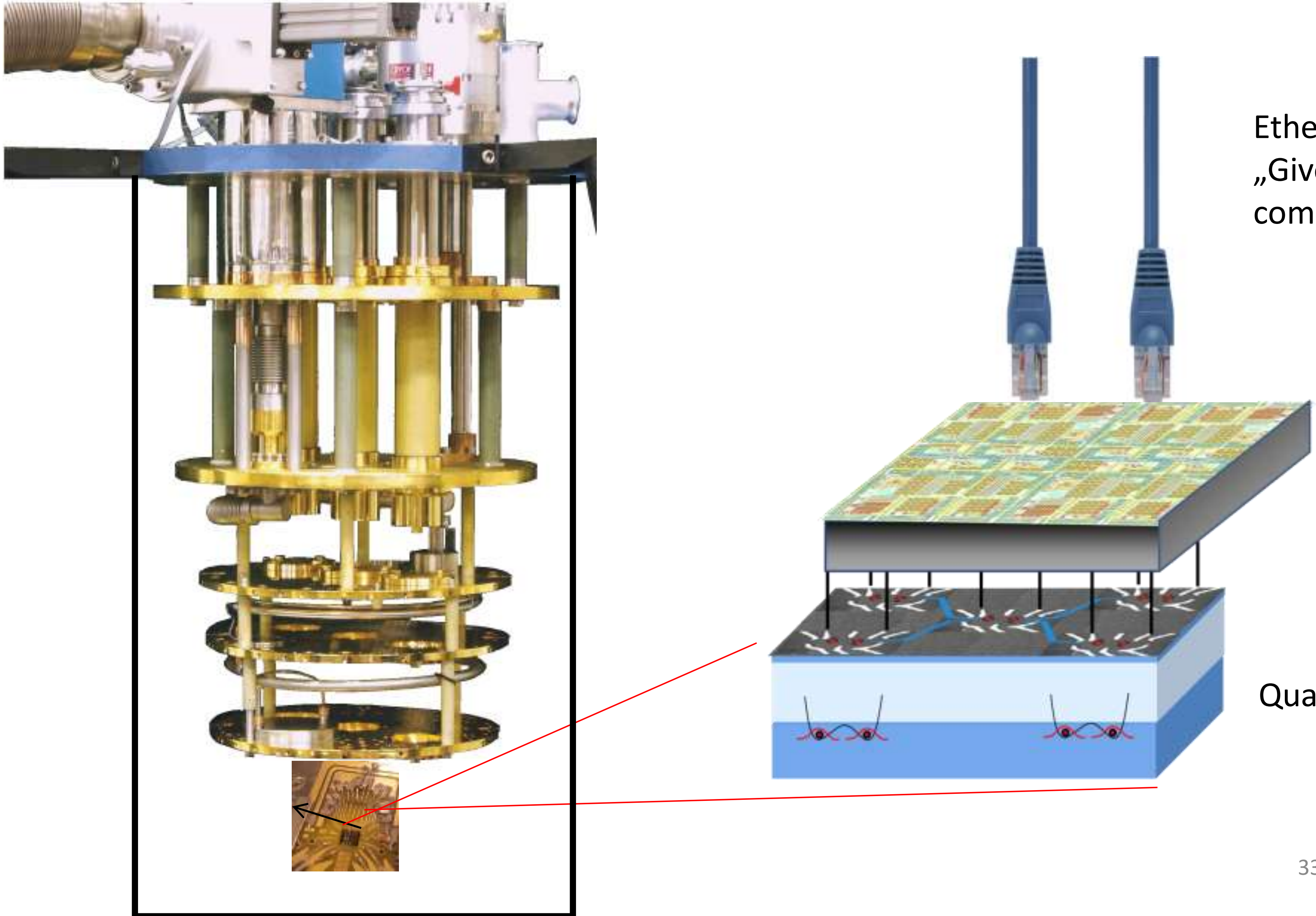
1 meter



Number of cables
~ 2x the number of qubits

Millions of qubits ???

Vision: Scalable architecture – needs cold analog & digital electronics



Ethernet –
„Give your quantum computer an IP address“

Signal generators, amplifiers, isolators, ADCs, DACs

Operating temperature: 4K

Quantum chip: T=0.02K

Outline

- **The nature of qubits**/quantum algorithms
- **Materials and devices for a quantum computer**
  - ***(Solid state perspective)***
- **Error correction and fault tolerance**
- **Strategies for 2D layouts for qubits**
- **Measurement, Isolation, Amplification**
- **The full system view**