Current Challenges for Quantum Computing

David DiVincenzo
CERNVirtual
10.06.2021

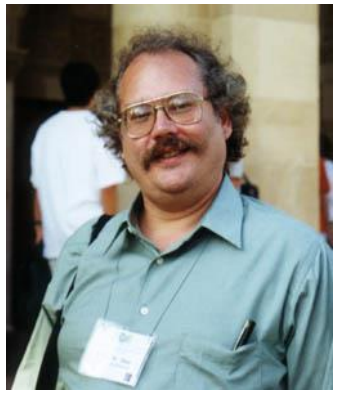
Back in 1959…

…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
APS meeting in 1959.

Fast quantum computation

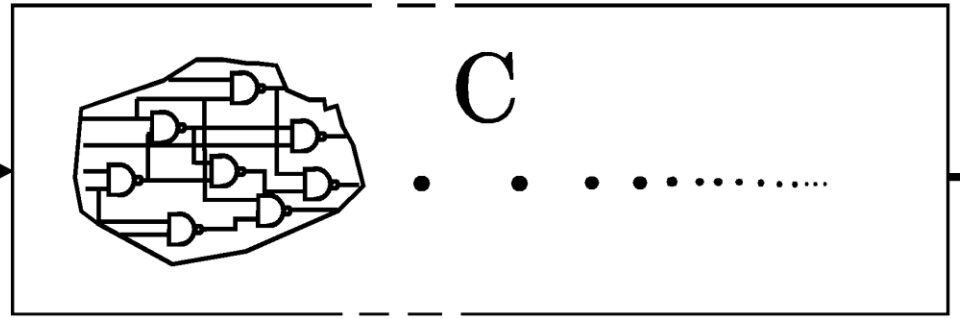
P. Shor, AT&T, 1994



Classical factoring problem required 8 months on hundreds of computers

RSA 129

1143816257578888676
6923577997614661201
0218296721242362562
5618429357069352457
3389783059712356395
8705058989075147599
290026879543541



Factors

3490529510847650949
1478496199038981334
1776463849338784399
0820577

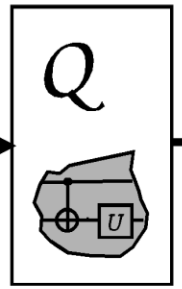
x

3276913299326670954
9961988190834461413
1776429679929425397
98288533

Factor k-digit number: time $\approx e^{\sqrt{k}}$

Same Input and Output, but Quantum processing of intermediate data gives

1143816257578888676
6923577997614661201
0218296721242362562
5618429357069352457
3389783059712356395
8705058989075147599
290026879543541



3490529510847650949
1478496199038981334
1776463849338784399
0820577

x

3276913299326670954
9961988190834461413
1776429679929425397
98288533

Factor k-digit number: time $\approx k^2$

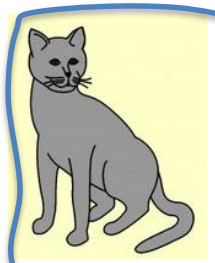
Shor's algorithm gives an exponential speedup for prime factorization compared with any known algorithm on an ordinary computer!

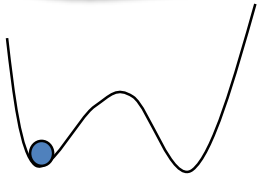
Outline

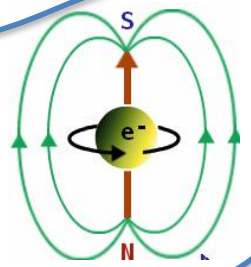
- **The nature of qubits/quantum algorithms**
- **Materials and devices for a quantum computer**
  - ***(Solid state perspective)***
- Fault tolerance, and the noise threshold theorem
- Strategies for 2D layouts for qubits
- Measurement, Isolation, Amplification
- The full system view

Qubit

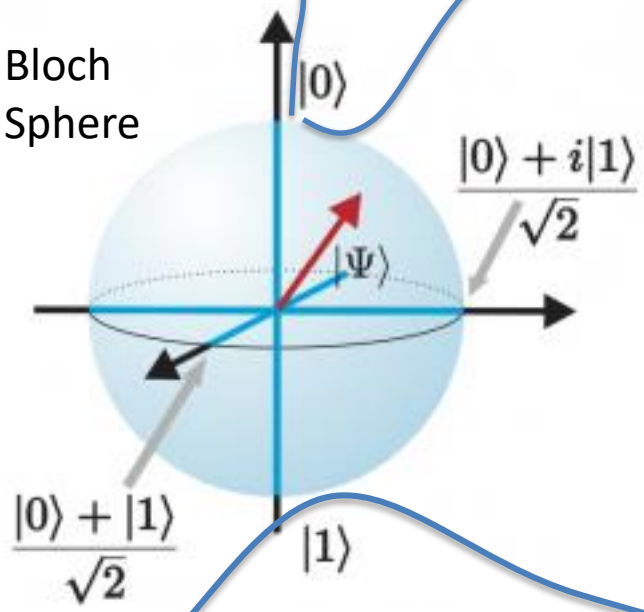
Definite state “0”

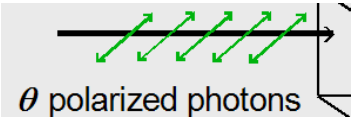


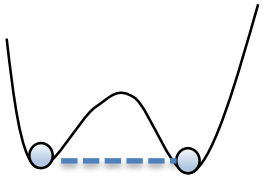


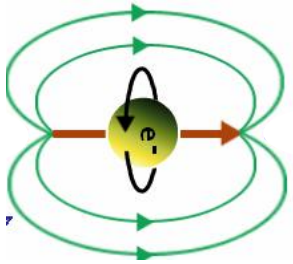


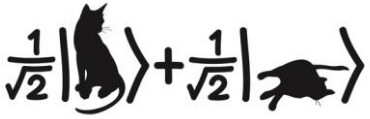
Bloch Sphere











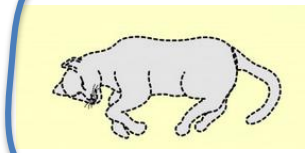
Superposition states (“halfway” shown)

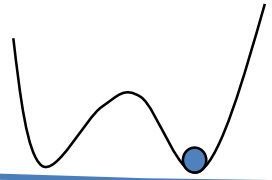
-- sometimes has a clear classical meaning, usually not

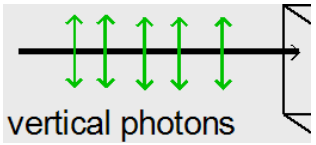
-- must be isolated from environment to exist

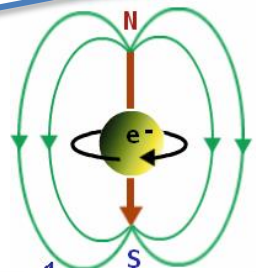
-- can couple to other qubits, then **entangled** states are formed, e.g., $\frac{1}{\sqrt{2}}(|000\rangle + |111\rangle)$

Definite state “1”



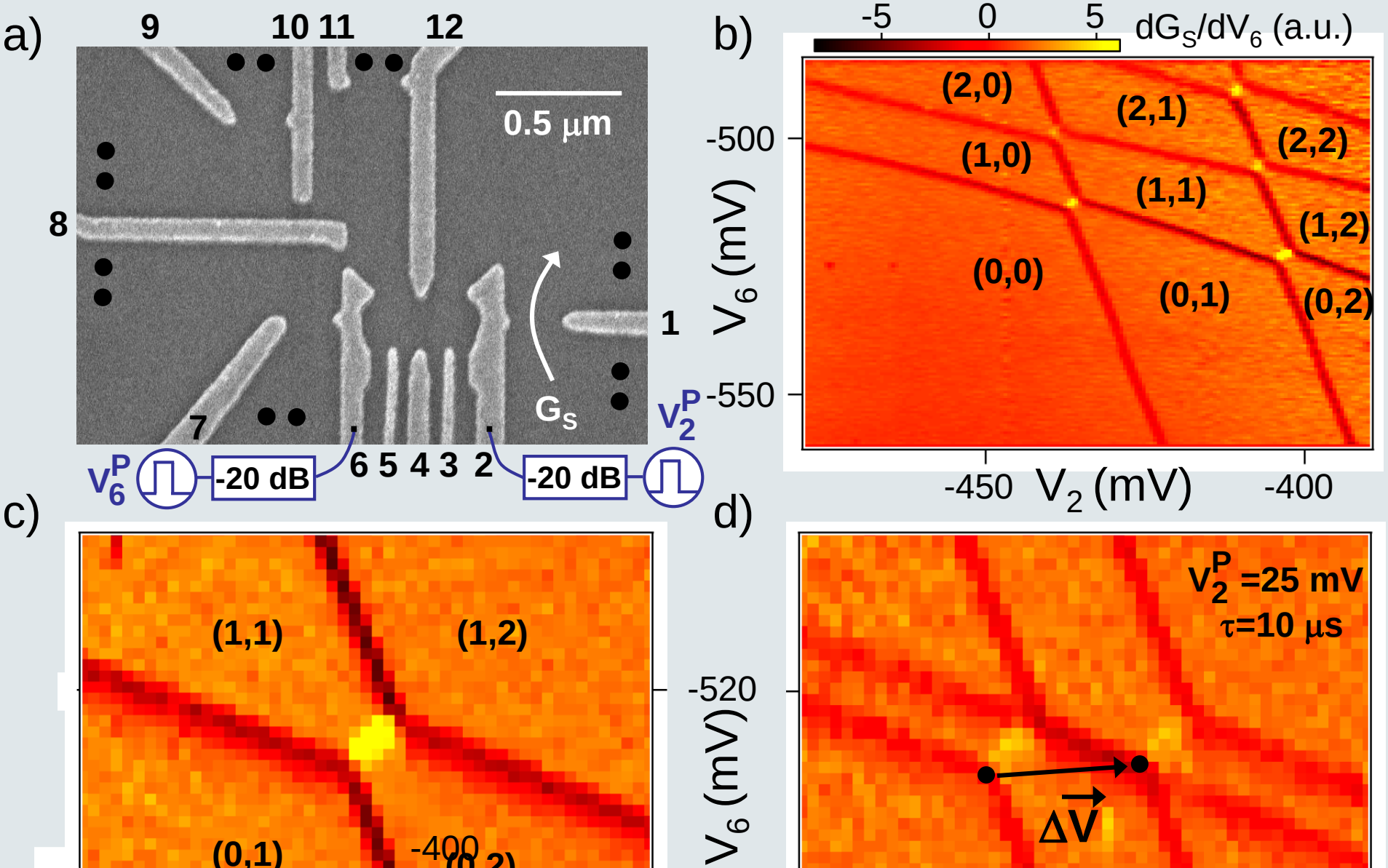






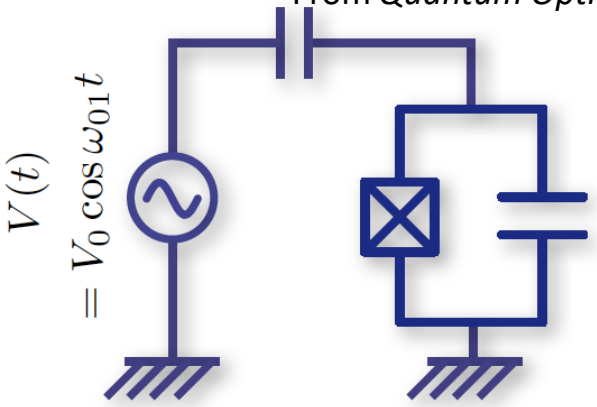
A possible qubit:
Single-electron semiconductor quantum dots

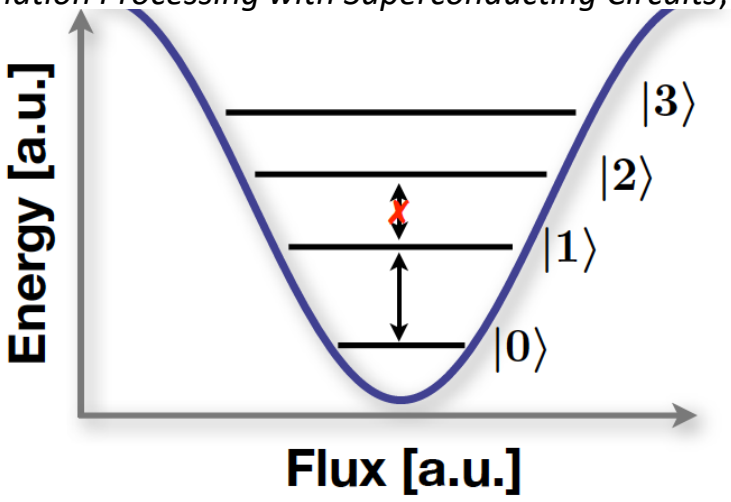
Harvard, c. 2004

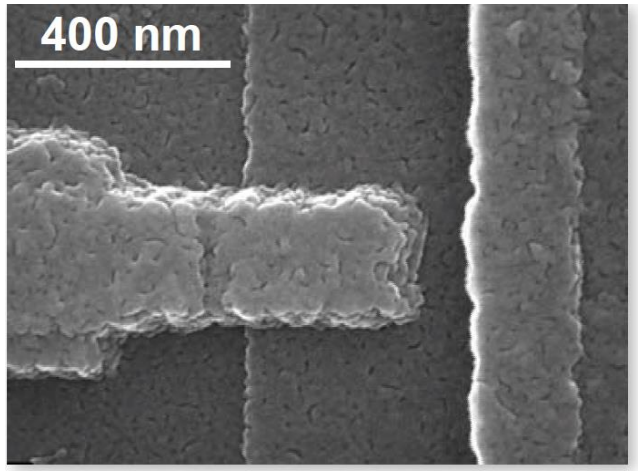


Another very promising family of qubits: superconducting circuits

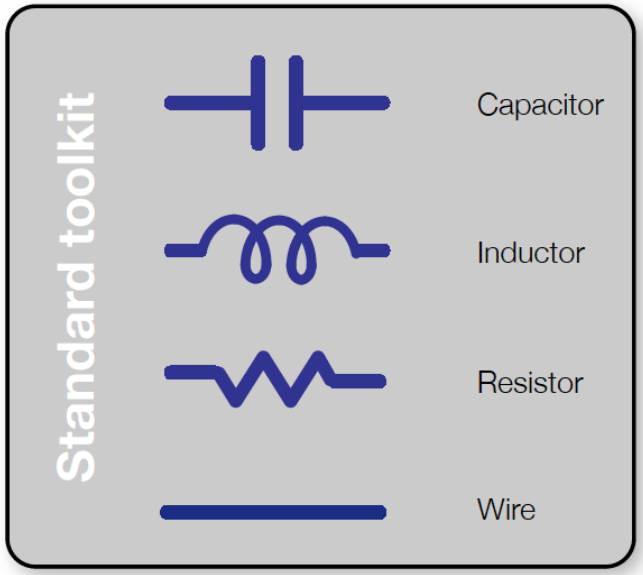
From *Quantum Optics and Quantum Information Processing with Superconducting Circuits*, A. Blais, 2011-used with permission.

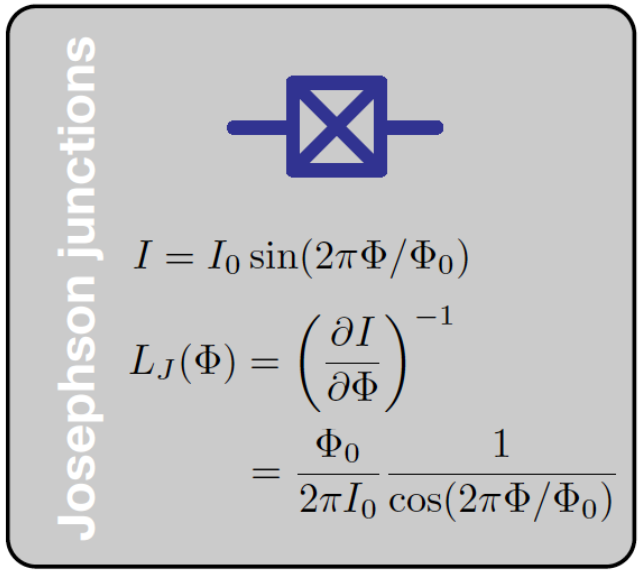




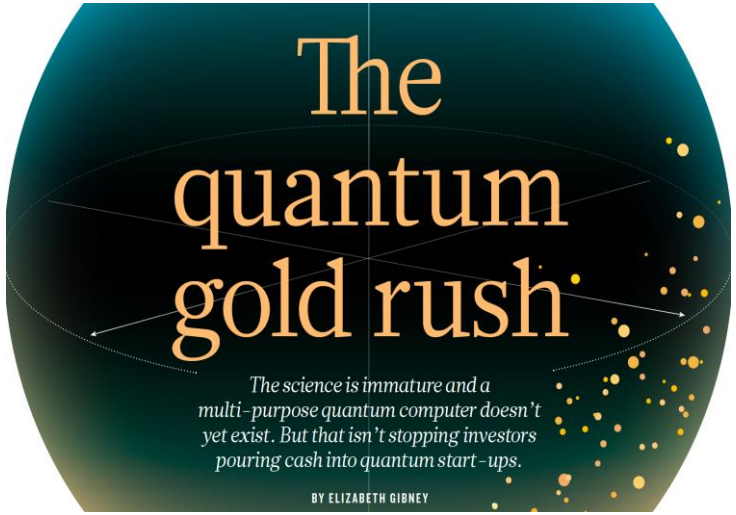


Nanoscale tunnel junction required – old technology





The Gallery



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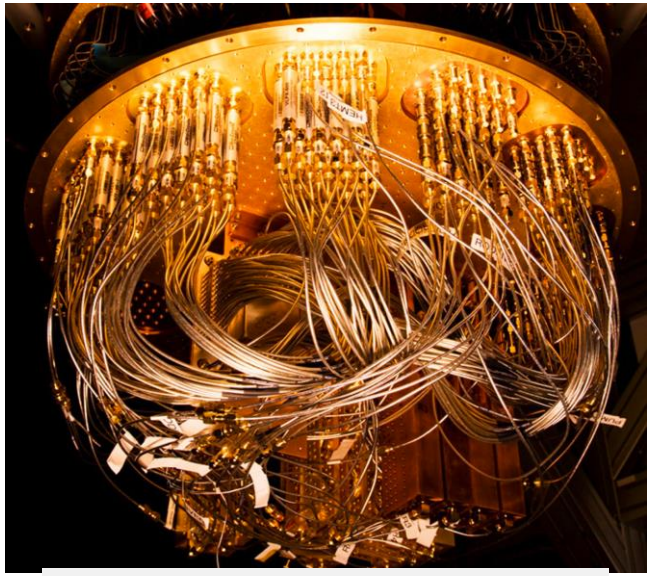
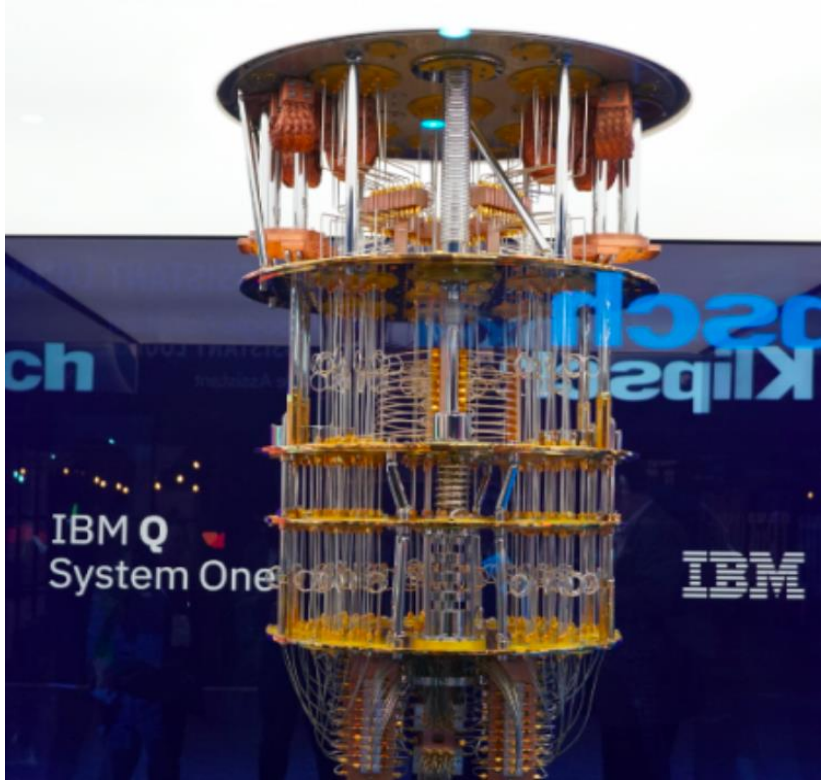


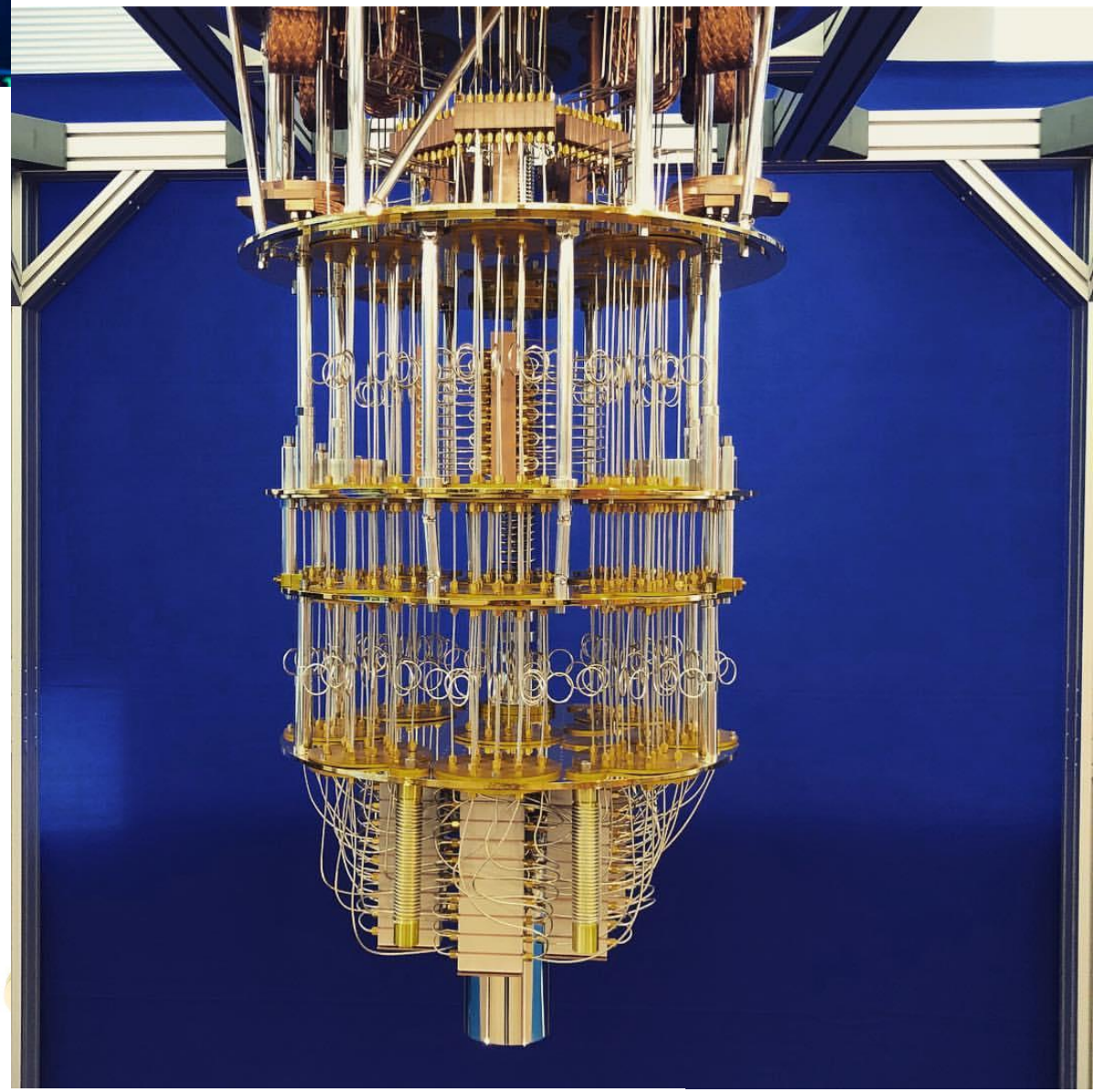


Quantum computers are here?

(IBM's 50-qubit superconducting quantum computer)

Certainly an amazing scientific instrument: An apparatus for controlled scattering of quantized radiation – think particle detectors

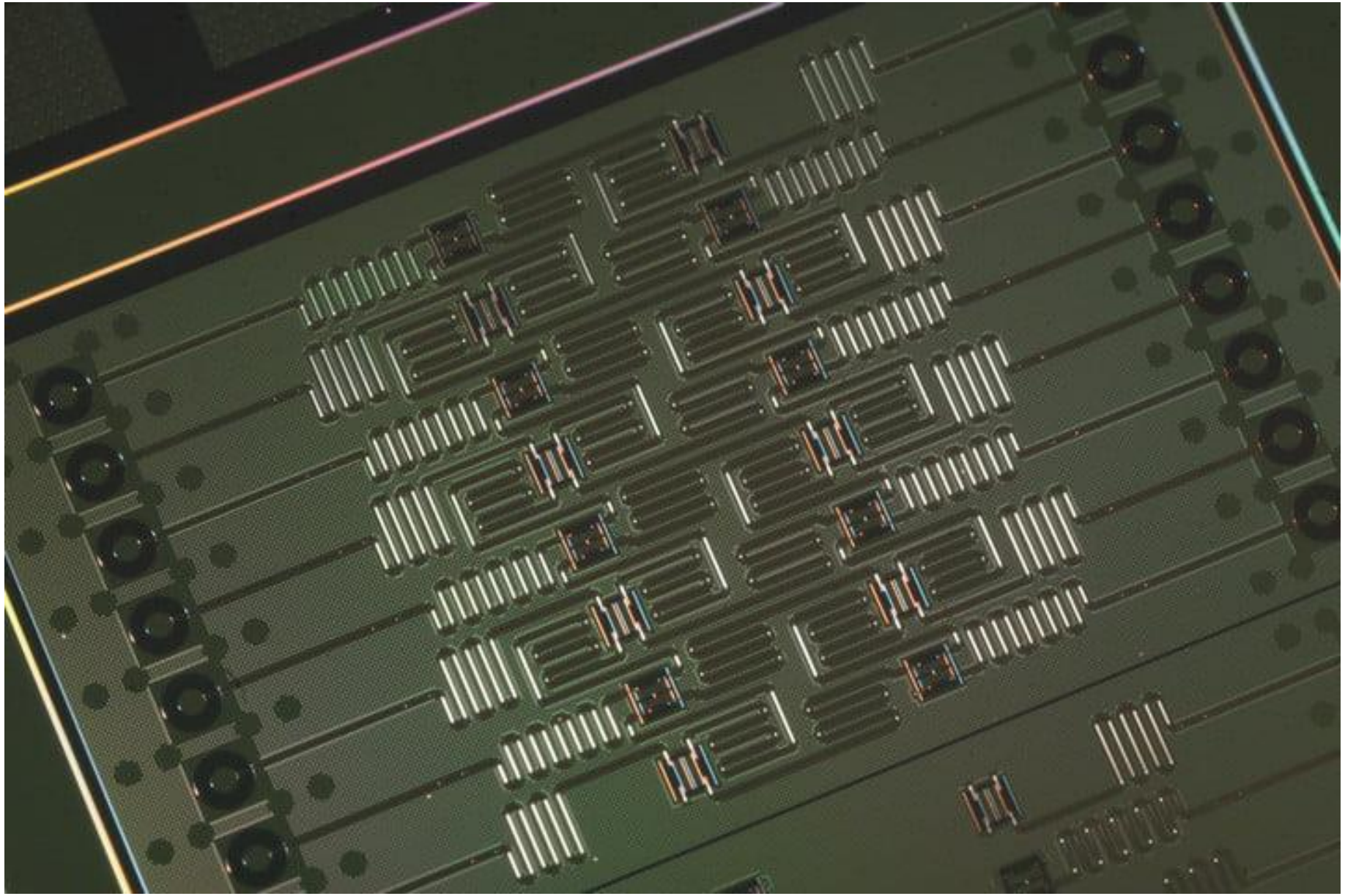
1 meter



Note growing size to accommodate huge cable bundles

@ IBM-Q

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



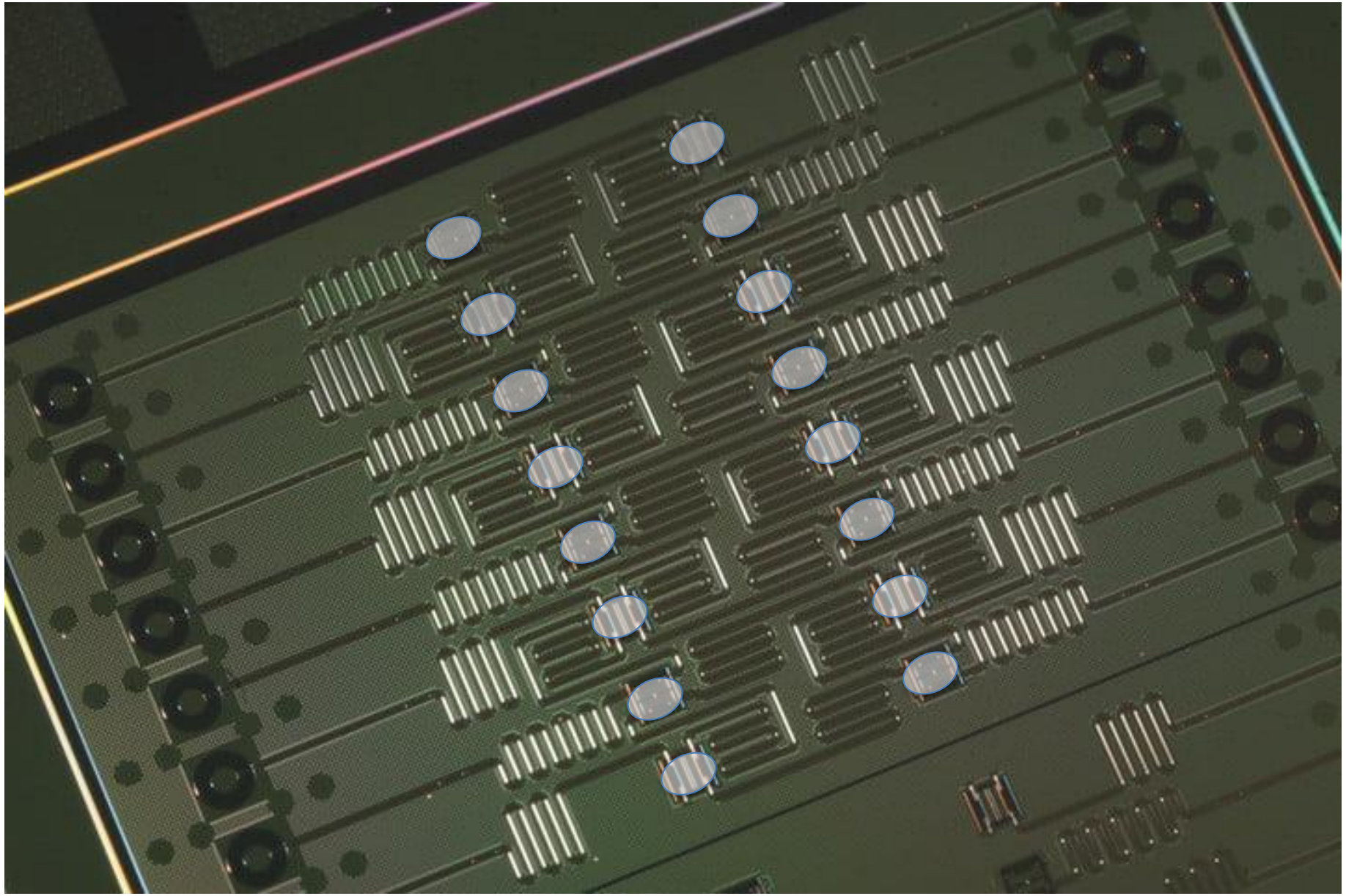
c. IBM 1 mm T=0.02 K

Metalized structure on Si chip

(all resemblance to normal chips ends there.)

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

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



c. IBM 1 mm T=0.02 K

Metalized structure on Si chip

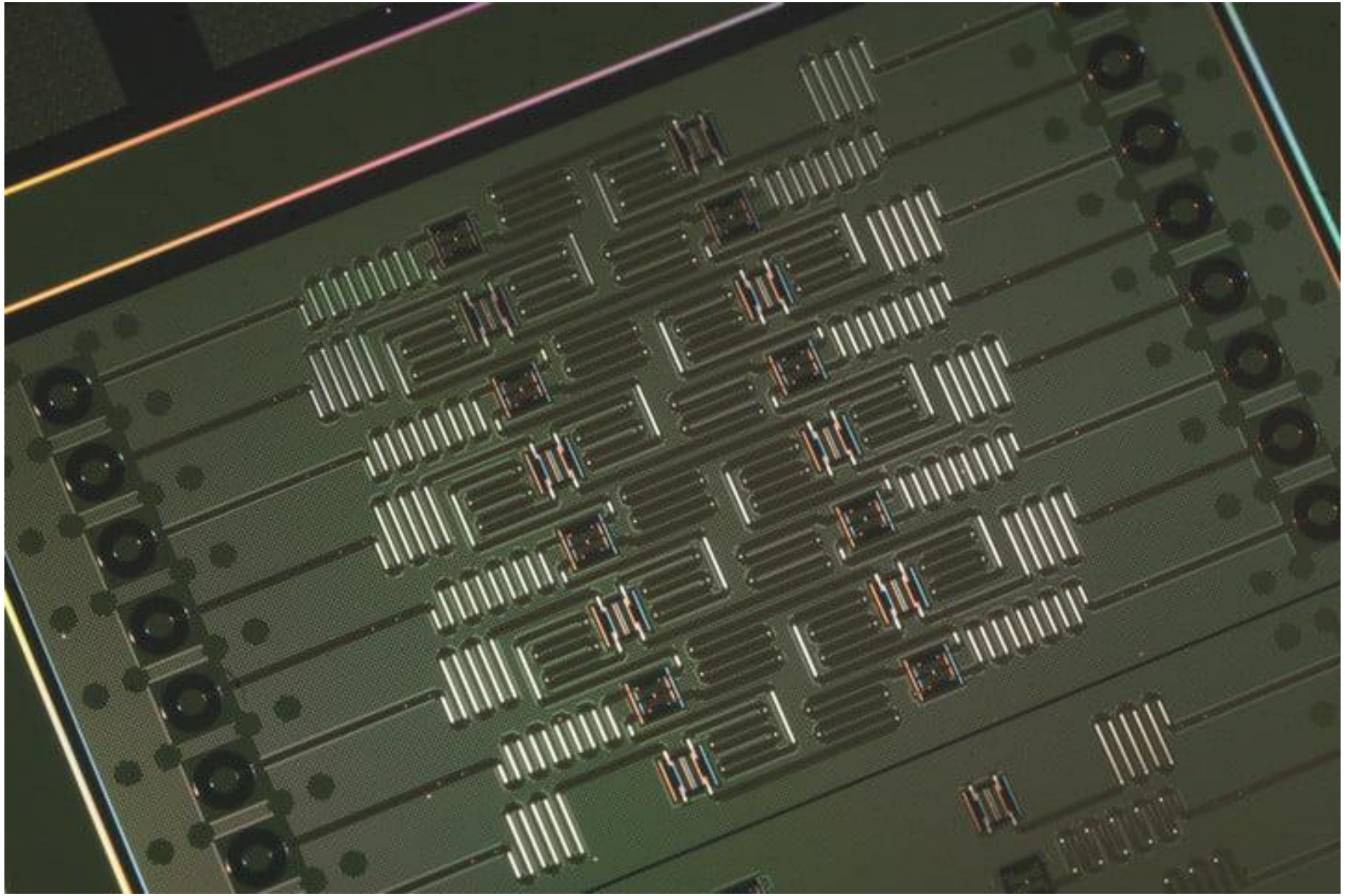
(all resemblance to normal chips ends there.)

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

1 mm



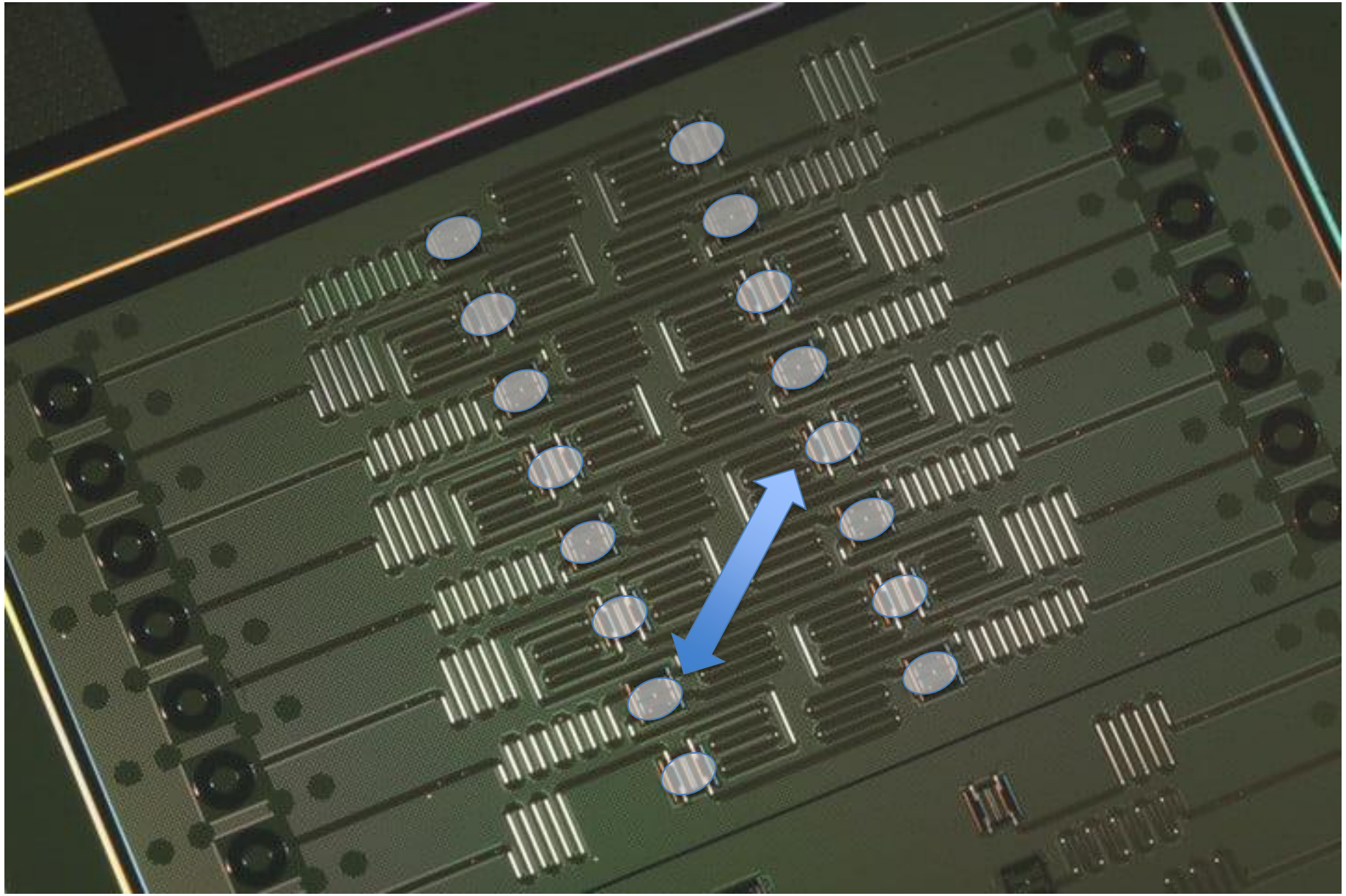
c. IBM

Another way of saying what parts are on the IBM chip:

46 resonators
All at microwave fequencies
All very high quality factor (10^7)
30 „normal“ CPW resonators
16 qubit resonators
--- 1 photon enters, no more
--- 0/1 is qubit

Kept almost perfectly still
T=0.02 K

Example of problematic situation: 16-qubit IBM chip



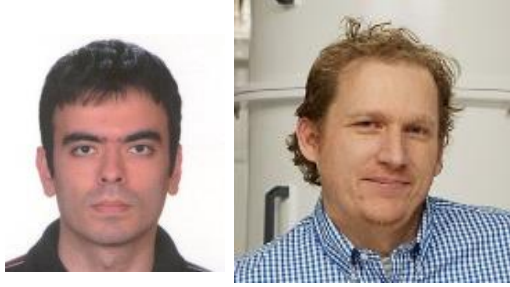
c. IBM 1 mm T=0.02 K

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!

Black-box modeling methodology

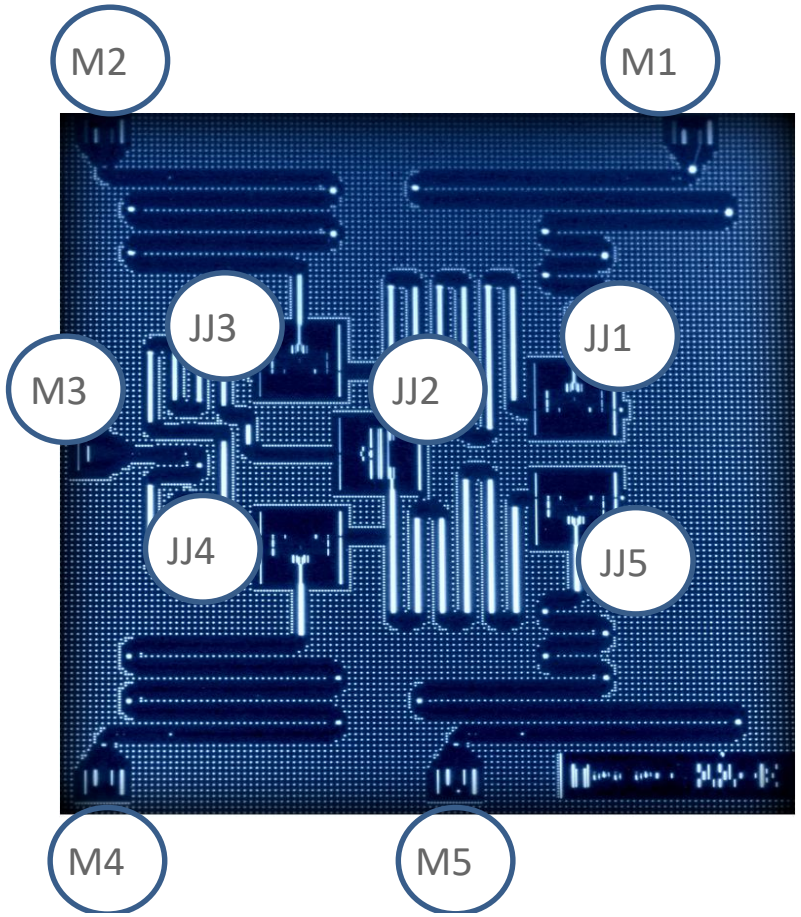


Work with Solgun, Gambetta (IBM)

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).

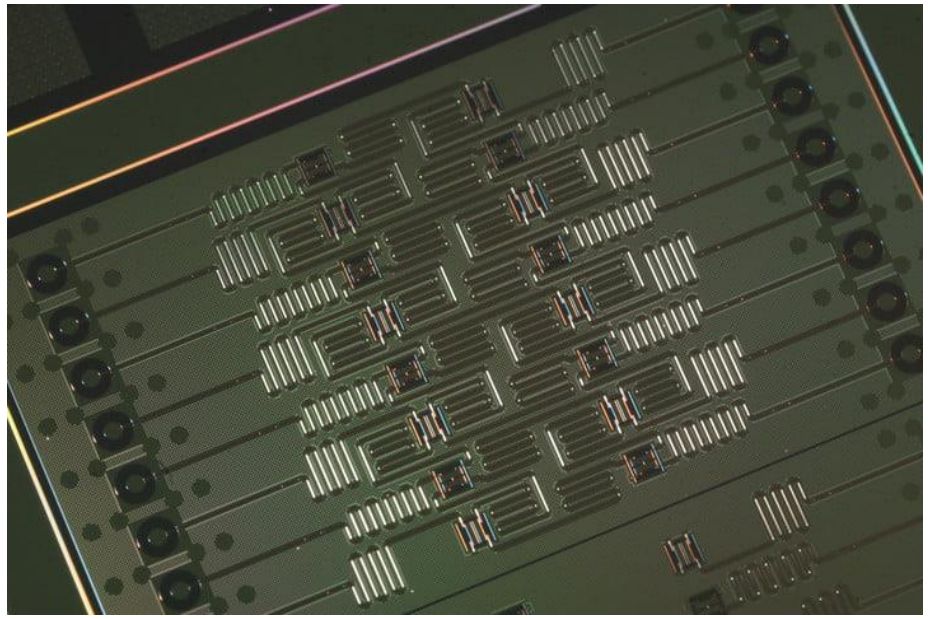
- Introduces new formulas for qubit J couplings, drive crosstalk, and other quantities, in terms of multiport impedance
- The 7-port "gray-box", or the 10-port IBM device on the right can be accurately simulated with HFSS, given the full impedance matrix
- E.g., J-coupling formula:

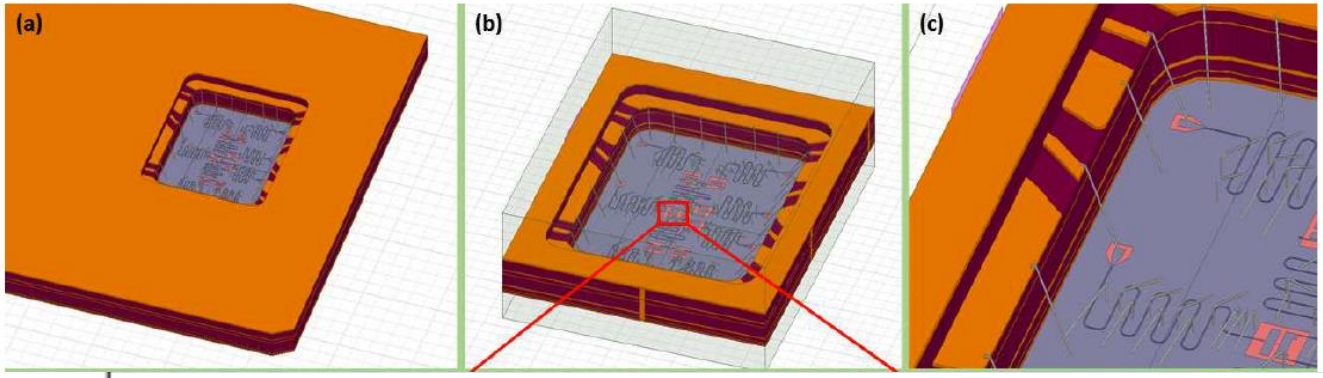


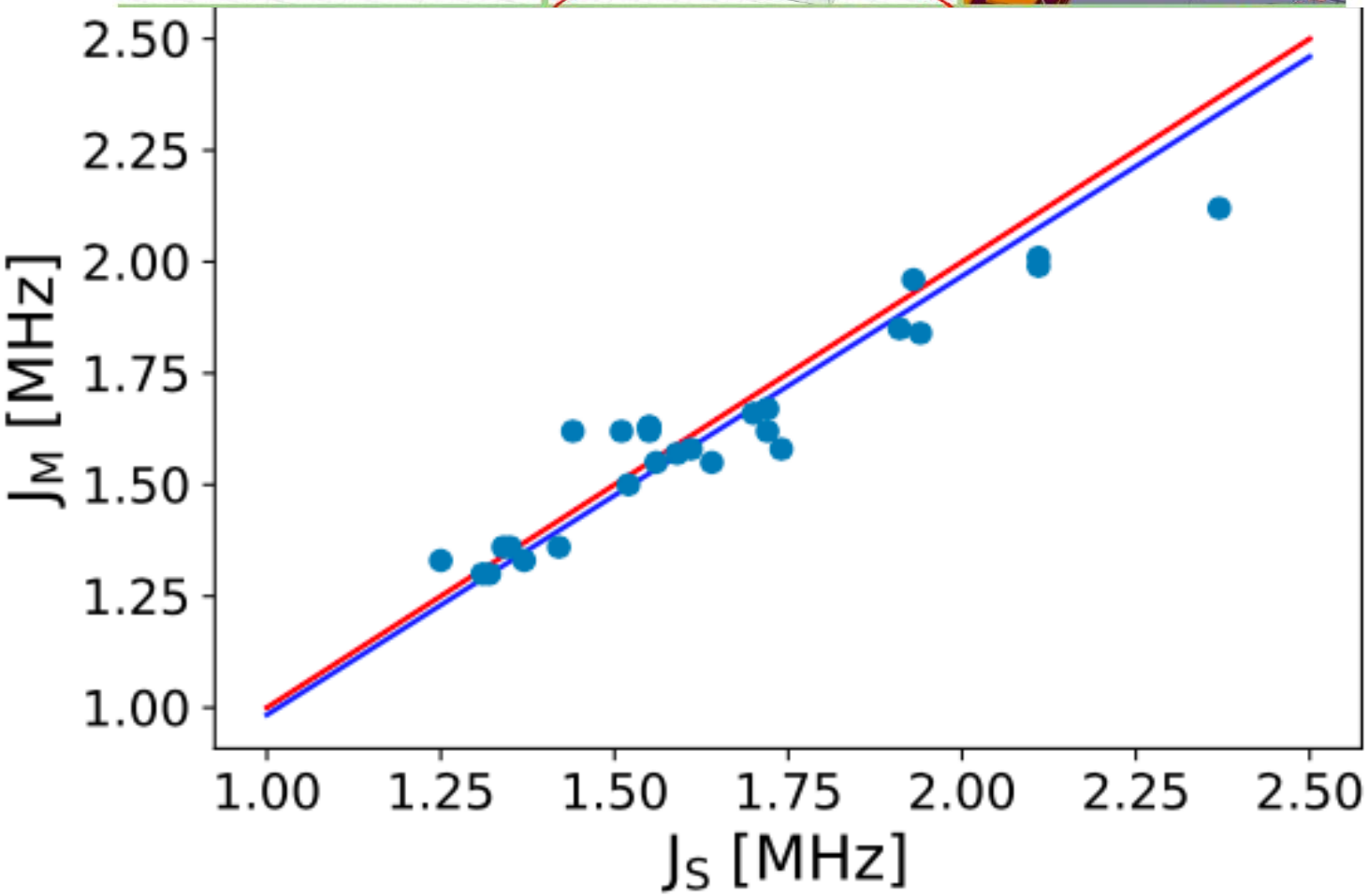
$$J_{ij} = -\frac{1}{4}\sqrt{\frac{\omega_i \omega_j}{L_i L_j}} \mathrm{Im}\left[\frac{Z_{ij}(\omega_i)}{\omega_i} + \frac{Z_{ij}(\omega_j)}{\omega_j}\right]$$

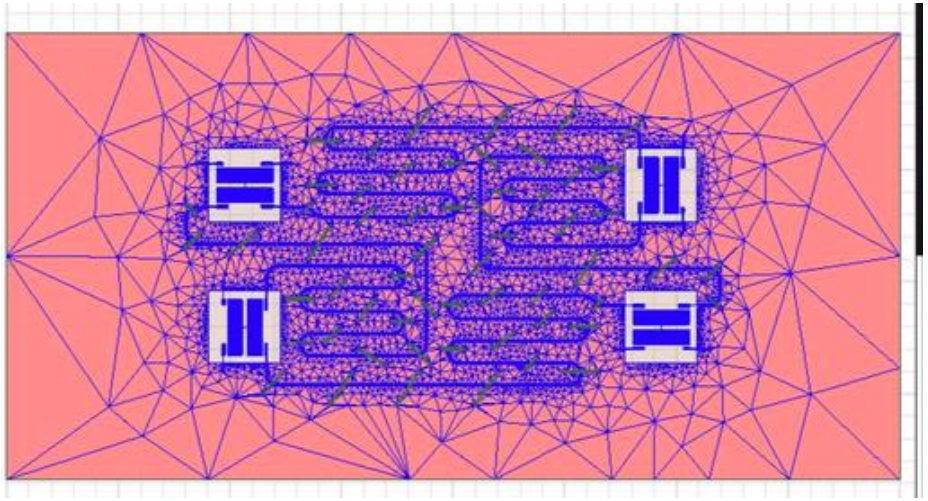
$$H = J_{ij}(X_i X_j + Y_i Y_j) + \ldots$$

Very good theory-experiment correspondence for J couplings









An impression of the meshing needed in the microwave simulation

Outline

- The nature of quantum algorithms
- What is a qubit
- Materials and devices for a quantum computer
- **Fault tolerance, and the noise threshold theorem**
- Strategies for 2D layouts for qubits
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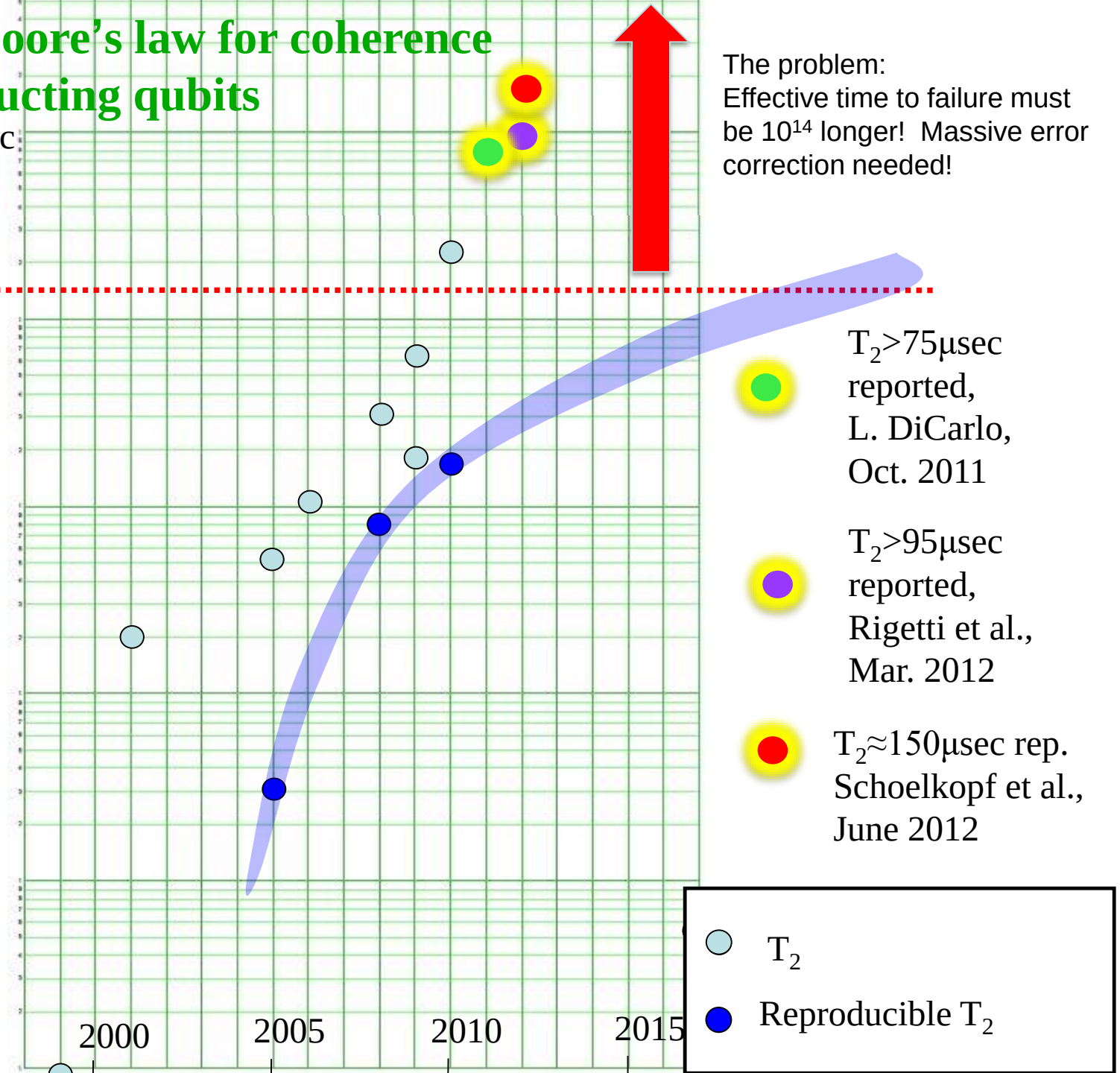
See JVH_IEDM_tutorial2014.pdf

Prospects: a Moore's law for coherence For superconducting qubits



The problem:
Effective time to failure must be 10^{14} longer! Massive error correction needed!

$t_{gate}/T_2 \approx 5 \times 10^{-3}$
= noise threshold
of 2D surface
code scheme

Coherence time of superconducting qubits

anticipated gate time approximately 30 nsec

T_2>75μsec reported, L. DiCarlo, Oct. 2011

T_2>95μsec reported, Rigetti et al., Mar. 2012

$T_2 \approx$150μsec rep. Schoelkopf et al., June 2012

Present-day experiments: multiqubit layout to achieve connectivity for quantum error correction

arXiv.org > quant-ph > arXiv:2102.13071

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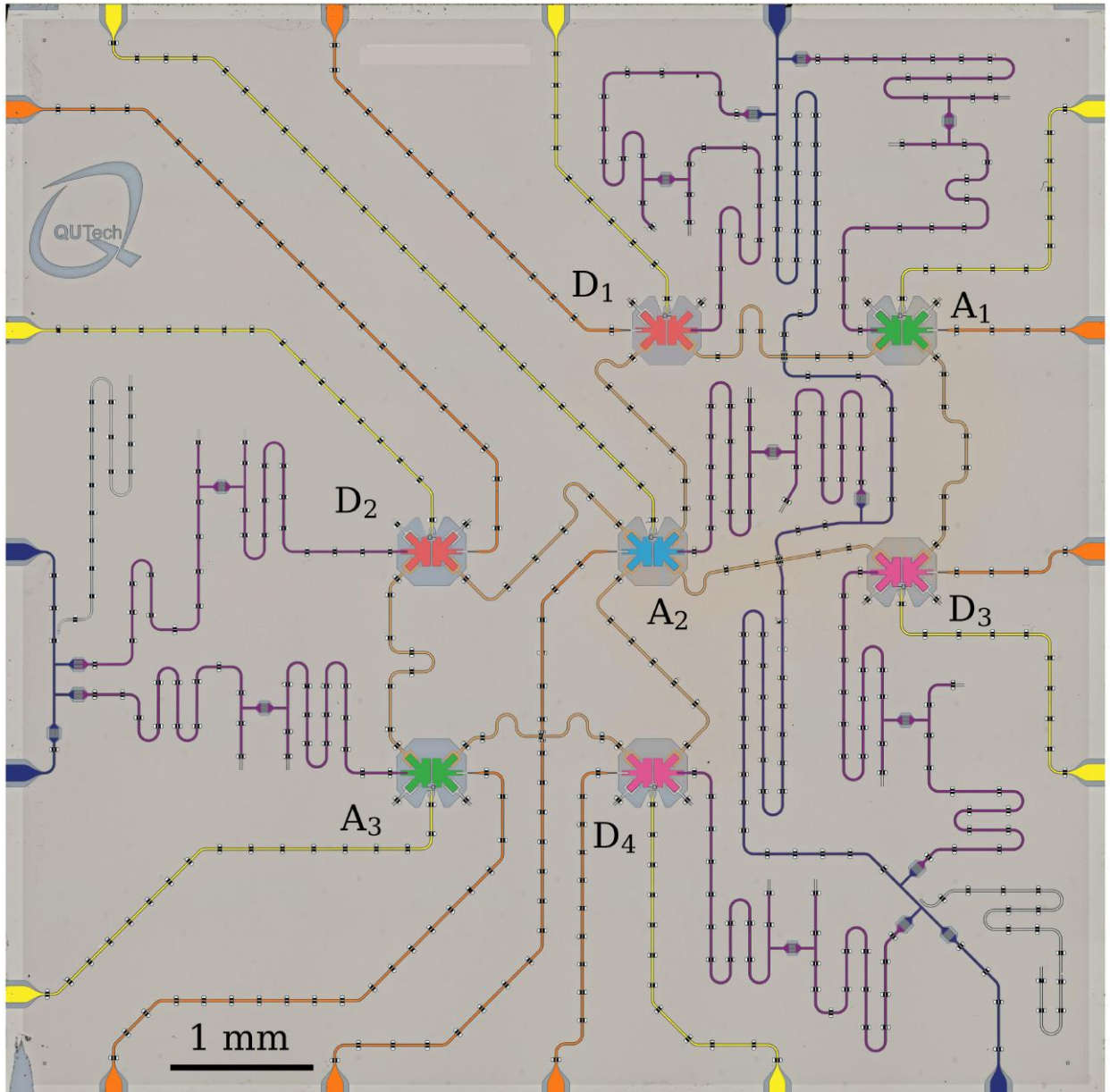
Quantum Physics

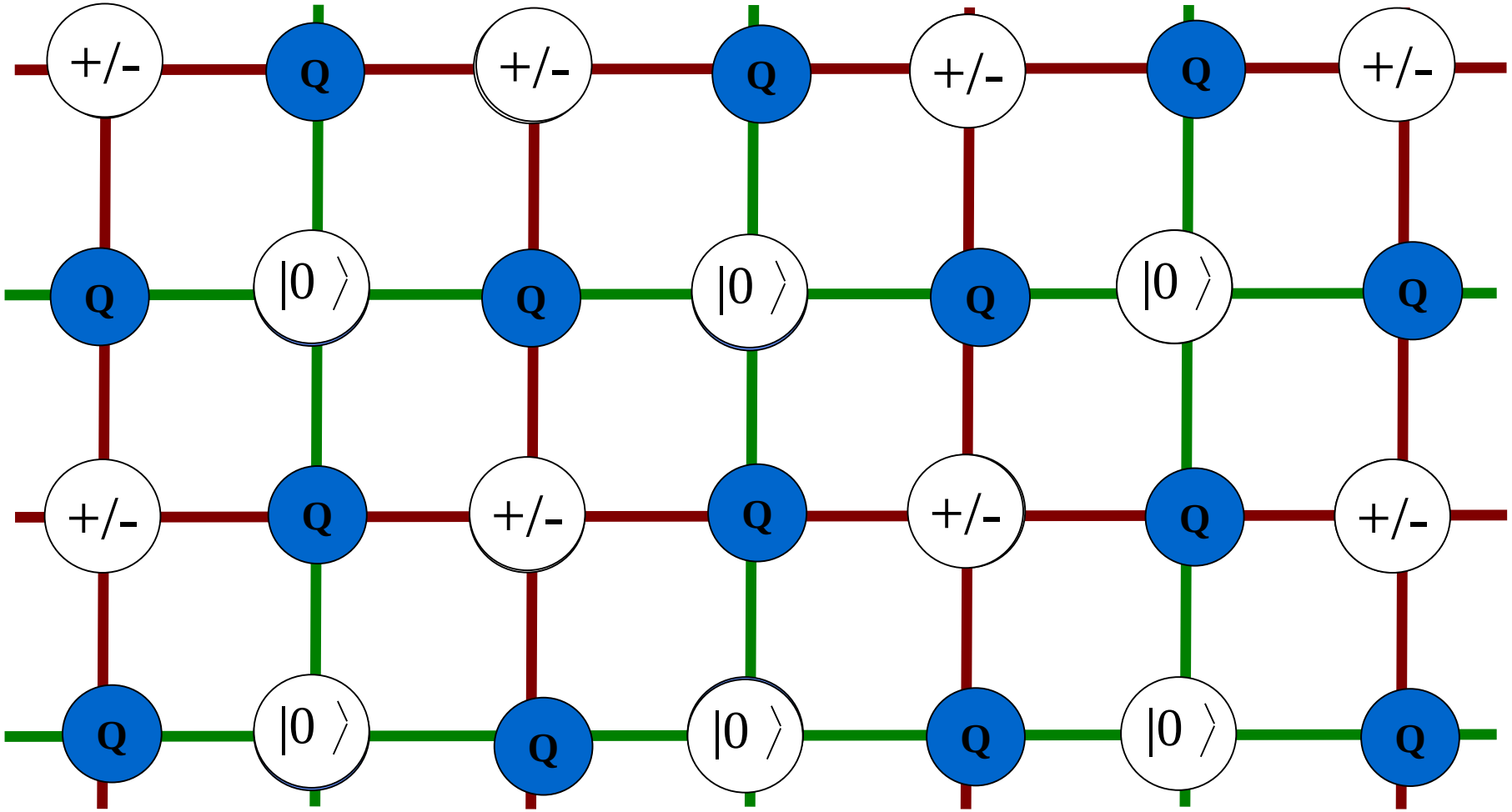
[Submitted on 25 Feb 2021]

Logical-qubit operations in an error-detecting surface code

J. F. Marques, B. M. Varbanov, M. S. Moreira, H. Ali, N. Muthusubramanian, C. Zachariadis, F. Battistel, M. Beekman, N. Haider, W. Vlothuizen, A. Bruno, B. M. Terhal, L. DiCarlo



Surface code fabric – one version of topological quantum error correction

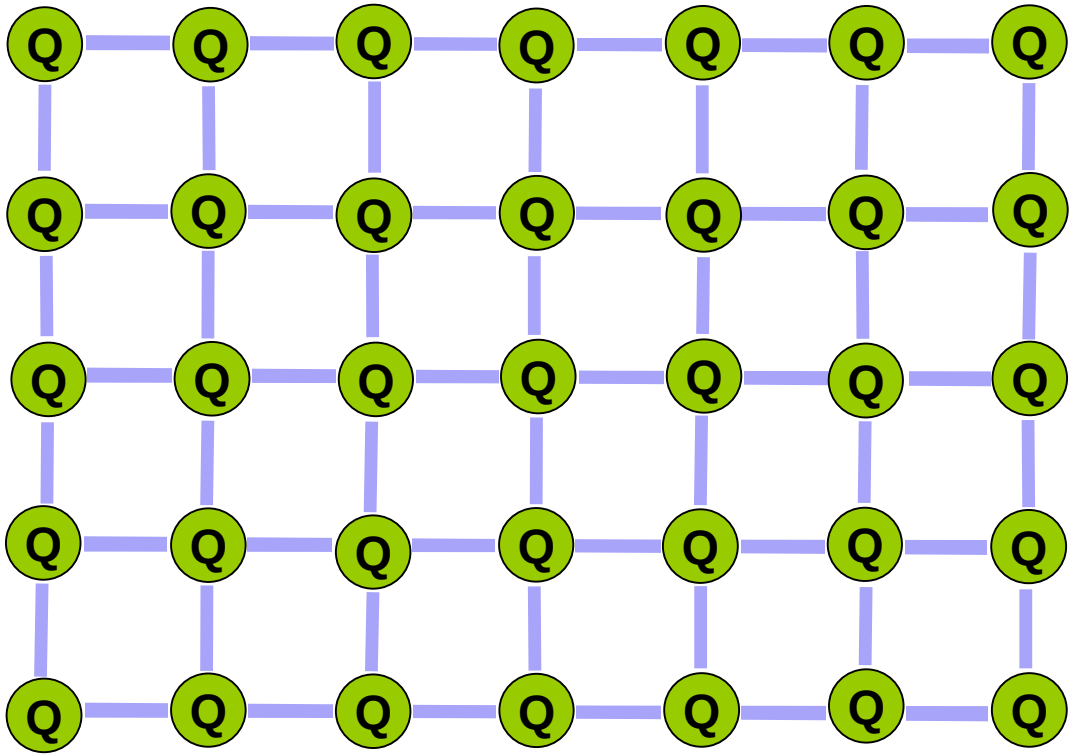


- ● Physical qubits encoding the quantum data
- ○ Physical qubits functioning as ancillas, which **must be repeatedly measured**

Topological 2D Surface Code

NB: topological error correcting code,
not topological quantum computing

- Theoretical results* show that effective fault tolerant quantum computing can be done with local interactions in 2D



c. 1% noise threshold

A. Kitaev, "Quantum Error Correction with Imperfect gates", In *Quantum Communication, Computing, and Measurement*, O. Hirota *et al*., Eds. (Plenum, New York, 1997).

*Robert Raussendorf and Jim Harrington, "Fault-Tolerant Quantum Computation with High Threshold in Two Dimensions," Phys. Rev. Lett. **98**, 190504 (2007).

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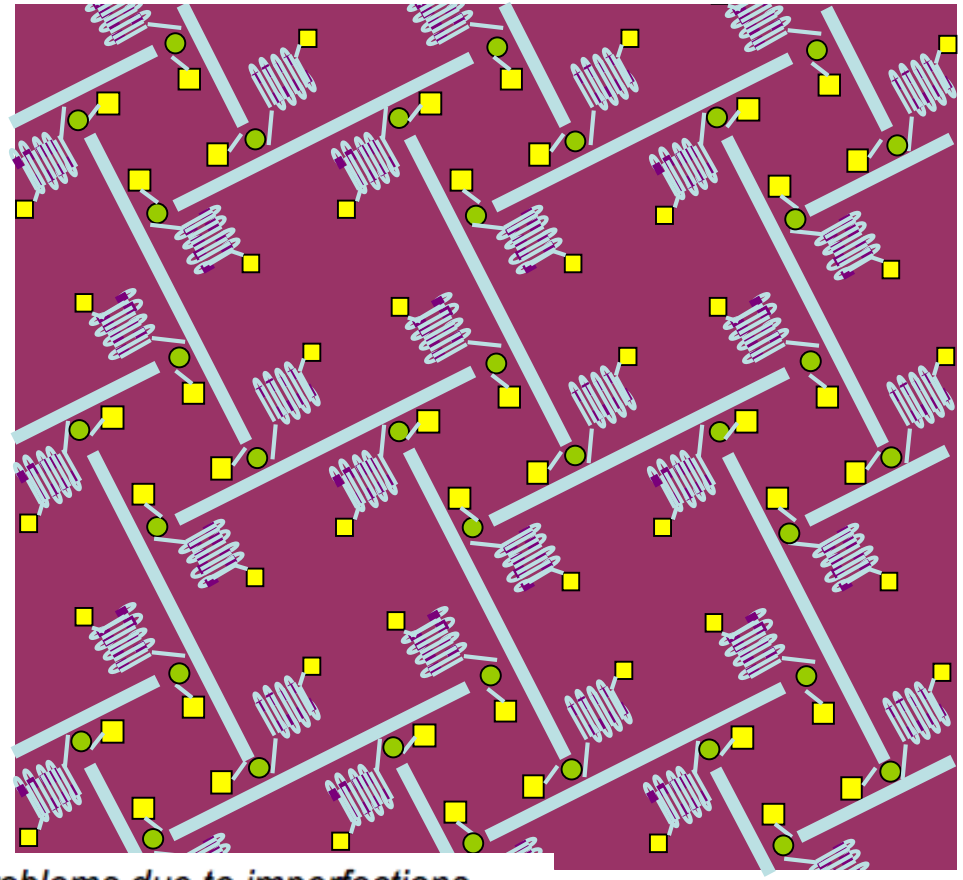
Regular square lattice of coupled qubits make an effective architecture for fault tolerance

- Qubits (green) coupled via high-Q superconducting resonators (gray)
- "skew-square" layout of qubits and resonators is one way to achieve abstract square
- Every qubit has a number of controller and sensor lines to be connected to the outside world (gold pads)



"In a machine such as this there are very many other problems due to imperfections. . . . At least some of these problems can be remedied in the usual way by techniques such as error correcting codes . . . But until we find a specific implementation for this computer, I do not know how to proceed to analyze these effects."

R.P. Feynman
"Quantum Mechanical Computers"
Optics News, February 1985

DP. DiVincenzo, "Fault tolerant architectures for superconducting qubits," Phys. Scr. T **137** (2009) 014020.

Present-day experiments: multiqubit layout to achieve connectivity for quantum error correction

arXiv.org > quant-ph > arXiv:2102.13071

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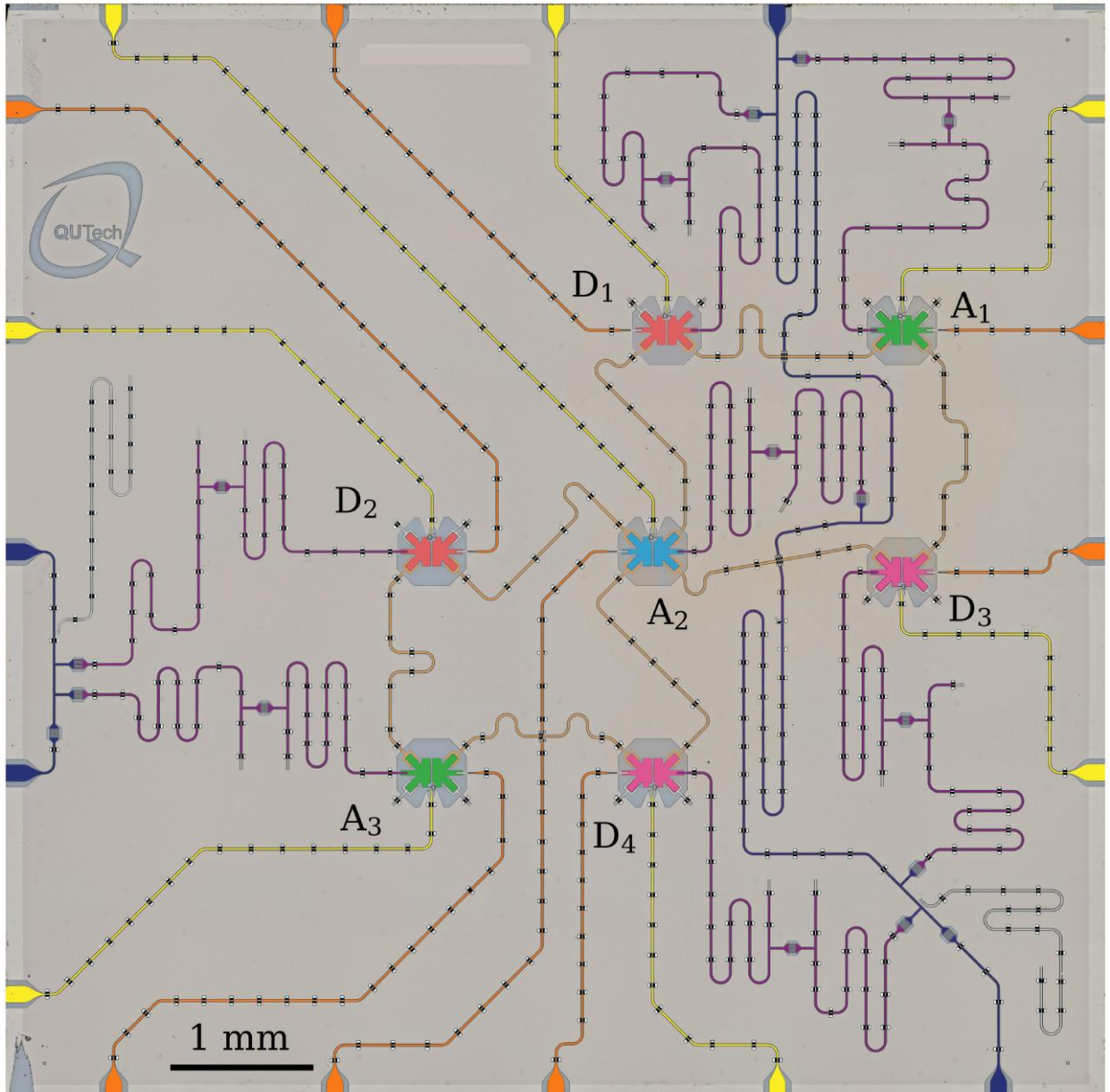
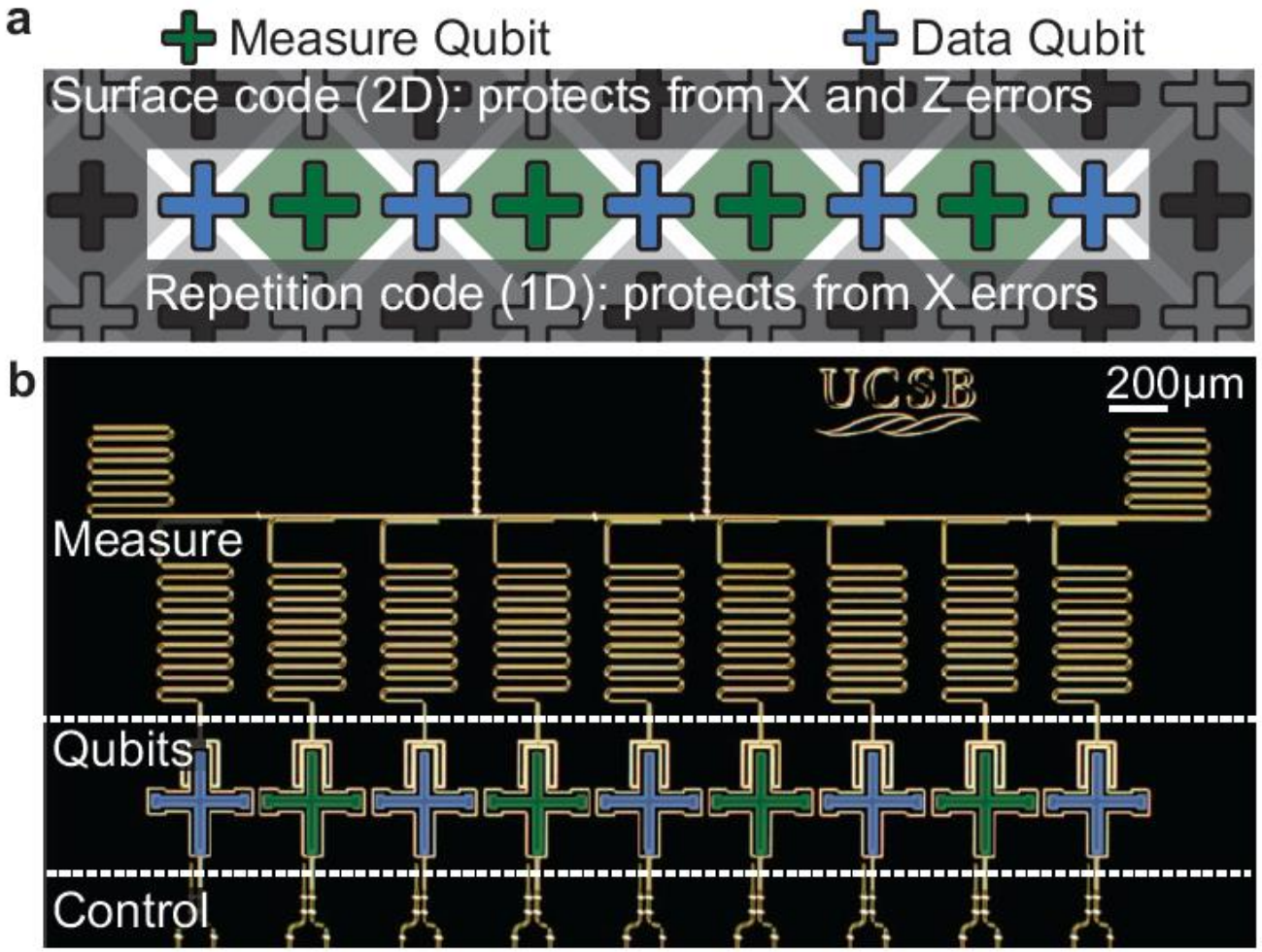


State of the art (2015):
Fully controlled 9-qubit device (UCSB/Google)



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

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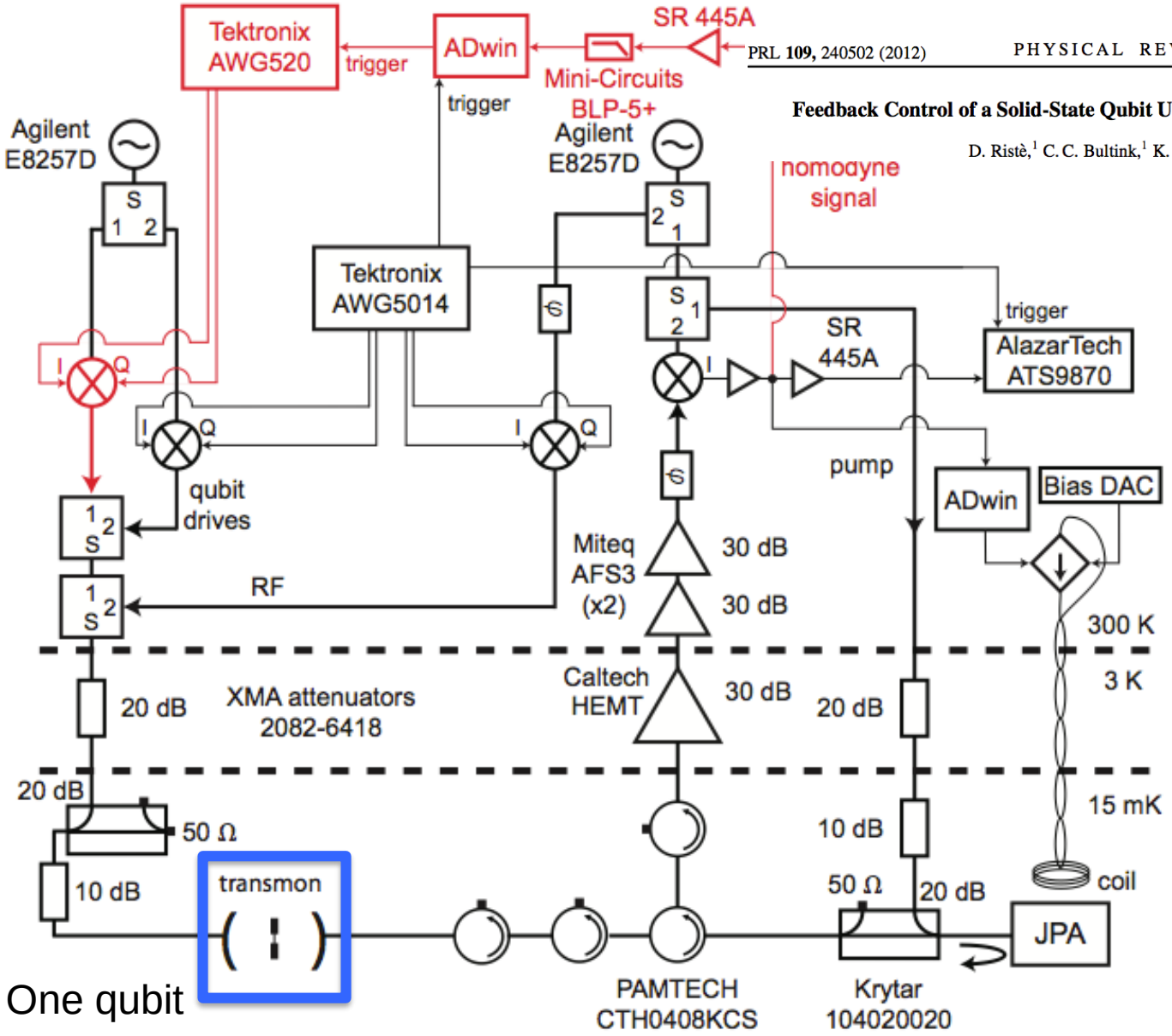
See JVH_IEDM_tutorial2014.pdf

Real instrumentation for qubit protection, manipulation, and measurement



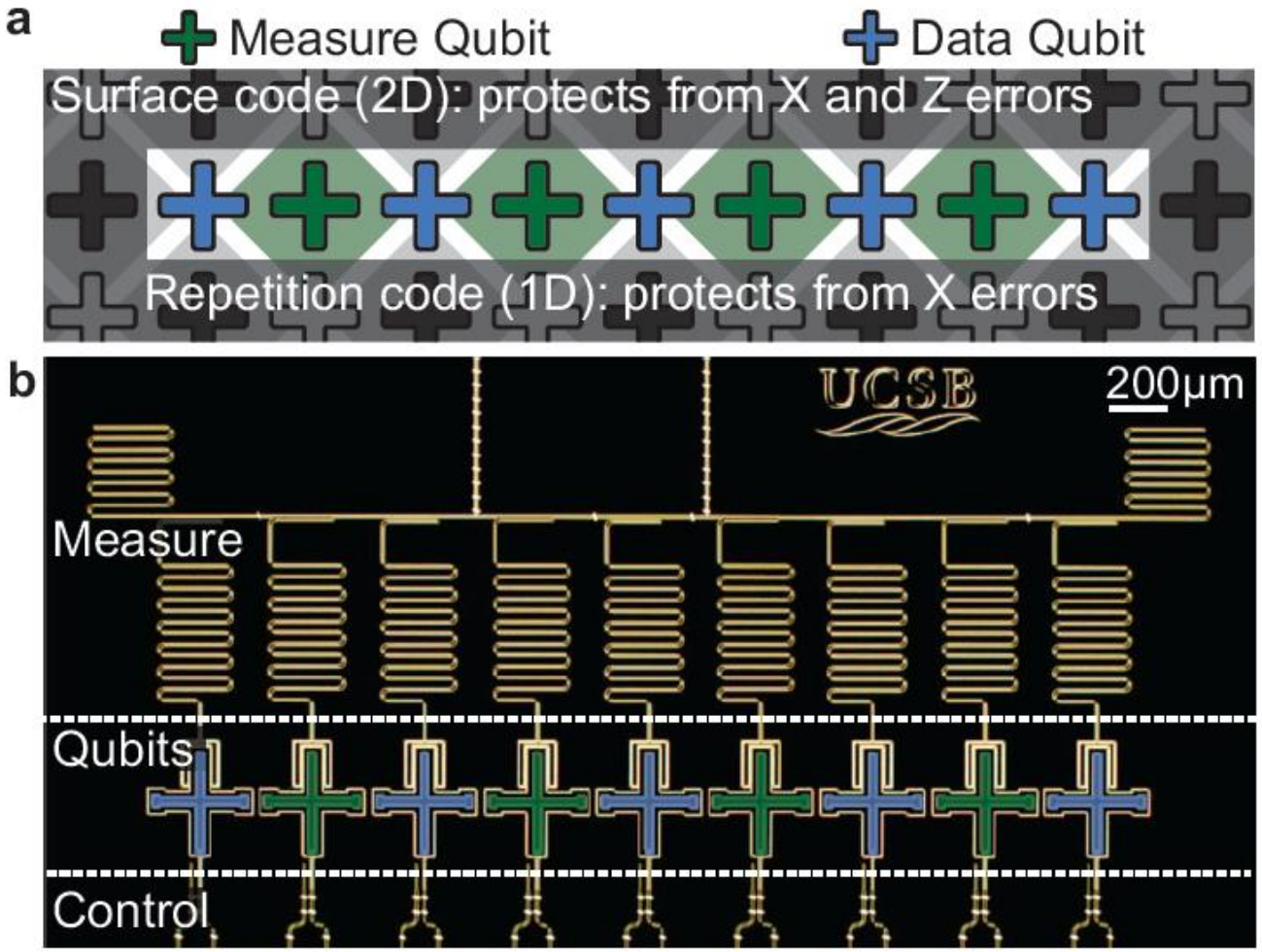
PRL 109, 240502 (2012) PHYSICAL REVIEW LETTERS week ending 14 DECEMBER 2012

Feedback Control of a Solid-State Qubit Using High-Fidelity Projective Measurement

D. Ristè,[1] C. C. Bultink,[1] K. W. Lehnert,[2] and L. DiCarlo[1]

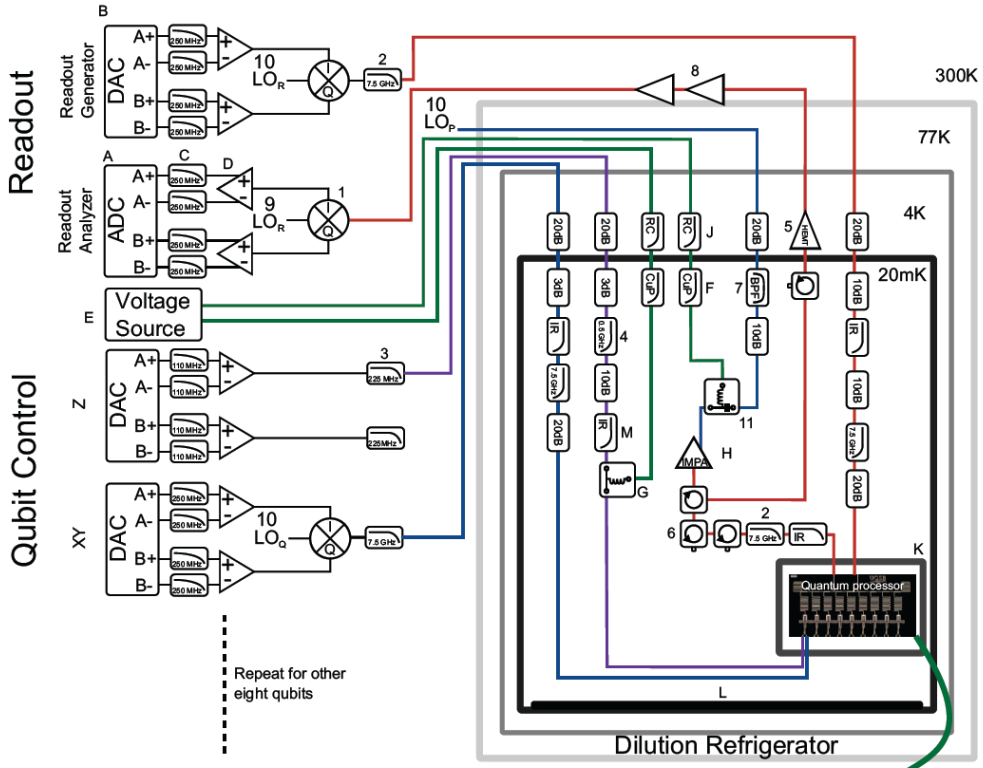
One qubit

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 AFS3-0010200-22-10P-4
9	Hittite HMC-T2100
10	Anritsu MG3692C
11	Sigatek 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

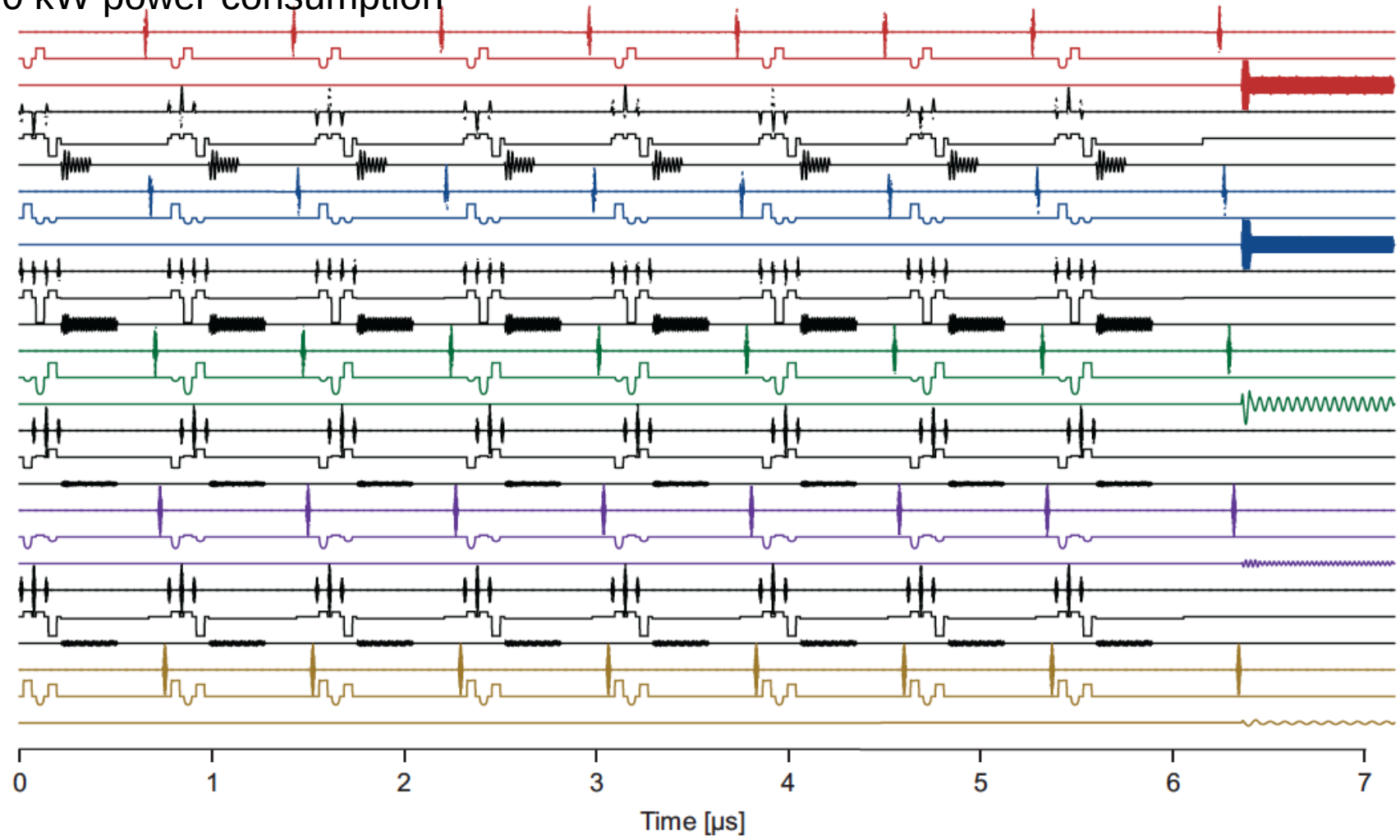


FIG. S27. **Waveform data for eight cycles of the nine qubit repetition code.**

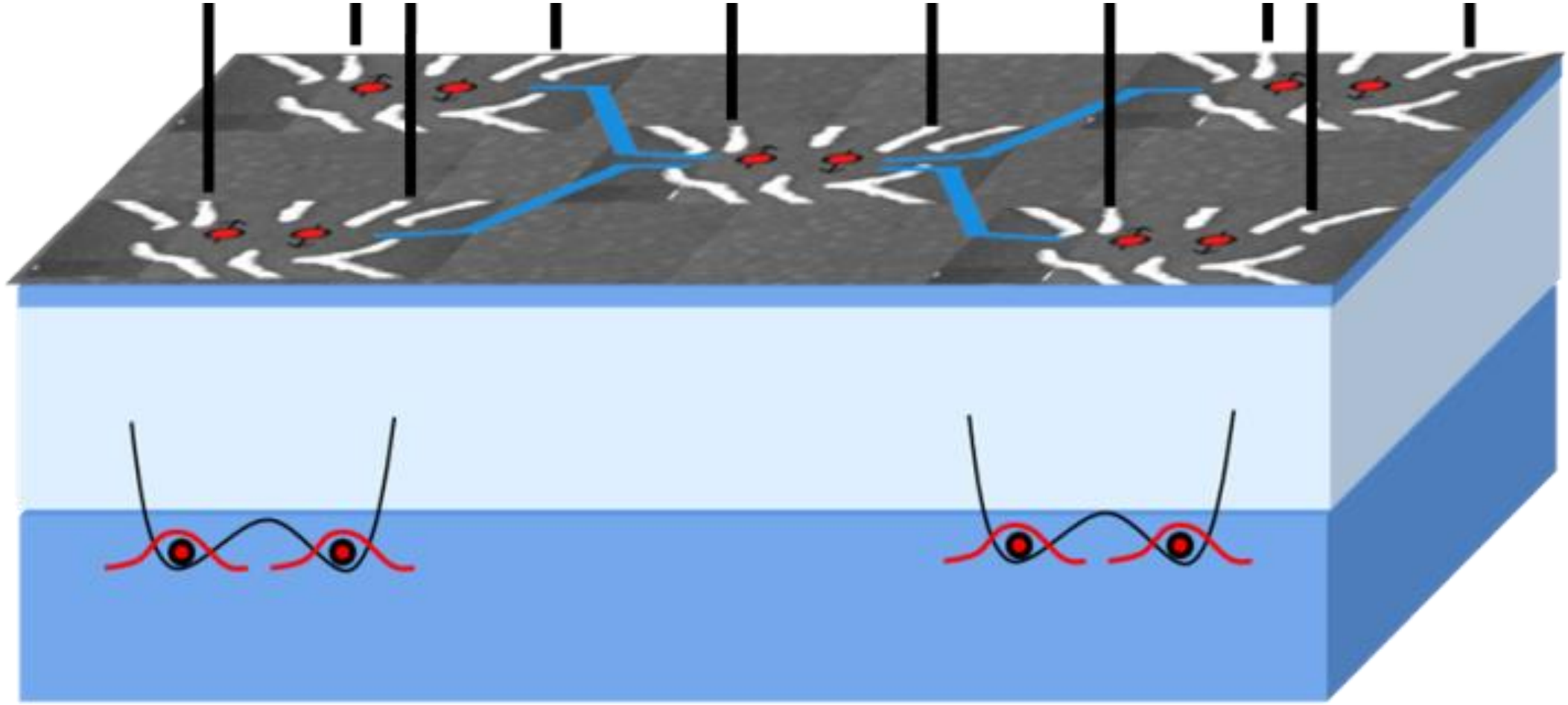
Outline

- The nature of quantum algorithms
- What is a qubit
- Criteria for the physical implementation of a quantum computer
- Fault tolerance, and the noise threshold theorem
- Strategies for 2D layouts for qubits
- Measurement, Isolation, Amplification
- **The full system view**

See JVH_IEDM_tutorial2014.pdf

Similar architecture concept, single-electron qubits
(can also achieve alternative “logntudinal” coupling

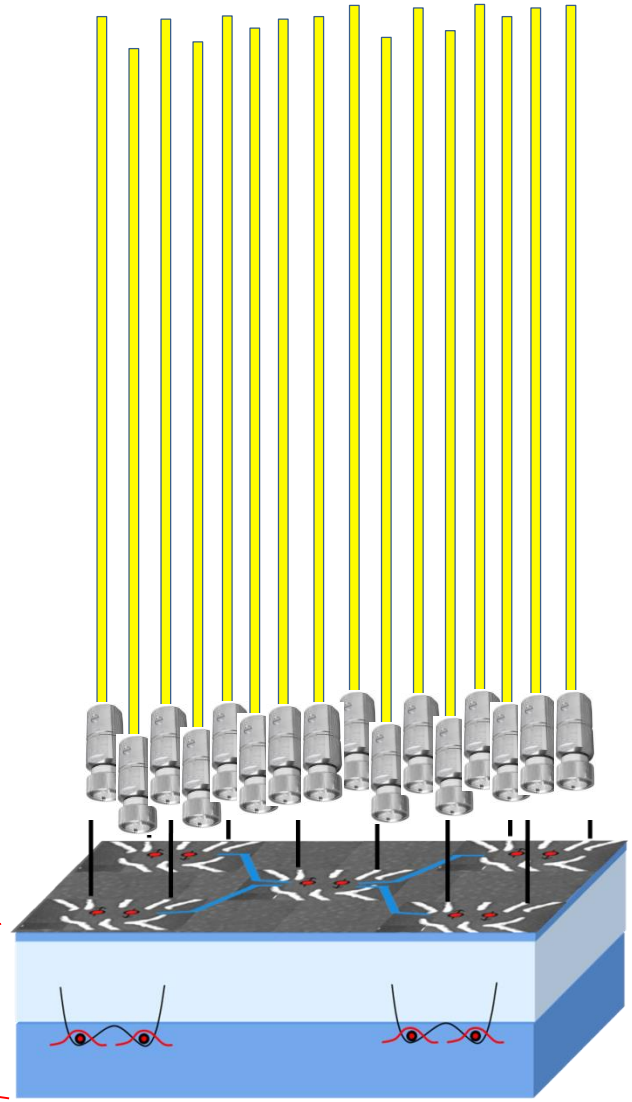
comment about the control lines:



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

Workhorse „dilution“ refrigerator

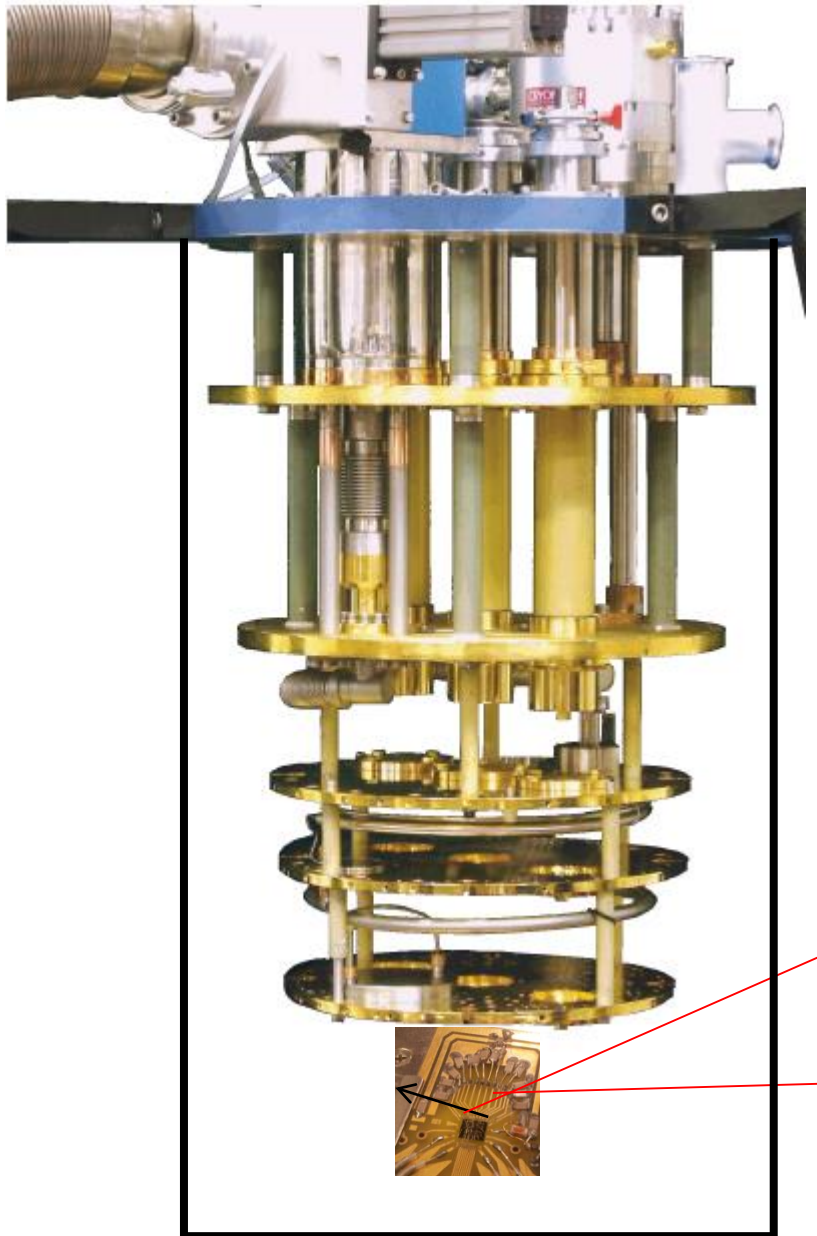
1 meter

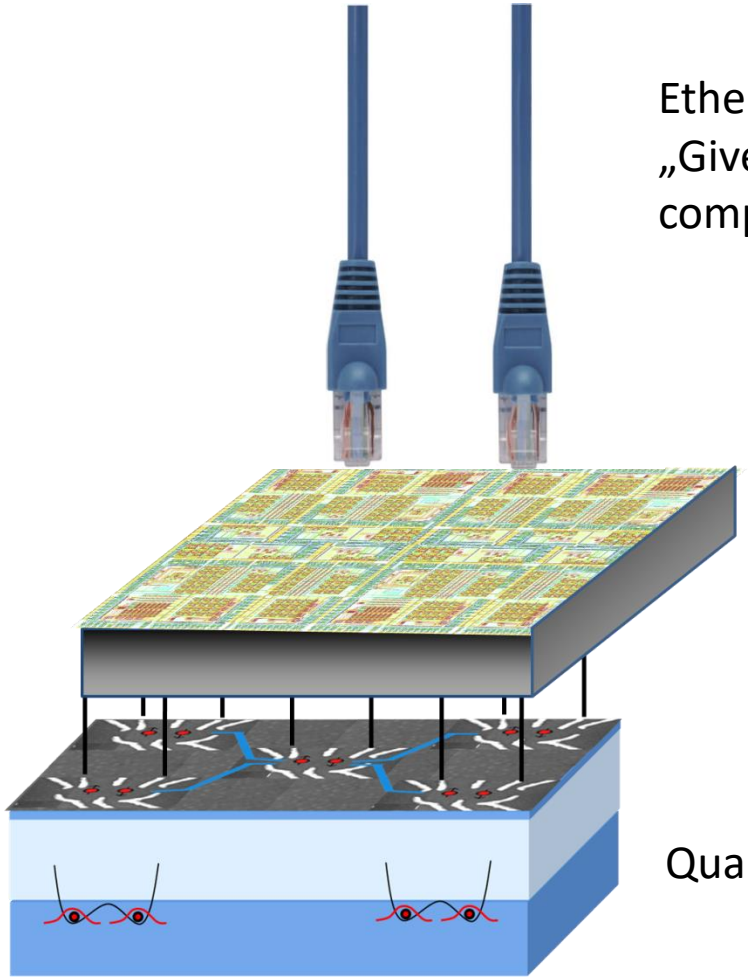


Number of cables
~ 2x the number of qubits

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

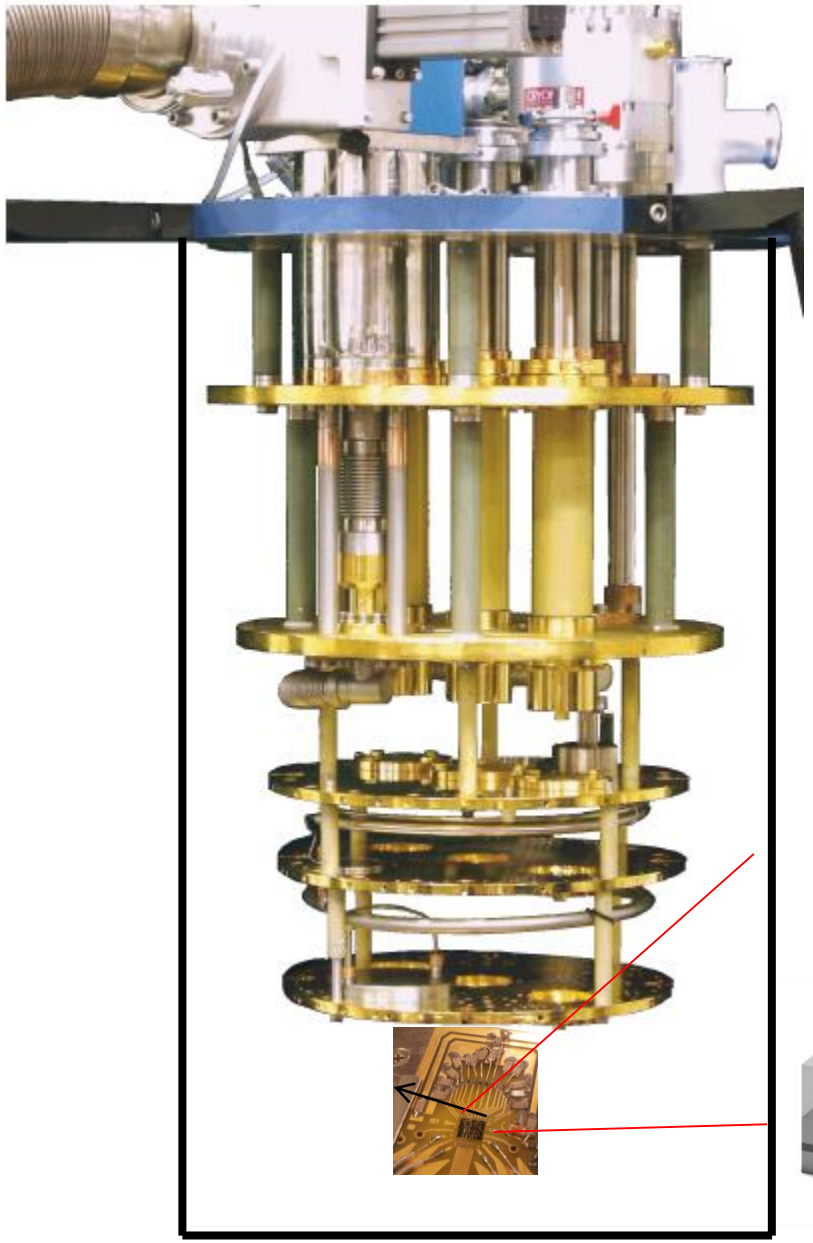
Quantum chip: T=0.02K

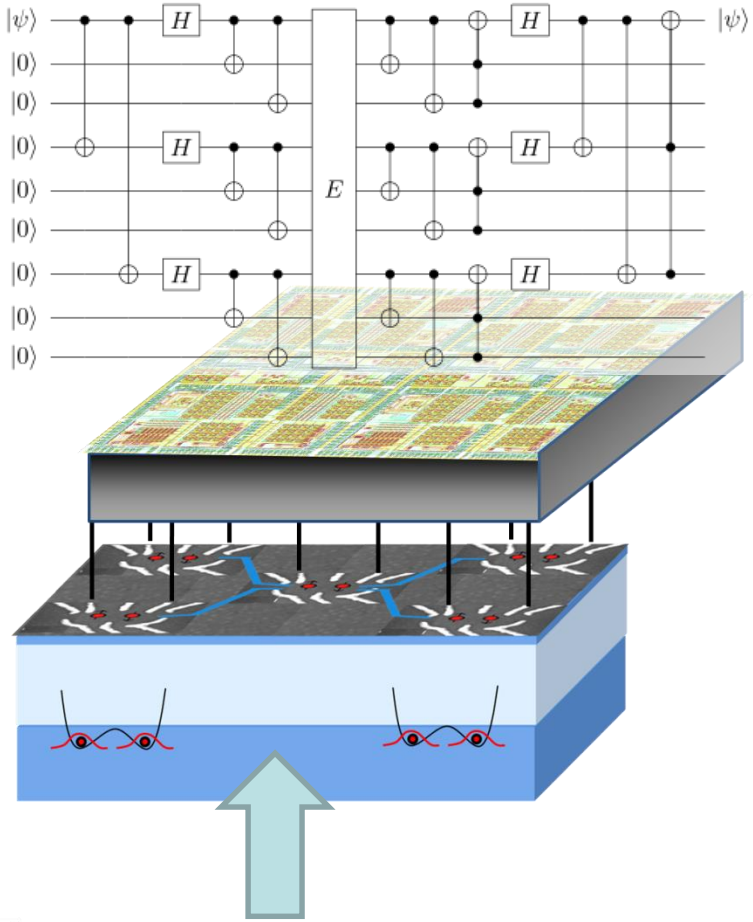
Outline -- Wrapup

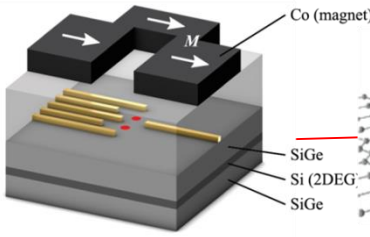
- The nature of quantum algorithms
- What is a qubit
- Materials and devices for a quantum computer
- Fault tolerance, and the noise threshold theorem
- Strategies for 2D layouts for qubits
- Measurement, Isolation, Amplification
- The full system view

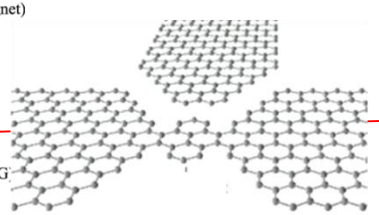
Useful Literature:

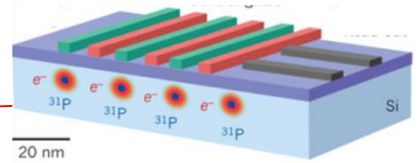
- N. David Mermin, *Quantum Computer Science* (Cambridge U. Press) 2007
- A. M. Zagoskin, *Quantum Engineering* (Cambridge U. Press) 2011
- M. H. Devoret and R. J. Schoelkopf, “Superconducting Circuits for Quantum Information: An Outlook” Science 8 March 2013: Vol. 339 no. 6124 pp. 1169-1174.
- www.qurope.eu Quantum Information Processing and Communication in Europe (2016 outlook and beyond)



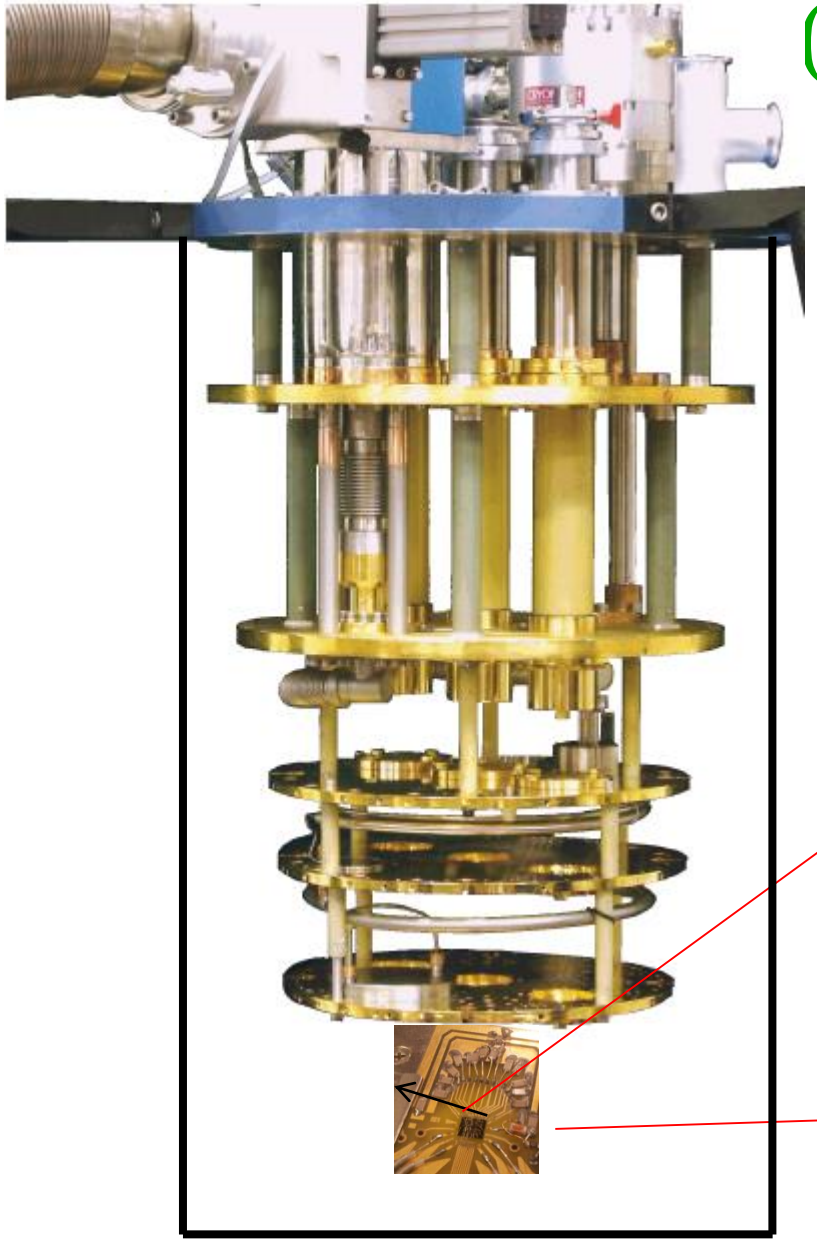

$|\psi\rangle$
$|0\rangle$
H
E

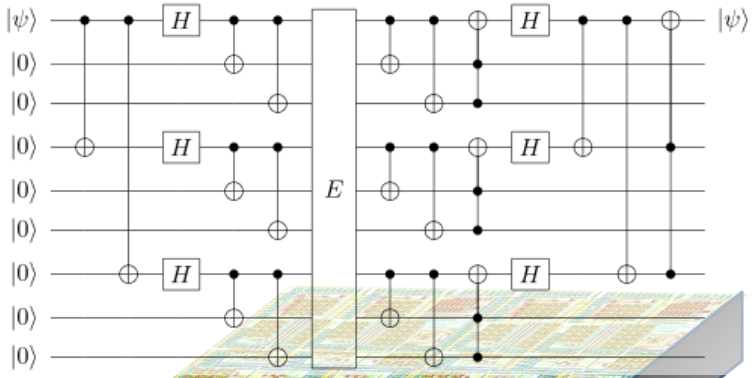

Co (magnet)
M
SiGe
Si (2DEG)
SiGe

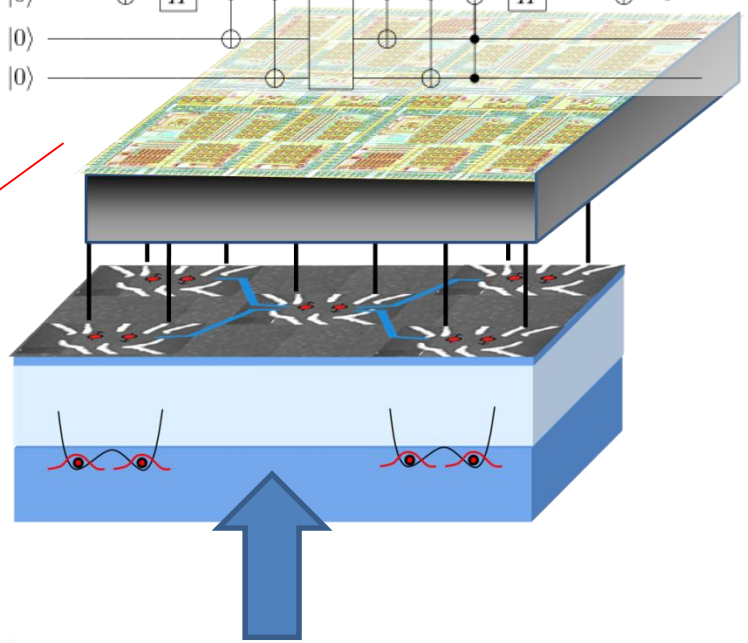


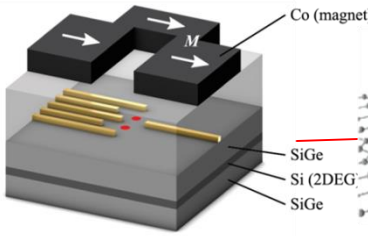

e^-
31P
Si
20 nm

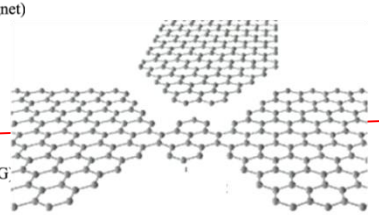
Vision: scalable architecture (H. Bluhm)

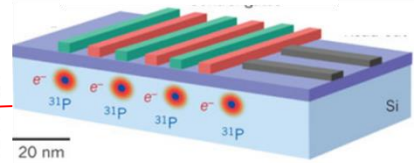












What will the first Quantum Computers Look Like – vs. a Conventional System?