Ways to Manipulate & Capture Quantum Chips On-Screen

Onri Jay Benally
University of Minnesota
Department of Electrical & Computer Engineering
Principal Investigator: Prof. Jian-Ping Wang

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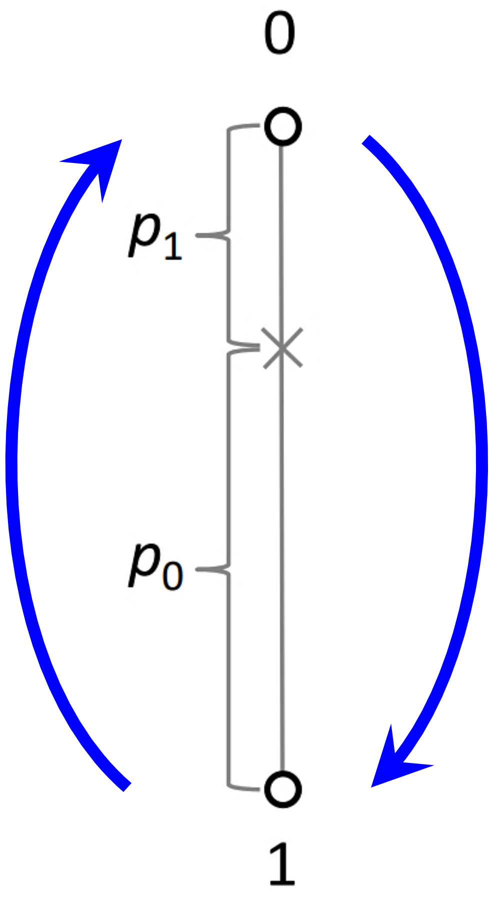
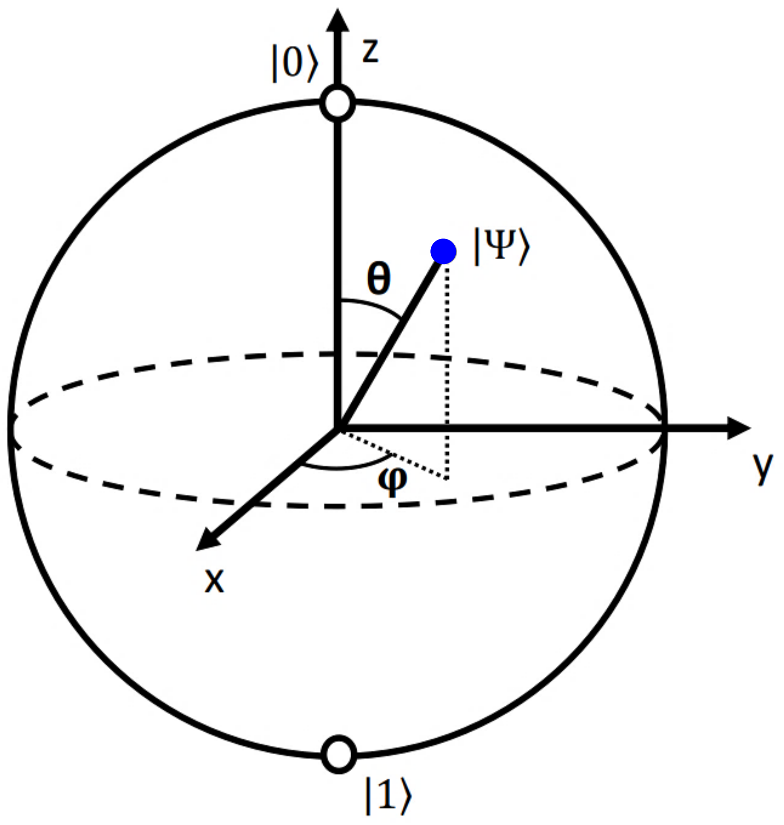
Table of Contents

IBM Research, *433-Qubit IBM Osprey Quantum Processor* (2022)

Deterministic vs. Probabilistic vs. Quantum Bits.





bits

binary digit

pbits

probabilistic bit

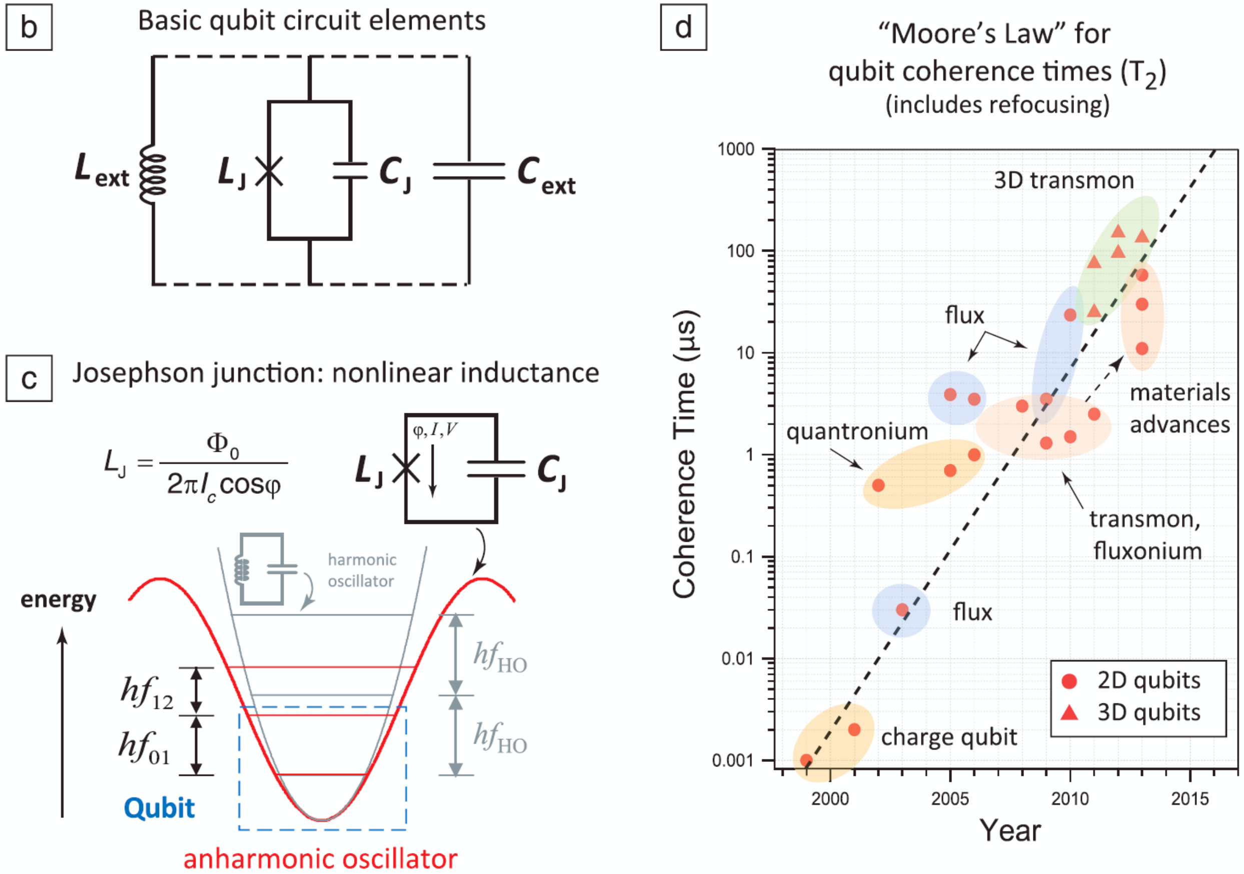
qubits

quantum bit

1. Ezratty et al., *Understanding Quantum Technologies* (2022)

Background & Motivation

- In 1982, Richard Feynman described an idea of creating quantum simulators, which would need physical devices that use quantum mechanical effects, rather than logic alone.
- Quantum bits = qubits (anharmonic oscillator).
- Qubits can either function as artificial atoms or be made of natural atoms.



1. Feynman, *Int. J. Theor. Phys.* (1981)
2. Oliver et al., *Materials Research Society* (2013)

More Background & Motivation

- Daniel Loss and David DiVincenzo.
  - Considered to have introduced the idea of using electron spins for quantum computing in 1996.
- Bruce Kane.
  - Developed a spin-based computer concept, “donor spin model” in 1998. (hybrid scheme using quantum dots & nuclear magnetic resonance from phosphorus).
- Quantum states created by qubits can be thought of as vectors, which can be modified by matrices.
  - Quantum state = vector
  - Qubit = matrix
- Physical qubits vs. logical qubits:
  - Usually takes 9-10 physical qubits* to represent 1 logical qubit.
  - Logical qubits are used to make **quantum gates**.

1. Loss et al., *Phys. Rev. A* (1998)
2. Kane, *Nature* (1998)

*Physical qubits can be grouped upwards of up to 1,000.

Comparison of Resources For Simulation

- Below is a chart representing logical qubits & their information processing capabilities.
- Compared to classical processing.

≈2-3 min of Processing Time

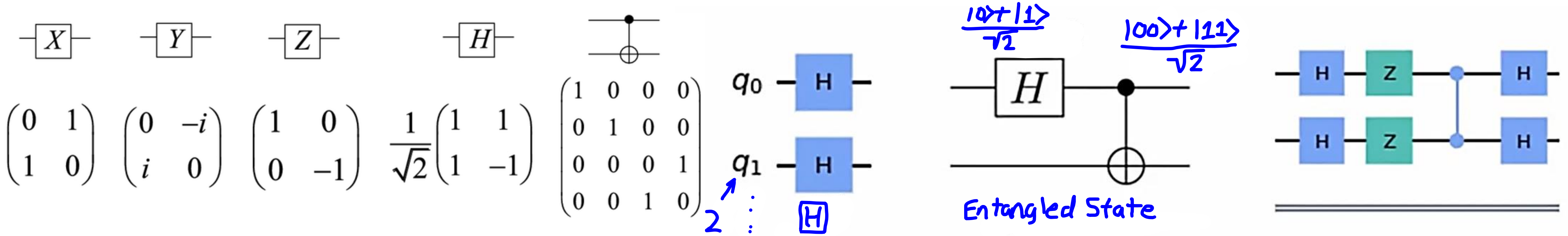
≈15-120 min of Processing Time

# of Qubits	Equivalent Classical Computer RAM	Equivalent Classical Computer Processing Time
10	128 bytes	2.6 microseconds
20	131 Kilobytes	0.26 milliseconds
30	134 Megabytes	0.27 seconds
40	137 Gigabytes	4.6 minutes
53	1 Terabyte	625 hours
63	1 Petabyte	73 years
100	1 Exabyte	10 trillion years
1,000	1.3×10^{232} Exabytes	8.5×10^{283} years

1. Adapted from: Oliver., *MIT Center for Quantum Engineering* (2021)

Important Qubit Gates

- Qubit gates are typically made of 1 or 2 logical qubits. (There can be **more**).
- Encode entangled information = Hadamard + Controlled NOT
- Decode entangled information = Controlled NOT + Hadamard
- Encode superposition = Hadamard + Hadamard



(a) (b) (c) (d) (e)

Putting qubits in superposition

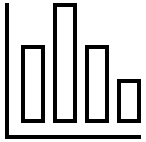
Bell measurements

2-qubit Grover diffusion circuit

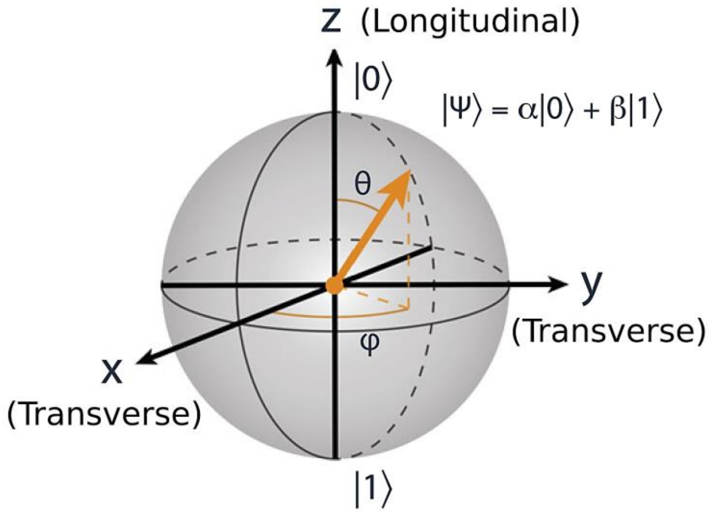
1. IBM, *Qiskit Textbook.* (2022)

Qubit State Visualizations

- Bloch sphere = useful in representing single-qubit gates (local view)
- Q-sphere = used for multi-qubit gates (global view)
- Statevector view = used for multi-qubit gates
- Probabilities view = used for multi-qubit gates
- Fractal view = used for multi-qubit gates

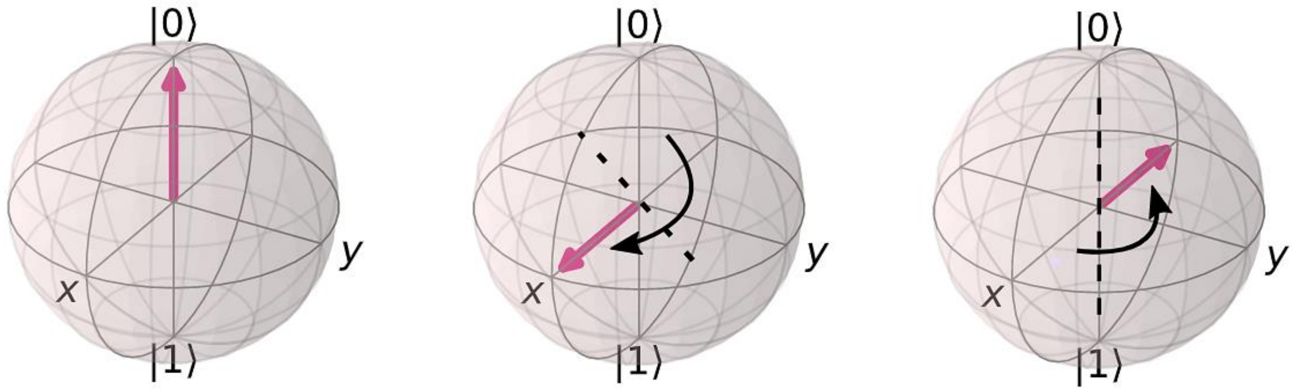


Bloch sphere

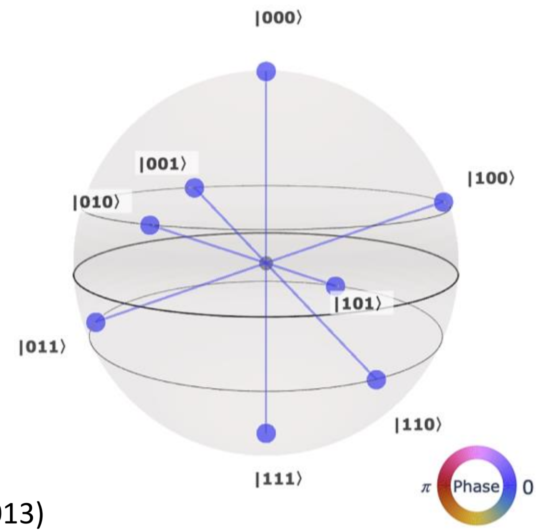


Example of 2 gates applied to a |0⟩ state:

Start | Apply H-gate | Apply Z-gate



Q-sphere

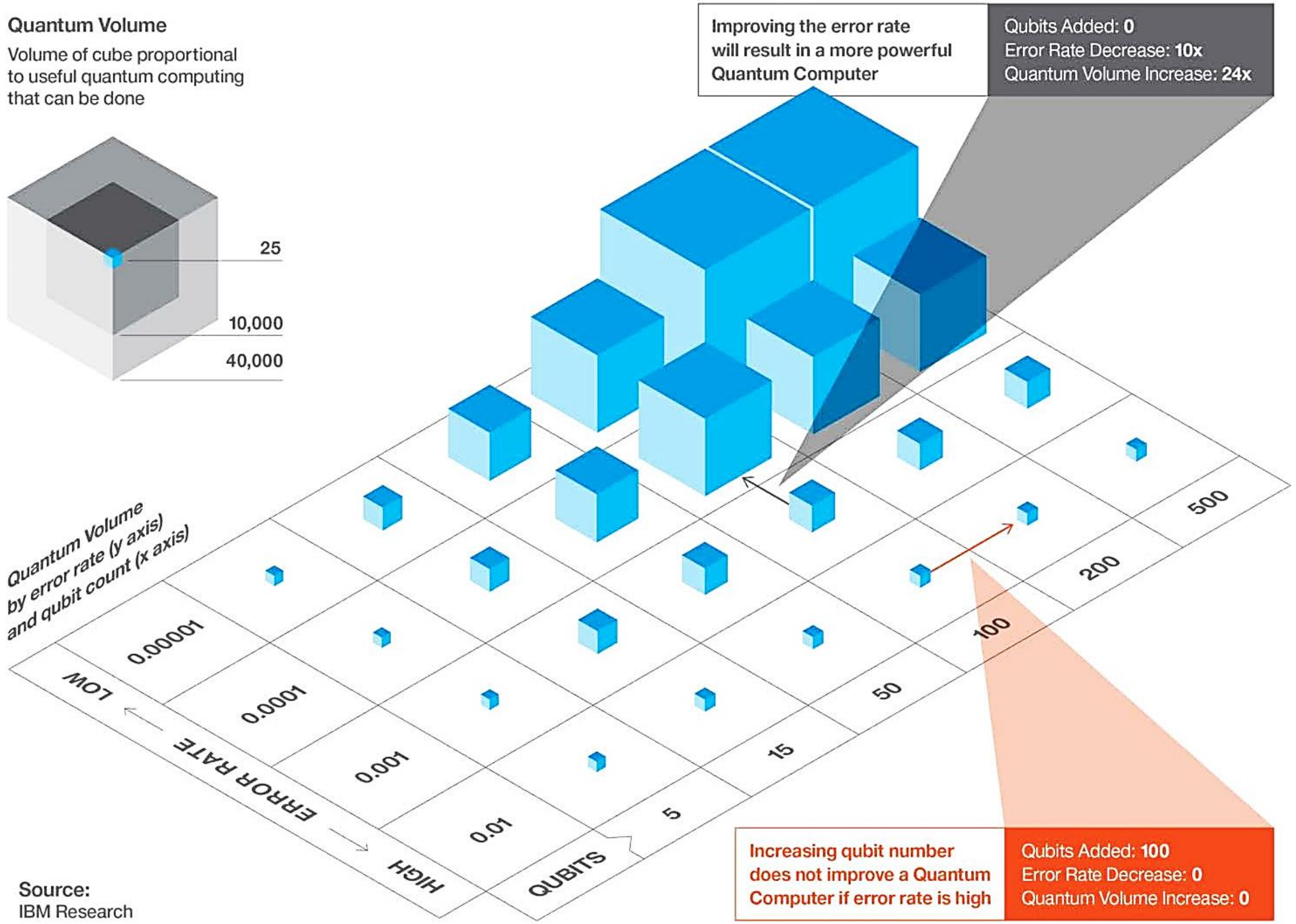


*qubits are typically initialized in the |0⟩ state.

1. Oliver et al., *Materials Research Society* (2013)
2. IBM, *Qiskit Textbook* (2022)

Quantum Volume & Qubit Quality

- Quantum volume (non-absolute metric): measurement of overall device performance.
  - Done by performing average gate fidelity, circuit depth, & width calculation with an algorithm.
- High error rates lead to decreased quantum volume.
  - Error rates are a measure of noise between 2 qubits.



*Fidelity: noise
** You may also have heard of **CLOPS**:
(Circuit Layer Operations Per Second)

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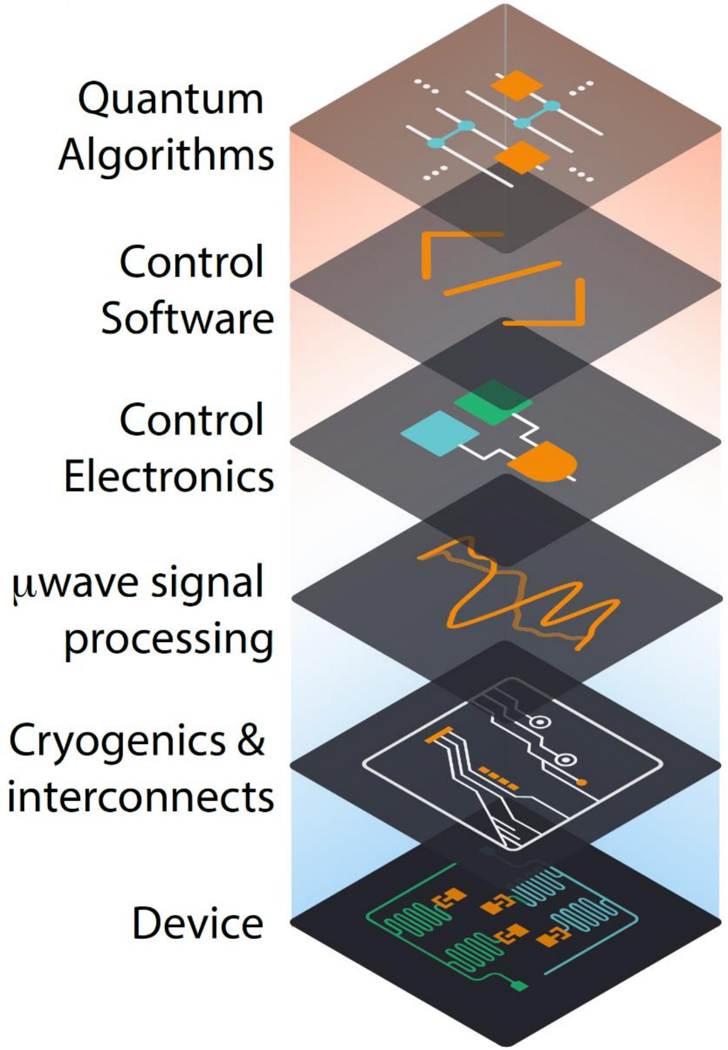
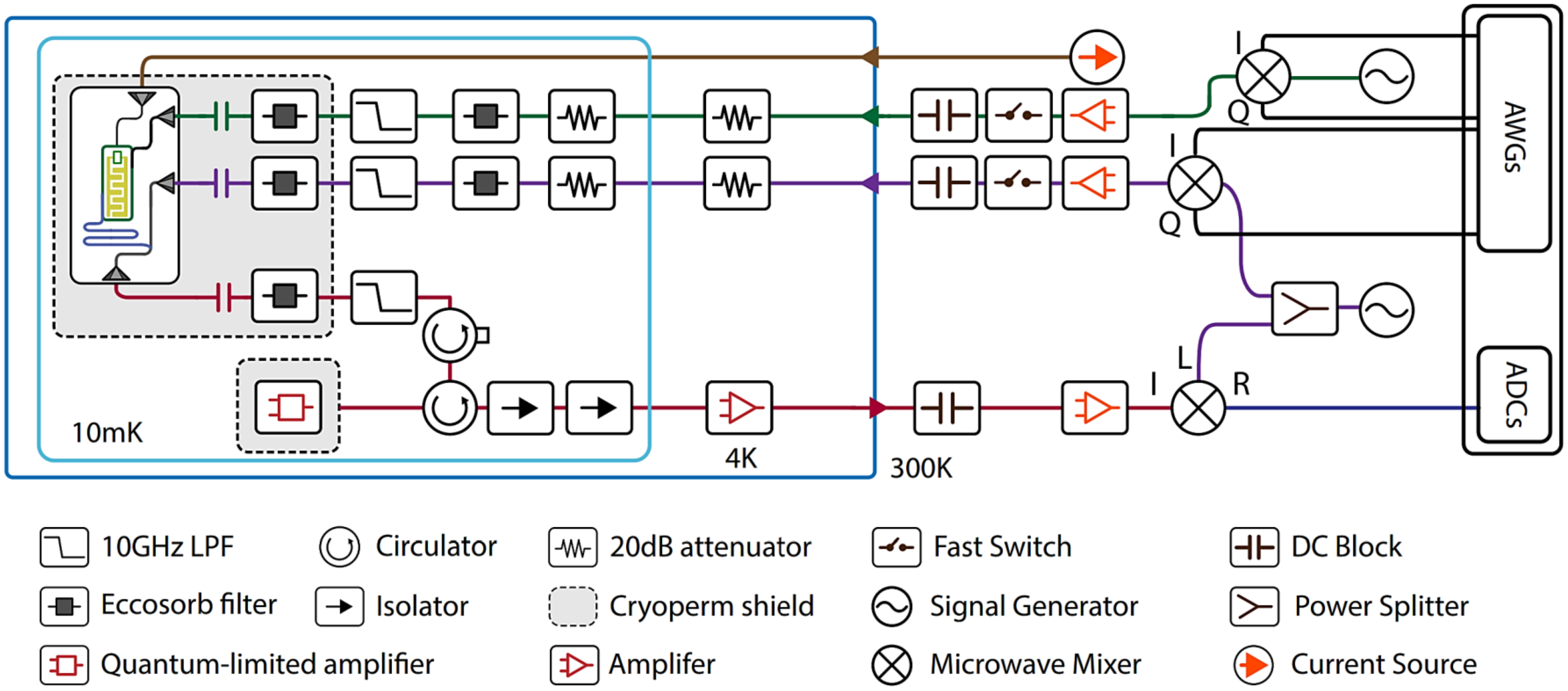
1. IBM Research, *Quantum Volume* (2018)

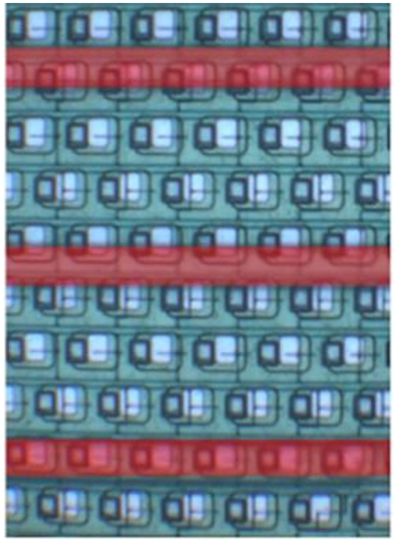
Quantum Stack vs. Quantum Device Control Schematic

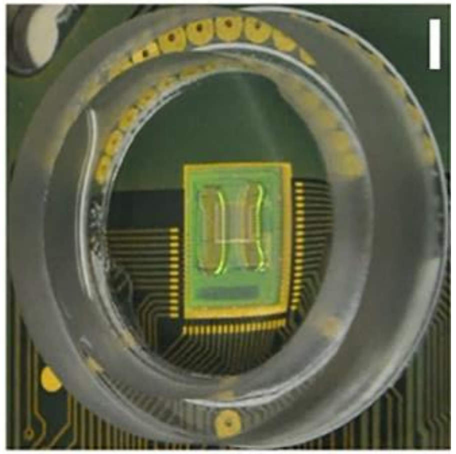


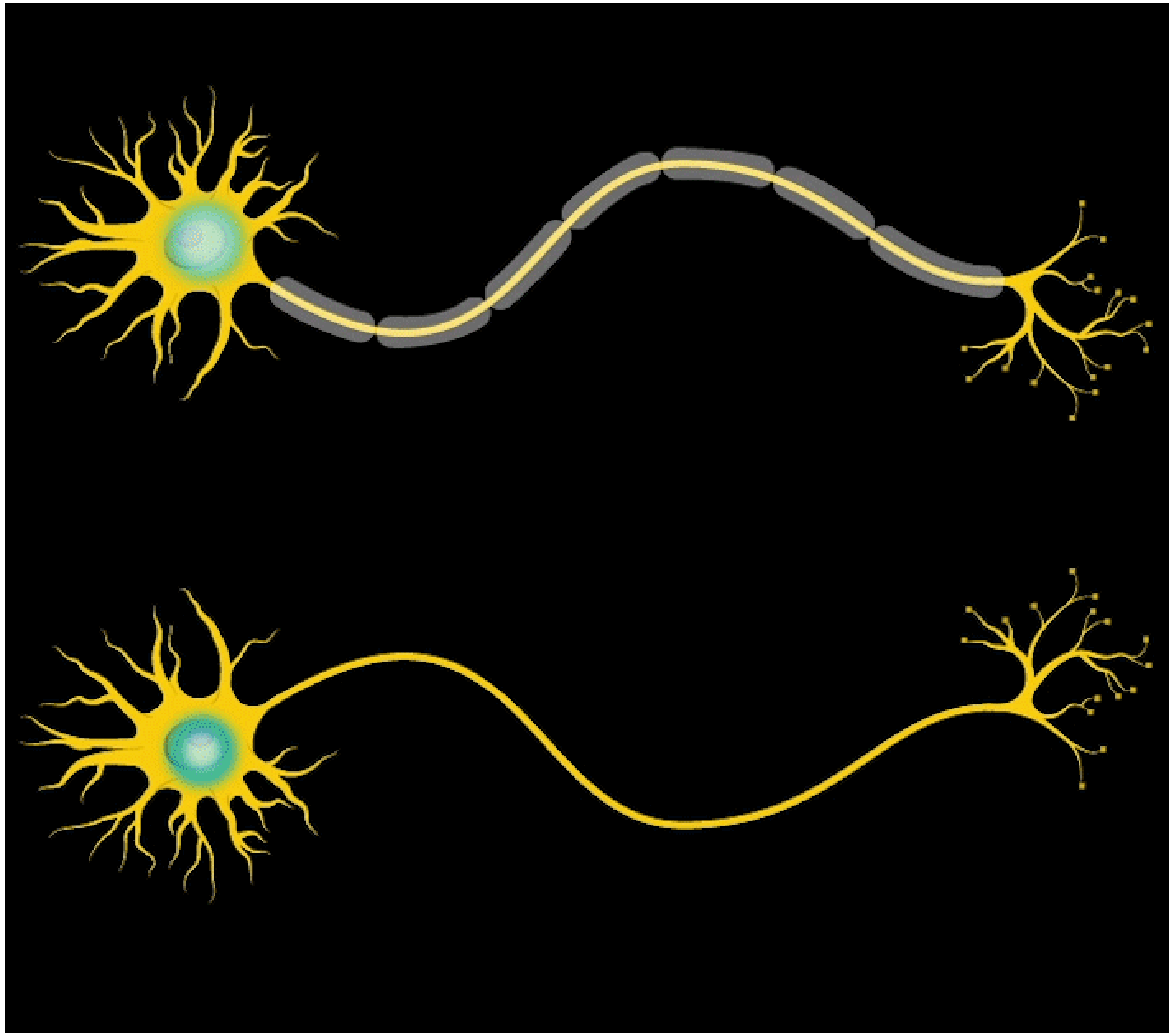


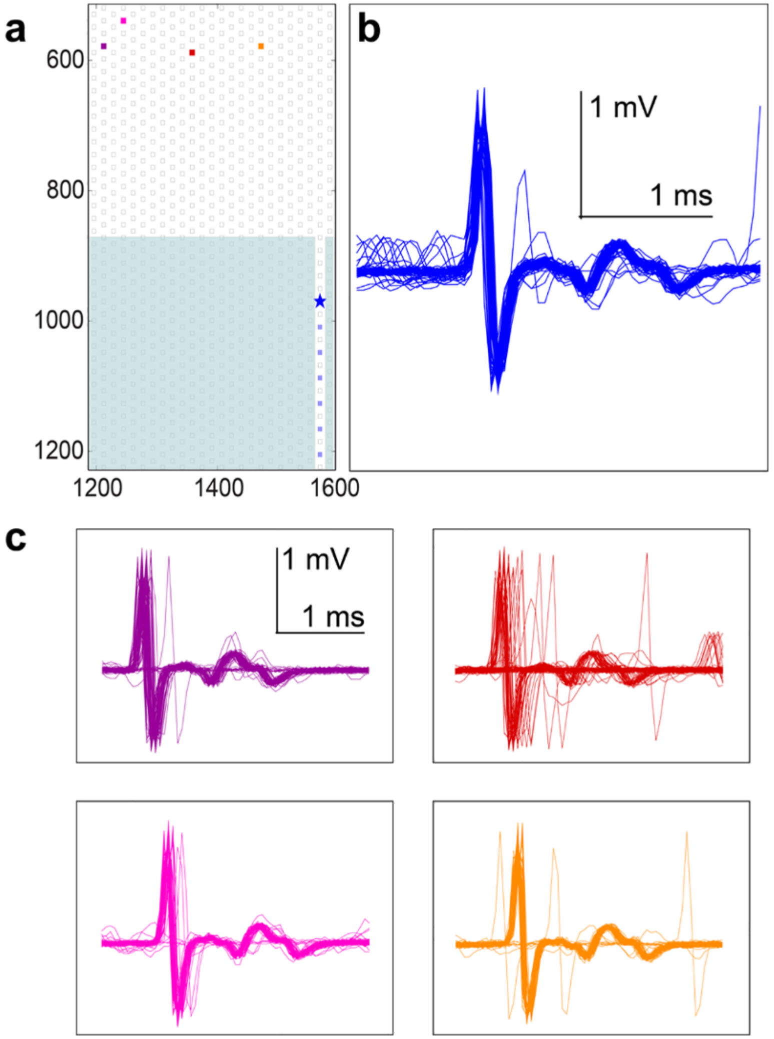
1. Gao et al., *arXiv* (2021)

Analogy: Detection of Neuron Impulse & Stimulation Spikes



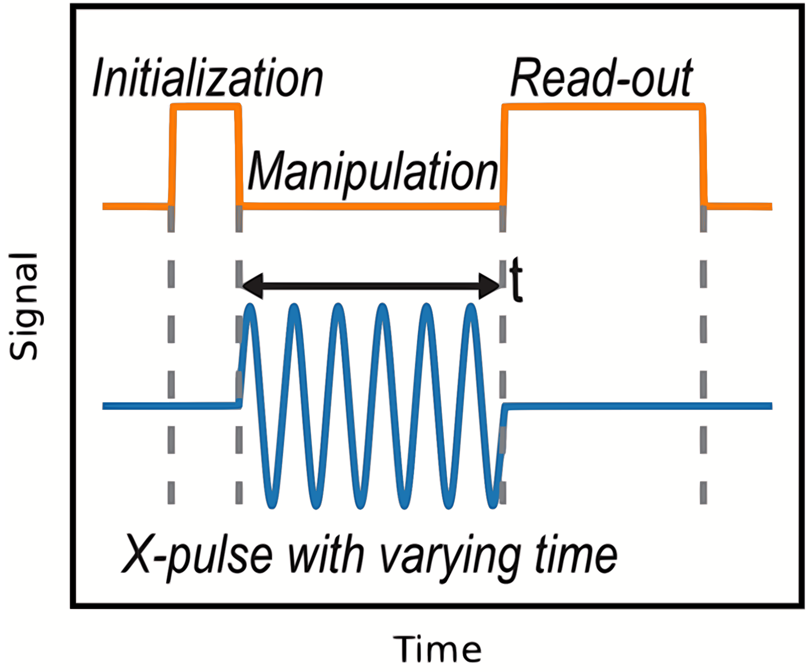


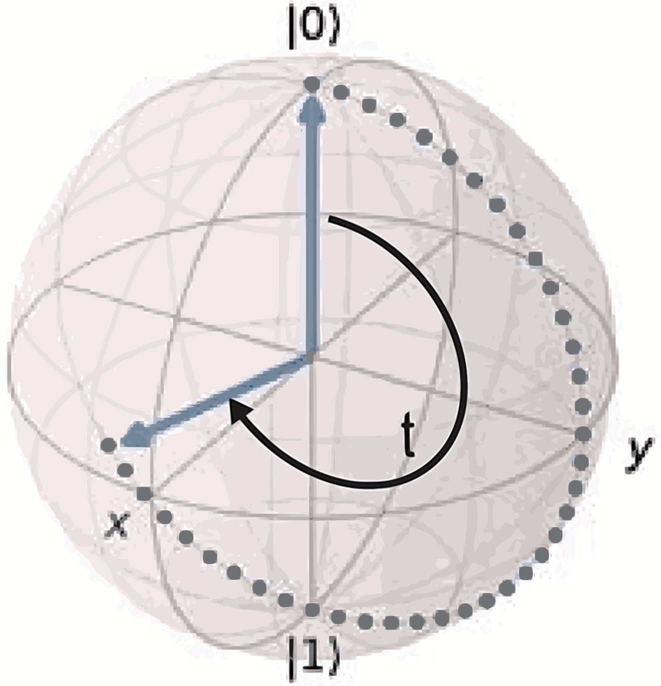


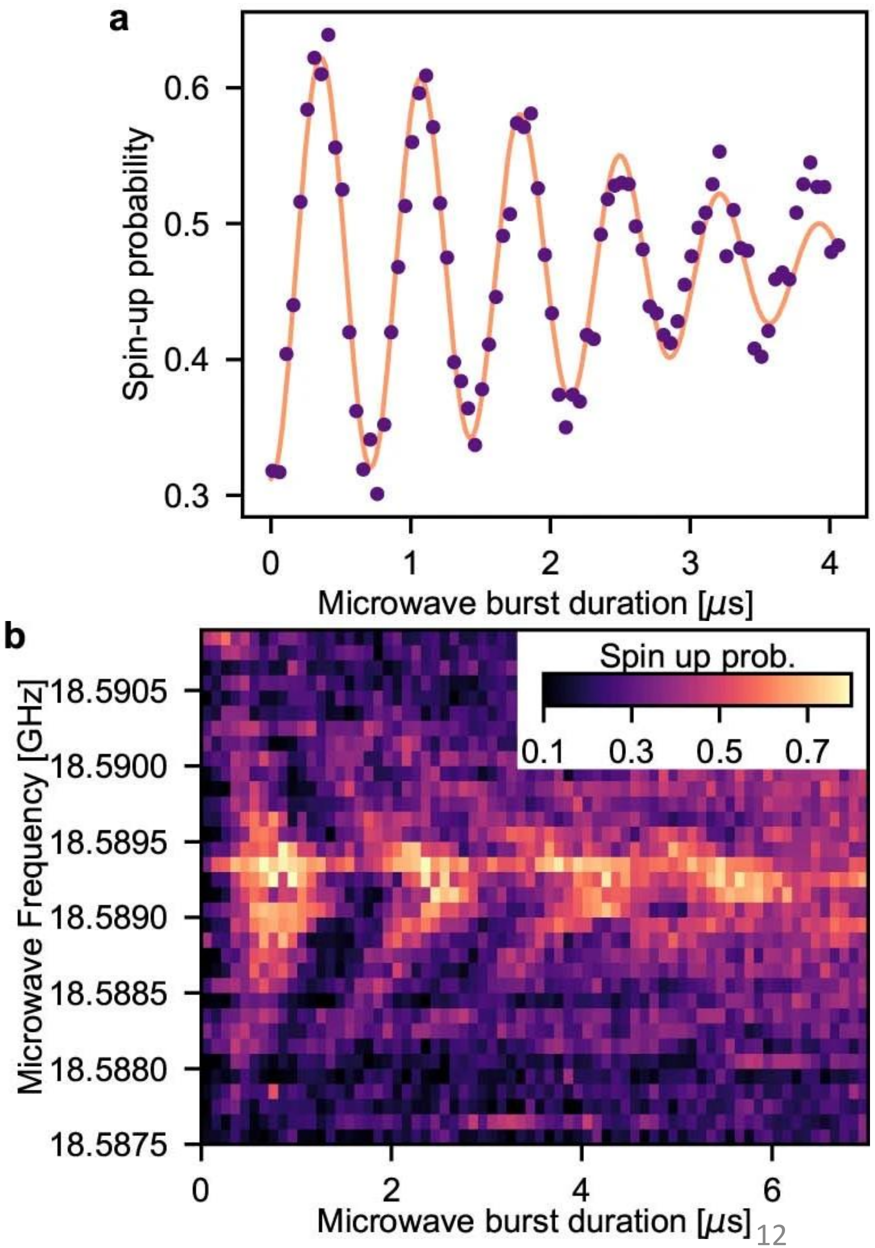


1. McGovern Institute, MIT (2019)
2. Lewandowska et al., *Plos One* (2015)

Qubit Drive & Measurement Pulse

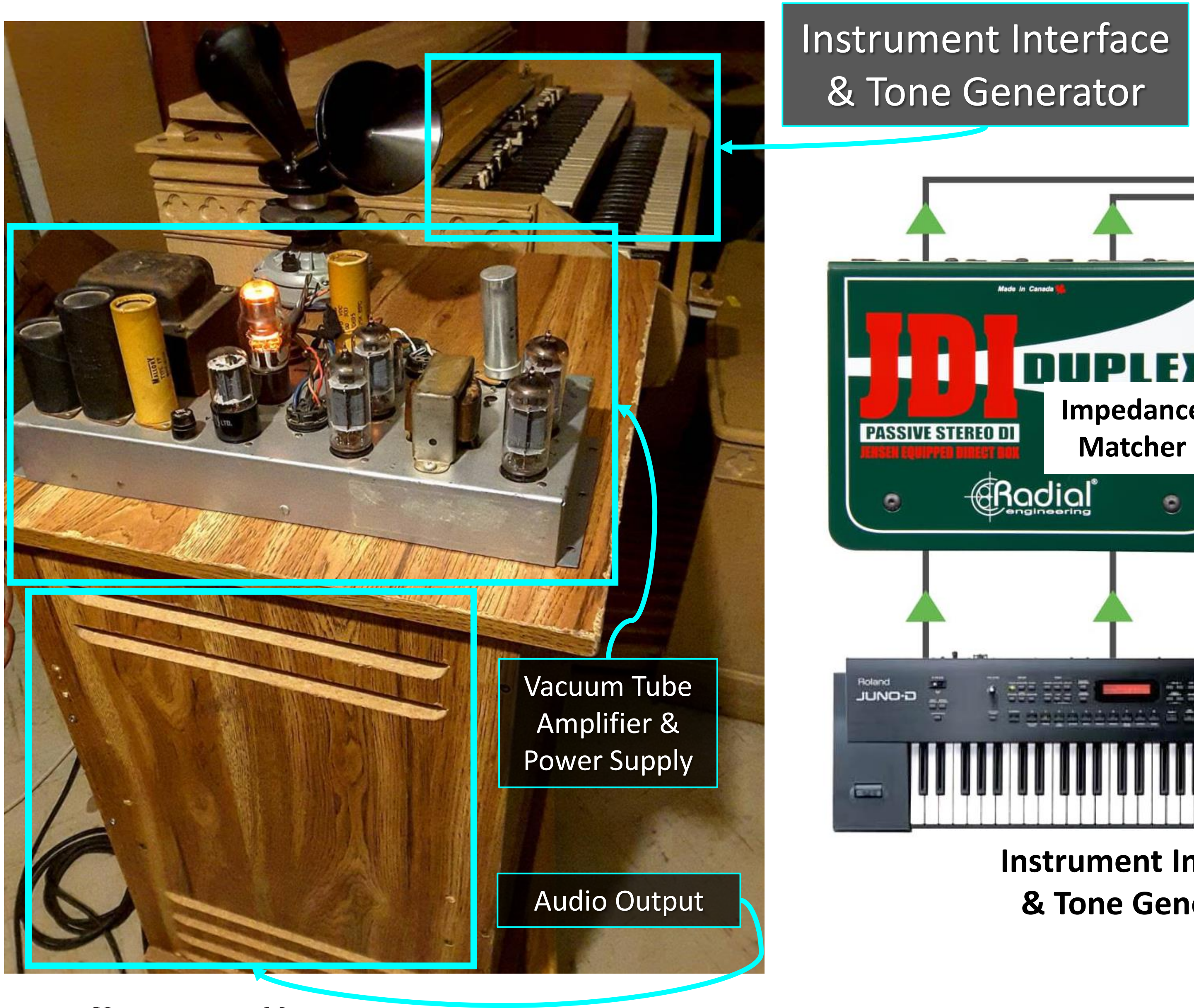


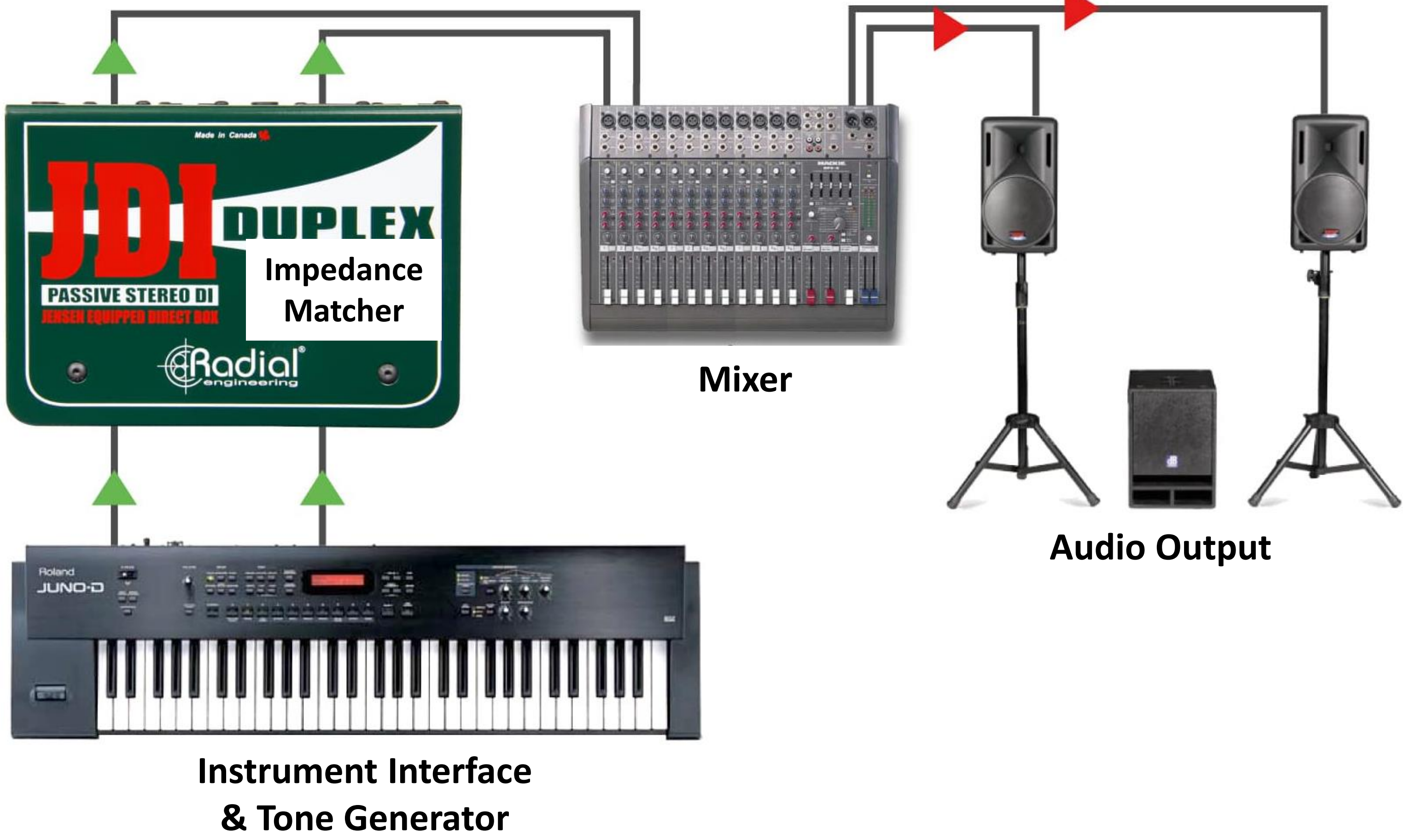




1. Dijk et al., *IEEE JOURNAL OF SOLID-STATE CIRCUITS* (2020)
2. Zwerver et al., *Nature Electronics* (2022)

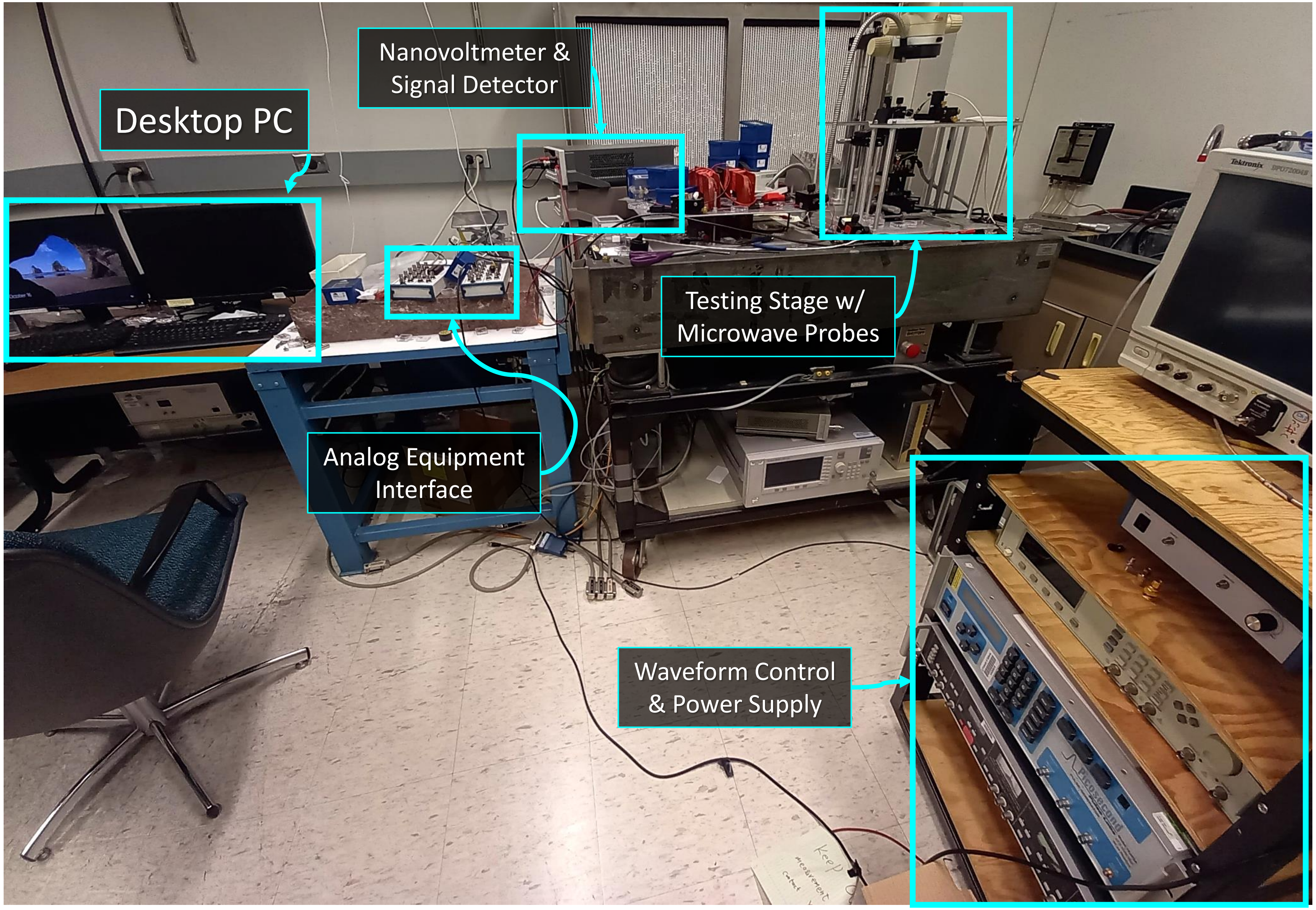
Analogy: Hammond Organ Setup



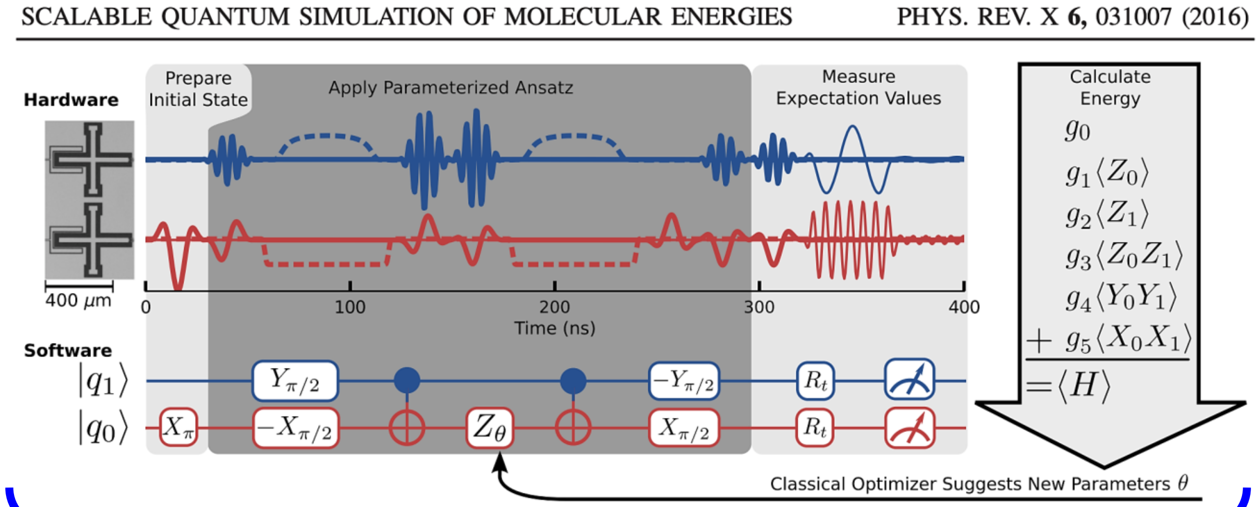


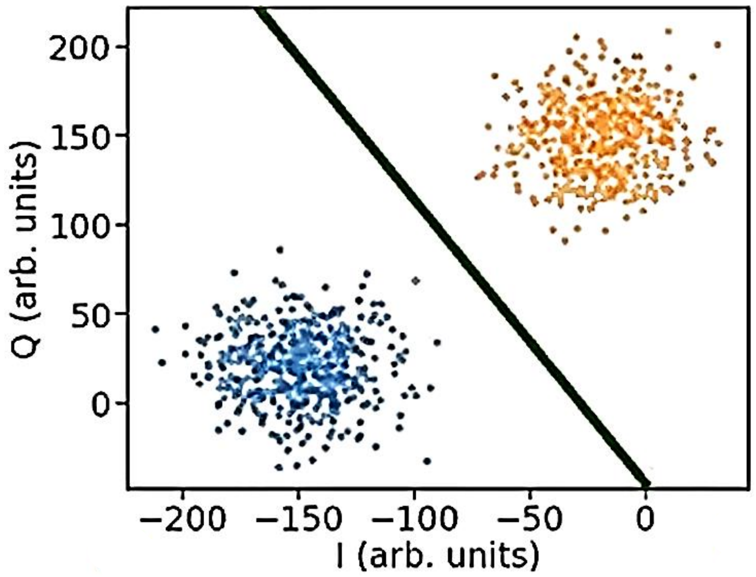
1. Taken from: radialeng.com

Comparison to Magnetics Lab: Testing & Measurement Setup



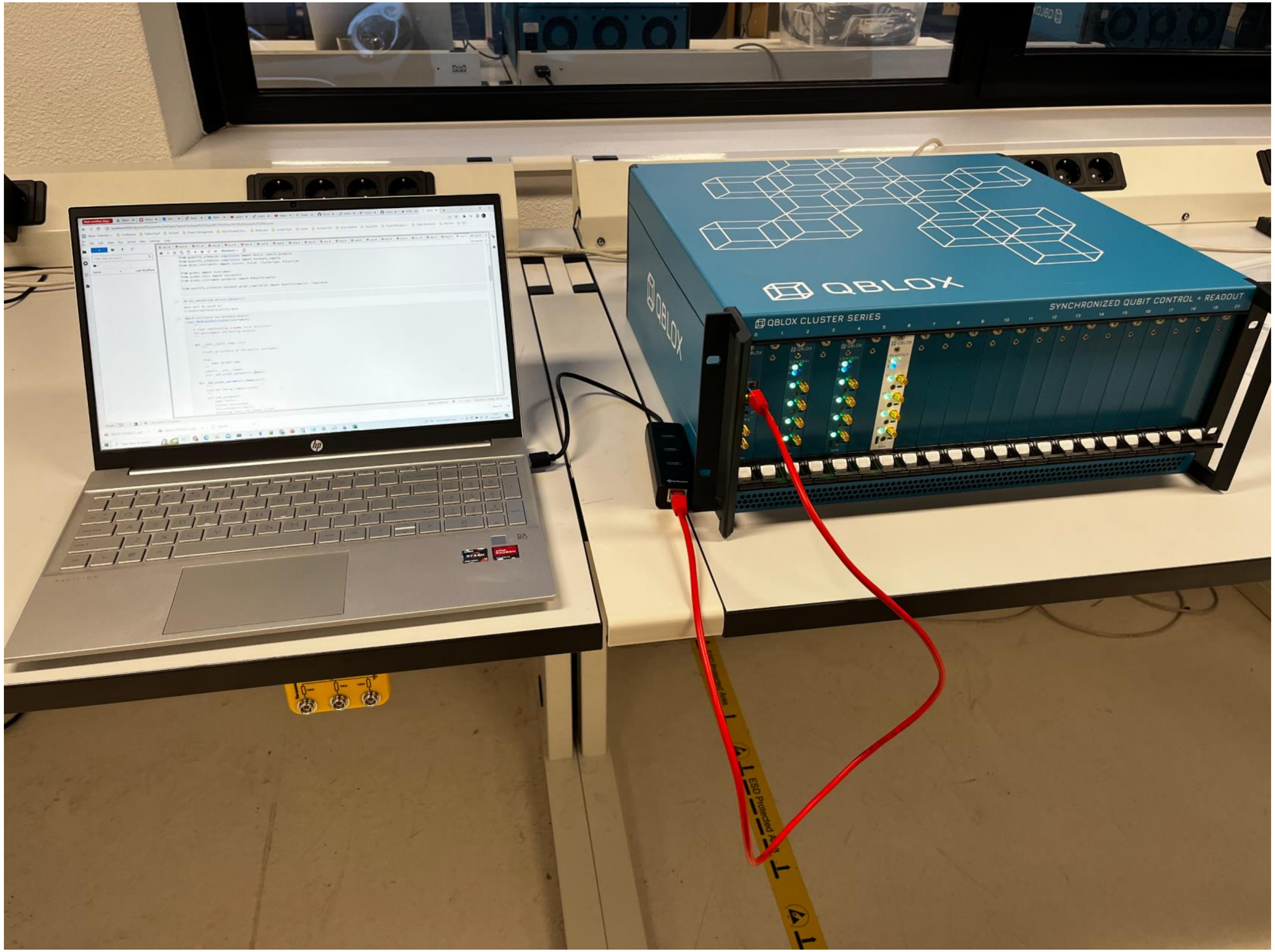
Qubit Drive & Measurement Pulse





1. Qblox Quantum, *Documentation and Tutorials* (2022)
2. O'Malley et al., *Phys. Rev. X* (2016)
3. Bron, *Centre for Quantum Technologies Online Talks* (2020)

Qubit Drive & Measurement Pulse



1. Qblox Quantum, *Documentation and Tutorials* (2022)

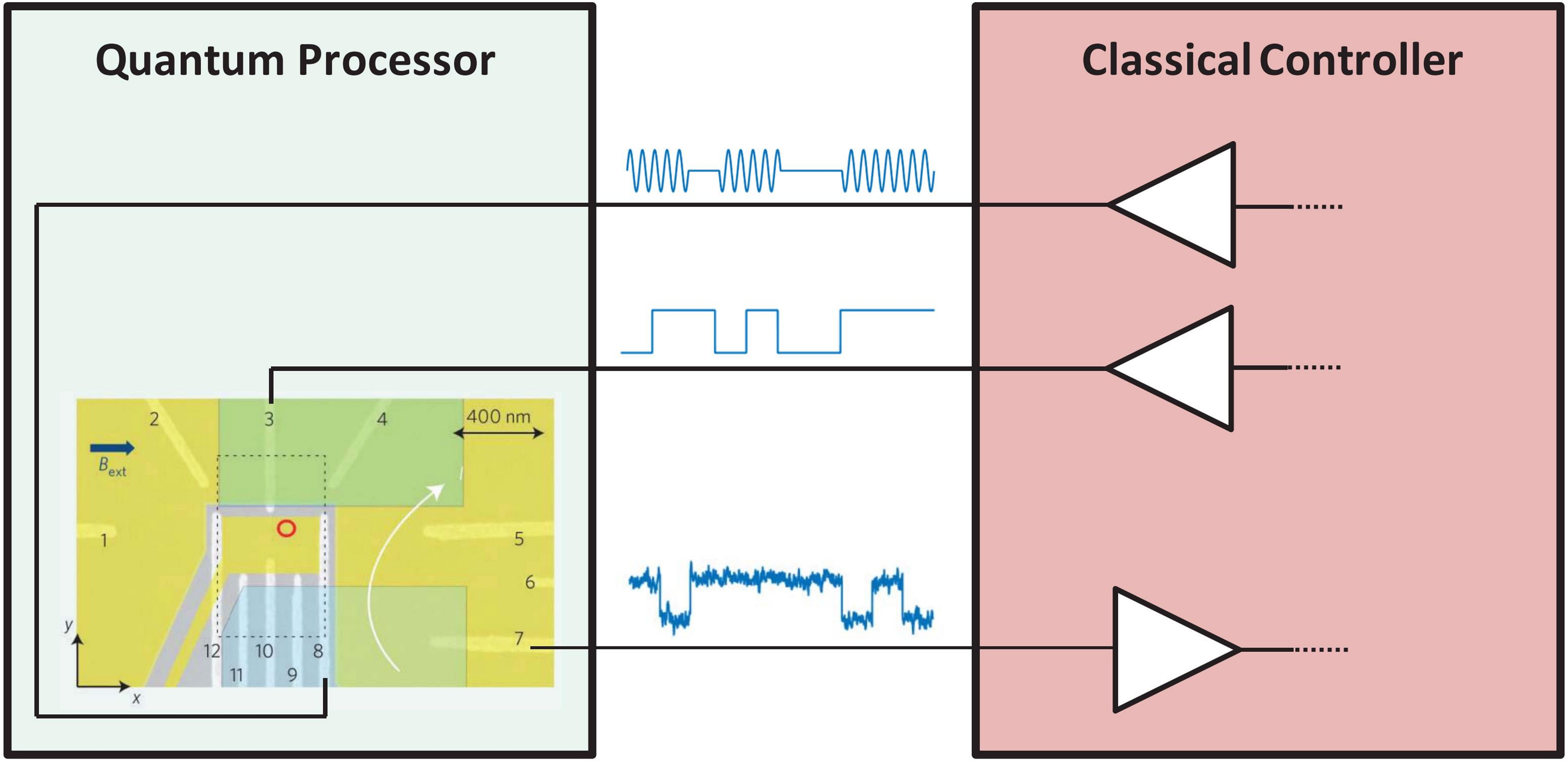
Quantum Systems Range in Size

- In configuring quantum machines, it is useful to know that **control components** have been made available in various sizes and formfactors.
- Control components for qubits can take up a lot of space, however an effort has been made to miniaturize them using Complementary Metal Oxide Semiconductor (CMOS) chips.

More Desktop-Like ⟷ ***More Server-Farm-Like**

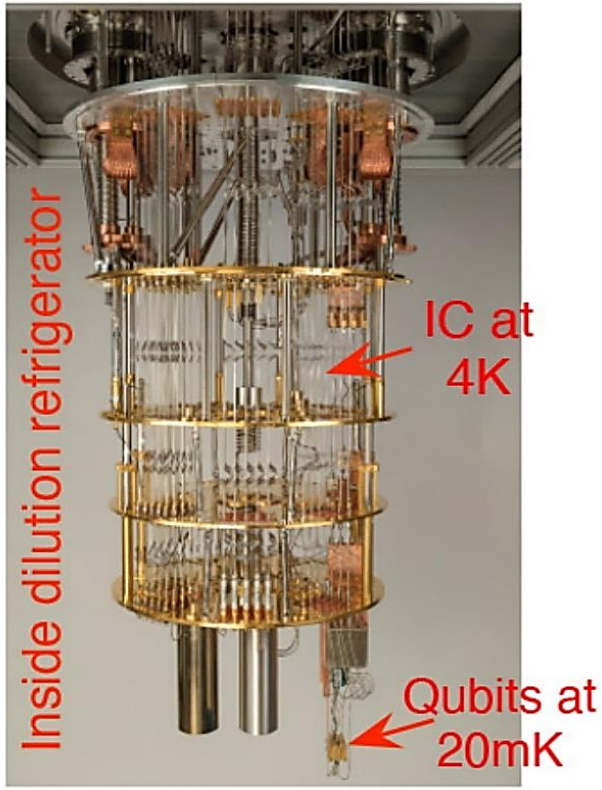
*Also called server-clusters

Generic Qubit Control System Configuration

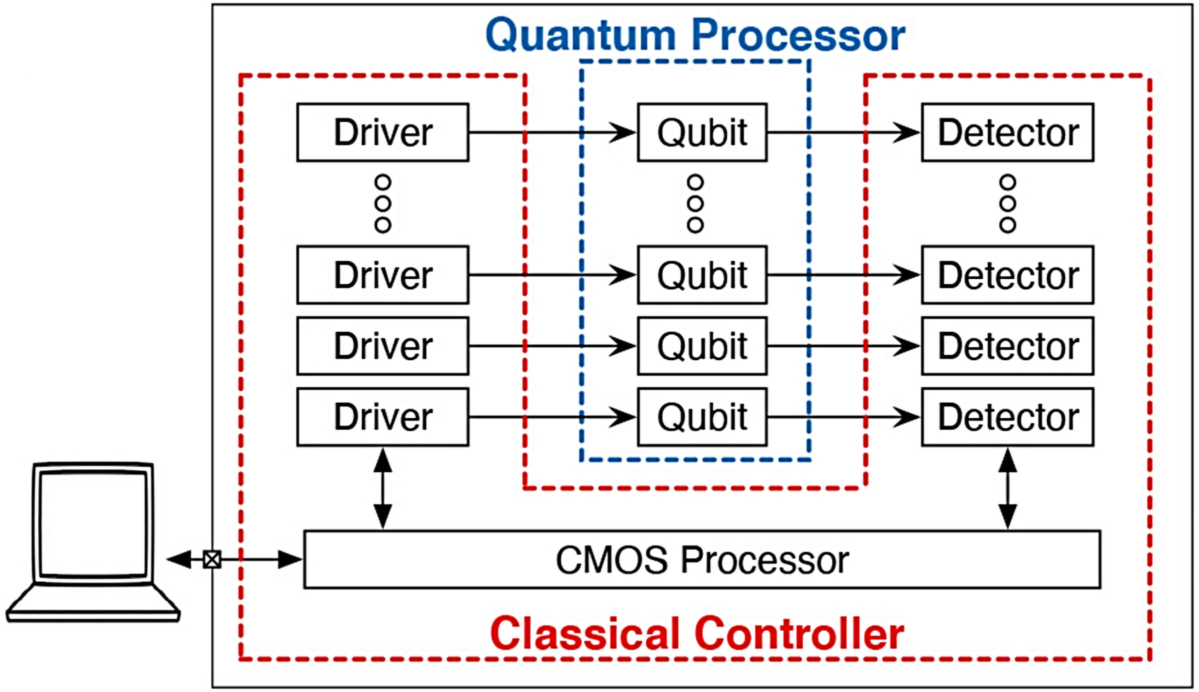


1. Patra et al., *IEEE JOURNAL OF SOLID-STATE CIRCUITS* (2018)

Intermediate Qubit Control System



Current state-of-the-art (controller + qubits = same chamber)

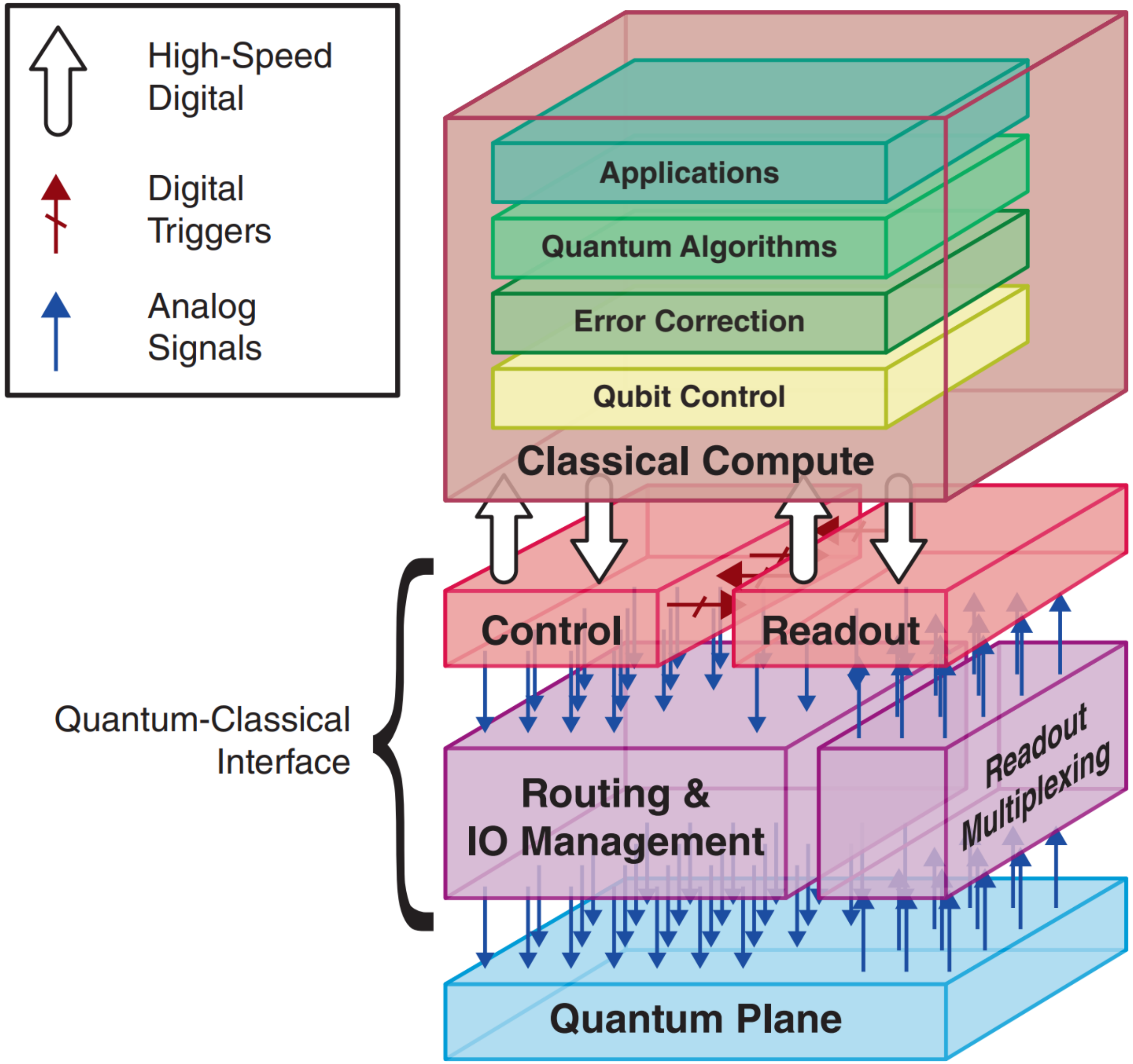


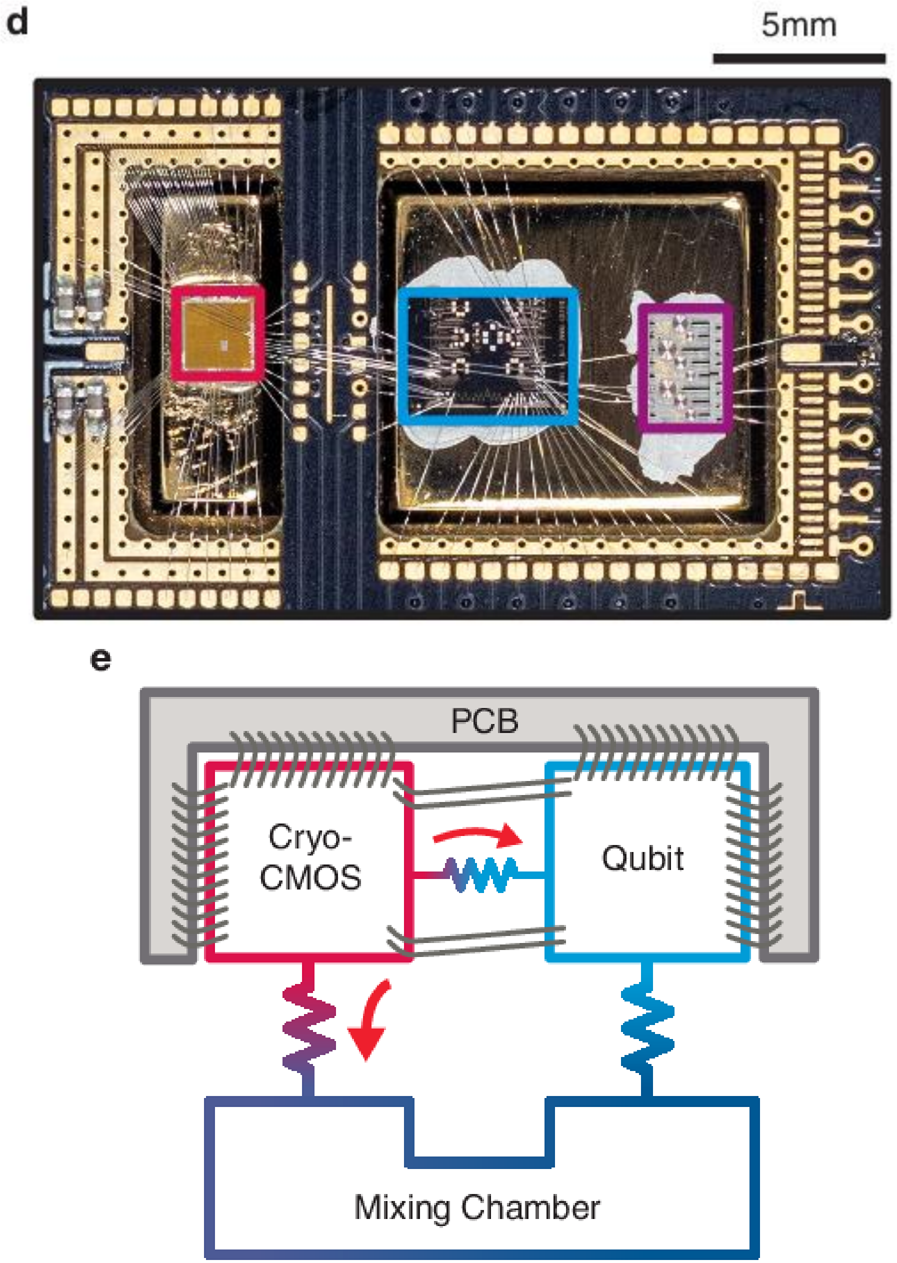
Single-Chip CMOS Quantum Computer (QCMOS)

Cryocooler by Montana Instruments (desktop size)

1. Staszewski et al., *IEEE Open Journal of the Solid-State Circuits Society* (2022)

Co-Integration Qubit Control System



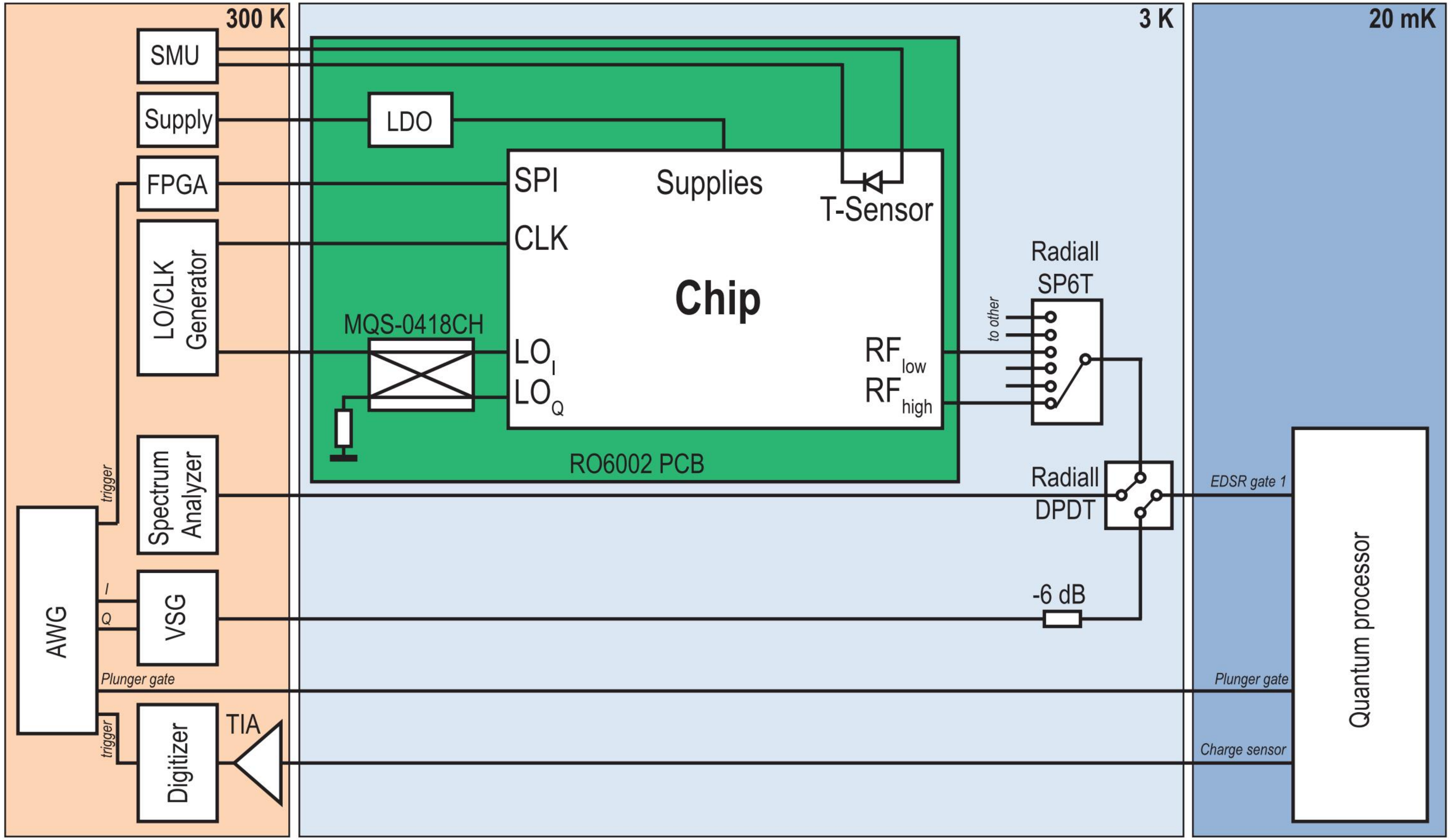


1. Microsoft Research (2021)

Example of Cryo-CMOS Qubit Measurement Setup

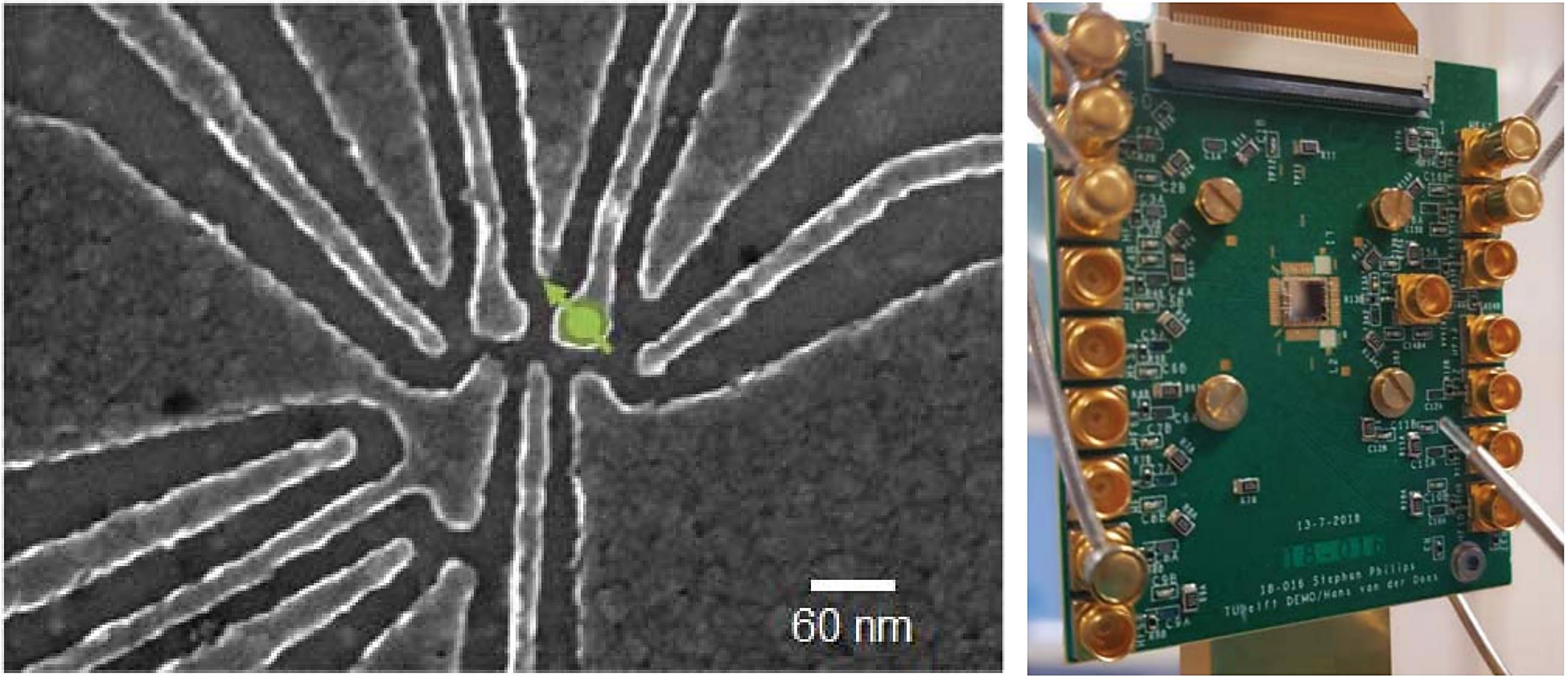
Chip at 3 K plate

Qubit at 10 mK



1. Dijk et al., *IEEE JOURNAL OF SOLID-STATE CIRCUITS* (2020)

Example of Cryo-CMOS Qubit Measurement Setup

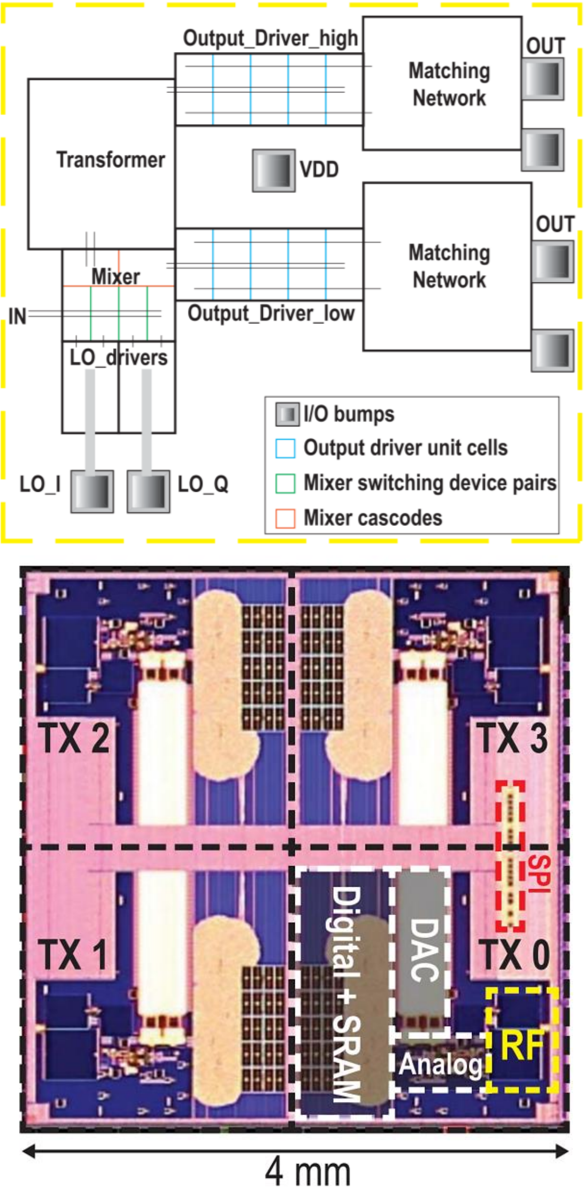


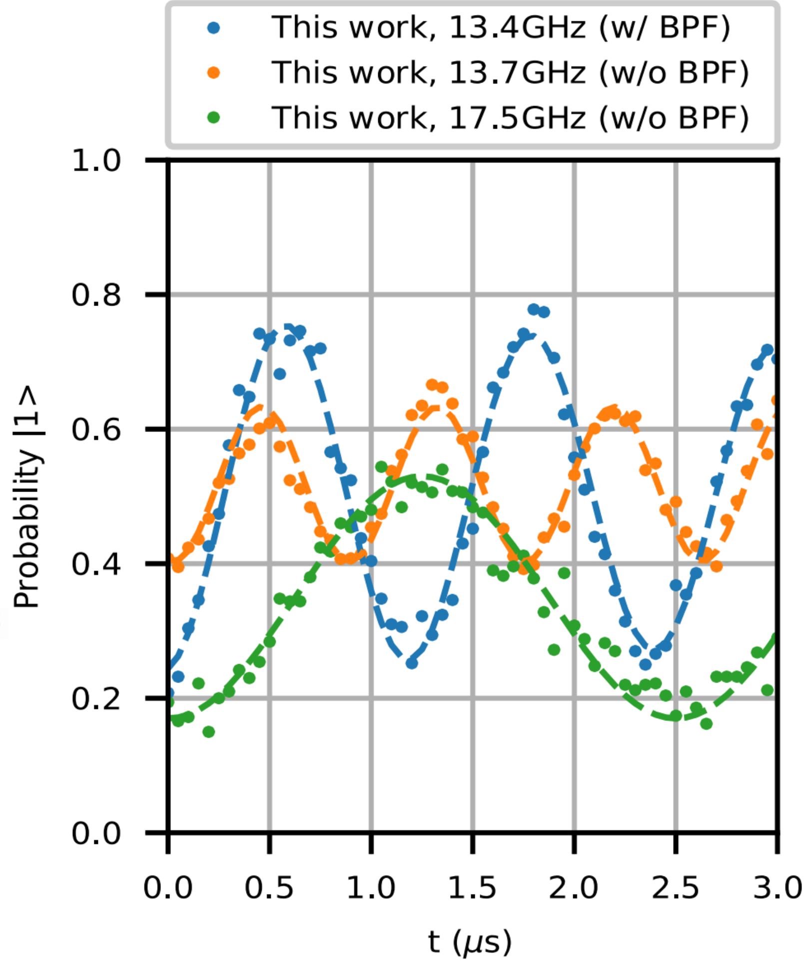
(a) (b)

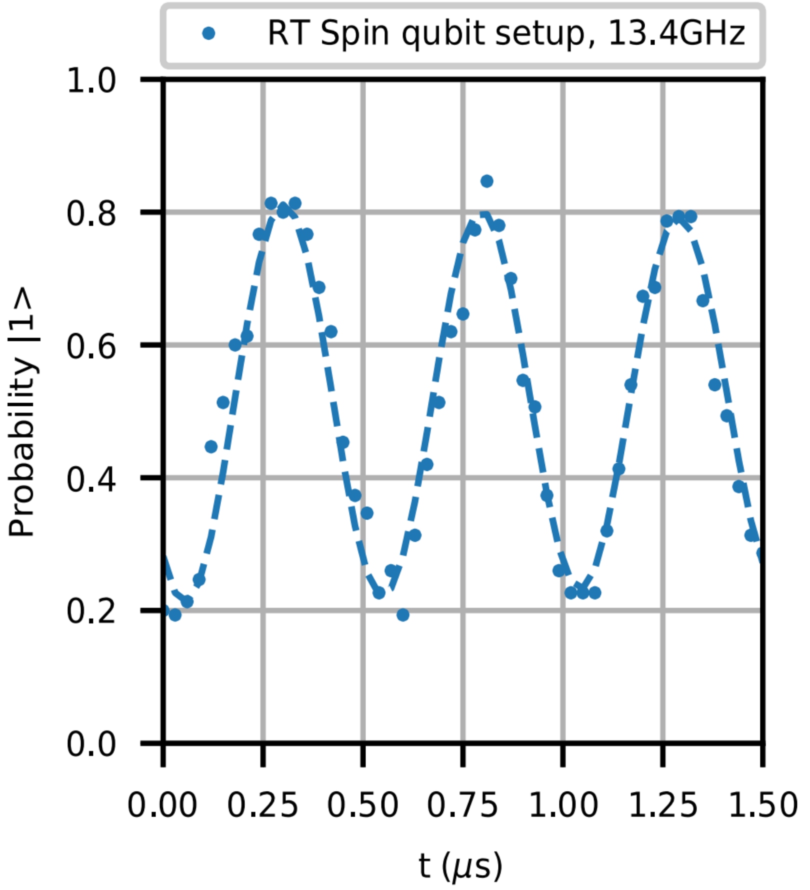
Fig. 21. (a) SEM image of a single spin qubit device. (b) PCB hosting the qubit chip.

1. Dijk et al., *IEEE JOURNAL OF SOLID-STATE CIRCUITS* (2020)

Example of Qubit Readout Using Cryo-CMOS







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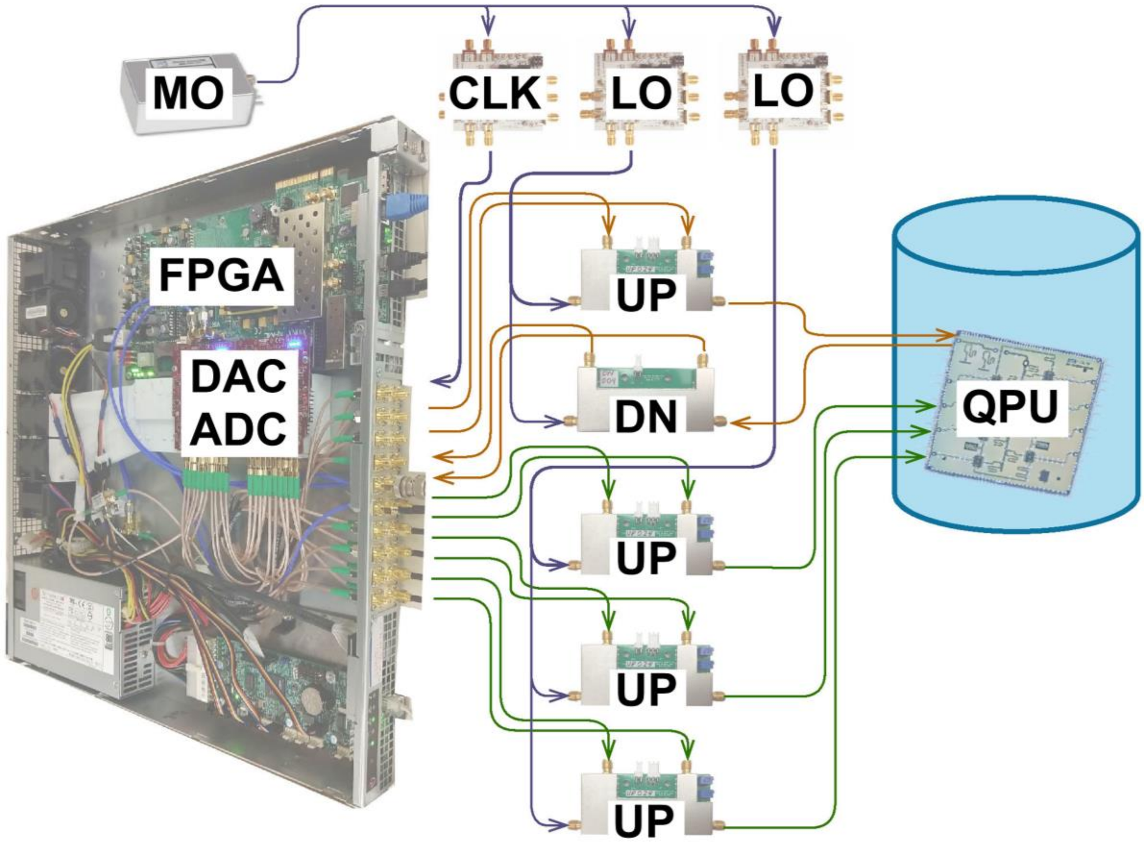
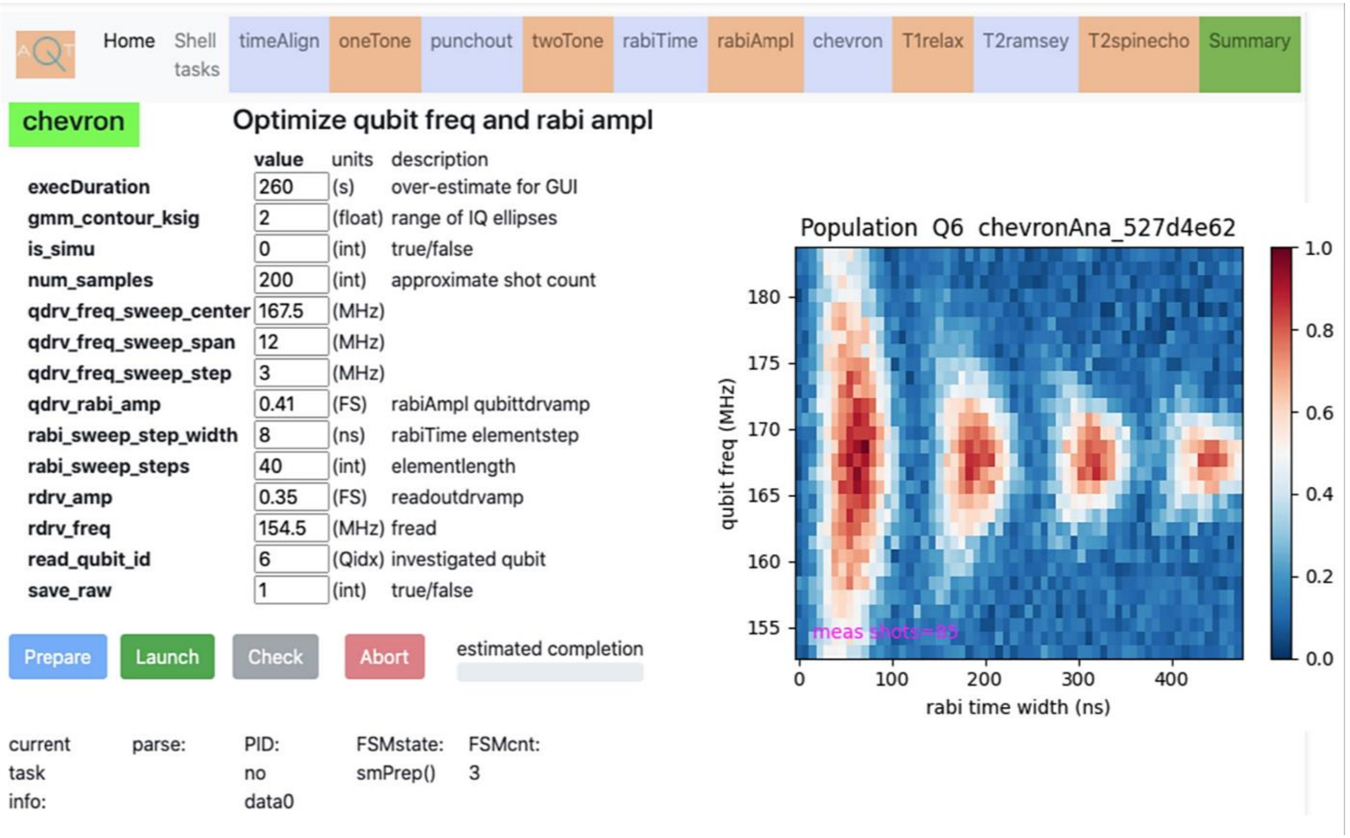
1. Dijk et al., *IEEE JOURNAL OF SOLID-STATE CIRCUITS* (2020)

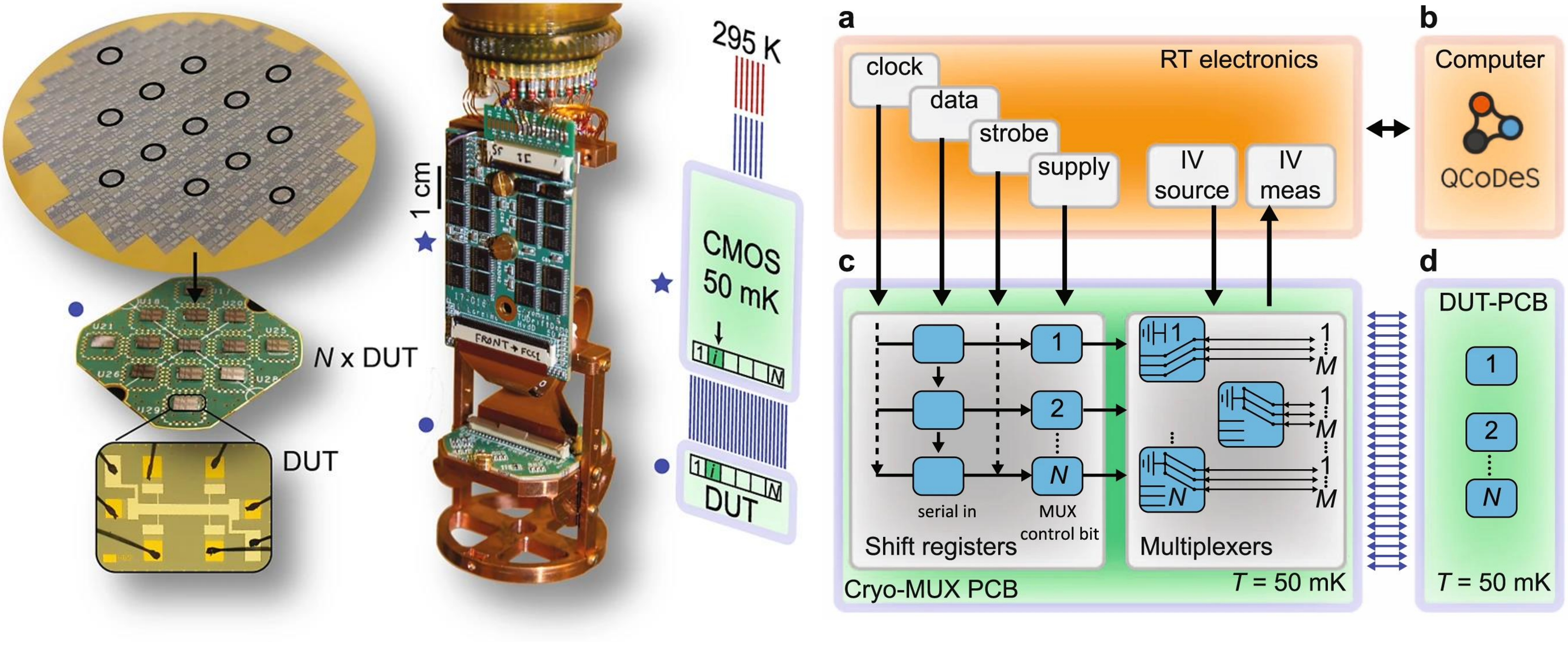
FPGA-Based Control of Quantum System





1. Xu et al., *IEEE Transactions on Quantum Engineering* (2021)

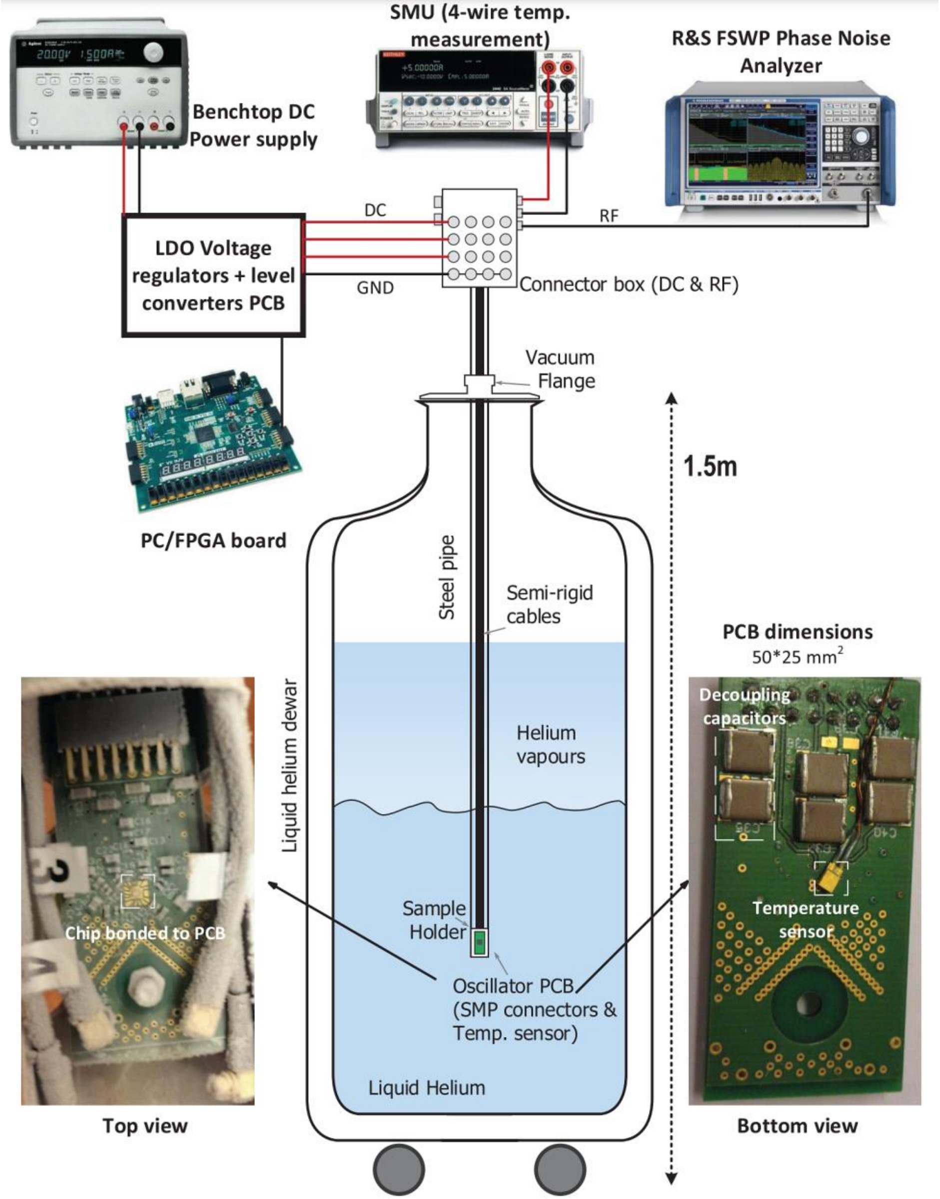
Commercial Cryo-CMOS Multiplexer Control of Qubits

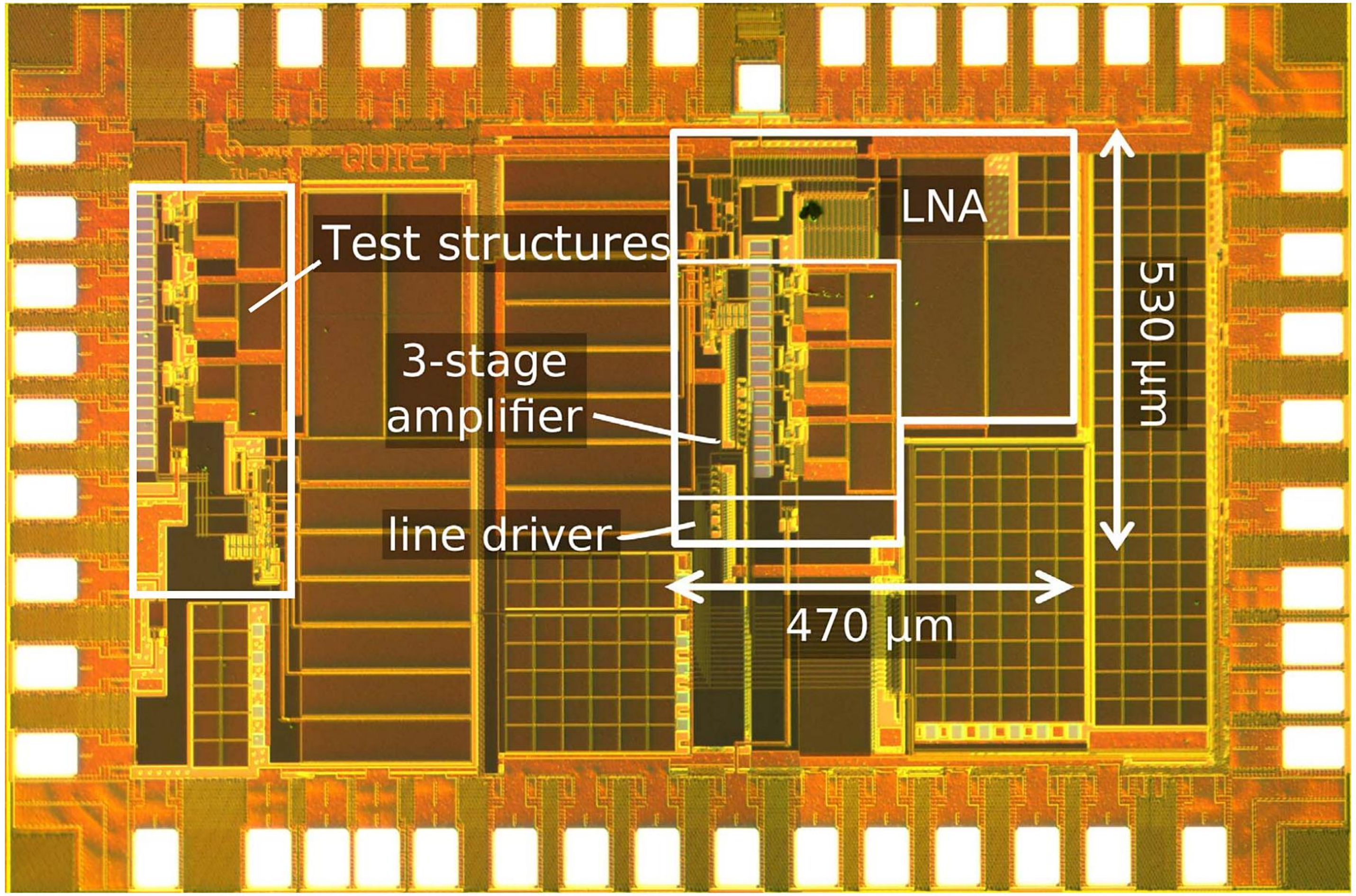


*DUT: Device Under Test

1. Paquelet Wuetz et al., *npj Quantum Inf* (2020)

FPGA & Cryo-CMOS Control of Qubits





1. Patra et al., *IEEE JOURNAL OF SOLID-STATE CIRCUITS* (2018)

*LNA: Low Noise Amplifier

Comparison of Cryogenic Interface Electronics

		This Work	ISSCC'22 [24]	ISSCC'21 [16]	VLSI'21 [23]	ISSCC'20 [17]	JSSC'19 [8]
Operating Temperature		3.5 K	3 K	4 K	77 K	3 K	3 K
Qubit Platform		Transmons	Transmons	Spin Qubits	Transmons	Spin Qubits	Transmons
Target fidelity		99.99% (expected)	N/A	99.99%	N/A	99.99%	99.99%
Power	Analog	Modulator: 8.3 mW[a] Readout: 20 mW/channel	Modulator: 11.4 mW[a]	Modulator: 40.1 mW[a] Readout: 10.6 mW/qubit	Modulator: 5.5 mW[a]	Modulator: 28.5 mW[a]	Modulator: 2 mW/qubit[a]
	Digital	3.8 mW @1.25 GHz	11.6 mW @1 GHz	10-140 mW[b] @1.6 GHz	2.6 mW @1 GHz	330 mW @1 GHz	N/A
Freq. Range		4.6–8.1 GHz @>-17 dBm	4.5–5.5 GHz @>-19 dBm	11-17 GHz @ >-10 dBm	2–7 GHz @>-28 dBm	2-20 GHz @ >-45 dBm	4-8 GHz
Multiplexing		Driver: 1 qubit Read: 8 qubits[d]	Driver: 1 qubit	Drive: 16 qubits[c,d] Read: 6 qubits[d]	Drive: 1 qubit	Drive: 32 qubits[c,d]	Driver: 1 qubit
LO Generation		Yes, PLL x 2	No, Off-Chip	No, Off-Chip	No, Off-Chip	No, Off-Chip	No, Off-Chip
Sampling Rate		Up to 1.5 GS/s	Up to 1 GS/s	Up to 2.5 GS/s	Up to 2 GS/s	Up to 1 GS/s	Up to 1 GS/s
DRAG pulse		No	YES	YES	No	YES	No
Driver Integrated Jitter		< 140 fs	N/A	N/A	N/A	N/A	N/A
Chip Area		5.3 mm^2	1.6 mm^2/channel	16 mm^2	0.39 mm^2/channel	4 mm^2/channel	1.6 mm^2
Technology		40 nm Bulk CMOS	14 nm FinFET	22 nm FinFET CMOS	40 nm Bulk CMOS	22 nm FinFET CMOS	22 nm Bulk CMOS

1. Kang et al., *IEEE JOURNAL OF SOLID-STATE CIRCUITS* (2022)

Example of Qubit Waveforms Converted to Music

Quantum Sound premiered on June 14, 2019, at Firehouse 12, a jazz concert hall and recording studio during the 24th International Festival of Arts and Ideas of New Haven, CT (USA). Spencer, Kyle, and Luke performed two back-to-back 35-minute musical sets, preceded by a 15-minute introduction to the quantum physics behind the performance, and followed by a 10-minute question-and-answer session between the audience and the artists.

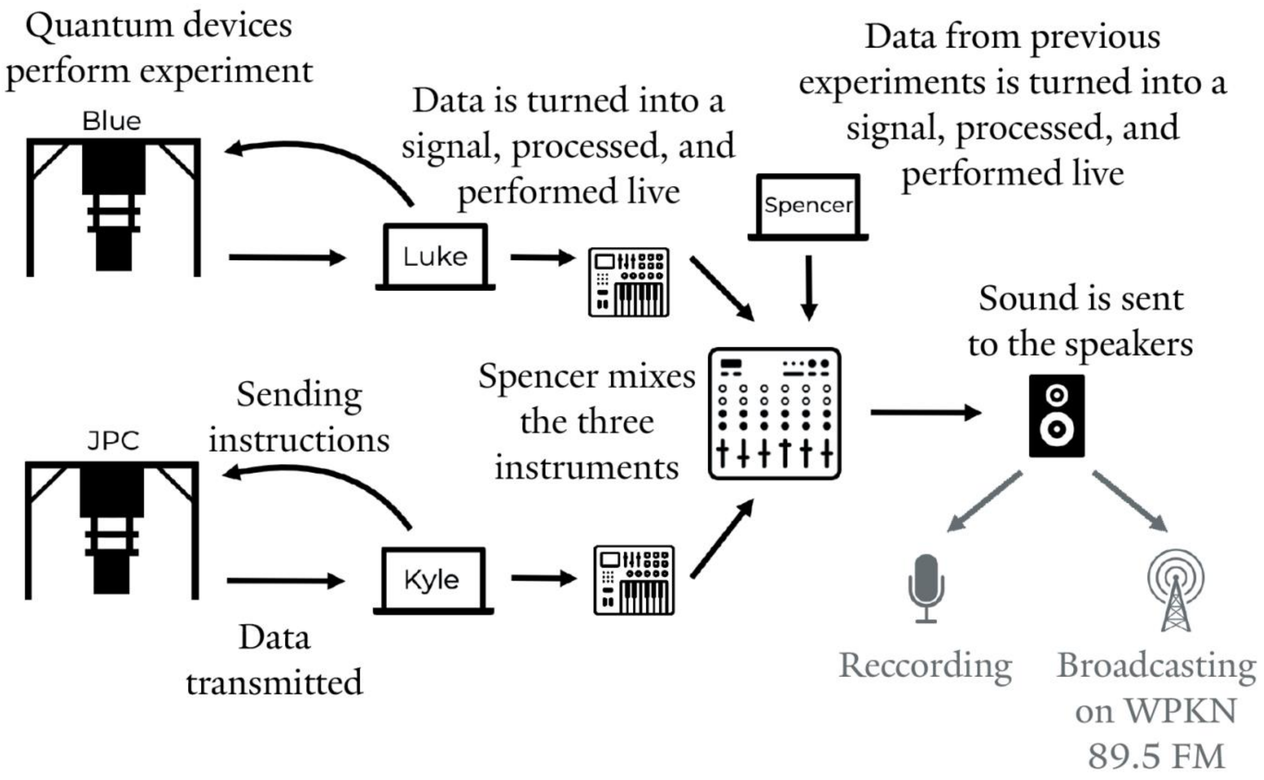
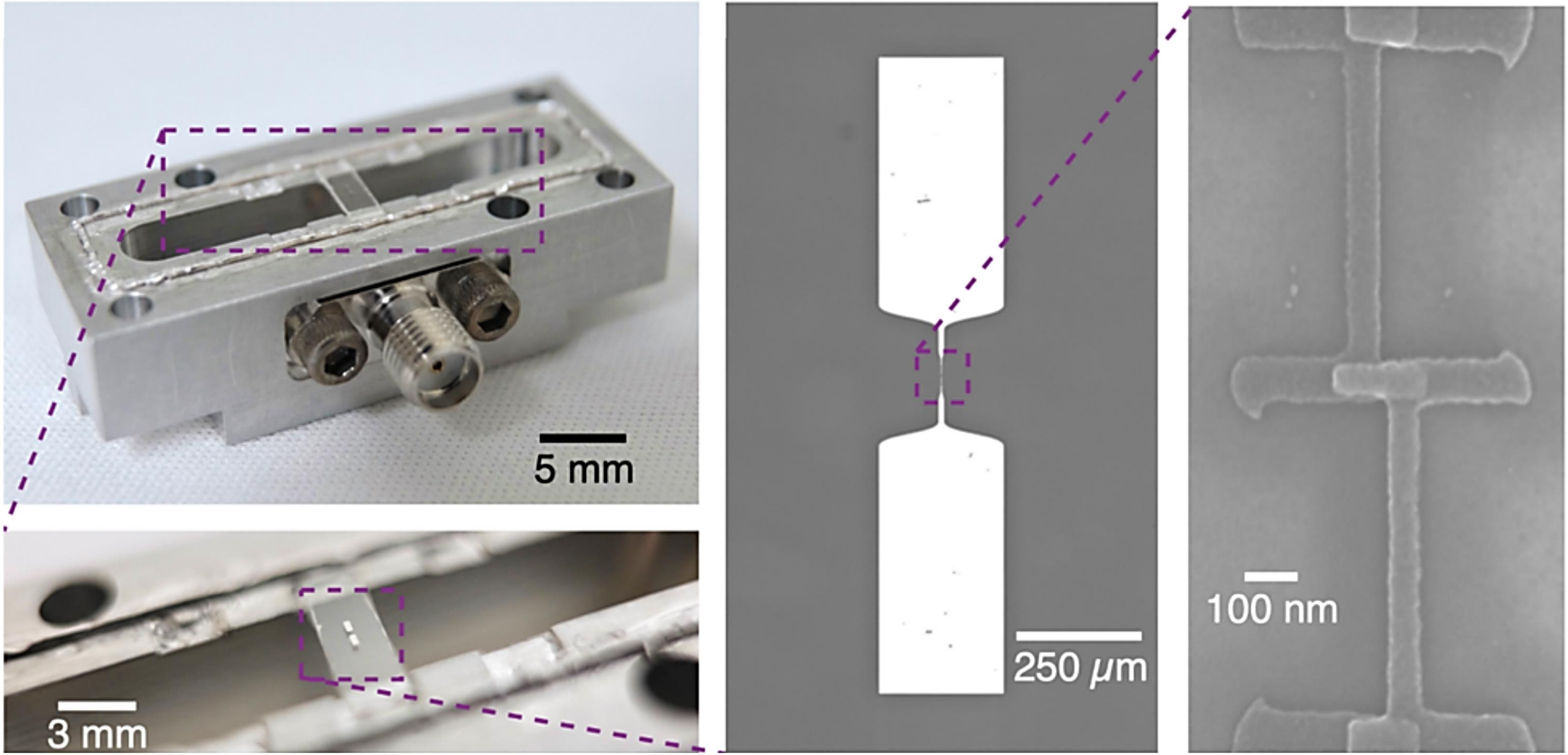


Figure 8 *- Diagram of data acquisition and process during the live performance to transform quantum signals into an audible musical experience.*

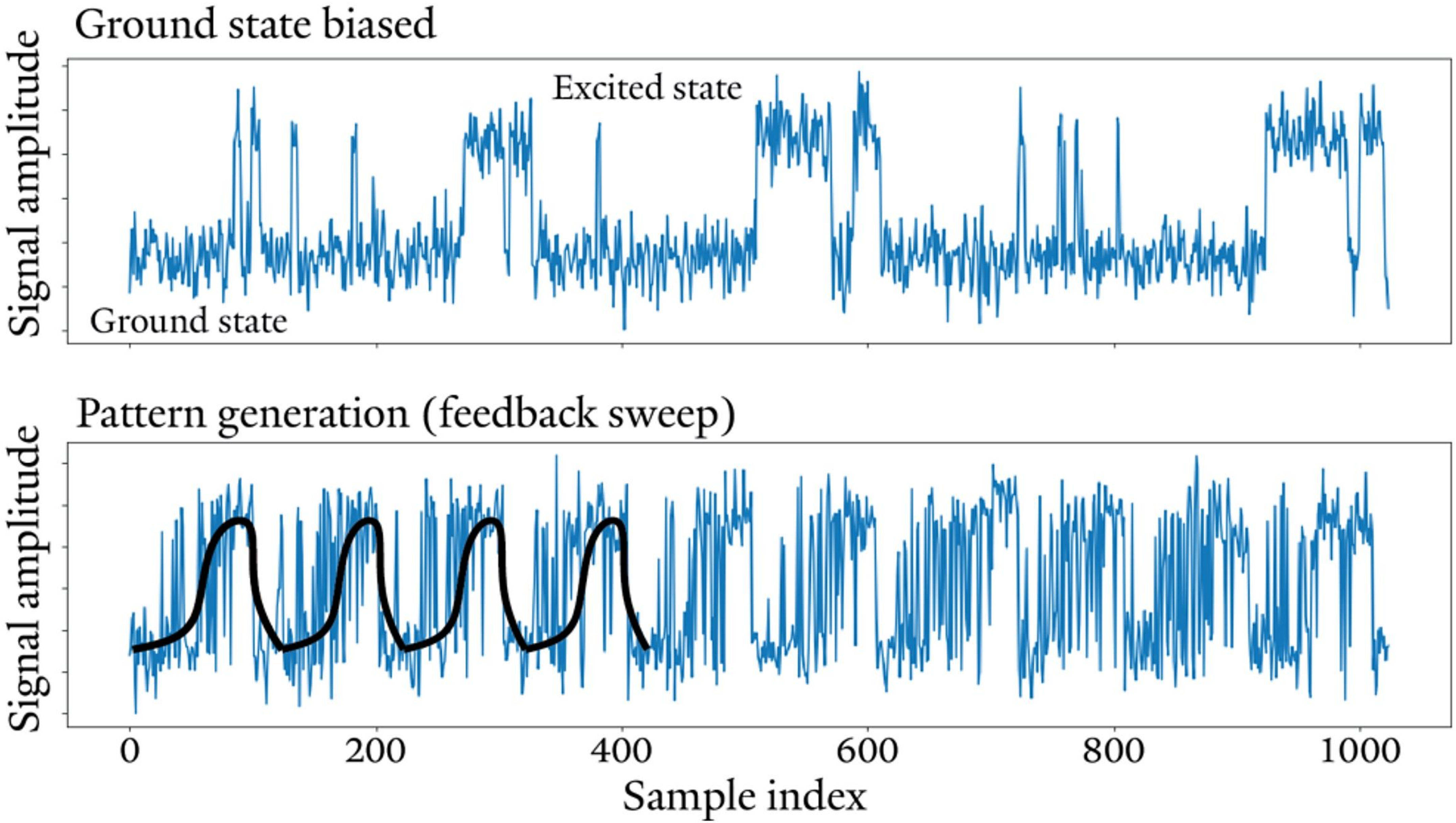
1. Topel et al. *arXiv* (2022)

Example of Audio Frequency Qubits Used in Music



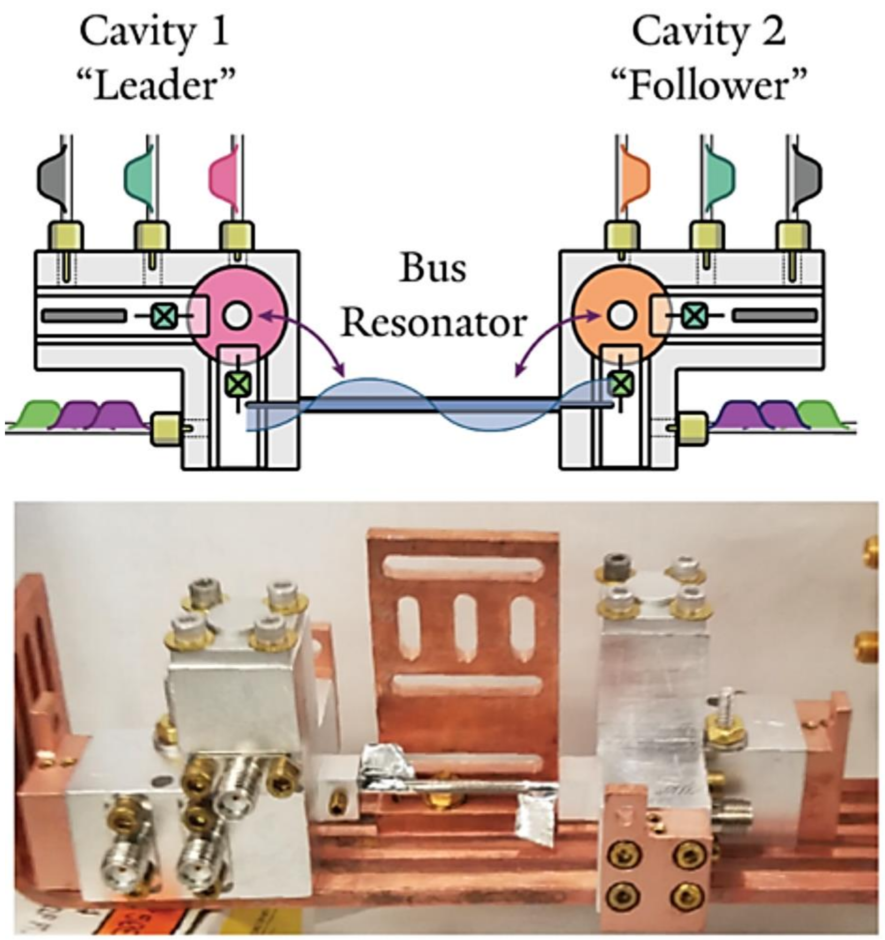
1. Topel et al. *arXiv* (2022)

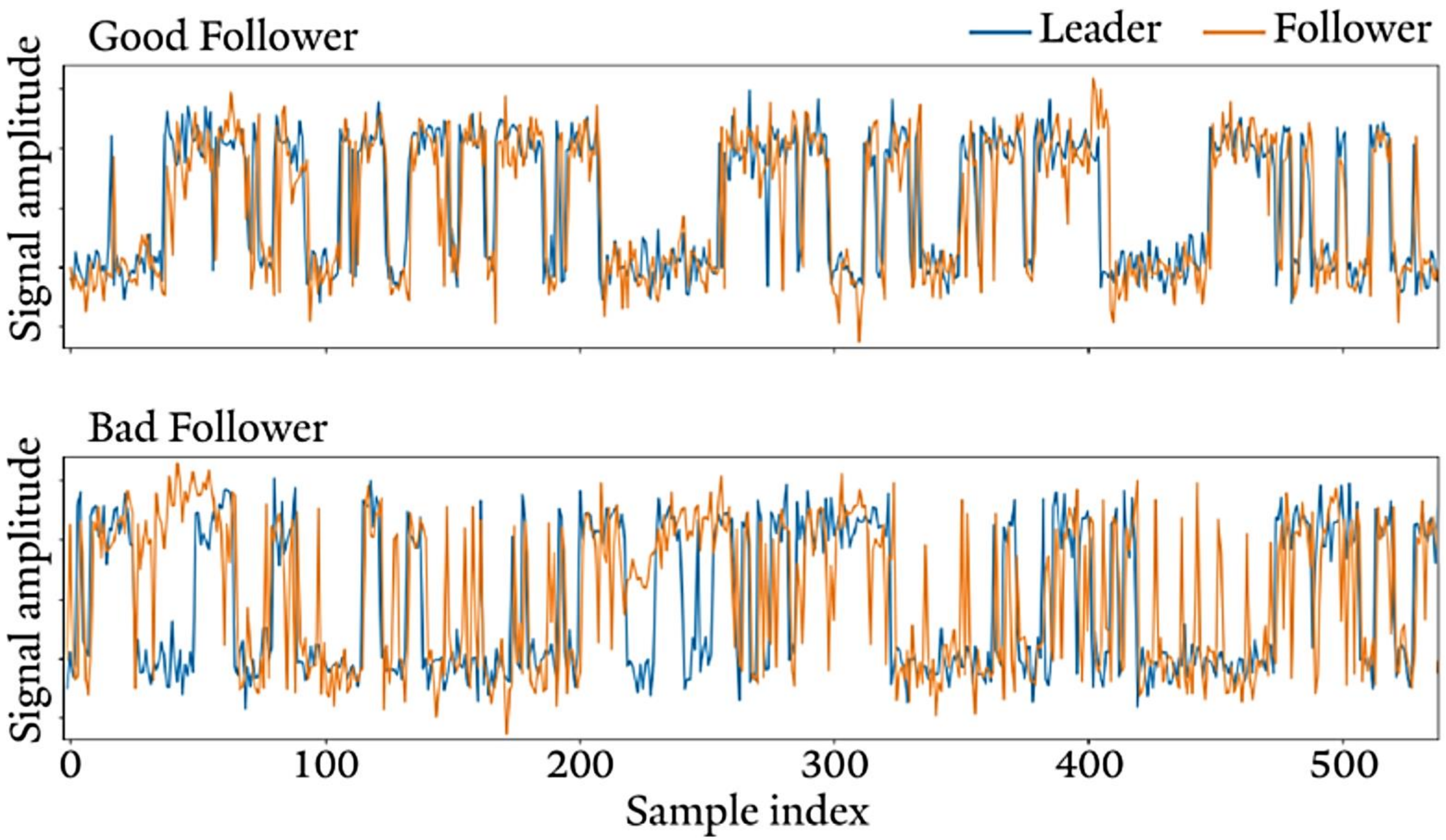
Example of Qubit Waveforms Converted to Music



1. Topel et al. *arXiv* (2022)

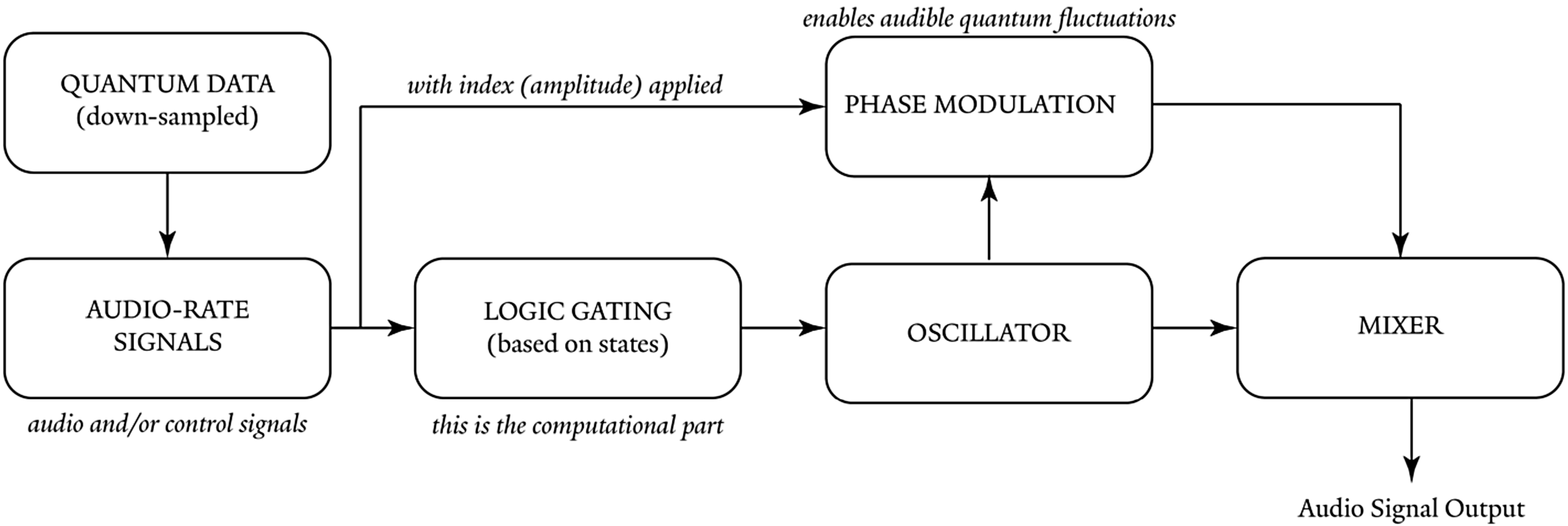
Example of Qubit Waveforms Converted to Music





1. Topel et al. *arXiv* (2022)

Example of Qubit Waveforms Converted to Music



Available for listening at: QuantumInstitute.yale.edu/Quantum-Sound

1. Topel et al. *arXiv* (2022)

Summary

- Qubits can be made of natural atoms or artificial atoms, controllable by signal pulses.
- The physical machine setup can be compared with audio or neuron stimulation technologies.
  - More or less.
- Operation of quantum systems can be automated with interfaces.
- Control hardware ranges from large analog cable to chip-based configurations.
  - This can be leveraged to miniaturize a quantum system.
- Thanks for tuning in.

Quantum Jobs

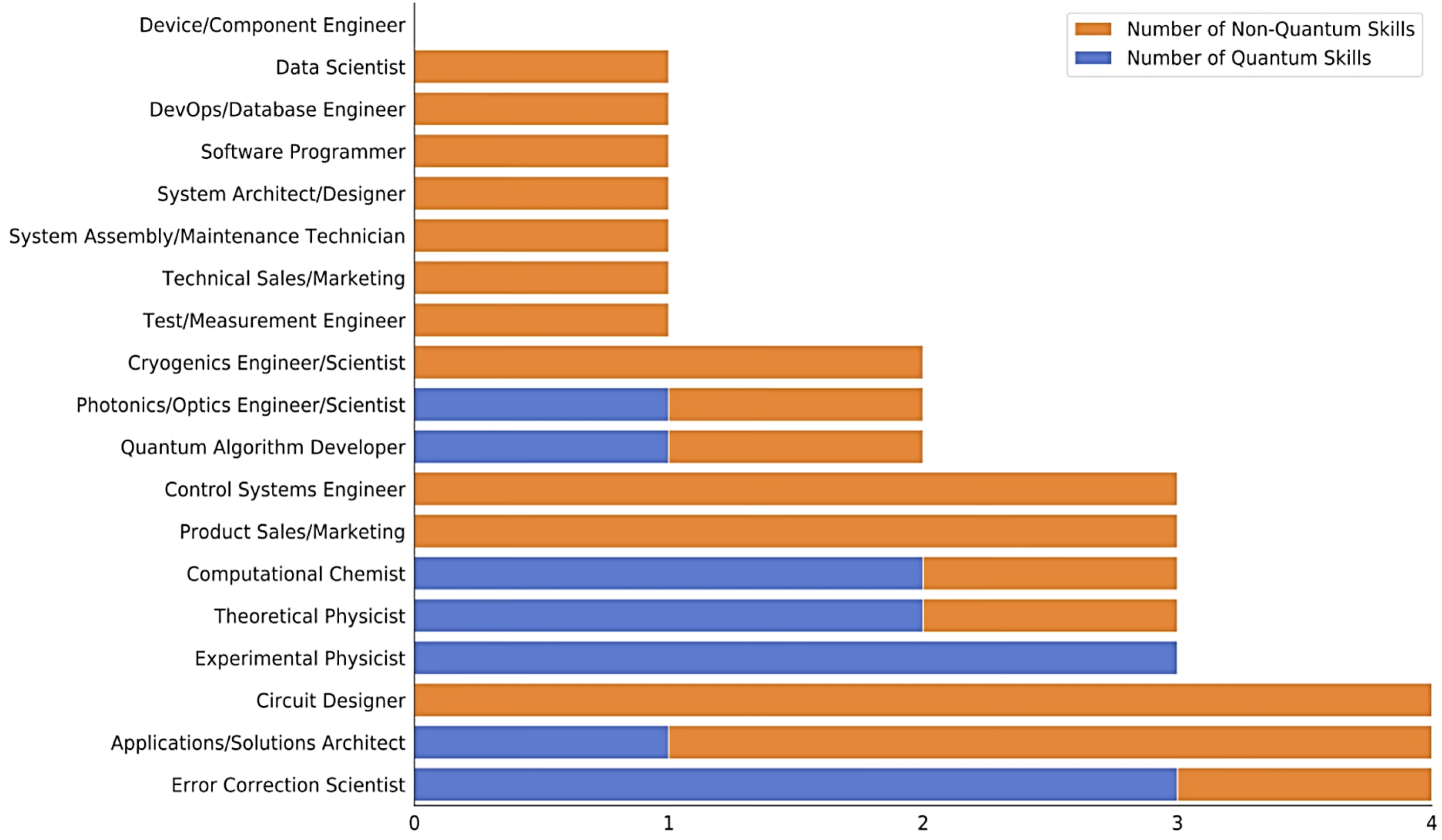


FIG. 2: The number of important quantum (blue) and non-quantum (orange) skills needed for each job type. Note that not all job types in the quantum workforce need important quantum skills, as discussed in the text.

Source: arXiv:2109.03601v1

Examples of Problems Solvable by Quantum Processors

Category	Applications	Value creation potential[1] ($B) Low	High
Cryptography ($40-$80B)	Encryption/decryption	$40	$80
Optimization ($100-$220B)	Aerospace: Flight route optimization	$20	$50
	Finance: Portfolio optimization	$20	$50
	Finance: Risk management	$10	$20
	Logistics: Vehicle routing/network optimization	$50	$100
Machine learning ($150-$220B)	Automotive: Automated vehicle, AI algorithms	$0	$10
	Finance: Fraud and money-laundering prevention	$20	$30
	High tech: Search and ads optimization	$50	$100
	Other: Varied AI applications	$80+	$80+
Simulation ($160-$330B)	Aerospace: Computational fluid dynamics	$10	$20
	Aerospace: Materials development	$10	$20
	Automotive: Computational fluid dynamics	$0	$10
	Automotive: Materials and structural design	$10	$15
	Chemistry: Catalyst and enzyme design	$20	$50
	Energy: Solar conversion	$10	$30
	Finance: Market simulation (e.g. derivatives pricing)	$20	$35
	High tech: Battery design	$20	$40
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1. Bobier et al., *BCG.* (2021)

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