Control Hardware Interfaces for Quantum Information Systems

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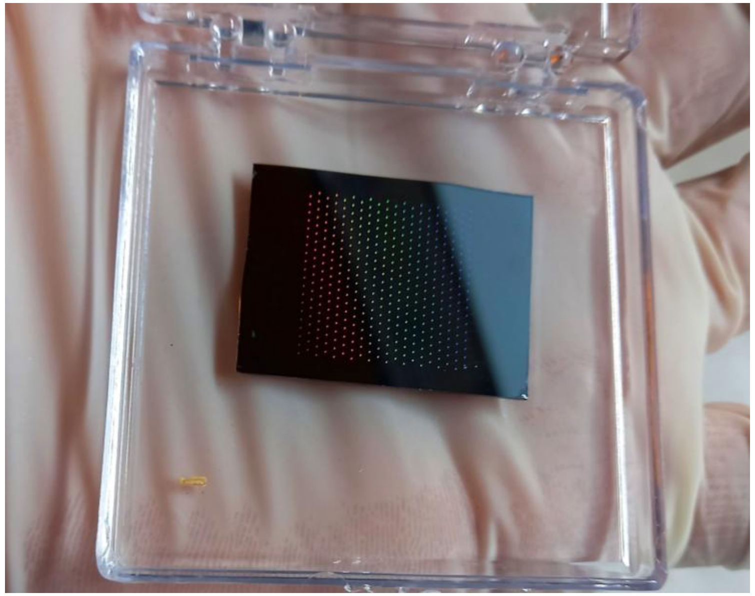
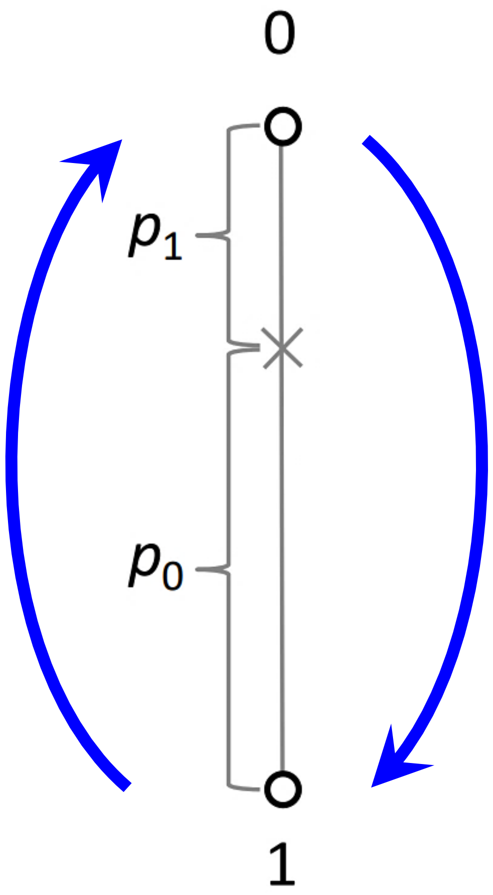
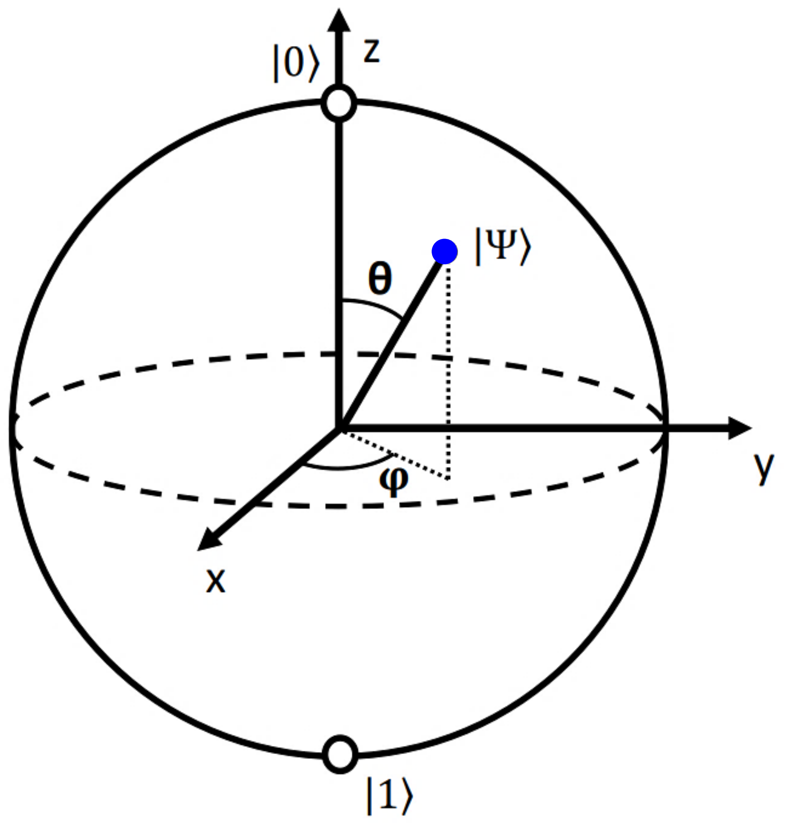


Onri Jay Benally, *400-Qubit Quantum Chip* (2023)

Deterministic vs. Probabilistic vs. Quantum Bits.





bits

binary digit

pbits

probabilistic bit

qubits

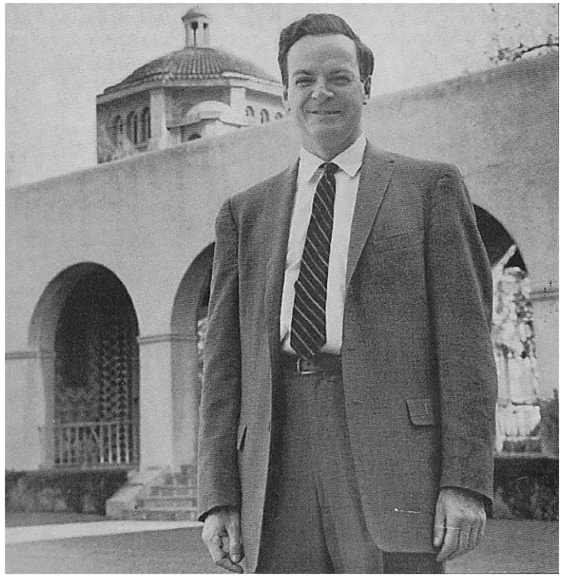
quantum bit

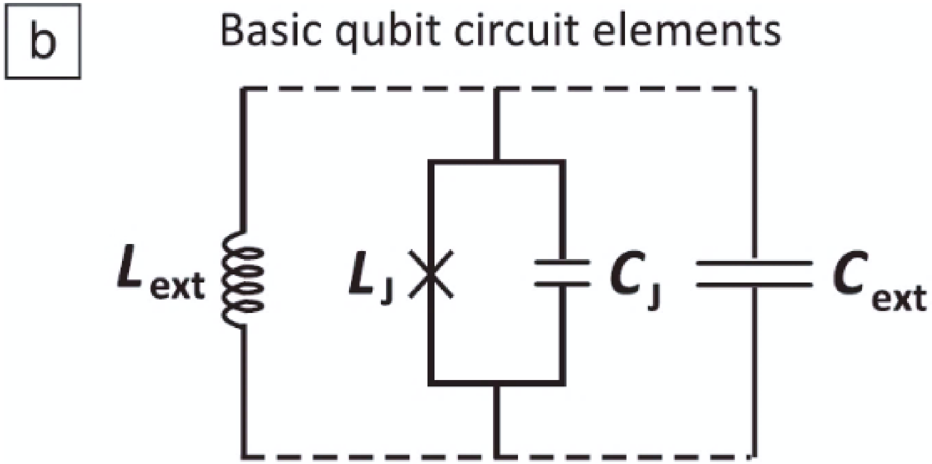
1. Ezratty, *Understanding Quantum Technologies* (2022)

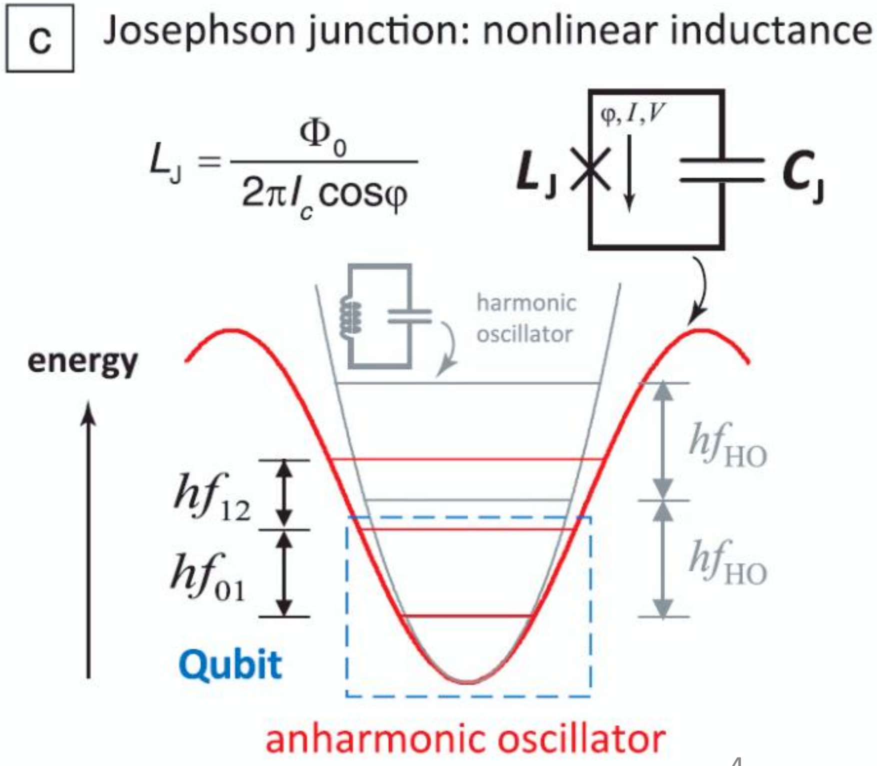
*normalized probabilities alternative

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.
- Qubit = matrix that can modify a vector (quantum state) = anharmonic oscillator.
- Physical qubits can consist of artificial atoms or be made of natural atoms.
- In quantum circuits, resonance frequencies (oscillator energy) = **computational bases**.



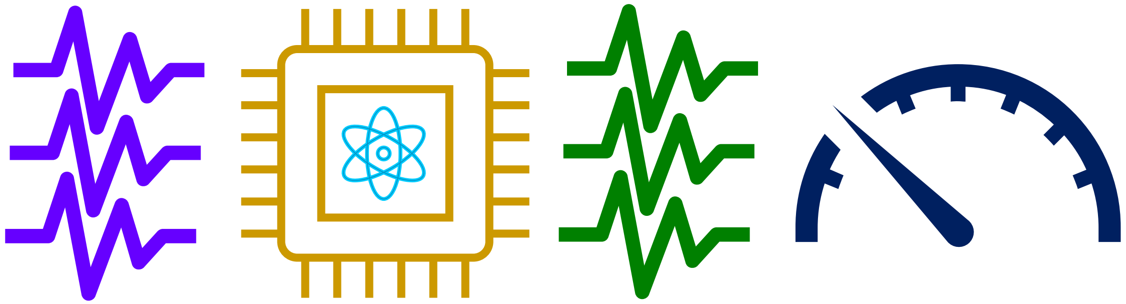




1. Feynman, *Int. J. Theor. Phys.* (1981)
2. Oliver et al., *Materials Research Society* (2013)
3. Wikimedia Commons

DiVincenzo Criteria (Standard for Quantum Computation)

- **Well-characterized** & **scalable** qubits.
- Qubit **initialization** (repeated & acceptable state preparation).
- Long **decoherence** times (retention of quantum properties).
- Universal set of **gates** (for arbitrary operations).
- **Measurement** capability of individual qubits (for readout of quantum algorithms).



1. DiVincenzo, *Fortschr. Phys.* (2000)

Overall Stress on The Energy Grid

Exascale-class HPE Cray EX: (21 MW)

US exascale system upgrade to Aurora: **60 MW** in 2023.

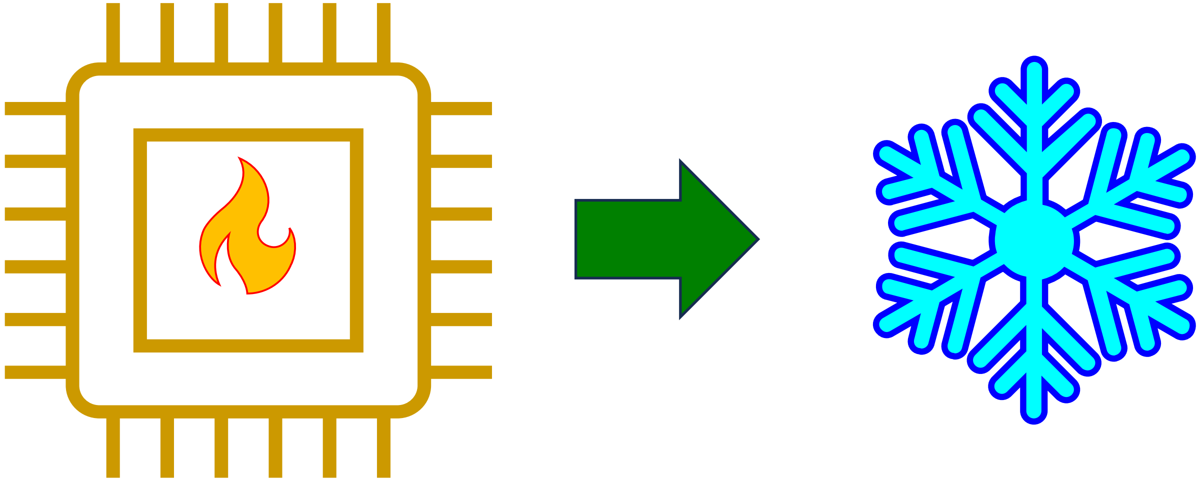
IBM Quantum System One: (<50 kW)

System Two upgrade: **<140 kW** in 2023

1. Oak Ridge National Lab 2. IBM Research 3. Ezratty, *arXiv* (2023)

Big Idea

Heat Management



A Bigger Picture

Exascale-class HPE Cray EX:
(21 MW)

US exascale system upgrade to Aurora: **60 MW** in 2023.

IBM Quantum System One:
(<50 kW)

System Two upgrade: **<140 kW** in 2023

By combining both systems & allocating the specific application, the energy cost can be justified, leading to a <u>new high-performance computation resource</u>:

Quantum Supercomputing

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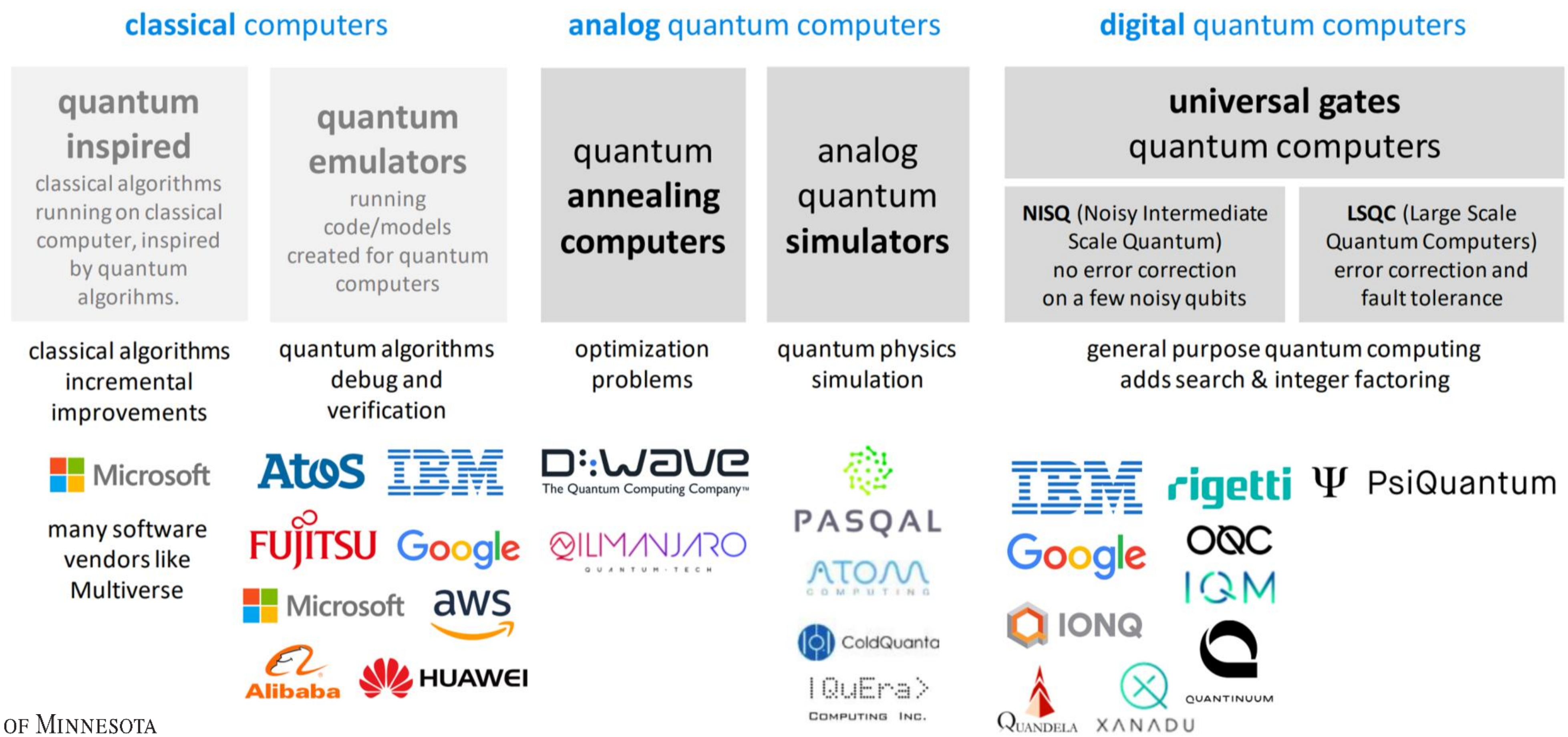
1. Oak Ridge National Lab 2. IBM Research 3. Ezratty, *arXiv* (2023)

Digital vs. Analog Quantum Computing

- **NISQ** = Noisy Intermediate Scale Quantum.
  - (Tends to contain zero to little error correction, aka **1:1 ratio** of logical:physical qubits).
- **FTQC** = Fault-Tolerant Quantum Computing.
  - (Implements passive or active quantum error correction into architecture).



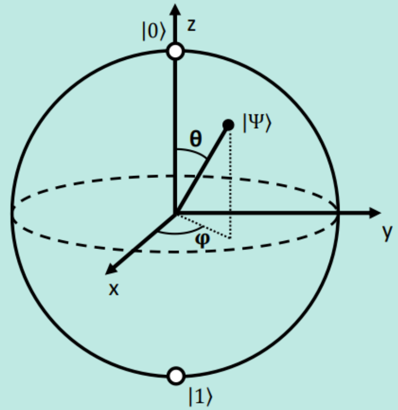
1. Ezratty, *arXiv* (2022)

Key Ideas for Quantum Information Systems

- Analog (quantum) computing = Involves a varying signal between 2 states rather than switching of states.
- Digital (quantum) computing = Involves switching of 2 or more basis states.

Direct Variable vs Continuous Variable encoding of quantum information

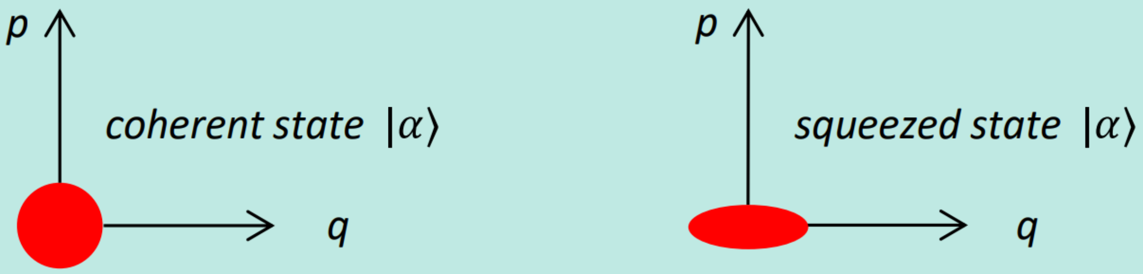
DV: encoding in qubits



Discrete basis : $|\Psi\rangle = \alpha|0\rangle + \beta|1\rangle$

Finite-dimentional Hilbert space

CV: encoding in continuous states, e.g. eigenstates of electromagnetic field quadratures $\hat{q}, \hat{p}$



Continuous basis : $|\Psi\rangle \propto \int d^2\alpha\psi(\alpha)|\alpha\rangle$

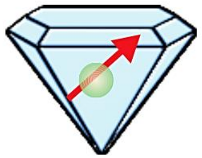
Infinite-dimentional Hilbert space

*abstract space of possibilities **reduced quantities exist as well

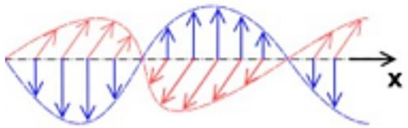
1. Ezratty, *arXiv* (2022)

Discrete vs. Continuous Variable Quantum Computing

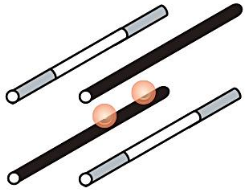
Discrete-Variable



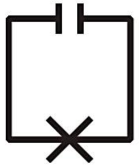
Diamond NV centers



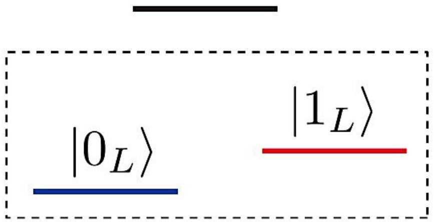
Photon Polarisation



Trapped Ion

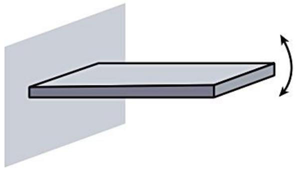


Superconducting Circuit

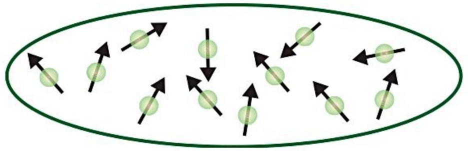


Finite individually addressable states

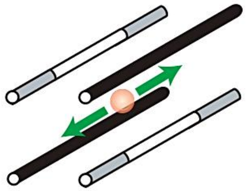
Continuous-Variable



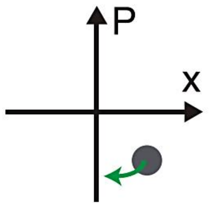
Mechanical Oscillator



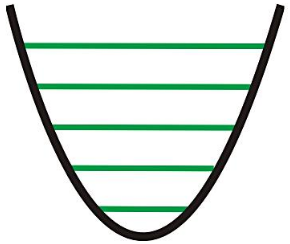
Spin Ensemble



Ion Motion



Optical Mode



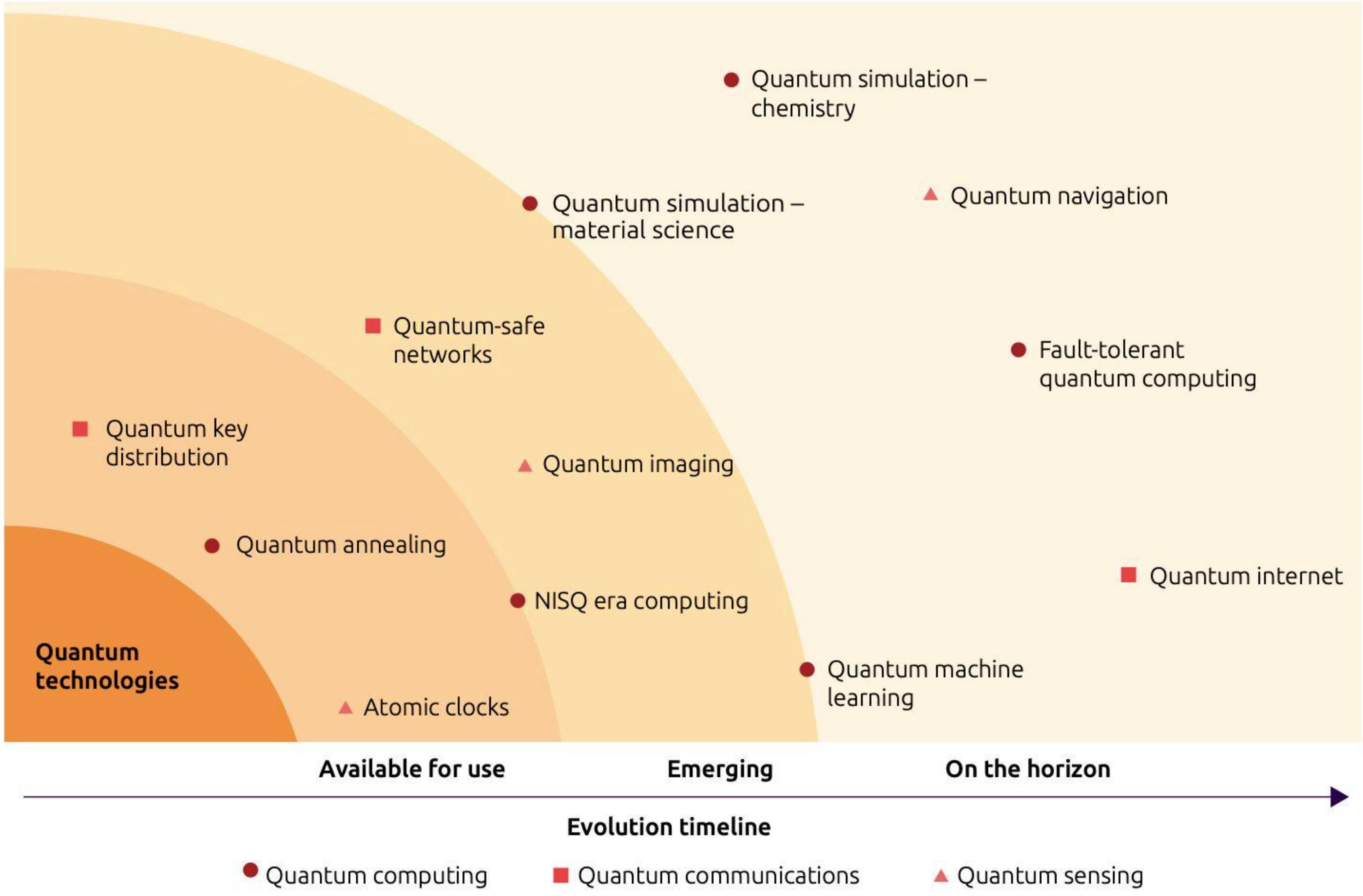
$|0_L\rangle$?

$|1_L\rangle$?

Infinite non-individually addressable states

1. Ezratty, *arXiv* (2022)

Examples of Problems Solvable by Quantum Processors

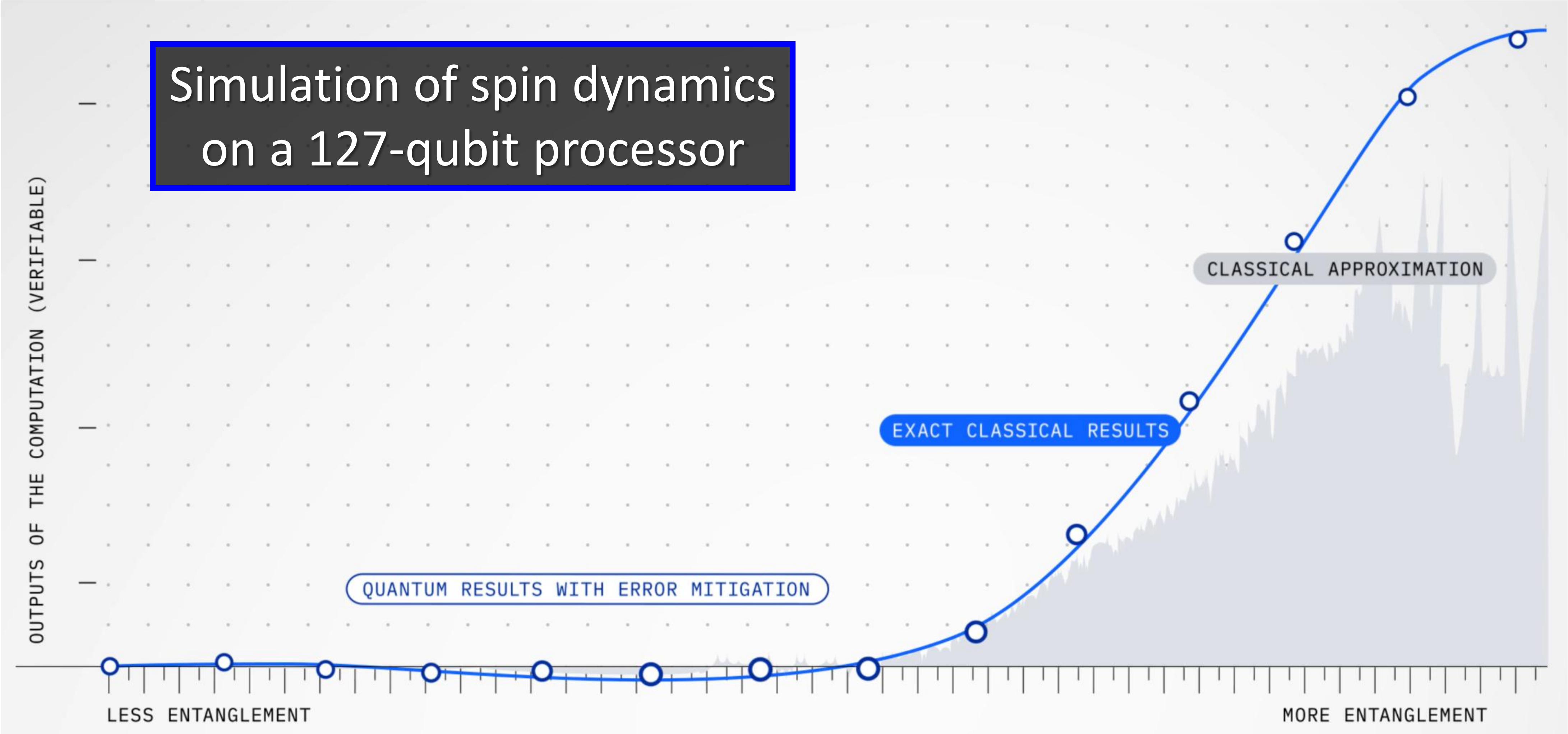


Source: Capgemini Research Institute analysis.

Definitions of stages:
Available for use: Ready to be deployed in a limited way to at least one commercial application.
Emerging: several proofs of concept developed, but not ready for commercial deployment.
On the horizon: At proof-of-principle stage; requires several technical breakthroughs to advance to the next stage.

1. Capgemini Research Institute

Recent News in High Performance vs. Quantum Computation



- Y-axis represents accuracy, both axes are in arbitrary units (A.U.)
- Exact classical results are analytical calculations (simplified model)
- Classical approximation results are numerical calculations performed on a supercomputer

1. IBM Research

Quantum Algorithms to Target Problems

Variational Quantum Algorithms

VQE — **quantum physics simulations** (chemistry, condensed matter, …). variational quantum eigensolvers are hybrid algorithm using variational methods to find the lowest energy state of a given Hamiltonian. So far done with 2 to 3 atoms molecules.

QAOA — **optimization applications** hybrid algorithm using variational methods to find approximate solutions to combinatorial optimization problems. Includes integer factoring.

VQLS — **variational quantum linear solver** used in machine learning and to solve partial differential equations.

QML — **machine learning**. variational quantum circuit learning, quantum support vector machines, quantum neural networks, and quantum principal component analysis. Better explore solution space.

most studied NISQ avenues

large depth algorithms

QFT based — **quantum phase estimates** used in chemical simulations, HHL for **linear algebra**, quantum machine learning, partial differential equations, etc.

search — **oracle based search** algorithms like Grover, **quantum walks**, hidden subgroup problems, TSP, …

factoring — **Shor integer factoring and dlog** algorithms

FTQC algorithms

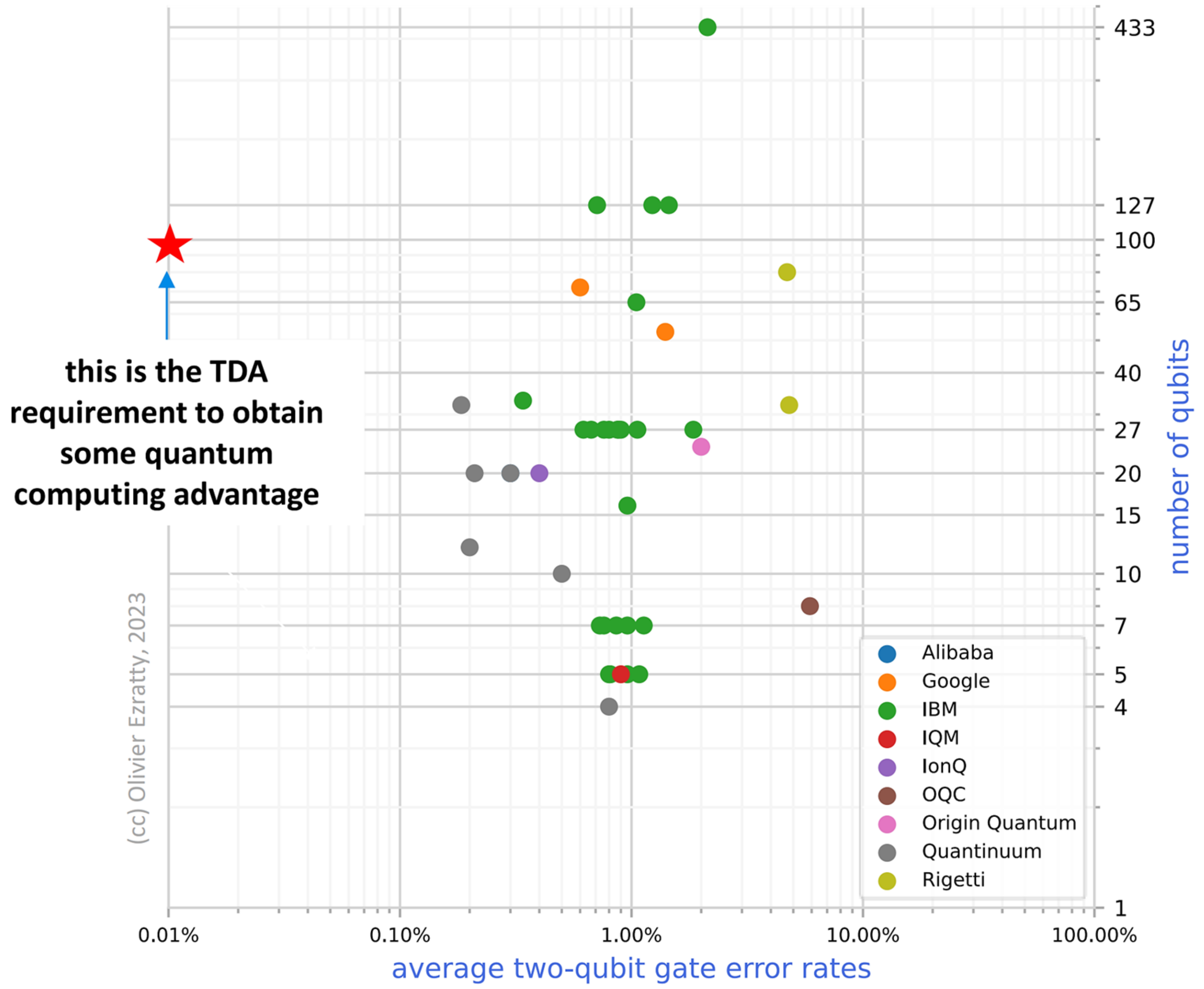
1. Ezratty, *arXiv* (2023)

NISQ Gate-Based Hardware Resource Requirements

		NISQ	FTQC
Physical qubit numbers		50-1000s	9000-Millions
Algorithmic qubit error rates ϵ		$10^{-3} \leq \epsilon \leq 10^{-7}$	$10^{-5} \leq \epsilon \leq 10^{-15}$
Required physical qubit fidelities		99.9% to 99.99999%	≈99.9%
Error processing techniques		Quantum error suppression	
		Quantum error mitigation	Quantum error correction
Algorithms	VQE, QAOA, QML	Yes	Yes
	Oracle-based search	No	Yes
	QFT-based	No	Yes (HHL, Shor, …)
Qubit challenges		Average # to create very high-fidelity qubits	Very large set of entangled qubits w/ good fidelities
Other challenges		Error mitigation scaling, # of Pauli strings, & shots w/ VQE	Quantum memory/ qRAM, error correction, & overhead energetics

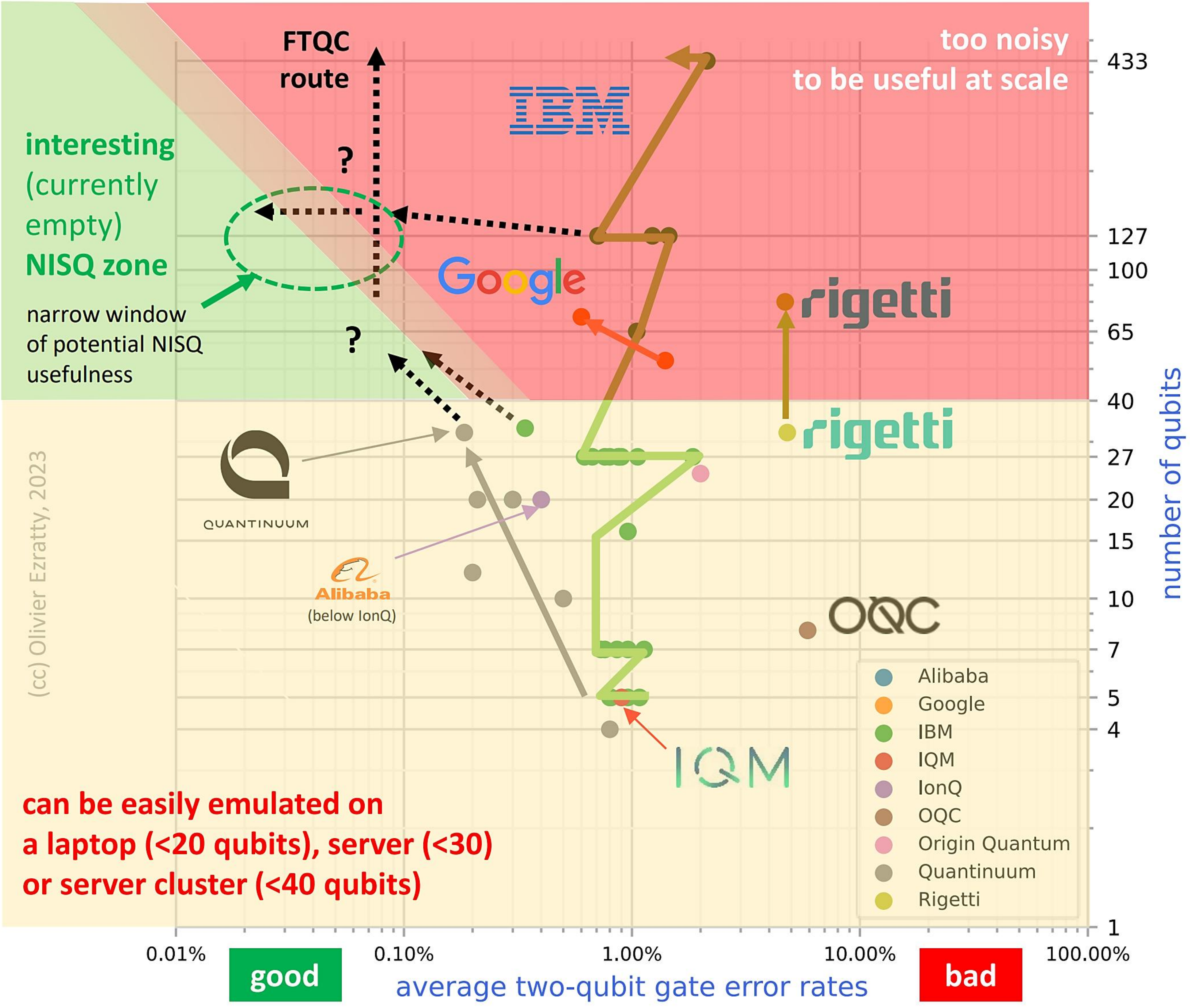
1. Adapted from: Ezratty, *arXiv* (2023)

Qubit Usefulness in the Current Stage



1. Ezratty, *arXiv* (2023)

Qubit Usefulness in the Current Stage

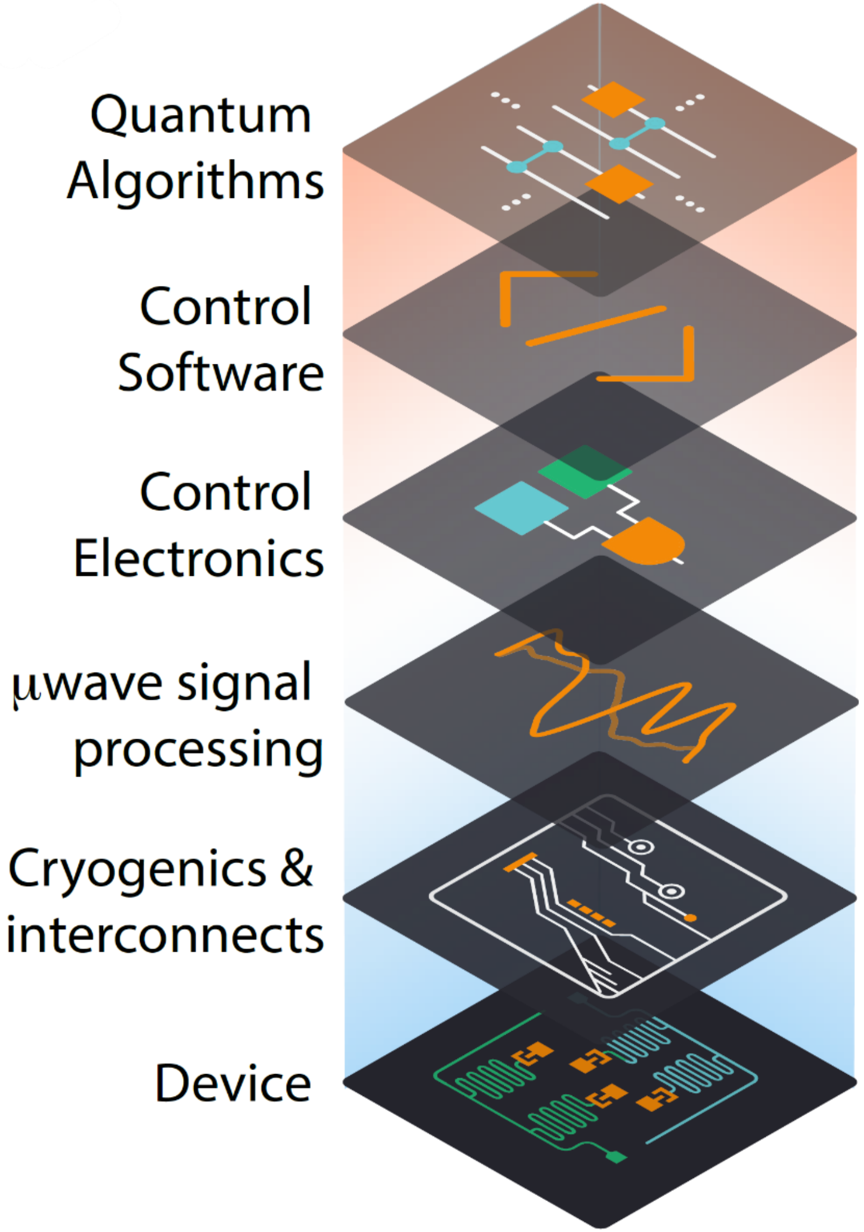


1. Ezratty, *arXiv* (2023)

Quantum Stack

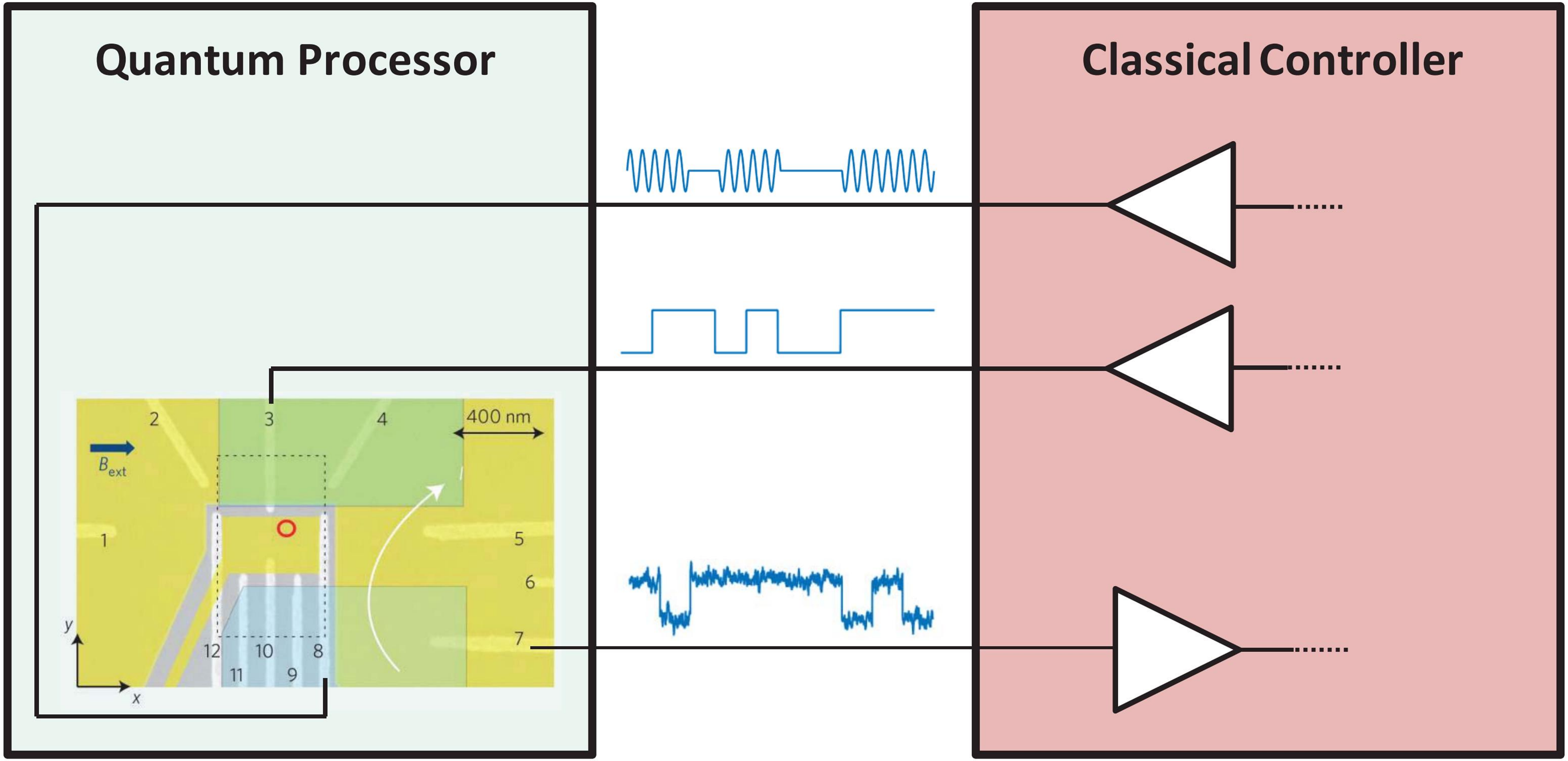
Software

Hardware



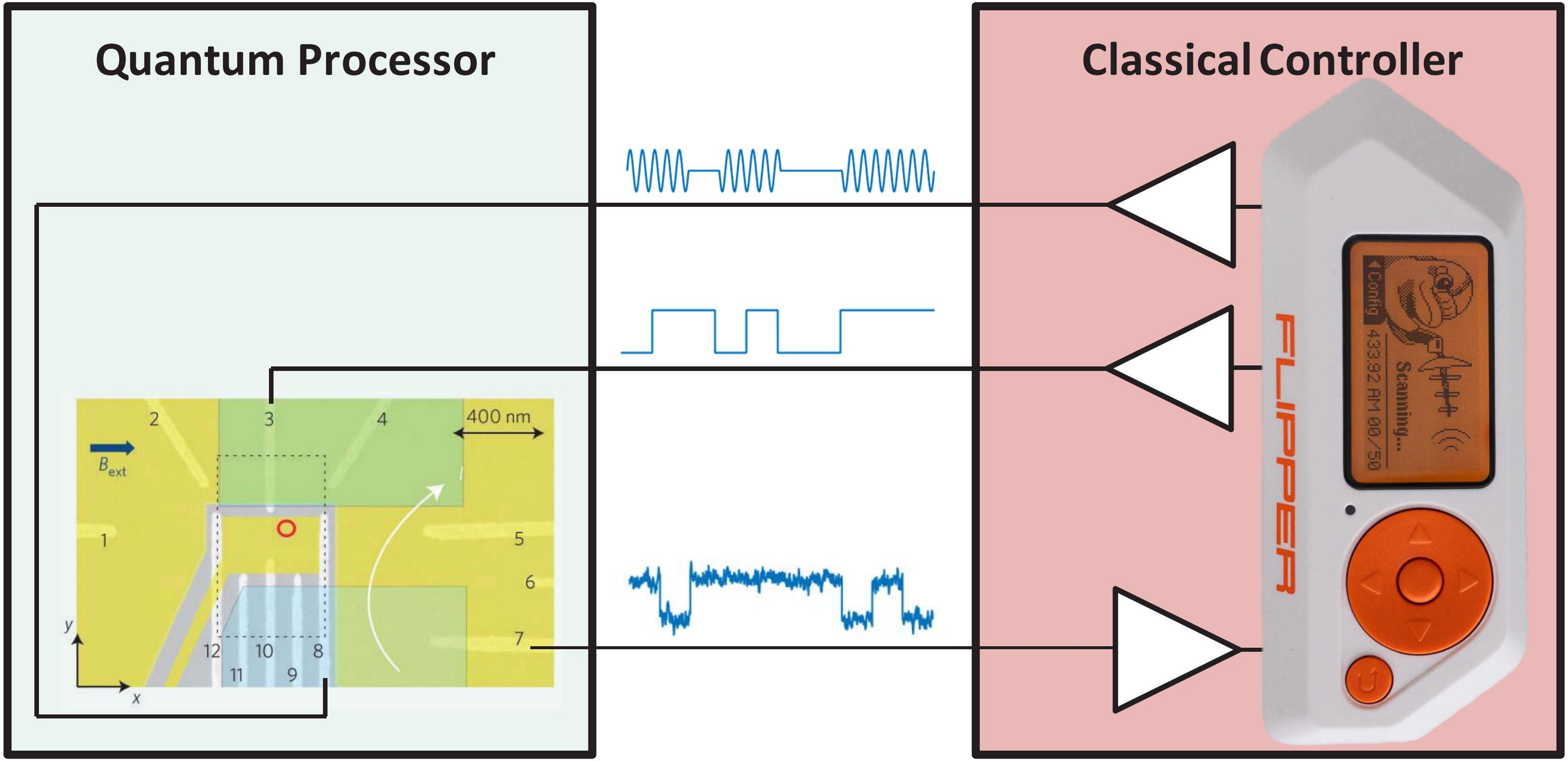
1. Gao et al., *arXiv* (2021)

Generic Qubit Control System Configuration



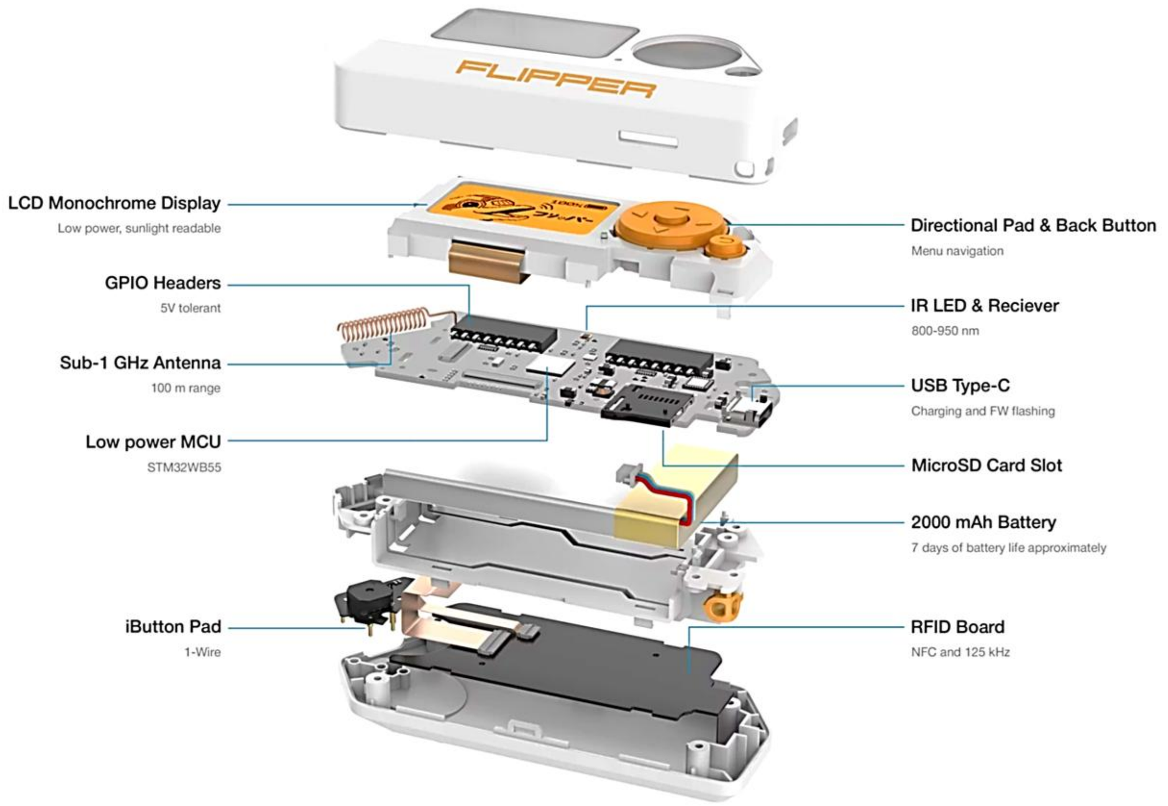
1. Patra et al., *IEEE J. Solid-State Circuits* (2018)

Generic Qubit Control System Configuration



1. Patra et al., *IEEE J. Solid-State Circuits* (2018)
2. Wikimedia Commons

Analogy: Flipper Zero (Software-Defined Radio Transceiver)



Step 1
- Detect incoming code1
- Jam signal
- Record code1

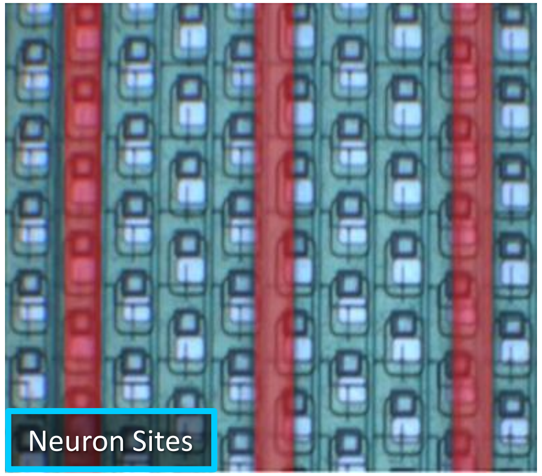
Step 2
- Detect incoming code2
- Jam signal
- Record code2

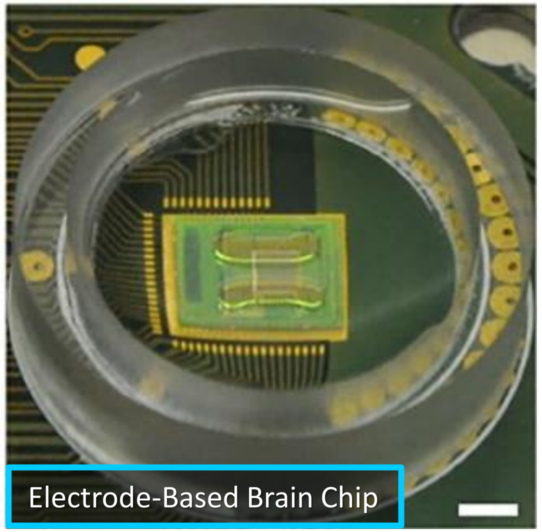
Step 3
- Replay code1
- Replay code2

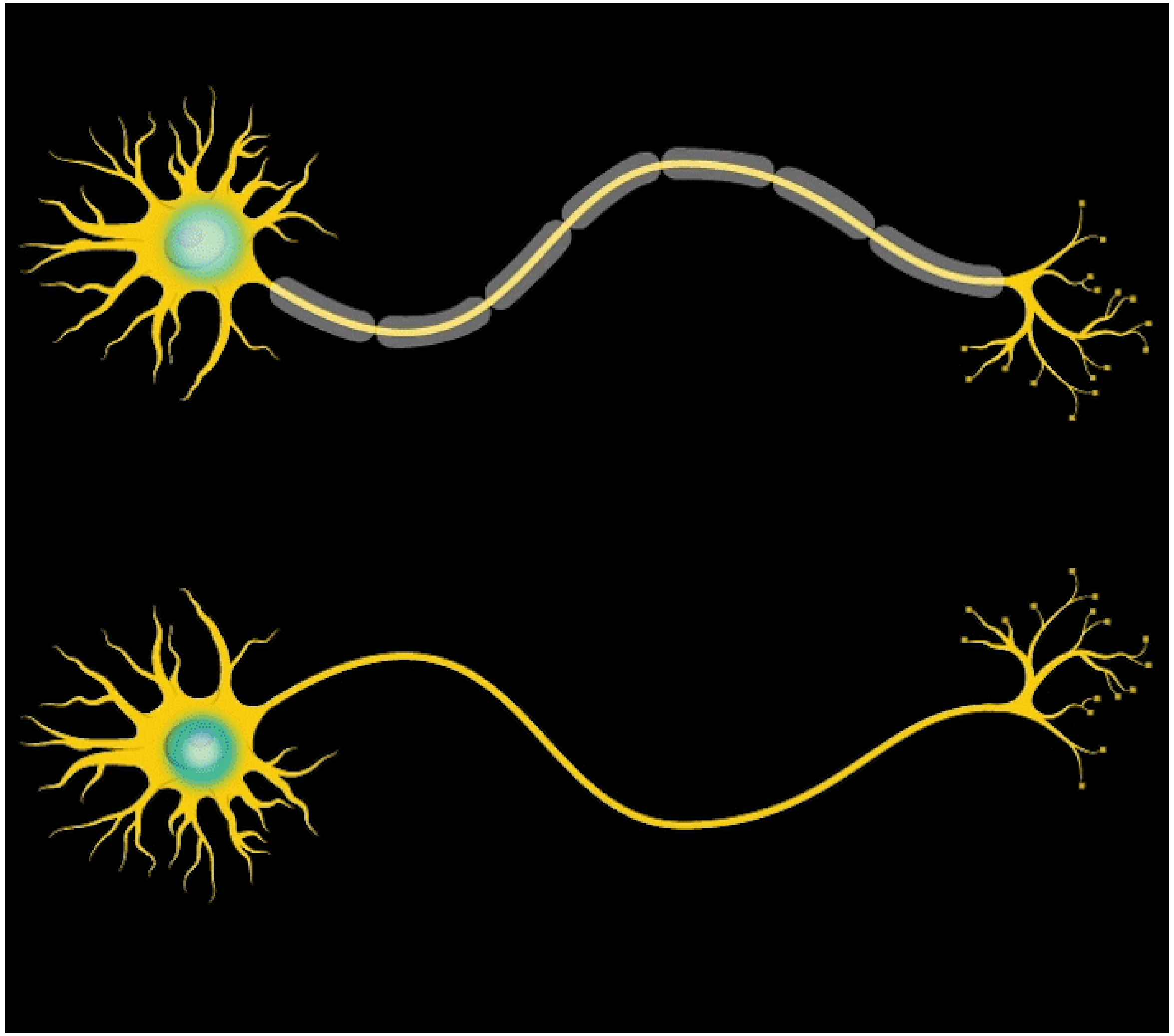
- Used for wireless/ wired control of IoT systems, home appliances, RFID, NFC, & other access control systems.
- Relies on sequences of response signals from a target.
- Works with a wide range of frequencies (≈300-928 MHz), IR included.
- Banned in some countries.

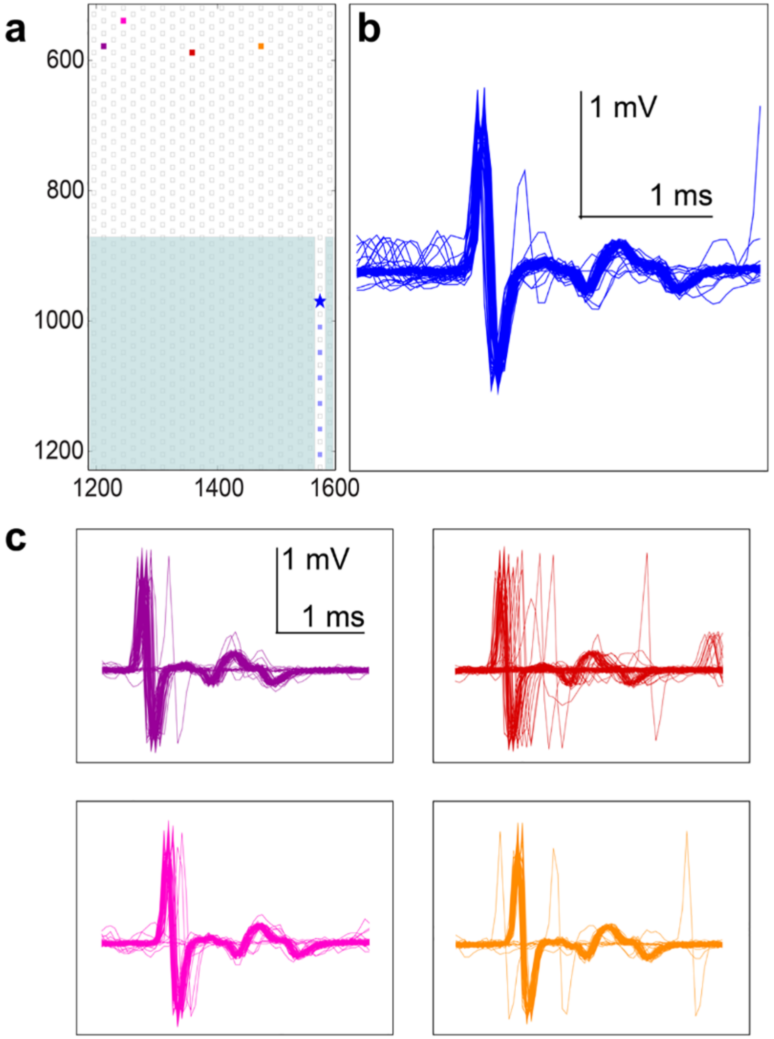
1. Taken from: flipperzero.one
2. Muller, *This Toy Can Open Any Garage* (2018)

Analogy: Detection of Neuron Impulse & Stimulation Spikes



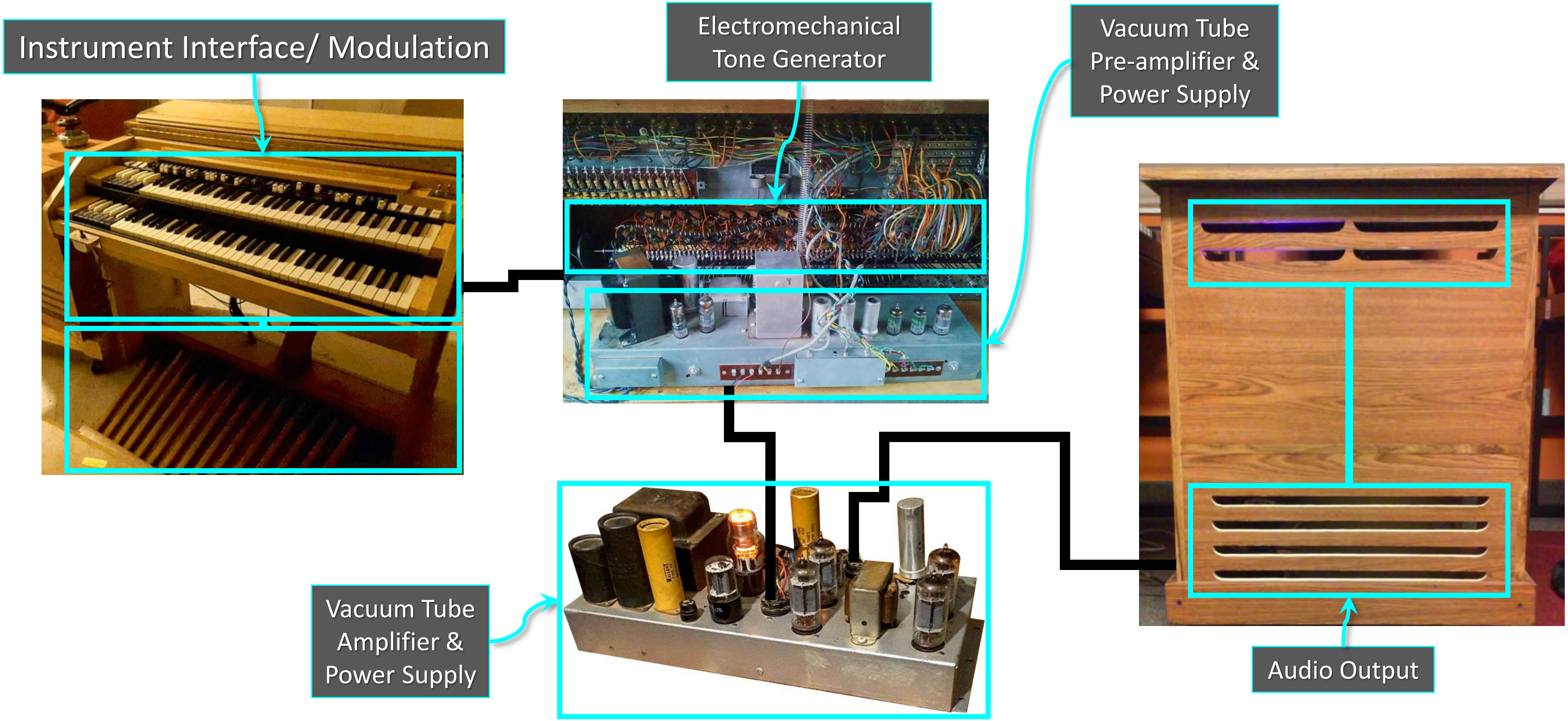






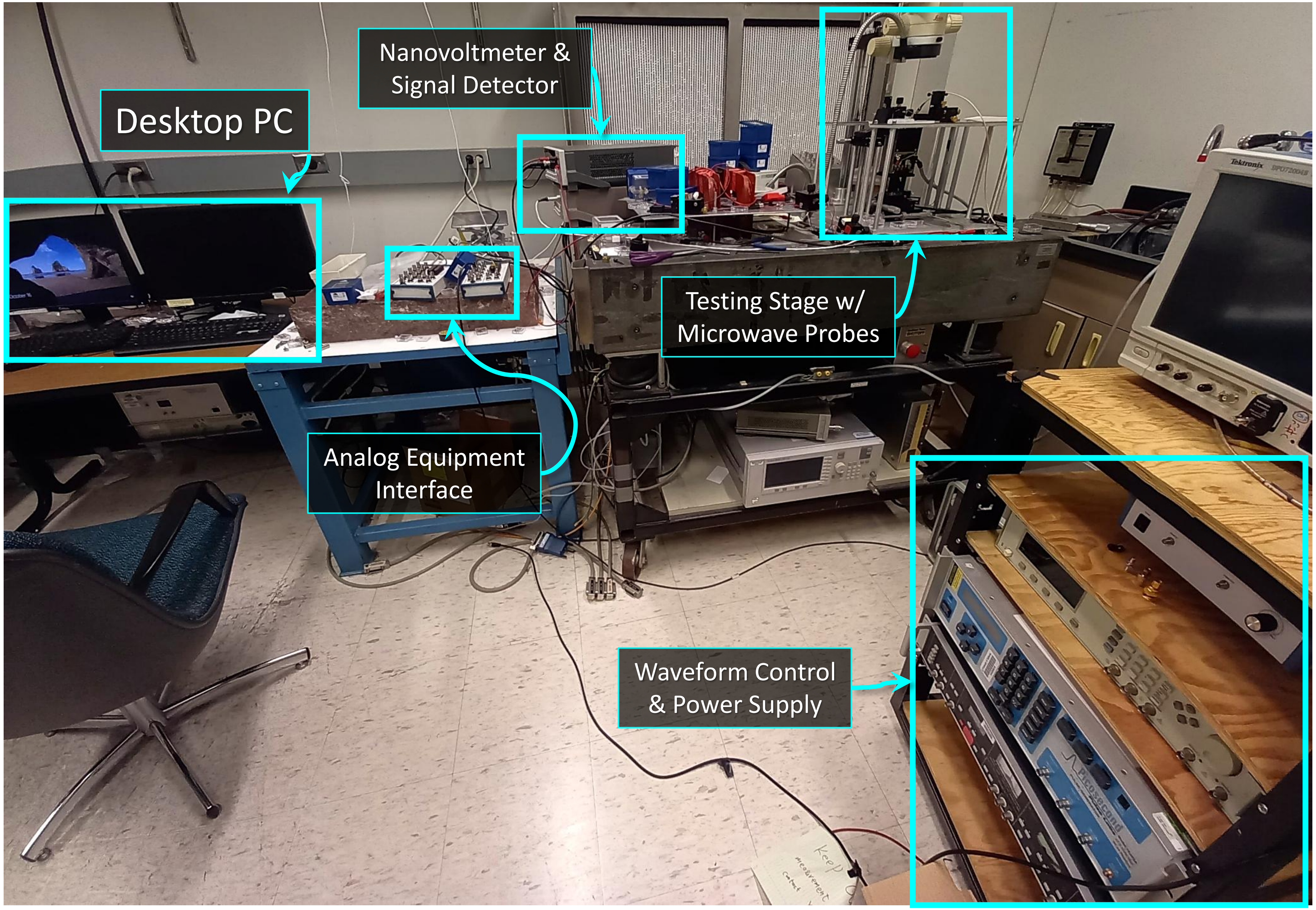
1. McGovern Institute, MIT (2019)
2. Lewandowska et al., *Plos One* (2015)

Analogy: 1957 Hammond Organ Setup

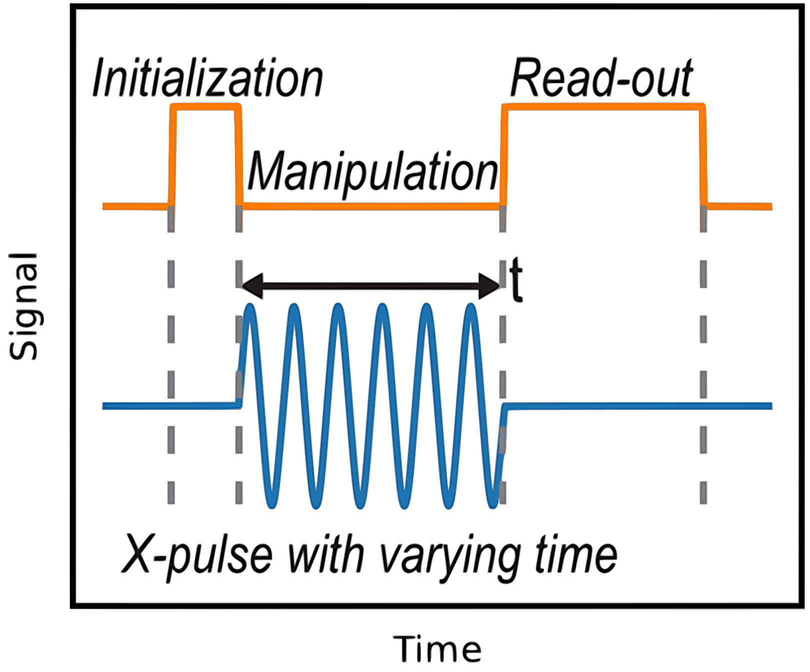


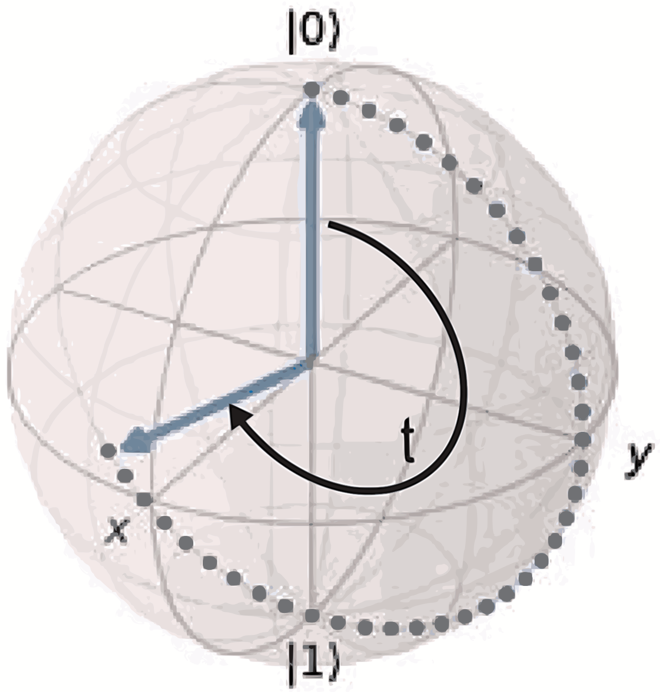
*These tone generators are also called “tone wheel generators”

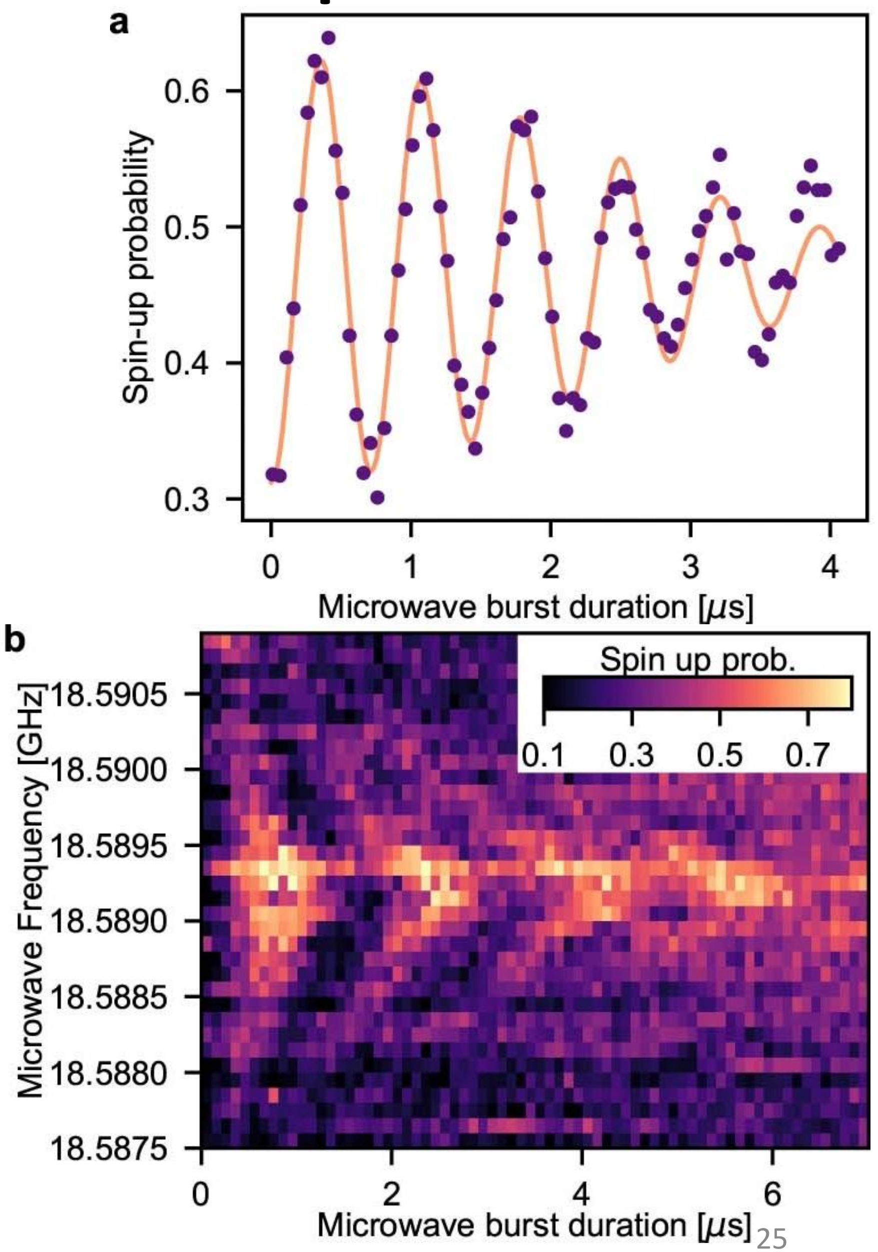
Comparison to Magnetics Lab: RF Testing & Measurement Setup



Qubit Drive & Readout Pulse Sequence

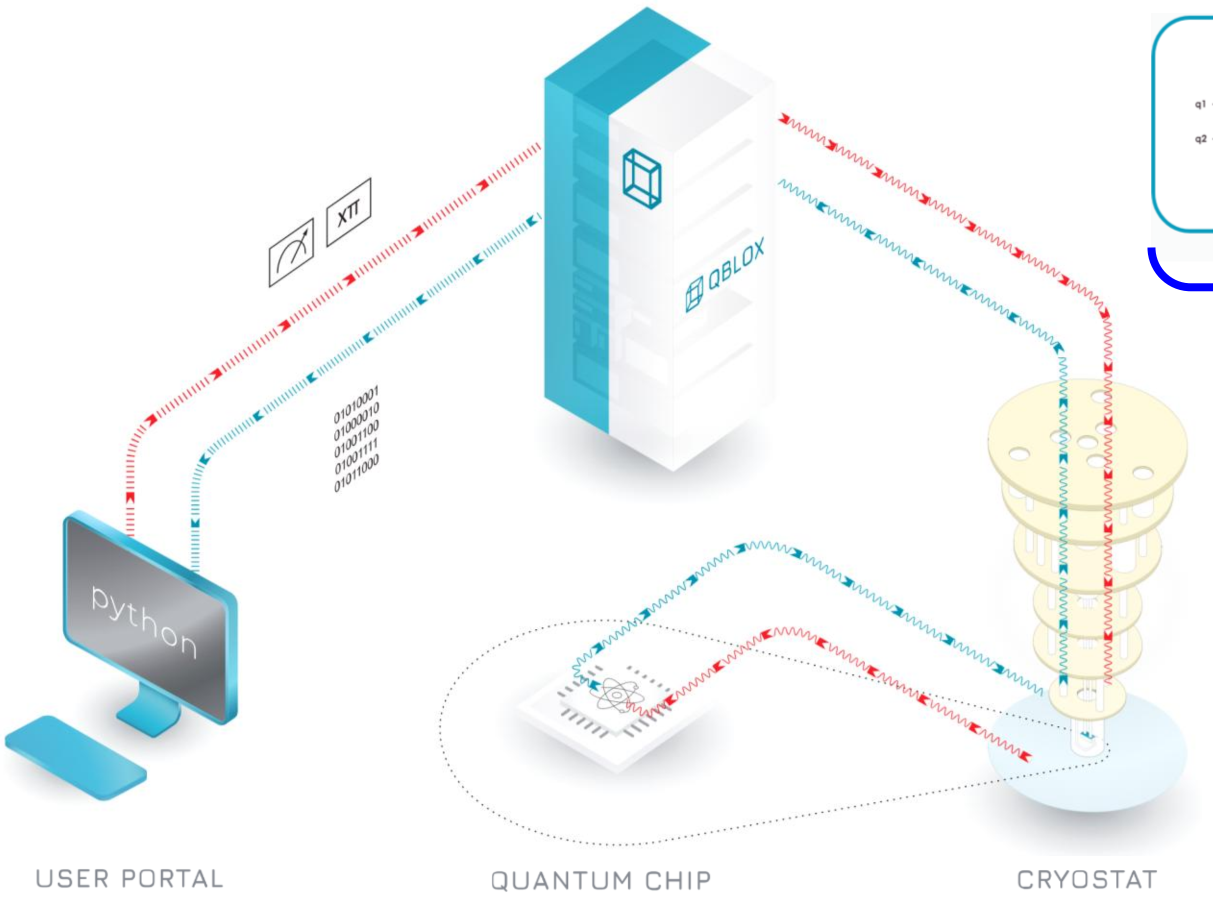


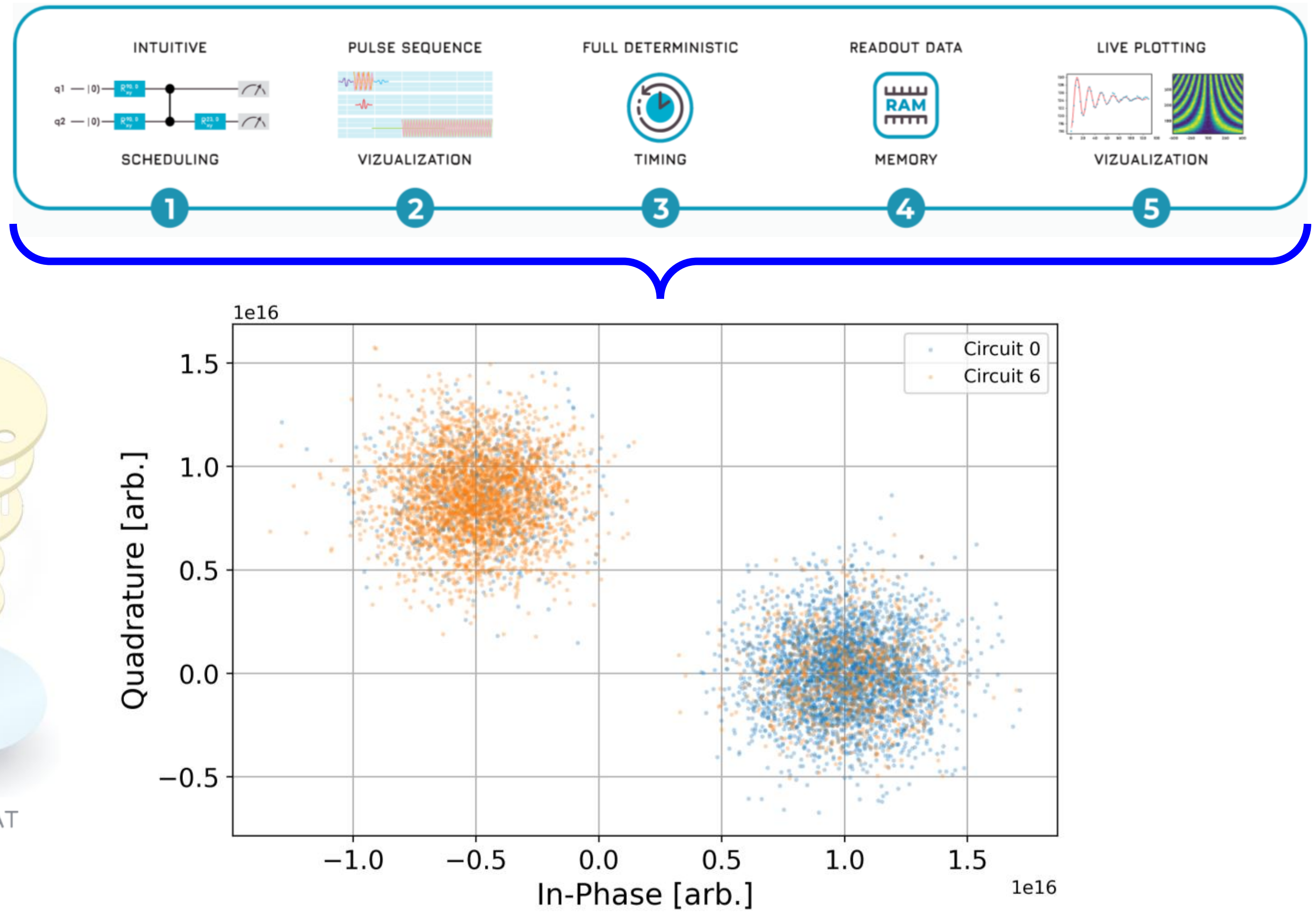




1. van Dijk et al., IEEE J. Solid-State Circuits 55, 11, 2930–2946 (2020)
2. Zwerver et al., *Nat Electron* 5, 184–190 (2022)

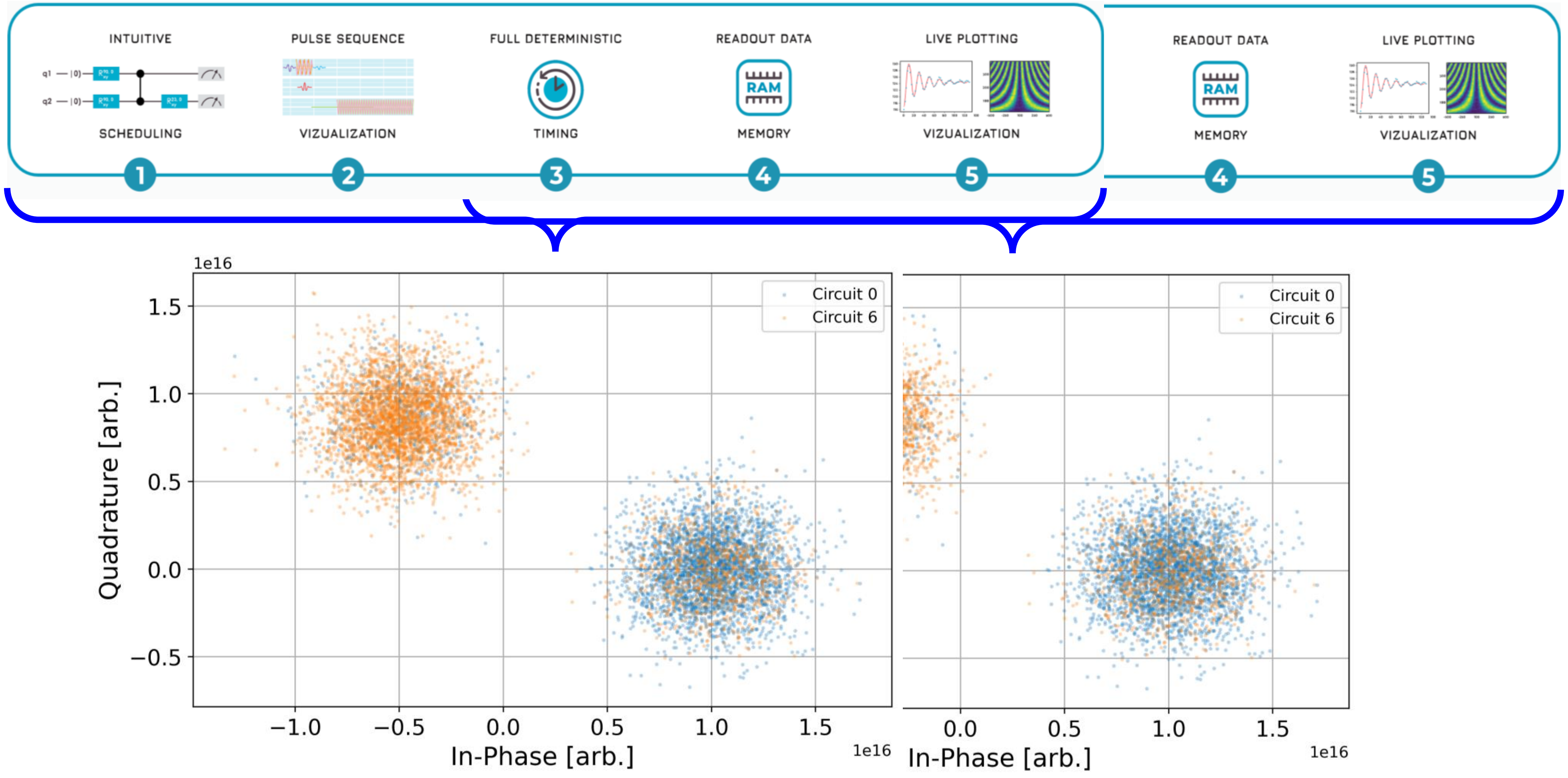
Qubit Drive & Readout Pulse Sequence





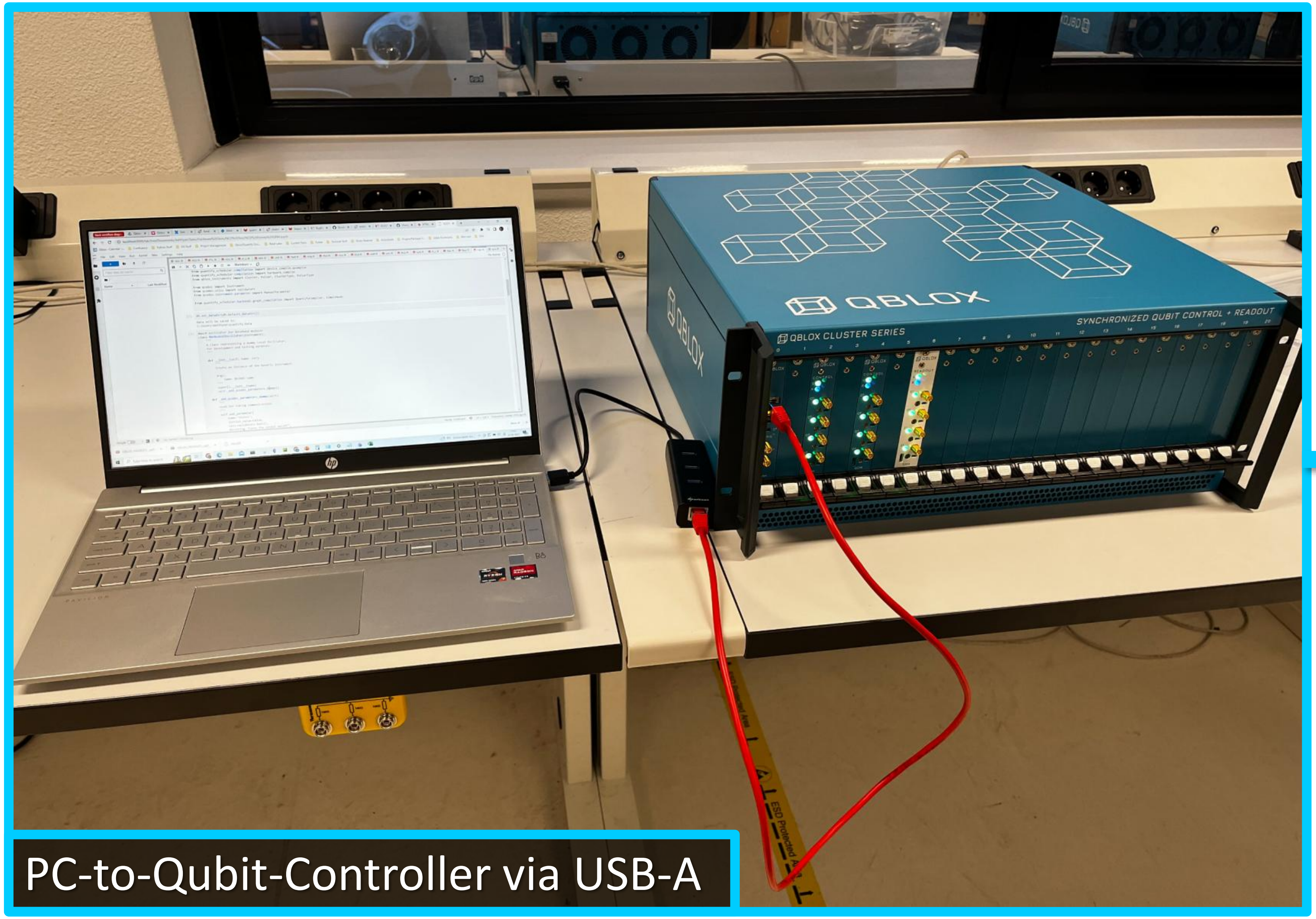
1. Qblox Quantum, *Documentation and Tutorials* (2022)

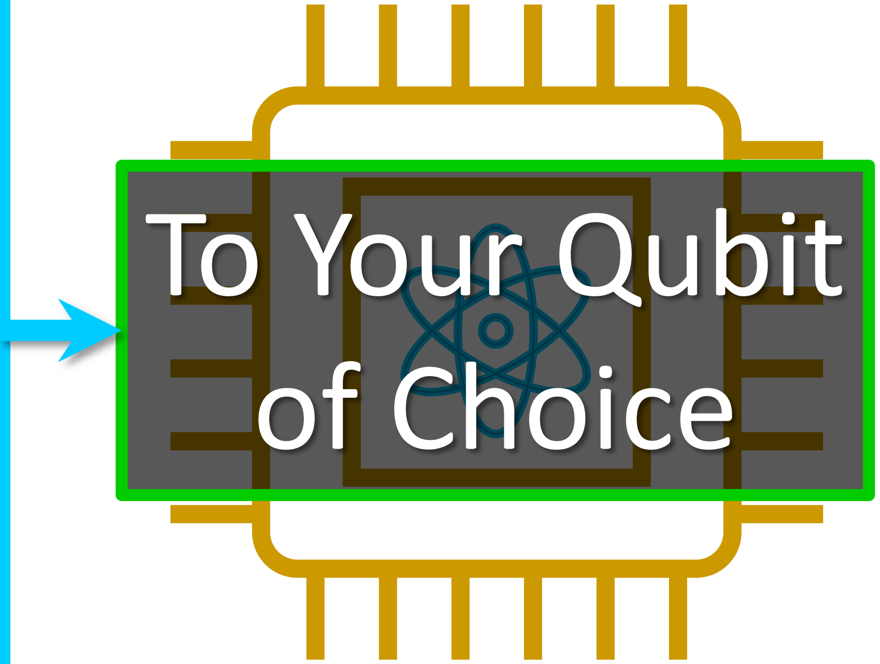
Qubit Drive & Readout Pulse Sequence



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

Compact Qubit Drive & Readout Pulse Setup





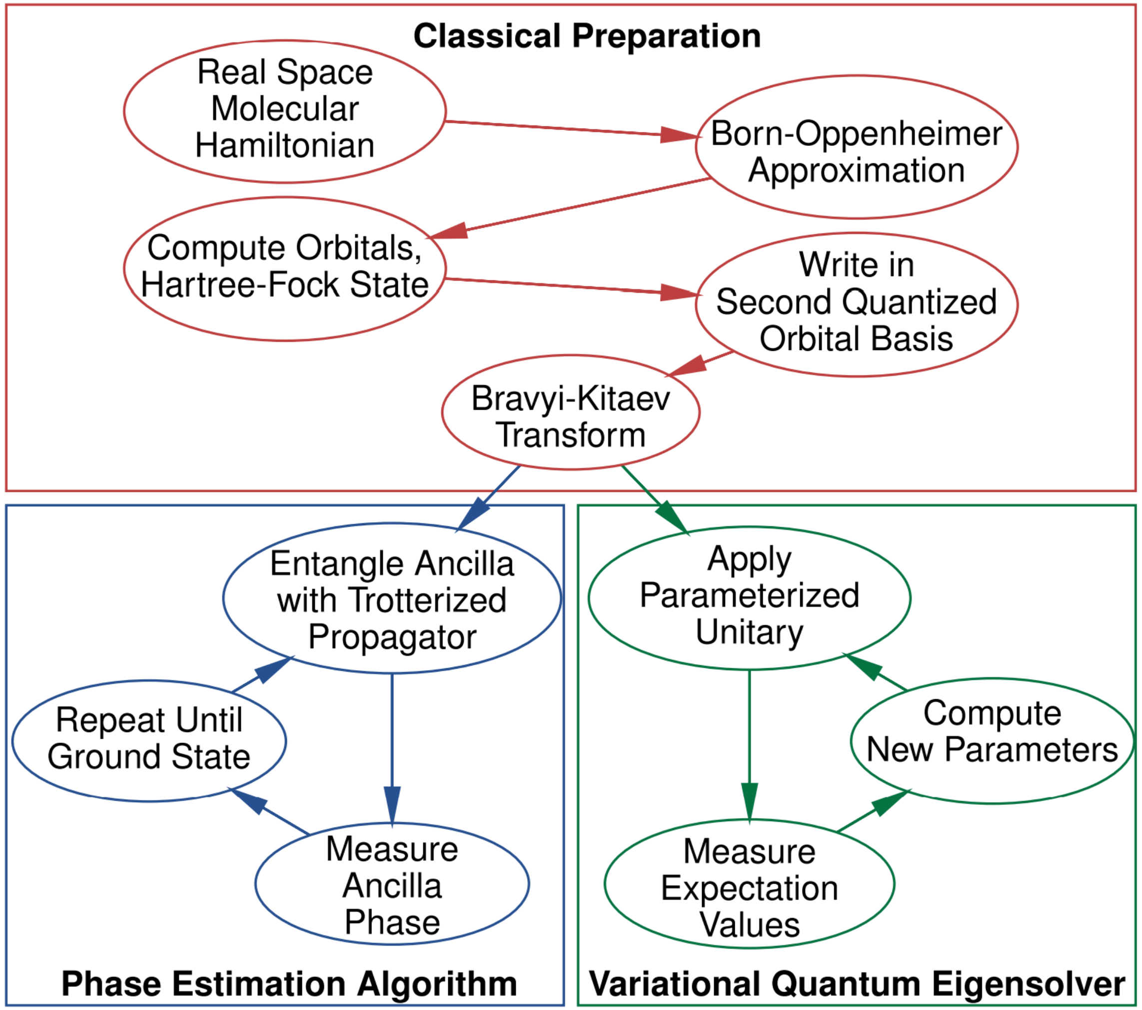
1. Qblox Quantum, *Documentation and Tutorials* (2022)

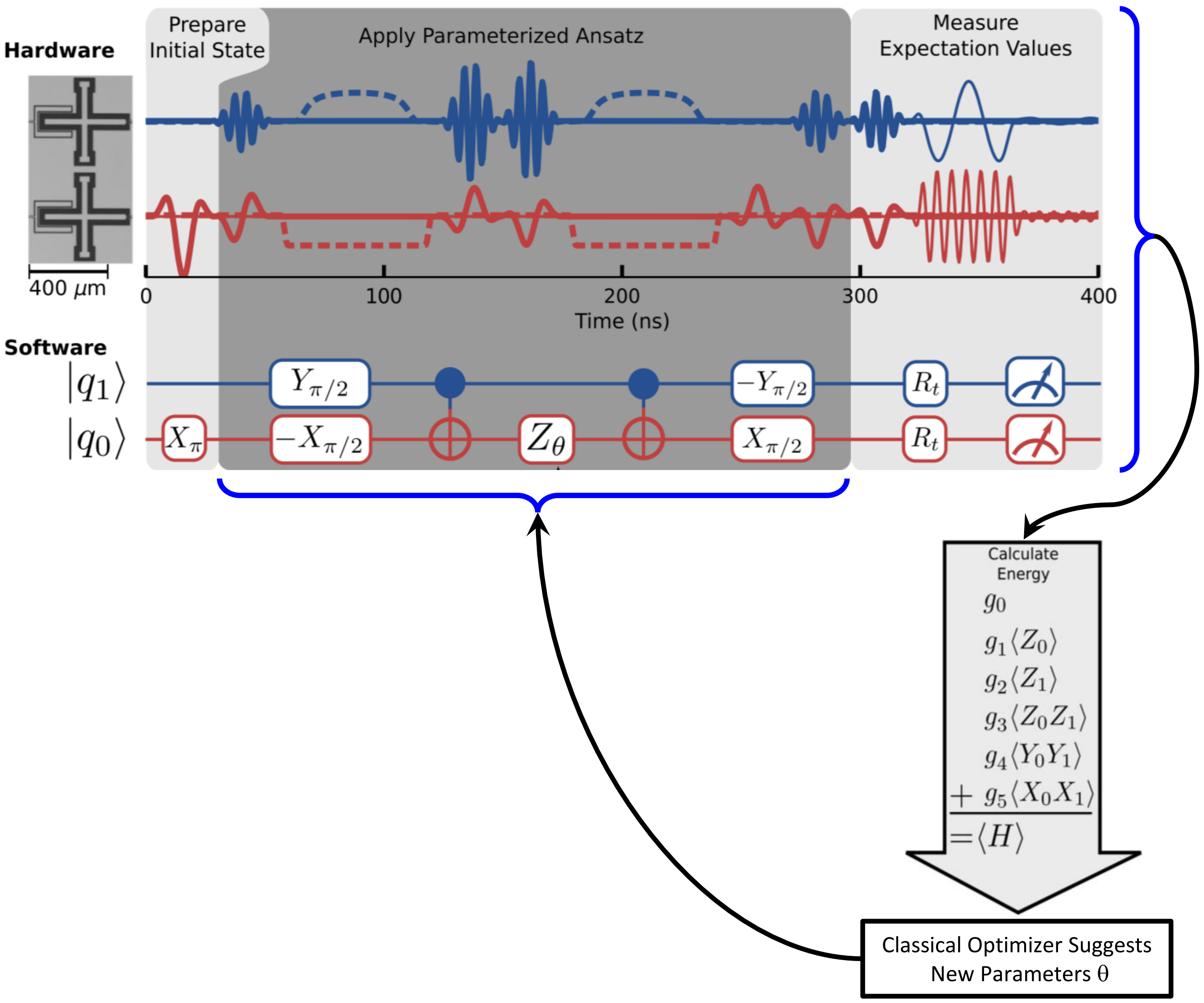
Waveforms for Qubit Gate Drive & Readout

Technology	T_2^*	1-Qubit gate	2-Qubit gate	Qubit read-out	DC-Biasing
Superconducting qubits (Transmons)	2.5 us	~ 6 GHz 20 ns	12ns 40 ns	7-8 GHz, ~ 1 us	flux-bias current
Single-electron spin qubits in a quantum dot	120 us	13-40 GHz ~ 1 us	~ 100 ns		gate voltage
Single-electron spin qubits in a donor system	160 us	30-50 GHz ~ 1 us	~ 100 ns		gate voltage
Singlet-triplet qubit	700 ns	~ 1 ns	~ 1 us		gate voltage
Exchange-only qubit	2.3 us	10 ns ...1 us	Sequence of pulses between different quantum dots		gate voltage
Hybrid qubit	< 10 ns	~ 100 ps	Sequence of pulses between different quantum dots		gate voltage

1. van Dijk et al., *Microprocessors and Microsystems* (2019)

Example of Required Steps to Compute Molecular Energies





1. van Dijk et al., *Microprocessors and Microsystems* (2019)

2. Adapted from: O'Malley et al., *Phys. Rev. X*, 6 (2016)

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 cryo-compatible Complementary Metal Oxide Semiconductor (CMOS) chips.

More Desktop-Like

***More Server-Farm-Like**

*Also called server-clusters

Quantum Systems Range in Size

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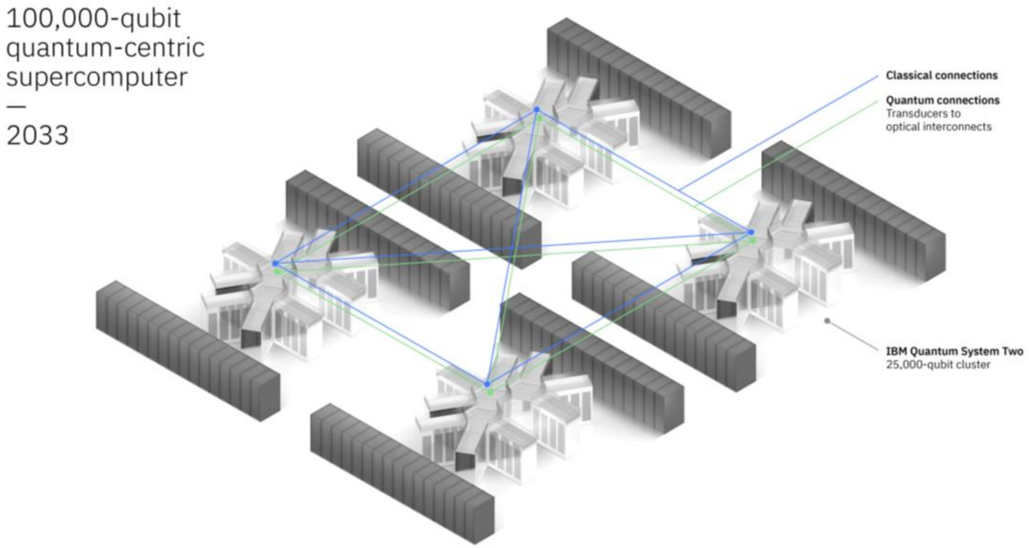


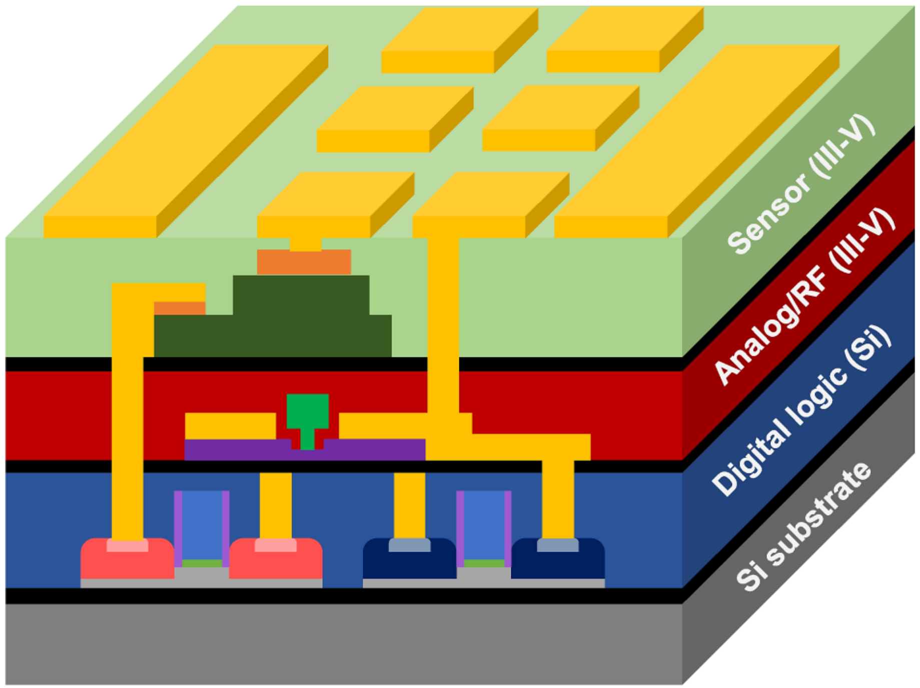
More Desktop-Like ⟷ ***More Server-Farm-Like**

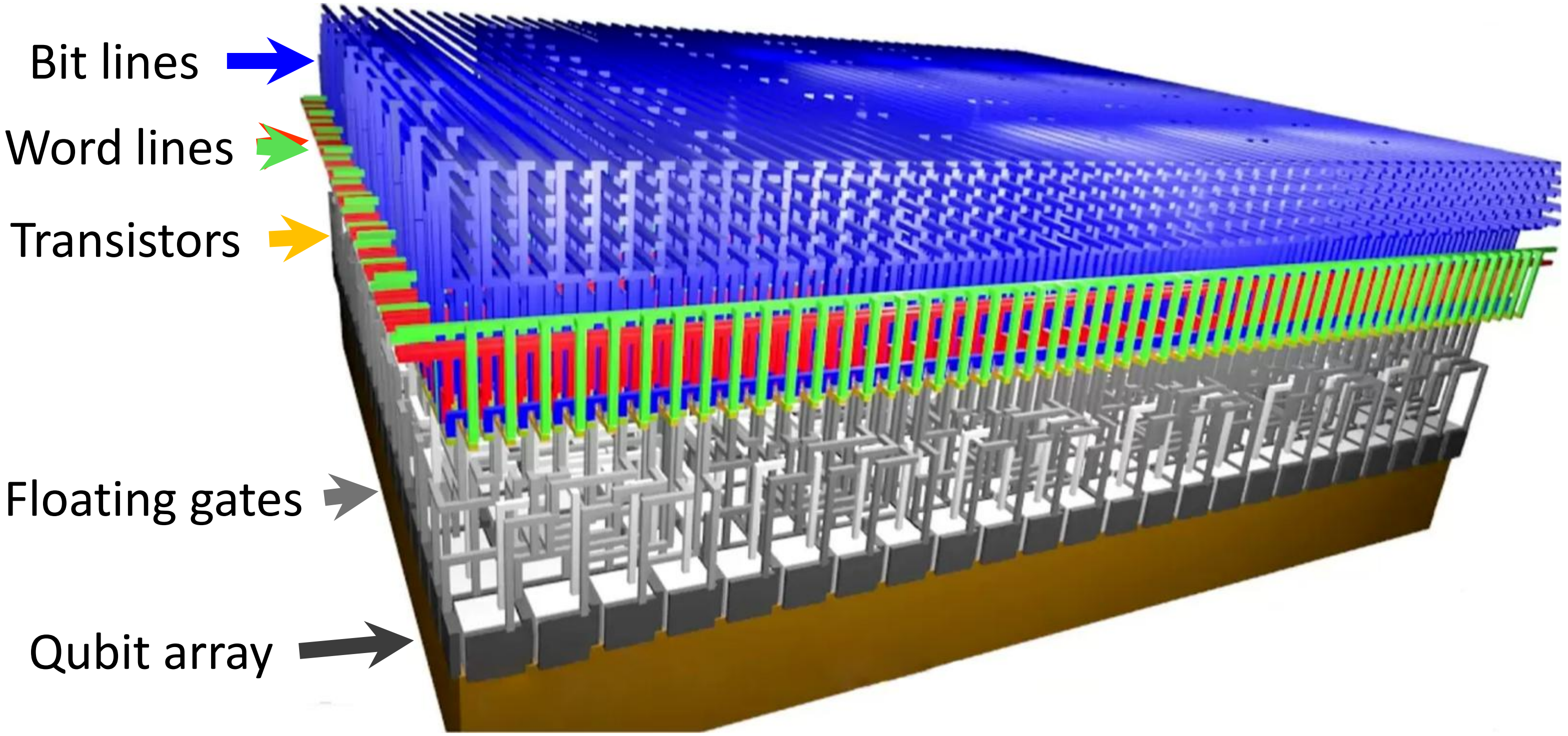
1. SpinQ, *Gemini 2 [2-Qubit System]* (2022)
2. IBM Research

*Also called server-clusters

Digital Integrated Chip vs. Quantum Integrated Chip

- Typically, in an integrated quantum circuit the **larger components** sit at the **top**, while the **smaller components** exist at the **bottom**.
  - Like conventional classical chips.

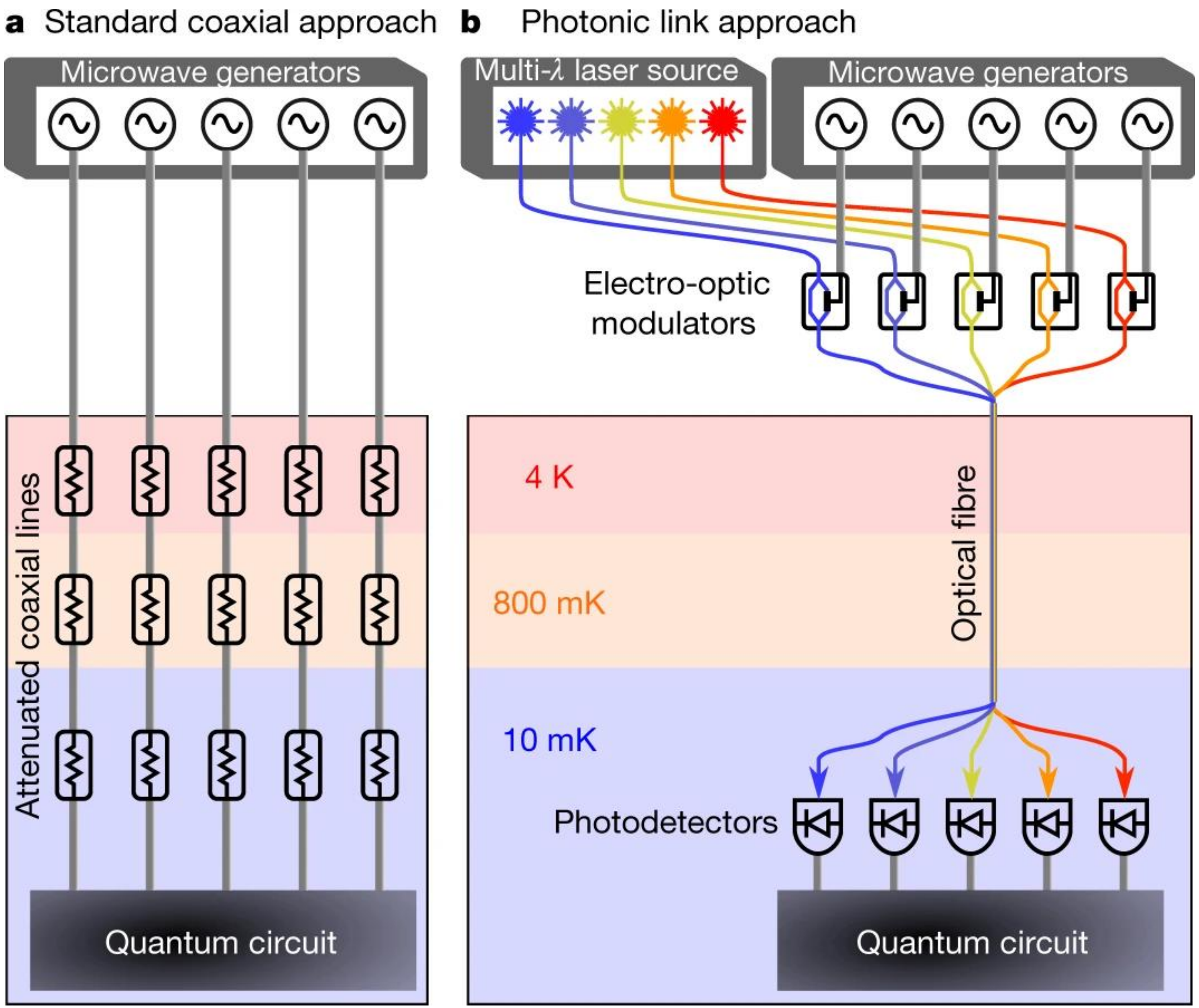


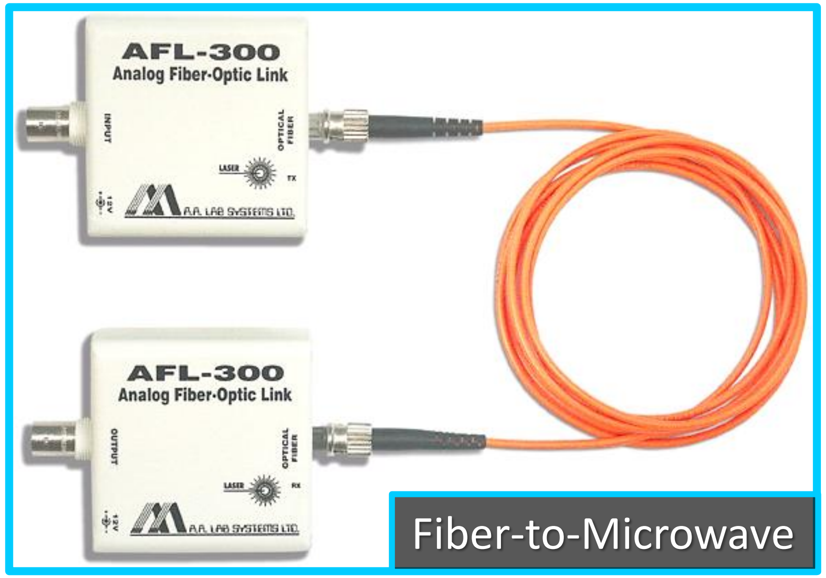


1. Wikimedia Commons – KAIST
2. Veldhorst et al., *Nat Commun* (2017)

*Word lines = green & red bars on quantum integrated chip

Qubit Control System: From Co-Axial to Optical Fiber





-OR-

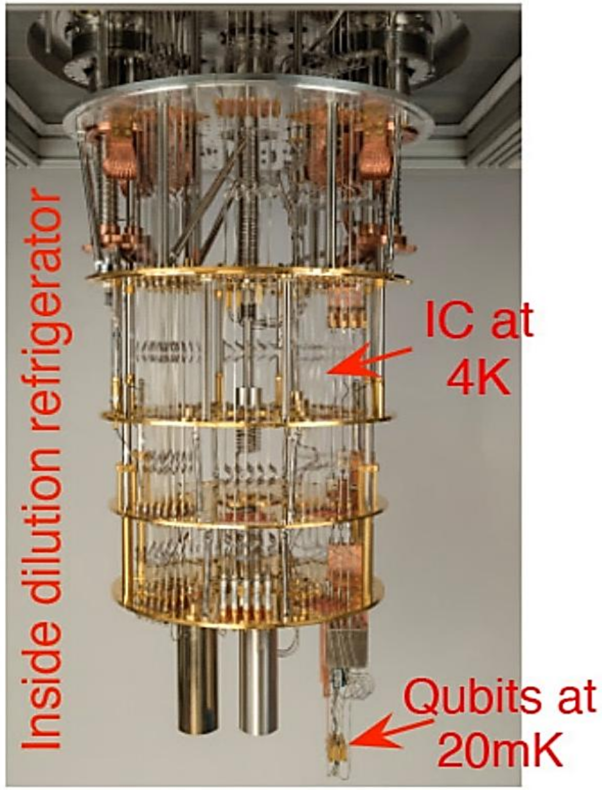
1. Lecocq et al., *Nature* (2021)

2. lab-systems.com

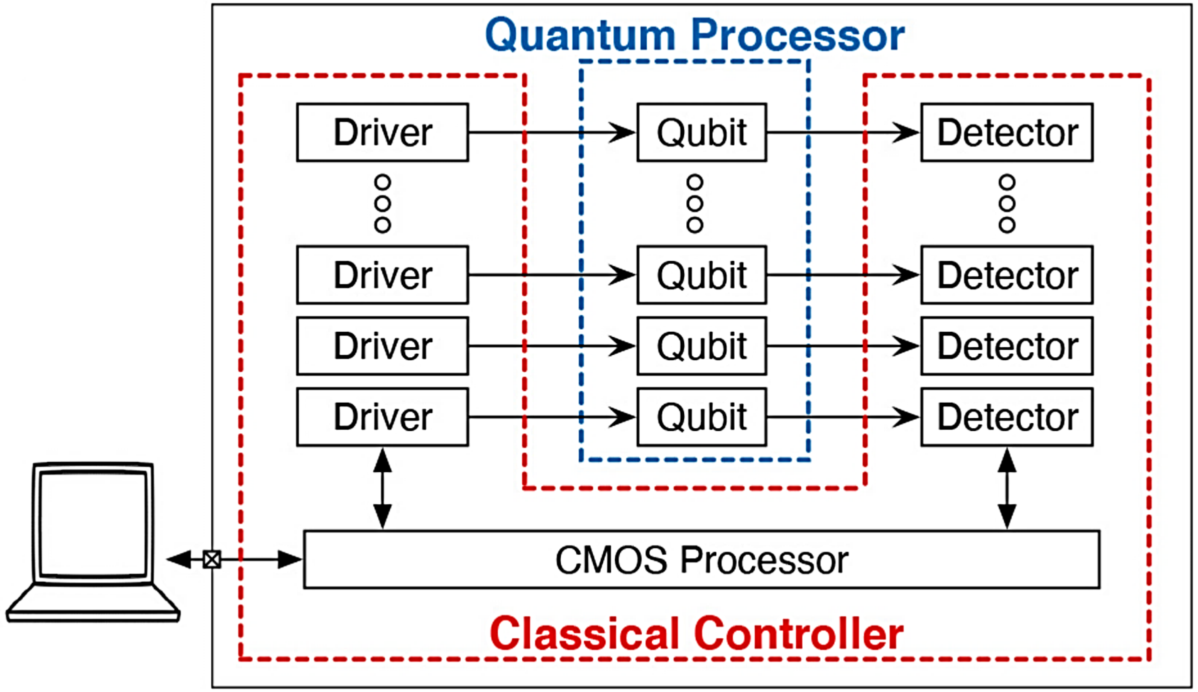
3. rfoptic.com

*RF: Radio Frequency

Intermediate Qubit Control System



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

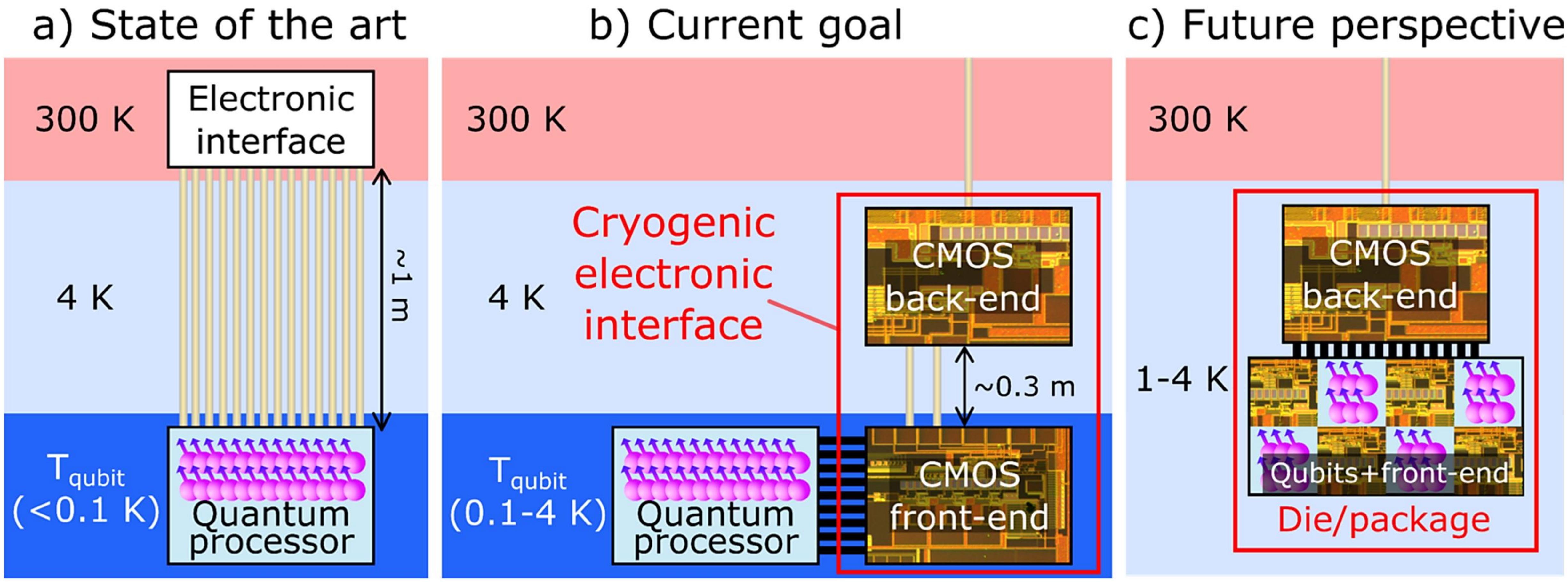


Single-Chip CMOS Quantum Computer (QCMOS)

Cryocooler by Montana Instruments (desktop size)

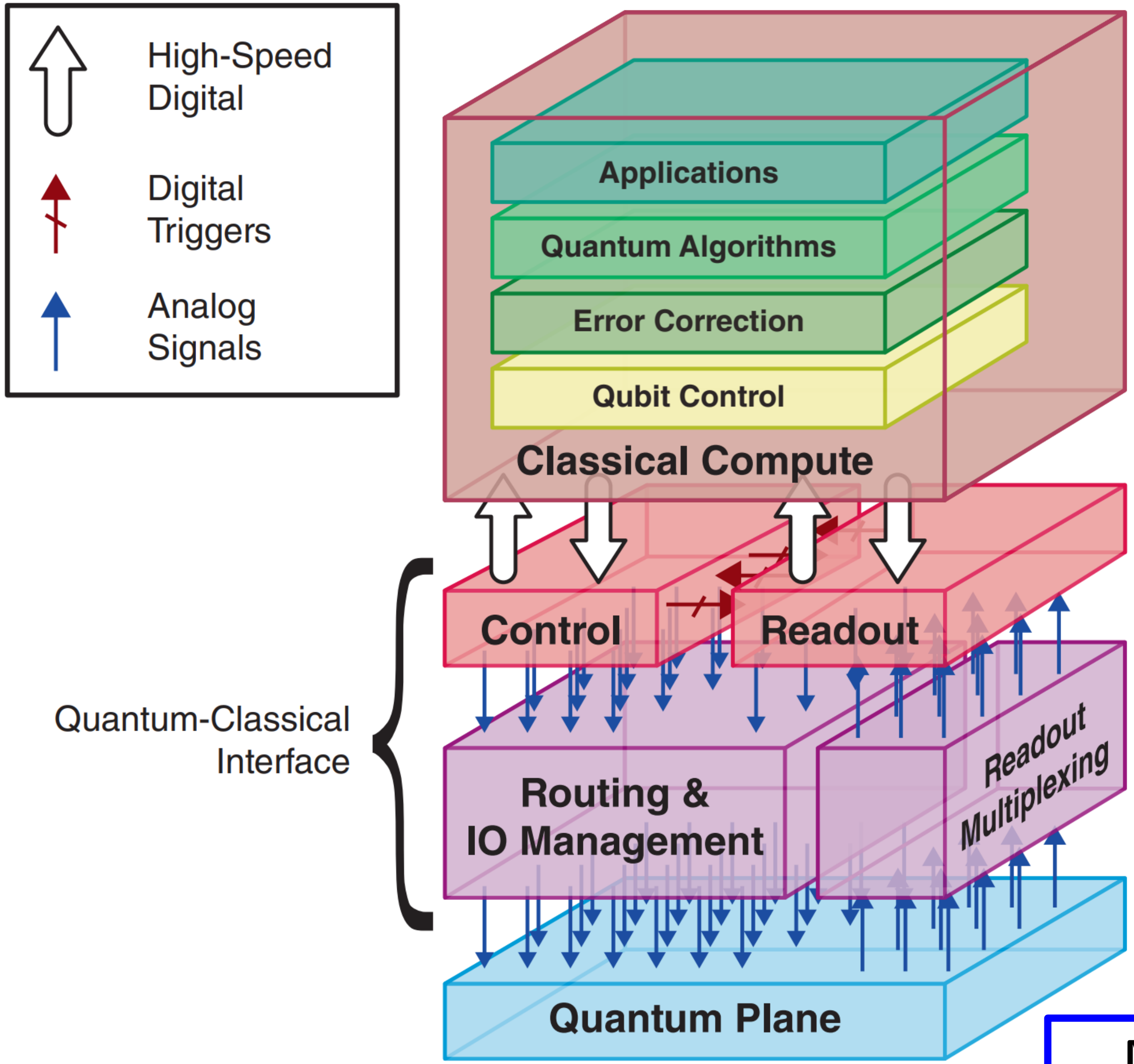
1. Staszewski et al., *IEEE Open Journal of the Solid-State Circuits Society* (2022)

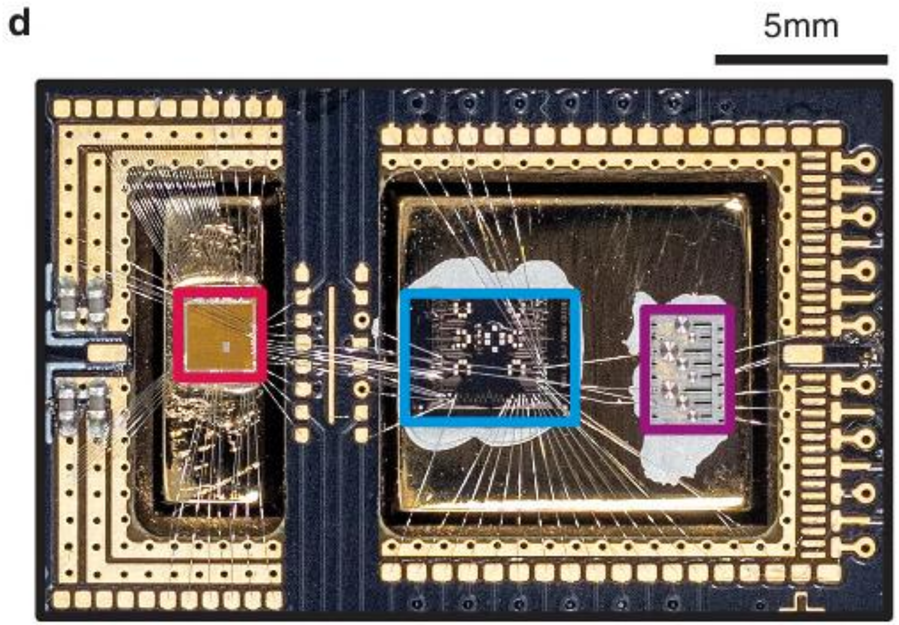
Qubit Control System: Towards Co-Integration

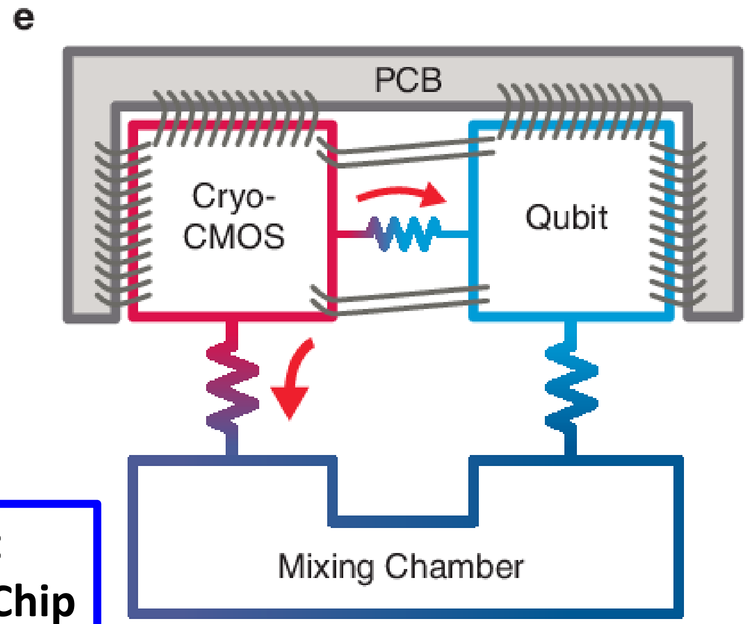


1. Sebastiano et al., *IEEE IEDM* (2020)

Co-Integrated Qubit Control System



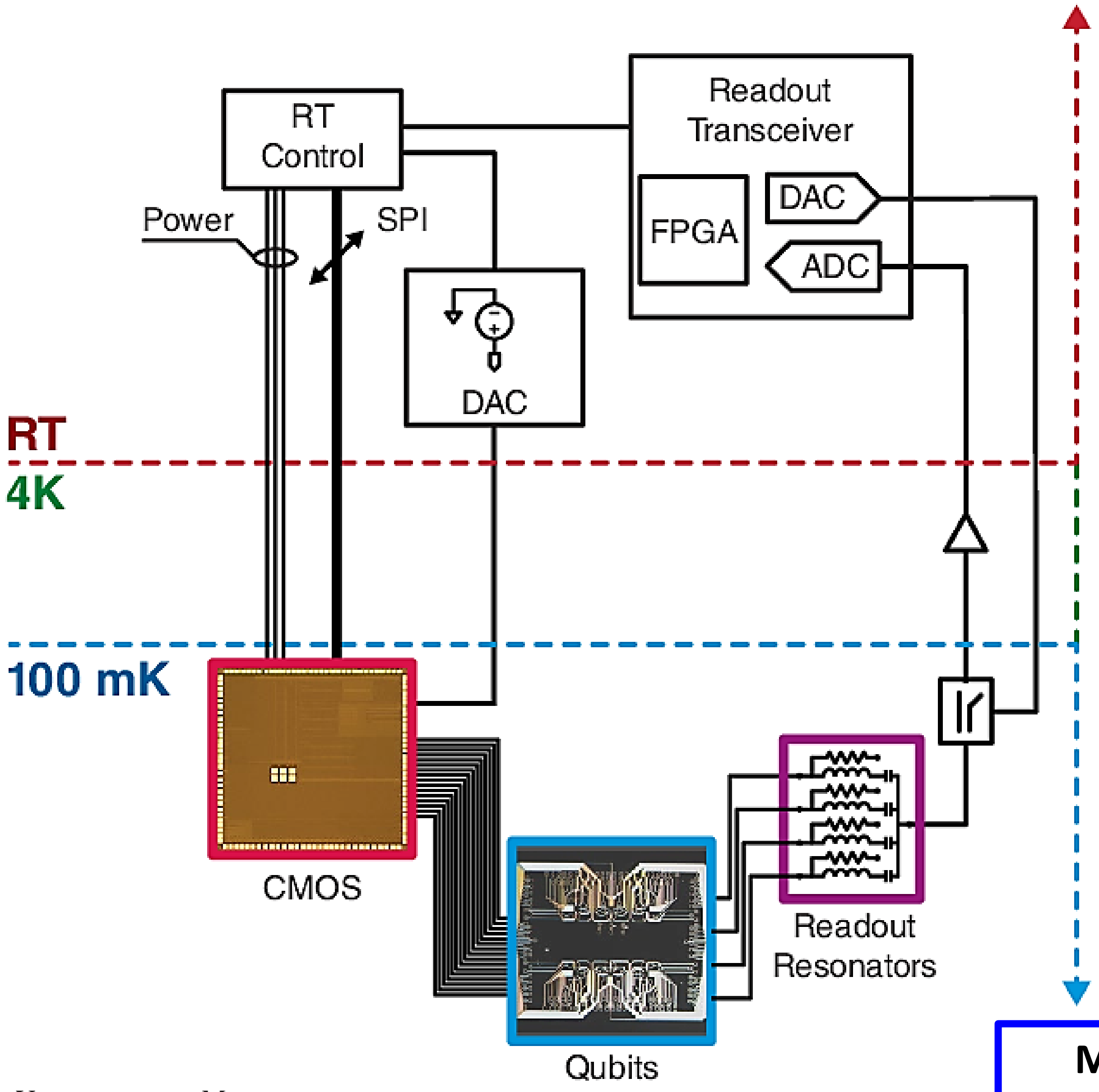


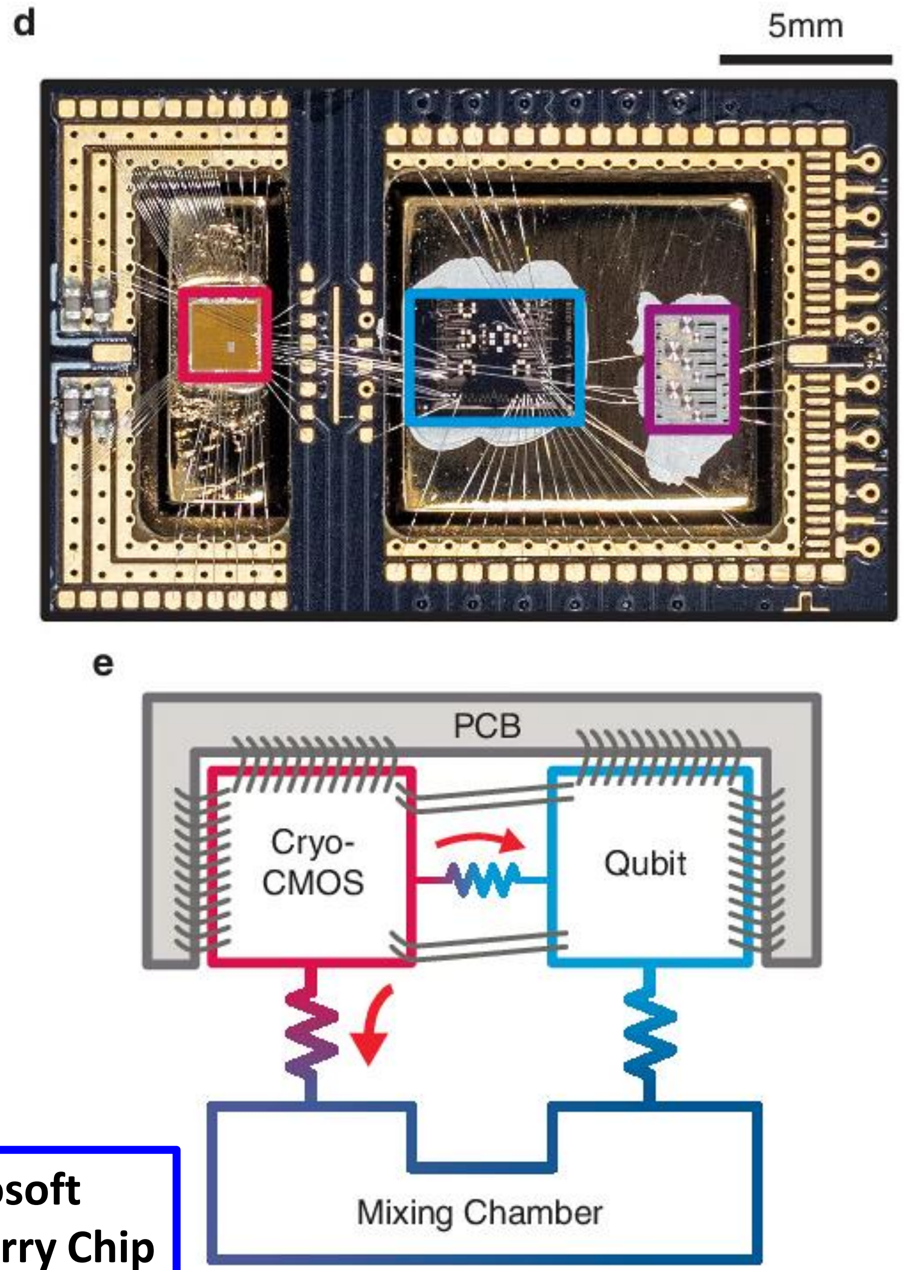


Microsoft Gooseberry Chip

1. Microsoft Research (2021)

Co-Integrated Qubit Control System

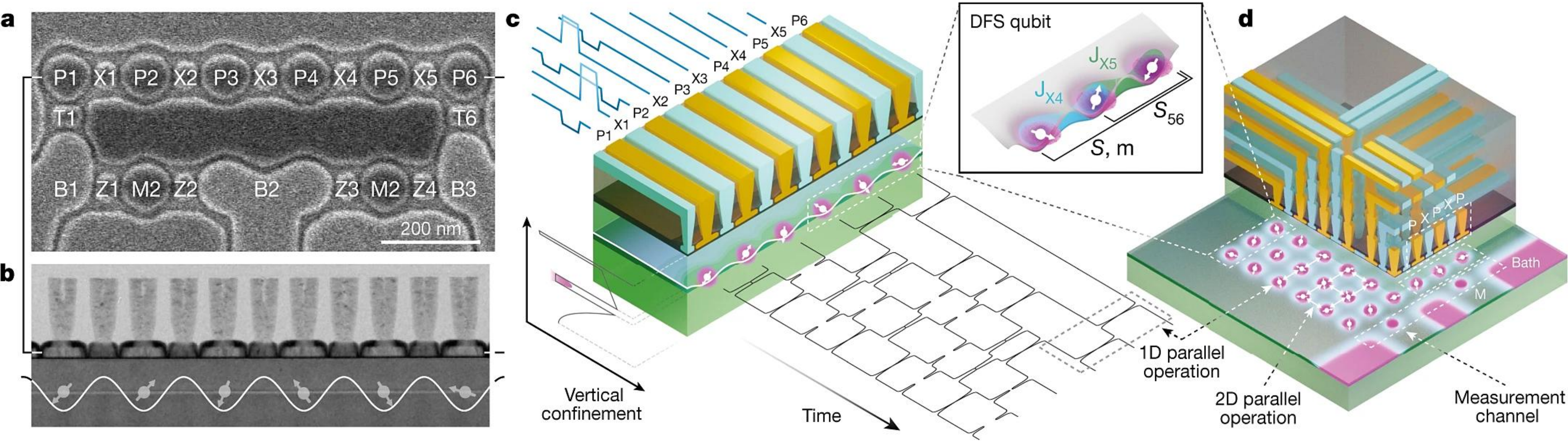




Microsoft Gooseberry Chip

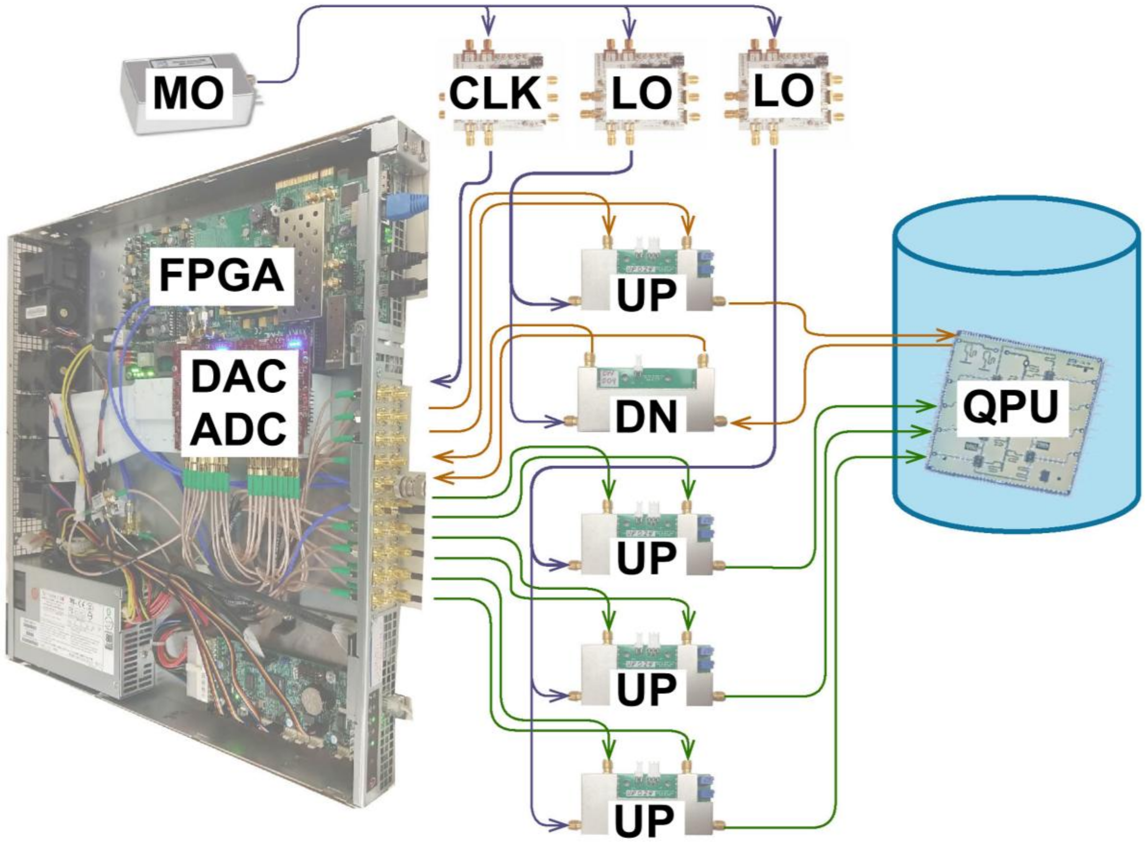
1. Microsoft Research (2021)

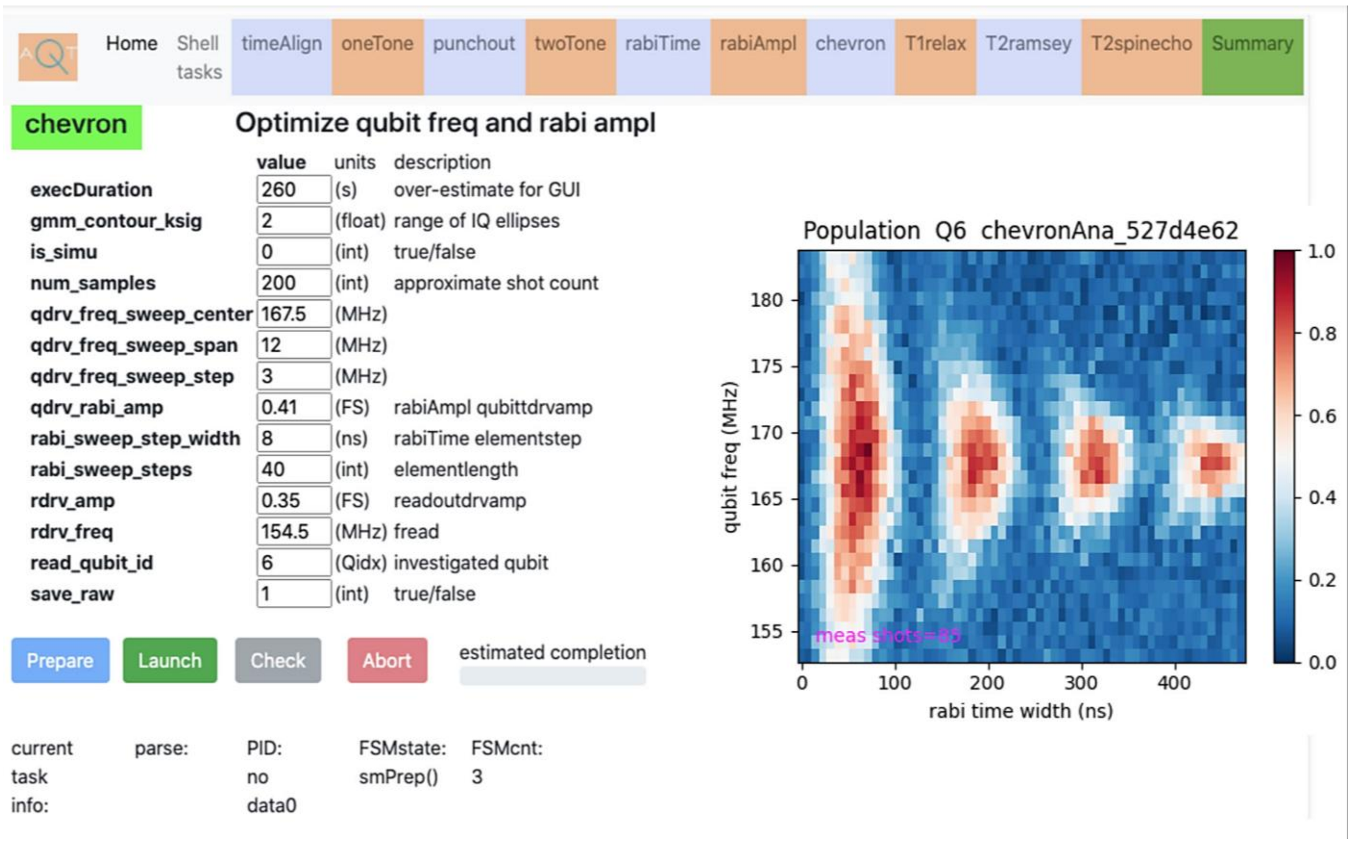
Example of Encoded Spin Qubits with 6 Quantum Dots



1. Weinstein et al., *Nature* (2023)

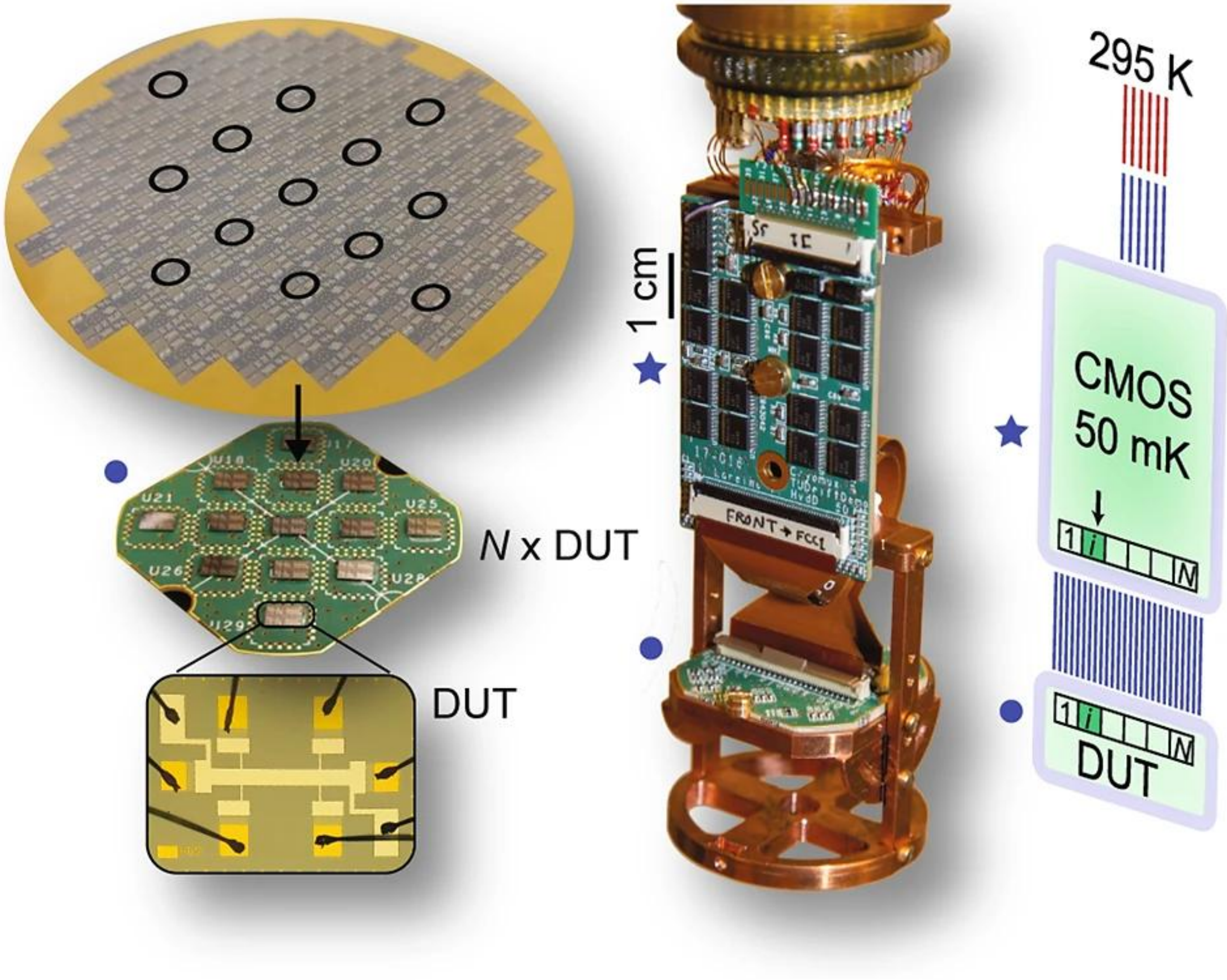
External FPGA-Based Control of Qubits

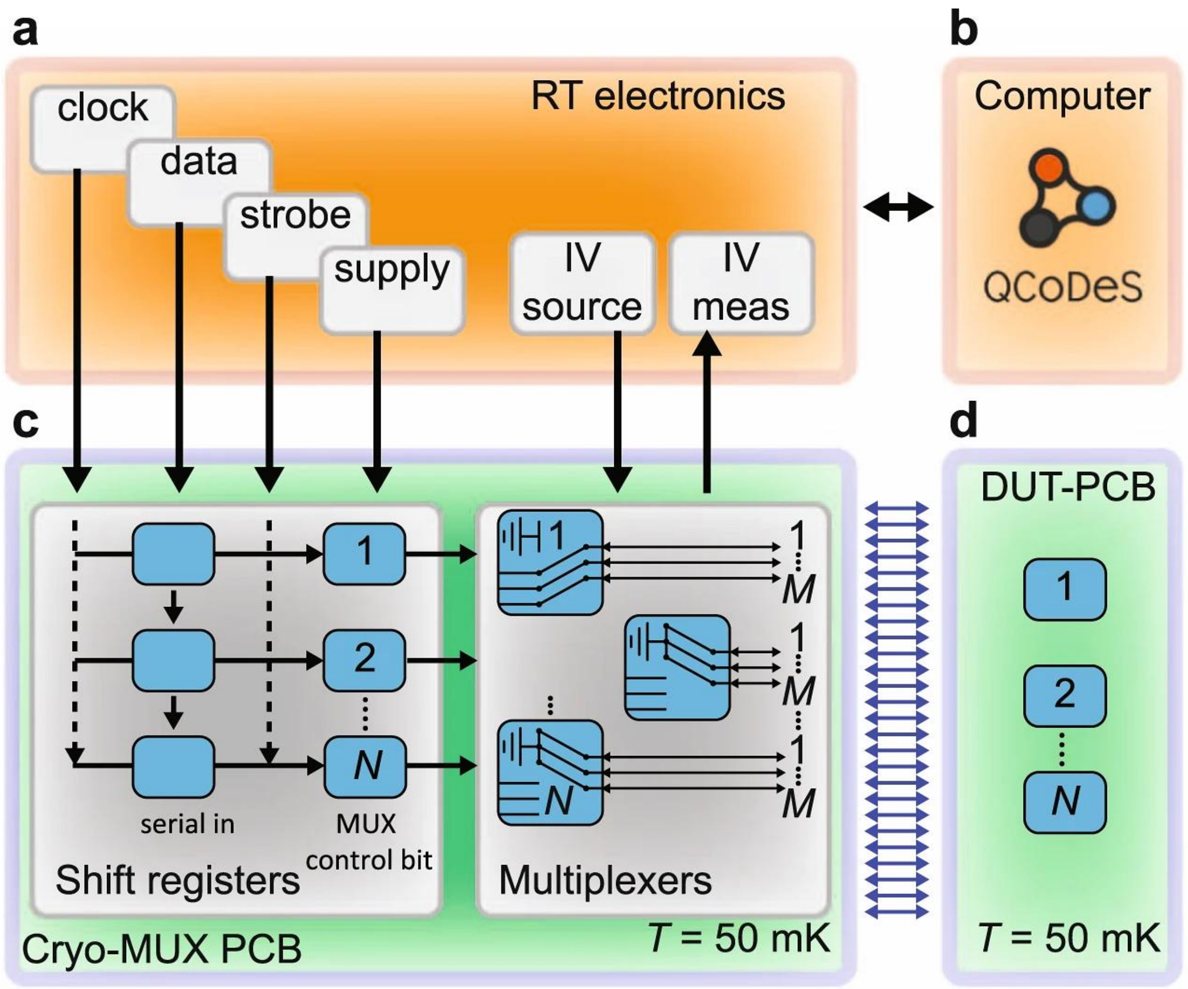




1. Xu et al., *IEEE Transactions on Quantum Engineering* (2021)

Commercial Cryo-CMOS Multiplexer Control of Qubits



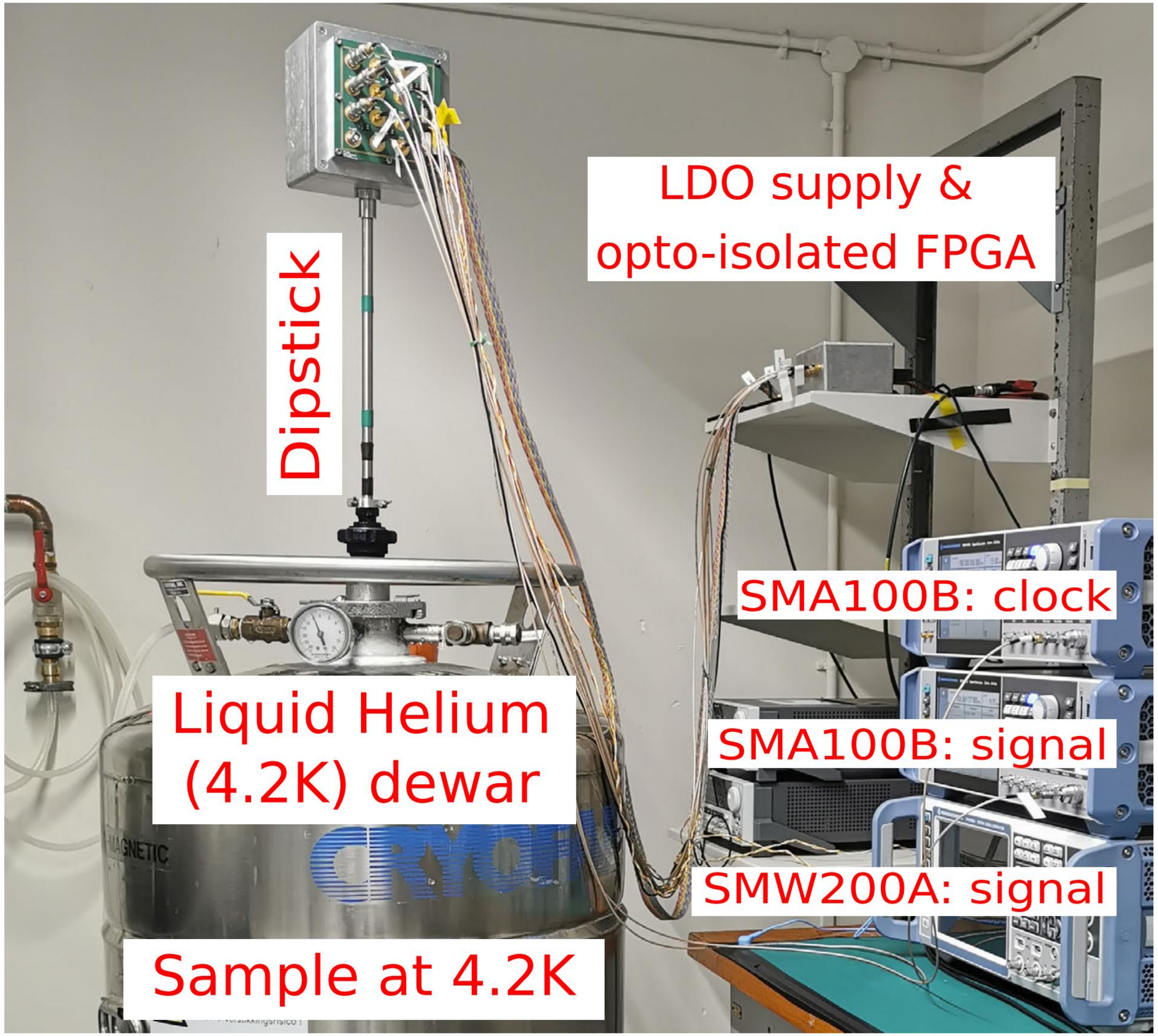


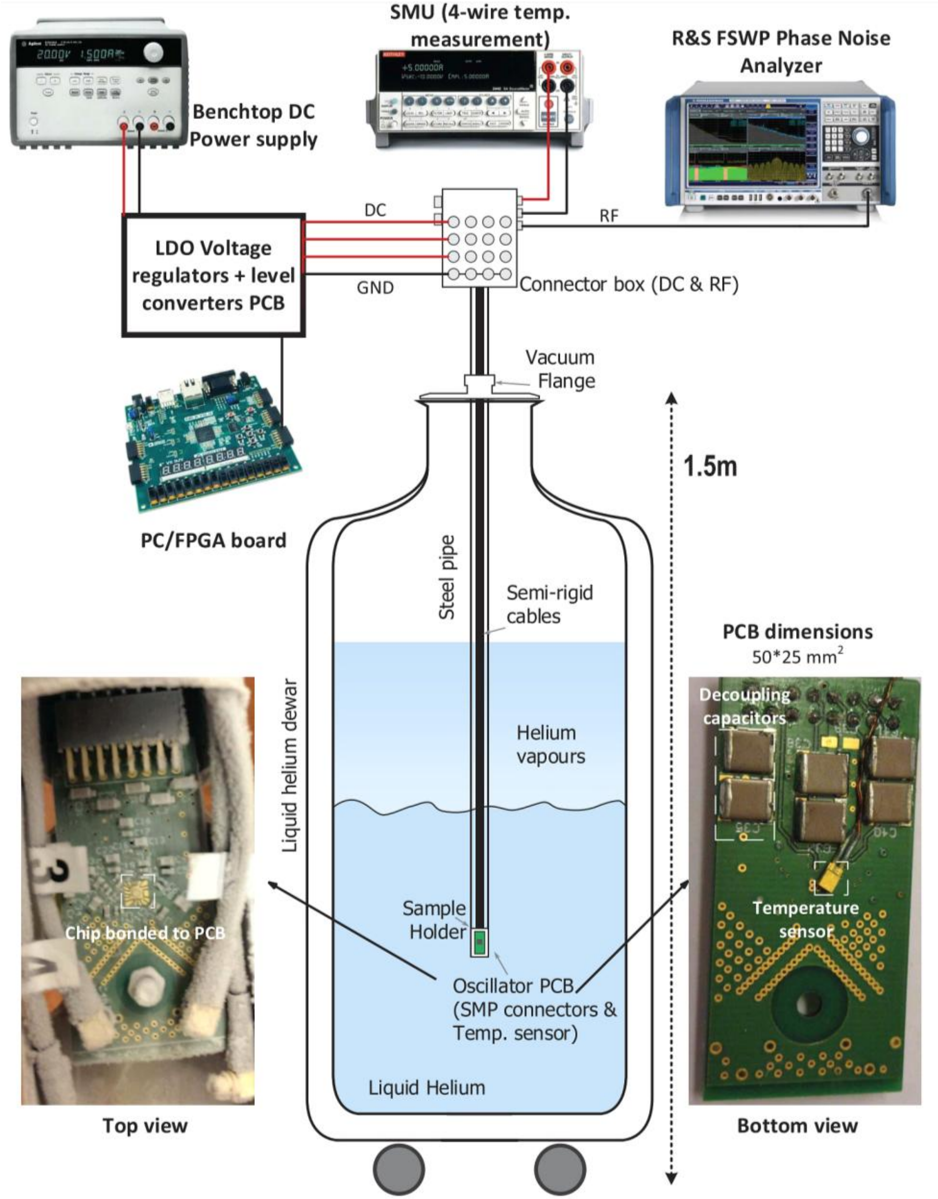
*DUT: Device Under Test

- ”dumb” electronics at 300 K
- “smart” electronics at 50 mK

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

External FPGA & Cryo-CMOS Control/Readout of Qubits



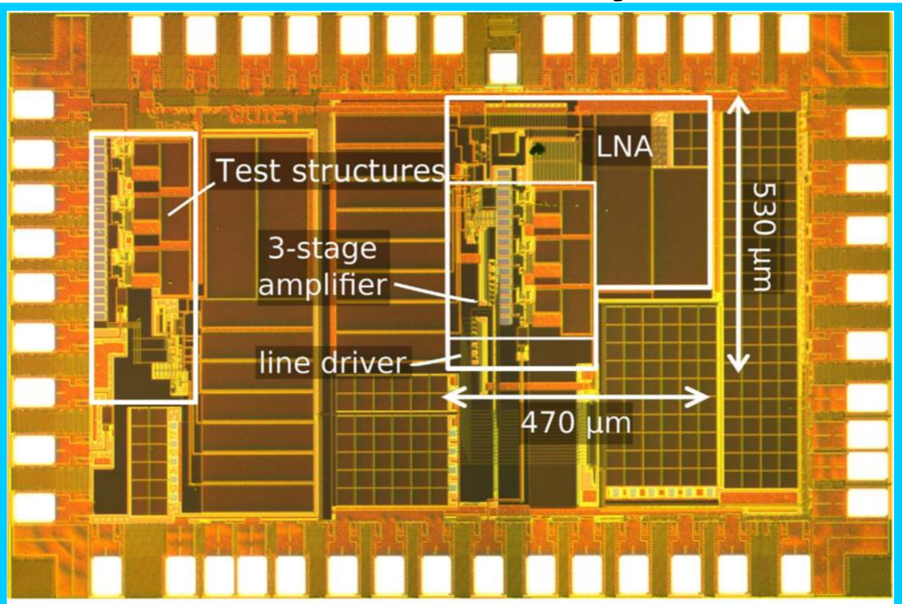


1. Patra et al., *IEEE J. Solid-State Circuits* (2018)
2. Kiene et al., *IEEE J. Solid-State Circuits* (2023)

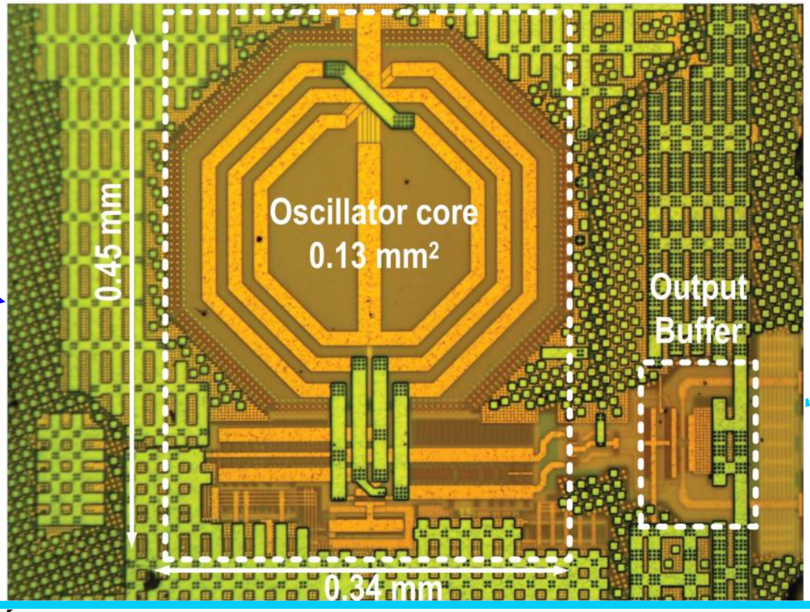
*LNA: Low Noise Amplifier

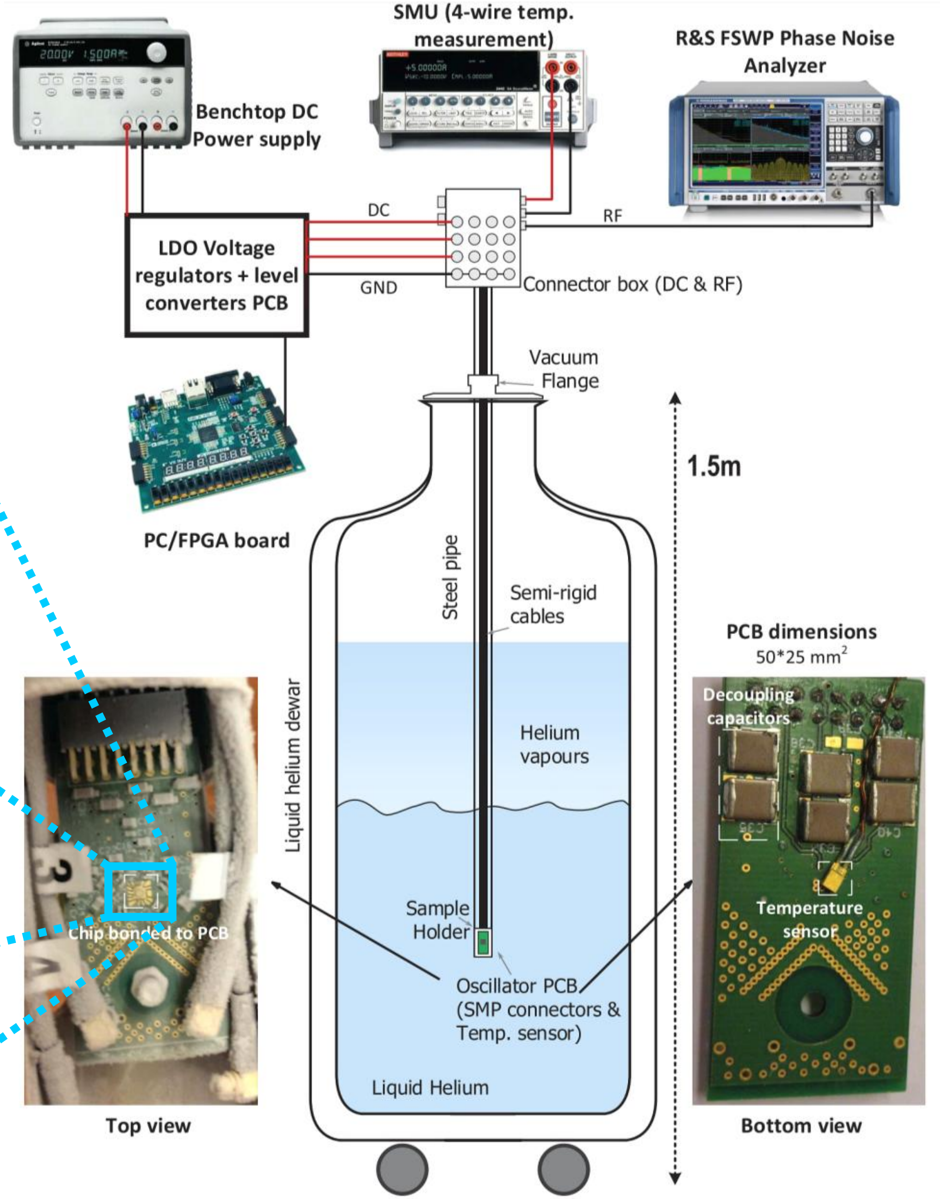
External FPGA & Cryo-CMOS Control/Readout of Qubits

CMOS Amplifier



CMOS Oscillator

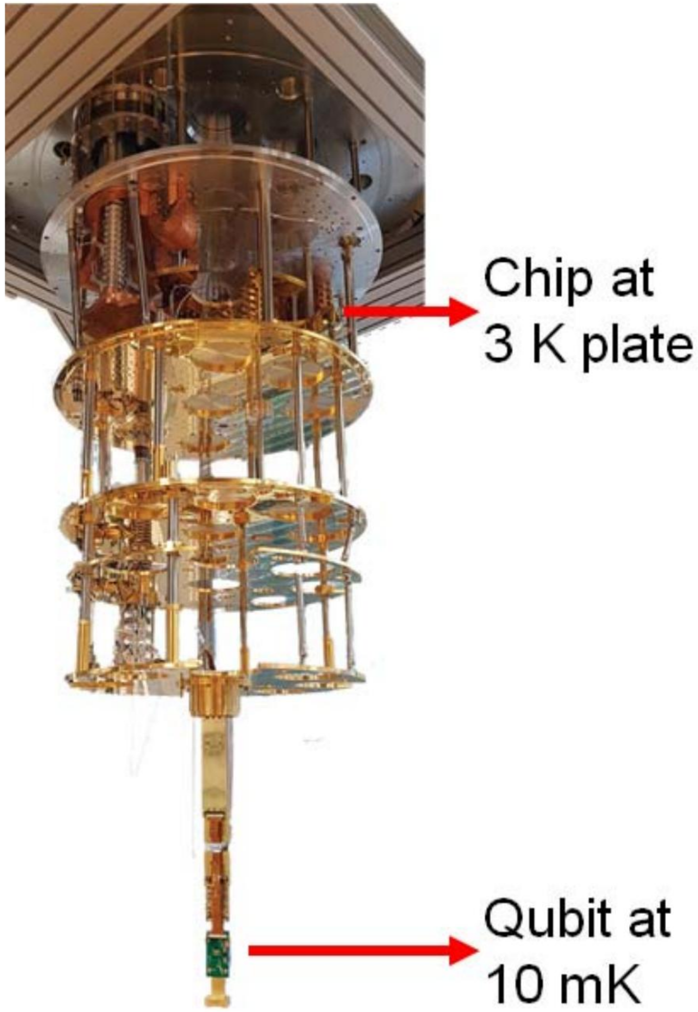


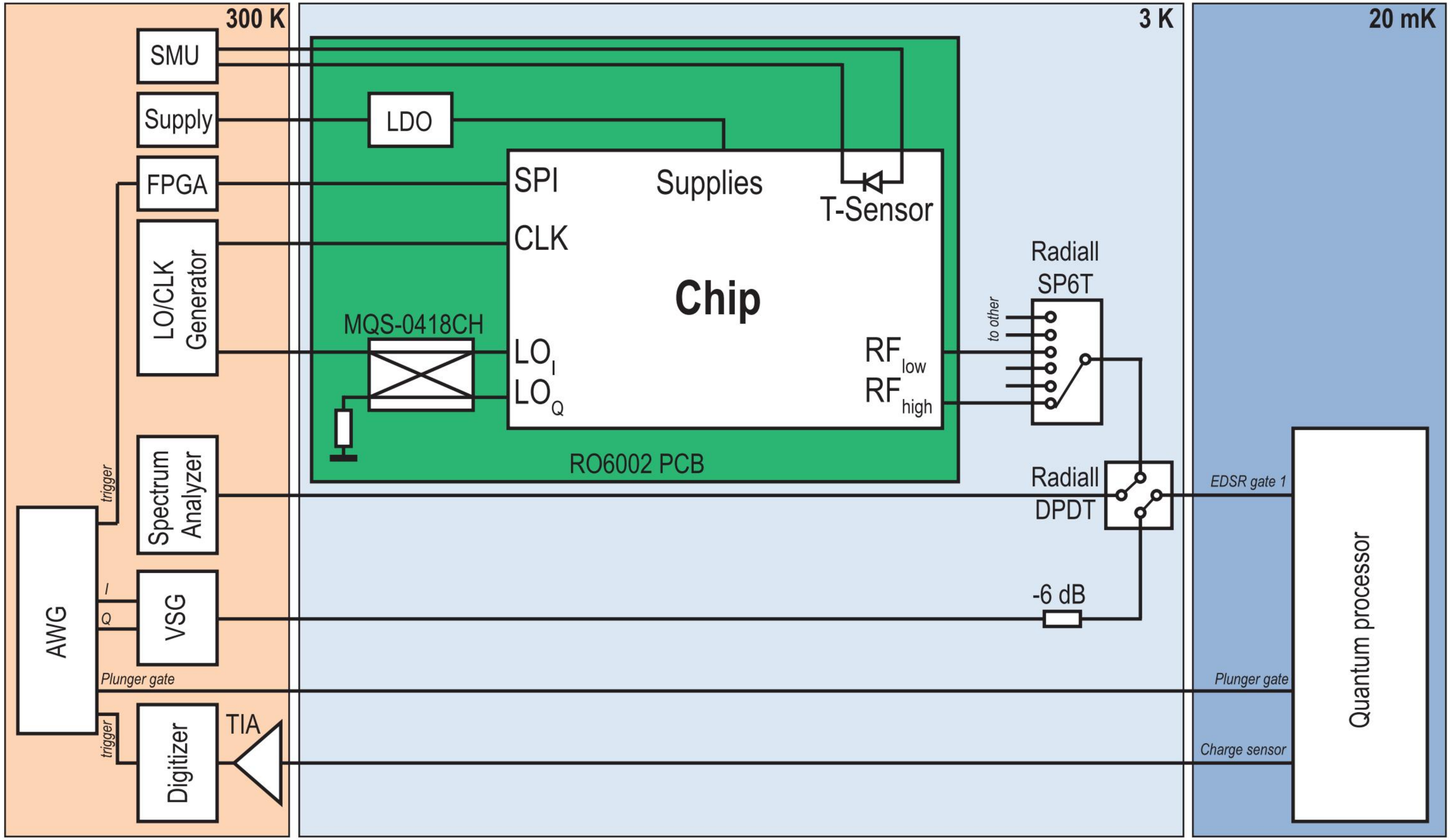


1. Patra et al., *IEEE J. Solid-State Circuits* (2018)

- LNA: Low Noise Amplifier = spin qubit RF reflectometry readout
- Oscillator (Digitally Controlled) = spin qubit state manipulation

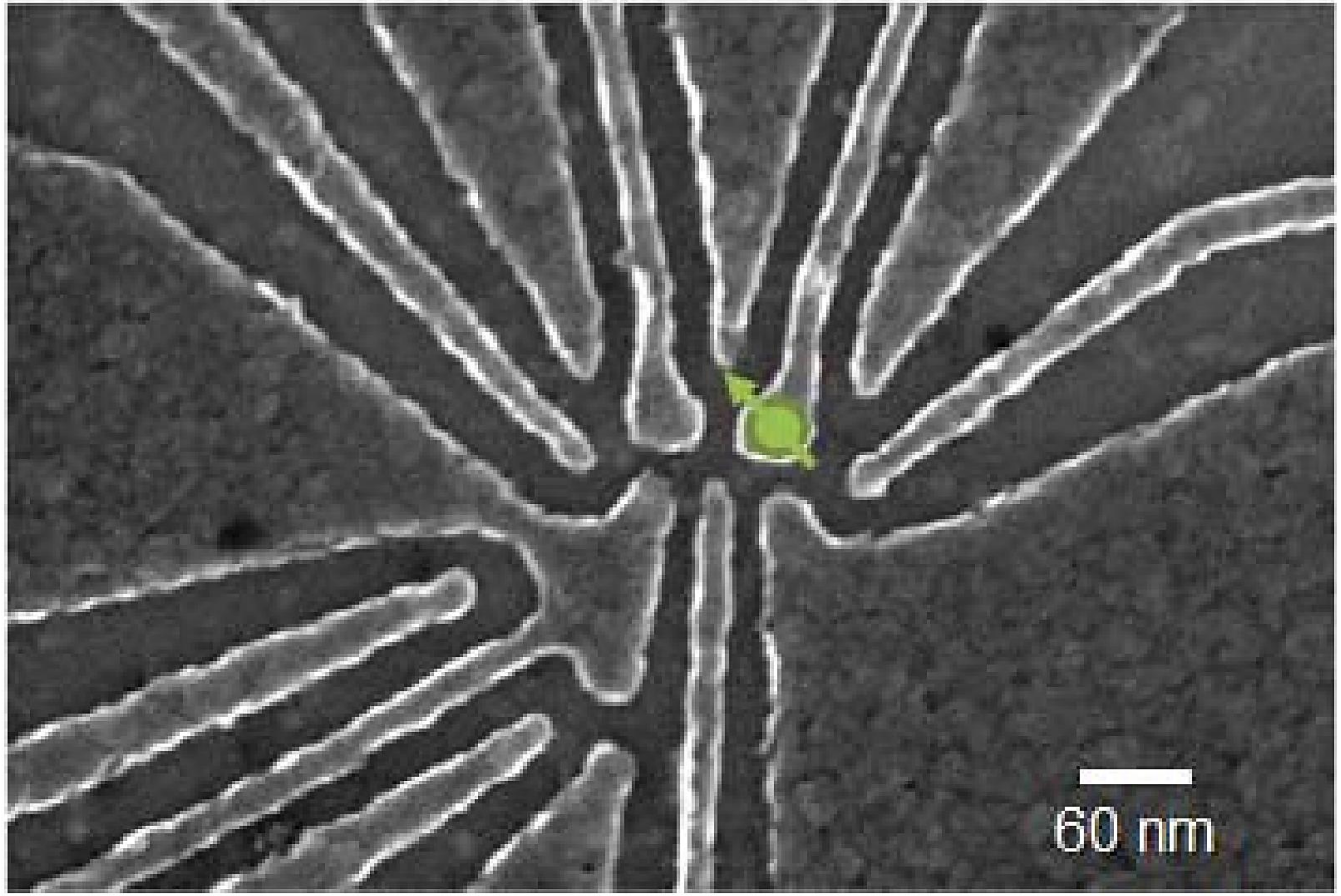
Example of Cryo-CMOS Qubit Control Setup





1. van Dijk et al., *IEEE J. Solid-State Circuits* (2020)

Example of Cryo-CMOS Qubit Control Setup



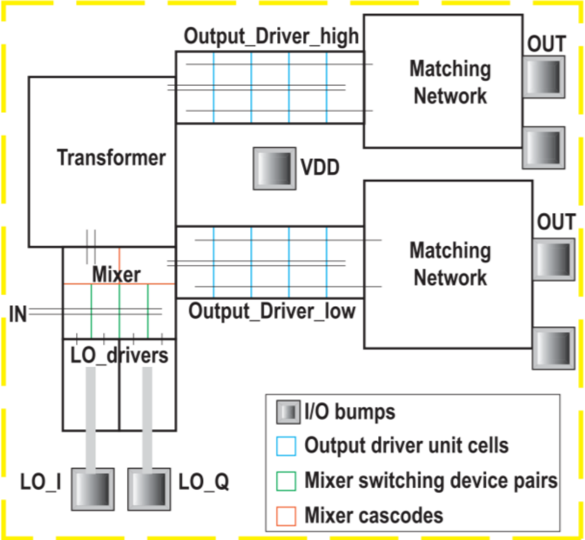
(a)

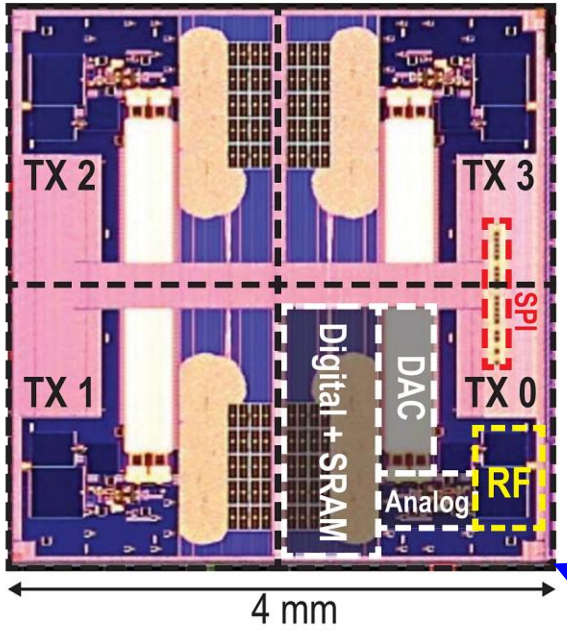
(b)

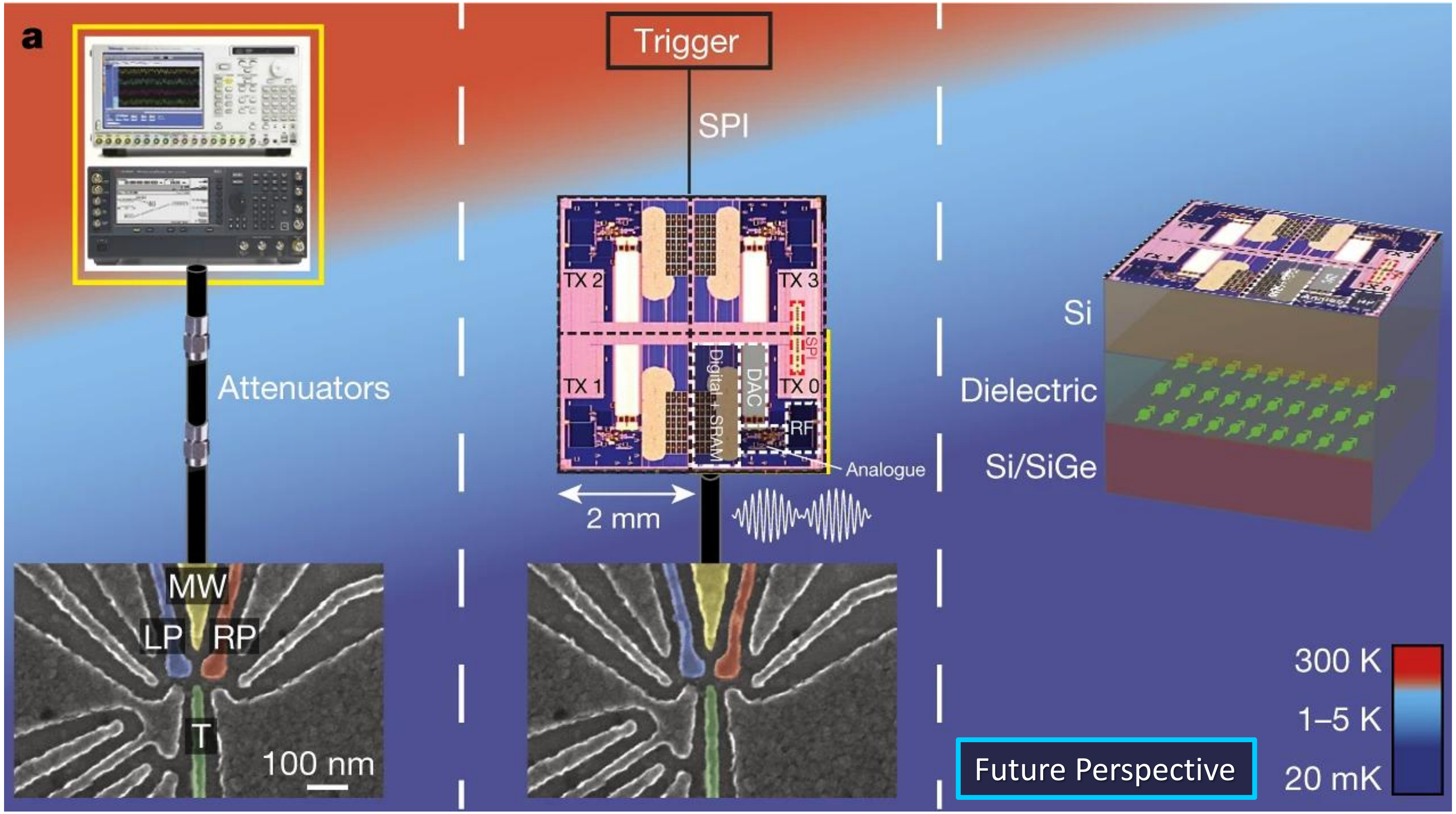
Patterned Single Spin Qubit Device

1. van Dijk et al., *IEEE J. Solid-State Circuits* (2020)

Example of Qubit Control Using Cryo-CMOS



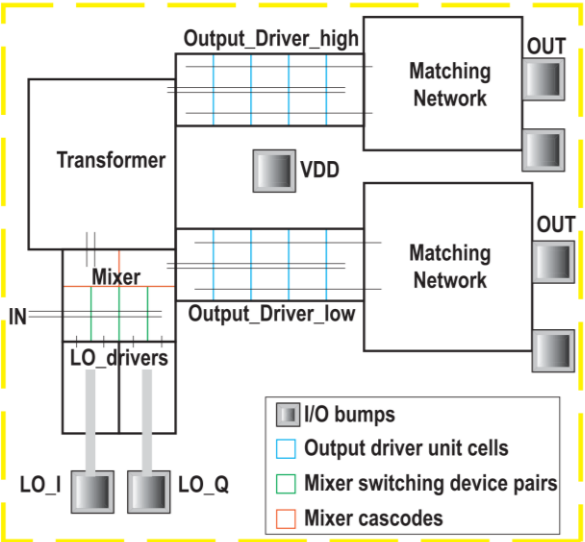


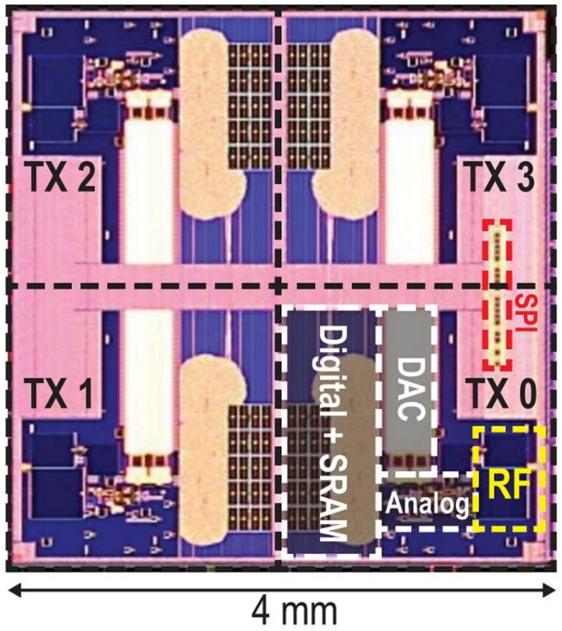


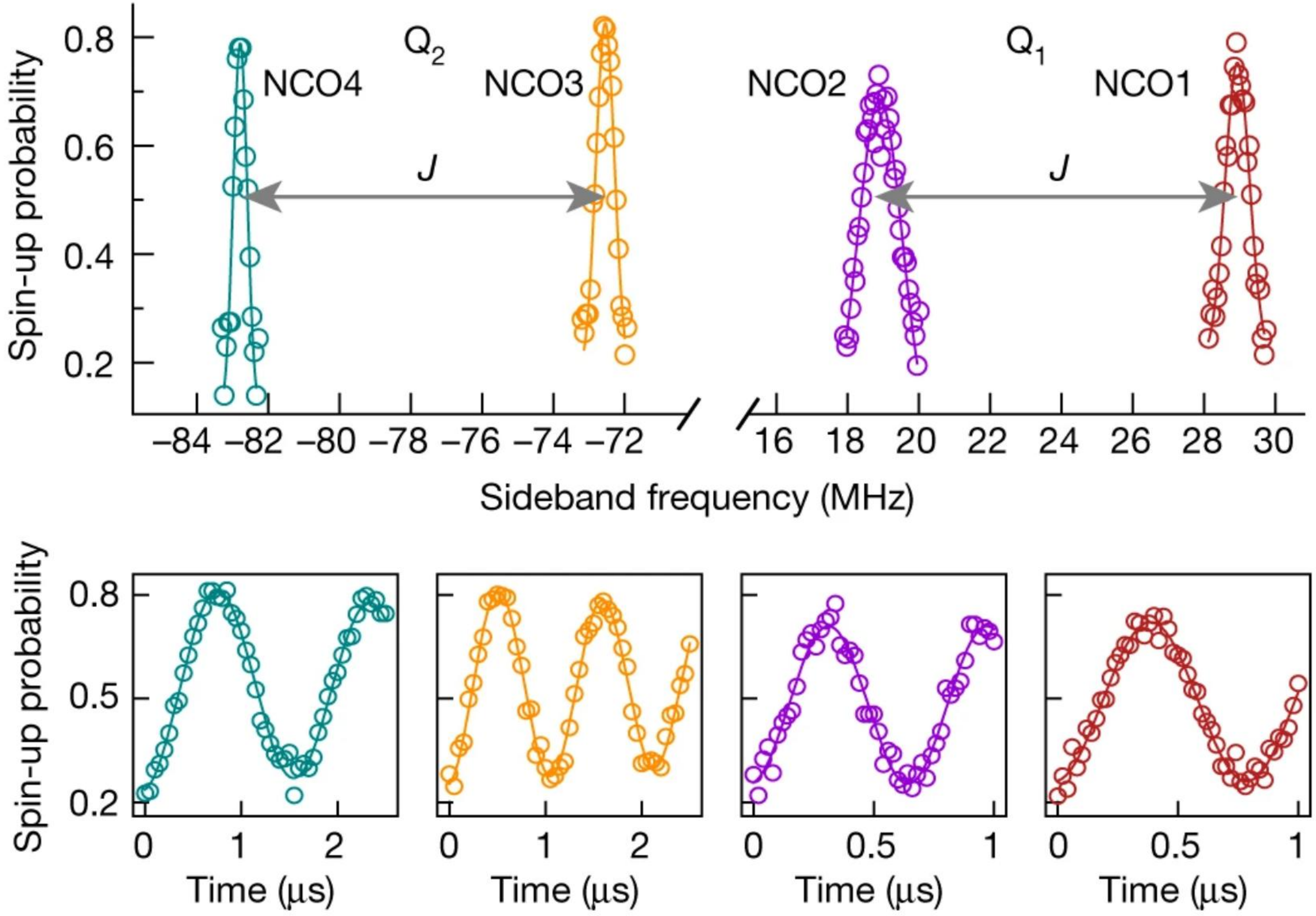
Intel Horse Ridge Chip

1. van Dijk et al., *IEEE J. Solid-State Circuits* (2020)

Example of Qubit Readout Using Cryo-CMOS







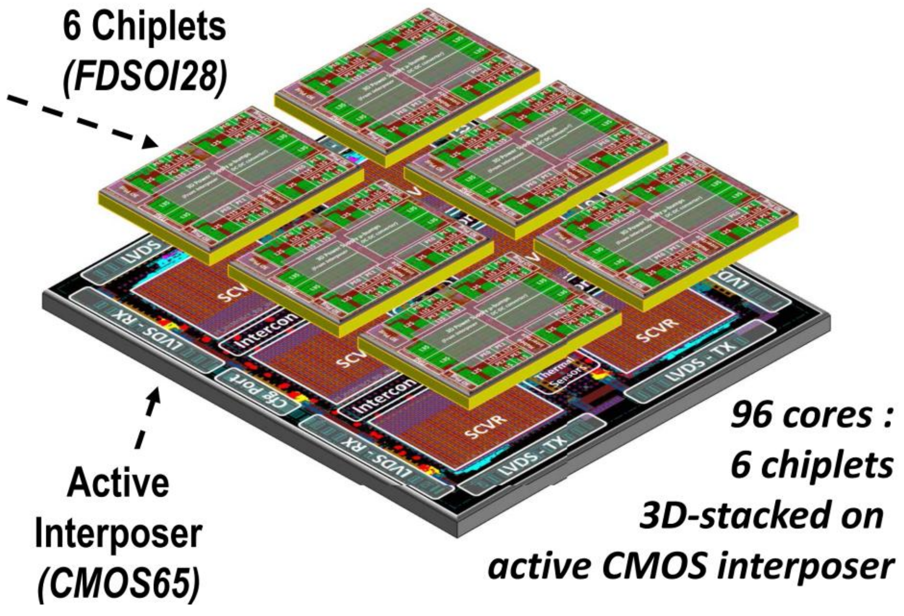
1. van Dijk et al., *IEEE J. Solid-State Circuits* (2020)

Comparison of Cryogenic Interface Electronics

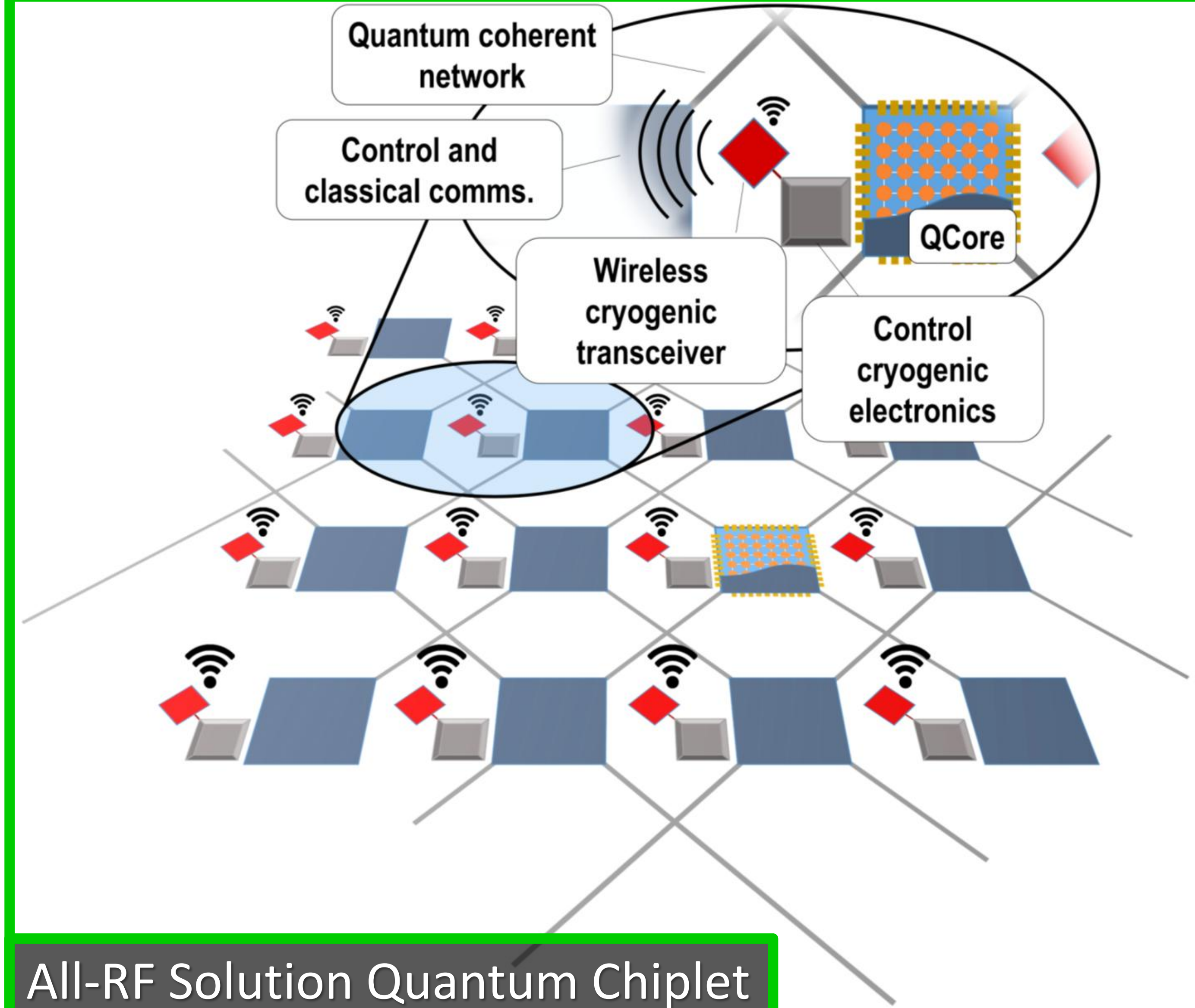
		This Work	ISSCC'22 [24]	ISSCC'21 [16]	VLSI'21 [23]	ISSCC'20 [17]	JSSC'19 [8]
Operating Temperature		3.5 K	3 K	4 K	77 K	3 K	3 K
Qubit Platform		Transmons	Transmons	Spin Qubits	Transmons	Spin Qubits	Transmons
Target fidelity		99.99% (expected)	N/A	99.99%	N/A	99.99%	99.99%
Power	**Analog**	Modulator: 8.3 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 J. Solid-State Circuits* (2022)

Towards Multi-Core Quantum Chiplet Architecture



96-Core Classical Chiplet



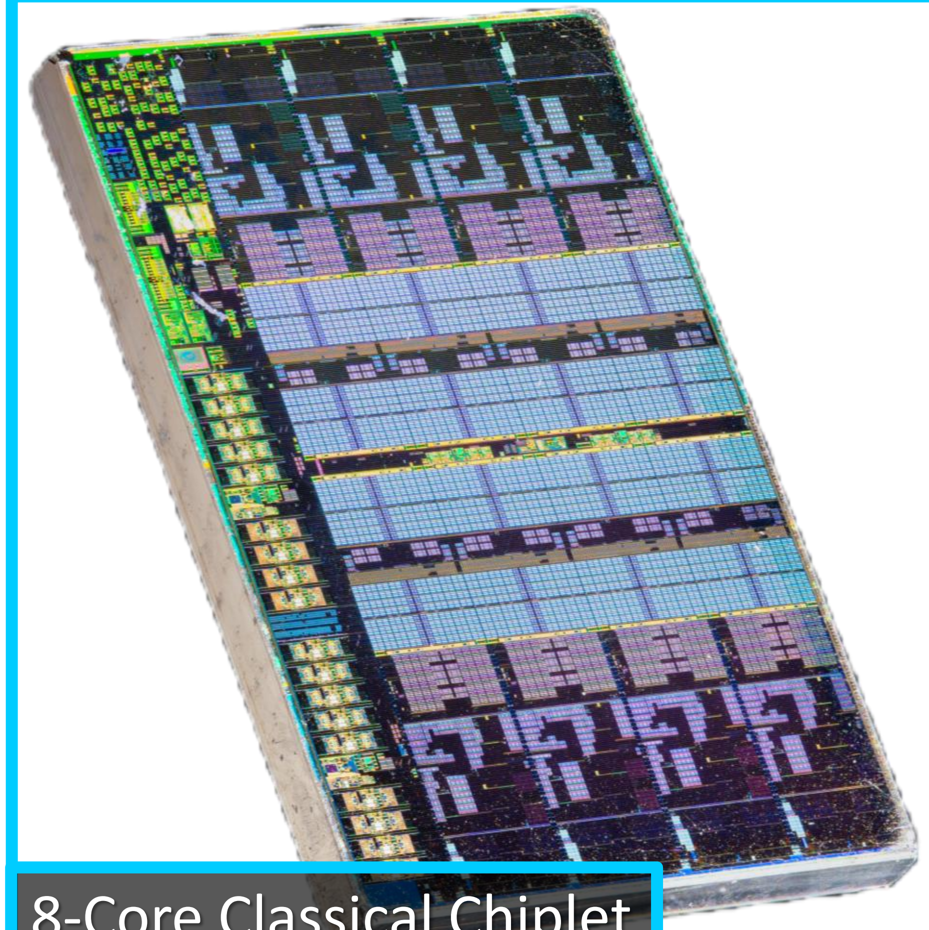
All-RF Solution Quantum Chiplet

*Chiplet: clusters of cores

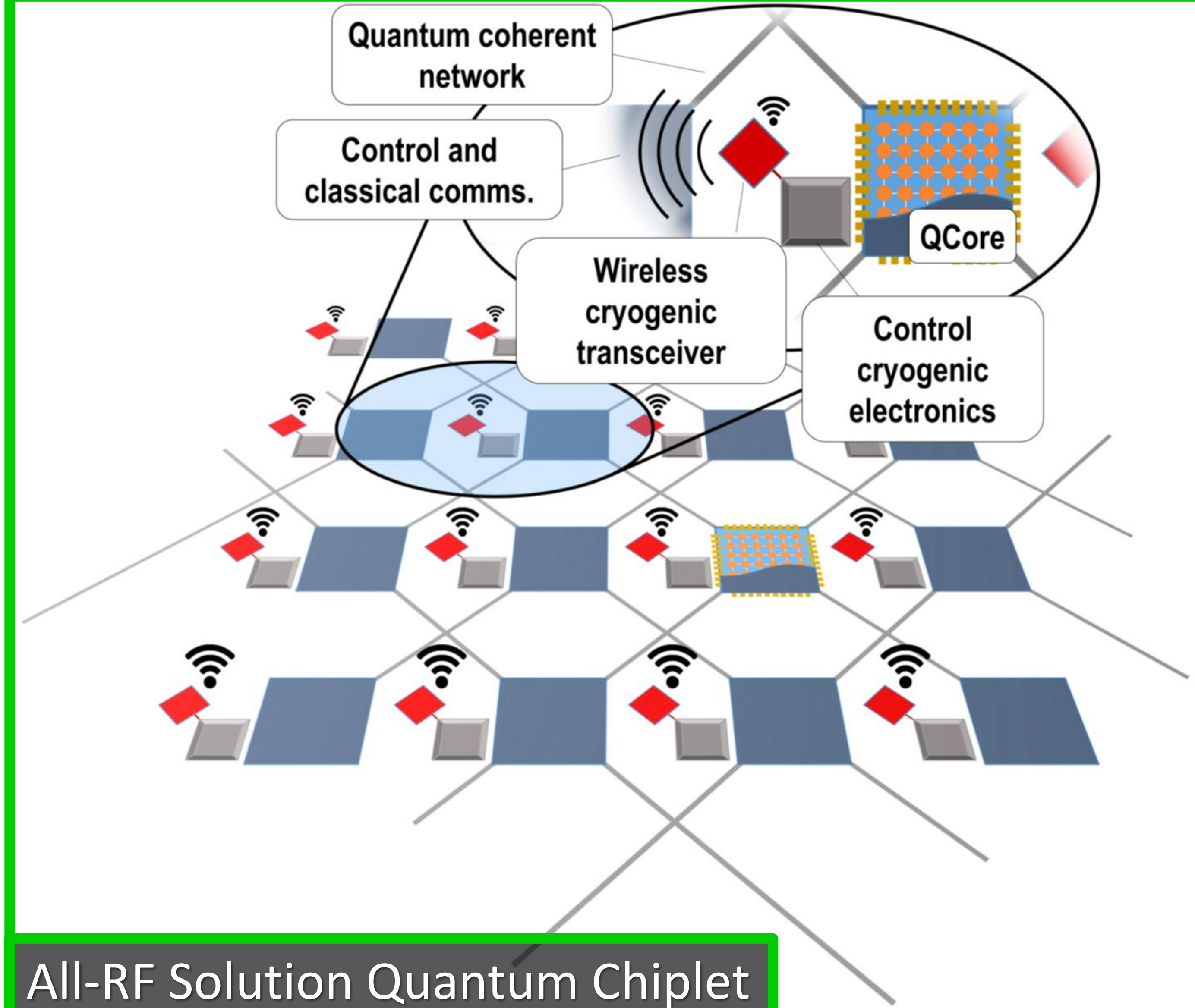
1. Vivet et al., IEEE *J. Solid-State Circuits* (2021)

2. Alarcon et al., *arXiv* (2023)

Towards Multi-Core Quantum Chiplet Architecture



8-Core Classical Chiplet



All-RF Solution Quantum Chiplet

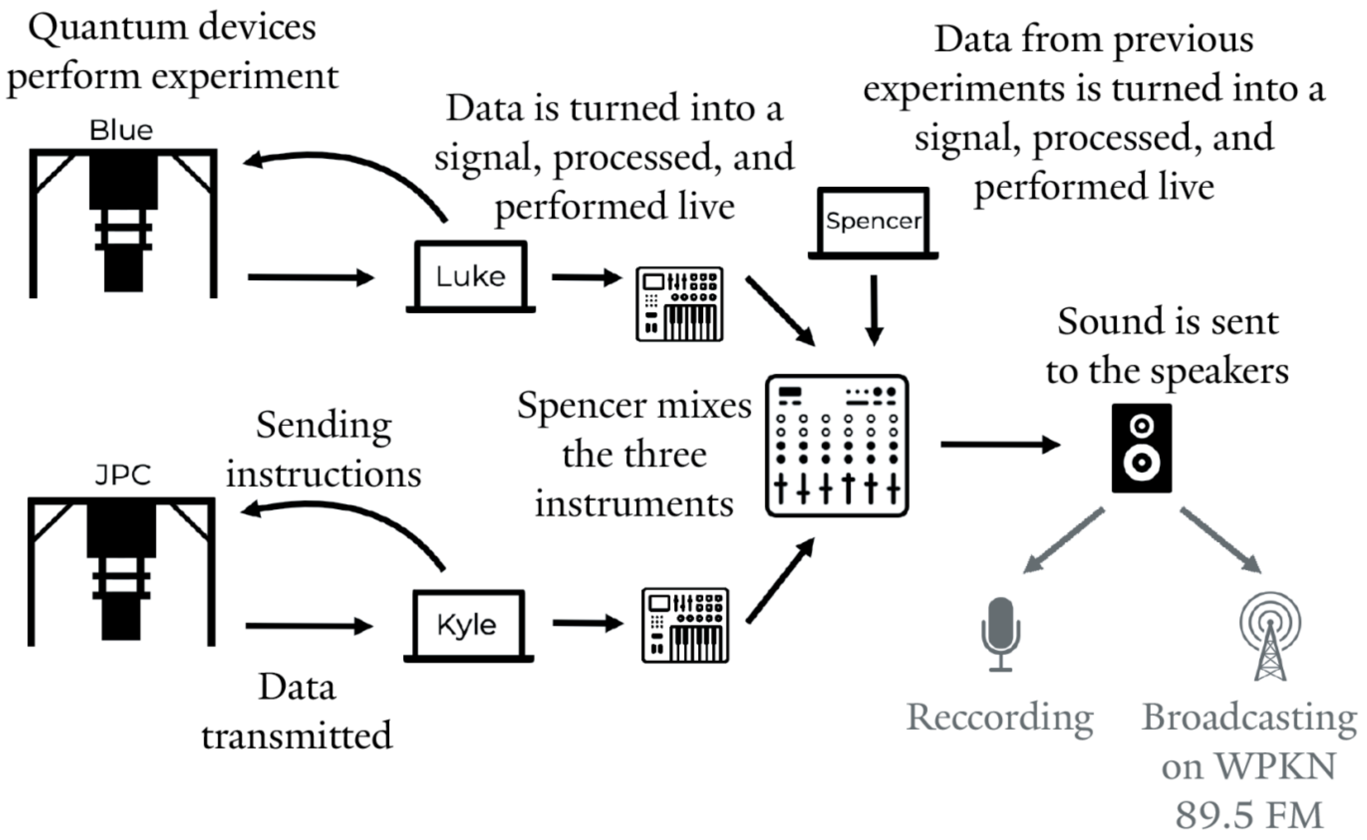
*Chiplet: clusters of cores

1. Fritzchens Fritz, AMD Ryzen *7800X3D* (2023)

2. Alarcon et al., *arXiv* (2023)

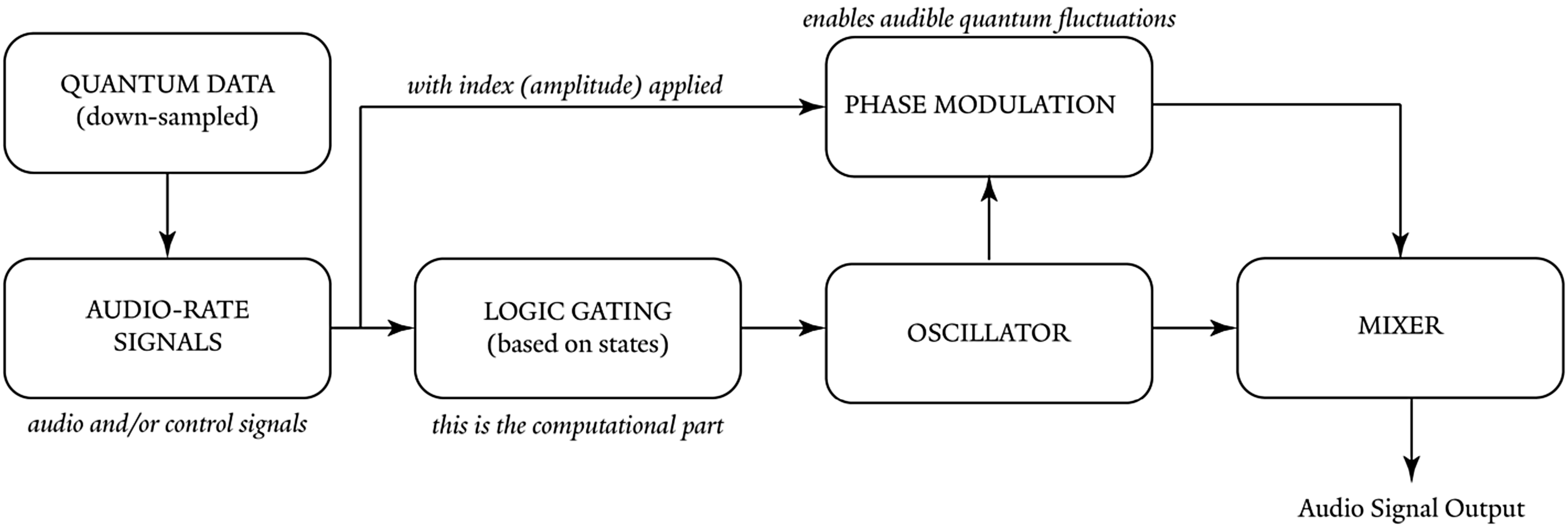
Example of Qubit Waveforms Converted to Music

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.



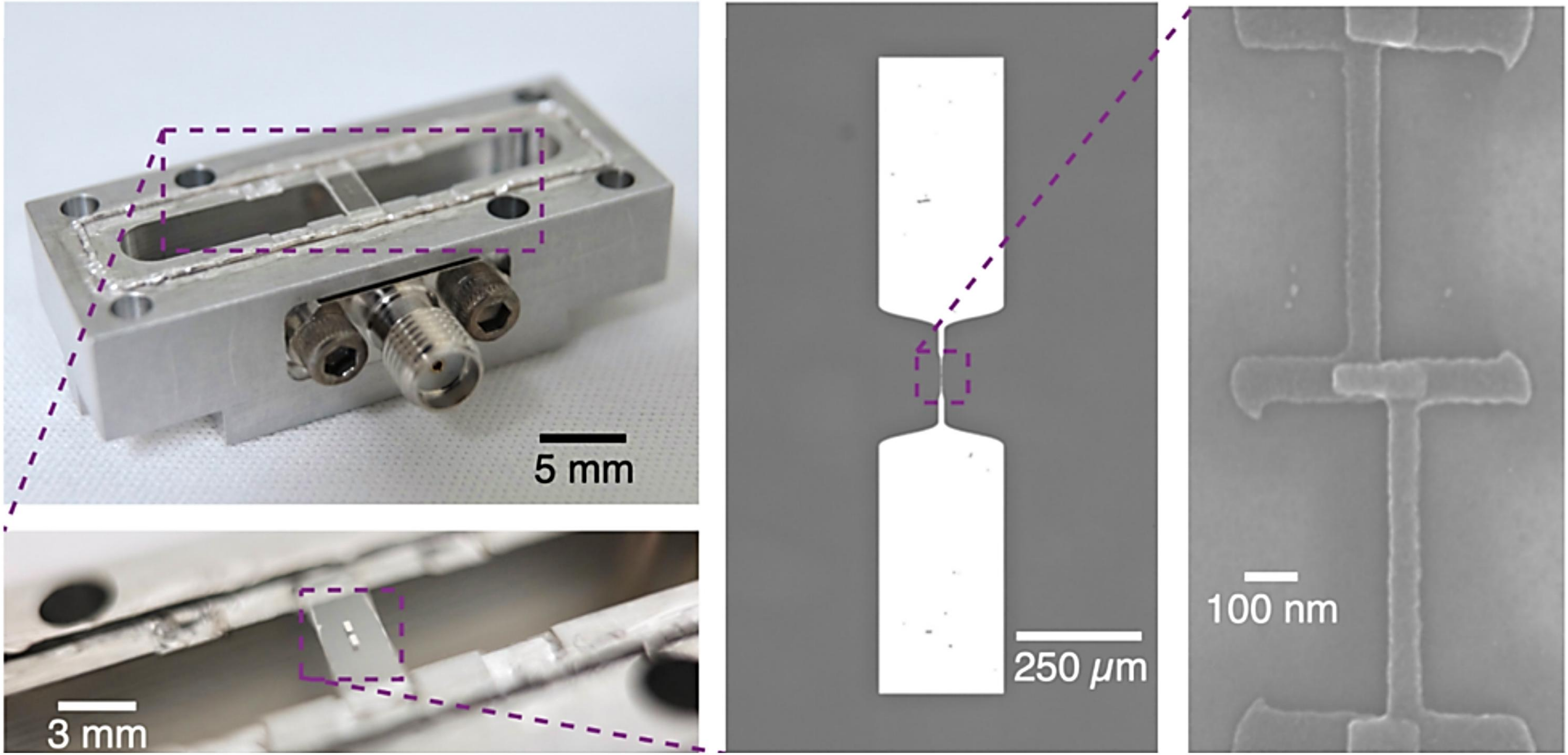
1. Topel et al. *arXiv* (2022)

Example of Qubit Waveforms Converted to Music



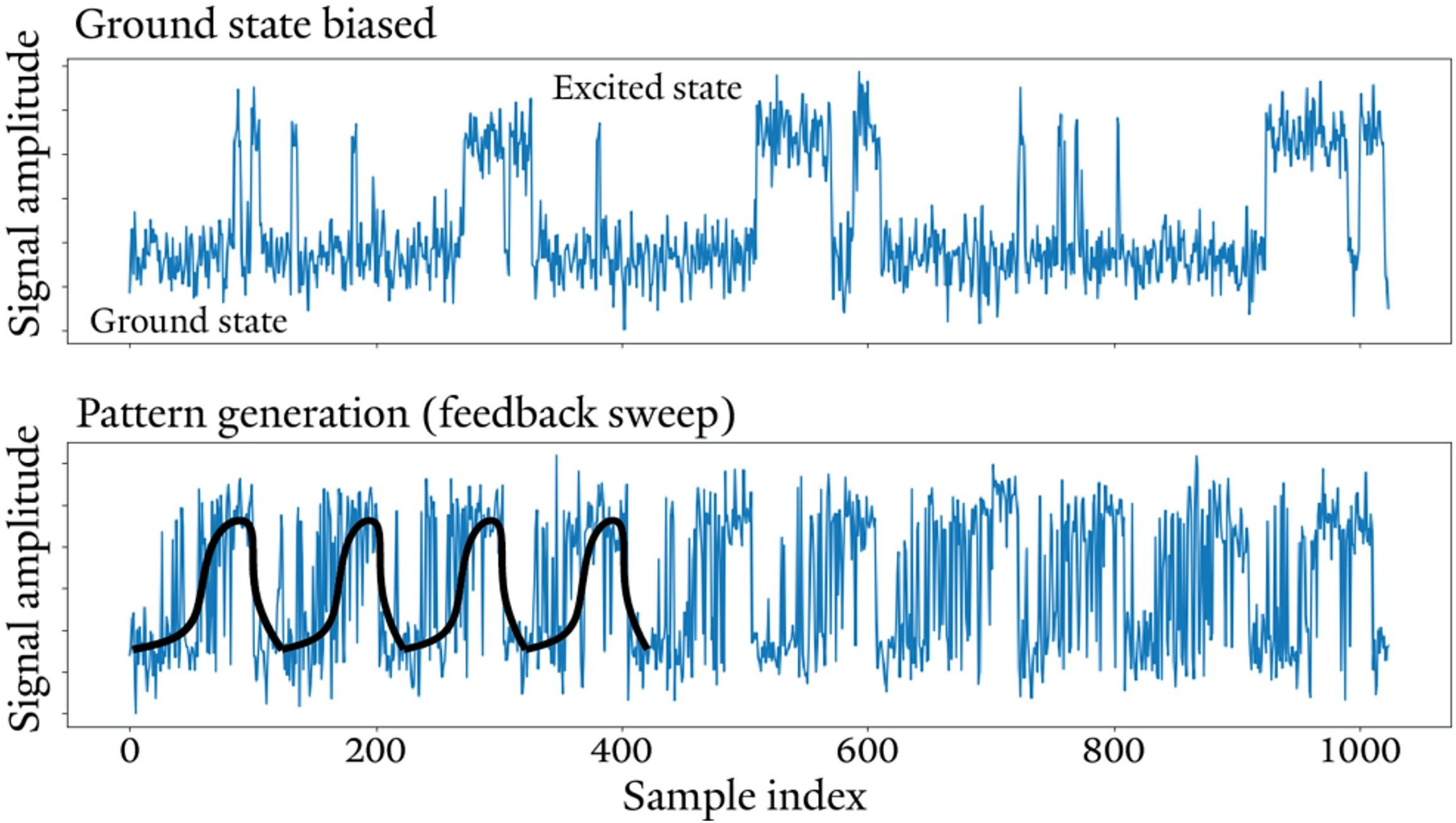
Available for listening at: QuantumInstitute.yale.edu/Quantum-Sound

Example of Audio Frequency Qubits Used in Music



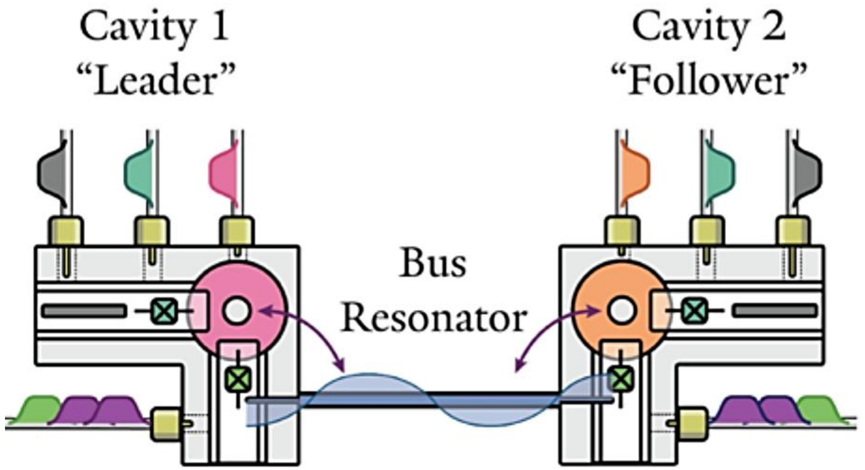
1. Topel et al. *arXiv* (2022)

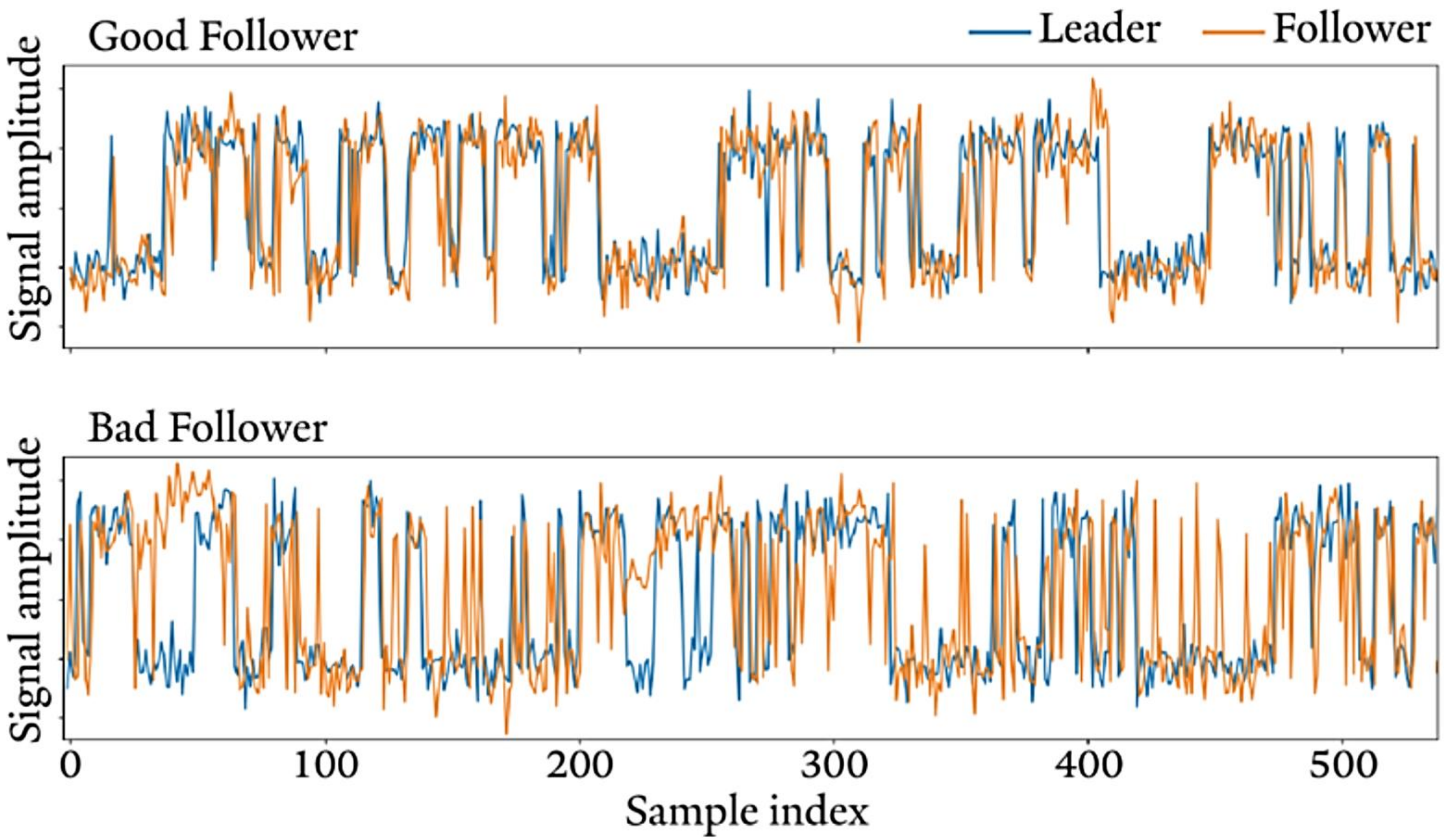
Example of Qubit Waveforms Converted to Music



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

Example of Qubit Waveforms Converted to Music



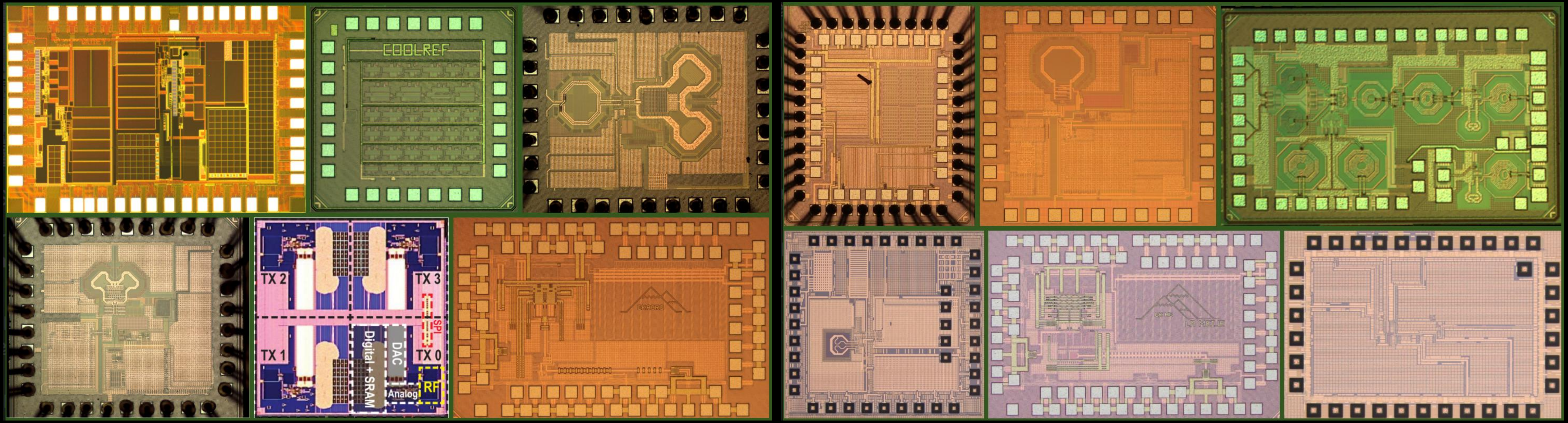


1. Topel et al. *arXiv* (2022)

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.
- There are many configuration options available.

Bonus: Quantum Integrated Circuits (Control/ Readout)

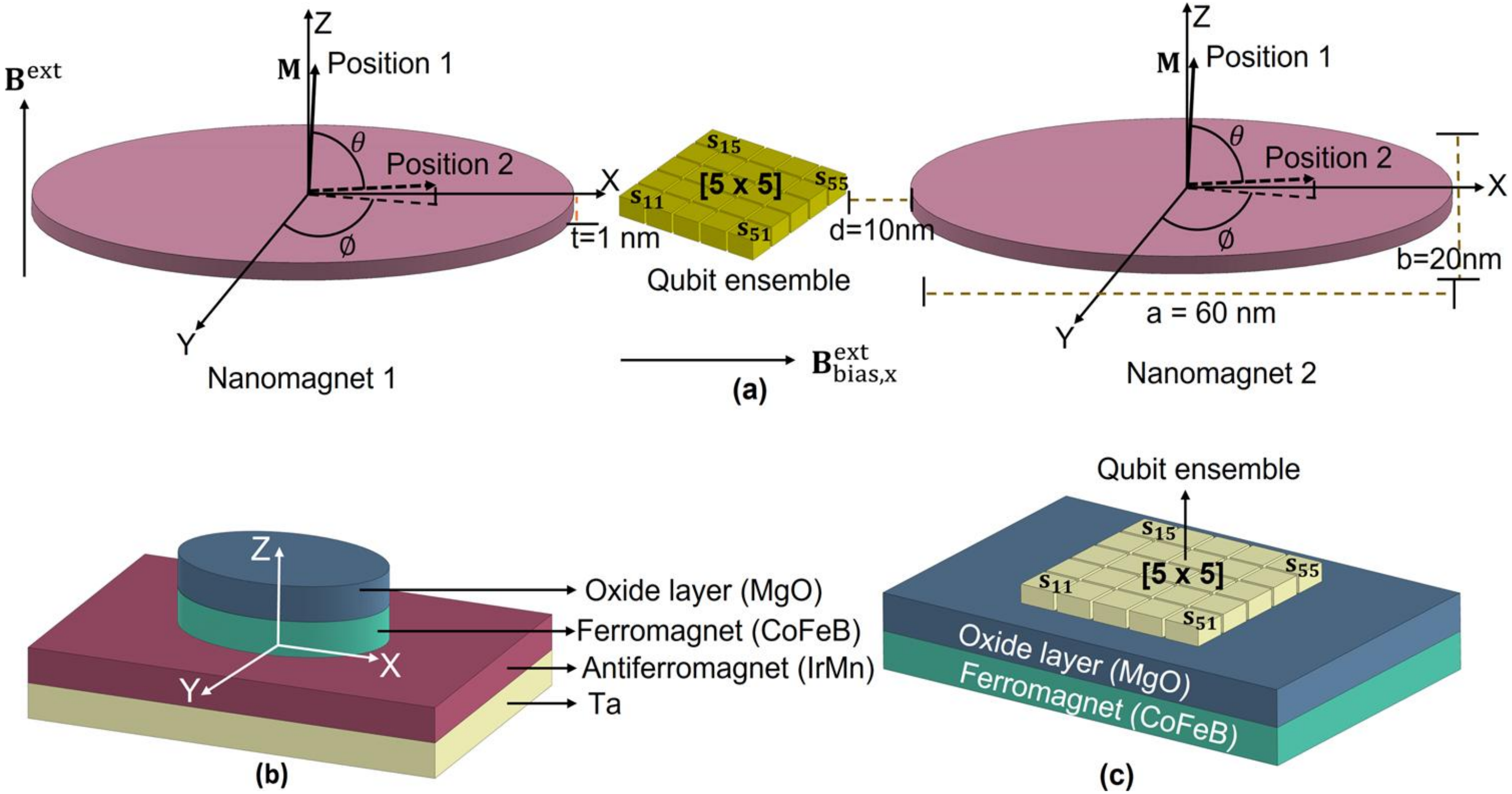


Taken from: tudelft.nl

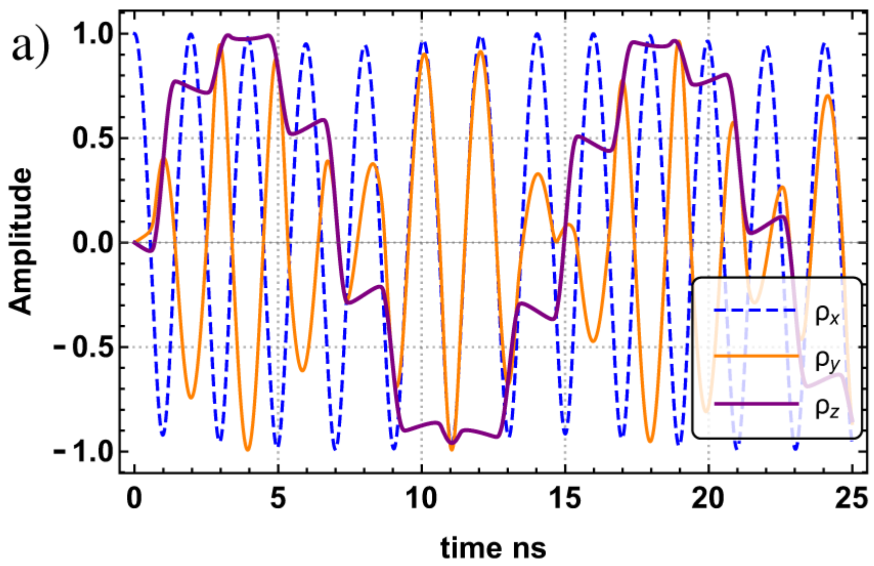
Bonus: Documented Spin Qubit Approaches

The following slides are based on the use of micromagnetic computation tools such as MuMax & finite element simulation platforms such as QTCAD for spin qubits & their readout mechanisms.

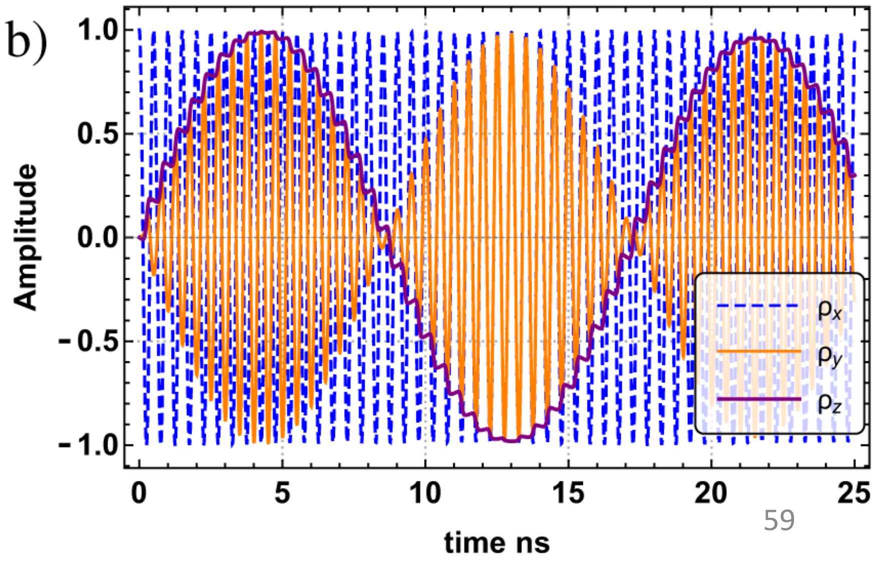
Bonus: Qubit Nanomagnetic Simulation (Voltage Control)



Qubit Ensemble Driven at 500 MHz



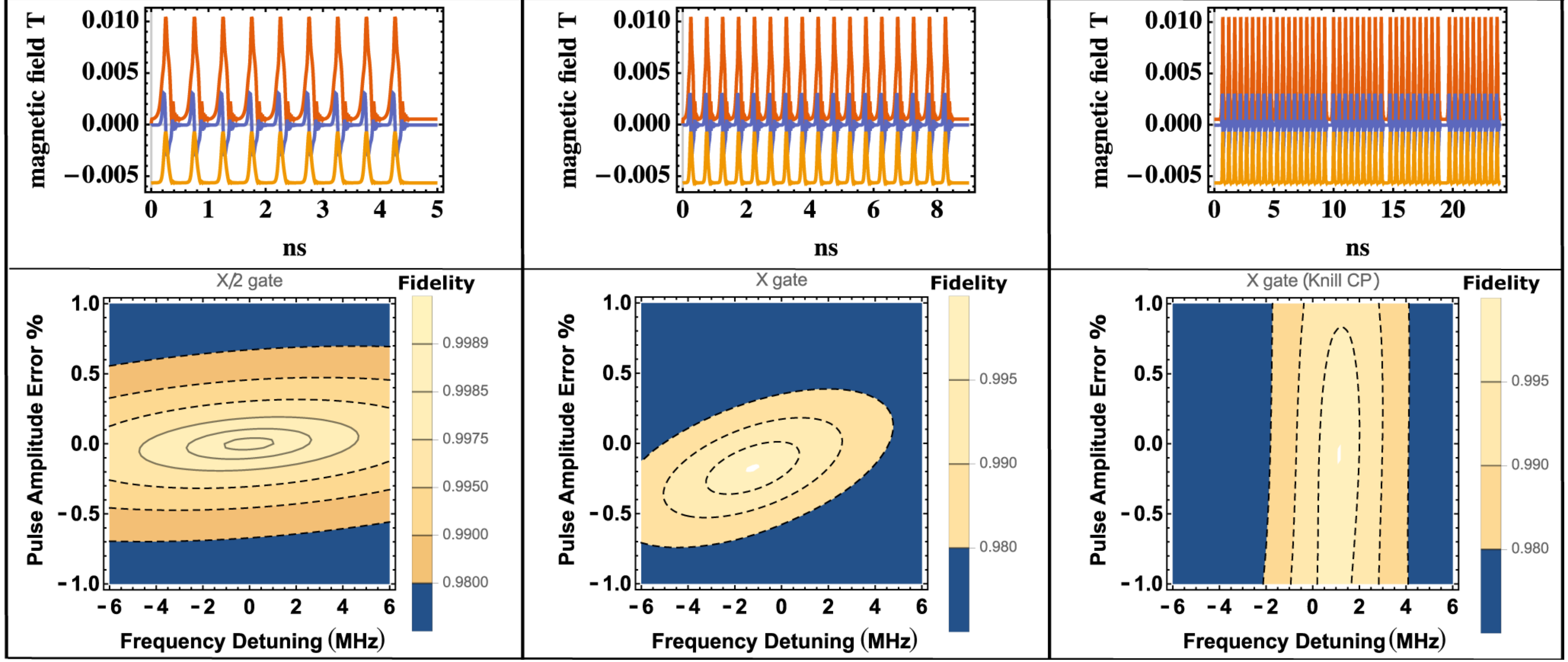
Qubit Ensemble Driven at 2 GHz



1. Niknam et al. *Nature* (2022)

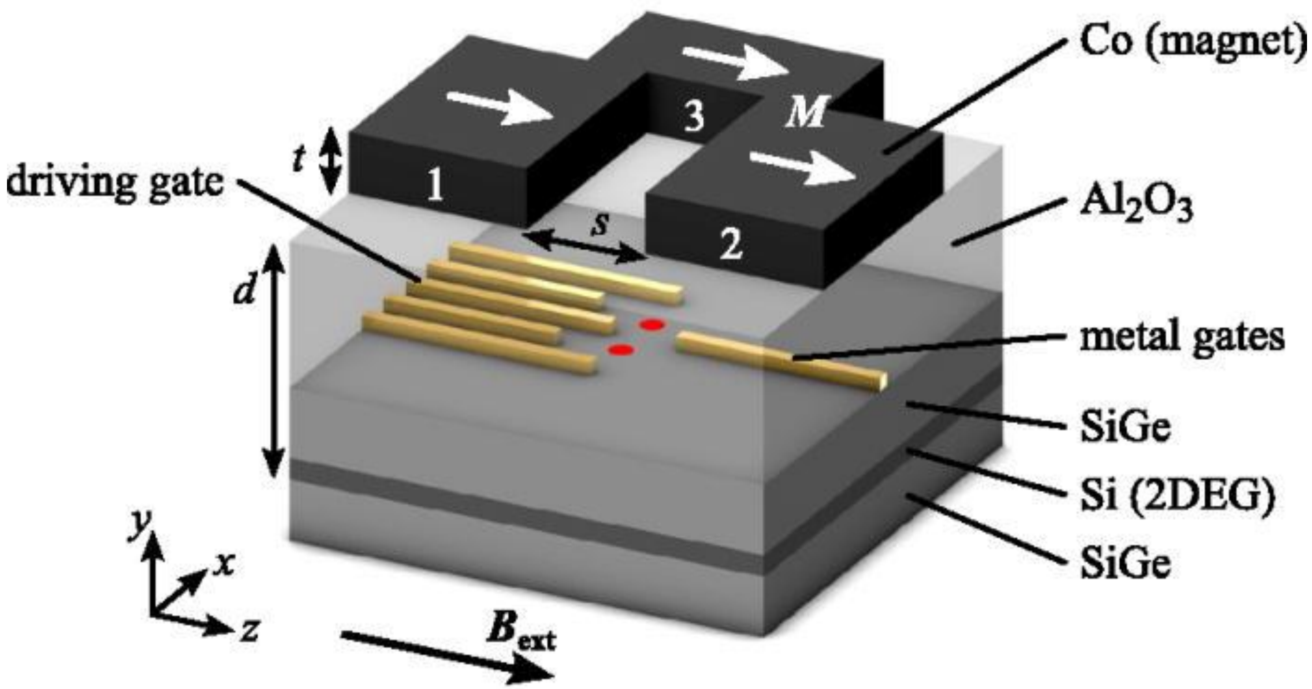
Bonus: Qubit Nanomagnetic Simulation (Voltage Control)

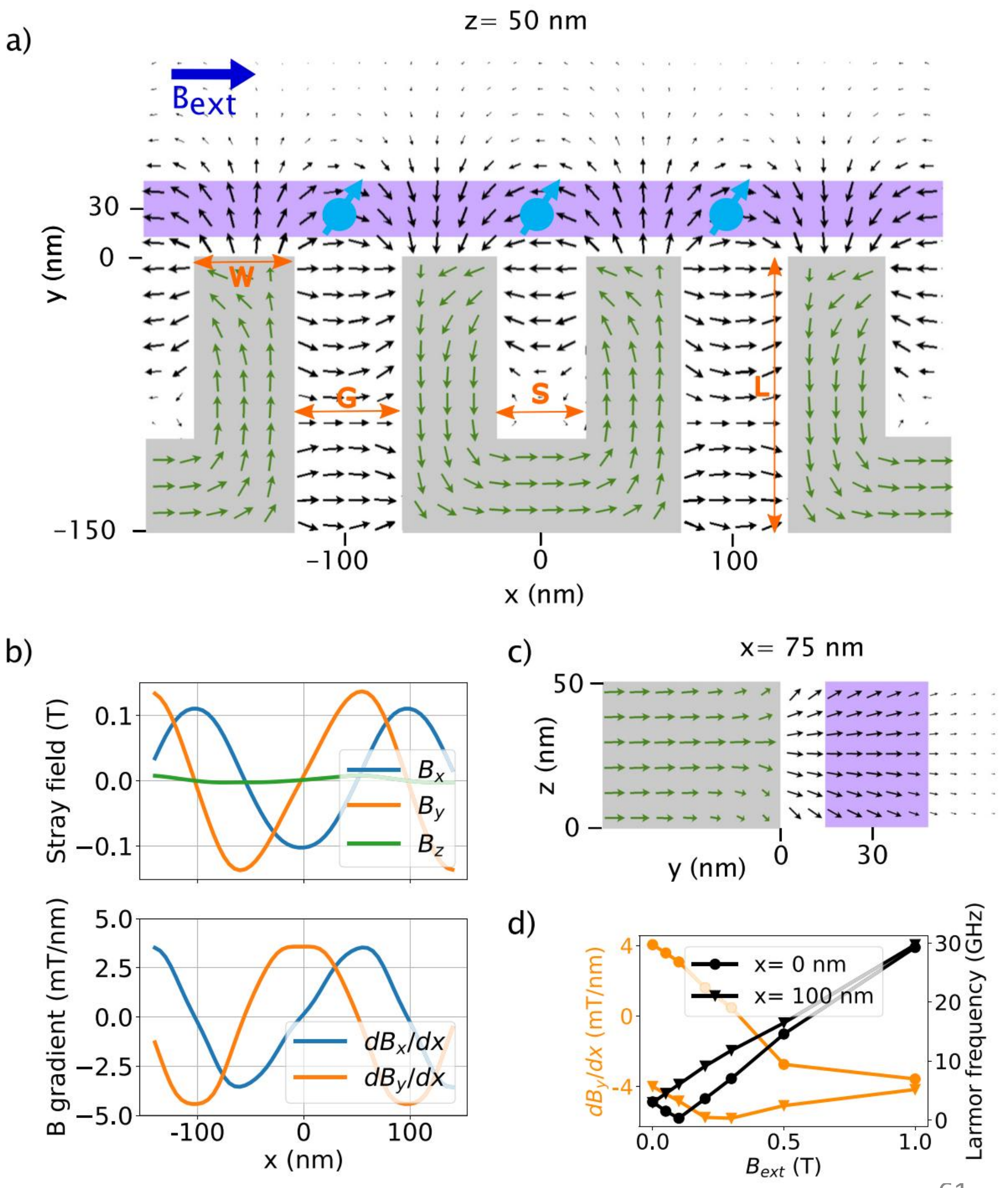
Gate X/2	Gate X	Gate X Knill CP
$\mathcal{H} = \exp\left(\frac{i}{2}\frac{\pi}{2}\sigma_X\right)$	$\mathcal{H} = \exp\left(\frac{i}{2}\pi\sigma_X\right)$	$\mathcal{H} = \exp\left(\frac{i}{2}\pi\sigma_X\right)$
Central qubit fidelity: 0.9997 ± 10^{-4}	Central qubit fidelity: 0.9987 ± 10^{-4}	Central qubit fidelity: 0.9993 ± 10^{-4}
Average fidelity: 0.9990 ± 10^{-4}	Average fidelity: 0.9952 ± 10^{-4}	Average fidelity: 0.9979 ± 10^{-4}



1. Niknam et al. *Nature* (2022)

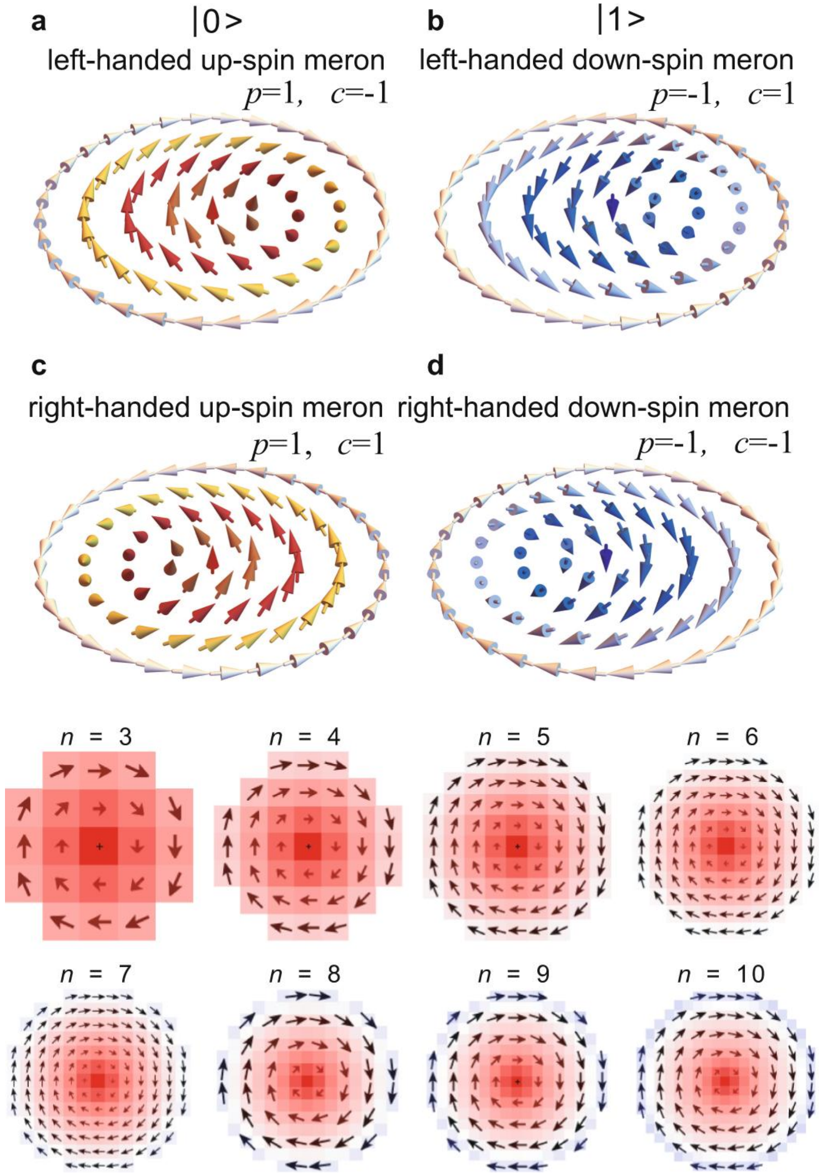
Bonus: Spin Qubit Manipulation Simulation

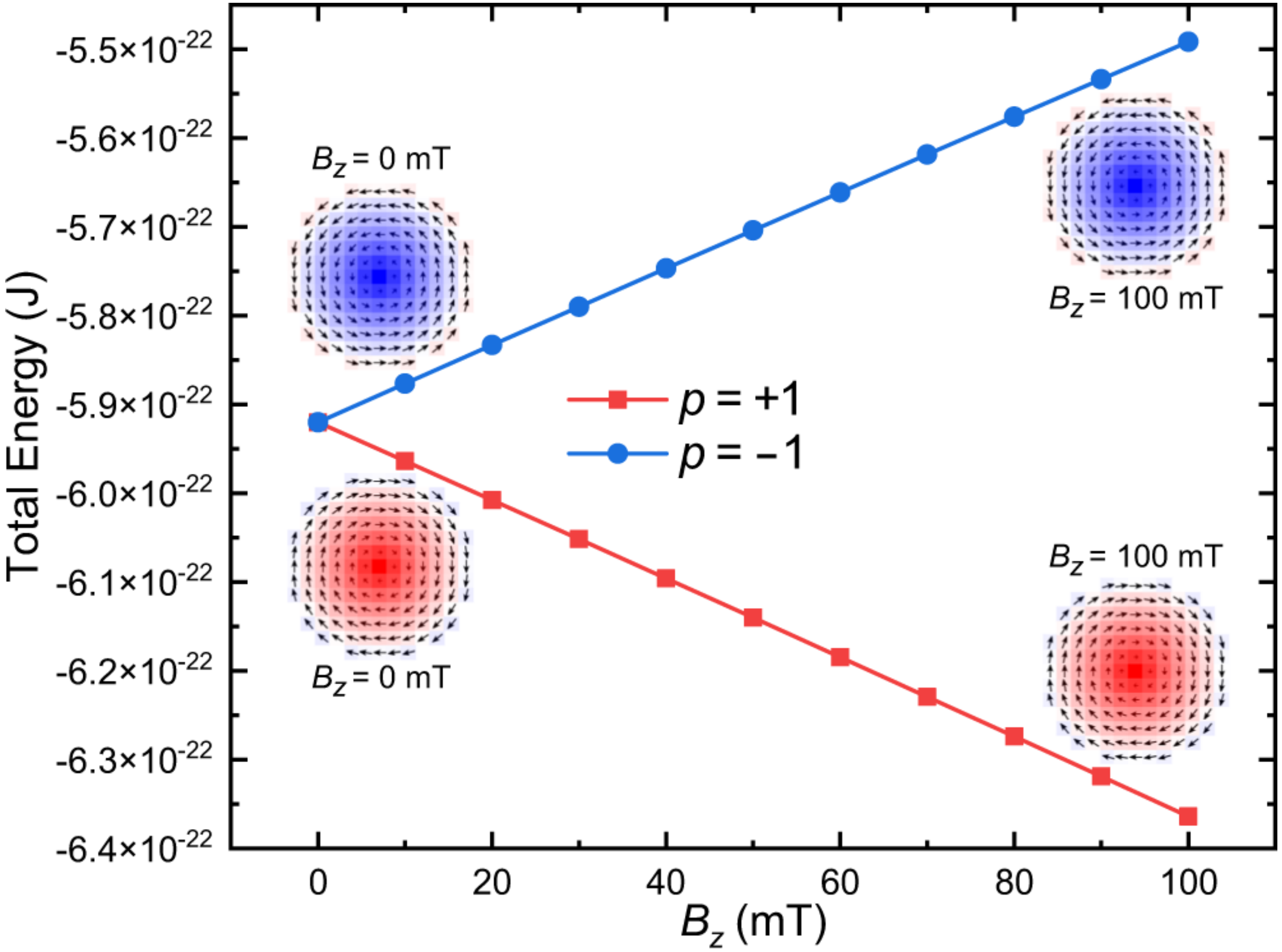




1. Neumann et al. *arXiv* (2015)

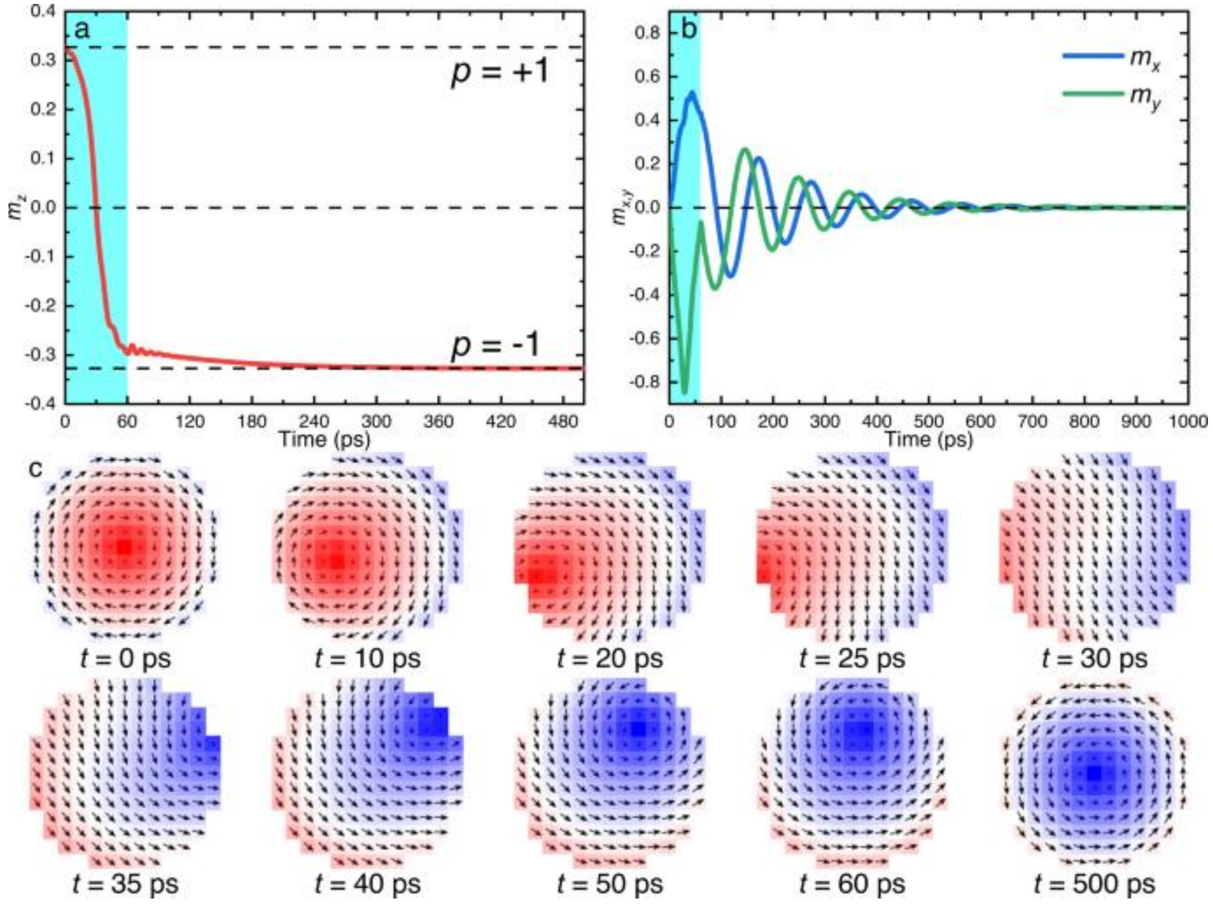
Bonus: Magnetic Nanodisk Spin Qubit Simulation

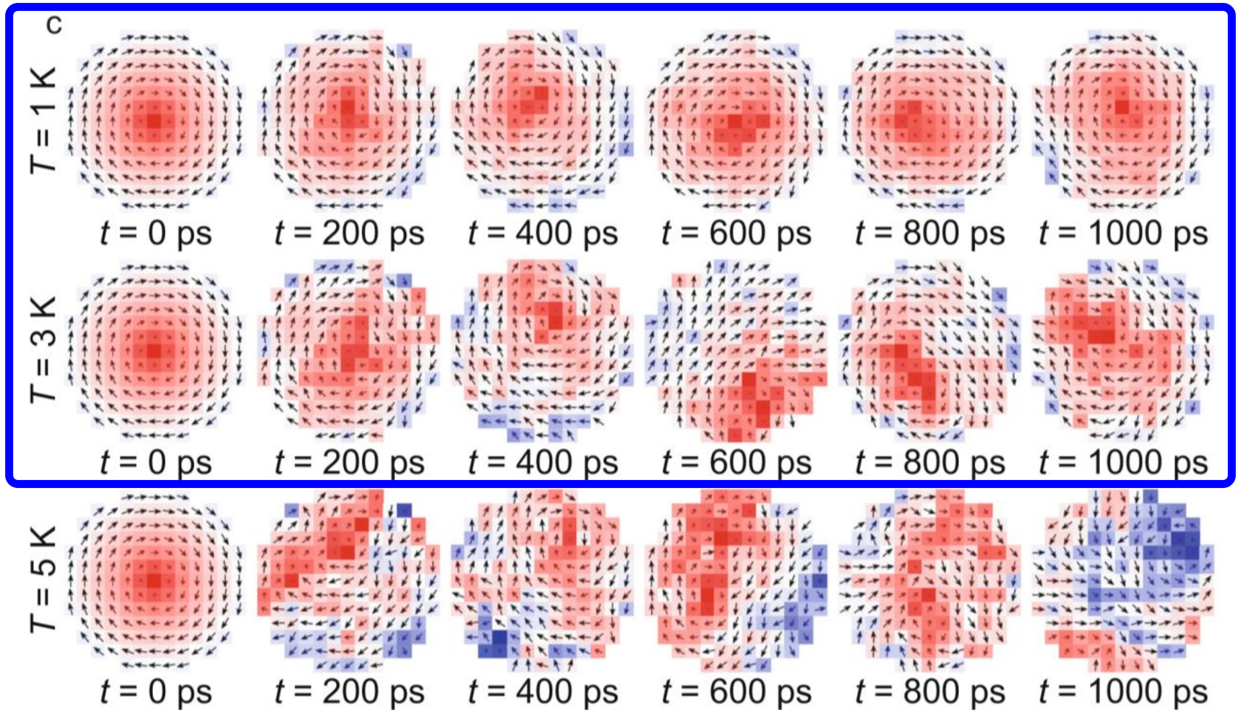




1. Xia et al. *Communications Materials* (2022)

Bonus: Nanodisk Qubit Switching vs. Thermal Stability



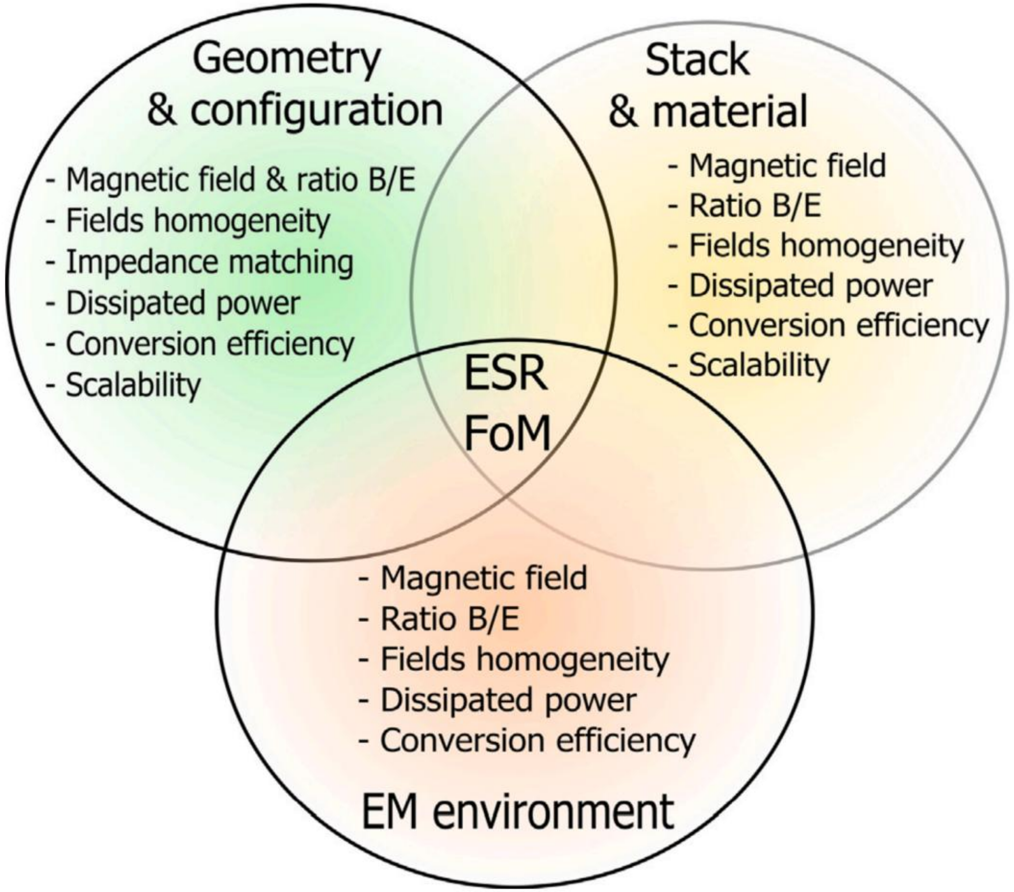


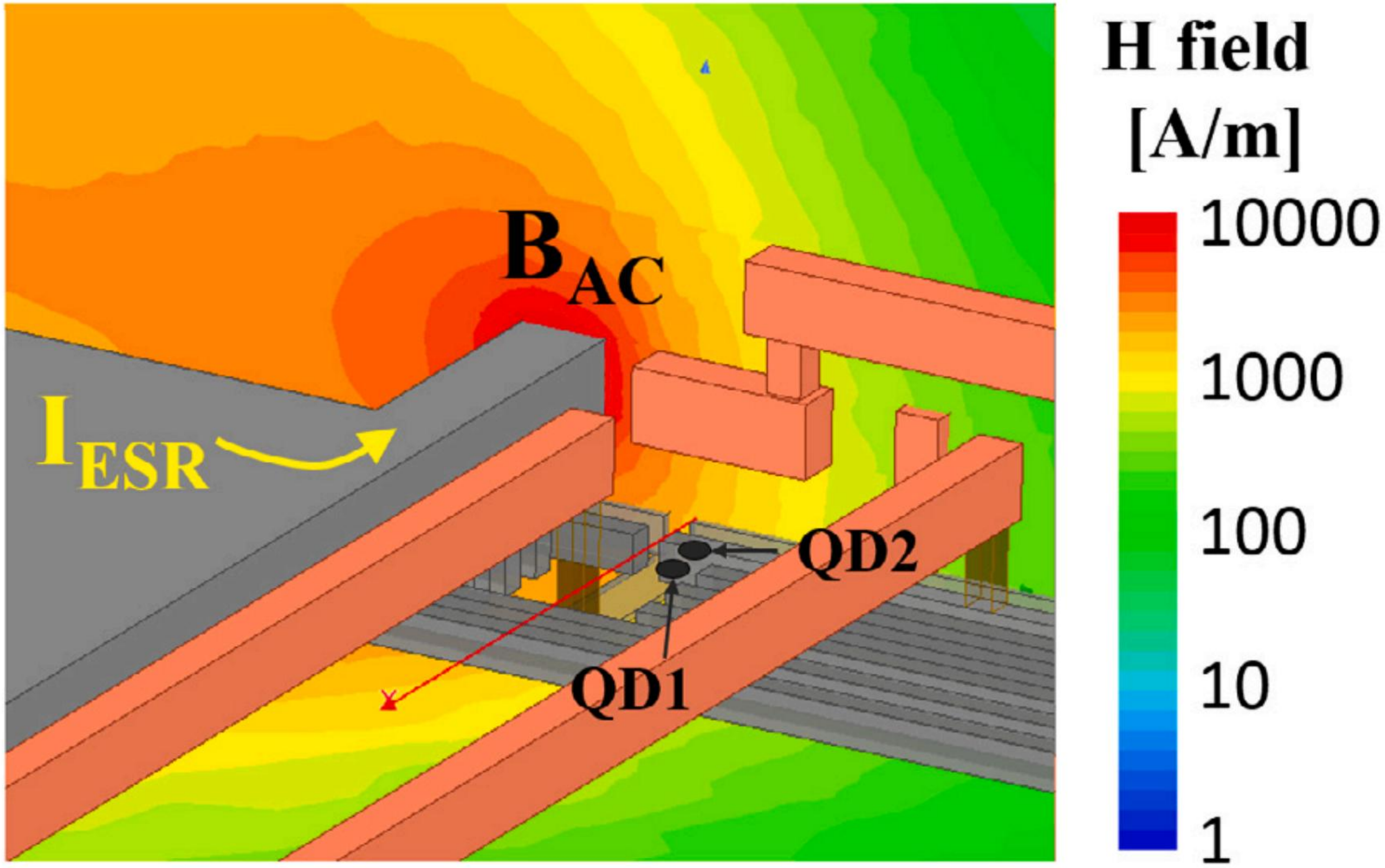
Read out

The polarity can be observed by the full-field soft X-ray transmission microscopy[30,31], magnetic force microscopy[24,43], or magnetic tunneling junction[44]. The polarity is fixed to be up or down by the observation. Hence, the quantum state is fixed to be $|s_1 s_2 \cdots s_N\rangle$ with $s_j = 0, 1$ as in the standard quantum computation.

1. Xia et al. *Communications Materials* (2022)

Bonus: Spin Qubit & Electron Spin Resonance Simulation





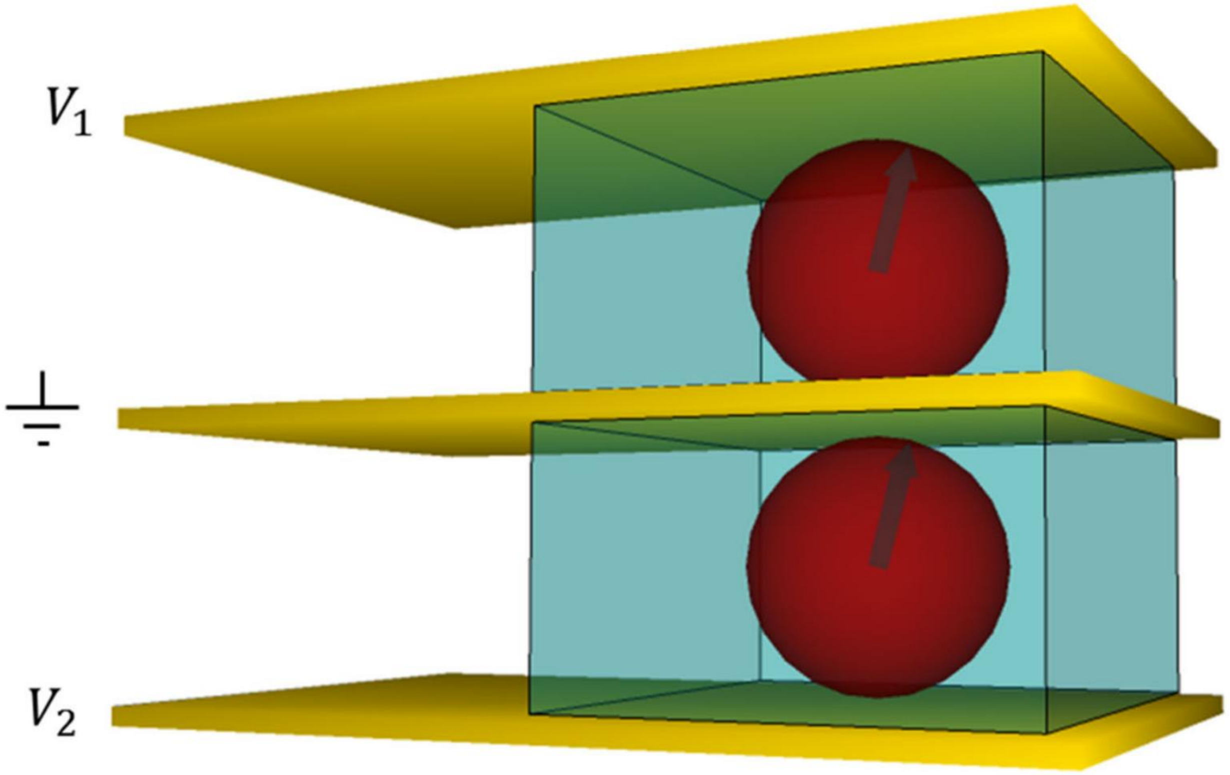
1. Jacquinot et al. *Solid-State Electronics* (2023)

Bonus: Magnetic Cluster Qubit Energy Calculation

The Hamiltonian for a multiqubit system can be written as

$$H = -\sum_i \hbar w_0^i \boldsymbol{S}_z^i + \sum_i \hbar w_1^i \boldsymbol{S}_x^i \cos(w_{mf}^i t - \phi^i) - \sum_{i<j} J_{ij}^c \boldsymbol{S}^i \cdot \boldsymbol{S}^j \qquad (19)$$

where J_{ij}^c is the coupling strength between the ith and jth qubit. The coupling strength J_{ij}^c may decay quickly with distance separating qubits, which makes it difficult to directly entangle two nonadjacent qubits. However, one can still entangle any two qubits by a series of operations on subsequent neighboring qubits.



1. Dorroh et al., *IEEE Transactions on Quantum Engineering*, 1 (2020)

Bonus: Spin Qubit Simulation (QTCAD Models)

Device geometry

- Gate geometry from layout file
- Heterojunction & design rules from Python API
- More complex 3D geometries from Gmsh

Mesh file

Electrostatics

- Define boundary conditions (Ohmic, Schottky, etc.) and applied potentials
- Define doping densities
- Solve non-linear Poisson equation
- Get carrier confinement potential

V(r)

Schrödinger solver

- Solve single-body Schrödinger's equation within k-p theory
  - Effective mass (electrons)
  - Luttinger-Kohn (holes)
- Get envelope function eigenbasis
- Get gate lever arms

$\{\psi_i(\mathrm{r}), E_i\}$

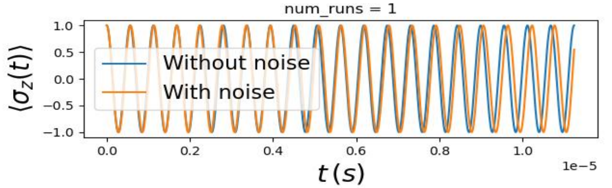
Many-body solver

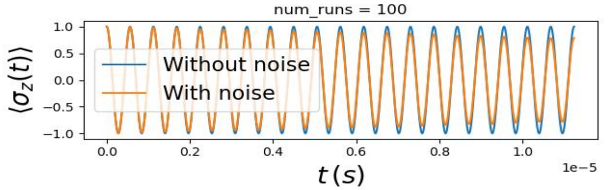
- Assemble many-body Hamiltonian including Coulomb interactions
- Exactly diagonalize in truncated basis set
- Get many-body eigenenergies and eigenfunctions

$\{\hat{H}_{MB}, \Psi^i{}_{MB}(\mathrm{r}), E^i{}_{MB}\}$

Quantum dynamics feature

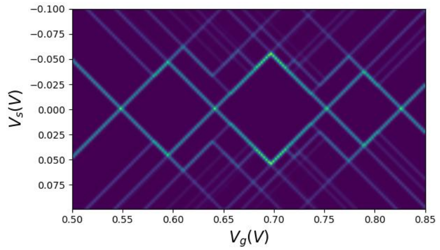
- Get the Hamiltonian corresponding to a realistic device geometry
- Find matrix elements of perturbations due to control fields or noise
- Interface with QuTiP to calculate quantum dynamics and calculate
  - Rabi oscillations (e.g. micromagnet or spin-orbit EDSR)
  - Gate fidelity





Transport feature

- Master equation solver in sequential tunneling regime
- Get transport peaks and charge stability diagram including Coulomb blockade



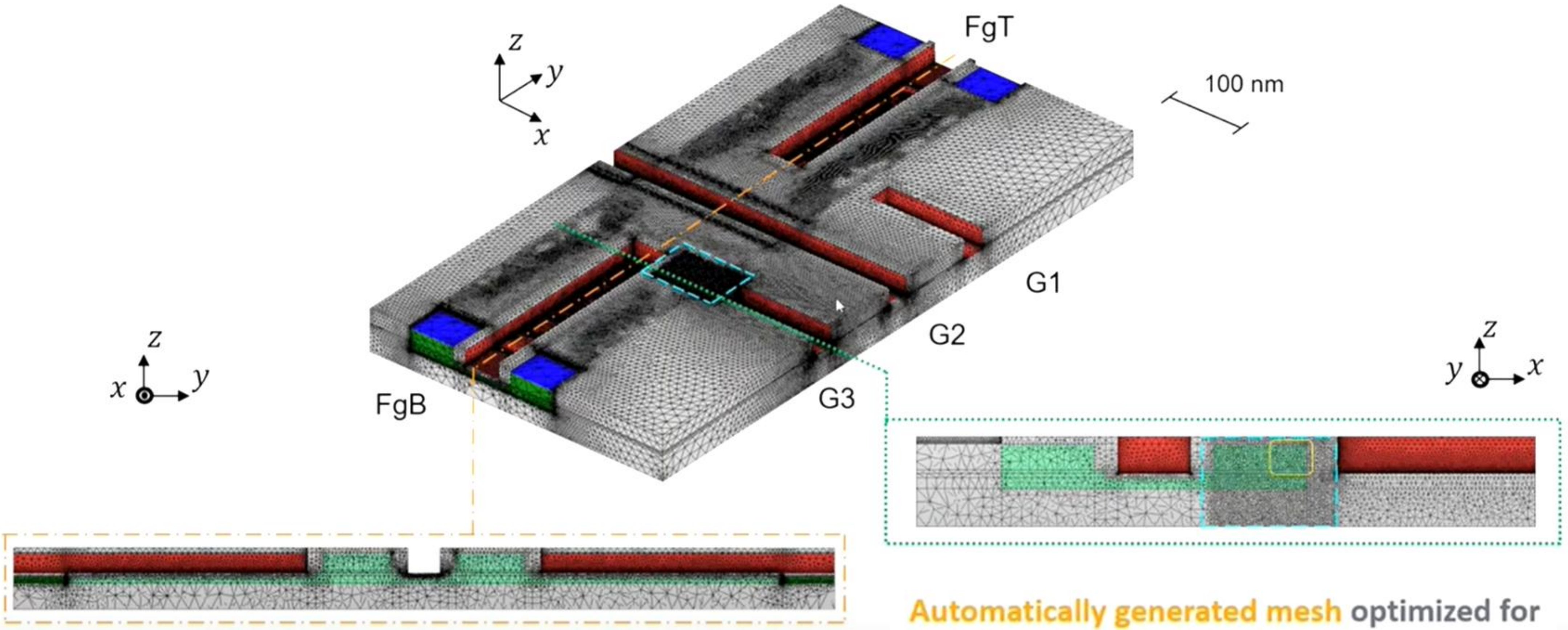
*QTCAD: Quantum Technology Computer Aided Design

From device layout to qubit performance metrics.

1. Adapted from: nanoacademic.com/solutions/qtcad
2. Beaudoin et al. *App. Phys. Lett.* (2022)

Bonus: Spin Qubit Simulation

QTCAD demonstration: Adaptive meshing for robust convergence at sub-K temperature



Automatically generated mesh optimized for robust convergence of QTCAD's non-linear Poisson solver (Thomas-Fermi approximation)

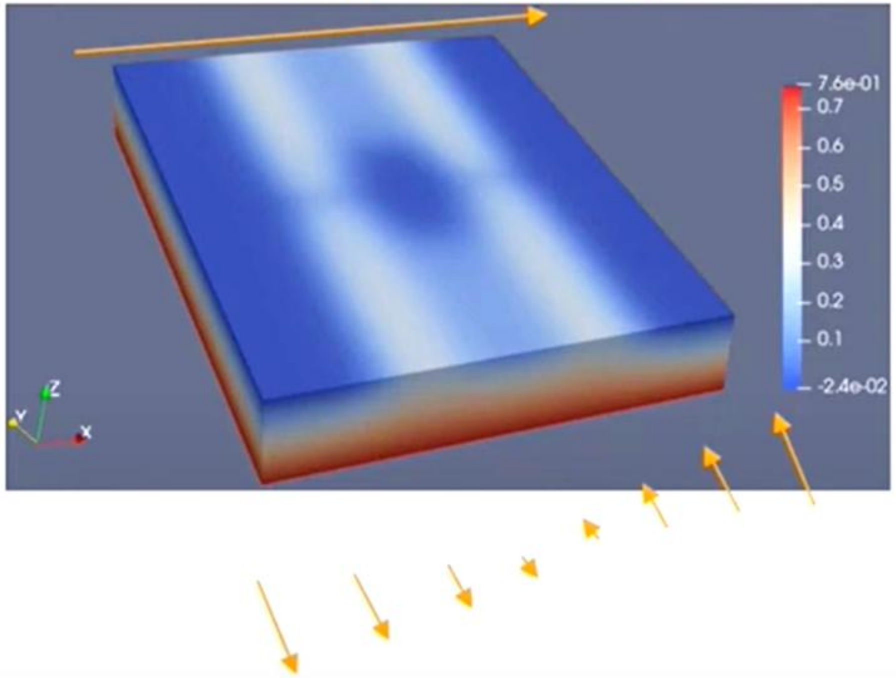
1. nanoacademic.com/solutions/qtcad
2. Beaudoin et al. *App. Phys. Lett.* (2022)

Bonus: Spin Qubit Simulation

NANOACADEMIC
TECHNOLOGIES

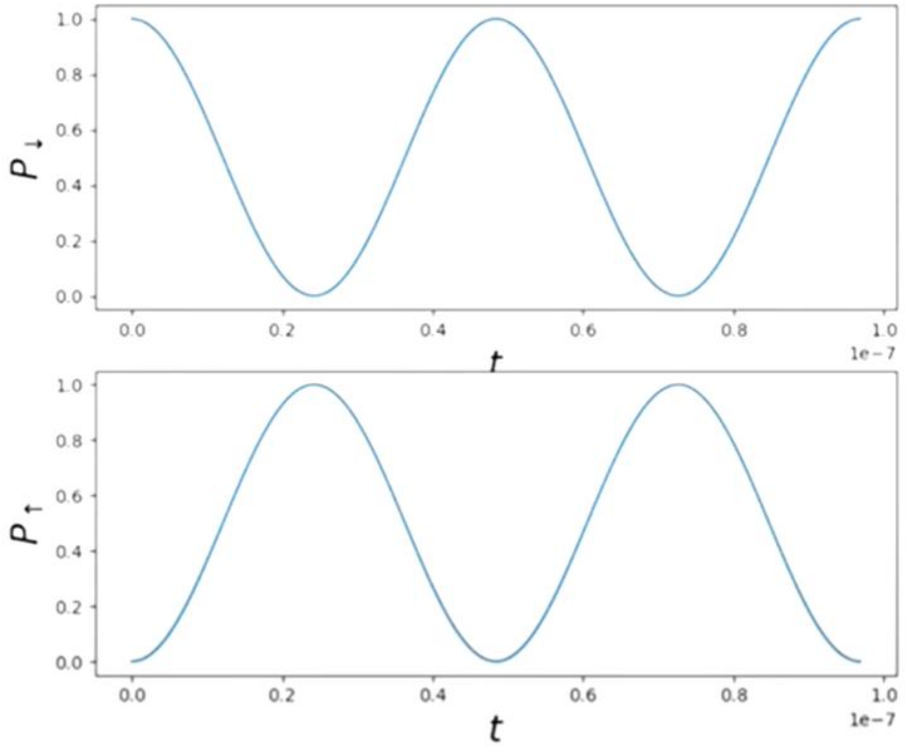
- Both spin-orbit coupling based or micromagnet EDSR

Uniform background magnetic field



Slanting field from micromagnet

Rabi oscillations under modulations of top-right gate

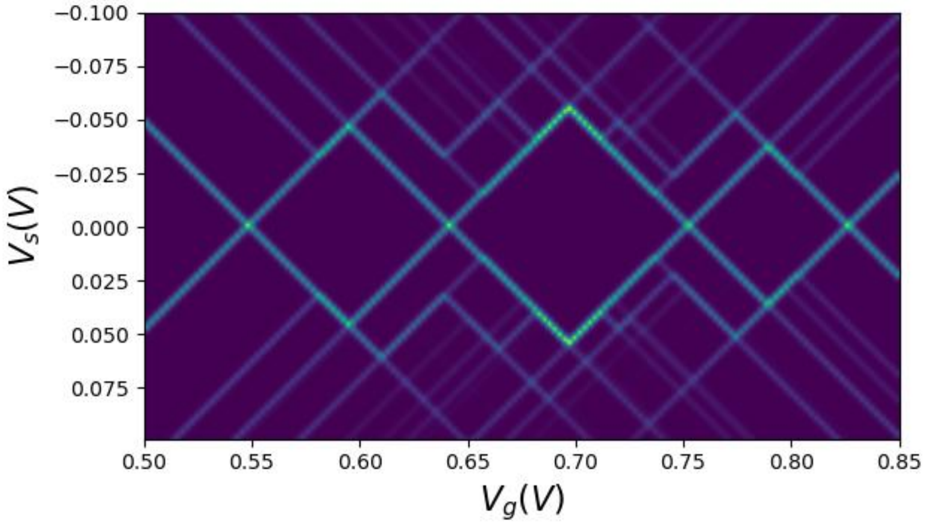


We can go all the way from device layout to single-qubit control.

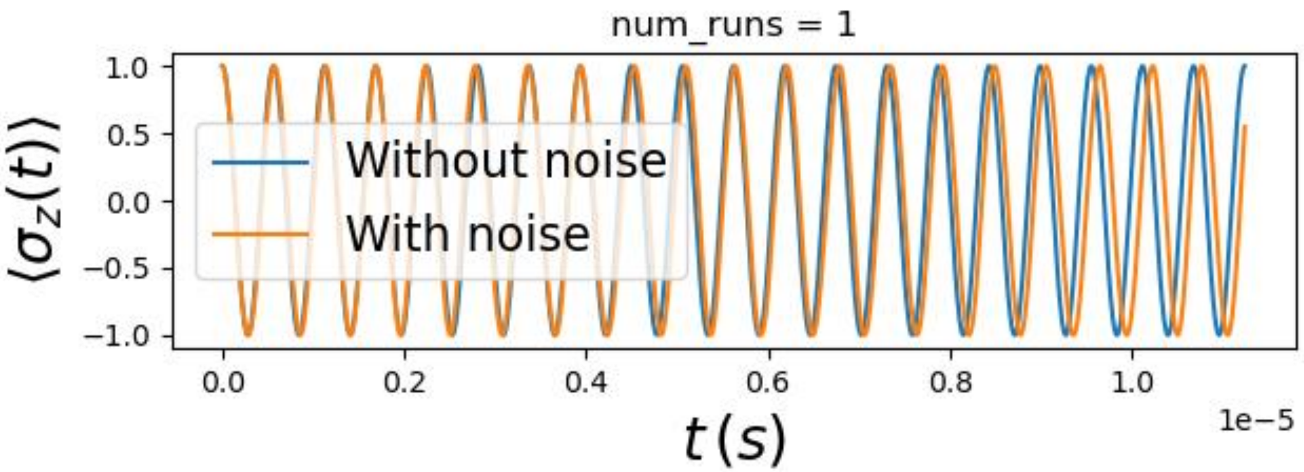
1. nanoacademic.com/solutions/qtcad
2. Beaudoin et al. *App. Phys. Lett.* (2022)

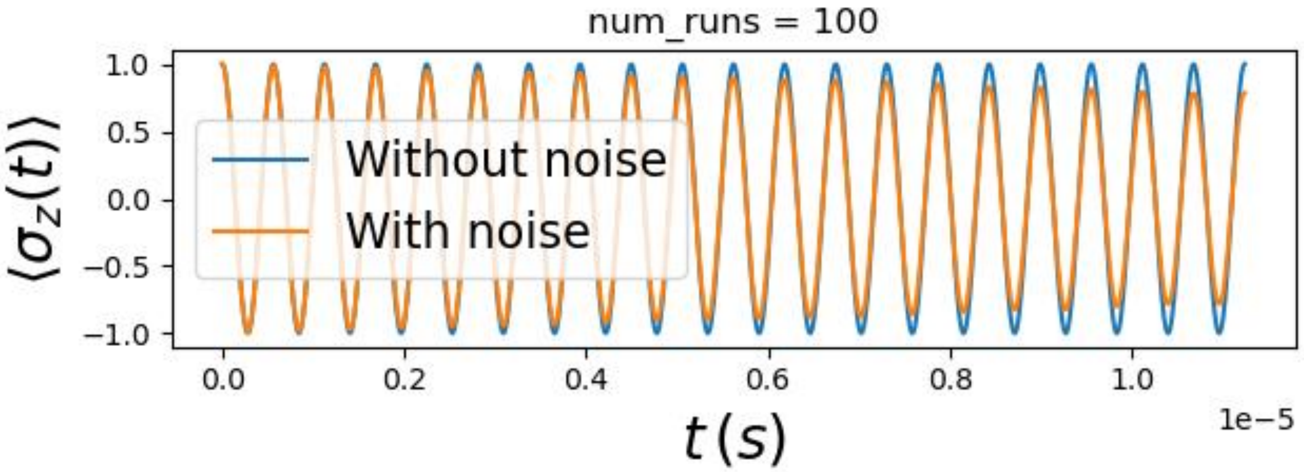
Bonus: Spin Qubit Simulation

Charge Stability Diagrams

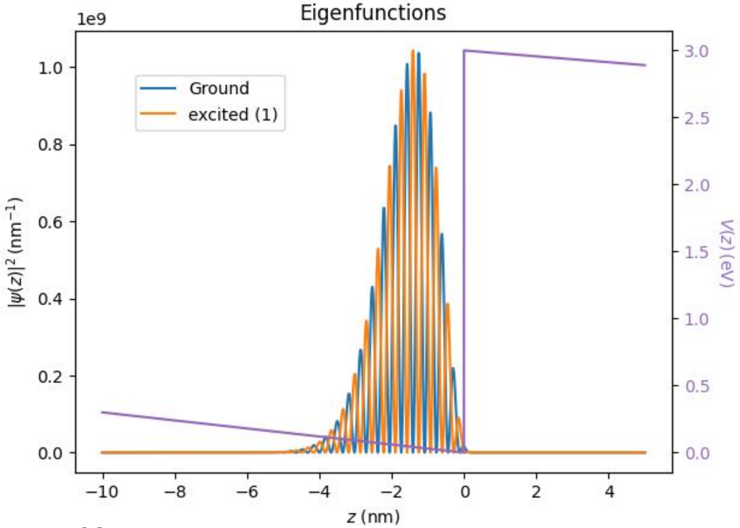


Electric Dipole Spin Resonance





Spin Valley Coupling



1. nanoacademic.com/solutions/qtcad
2. Beaudoin et al. *App. Phys. Lett.* (2022)