Challenges and Opportunities for VLSI Electronics Operating in Cryogenic Environments

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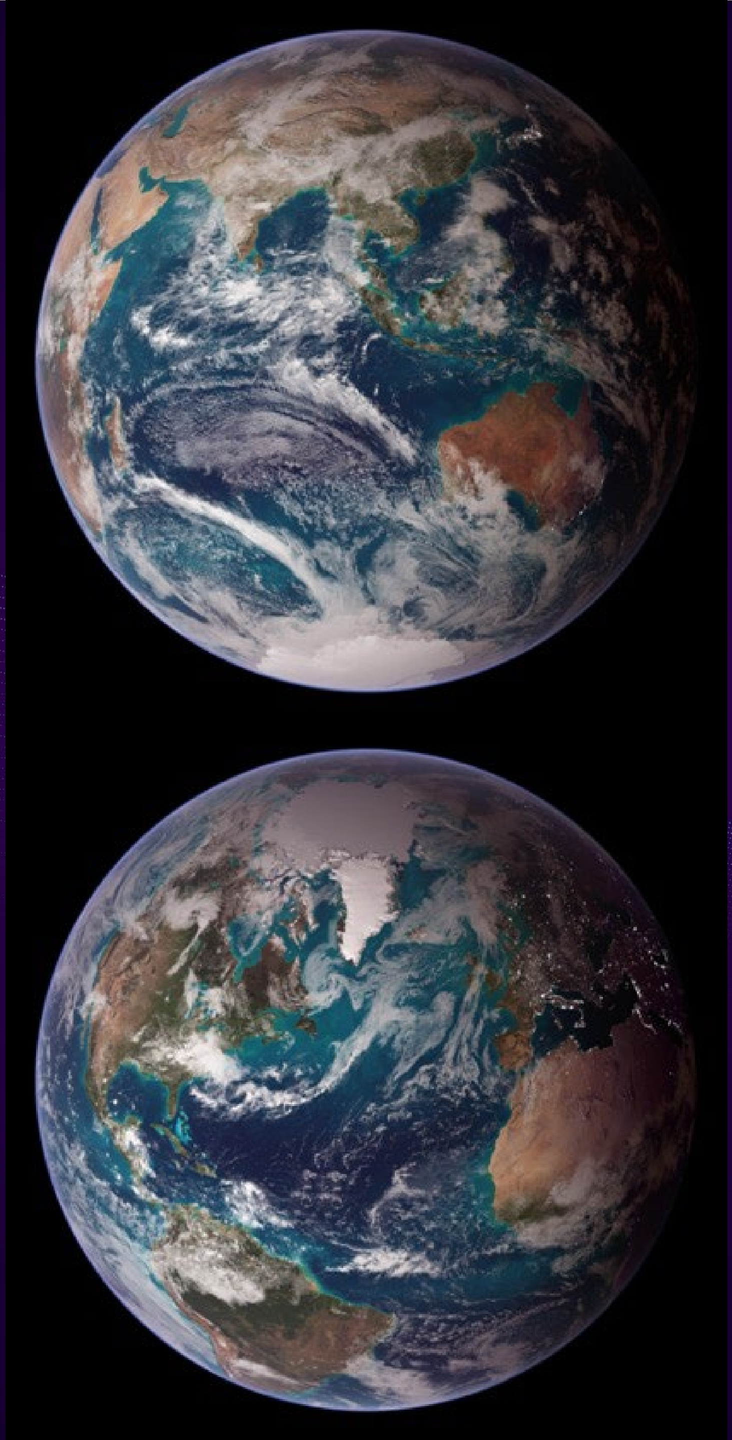
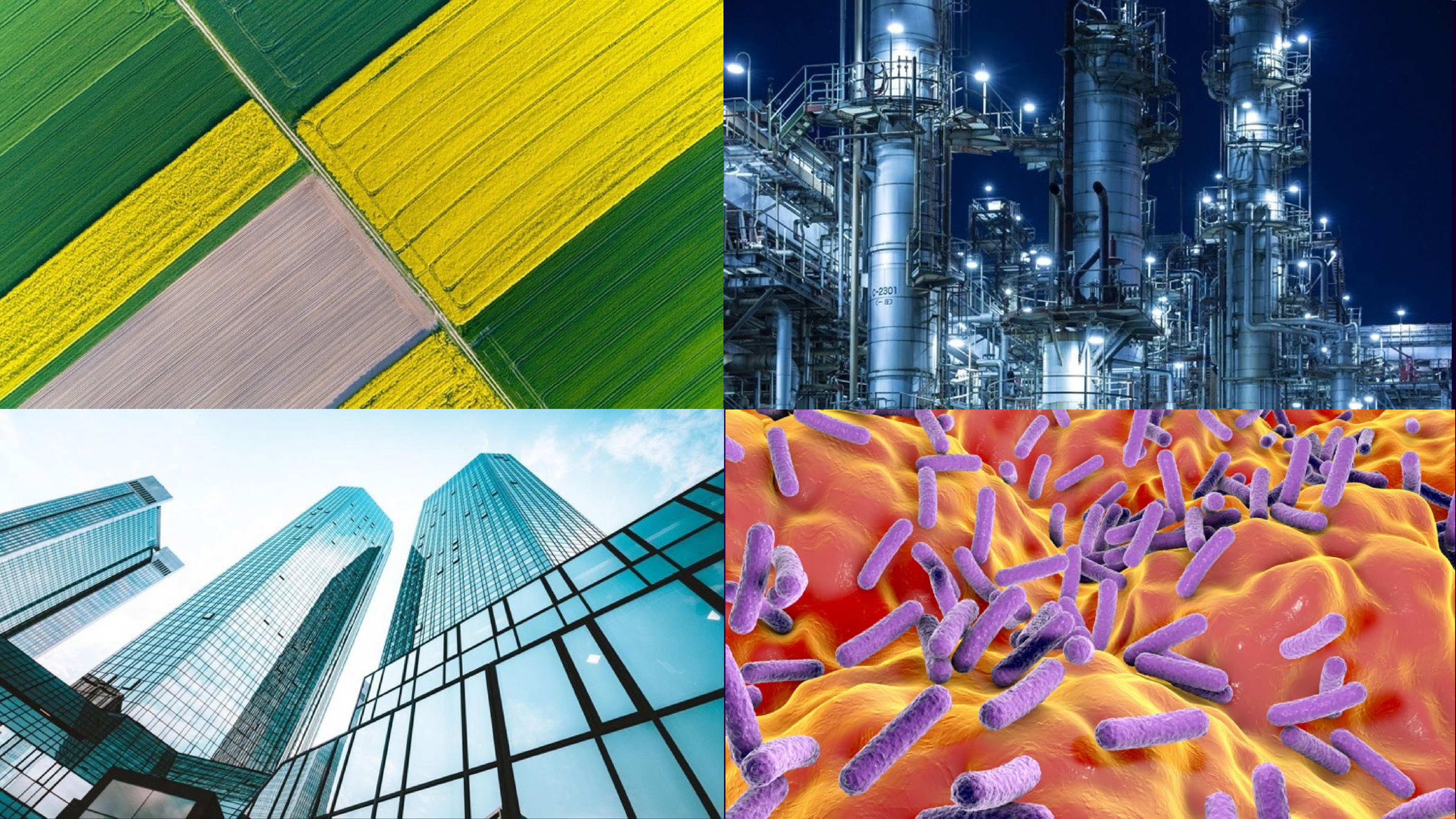
We are on a small planet …



… with big problems to solve



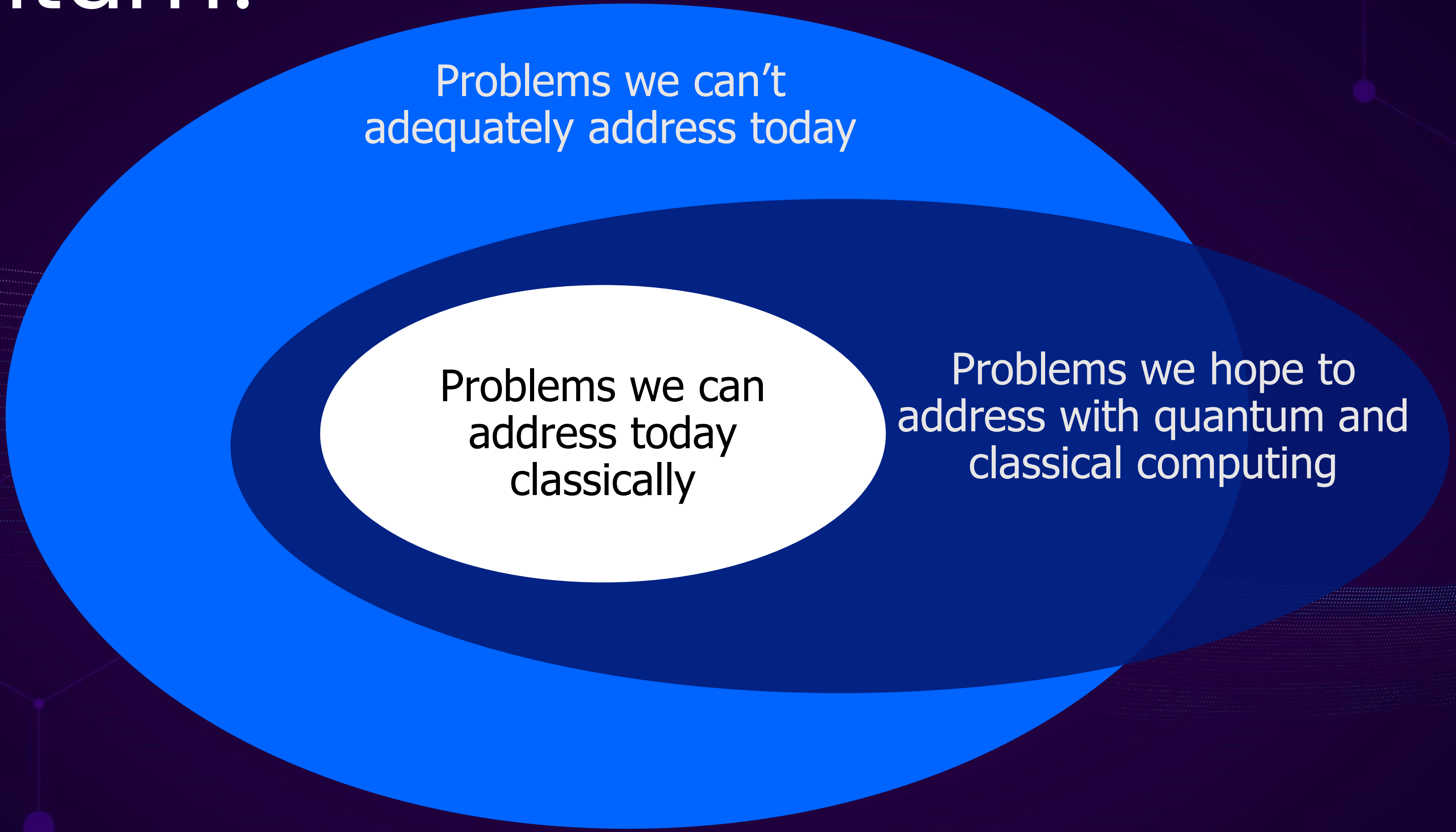
Improved nitrogen-fixation process for creating ammonia-based fertilizer

New catalysts to make CO_2 conversion into hydrocarbons more efficient and selective

Better financial models to improve stability, predictability and growth of world economies

New classes of antibiotics to counter the emergence of multidrug-resistant bacterial strains

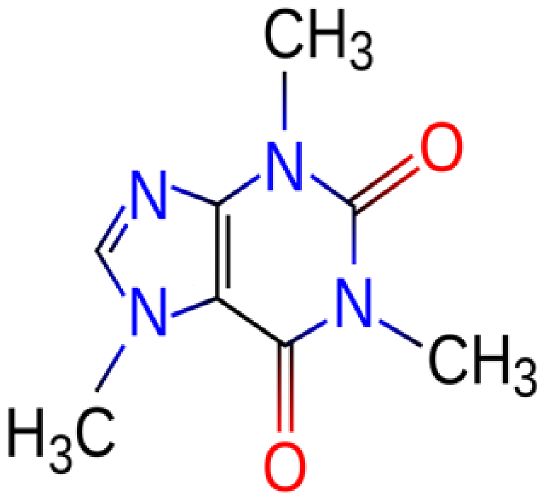
Why quantum?



Despite how sophisticated digital "classical" computing has become, there are many scientific and business problems for which we've barely scratched the surface

Computing with caffeine

- If our best classical computers are so powerful, shouldn't we be able to perfectly simulate molecules and chemical reactions?
- This would allow us to accelerate discovery of new compounds and processes for healthcare, materials, alloys, and sustainable energy creation
- Let's consider caffeine …



Computing with caffeine

- We would need approximately 10^{48} bits to represent the energy configuration of a single caffeine molecule at a single instant in a classical computer

  This is 1 to 10% of the total number of atoms in the Earth

- 10^{48} =
  1,000,000,000,000,000,
  000,000,000,000,000,000,
  000,000,000,000,000

Computing with caffeine

- Although it's impossible to completely represent the molecular configuration of caffeine on today's most powerful supercomputers, we could represent it using 160 logical qubits.

Exponential progress—

Executed by IBM ✓
On target

IBM Quantum

2019 ✓	2020 ✓	2021 ✓	2022 ✓	2023	2024	2025	2026+
Run quantum circuits on the IBM cloud	Demonstrate and prototype quantum algorithms and applications	Run quantum programs 100x faster with Qiskit Runtime	Bring dynamic circuits to Qiskit Runtime to unlock more computations	Enhancing applications with elastic computing and parallelization of Qiskit Runtime	Improve accuracy of Qiskit Runtime with scalable error mitigation	Scale quantum applications with circuit knitting toolbox controlling Qiskit Runtime	Increase accuracy and speed of quantum workflows with integration of error correction into Qiskit Runtime

Enterprise Developers and System Integrators

- Prototype quantum software functions (on target) → Quantum software functions
  - Machine learning | Natural science | Optimization

Quantum Computational Scientists

- Quantum algorithm and application modules ✓
  - Machine learning | Natural science | Optimization
- Middleware for Quantum
  - Quantum Serverless (on target)
  - Intelligent orchestration
  - Circuit Knitting Toolbox
  - Circuit libraries

Quantum Physicists

- Circuits ✓
- Qiskit Runtime ✓
  - Dynamic circuits ✓
  - Threaded primitives (on target)
  - Error suppression and mitigation
  - Error correction

System Modularity

- Falcon ✓ — 27 qubits
- Hummingbird ✓ — 65 qubits
- Eagle ✓ — 127 qubits
- Osprey ✓ — 433 qubits
- Condor (on target) — 1,121 qubits
- Flamingo — 1,386+ qubits
- Kookaburra — 4,158+ qubits
- Scaling to 10K-100K qubits with classical and quantum communication
- Heron (on target) — 133 qubits x p
- Crossbill — 408 qubits

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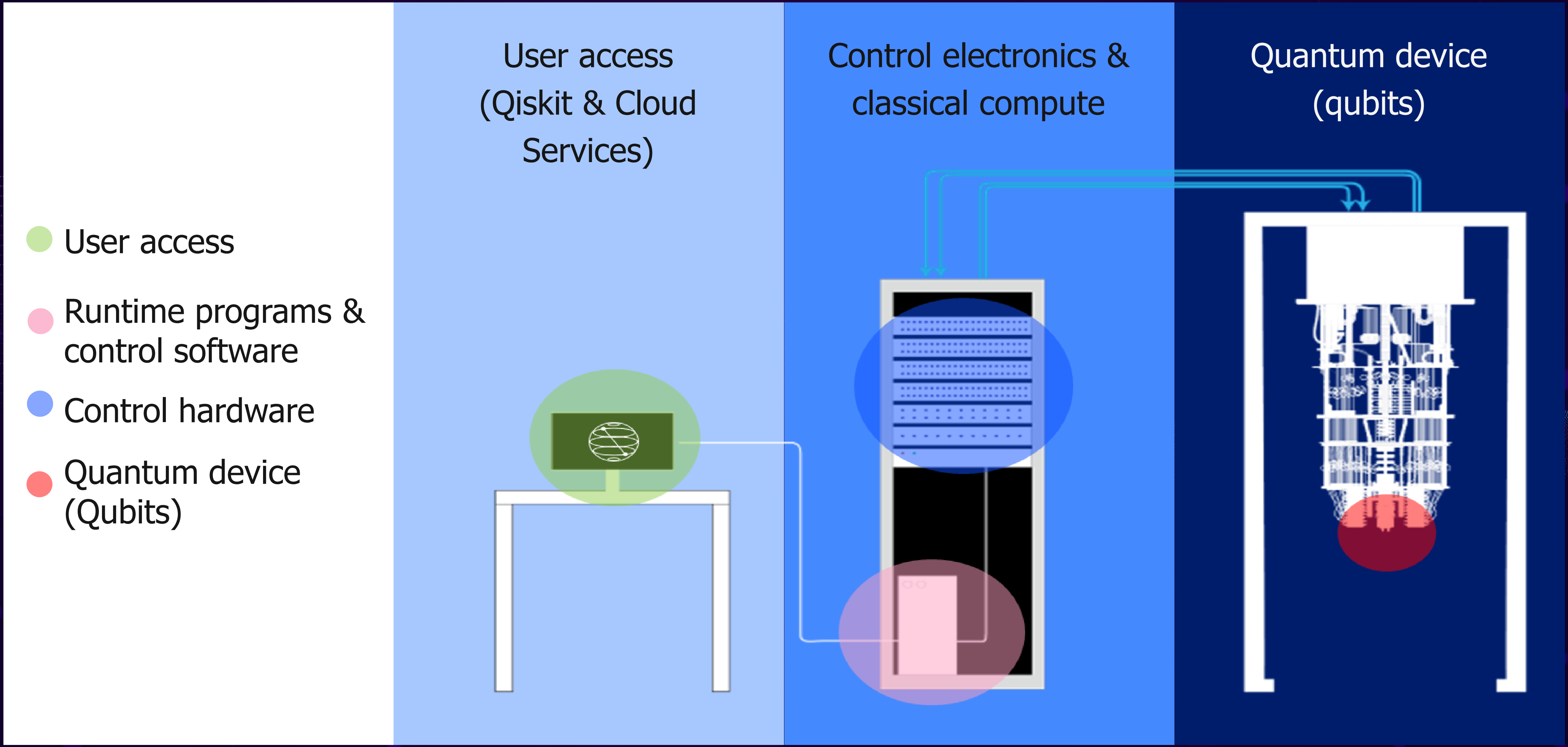
—But fully delivering on quantum computing's promise demands large numbers of physical qubits: *enabling scaling is a critical challenge*

Basic Elements of a Quantum System



Control and readout of qubit state

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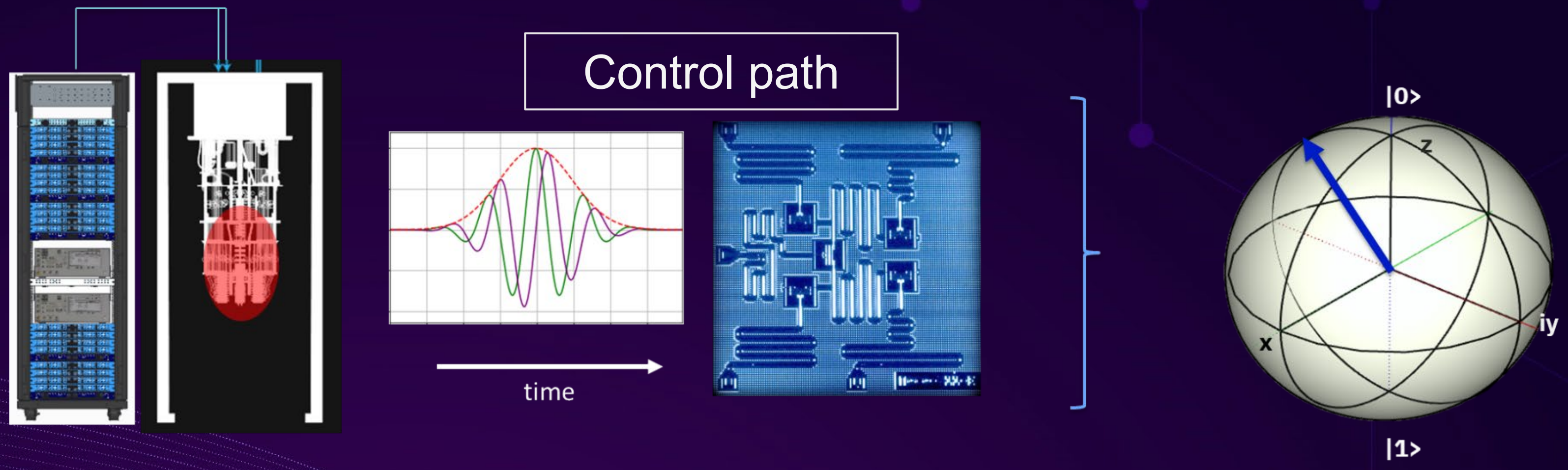
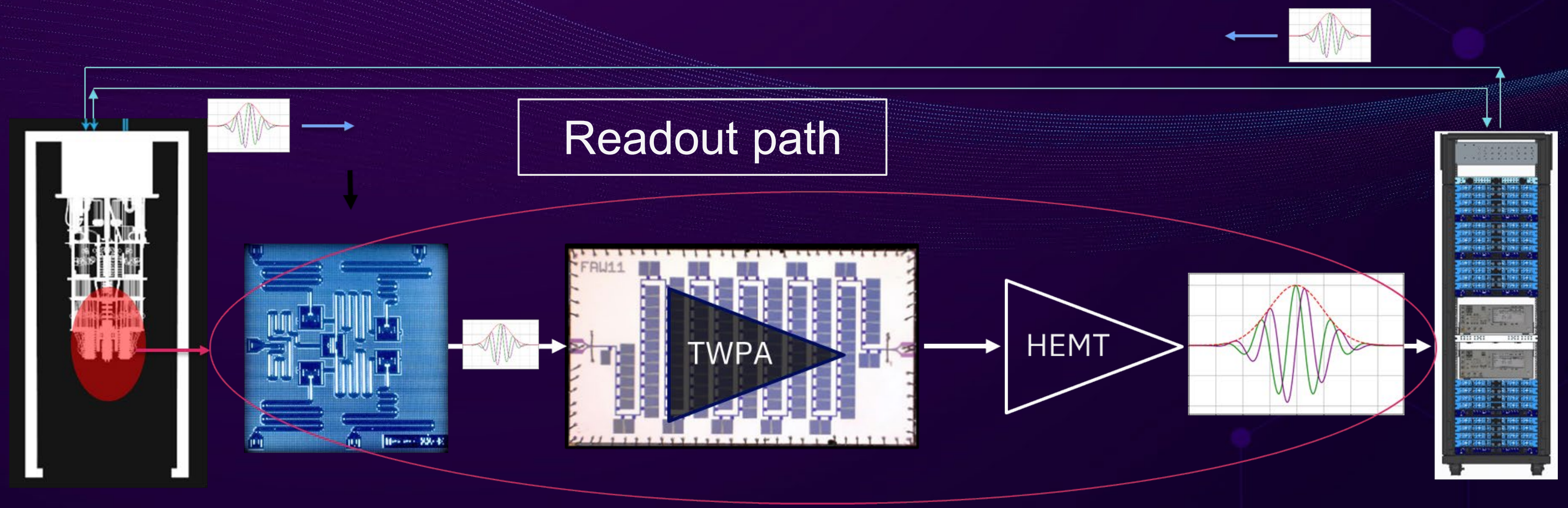
Control:

- Microwave pulses drive qubit state around the Bloch sphere
- Arbitrary waveform generators used to create signals



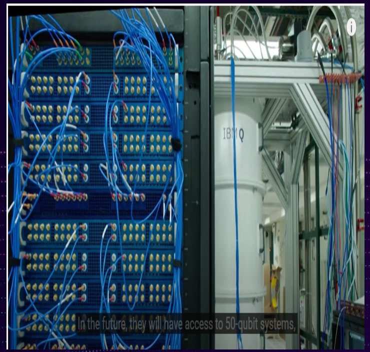
Readout:

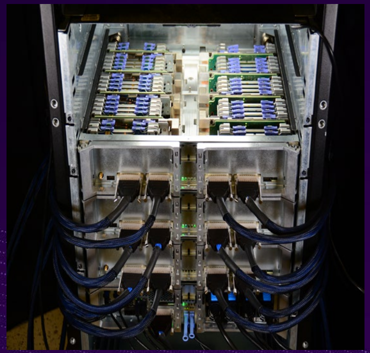
- Qubit state acts to shift associated readout resonator frequency
- State detected by measuring the phase shift of applied centered resonant tone



Low phase noise, well-controlled amplitude, and excellent stability required

Control electronics evolution for quantum computing system scaling

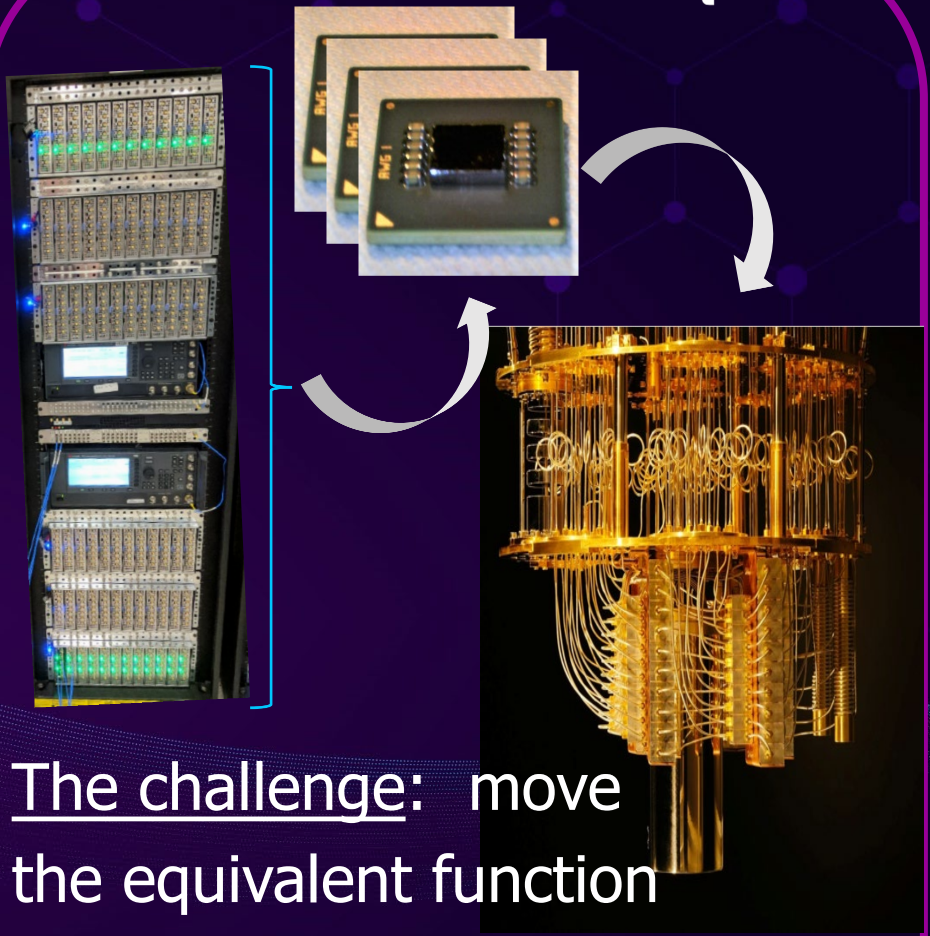




20 qubits/rack → 72 qubits/rack → 1000 qubits/rack → . . .

Enormous progress—but support for 100s of thousands of qubits demands a paradigm shift

Highly integrated CMOS in the fridge offers a promising path to scaling



The challenge: move the equivalent function of racks of electronics into a dilution fridge—meeting its limited cooling & I/O capacity

Context—and challenges

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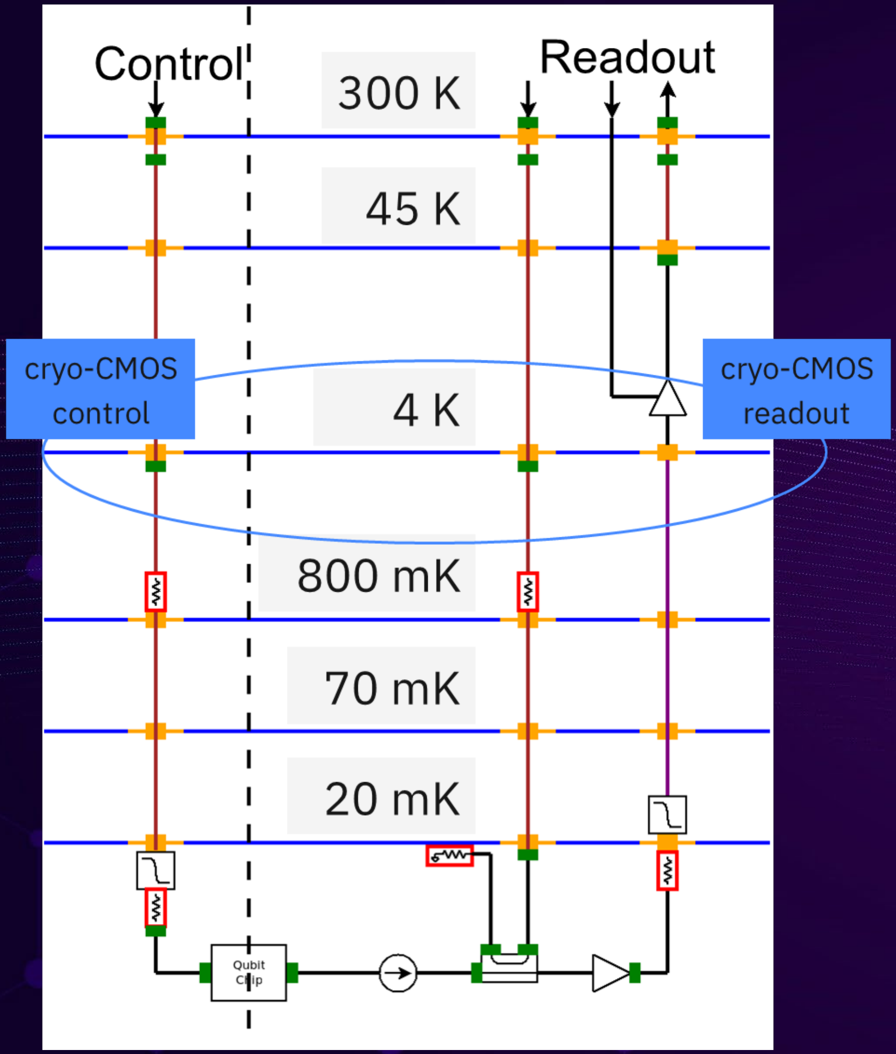
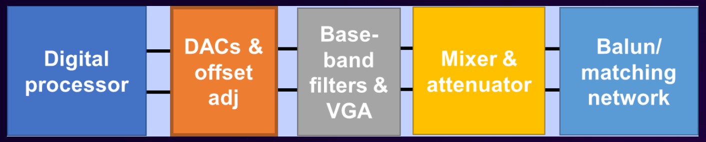


Challenges to fridge electronics introduction

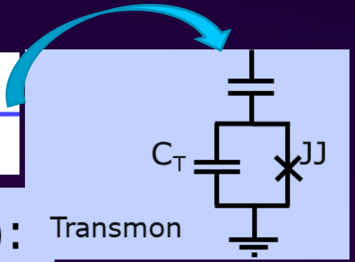
- I/O density: limited room for cables & connectors
- Operating within limited cooling power of the cryostat's ~4K stage—*while achieving relevant scale*
- Producing high-fidelity qubit control signals at levels ~ -100dBm
- Sensing and processing qubit readout signals at levels ~ -120dBm

Net: Create ultra-low noise, ultra-stable signals coordinated with broader system (including calibration support) using electronics that dissipate virtually no power!

Example cryo-CMOS state controller and its operation



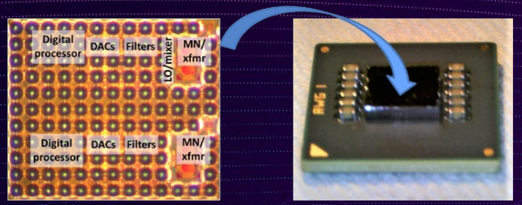
Single channel of qubit state controller



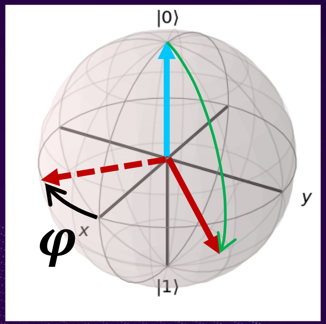
Waveform (simplified):

$$V(t) = \gamma \cdot E(t)\cos(\omega t + \varphi)$$

amplitude, envelope, frequency, phase

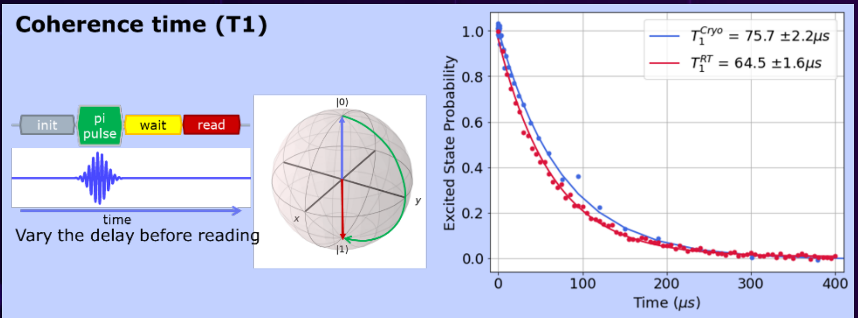


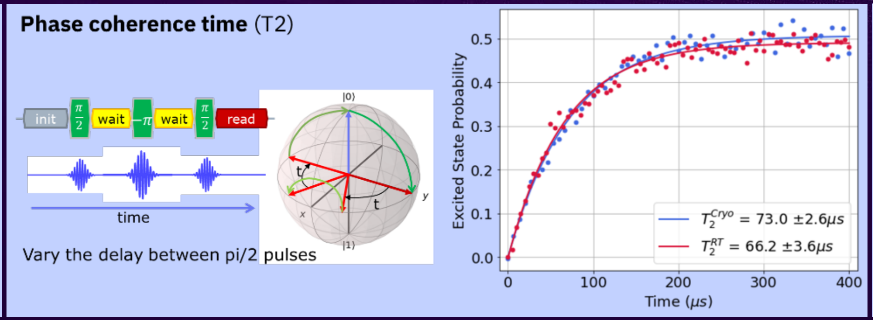
Realized in dual-channel test chip (14nm CMOS), flip-chip package

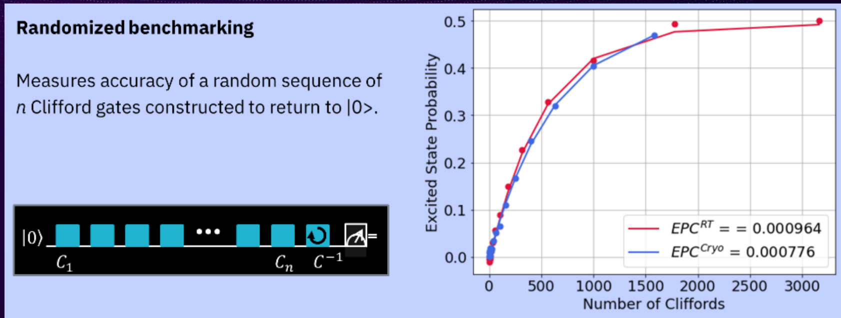


- RF & qubit frequency must match
- Phase sets rotation *axis*
- Integral of amplitude x envelope determines *extent of the rotation*

- <u>Implementation</u>: complex mixed-signal design [custom processor with compiled SRAM, RF DAC]







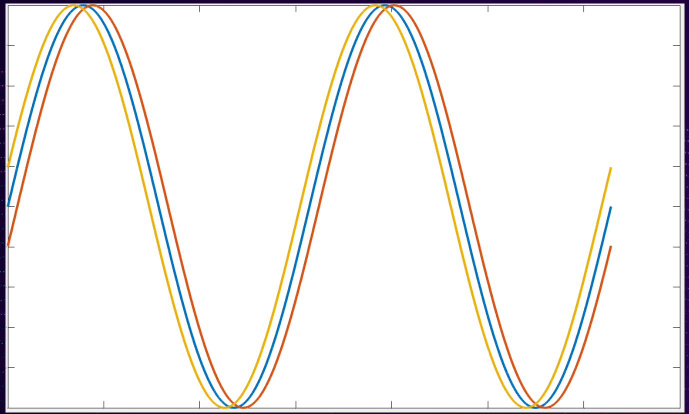
Measured results show performance similar to that achieved using room temperature control—but. . .

Frank et al, ISSCC 2022
Chakraborty et al, JSSC 2022

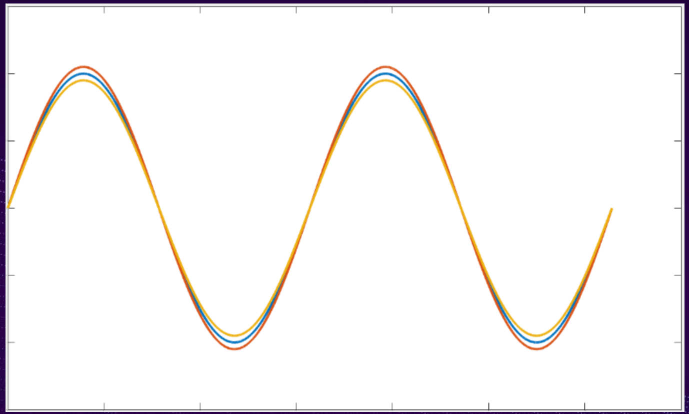
What could go wrong?

RF control error sources

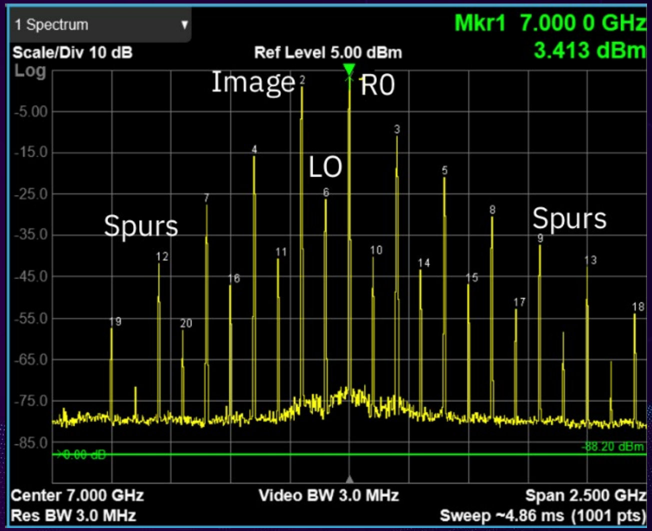
Phase noise



Amplitude noise



Mixer sidebands



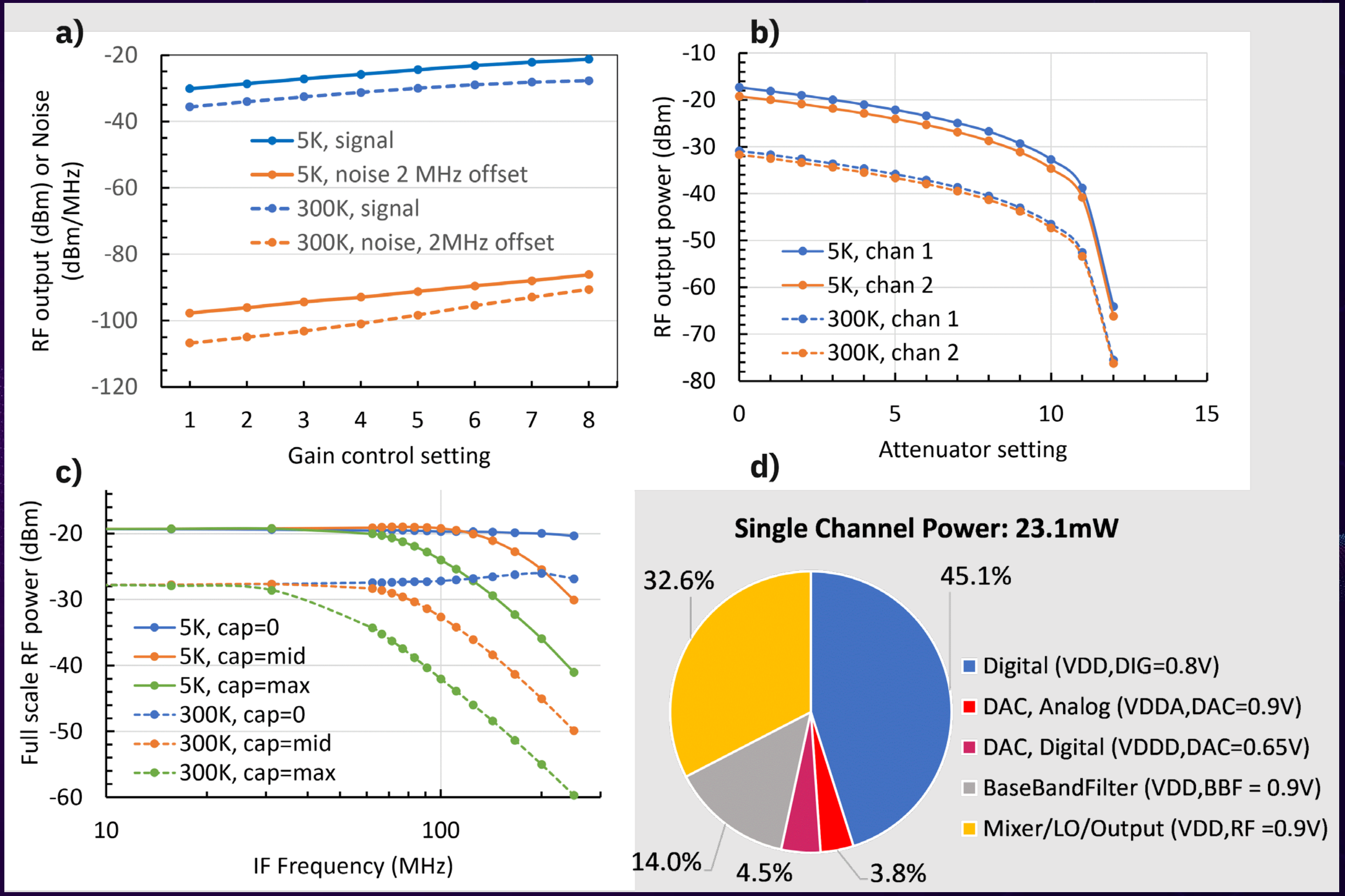
Sidebands can overlap transitions; noise away from intended microwave tone can have other impacts

- Potential problems: high frequency noise, low frequency noise (drift), accuracy (# of bits), cross talk

- Note: flux control suffers from similar sensitivity to non-idealities, including amplitude noise, control signal tails, and flux noise

What else might go wrong?

- Cryogenic device-level behavior of devices is not well predicted by models
  → analog performance surprises
- Cryogenic behavior of library elements not well predicted by abstractions
  → digital/memory performance surprises
- Cooling power (~1-4 W at 4K plate for current cryostats) does not stretch far without extreme per-channel efficiency (20 mW/qubit will not get us there!)
- Integration in system may surface packaging, reliability, serviceability, and other challenges



Frank et al, ISSCC 2022

Future investments to drive success: scalable quantum computing through cryo-CMOS

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<u>Technology advancement:</u>

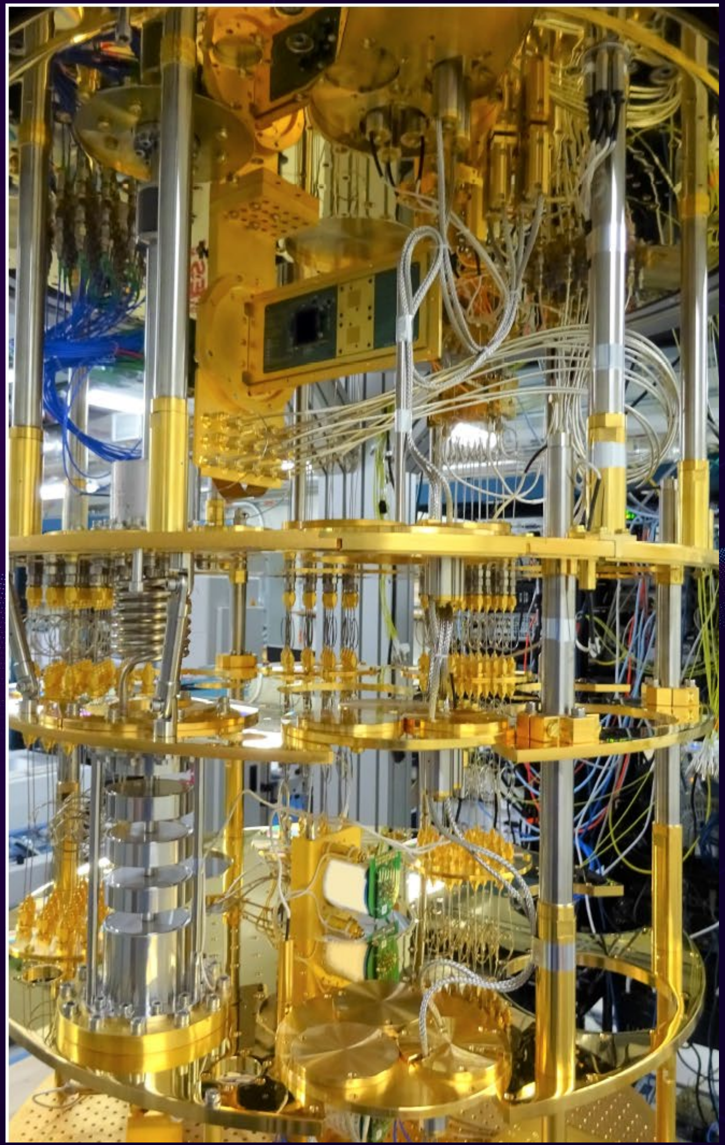
- Enable advanced node reduced supply operation
- Device/interconnect modeling accurate below 20 K
- Improved thermal solutions/modeling at low temperatures

<u>System and packaging advancement:</u>

- Stress effects at 20 K and below
- Low temperature reliability modeling for CMOS & components
- New connectivity solutions—to room temperature electronics and to the qubit plane

<u>Design advancement:</u>

- High performance/low power RF control, flux control, communication, and processing solutions
- Scalability breakthroughs



Electronics for quantum computing is presently a low-volume application—investment is <u>necessary</u> to accelerate progress

THANK YOU