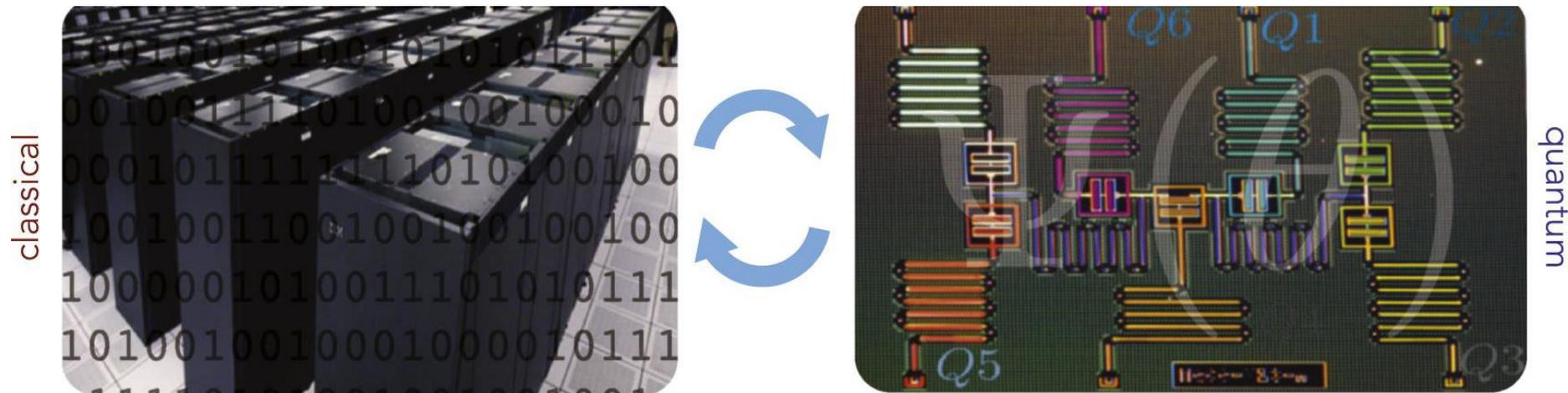


# Measurement Challenges for Scaling Superconductor-based Quantum Computers

Peter Hopkins  
Superconductive Electronics Group  
NIST  
Department of Commerce  
Boulder, CO  
June 23, 2022



Source: <https://www.nature.com/articles/d41586-021-03476-5>



Richard Feynman (1981): “Nature isn't classical ... to make a simulation of nature, you'd better make it quantum mechanical”

## Quantum Computers Solve Problems that Cannot be Solved by Digital Systems

and... calculation space can  
double with each additional  
qubit



- Quantum processes in physics, chemistry, and biology
- Cryptography
  - ✓ **Factoring large numbers into their primes (1994 – Shor algorithm)**
  - ✓ Quantum cryptography
- Large optimization problems
  - Economics, risk analysis, etc.
- AI/Machine Learning
- Many more

# Quantum Computing Technologies

## 1. Trapped ions/ atoms

Honeywell/Quantinuum, IonQ, Atom Computing, ...

- First demonstrations (NIST, 1995)
- Most stable qubits, most accurate quantum operations to date

## 2. Superconductor-based circuits

USTC, Google, IBM, Amazon, Intel, Fujitsu, D-Wave, ...

- Front runner (for now)
- First to achieve “Quantum Supremacy”

## 3. Semiconductor-based circuits

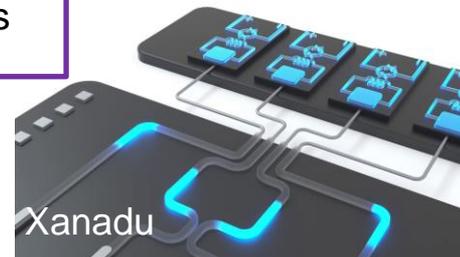
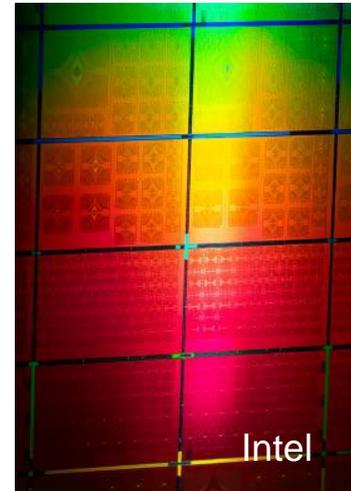
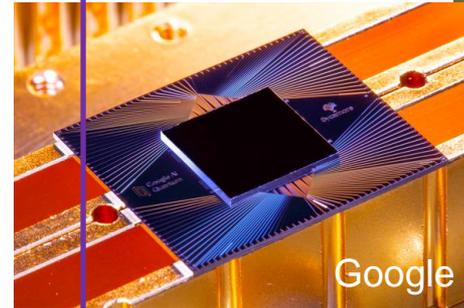
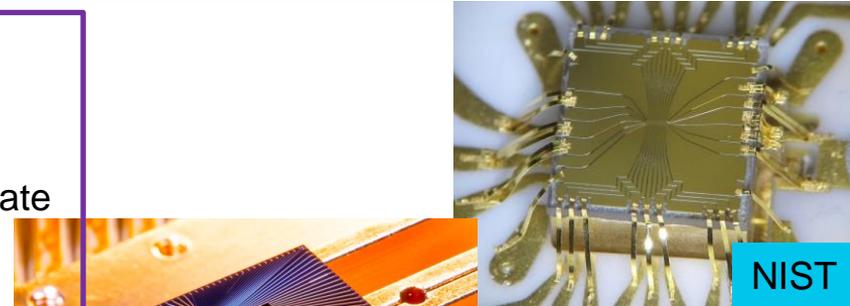
Intel, Silicon Quantum Computing, QuTech, Microsoft, ...

- most scalable? Integrated classical and quantum electronics

## 4. Photonic (integrated)

(Xanadu, Psi Quantum, ...)

- Scalable, most compatible with quantum networking



# SC: How Many (Physical) Qubits?

**>> 1 Million!\***



Austin Fowler, et al., *Phys. Rev. A*, (2012)  
"Surface codes: Towards practical large-scale quantum computation." (Google)



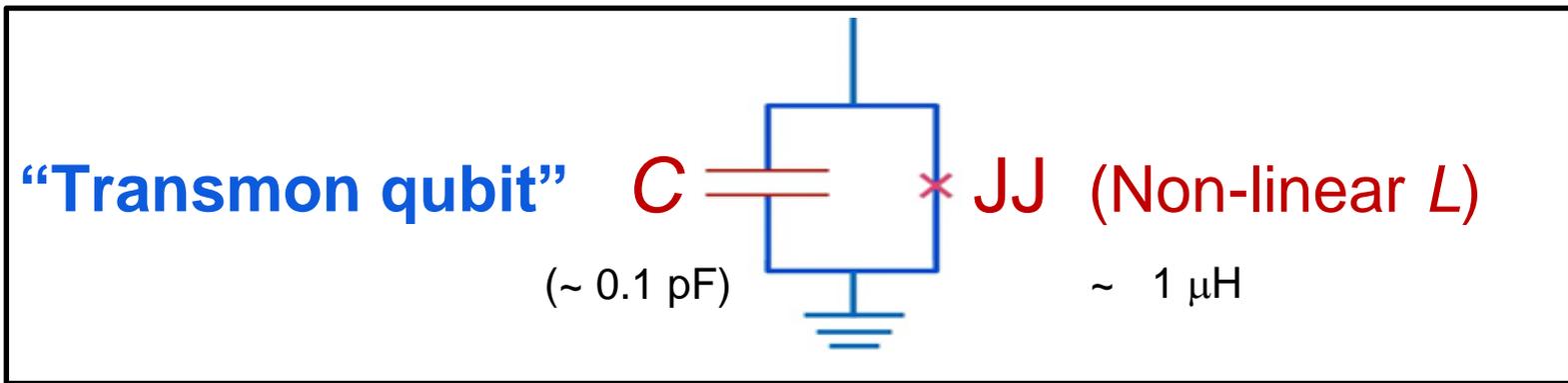
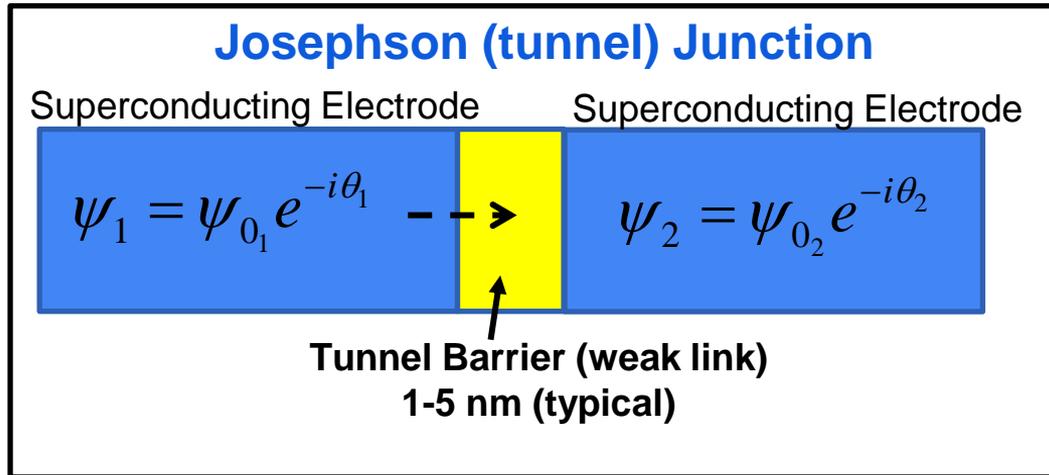
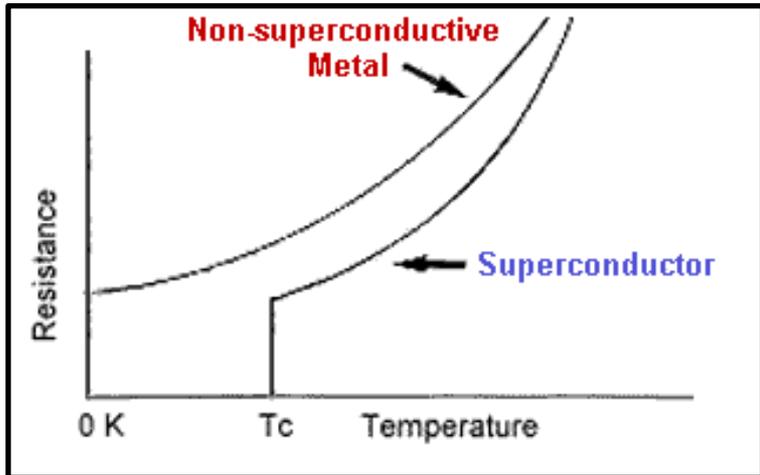
Source:  
<https://www.wired.com/story/quantum-computing-here-but-not-really/>

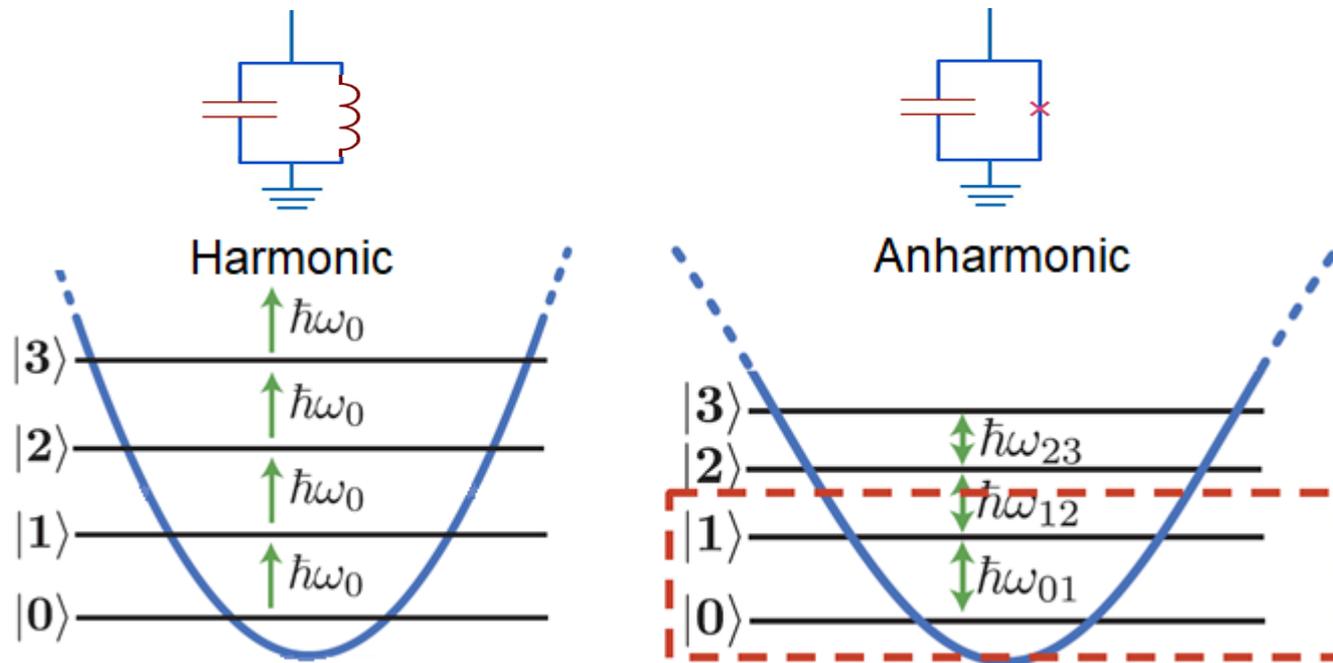
## Measurement Challenges for Scaling

- Cryogenic Microwave Reference Sources
- On-wafer Microwave testing
- On-wafer Cryogenic calibration standards

Assumption: Superconductor-based microwave qubits

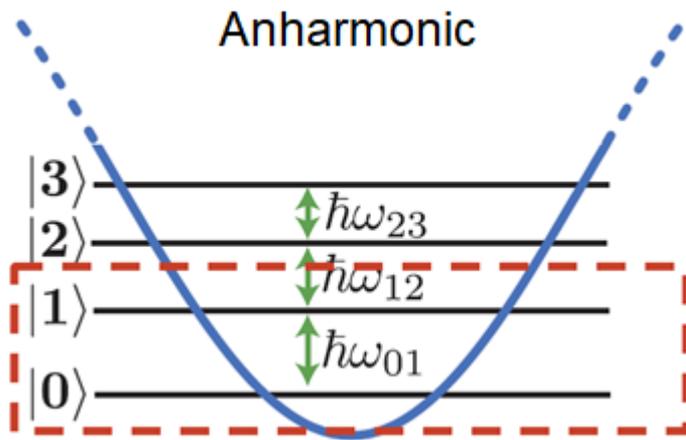
# Superconductor, Josephson junction, Qubit





- Two Quantized Levels can be isolated from the rest
- Results in Simple Quantum System (two-level system)

# Microwave Qubits need to be very cold



$$E_{01}/h \sim 4\text{-}8 \text{ GHz}$$

$$E_{01}/(h \cdot k_B) \sim 0.2\text{-}0.4 \text{ K}$$

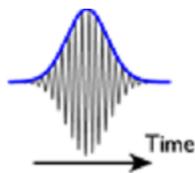
Quantum regime:  $E_{01} \gg k_B T$ ;

$T < 0.05 \text{ K} \rightarrow$  *Dilution refrigerator required*

## Bloch Sphere

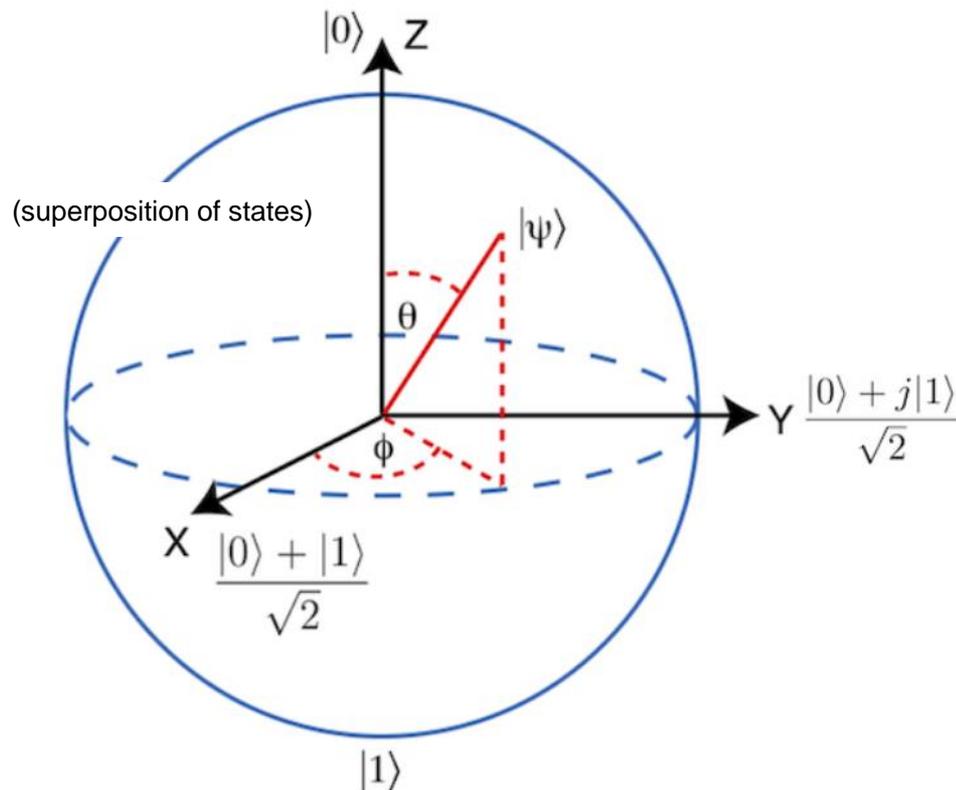
- Describes time evolution of Single Two-State Qubit

- Microwave pulses are used to initialize state (<100 ns)

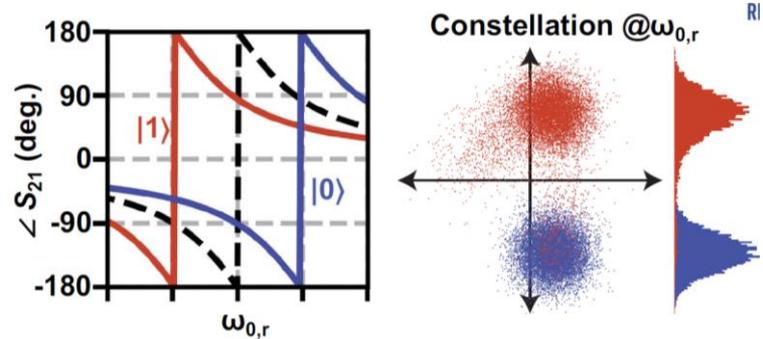
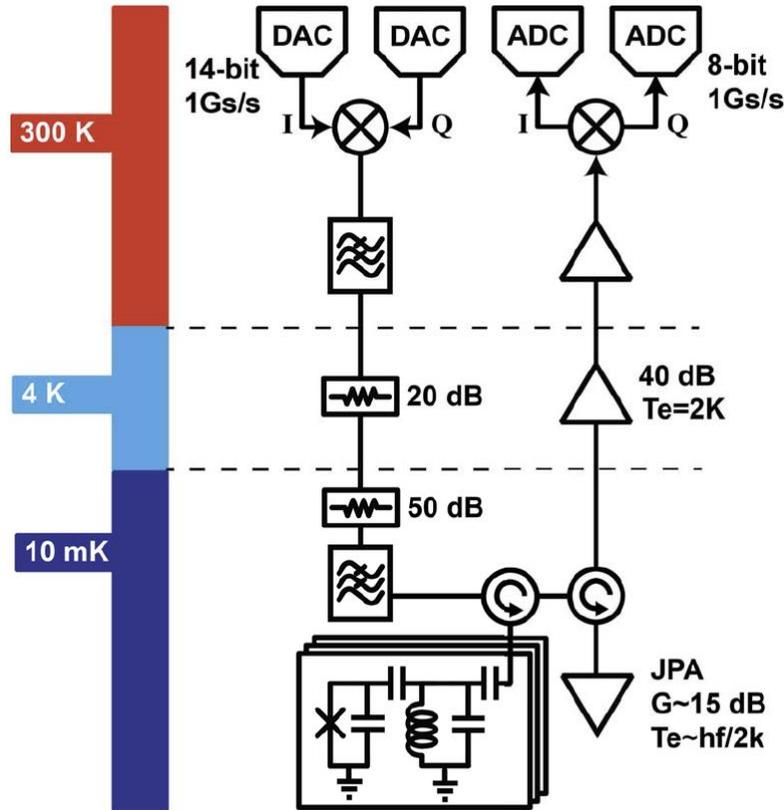


- Microwave pulses are used to perform qubit “gates”

- Timing selects axis of rotation;  
Amplitude selects amount (angle)

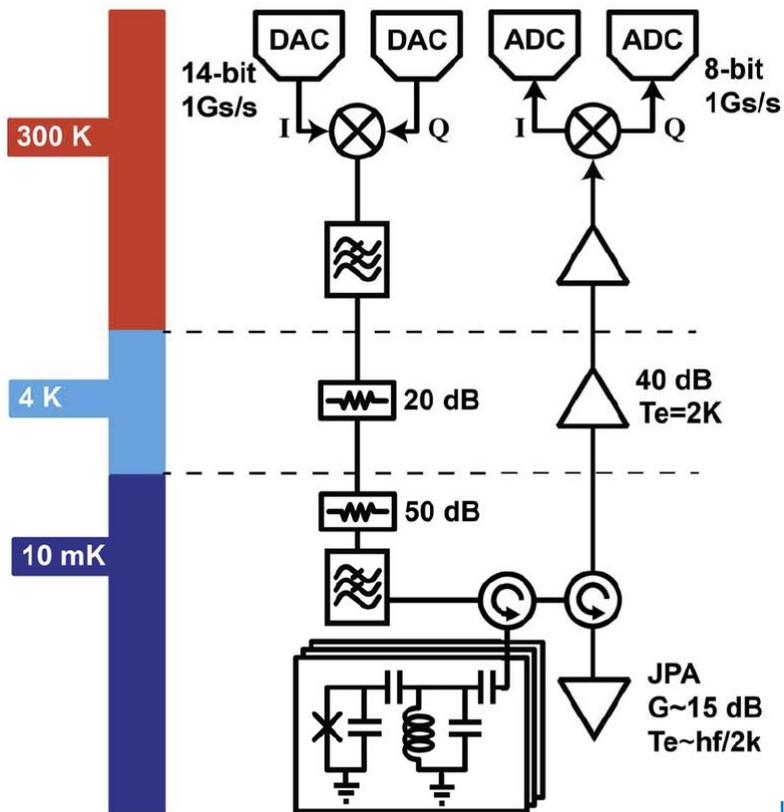


# Microwave Readout of Qubits



- Qubit coupled to Linear Resonator
- Coupling shifts Linear Resonator frequency depending on state of qubit
- Microwave reflectometer measures phase of resonator
- Probability: statistics of many runs

# Readout measurement challenges



- Low power
- ultralow-noise microwave amplification (parametric amplifiers)
- High fidelity (low error rate)
- cryogenic operation
- Error correction

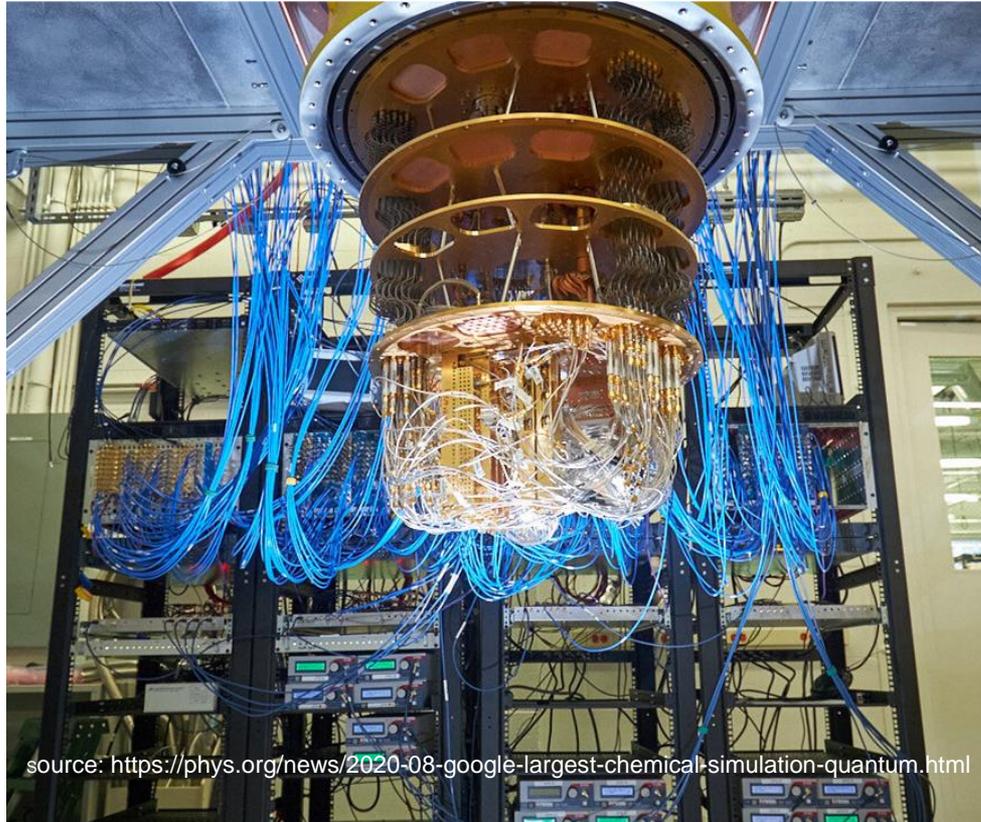
- **Cryogenic Microwave Reference Sources**
- On-wafer Microwave testing
- On-wafer Cryogenic calibration standards

# Integrating qubit control and readout

Lab Demos:  
Room Temperature  
Control and Readout

Need integrated,  
scalable, lower  
latency solution

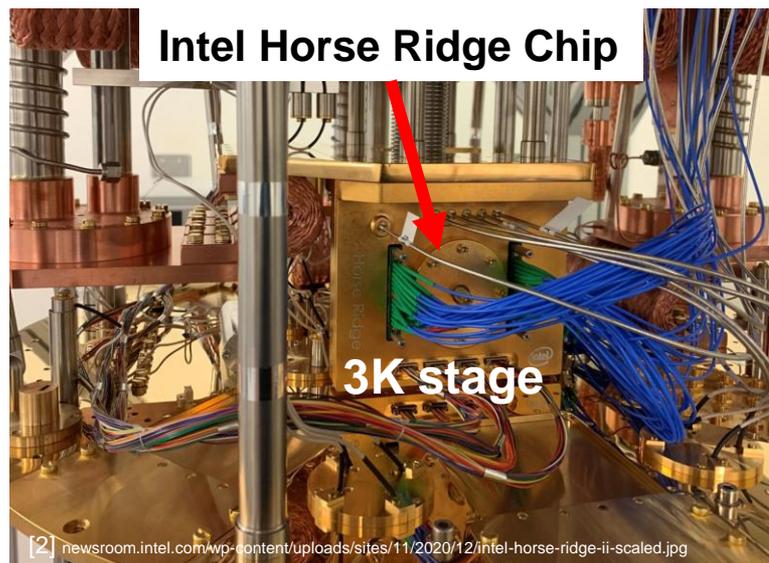
-But-  
limited cooling power



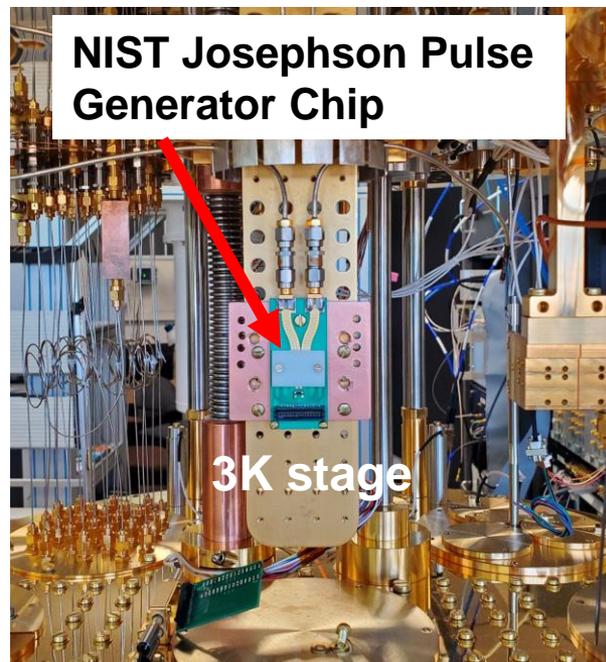
source: <https://phys.org/news/2020-08-google-largest-chemical-simulation-quantum.html>

# Cryogenic qubit control prototypes

## Cryo-CMOS electronics (Google, Intel, Delft, ..)



## Superconductor control electronics

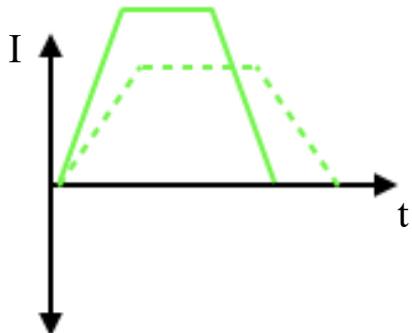


- [1] J. Bardin et al., *IEEE Journal of Solid-State Circuits* (2019)
- [2] Van Dijk et al., *IEEE Journal of Solid-State Circuits* (2020)

- [3] R. McDermott and M. G. Vavilov, *Phys. Rev. Applied* (2014)
- [4] E. Leonard, et al., *Phys. Rev. Applied* (2019)
- [5] L. Howe et al. (NIST), *PRX Quantum* (2022)

# Pulse-Driven JJs Produce Quantized Pulses

Input current bias pulse  
(not quantized)



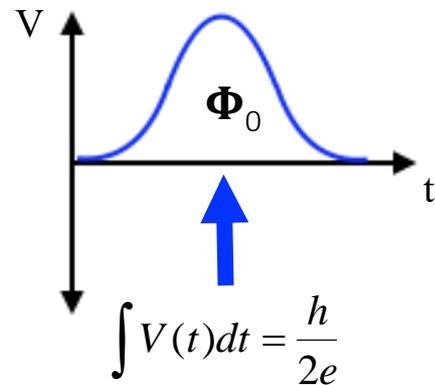
Josephson junction  
(JJ)



Superconducting phase  
across junction ( $\phi$ )  
→ Rotates by  $2\pi$



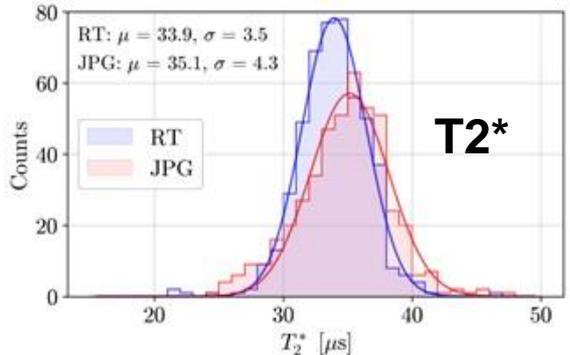
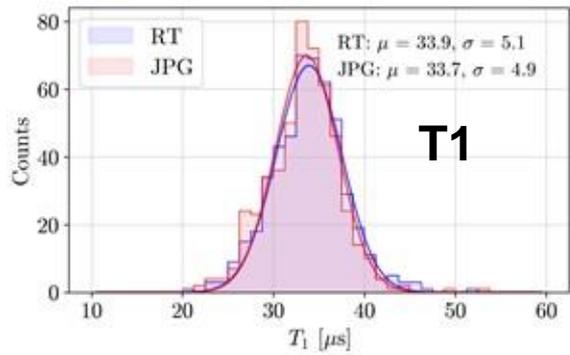
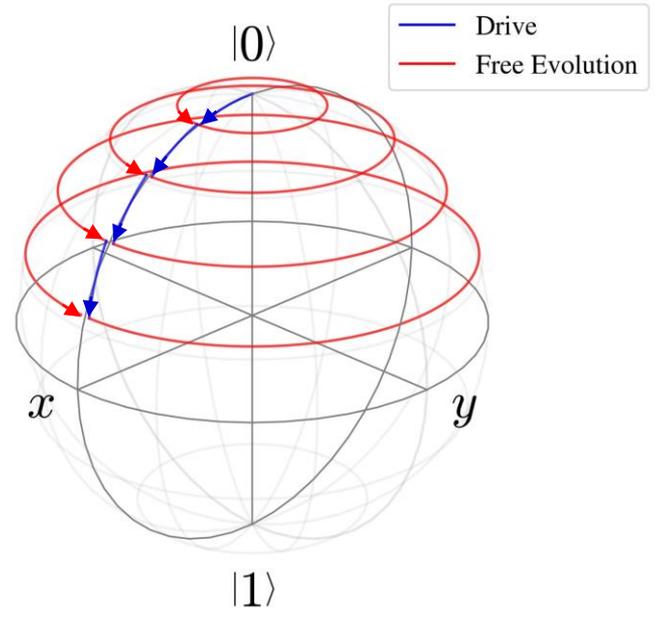
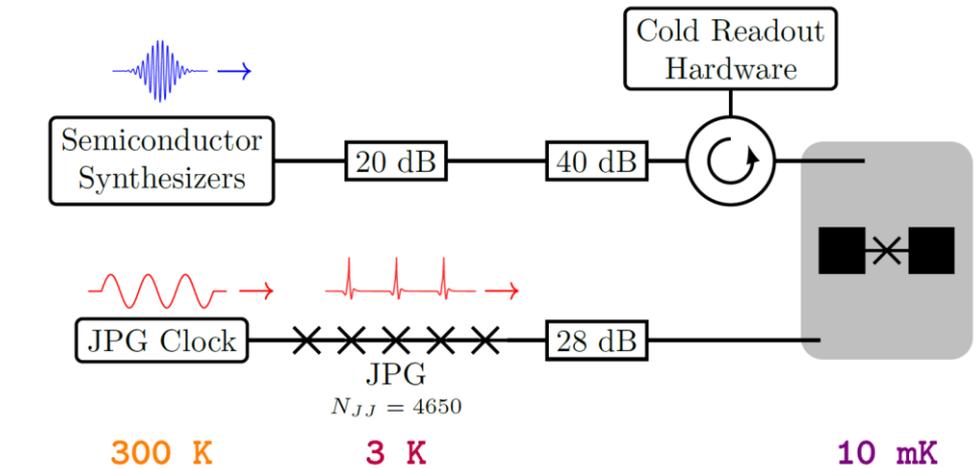
Output voltage pulse  
(quantized area)



$$\int V(t)dt = \frac{h}{2e} * N$$

- **Basis of primary DC and AC voltage standards**
- **Stable, self-calibrated, repeatable, reproducible**

# Digital Qubit Control with NIST Chip



- 1.5% Gate fidelity difference (TBD)

- Cryogenic Microwave Reference Sources
- **On-wafer Microwave testing**
- On-wafer Cryogenic calibration standards

# Cryogenic Front-end for Vector Network Analyzer

*Single Instrument Microwave Tool-Kit  
for Scaling Quantum Computers*

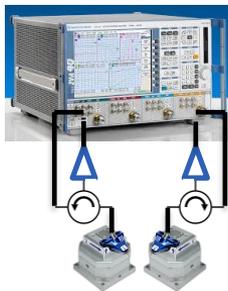
## Capabilities (4-8 GHz)

- On-wafer/chip
- scattering parameters
- Impedances
- voltage and current waveforms
- nonlinear distortion
- Noise

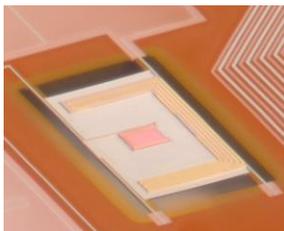
## Objective

- full microwave characterization
- SC and semiconductor-based microwave qubits
- Wafer verification, accurate models

**World's Most Sensitive Vector  
Network Analyzer**

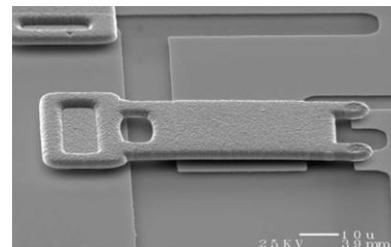


**Ultra-Sensitive Microwave  
Power Sensor**

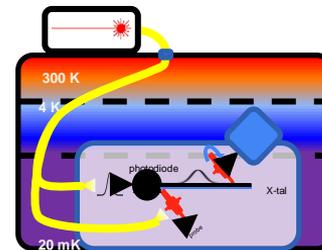


**mK Test Environment**

**World's First mK Microwave  
Variable-Impedance Load**



**World's First mK Electrical-  
Phase Standard**



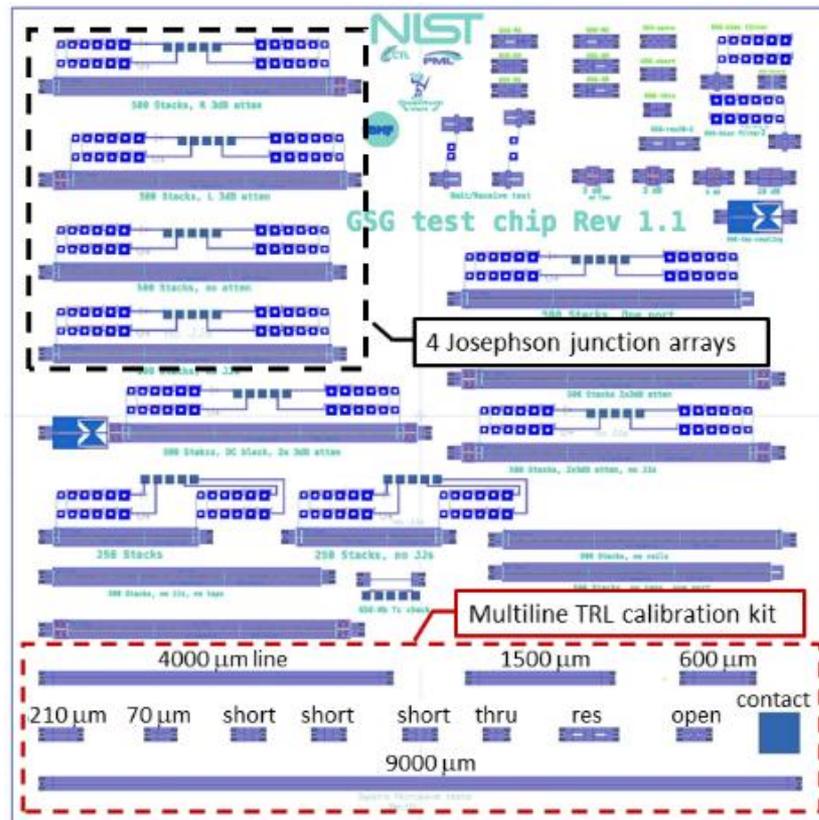
- Cryogenic Microwave Reference Sources
- On-wafer Microwave testing
- **On-wafer Cryogenic calibration standards**

# Cryogenic calibration standards

- On-wafer TRL (through-reflect-line)
- Superconducting films
- Compatible fabrication with DUTs
- 2-tier calibration process

J. A. Brevik et al., *Conference on Precision Electromagnetic Measurements (CPEM)*, 2020, pp. 1–2.

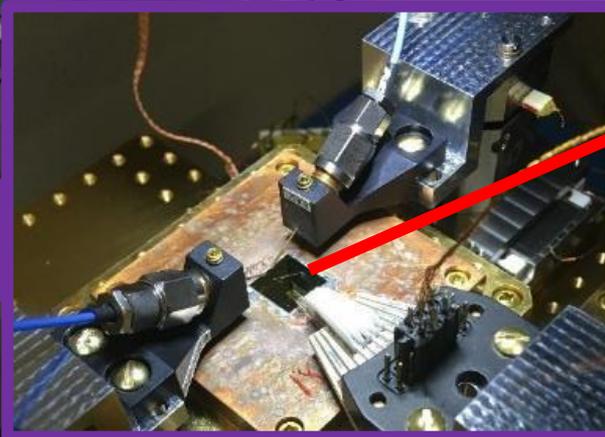
A. S. Boaventura et al., *IEEE Trans. Appl. Supercond.*, vol. 31, no. 9, pp. 1-9, Art no. 1700409 (2021).



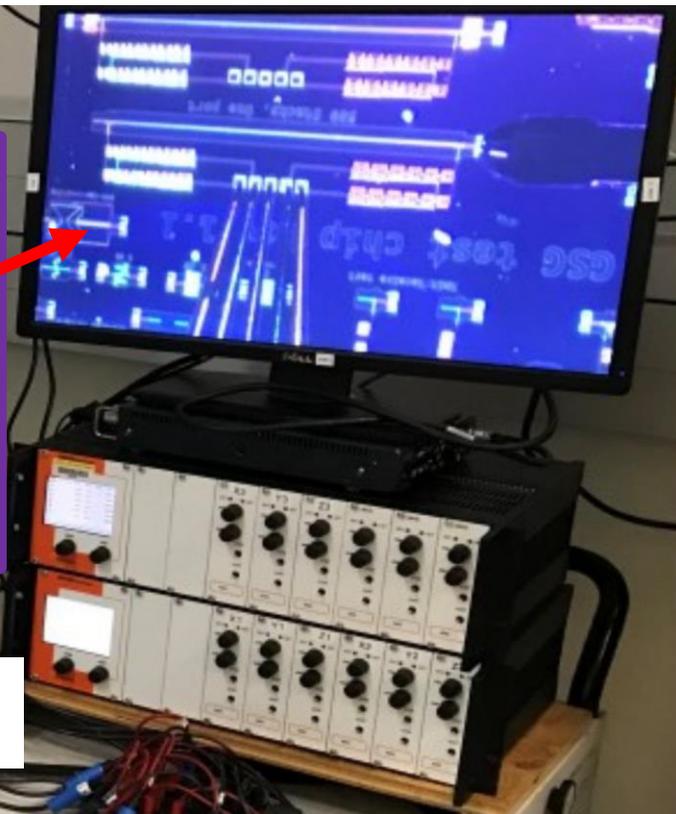
# • Cryogenic calibration standards

4 K On-wafer Ref. Plane

4 K Cryocooler



Coax. Ref. Plane



- Many, many challenges for scaling Superconductor-based QCs
- NIST is developing measurement science and standards for scaling superconductor microwave qubits (4 - 8 GHz):

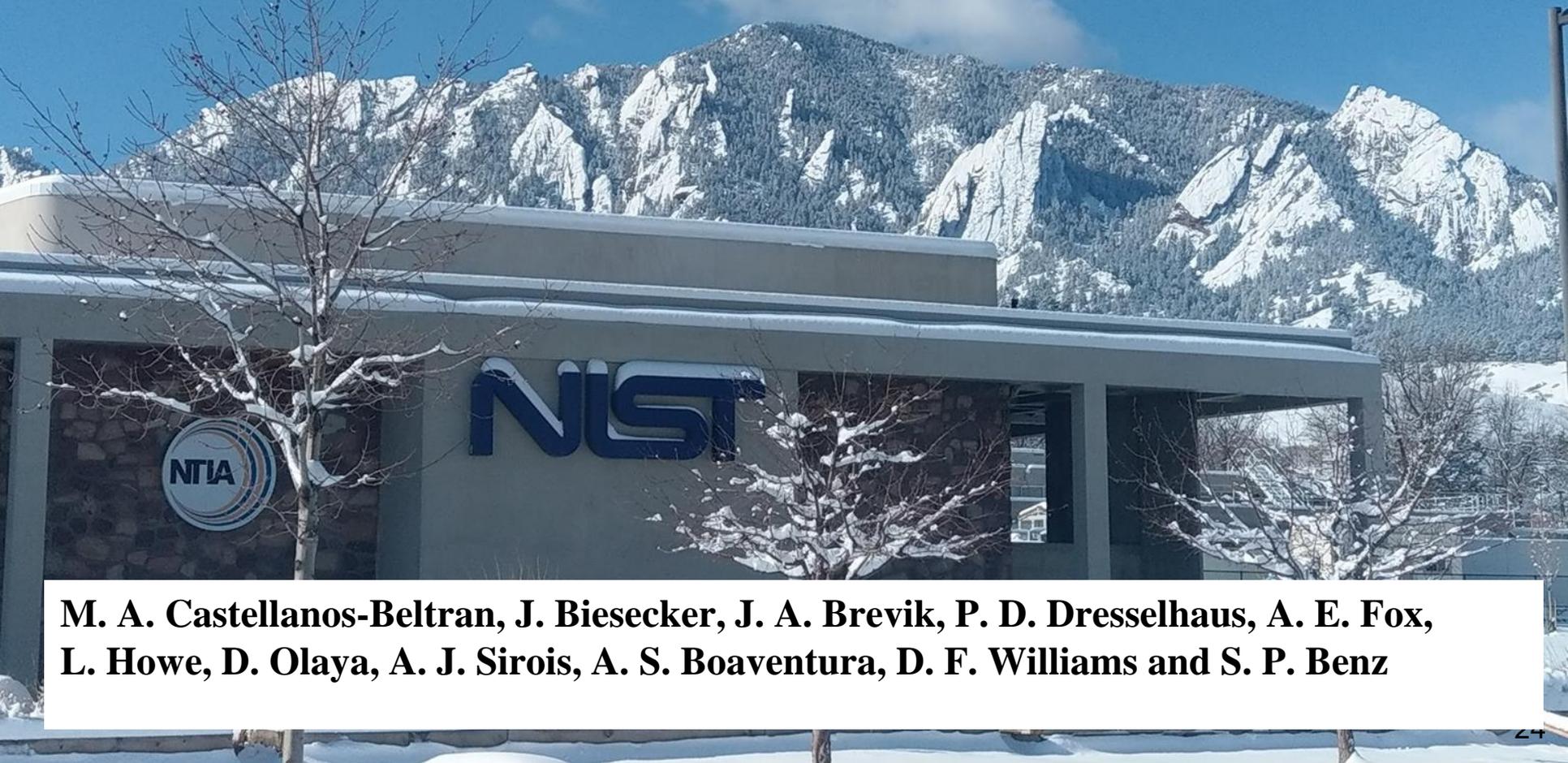
## Next steps

1. Qubit control with co-located SC source (Univ of Wisc/Syracuse)
2. Deploy VNA front-end in dilution refrigerator and calibrate with on-wafer cal kit at mK.

Contact info:

- [Peter.Hopkins@nist.gov](mailto:Peter.Hopkins@nist.gov)

# Thank You!



**M. A. Castellanos-Beltran, J. Biesecker, J. A. Brevik, P. D. Dresselhaus, A. E. Fox,  
L. Howe, D. Olaya, A. J. Sirois, A. S. Boaventura, D. F. Williams and S. P. Benz**