IEEE CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), January 2022.
Plenary presentation M1Or-PL given at CEC-ICMC 2021, July 19-23, 2021, Virtual.

The Promise of Superconducting Quantum Information Processing

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Lawrence Berkeley National Laboratory
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BERKELEY LAB

quantumsystemsaccelerator.org

Advanced Quantum Testbed
Computational Research Division (CRD)
AQT at Berkeley Lab

aqt.lbl.gov

Quantum Nanoelectronics Laboratory

qnl.berkeley.edu

CEC/ICMC 21
Plenary
July 19, 2021

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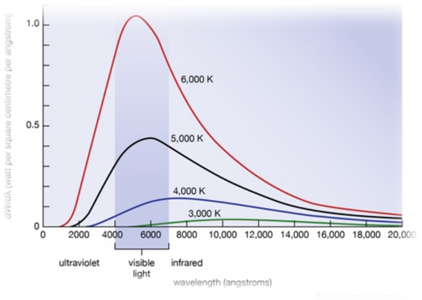
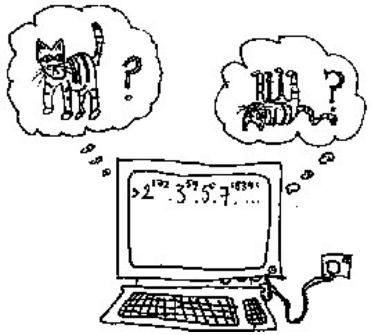
Quantum: Thought Experiment to Technical Revolution

Predicament: Emission spectra of solids/gases unexplained by classical physics



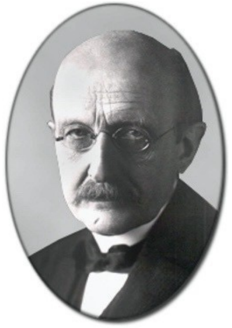
Pottery: Objects in a kiln glow the same color

Promise: Quantum information technologies for communication, sensing, and computation



www.physik.uzh.ch

Postulate: Quantization of energy in atoms & springs

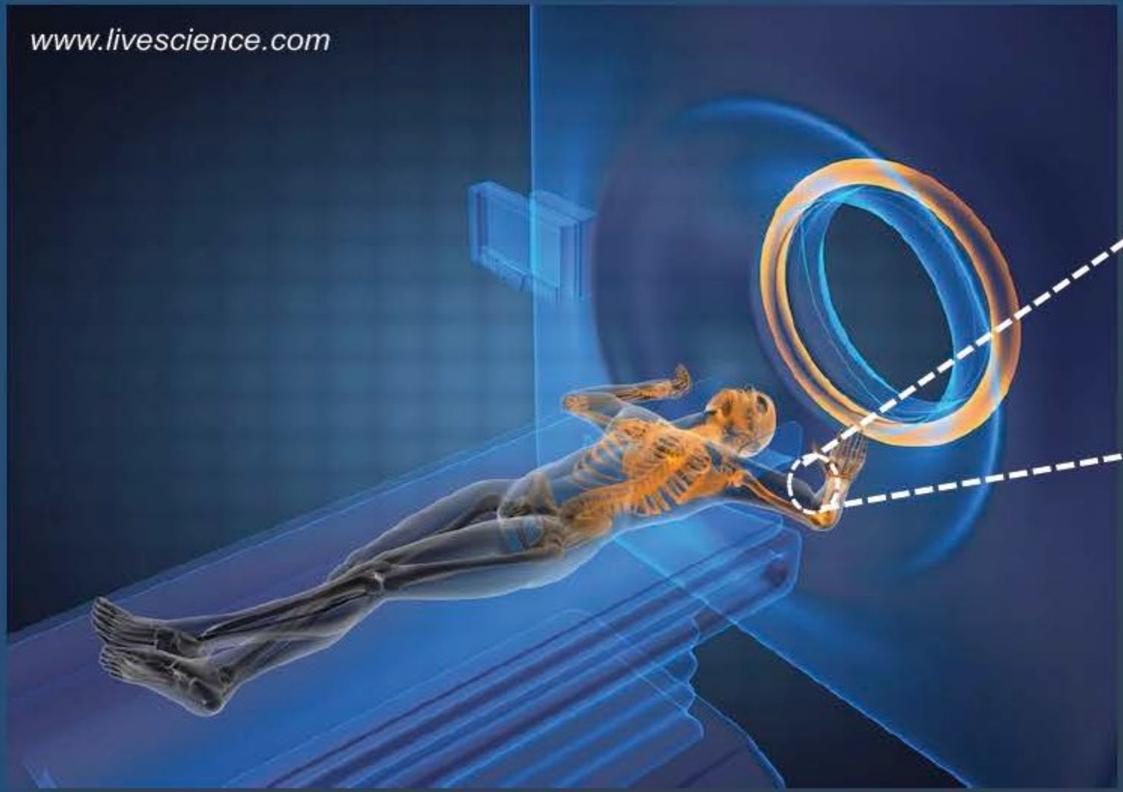


Puzzle: Quantum theory predicts highly correlated (entangled) states

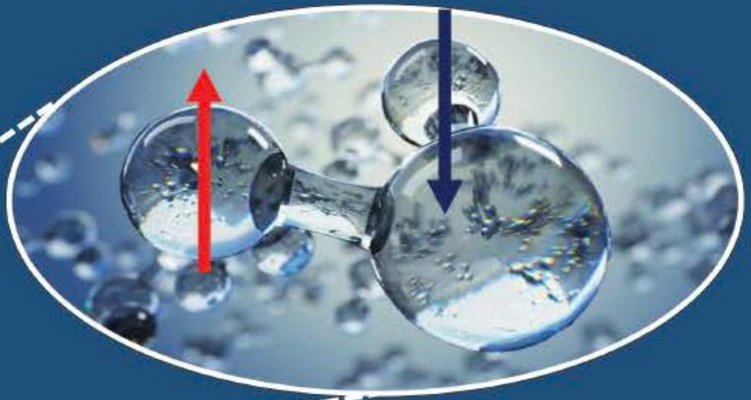
Problem: Converting entanglement into an engineering resource

The Quantum World Around Us

A MRI Scan Relies on Quantum Mechanics!

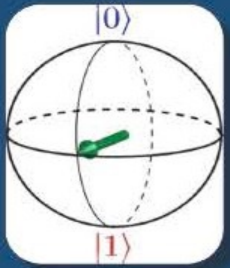


Water molecules have two hydrogens which have nuclear spin (up or down)



Apply magnetic field to measure spin

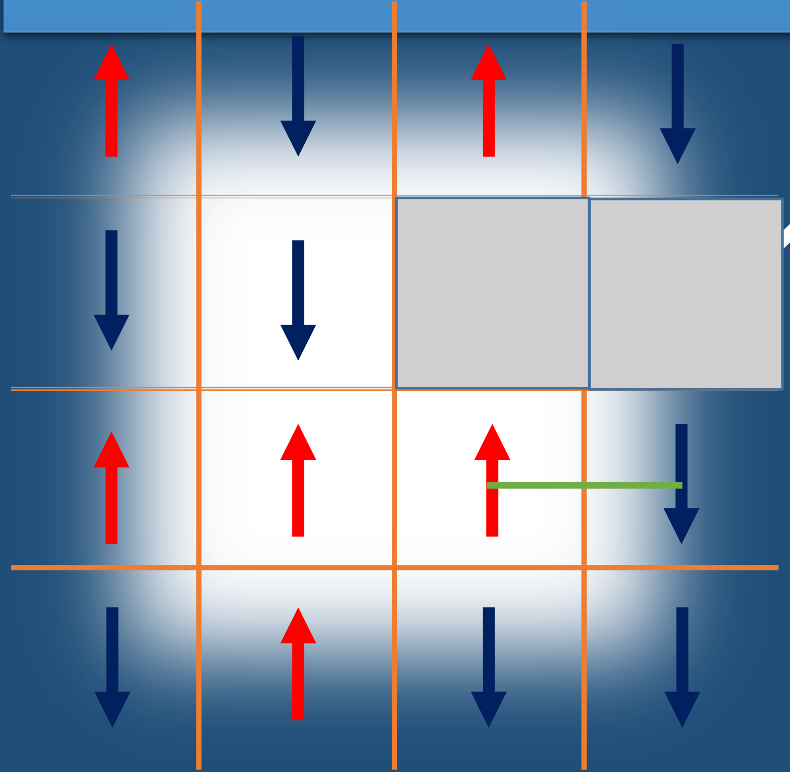
- Always observe ↑ or ↓
- Prepare superposition: ← = ↑ + ↓
- Would measure: 50% ↑ , 50% ↓



QUANTUM SYSTEMS CAN EXIST IN MANY DIFFERENT CONFIGURATIONS, EVEN IF WE CAN'T OBSERVE ALL OF THEM!

The Power of Entanglement

- Let's build a computer one spin (quantum bit) at a time !
- Unlike MRI which measures average properties of a group of spins, we need to address each spin individually



- Measurement reveals state to be ↑
- If we don't observe, state is (**a** · ↑ + **b** · ↓) and described by 2 numbers {a,b}
- Adjacent bit is (**c** · ↑ + **d** · ↓) and described by 2 numbers {c,d}
- Couple these two bits and consider product: (a · ↑ + b · ↓) X (**c** · ↑ + **d** · ↓)

ac · ↑↑ + **ad** · ↑↓ + **bc** · ↓↑ + **bd** · ↓↓

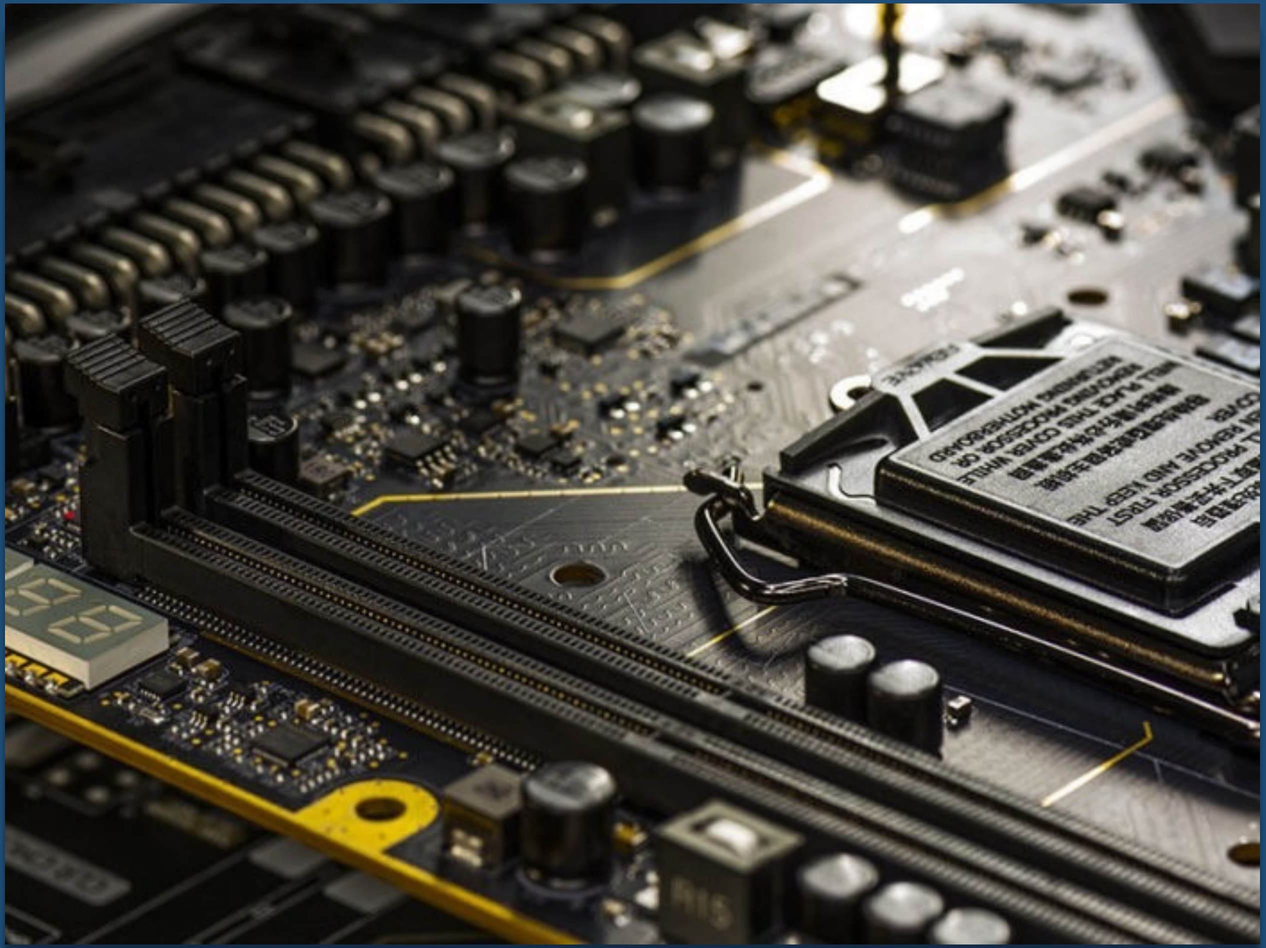
cannot describe

Entangled State → ↑↑ + ↓↓

If a = 0, lose **ac** · ↑↑
If d = 0, lose **bd** · ↓↓

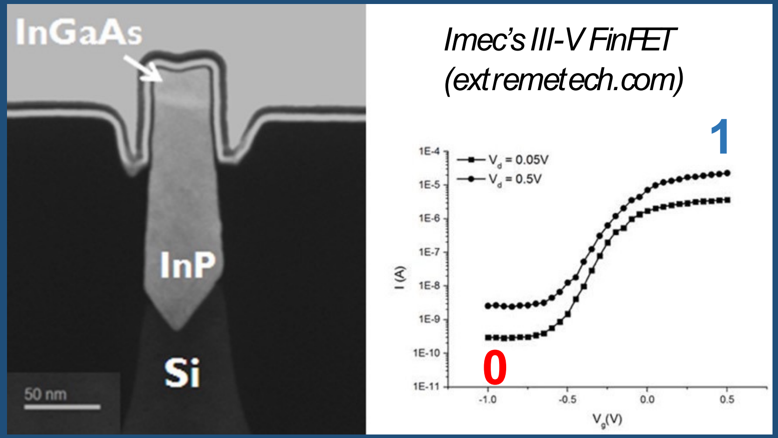
2^N >> 2N: NEED MORE NUMBERS THAN PARTICLES IN THE UNIVERSE TO DESCRIBE ~ 300 ENTANGLED QUBITS

The Quantum Information Paradigm Shift



(Z370: www.pcworld.com)

- Start with a good switch…



- Advanced materials science, electromagnetism, and thermodynamics at the nm scale
- Different functional units (processor, memory,..)
- Advanced packaging/controls
- Well matched algorithms

QUANTUM IS FUNDAMENTALLY DIFFERENT AT ALL LEVELS!

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Potential Quantum Advantage

- Pattern detection / Fourier analysis
- Efficiently searching a large database
- Finding energy (cost) minima
- Matrix math
  - Systems of equations
  - Machine learning
  - Diagonalization

Challenges:

i. Decoherence limits complexity (need >100 gates with 99.9 fidelity)

ii. Error correction / resource scaling (data input/output, error correction, …)

High-tech	• Machine learning and artificial intelligence, such as neural networks • Search • Bidding strategies for advertisements • Cybersecurity • Online and product marketing • Software verification and validation	IBM, Telstra, Alibaba, Baidu, Google, Samsung, Microsoft
Industrial goods	• Logistics: scheduling, planning, product distribution, routing • Automotive: traffic simulation, e-charging station and parking search, autonomous driving • Semiconductors: manufacturing, such as chip layout optimization • Aerospace: R&D and manufacturing, such as fault-analysis, stronger polymers for airplanes • Material science: effective catalytic converters for cars, battery cell research, more-efficient materials for solar cells, and property engineering uses such as OLEDS	Airbus, BMW, NASA, Volkswagen, Northrop Grumman, Lockheed Martin, Daimler, Honeywell, Raytheon, Bosch
Chemistry and Pharma	• Catalyst and enzyme design, such as nitrogenase • Pharmaceuticals R&D, such as faster drug discovery • Bioinformatics, such as genomics • Patient diagnostics for health care, such as improved diagnostic capability for MRI	BASF, JSR, Biogen, DuPont, Dow Chemical, Amgen
Finance	• Trading strategies • Portfolio optimization • Asset pricing • Risk analysis • Fraud detection • Market simulation	J.P. Morgan, Barclays, Commonwealth Bank, Goldman Sachs
Energy	• Network design • Energy distribution • Oil well optimization	Dubai Electricity & Water Authority, BP

Source: BCG analysis.

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The New York Times

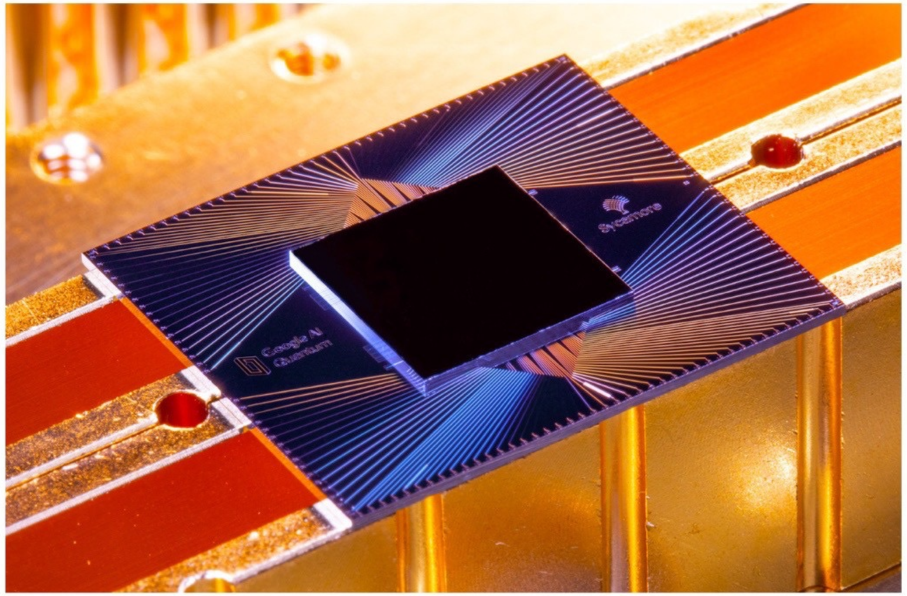
Why Google's Quantum Supremacy Milestone Matters

The company says its quantum computer can complete a calculation much faster than a supercomputer. What does that mean?

By Scott Aaronson

Dr. Aaronson is the founding director of the Quantum Information Center at the University of Texas at Austin.

Oct. 30, 2019



Google A.I. Quantum's Sycamore processor. Erik Lucero/Google

Google researchers in Santa Barbara, California, say their advance may lead to near-term applications of quantum computers. ISTOCK.COM/JHVEPHOTO

IBM casts doubt on Google's claims of quantum supremacy

By Adrian Cho | Oct. 23, 2019 , 5:40 AM

AAAS Science

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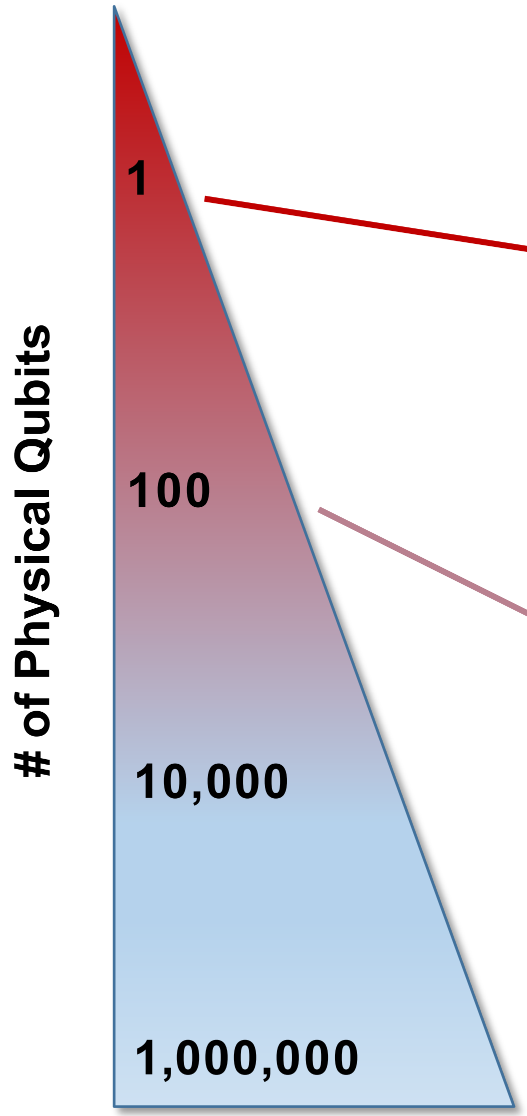
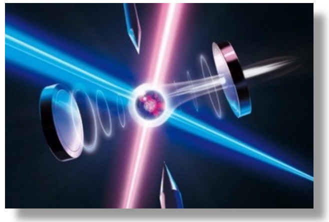
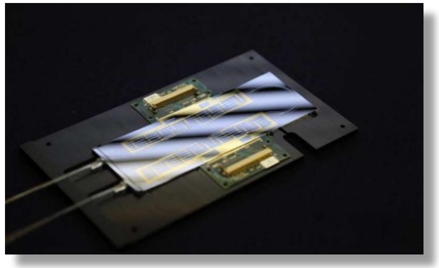
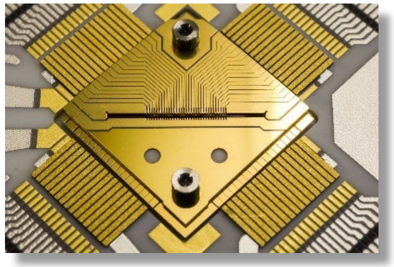
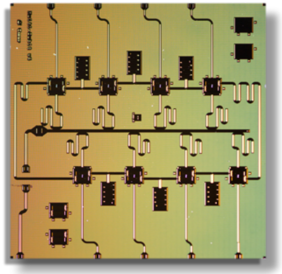
From Art to Architecture







Communication & Sensing

Noisy, Intermediate Scale Quantum (NISQ) Era

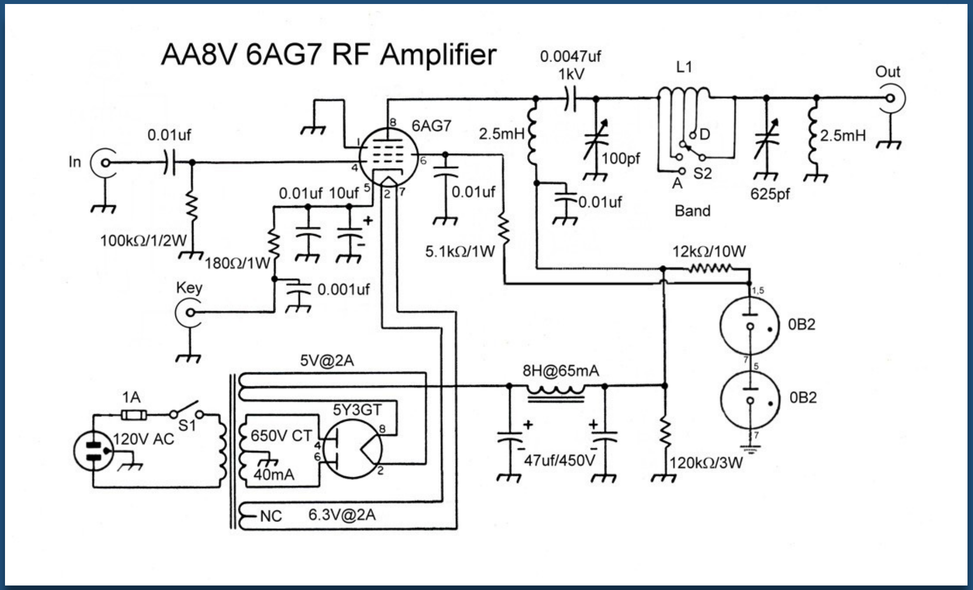
- 10-100 physical qubits
- Minimal error correction
- Purely quantum & hybrid algorithms
- < 100 Logical gate operations

- Cannot be simulated by classical devices
- First quantum computations
- Reveal scaling of quantum advantage
- Growth of error resilience; novel QEC
- Growth of new classical computing hardware

Fault-tolerant, Universal Computation

SUPERCONDUCTING QUANTUM PROCESSORS

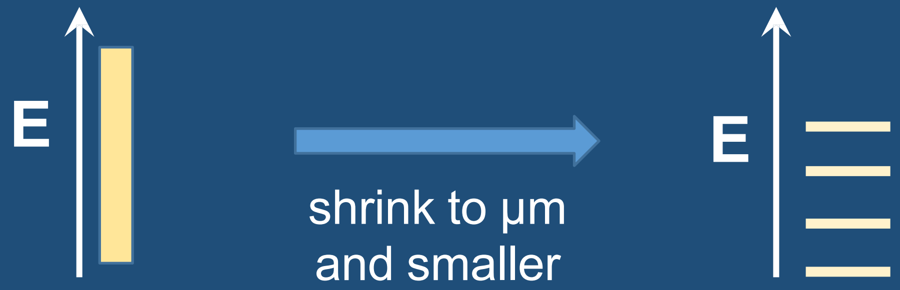
Accessing the Quantum World



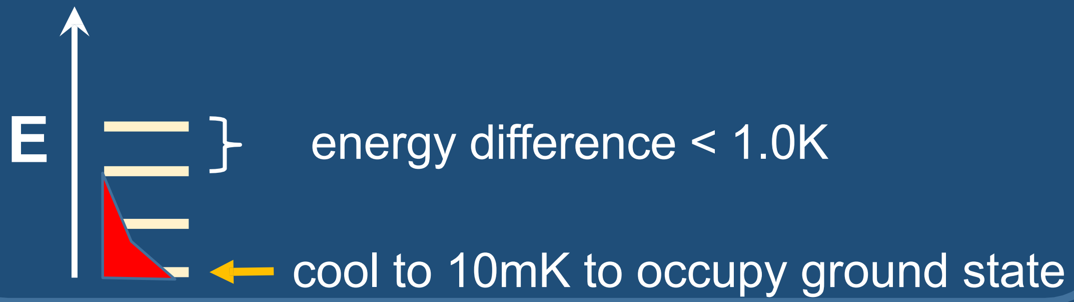
- Combination of *R, L, C* (linear or nonlinear)
- Excite with voltages / currents (AC or DC)
- Classically, these quantitates can take on any continuous values

QUANTUM MECHANICS SAYS THESE QUANTITIES CAN BE DISCRETE!

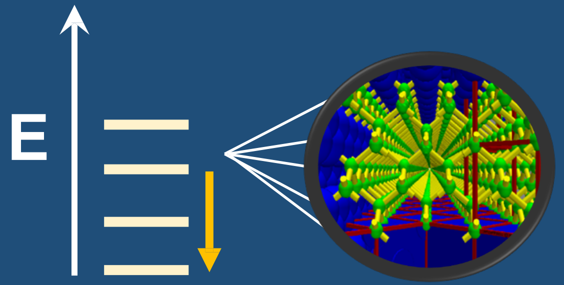
- Granularity becomes apparent at the nanoscale



- Cryogenic operation to occupy single state



- Isolate from environment (loss/dephasing)



decoherence due to coupling to unwanted resonances

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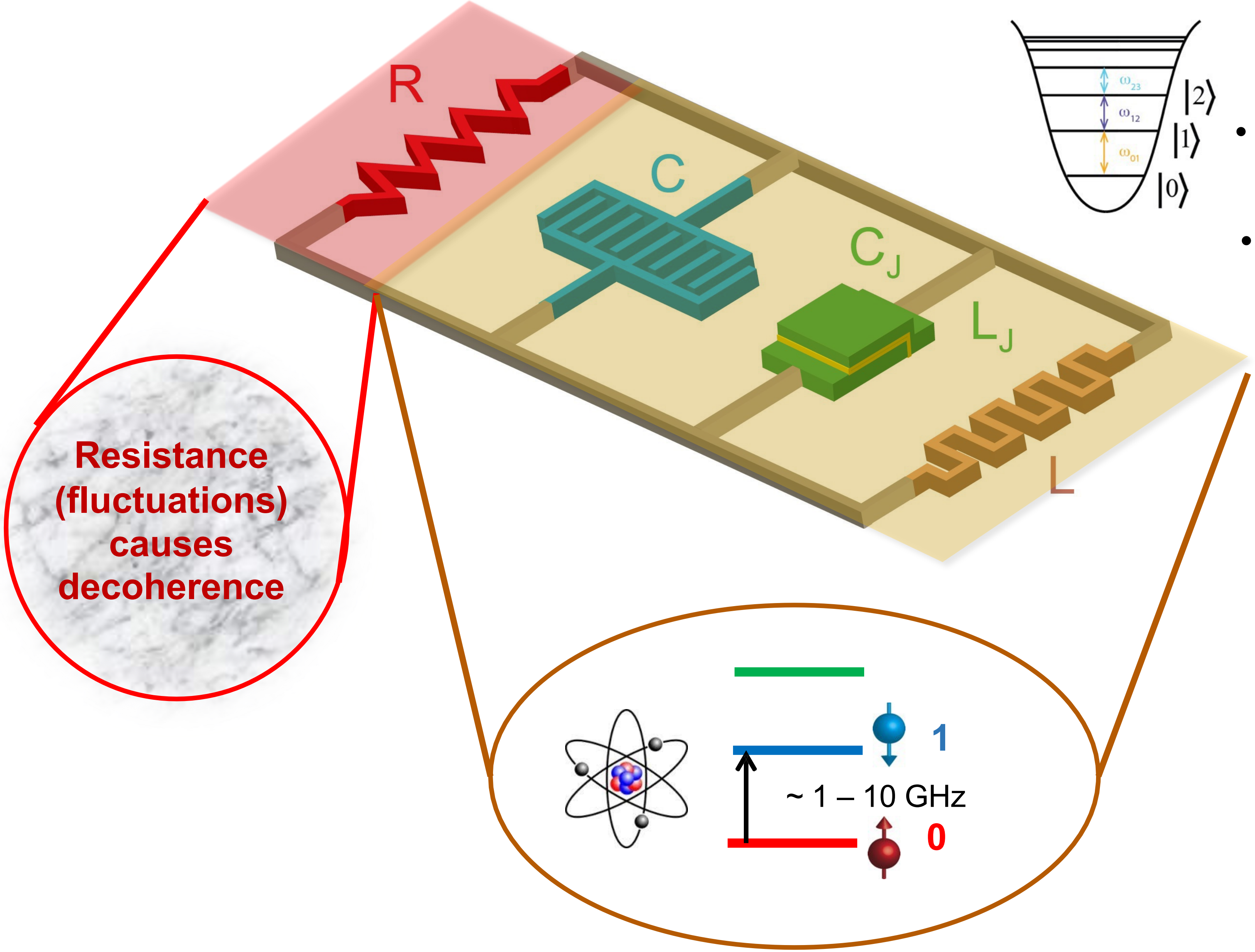
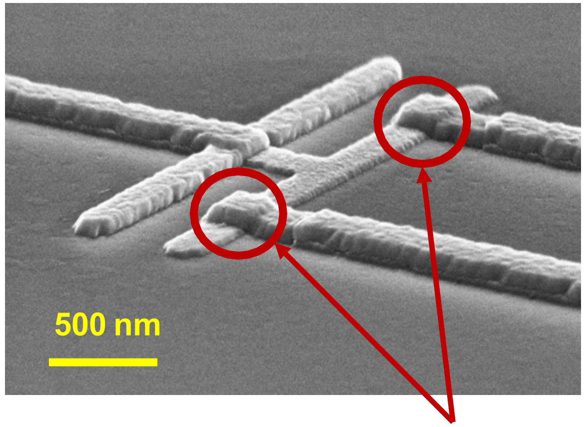
Starting From a Nonlinear Oscillator

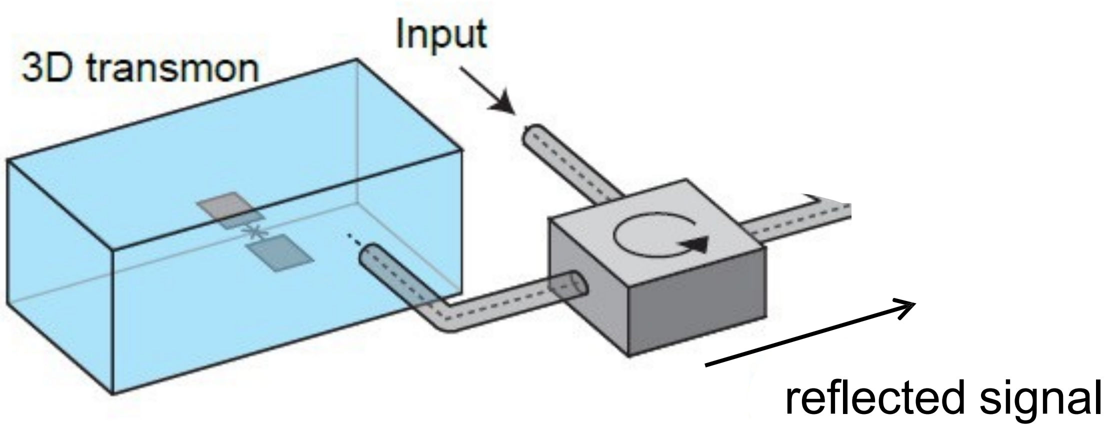


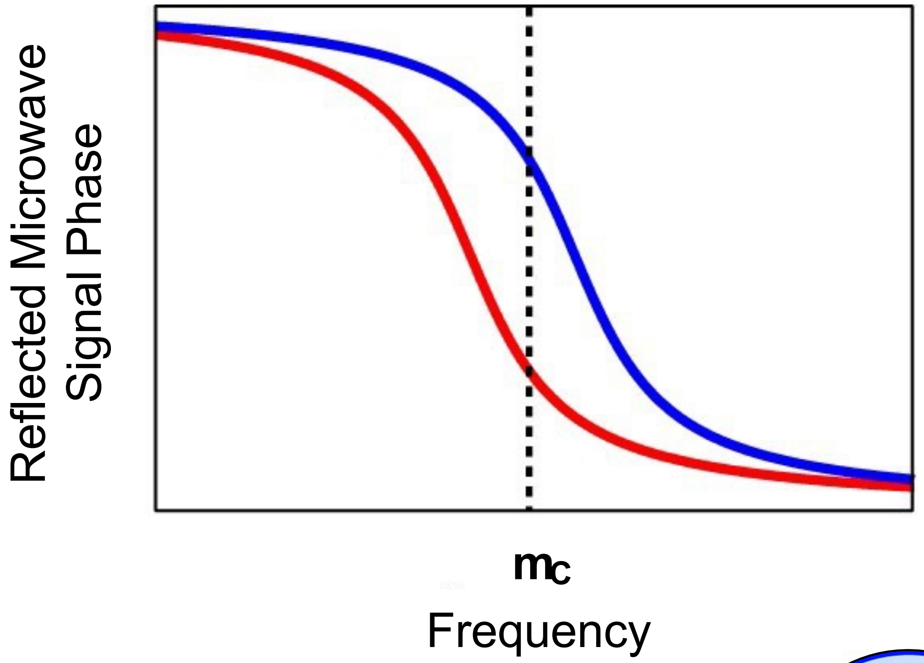
- Classical harmonic oscillator (parabolic potential) : all energies (currents) are allowed
- Quantum harmonic oscillator: only certain energies (currents) are allowed
- Tunnel junction (cosine potential) ➔ Nonlinear, isolate 0, 1



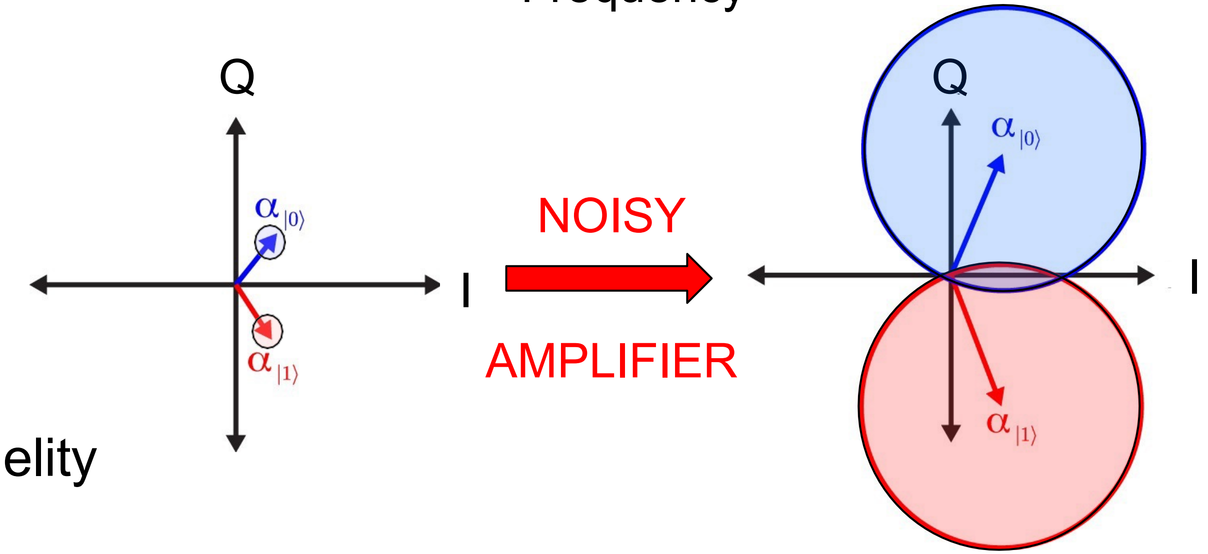
Al/AlOx/Al Josephson tunnel junctions

Qubit Readout with Microwave Reflectometry



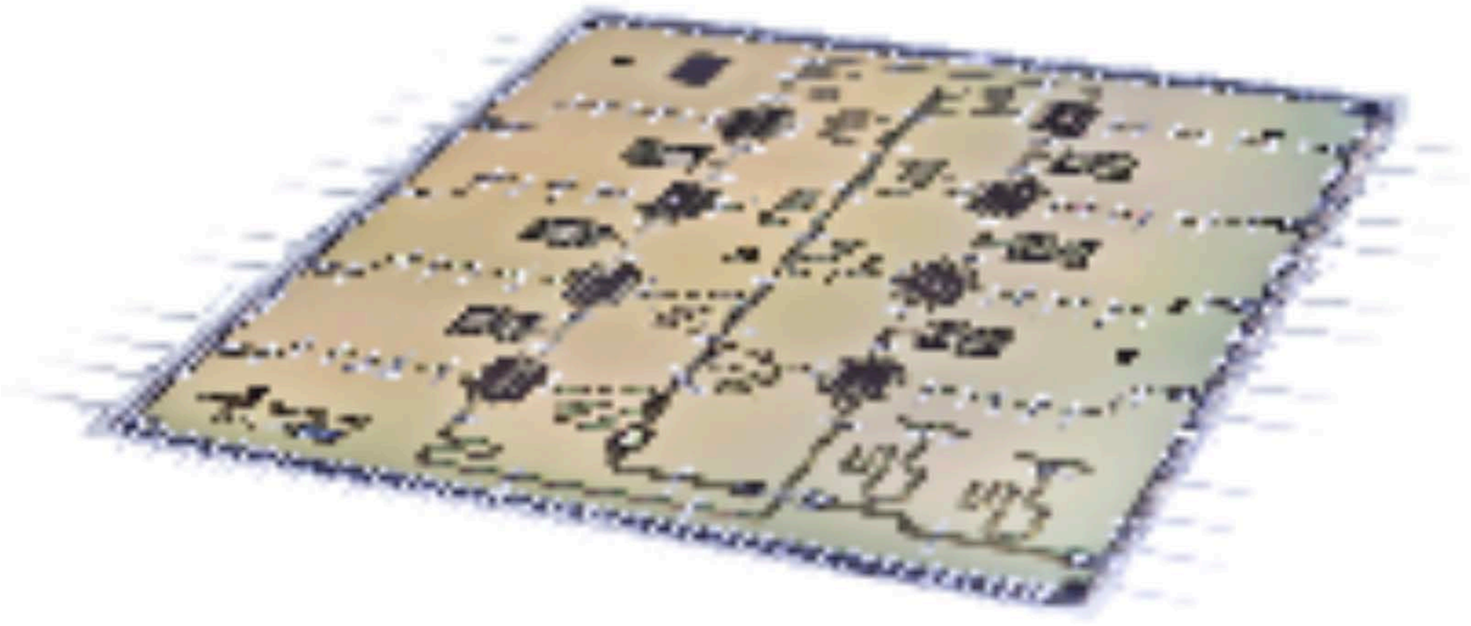


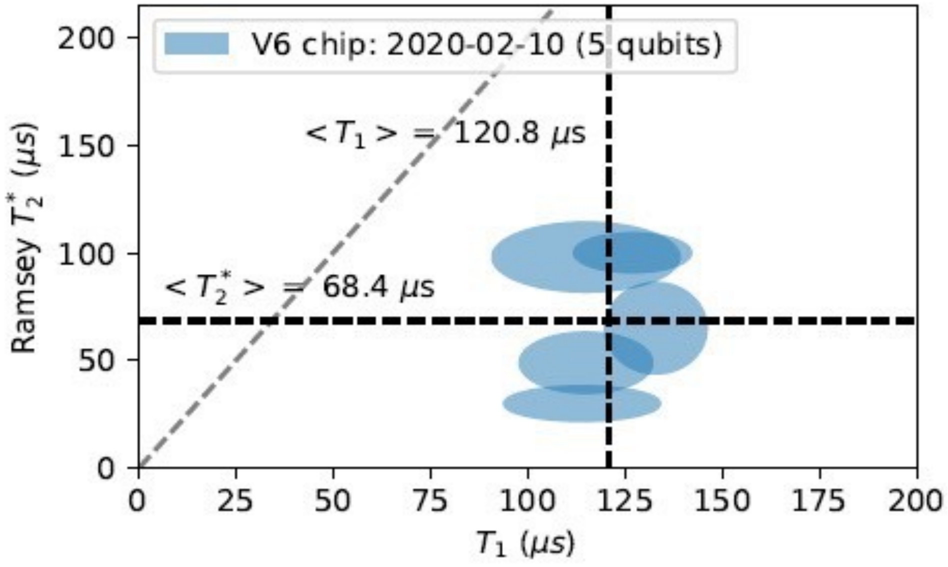
$$A\sin(\omega t+\phi) = A\sin(\omega t)\cos(\phi) + A\cos(\omega t)\sin(\phi)$$
$$= \underbrace{[A\cos(\phi)]}_{\text{I}}\sin(\omega t) + \underbrace{[A\sin(\phi)]}_{\text{Q}}\cos(\omega t)$$

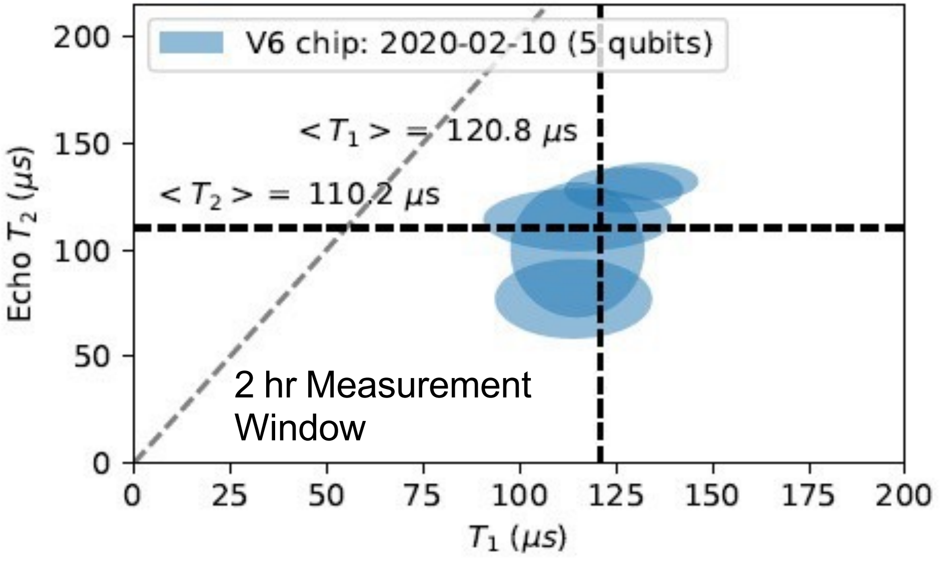


- Homodyne measurement: Voltage (Phase ‘Q’)
- Use superconducting amplifiers for single shot fidelity

Multiqubit Chip Quantum Coherence

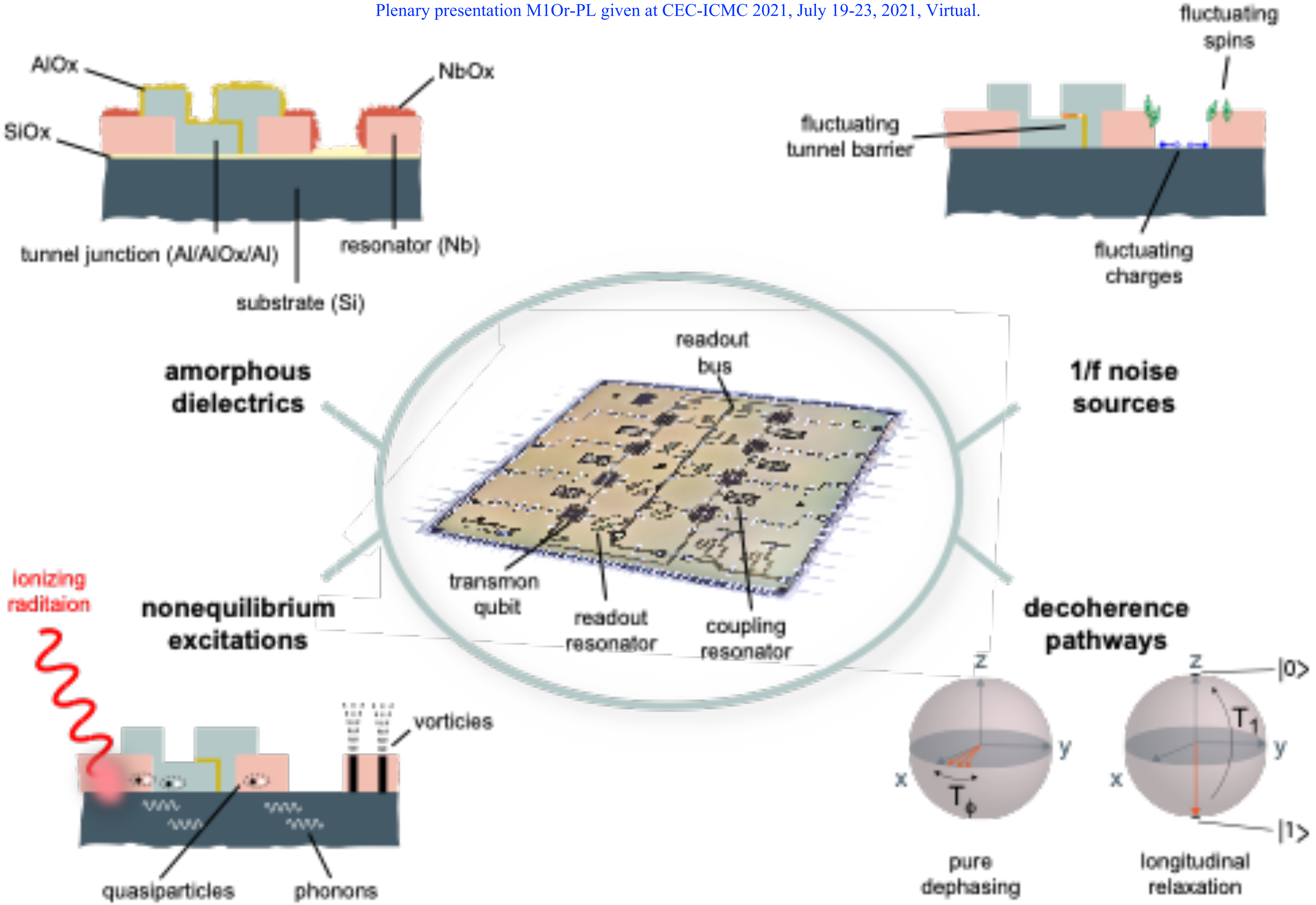






- Bit flip ~ 10 ns, Entangling gate ~ 100-500 ns
- Improve materials
- Use noise resilient circuits (symmetry/topology)
- Active noise mitigation

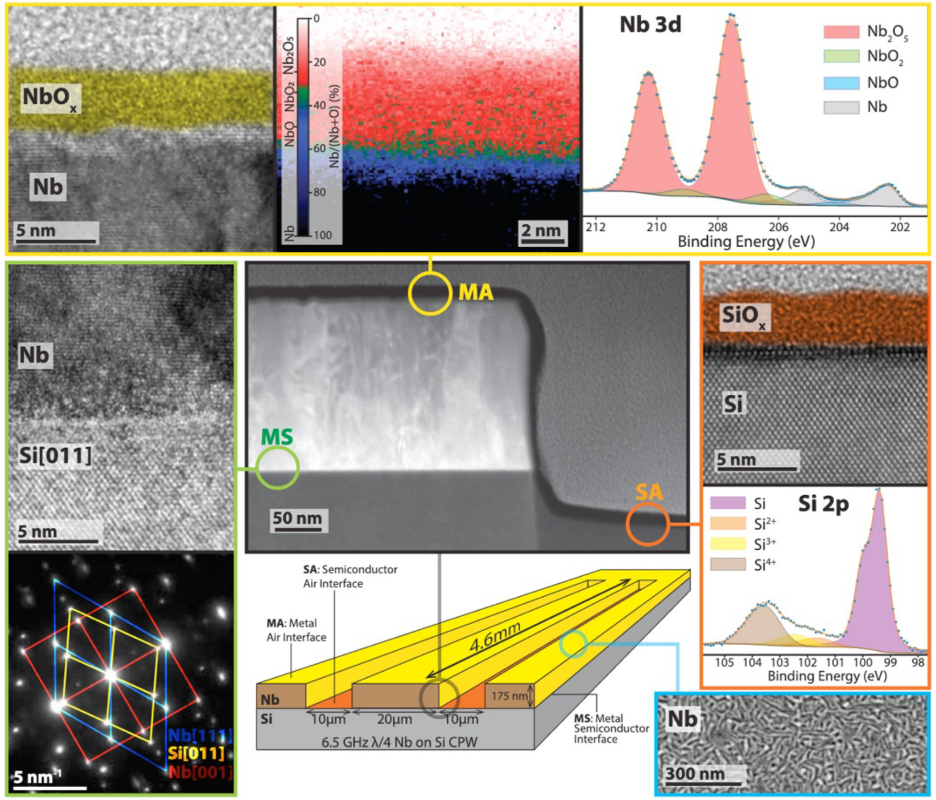
BETTER QUBITS

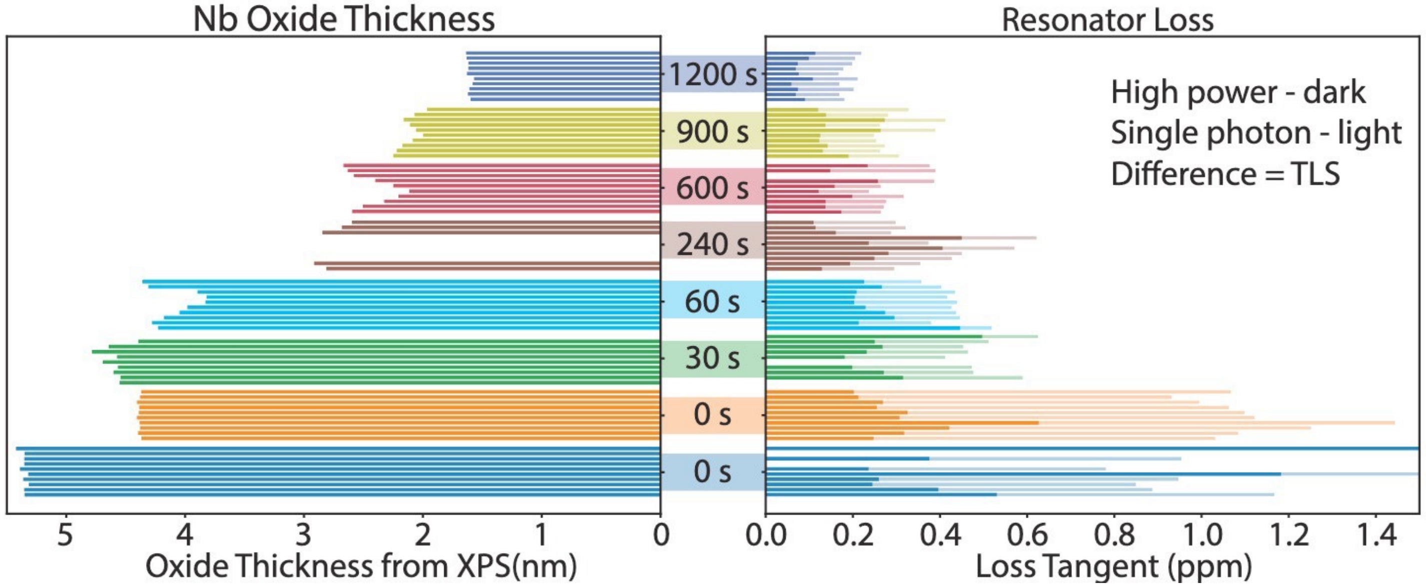

AlOx
NbOx
SiOx
tunnel junction (Al/AlOx/Al)
resonator (Nb)
substrate (Si)
fluctuating spins
fluctuating tunnel barrier
fluctuating charges
amorphous dielectrics
1/f noise sources
readout bus
transmon qubit
readout resonator
coupling resonator
ionizing raditaion
nonequilibrium excitations
decoherence pathways
vorticies
quasiparticles
phonons
z
y
x
T_ϕ
pure dephasing
|0>
|1>
T_1
longitudinal relaxation

Controlling Surfaces and Interfaces

Localization and reduction of superconducting quantum coherent circuit losses

M. Virginia P. Altoé[1*], Archan Banerjee[2,3*], Cassidy Berk[1*], Ahmed Hajr[3,4,5*], Adam Schwartzberg[1], Chengyu Song[1], Mohammed Al Ghadeer[6], Shaul Aloni[1], Michael J. Elowson[1], John Mark Kreikebaum[2,3], Ed K. Wong[1], Sinead Griffin[1], Saleem Rao[6], Alexander Weber-Bargioni[1], Andrew M. Minor[1,7], David I. Santiago[3,4], Stefano Cabrini[1], Irfan Siddiqi[2,3,4], and D. Frank Ogletree[1†]

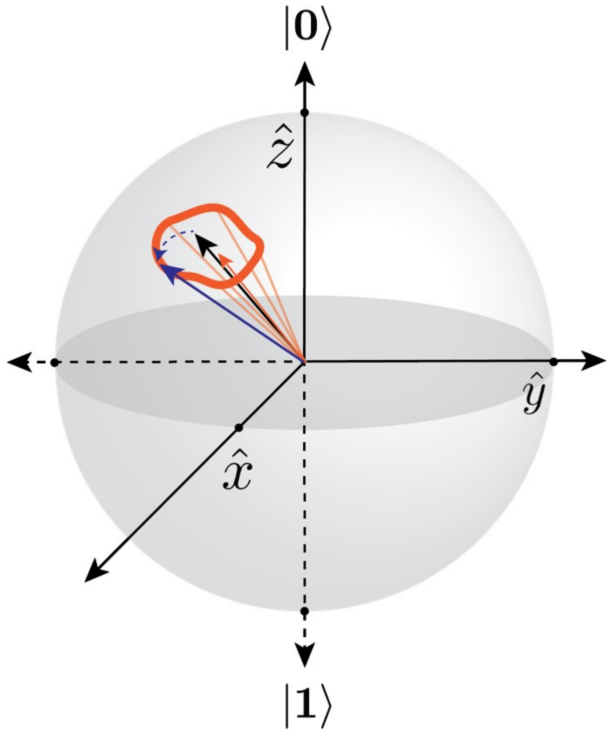


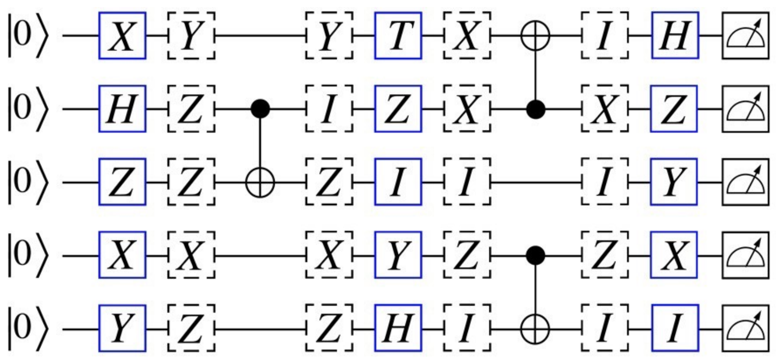


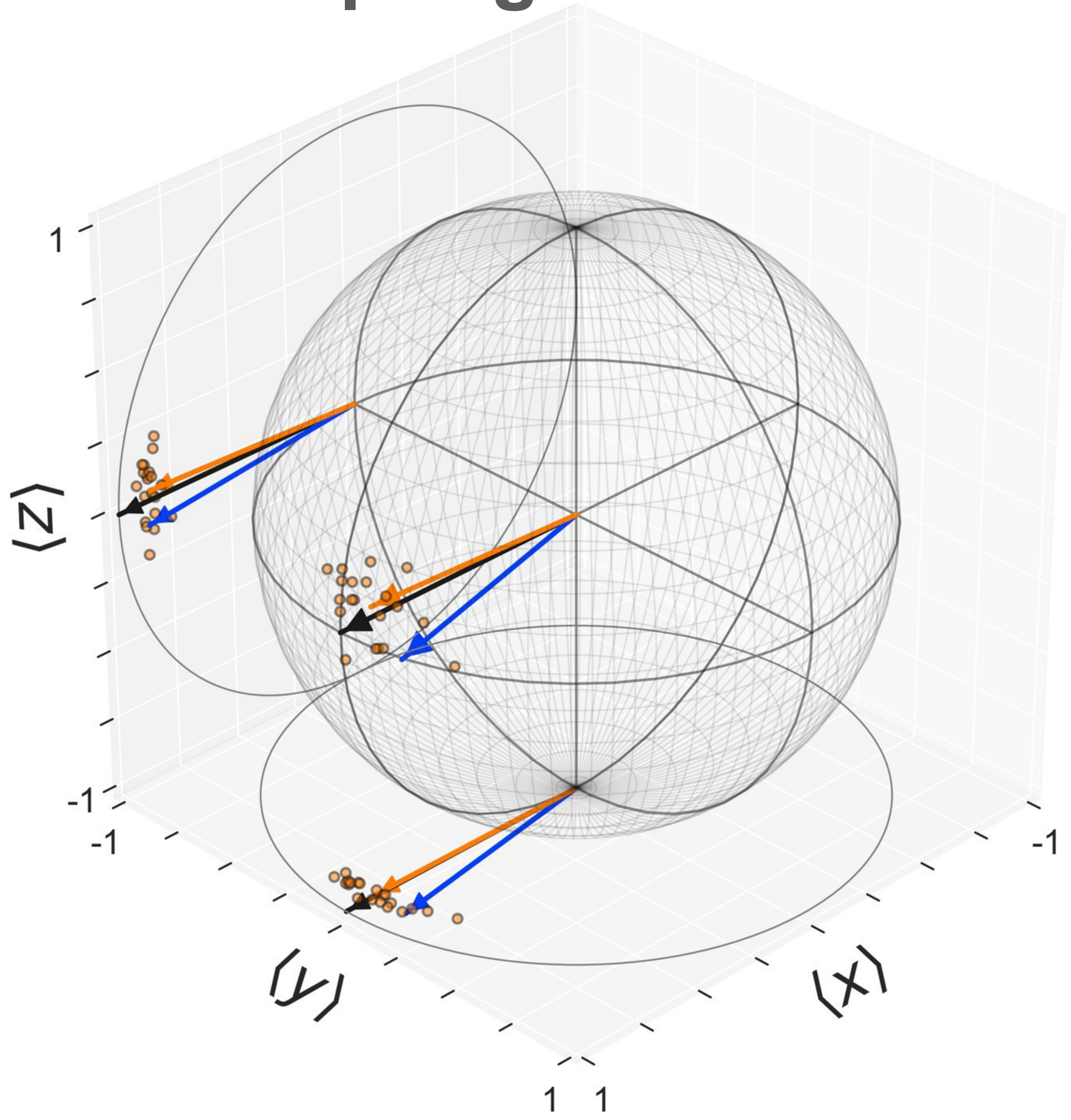
Next Steps: Decoherence due to Non-Equilibrium Phenomena

- Quasiparticles & Phonons (localize effects of pair breaking)
- Fluctuations of Coherence (correlate with JJ non-uniformity & spectral diffusion of glassy films)
- Strain Induced Magnetism & Loss/Noise (verify presence & mitigate)

Noise Tailoring using Randomized Compiling







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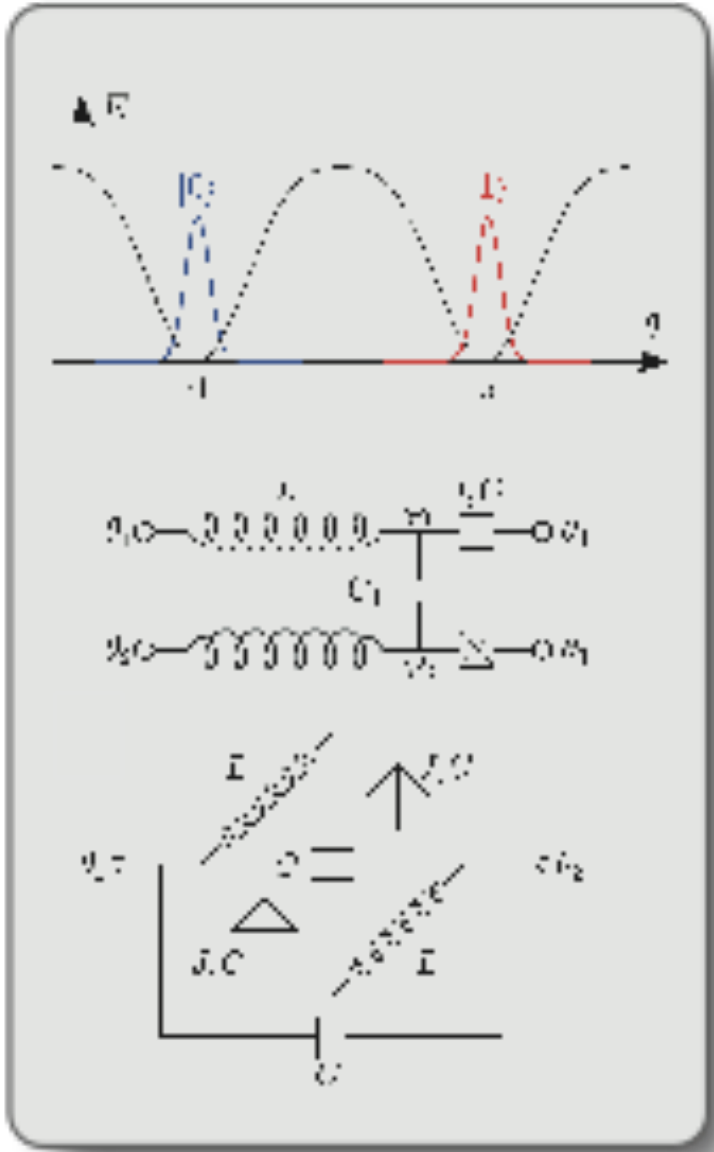
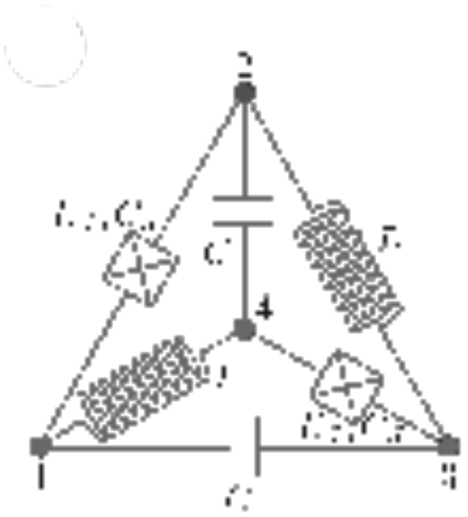
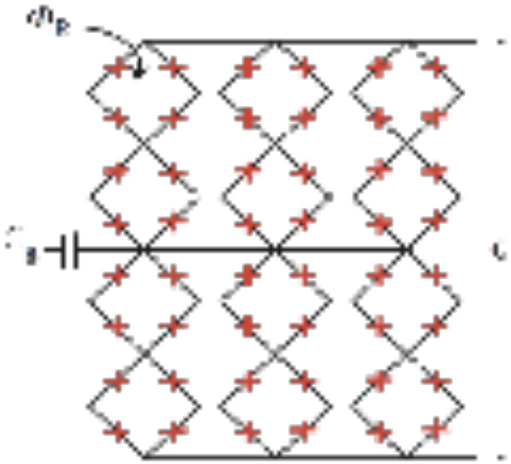
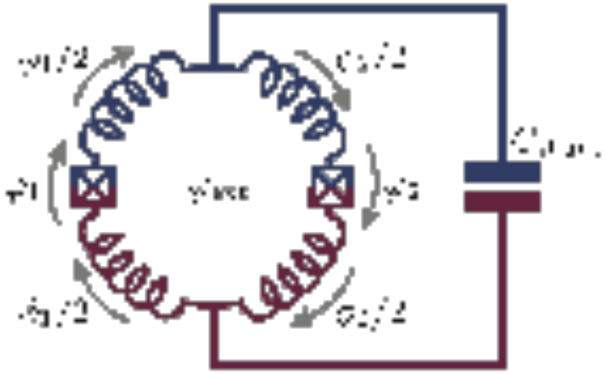
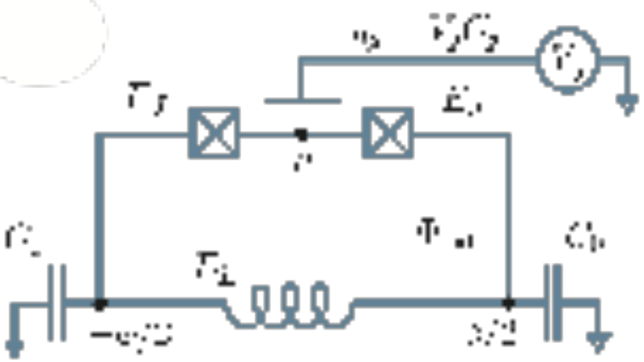
Noise Protected Qubit Architectures







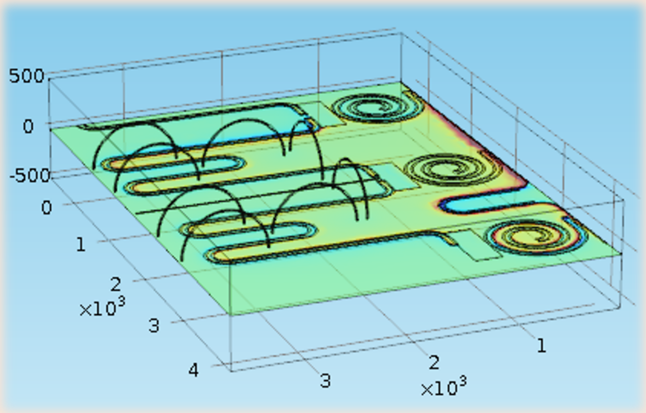




CRYOPACKAGING

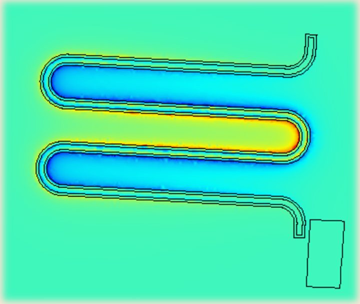
Quantum Chatter

Spurious mode Identification

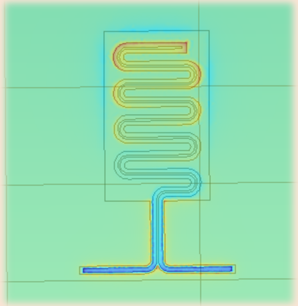


Hybrid CPW-CPS Resonators

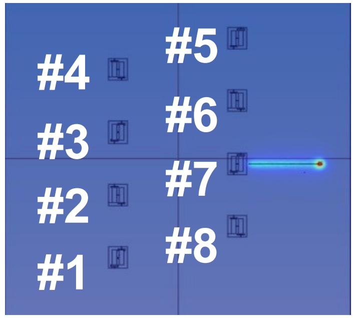
10 GHz slotline mode



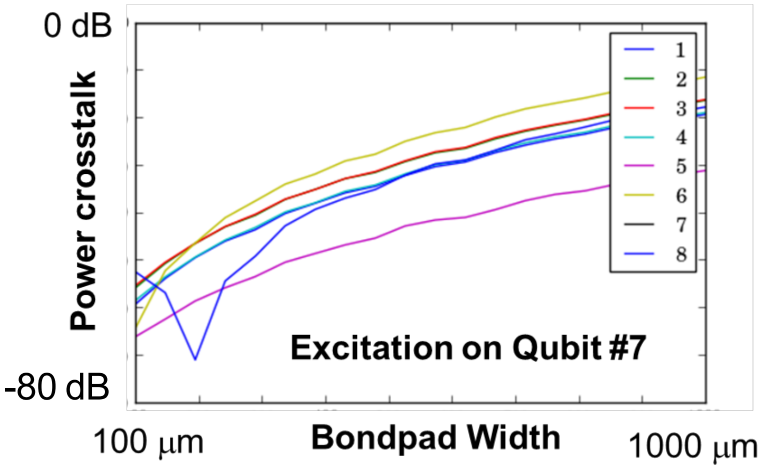
17 GHz slotline mode



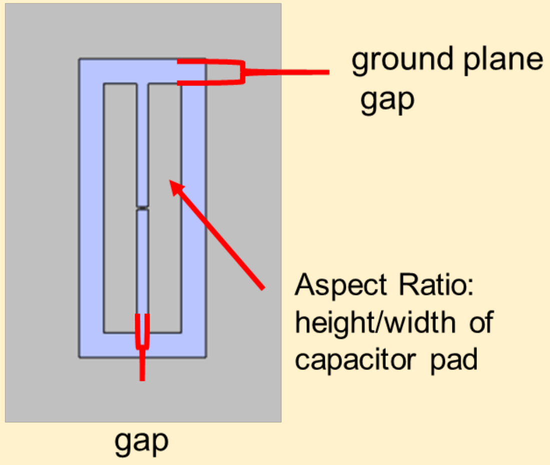
Crosstalk



100x100 um² bondpad

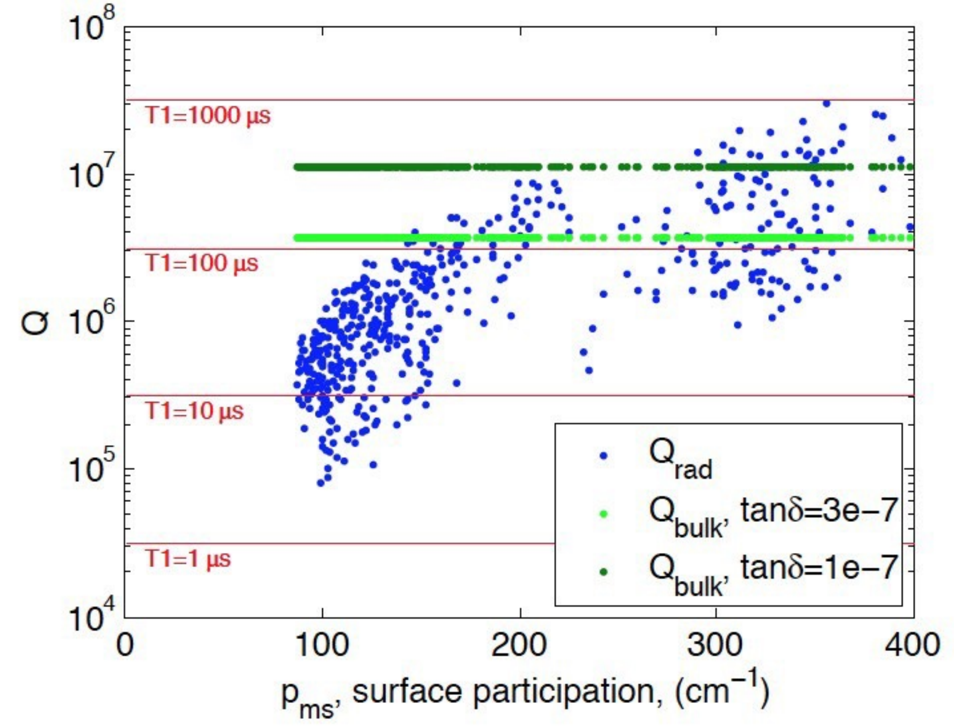


Parameters Varied:



Resonance freq. 5-6 GHz

Geometry: Radiation Q vs. Surface Loss



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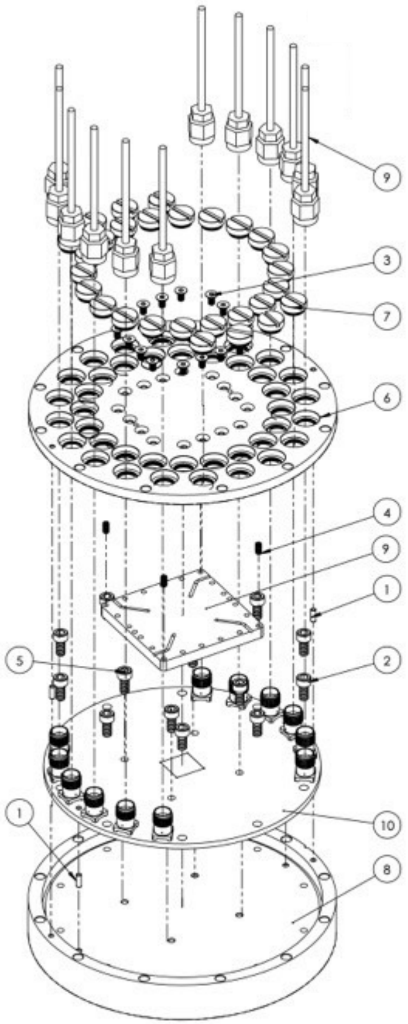
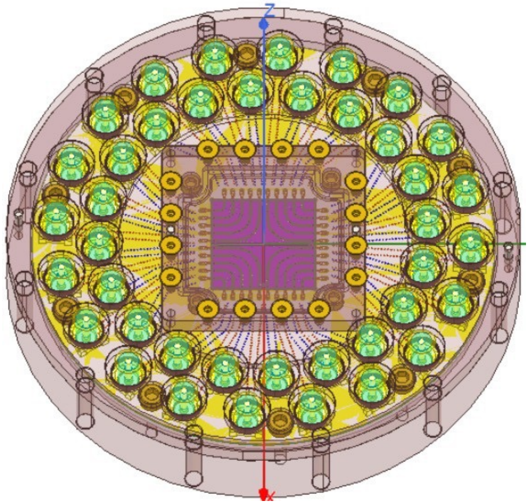
Cryopackaging



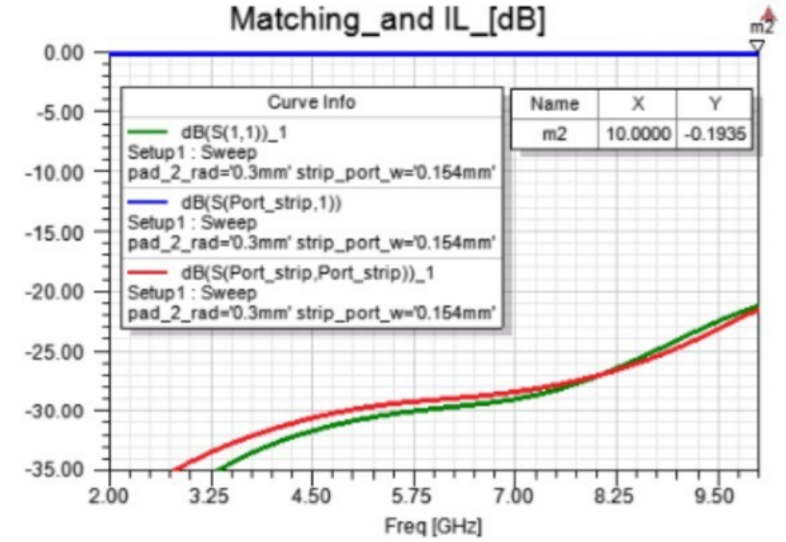
12-line version for Trailblazer chip

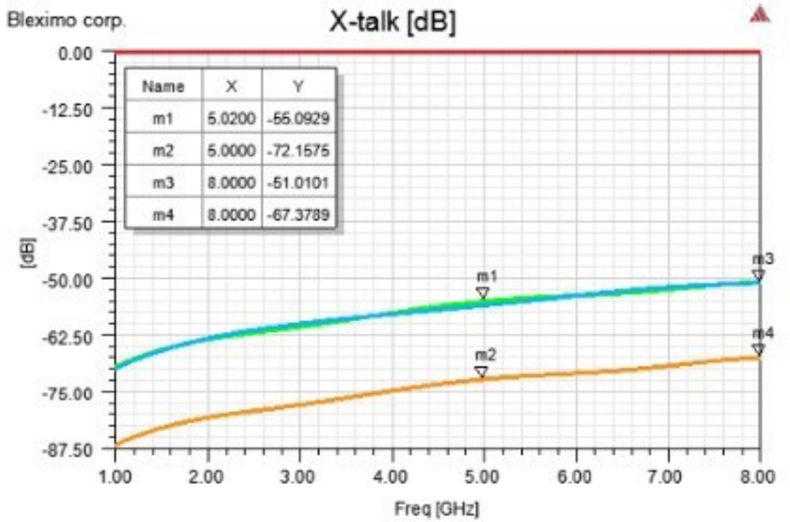
GEN2 PACKAGING WAS DESIGNED TO ACCOMMODATE UP TO 20 X 20 mm^2 CHIPS WITH UP TO 40 RF LINES AND STRIPLINE PRINTED CIRCUIT BOARDS TO MININIMIZE CROSS-TALK



SIMULATIONS

- Input port matching < -25dB over 2-8 GHz band (-30dB at 5 GHz)
- Next-neighbor cross-talk levels is below -55dB over 2-8 GHz band for the closest pair of lines on the Trailblazer chip and below -72dB for other pairs of lines





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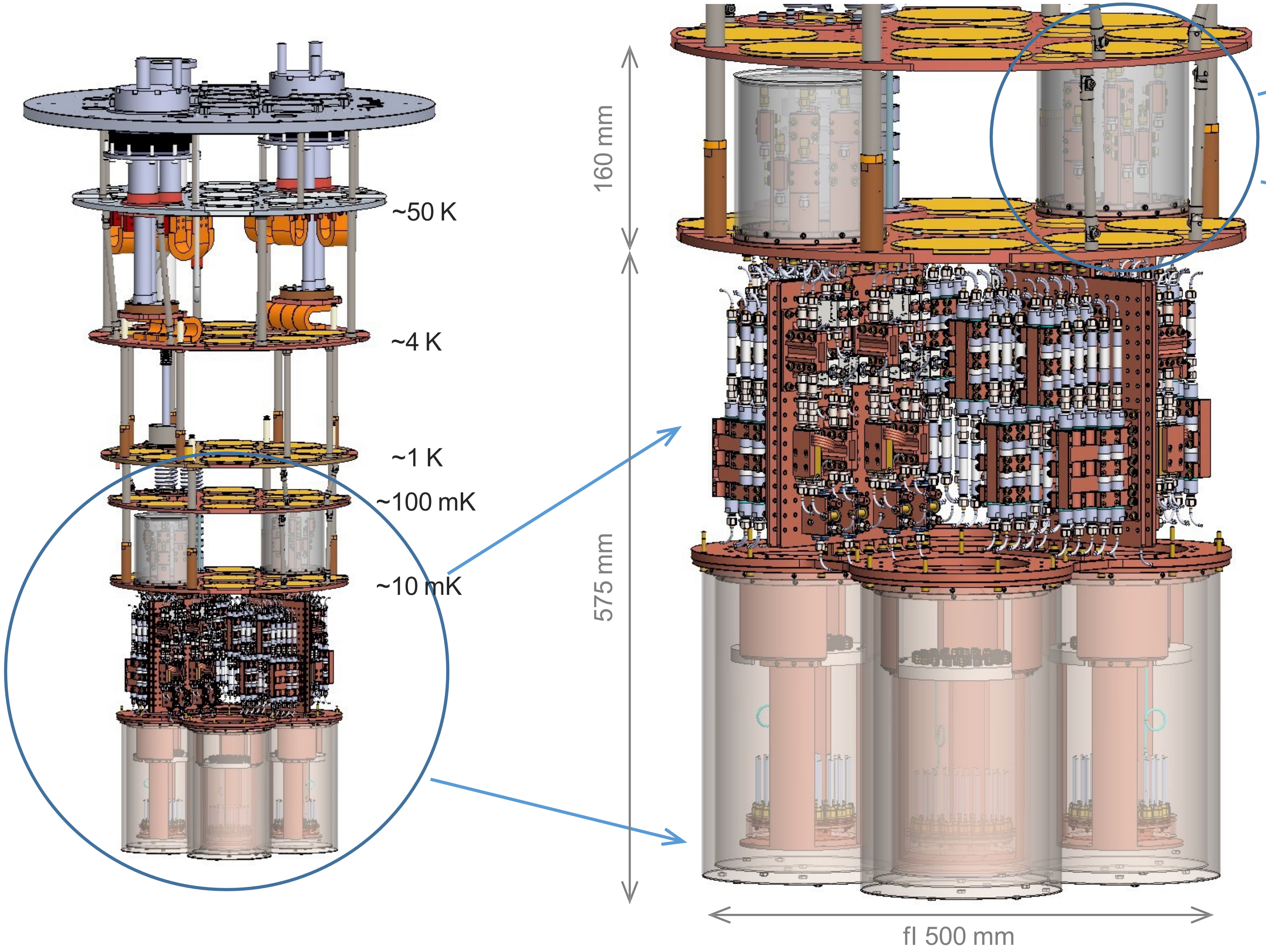
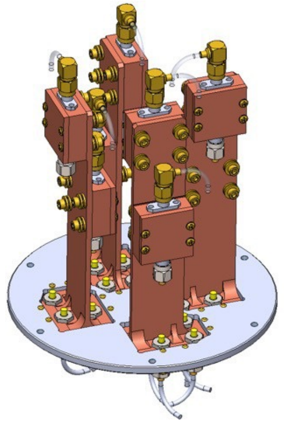
Experimental Stage





UCB-designed TWPAs (@10 mK) in E&M shielding

16x total – one per superconducting read-out line

"CONTROL VOLUME"
Bracketry & breadboard plates for supporting and thermalizing microwave components (filters, isolators, circulators, directional couplers, etc.)

"SAMPLE VOLUME"

Separated into four identical segments

Each segment has access to 40 RF lines, including 4 superconducting lines

Breadboard-based design allows extreme flexibility in building various microwave control and readout solutions

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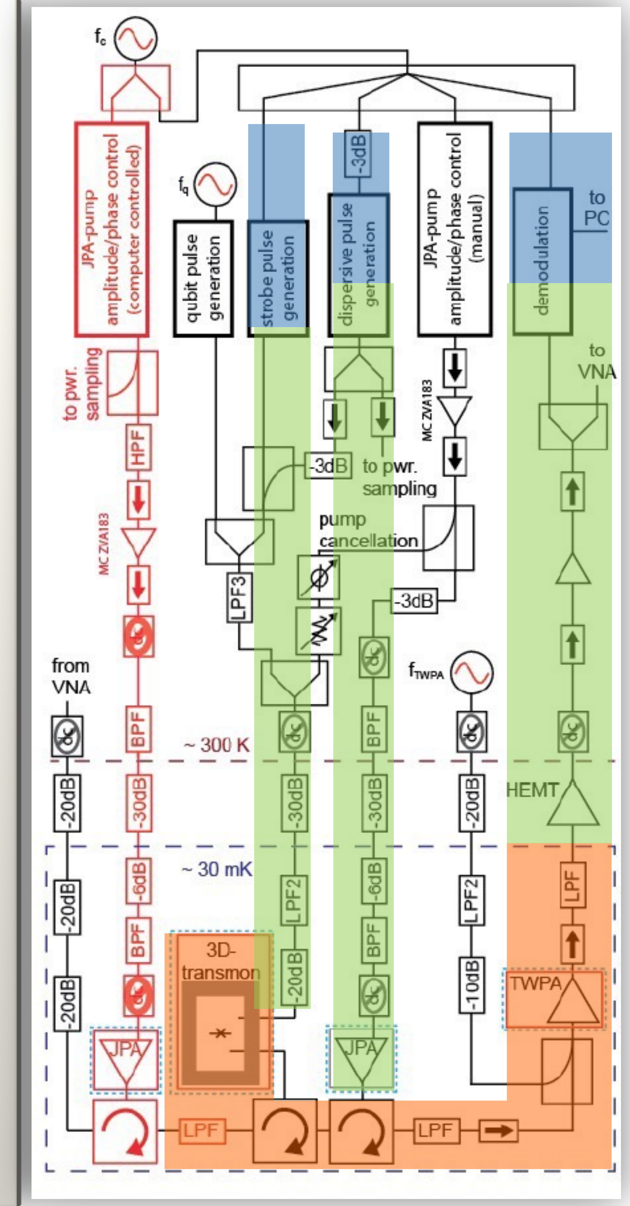
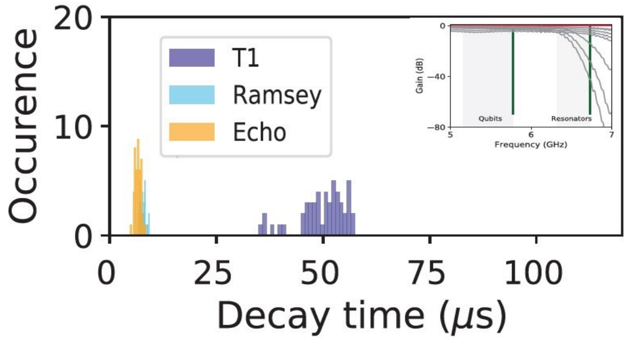
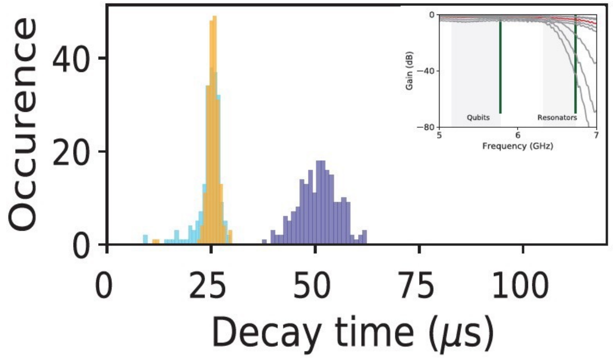
Tyranny of Wires!

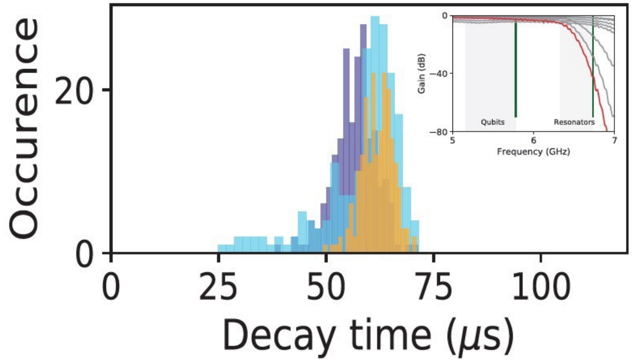
Mixed Signals in a Quantum Processor

- Classical Digital
- Classical Analog
- Quantum Coherent









- **Need to reduce wire count !**
- **Need to reduce wire complexity**
- **Quantum data transmission & conversion**
  - optical
  - acoustic
  - classical analog
  - classical digital
- **Cryogenic data processing ?**

EXECUTING ALGORITHMS WITH NOISY HARDWARE

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QITE Algorithm

Principle of Quantum Imaginary Time Evolution

Motta et al., *Nature Physics* 16, 205-210 (2020)
S. Sun et al., *PRX QUANTUM* 2, 010317 (2021)
K. Yeter-Aydeniz et al., *npj Quantum Information* **6**, 63 (2020)

Time evolution under a Hamiltonian: $|\Psi(t)\rangle = \sum_m c_m e^{-iE_m t/\hbar} |\Phi_m\rangle$

Imaginary time: $t \rightarrow i\beta$

$$|\Psi(\beta)\rangle = \sum_m c_m e^{-E_m \beta/\hbar} |\Phi_m\rangle \underset{\beta\to\infty}{\sim} c_0 e^{-E_0\beta/\hbar} |\Phi_0\rangle$$

Ground state

Non unitary evolution

- Implement a non-unitary evolution?
  - Trotter-Suzuki in the imaginary time step
  - *Unitarize* at each step
  - The Generator $A_!$ is calculated using a linear system of equations

Unitary evolution

$$|\Psi_{n+1}\rangle = \frac{e^{-\Delta\tau \hat{H}/\hbar} |\Psi_n\rangle}{||e^{-\Delta\tau \hat{H}/\hbar} |\Psi_n\rangle ||} = e^{-i\Delta\tau \hat{A}_n/\hbar} |\Psi_n\rangle$$

- No ansatz
- No classically hard optimization
- Measurements needed depend on the Hamiltonian
- Easy extension to thermal states

- Not a fixed depth algorithm

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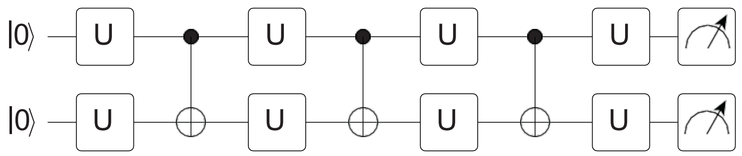
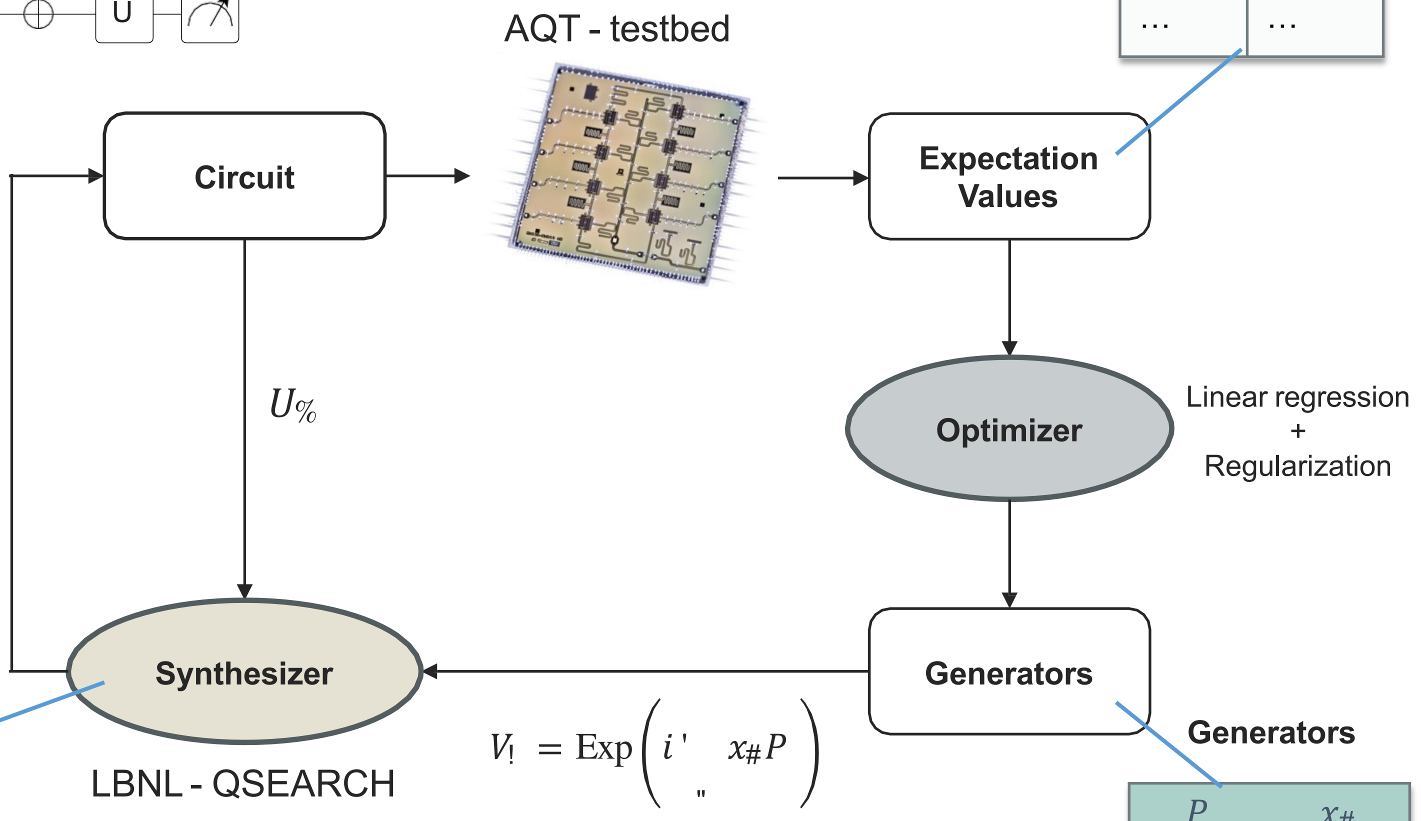
QITE Workflow



Measurement

Obs.	Value
$\langle IX \rangle$	0.25
$\langle ZY \rangle$	0.1
…	…



CNOT gates

N	QISKIT	QFAST	QSEARCH
2	3	3	3
3	30-35	10-12	7-12
4	160-200	70-80	30-50

Generators

P	$x_\#$
XX	0.1
XZ	-0.5
…	…

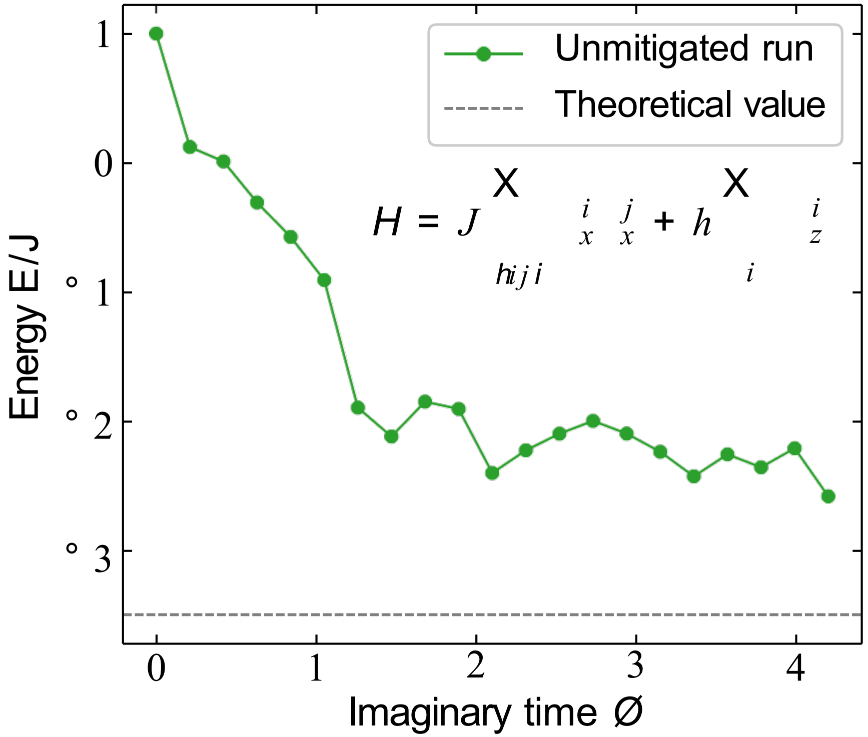
Symmetries of H:

- Reduce the number of observables needed
- Add constraints to the generators

Example of symmetries for the TFIM 3 qubits:
- ZZZ
- Central symmetry
- Time-reversal symmetry

→ 3 parameters for the generators

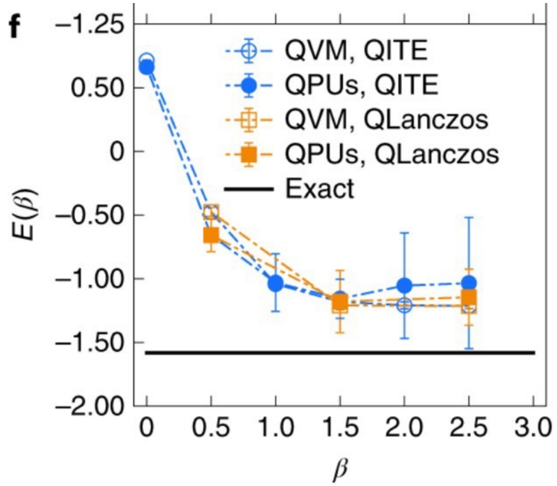
→ 7 Pauli measurements per step



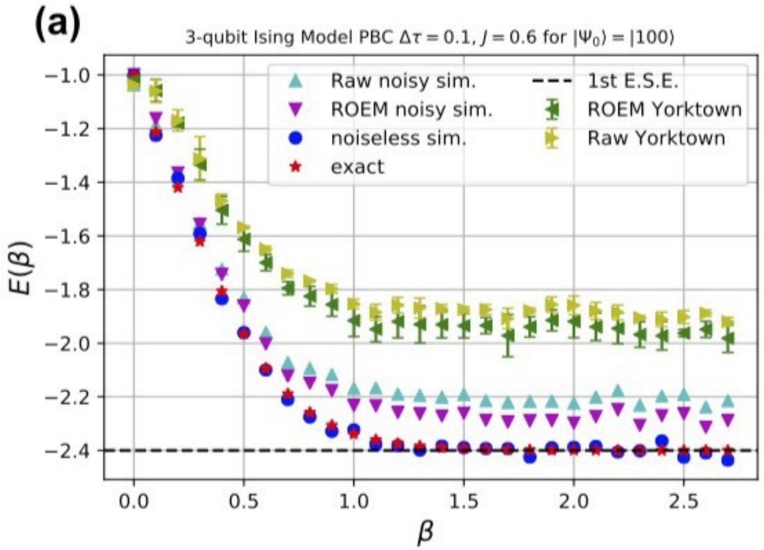
- 7 measurements (7 * 5000 shots) at each step
- ~ 12 CZ gates at each step
- 20 steps here

3 Qubit Dry run, AQT hardware

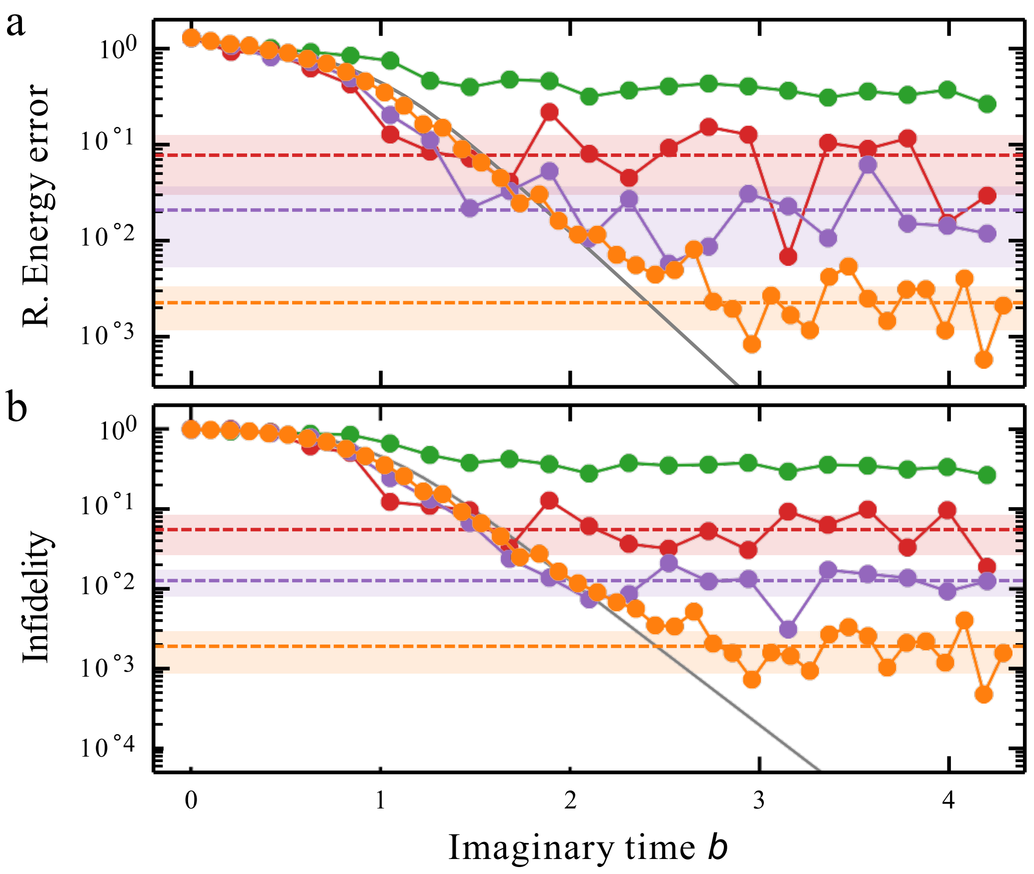
Motta *et al. Nature Physics* **16**, 205-210 (2020)



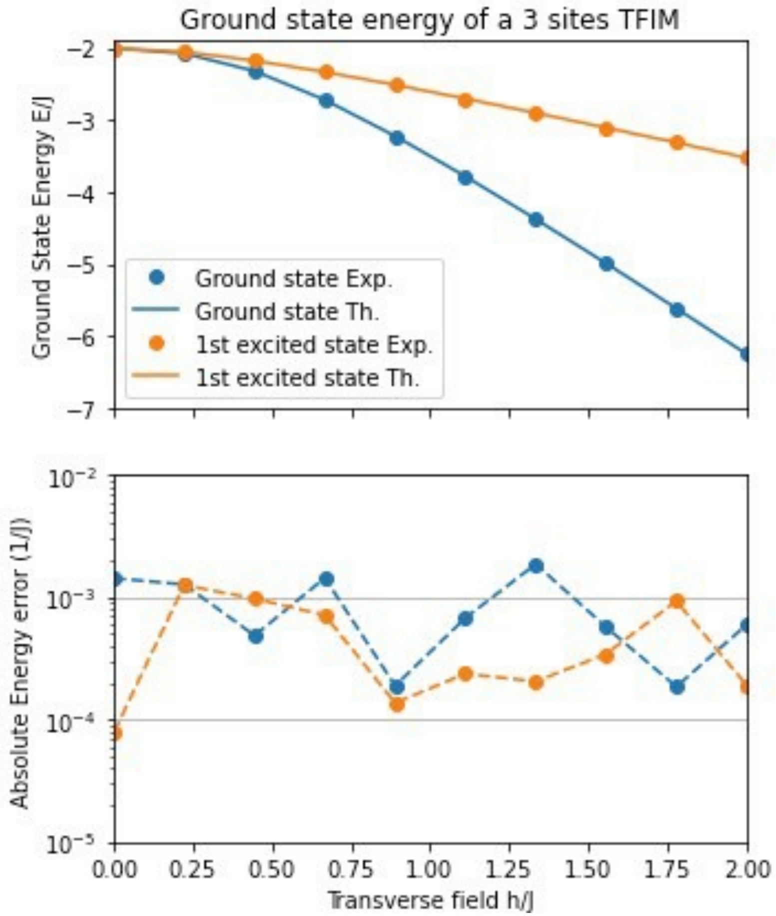
K. Yeter-Aydeniz *et al. New J. Phys.* **23**, 043033 (2021)

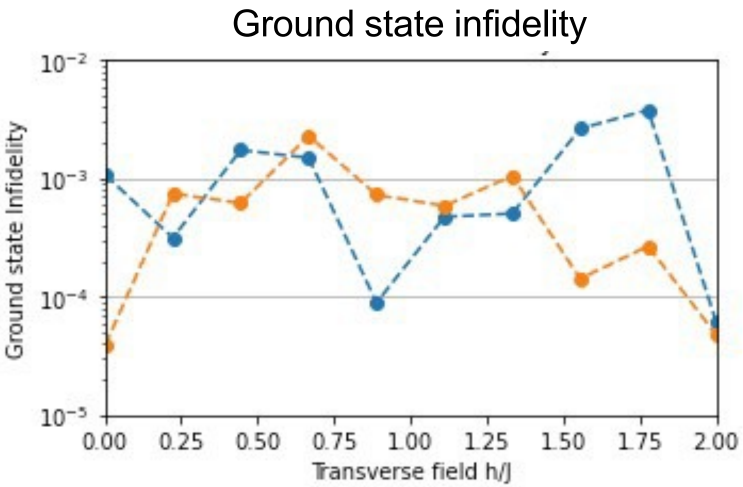


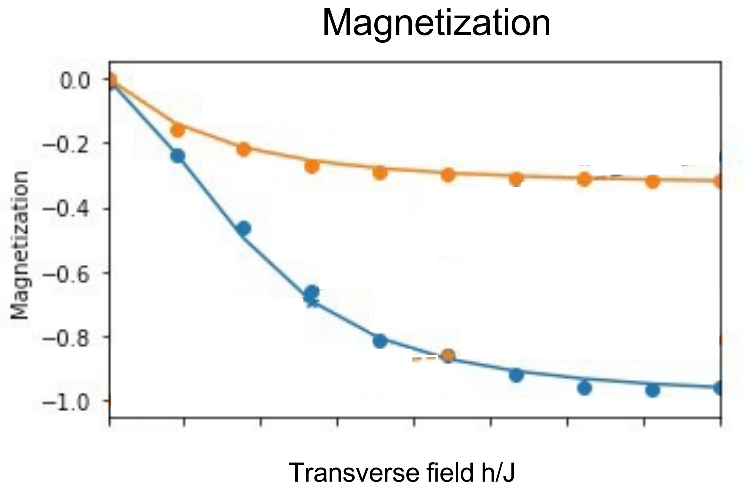
$$H = J \sum_{\langle ij \rangle} {}^{i}_{x} \, {}^{j}_{x} + h \sum_{i} {}^{i}_{z}$$



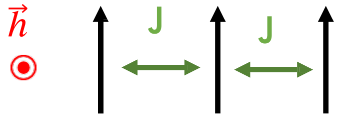
QITE TFIM 3 Sites: Ground and 1st Excited State







3 qubits Transverse Field Ising Model (TFIM)



- Algorithm stable
- Remaining error doesn't seem to depend on Hamiltonian

The Team

ASSEMBLING RESEARCHERS IN PHYSICS, CHEMISTRY, COMPUTER SCIENCE, AND ENGINEERING TO EXPLORE THE QUANTUM FRONTIER

Research Staf

- Anastasia Butko
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- Gang Huang
- Costin Iancu

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- Lawrence Doolittle
- Wim Lavrijsen
- Thorsten Stezelberger

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- Cassidy Berk
- Machiel Sebastiaan Blok
- Gerwin Koolstra
- Xiaotao Liu
- Jie “Roger” Luo
- Alexis Morvan
- Kasra Nowrouzi
- Jean-Loup Ville
- Yilun Xu

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- Trevor Chistolini
- Akel Hashim
- John Mark Kreikebaum
- Bradley Mitchell
- Marie Lu
- William Livingston

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Massachusetts Institute of Technology

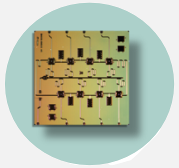
LINCOLN LABORATORY
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

bleximo

Q-CTRL

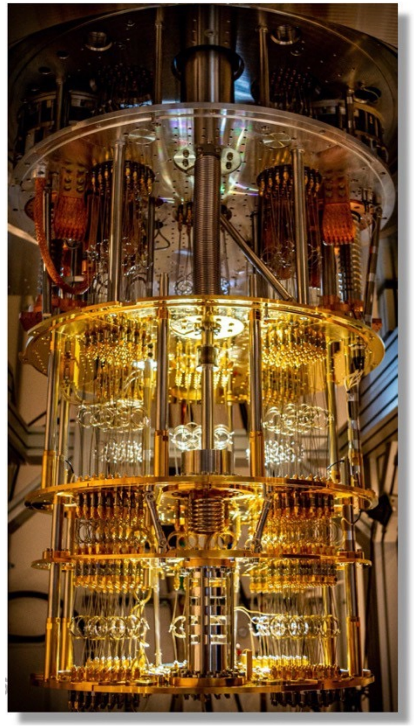
quantumbenchmark

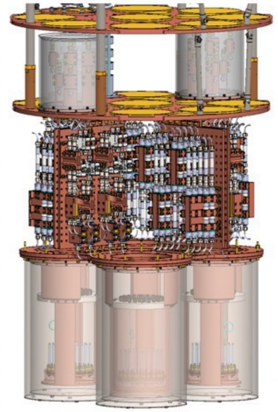
Advanced Quantum Testbed
(aqt.lbl.gov)



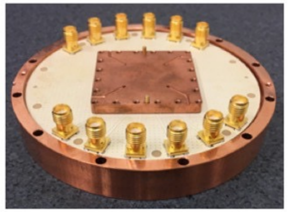
Superconducting Quantum Processors at the Entanglement Frontier

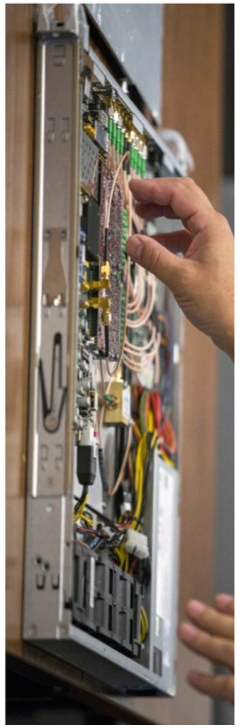
1 mW Dilution fridge	Cold stage	Commercial Control	LBNL/ATAP Control	3D Integrated Quantum Processor Units (QPU)	Team: LBNL, UC Berkeley, Bleximo, MIT-LL

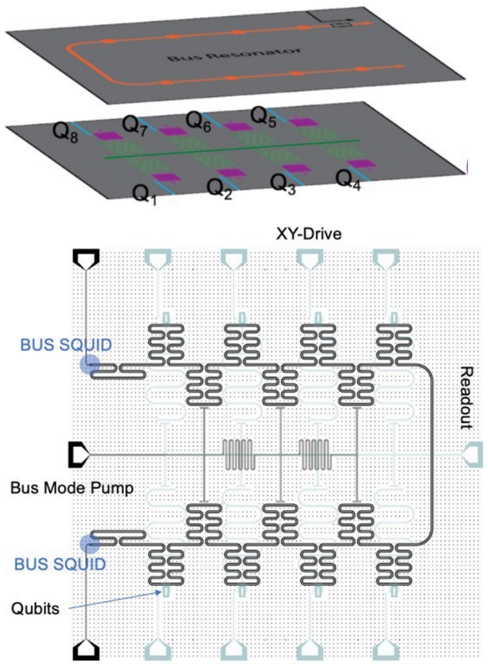




bleximo







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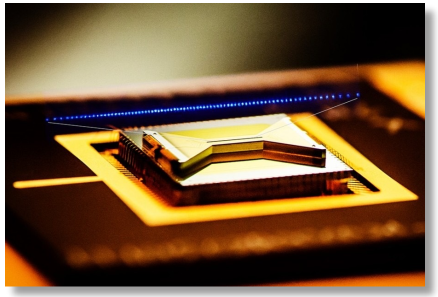
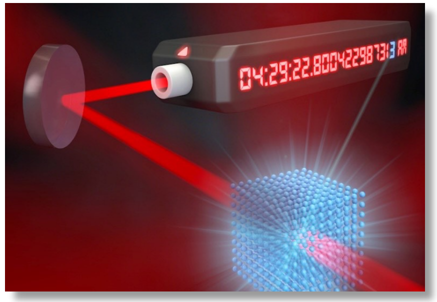
Quantum Systems Accelerator (quantumsystemsaccelerator.org)

Catalyzing national leadership in quantum information science to co-design the algorithms, quantum devices, and engineering solutions needed to deliver certified quantum advantage in Department of Energy scientific applications.

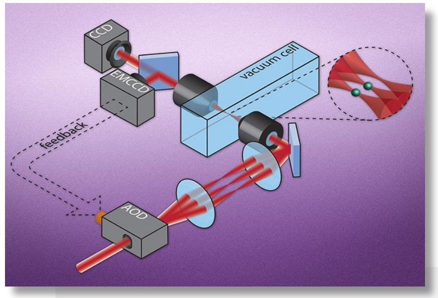
Trapped Ions



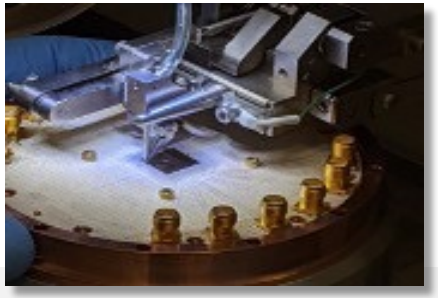
Atomic Tweezers



Rydberg Simulators



Superconducting Circuits



BERKELEY LAB Lawrence Berkeley National Laboratory	Sandia National Laboratories	MIT LINCOLN LABORATORY
Berkeley UNIVERSITY OF CALIFORNIA	Caltech	HARVARD UNIVERSITY
University of Colorado Boulder	Duke PRATT SCHOOL OF Engineering	MIT
Tufts UNIVERSITY	UNIVERSITY OF MARYLAND	UNIVERSITÉ DE SHERBROOKE
NM	USC	TEXAS The University of Texas at Austin

Future Directions

Critical Enablers

- Resource efficient error detection/correction
- Robust fabrication of high coherence devices (metals, insulators, 3D integration)
- Circuit elements beyond JJs (super-inductances, phase slip junctions, …)
- Suppression of nonequilibrium excitations (quasiparticles, phonons, …)
- Quantum signal processing hardware (multiplex, convert, interconnect…)
- Flexible cryogenic systems (EMI shielding, modularity, electronics, wiring,…)

Open Questions

- What is the optimal balance between noise-protection vs. materials perfection?
- Is it possible to achieve quantum advantage with noisy hardware? What algorithms? benchmarks?
- What problems are best suited for digital computation vs. analog emulation?
- Can we efficiently simulate dynamics problems? What are the useful ones?