National Quantum Information Science Research Centers

Jim Misewich
Associate Laboratory Director for Energy and Photon Sciences
Brookhaven National Laboratory

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5 DOE National QIS Research Centers

C²QA	Co-design Center for Quantum Advantage *Lead Lab: BNL*	C²QA aims to overcome the limitations of NISQ computer systems to achieve quantum advantage for scientific applications using superconducting microwave circuits, and hybrid superconducting/optical devices for quantum communication.
Q-NEXT	Next Generation Quantum Science and Engineering *Lead Lab: ANL*	Q-NEXT focuses on manipulating and distributing entangled states of matter. Its mission is to deliver quantum interconnects, communications links, networks of sensors, simulation testbeds, and a national resource for pristine materials for devices.
Quantum Systems Accelerator	Quantum Systems Accelerator *Lead Lab: LBNL*	QSA pairs advanced quantum prototypes — based on neutral atoms, trapped ions, and superconducting circuits — with algorithms specifically designed for imperfect hardware to demonstrate optimal applications computing, materials science, and fundamental physics.
Quantum Science Center	Quantum Science Center *Lead Lab: ORNL*	QSC designs materials that enable topological quantum computing; implementing new quantum sensors to characterize topological states and detect dark matter; and designing quantum algorithms and simulations of quantum materials, chemistry, and quantum field theories.
SQMS	Superconducting Quantum Materials and Systems Center *Lead Lab: FNAL*	SQMS seeks transformational advances in the major cross-cutting challenge of understanding and eliminating the decoherence mechanisms in superconducting 2D and 3D devices, with the goal of enabling construction and deployment of superior systems for computing and sensing.

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Co-design Center for Quantum Advantage (C^2QA)

Challenge: Noise limits scalability and reliability of quantum computers and quantum communication

C^2QA Mission: Build the bridge to go beyond the current "noisy intermediate-scale quantum" (NISQ) to the post-NISQ era

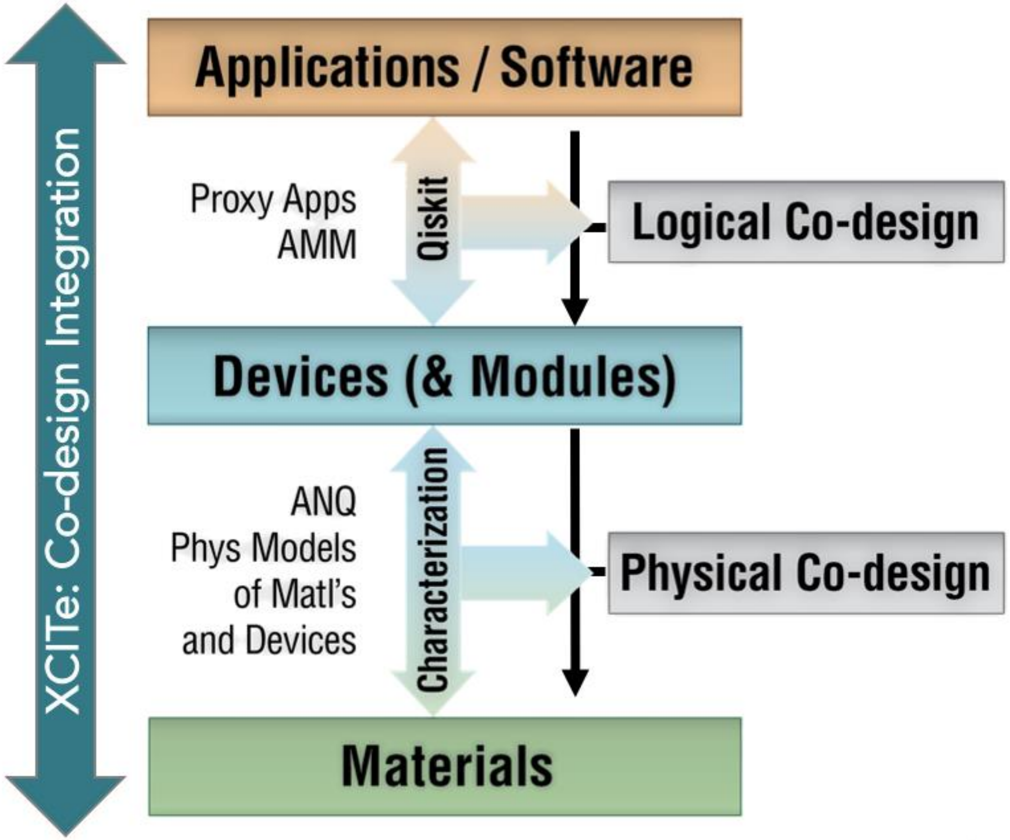
Goal: Provide the basic science advances and co-design work to create a clear architecture roadmap and the new technologies required for the US quantum ecosystem to build full-stack systems offering useful quantum advantage for DOE science

Technology focus: Superconducting modules and clusters linked by optical quantum communication

Organizing principle: Breaking research silos: quantum co-design

- Science applications/software/algorithms
- Devices/hardware
- Materials
- Cross-cutting Co-design Integration Team (XCITe)

Funding: $115M over five years



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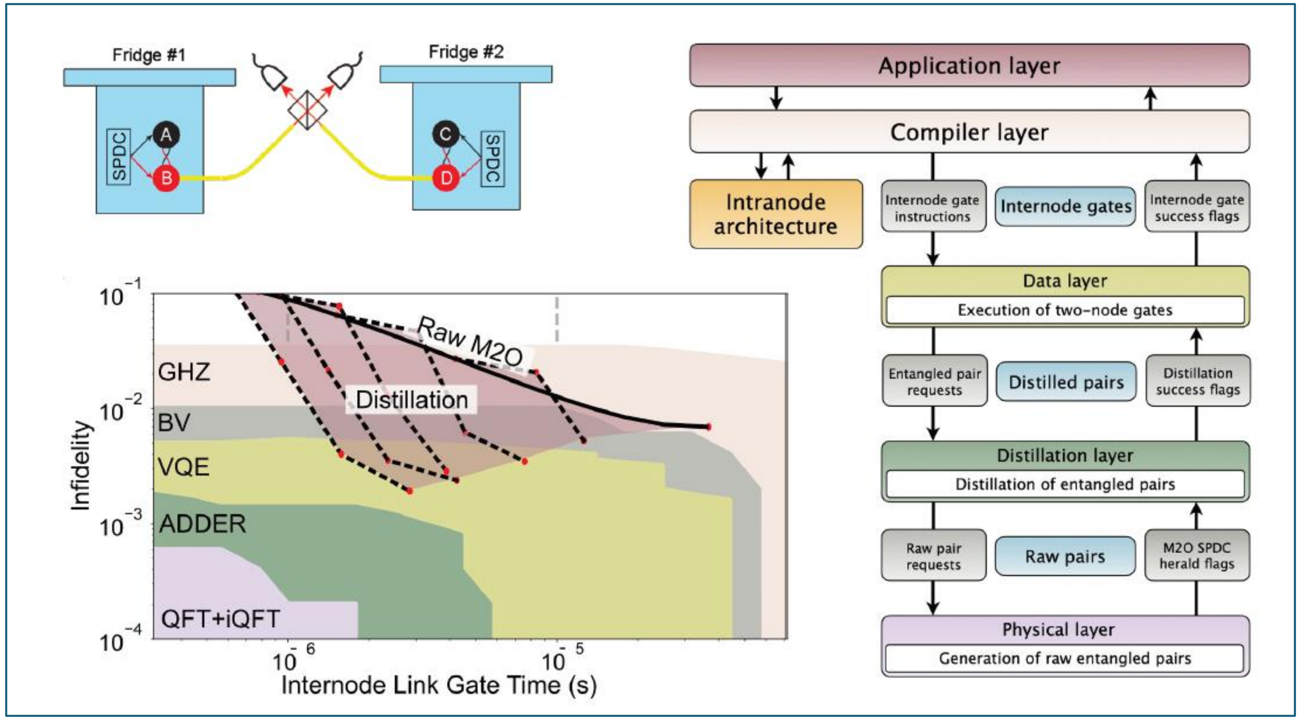
Architectures for Multinode Superconducting Quantum Computers



Achievement in Technical Areas of Interest

Cross-thrust, multi-institutional team of collaborators from Co-design Center for Quantum Advantage (C^2QA) worked together to employ a ‘co-design’ inspired approach to quantify overall multinode quantum computers (MNQC) performance of hardware models of internode links, entanglement distillation, and local architecture.

Significance & Impact

- built a framework for the evaluation of hardware and software performance that quantifies current technology performance
- uncovered key hardware/software trade-offs in link time vs. error rate of links
- developed a research roadmap towards many-fridge systems capable of performing advanced algorithms: chemistry dynamics, optimization, and factoring, etc.

Details

— 4 labs, 9 universities, and IBM studied the full hardware + software stack distributed systems from communication hardware to algorithms.

Reference: Architectures for Multinode Superconducting Quantum Computers (arXiv:2212.06167v1).
Authors: M. DeMarco, I. Chuang, N. Wiebe, D. McKay, A. Li, et.al.

Discover New Quantum Materials to Enhance Quantum Computers

Achievement in Technical Areas of Interest

Detailed understanding of loss mechanisms in superconducting qubits due to two-level defects in materials.

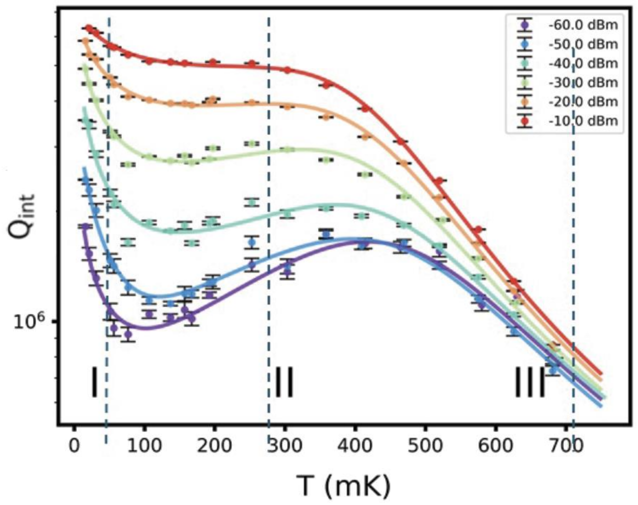
Method

Studied superconducting materials in linear resonators as proxy for qubits.

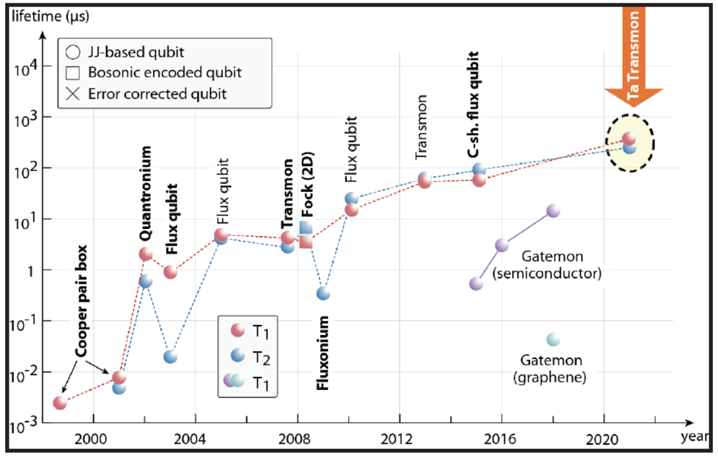
Significance & Impact

By replacing niobium with tantalum, we achieved:

- an order of magnitude improvement in packaging loss
- 4x improvement in two-level systems loss

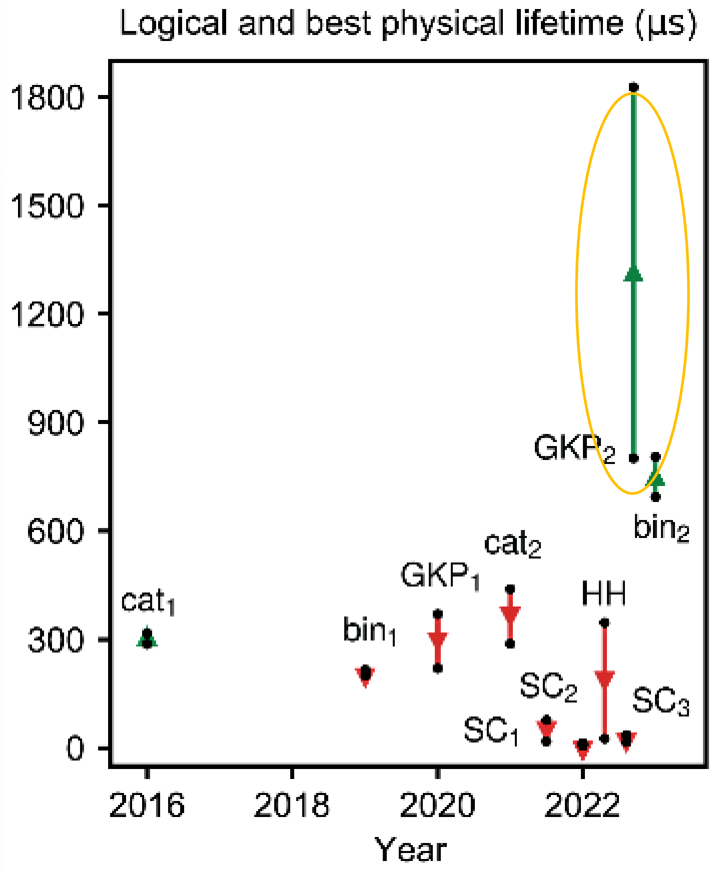


Measuring the Q of tantalum resonators as a function of temperature (x-axis) and power (color lines). Data was fit to a model of two-level system defects in nearby dielectrics. Higher Q indicates lower losses, which means longer photon memory or coherence time.



Data adapted from Kjaergaard et al, arXiv:1905.13641 (2020) and Place et. al. Nature Commun. 12, 1779 (2021)

Real-time quantum error correction beyond break-even



	QEC experiment
$\mathbf{cat_1}$	N. Ofek *et al.,* (Nature, 2016)
$\mathbf{bin_1}$	L. Hu *et al.,* (Nature Physics, 2019)
$\mathbf{GKP_1}$	P. Campagne-Ibarcq *et al.,* (Nature, 2020)
$\mathbf{cat_2}$	J. Gertler *et al.,* (Nature, 2021)
$\mathbf{SC_1}$	S. Krinner *et al.,* (Nature, 2022)
$\mathbf{SC_2}$	Y. Zhao *et al.,* (PRL, 2022)
$\mathbf{SC_3}$	Google Quantum AI (arXiv:2207.06431, 2022)
HH	N. Sundaresan *et al.,* (arXiv:2203.07205, 2022)
$\mathbf{bin_2}$	Z. Ni *et al.,* (arXiv:2211.09319, 2022)
$\mathbf{GKP_2}$	This work

Comparison of QEC experiments (figure legend)

The vertical axis here shows the time during which a qubit can maintain an arbitrary state (i.e., the lifetime averaged over all states on the qubit Bloch sphere). For each experiment, the arrow tail indicates the lifetime of the best passive qubit encoded in the system, and the arrow head indicates the lifetime of an actively error-corrected logical qubit. In most experiments to date, actively doing error correction harms the quantum coherence of the system (red arrows pointing down). Our experiment is the first to demonstrate significant improvement of the qubit lifetime with QEC (factor **2.3x**). The experiment selection criteria include: (i) protecting all axes of the qubit Bloch sphere, (ii) performing multiple cycles of QEC, (iii) not relying on the post-selection.

Significance & Impact

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- **First demonstration of beyond break-even real-time quantum error correction**
- **Set the new record in superconducting circuits for (i) logical qubit lifetime, (ii) QEC gain, (iii) logical error probability per cycle**

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Details

- Gottesman-Kitaev-Preskill encoding of a qubit into an oscillator (a.k.a. grid code)
- Real-time reinforcement learning to optimize QEC circuit parameters
- Tantalum fabrication technique for ancilla transmon chip

Reference: Real-time quantum error correction beyond break-even. Nature 616, 50–55 (2023). https://doi.org/10.1038/s41586-023-05782-6

Authors: V. V. Sivak, A. Eickbusch, B. Royer, S. Singh, I. Tsioutsios, S. Ganjam, A. Miano, B. L. Brock, A. Z. Ding, L. Frunzio, S. M. Girvin, R. J. Schoelkopf & M. H. Devoret

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Exponential quantum speedup in simulating coupled classical oscillators

Scientific Achievement

We provide an algorithm for simulating systems of coupled masses and springs on quantum computers that offers a provable exponential advantage over classical algorithms. We achieve this by mapping the dynamics of the coupled oscillators to a Schrodinger equation which we simulate using new Hamiltonian simulation methods.

Significance and Impact

Very few new classes of provable exponential speedups have been developed. The last broad class of such problems was discovered in 2009. Our work provides such an advantage to a wide range of problems in engineering, neuroscience and chemistry. This work when released became the most cited result for the year on SCIRATE (a website where scientists vote on the importance of new arXiv papers).

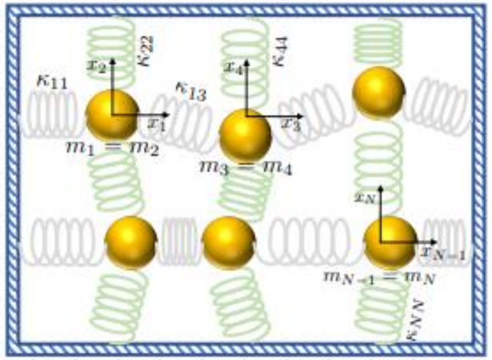

FIG. 1. An example system of $N/2$ oscillators in two spatial dimensions, which can be represented using N oscillators in one dimension. This is possible since the equation of motion in two dimensions is just two equations of motion in one dimension. Thus, we can use $x_1(t)$ for the first coordinate of the first mass and $x_2(t)$ for the second coordinate of the first mass (since both entries correspond to the same mass, $m_1 = m_2$, and so on).

Reference arXiv:2303.13012v1 [quant-ph]

Authors Ryan Babbush, Dominic W. Berry, Robin Kothari, Rolando D. Somma, Nathan Wiebe.

Pacific Northwest National Laboratory · Macquarie University · Google · C²QA Co-design Center for Quantum Advantage

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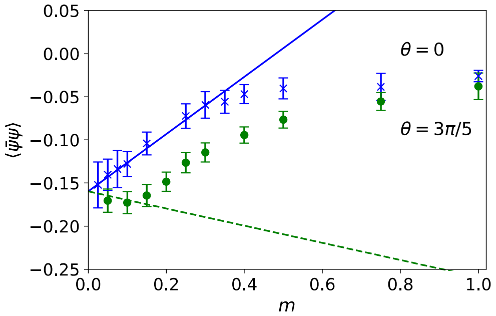
HEP Leverage

Quantum Computing: Lattice Field Theory

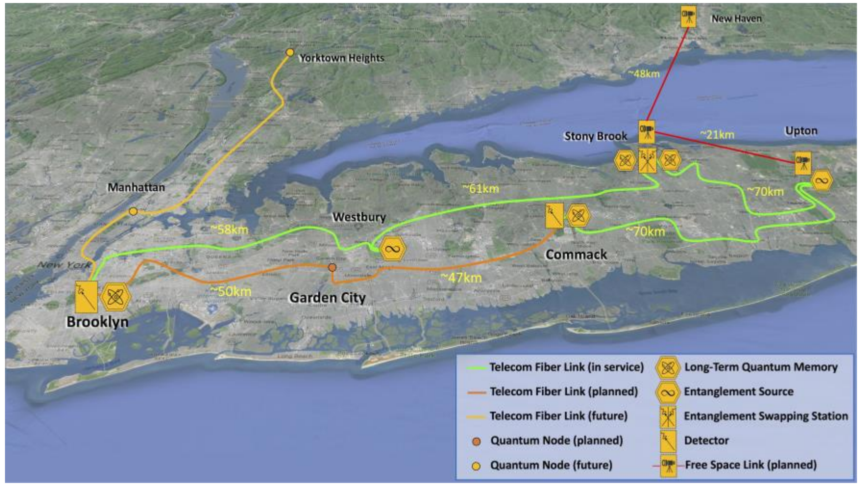


- Quantum State preparation of LFT using adiabatic process evolving a trivial state
- We demonstrate this protocol in Lattice Quantum Electro Dynamics (QED) in 1+1 space-time dimension (Schwinger Model) with continuum limit (left plot)

(Phys. Rev. D 105, 094503, B. Chakraborty, M. Honda, T. Izubuchi, Y. Kikuchi, and A. Tomiya)

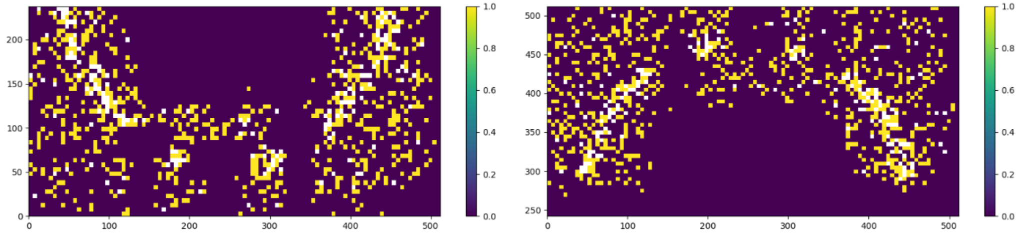
Quantum Networking

Entanglement Distribution



Quantum Sensing

Ghost imaging



C^{2}QA Workforce Development Programs

- ★ Affiliates Program
- ★ QIS Career Fair
- ★ Quantum Computing Virtual Summer School
- ★ Faculty Outreach & Development Programs
- ★ DOE Internship Programs
- ★ Quantum Thursdays

...and a host of others for all ages and stages in the quantum educational spectrum

https://www.bnl.gov/quantumcenter/

C^{2}QA 2023 Impact By the Numbers

Hosted Fall 2022 QIS Career Fair with 490+ attendees & 27 exhibitors

83 published papers, 198 preprints and conference proceedings

12 invention products including 9 open-source software packages attributed to C^{2}QA

350+ people working on 100+ projects to advance quantum computing

4 educational outreach programs offered including Quantum Thursdays and Speakers Colloquia

27 institutions (including 2 affiliates) from national labs, industry, and academia

88 Principal Investigators and Research Scientists

8 summer school offerings for K-12, undergrads, grad students, postdocs & faculty

1 of 5 U.S. Department of Energy National QIS Research Centers addressing quantum challenges

3 technical areas (thrusts) and 1 crosscutting team focused on software, devices, & materials co-design

With additional support from

Affiliates

Thank You

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