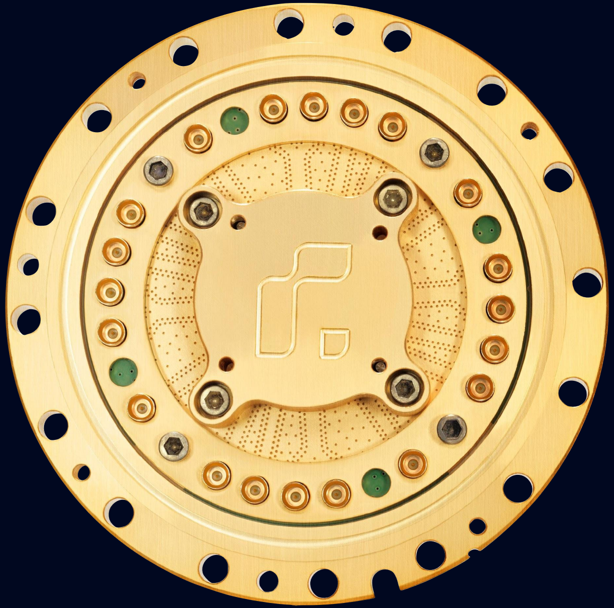
FULL-STACK QUANTUM COMPUTING WITH SUPERCONDUCTING QUBITS



Special colloquium on quantum technologies
September 16th, 2019
Fermilab
Batavia, IL

Chad Rigetti
Founder and CEO
chad@rigetti.com
@chadrigetti

Outline:

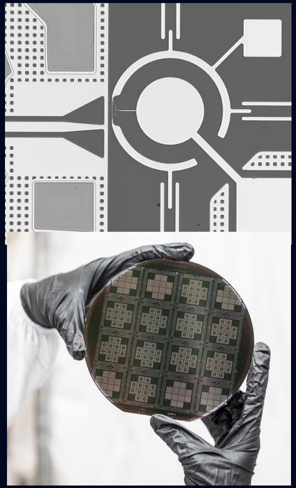
- Intro to Rigetti and QC
- QPU technologies
- Algos + Applications
- Opportunities for HEP

Fermilab

rigetti

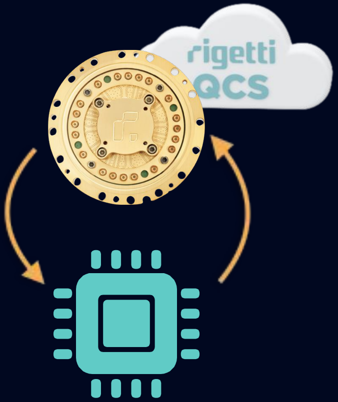
Full-stack

- Chip
- Cryo-RF
- Control Systems
- QPU
- Cloud integration
- Algos + Apps



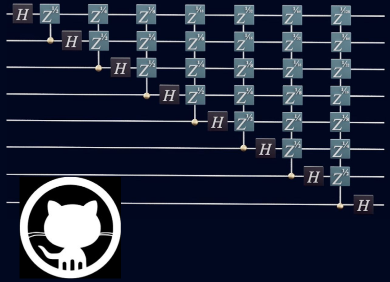
U.S.-Based Captive Foundry

- Superconducting quantum circuits
- Josephson junctions, TSVs, Caps
- 3D integration and packaging



Hybrid Quantum-Classical Architecture in the Cloud

- Quantum Instruction Language (Quil)
- Quil-based compiler (quilc)
- Quantum virtual machine (QVM)
- Forest SDK



Algorithms & Applications

- Develop & tailor algorithms for hybrid architecture
- Distribute Rigetti and partner libraries and applications

Better Accuracy

Reduce approximations needed to make problems computable.

Higher Speed

Encode & manipulate data in an exponentially large state space.

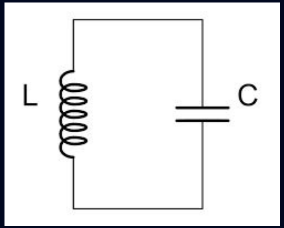
Lower Cost

Quantum computing largely decouples compute power from energy consumption.

Market Outlook

$13Bn by 2022
$25-50Bn by 2030s

SUPERCONDUCTING QUANTUM INTEGRATED CIRCUITS



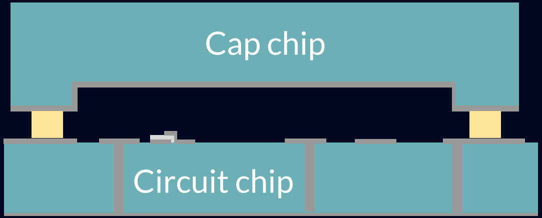
quantized charge, flux

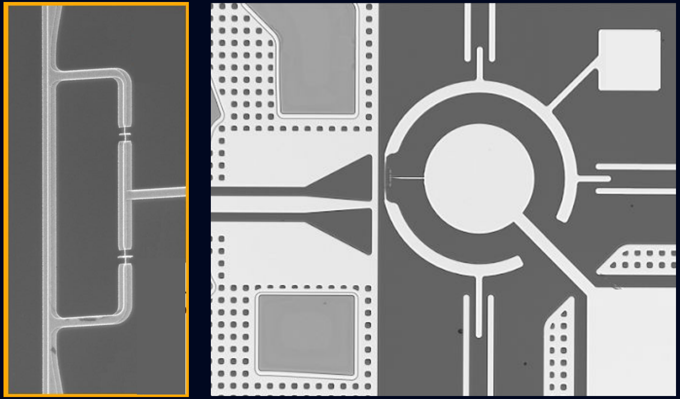
$$\hat{a} \equiv \frac{1}{\sqrt{\hbar\omega}}\left(\frac{\hat{\Phi}}{\sqrt{2L}} - i\frac{\hat{Q}}{\sqrt{2C}}\right)$$

nonlinear Josephson potential

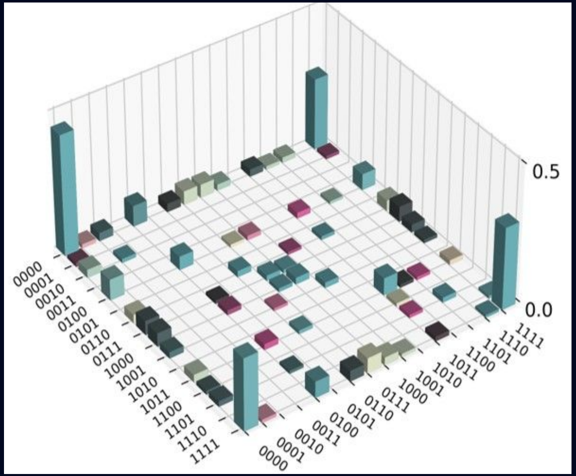
$$\hat{H}_{tot} = E_J \cos(\hat{\Phi}/\Phi_0) + \frac{\hat{Q}^2}{2C}$$

scalable chip architecture





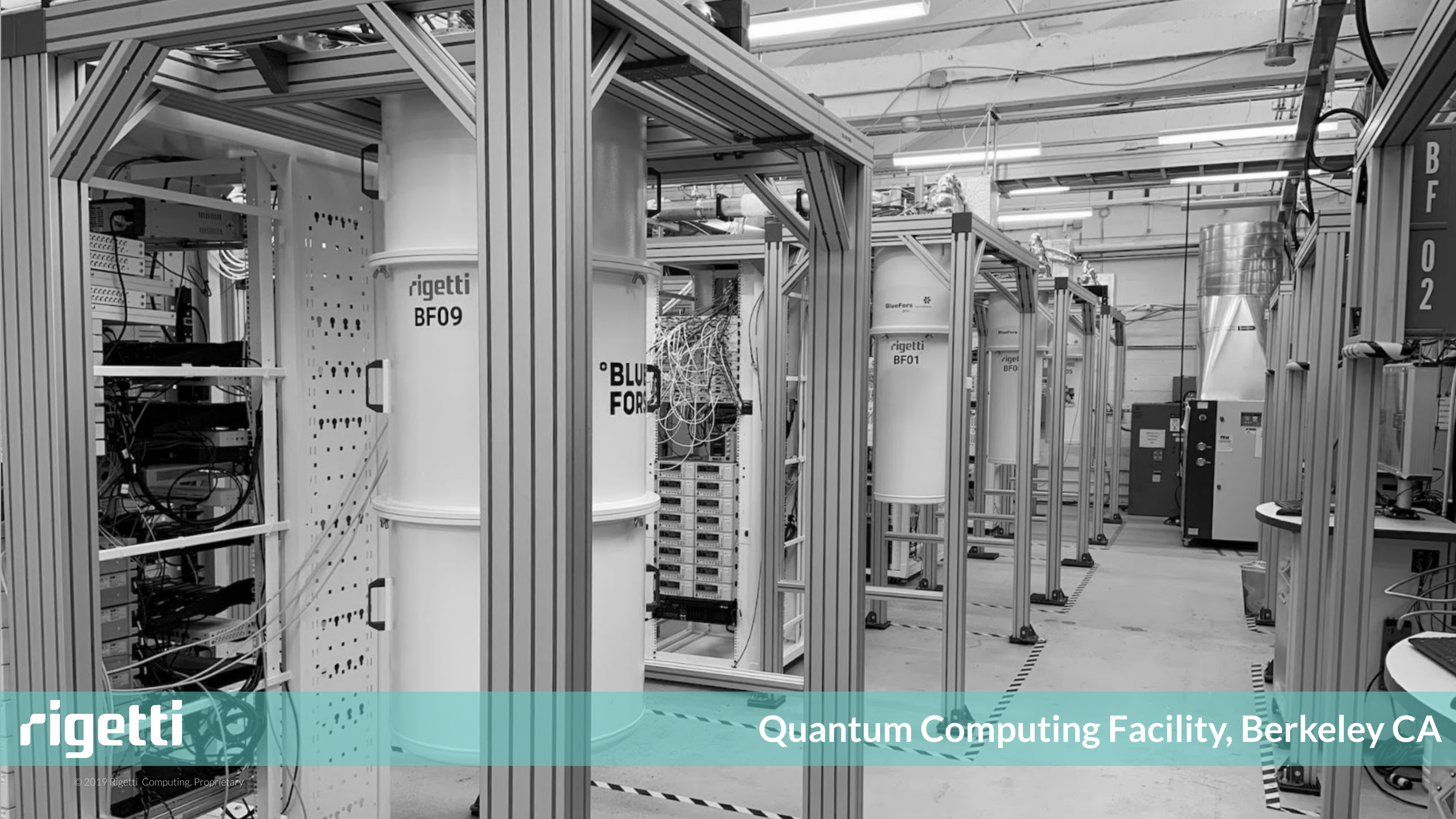
High-fidelity two-qubit gates



Circuit-QED: qubits coupled to high-Q resonators for readout

Rigetti Fab-1

Fremont, CA



Quantum Computing Facility, Berkeley CA

QUANTUM CLOUD SERVICES TODAY

Enterprise and Government Users

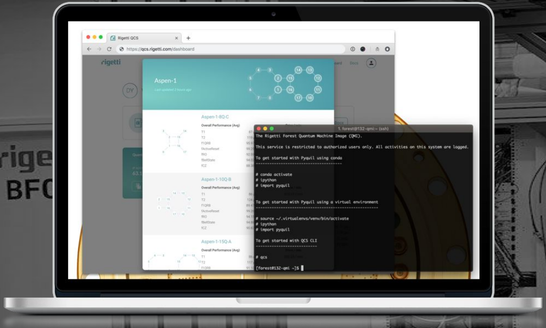
(not exhaustive)

10 Global Fortune 500 companies in:

- Pharma
- Finance
- Chemicals
- Defense
- Consulting
- Manufacturing
- Insurance

4 National Labs

2 International research entities



```
The Rigetti Forest Quantum Machine Image (QMI).

This service is restricted to authorized users only. All activities on this system are logged.

To get started with Pyquil using conda
--------------------------------------

# conda activate
# ipython
# import pyquil

To get started with Pyquil using a virtual environment
------------------------------------------------------

# source ~/.virtualenvs/venv/bin/activate
# ipython
# import pyquil

To get started with QCS CLI
---------------------------

# qcs

[forest@132-qmi ~]$
```

Research Partners

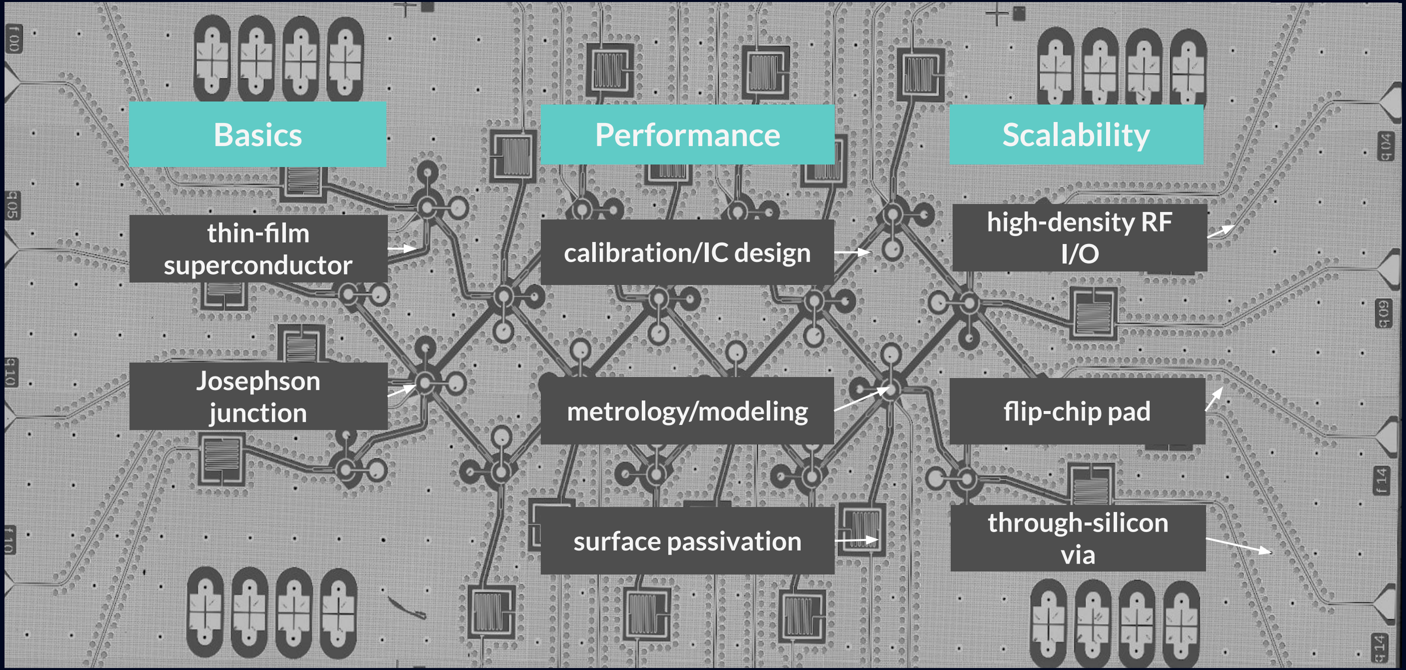
Caltech
EPFL École Polytechnique Fédérale de Lausanne
universität innsbruck
King's College London
Harvard University
Macquarie University
University of Toronto
USC University of Southern California
Bar-Ilan University
Stanford University
Berkeley University of California
The University of Edinburgh

Application Partners

OTI
QULAB
ProteinQure
Strange Works
Riverlane
Zapata
Phasecraft
Agnostiq Labs
GTN LTD
1QBit
ASI Data Science
Q^xBranch
rahko
Heisenberg Quantum Simulations
Quantum Native Systems QunaSys
Entropica Labs
QC Ware
Horizon Quantum Computing

- Currently Available 16Q QPUs
- 4,000 users have run 120M jobs on our platform
- 100+ active customers

QPU ROADMAP AND CHALLENGES



Basics	Performance	Scalability
thin-film superconductor	calibration/IC design	high-density RF I/O
Josephson junction	metrology/modeling	flip-chip pad
	surface passivation	through-silicon via

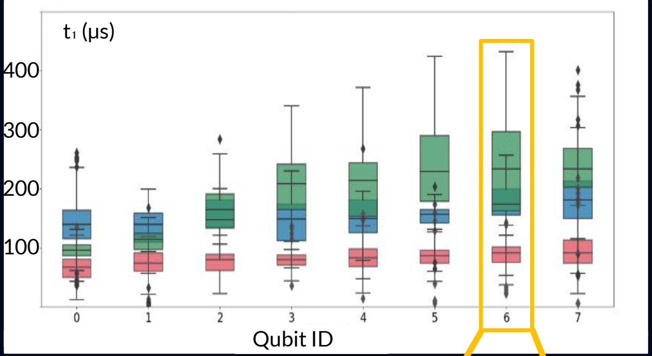
Rigetti Acorn

Chip Roadmap

Year	#	2Q Error
2016	1-4	>40%
2017	8	10-20%
2018-19	16	5-7%
2020	30+	3-4%
2021	100+	1-2%

TECHNOLOGY PROGRESS SNAPSHOT: COHERENCE

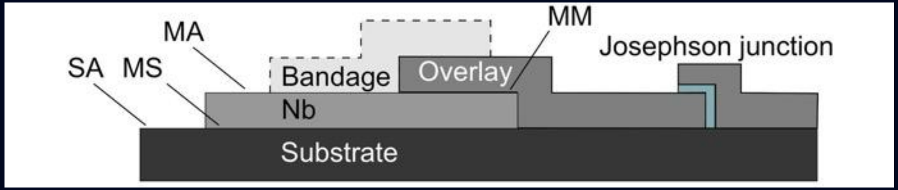
Coherence Times



🟩 Jul 2019
🟦 Feb 2019
🟥 May 2018

>200μs T_1

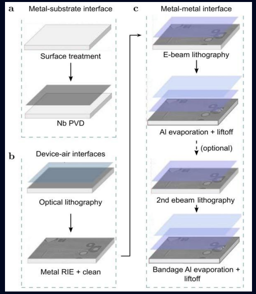
Device Interfaces



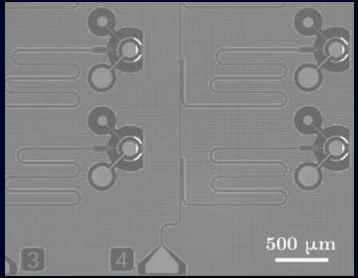
MS: Metal-Substrate | SA: Substrate-Air | MA: Metal-Air | MM: Metal-Metal

Isolate single interfaces, test iterative fabrication parameters

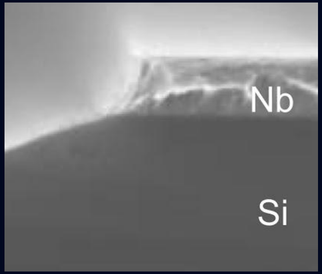
Fabrication Flow



Qubit Coherence Test



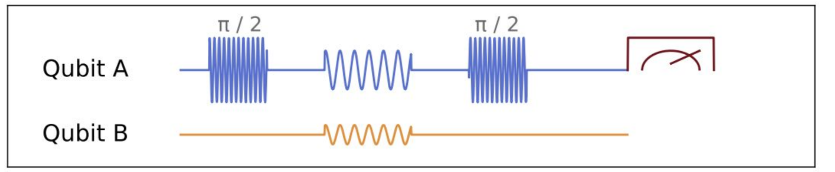
Metrology

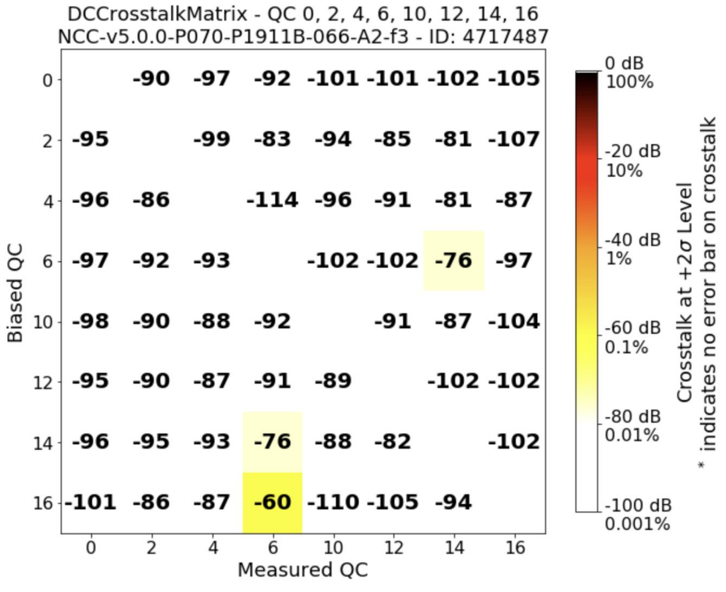


Nersisyan*, Poletto*, Alidoust*, Manenti*, et al arXiv:1901:08042 (2019)

TECHNOLOGY PROGRESS SNAPSHOT: CROSS-TALK

Combination of superconducting through-silicon vias and caps reduces cross-talk

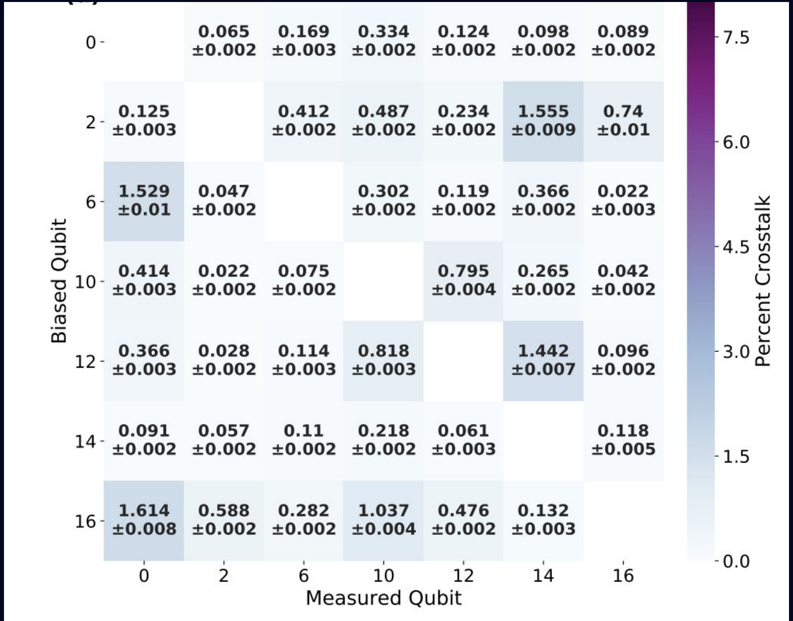




	0	2	4	6	10	12	14	16
0		-90	-97	-92	-101	-101	-102	-105
2	-95		-99	-83	-94	-85	-81	-107
4	-96	-86		-114	-96	-91	-81	-87
6	-97	-92	-93		-102	-102	-76	-97
10	-98	-90	-88	-92		-91	-87	-104
12	-95	-90	-87	-91	-89		-102	-102
14	-96	-95	-93	-76	-88	-82		-102
16	-101	-86	-87	-60	-110	-105	-94	

DC on-chip cross-talk: -60 to -100dB

RF cross-talk: ~0.05-1%

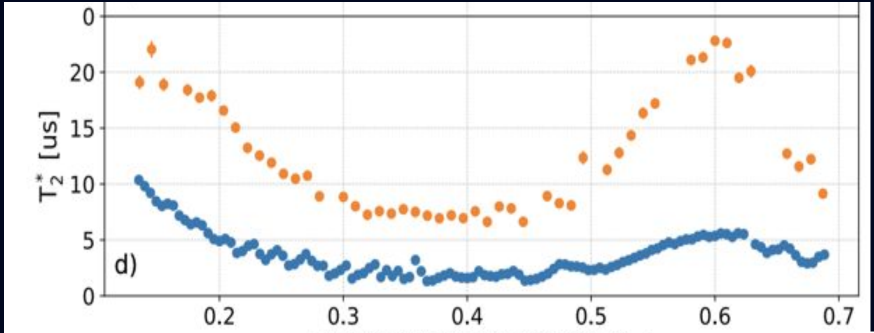


	0	2	6	10	12	14	16
0		0.065 ±0.002	0.169 ±0.003	0.334 ±0.002	0.124 ±0.002	0.098 ±0.002	0.089 ±0.002
2	0.125 ±0.003		0.412 ±0.002	0.487 ±0.002	0.234 ±0.002	1.555 ±0.009	0.74 ±0.01
6	1.529 ±0.01	0.047 ±0.002		0.302 ±0.002	0.119 ±0.002	0.366 ±0.002	0.022 ±0.003
10	0.414 ±0.003	0.022 ±0.002	0.075 ±0.002		0.795 ±0.004	0.265 ±0.002	0.042 ±0.002
12	0.366 ±0.003	0.028 ±0.002	0.114 ±0.003	0.818 ±0.003		1.442 ±0.007	0.096 ±0.002
14	0.091 ±0.002	0.057 ±0.002	0.11 ±0.002	0.218 ±0.002	0.061 ±0.003		0.118 ±0.005
16	1.614 ±0.008	0.588 ±0.002	0.282 ±0.002	1.037 ±0.004	0.476 ±0.002	0.132 ±0.003	

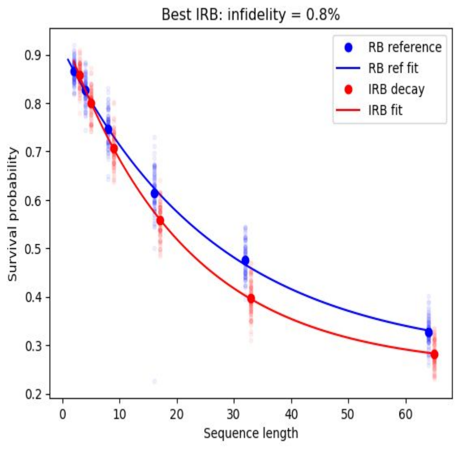
Abrams et al, arXiv:1908.11856

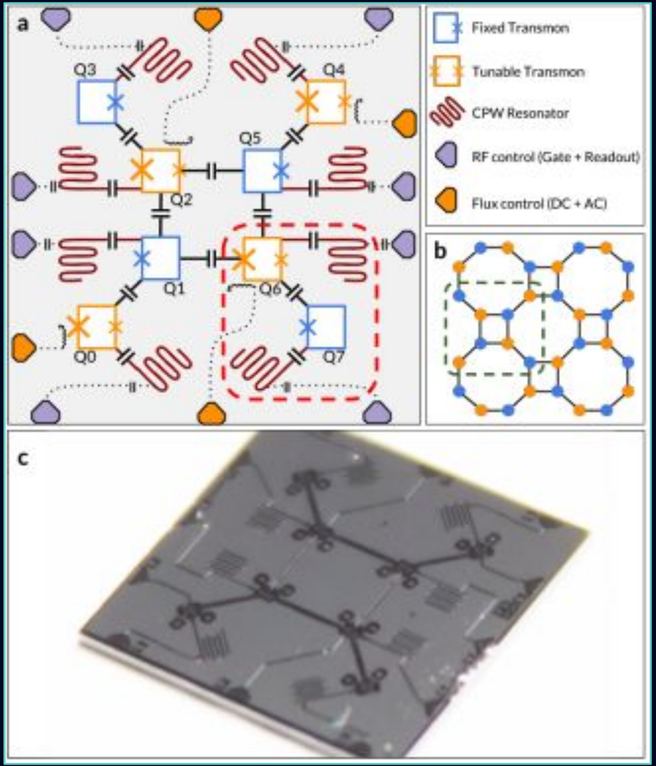
TECHNOLOGY PROGRESS SNAPSHOT: 2Q GATES

Parametrically Activated 2Q Gates Protected from Flux Noise Achieve 99% Fidelity



99.2 ± 0.15% 2Q Gate Fidelity





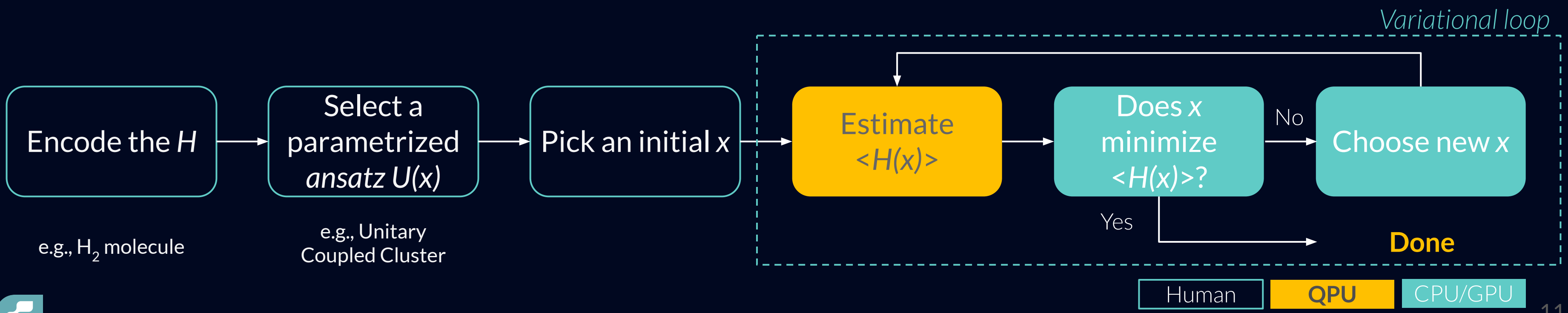
- T1 naturally fluctuates by ~ 2.5x (12-30μs)
- 2Q gate error rate follows T1 variation, 0.8-2.0%
- Gate and Hamiltonian are fully understood, and coherence limited.

Hong et al, arXiv: 1901.08035

TWO MAJOR HYBRID ALGORITHMS: VQE* & QAOA**

Algorithms	**VQE:** Variational Quantum Eigensolver	**QAOA:** Quantum Approximate Optimization Algorithm
Objective	Find lowest-lying eigenvalue of a Hamiltonian	Find a solution that minimizes a cost function
Example application	Molecule ground-state calculations	Approx. solution for combinatorial optimization

Overall approach



Variational loop

Encode the H

e.g., H_2 molecule

Select a parametrized *ansatz* $U(x)$

e.g., Unitary Coupled Cluster

Pick an initial x

Estimate $\langle H(x) \rangle$

Does x minimize $\langle H(x) \rangle$?

No

Choose new x

Yes

Done

Human | QPU | CPU/GPU

* Peruzzo et al., arXiv:1304.3061 ** Farhi, Goldstone, Gutmann, arXiv:1411.4028

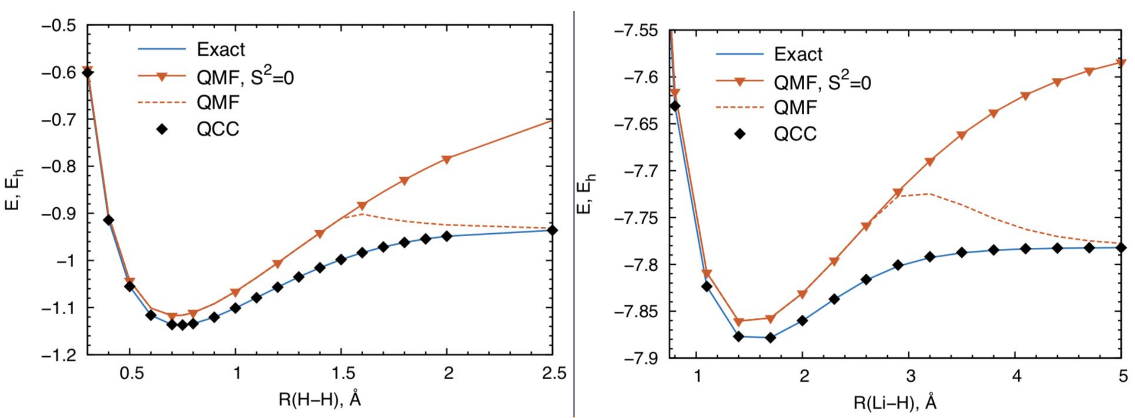
EXAMPLE APPLICATIONS OF VQE

Ground-state and potential energy curve calculations

Simulation of H2 and LiH ground state with chemical accuracy on Rigetti QCS, using qubit coupled-cluster (QCC) ansatz, leveraging a variation of UCC implemented directly in qubit space.

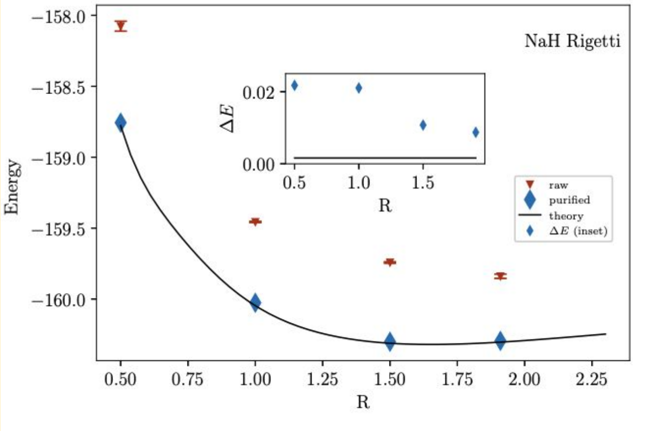
Ryabinkin *et al*, arXiv:1809.03827 [quant-ph]

Has now also been applied to water, results to be published soon.



Proper description of NaH dissociation on Rigetti QCS, using 2-body reduced density matrix to calculate energy and subsequent "purification" to remove the mixing of pure states due to noise.

McCaskey *et al*, arXiv:1905.01534

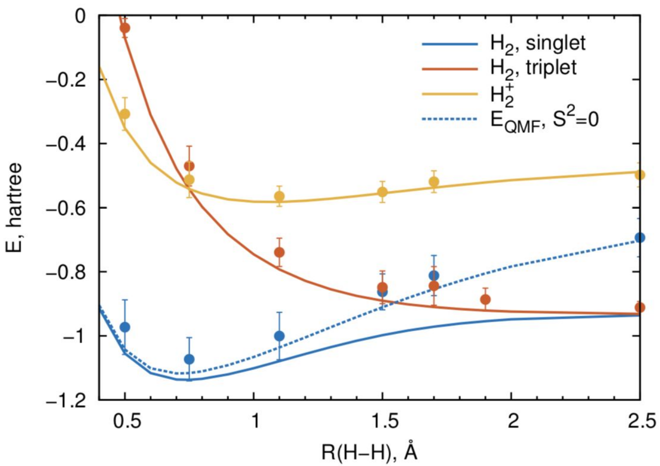


EXTENDING VQE TO COMPUTE EXCITED STATES

High-accuracy calculation of energy spectra with stronger potential to outperform classical algos

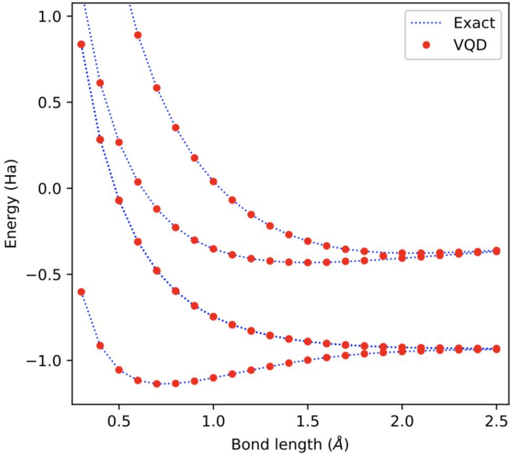
Simulation of H2 first and second excited states on Rigetti QCS, capturing features which are classically intractable for larger molecules; the method uses a constrained version of VQE.

Ryabinkin *et al.* arXiv:1806.00461 [physics.chem-ph]



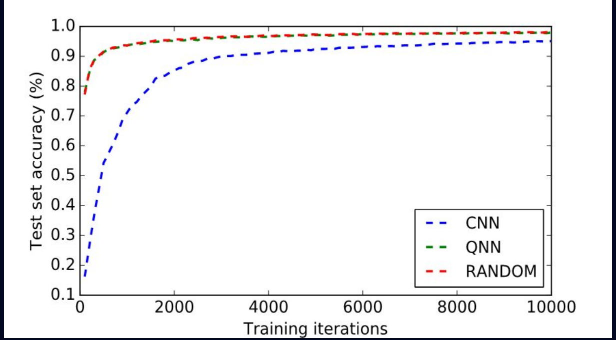
Simulation of up to 3rd excited states for H2, using variational quantum deflation, a VQE-based approach without additional qubit overhead and at most 2x deeper circuit.

Higgot *et al.* arXiv:1805.08138 [quant-ph]



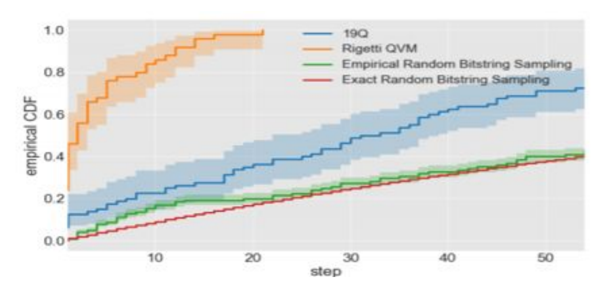
CAN QUANTUM COMPUTING BOOST MACHINE LEARNING?

Early Exploratory Work



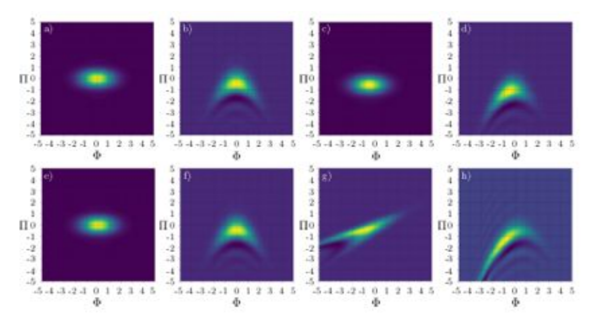
Quanvolutional neural networks (QNN) leverage nonlinear transformations natural to quantum computers to extract features from images. QNNs increased accuracy over CNNs without the quantum layer.

Henderson et al, arXiv:1904.04767



An **unsupervised machine learning** problem using clustering. This is the largest demonstration ever of a hybrid algorithm on a gate-model processor

Otterbach et al, arXiv:1712.05771

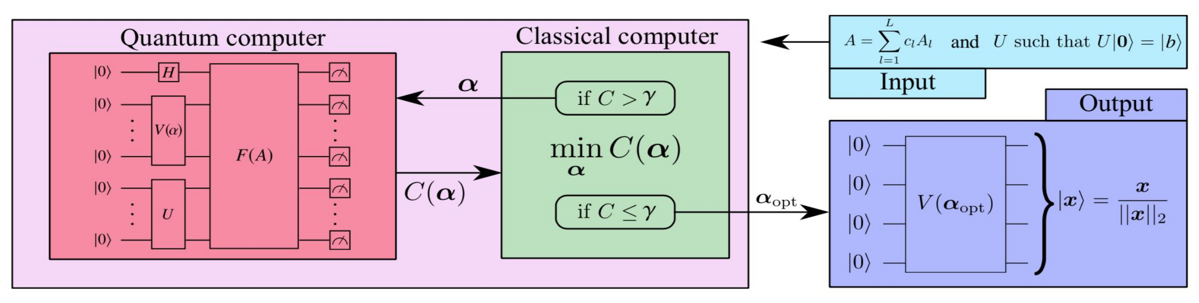


Developed Backwards Quantum Propagation of Phase Errors, enabling multiple **universal optimization method for training deep neural networks** on a quantum computer

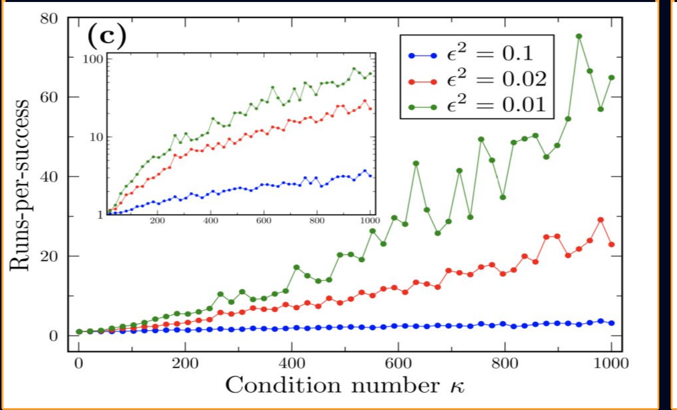
Verdon et al, arXiv:1806.09729

SOLVING LINEAR SYSTEMS WITH VARIATIONAL ALGOS

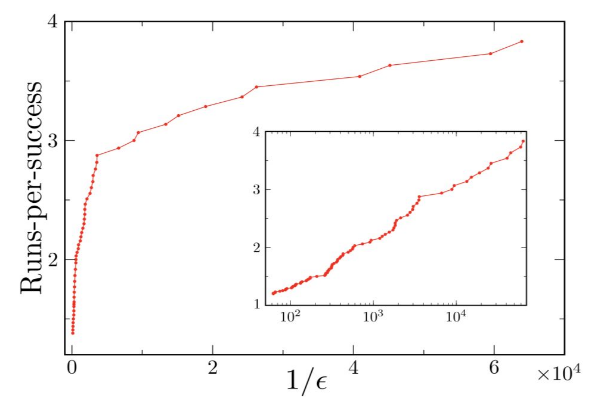
Solving *N*x*N* linear systems, *A* |*x*> = |*b*>



Sub-exponential scaling with condition number *κ*, ratio of largest to the smallest singular values in *A*



Logarithmic scaling with inverse precision 1/*ϵ*



Variational Quantum Linear Solver (VQLS):

Variationally minimize the overlap between |*b*> and *A*|x>

- Implemented on Rigetti QCS for *N*=32 (5 qubits)
- Efficient runtime and quantum circuit to estimate overlap
- Runs w fixed depth circuit and shows some resilience to noise

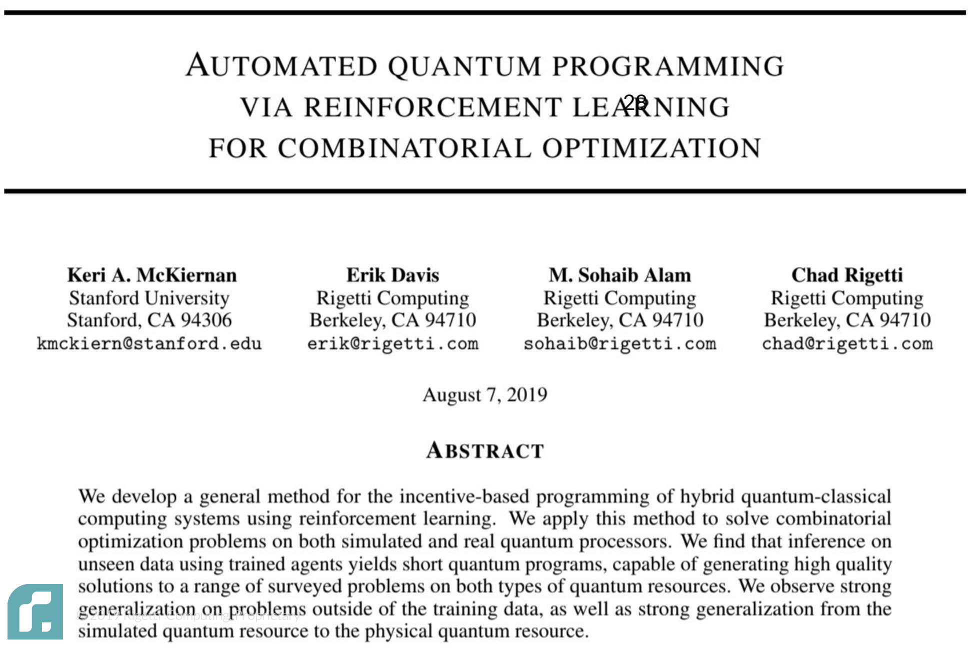
Bravo-Prieto et al, arXiv: 1909.05820 (Sandia)
An et al, arXiv:1909.05500 (Berkeley)

Xu et al, arXiv:1909.03898 (Oxford)

CAN MACHINE LEARNING HELP DESIGN BETTER HYBRID ALGORITHMS?

Can we use a **machine learning agent** (instead of human-designed templates) to ***generate* the ansatz**?

rigetti +



AUTOMATED QUANTUM PROGRAMMING VIA REINFORCEMENT LEARNING FOR COMBINATORIAL OPTIMIZATION

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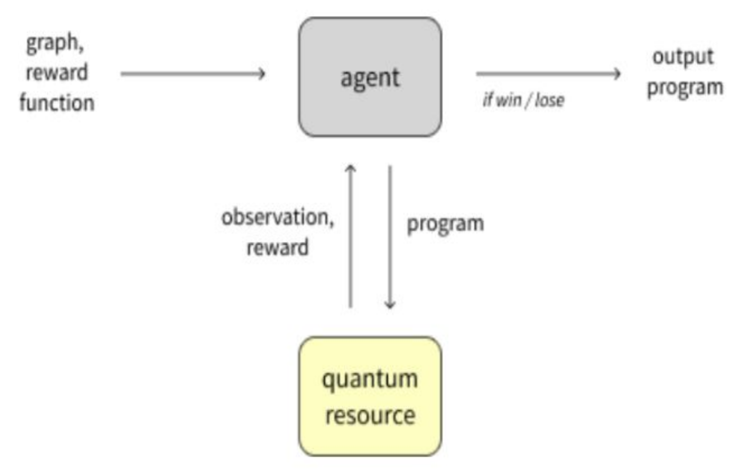
August 7, 2019

ABSTRACT

We develop a general method for the incentive-based programming of hybrid quantum-classical computing systems using reinforcement learning. We apply this method to solve combinatorial optimization problems on both simulated and real quantum processors. We find that inference on unseen data using trained agents yields short quantum programs, capable of generating high quality solutions to a range of surveyed problems on both types of quantum resources. We observe strong generalization on problems outside of the training data, as well as strong generalization from the simulated quantum resource to the physical quantum resource.



McKiernan et al, arXiv:1908.08054

https://github.com/rigetti/gym-forest

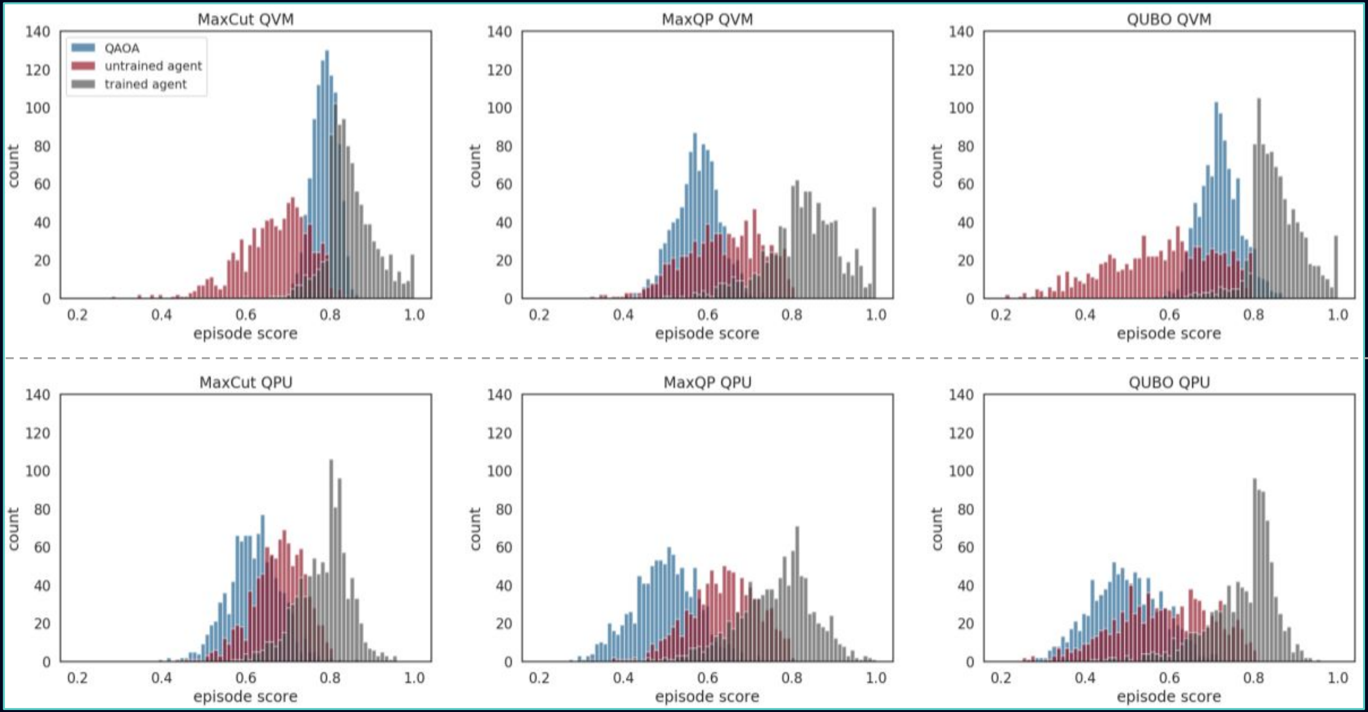
CAN MACHINE LEARNING HELP DESIGN BETTER HYBRID ALGORITHMS?

Using reinforcement learning agent to generate quantum circuits can reduce gate depths and sensitivity to noise

QAOA 🟦

Untrained agent 🟥

Trained agent ⬜



Run on noiseless simulator

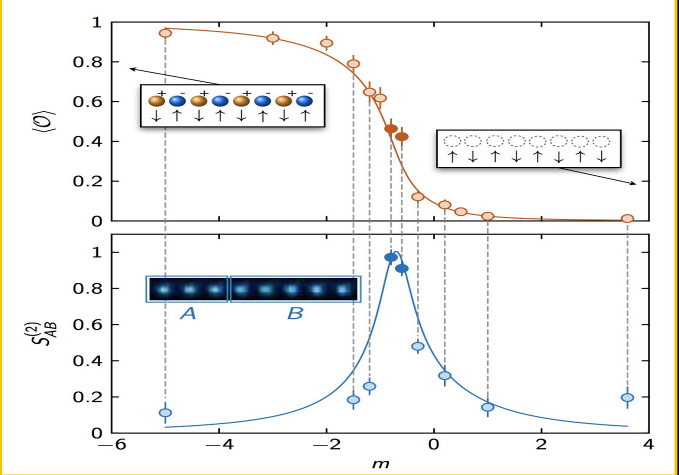
Run on Rigetti Aspen QPU

McKiernan et al, arXiv:1908.08054 https://github.com/rigetti/gym-forest

QUANTUM COMPUTING FOR HIGH ENERGY PHYSICS

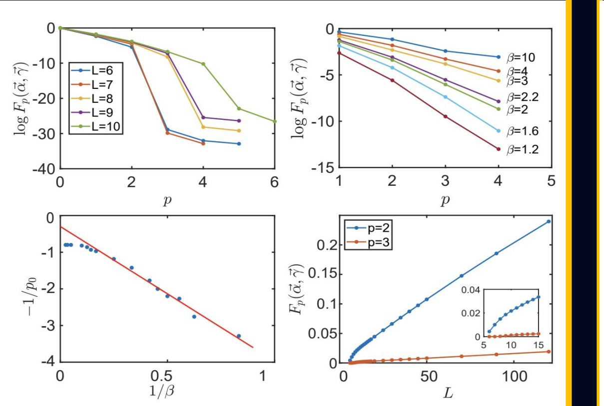
Phase transitions in quantum field theories*: Demo of variational hybrid algorithms to calculate a quantum phase transition in the Schwinger model.

C. Kokail et al, arXiv:1810.03421 (Innsbruck)



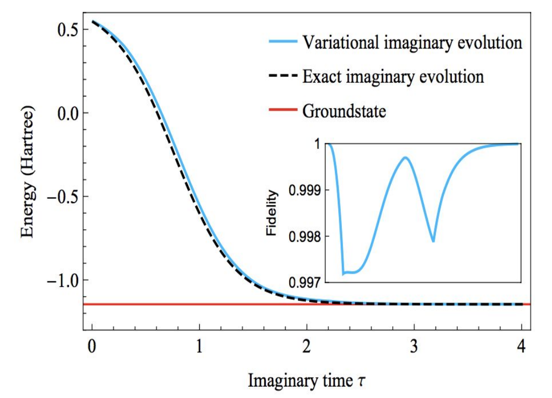
Thermal quantum simulation: Variational preparation of thermal Gibbs states (classically hard). Pathway towards studying quantum field theories at finite temperature.

Jingxiang Wu, Timothy H. Hseih, arXiv:1811.11756 (Waterloo)



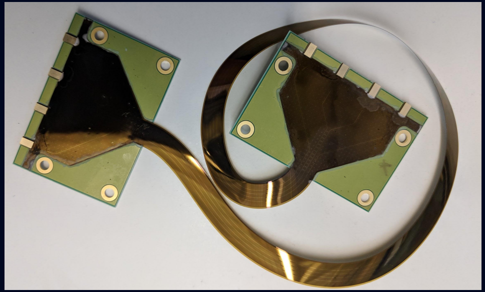
Simulating non-Unitary dynamics with imaginary time evolution: Variational simulation of Wick-rotated systems.

S. McArdle et al, arXiv:1804.03023 (Oxford)



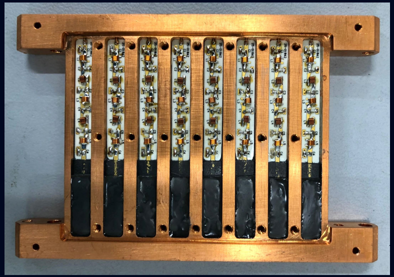
SCALING UP: CRYOGENIC PLATFORM

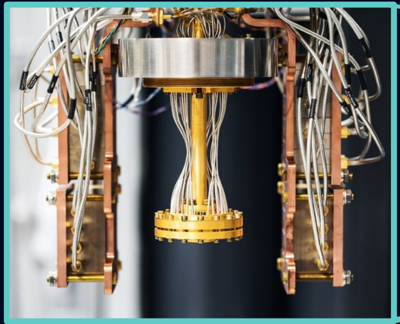
Flex cables connecting MX plate to RT electronics



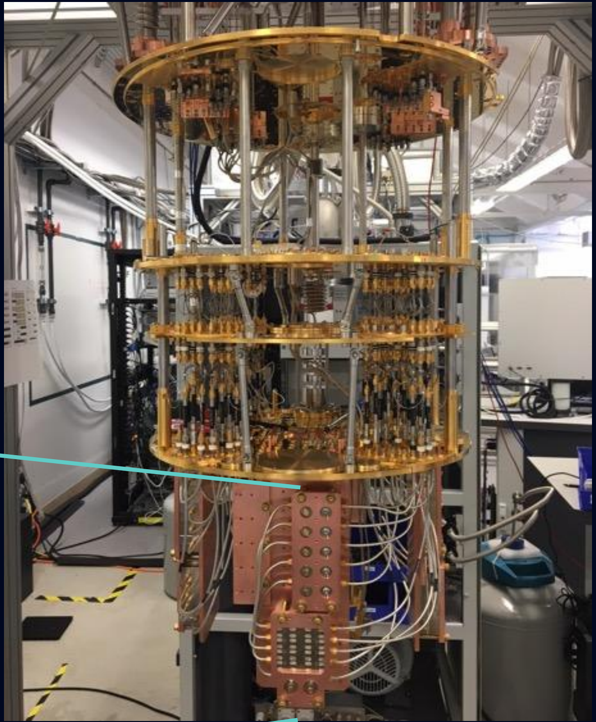
Flex reduces footprint 10x (from coax)

Integrated attenuators and filters





MX Plate Wiring and 32 I/O Quantum Processor Packaging



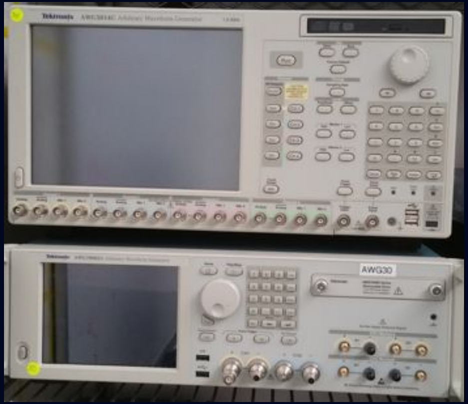
Cryogenic dilution refrigerator

SCALING UP: ELECTRONICS

2013-2015

General Test Equipment

AWG + Mixers
Precision current sources VNA



2016-2017

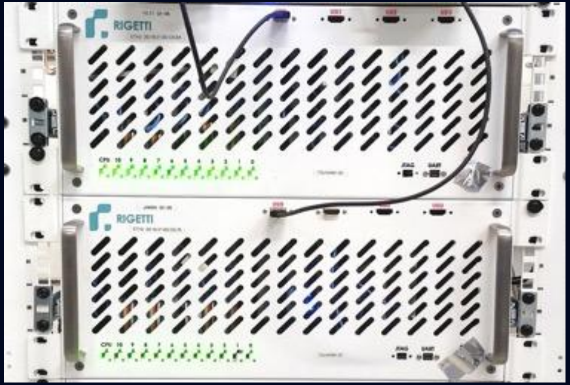
Off-the-shelf customizable instrumentation

Software defined radio (USRP)
Precision current source

2018-2019

Fully custom solution

Custom waveform generation; DC current source; processor

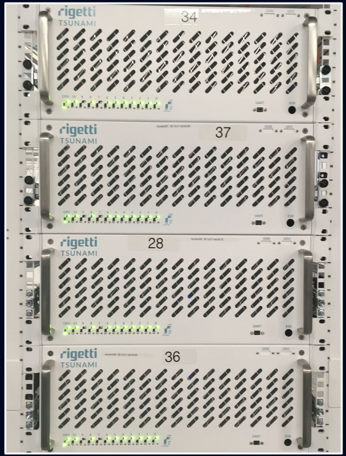


SCALING UP: ELECTRONICS

Custom Hardware:

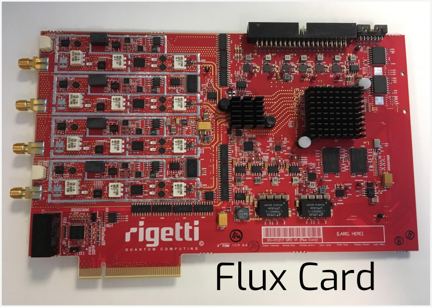
Direct digital microwave transmit and receive with FPGA logic:

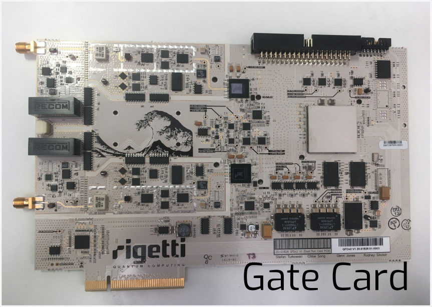
Built for high performance quantum algorithm implementation

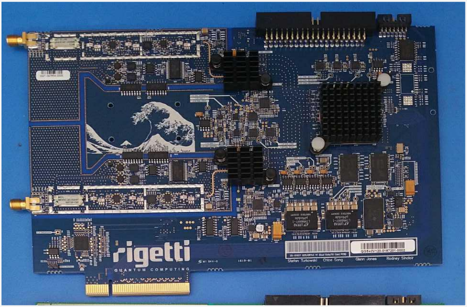


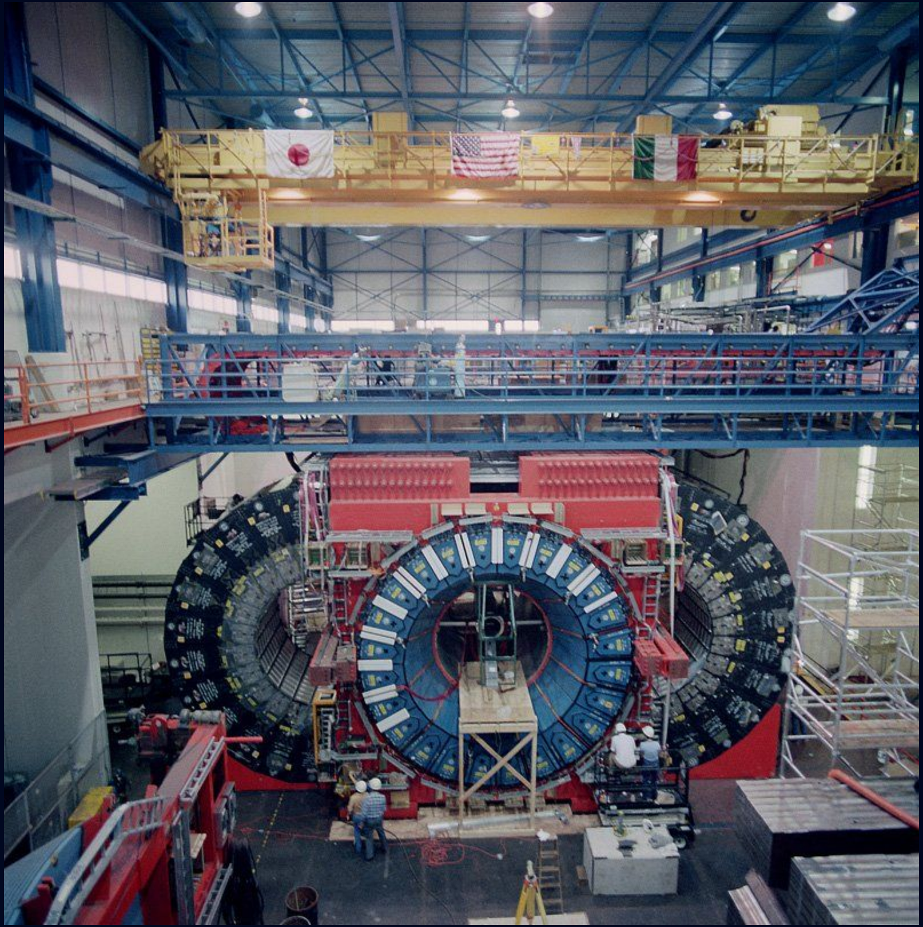
Key challenges in building custom electronics solutions

- Low-latency architectures for hybrid q-c computing, FTQC etc
- Achieving high temperature stability and better calibration
- Designing stable architecture to maintain phase coherence across all channels
- Bandwidth, dynamic range, noise etc


Flux Card


Gate Card

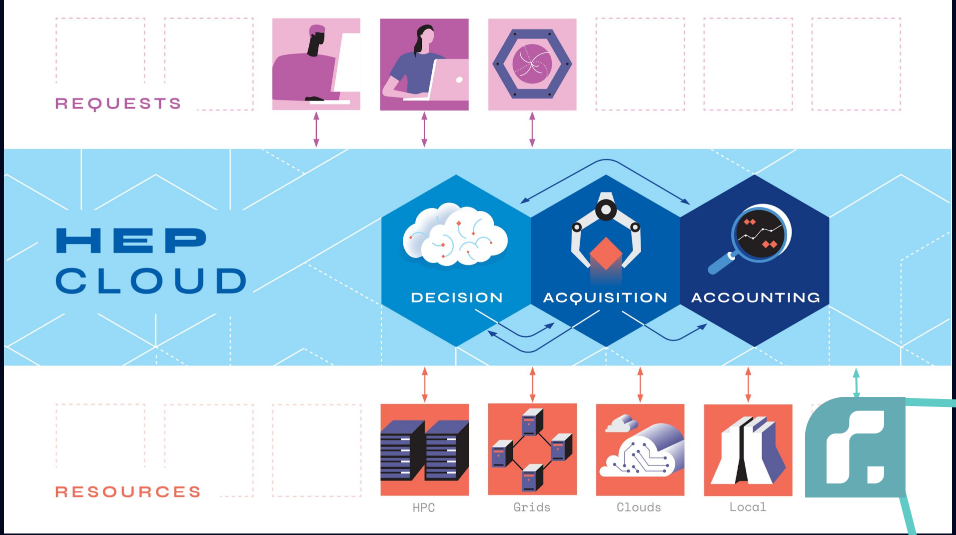





LINK

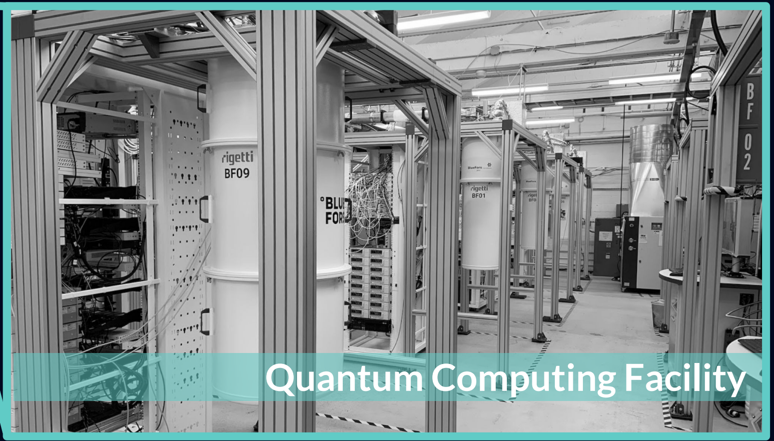
DISTRIBUTIONS AND INTEGRATIONS

Accelerating Quantum Sciences with Quantum Computing



Integrate quantum processors
into the HEP cloud in order to
expand the understanding of our universe.

Discover hybrid quantum-classical methods for HEP, ML, and data processing that can be made available to a broad community of researchers through HEP cloud


Quantum Computing Facility

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