Practical Quantum Computing with Trapped Ions

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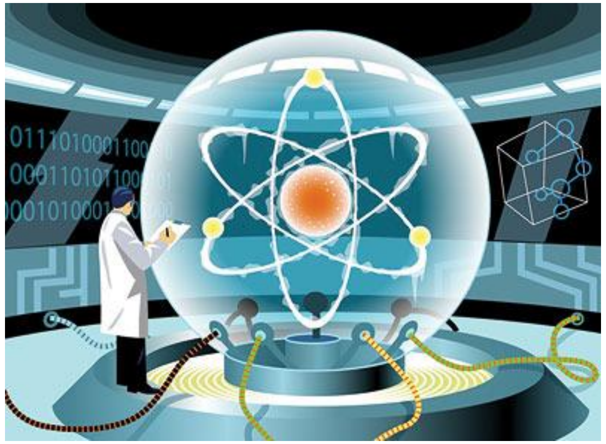
Computation in Sciences

- What was science like before computers were available?
- Computation has made a huge impact in ALL scientific disciplines
  - Computational Physics, Computational Chemistry, Systems Biology
  - Numerical simulation and CAD in vast areas of science and engineering
  - Expanding to machine learning and AI, impacting in all areas of society
- Development of new computational methods vs advanced hardware
  - Progress in HW is critical in the early days to get ideas flowing
  - Methods development accelerates the impact faster than new HW

New science is enabled by computational technology!!

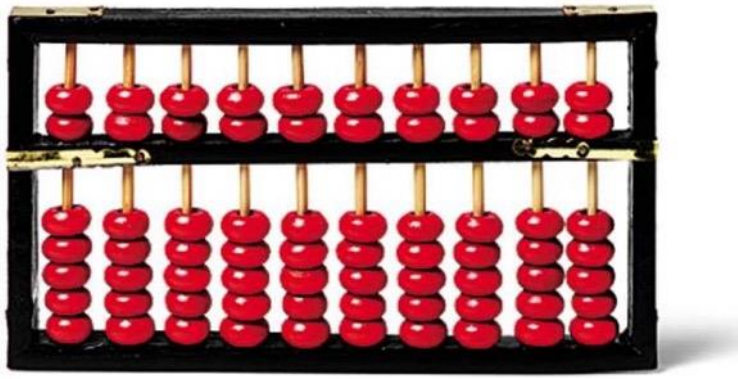
What is a Quantum Computer?

"A quantum computer differs more from a classical computer……

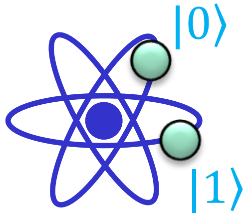


…than a classical computer differs from an **ABACUS**"

William Phillips
1997 Nobel Laureate

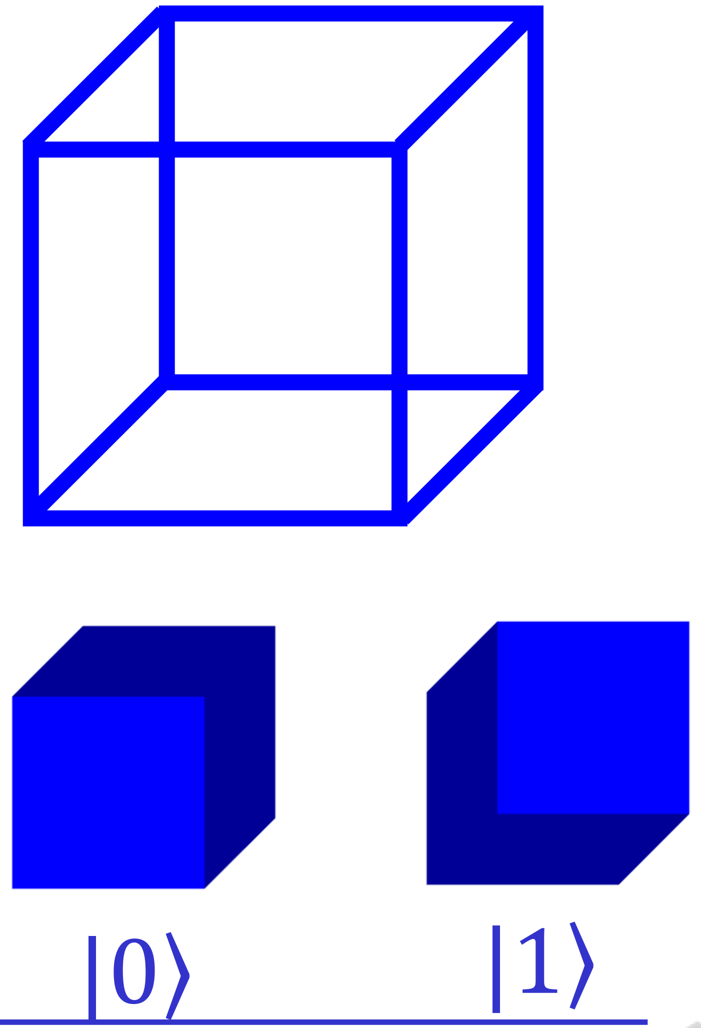


Critical Quantum Feature I: Superposition

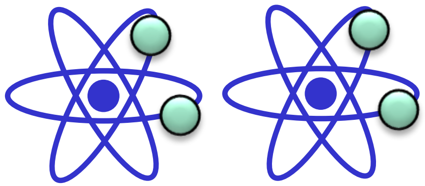


A classical bit: 0 or 1

qubit: $|\psi\rangle = a|0\rangle + b|1\rangle$

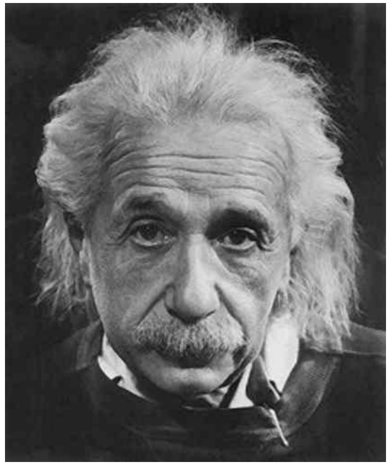


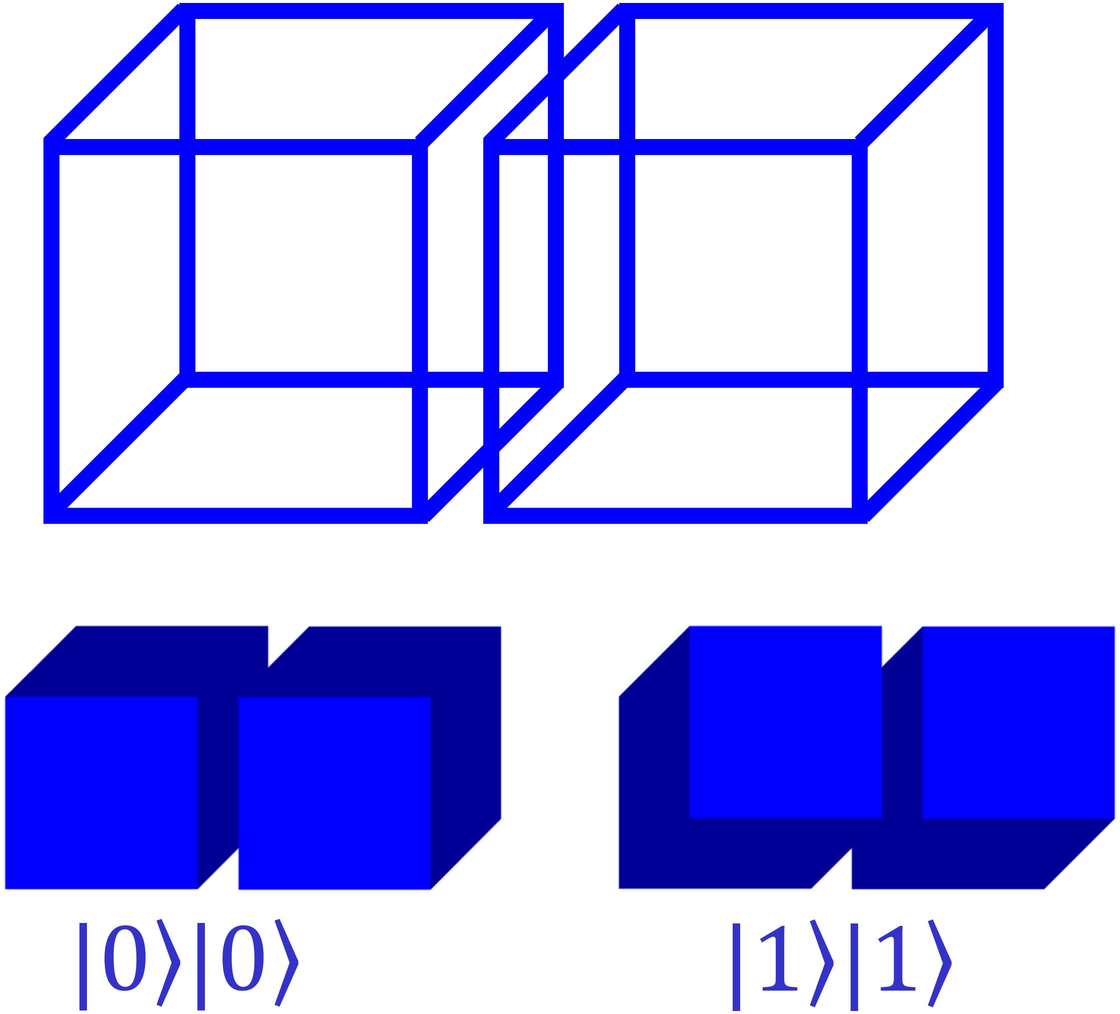
Critical Quantum Feature II: Entanglement



qubits: $|\psi\rangle = a|00\rangle + b|11\rangle$

"spooky action-at-a-distance"
(A. Einstein)





entanglement: "wiring *without wires*"

GOOD NEWS…

parallel processing on 2^N inputs

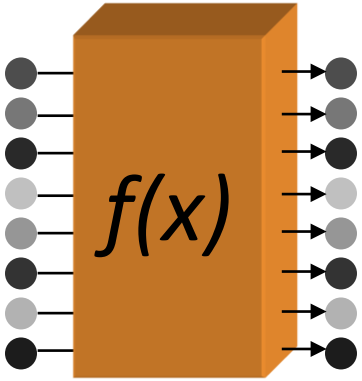
…BAD NEWS…

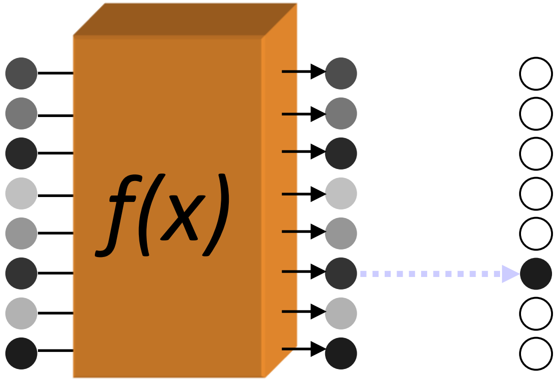
measurement gives random result

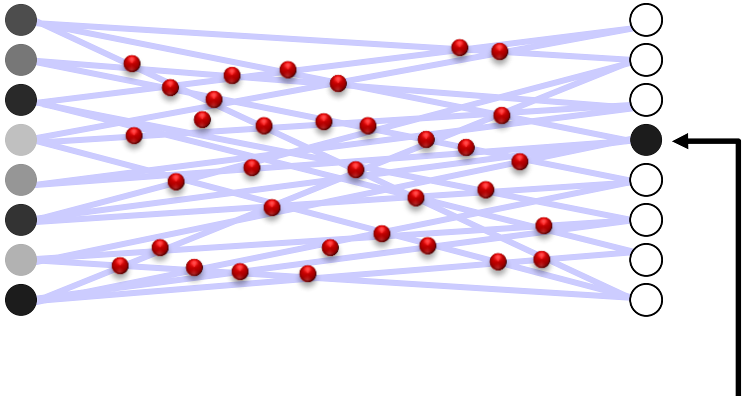
…GOOD NEWS!

quantum interference

e.g., $N=3$ qubits







depends on *all* inputs

$$a_0|000\rangle + a_1|001\rangle + a_2|010\rangle + a_3|011\rangle$$
$$a_4|100\rangle + a_5|101\rangle + a_6|110\rangle + a_7|111\rangle$$

N=300 qubits have more configurations than there are particles in the universe!

David Deutsch (early 1990s)

Application: Factoring Numbers

A quantum computer can factor numbers **exponentially faster** than classical computers

39 = 3 × 13 (…easy)
3864788462100938762143232563 1 = **?** × **?**

Key generation	$n = P * Q$ $d * e = 1 \bmod \Phi(n)$
Encryption	$c = m^e \bmod n$ Public Key(n,e)
Decryption	$m = c^d \bmod n$ private key (d)

Physics of Trapped Ion Quantum Computing

Search for The "Perfect Qubit"?

- What is a good criteria for defining a "Perfect Qubit"?

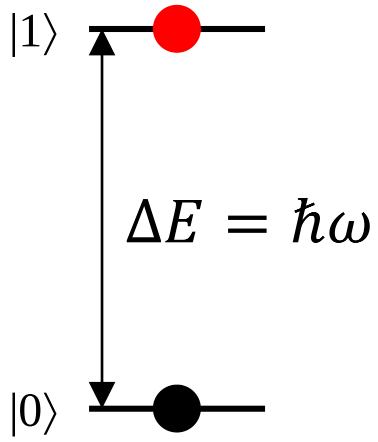
$$|\psi\rangle = e^{i\gamma}\left(\cos\frac{\theta}{2}|0\rangle + e^{i(\omega t+\varphi)}\sin\frac{\theta}{2}|1\rangle\right)$$

$$T_1 = \infty$$

Zero Decay Errors

$$T_2 = \infty$$

Zero Dephasing Errors



For hyperfine ground state of H, the spontaneous transition rate is estimated to be **2.9×10^{-15} per second**, or **1 per 11 million years**

For hyperfine ground state of Cs

Cs ν_{HF} = 9 192 631 770 Hz (EXACT!!)

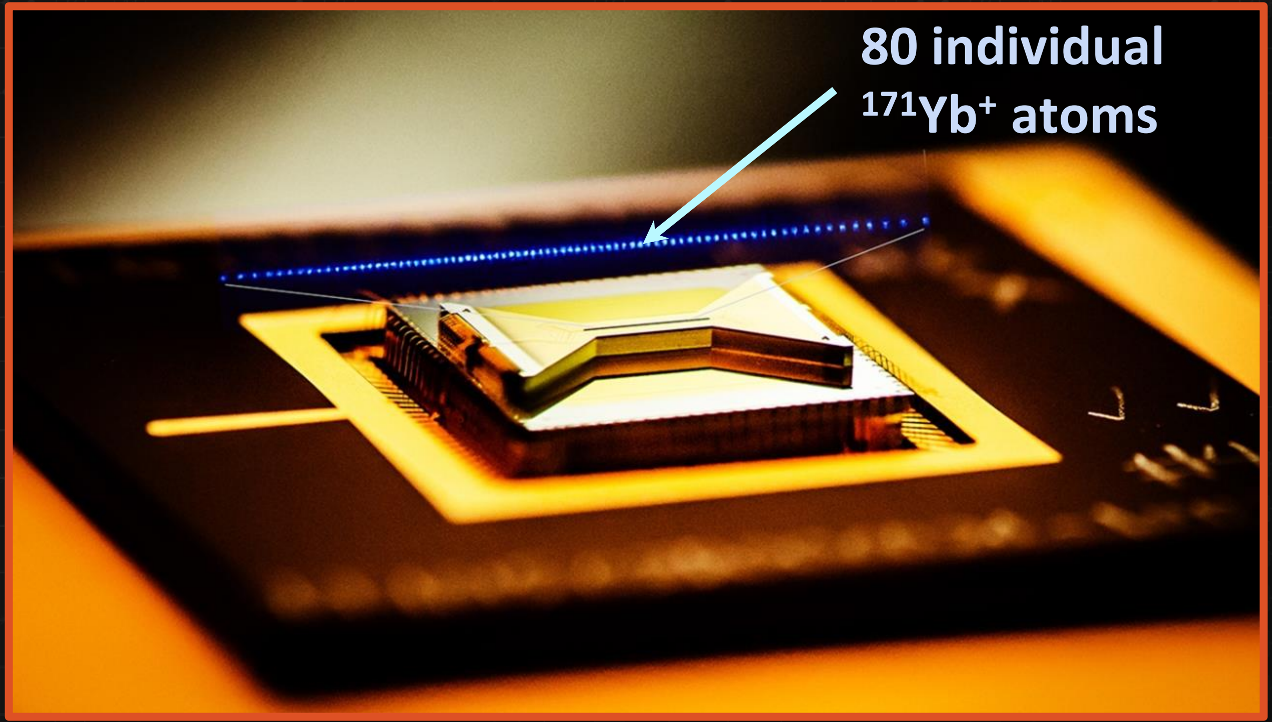
- $T_2 \approx$ 1sec baseline (Olmschenk et al., PRA 76, 052314, 2007)
- $T_2 \approx$ 5500 sec (P. Wang et al., Nature Comm. 12, 233, 2021)

Hyperfine Ground State of an Atom is an ideal choice

Trapped Ion Hyperfine Qubit: $^{171}Yb^{+}$

- Qubit initialization by **optical pumping**:
  - Very high fidelity (**error ~10^{-6}**) limited by off-resonant scattering
- Qubit Measurement by **resonance fluorescence**:
  - High fidelity (**~10^{-3}-10^{-4}**) limited by off-resonant scattering, dark counts
- Single-qubit gates by **off-resonant Raman transitions**:
  - Very high fidelity (**~10^{-4}-10^{-5}**) limited by spontaneous emission, laser noise
- Two-qubit gates by **state-dependent force from Raman transitions**:
  - High fidelity (**~10^{-3}-10^{-5}**) limited by spontaneous emission, laser noise

IONQ Qubit Technology

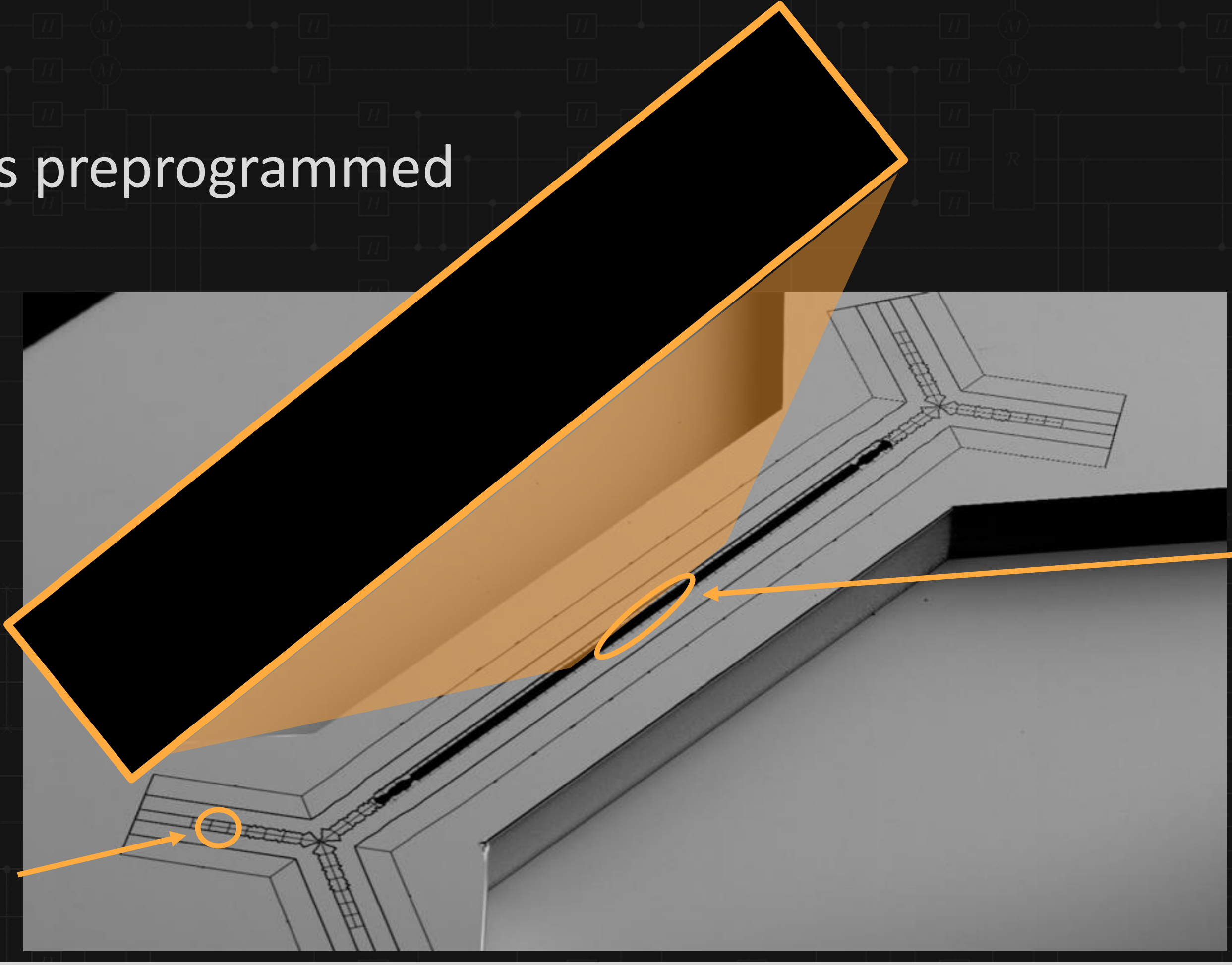


Sandia National Laboratories

Based on Individual Atoms, with Fully Flexible Control

IONQ Autoloading Register

N=23 qubits preprogrammed

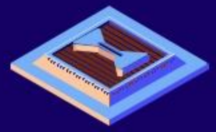


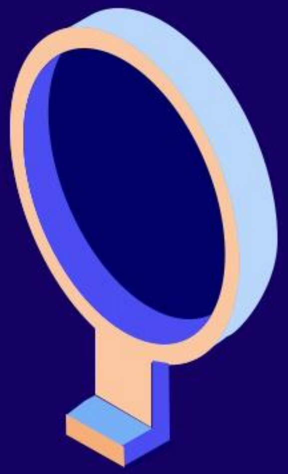
Quantum Computing zone

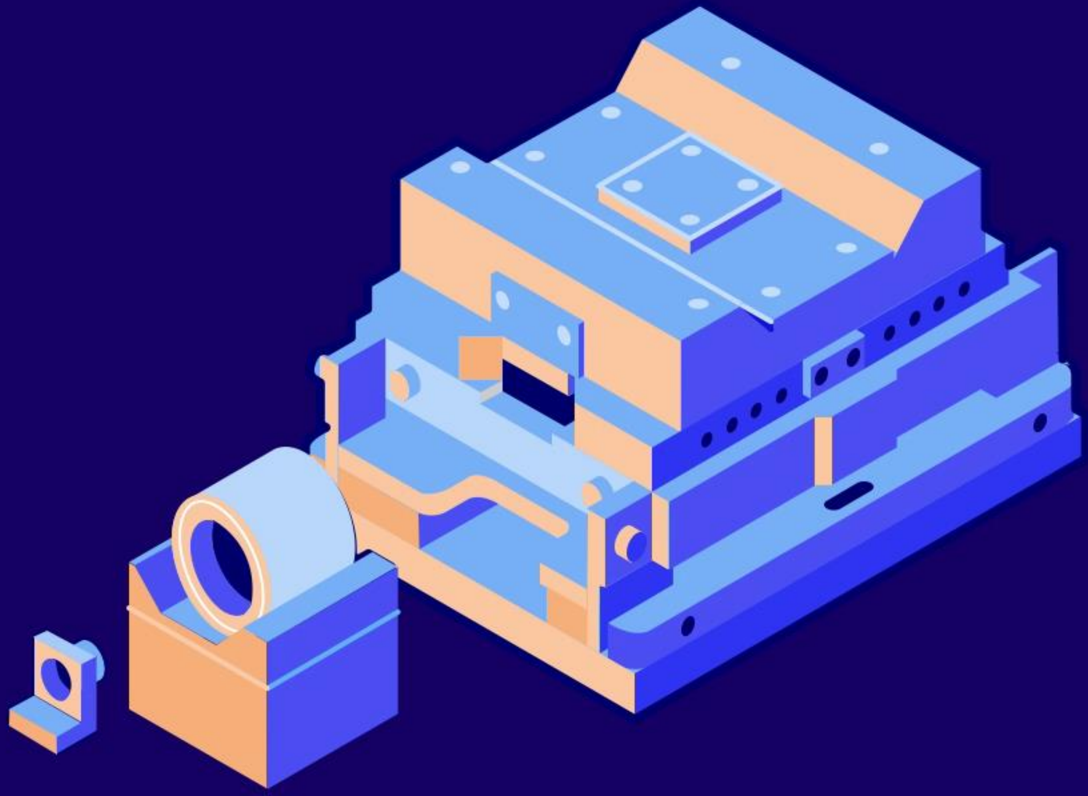
Loading zone

IONQ

Quantum Computer Module







Plenty of Room for New Physics

- Errors are dominated by systematic and control errors
  - Innovation in coherent control and error mitigation techniques
  - Robust hardware designs can reduce or eliminate most of these errors
- Error cancellation at the circuit level
- Multi-qubit entangling gates
- Nifty crosstalk cancellation techniques
- Gate performance maintained at dozens of qubits

All In Software!!

Quantum Computer for Users

Useful Near-Term Quantum Algorithms

- **Quantum Machine Learning (QML)**: Quantum advantages proven for

  Learning complex patterns w/ quantum feature maps (arXiv:2010.02174)

  Exponential gain in predicting certain worst-case error (arXiv:2101.02464)

  Quantum correlations used in generative modeling (arXiv:2101.08354)

- **Quantum Chemistry** and **Materials Studies**

  Variational quantum eigensolvers (VQE) for energy estimation

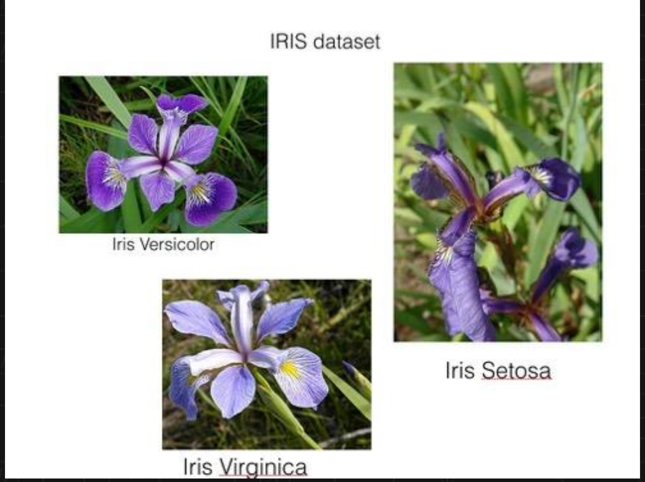
  Quantum simulation of dynamics of excitation

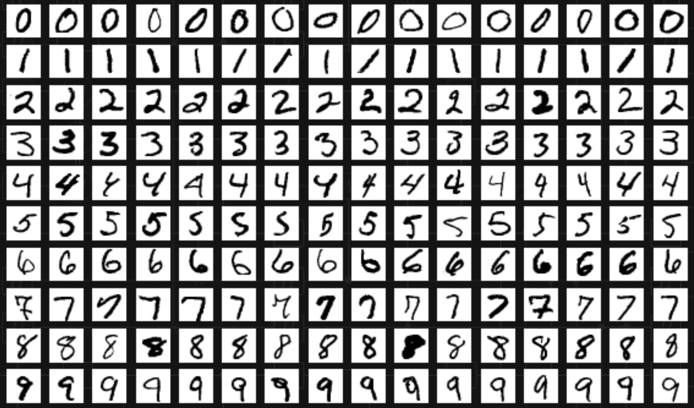
  Study of quantum many-body phenomena

- **Optimization Problems**: Quantum Approximate Optimization Algorithm

QML Example: Nearest Centroid Classifier

Data Set

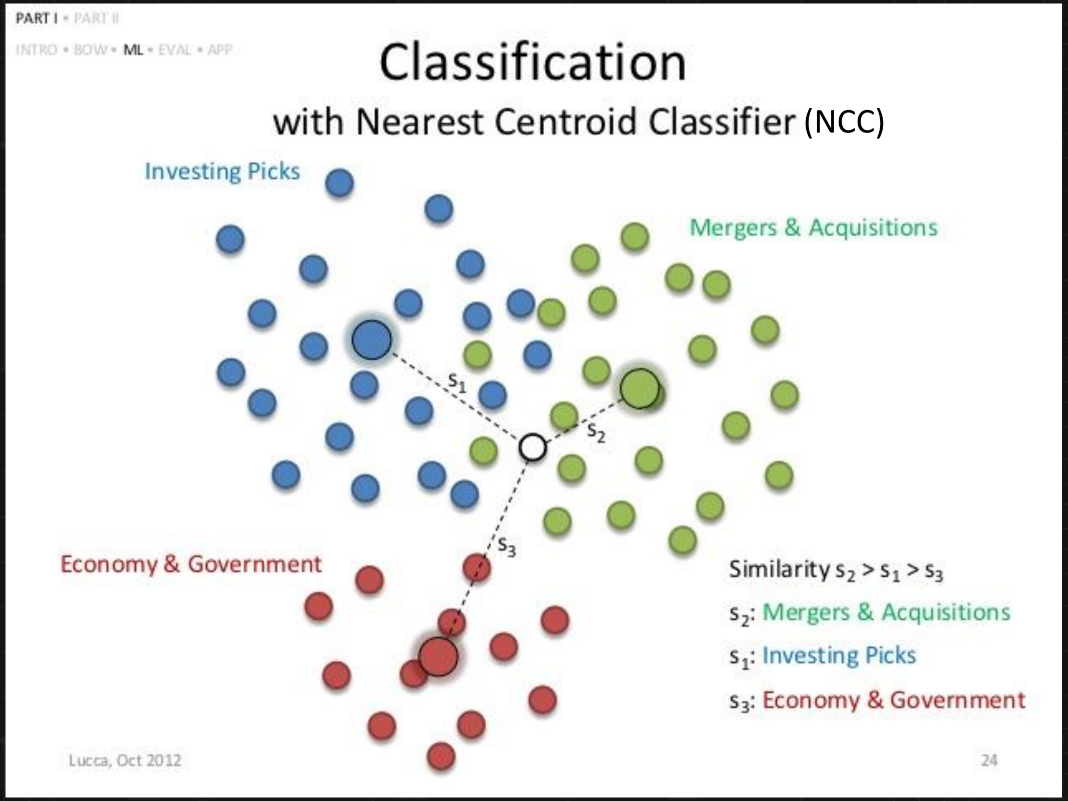




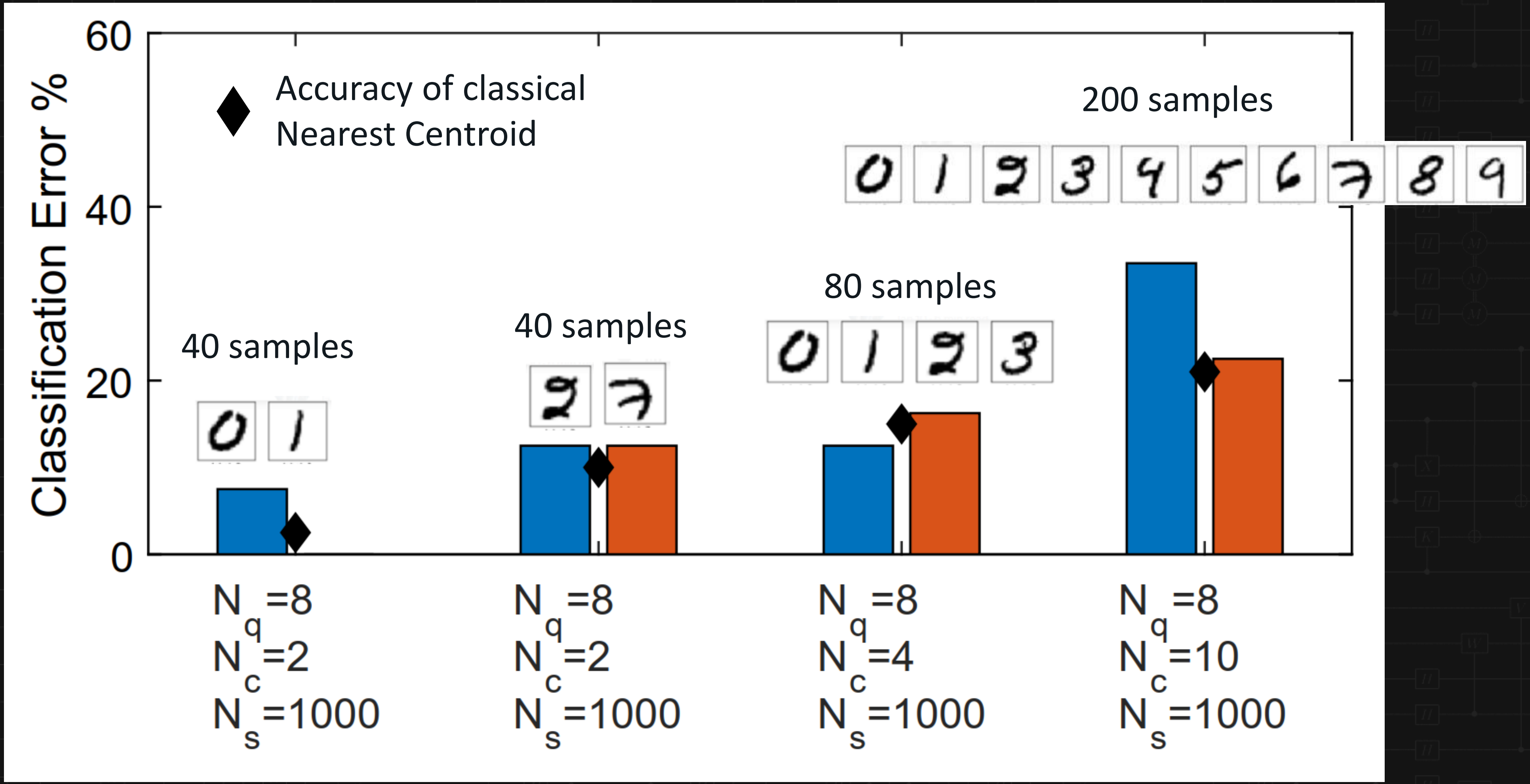
Fit your model:
Find centroids of
each class of training data

Predict labels of new data:
Compute distance to centroids
QUANTUMLY to assign labels
of the nearest centroid

Classification Model

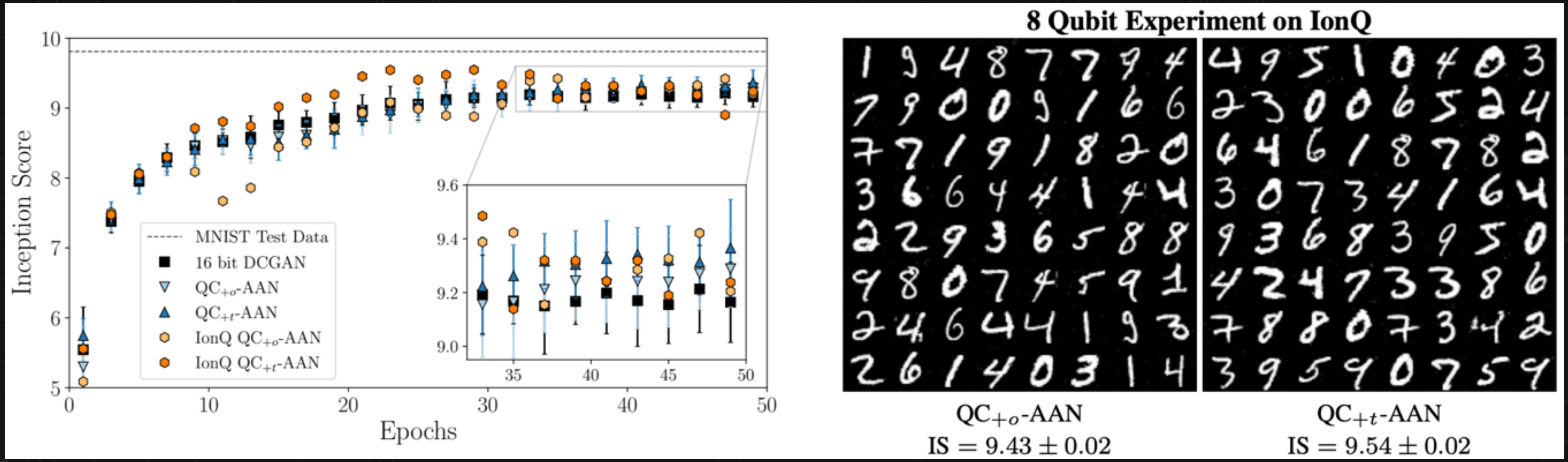


QML NCC: MNIST Database on 8 Qubits



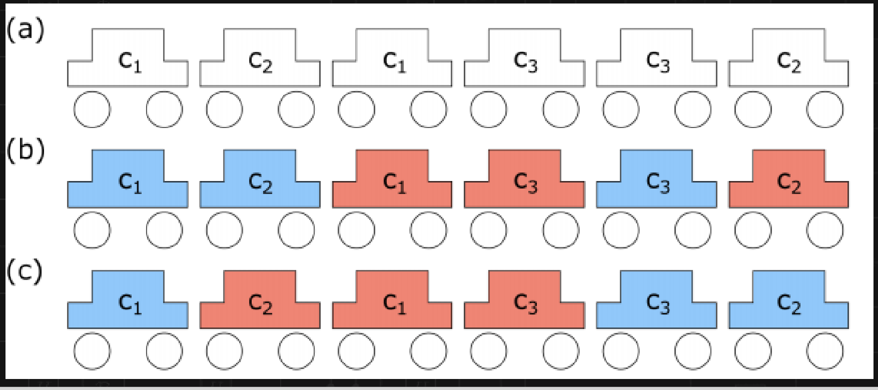
Other Examples

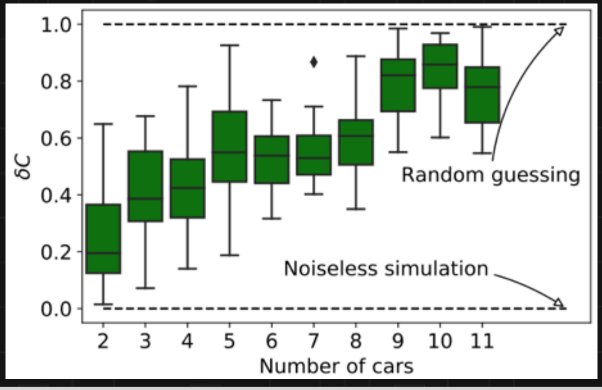
- Generating high-resolution handwritten digits



M. S. Rudolph et al., arXiv:2012.03924 (2020)

- Binary Paint Shop problem with QAOA



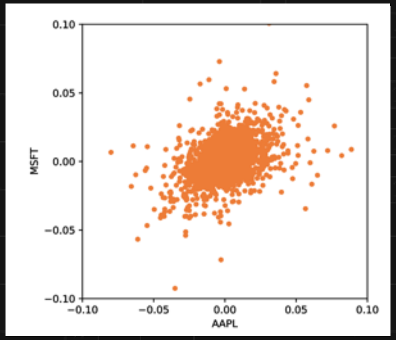


M. Streif et al., arXiv:2011.03403 (2020)

Joint Probability Distribution: Copula

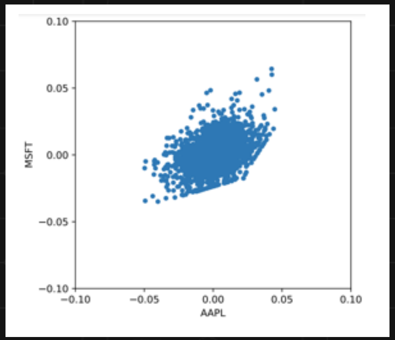
- Ion trap quantum computers are used to explore **Multi-variate machine learning techniques** using copulas
- **More efficient traning** and Accurate models that capture outliers

Target Distribution



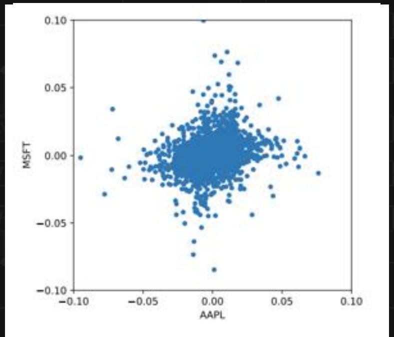
From training data

Classical GAN



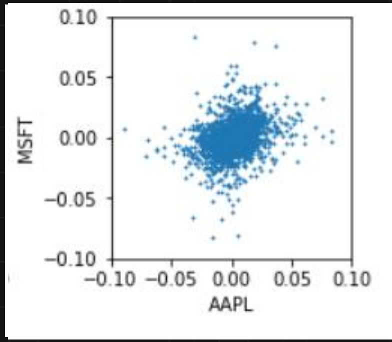
After 20,000 Iterations

Quantum GAN



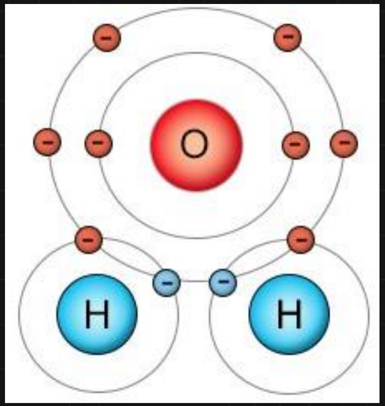
After 1,000 Iterations

Quantum CBM

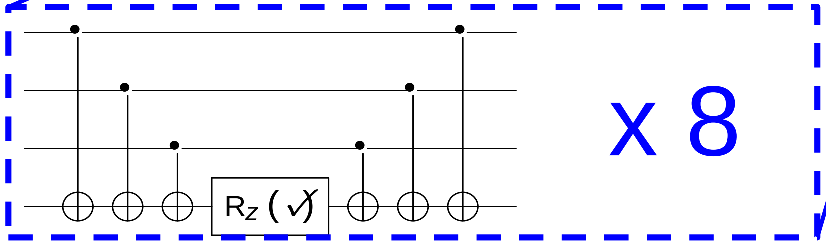


After 26 Iterations

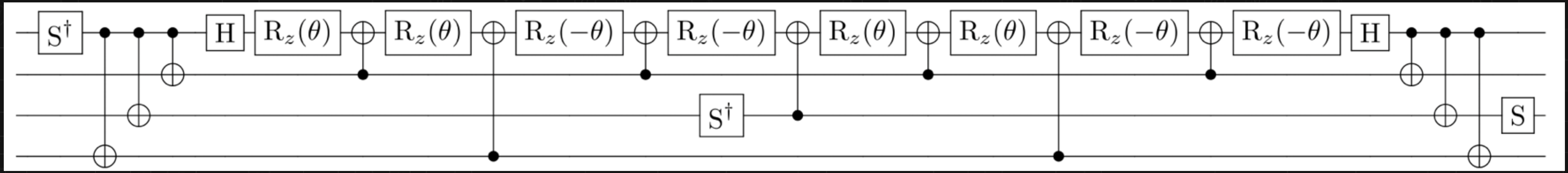
Quantum Chemistry Example: VQE



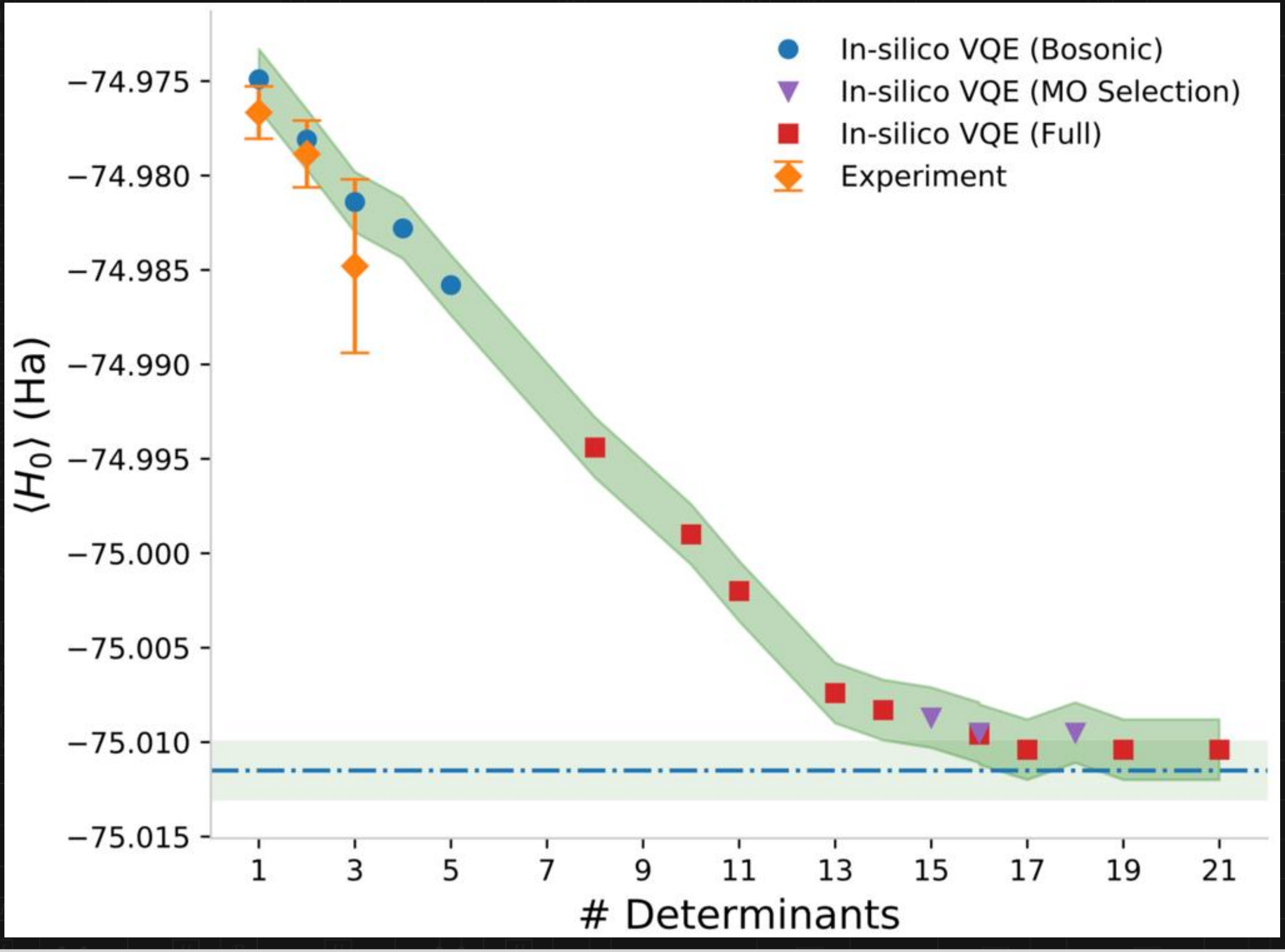
$$\hat{H} = \sum_{p,q} h_{pq} c_p^\dagger c_q + \sum_{p,q,r,s} h_{pqrs} c_p^\dagger c_q^\dagger c_r c_s$$



Order of Approx.	Naïve qubits	Naïve gates	Optimized qubits	Optimized gates	Binding Energy (Hartrees)
Baseline					-74.9624
+1 term	4	40	2	2	-74.9749
+2 terms	4	80	2	2	-74.9781
+3 terms	8	112	4	6	-74.9804
+4 terms	8	144	4	8	-74.9828
+5 terms	10	232	5	10	-74.9858
+8 terms	10	264	10	60	-74.9944
+10 terms	10	348	10	84	-74.9990
+11 terms	10	532	10	92	-75.0020
+13 terms	10	596	10	116	-75.0074
+15 terms	10	648	10	136	-75.0087
+19 terms	12	730	11	157	-75.0104
+21 terms	12	800	11	178	-75.0104
EXACT:					**-75.0116**



Quantum Chemistry Example: VQE



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+15 terms	10	648	10	136	-75.0087
+19 terms	12	730	11	157	-75.0104
+21 terms	12	800	11	178	-75.0104
EXACT:					**-75.0116**

Y. Nam et al., npj Quant. Inf. 6, 1 (2020)

Summary and Conclusion

- Quantum computers provide **fundamentally new way of computation**
  - Started out in Physics, transitioning into technology, **FAST**
  - New types of algorithms enable new types of applications
- Availability of **fully-connected programmable quantum computers**
  - Provides a testing ground for novel quantum algorithms
  - Continued performance scaling is key to enabling new approaches to challenging problems
- Progress in **QML, quantum chemistry and QAOA** algorithms
  - Optimization for hardware provide performance improvements
- Opportunities to explore and enable **new approaches computational sciences**

Team and Collaboration

- Duke Team
  Peter Maunz
  Taehyun Kim
  So-Young Baek
  Kai Hudek
  Caleb Knoernschild
  Kyle McKay
  Andre van Rynbach
  Emily Mount
  Daniel Gaultney
  Muhammed Ahsan
  Rachel Noek
  Stephen Crain
  Geert Vrijsen
  Volkan Inlek
  Ye Wang
  Junki Kim
  Yuhi Aikyo
  Clinton Cahall
  Chao Fang
  Robert “Tripp” Spivey
  George Schwartz
  Ke Sun
  Jacob Whitlow
  Ely Novakoski

- **Ken Brown** Group (Duke)
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  Michael Newman
  Jyothi Saraladevi
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  Gloria Jia
  James Leung
  Muyuan Li
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  Shilin Huang
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  Evan Reed
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  Phoebe Chen
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  Leon

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  Volkan Inlek
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  Kristi Beck
  Marko Cetina
  Michael Goldman
  Kevin Landsman
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