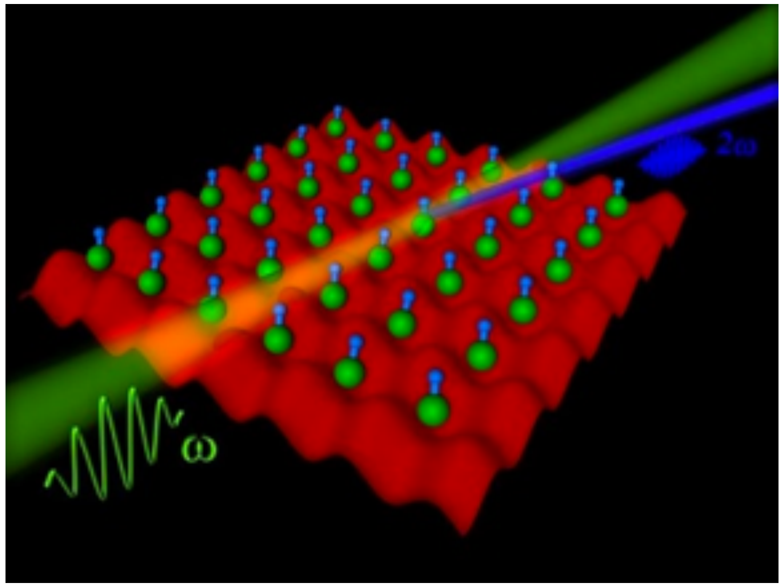
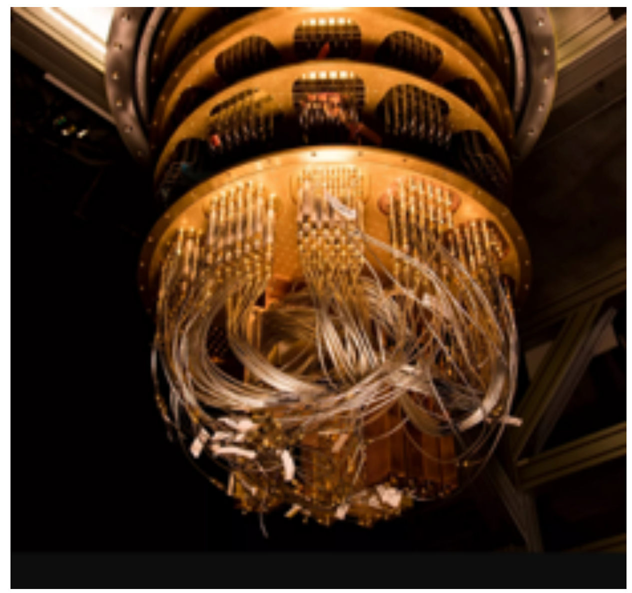
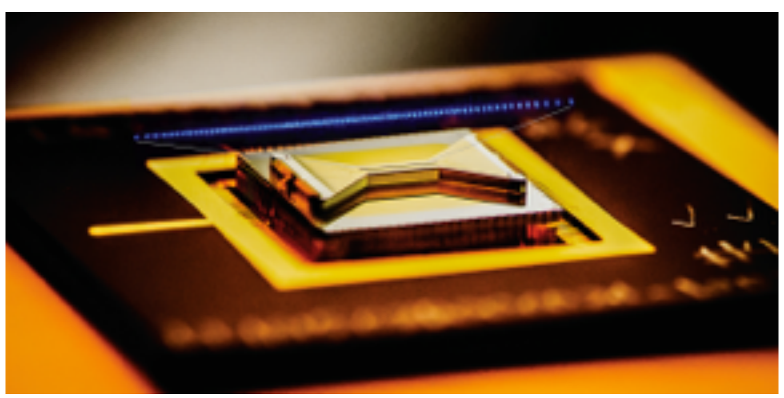
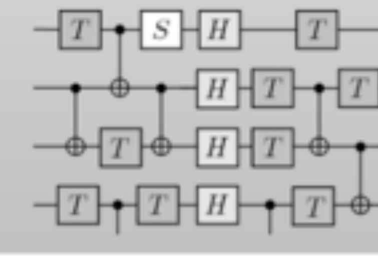






Algorithms
Identify problem
Map to qubits and gates



Quantum Software
Express in native gates/connectivity
Compile & compress circuits
Deploy error correction strategy

Control Engineering
Implement Hamiltonian control with E/M fields

$$i\hbar \frac{\partial|\Psi\rangle}{\partial t} = H(t)|\Psi\rangle$$

Qubit Technology
Interface control fields with qubit system

CompF6:

Quantum Computing

Snowmass, 5-8 October, 2020
Session 102 QIS for HEP, 6-Oct, 1.30pm Central Time

Travis Humble (ORNL)
Gabe Perdue (FNAL)
Martin J Savage (UW)

HEP and QC+T - Overview Points

* **Quantum technology has the potential to provide unique capabilities to address important HEP challenges**

* **HEP has world-leading S+T capabilities to deliver important advances in QIS**

* **Significant "new money" funding opportunities in QIS**
  * will not "cannibalize" existing HEP program

* **QIS is "organizationally new" to HEP**
  * organize a coherent "full-stack" plan in Snowmass process
    * scientific opportunities

2019 Sees the First Quantum Advantage in Computing

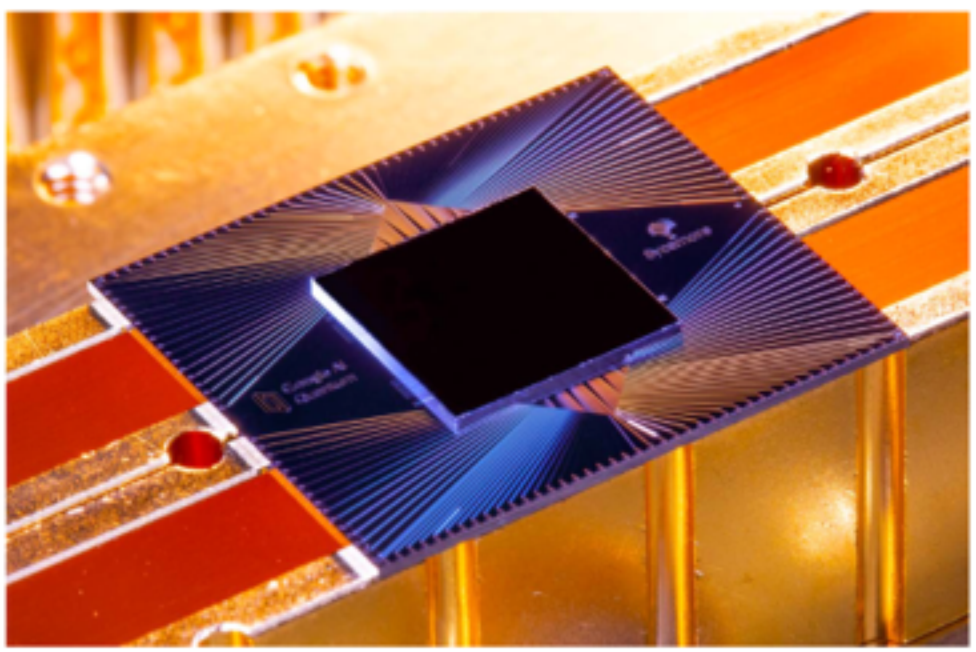
- Programmable Digital Quantum Computer
- Random Gate Operations on 53 qubits

Article [Nature 574, pages 505–510 (2019), 23 October 2019]

Quantum supremacy using a programmable superconducting processor

https://doi.org/10.1038/s41586-019-1666-5
Received: 22 July 2019
Accepted: 20 September 2019
Published online: 23 October 2019

Frank Arute[1], Kunal Arya[1], Ryan Babbush[1], Dave Bacon[1], Joseph C. Bardin[1,2], Rami Barends[1], Rupak Biswas[3], Sergio Boixo[1], Fernando G. S. L. Brandao[1,4], David A. Buell[1], Brian Burkett[1], Yu Chen[1], Zijun Chen[1], Ben Chiaro[5], Roberto Collins[1], William Courtney[1], Andrew Dunsworth[1], Edward Farhi[1], Brooks Foxen[1,5], Austin Fowler[1], Craig Gidney[1], Marissa Giustina[1], Rob Graff[1], Keith Guerin[1], Steve Habegger[1], Matthew P. Harrigan[1], Michael J. Hartmann[1,6], Alan Ho[1], Markus Hoffmann[1], Trent Huang[1], Travis S. Humble[7], Sergei V. Isakov[1], Evan Jeffrey[1],



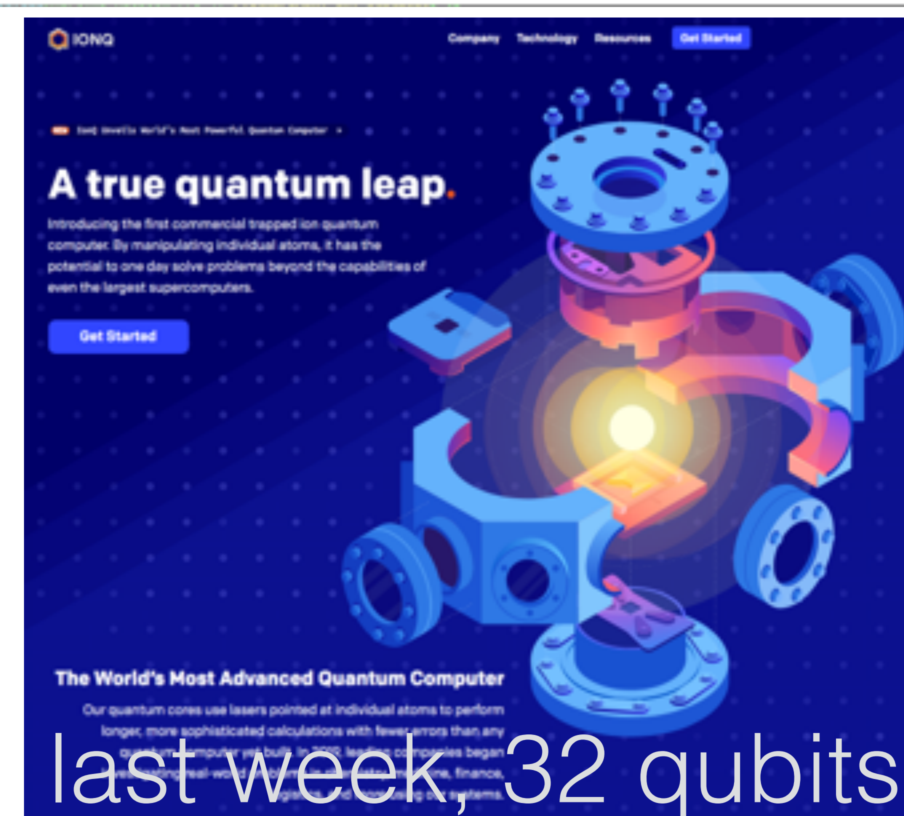
Credit: Erik Lucero/Google

In mid-September, the *Financial Times* revealed that Google was preparing to publish a scientific paper showing that it had built a 54-qubit quantum computer that could solve a maths problem in 3 minutes and 20 seconds that would take the world's fastest supercomputer around 10,000 years to solve.

IBM

IBM Research Blog Topics Labs About

October 21, 2019 | Written by: Edwin Pednault, John Gunnels



last week, 32 qubits

2020 : DOE and NSF : Funding for Quantum Centers

C²QA Co-design Center for Quantum Advantage

QUANTUM SCIENCE CENTER

QUANTUM SYSTEMS ACCELERATOR
Catalyzing the Quantum Ecosystem

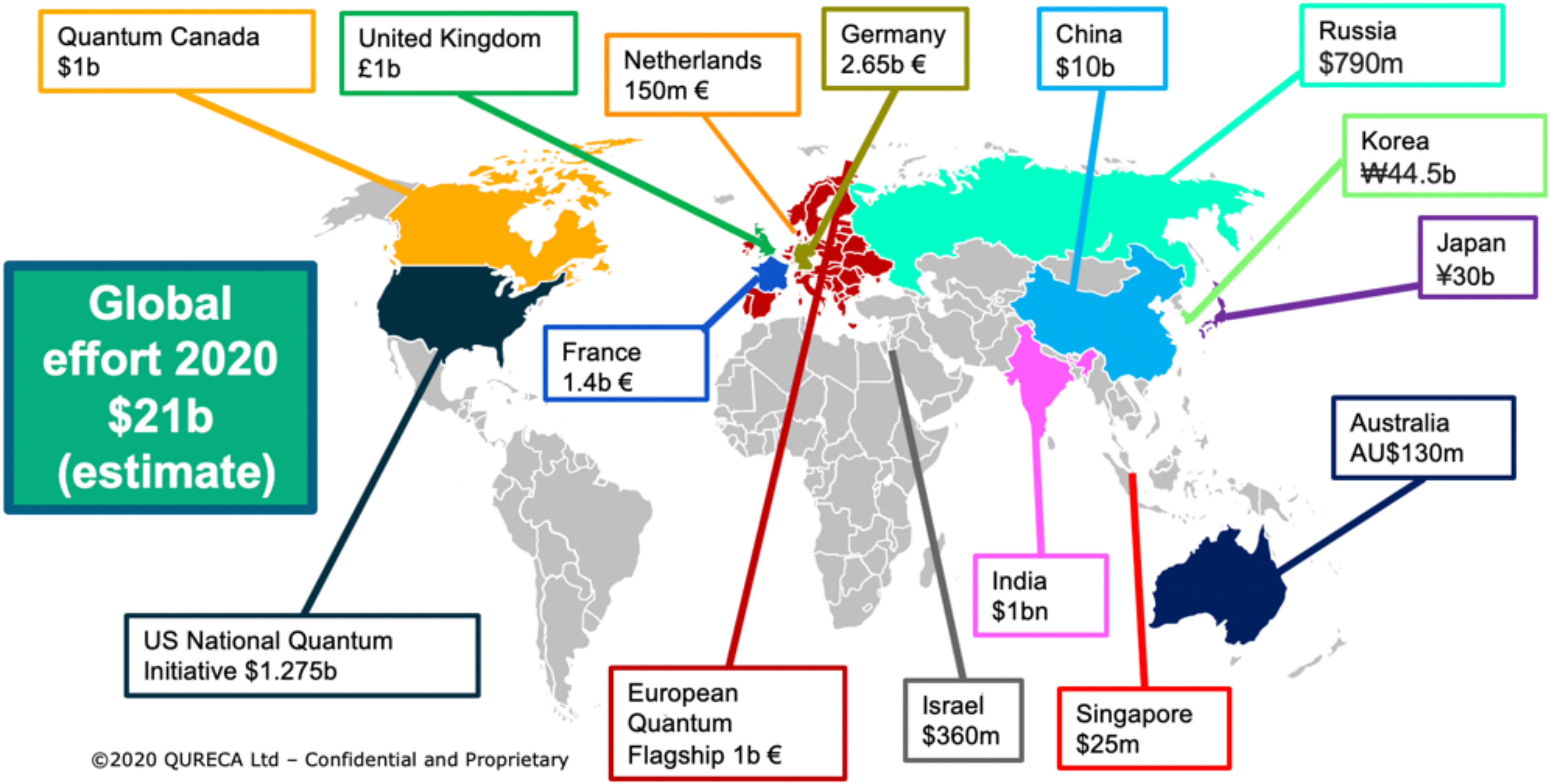
Q-NEXT
NEXT GENERATION QUANTUM SCIENCE AND ENGINEERING

Superconducting Quantum Materials and Systems Center
A national center for advancing quantum science and technology

NSF is establishing three institutes:

- NSF Quantum Leap Challenge Institute for Enhanced Sensing and Distribution Using Correlated Quantum States. Quantum sensors that can measure everything from radiation levels to the effects of gravity will be more sensitive and accurate than classical sensors. This institute, led by the University of Colorado, will design, build, and employ quantum sensing technology for a wide variety of applications in precision measurement.
- NSF Quantum Leap Challenge Institute for Hybrid Quantum Architectures and Networks. Developing more robust quantum processors is a significant challenge in quantum information science and engineering. This institute, led by the University of Illinois, Urbana-Champaign, will build interconnected networks of small-scale quantum processors and test their functionality for practical applications.
- NSF Quantum Leap Challenge Institute for Present and Future Quantum Computing. Today's quantum computing prototypes are rudimentary, error-prone, and small-scale. This institute, led by the University of California, Berkeley, plans to learn from these to design advanced, large-scale quantum computers, develop efficient algorithms for current and future quantum computing platforms, and ultimately demonstrate that quantum computers outperform even the best conceivable classical computers.

International Funding for QIS



https://www.qureca.com/overview-on-quantum-initiatives-worldwide/

CERN meets quantum technology

The CERN Quantum Technology Initiative will explore the potential of devices harnessing perplexing quantum phenomena such as entanglement to enrich and expand its challenging research programme

30 SEPTEMBER, 2020 | By Matthew Chalmers

https://home.cern/news/news/computing/cern-meets-quantum-technology

CompF6 - Themes

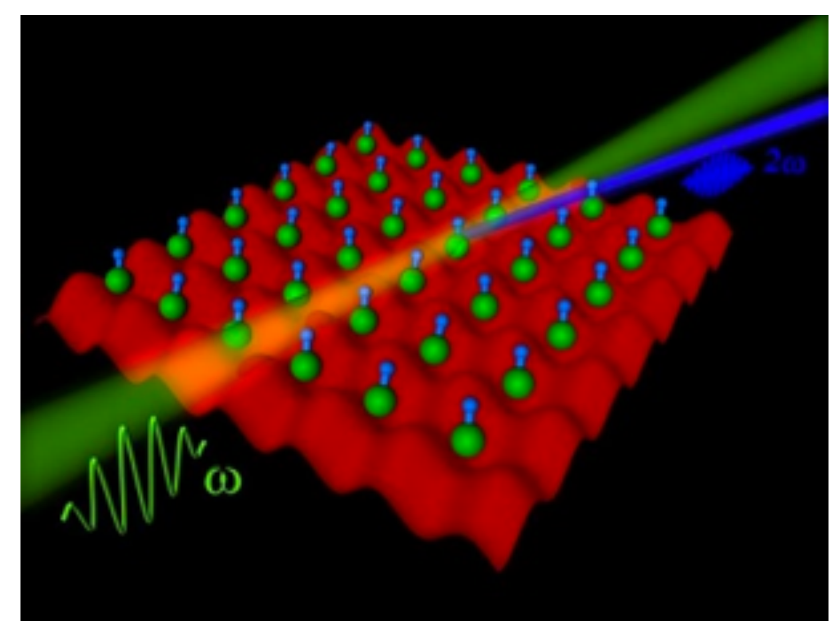
- **Applications of Quantum Computing**
  - QFT simulations
  - Particle Tracking and event reconstruction
  - Quantum machine learning
  - Tensor methods

- **Infrastructure for Quantum Computing**
  - Networks and sensors using quantum devices
  - Tools and software to enable access to infrastructure
  - Access to programmable quantum computers and simulators
  - Ethics

2017 : First Quantum Devices for Scientific Applications

rigetti

IONQ

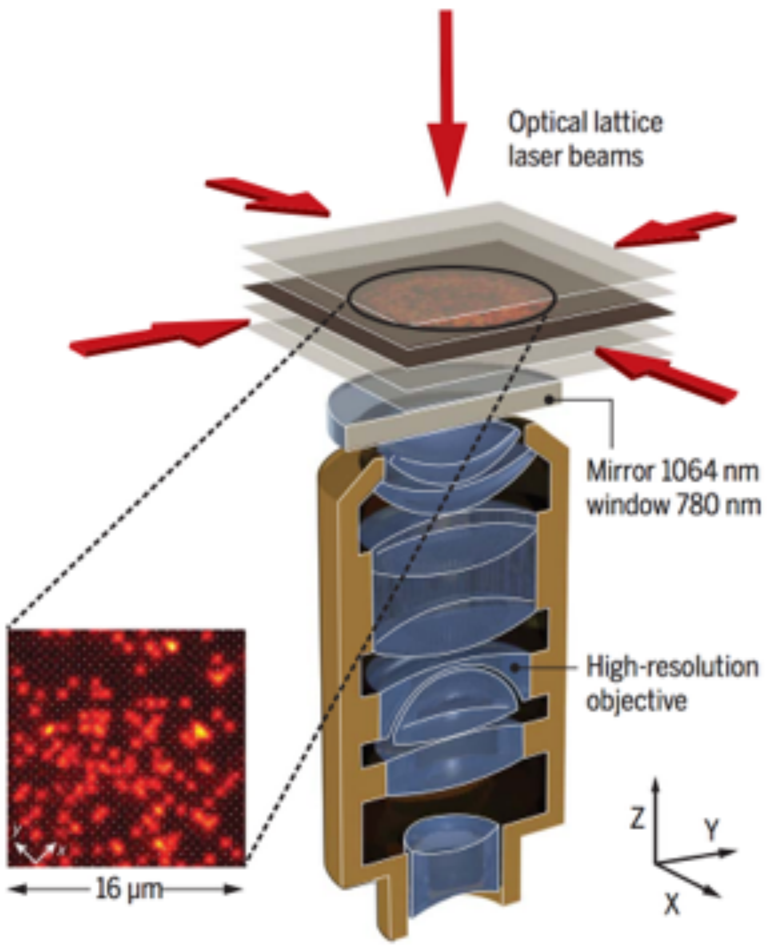


Hemmerling, Cornel, https://www.photonics.com/Article.aspx?AID=64150

NISQ-era quantum devices for applications

Analog, Digital and Hybrid Simulation

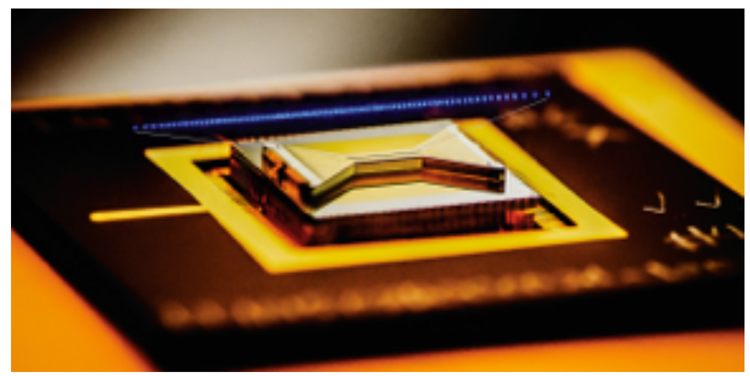
analog simulations

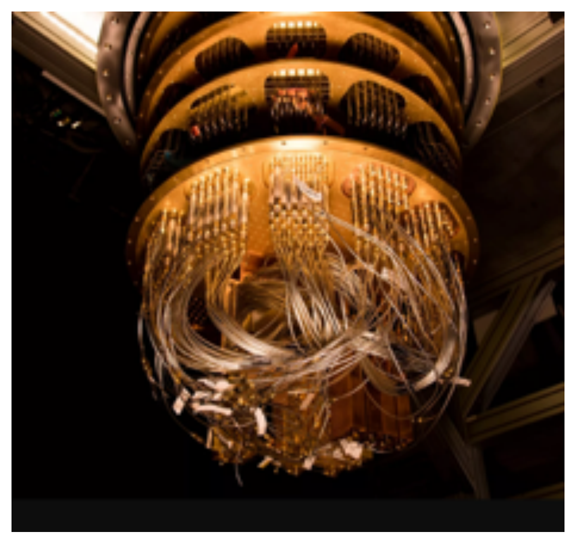


H : native to system
e.g. atoms in optical lattices
SRF cavities
BECs

systematics?

digital computations





e.g. trapped-ions,
superconducting qubits
H : universal gate sets

NISQ, a while before error-corrected

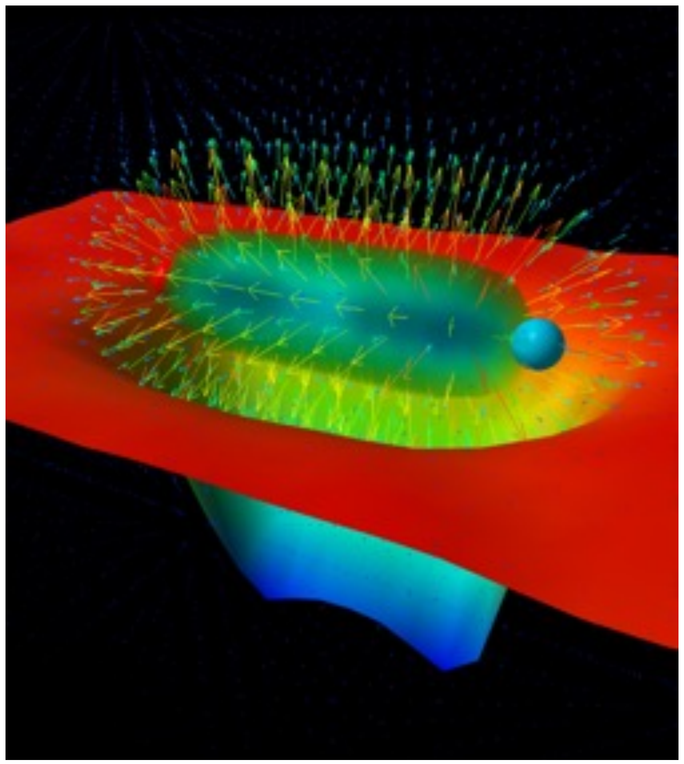
Hybrid

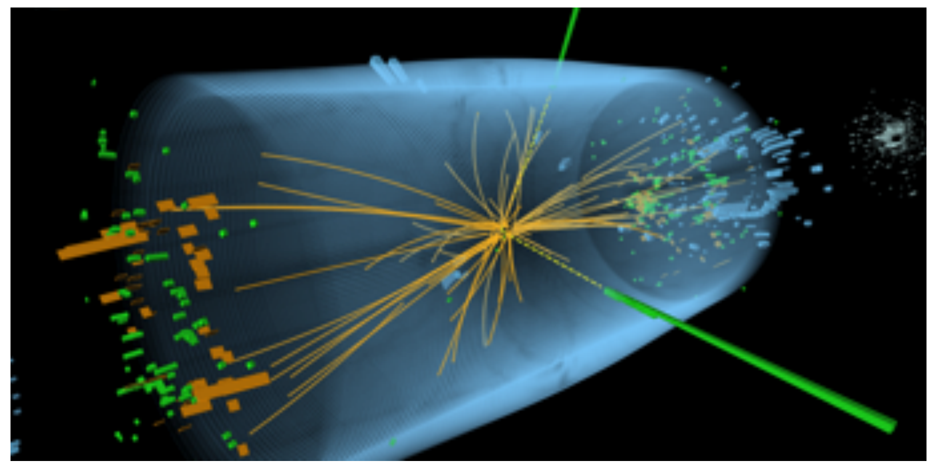
QPU “like” a GPU
for the intrinsically
quantum parts of the
computation

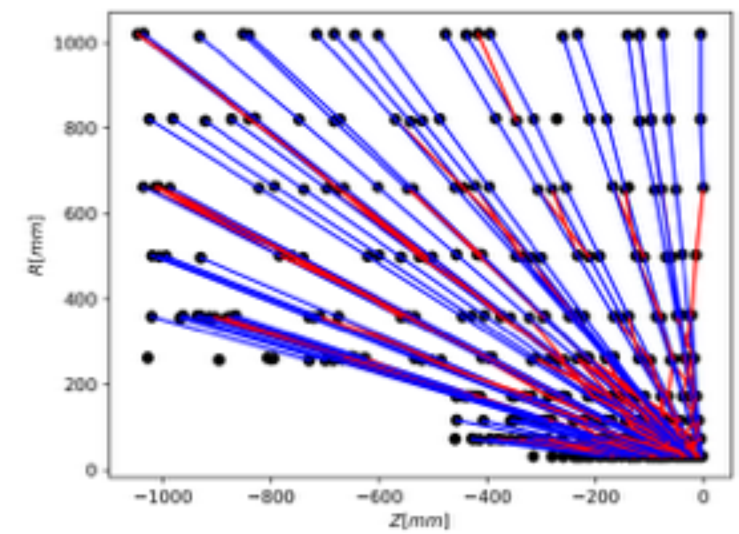
Scaling?

Jacob F. Sherson, Christof Weitenberg, Manuel Endres, Marc Cheneau, Immanuel Bloch, and Stefan Kuhr. Single-atom-resolved fluorescence imaging of an atomic Mott insulator. Nature, 467(7311):68–72, 09 2010.

Where to look for a quantum advantage - examples







Quantum Field Theories and Fundamental Symmetries

- indefinite particle number
- gauge symmetries and constraints
- entangled ground states

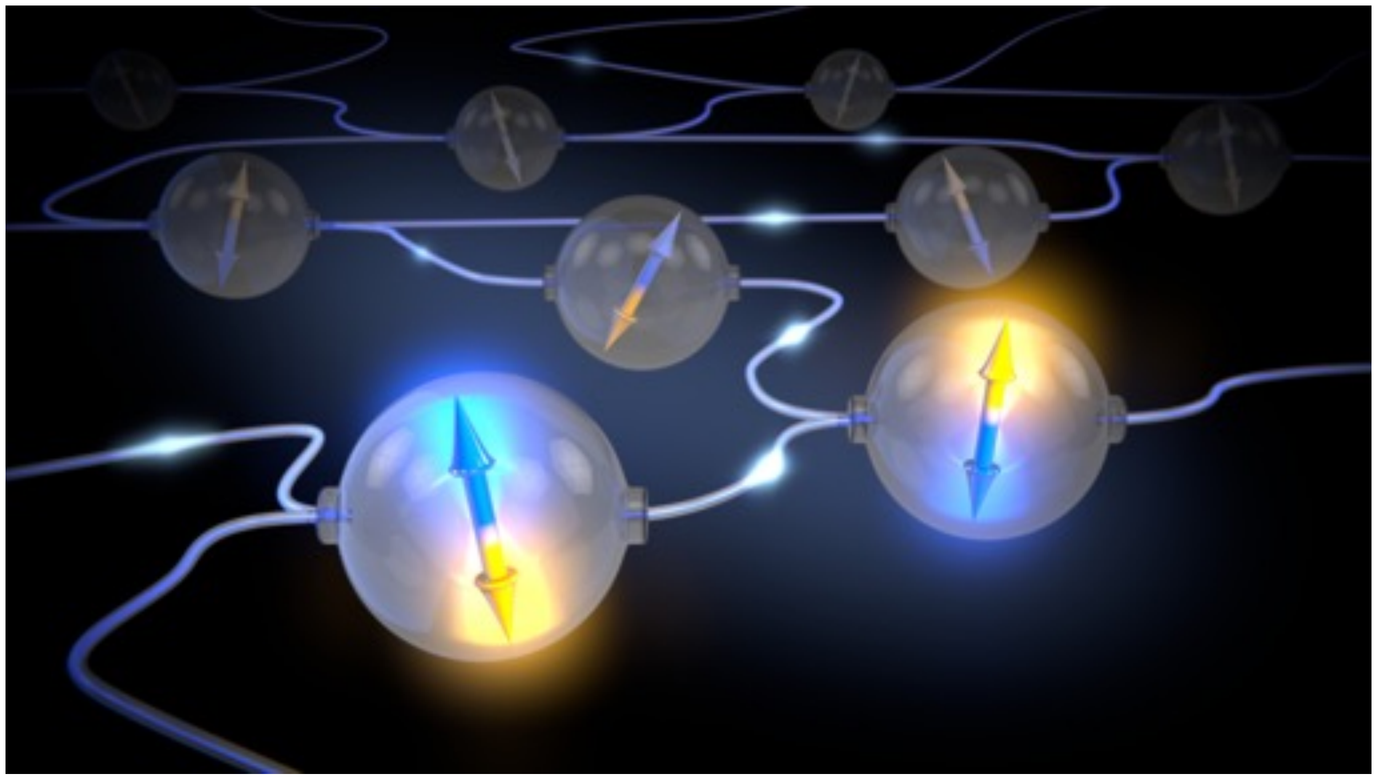
Real-Time Dynamics

- neutrino-nucleus interactions
- early universe
  - phase transitions
- parton showers
- fragmentation

Track/Event Reconstruction

- Large projected classical resource requirement for LHC
- Quantum Machine Learning

Communication, Sensing and Tools



- Network of sensors
  - entanglement used to increase sensivity
  - sqrt(N) enhancements
  - filters out uncorrelated noise
    - enhnace signal to noise

- **Entangled delocalized quantum systems**
  - quantum information transfer between quantum systems
  - quantum information processing
  - interacting with local environment (sensors)
  - delocalized quantum computers

Quantum sensors for quantum computers and networks

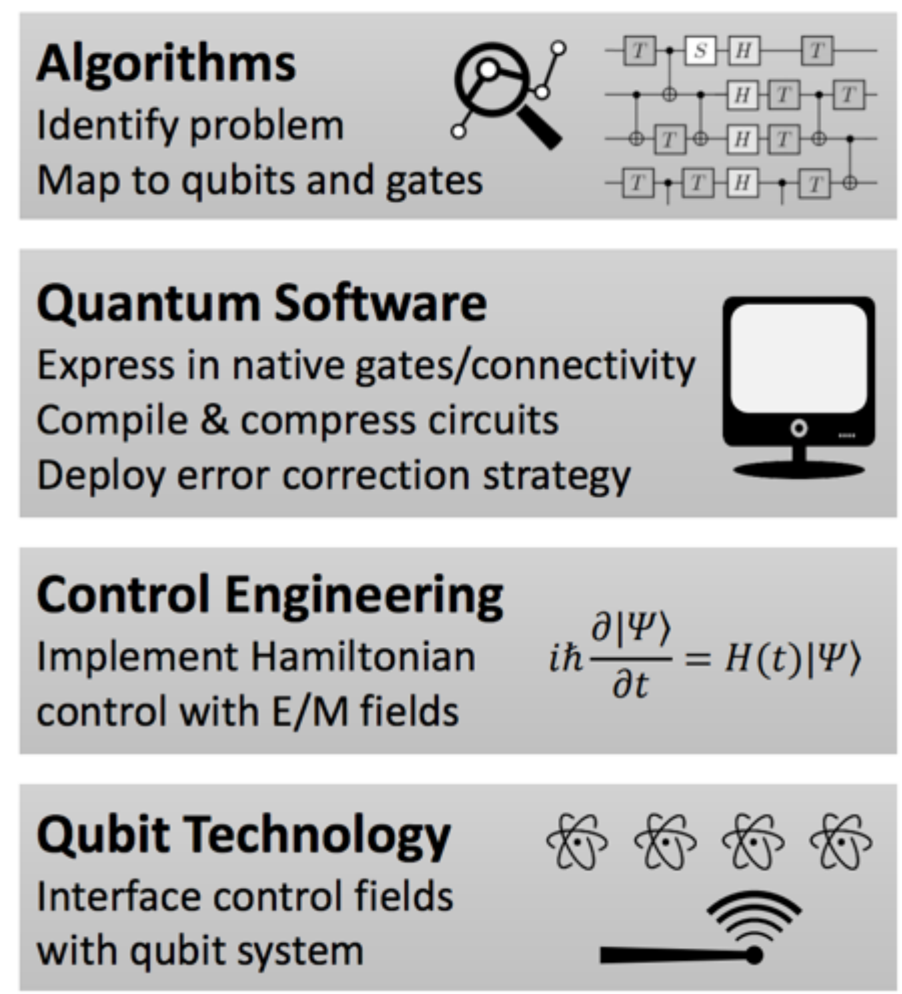
https://arxiv.org/abs/2008.06074 https://arxiv.org/abs/1803.11306

CompF6 - Required to Go Forward

- **Intersection of QFTs, Tensor Methods and QC**
  - HEP theory has a key role to play
    - algorithms, effective theories, renormalization group,…
    - error correction, mappings, topological field theories,
    - conformal theories, AdS/CFT
    - entanglement, fundamental physics

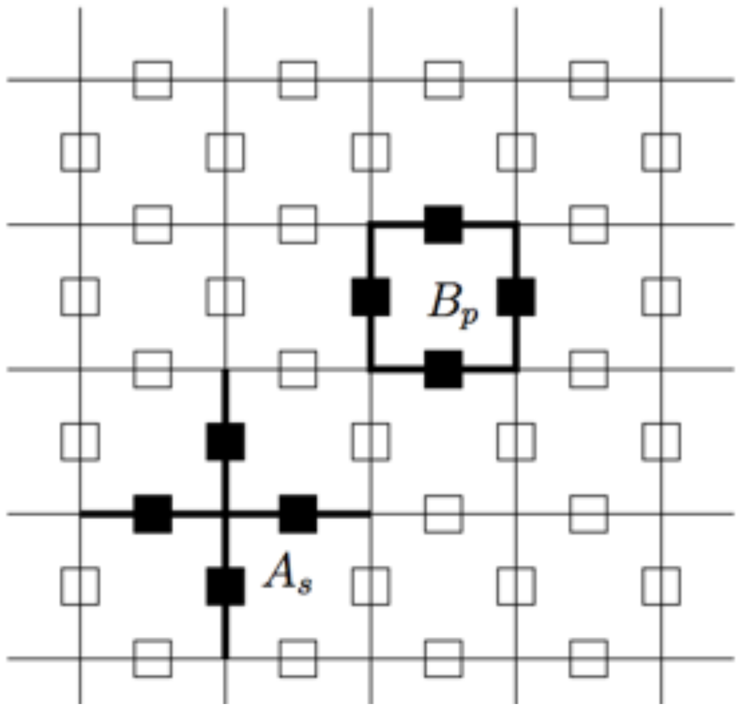
- **Partnerships**
  - essential to facilitate science-to-commodity
  - collaborations between universities, labs, tech companies
    - SciDAC-esque ?

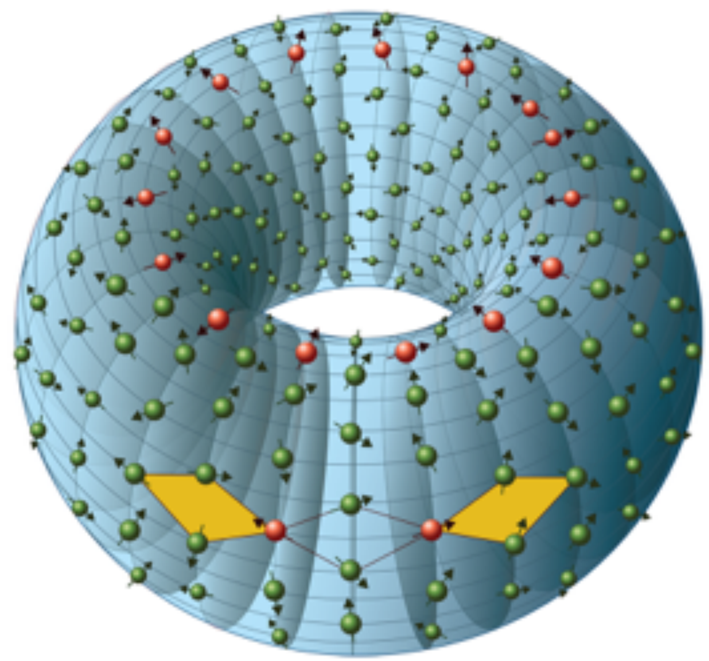
- **Workforce Development is critical**
  - enhance early career experience



Digital Simulation
Lattice Theories: Logical Qubits and Error Correction

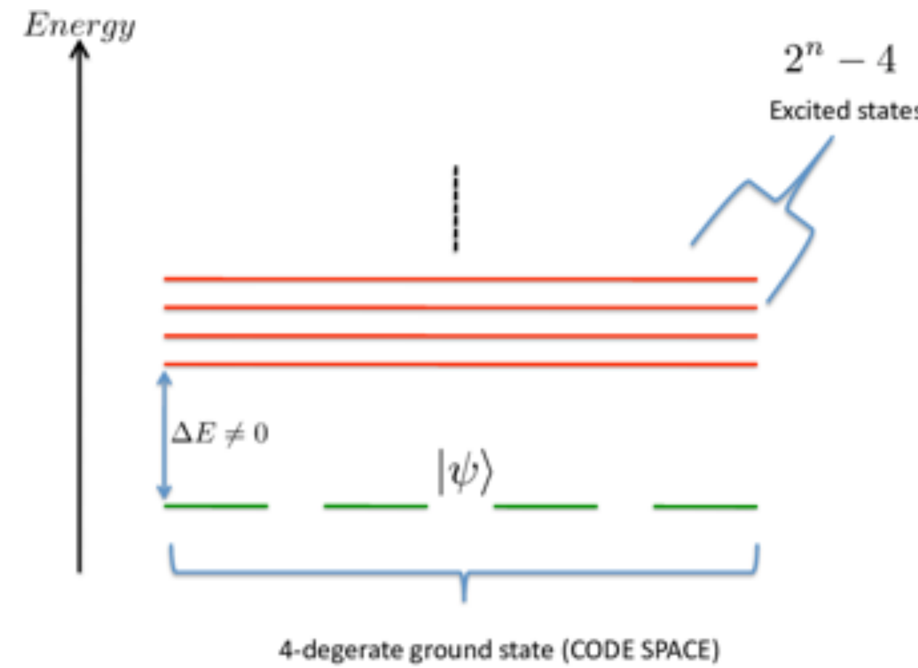
Kitaev (1997)

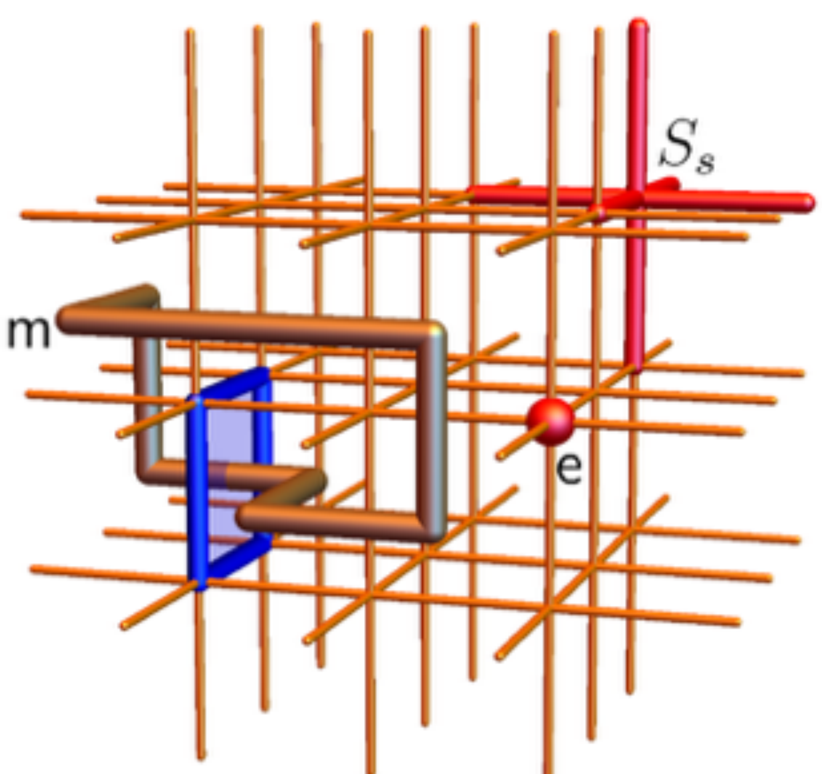




Kitaev-Laumann (2009)

$$H_T = -J_e \sum_s A_s - J_m \sum_p B_p$$





Quantum Spin Liquids: a Review

Lucile Savary[1], Leon Balents[2]

Summary

- Quantum Computing/Networks/Sensing is here
  - remarkable progress in controlling entanglement and coherence
  - simple small devices available for applications and learning

- Theoretical, experimental and computational tools within HEP will advance and be advanced by QIS
  - it is a new frontier in HEP research and in Snowmass process

Requires a deliberate process (Snowmass) to effectively integrate QIS into HEP planning to accelerate advances in QIS and HEP.

FIN

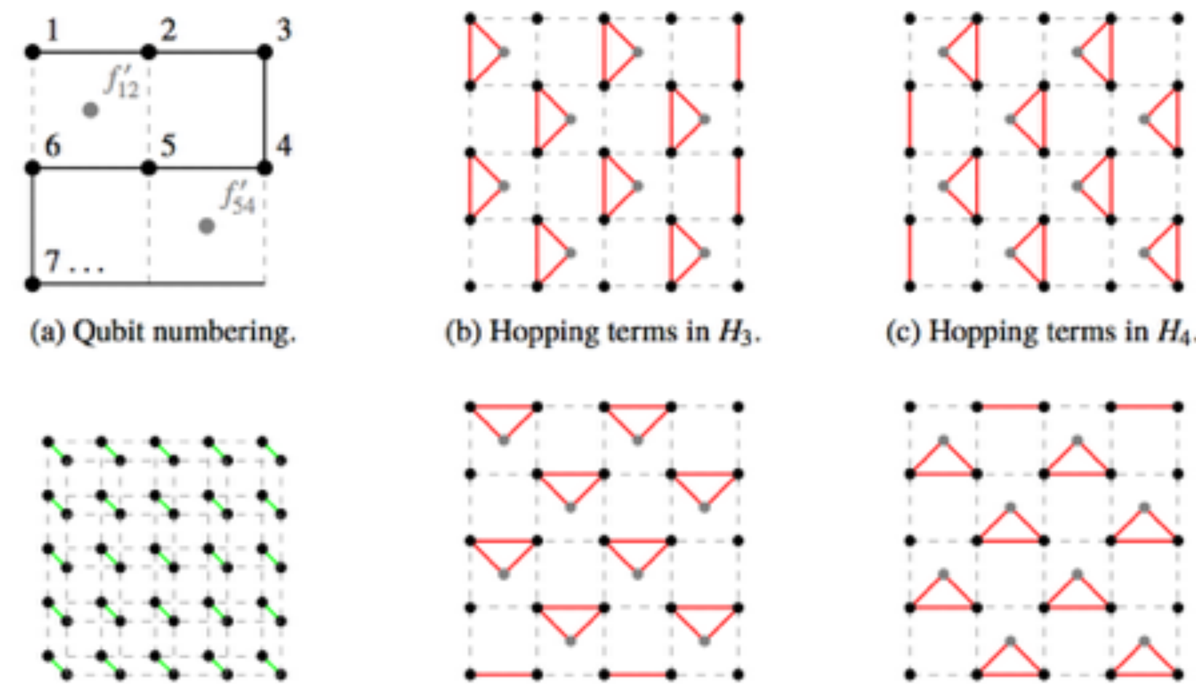
Digital Simulation
New ``Tricks"

Hamiltonian Simulation Algorithms for Near-Term Quantum Hardware

Laura Clinton*[1,2], Johannes Bausch†[1,3], and Toby Cubitt‡[1]

[1]PhaseCraft Ltd.
[2]Department of Computer Science, University College London
[3]Department of Applied Mathematics and Theoretical Physics, University of Cambridge

March 2020



(a) Qubit numbering. (b) Hopping terms in H_3. (c) Hopping terms in H_4.
(d) On-site terms in H_5. (e) Hopping terms in H_1. (f) Hopping terms in H_2.

$$H_{\mathrm{FH}} := \sum_{i=1}^{N} h^{(i)}_{\text{on-site}} + \sum_{i<j,\sigma} h^{(i,j,\sigma)}_{\text{hopping}} := u \sum_{i=1}^{N} a^\dagger_{i\uparrow} a_{i\uparrow} a^\dagger_{i\downarrow} a_{i\downarrow} + v \sum_{i<j,\sigma} \left(a^\dagger_{i\sigma} a_{j\sigma} + a^\dagger_{j\sigma} a_{i\sigma} \right).$$

$$h^{(i)}_{\text{on-site}} \to \frac{u}{4} \left(\mathbb{1} - Z_{i\uparrow}\right)\left(\mathbb{1} - Z_{i\downarrow}\right)$$

$$h^{(i,j,\sigma)}_{\text{hopping,hor}} \to \frac{v}{2} \left(X_{i,\sigma} X_{j,\sigma} Y_{f'_{ij},\sigma} + Y_{i,\sigma} Y_{j,\sigma} Y_{f'_{ij},\sigma} \right)$$

$$h^{(i,j,\sigma)}_{\text{hopping,vert}} \to \frac{v}{2} (-1)^{g(i,j)} \left(X_{i,\sigma} X_{j,\sigma} X_{f'_{ij},\sigma} + Y_{i,\sigma} Y_{j,\sigma} X_{f'_{ij},\sigma} \right),$$

Together with new Trotter product formulae error bounds, and a novel low-weight fermionic encoding, this improves upon state-of-the-art results by over three orders of magnitude in circuit-depth-equivalent.

$$e^{i\delta Z_1 Z_2 Z_3} \approx e^{-i\sqrt{\delta/2} Z_1 X_2} e^{i\sqrt{\delta/2} Y_2 Z_3} e^{i\sqrt{\delta/2} Z_1 X_2} e^{-i\sqrt{\delta/2} Y_2 Z_3},$$

$$e^{i\delta Z_1 Z_2 Z_3 Z_4} \approx e^{-i0.22\delta^{2/3} Y_2 Z_3 Z_4} e^{-i1.13\delta^{1/3} Z_1 X_2} e^{i0.44\delta^{2/3} Y_2 Z_3 Z_4} e^{i1.13\delta^{1/3} Z_1 X_2} e^{-i0.22\delta^{2/3} Y_2 Z_3 Z_4}.$$

See also, Childs *et al*
https://arxiv.org/pdf/1912.08854.pdf