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Fermilab U.S. DEPARTMENT OF ENERGY Office of Science

Quantum Computing

Elizabeth Sexton-Kennedy for James Amundson, *Fermilab, Batavia, Illinois USA*

CHEP 2018

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Introduction

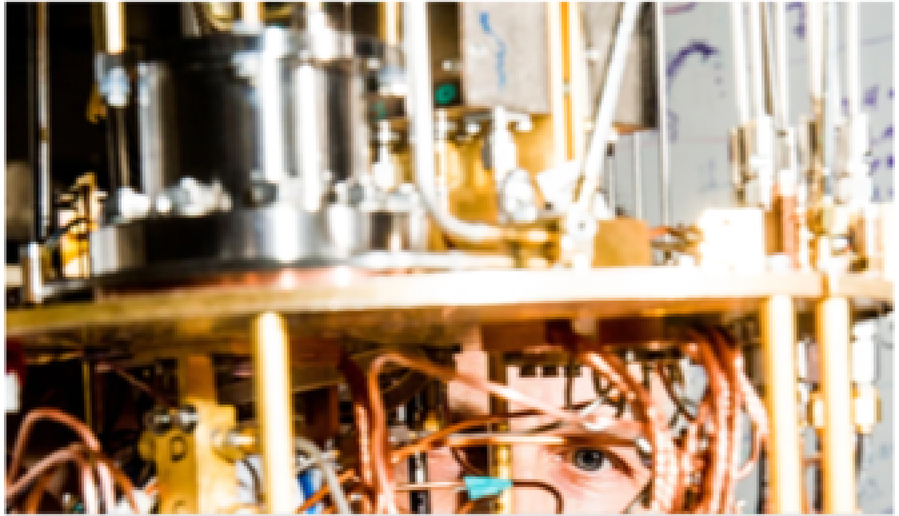
- DISCLAIMER: This is Jim's talk and unfortunately he could not be here, so I will do my best to present it.
- At the last CHEP we heard a talk about Quantum Computing from a hardware perspective.
- Jim is a software algorithm person and he will concentrate more on that.
- 20months is a long time in Quantum Information Science, QIS
- The Josephson Junction technology we heard about then has evolved as predicted and we now have "mid-range" devices available on the cloud.

Quantum Computing Excitement

Nov. 13, 2017

The New York Times

Yale Professors Race Google and IBM to the First Quantum Computer



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More Quantum Computing Excitement

October 16, 2017 THE WALL STREET JOURNAL.

Europe is not immune

ZEIT ONLINE

January 30, 2018

Suche

Politik Gesellschaft Wirtschaft Kultur Wissen Digital Campus Arbeit Entdecken Sport ZEITmagazin mehr #D18

AUS DER SERIE

Die Zumutung

Technologie

Wie funktioniert ein Quantencomputer?

Zwanzig Jahre lang waren Quantencomputer eine fixe Idee von Grundlagenforschern. Nun investieren Google, IBM und Microsoft, die EU und China, Geheimdienste und sogar Volkswagen in die mysteriöse Technologie. Warum?

Von **Max Rauner**

"For twenty years, quantum computers were a fixed idea of basic researchers. Now Google, IBM and Microsoft, the EU and China, intelligence agencies and even Volkswagen invest in the mysterious technology. Why?"

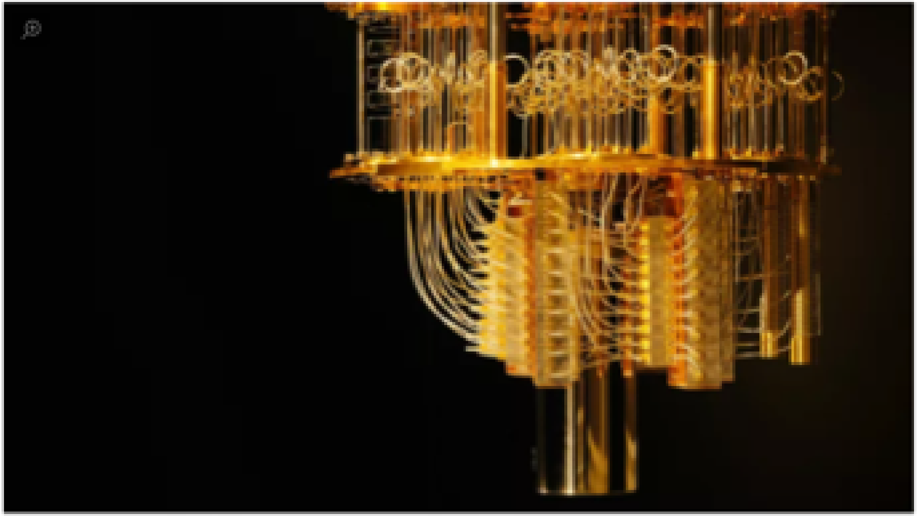
Quantum Computing Excitement Has Reached the U.S. Congress

June 8, 2018

GIZMODO

Two Quantum Computing Bills Are Coming to Congress

Ryan F. Mandelbaum
6/08/18 5:26pm · Filed to: QUANTUM COMPUTING



A dilution refrigerator from an IBM quantum computer.
Photo: IBM Research (Flickr)

…and Congress Appropriates money

At the Beginning

- Where are we on the Hype Curve?
- According to Wikipedia:

Technology Trigger: A potential technology breakthrough kicks things off. Early proof-of-concept stories and media interest trigger significant publicity. Often no usable products exist and *commercial viability is unproven.*

Hype cycle

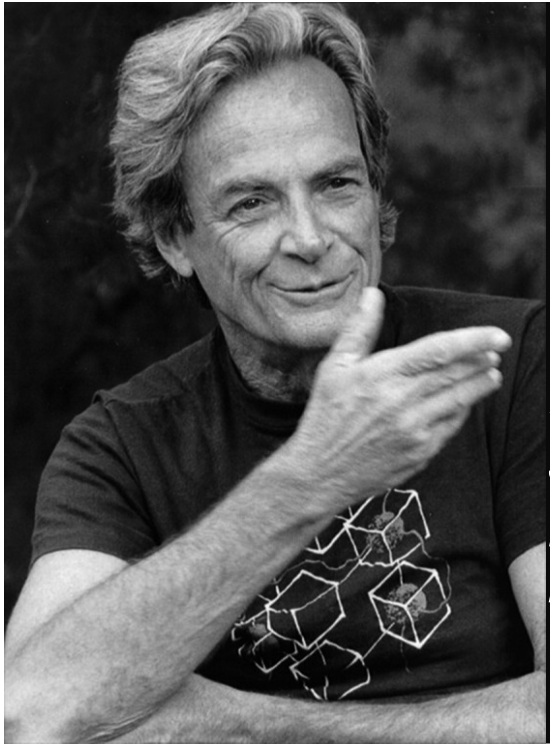
A Classical Take on Quantum Computing

Marcus Aurelius on Quantum Computing:

Anything in any way beautiful derives its beauty from itself and asks nothing beyond itself. Praise is no part of it, for nothing is made worse or better by praise.

A Quantum Take on Quantum Computing

Feynman was one of the originators of the idea…



Trying to find a computer simulation of physics seems to me to be an excellent program to follow out

. . .

the real use of it would be with quantum mechanics

. . .

Nature isn't classical . . . and if you want to make a simulation of Nature, you'd better make it quantum mechanical, and by golly it's a wonderful problem, because it doesn't look so easy.

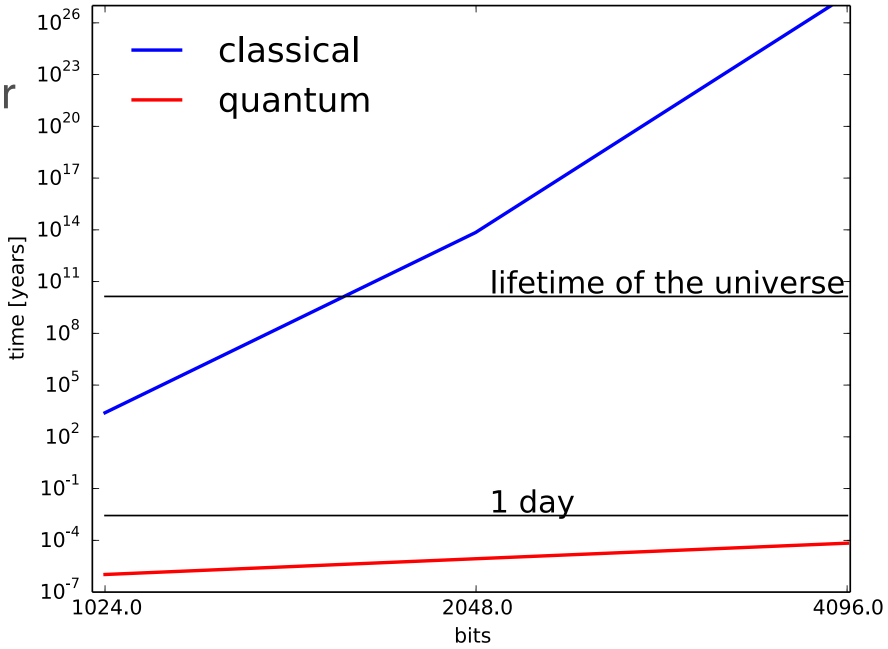
—1981

Where the Excitement Started

- Peter Shor: A general-purpose quantum computer could be used to efficiently factor large numbers
  - Shor's Algorithm (1994)
  - Resource estimates from LA-UR-97-4986 "Cryptography, Quantum Computation and Trapped Ions," Richard J. Hughes (1997)

num size	1024 bits	2048 bits	4096 bits
qubits	5124	10244	20484
gates	3×10^{10}	2×10^{11}	2×10^{12}

Analog of clock cycles in classical computing



n.b. This is an old estimate; improvements have been made in the meantime.

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Quantum Information

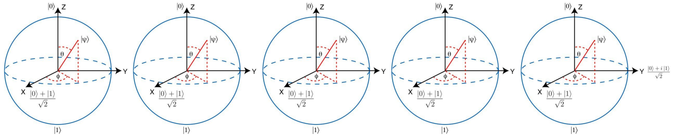
n classical 2-state systems: *n* bits of information

$b_1 \ldots b_n$

b_1 b_2 b_3 … b_n

n quantum 2-state systems: 2^n “bits” of information

$a_1 \ldots a_k$ where $k = 2^n$

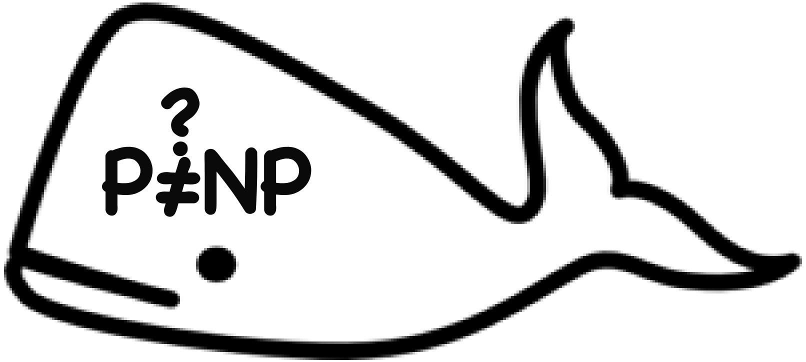


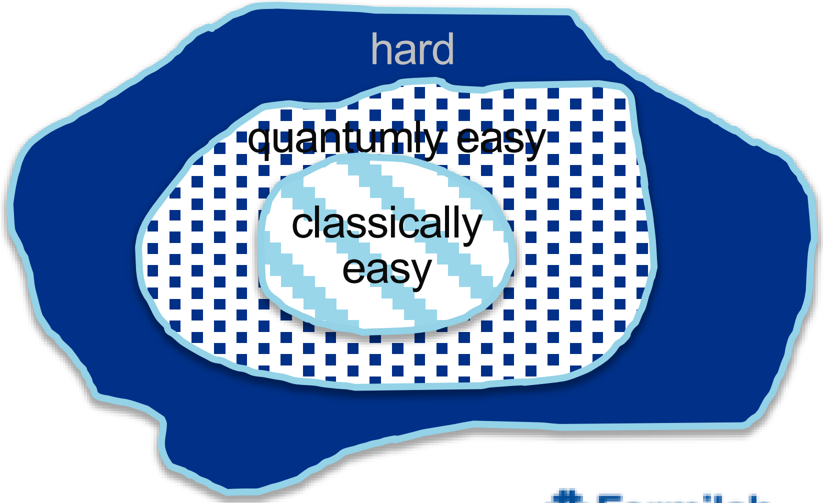
$$|\psi\rangle = a_1|0\ldots00\rangle + a_2|0\ldots01\rangle + a_3|0\ldots10\rangle + \ldots + a_k|1\ldots11\rangle$$

https://indico.cern.ch/event/587955/contributions/2935787/attachments/1683174/2707552/CHEP2018.QPR.HEP.pdf

Theoretical Computer Science

- Classical Computing
  - “Easy” problems can be solved in “polynomial time” (**P**)
  - “Hard” problems require “nondeterministic polynomial time” (**NP**)
    - Proving P ≠ NP is a great unsolved problem in computer science
- Quantum Computing
  - Some problems are easy in quantum computing, but hard in classical computing -> quantum complexity classification
  - Some problems appear to be hard either way



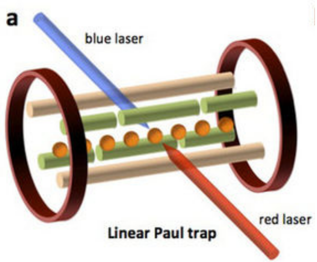


Quantum Algorithms

- Shor's Algorithm: factorization -- Speedup: Superpolynomial
- Grover's Algorithm: search -- Speedup: Polynomial
- If there exists a positive constant α such that the runtime C(n) of the best known classical algorithm and the runtime Q(n) of the quantum algorithm satisfy $C=2^{\Omega(Q\alpha))}$ then the speedup is superpolynomial, otherwise it's polynomial.
- Many more available at the Quantum Algorithm Zoo
  https://math.nist.gov/quantum/zoo/
  - **A catalog of 60 quantum Algorithms in 3 categories:**
    - **Algebraic and Number Theoretic Algorithms -> cryptography**
    - **Oracular Algorithms→ optimization and machine learning**
    - **Approximation and Simulation Algorithms -> quantum physics and chemistry**

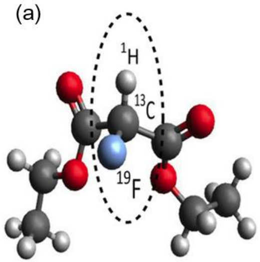
Current and Near-term Quantum Hardware

Ion trap



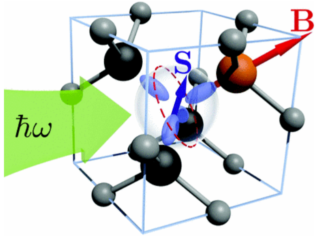
Scientific Reports 4, 3589 (2014)

NMR



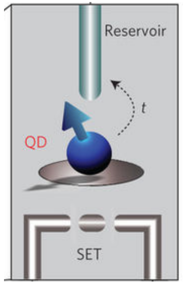
Sci. China Phys. Mech. Astron. 59:630302 (2016)

NV center



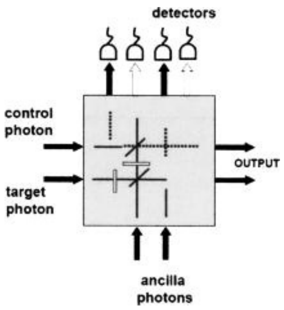
Phys. Rev. B 86, 125204 (2012)

Quantum dot



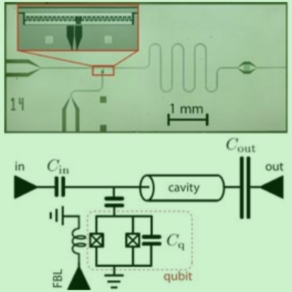
4 Nature Nanotechnology 9, 981–985 (2014)

Linear optical



J. Opt. Soc. Am. B, 24, 2, 209-213 (2007)

Superconducting



Ann. Phys. (Berlin) 525, 6, 395–412 (2013)

- Thanks to Andy Li
  - Fermilab Scientific Computing Division's first quantum computing postdoc!

… many more

- Superconducting is the most prominent commercial HW and was presented at CHEP2016

Current Commercial Quantum Computing Efforts

- Many companies have announced that they have produced small quantum computers in the 5-72 qubit range
  - Google, IBM, Intel, Rigetti ← use superconducting Josephson Junction technology
  - IonQ ← use ion traps
  - Other companies…
  - Academic efforts…
  - D-Wave
    - Quantum Annealing machine
      - Subject of a much longer talk
- At 2016 CHEP we heard how a 3 Qbit system was used to solve a Quantum Chemistry problem. Growth in size is as predicted.

Counting Qubits is Only the Beginning

- The number of gates that can be applied before losing quantum coherence is the limiting factor for most applications
  - Current estimates run few – thousand
  - Not all gates are the same
    - The real world is complicated
- IBM has a paper proposing a definition of "Quantum Volume"
  - Everyone else seems to dislike the particular definition
  - The machines with the largest number of qubits are unlikely to have the largest quantum volume

From the earlier factoring estimate

num bits	1024 bits	2048 bits	4096 bits
qubits	5124	10244	20484
gates	$3x10^{10}$	$2x10^{11}$	$2x10^{12}$

- "Logical qubits" incorporating error correction are the goal
  - Probably require ~1000 qubits per logical qubit
    - Minimum fidelity for constituent qubits is the current goalpost

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Fermilab Quantum Efforts

- Fermilab has a mixture of on-going and proposed work in quantum computing in four areas:
  - Quantum Computing for Fermilab Science
  - HEP Technology for Quantum Computing
  - Quantum Technology for HEP Experiments
  - Quantum Networking

Quantum Computing for Fermilab Science

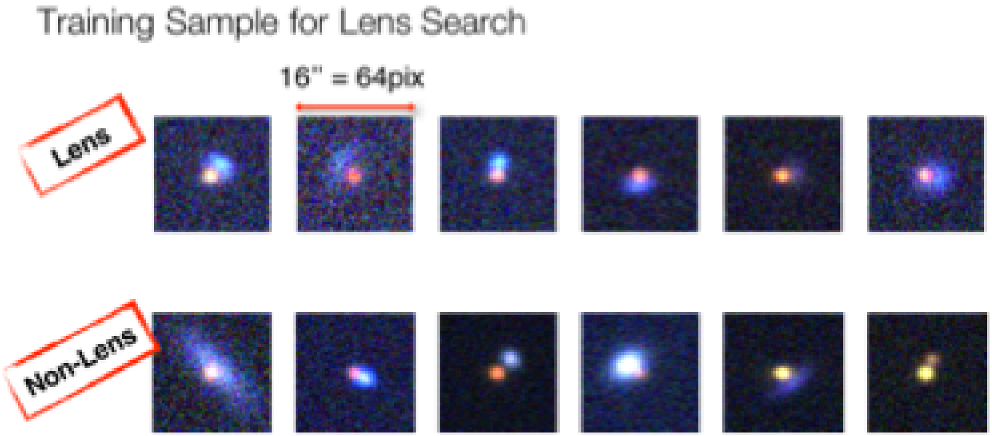
- Quantum Computing will require the sort of infrastructure Fermilab already provides for classical computing
  - HEPCloud will extend to Quantum Computing
  - On-going testbed effort in collaboration with Google
    - Partially funded by Fermilab LDRD
- Three promising areas for quantum applications in the HEP realm
  - Optimization
    - Area under active investigation in the quantum world
    - NP-hard problems
    - Quantum Approximate Optimization Algorithm (QAOA)
      - Farhi, Goldstone and Gutmann xarg
      - proposed for finding approximate solutions to combinatorial optimization problems.
  - Machine Learning
    - Computationally intensive
    - Also under active investigation in the quantum world
  - Quantum Simulation
    - Good reason to believe that quantum systems should be well-suited to quantum computation

Fermilab Quantum Application Efforts

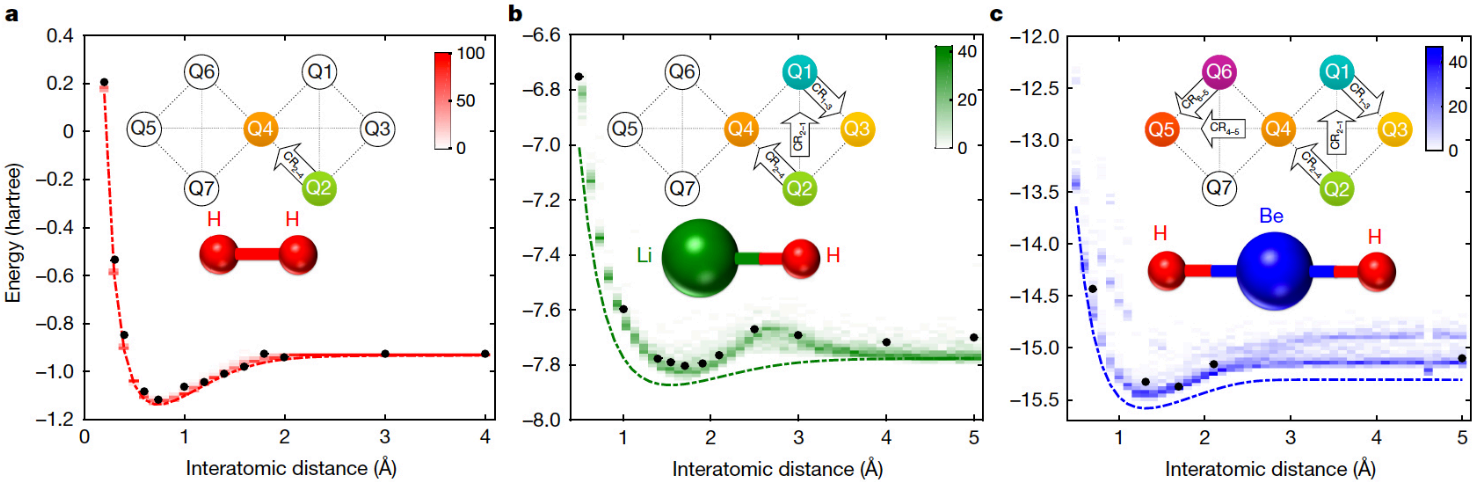
- Quantum Optimization and Machine Learning
  - Proposed work by Gabe Perdue, et al.
- Quantum Information Science for Applied Quantum Field Theory
  - Marcela Carena, et al., including JFA (Amundson)
  - Scientific Computing Division/Theory Department collaboration
    - FNAL: James Amundson, Walter Giele, Roni Harnik, Kiel Howe, Ciaran Hughes, Joshua Isaacson, Andreas Kronfeld, Alexandru Macridin, Stefan Prestel, James Simone, Panagiotis Spentzouris, Dan Carney (U. Maryland/FNAL)
    - Also includes University of Washington (David Kaplan and Martin Savage) and California Institute of Technology (John Preskill)
  - First effort from Fermilab: Digital quantum computation of fermion-boson interacting systems

Quantum Optimization and Machine Learning

- Partnering with Lockheed Martin to bring quantum computing to bear on a machine learning project in astrophysics.
- Several exploratory projects leveraging a D-wave annealer: star / galaxy classification, anomaly detection, and autoencoders (possibly for compression or simulation).
- Large focus on exploring data representations (flexible resolution requirements, and multiple sorts of data available for each object), matching data representation to hardware, and building workflows.
- Astrophysics chosen over some other domains (e.g. neutrino physics) because we have scientifically interesting data that is low enough in dimensionality to be compatible with modern quantum hardware.
- Gabe Perdue and Brian Nord



Successful Quantum Simulation



- Quantum Chemistry has the first big successes in quantum simulation.
- GitHub has a project for general simulations of interacting fermions.
- However, interesting HEP systems, e.g., QCD, also require boson-fermion interactions.

OpenFermion

https://github.com/quantumlib/OpenFermion

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Digital quantum computation of fermion-boson interacting systems

- Previous encoding schemes for bosons on quantum computers had errors of O($n_{occupation}/n_{qubits}$)
- Alexandru Macridin, Panagiotis Spentzouris, James Amundson, Roni Harnik
  - Digital quantum computation of fermion-boson interacting systems
    - [arXiv:1805.09928]
    - Accurate and efficient simulation of fermion-boson systems; *simple enough for use on near-term hardware*
  - Electron-Phonon Systems on a Universal Quantum Computer
    - [arXiv:1802.07347]
    - First application was to polarons – electron dressed by phonons. Cross-disciplinary interest.

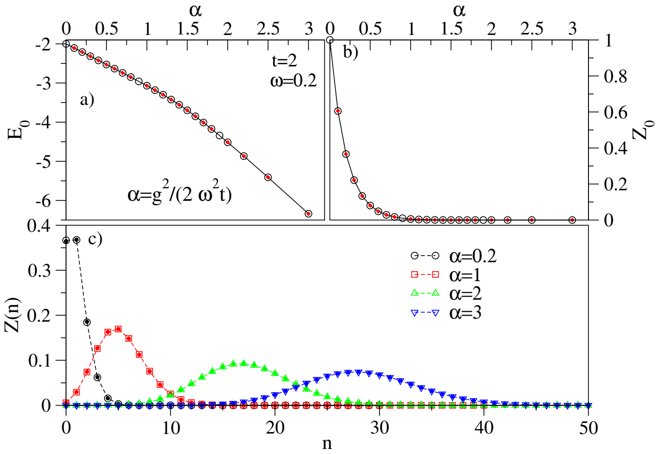


FIG. 4. $n_x = 6$ qubits per HO. The energy (a) and quasiparticle weight (b) for the 2-site Holstein polaron versus coupling strength. (c) The phonon number distribution for different couplings. The open (full) symbols are computed using exact diagonalization (QPE algorithm on a quantum simulator).

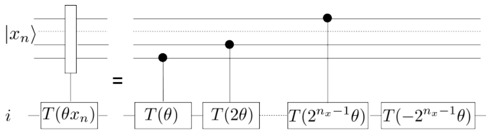
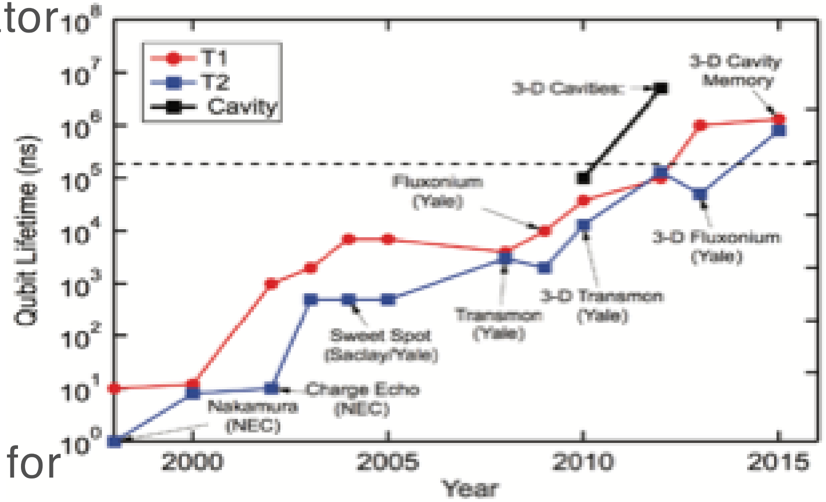


FIG. 3. Circuit for $\exp(-i\theta c_i^\dagger c_i \tilde{X}_n)|i\rangle \otimes |x_n\rangle$. The phase shift angle is $\theta(x_n - N_x/2) = \theta \sum_{r=0}^{n_x-1} x_n^r 2^r - \theta 2^{n_x-1}$, where $\{x_n^r\}_{r=\overline{0,n_x-1}}$ take binary values.

HEP Technology for Quantum Computing

SRF resonators

- Ultra-High Q Superconducting Accelerator Cavities for Orders of Magnitude Improvement in Qubit Coherence
  – Alex Romanenko, et al.



- Novel Cold Instrumentation Electronics for Quantum Information Systems
  – Davide Braga, et al.

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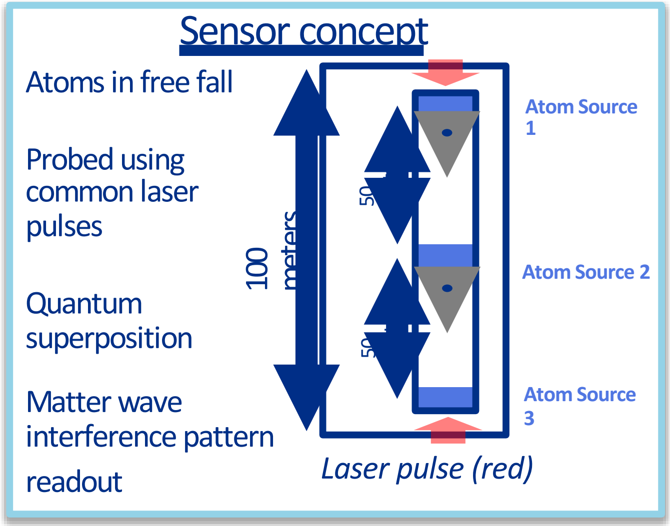
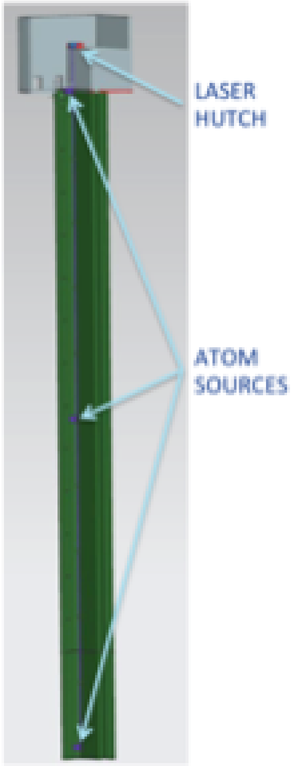
Quantum Technology for HEP Experiments

- Matter-wave Atomic Gradiometer Interferometric Sensor (MAGIS-100)
  - Robert Plunkett, et al.
- Skipper-CCD: new single photon sensor for quantum imaging
  - Juan Estrada, et al.
- Quantum Metrology Techniques for Axion Dark Matter Detection
  - Aaron Chou, et al.





CAD model of detector in 100-meter MINOS shaft)

https://indico.cern.ch/event/686555/contributions/2977589/attachments/1681093/2700822/magis-100-ICHEP_2018.pdf

Quantum Networking

- Quantum Networking is outside the scope of this talk
  - We are working on it at Fermilab, in collaboration with the California Institute of Technology
  - Quantum Communication Channels for Fundamental Physics
    - Maria Spiropulu, et al. (California Institute of Technology)

Conclusions

- Quantum computing holds the promise of remarkable new computational capabilities
  - The future is not here yet
    - … but we are getting there
- Fermilab has quantum computing efforts on many fronts
  - Quantum Applications
  - HEP technology for QC
  - QC technology for HEP experiments
  - Quantum Networking

https://www.smbc-comics.com/comic/the-talk-3

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