

Near-term Applications of Quantum Computing

6-7 December 2017
Fermilab - Wilson Hall
US/Central timezone

Confirmed Speakers

Timetable (with presentation material)

Registration

... [Registration Form](#)

[Participant List](#)

[Accommodations](#)

[General Information](#)

[Wilson Hall](#)

This meeting will bring together a small group of experts in high energy physics and quantum computing. The focus is to identify problems and algorithms that are expected to be feasible on quantum computing systems in the near term.

In particular, we hope to:

- discuss how different disciplines have cast their problems of interest into a form amenable to quantum computing
- discuss the complexity of problems that have been addressed with state-of-the-art quantum architectures
- learn how quantum computing ties into the HEP computing model, and how existing code frameworks, languages and toolkits could be leveraged for HEP computing
- understand how current challenges in HEP computing / calculations (machine learning, dynamics of strongly interacting field theories and scattering amplitudes, experimental event reconstruction bottlenecks) could benefit from quantum algorithms and architectures, and how HEP could provide benchmark problems for quantum computers.

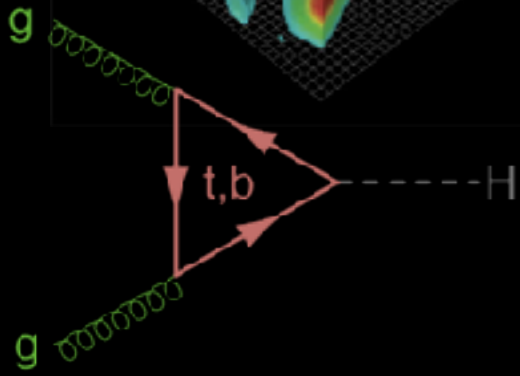
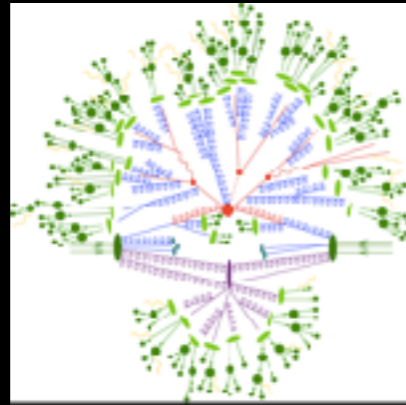
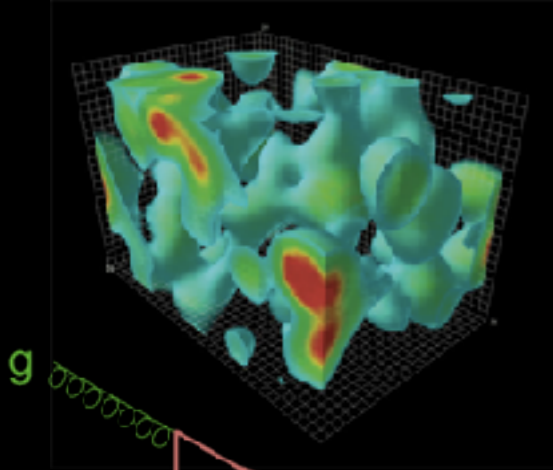
Summary Report

Kiel Howe, Fermilab, 3/5/18 for Jefferson Lab Computing Round Table

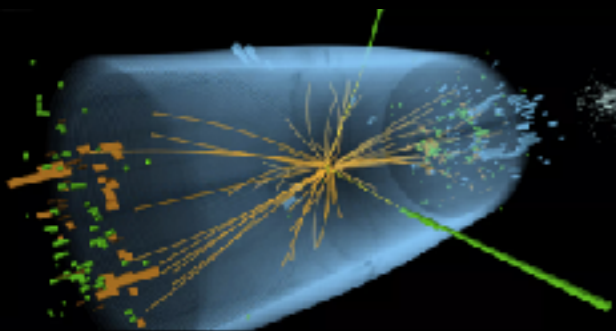
On behalf of the workshop organizers (Walter Giele, Stefan Prestel, James Simone, Marcela Carena, Joseph Lykken, K.H.)

Fermilab Theory

Finding the predictions of field theories (SM and Beyond)



*backgrounds,
new searches,
new experiments*

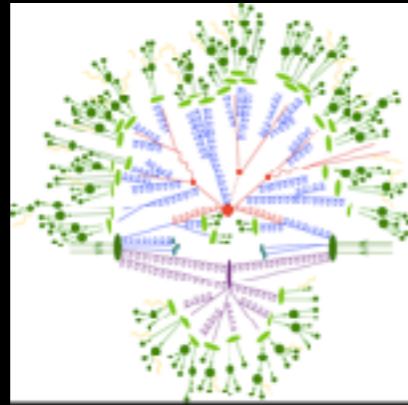
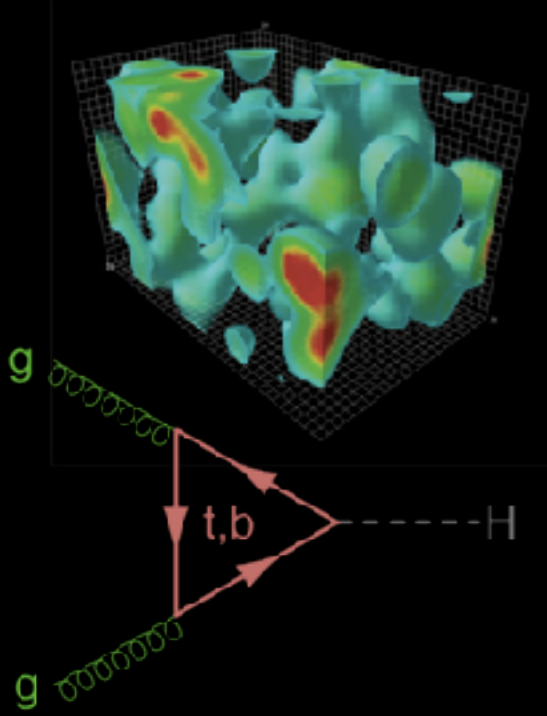


*experiments on
the universe*

Fermilab Theory

QUANTUM

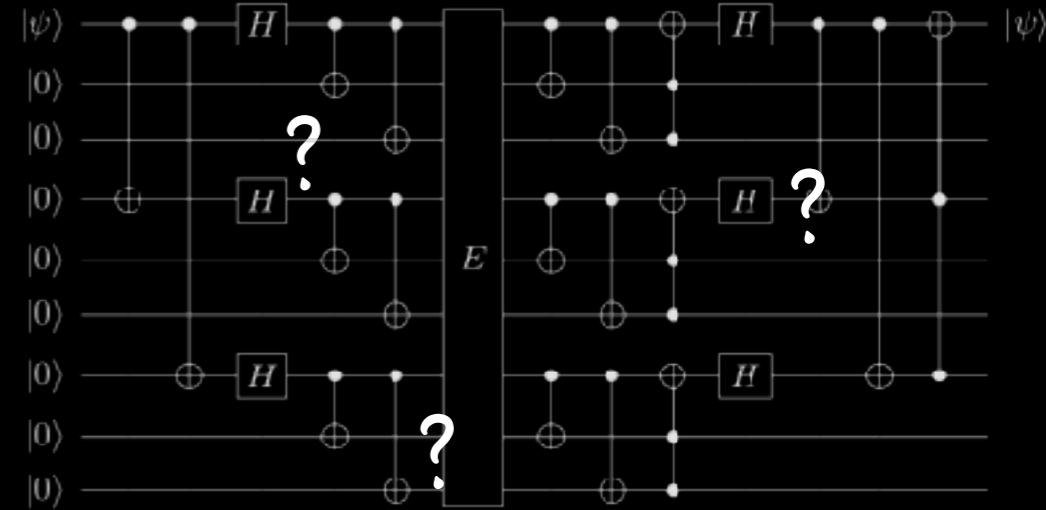
Finding the predictions of field theories (SM and Beyond)



Quantum Gravity?
new BSM?



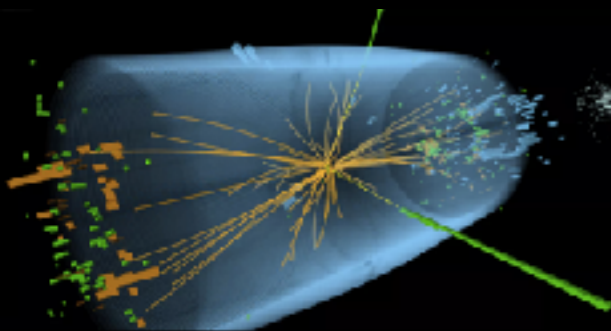
Mapping field theories (SM and Beyond) to controllable finite quantum systems



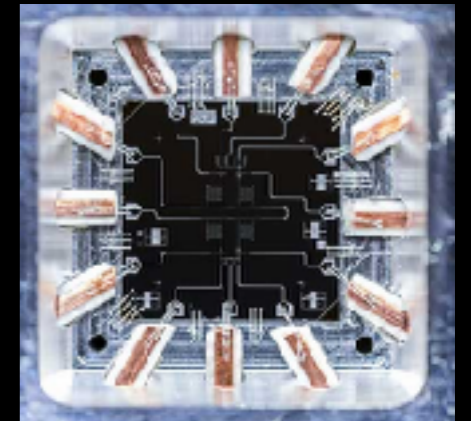
new algorithms?
backgrounds,
new searches,
new experiments



new algorithms?
new architectures?



Quantum Sensors?



experiments on
the universe

experiments on
quantum hardware

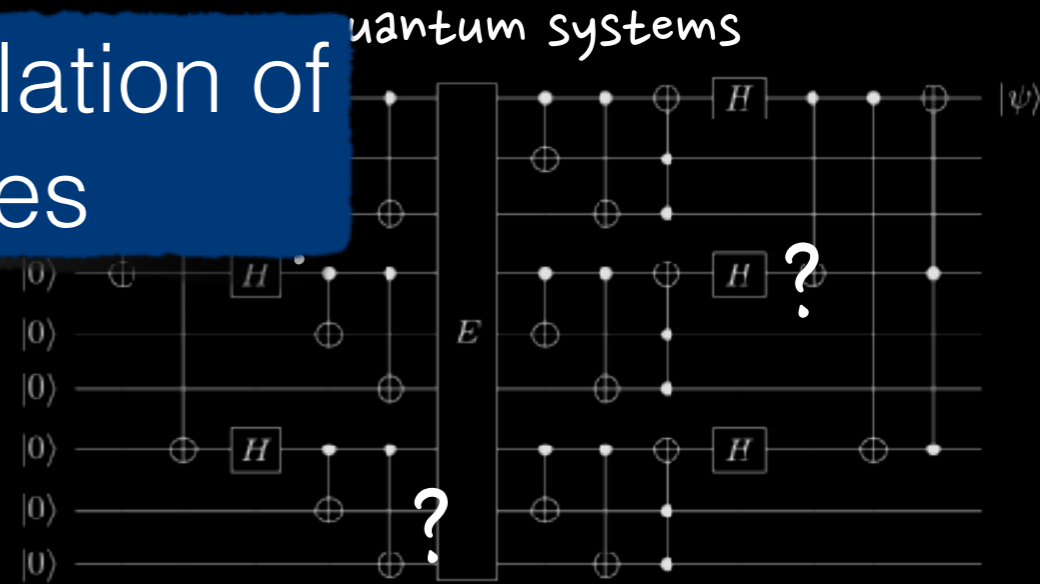
Fermilab Theory

QUANTUM

Finding the predictions of field theories (SM and Beyond)

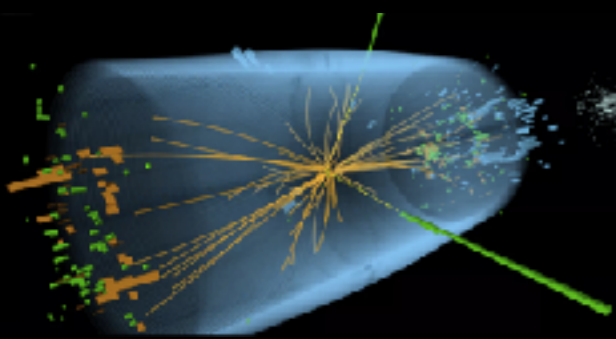
Mapping field theories (SM and Beyond) to controllable finite quantum systems

1) Quantum Simulation of Field Theories



2) Optimization problems on quantum annealers

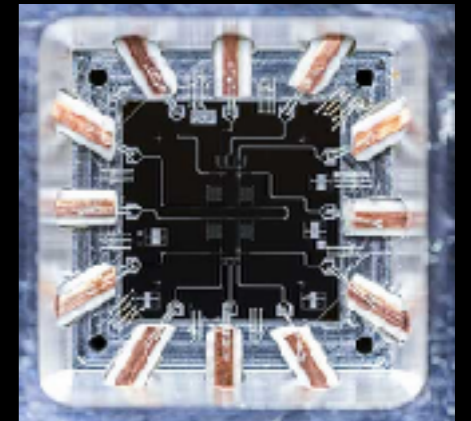
3) Quantum Algorithm Development Stack



Quantum Sensors?



4) Fermilab Quantum Computing Testbed




experiments on the universe

experiments on quantum hardware

Quantum Simulations of Field Theory...

Simulating Quantum Field Theories on a Quantum Computer

Stephen Jordan

NIST  UNIVERSITY OF MARYLAND

<https://indico.fnal.gov/event/15222/contribution/11>

universal quantum computer

Quantum Simulation of Abelian and non-Abelian Gauge Theories

Uwe-Jens Wiese

Albert Einstein Center for Fundamental Physics
Institute for Theoretical Physics, Bern University

Near-Term Applications of Quantum Computation
Fermilab
December 6-7, 2017





<https://indico.fnal.gov/event/15222/contribution/12>

analog quantum simulators


Quantum Simulating Lattice Gauge Theories with Optical Lattices

Yannick Meurice

University of Iowa

Work done with Philipp Preiss (Heidelberg), Shan-Wen Tsai (UCR), Judah Unmuth-Yockey (U. Iowa/Syracuse), Li-Ping Yang (Chongqing U.) and Jin Zhang (UCR)

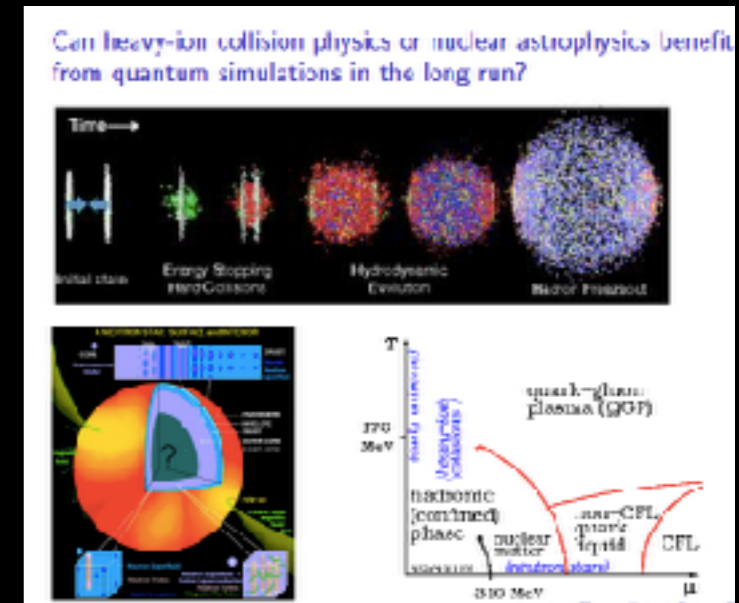
Near-term Applications of Quantum Computing
Fermilab, November 7, 2017



<https://indico.fnal.gov/event/15222/contribution/13>

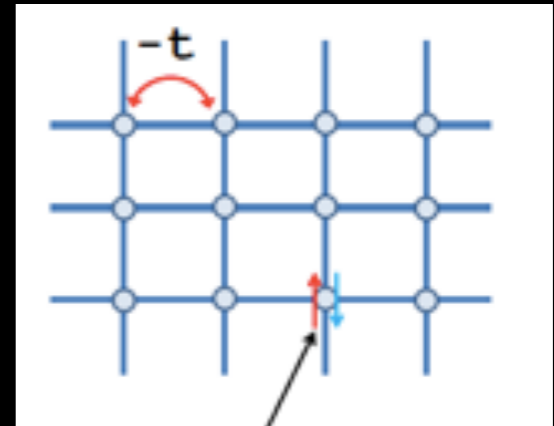
Quantum Advantage

- Fermionic Sign problem ~~Lattice QCD~~
- Chemical potential (finite-density)
- Real-time Processes (scattering, hadronization, fragmentation [jlab 12]...)
- Strong Coupling ~~Perturbative Methods~~



...and disadvantage

- Space(time) Latticization (same as lattice QCD)
 - analog = continuous time (optical lattice)
 - digital = discrete steps (gates / pulses)
- Field/particle number space discretization
 - Quantum Link Models (Wiese),
 - Spin Truncation (Meurice),
 - Discrete Field Space (Jordan)



LHC in a Quantum Computer

A QFT Computational Problem

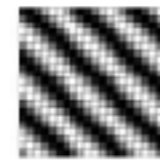
Input: a list of momenta of incoming particles.

Output: a list of momenta of outgoing particles.



Representing Quantum Fields

A field is a list of values, one for each location in space.



A quantum field is a superposition over classical fields.

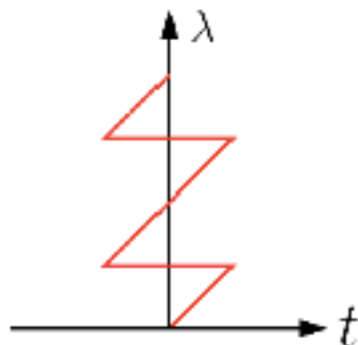
$$\frac{1}{\sqrt{2}} \left| \begin{array}{c} \text{diagonal stripes} \\ \text{diagonal stripes} \end{array} \right\rangle - \frac{i}{\sqrt{2}} \left| \begin{array}{c} \text{diagonal stripes} \\ \text{diagonal stripes} \end{array} \right\rangle$$

A superposition over bit strings is a state of a quantum computer.

Adiabatic State Preparation

Solution: intersperse backward time evolutions with time-independent Hamiltonians.

This winds back dynamical phase on each eigenstate without undoing adiabatic change of basis.



Simulating Detectors

- Measure energy in localized regions:



- Need smooth envelope function to avoid excessive vacuum noise!

$$H_f = \sum_{\mathbf{x}} f(\mathbf{x}) \mathcal{H}(\mathbf{x})$$

Quantum Info
inspired detectors
-> See Dan Carney's Talk
<https://indico.fnal.gov/event/15222/contribution/10>

Near-term? variation eigensolver & MERA

Optical Lattice



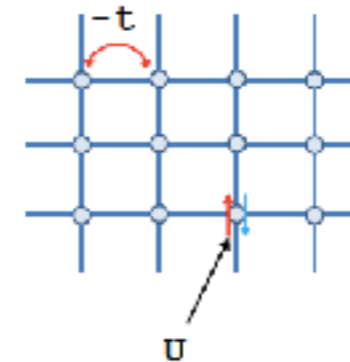
Meurice - Bloch Group

The Bose-Hubbard model

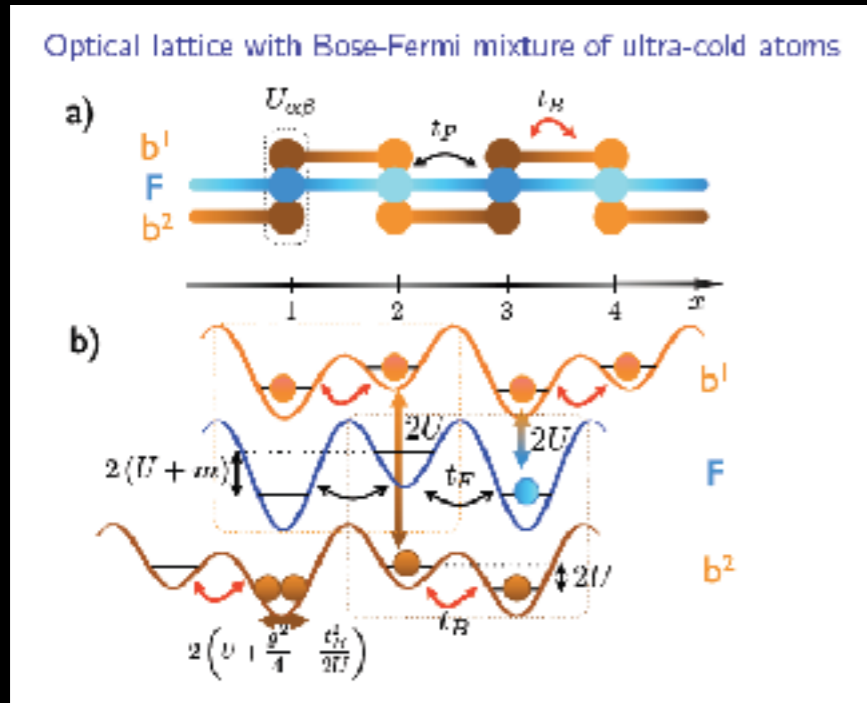
The Hubbard model Hamiltonian is

$$H = t \sum_{\langle ij \rangle} (a_i^\dagger a_j + h.c.) + \frac{U}{2} \sum_i n_i^2 - \mu \sum_i n_i$$

where t characterizes the tunneling between nearest neighbor sites and U controls the onsite Coulomb repulsion. These interactions can be approximately recreated with the atoms trapped in an optical lattice.



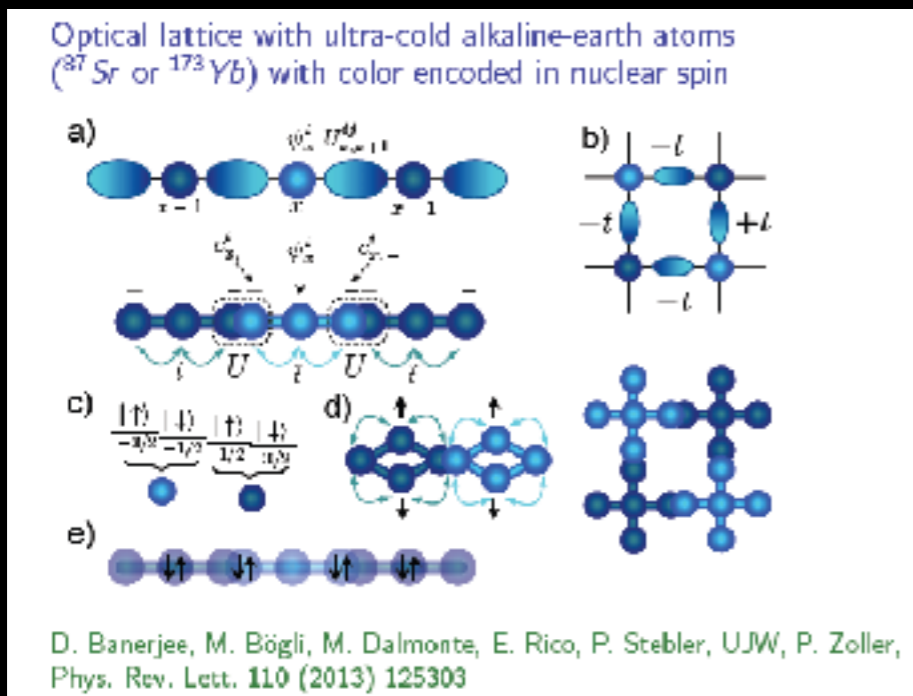
Fields as atoms



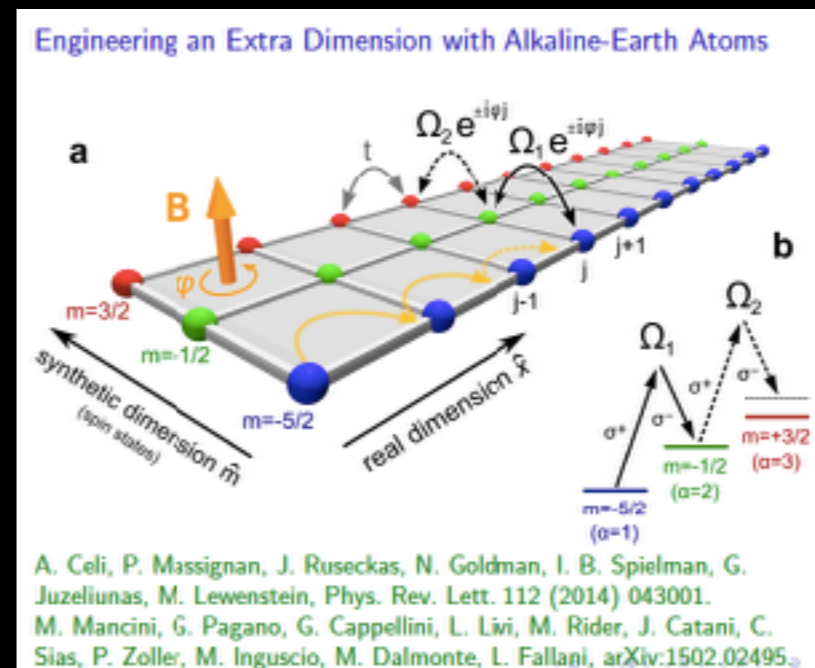
Weise

Mixtures of bosonic and fermionic atoms (U(1) link theory)

Weise



Weise

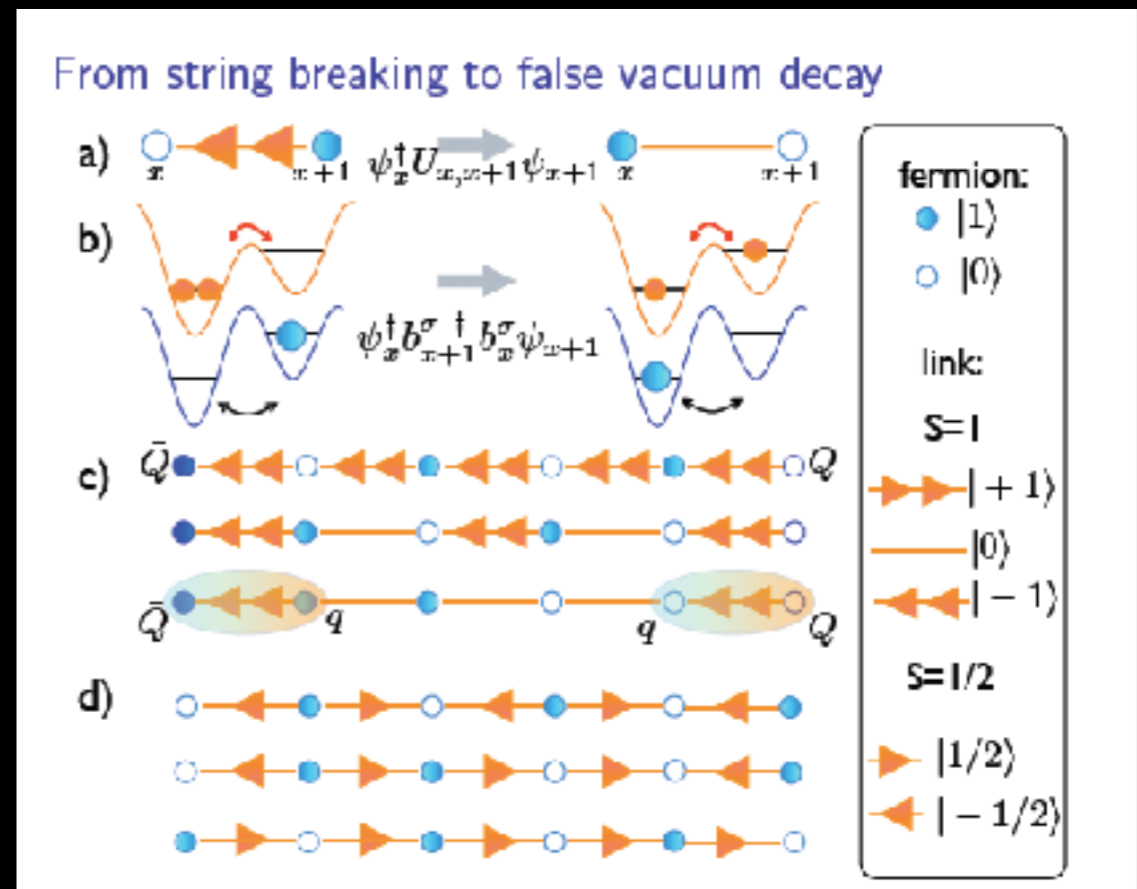


Encoding non-abelian interactions in spin

Encoding extra dimensions in spin

Toy Problems

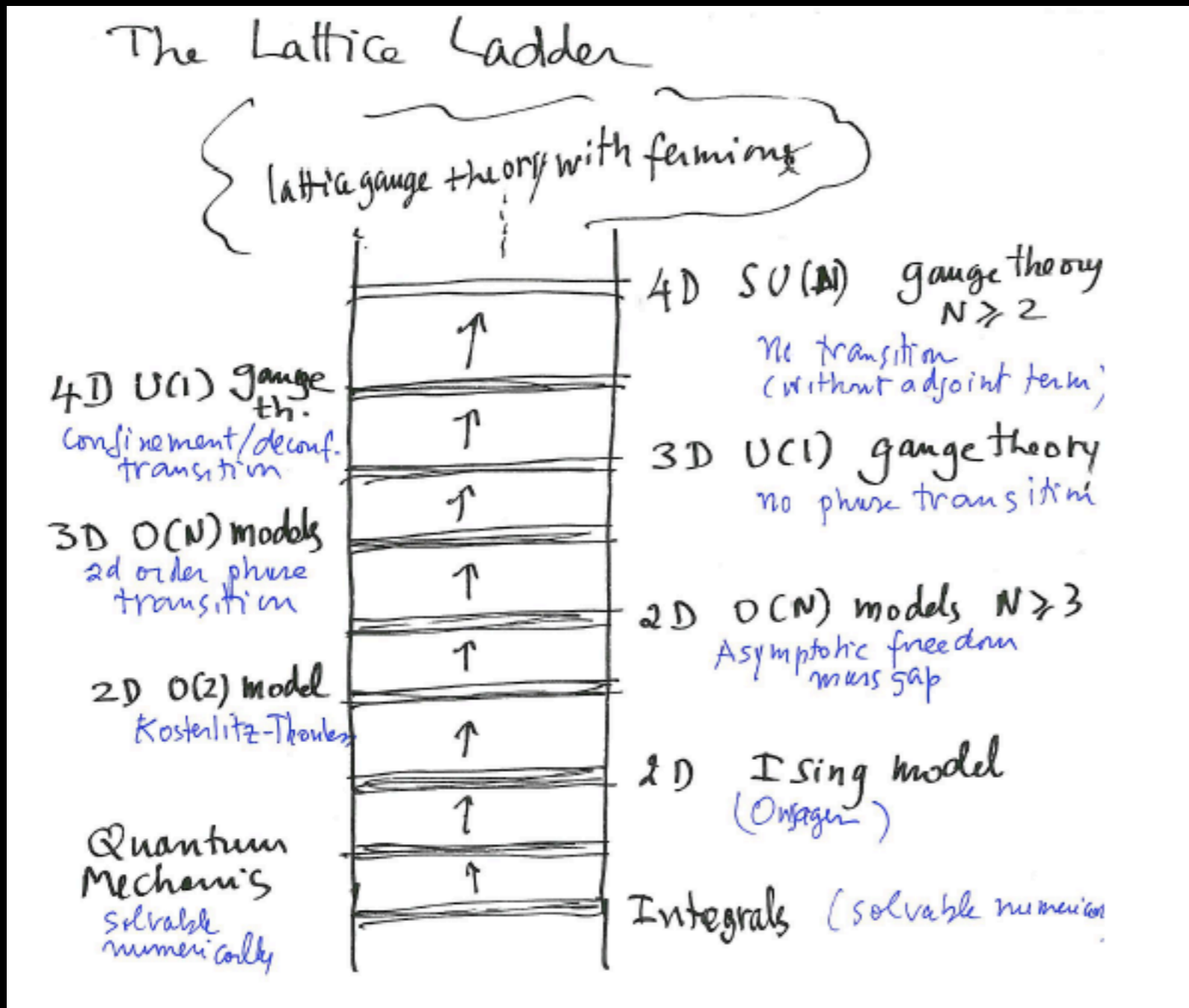
“Real-time evolution of gauge string breaking”



Weise

Toy Model + Toy Gauge Theory \rightarrow Real Problem + SU(3)

Ladder to the future...



Meurice

Meurice

“Large optical lattices ($L \sim 1000$) are part of the future”

Optimization Problems on Quantum Annealers

<https://indico.fnal.gov/event/15222/contribution/3>

Machine learning of a Higgs decay classifier via quantum annealing

...

Presenter: Joshua Job¹

Reference: "Solving a Higgs optimization problem with quantum annealing for machine learning", forthcoming, *Nature*

Collaborators: Alex Motz², Jean-Roch Vlimant², Daniel Lidar¹, Macia Spiropalu²

Associations: 1 Department of Physics, Center for Quantum Information Science & Technology, University of Southern California; 2 Department of Physics, California Institute of Technology; 3 Department of Electrical Engineering, Chemistry and Physics, Center for Quantum Information Science & Technology, University of California, Berkeley

Can the D-wave architecture work for real HEP problems?

Yes

Statistical Aspects of Quantum Computing

Yazhen Wang

Department of Statistics
University of Wisconsin-Madison
<http://www.stat.wisc.edu/~yzwang>

Near-term Applications of Quantum Computing
Fermilab, December 6-7, 2017

<https://indico.fnal.gov/event/15222/contribution/6>

<https://indico.fnal.gov/event/15222/contribution/9>

Evidence for a Scaling Advantage on a Quantum Annealer

Daniel Lidar, USC

Fermilab Workshop on
Near-term Applications of Quantum Computing
Dec. 7, 2017

Tameem Albash & DL
[arXiv:1705.07452](https://arxiv.org/abs/1705.07452)



Information Sciences Institute

USC Dornsife



USC Viterbi
School of Engineering

Will it be worth putting HEP problems on the D-wave?

Not yet?

D-Wave

USC Viterbi School of Engineering Information Sciences Institute
 USC-Lockheed Martin Quantum Computation Center

Superconducting flux qubits

DW1 "Rainier" 128q
 Oct 2011

DW2 "Vesuvius" 512q
 March 2013

DW2X "Washington" 1152q

Los Alamos (DW2X)

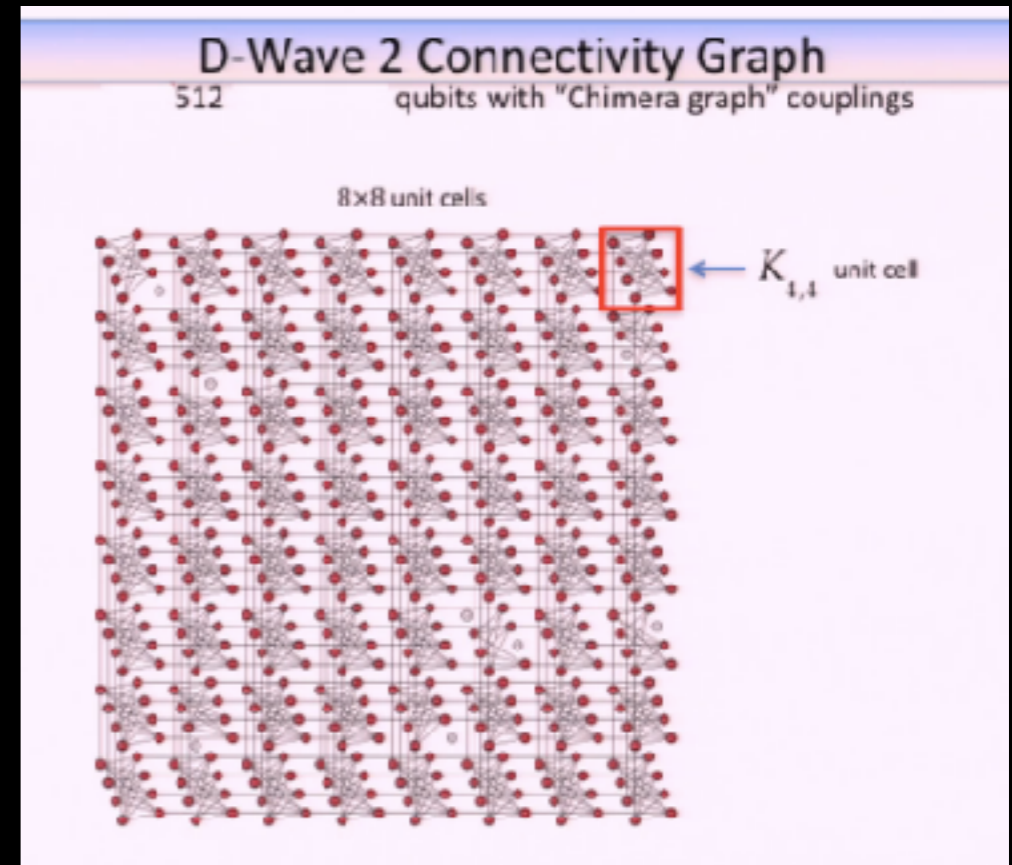
DW2000Q:

- TDS (own)
- Oak Ridge (cloud)
- U of Toronto (cloud)

NASA/Google:

- DW2 Aug 2013
- DW2X Sep 2015

Lidar



Lidar

Goal:

find the ground state energy, or sample from the Gibbs distribution of the **classical** Ising model:

$$H_{\text{Ising}} = \sum_{j \in V} h_j \sigma_j^z + \sum_{(i,j) \in E} J_{ij} \sigma_i^z \sigma_j^z$$

$\{\sigma_j^z = \pm 1\}_{j=1}^N$ (later Pauli matrices)

$\{J_{ij}, h_j\}$ are "program parameters"

Lidar

Finding a speed-up

Certifiable speedup **requires** optimality

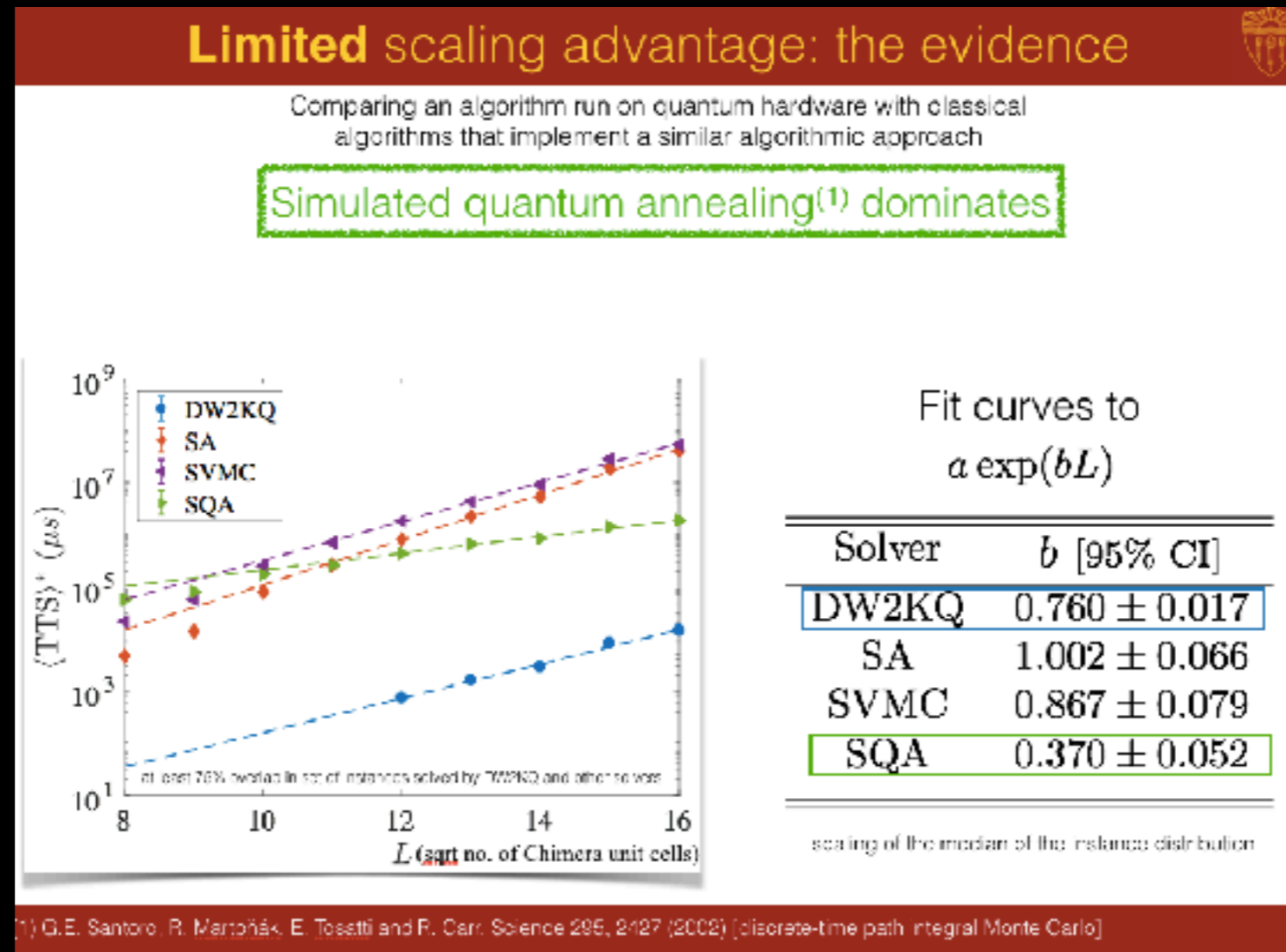
- An experimental demonstration of even a **limited** scaling advantage did not exist until now
- Culprit for quantum annealers:
 - Decoherence and noise
 - Annealing times too long:
the curse of sub-optimality^(1,2)

$$\text{TTS} = t_a \times (\text{no. of repetitions to get to 99\%}) = t_a \frac{\log(1-0.99)}{\log(1-p_{\text{CS}}(t_a))}$$

The **optimal annealing time** t_a is that which **minimizes** the TTS for fixed problem size N

Scaling cannot be trusted unless optimal t_a has been identified^(1,2).

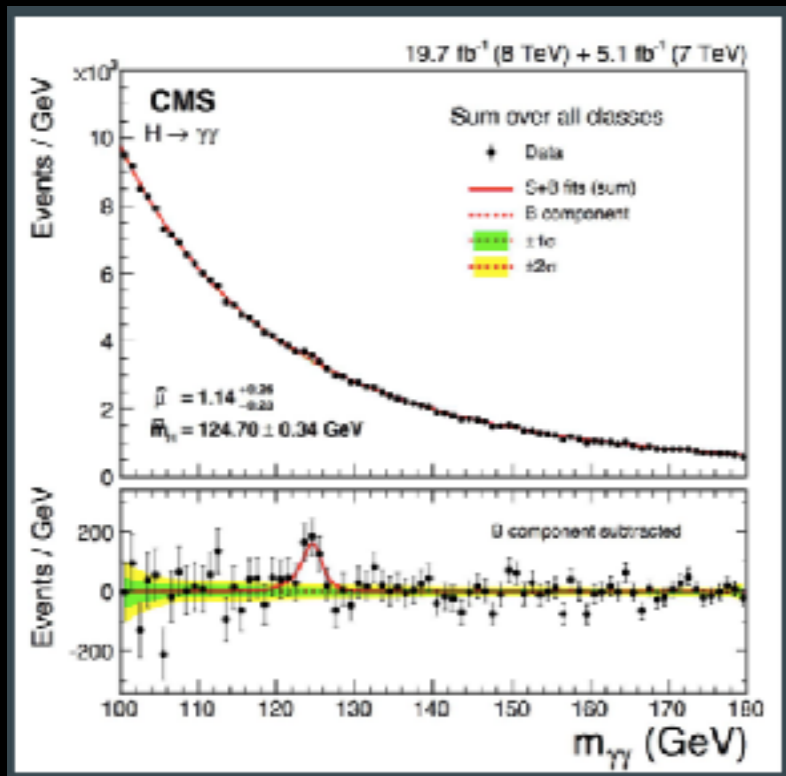
Scaling Advantage



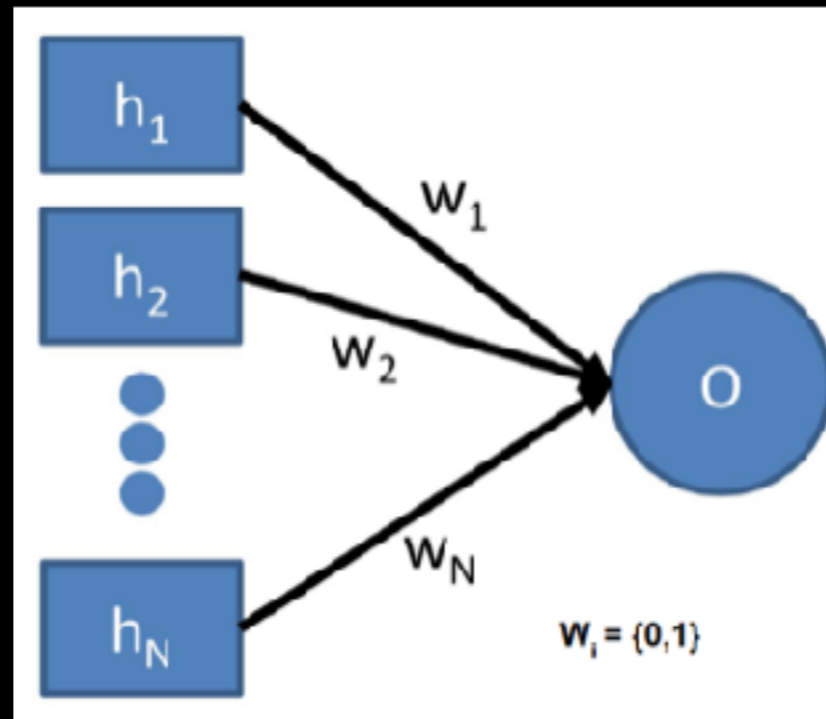
Lidar

- >Future of QC depends on scaling advantages
- >Need *careful* comparison w/classical computing

Higgs Quantum Machine Learning



Job



Job



Job

D-Wave: Map weights to spins
 Training data error minimized by hamiltonian

ROC curves

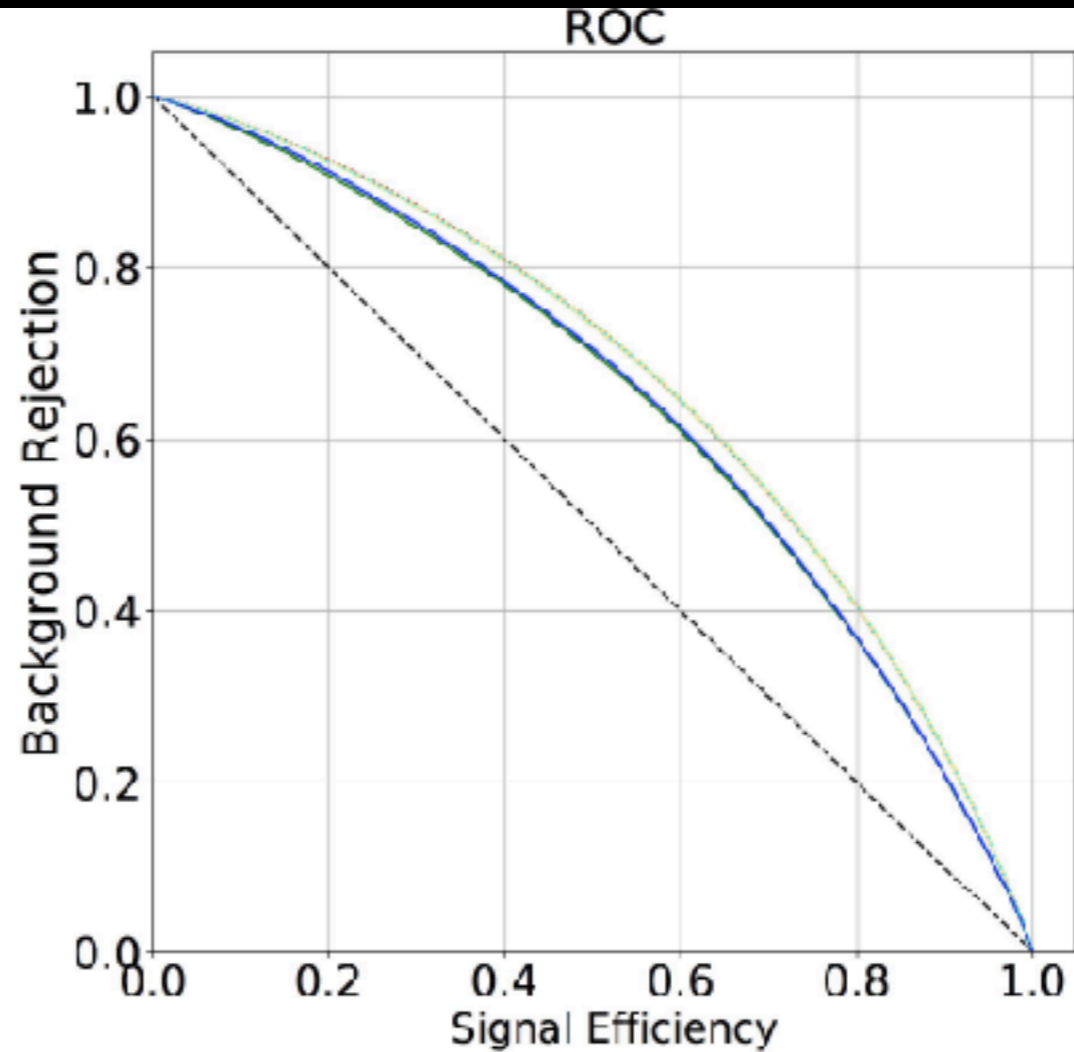
Color key:

D-Wave (DW) - green

Simulated annealing (SA) -
blue

XGBoost (XGB, decision trees)
- cyan

Deep Neural Net (DNN) - red



Job

- > Competitive w/classical computing
- > Applicable for other HEP optimization problems
- > Will there be a (quantum) scaling advantage?

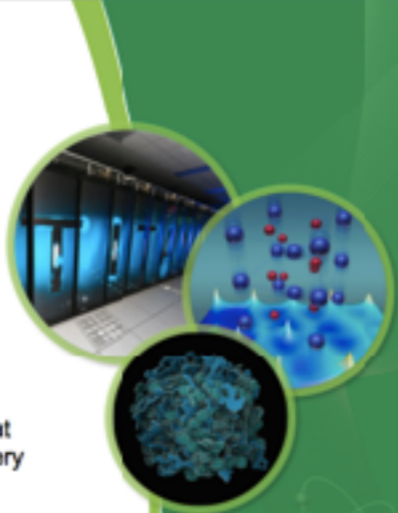
Quantum Algorithm Development Stack

<https://indico.fnal.gov/event/15222/contribution/7>

Presented to Fermilab Quantum Computing Workshop

Systems and Software for Quantum Computing

Travis Humble
Quantum Computing Institute
Oak Ridge National Laboratory



This presentation provides an overview of quantum computing at ORNL and our efforts to use these systems for scientific discovery and energy security.

This work is supported by the DOE ASCR program office through awards from the Early Career Research, the Quantum Testbed Pathfinder, and the Quantum Algorithm Teams programs.

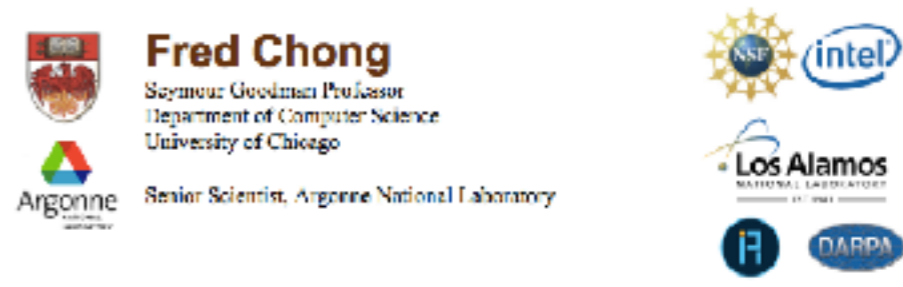
ORNL is managed by UT-Battelle for the US Department of Energy
Presented 5 DEC 2017

OAK RIDGE
National Laboratory

<https://indico.fnal.gov/event/15222/contribution/8>

Software for Large-Scale and Near-Term Quantum Computing

Fred Chong
Seymour Goodman Professor
Department of Computer Science
University of Chicago
Senior Scientist, Argonne National Laboratory



With Margaret Martinez, Diana Franklin, Peter Shor, Eddie Farhi, Aram Harrow, Ken Brown, Ali Javadi Abhari, Adam Holmes, Yonatan Ding, Yiyang Shi, Ryan Wu, Pranay Goktal, Lunkui Zhang, Ash Winer

(U. Chicago, Princeton, MIT, (GA)tech)

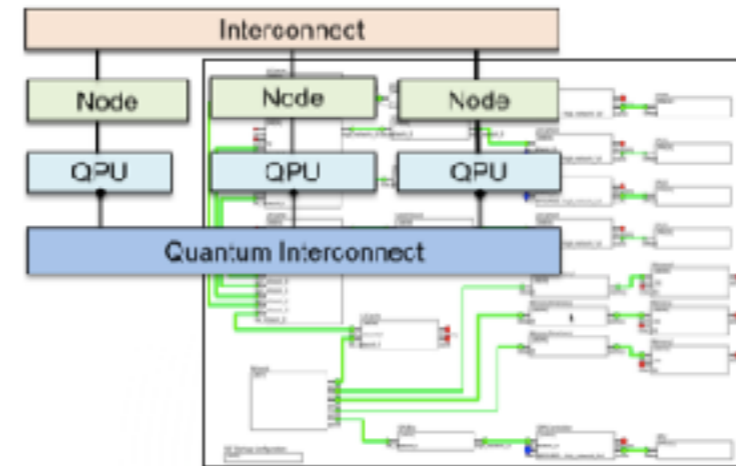
How does QPU function as a scientific computing resource?

Can compilers and codesign optimize for limited near term resources?

Systems and Software for Quantum Computing

Summary

- We are developing system software to integrate QPU's with scientific workflows for HPC
- We are using modeling and simulation to characterize performance of current devices
- We are evaluating when QPU's can accelerate scientific applications



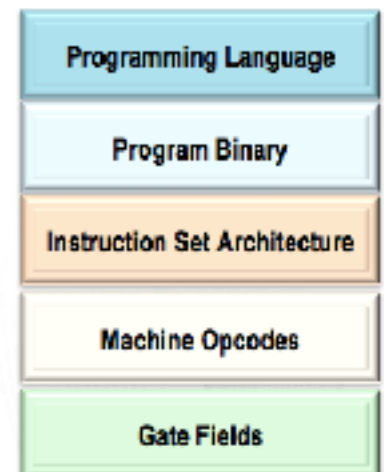
Humble

- standardized abstraction layer for different hardware
- enabling codesign and robust instruction sets
- framework for benchmarking and simulation of devices

Quantum Binaries for Future Systems

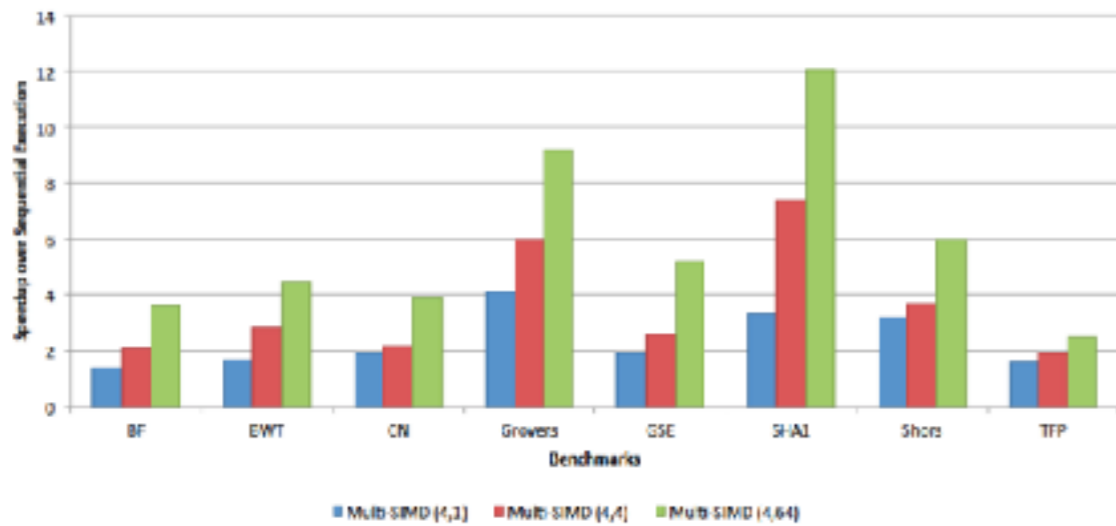
- In principle, programming models translate DSLs into executable instructions, i.e., binaries
 - All existing QPL's create interpreted representations
 - Actual QPU scheduling is based on interpreter runtime
- We are developing application binary interfaces (ABI's) for the quantum hardware abstraction layers (HAL)
 - XACC uses a virtual machine paradigm to standardize the interfaces different QPU devices
 - Current API/ABI's for IBM, Rigetti, D-Wave, simulators
 - ABI manages program interaction with system and devices, including QPU and memory
 - Memory management is the hardest part due to no-cloning, blocking penalties

Language Hierarchy



Humble

Logical Speedup Estimates

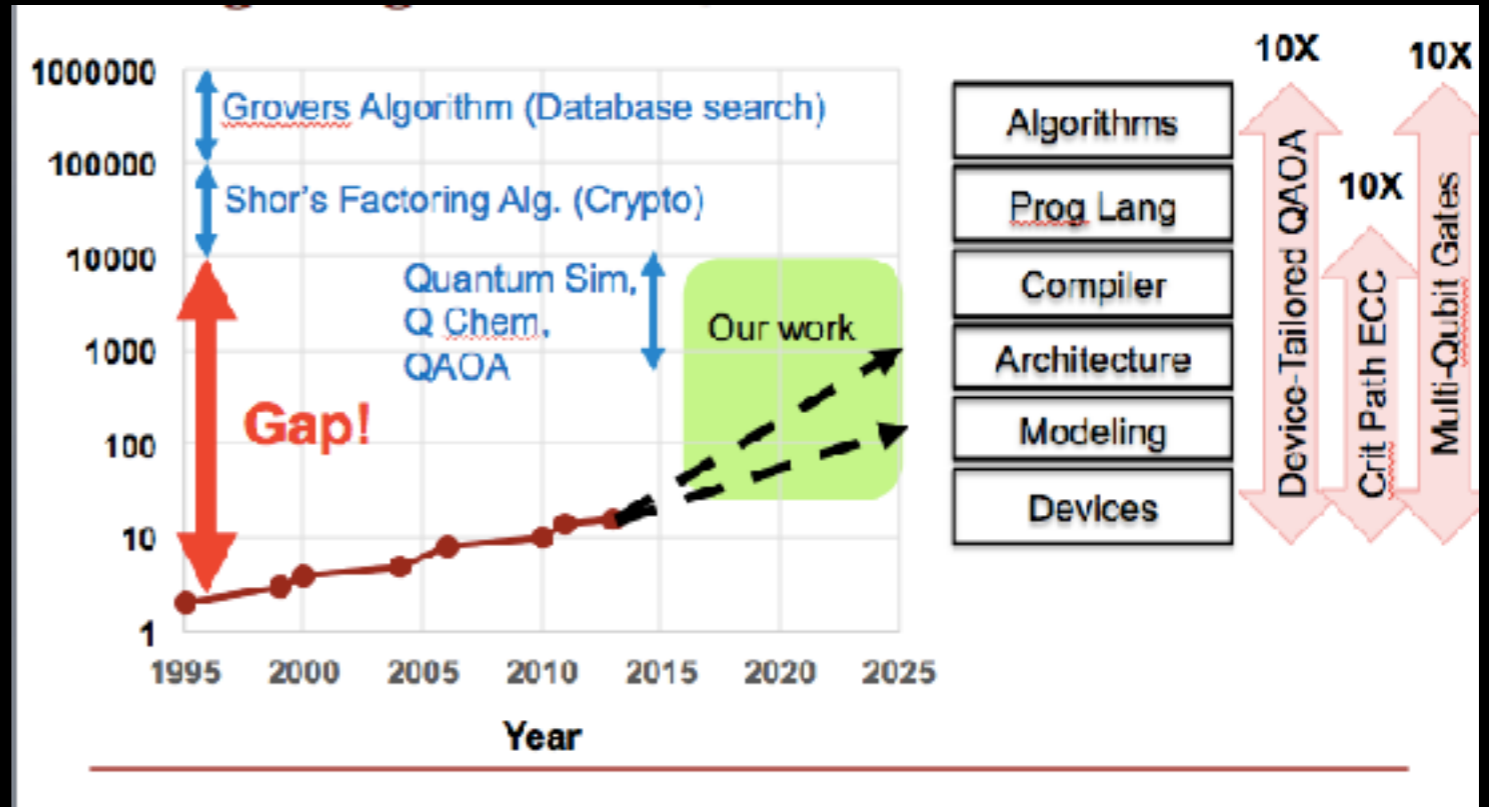


Speedup algorithms with compilation:
parallel gates (MIMD)
optimal rotations

Chong

Optimize Target Problem
Tailored gates
Optimize error correcting

...



Chong

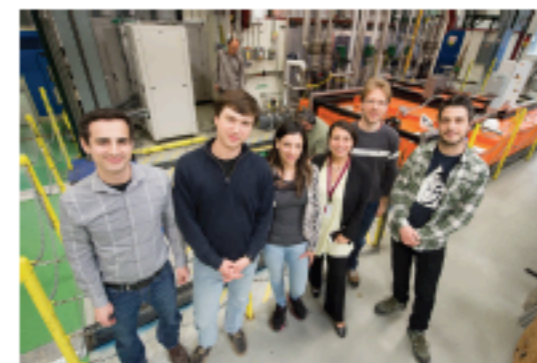
Fermilab Quantum Computing Testbed

Fermilab Quantum Hardware Initiatives

- Quantum sensors
 - Adapting quantum devices for use as quantum sensors for particle physics experiments such as direct dark matter detection
- Superconducting technologies
 - Some quantum computers use superconducting cavities similar to those we develop for accelerators.
- Quantum networks
 - We have agreed to host a quantum network on site in collaboration with Caltech and AT&T



Quantum sensors for axion search LDRD by Aaron Chou, Andrew Sonnenschein, and Dan Bowring



Fermilab SRF group is in a R&D collaboration with U. Chicago and Argonne



Quantum networks visit with John Donovan of AT&T

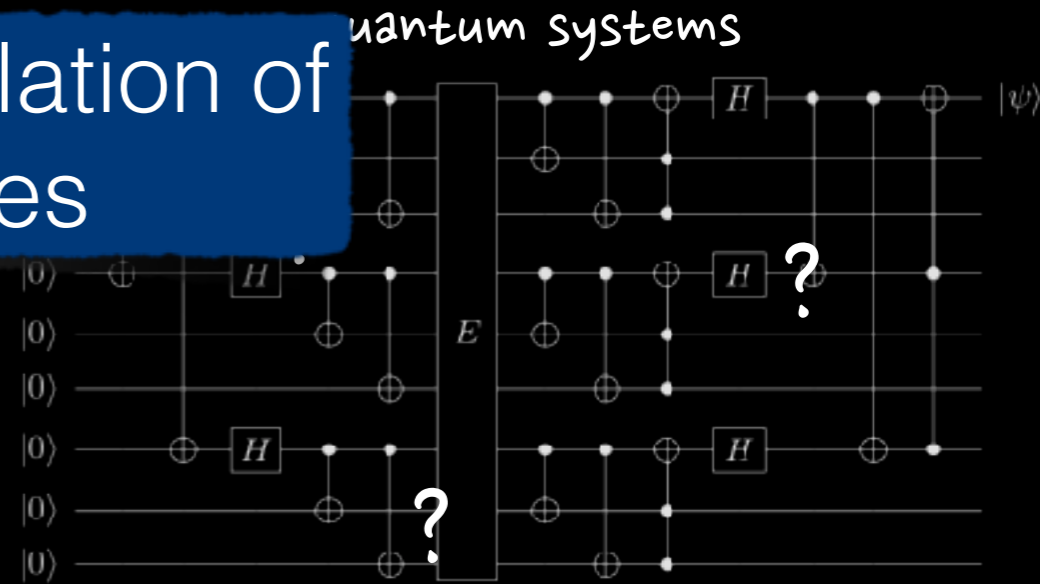
Fermilab Theory

QUANTUM

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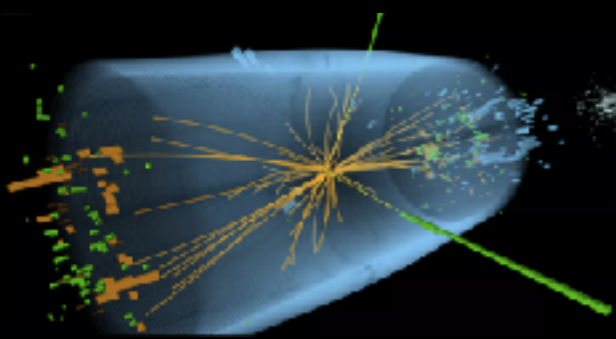
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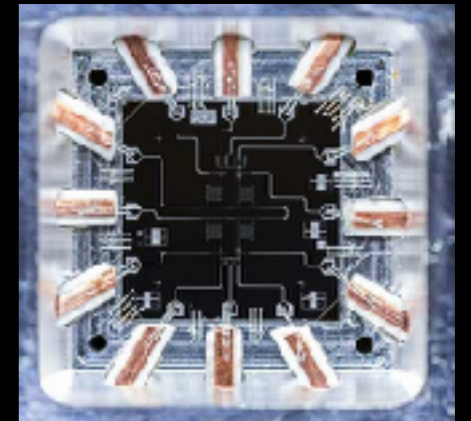
3) Quantum Algorithm Development Stack



Quantum Sensors?



4) Fermilab Quantum Computing Testbed



experiments on the universe

experiments on quantum hardware



Next Steps

Next steps in Quantum Science for HEP

21-22 May 2018
Fermilab - Wilson Hall
US/Central timezone

<https://indico.fnal.gov/event/16467/>