Research Spotlight Forum

6.4.19 Quantum Information Sciences

The Center for Quantum Information and Control (CQuIC)

PRESENTED BY:

Ivan H. Deutsch, Director of the Center for Quantum Information and Control, Department of Physics and Astronomy, University of New Mexico

Sandia National Laboratories | Georgia Institute of Technology | ILLINOIS | PURDUE UNIVERSITY | THE UNIVERSITY OF TEXAS AT AUSTIN

THE UNIVERSITY OF NEW MEXICO | NM STATE UNIVERSITY | NEW MEXICO TECH SCIENCE • ENGINEERING • RESEARCH UNIVERSITY

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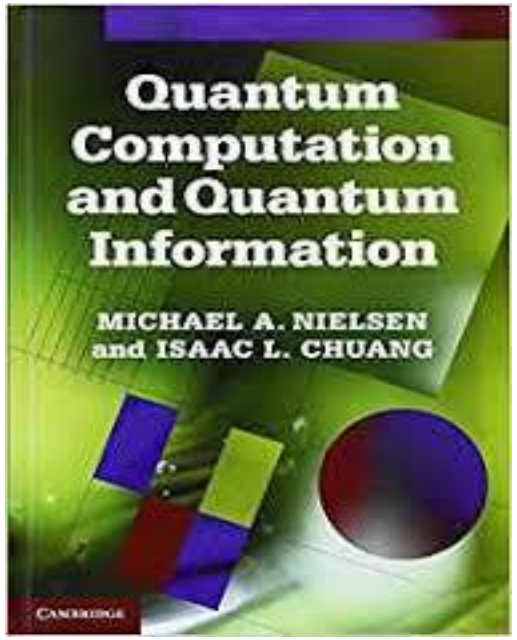
ABOUT CQuIC: History

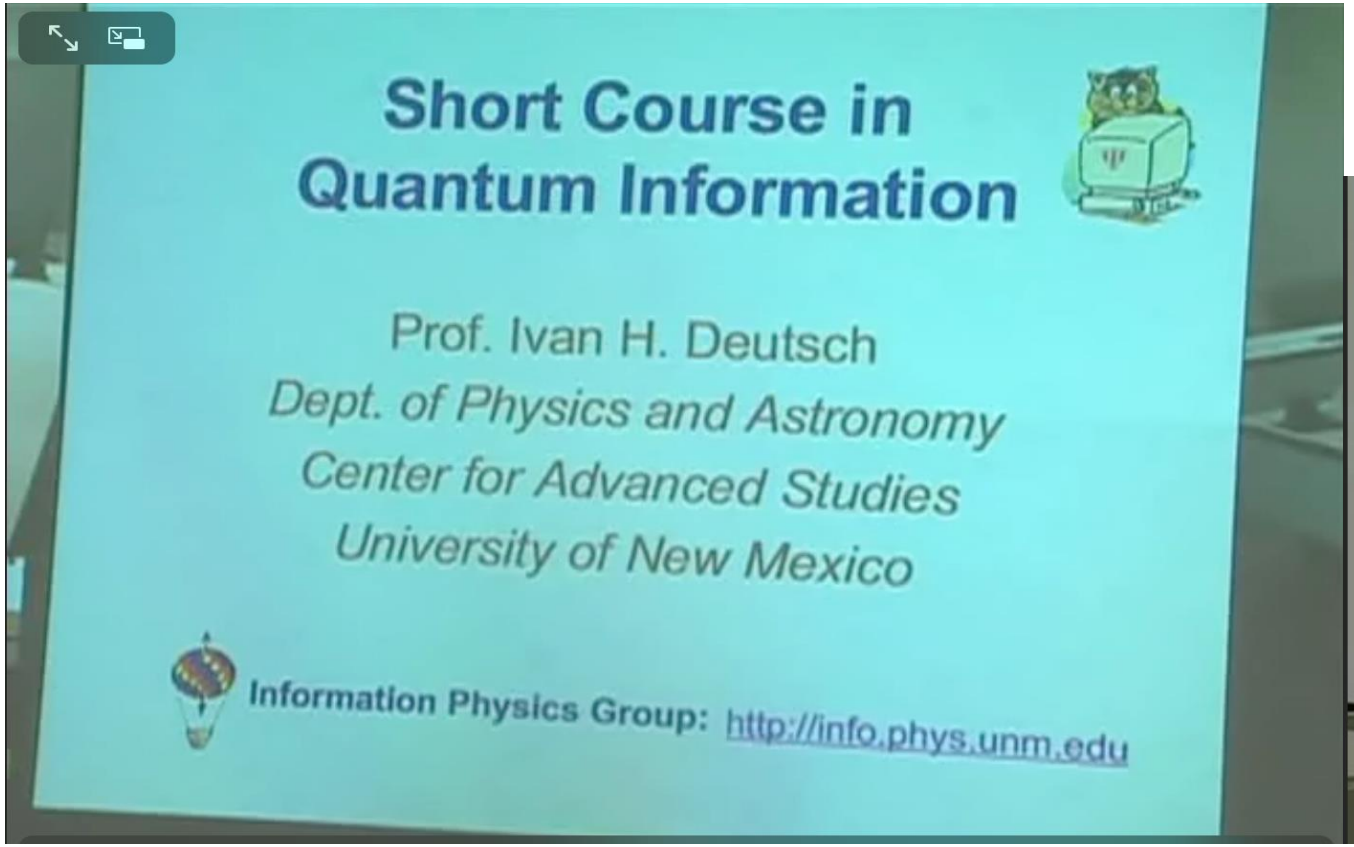
- Quantum Information Science has a long history at UNM, going back to 1995 when Caves and Deutsch formed the “Information Physics Group” with the Center for Advanced Studies.



* Mike Nielsen: UNM PhD 1998

* Ike Chuang: Los Alamos Postdoc 1997-98

ABOUT CQuIC: History



ABOUT CQuIC: History

- Quantum Information Science has a long history at UNM, going back to 1995 when Caves and Deutsch formed the “Information Physics Group” with the Center for Advanced Studies.

- In 2009 the Center for Quantum Information and Control (CQuIC) was created, funded by the National Science Foundation.

- In 2016 CQuIC became an NSF-funded Focused Research Hub in Theoretical Physics (FRHTP) – one of two in the nation.

ABOUT CQuIC: Mission and Focus

- An interdisciplinary center for Quantum Information Science bringing together physics, chemistry, and information science for fundamental studies and applications in computation, simulations, and communication, and metrology.

- Research Focus Areas
  - Quantum Information Theory
  - Quantum Optics / AMO Physics
    - Quantum Computation
    - Quantum Simulation
    - Quantum Communication
    - Quantum Metrology

- Key Words
  - Quantum Control, Measurement, Tomography, Algorithms, Error Correction, Many-body Physics, Tensor-Networks, Quantum Chemistry, Atomic Ions and Neutrals, Nanophotonics, Open Quantum Systems, Complexity, Chaos, NISQ, Co-Design.

ABOUT CQuIC: Core Faculty

T. Albash
ECE

S. R. Atlas
P&A/CCB

F. E. Becerra
P&A/OSE

C. M. Caves
P&A

E. J. Crosson
P&A/CS

A. Miyake
P&A

ABOUT CQuIC: National Laboratory Adjunct/Research Faculty

Sandia National Laboratories

A. Baczewski

G. Biedermann

R. Blume-Kohout

Y-Y. Jau

A. Landahl

S. Carr

P. Schwindt

Los Alamos NATIONAL LABORATORY

M. Boshier

P. Coles

R. Somma

ABOUT CQuIC: Students

ABOUT CQuIC: Postdocs

National Science Foundation
Focused Research Hub in Theoretical Physics

FRHTP Postdocs

Chris Jackson

Raf Alexander

Sayonee Ray

Pablo Poggi

ABOUT CQuIC: SQuInT

Outreach to scientific community: CQuIC is the administrative home of the Southwest Quantum Information and Technology (SQuInT) Network (27 node institutions) and organizer of the SQuInT Annual Workshop.

Founding organizer: Ivan Deutsch 1997-2016

Chief organizer: Akimasa Miyake, 2016-present

ABOUT CQuIC: SQuInT

ABOUT Akimasa Miyake

- Brief biography:

PhD in Physics, University of Tokyo

Associate Professor of Physics & Astronomy, UNM.

- Research areas:

Theory of quantum computation, simulation, software, algorithms.

Keywords:

List keywords related to your work and research interests:

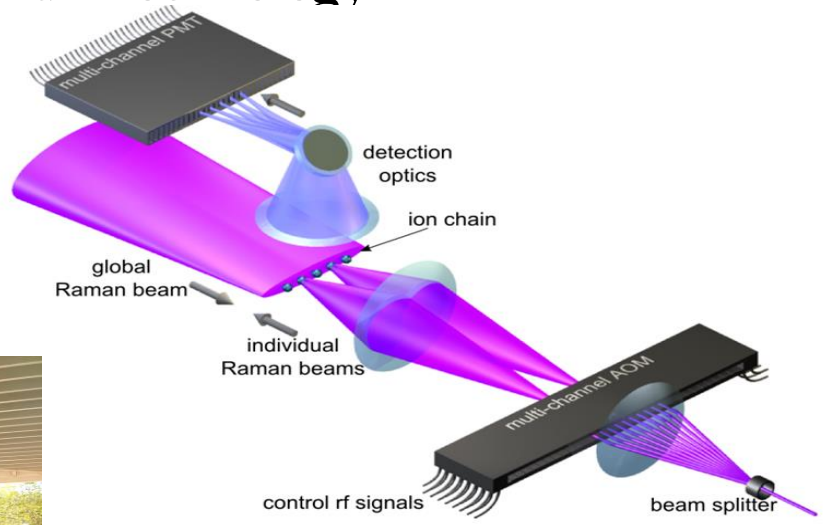
quantum computation, many-body simulation, software, ion-trap QIP, and NISQ applications.

CURRENT WORK IN QUANTUM INFORMATION SCIENCES - Miyake

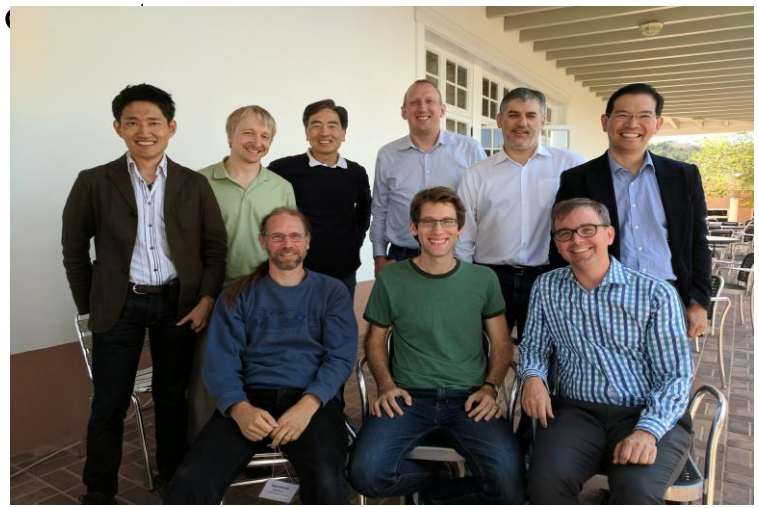
Briefly describe the current work you do in this area or in areas that might be supplemental to this area.

- **Making a practical 50-qubit quantum computer with ion-trap quantum technology**

Miyake contributions are (i) co-designing the hardware and software for the best computational performance, and (ii) developing near-term quantum algorithms and applications which function without quantum error



NSF STAQ Project



CURRENT WORK IN QUANTUM INFORMATION SCIENCES - Miyake

Briefly describe the current work you do in this area or in areas that might be supplemental to this area.

- **Making a practical 50-qubit quantum computer with ion-trap quantum technology**

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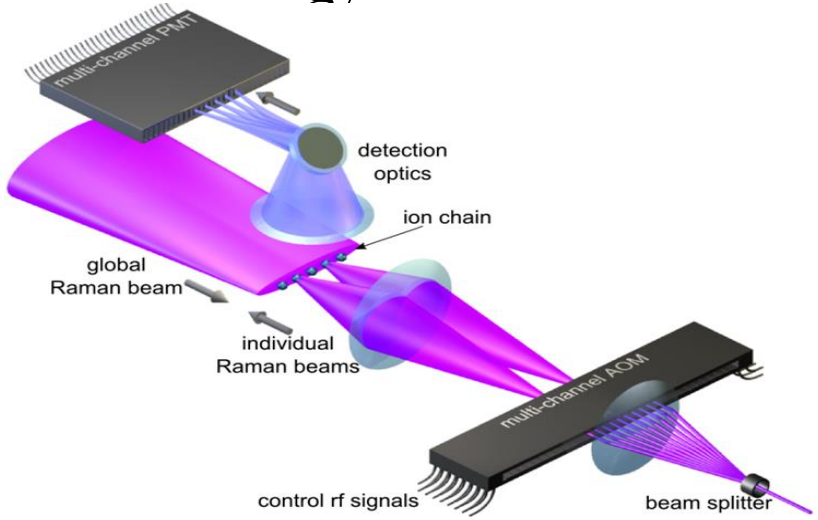
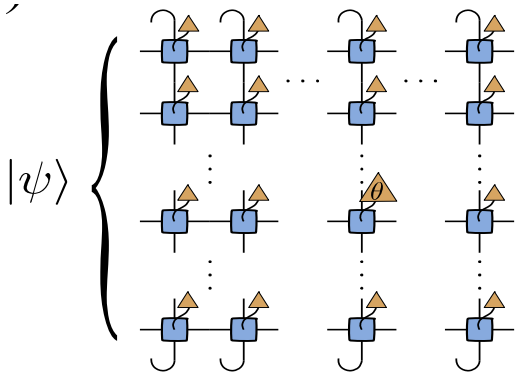


- **Analyzing physics and complexity of many-body entangled states**

Tensor network descriptions and other new variational tools like machine learning.



ABOUT F. Elohim Becerra

- Brief biography:

PhD in Physics, University of Maryland

Assistant Professor of Physics & Astronomy, UNM.

- Research areas:

Experimental quantum optics and AMO physics. Quantum communication and networking.

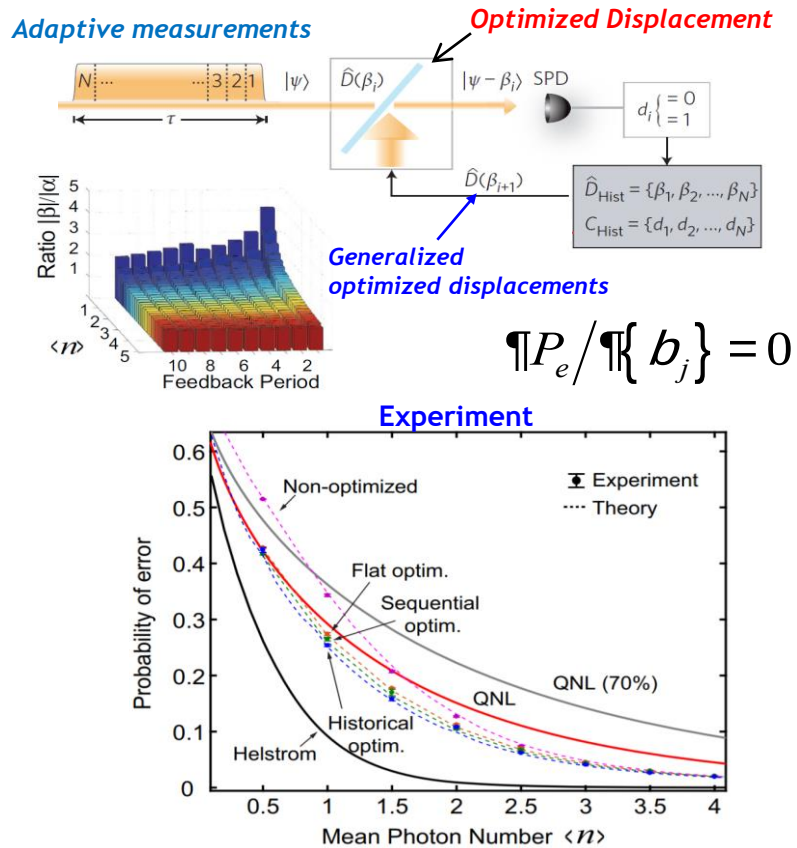
Keywords:

List keywords related to your work and research interests:

Quantum optics, laser cooled atoms, quantum memory, single photon counting, quantum channel capacity,

CURRENT WORK IN QUANTUM INFORMATION SCIENCES - Becerra

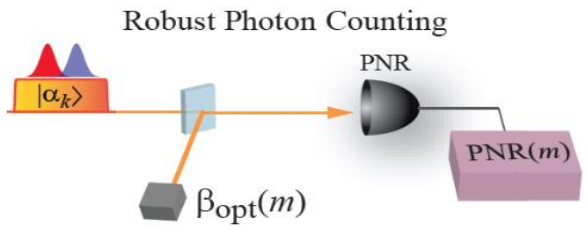
Multi-state discrimination: Optimized Strategies



$$\partial P_e / \partial \{ b_j \} = 0$$

A. R. Ferdinand, M. T. DiMario, F. E. Becerra, npj Quantum Information **3**, 43 (2017)

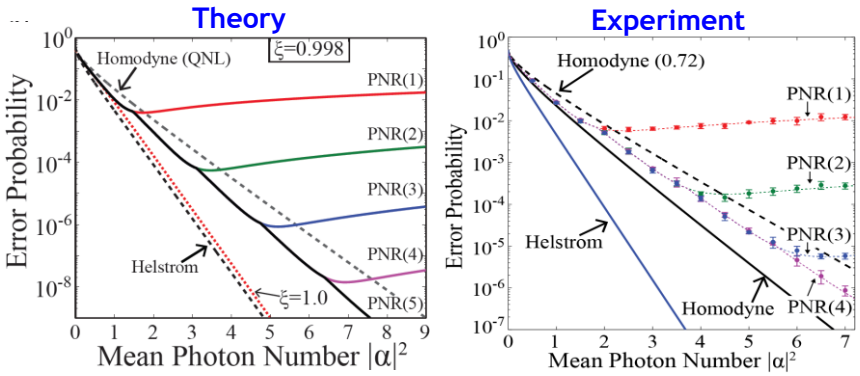
Single-shot robust PNR measurements



Strategy

Photon number resolving (PNR) detection → *provides robustness to noise*

Single-shot measurements → *allows scalability*

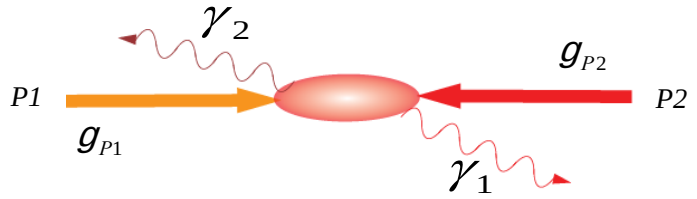


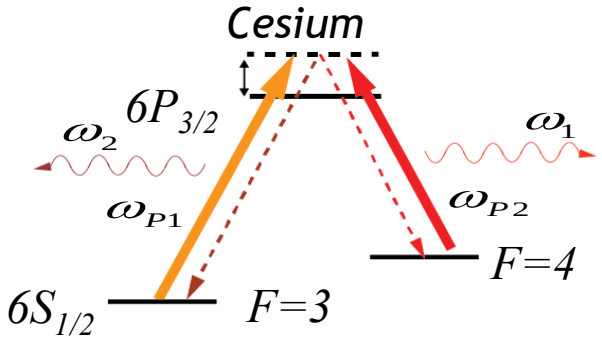
M. T. DiMario and F. E. Becerra, Phys. Rev. Lett. **121**, 023603 (2018)

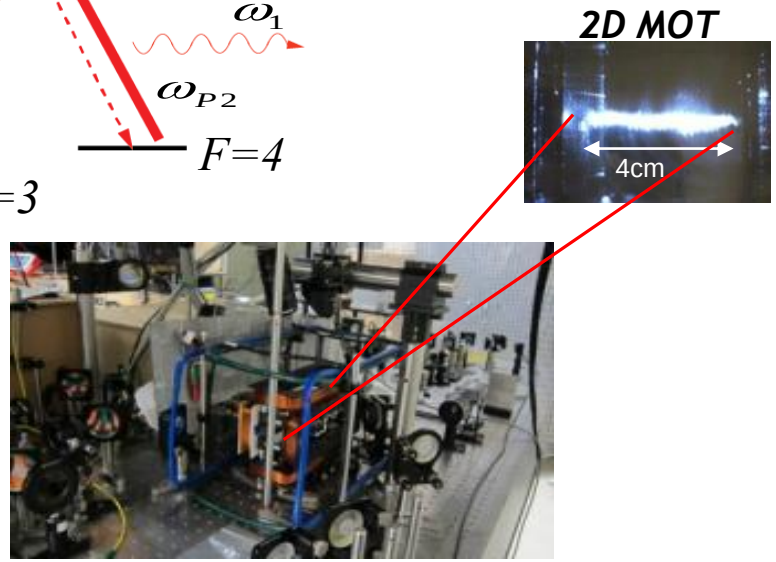
CURRENT WORK IN QUANTUM INFORMATION SCIENCES - Becerra

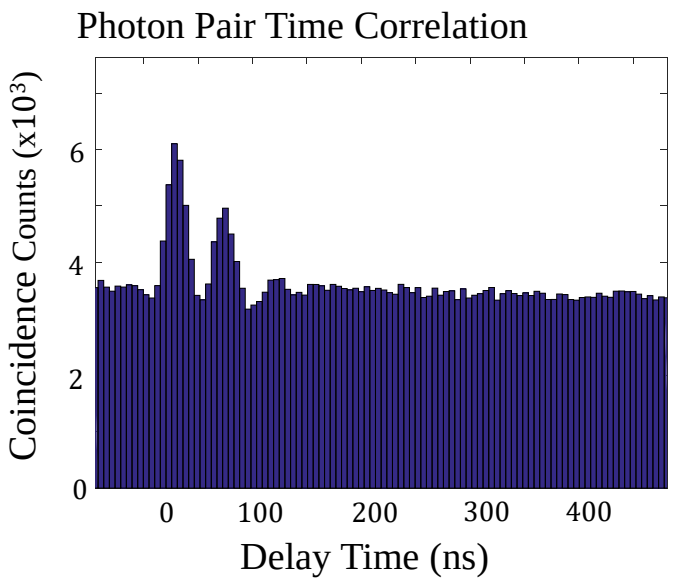
Atom-Photon interfaces: Sources and Memories

Photons from Four Wave Mixing (FWM)









ABOUT E. Crosson

- Brief biography:

PhD in Physics, University of Washington

Assistant Professor of Physics & Astronomy and Computer Science, UNM.

- Research areas:

Theory of Quantum Computation, Hamiltonian Complexity, Quantum Error Correction, Quantum Algorithms, Quantum Simulation

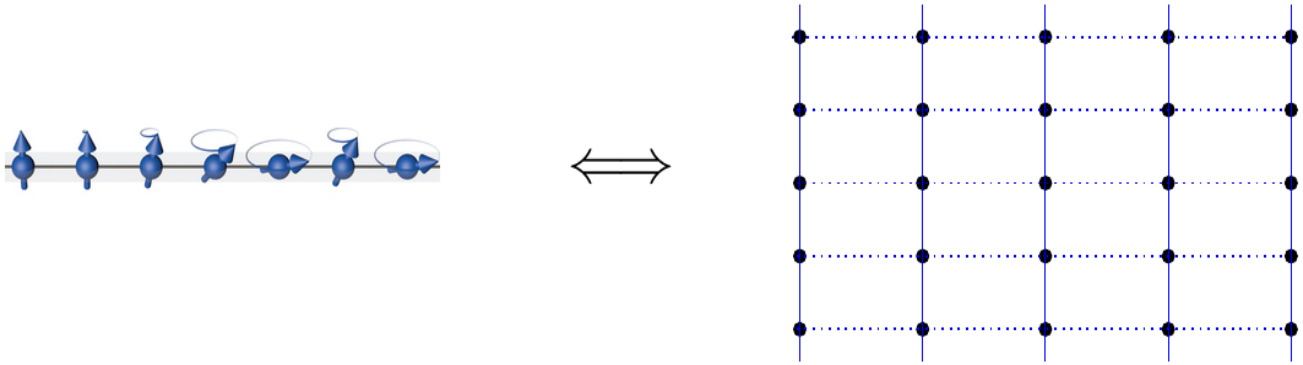
Keywords:

List keywords related to your work and research interests:

quantum computation, quantum annealing, complexity, algorithms, quantum machine learning

CURRENT WORK IN QUANTUM INFORMATION SCIENCES - Crosson

For over 40 years QMC has been applied to computational studies of spin chains, but the convergence was only understood heuristically.



In 2018, Crosson and Harrow theoretically justified the success of QMC for spin chains without a sign problem by rigorously analyzing the convergence of the path integral QMC Markov chain.

$$H = \sum_{i=1}^{n} \alpha_{i,i+1} Z_i Z_{i+1} + \sum_{i=1}^{n} b_i Z_i$$

$$+ \sum_{i=1}^{n} \Gamma_i X_i + \sum_{i=1}^{n} g_{i,i+1} \left(X_i X_{i+1} + Y_i Y_{i+1} \right)$$

Rapid mixing of path integral Monte Carlo for 1D stoquastic Hamiltonians. Crosson, Harrow. 2018.

CURRENT WORK IN QUANTUM INFORMATION SCIENCES - Crosson

It is an open question whether there exists *good* quantum stabilizer codes (linear distance, constant rate) with low-weight (local) stabilizer generators.

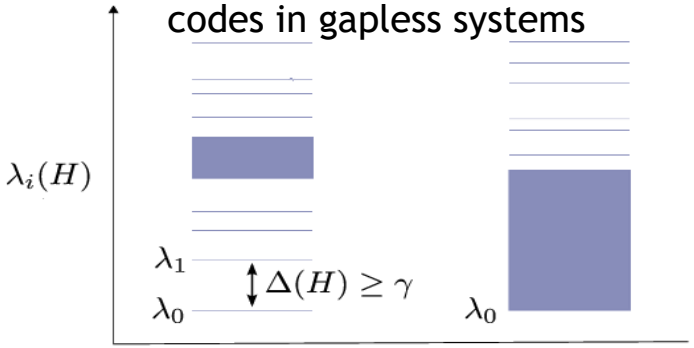
The conjecture that such codes exist is the Quantum LDPC conjecture.

Crosson, with collaborators at Caltech and UC Berkeley, recently gave the first example of almost-good codes with local checks, albeit using approximate codes with noncommuting local constraints.

Besides a new framework for building local checks for any quantum codes with efficient encoding circuits, this work also introduced a new methods for analyzing spectral gaps of high-dimensional quantum spin systems.

Quantum Error Correction

Approximate quantum error correcting codes in gapless systems



Good approximate quantum LDPC codes from spacetime circuit Hamiltonians. Bohdanowicz, Crosson, Nirkhe, Yuen. Symposium on the Theory of Computation, 2019.

ABOUT S. Atlas

- Brief biography:

PhD in Chemical Physics, Harvard University

Research Professor of Physics & Astronomy and Chemistry & Chemical Biology, UNM.

- Research areas:

Quantum chemistry, materials, density-functional theory, high-performance computing

Keywords:

List keywords related to your work and research interests:

quantum computation for quantum chemistry, high-performance computing, machine learning

CURRENT WORK IN QUANTUM INFORMATION SCIENCES - Crosson

Atlas lab (Susan R. Atlas, Physics & Astronomy):

Quantum Chemistry: Design and implementation of principled models for density functional theory (DFT) electronic structure calculations of molecules and materials. The objective is to utilize qubit entanglement to model spatially-complex quantum correlations between electrons and encode the correlations as nonlocal density functionals. Unlike most quantum chemical methods, DFT is formally based on the 3D electron density rather than the many-electron wave function.

Two approaches are being explored:

(1) data analysis of pair interaction patterns in the exchange-correlation energy, using machine learning and data modeling algorithms tailored for quantum computers, and applied to large chemical datasets; and

(2) implementation of nonlocal functionals embodying explicit frequency and wave vector response.

ABOUT T. Albash

- Brief biography:

PhD Physics, University of Southern Calfornia

Assistant Professor of Electrical & Computer Engineering, UNM.

- Research areas:

Theory of adiabatic quantum computing, heuristic quantum algorithms, quantum simulation

Keywords:

List keywords related to your work and research interests:

Quantum Algorithms, quantum simulation, optimization, NISQ

T. Albash Research Overview

- Characterizing and benchmarking quantum annealers
  - Development of master equations for open quantum system modeling (Phys. Rev. A 97, 022116 (2018))
  - Scaling requirements for implementation errors (Quantum Sci. Technol. 4 02LT03 (2019))
  - First demonstration of optimal annealing times and true performance assessment for a D-Wave processor (Phys. Rev. X 8, 031016 (2018))
  - IARPA's QEO Performer Team Task 3 "Verification and Validation" Leader

Role of non-stoquasticity in quantum adiabatic optimization

- New example of exponential speedup over stoquastic counterpart (Phys. Rev. A 99, 042334 (2019))

Quantum Monte Carlo implementations

- New quantum Monte Carlo algorithm (Phys. Rev. E 96, 063309 (2017))

ABOUT I. H. Deutsch

- Brief biography:

PhD in Physics, UC Berkeley, Regents' Professor of Physics & Astronomy, UNM.

Director Center for Quantum Information and Control (CQuIC)

- Research areas:

QI in AMO systems, quantum control and measurement, quantum complexity and simulation.

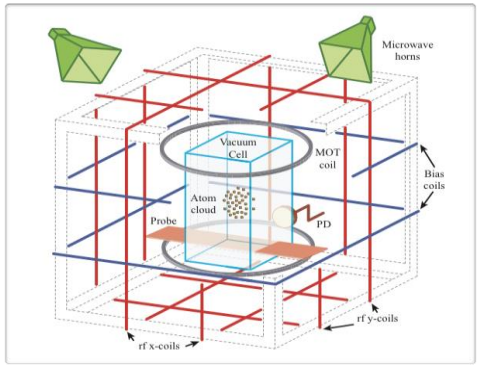
Keywords:

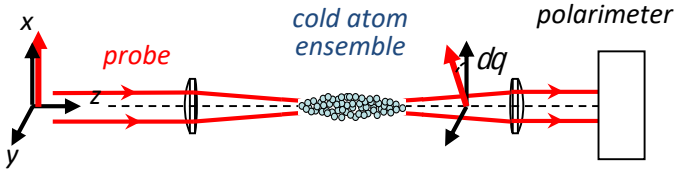
List keywords related to your work and research interests:

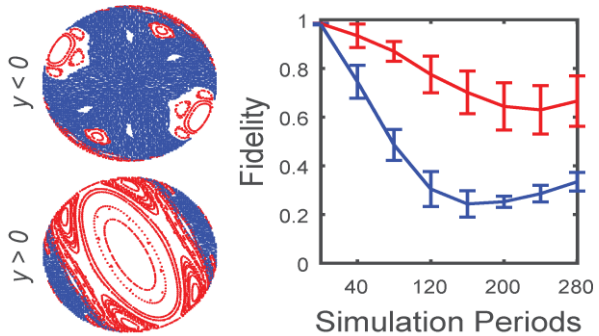
Quantum control, quantum measurement, quantum tomography, quantum optics, quantum simulation, quantum chaos. Rydberg atoms, boson sampling, spin squeezing.

CURRENT WORK IN QUANTUM INFORMATION SCIENCES - Deutsch

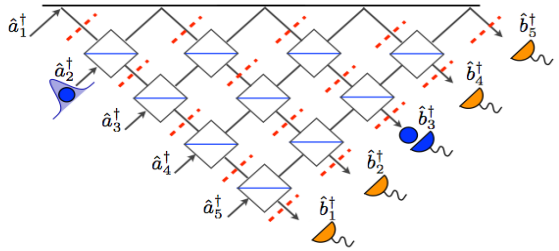
Quantum Control of Atomic Spins

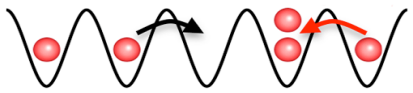






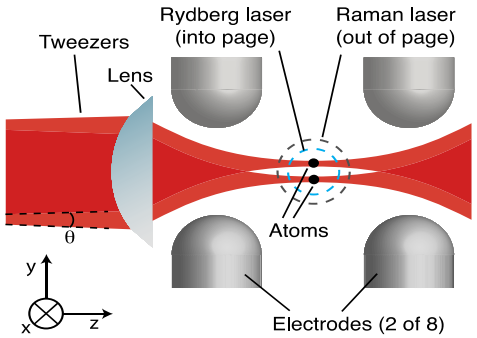
Quantum Computational Supremacy in Quantum Simulation





Boson sampling

Building Quantum Information Processors



Biedermann
Sandia

CURRENT WORK IN QUANTUM INFORMATION SCIENCES - Deutsch

Seeking answers to the Big Questions

"A major challenge for research using analog quantum simulators is identifying accessible properties of quantum systems which are robust with respect to error, yet are also hard to simulate classically."

J. Preskill, "Quantum Computing in the Noisy Intermediate-Scale Quantum (NISQ) era and beyond." Keynote Address at Quantum Computing for Business, 5 December 2017."

CURRENT WORK IN QUANTUM INFORMATION SCIENCES - Deutsch

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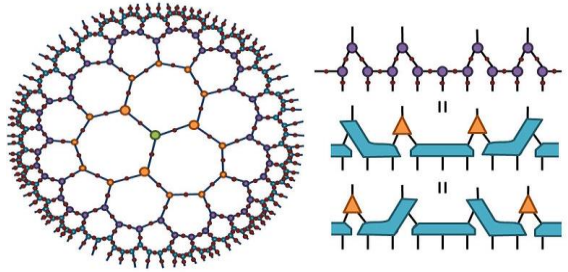
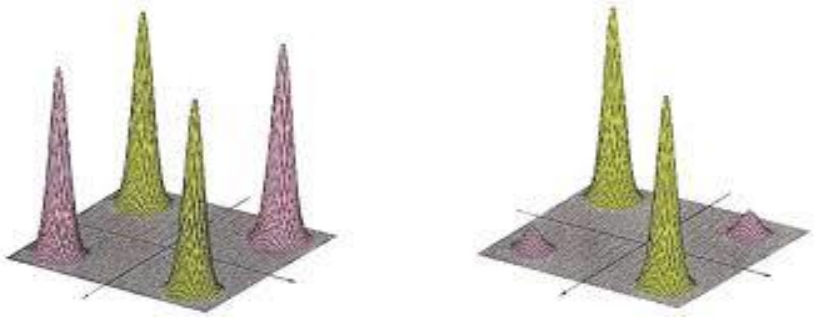
Entanglement – The Dual-Edged Sword

- Entanglement within system - complex matter.



- Entanglement with environment - decoherence.



CURRENT WORK IN QUANTUM INFORMATION SCIENCES - Deutsch

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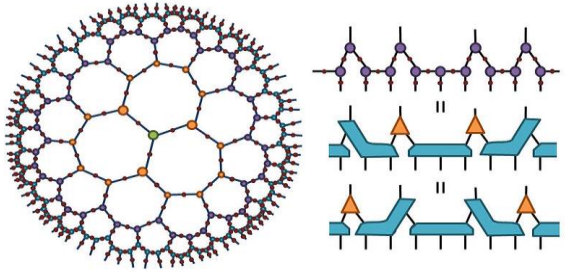
Big Question: What is the relationship between robustness and complexity?

- Are "complex systems" hypersensitive to imperfections?
- Are "robust systems" efficiently simulatable?
- What are the implications for analog quantum simulation?
- What are the implication for the natural world?

Entanglement – The Dual-Edged Sword

- Entanglement within system – complex matter.



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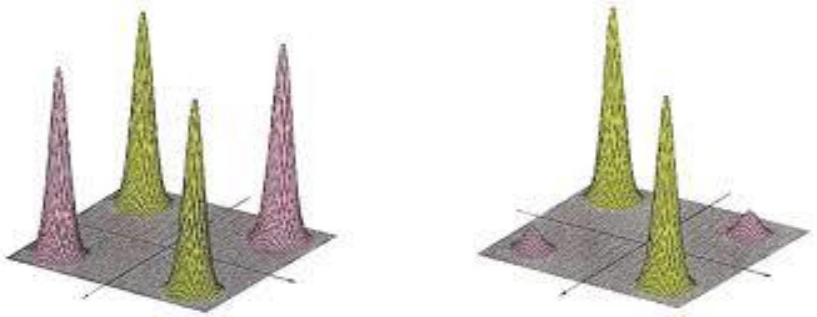

CURRENT WORK IN QUANTUM INFORMATION SCIENCES - Deutsch

Quantum Complexity

Kinematic Complexity:
- Hilbert space dimension grows exponential large with number of subsystems.
- Information stored in *correlations* (entanglement).

Dynamical Complexity:
- Information stored locally is "scrambled" nonlocally.
- Quantum chaos and hypersensitivity to perturbations.
- Kolmogorov-Sinai Entropy

Computational Complexity
- Polynomial hierarchy
- Quantum computational power

FUNDING SOURCES

CQuIC's current total funding is about $5 M

The source are given below: $2.5M
- Internal UNM (College of Arts & Sciences)
- Center-wide Funding
  - NSF FRHP Center Grant
  - NSF NRT (pending)

- Individual investigators - Total $2.5M
  - NSF TAMOP, PI: Deutsch
  - NSF QIS, PI: Miyake
  - NSF CAREER, PI: Becerra
  - NSF STAQ, PI: Miyake
  - NSF QIS, PI: Deutsch
  - Sandia Academic Alliance, PI: Deutsch
  - IARPA QEO, PI; Crosson
  - Google Focus, Co-PIs: Deutsch & Miyake
  - Google Focus, PI: Crosson

RESEARCH NEEDS

Making the Academic Alliance Work

- Not just about individual investigators – about joint programs
- Role of PhD students – research at Sandia National Labs
- Workforce development – creating the pipeline of a "quantum smart" workforce
- A vision for the National Quantum Initiative