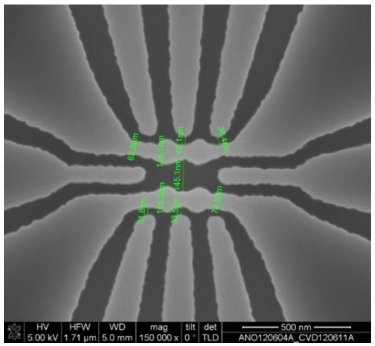
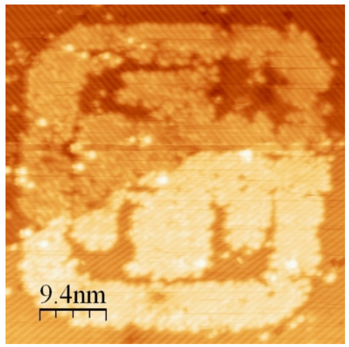
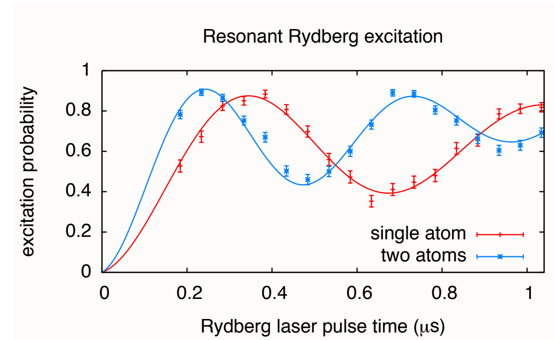
Exceptional service in the national interest

Sandia National Laboratories







Applications of Quantum Computing SNL Investigation

Andrew J. Landahl & Ojas D. Parekh

Sandia National Laboratories

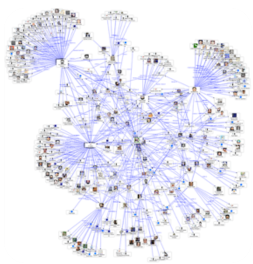
5 February 2015

Applications of Quantum Computing

Sandia National Laboratories

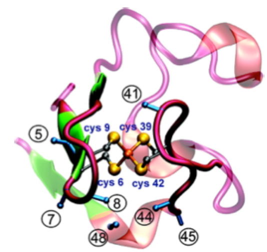
50+ algorithms: http://math.nist.gov/quantum/zoo

Data Science



- Pattern finding
  - Cryptography
  - Graph properties
- Linear algebra
- NP-hard optimization? (doubtful)

Physical Science



- Chemistry
  - Thermal rates
  - Molecular energies
  - Chemical reactions
- Condensed matter properties
- Other (QCD, Hawking rad., …)

Important hardware questions

1. Is it quantum?
2. Is it fault-tolerant?
3. Is it universal?
4. Is it big enough?

Adiabatic quantum computing @ D-Wave, 2010

1. Unclear.
2. Unclear.
3. No.
4. Unclear.

AQUARIUS™

Adiabatic quantum architectures in ultracold systems

LDRD

LABORATORY DIRECTED RESEARCH & DEVELOPMENT

Adiabatic quantum optimization

Sandia National Laboratories

a.k.a. *Quantum Annealing*

QUBO: Quadratic Unconstrained Binary Optimization

$$H_{\text{init}} = \sum_{i=1}^{n} \sigma_x^{(i)} \quad \longrightarrow \quad H_{\text{final}} = \sum_{i=1}^{n} h_i \sigma_z^{(i)} + \sum_{i,j=1}^{n} J_{ij} \sigma_z^{(i)} \otimes \sigma_z^{(j)}$$

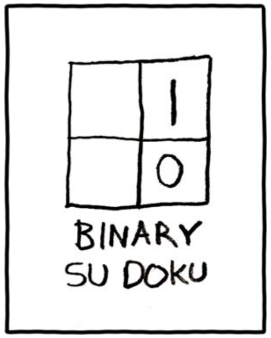
Not adiabatic

"Solves" NP-hard problem:

$$\min_{z \in \{-1,1\}^n} f(z) = \sum_{i=1}^{n} h_i z_i + \sum_{i,j=1}^{n} J_{ij} z_i z_j$$

Numerous practical problems expressible in this way

- Planning
- Scheduling
- FPGA routing
- Data mining
- Resource allocation
- Verifying digital circuits
- Sudoku



Extensive list at www.nada.kth.se/~viggo/problemlist/compendium.html

Even if ideally implemented, it may take exponentially long for a quantum annealer to solve QUBO problems!

AQUARIUS™

Adiabatic quantum architectures in ultracold systems

LDRD Grand Challenge Project FY11 to FY13

VISION:

Develop a quantum-computing architecture whose resource requirements are more achievable than conventional approaches due to the intrinsic noise immunity offered by adiabatic physics

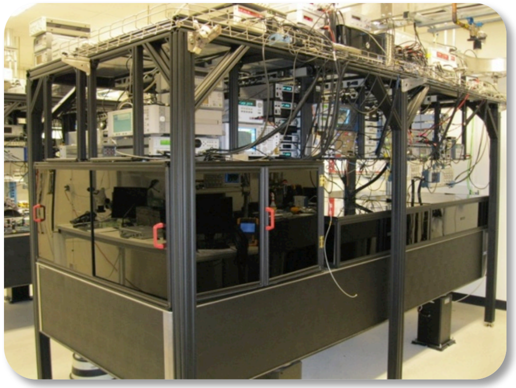
OBJECTIVES:

- Demonstrate two-qubit *special-purpose* adiabatic quantum optimization algorithms in:
    1. Neutral atoms trapped by a nanofabricated optical-trap array
    2. Electrons trapped by semiconductor nanostructures
- And for these technologies to:
    3. Evaluate the potential for fault-tolerant general-purpose adiabatic quantum computation architectures through design & simulation

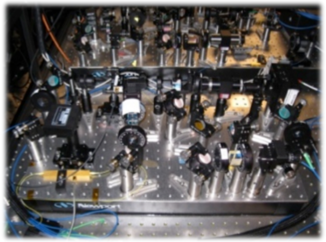
Cs-atom adiabatic quantum computer

Sandia National Laboratories

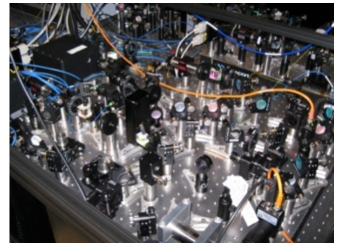
Neutral Cs atoms in an optical trap array



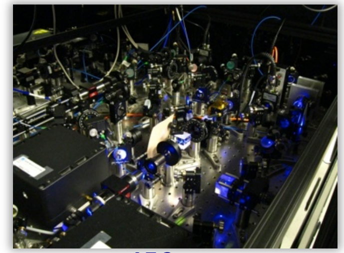
Optical atom trapping & control lab



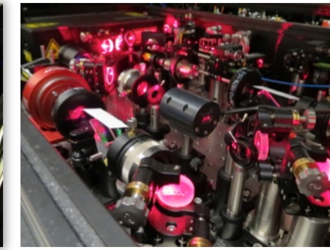
852 nm



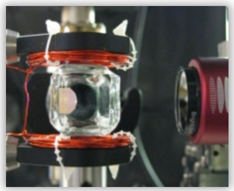
1038 nm



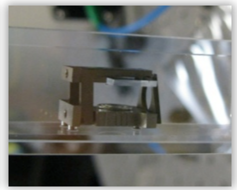
459 nm



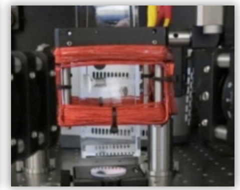
318 nm



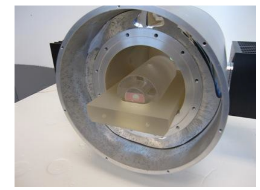
Pyrex cell



Quartz cell

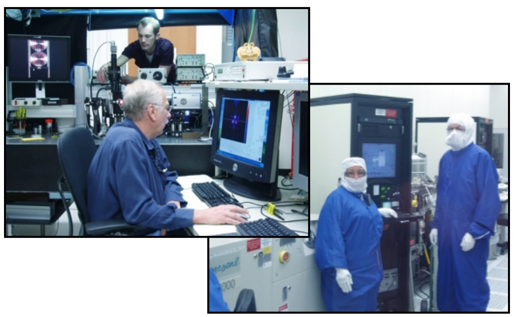


ITO cell

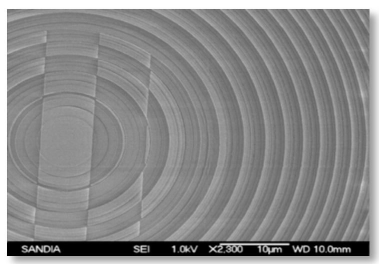


High-finesse cavity

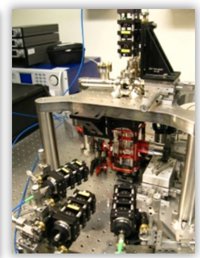
FPGA control system



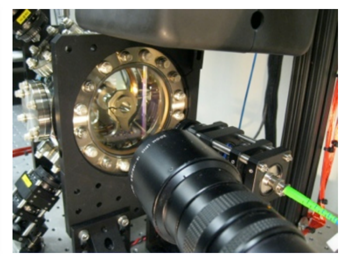
Diffractive-optic element (DOE) fab & test laboratories



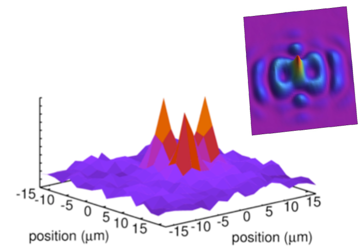
2-trap DOE



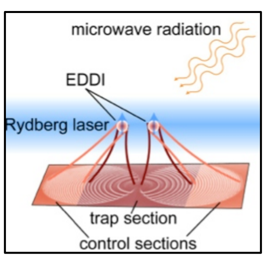
DOE testing



Surface-effect testing



2-trap & 3-trap imaging



$$H(s) = \left[\frac{1}{2}\sum_i b_i(s)\sigma_x^{(i)} + \frac{1}{2}\sum_i h_i(s)\sigma_z^{(i)} + \frac{1}{4}\sum_{ij} J_{ij}(1 \pm \sigma_z^{(i)})(1 \pm \sigma_z^{(i)}) \right]$$

9.2 GHz µw or two-photon 852 nm stimulated Raman

852 nm light shifts

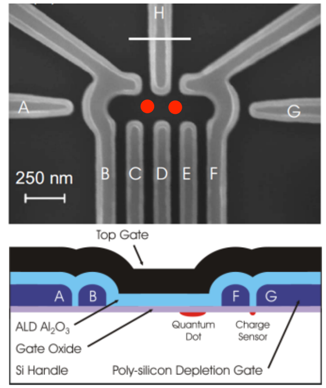
1038 nm + 459 nm or 318 nm Rydberg interactions

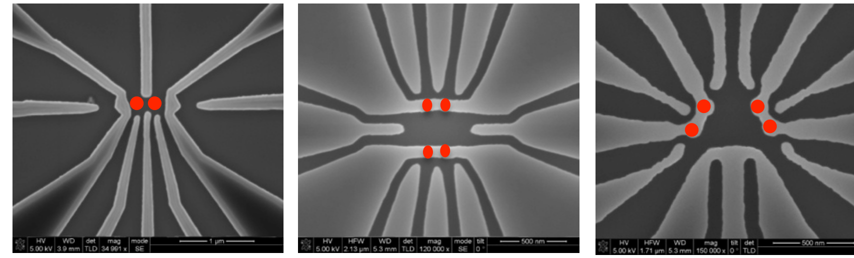
Si-qubit adiabatic quantum computer

Sandia National Laboratories

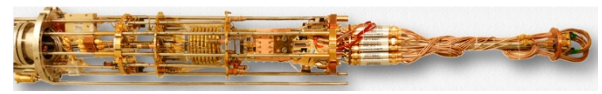
Double-quantum-dot Si charge qubits

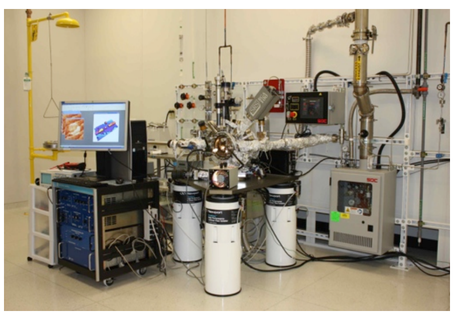
Cryogenic electronics lab



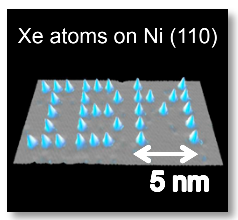


One- and two-qubit devices; 1 qubit = 1 pair quantum dots

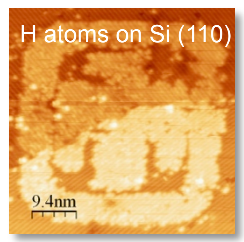




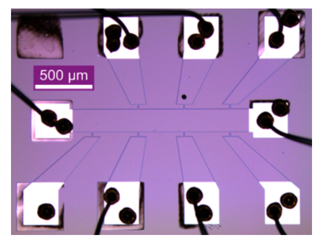
Atomic-precision fabrication lab



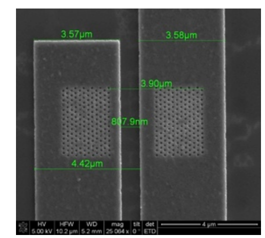
D.M. Eigler et al. *Nature* (1990)



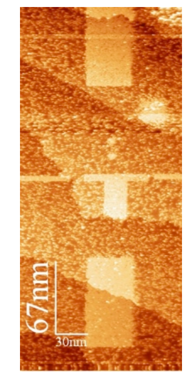
0.7 nm features



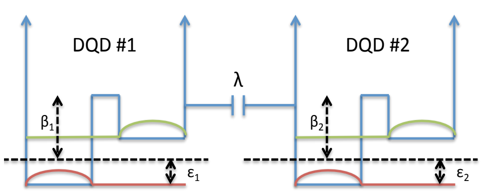
Hall bar (P donors)



Nanowire



Charge qubit



$$H(s) = \left[\frac{1}{2} \sum_i \varepsilon_i(s) \sigma_x^{(i)} + \frac{1}{2} \sum_i \beta_i(s) \sigma_z^{(i)} + \frac{1}{4} \sum_{ij} \lambda_{ij} (1 \pm \sigma_z^{(i)})(1 \pm \sigma_z^{(i)}) \right]$$

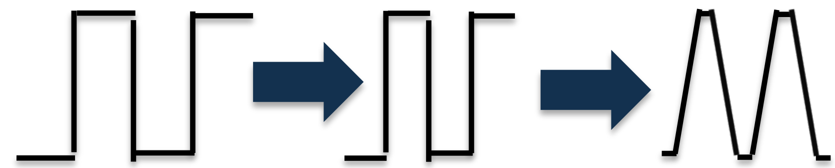
Tunnel barrier (neV – meV)

Detuning (+/- meV)

Capacitive Coulomb interaction (25 – 85 μeV)

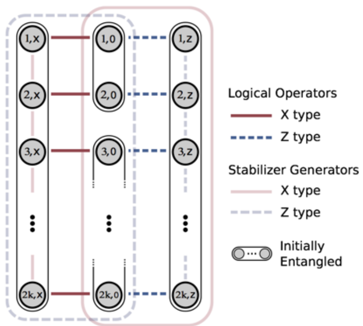
AQUARIUS conclusions

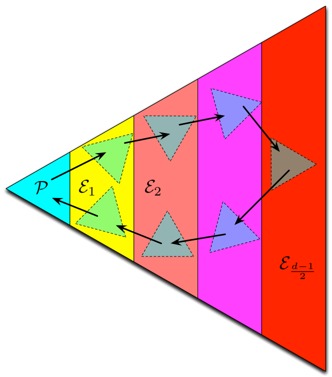
Is it quantum?



- Ran 1- & 2-qubit algorithms on our machines, but…
- …answers on Si machine found by relaxation, not adiabatic effects.

Is it fault-tolerant?

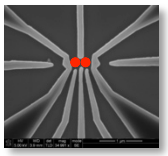




- Invented new QEC for AQC, but…
- …full-blown AQO fault tolerance seems unlikely.

Is it universal?

- Designed a quantum-dot layout for universal AQC, but…
- …building it near-term seems implausible.



Legacies

- **Staff:** Large, cross-center expertise in QIS at Sandia.
- **STM fab @ 0.7 nm:** On beyond qubits! New paradigm for nanoelectronic fab.
- **Atom trapping lab:** now used for precision metrology, high-fidelity quantum gates.