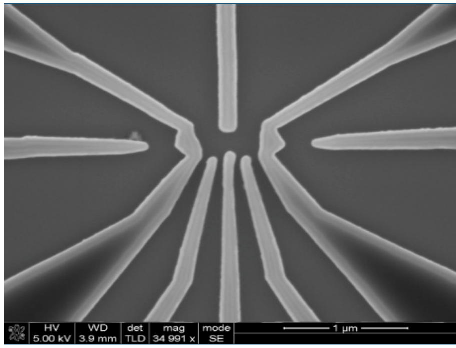
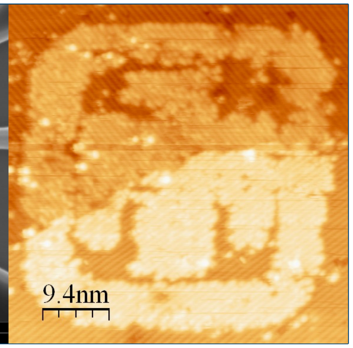
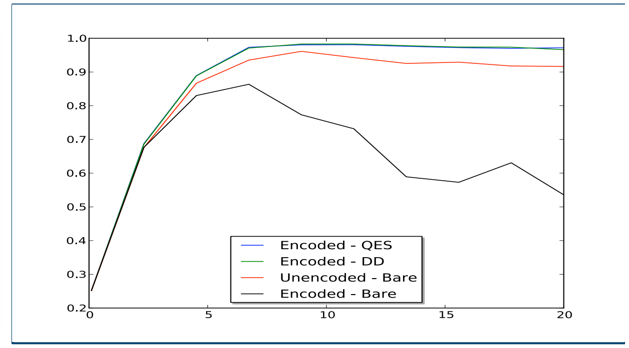
Exceptional service in the national interest

Sandia National Laboratories







Adiabatic quantum computing at Sandia

Andrew J. Landahl

1/20/12

This work was supported in part by the Laboratory Directed Research and Development program at Sandia National Laboratories.

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

#1 Grand Challenge for QIS

Sandia National Laboratories

- Building a large general-purpose quantum computer is hard.

- World record number of addressable entangled qubits (scalable technology) : 14 qubits.

[Monz et al, PRL **106**, 130506, 2011 (Ion trap, Blatt group, Innsbruck)]

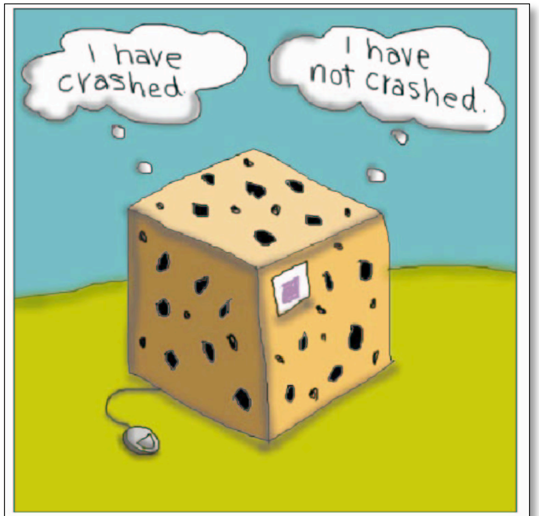
- World record simulated (error-free) universal quantum computer: 42 qubits.

[Michielsen, 2010 (Julich JUGENE supercomputer: 15707 = 113 × 139)]

- Qubits needed to simulate an ideal circuit on 300 ideal qubits: a **billion** qubits.*

* Gates in ideal circuit: 10^9, qubit error rate: 10^{-6}, 2-qubit gate error rate: 10^{-4}, 1-qubit gate error rate: 10^{-3}.

[Steane, 2007 (Ion trap tech., quantum circuit architecture)]



Schrödinger's computer. —Sally O. Lee

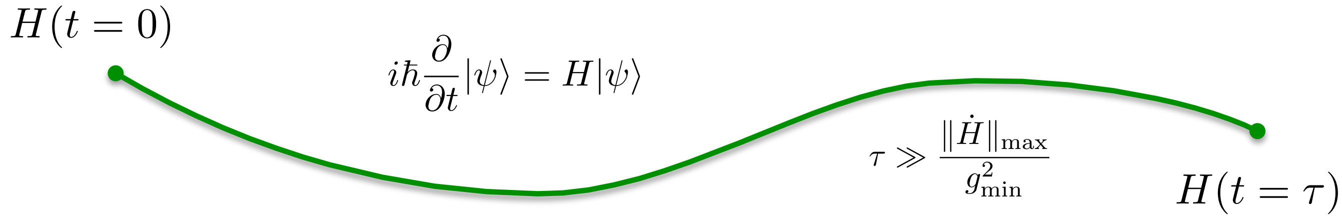
→ Vast numbers of qubits are used for error correction!

- **Options for reducing qubit overhead:**
  - Better hardware
  - Better error correction schemes
  - Better computer architecture!

Adiabatic quantum computing 101

Sandia National Laboratories

0. Encode
1. Initialize
2. Evolve
3. Readout



Clearing up common misconceptions about adiabatic quantum computing:

- Adiabatic quantum computing is not analog computing.
- Adiabatic quantum computing is universal.
- Adiabatic quantum computing is not slow. (At least for universal AQC.)
- Adiabatic quantum computing is technology-independent.
- Adiabatic quantum computing appears to be robust to realistic noise sources.
- Adiabatic quantum computing has yet to be proven strictly fault-tolerant.

DiVincenzo criteria

1. Fiducial state initializable?
2. Qubit measurable?
3. Long coherence times?
4. Gates universal?
5. Scalable?

New criteria

1. *Superposition ground state* initializable?
2. Qubit measurable?
3. *Small transition amplitudes to excited states?*
4. *Couplings universal?*
5. Scalable?

If the adiabatic quantum computing architecture can reduce the number of qubits needed to implement algorithms by a factor of a million, then it's a really big deal, even if a million is "only a constant."

A Sandia Grand Challenge

Sandia National Laboratories

AQUARIUS™

Adiabatic quantum architectures in ultracold systems

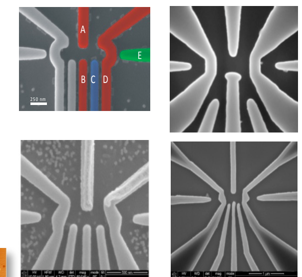
Oct. 2010 to Sep. 2013

Vision

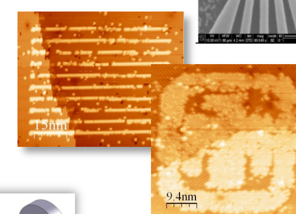
- Develop a quantum-computing architecture whose resource requirements are more achievable than conventional approaches due to the intrinsic noise immunity offered by adiabatic physics

The adiabatic architecture could be a game-changer for quantum computing.

Science & Technology Challenges

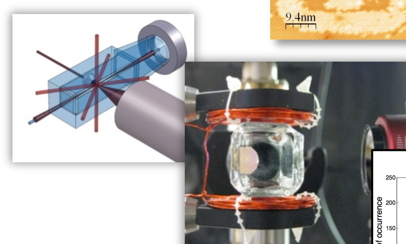


- Experimental proof of adiabatic quantum computing (AQC) in a scalable technology
- Theoretical design of a universal fault-tolerant AQC architecture

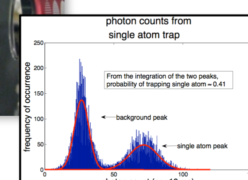


Deliver a prototype and a path forward to scale-up.

Objectives of AQUARIUS



- Demonstrate special-purpose two-qubit AQC optimization algorithms in
  - Neutral atoms trapped by a nanofabricated optical array
  - Semiconductor electrons trapped by nanofabricated structures

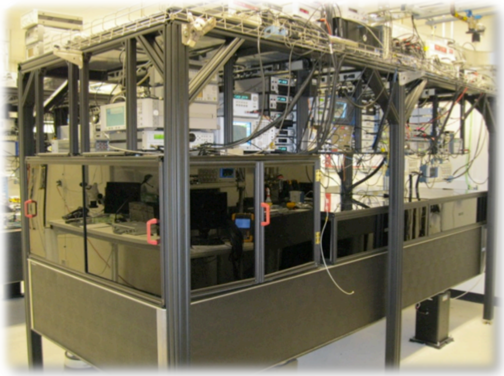


- Assess the potential for universal fault-tolerant AQC architectures through design & simulation.

Deliver prototypes in representative technologies & pursue a scalable design for general-purpose computing.

AQUARIUS labs & facilities

Sandia National Laboratories



Optical atom trapping & control lab

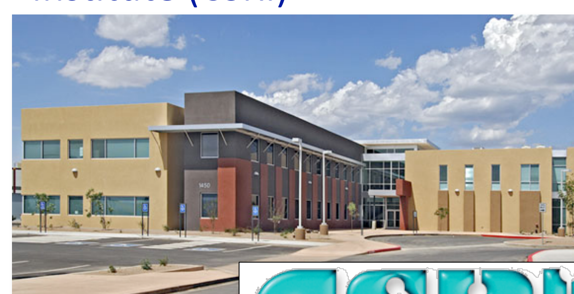
Cryogenic materials & electronics measurement lab

Atomic-precision lithography (STM) lab

Microsystems and Engineering Sciences Applications (MESA)

Center for Integrated Nanotechnologies (CINT)

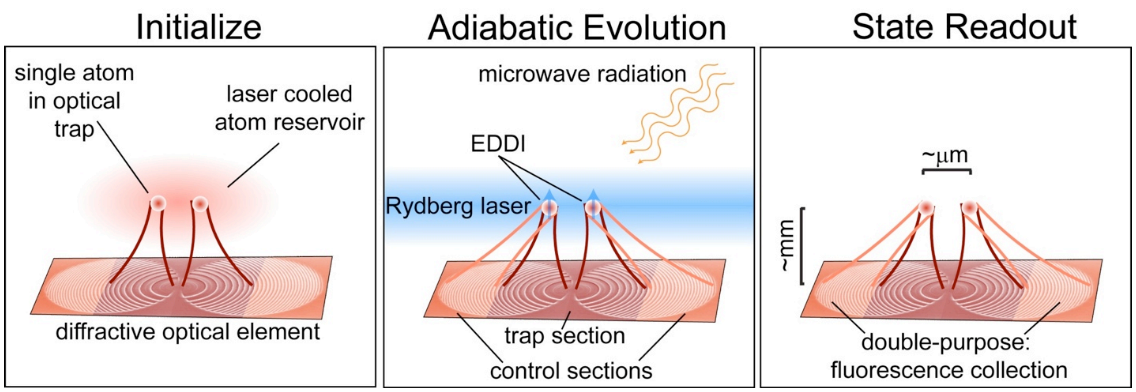
Computer Science Research Institute (CSRI)



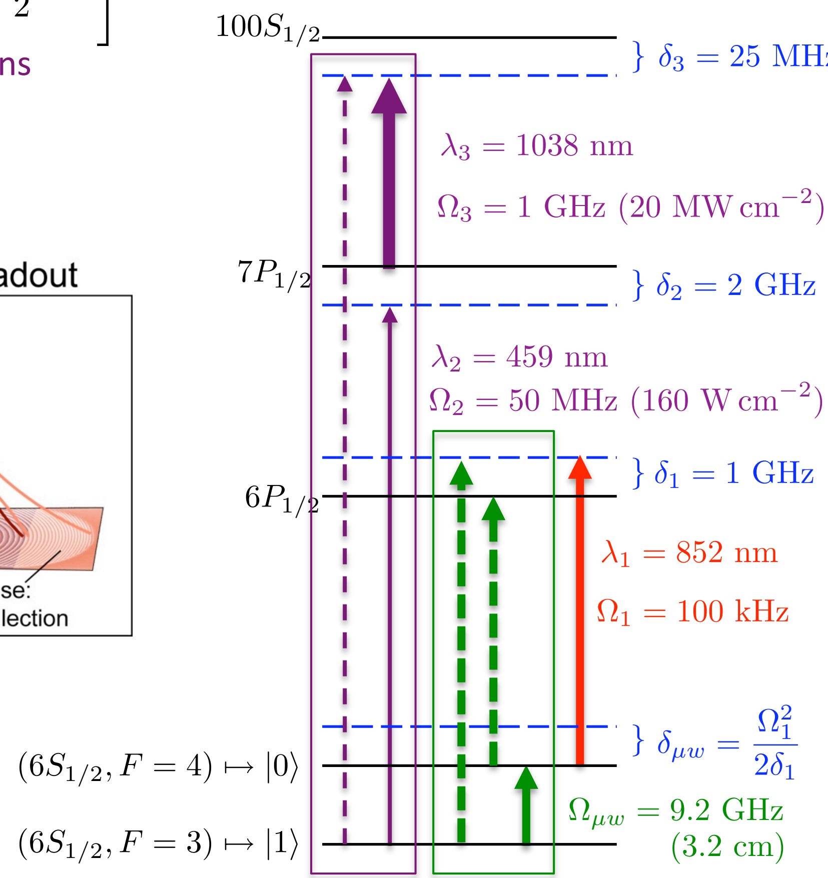
Neutral-atom AQC: Theory

$$H = \frac{\hbar}{2}\left[\sum_i \Omega_{\mu w}^{(i)}(s)\sigma_x^{(i)} + \sum_i \delta_{\mu w}^{(i)}(s)\sigma_z^{(i)} + \sum_{ij}\frac{\Omega^{(i)}\Omega^{(j)}}{8\delta_2(s)^3}\frac{(1\pm\sigma_z^{(i)})}{2}\frac{(1\pm\sigma_z^{(j)})}{2}\right]$$

Microwaves/ two-photon Raman | Light shifts | Rydberg interactions

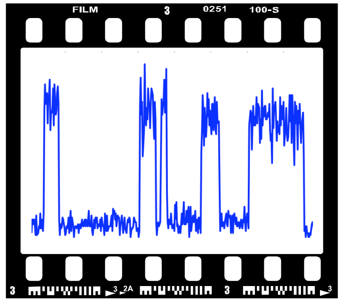


Cs level structure

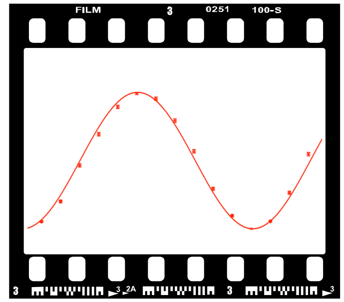


Neutral-atom AQC: Timeline

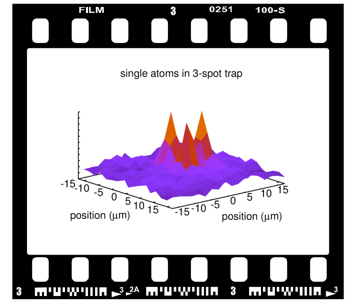
Observed MOT



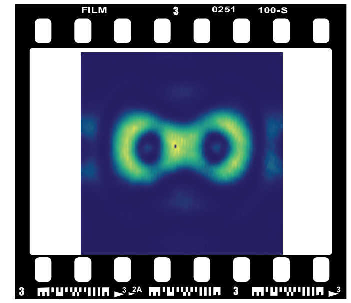
Single atom "jumps" observed in dipole trap flourescence



Microwave rotations on single atom—σ_x



First demonstration of single atoms in DOE

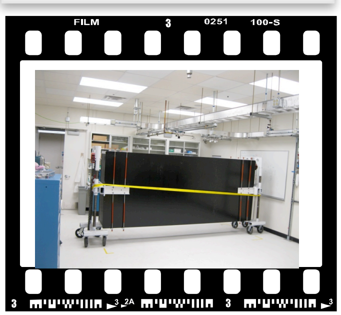


First signals from "BoB" DOE—collaboration with Wisconsin

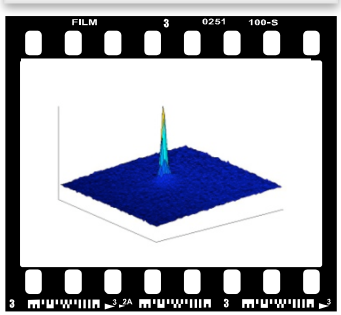
month

12 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11

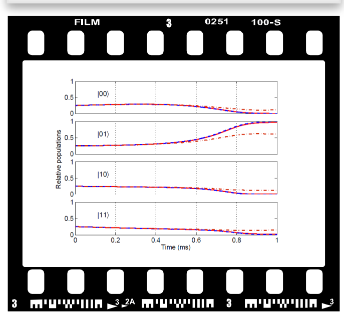
Lab space obtained



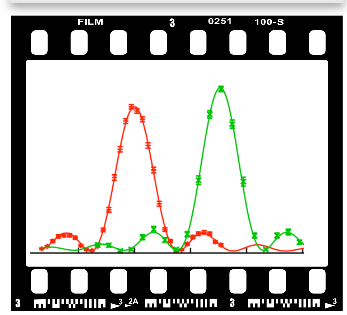
First Trapping in Dipole trap



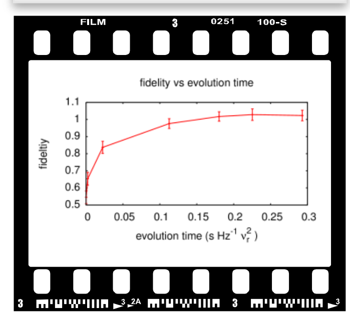
Noise model developed
Collaboration with UNM



Light Shift—σ_z



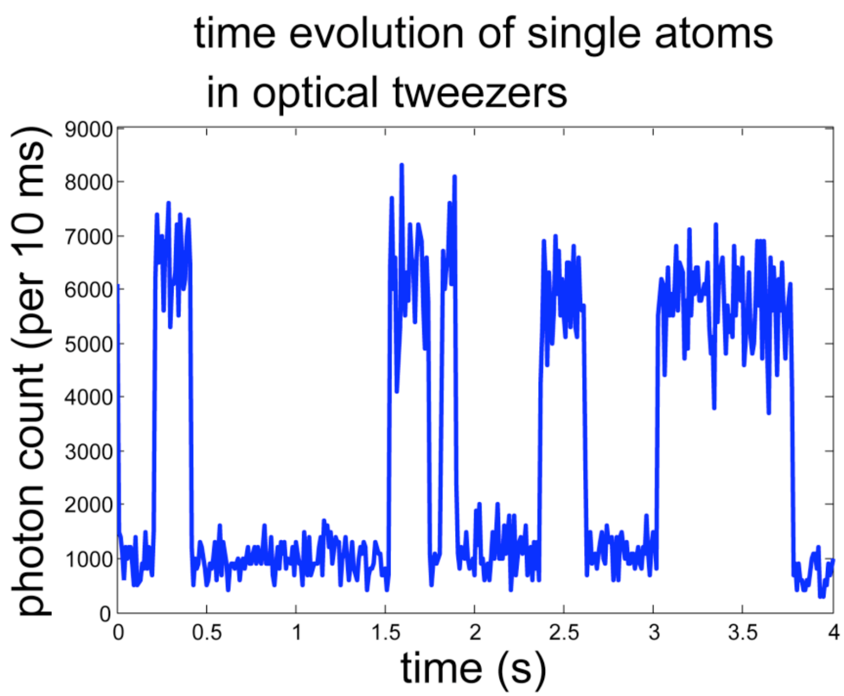
Single atom adiabatic evolution

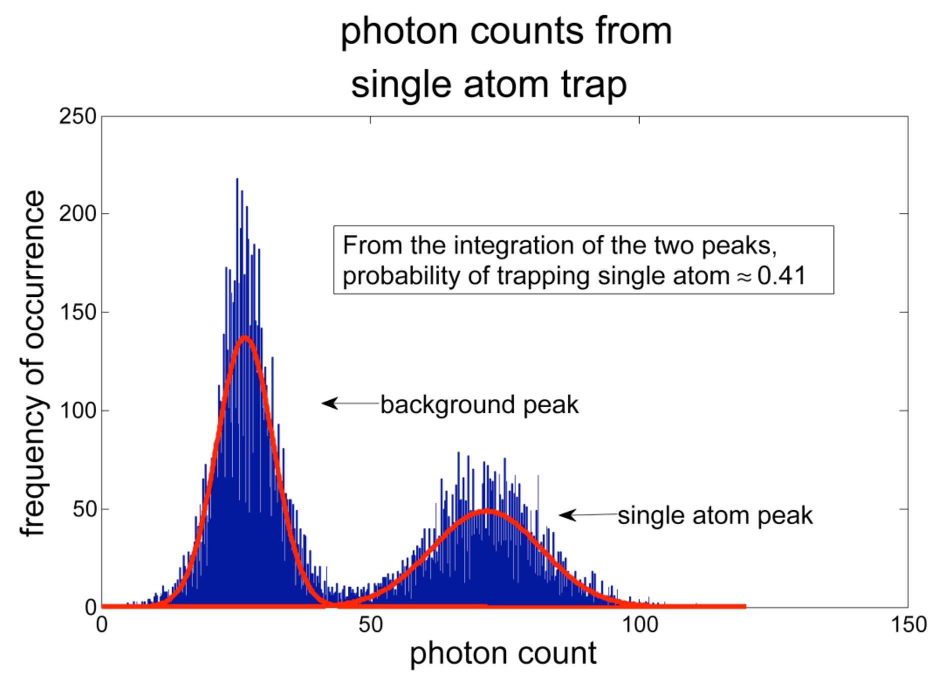


Neutral-atom AQC: Single atoms

Sandia National Laboratories

❑ Trapping single atoms in an optical dipole trap





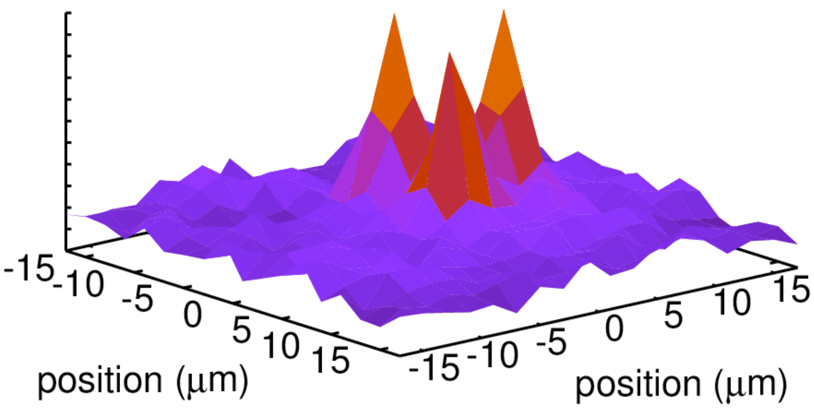
- "Jumps" in photon count rate indicate a single atom entering or leaving
- Collisional blockade limits trapped number of atoms to 1

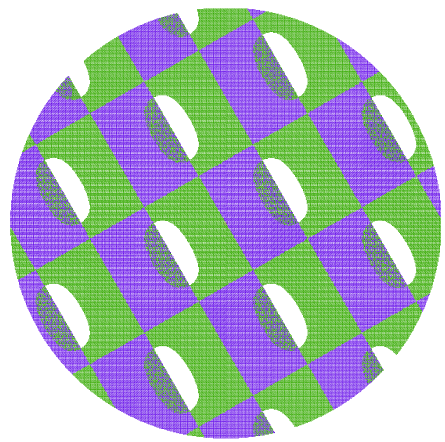
- Absence of third peak indicates collisional blockade is active

Neutral-atom AQC: DOEs

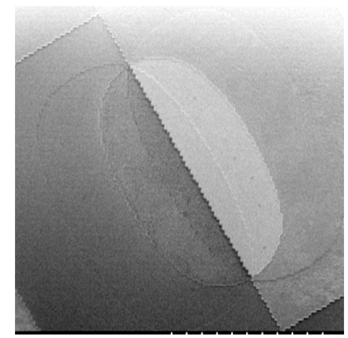
- Using DOE to trap single atoms in multiple traps
  - An enabling technology for complex control

single atoms in 3-spot trap

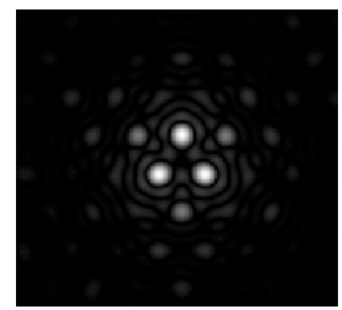




Phase shift pattern



SEM



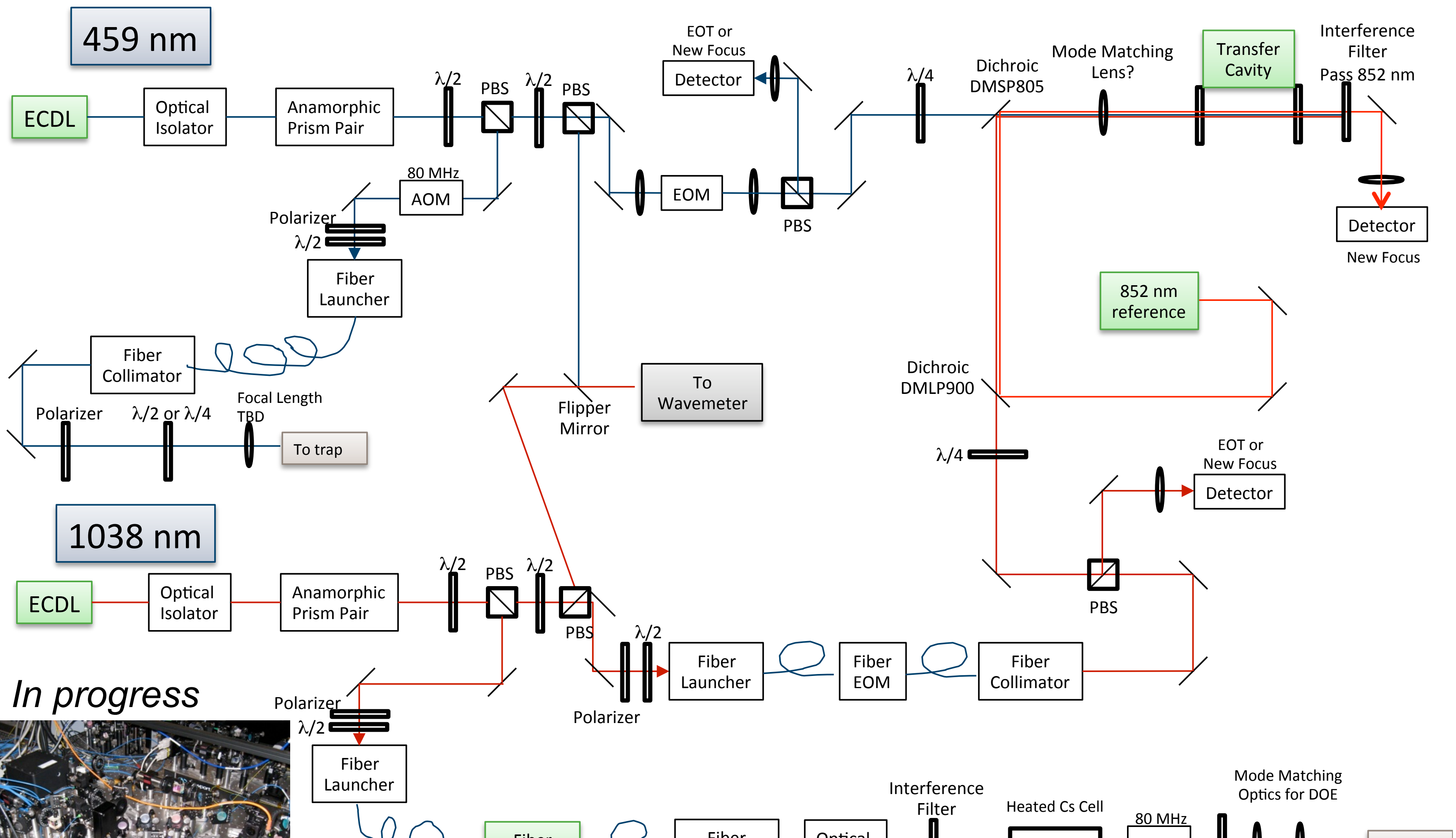
Numerical

- Three traps
- Nine micron separation
- Artifacts are manageable

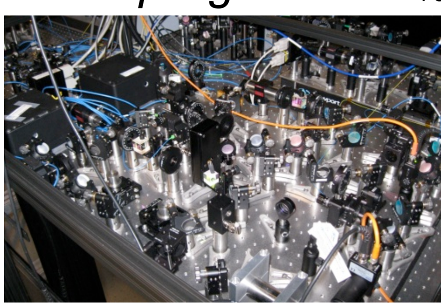
- Analytic phase
- Four levels
- 2 mm pixels

Two-photon Rydberg laser

Sandia National Laboratories

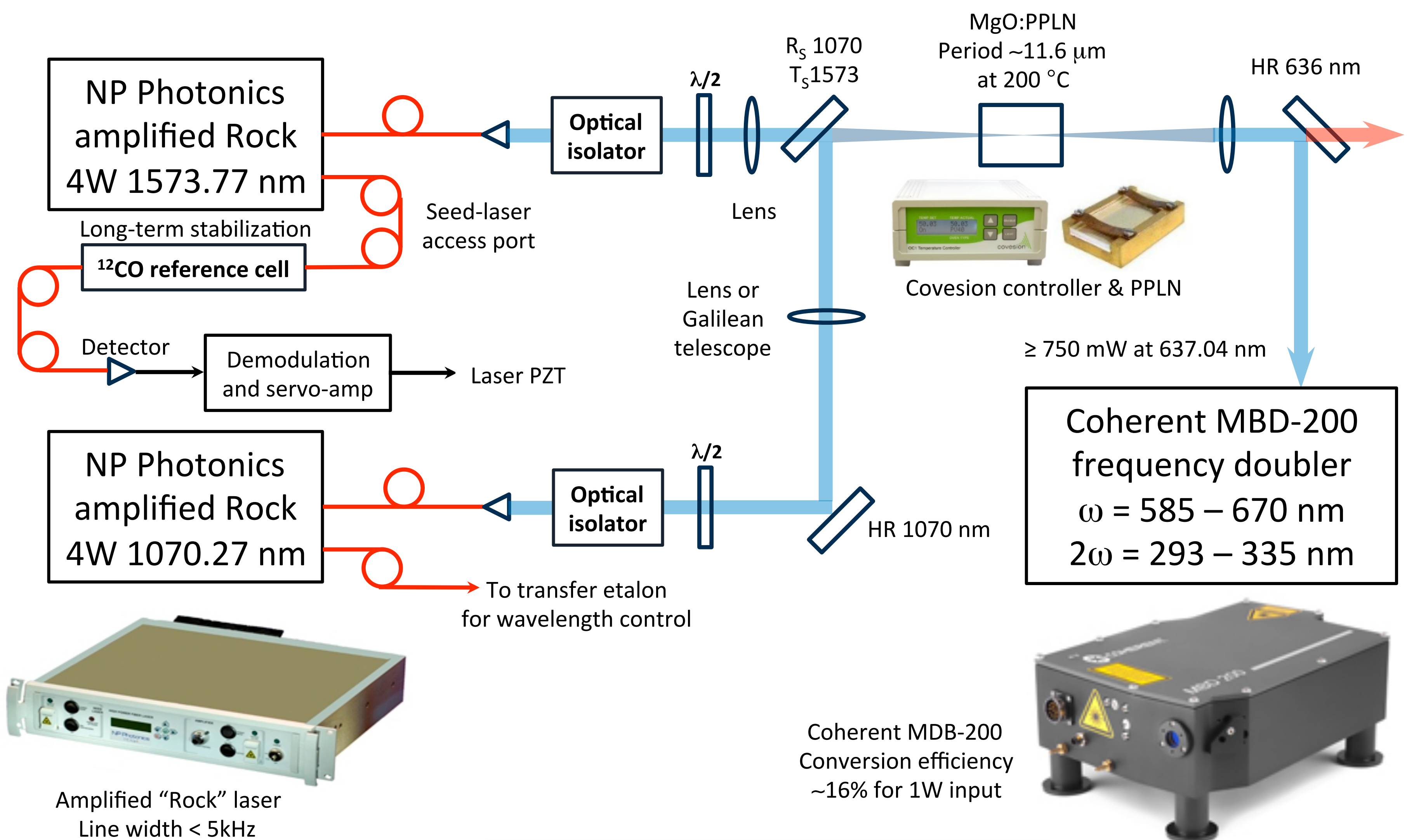


In progress



Direct-transition 318 nm Rydberg laser

Sandia National Laboratories



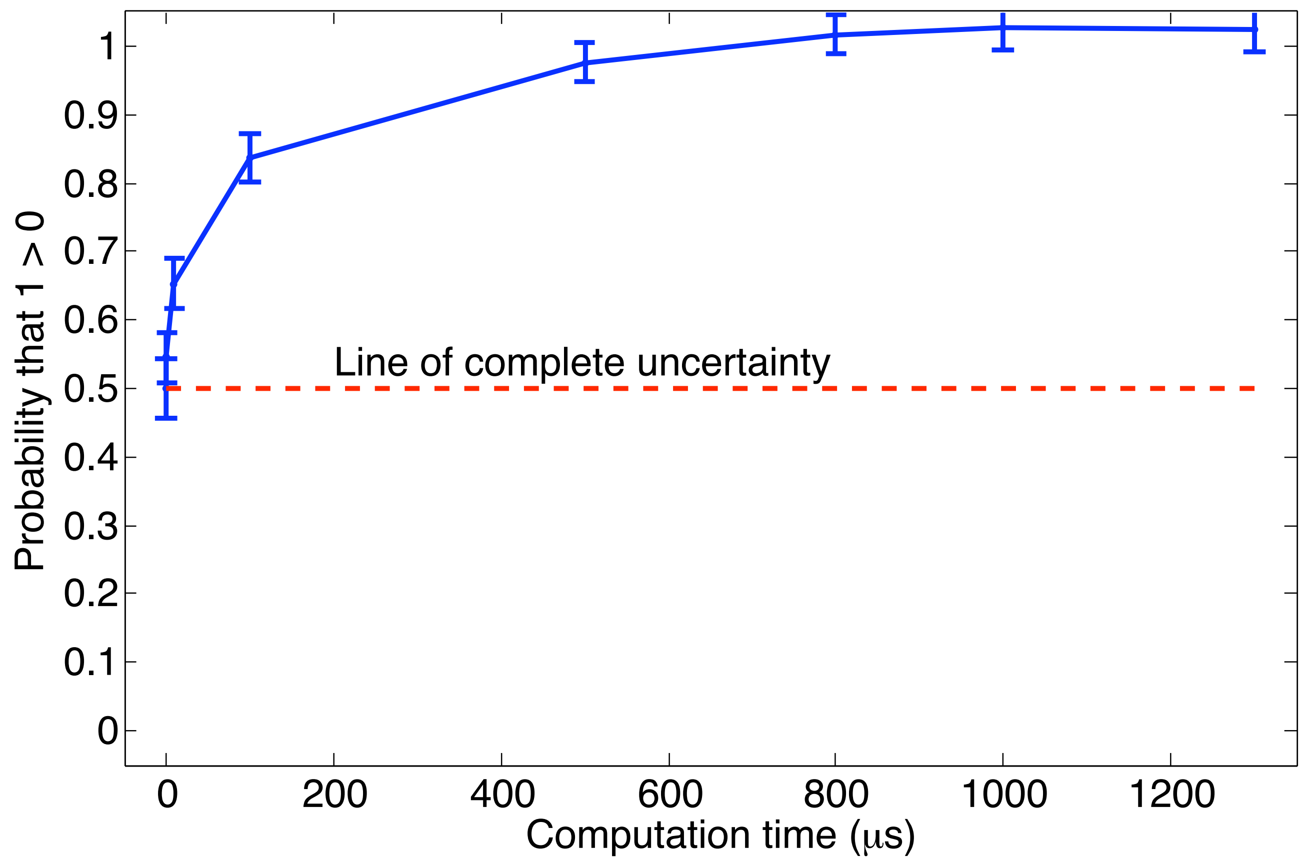
100 mW is enough for 10 atoms

Sandia's first quantum calculation

Sandia National Laboratories

"LUBO:" Linear Unconstrained Binary Optimization $\min x, \quad x \in \{0,1\}$

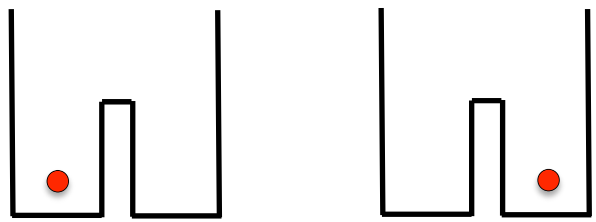
$$\sigma_x \rightarrow \sigma_x + 27\sigma_z$$



Conclusion: 0 < 1, with high probability

Semiconductor AQC: Theory

Double-well qubits



$|0\rangle = |1\rangle_L|0\rangle_R$ $|1\rangle = |0\rangle_L|1\rangle_R$

Charge qubit
Short T_2 but easier to work with

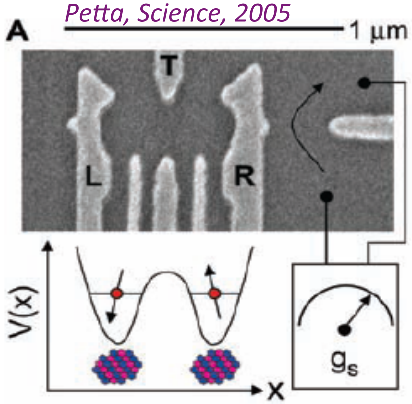
$|0\rangle = \frac{|\uparrow\rangle_L|\downarrow\rangle_R + |\downarrow\rangle_L|\uparrow\rangle_R}{\sqrt{2}}$ $|1\rangle = \frac{|\uparrow\rangle_L|\downarrow\rangle_R - |\downarrow\rangle_L|\uparrow\rangle_R}{\sqrt{2}}$

Spin qubit
Long T_2 but harder to work with

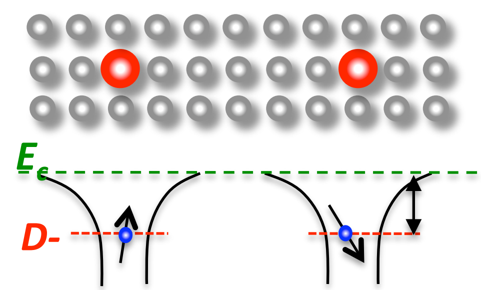
(Electrical readout for both types, though.)

Two semiconductor approaches to generating double-well qubits

Petta, Science, 2005



Double quantum dot

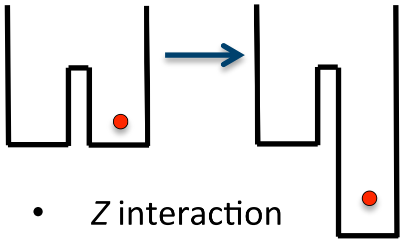


Pair of implanted donors

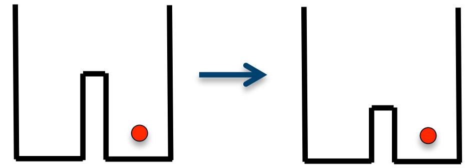
Semiconductor AQC: Theory

Sandia National Laboratories

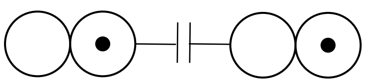
Available interactions



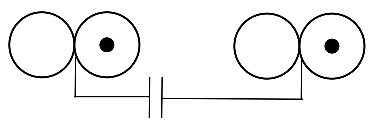
- *Z* interaction



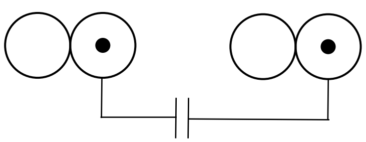
- *X* interaction



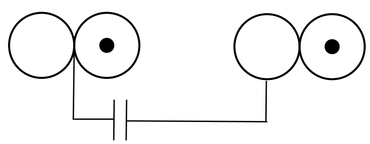
ZZ interaction



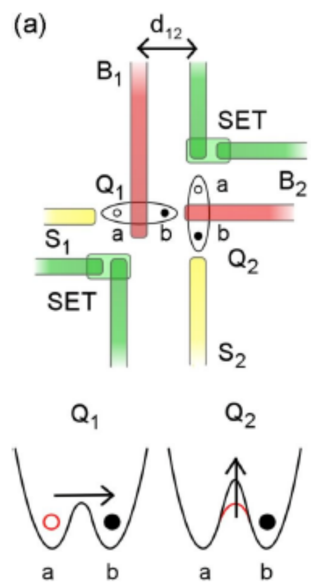
XX interaction



−*ZZ* interaction



XZ interaction

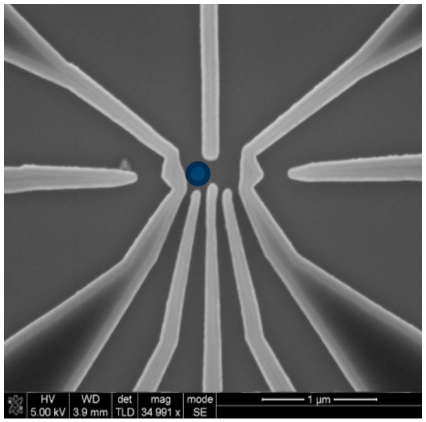


X, XZ, XX interactions have yet to be demonstrated but have been proposed for some time. (e.g., Hollenberg et al.)

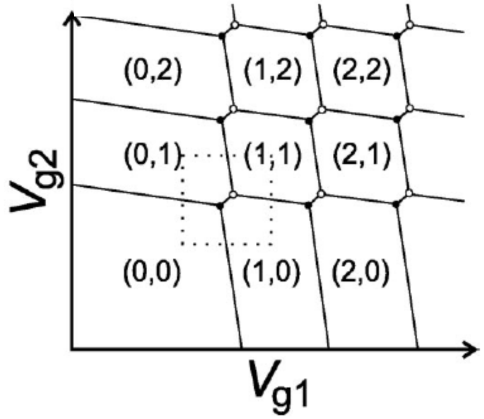
Semiconductor AQC: DQD

Sandia National Laboratories

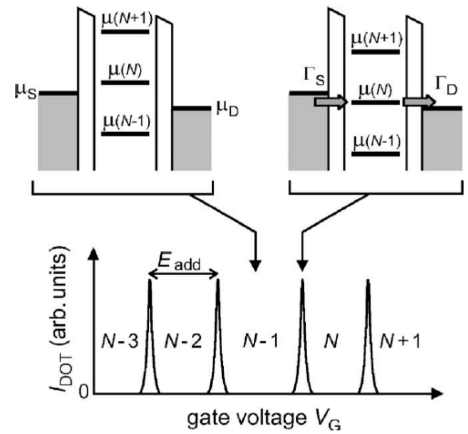
Gated DQD



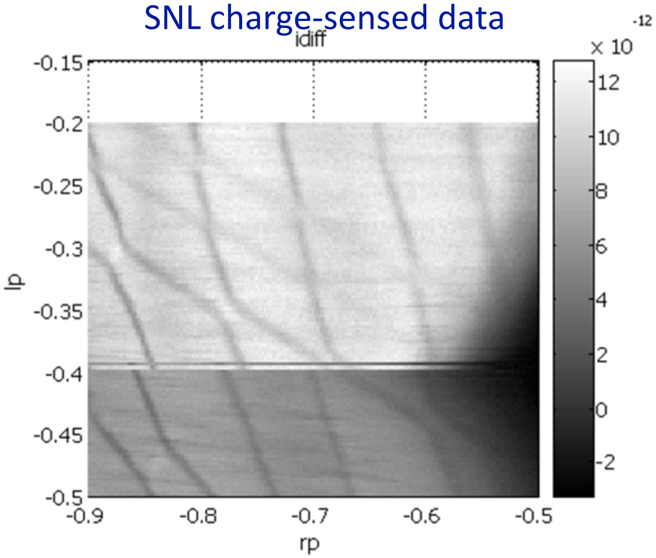
Honeycomb diagram



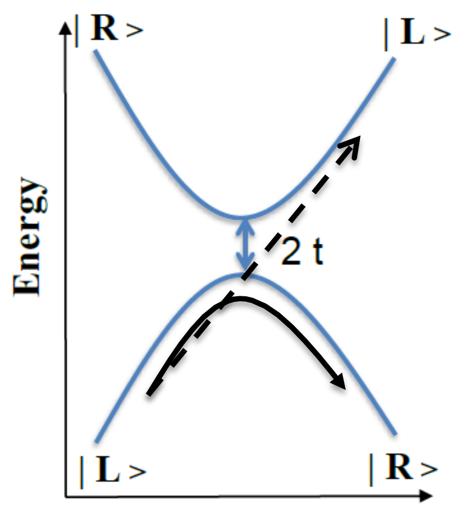
Coulomb blockade

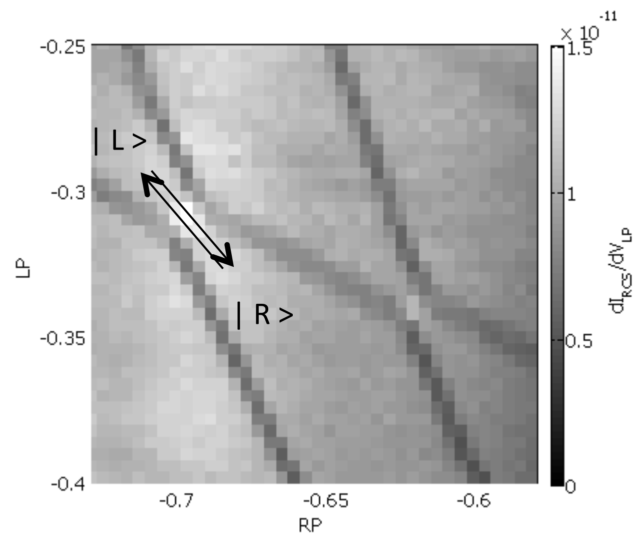


SNL charge-sensed data



Beginning charge-qubit adiabatic evolution studies (SNL)





Atomic-precision devices

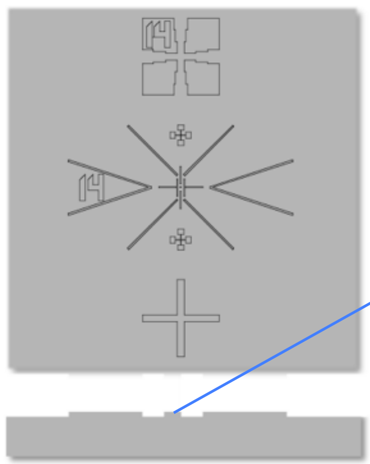
M. Y. Simmons *et al.*, U. New South Wales, CQCCT, Australia

1. Start w clean Si(001)

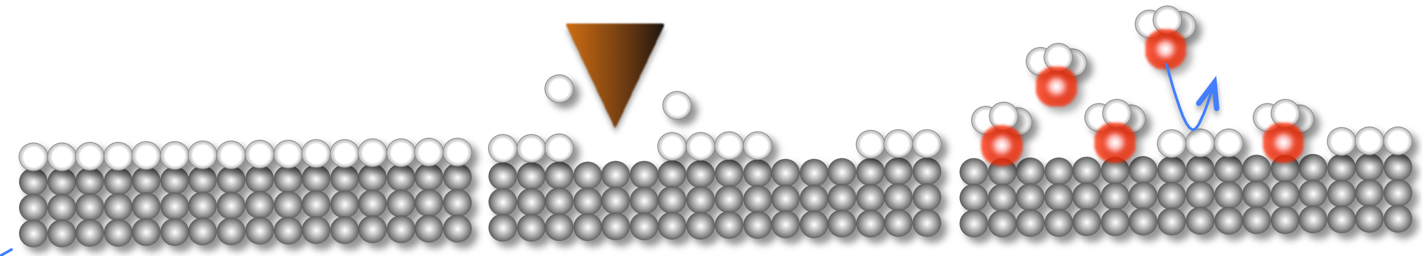
2. Adsorb H resist
Self-limiting 1 monolayer

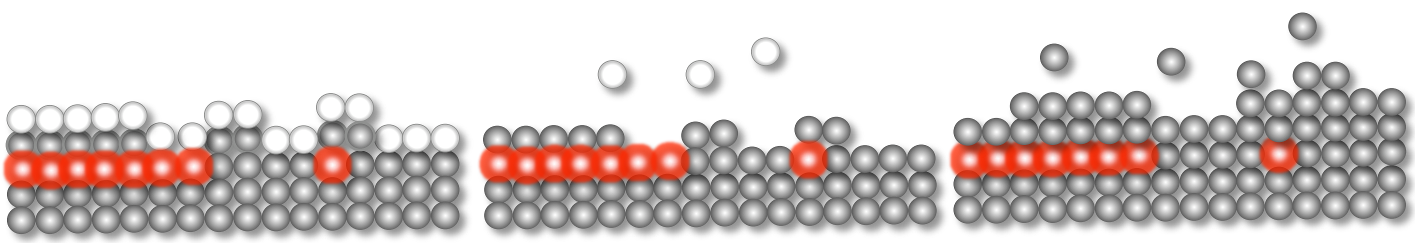
3. Pattern w STM
Atomic-precision

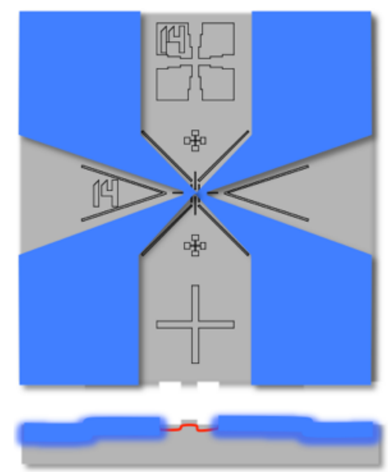
4. Adsorb PH_3



Etched alignment marks







5. Incorporate P
-Anneal→ Si-P swap
-H resist constrains P

6. Desorb H
anneal

7. Bury P in Si

8. Add contacts
Al depo+liftoff

Atomic-precision devices

Sandia National Laboratories

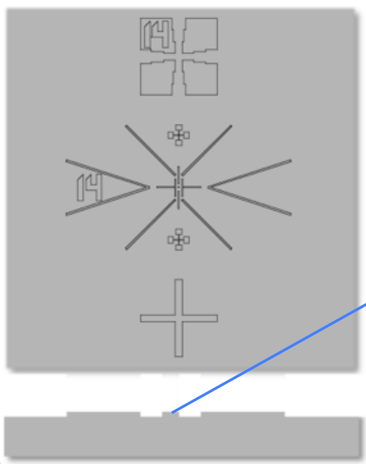
Testing PH_3 system

1. Start w clean Si(001)

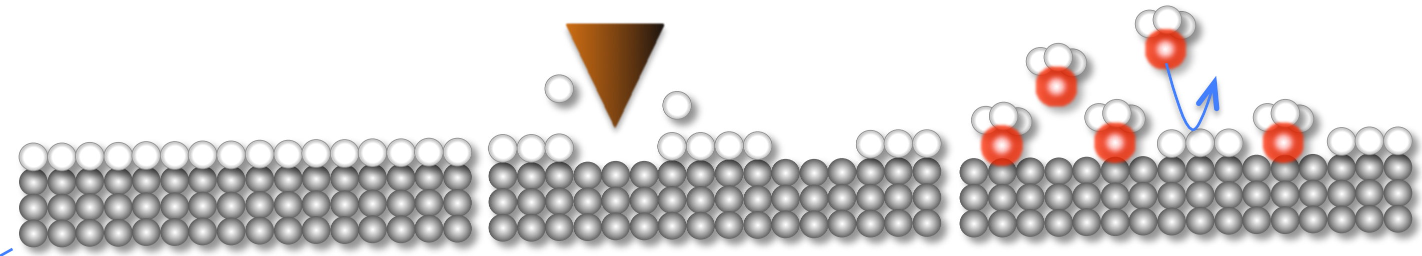
2. Adsorb H resist
Self-limiting 1 monolayer

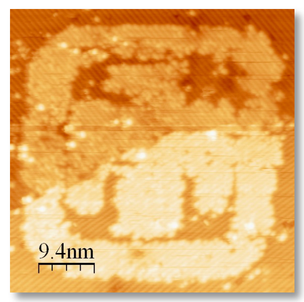
3. Pattern w STM
Atomic-precision

4. Adsorb PH_3

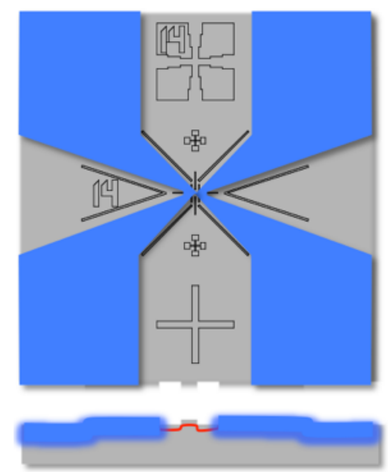


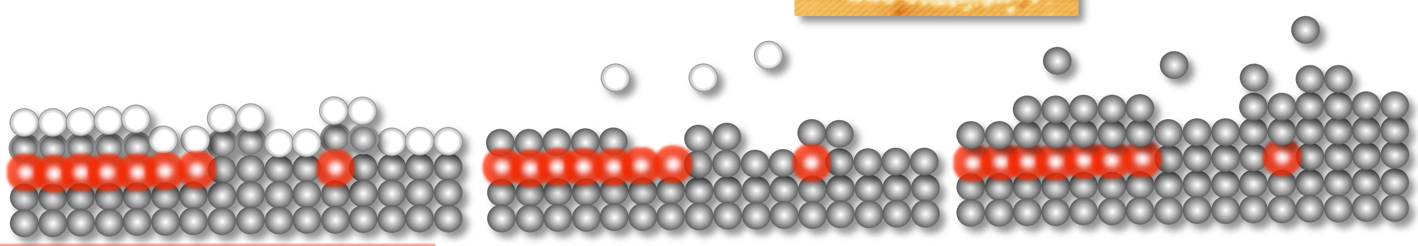
Etched alignment marks





Al depo+liftoff





5. Incorporate P
-Anneal→ Si-P swap
-H resist constrains P

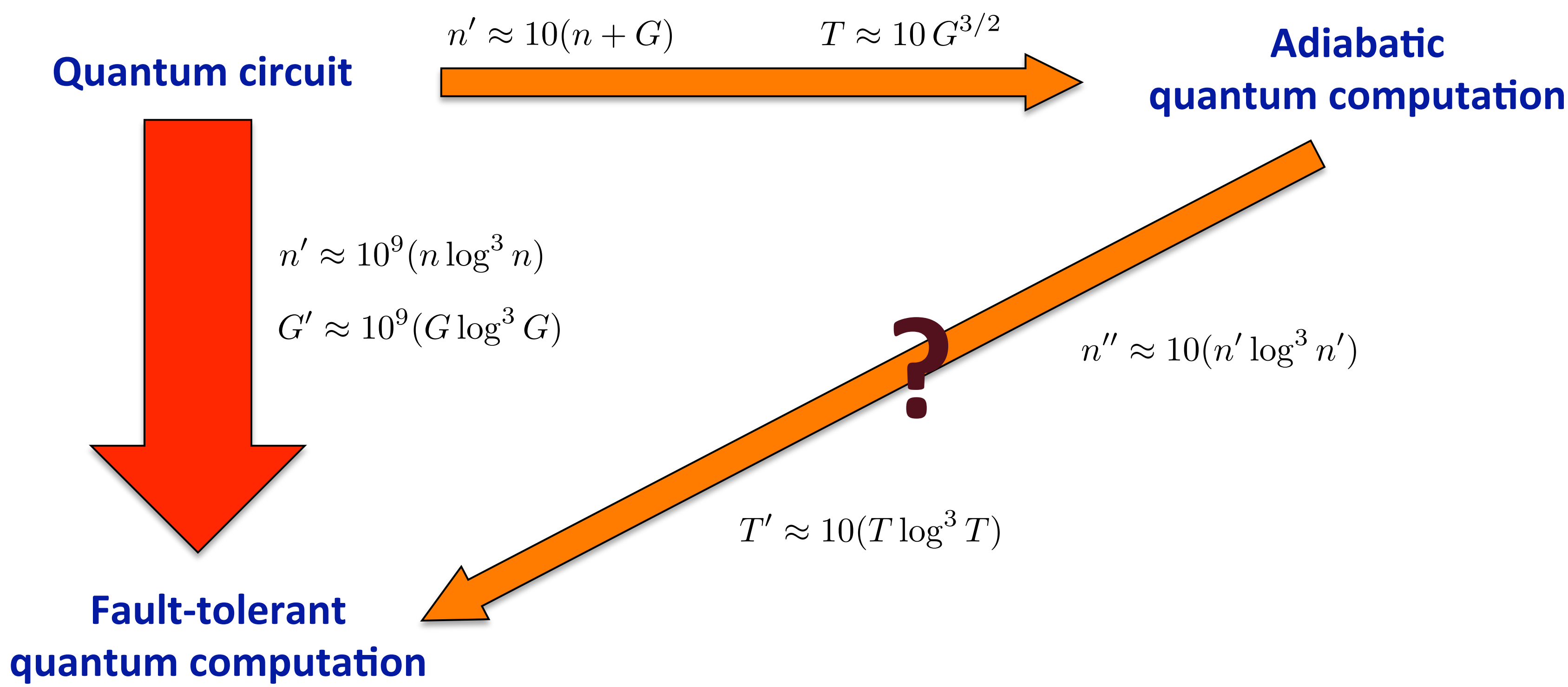
6. Desorb H
anneal

7. Bury P in Si

8. Add contacts

Universal fault-tolerant AQC

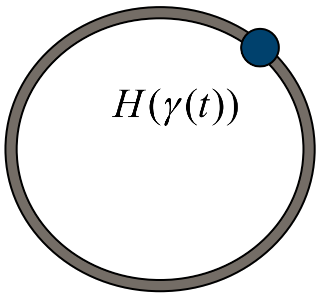
Sandia National Laboratories



Challenge 1: Creating a map from circuits to AQC that is realistic for hardware

Challenge 2: Creating a map from AQC to FTQC. (Is it even necessary?)

Holonomic AQC

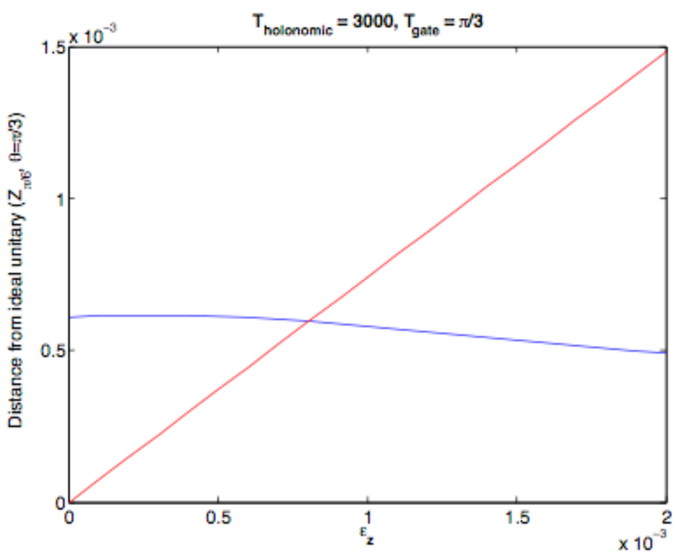


$|\psi\rangle \rightarrow U\,|\psi\rangle$

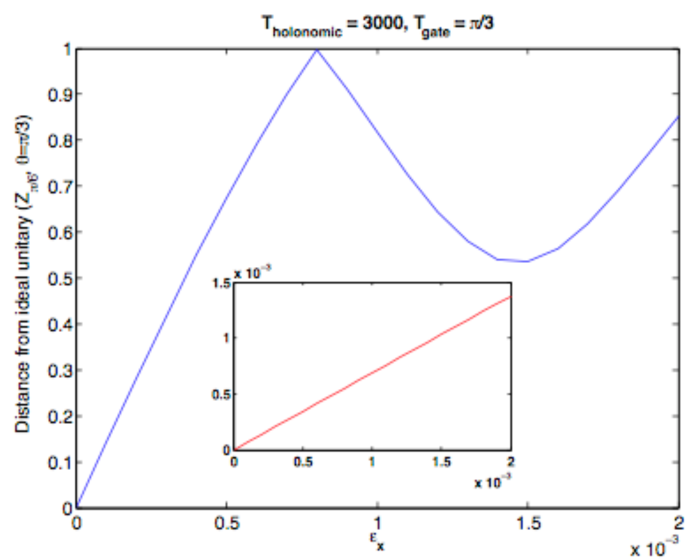
$$Z_{\theta/2} : -IX \rightarrow -ZZ \rightarrow -I(X\cos\theta + Y\sin\theta) \rightarrow -IX$$

$$CNOT : -IZZI - IXXI \rightarrow -XXII - IIZZ \rightarrow -IZII - IIXI \rightarrow -IZZI - IXXI$$

$$\tilde{U}_H = \mathcal{T}\exp\left[-i\int_0^{3T} \alpha(t)IX + \beta(t)(1+\epsilon_z)ZZ + \gamma(t)I(\cos\theta X + \sin\theta Y) + \epsilon_x(IX + XI)dt\right]$$



Robust to ZZ noise (red: conventional gate, blue: holonomic gate)



Not robust to X noise (red: conventional gate, blue: holonomic gate)

Extremely sensitive to degeneracy-splitting noise

DD v. QES 4 AQC

QUBO in the [[4,2,2]] quantum error-correcting code [Jordan, Farhi, Shor, 2005]

$$H_0 = (X_1 + X_2)$$
$$H_1 = Z_1 - Z_2 + Z_1 Z_2$$
$$H(s) = (1-s)H_0 + sH_1$$

→

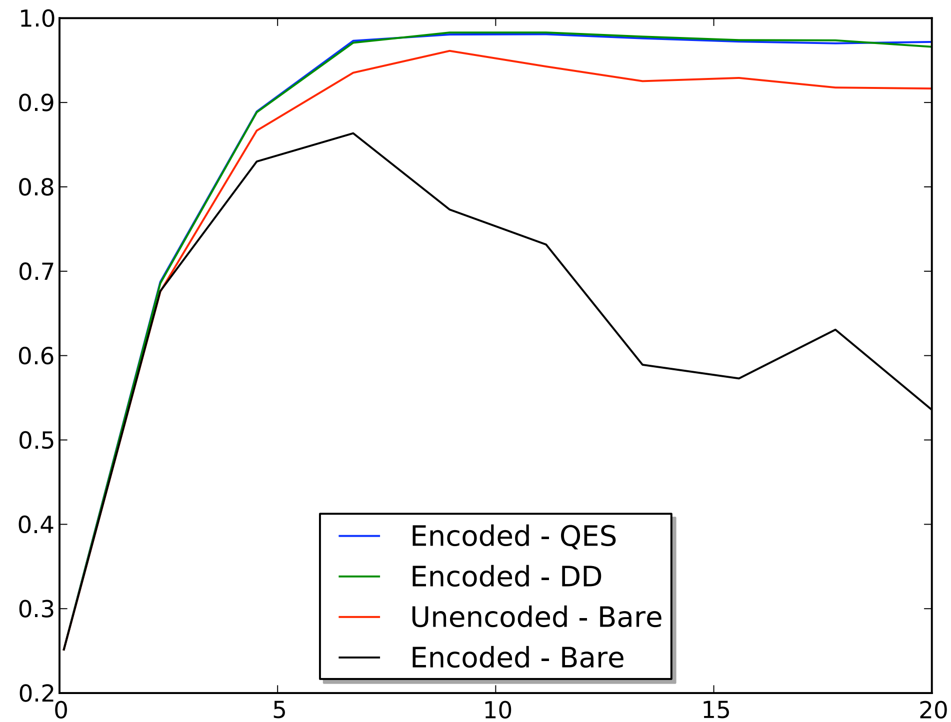
$$H_0 = (X_1 X_2 + X_1 X_3)$$
$$H_1 = Z_2 Z_4 - Z_3 Z_4 + Z_2 Z_3$$
$$H(s) = (1-s)H_0 + sH_1$$

$$H = H_{\mathrm{QUBO}}(t) + \sum_i \eta_i(t) Z_i + H_{\mathrm{ctrl}}$$

$$S(\omega) \simeq \frac{10^{-3}}{\omega}$$

[Kitaev, 1997] [Lidar, 2007]

$$H_{\mathrm{ctrl}} = \begin{cases} \Omega(XXXX + ZZZZ) & \mathrm{QES} \\ \sum_j \frac{\pi}{2}(ZZZZ \times XXXX)\delta(\mathrm{mod}_\pi \Omega t) & \mathrm{DD} \end{cases}$$



DD and QES perform nearly identically

Encoding without QES/DD is *very bad*

Synopsis

- The adiabatic quantum architecture appears on paper to have great implementation robustness, potentially radically reducing the resources needed to implement quantum algorithms
- At Sandia, we are investigating this with two proof-of-principle demonstrations in complementary hardware (neutral atoms and semiconductors)
- We have run a program our first adiabatic quantum processor (neutrals) and the second in quantum dots is on the way.
- We are exploring potential universal AQC constructions for realistic hardware, and the scale at which fault-tolerance might be necessary
- Stay tuned…

AQC 2012: Mar. 7-8, Albuquerque, NM

Sandia National Laboratories

Theme: Challenges to implementation

Invited speakers (confirmed):

- Daniel Lidar
- Frank Gaitan
- Mark Saffman
- Andy Sachrajda
- Mohammad Amin

Website coming online soon!