SAND2012-9240C

Exceptional service in the national interest

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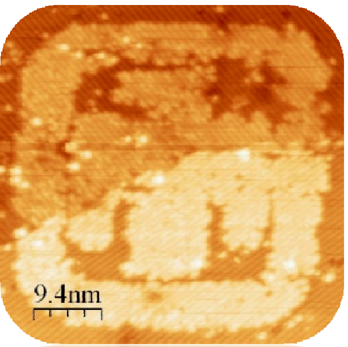
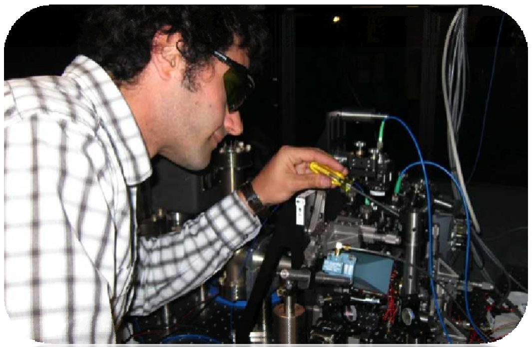
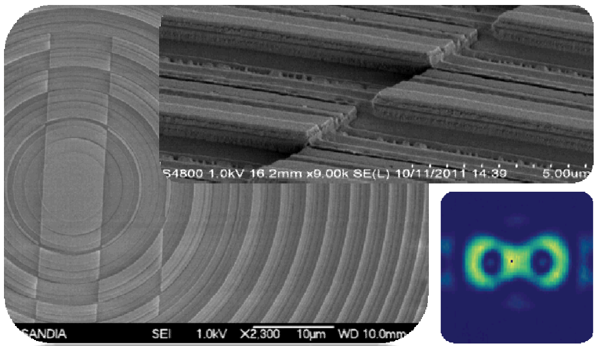
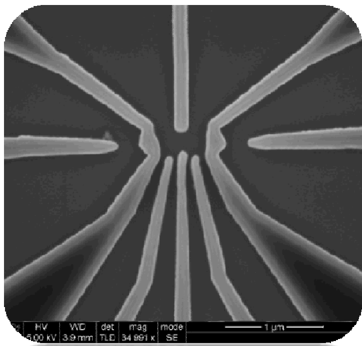








Adiabatic Quantum Computing

Andrew J. Landahl

Principal Quantum Information Scientist, Sandia National Laboratories

National Laboratory Research Associate Professor, University of New Mexico

Vice Chair, American Physical Society Topical Group on Quantum Information

10/26/12

Quantum Information Science

Sandia National Laboratories

Unraveling Nature's limits and capabilities

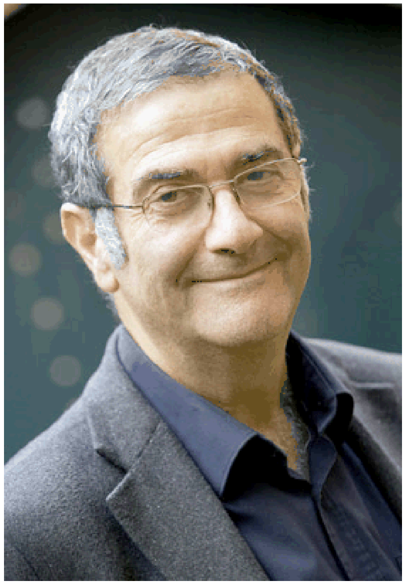


Photo: © CNRS

Serge Haroche

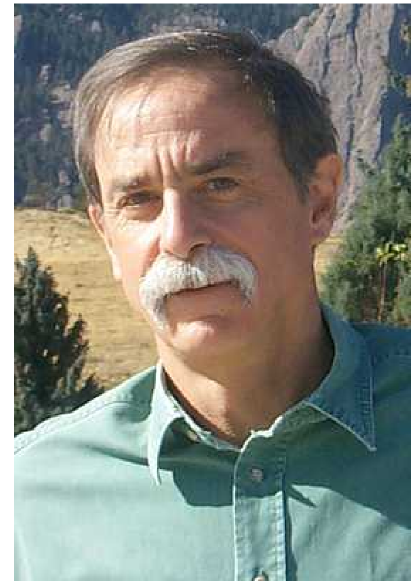


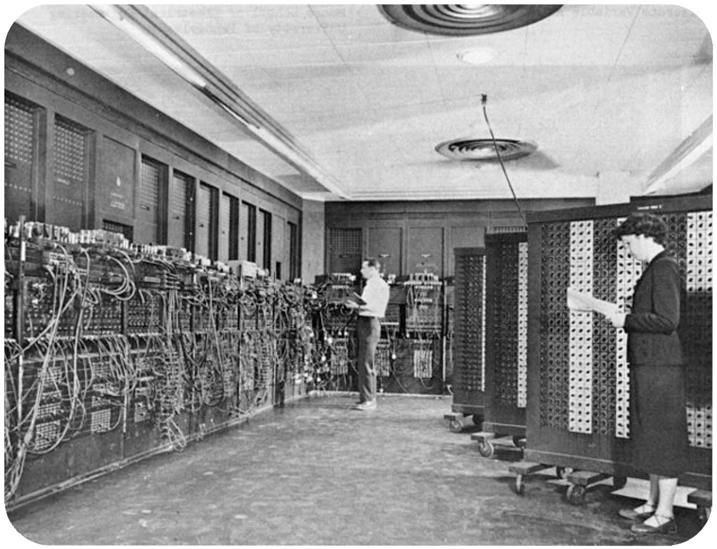
Photo: © NIST

David J. Wineland

"for ground-breaking experimental methods that enable measuring and manipulation of individual quantum systems"

Computer miniaturization

More powerful AND more portable

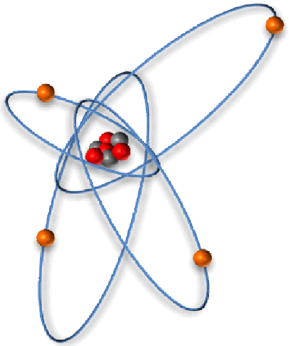


ENIAC, 1946

iPod nano, 2011

Quantum information

The laws of physics are different here



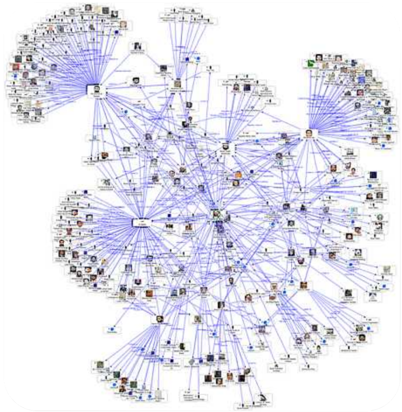
$$i\hbar \frac{\partial}{\partial t}|\Psi\rangle = H|\Psi\rangle$$

Wave nature • Superposition • Uncertainty • Entanglement • No-cloning

The laws of *information* are different here!

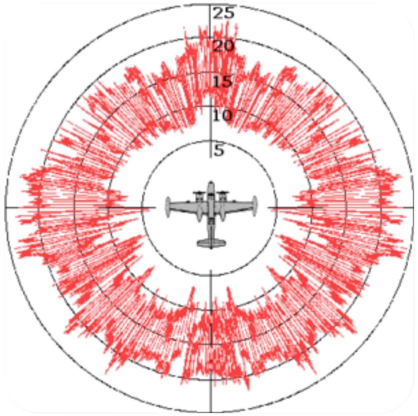
Quantum computing

Dramatic speedups for some problems



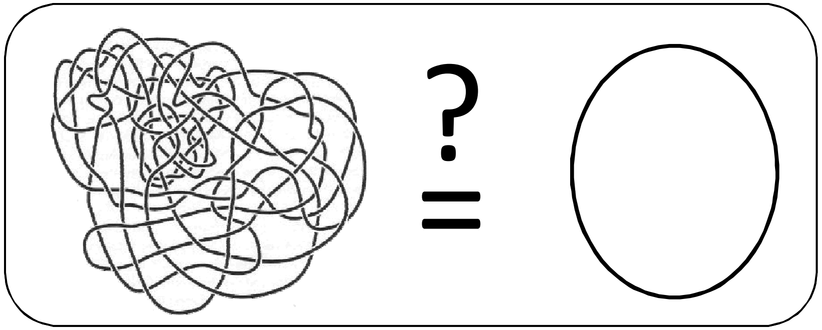
Big data

Cryptanalysis

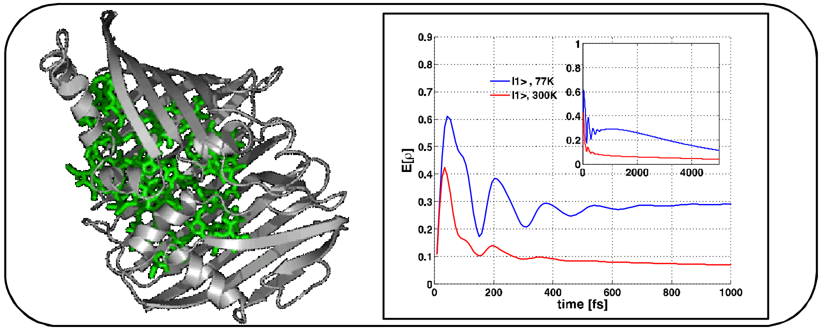


EM scattering

Sarovar *et al.*, Nature Physics (2010); doi:10.1038/nphys1652



Knot theory



Quantum simulation

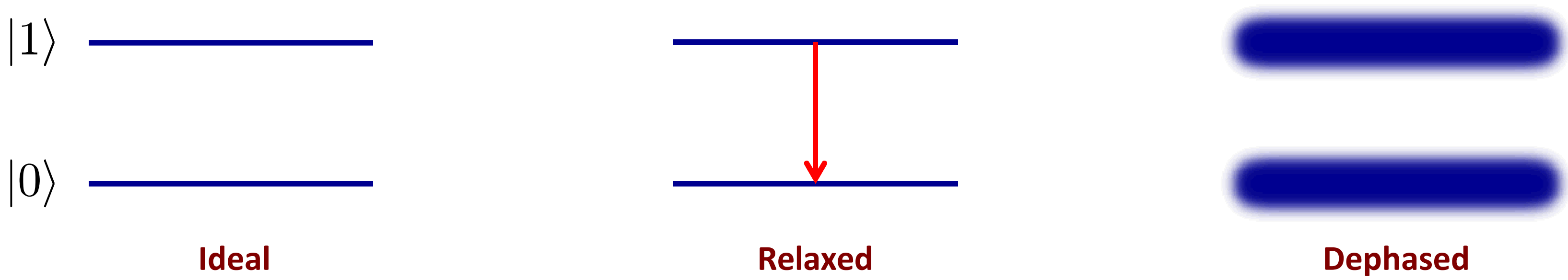
Over 40 quantum algorithms with speedups over their classical counterparts known

http://math.nist.gov/quantum/zoo

Decoherence

With great power comes great fragility

The two biggest culprits: Relaxation (T_1) and Dephasing (T_2)



$$\frac{1}{\sqrt{2}}\left(|0\rangle + e^{i(E_1 - E_0)t/\hbar}|1\rangle\right)$$

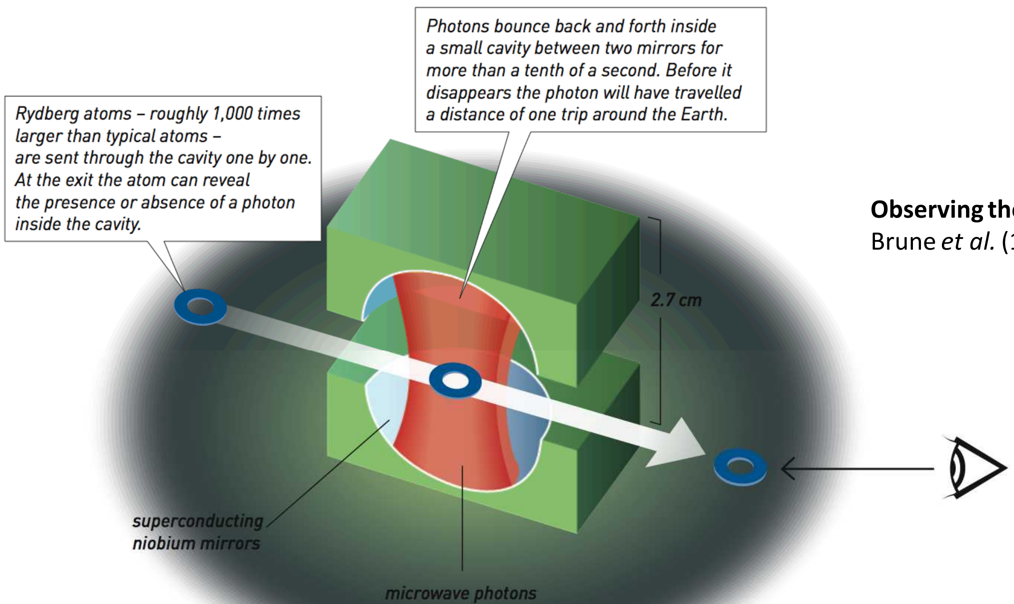


Figure 3. In the Serge Haroche laboratory in Paris, in vacuum and at a temperature of almost absolute zero, the microwave photons bounce back and forth inside a small cavity between two mirrors. The mirrors are so reflective that a single photon stays for more than a tenth of a second before it is lost. During its long life time, many quantum manipulations can be performed with the trapped photon without destroying it.

Image: © Royal Swedish Academy of Sciences

Observing the progressive decoherence of the "meter" in a quantum measurement
Brune *et al.* (1996), doi:10.1103/PhysRevLett.77.4887

- Outer orbiting electron in atom is the qubit.
- About 10 photons in cavity entangle with atom.
- Photons shift phase (energy) of 0 and 1 differently.
- Photons escape (slowly!) from cavity.
- Superposition lasted several microseconds!
- A grandfather clock dephases in less than 10^{-40} s.

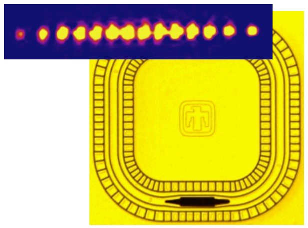
Quantum information hardware

Sandia National Laboratories

It's a wide open horse race

AMO hardware (Atomic, Molecular, and Optical)

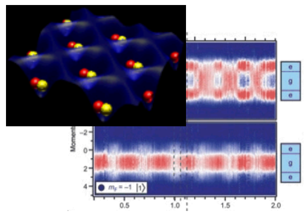
Trapped ion quantum chip



TODAY: 14-qubit entangled state generated.

Monz *et al.* (2011), doi:10.1103/PhysRevLett.106.130506

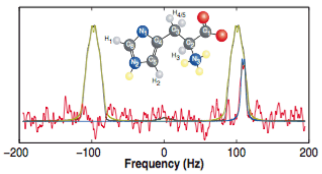
Trapped neutral atoms



TODAY: 60,000 parallel 2-qubit gates demonstrated.

Anderlini *et al.* (2007), doi:10.1038/nature06011

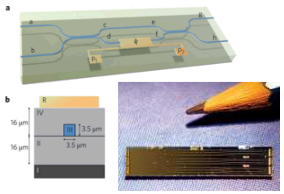
Nuclear magnetic resonance



TODAY: 12-qubit circuits benchmarked.

Negrevergne *et al.* (2006), doi:10.1103/PhysRevLett.96.170501

Photonic quantum chip

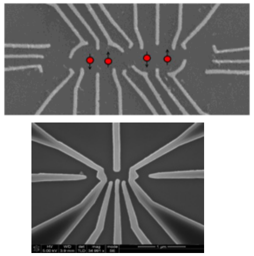


TODAY: 10-qubit photonic chip demonstrated.

Matthews *et al.* (2009), doi:10.1038/nphoton.2009.93

CMP hardware (Condensed Matter Physics)

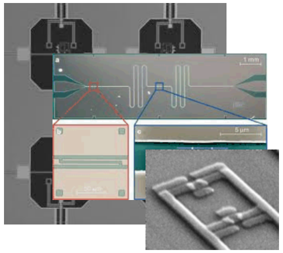
Semiconductor quantum-dot chip



TODAY: 1-qubit GaAs gates (spin); 1-qubit Si device demonstrated (charge).

Foletti *et al.* (2009), doi:110.1038/nphys1424
Gorman *et al.* (2005), doi:10.1103/PhysRevLett.95.090502

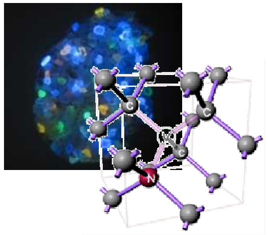
Superconducting quantum chip



TODAY: 3-qubit entanglement (phase); 3-qubit error correction (charge); 2-qubit CNOT gate (flux).

Neeley *et al.* (2010), doi:10.1038/nature09418
Reed *et al.* (2011), doi:10.1038/nature10786
Plantenberg *et al.* (2007), doi:10.1038/nature05896

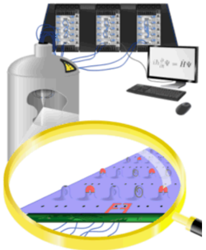
Nitrogen vacancies in diamond



TODAY: 2-qubit gates demonstrated.

van der Sar *et al.* (2012), arXiv:1202.4379

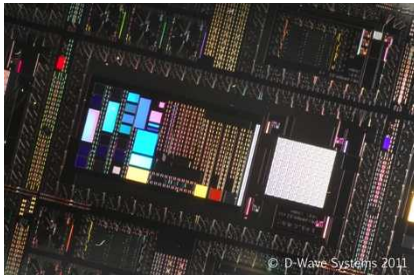
Topological quantum chip



TODAY: Zero qubits; FQHE anyons in question. Majorana fermions in topological insulators look promising.

Bonderson *et al.* (2011), doi:PhysRevLett.106.130505
Bonderson *et al.* (2010), arXiv:1003.2856

D-Wave Systems, Inc. special-purpose chip



TODAY: 128-qubit (superconducting flux) quantum annealing algorithms. Debate about "quantumness."

Quantum circuit architecture

Break it down, then build it up

1. *Digitize* states into qubits.

$$|x\rangle \mapsto |x_1\rangle|x_2\rangle\cdots|x_n\rangle$$

2. *Digitize* dynamics into a finite set of “gates.”

$$U \mapsto U_m U_{m-1}\cdots U_1$$

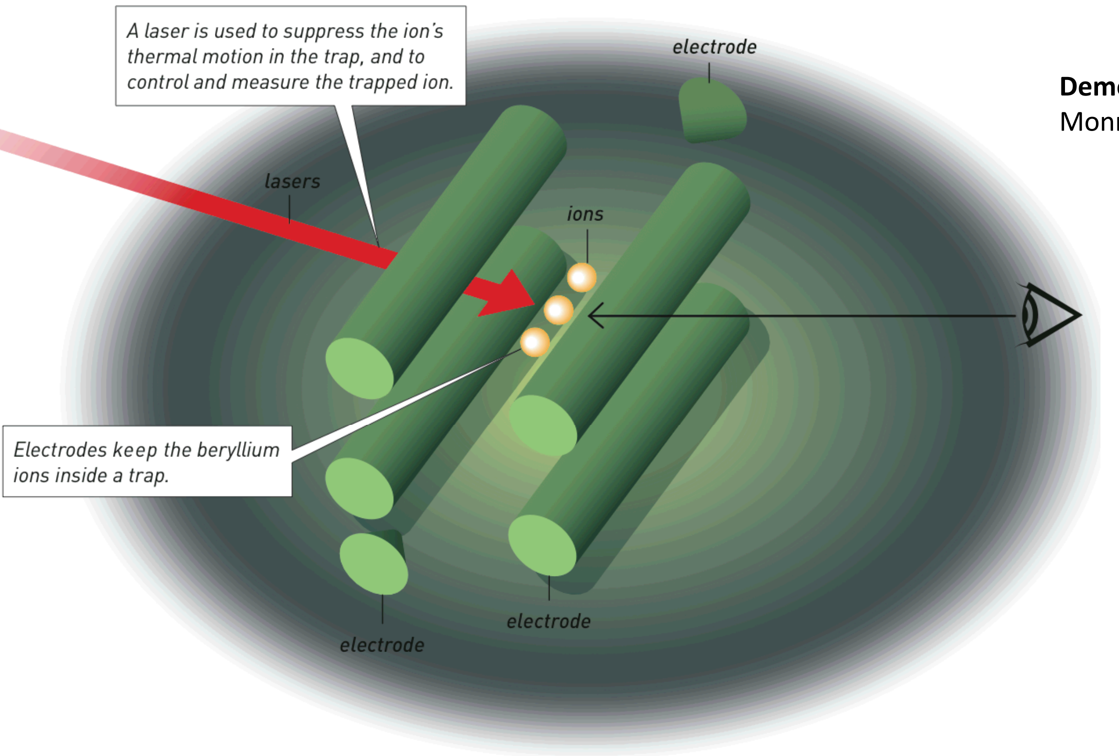


Figure 2. In David Wineland's laboratory in Boulder, Colorado, electrically charged atoms or ions are kept inside a trap by surrounding electric fields. One of the secrets behind Wineland's breakthrough is mastery of the art of using laser beams and creating laser pulses. A laser is used to put the ion in its lowest energy state and thus enabling the study of quantum phenomena with the trapped ion.

Image: © Royal Swedish Academy of Sciences

Demonstration of a fundamental quantum logic gate
Monroe *et al.* (1995), doi:10.1103/PhysRevLett.75.4714

- Outer orbiting electron in ion is qubit 1.
- Vibrational mode of ion is qubit 2.
- Laser pulse flips ion mode conditioned on electron state.
- Gate implemented is “Controlled NOT”
- 14 qubits entangled in ion trap today (world record)

Fault-tolerant quantum computing

Sandia National Laboratories

The great promise…with a catch!

Accuracy threshold theorem for fault-tolerant quantum computation:

As long as qubits and gates are "good enough," one can implement arbitrarily reliable quantum circuits with "sufficient redundancy."

1. "Good enough"

   Error per gate at about 10^{-4}

   TODAY: Not quite there, but getting close

2. "Sufficient redundancy"

   More than 99.99997% redundancy

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

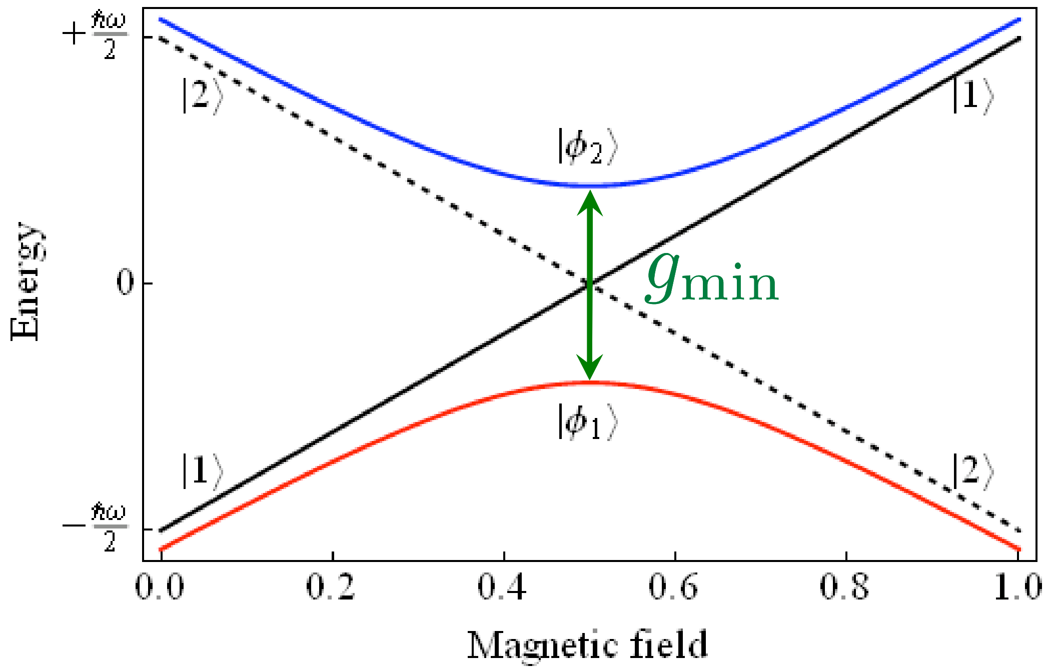
   TODAY: Are you kidding?

Adiabatic quantum physics

Adiabatic: Impassible [Greek: ἀ- ("not"), διὰ- ("through"), and βαῖνειν ("to pass")].

Thermodynamic adiabatic process: No heat transfer into or out of system.

Quantum adiabatic process: No population transfer into or out of a specified energy eigenspace.



Adiabatic theorem: If the initial state is $|E(0)\rangle$, then in the limit as $T \to \infty$, the final state is $|E(1)\rangle$.

Adiabatic approximation: If $T \gg \frac{|\langle E_1|\dot{H}|E_0\rangle|_{\max}}{g_{\min}^2}$, then the evolution is adiabatic with high probability.

Adiabatic quantum computing

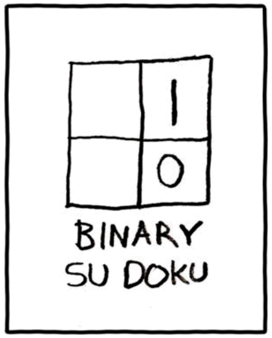
Slow down, and the answer will come

1. Digitize states into qubits.

2. Digitize *Hamiltonian* into a finite set of interactions.

$$H\left(\tfrac{t}{T}\right) = \left(1 - \tfrac{t}{T}\right) H_0 + \tfrac{t}{T} H_1 \qquad\qquad H = \sum_i \alpha_i K_i$$

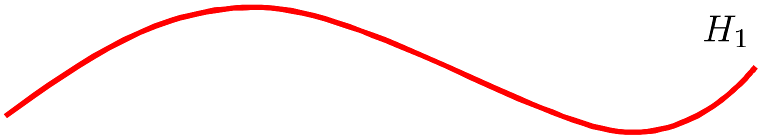
3. Load problem into final Hamiltonian of an adiabatic evolution; it's ground state is the output of the program!



Example: Quadratic Unconstrained Binary Optimization (QUBO)

$$\min_{x \in \{-1,1\}} f(x) = \sum_{i=1}^{n} h_i x_i + \sum_{i,j=1}^{n} J_{ij} x_i x_j$$

$$H_1 = \sum_{i=1}^{n} h_i \sigma_i^z + \sum_{i,j=1}^{n} J_{ij} \sigma_i^z \sigma_j^z$$



$$H_0 = \sum_{i=1}^{n} \sigma_i^x$$

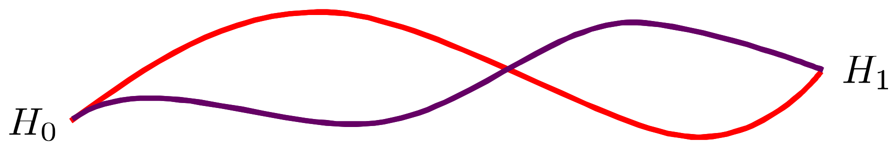
Challenge: This is "NP-hard." Does the gap shrink exponentially with *n*?

Quantum Computer, Heal Thyself!

Sandia National Laboratories

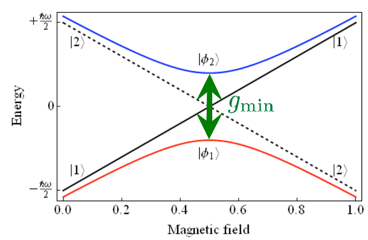
Adiabatic physics may suppress dominant errors

1. Robust to control errors



"Let your path wander, but arrive at your destination."

2. Relaxation suppressed by the energy gap



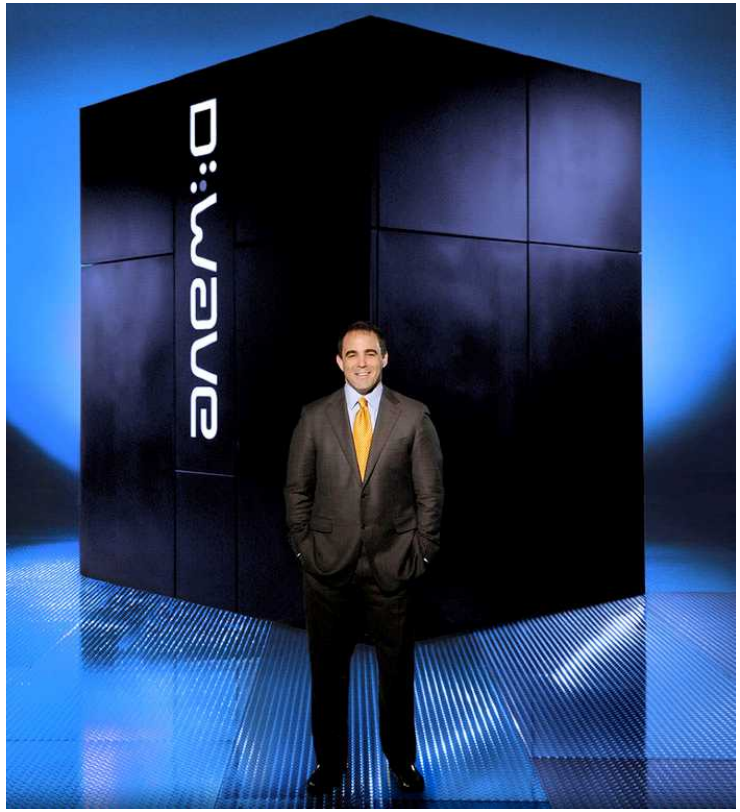
$$p_{\text{relax}} \sim e^{-g/kT}$$

3. Dephasing in the instantaneous energy eigenbasis is irrelevant.

$$|E_0(t)\rangle = e^{i\theta}|E_0(t)\rangle$$

But does it work?

Inquiring minds want to know



$\times 10^7$

AQUARIUS™

Adiabatic quantum architectures in ultracold systems

Sandia National Laboratories

Sandia "Grand Challenge" project objectives: (2010-2013)

Build and test quantumness/robustness of two-qubit adiabatic quantum computers for QUBO using

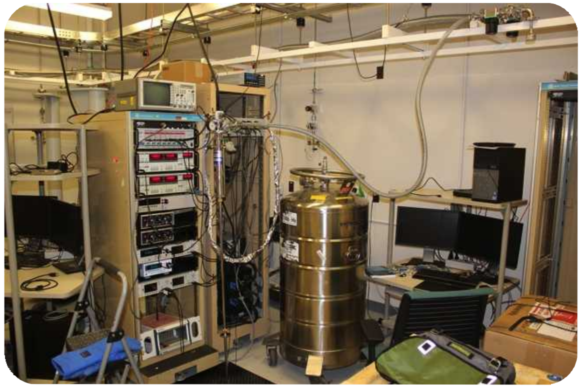
1. (AMO) Neutral atoms trapped by a microfabricated optical-trap array, and
2. (CMP) Electrons trapped by semiconductor nanostructures

and for these technologies

3. Evaluate the potential for general-purpose fault-tolerant adiabatic quantum computation architectures through design & simulation.

New labs constructed:

Optical atom trapping & control lab



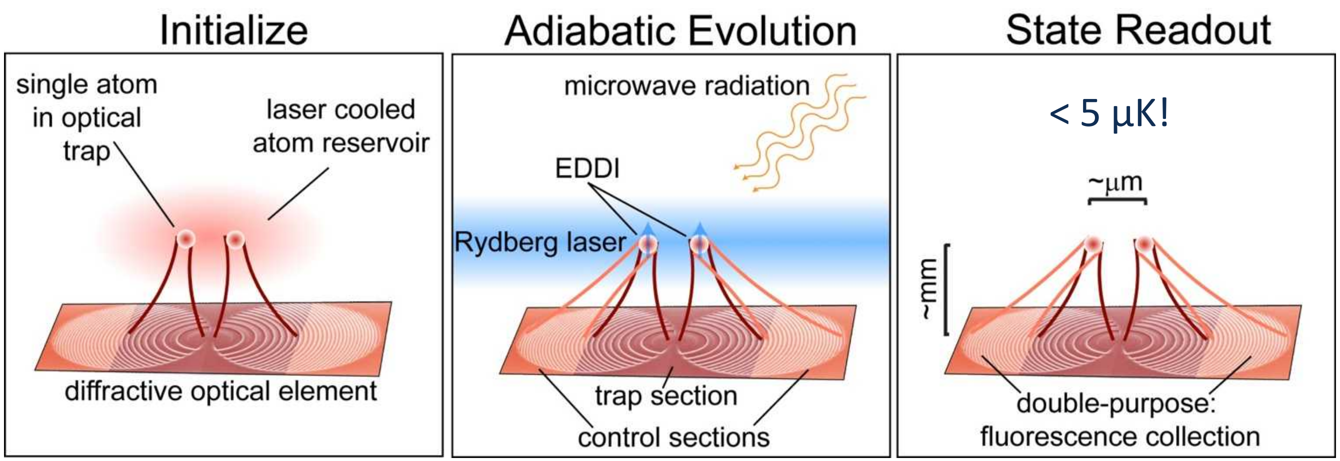
Cryogenic materials & electronics measurement lab

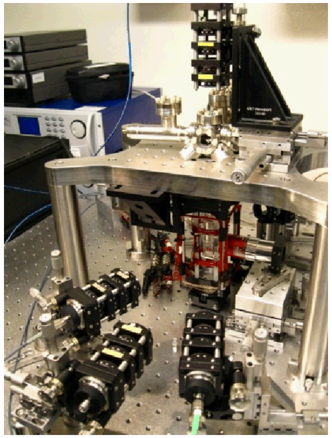
Atomic-precision lithography lab

Trapping & controlling cesium

Sandia-fabricated diffractive optics

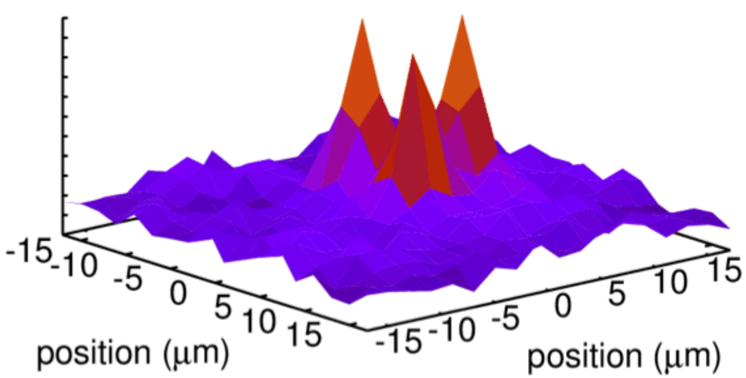
- Fabricated & used **world-first diffractive optical elements** for trapping and controlling individual atoms.

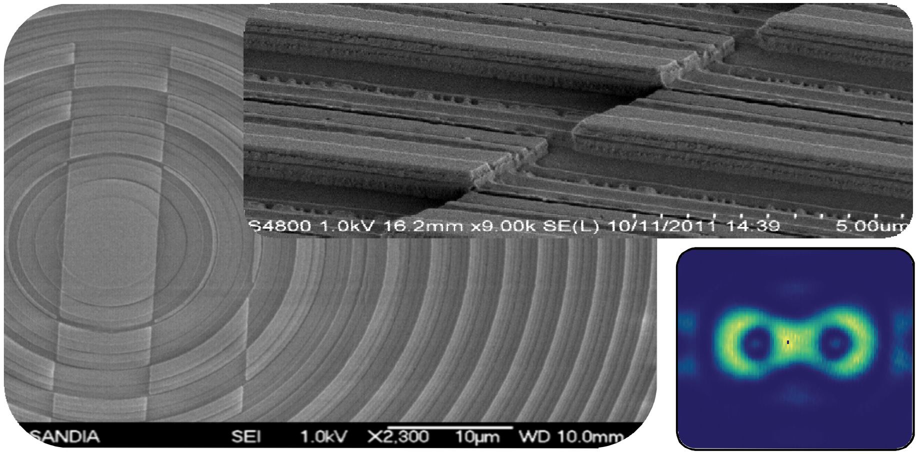




DOE test platform

single atoms in 3-spot trap

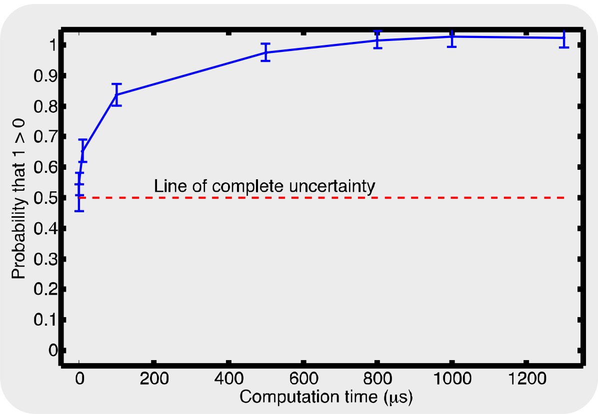




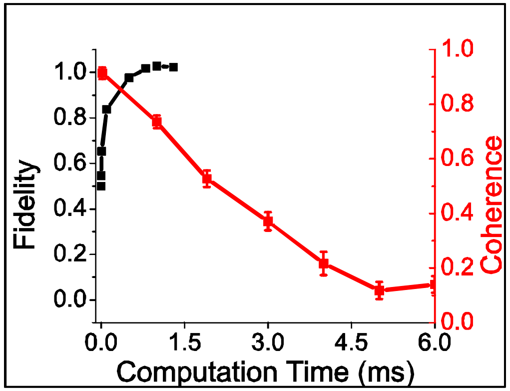
Evidence of robustness

Validating claims…for one qubit

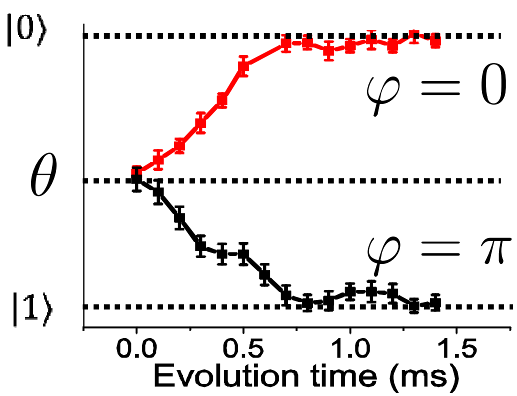
- Built **Sandia's first functioning one-qubit quantum computer.**
  - Inaugural calculation: **"1 is greater than 0 … with high probability."**



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



- Demonstrated excited-state adiabatic evolution: Behavior is quantum, not relaxation.

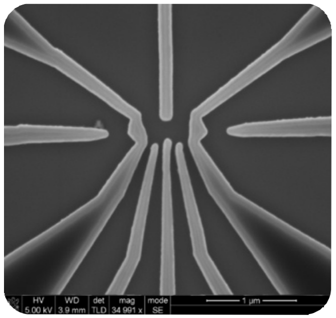


$$|\psi_0\rangle = \sin\frac{\theta}{2}|0\rangle + e^{i\varphi}\cos\frac{\theta}{2}|1\rangle$$

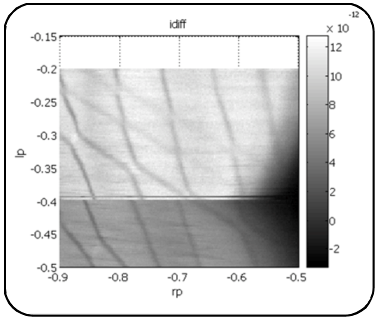
Quantum-dot qubits

Not adiabatic yet, but have promise of integration

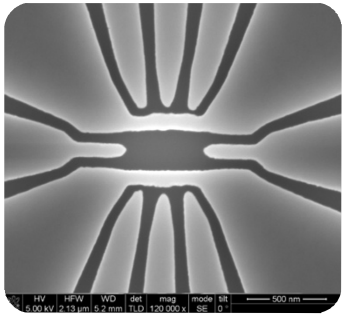
- Invented **world-first semiconductor adiabatic charge qubit.**
  - Built one- and two-qubit silicon quantum dot devices realizing the idea.



One-qubit device



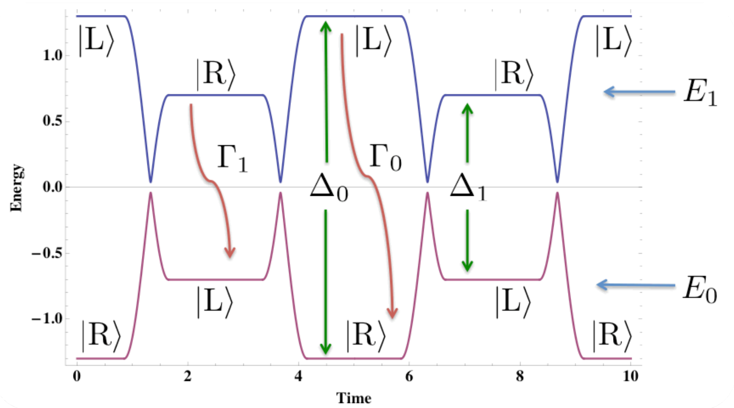
Single-electron occupancy

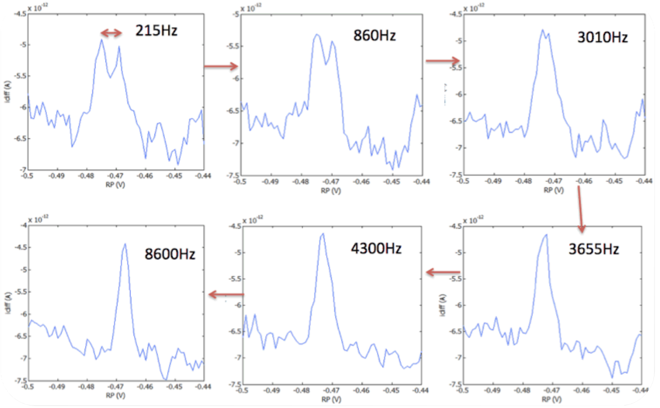


Two-qubit device

- Si devices
- 100 mK.

- Invented **world-first benchmarking test for "quantumness" of adiabatic qubits.**
  - Used the test to measure charge qubit relaxation times
  - Switching speed currently too slow to prove adiabaticity





Atomic-precision lithography

Sandia National Laboratories

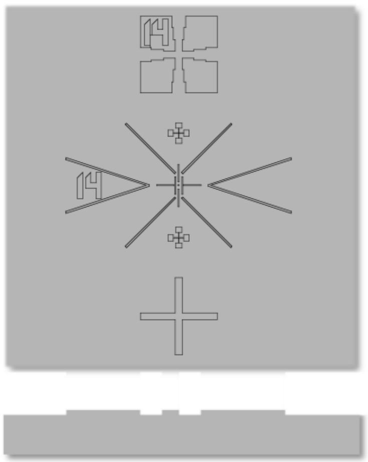
There's no more room at the bottom

☑**Start w clean Si(001)**

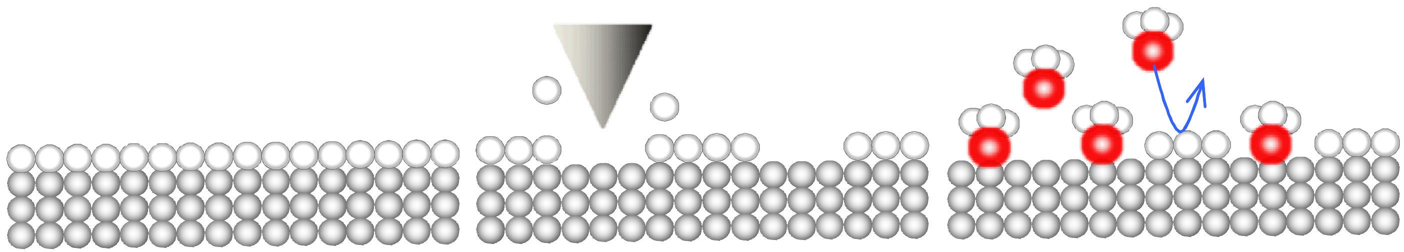
☑**Adsorb H resist**
Self-limiting 1 monolayer

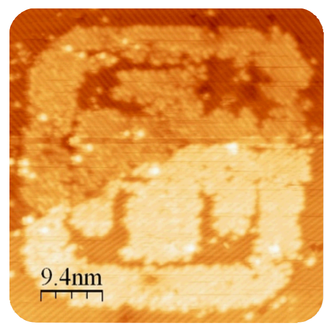
☑**Pattern w STM**
Atomic-precision

☑ **Adsorb PH_3**



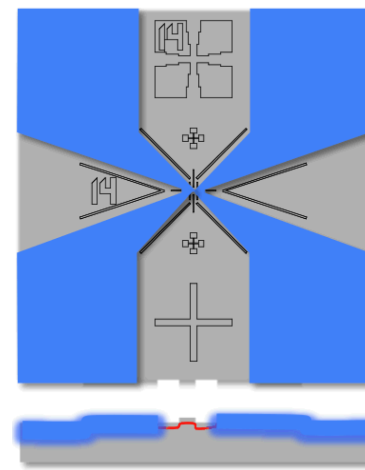
Etched alignment marks

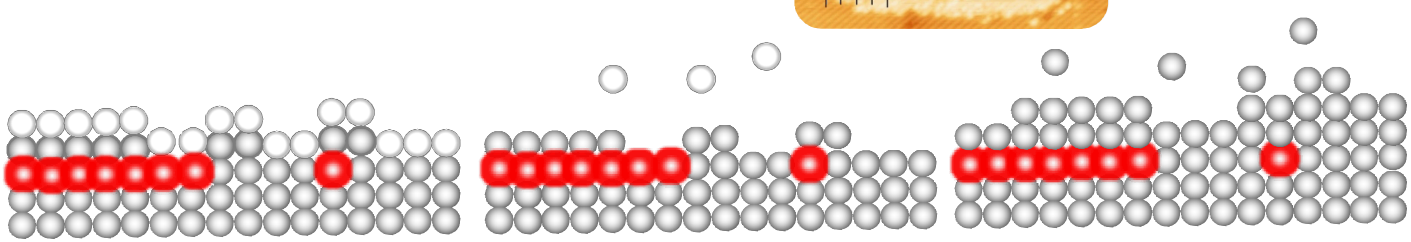




0.7 nm features!

Al depo+liftoff





☑**Incorporate P**
-Anneal➔ Si-P swap
-H resist constrains P

☑**Desorb H**
anneal

☑**Bury P in Si**

☑**Add contacts**

A new era

A quantum leap in our mastery of information

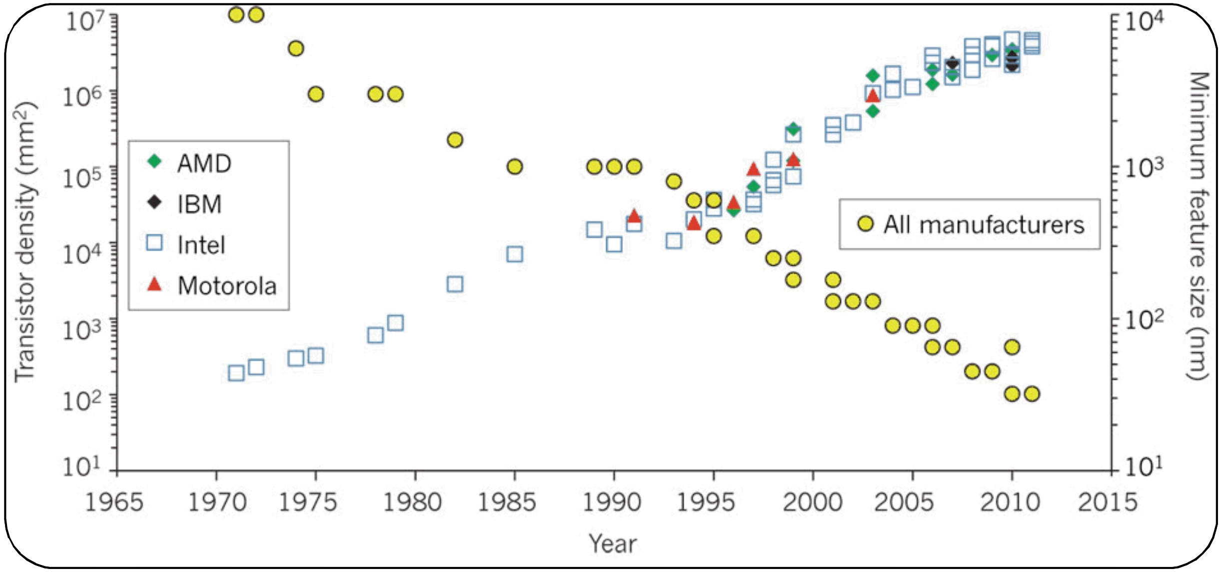
Join the APS Topical Group on Quantum Information (GQI) today!

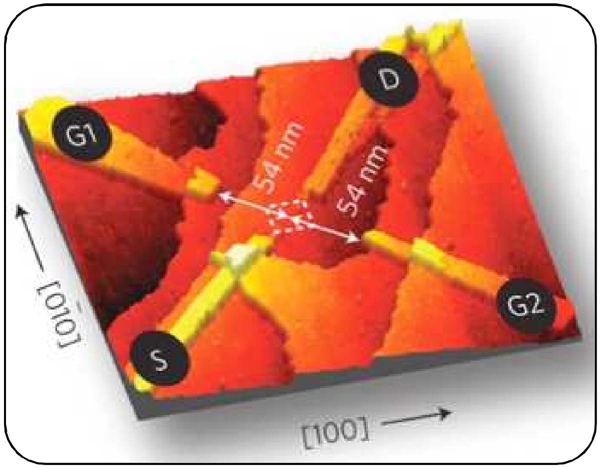
Backup slides

Single-electron bits

The ultimate limit of electronic computing

Ferain *et al.*, Nature (2011); doi:10.1038/nature10676





A single-atom transistor
Fuechsle *et al.*, Nature Nanotechnology (2012); doi:10.1038/nnano.2012.21

Quantum information software

Quantum error correction expels decoherence!

$$\frac{1}{\sqrt{2}}\left(|0\rangle + |1\rangle\right)$$

$$\frac{1}{\sqrt{2}}\left(|0\rangle|0\rangle|1\rangle + |1\rangle|1\rangle|0\rangle\right)$$

Checks:

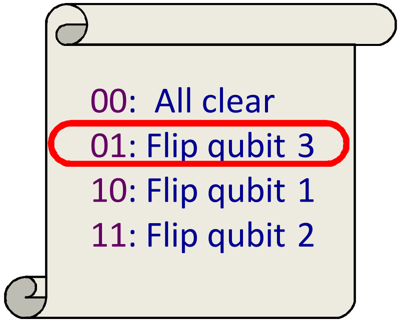
- ✓ First 2 bits the same?
- ✗ Second 2 bits the same?

Syndrome:

0

1

Diagnosis:



The neutral-atom qubit

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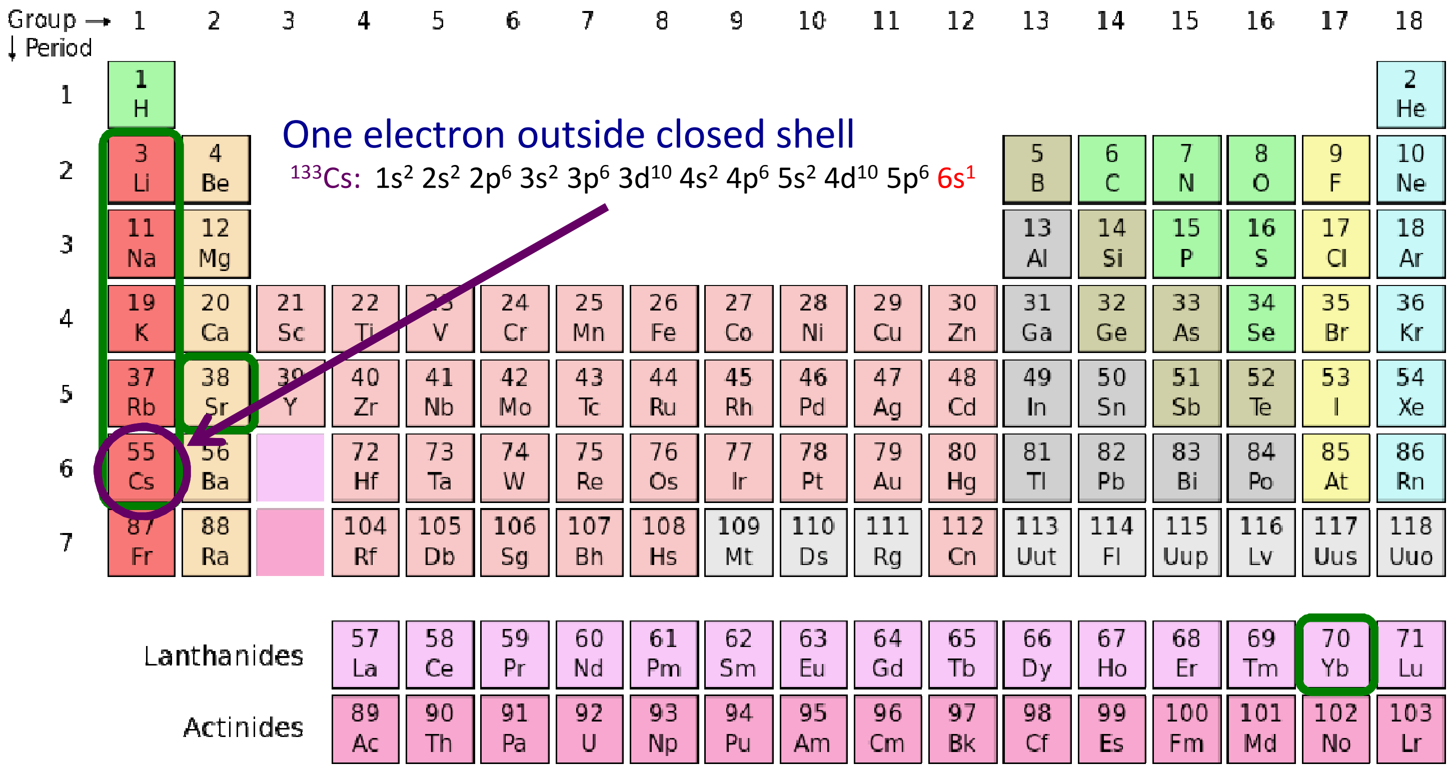
It's not just fine—it's hyperfine!

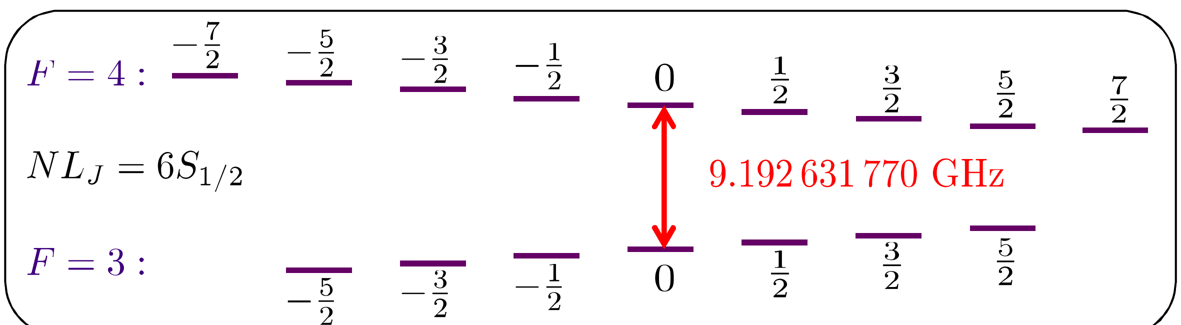


Fine structure

$\hat{\mathbf{J}}_{\rm el} = \hat{\mathbf{L}}_{\rm el} + \hat{\mathbf{S}}_{\rm el}$ $\qquad S_{\rm el} = \frac{1}{2}$

Hyperfine structure

$\hat{\mathbf{F}} = \hat{\mathbf{J}}_{\rm el} + \hat{\mathbf{I}}_{\rm nuc}$ $\qquad I_{\rm nuc} = \frac{7}{2}$



QUBO with cesium atoms

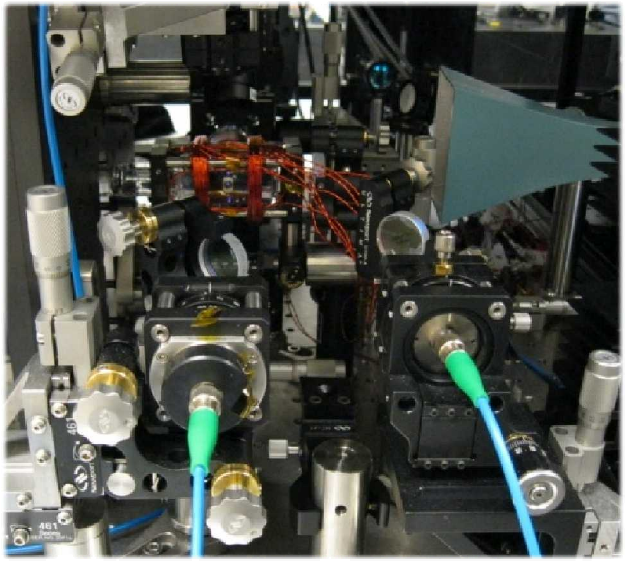
Interactions controlled by lasers and microwaves

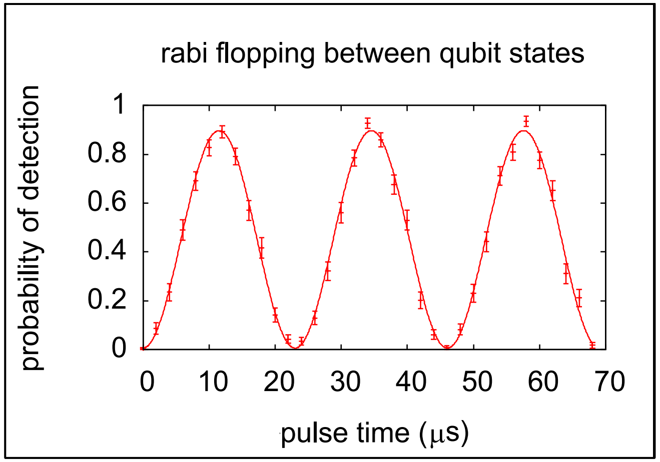
$(6S_{1/2}, F = 4) \mapsto |0\rangle$

$\omega_{\mu\mathrm{w}} \approx 9.2$ GHz

$(6S_{1/2}, F = 3) \mapsto |1\rangle$

$$H = \frac{\hbar}{2}\omega_{\mu\mathrm{w}}\sigma_x$$





Actual data

QUBO with cesium atoms

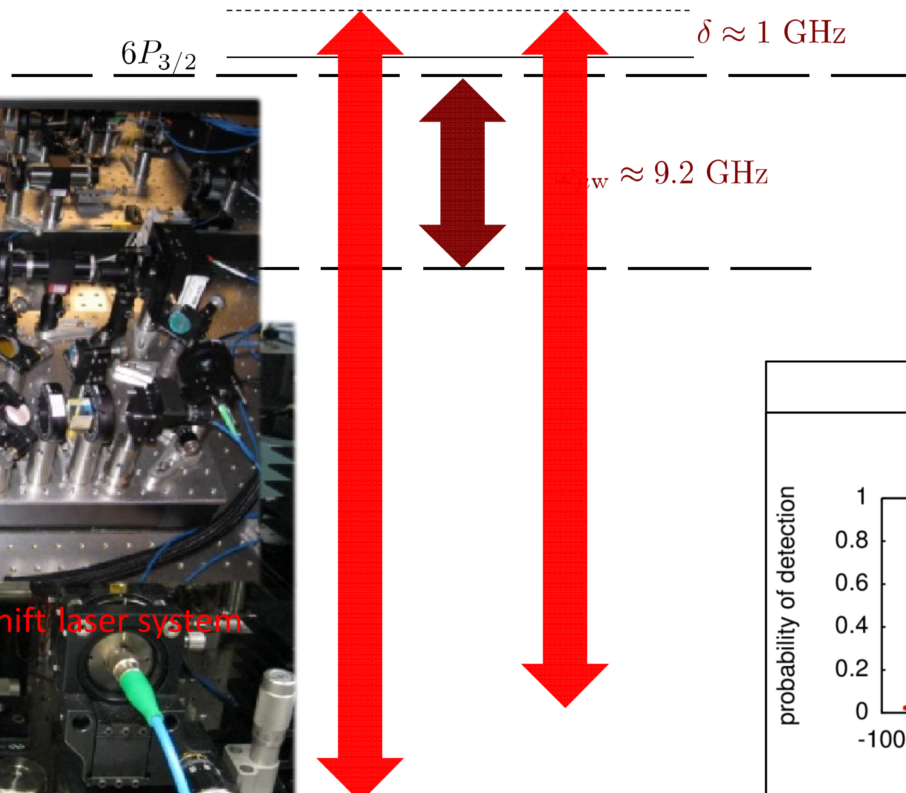
Interactions controlled by lasers and microwaves

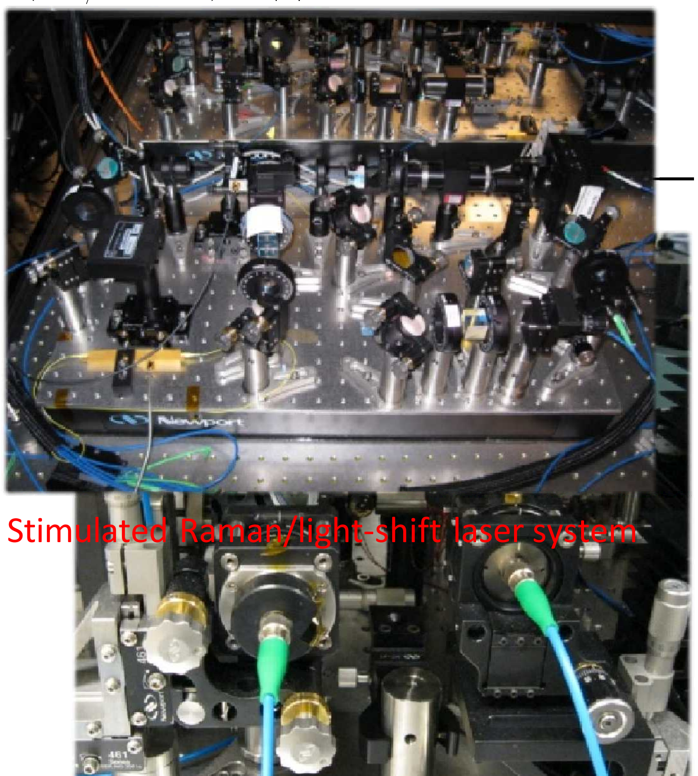
$\lambda \approx 852$ nm

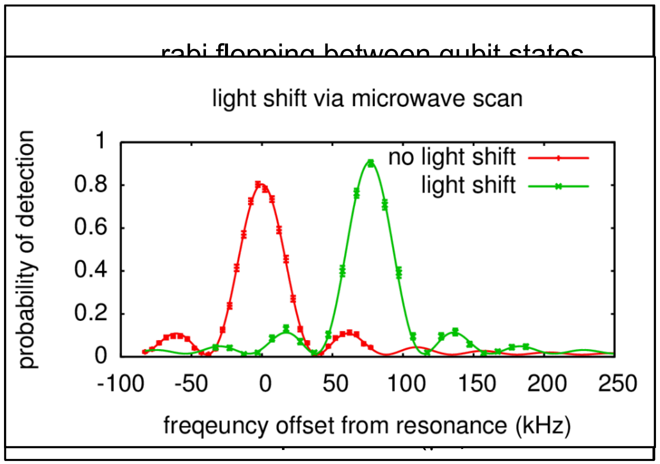
$\omega \approx 100$ kHz

$$H = \frac{\hbar}{2}\omega_{\mu w}\sigma_x$$

$$H = \frac{\hbar}{2}\omega\sigma_x$$







Actual data

QUBO with cesium atoms

The Rydberg blockade

$90P_{3/2}$

$\delta \approx 20\ \text{MHz}$

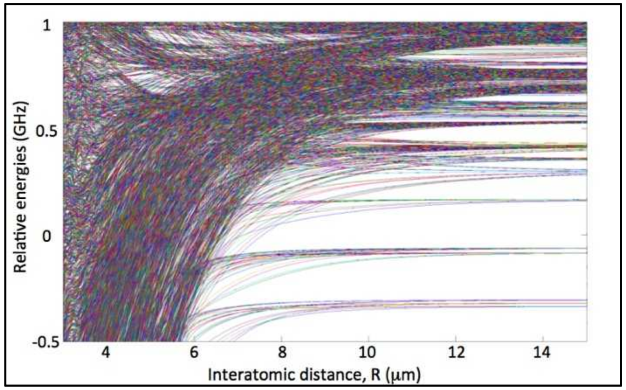
$\lambda = 318\ \text{nm}$

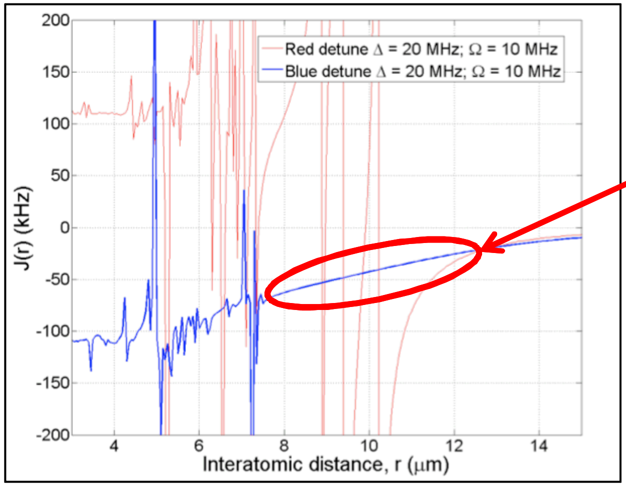
$\Omega = 10\ \text{MHz}$

$(6S_{1/2}, F=4) \mapsto |0\rangle$

$(6S_{1/2}, F=3) \mapsto |1\rangle$

1 micron atom!





Sane region

8-12 micron spacing

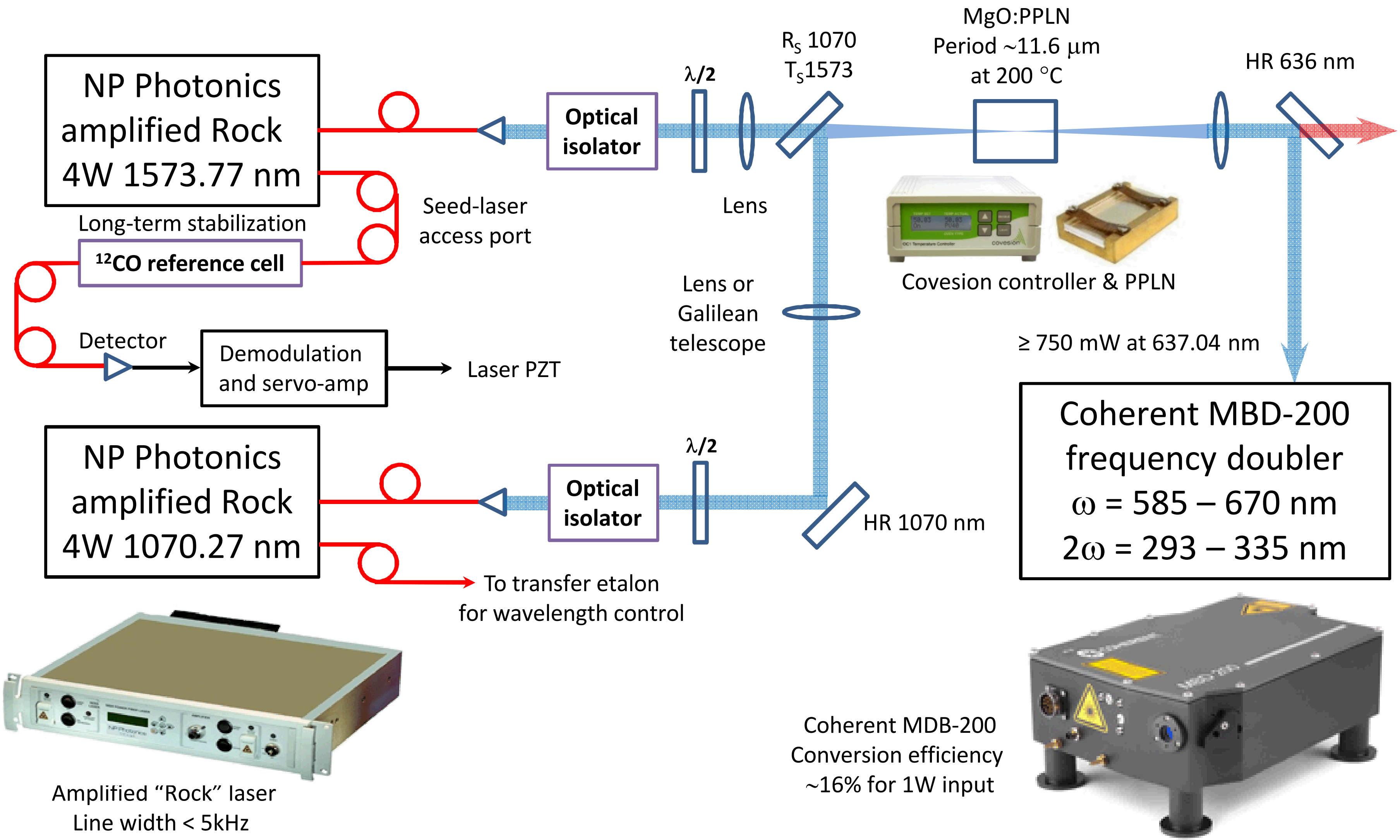
$90P_{3/2}$

$H = J(r)\sigma_z\sigma_z$

A 100 mW, 318 nm laser system

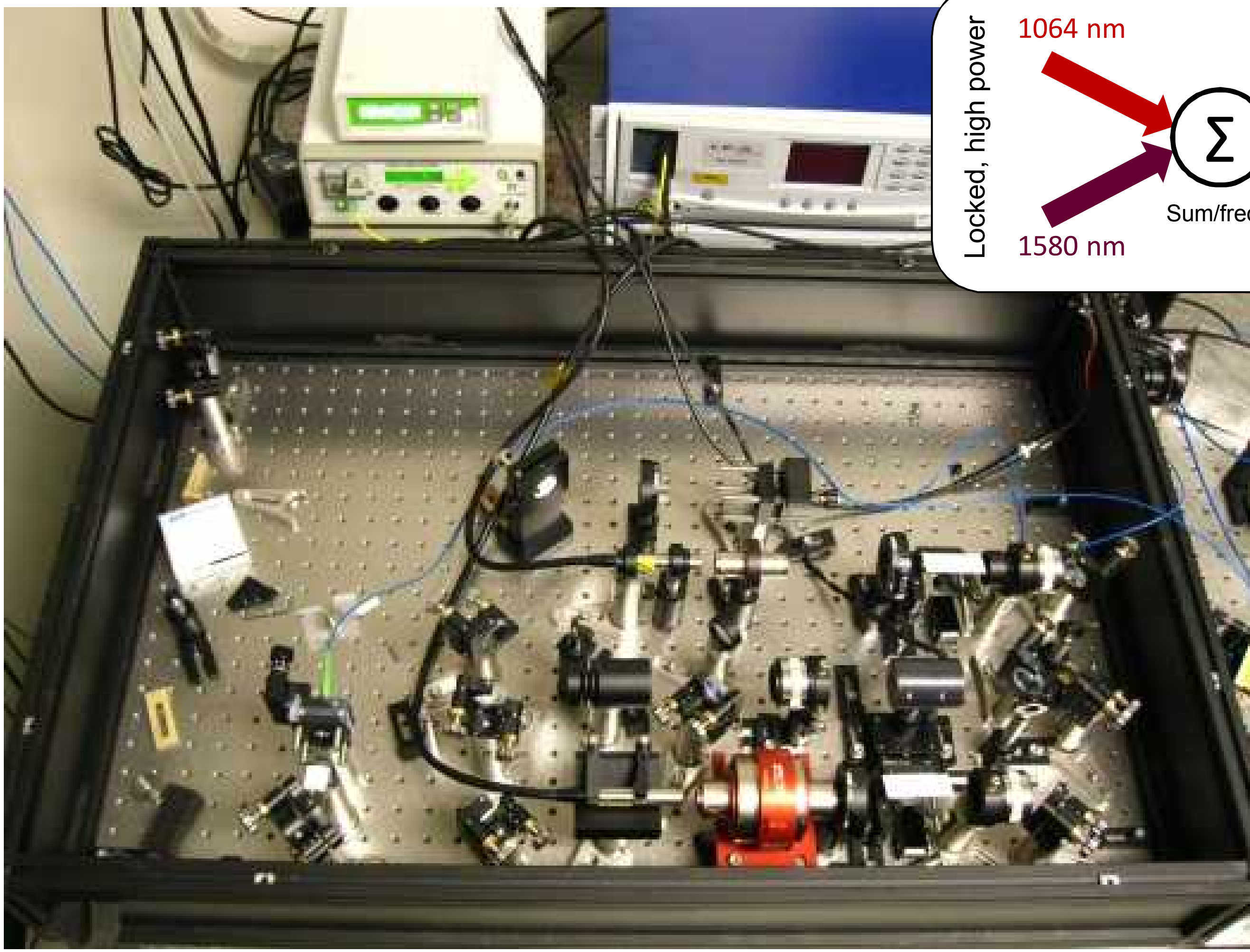
Sandia National Laboratories

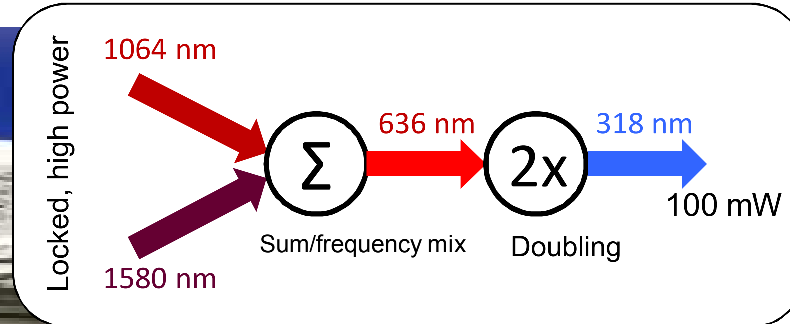
It's complicated



A 100 mW, 318 nm laser system

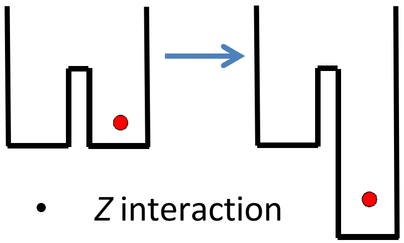
It’s complicated



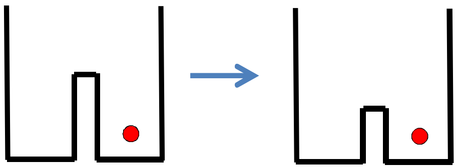


The silicon charge qubit

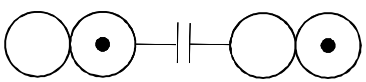
A double-well potential



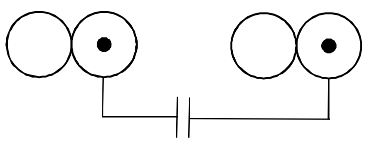
- *Z* interaction



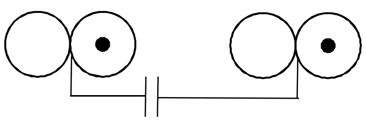
- *X* interaction



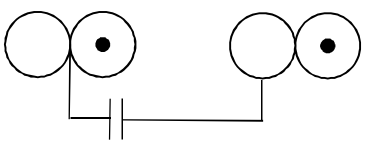
ZZ interaction



−*ZZ* interaction



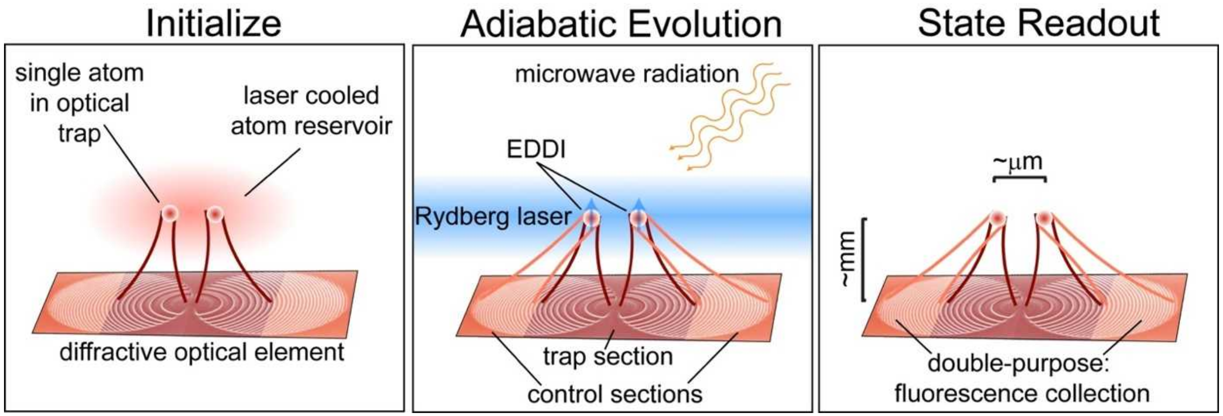
XX interaction



XZ interaction

QUBO with ^{133}Cs

Spinoff optics technology



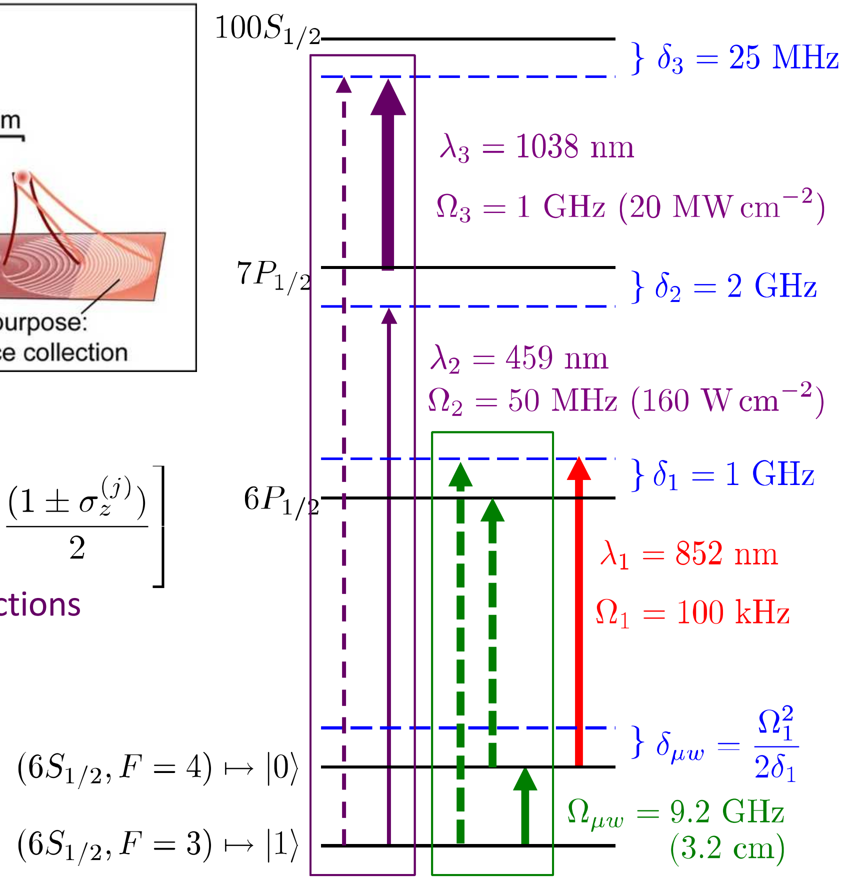
$$H = \frac{\hbar}{2}\left[\sum_i \Omega_{\mu w}^{(i)}(s)\sigma_x^{(i)} + \sum_i \delta_{\mu w}^{(i)}(s)\sigma_z^{(i)} + \sum_{ij} \frac{\Omega^{(i)}\Omega^{(j)}}{8\delta_2(s)^3}\frac{(1\pm\sigma_z^{(i)})}{2}\frac{(1\pm\sigma_z^{(j)})}{2}\right]$$

Microwaves/ two-photon Raman

Light shifts

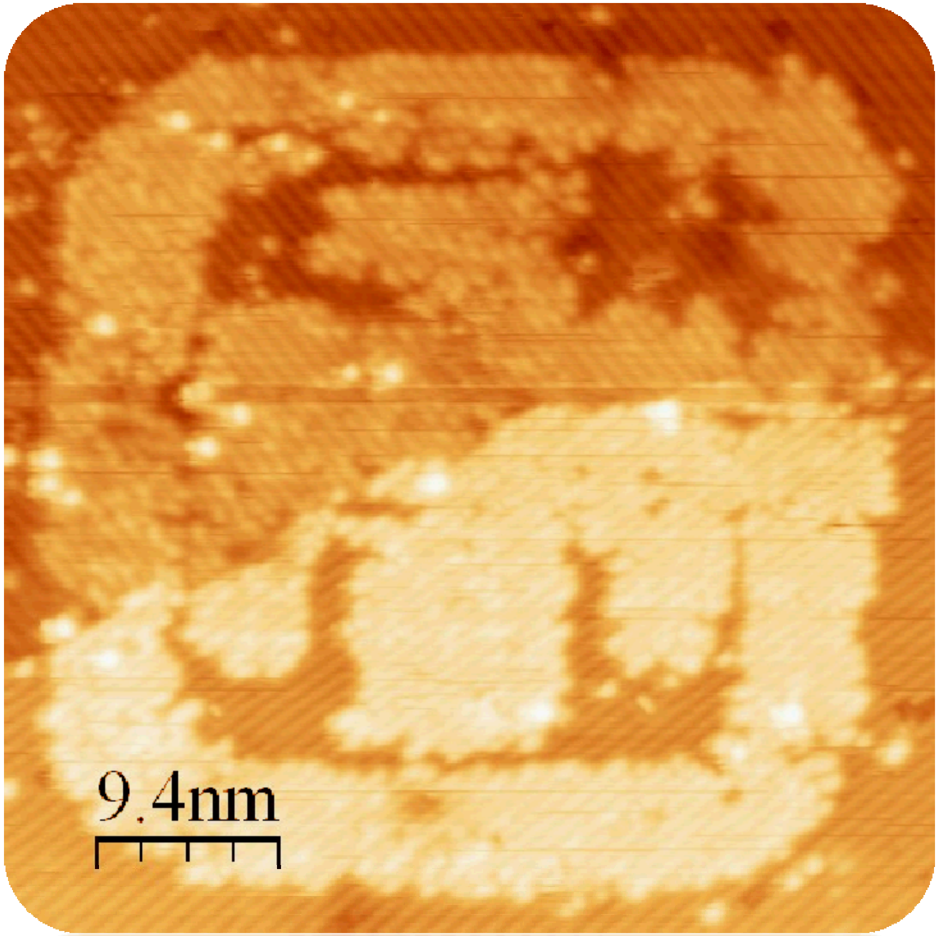
Rydberg interactions

Cs level structure



The Sandia nanologo

Atom-sized features



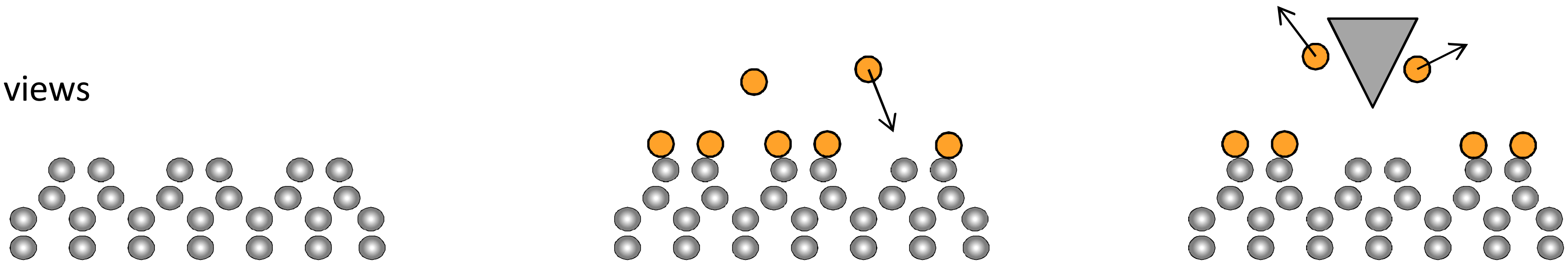
Results: Atomic-precision lithography

Sandia National Laboratories

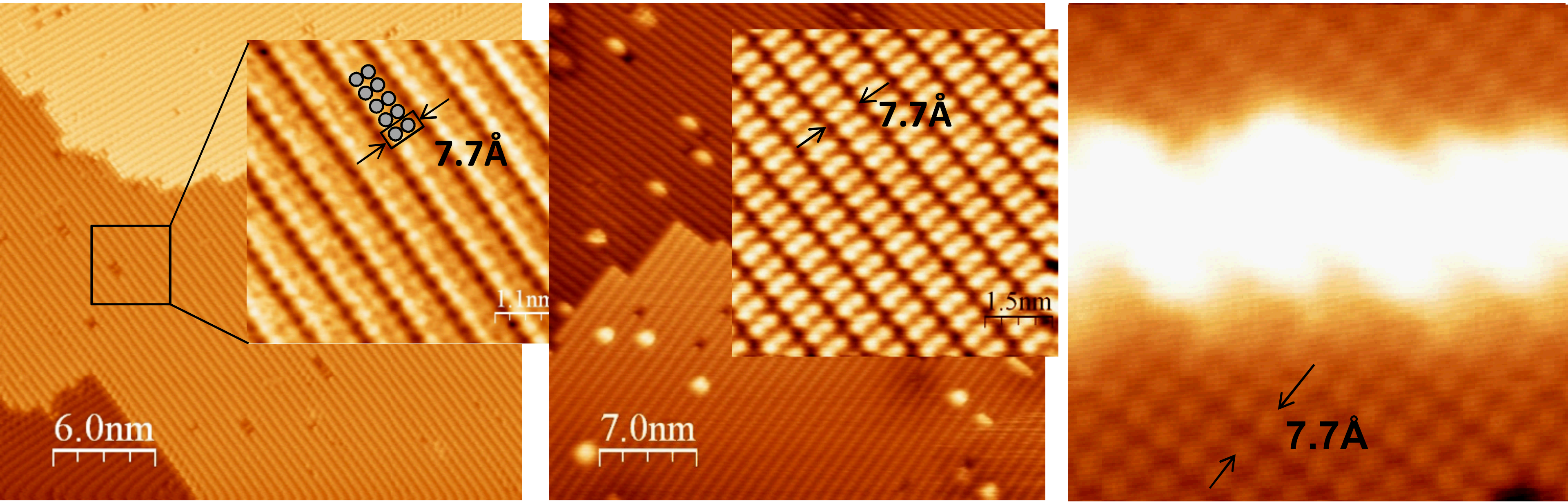
0.7 nm lithography

1. Demonstrated clean Si(001)
2. Low-defect H resist layers
3. Atomic-precision windows in resist

Side views



Top views



Si(100)-2x1

Si(100)-2x1-monohydride