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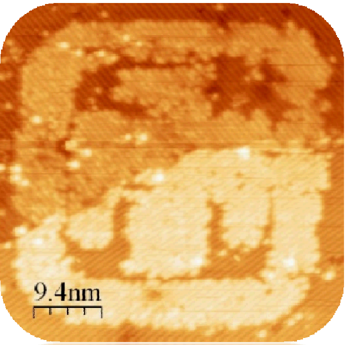

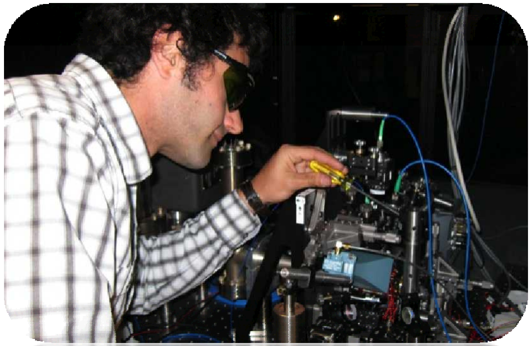
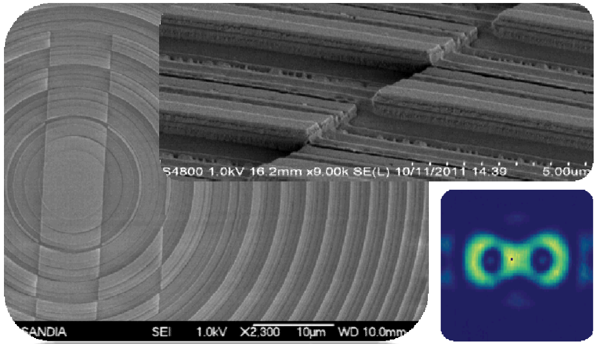
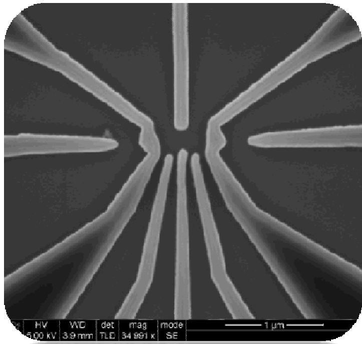

Are the promises of adiabatic quantum computing real?

Andrew J. Landahl

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National Laboratory Research Associate Professor, University of New Mexico

10/26/12

Abstract:

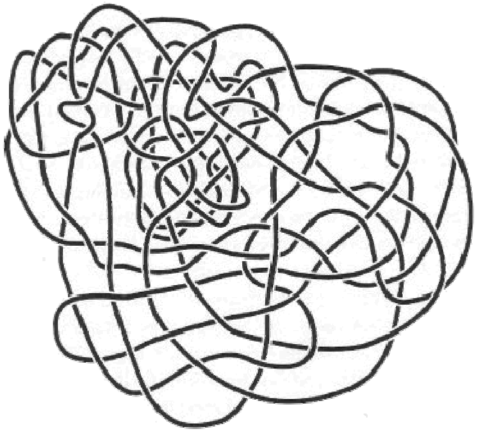
Adiabatic quantum computing shows great promise…on paper, at least. Some have argued that they could be used to solve certain NP-hard combinatorial optimization problems efficiently. Others have proven they could be fully universal quantum computing machines. Most amazingly of all, many numerical and analytic studies predict that adiabatic quantum computers should be resistant to the dominant noise sources that cause quantum computers to crash: dephasing, relaxation, and control errors.

I will review the adiabatic quantum computing model, its implementation promises, and describe experiments we have been running at Sandia on our two one-qubit adiabatic quantum computers to test these claims at a small scale. One computer is realized by a neutral cesium atom trapped by optical tweezers while the other is realized by a quantum dot nanofabricated on a silicon substrate.

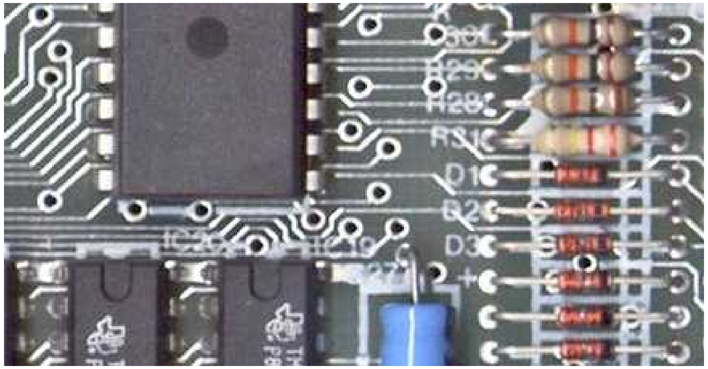
The adiabatic quantum computing model

Alternative computational models

Why study them?



They inspire new
algorithms and lower bounds



They inspire new
implementations

Adiabatic quantum computing

What's the input?

Program: $2^n \times 2^n$ unit-norm Hermitian matrix H indexed by $s \in [0,1]$.

- No computational power is lost by taking $H(s) = (1-s)H_0 + sH_1$
- Model is unaffected by taking H_0 to be the all-ones matrix.
- A *problem* is defined by a uniform family of $H(s)$, specified efficiently in n.
- H_1 is specified in a way such that its basis (the "computational basis") is known.

→ Essentially, the program is a sparse Hermitian matrix H_1.

N.B. Physicists denote the computational basis $\{\ \hat{e}_x\ \}_{x=1}^{2^n}$ by $\{\ |x\rangle\ \}_{x=1}^{2^n}$.

N.B. Physicists call H the "Hamiltonian."

Adiabatic quantum computing

What's the output?

Result: The lowest-eigenvalue eigenvector, as a "quantum state."

- State is $|\psi\rangle = \sum_{x=1}^{2^n} v_x |x\rangle$ stored in n "qubits."
- Does NOT return the v_x directly.
- To extract the v_x, one must "measure" the qubits.
- Measuring the n qubits yields label "x" with probability $|v_x|^2$.

→ Essentially, AQC allows one to sample from a distribution defined by the "ground state" of H_1.

What to do with AQC?

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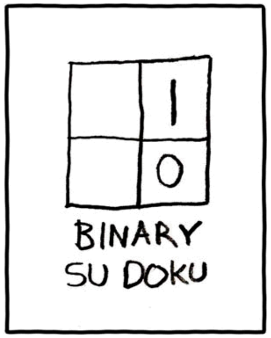
QUBO: Quadratic Unconstrained Binary Optimization

$$\min_{x \in \{-1,1\}^n} f(x) = h_0 + \sum_{i=1}^{n} h_i \, x_i + \sum_{i,j=1}^{n} J_{ij} \, x_i x_j$$

NP-hard



Idea: Encode QUBO in a *diagonal* problem Hamiltonian

- For one qubit, with $|0\rangle := \binom{1}{0}$ and $|1\rangle := \binom{0}{1}$, note that $\sigma_z := \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$ yields $\sigma_z|0\rangle = |0\rangle$ and $\sigma_z|1\rangle = -|1\rangle$.

- Using the tensor (Kronecker) product, express QUBO in H_1 as

$$H_1 = h_0 \, I + \sum_{i=1}^{n} h_i \, \sigma_z^{(i)} + \sum_{i,j=1}^{n} J_{ij} \, \sigma_z^{(i)} \otimes \sigma_z^{(j)}$$

→ Seems pretty implausible that any physical device could realize the AQC model for this class of problems efficiently

…but maybe it could outperform for "real-world" instance sizes.

What *else* to do with AQC?

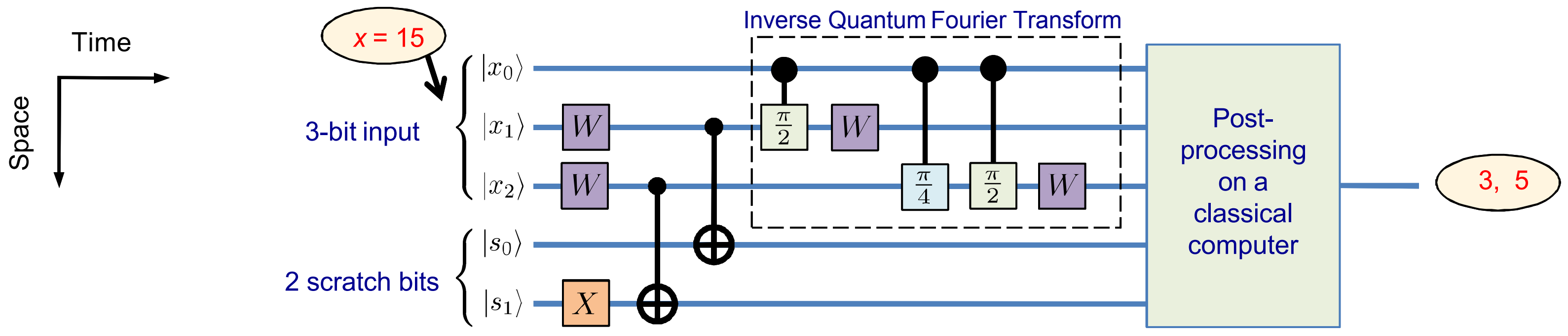
Universal quantum computation!

Quantum circuit model:

Program: Sequence of unitary *gates* (constant-sized transformations)

Result: The product of those gates acting on the n-qubit input vector as a “quantum state”

$$|\psi\rangle \rightarrow U_1|\psi\rangle \rightarrow U_2U_1|\psi\rangle \rightarrow \ldots \rightarrow U_m \ldots U_1|\psi\rangle$$



Quantum circuit for factoring 15 = 3 × 5

Universal AQC

Kitaev reinvents an old idea of Feynman's

Idea: Add extra "clock" qubits and construct H_1 so its ground state is the "history state" $|\eta\rangle$.

$$H_0 = H_{\text{in}} + H_{\text{clock-init}} \qquad\qquad H_1 = H_{\text{in}} + H_{\text{prop}}$$

$$H_{\text{in}} = \sum_{i=1}^{n} |1\rangle\langle 1|_i \otimes |0\rangle\langle 0|_{\text{clock}}$$

- Favors "If clock is 0, set data to 00…0."

$$H_{\text{clock-init}} = \sum_{t=1}^{T} |t\rangle\langle t|_{\text{clock}}$$

- Favors "Set clock to 0."

$$H_{\text{prop}} = \frac{1}{2}\sum_{t=1}^{T}\Big(I \otimes |t\rangle\langle t| + I \otimes |t-1\rangle\langle t-1| - U_t \otimes |t\rangle\langle t-1| - U_t^{\dagger} \otimes |t-1\rangle\langle t|\Big)$$

- Favors "Set state to history state."

$$|\eta\rangle = \frac{1}{\sqrt{T+1}}\Big[|0\rangle|0\rangle + U_1|0\rangle|1\rangle + U_2U_1|0\rangle|2\rangle + \cdots + (U_T \ldots U_1)|0\rangle|T\rangle\Big]$$

AQC Complexity

Need to know how model is implemented to answer

Schrodinger equation

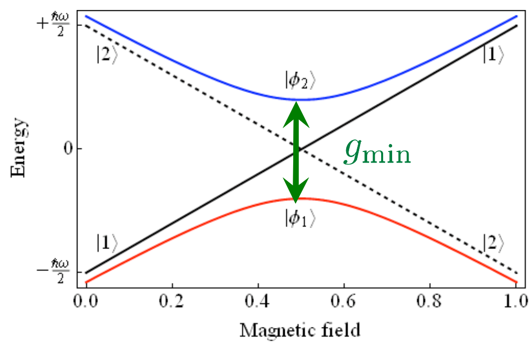
$$i\hbar\frac{d}{dt}|\psi(t)\rangle = H(\tfrac{t}{T})|\psi(t)\rangle$$

- Instantaneous energy eigenbasis

$$H\left(\tfrac{t}{T}\right) = \sum_E E\left(\tfrac{t}{T}\right)\ \left|E\left(\tfrac{t}{T}\right)\right\rangle\left\langle E\left(\tfrac{t}{T}\right)\right|$$

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

Quantum adiabatic process: No state transfer into or out of the instantaneous eigenspace.



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

- More rigorously: $\||\psi(T)\rangle - |E_0(1)\rangle\| \leq \frac{1}{T}\left[\frac{\|\dot{H}\|}{g^2}(0) + \frac{\|\dot{H}\|}{g^2}(1) + \int_0^1 ds\left(\frac{7\|\dot{H}\|^2}{g^3} + \frac{\|\ddot{H}\|}{g^2}\right)\right]$

Promises of AQC

Weak on algorithms, but strong on imlementation

Has it inspired new algorithms or lower bounds?

- **Combinatorial optimization**
  - Expression as eigenvector problems not particularly new
  - Unable to say anything definitive about complexity yet, but likely not efficient for NP-hard problems
  - Even absent proofs, could yield speedups for "real-world" instance sizes. ($$$; €€€)
- **Quantum circuit simulation**
  - Not particularly "natural." Lacks a convincing "blueprint" for a real Hamiltonian.
  - Best-known slowdown is quartic, which would erase many known quantum speedups.

Does it promise implementation advantages?

- YES!!!
- Predicted to be robust to dephasing errors, relaxation errors, thermal errors, and control errors.
- Could reduce the number of qubits needed to implement algorithms by ORDERS OF MAGNITUDE.

Implementation advantage promises

Quantum Information Science

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A banner year

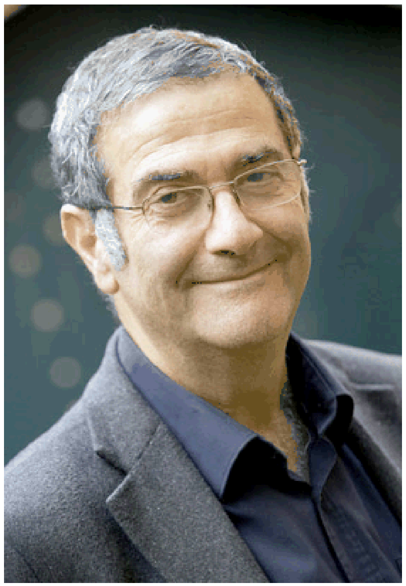

Photo: © CNRS

Serge Haroche

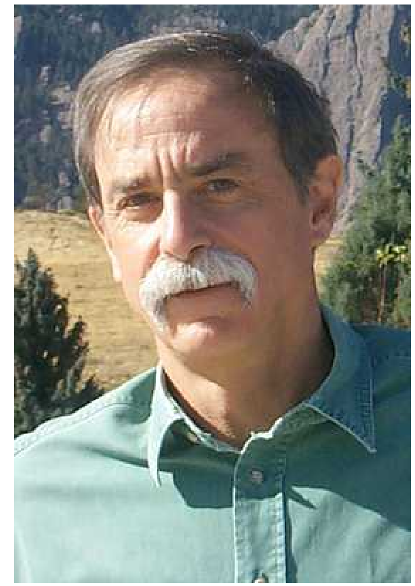

Photo: © NIST

David J. Wineland

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

Quantum information hardware

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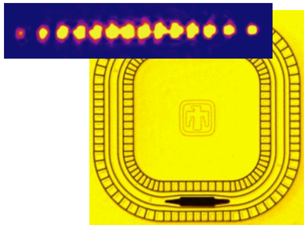
It's a wide open horse race

AMO hardware (Atomic, Molecular, and Optical)

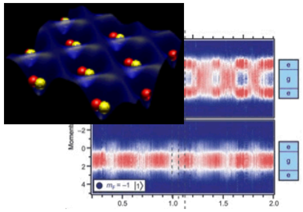
Trapped ion quantum chip



TODAY: 14-qubit entangled state generated.

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

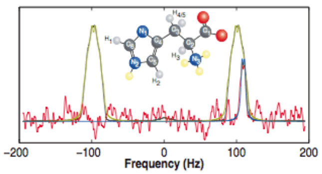
Trapped neutral atoms



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

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

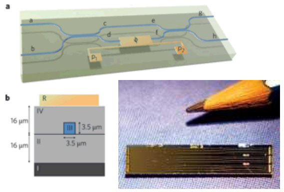
Nuclear magnetic resonance



TODAY: 12-qubit circuits benchmarked.

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

Photonic quantum chip

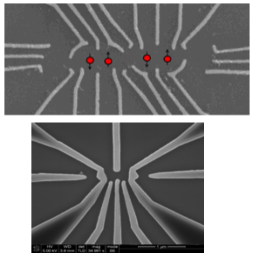


TODAY: 10-qubit photonic chip demonstrated.

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

CMP hardware (Condensed Matter Physics)

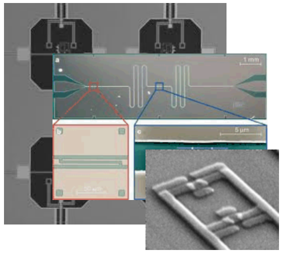
Semiconductor quantum-dot chip



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

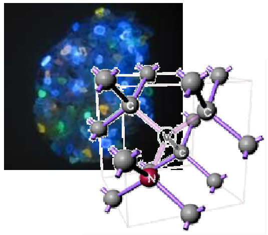
Superconducting quantum chip



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

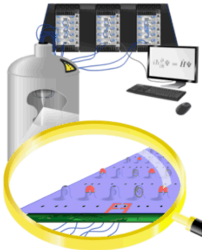
Nitrogen vacancies in diamond



TODAY: 2-qubit gates demonstrated.

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

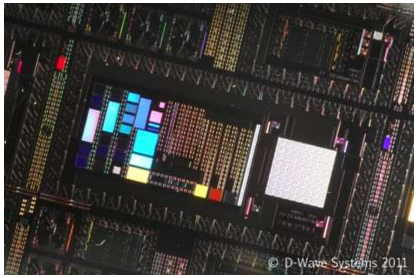
Topological quantum chip



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

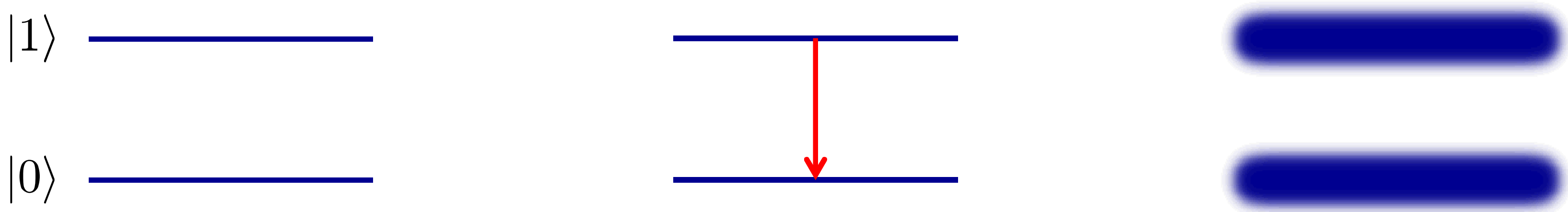


TODAY: 128-qubit (superconducting flux) quantum annealing algorithms. Debate about "quantumness."

Decoherence

With great power comes great fragility

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



Ideal | **Relaxed** | **Dephased**

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

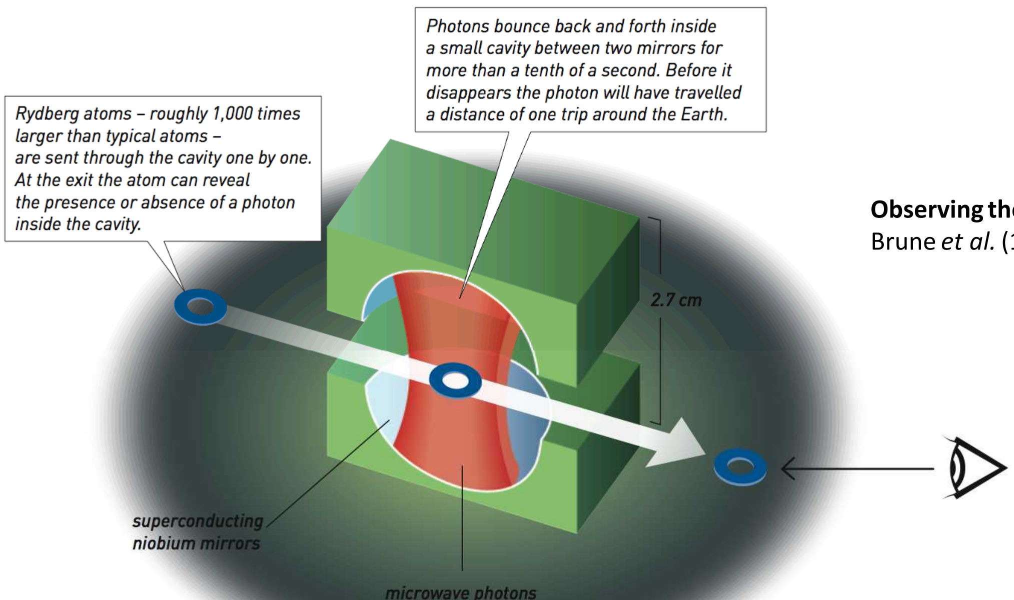


Figure 3. In the Serge Haroche laboratory in Paris, in vacuum and at a temperature of almost absolute zero, the microwave photons bounce back and forth inside a small cavity between two mirrors. The mirrors are so reflective that a single photon stays for more than a tenth of a second before it is lost. 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 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."

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

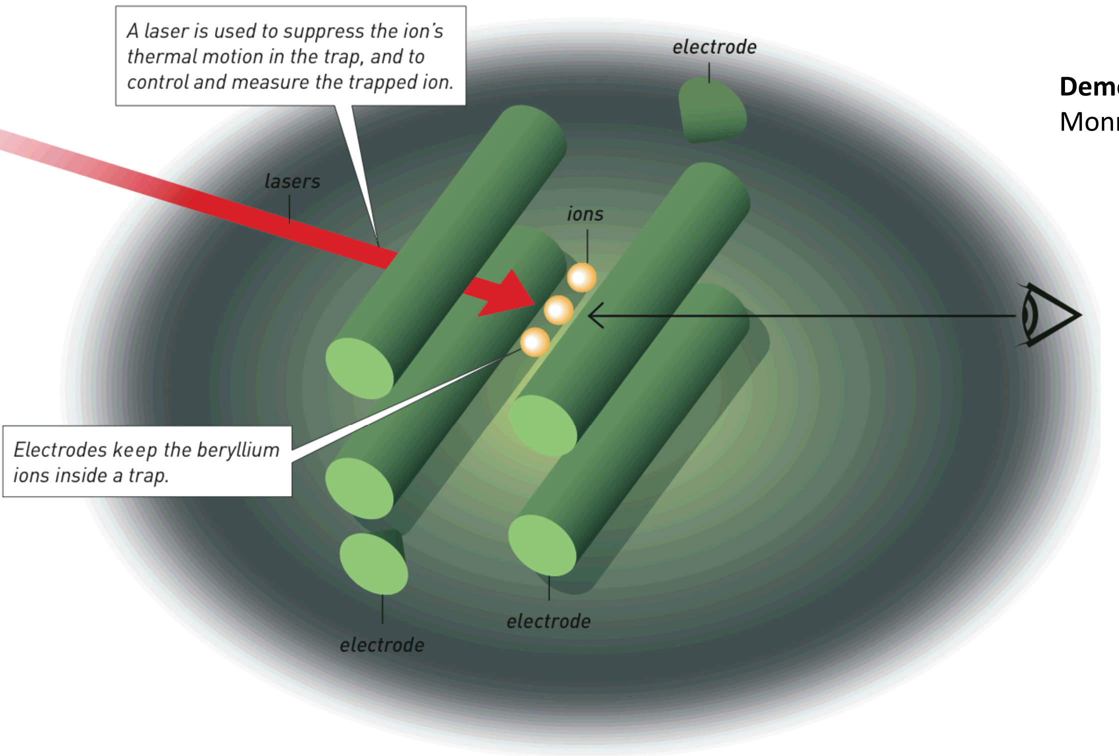


Figure 2. In David Wineland's laboratory in Boulder, Colorado, electrically charged atoms or ions are kept inside a trap by surrounding electric fields. One of the secrets behind Wineland's breakthrough is mastery of the art of using laser beams and creating laser pulses. A laser is used to put the ion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

Image: © Royal Swedish Academy of Sciences

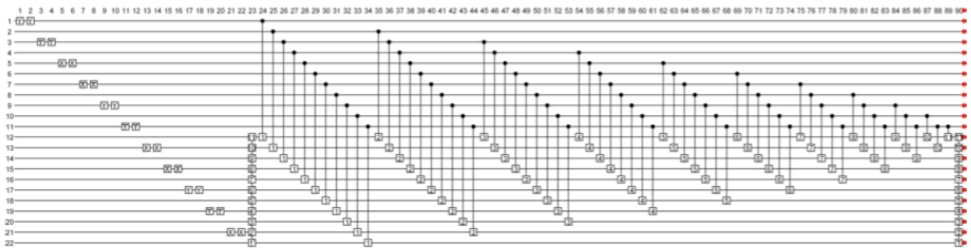
Demonstration of a fundamental quantum logic gate
Monroe *et al.* (1995), doi:10.1103/PhysRevLett.75.4714

- 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)

Scale of quantum computing

How big is “big enough” to be useful?

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

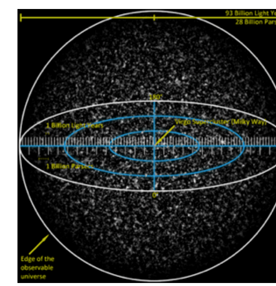


Example of a quantum circuit simulated by Jugene

Jugene: 9th fastest supercomputer

- Qubits needed to hold more amplitudes than atoms in the observable universe: 266 qubits.*

*Holevo’s Theorem: Only 266 bits’ worth can be read out.



- Qubits needed to *simulate* an ideal circuit on 300 ideal qubits with a realistically faulty quantum computer: **Over 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}.

The circuit architecture is a siren song! While the gates & qubits may be simple, enormous numbers of them may be needed in realistic devices to be useful.

Monz *et al.* (2011), doi:10.1103/PhysRevLett.106.130506
De Raedt *et al.* (2007), doi:10.1016/j.cpc.2006.08.007
Holevo (1973), http://mi.mathnet.ru/eng/ppi903
Steane (2007), http://www.rintonpress.com/xqic7/qic-7-3/171-183.pdf

Fault-tolerant quantum computing

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

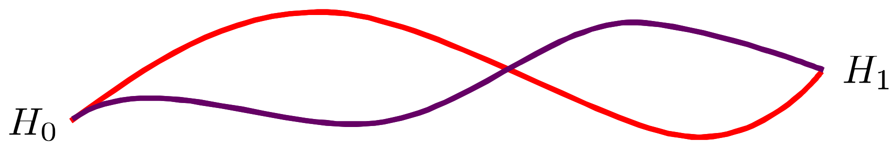
   [Steane, 2007 (Ion trap tech., quantum circuit architecture)]

   TODAY: Are you kidding?

Quantum computer, heal thyself!

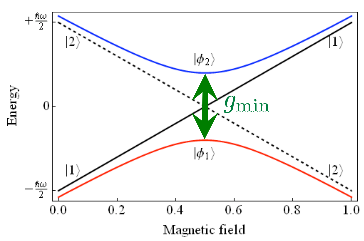
Adiabatic physics may suppress dominant errors

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 (states are *rays*).

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

AQC promises

In theory, implementing it should be very robust!

1. Should be able to run *any* quantum algorithm, if the repertoire of interactions is sufficiently rich.
2. Should be robust to
   - Damping (T_1) noise (which occurs in the instantaneous energy eigenbasis).
   - Dephasing (T_2) noise (which shifts energy levels).
   - Thermal (kT) noise (because of the gap).
   - Control errors that are adiabatic (because any adiabatic path works).
3. Should *not* be robust to
   - Measurement errors.
   - Leakage errors.
4. *May* be commensurate with some "software" error-suppression techniques.
5. Has yet to be proven fault-tolerant.
6. Lacks a clear "blueprint" for universal computing in realistic hardware.

AQUARIUS: Sandia’s Grand Challenge to validate some of the promises of AQC

Overview

Sandia National Laboratories

The important R&D questions to answer are:

- Are the theoretical promises of robustness borne out in real hardware?
  (E.g., in representative AMO and CMP technologies?)
- Develop a blueprint for a universal adiabatic architecture for real hardware.
- Assess the need for fault-tolerant design for real hardware.
- If needed, devise a way to make the adiabatic architecture fault tolerant.

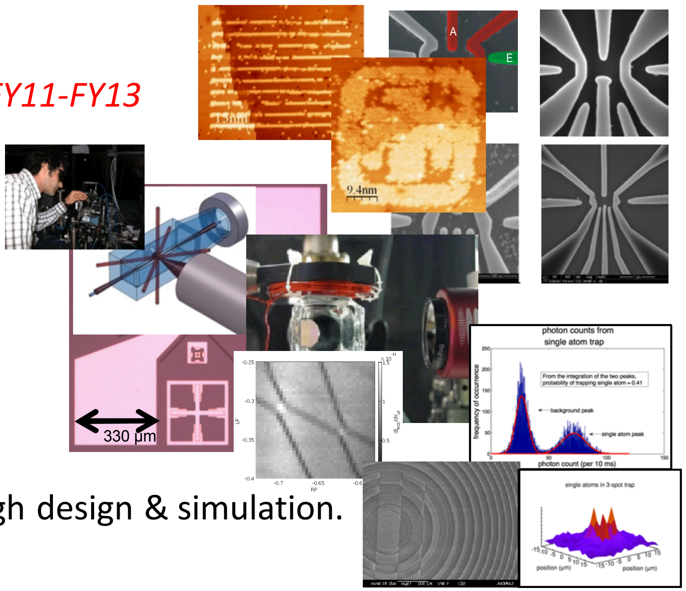
AQUARIUS™

Adiabatic quantum architectures in ultracold systems

An internally-funded Sandia "Grand Challenge" project FY11-FY13

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.



AQUARIUS labs & facilities

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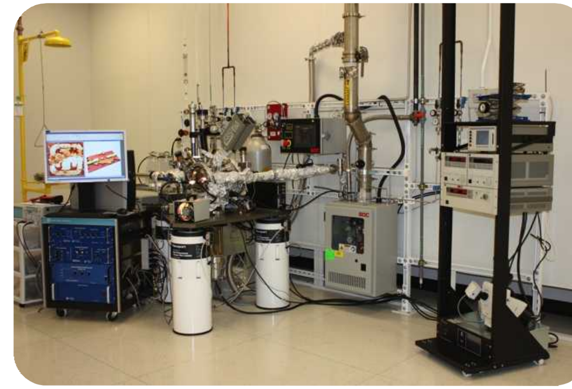
Draws upon diverse resources at Sandia

Optical atom trapping & control lab

Cryogenic materials & electronics measurement lab



Atomic-precision lithography lab

Microsystems and Engineering Sciences Applications (MESA)

MESA

Center for Integrated Nanotechnologies (CINT)

Computer Science Research Institute (CSRI)

CSRI
Computer Science Research Institute

The neutral-atom qubit

It’s not just fine—it’s hyperfine!

Group → / ↓ Period	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	1 H																	2 He
2	3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
5	37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
6	55 Cs	56 Ba		72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
7	87 Fr	88 Ra		104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn	113 Uut	114 Fl	115 Uup	116 Lv	117 Uus	118 Uuo

Lanthanides	57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
Actinides	89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr

One electron outside closed shell

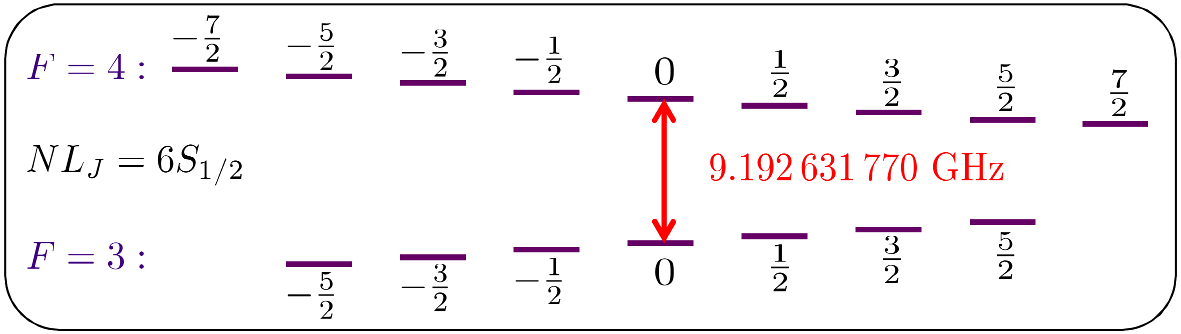
^{133}Cs: $1s^2\ 2s^2\ 2p^6\ 3s^2\ 3p^6\ 3d^{10}\ 4s^2\ 4p^6\ 5s^2\ 4d^{10}\ 5p^6\ 6s^1$

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

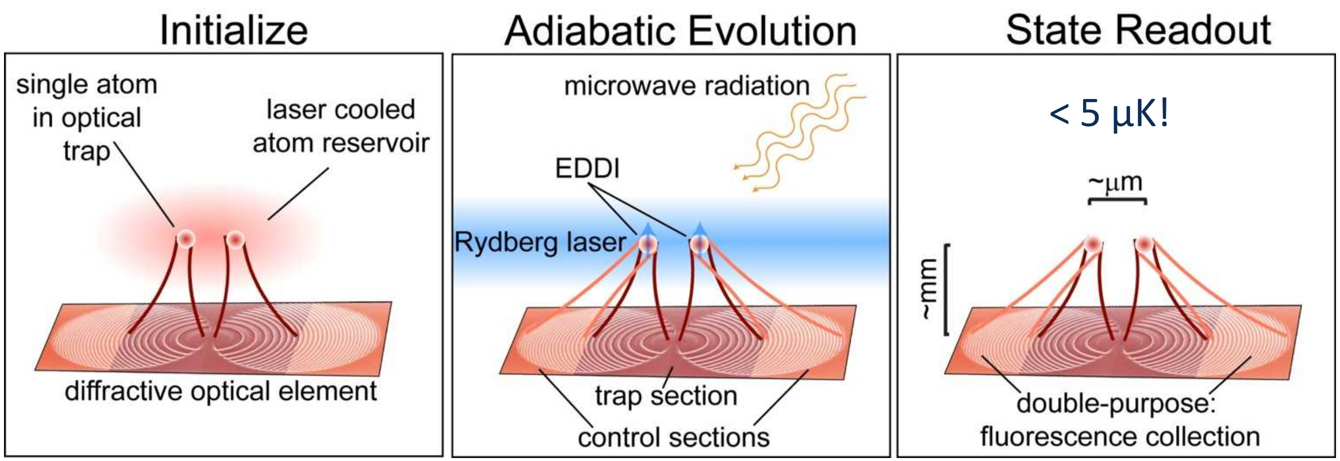
$$\hat{\mathbf{F}} = \hat{\mathbf{J}}_{\rm el} + \hat{\mathbf{I}}_{\rm nuc} \qquad I_{\rm nuc} = \frac{7}{2}$$

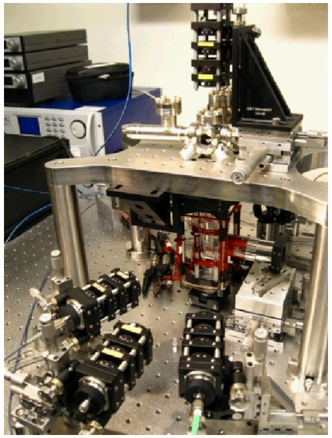


Trapping & controlling cesium

Sandia-fabricated diffractive optics

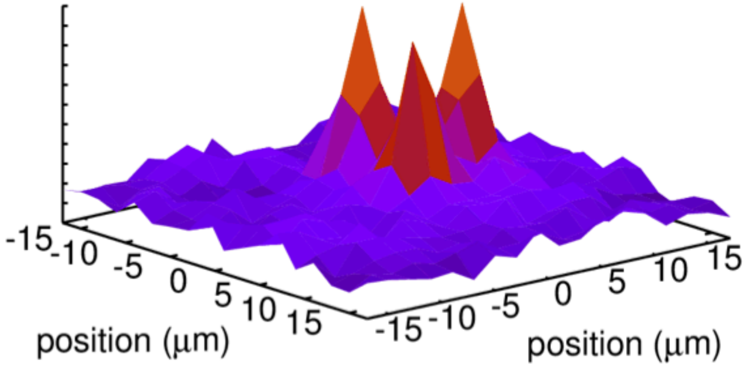
- Fabricated & used **world-first diffractive optical elements** for trapping and controlling individual atoms.

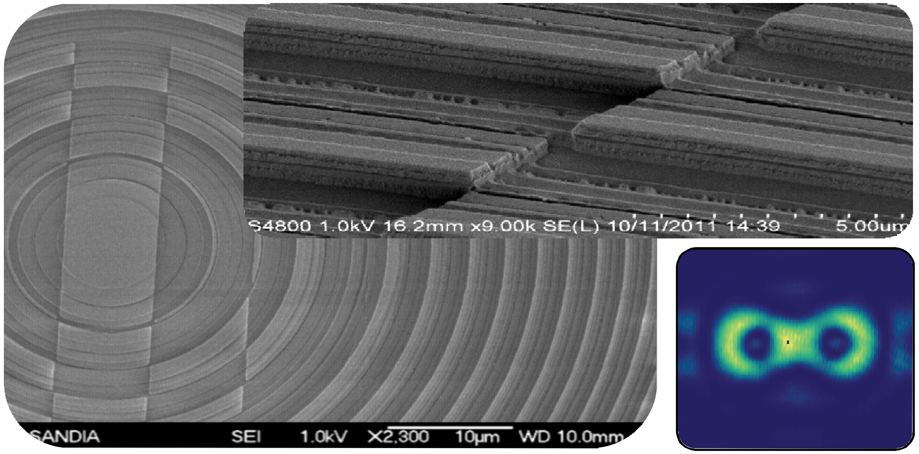




DOE test platform

single atoms in 3-spot trap

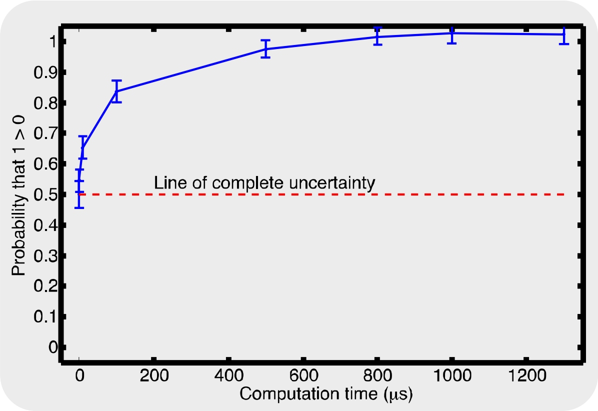




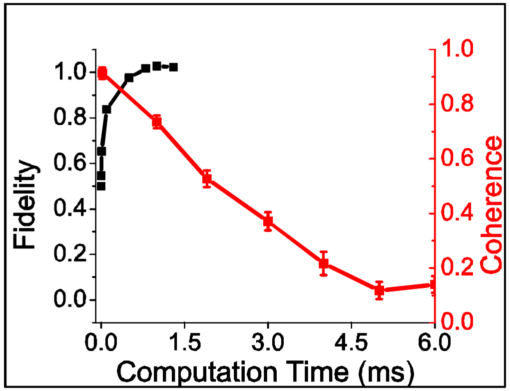
Evidence of robustness

Validating claims…for one qubit

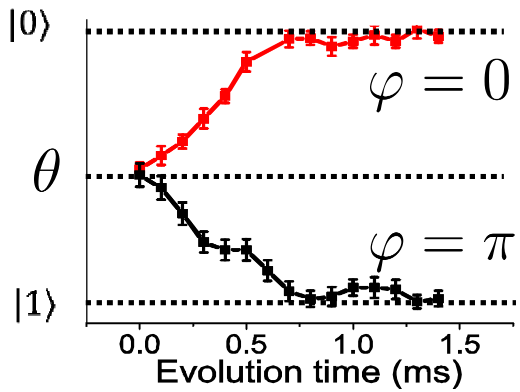
- Built **Sandia's first functioning one-qubit quantum computer.**
  - Inaugural calculation: **"1 is greater than 0 … with high probability."**



$$\sigma_x \to \sigma_x + 27\sigma_z$$



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



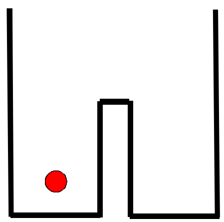
$$|\psi_0\rangle = \sin\frac{\theta}{2}|0\rangle + e^{i\varphi}\cos\frac{\theta}{2}|1\rangle$$

Quantum-dot qubits

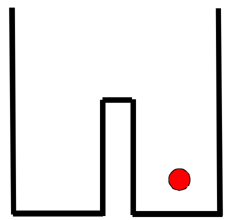
Sandia National Laboratories

“Artificial atoms” with more tunable properties

Theory: Double-well electron qubits



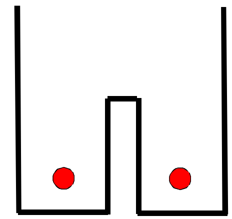
$|0\rangle = |1\rangle_L|0\rangle_R$



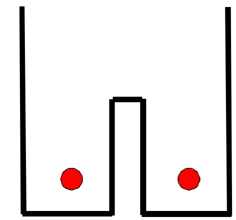
$|1\rangle = |0\rangle_L|1\rangle_R$

Charge qubit

Short T_2 but easier to work with & stable ground state



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



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

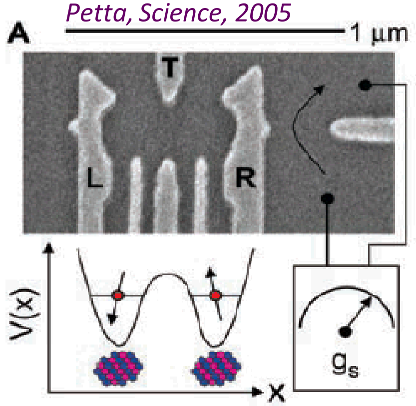
Spin qubit

Long T_2 but harder to work with & metastable ground state

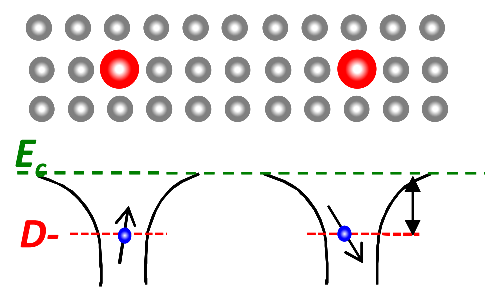
(Electrical readout for both types, though.)

AQUARIUS hardware approach: Near-term (dots) & long-term (donors)

Petta, Science, 2005



Double quantum dot (DQD)

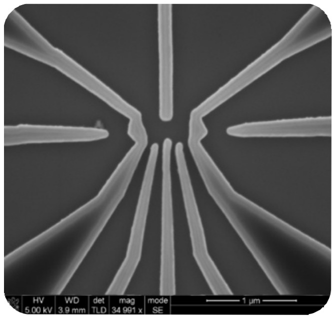


Pair of donors

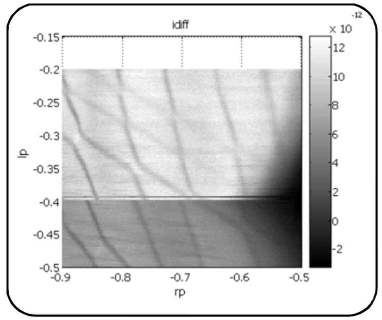
Quantum-dot qubits

Not adiabatic yet, but have promise of integration

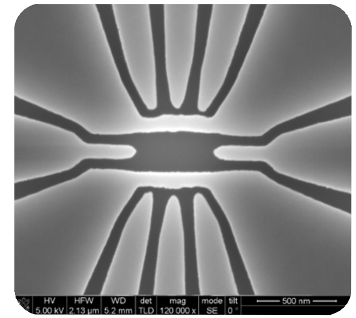
- Invented **world-first semiconductor adiabatic charge qubit.**
  - Built one- and two-qubit silicon quantum dot devices realizing the idea.



One-qubit device



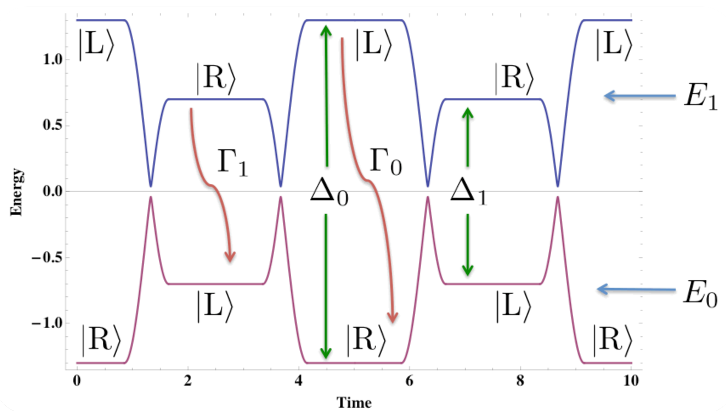
Single-electron occupancy

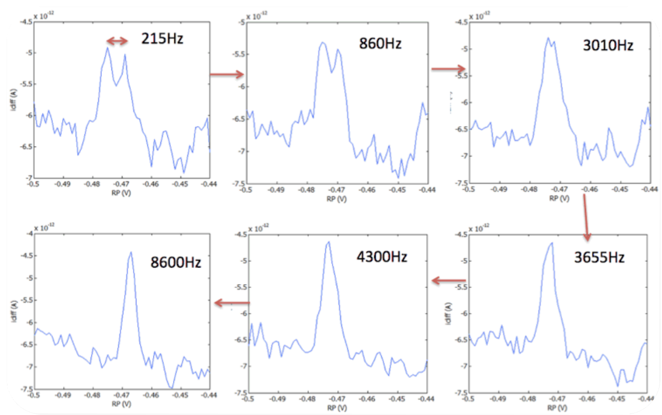


Two-qubit device

- 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

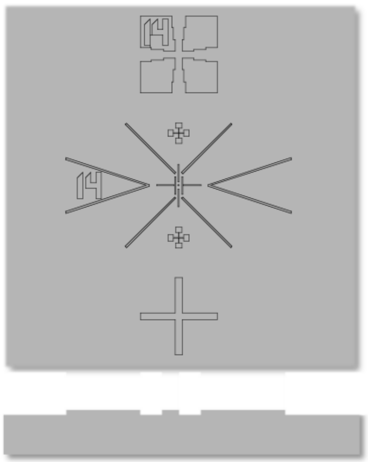
There’s no more room at the bottom

☑Start w clean Si(001)

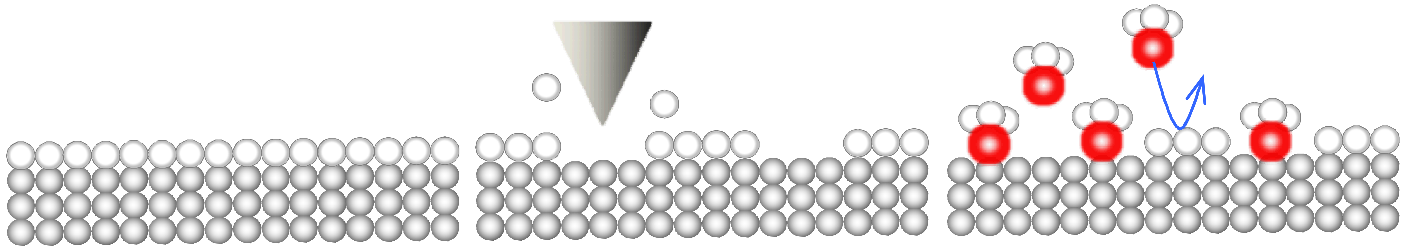
☑Adsorb H resist
Self-limiting 1 monolayer

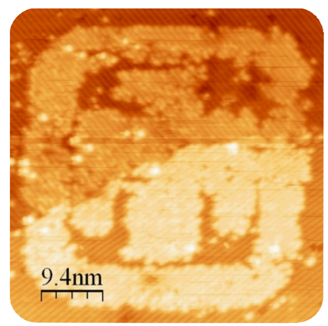
☑Pattern w STM
Atomic-precision

☑ Adsorb PH_3



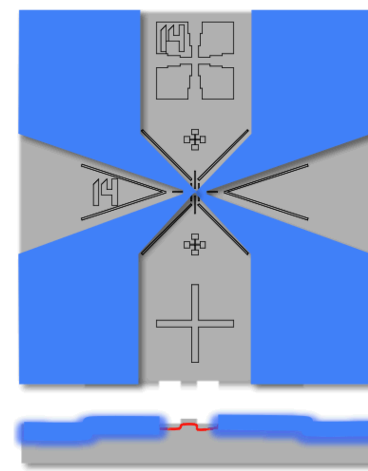
Etched alignment marks

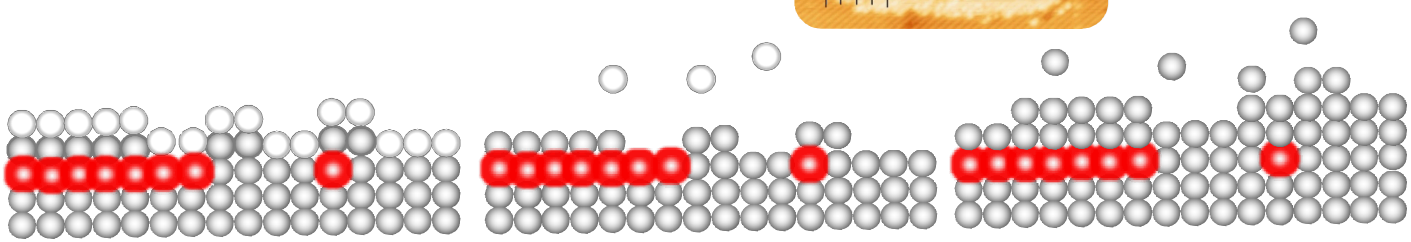




0.7 nm features!

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

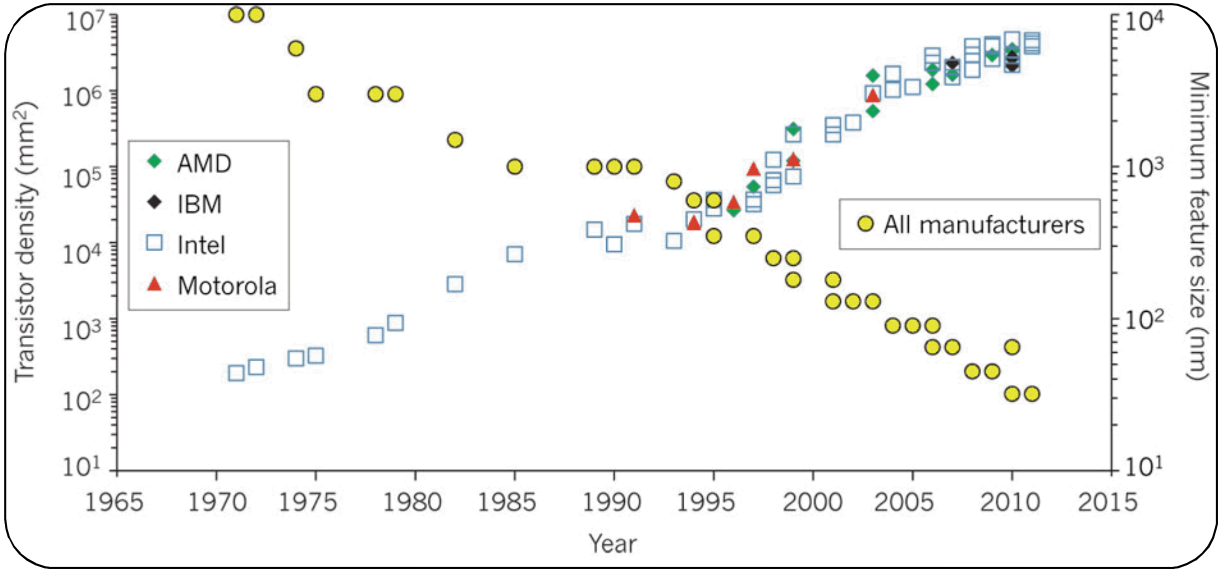
A quantum leap in our mastery of information

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

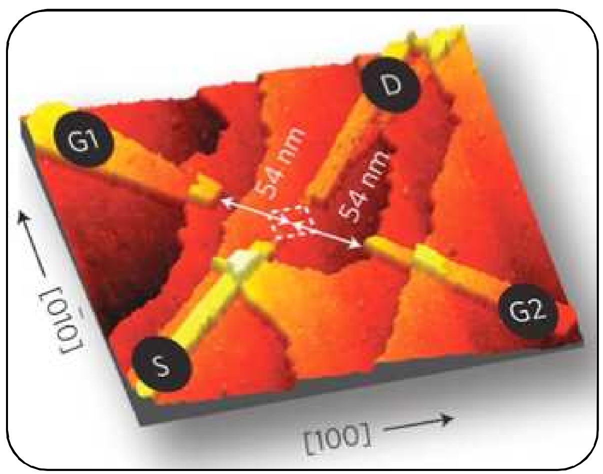
Backup slides

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:

00: All clear
01: Flip qubit 3
10: Flip qubit 1
11: Flip qubit 2

QUBO with cesium atoms

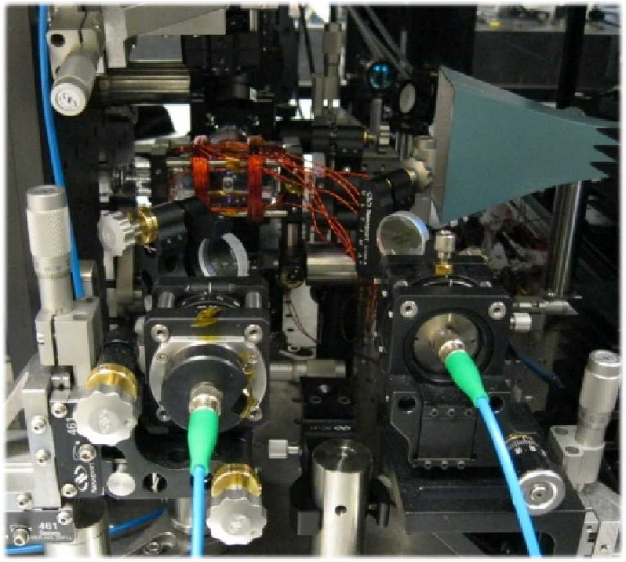
Interactions controlled by lasers and microwaves

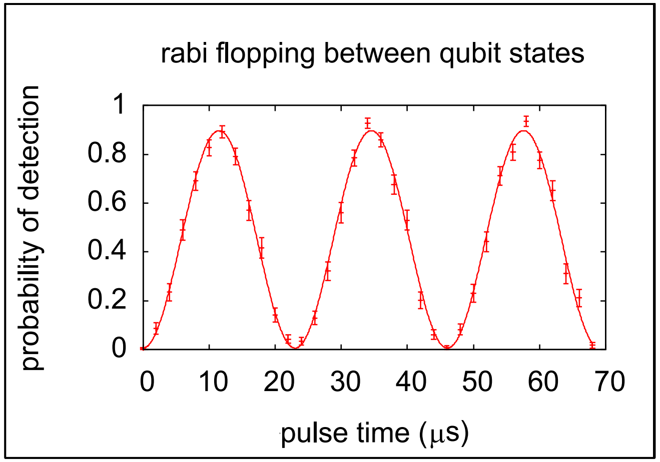
$(6S_{1/2}, F=4) \mapsto |0\rangle$

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

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

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





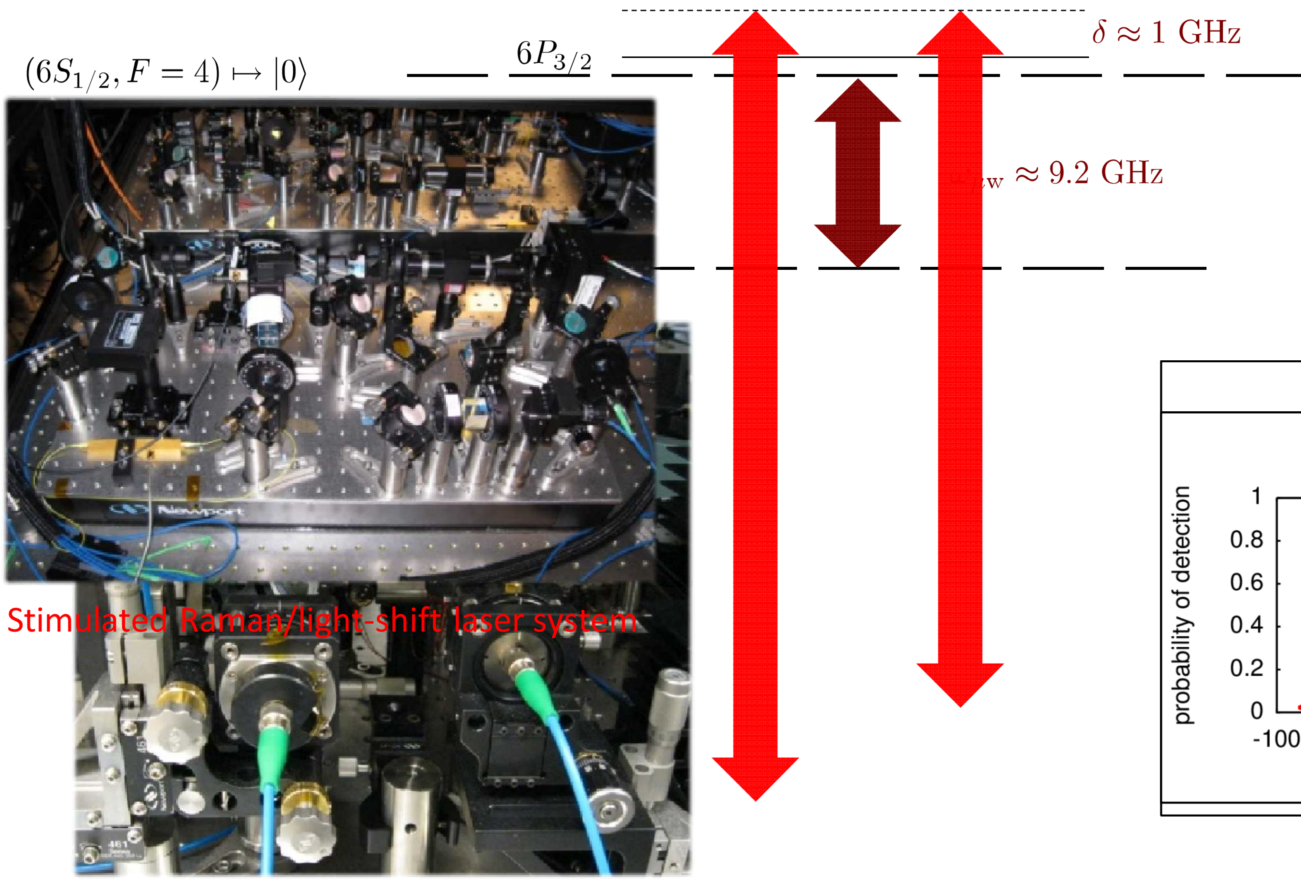
Actual data

QUBO with cesium atoms

Interactions controlled by lasers and microwaves

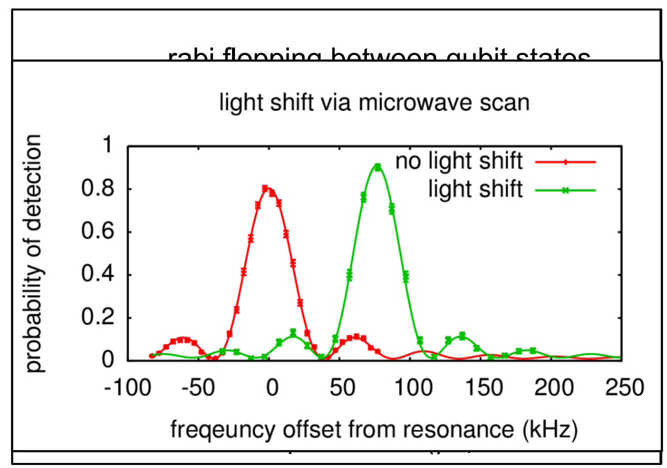
$\lambda \approx 852$ nm

$\omega \approx 100$ kHz



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

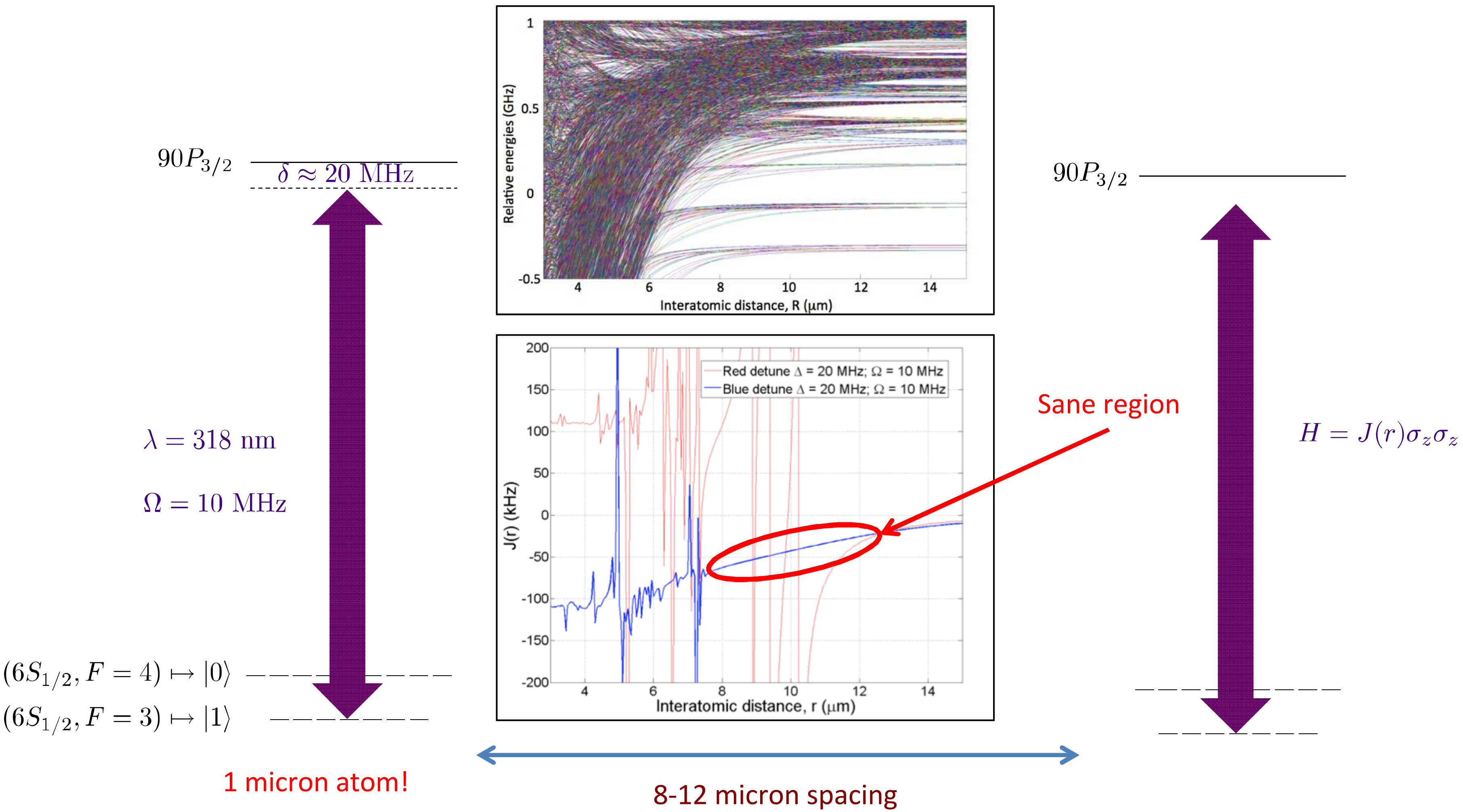
$H = \frac{\hbar}{2}\omega\sigma_x$



Actual data

QUBO with cesium atoms

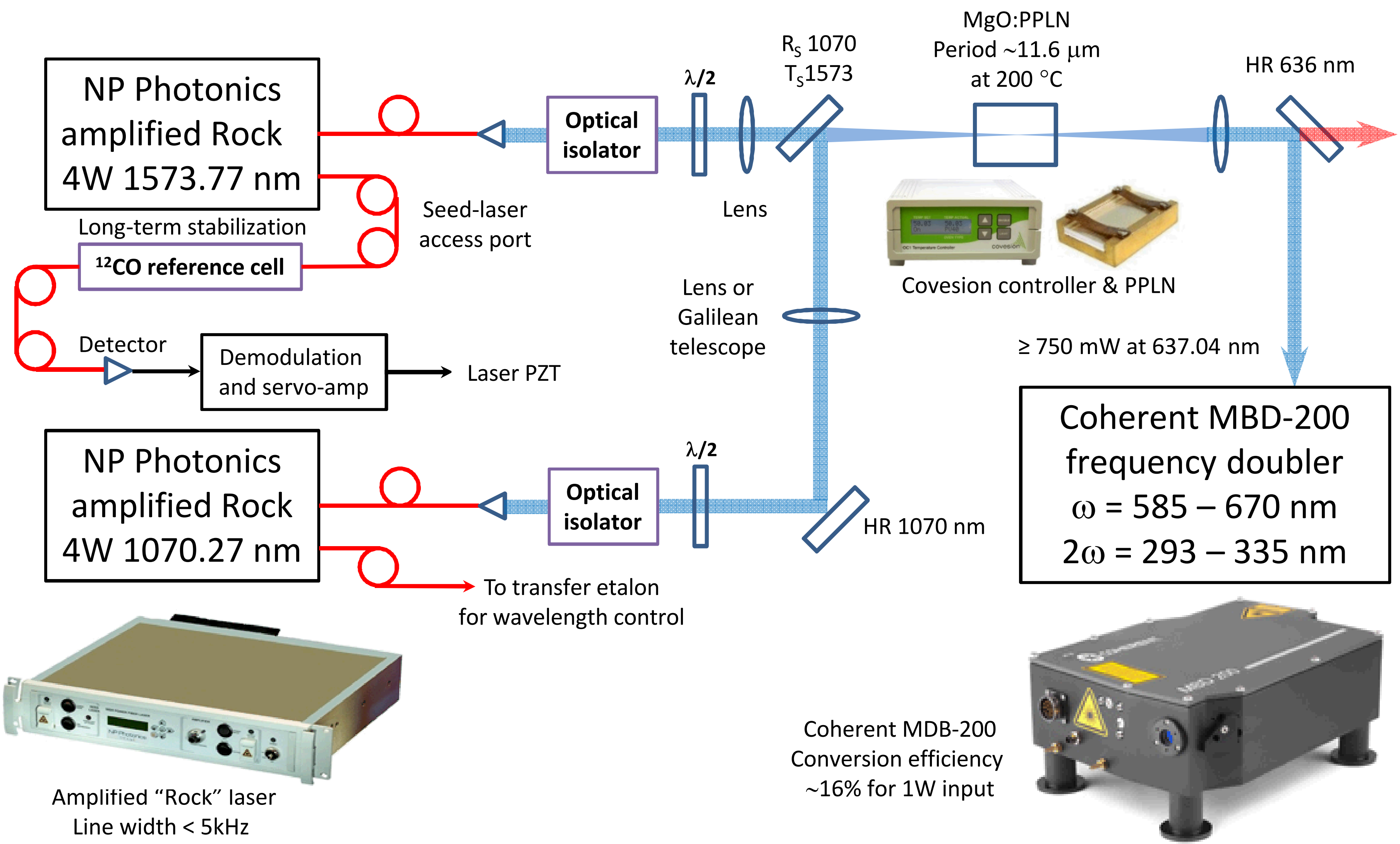
The Rydberg blockade



A 100 mW, 318 nm laser system

Sandia National Laboratories

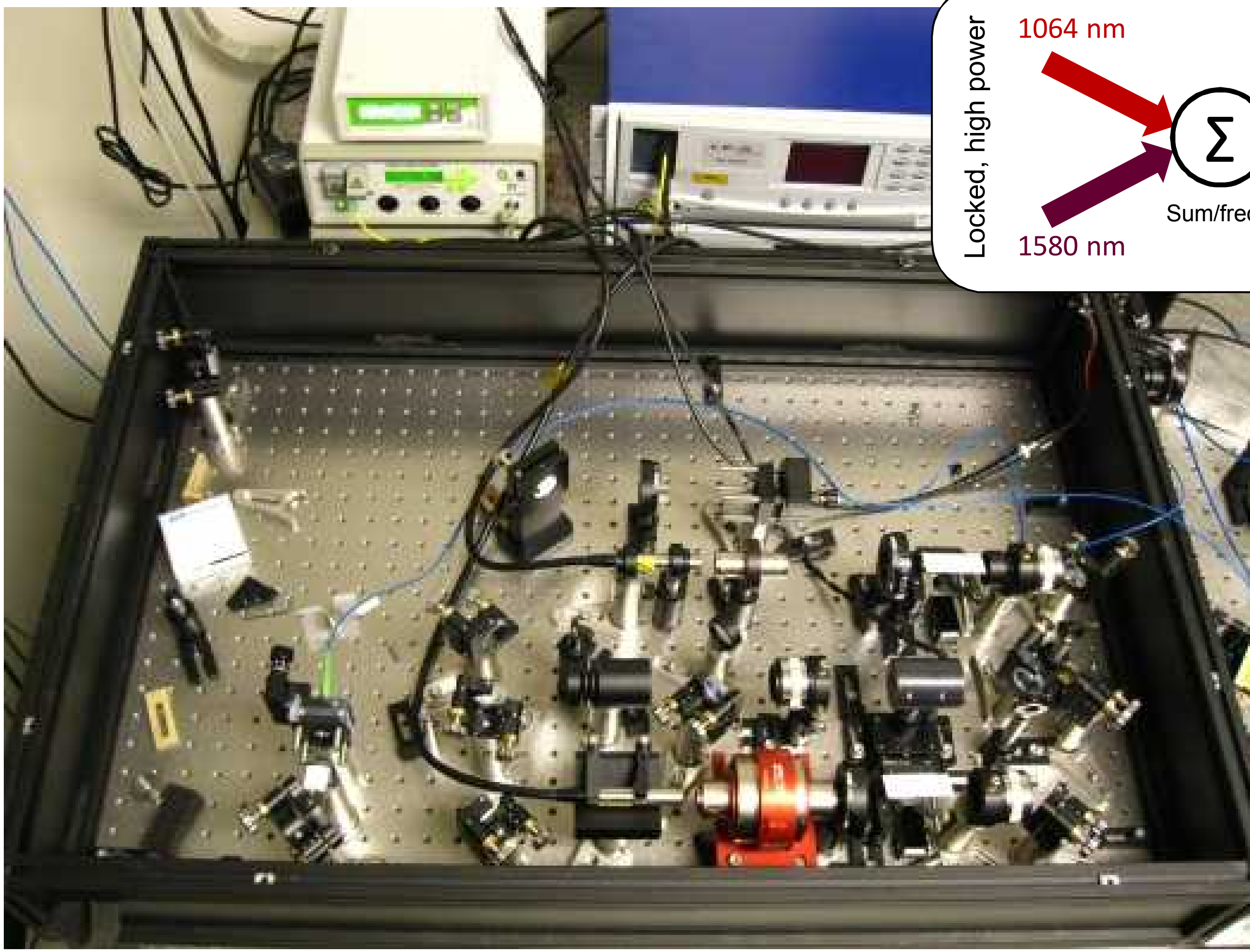
It's complicated

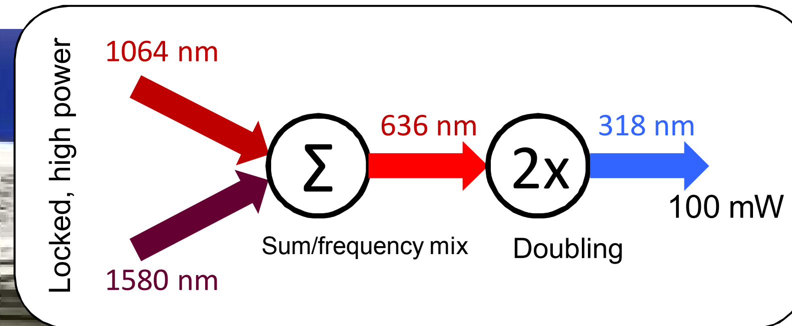


A 100 mW, 318 nm laser system

Sandia National Laboratories

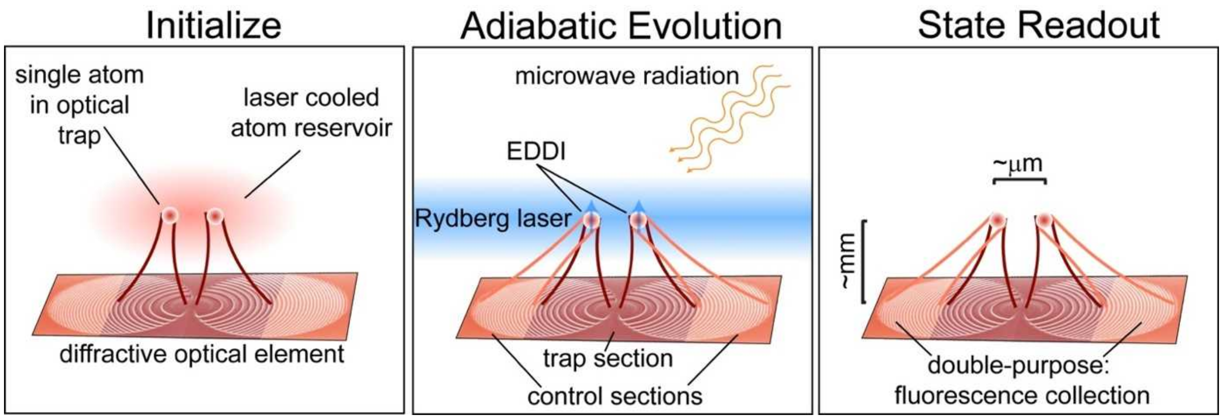
It's complicated





QUBO with ^{133}Cs

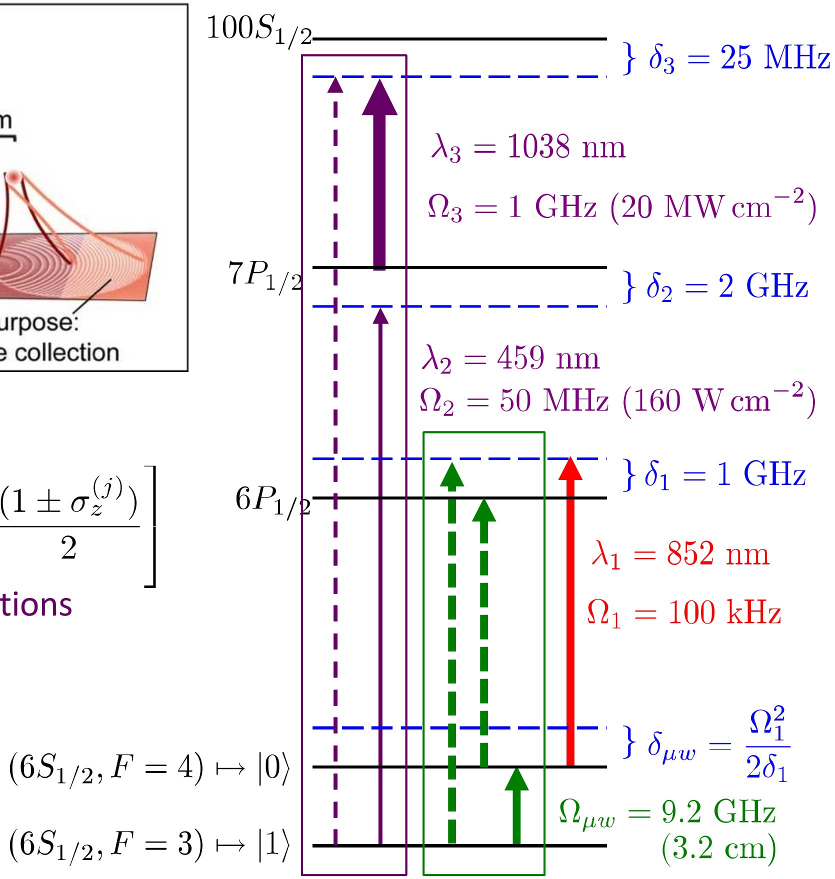
Spinoff optics technology



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

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

Cs level structure



Semiconductor AQC

Theory: Double-well electron qubits

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

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

Charge qubit

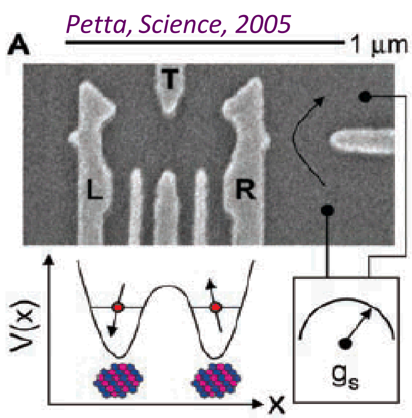
Short T_2 but easier to work with & stable ground state

Spin qubit

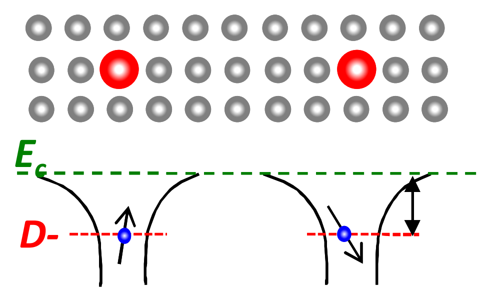
Long T_2 but harder to work with & metastable ground state

(Electrical readout for both types, though.)

AQUARIUS hardware approach: Near-term (dots) & long-term (donors)



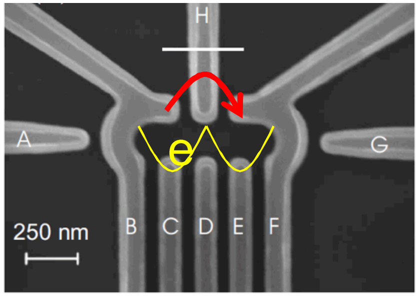
Double quantum dot (DQD)

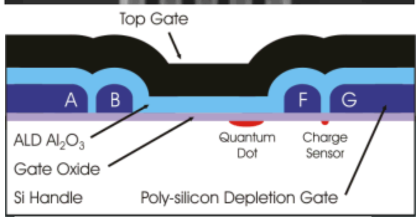


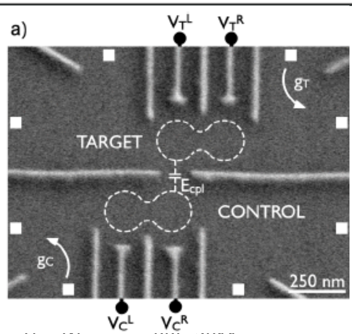
Pair of donors

DQD Charge qubits: Theory

Sandia National Laboratories

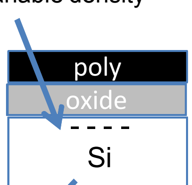




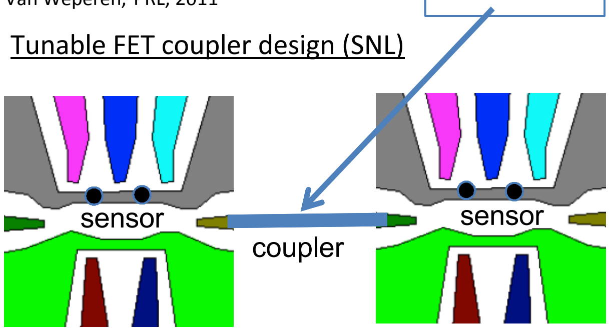


van Weperen, PRL, 2011

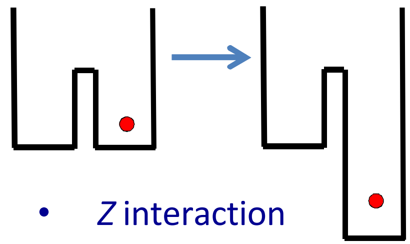
Metallic connector w/ variable density



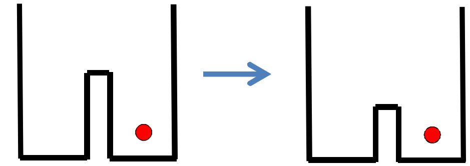
Tunable FET coupler design (SNL)



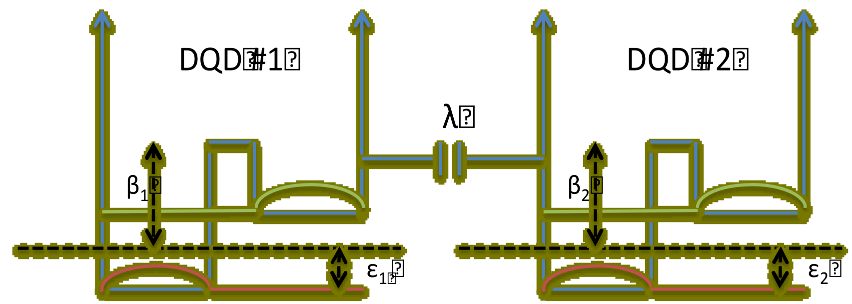
Theory: Set of plausible interactions



- *Z* interaction



- *X* interaction



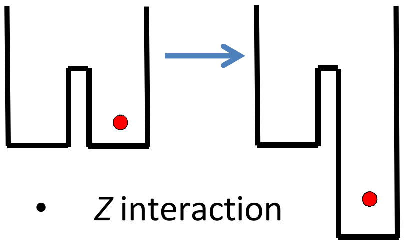
- *ZZ* interaction

- ε = detuning, can modulate by gate voltages ±meV (−12 K to 12K)
- β = tunnel barrier height, can tune neV to meV (120 mK to 12 K)
- λ = Coulomb interaction, can tune 25-85 μeV (0.25 K to 1 K)

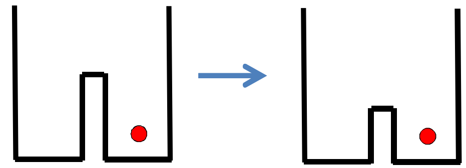
Tuning Coulomb interaction by barrier voltage or FET coupler will be difficult!

The silicon charge qubit

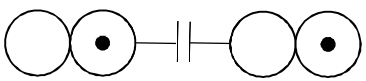
A double-well potential



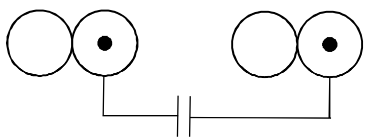
- *Z* interaction



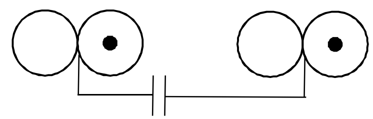
- *X* interaction



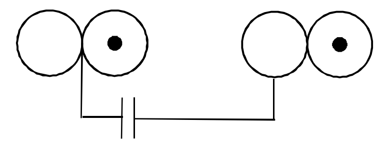
ZZ interaction



−*ZZ* interaction



XX interaction



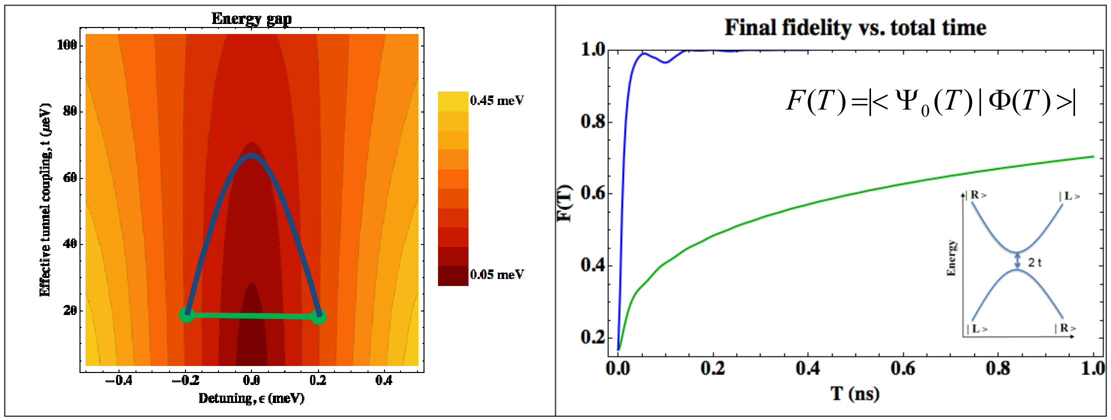
XZ interaction

DQD QUBO & beyond: Theory

Using previously described interactions, can solve QUBO:

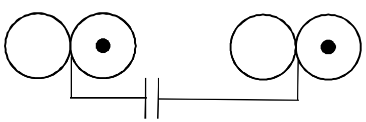
$$H = \sum_i \beta_i(s)\sigma_x^{(i)} + \sum_i \epsilon_i(s)\sigma_z^{(i)} + \sum_{ij} \lambda_{ij}(s)\sigma_z^{(i)}\sigma_z^{(j)}$$

For small-sized problems, can optimize adiabatic path to increase fidelity

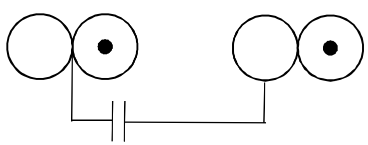


- Simulation: Energy gap is 5 to 500 μeV, runtime is ~1 ns.

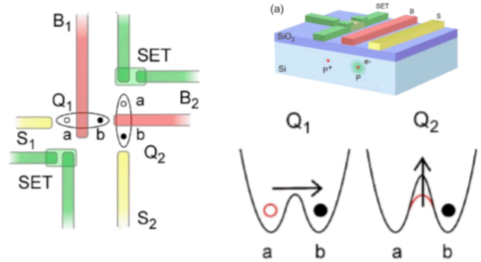
Universal AQC requires ***additional*** interactions:



XX interaction



XZ interaction



Hollenberg *et al.* (2004), doi:10.1103/PhysRevB.69.113301

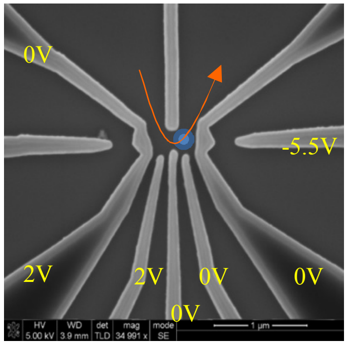
Open questions:

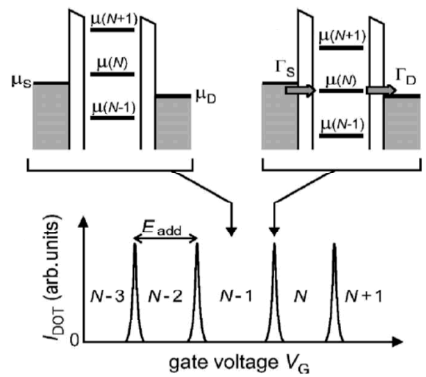
- How plausible is this?
- Is *Y* needed?

DQD AQC: Experimental results

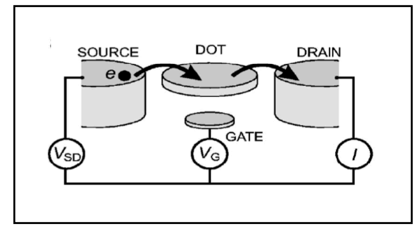
Sandia National Laboratories

Charge-sensed a ***single-well***, ***single-electron*** quantum dot

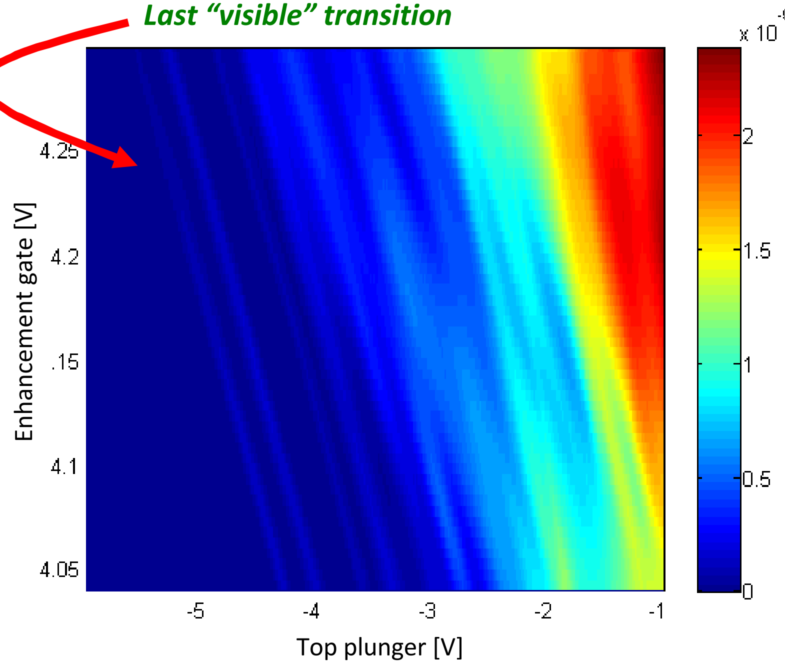




Current goes through QD when levels lines up



Last "visible" transition



Edge of transport through dot observed!

Two most likely reasons:

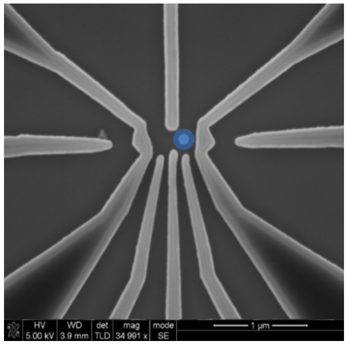
- Tunnel barrier is gradually turning off (often the case)
- Last electron

This case is not gradual and no additional transitions are observed over reasonably large V_{top} scan and V_{sd}

→ Strong evidence for single-electron occupation!

DQD AQC: Experimental results

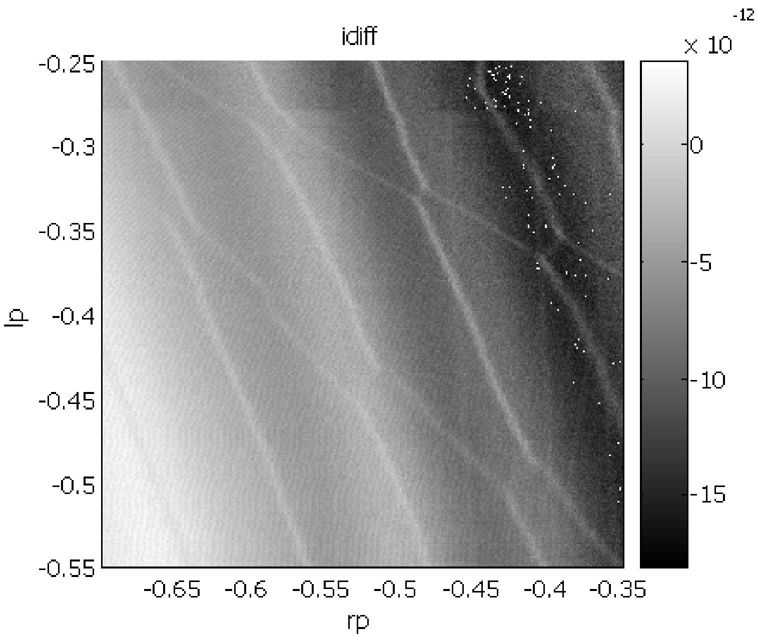
Charge sensing of a ***double-well*** quantum dot



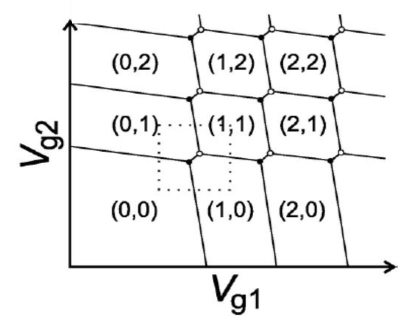
Strategy:

- Fill dot region with electrons.
- Form a single well.
- *<Dial down to single electron>*
- Deform potential to double well.
- Balance charge sensor with the dot.

It's easier to start with a many-electron dot first; for AQC single-electron discrimination of a many-electron DQD is sufficient.



- Coulomb blockade has richer "honeycomb" structure for DQDs.
- **We are not at single-electron occupation yet.** (Charge sensor balancing TBD.)



→ However, we have enough to test adiabaticity of evolutions!

Testing adiabaticity: theory

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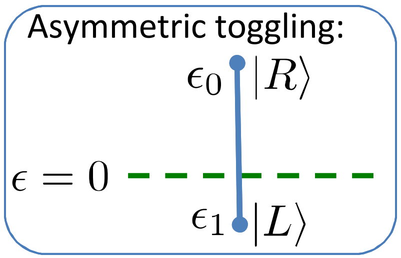
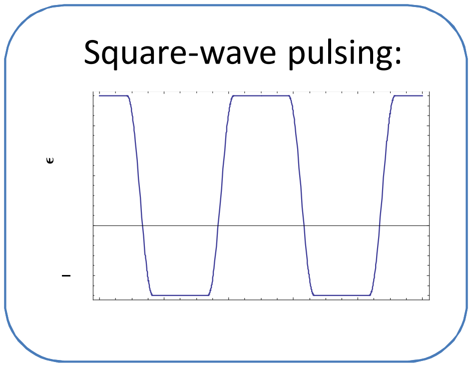
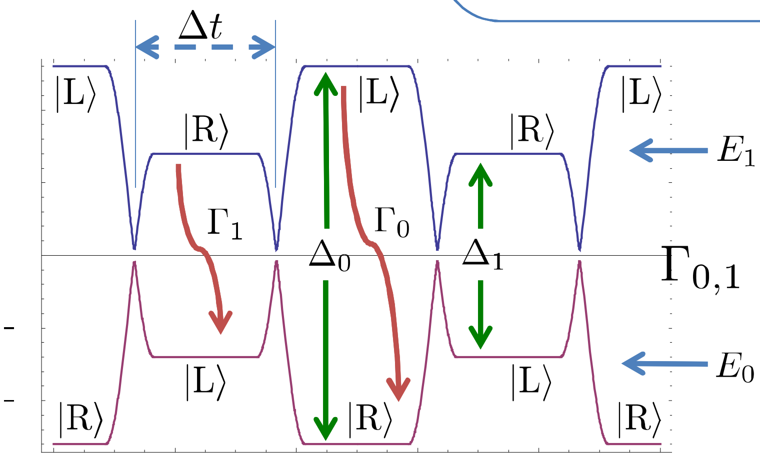
Adiabaticity testing

If relaxation and adiabatic evolution both drive one to the ground state, how do we disentangle the causes?

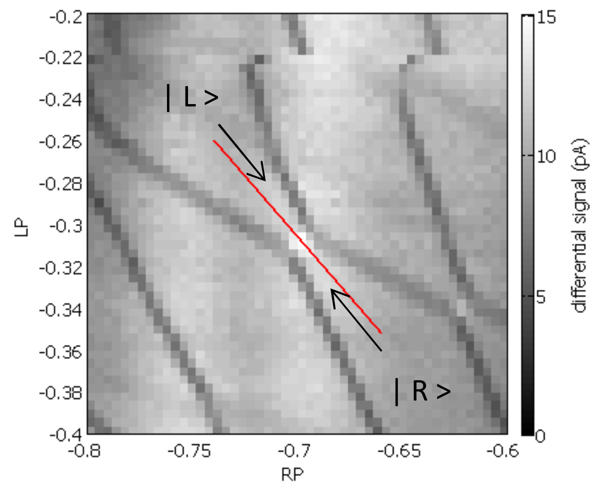
$$H = \beta\sigma_x + \epsilon(s)\sigma_z \qquad s := \frac{t}{T}$$







$\Gamma_{0,1}$ = relaxation rates

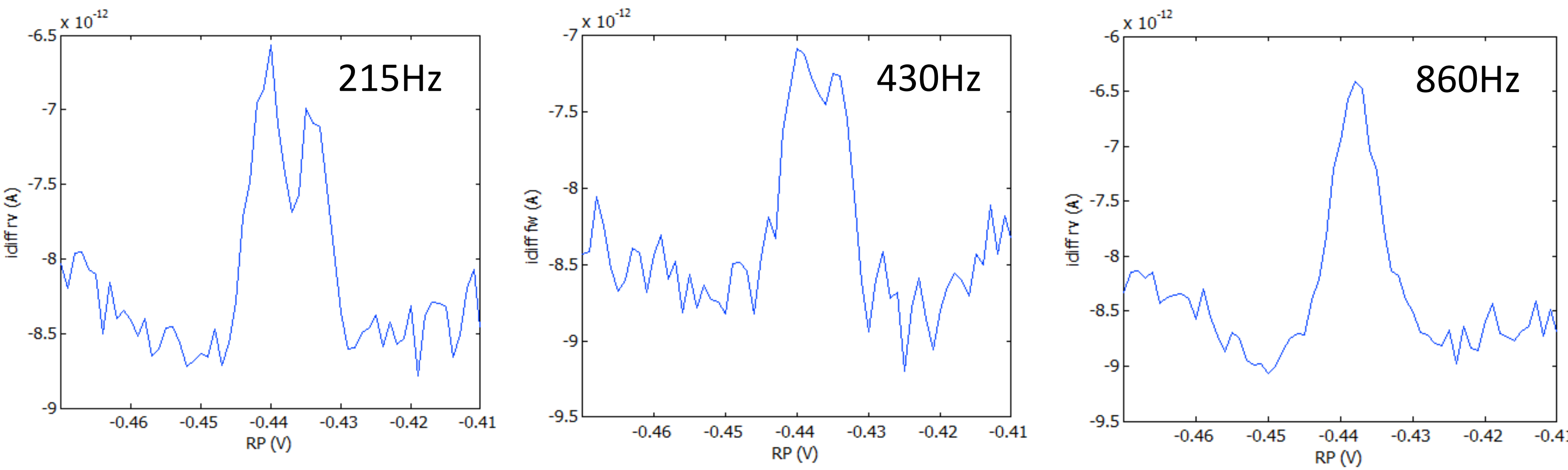


- As Δt grows, if evolution is nonadiabatic, time-averaged signal will transition from R-R-R-R (too fast to exhibit relaxation) to R-L-R-L-R-L (relaxation). → Finds relaxation timescale!
- Rerun experiment at a timescale faster than relaxation, and increase gap by increasing beta. An observed transition from R-R-R-R to R-L-R-L is signature of adiabaticity!

Testing adiabaticity: experiment

We are just now doing preliminary experiments probing the relaxation timescale

Testing three square-wave pulse frequencies. Two peaks indicate both R and L populate. One peak indicates only R populates.



We're developing some detailed noise models to allow us to extract T_1 from this data.

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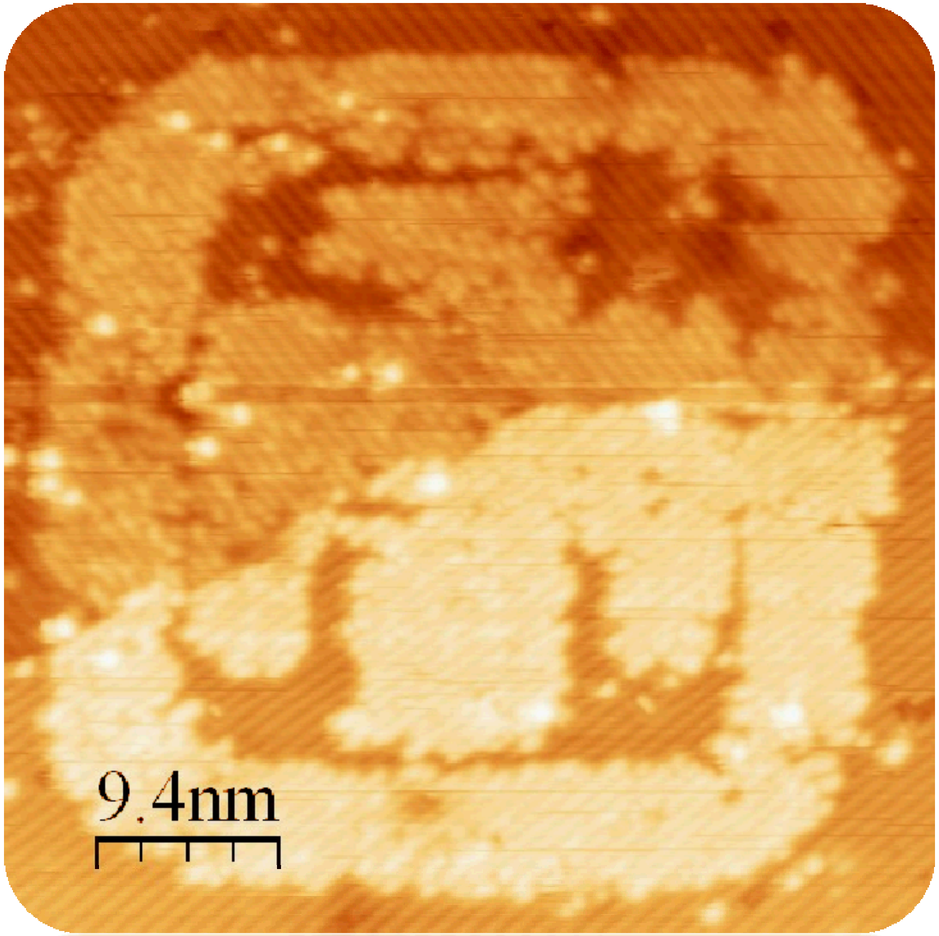
Atom-sized features

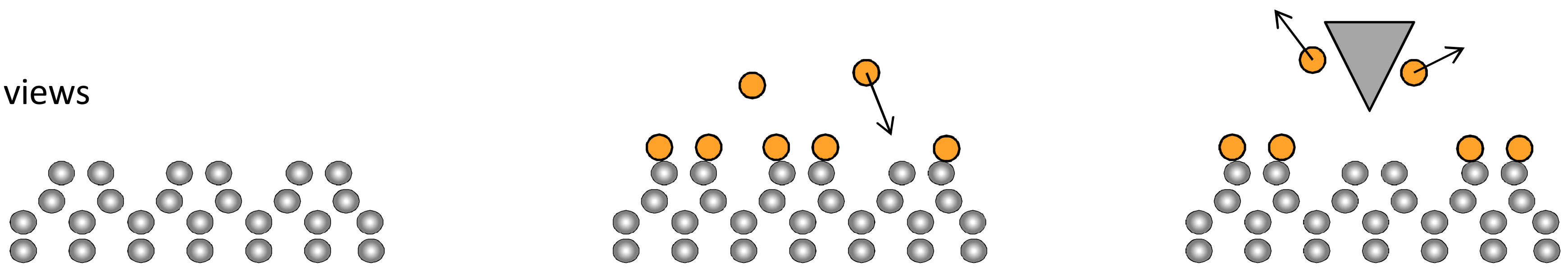


Results: Atomic-precision lithography

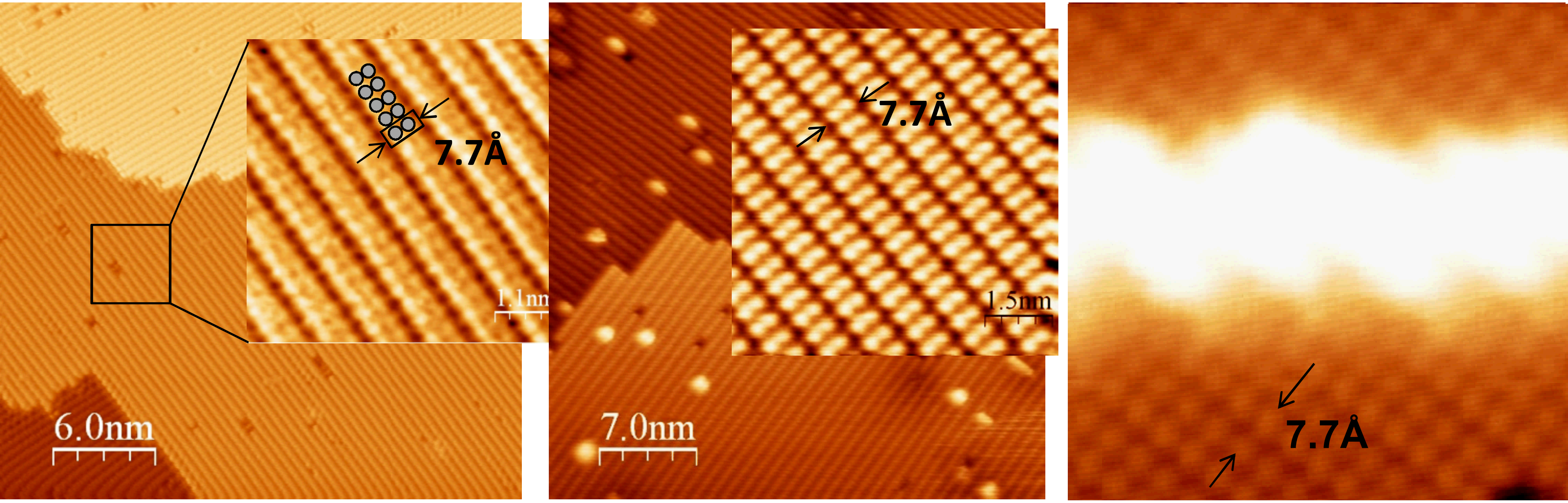
0.7 nm lithography

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