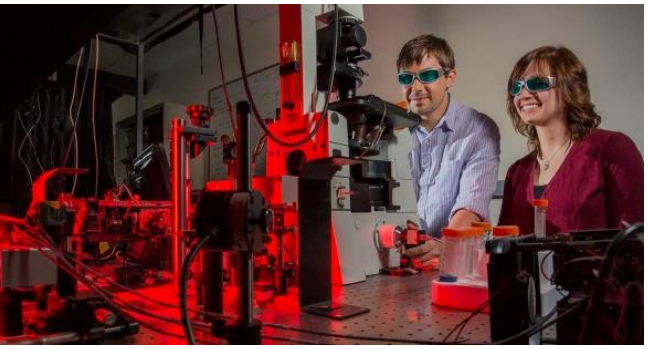
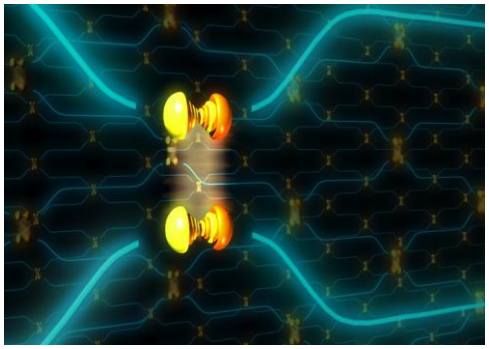
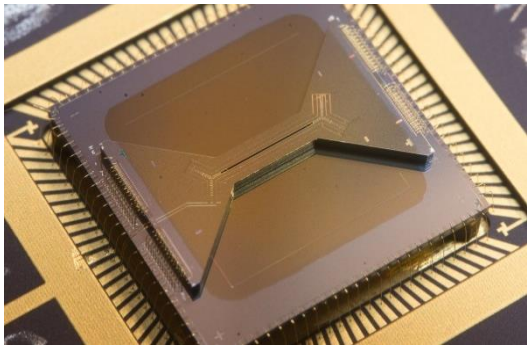
SAND2016-12190PE

Exceptional service in the national interest

Sandia National Laboratories



Quantum Information Science and Technology at Sandia

Clark Highstrete

Manager, Advanced Solid State Microsystems

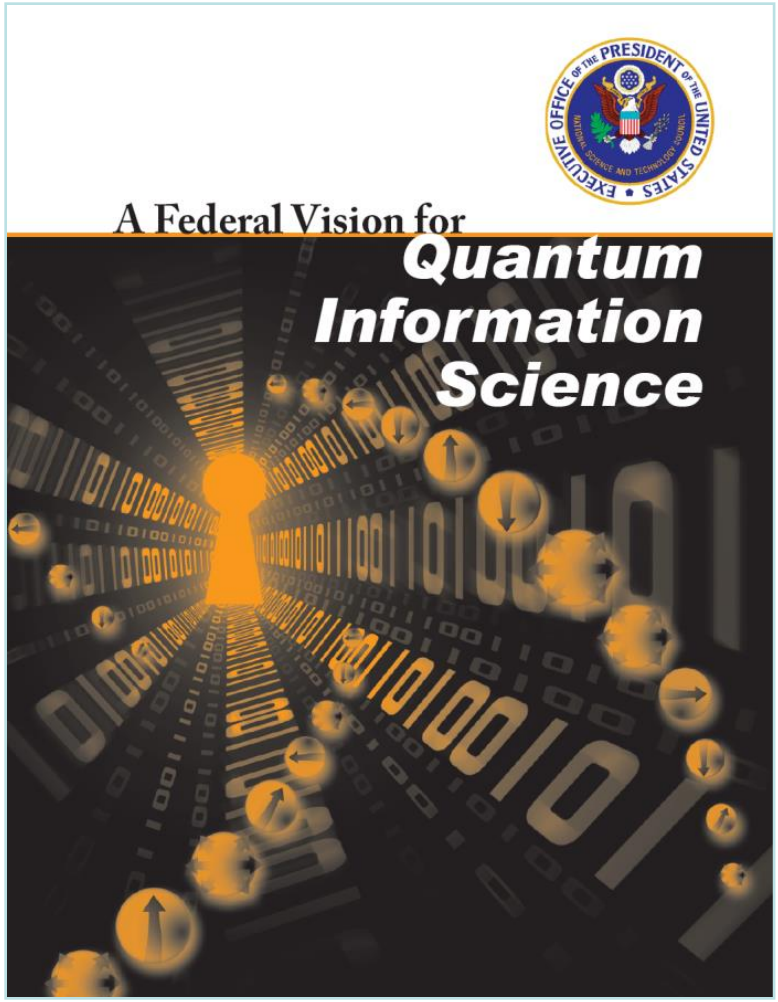
U.S. DEPARTMENT OF ENERGY

National Nuclear Security Administration

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. SAND No. 2012-5130P

QIS has national importance

January 5, 2009

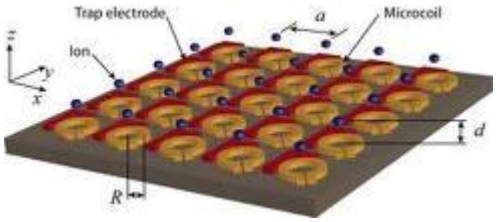


- "Quantum information science …. creates a new conceptual platform for a family of *potentially disruptive technologies*, adding a new stage to the already staggering impact of conventional information technology."
- "The ability to solve some of the "impossible" problems *would enhance discovery and economic strength*."
- "The United States' large stake in all these potential applications *warrants a cohesive national effort to achieve and maintain leadership* in the rapidly emerging field of quantum information science."

Promising applications of QIS

Sandia National Laboratories

Simulation



Computation/Algorithms

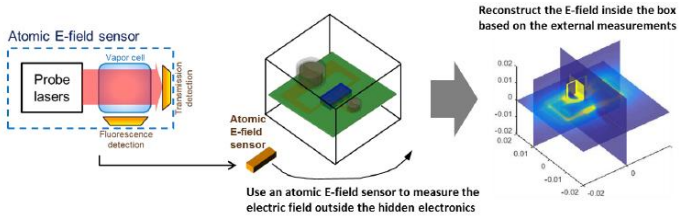
Unordered search:
Grover's Algorithm
Classical: O(N)
Quantum: $O(N^{1/2})$

2799783391 1221327870 8294676387 2260162107 0446786955 4285375600 0992932612 8400107609 3456710529 5536085606 1822351910 9513657886 3710595448 2006576775 0985805576 1357909873 4950144178 8631789462 9518723786 9221823983 =

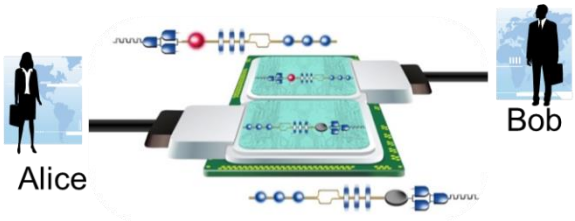
3532461934 4027701212 7260497819 8464368671 1974001976 2502364930 3468776121 2536794232 0005854795 6528088349
x
7925869954 4783330333 4708584148 0059687737 9758573642 1996073433 0341455767 8728181521 3538140930 4740185467

Schor's Algorithm
Classical: $O(N \log(N)) \approx n\, 2^n$
Quantum: $O(\log^2(N)) = n^2$

Precision sensing

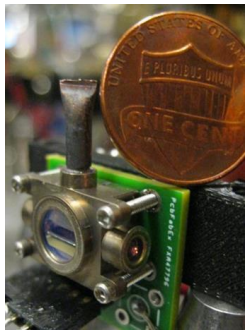


Secure Communication



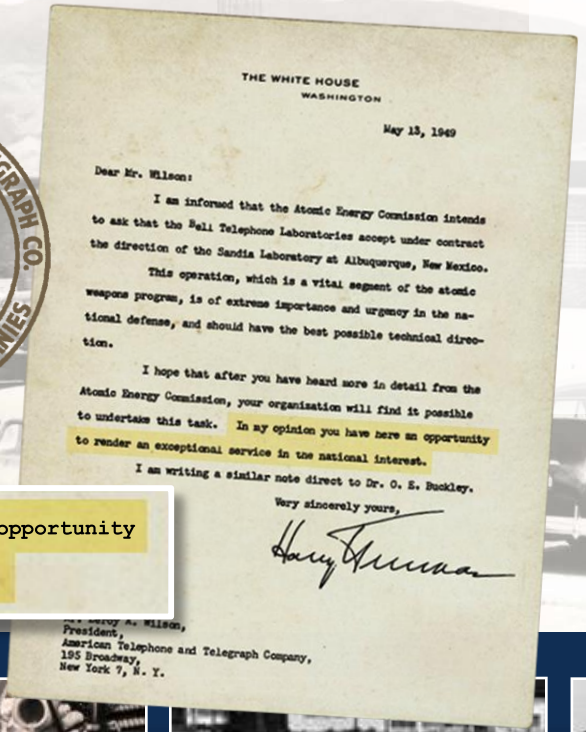
n = "size" (~ no. of bits)
$N = 2^n$ dimension

Precision time/frequency measurement



Sandia's history

Exceptional service in the national interest



THE WHITE HOUSE
WASHINGTON

May 13, 1949

Dear Mr. Wilson:

I am informed that the Atomic Energy Commission intends to ask that the Bell Telephone Laboratories accept under contract the direction of the Sandia Laboratory at Albuquerque, New Mexico.

This operation, which is a vital segment of the atomic weapons program, is of extreme importance and urgency in the national defense, and should have the best possible technical direction.

I hope that after you have heard more in detail from the Atomic Energy Commission, your organization will find it possible to undertake this task. In my opinion you have here an opportunity to render an exceptional service in the national interest.

I am writing a similar note direct to Dr. O. E. Buckley.

Very sincerely yours,

Harry Truman

[illegible] Wilson,
President,
American Telephone and Telegraph Company,
195 Broadway,
New York 7, N. Y.

to undertake this task. In my opinion you have here an opportunity to render an exceptional service in the national interest.

- **July 1945:** Los Alamos creates Z Division
- Nonnuclear component engineering
- **November 1, 1949:** Sandia Laboratory established

Sandia capabilities

Sandia leverages a unique set of capabilities to advance our understanding of Quantum Information Science and Technology

MESA

CINT

ASC Supercomputers

IBL

U.S. DEPARTMENT OF ENERGY

National Nuclear Security Administration

ASC™

Quantum Information S&T at Sandia

Sandia National Laboratories

QIS&T at Sandia: multidisciplinary, cross-Labs activity

- **Fundamentals:** atomic and condensed matter physics, noise models, photonics, optics, QIS theory
- **Fabrication:** device design/modeling, microelectronics fab, atomic-precision fab, integration, nanotechnology, photonics
- **Quantum devices:** theory, quantum/classical architectures, error correction, controls, mod/sim, testing
- **Quantum systems:** algorithms, applications, technology assessments

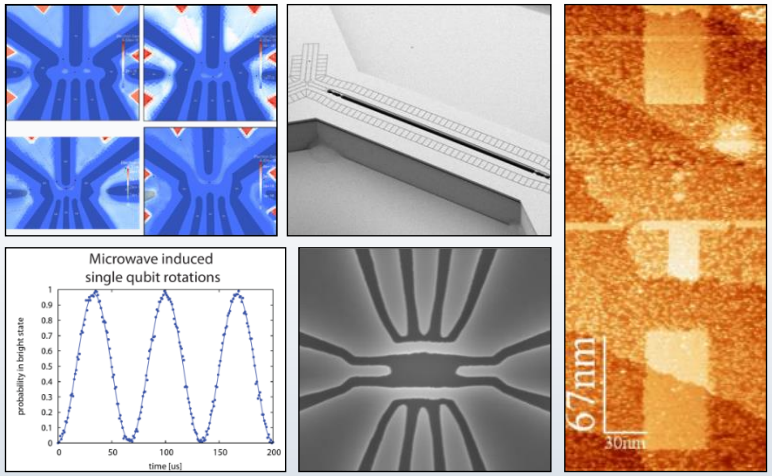
Expertise in key technologies

- **Physical qubits:** Si quantum dots/donors, trapped ions, neutral atoms
- **Logical qubits:** design
- **Architectures:** circuit, adiabatic
- **Algorithms/apps:** demonstrations, analysis, development

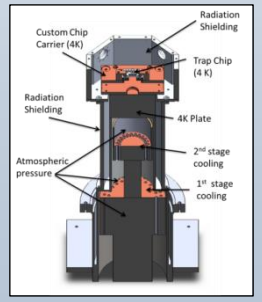
Unique, enabling facilities

- Microelectronics fabrication, atomic-scale fabrication, HPC

Systems engineering heritage



Sandia is engaged in QIS research in support of its missions. This research is motivated by advanced computing architectures and the fact that future engineered systems will require increased understanding of quantum effects.



The technical challenges are vast– solving them is our focus.

From bits to qubits

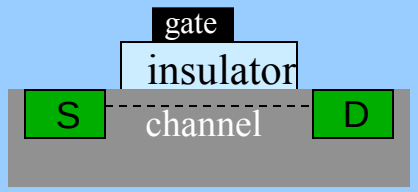
Sandia National Laboratories

bit

Logical basis: (0,1) integers

State: x=0 or x=1

Measurement: x=0 or x=1



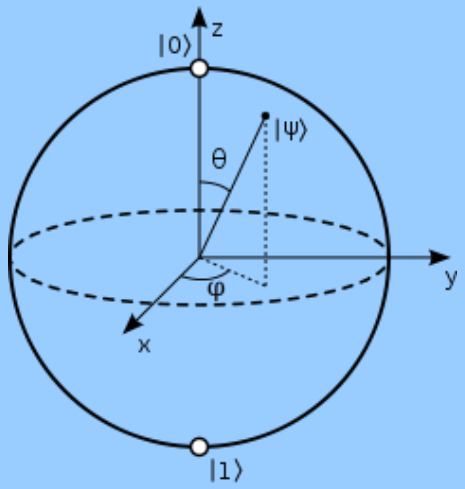
MOSFET

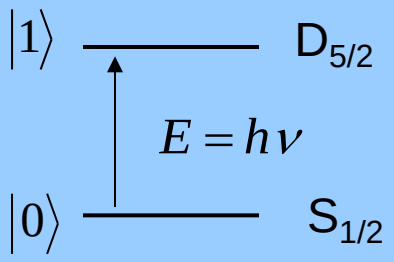
qubit

Logical basis: orthogonal vectors $|0\rangle, |1\rangle$

State: superposition $|\psi\rangle = c_0|0\rangle + c_1|1\rangle$

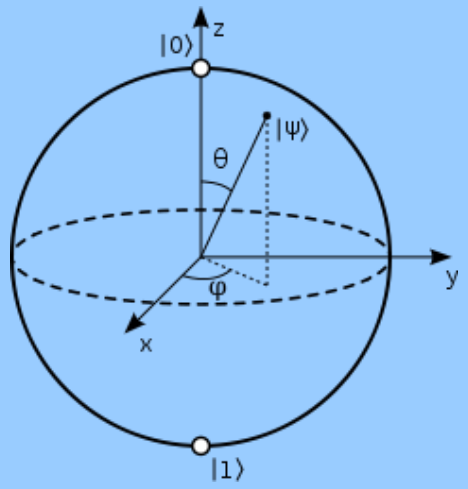
Measurement: $|\psi\rangle = |0\rangle$ *or* $\psi = |1\rangle$ $P_i = \dfrac{|c_i|^2}{\sum_j |c_j|^2}$





- Energy levels of an ion
- Photon paths or polarizations in an interferometer
- Spin directions of an electron
- Charge states in a quantum dot
- Mesoscopic currents in a superconductor

Transformation on qubits



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

NOT

$$|0\rangle \rightarrow |1\rangle$$
$$|1\rangle \rightarrow |0\rangle$$

$\sqrt{\text{NOT}}$

$$|0\rangle \rightarrow (|0\rangle - i|1\rangle)/\sqrt{2}$$
$$|1\rangle \rightarrow (|1\rangle - i|0\rangle)/\sqrt{2}$$

H

$$|0\rangle \rightarrow (|0\rangle + |1\rangle)/\sqrt{2}$$
$$|1\rangle \rightarrow (|1\rangle - |0\rangle)/\sqrt{2}$$

Multiple qubits

Sandia National Laboratories

Logical basis: $|00\rangle, |01\rangle, |10\rangle, |11\rangle$

2 qubits

State: superposition $|\psi\rangle = a_0|00\rangle + a_1|01\rangle + a_2|10\rangle + a_3|11\rangle$

Measurement: $|00\rangle, |01\rangle, |10\rangle, or\ |11\rangle$ $P_i = \frac{|a_i|^2}{\sum_j |a_j|^2}$ (can measure individual qubit)

e.g. Bell State: $|\psi\rangle = \frac{|00\rangle + |11\rangle}{\sqrt{2}}$

Measure qubit 1 → know qubit 2. Qubit states are correlated ("entangled")

Logical basis: $|000\rangle, |001\rangle, |010\rangle, |011\rangle, |100\rangle, |101\rangle, |110\rangle, |111\rangle$

3 qubits

Logical basis: 2^n *vectors*

General state: $|\psi\rangle = \sum_{x=0}^{2^n-1} c_x |x\rangle$

n qubits

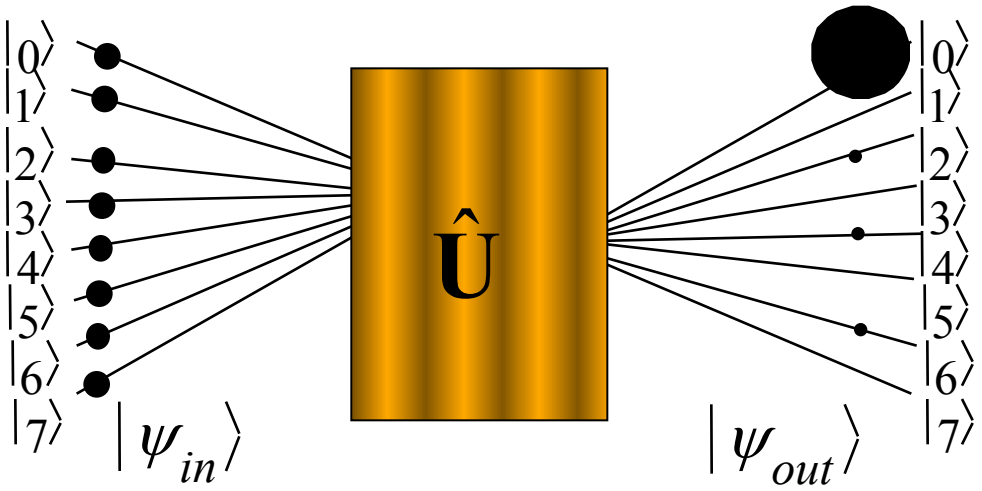
Entangled

$|\psi\rangle \neq |\phi_1\rangle \otimes |\phi_2\rangle \otimes |\phi_3\rangle$

The vector space grows exponentially

and … outcomes can interfere!

Quantum algorithms



Map input-output

$$|\psi_{out}\rangle = \hat{U}|\psi_{in}\rangle$$

$$|\psi_{in}\rangle = a_0|000\rangle + a_1|001\rangle + a_2|010\rangle + a_3|011\rangle + a_4|100\rangle + a_5|101\rangle + a_6|110\rangle + a_7|111\rangle$$

$$|\psi_{out}\rangle = b_0|000\rangle + b_1|001\rangle + b_2|010\rangle + b_3|011\rangle + b_4|100\rangle + b_5|101\rangle + b_6|110\rangle + b_7|111\rangle$$

"Quantum parallelism" + space exponential growth + interference =

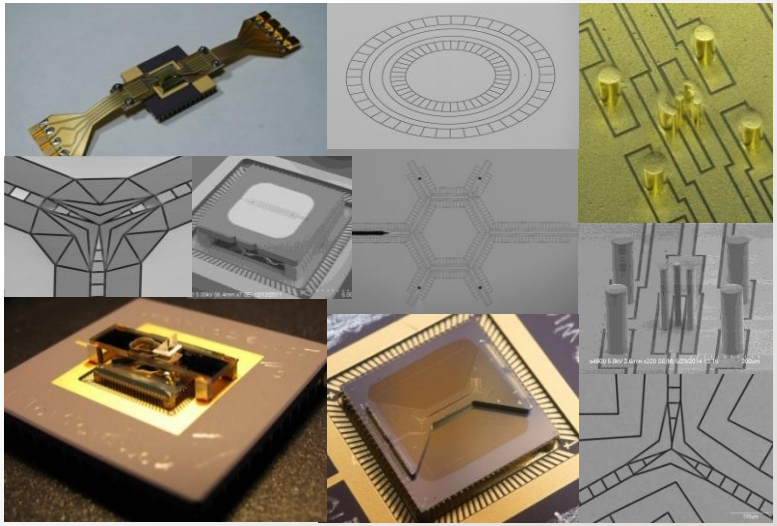
Quantum speedup

Simple quantum information processing elements

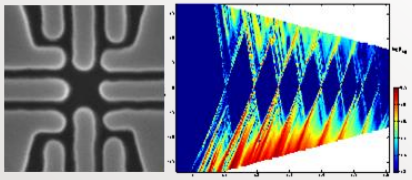
Sandia National Laboratories

- Two state system (energy eigenstate basis)
- Coherent control - state preparation
- Isolated from environment (avoid decoherence)
- Transport and interaction
- 2+ qubit conditional logic operation(s)
- Readout

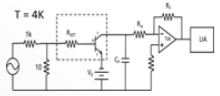
Sandia qubits



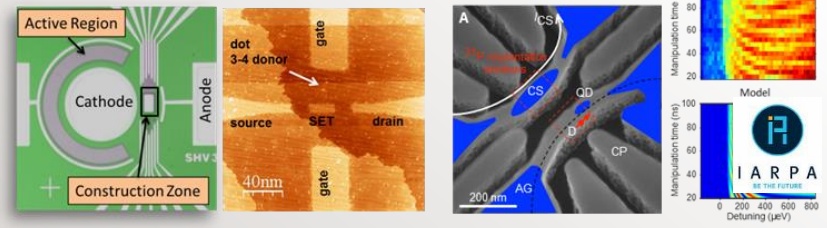
MOS-QD/Donor Platform



Cryogenic Electronics

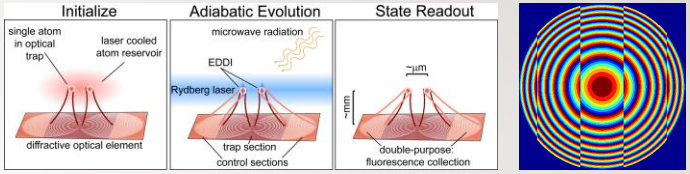


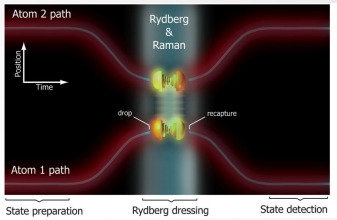
HEMT/HBT Amplifiers

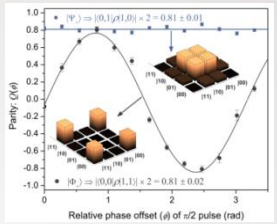


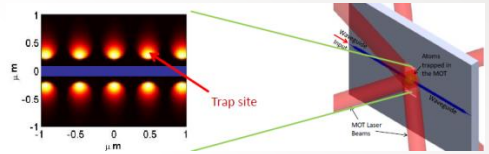
Individual Donor Incorporation

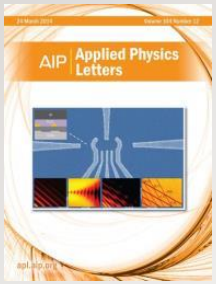
Coupled MOS/Donor Qubits

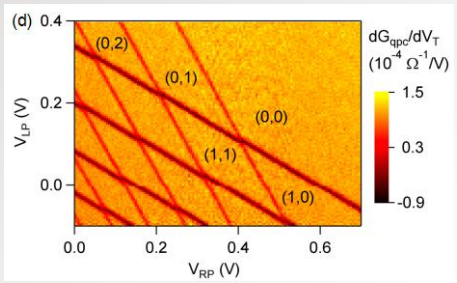




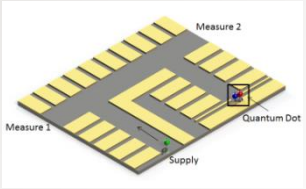




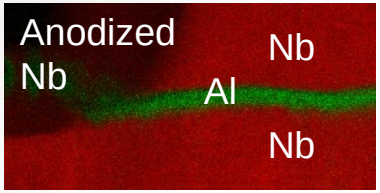




Hole DQD

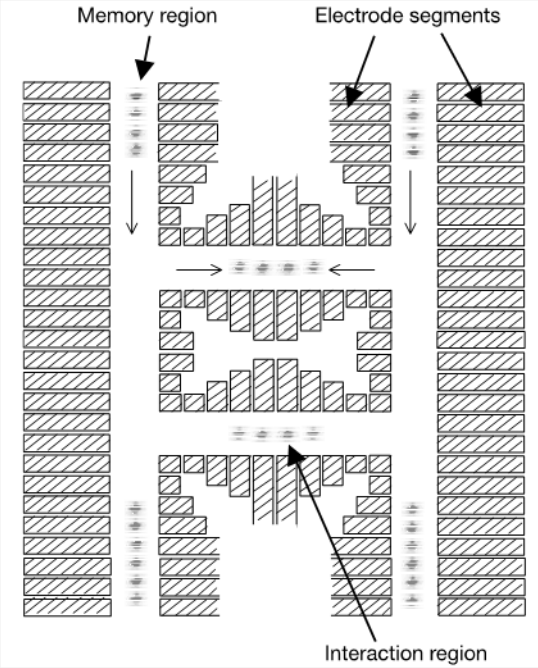


EON Trap



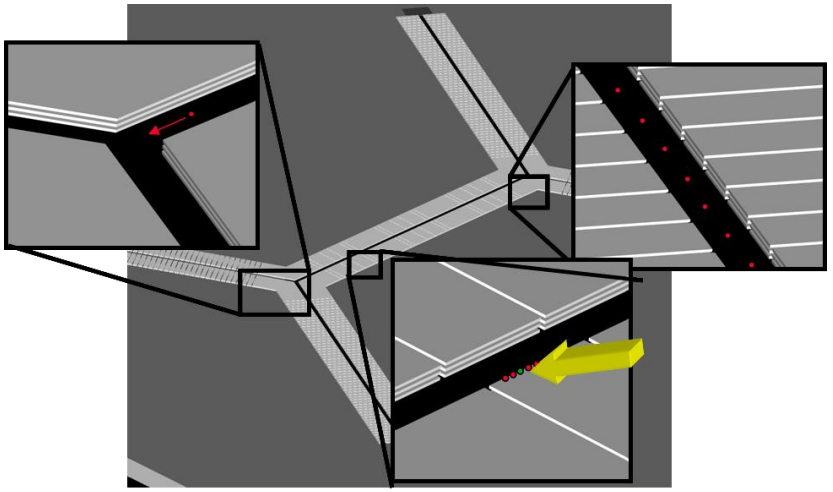
Josephson Junction

Trapped ion quantum information processor concept



Schematic of proposed ion trap array for quantum information processing

Kielpinsky, Monroe and Wineland, *Nature* **417**, 709 (2002)

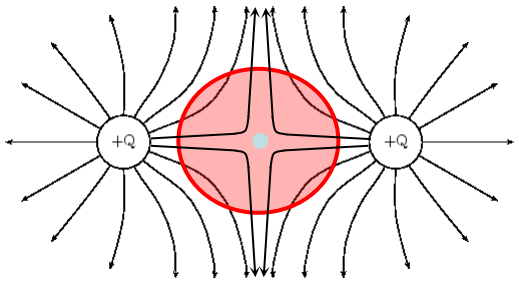


Sandia focus: critical bus elements / operations with microfabricated surface ion traps

Why use ions for qubits?

- **Well isolated** – single ions are physically separated from surrounding material.
- Qubit stored in internal structure of ion is **not perturbed by electric fields.**
- **Good "handle"** – charge of ion allows
  - Positional control of ion.
  - Interaction with neighbor.
- Up to **8 qubits have been demonstrated** with gate fidelities exceeding 99%.

Trapped ion qubits



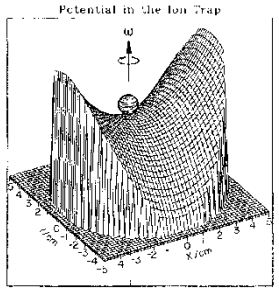
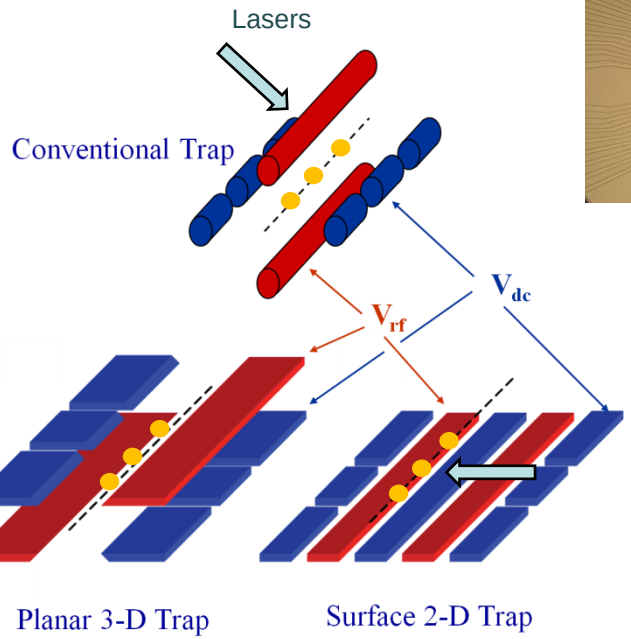
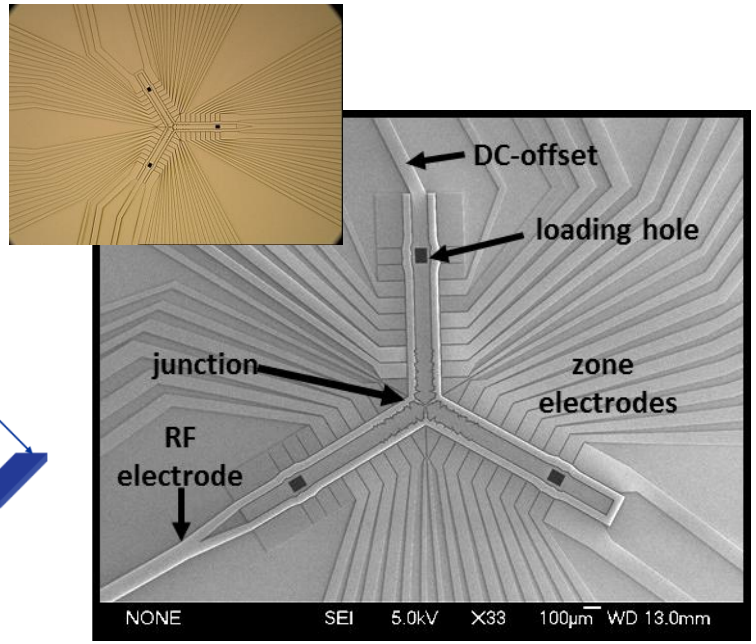
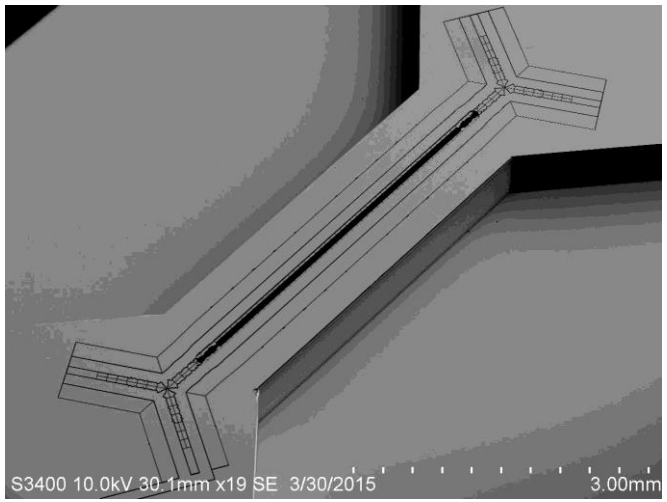


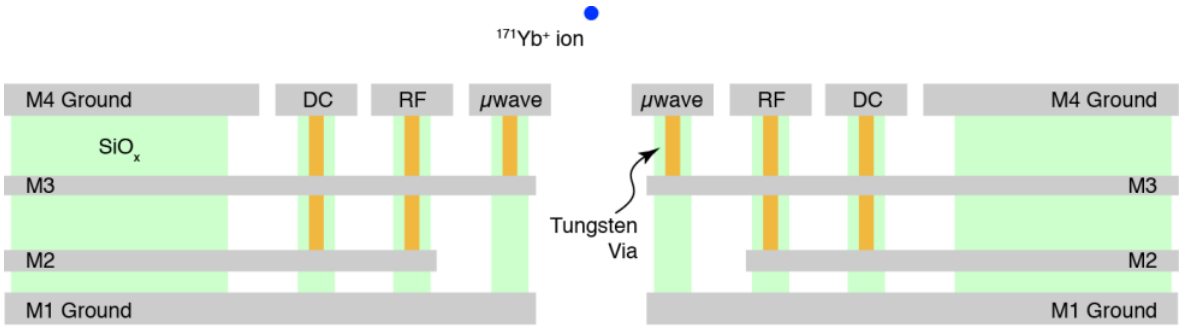
FIG. 8. Mechanical analogue model for the ion trap with steel-ball as "particle."

Rev. Mod. Phys., Vol. 62, No. 3, July 1990



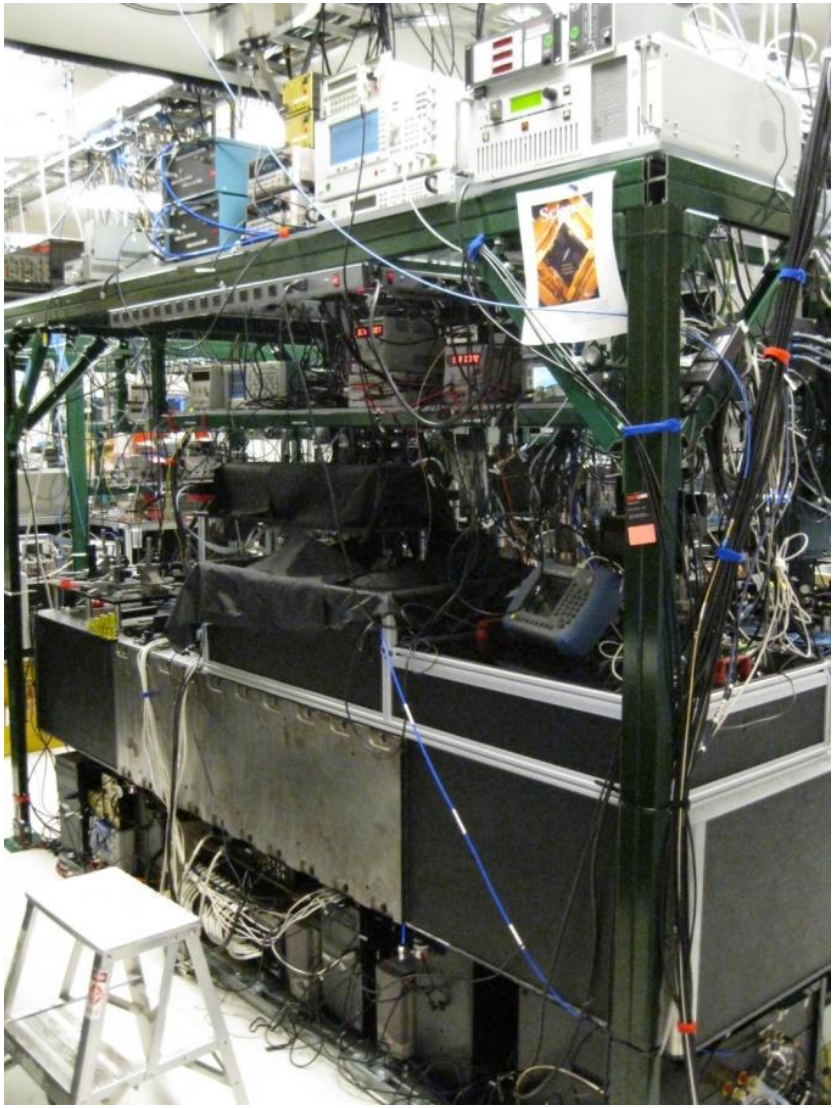


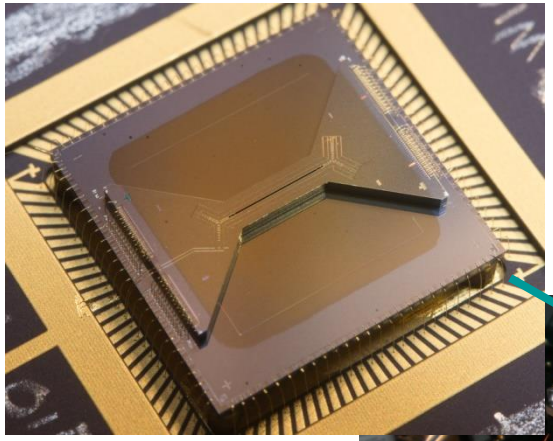


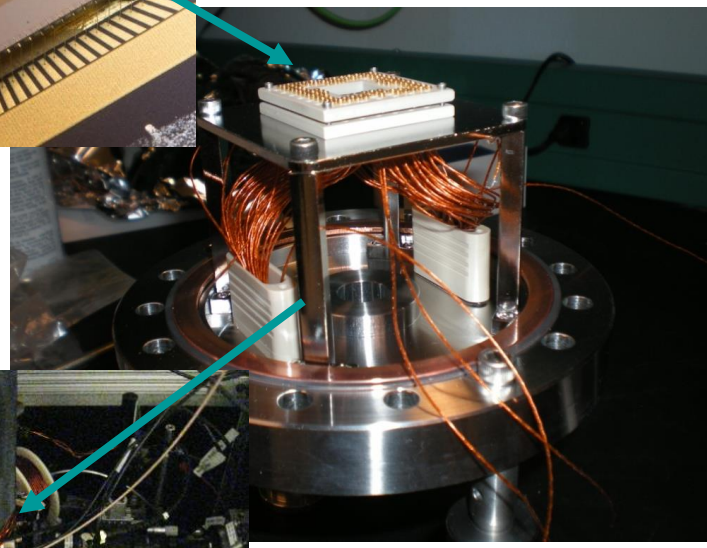


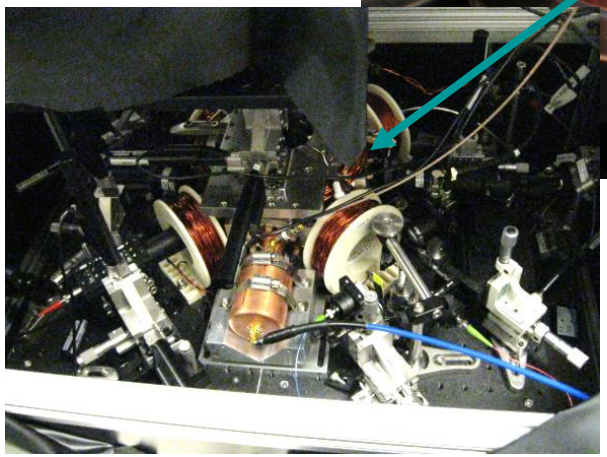
Trap operation

Sandia National Laboratories

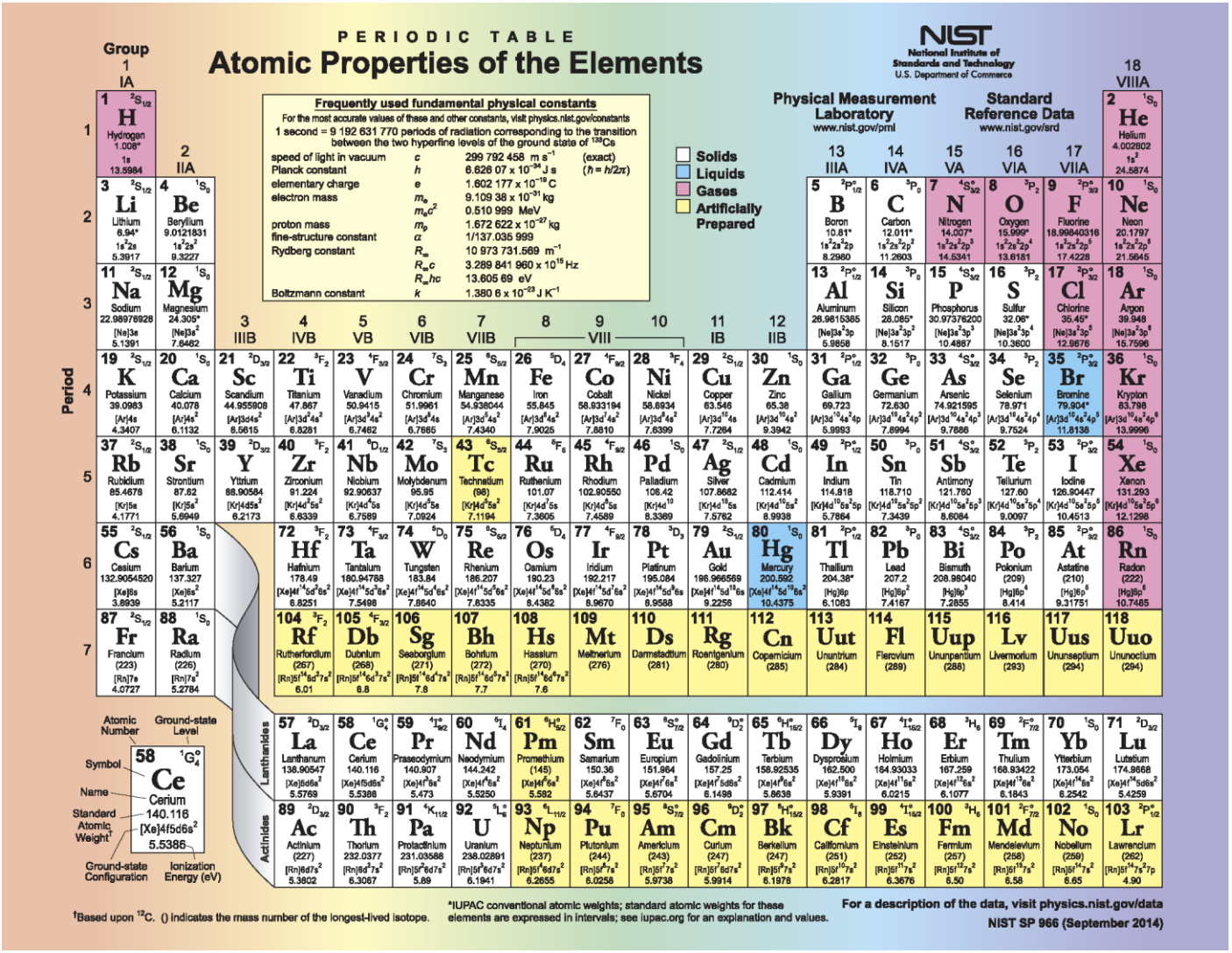








Ytterbium atom



70 $^1S_0$

Yb

Ytterbium

173.054

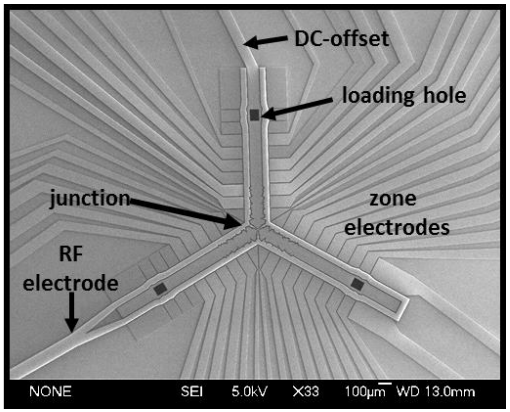
$[Xe]4f^{14}6s^2$

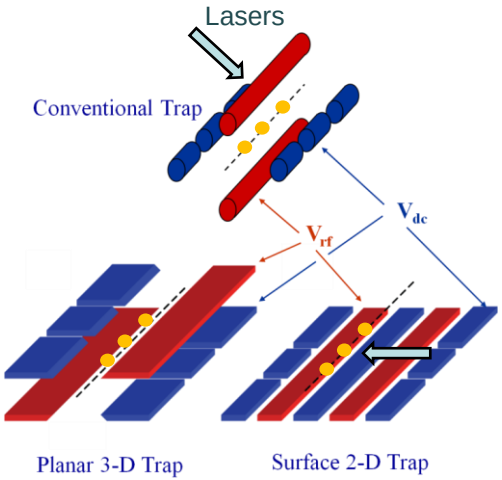
6.2542

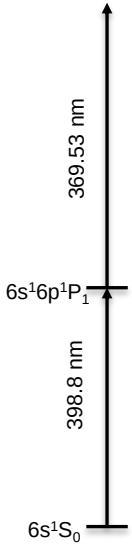
Isotope Abundance

168: 0.13%
170: 3.05%
171: 14.3%
172: 21.9%
173: 16.1%
174: 31.8%
176: 12.7%

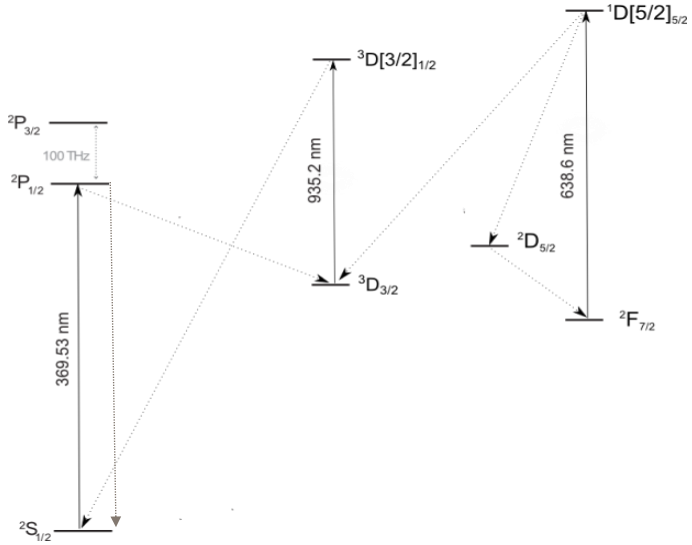
Yb^+ trapping



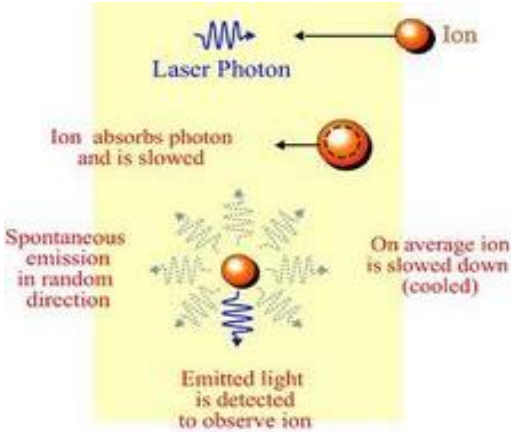




Yb Ionization



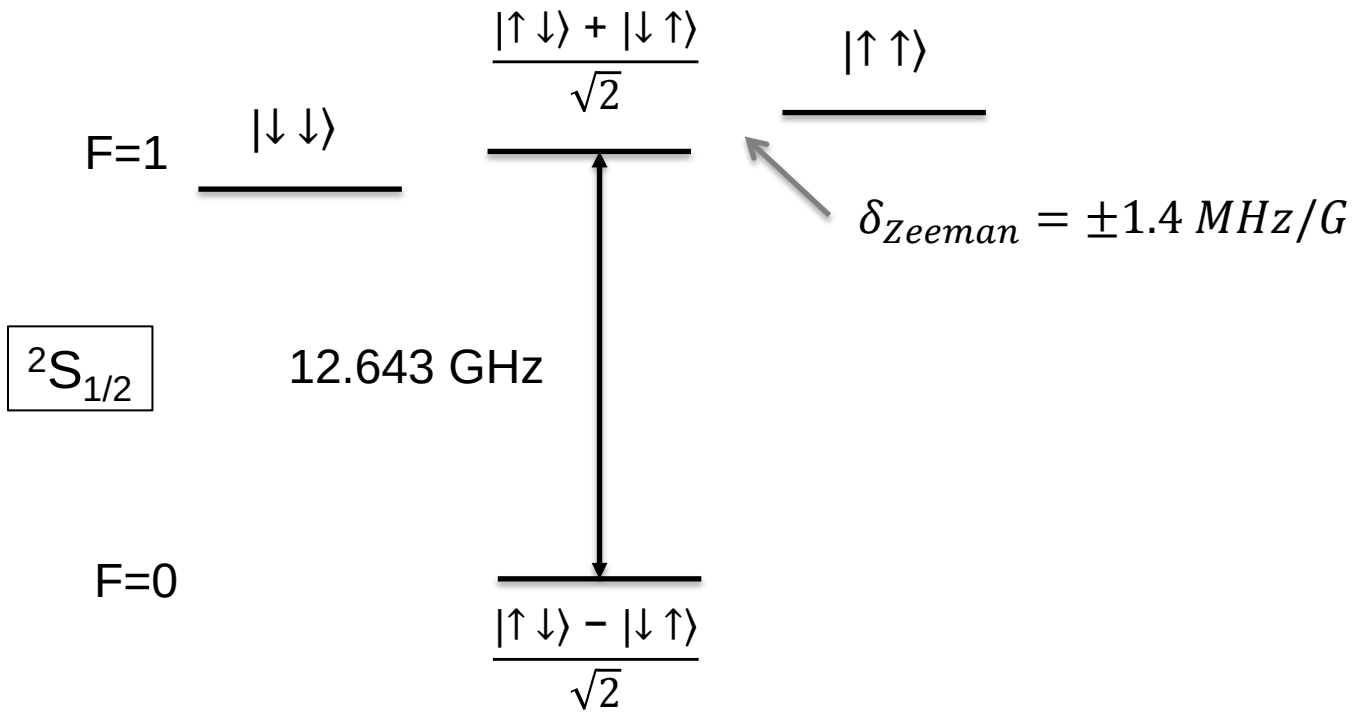
Yb$^+$ Trapping Scheme



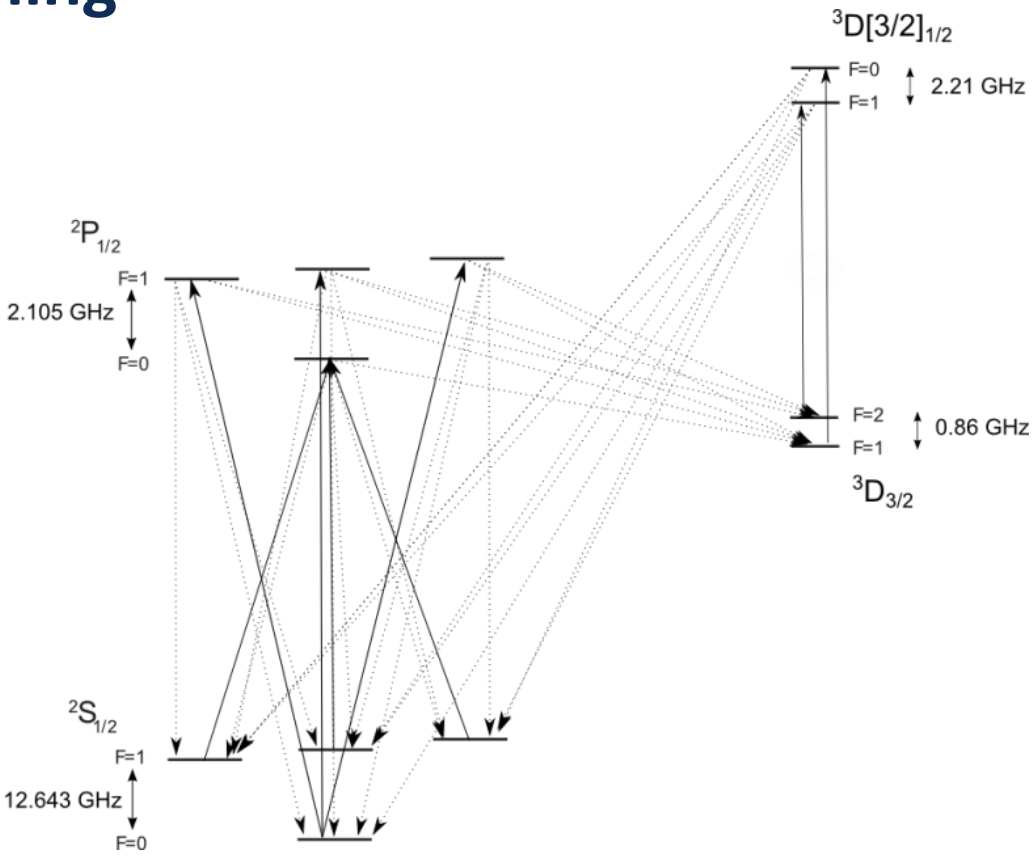
www.npl.co.uk

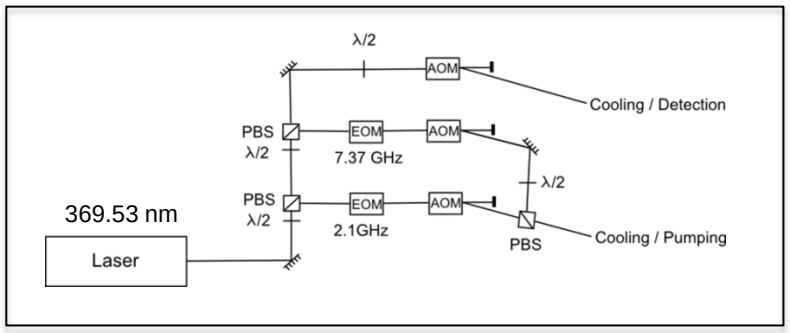
Doppler cooling

$^{171}Yb^{+}$ hyperfine qubit



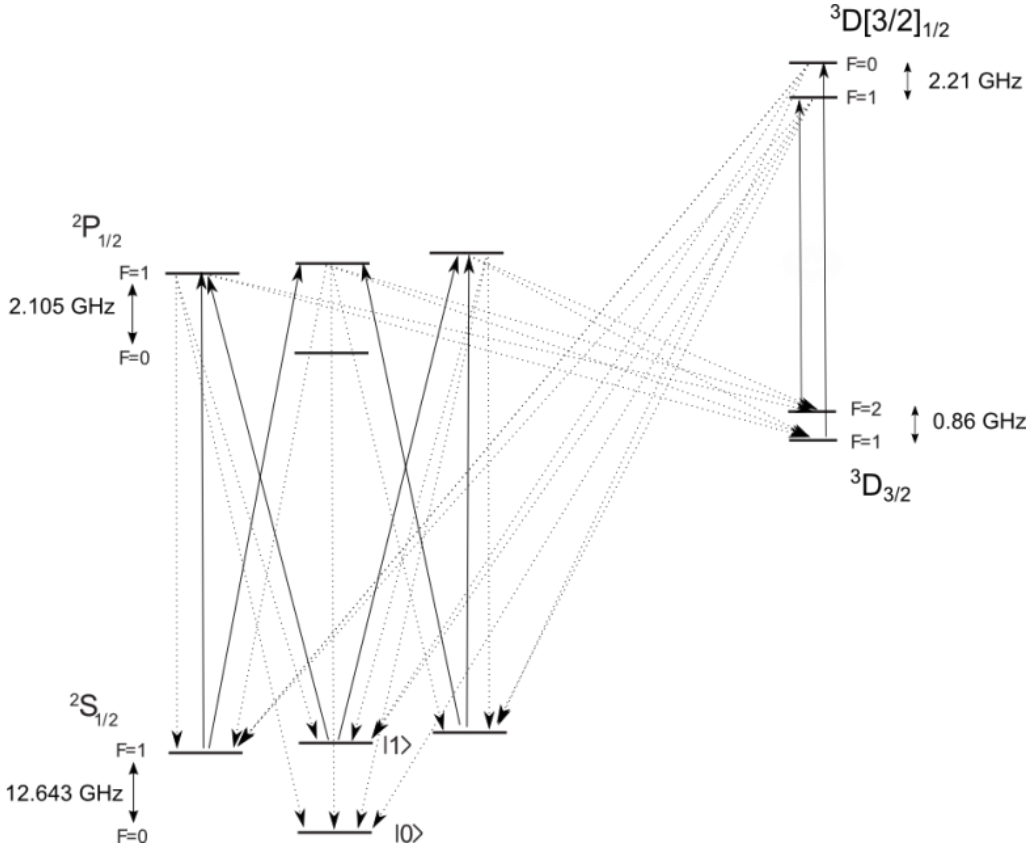
$^{171}Yb^{+}$ Cooling

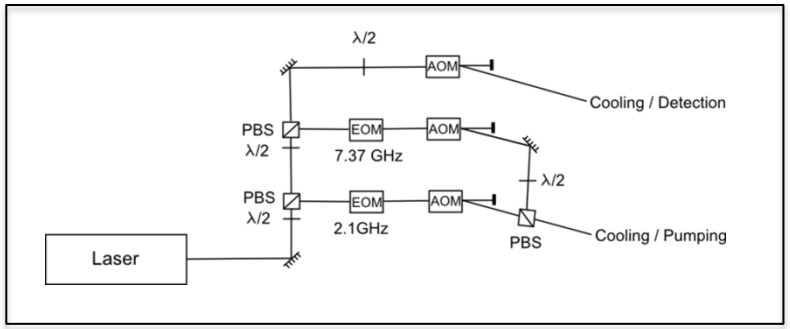




S. Olmschenk *et al.*, PRA **76**, 052314 (2007)

$^{171}Yb^{+}$ State Preparation

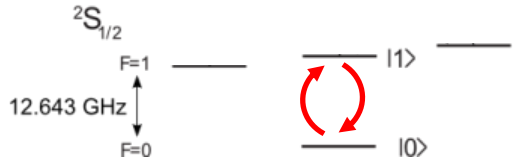




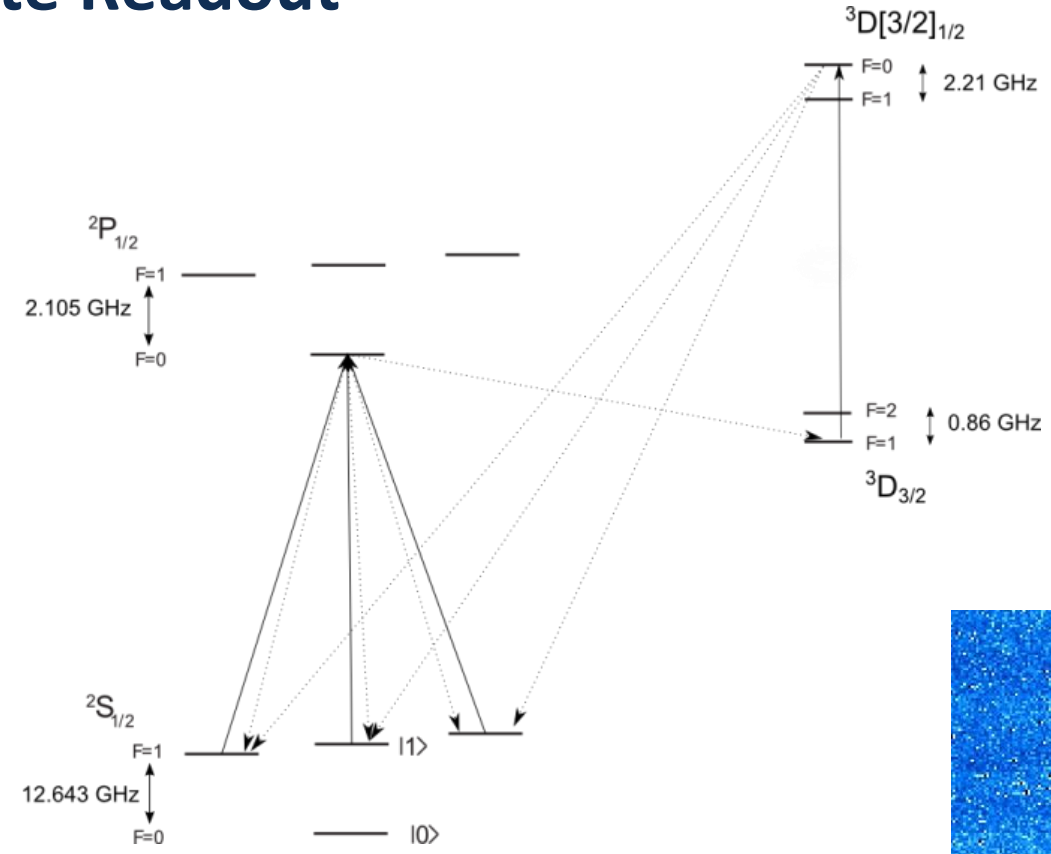
S. Olmschenk *et al.*, PRA **76**, 052314 (2007)

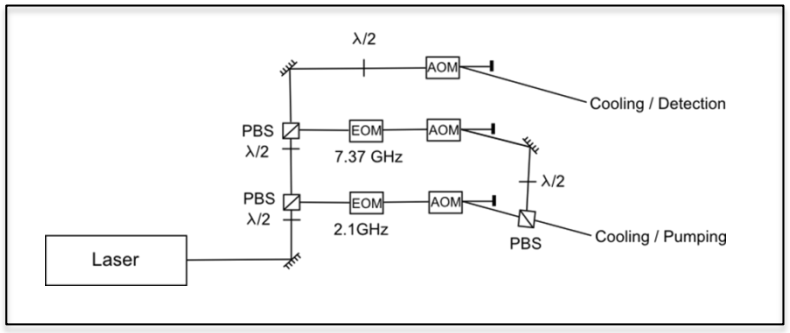
$^{171}Yb^{+}$ Qubit Rotations

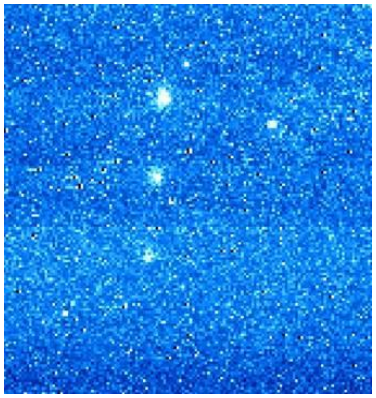
- Direct microwave illumination
- Raman lasers



$^{171}Yb^{+}$ State Readout

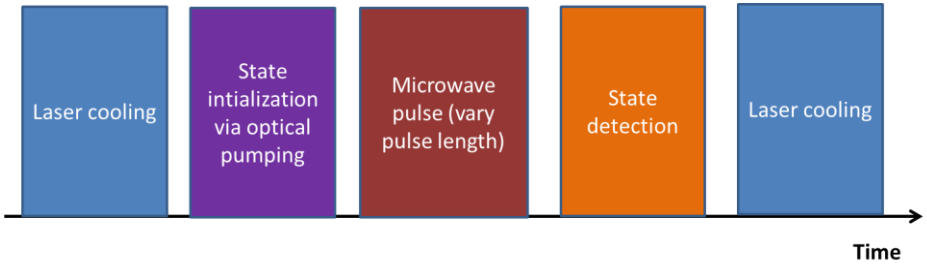


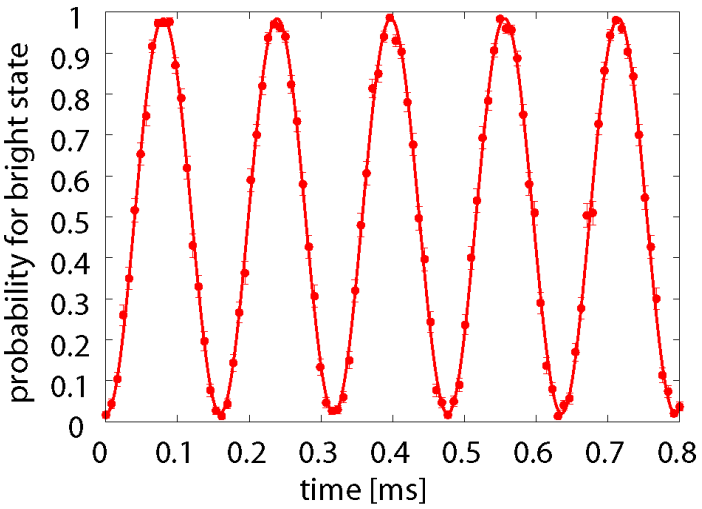


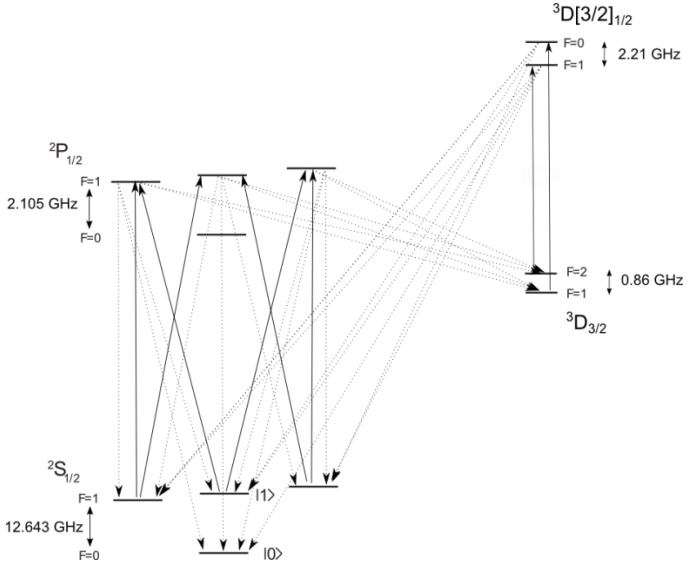


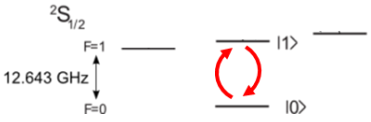
S. Olmschenk *et al.*, PRA **76**, 052314 (2007)

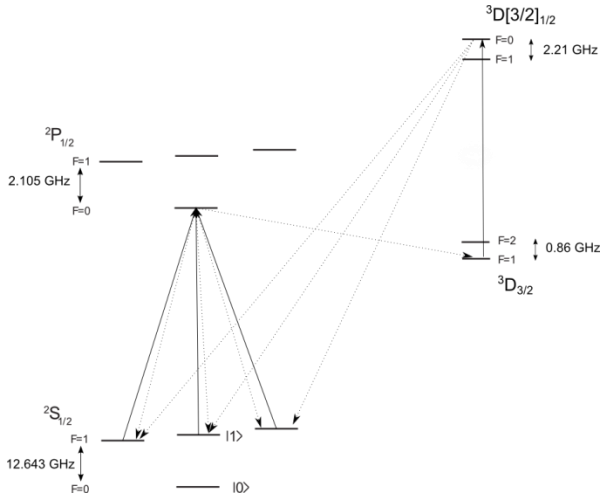
Coherent control: Rabi oscillations



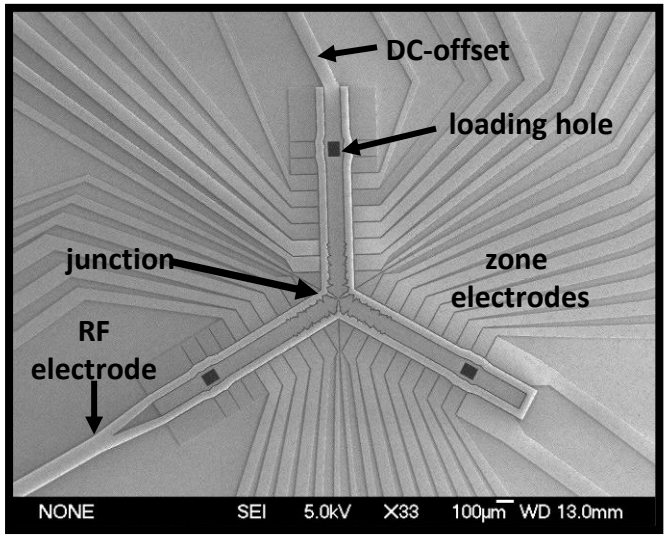


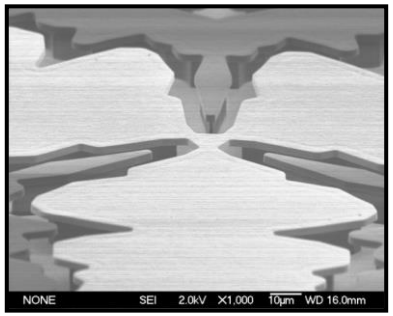


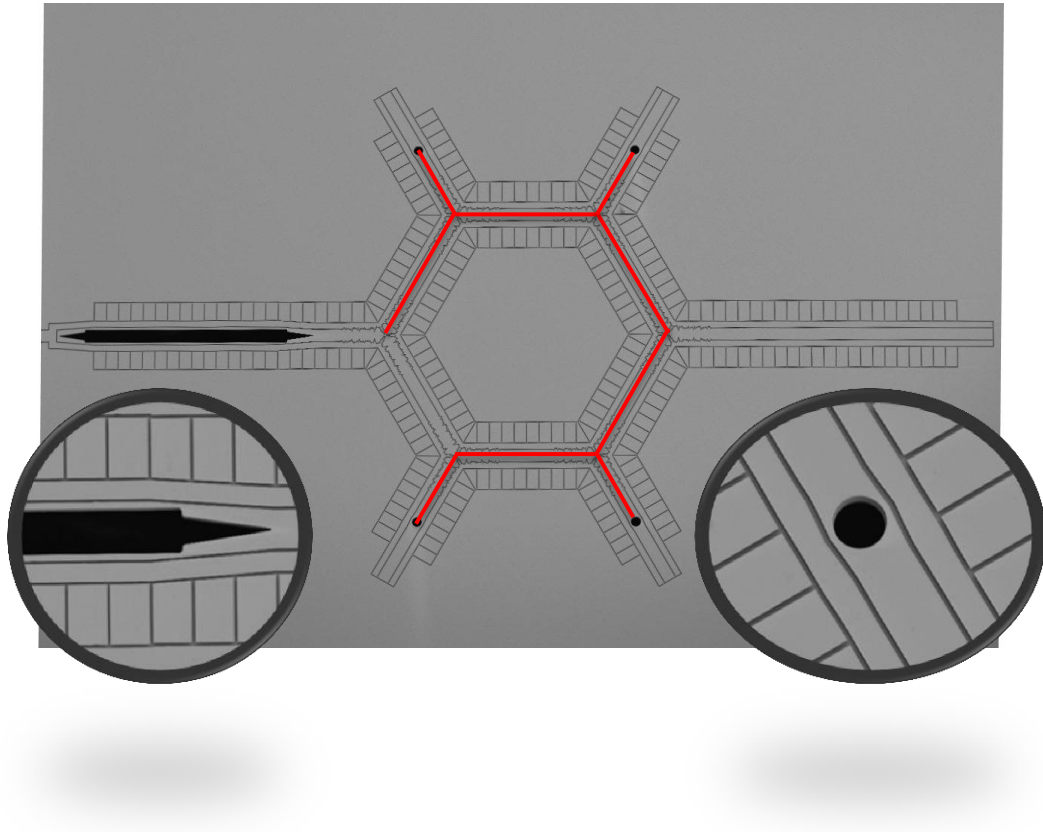




Junction and circulator traps



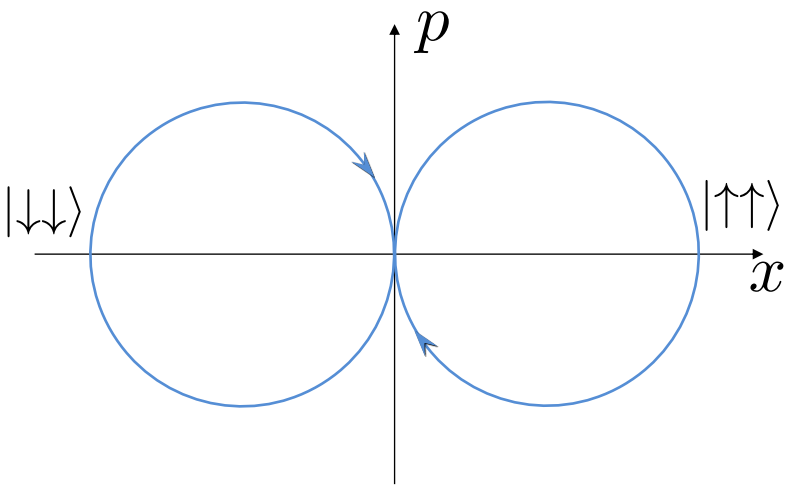




Entangling Gate

Sandia National Laboratories

Basic idea: Use common motion of the ions to mediate entanglement



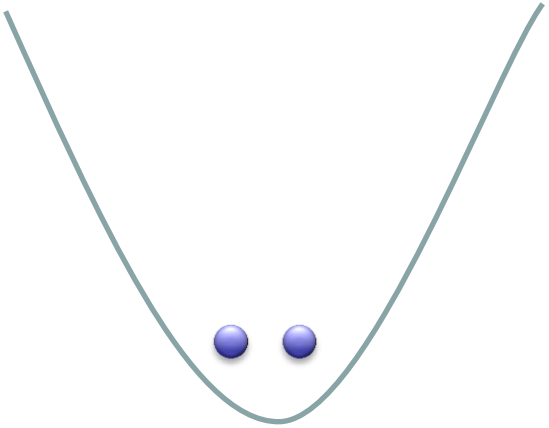
- Raman beams create *spin-dependent force*
- Force drives the ions away from and then back to their starting position

- Spin dependent phase remains

[1] K. Mølmer, A. Sørensen, PRL 82, 1835 (1999)
[2] A. Sørensen, K. Mølmer, PRL 82, 1971 (1999)
[3] A. Sørensen, K. Mølmer, PRA 62, 022311 (2000)

Two-qubit gate implementation

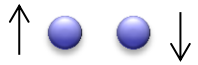
Interactions between ion qubits are realized via their Coulomb interaction in the trap



Transverse center of mass

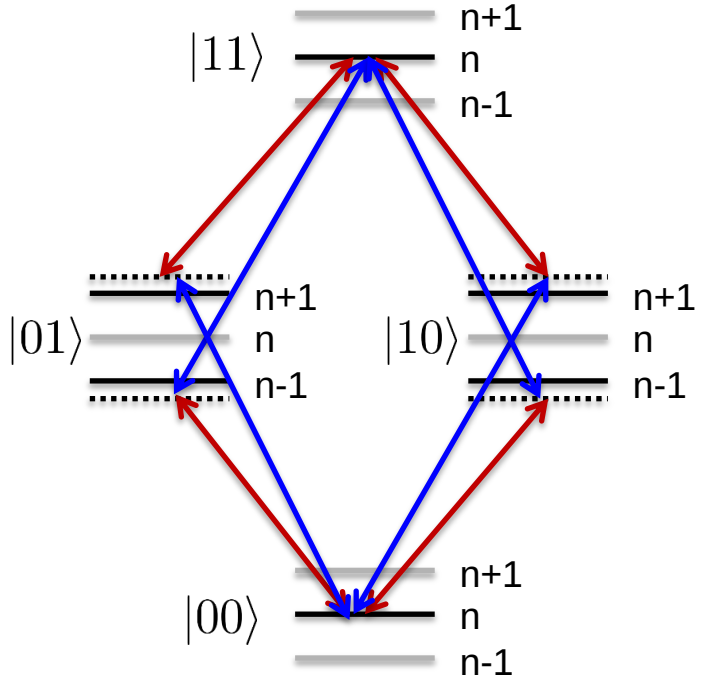
$\approx 60\ \mathrm{quanta/s}$

Transverse Tilt



$< 8\ \mathrm{quanta/s}$

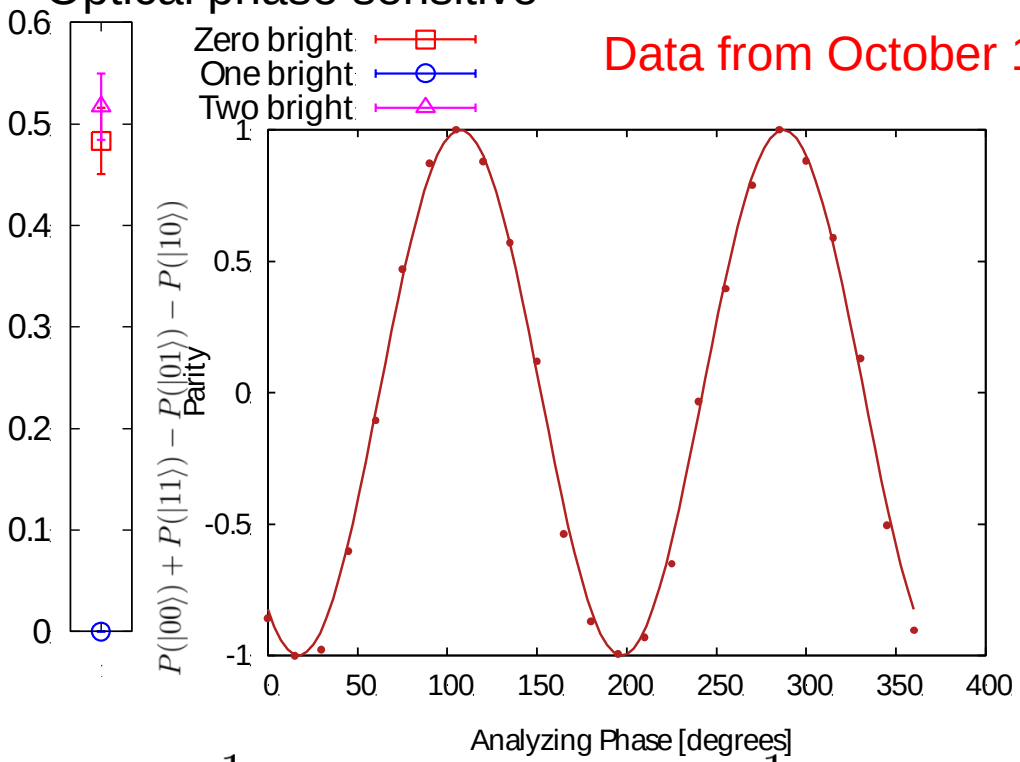
Heating rates



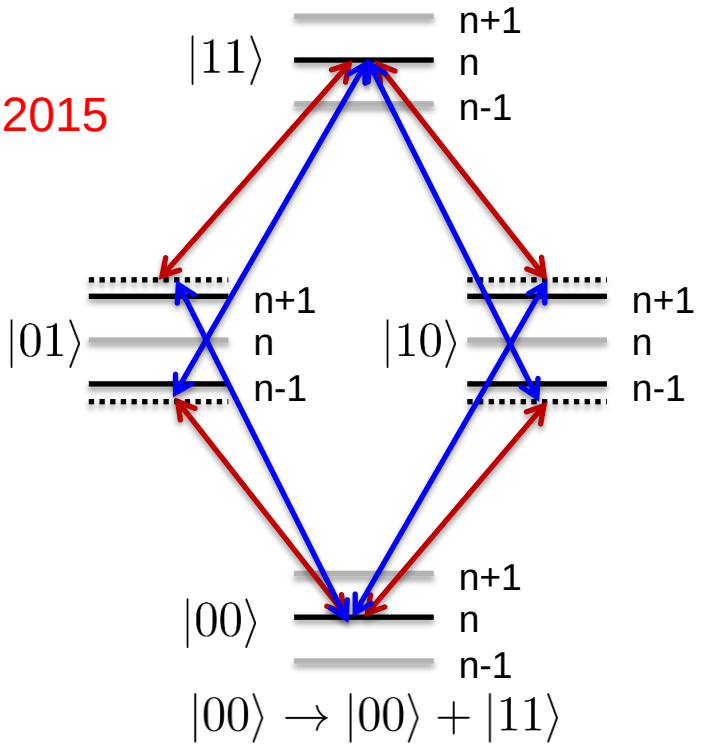
$$|00\rangle \rightarrow |00\rangle + |11\rangle$$

Two-qubit gate implementation

- Implemented using Walsh compensation pulses
- Optical phase sensitive



Data from October 10, 2015



$$\mathcal{F} = \frac{1}{2}(P(|00\rangle) + P(|11\rangle)) + \frac{1}{4}c = 0.977$$

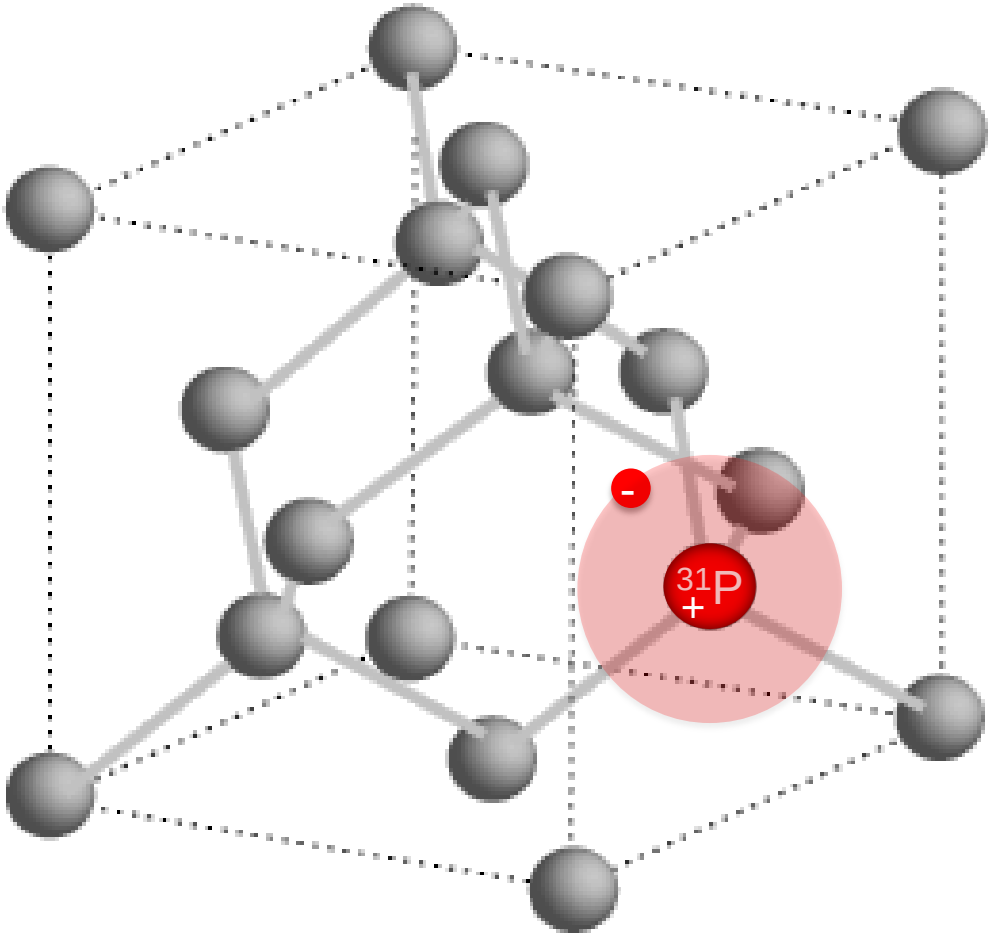
Data from February 12, 2015

$$\mathcal{F} = \frac{1}{2}(P(|00\rangle) + P(|11\rangle)) + \frac{1}{4}c \approx 0.995$$

Data from October 10, 2015

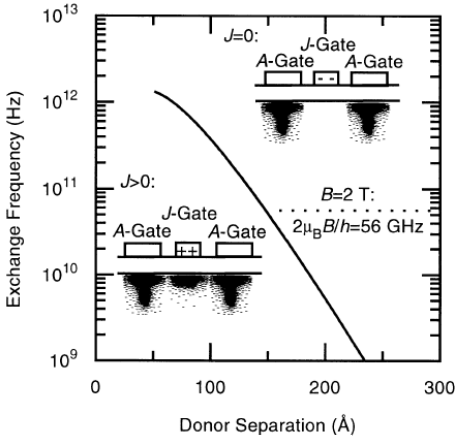
Donor atoms and quantum dots in silicon

14 $^3P_0$	15 $^4S^\circ_{3/2}$
Si	**P**
Silicon	Phosphorus
28.085*	30.97376200
$[Ne]3s^23p^2$	$[Ne]3s^23p^3$
8.1517	10.4867



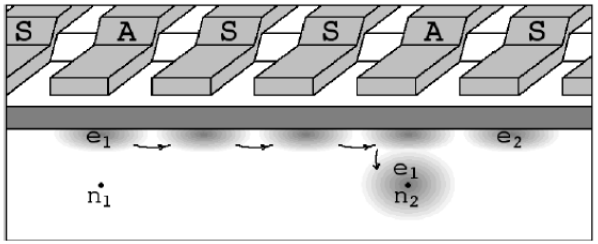
Donor & Donor-QD Architectures

Exchange btwn QDs



Kane (1998)

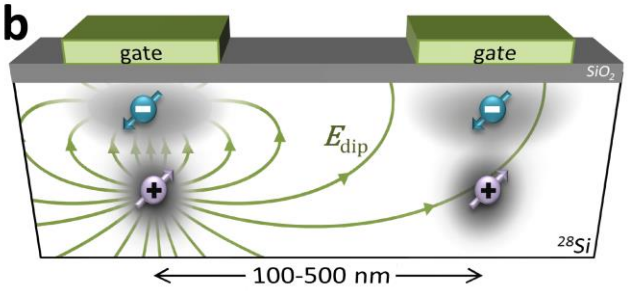
Transport along QDs



Skinner & Kane (2003)

Also: Hollenberg (2007), Morton (2009); Witzel (2015), Pica (2015)

Dipoles with QDs

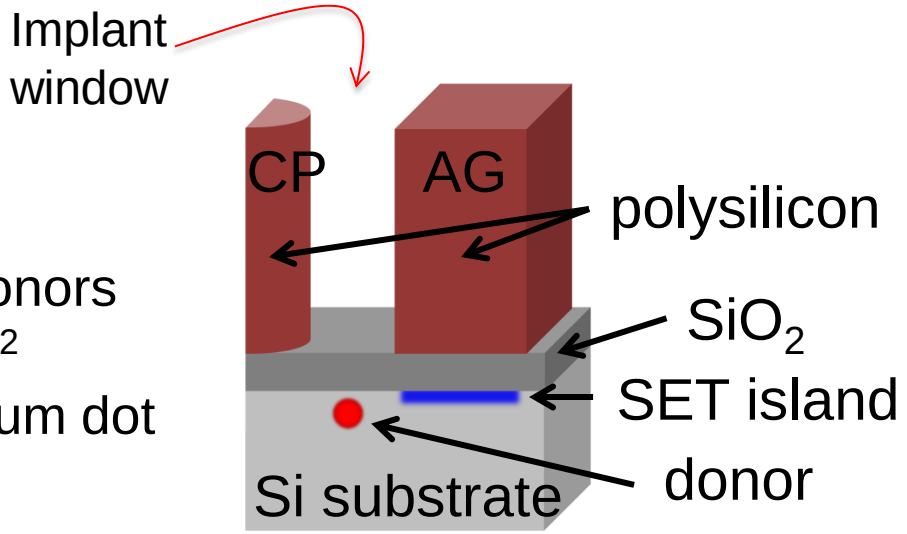


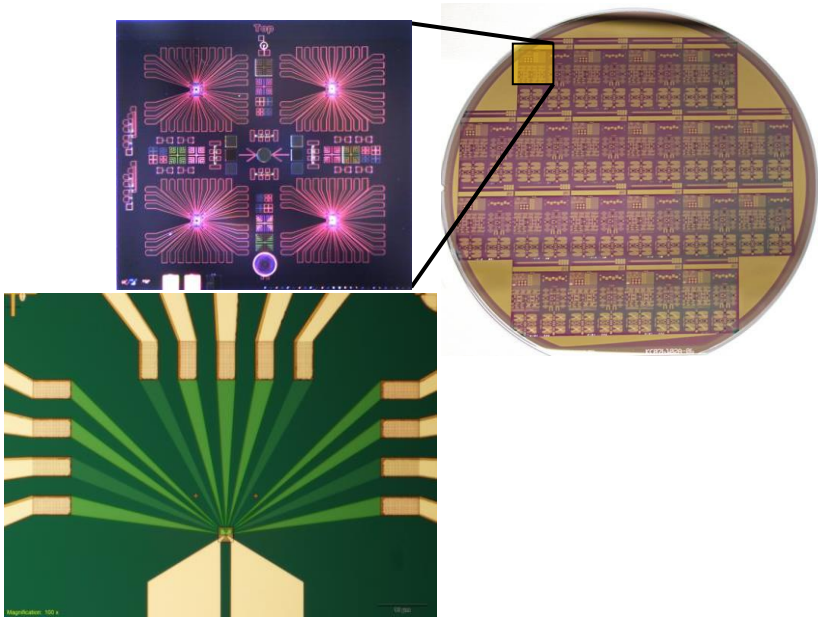
Tosi (2015)

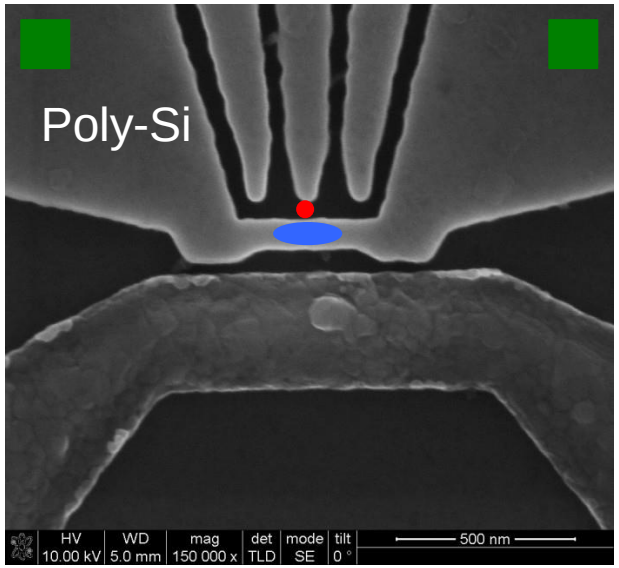
- Many appeals of donor qubits (e.g., potential for high fidelity, naturally same, compact, nuclear spin, built-in E-field selectivity, …)
- Quantum dots are a common element of many donor architectures
  - Exception – STM based concepts (e.g., Hill 2015)

Single Qubit Device Design

- ^{28}Si epilayer with 500 ppm ^{29}Si
- CMOS processing approach
- Poly-Si gated nanostructures
- Use Poly-Si for self-alignment of donors
- 45 kev P Donor implants: 4e11 cm^{-2}
- Donor qubit readout through quantum dot







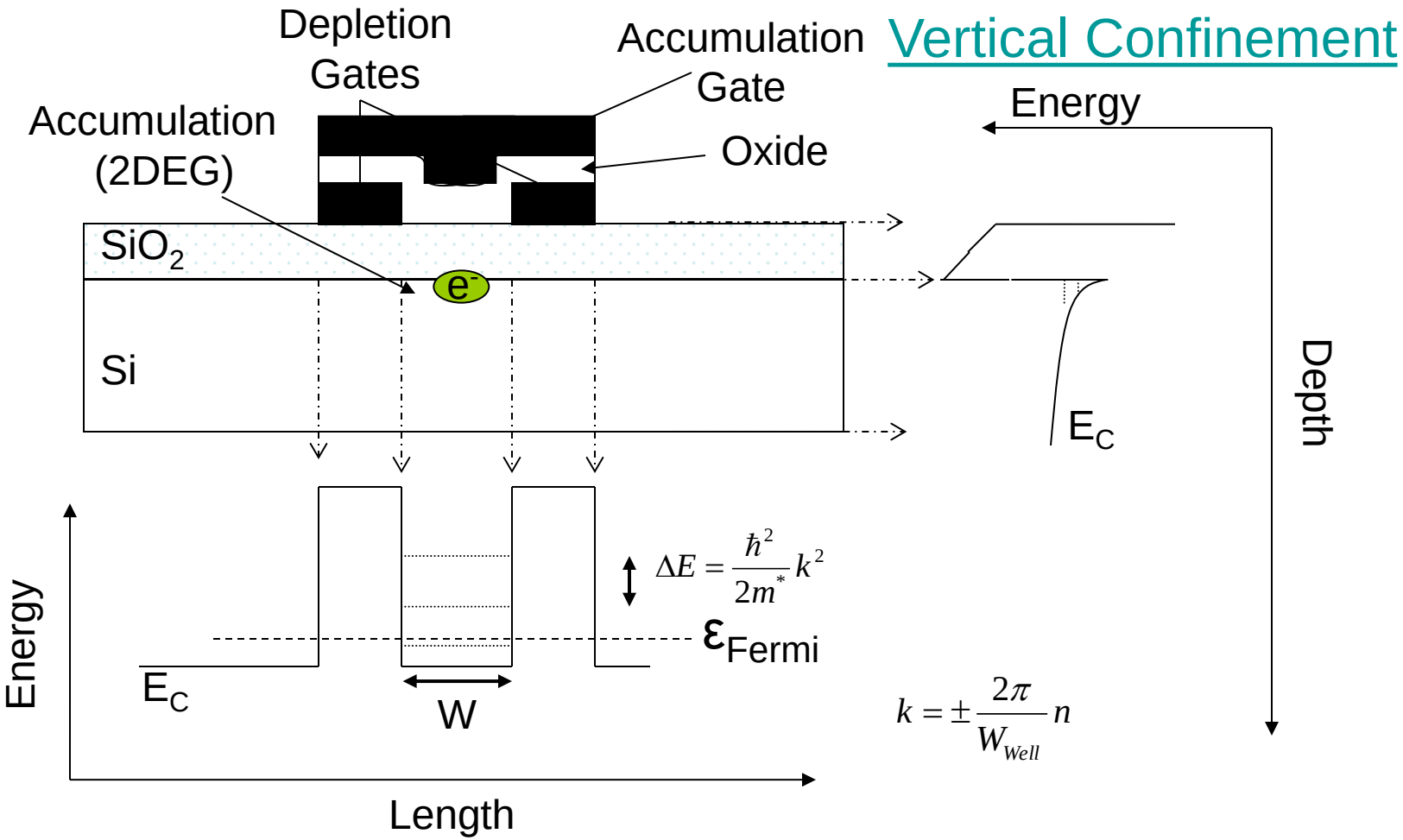
Ohmics

Donor

Quantum Dot

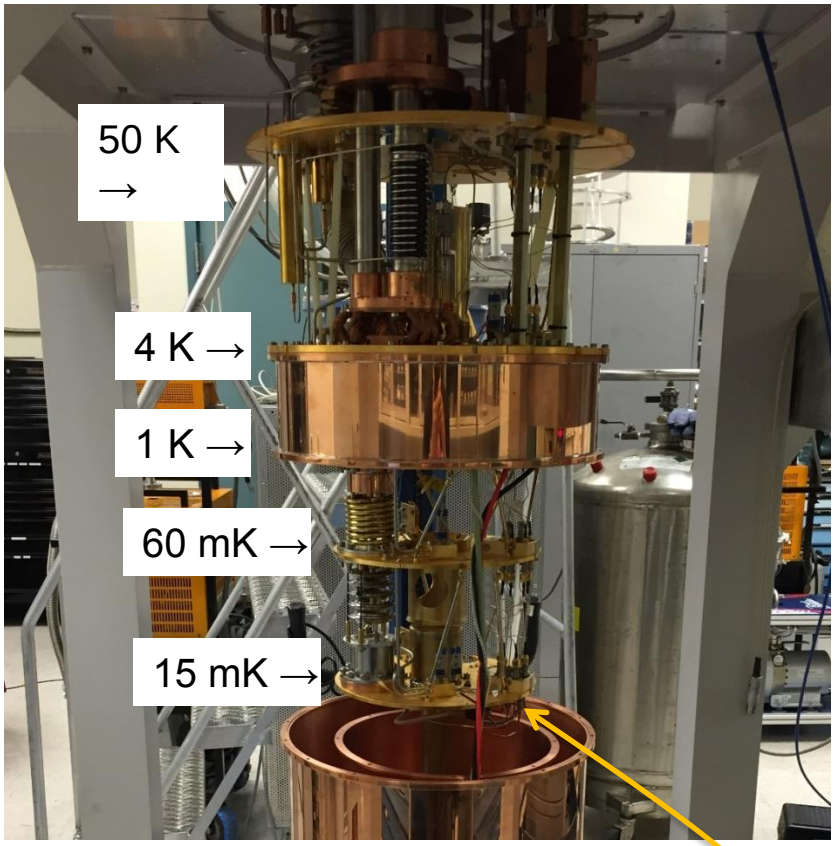
Al stripline

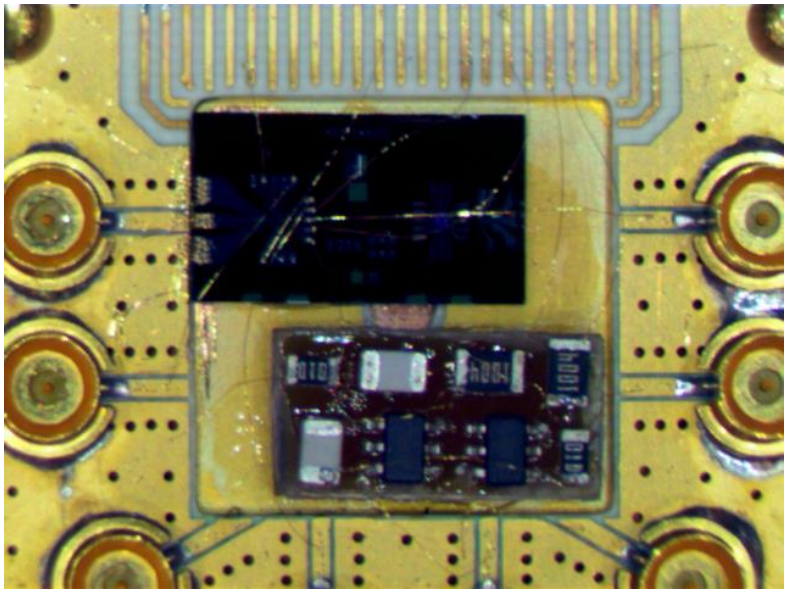
MOS quantum dots



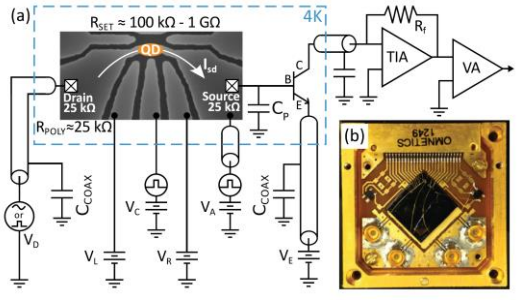
Lateral Confinement

Qubit operation

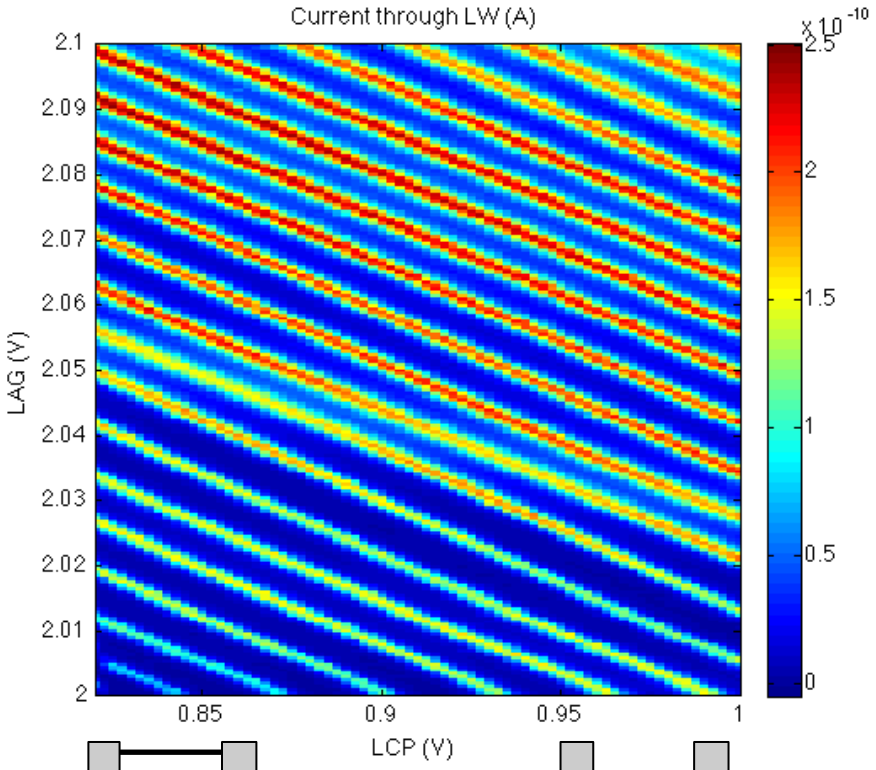


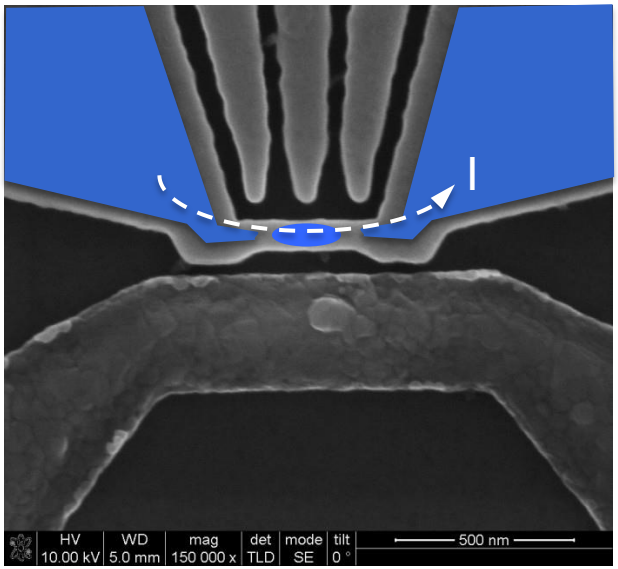


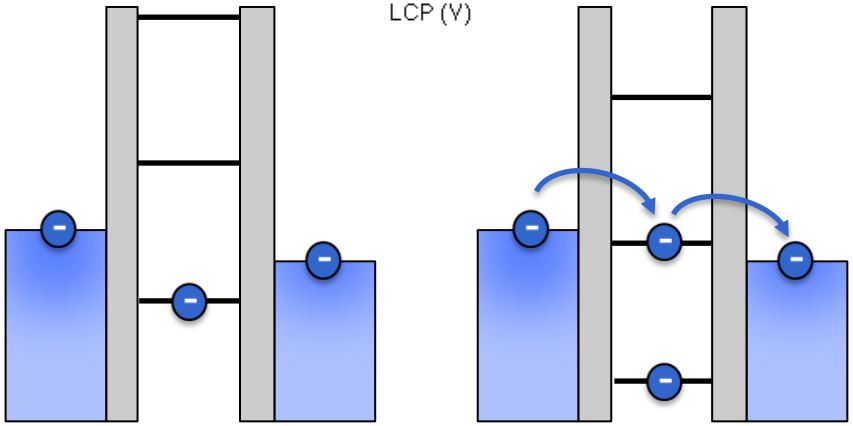
Two-Stage HEMT amplifier stage

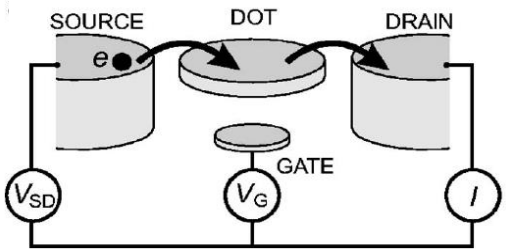


Quantum dot operation: Coulomb blockade

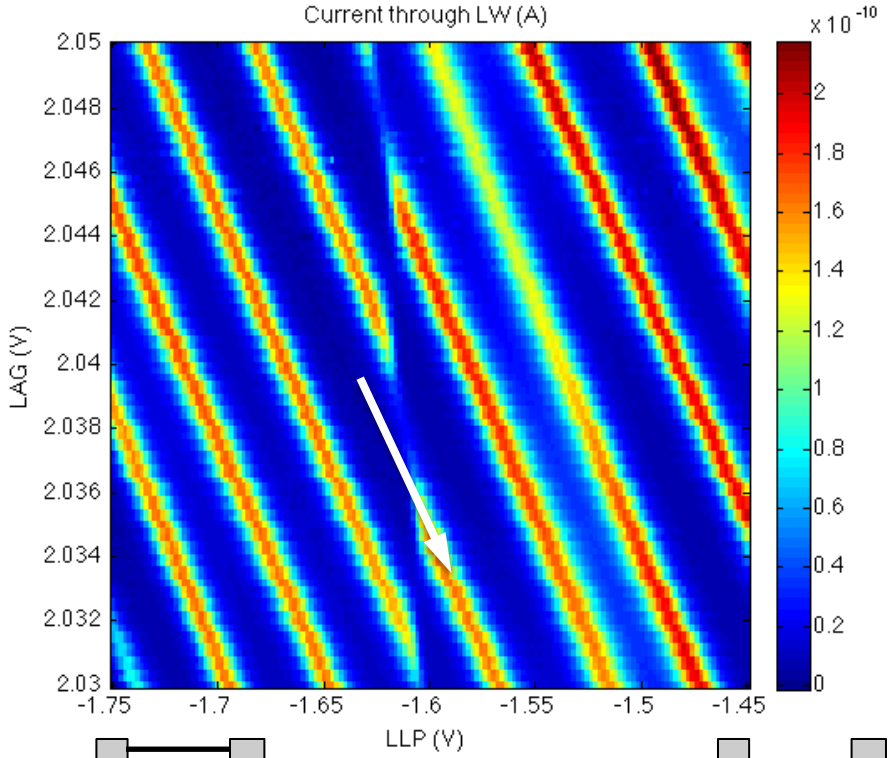


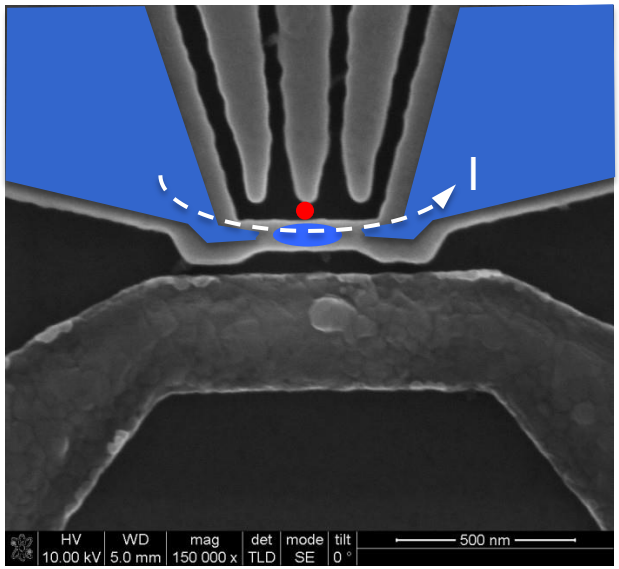


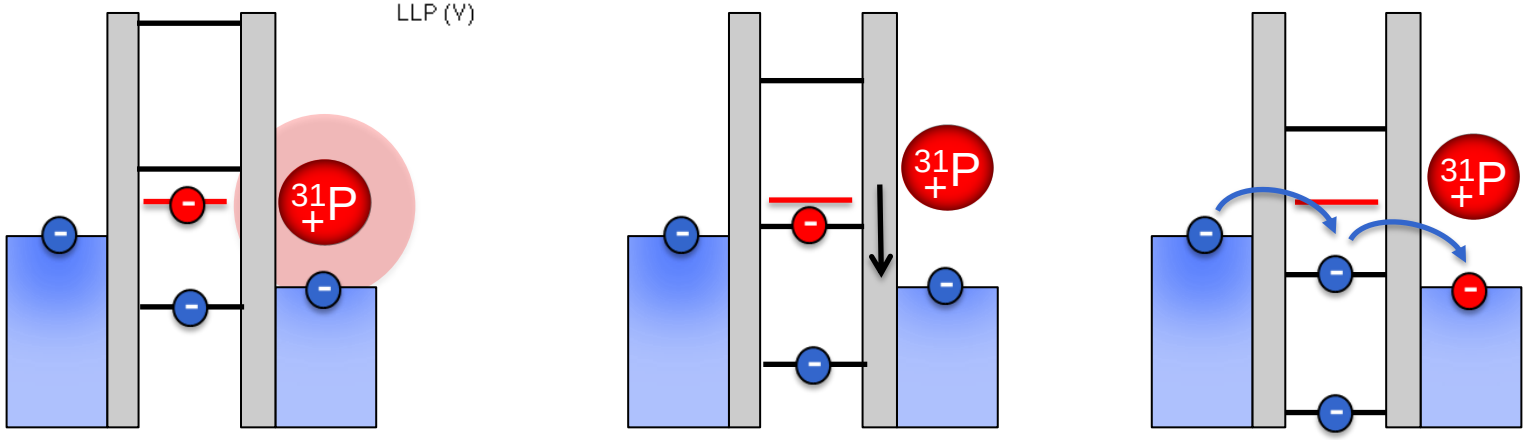




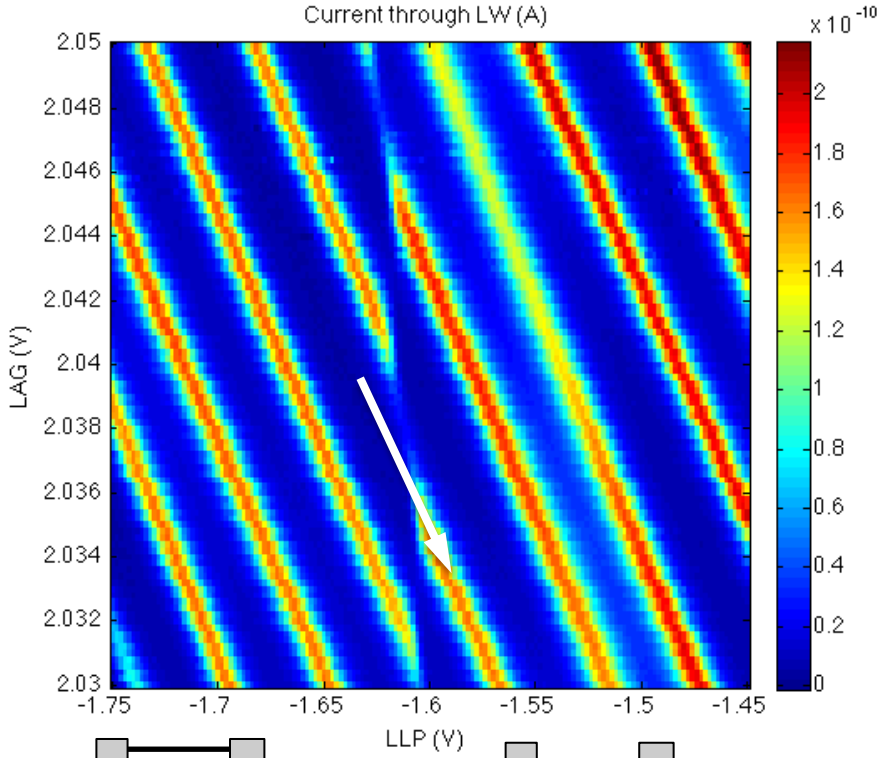
Donor ion gating effect

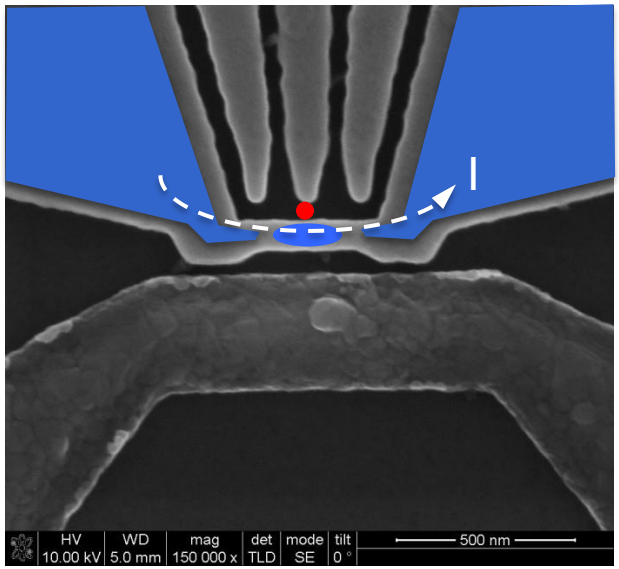


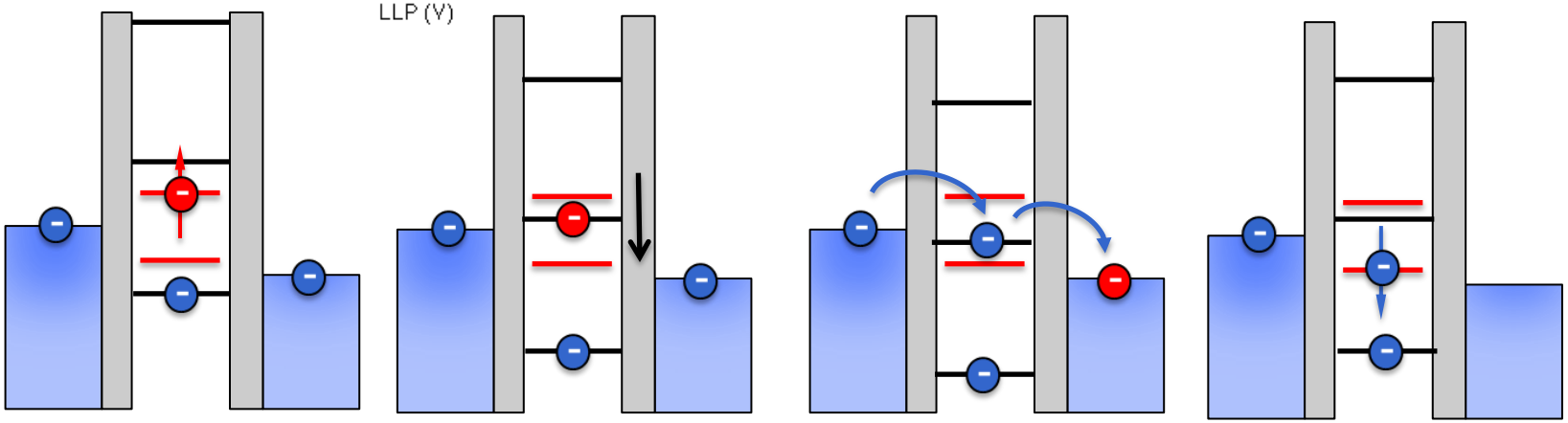




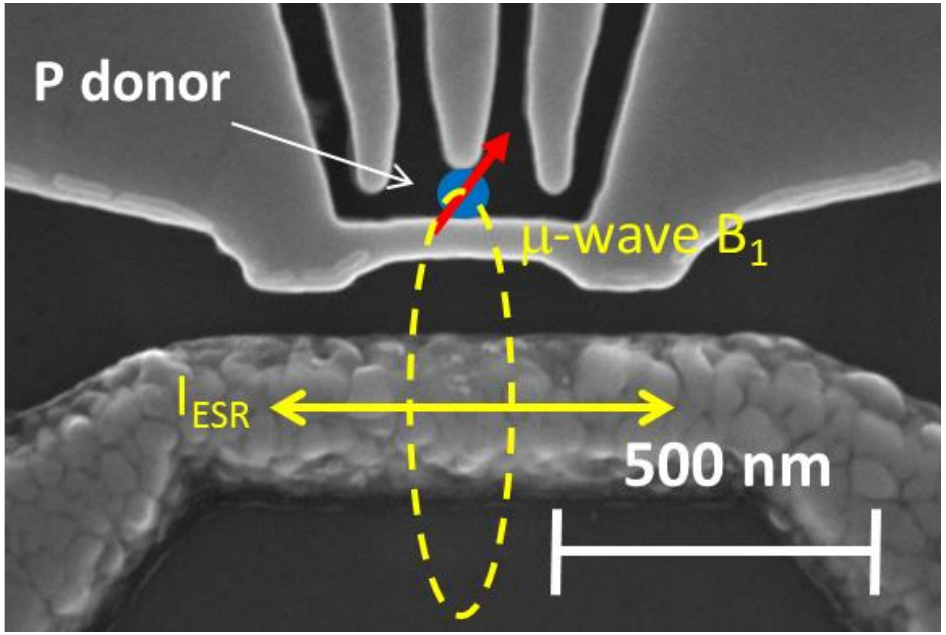
Spin readout and initialization



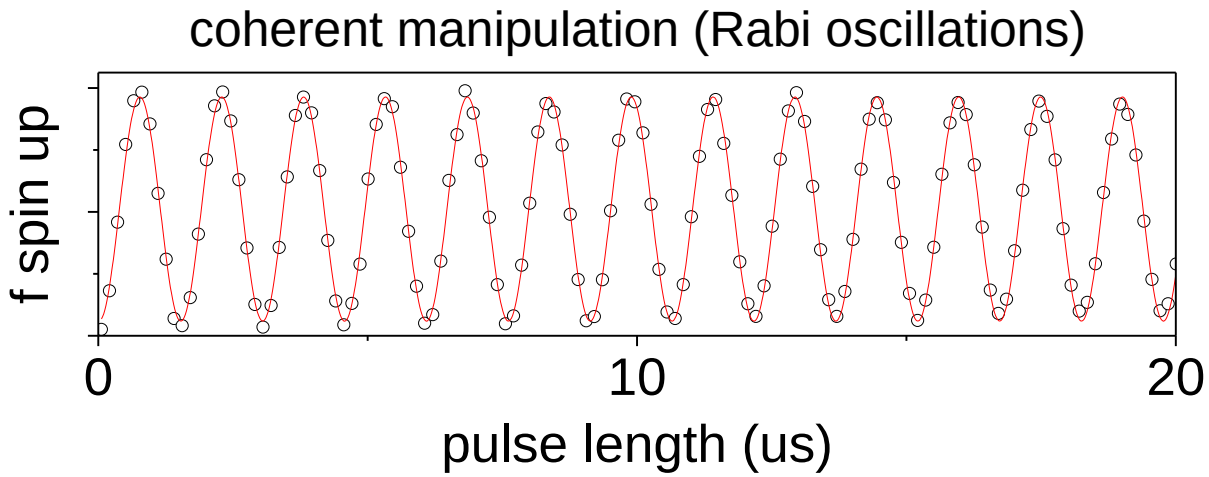




Single Qubit Coherent Control

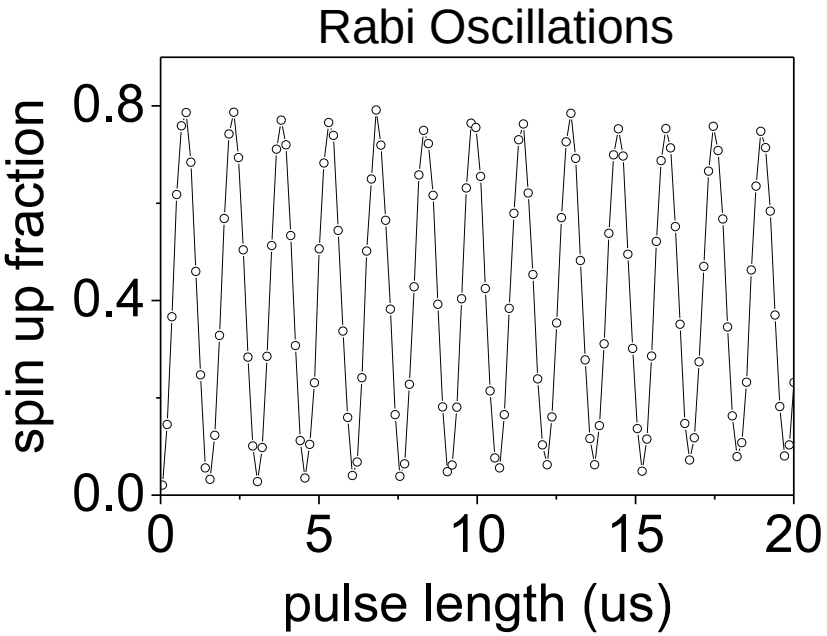


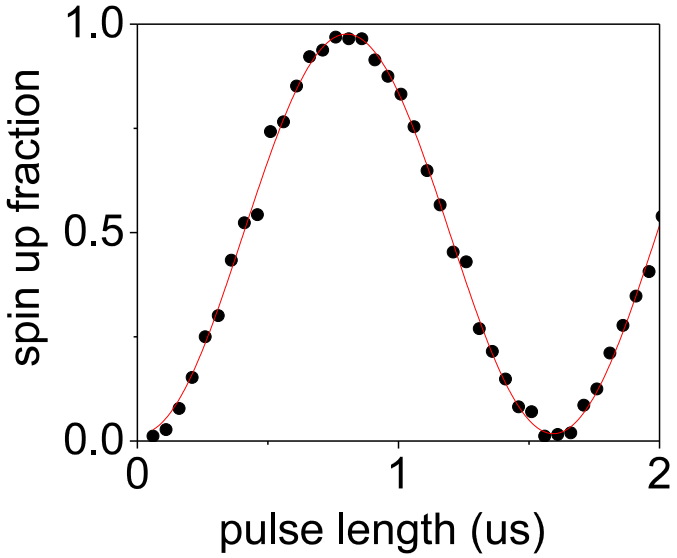
^{28}Si epitaxial layer
- 2.5 μm thick
- 500 ppm ^{29}Si (ToF SIMS)

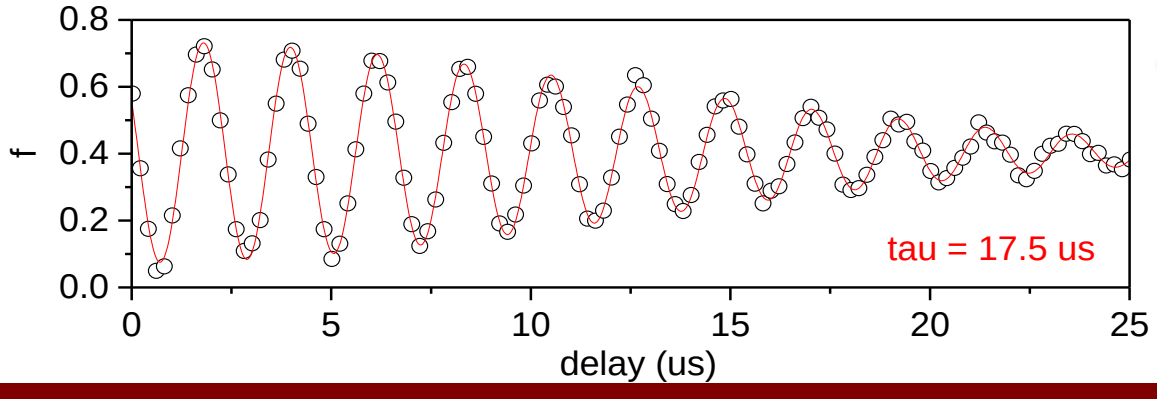


^{28}Si Qubit

Optimized Readout: 96% visibility
Bandwidth: 100 kHz



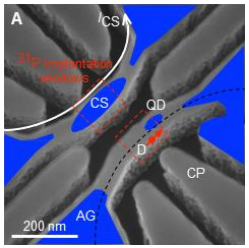




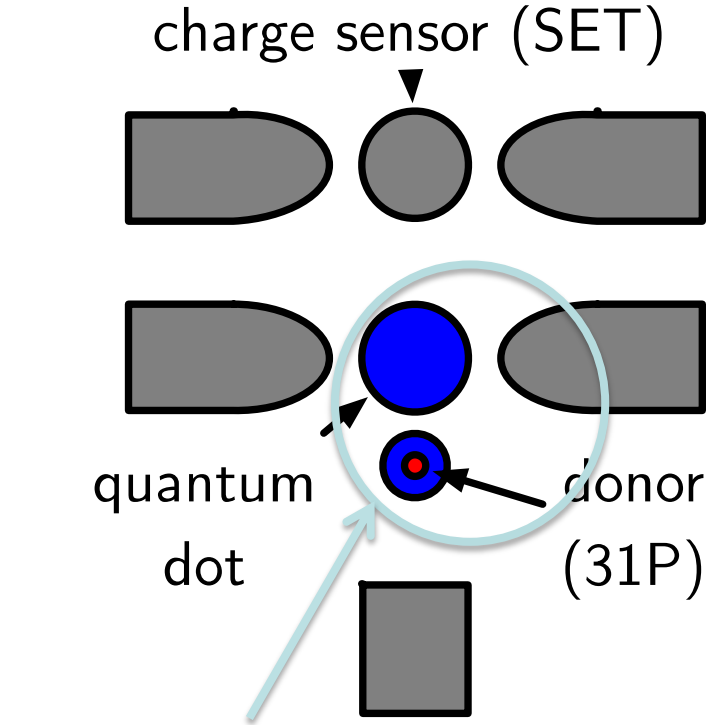
T_2^*=17.5 μs
$T_{2\ HE}$=310 μs

GST: 5% X/Y gate error

New scheme: use donor contact hyperfine interaction to rotate the spin



- Hybrid singlet-triplet qubit



- S-T Hamiltonian

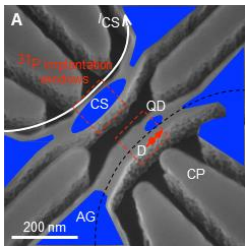
$$\hat{H}_{ST} = J(\epsilon)\hat{\sigma}_z + \Delta B_Z(\epsilon)\hat{\sigma}_x$$

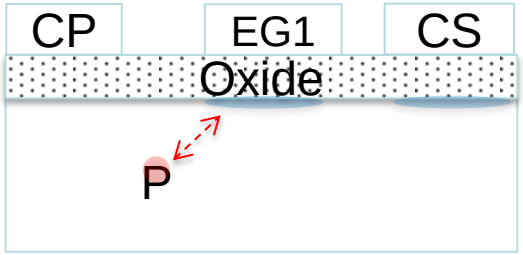
For electron on donor:

$$\hat{H} = (g\mu_B/\hbar)\boldsymbol{S}\cdot\boldsymbol{B}_{ext} + A\boldsymbol{S}\cdot\boldsymbol{I}$$

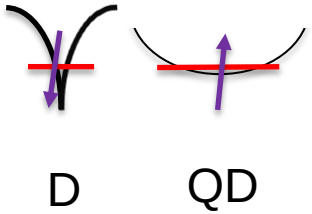
- Advantages
- Compact design: No need for **nuclear field bath**, **spin-orbit int.** or **micromagnet**.
- **Fast** rotation speed: Contact hyperfine interaction $A/2 \sim 58$ MHz gives **9 ns π rotation**.
- Get a **nuclear spin** for free.

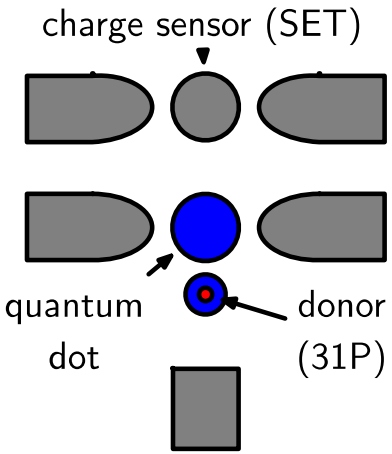
Approach: Couple a N=1 MOS-QD to a Buried Donor



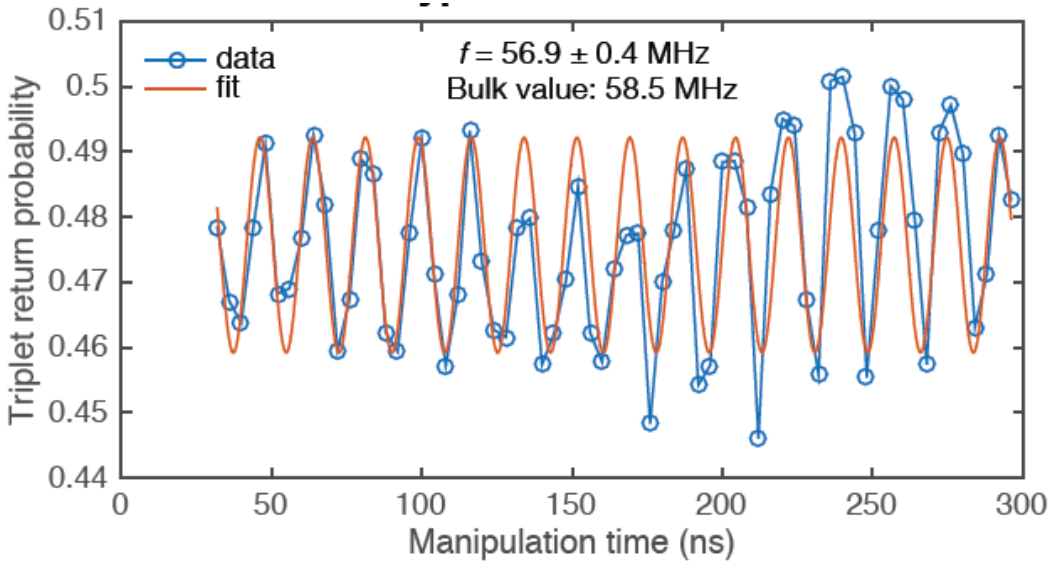


2-spin singlet-triplet qubit



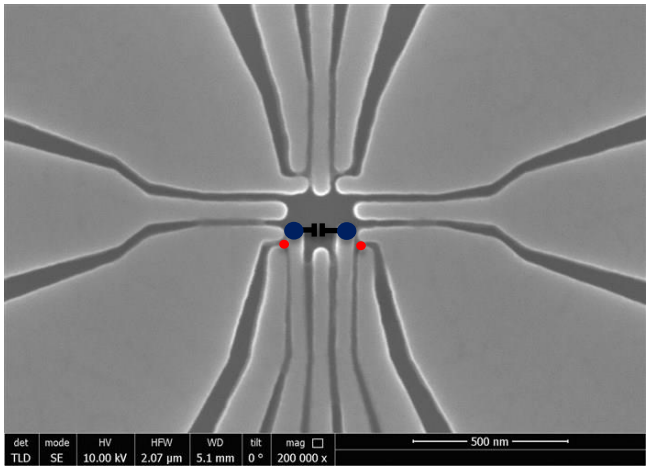


- We are able to electrically induce coherent behavior in the 2 electron system
- Reasonably good coherent behavior
- SNL first to demonstrate coherent coupling of a buried donor electron to a QD at the MOS interface



Possible future lay-out for two-qubit coupling

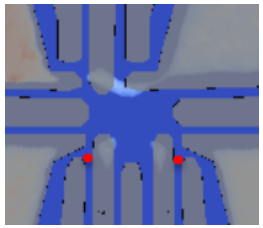
Sandia National Laboratories



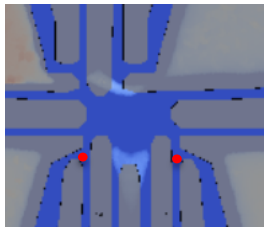
… and other approaches (J or shuttle)

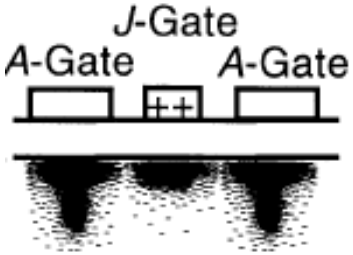
Exchange gate mediated by DQD

Small t

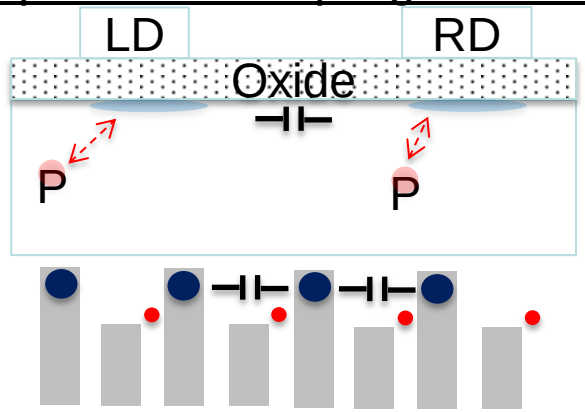


Enormous t

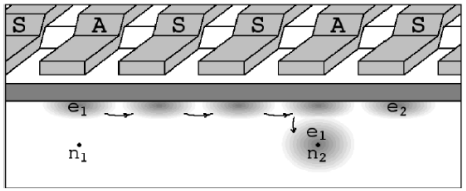


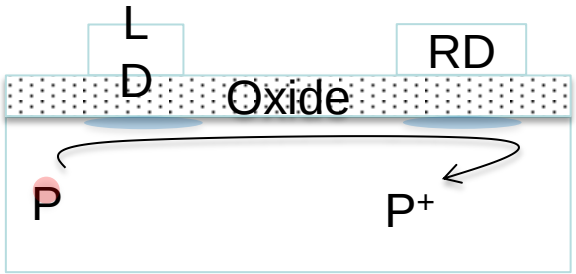


Capacitance coupling of MAJIQ-SWAG



Transport mediated by QDs



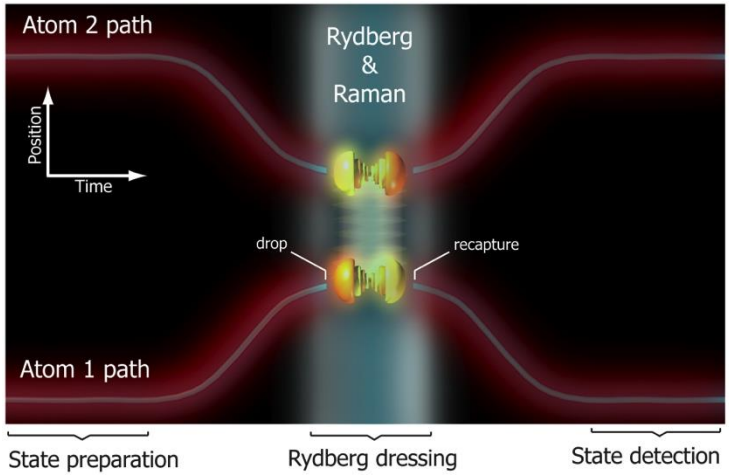


- Capacitance coupling by proximity for two qubit gate
- Approach uses energy selection of one of many donors in an ensemble & poly self-alignment
- Concept might be generalized to more (in a 1D line)

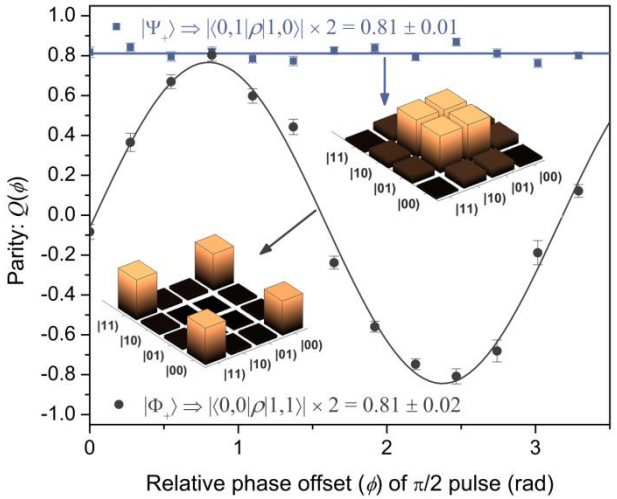
Entangling neutral atom qubits with a strong Rydberg-dressed interaction

Sandia National Laboratories

Entanglement sequence—dynamic atom positioning

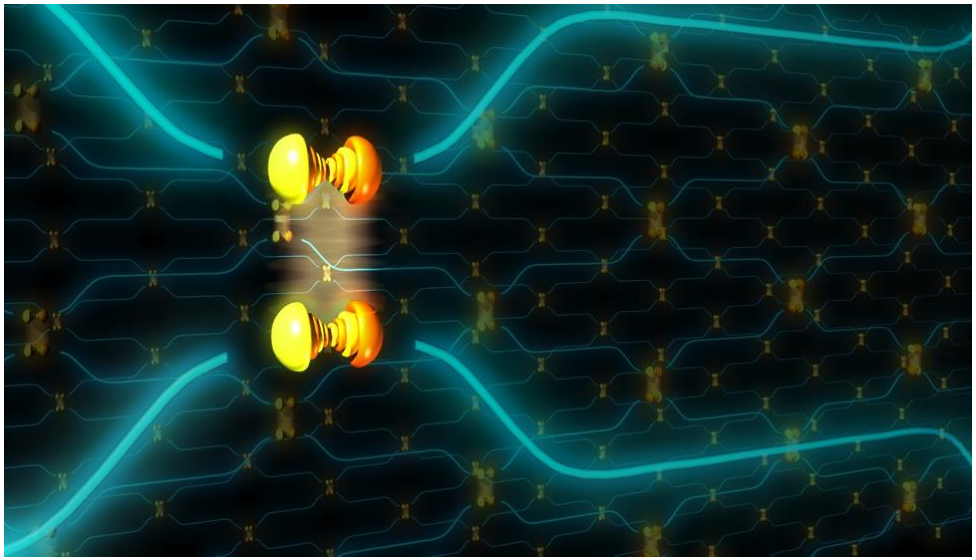


Entanglement verification—parity measurement



- We generate two Bell states:
  $(|0,1\rangle + |1,0\rangle)/\sqrt{2}$
  $(|0,0\rangle + |1,1\rangle)/\sqrt{2}$
- Varying the phase of a global π/2 pulse reveals ≥ 81% fidelity for both states.

Conceptual drawing of large scale entanglement



Applications include:

- Clocks
- Inertial sensing
- Quantum computation
- Quantum simulation

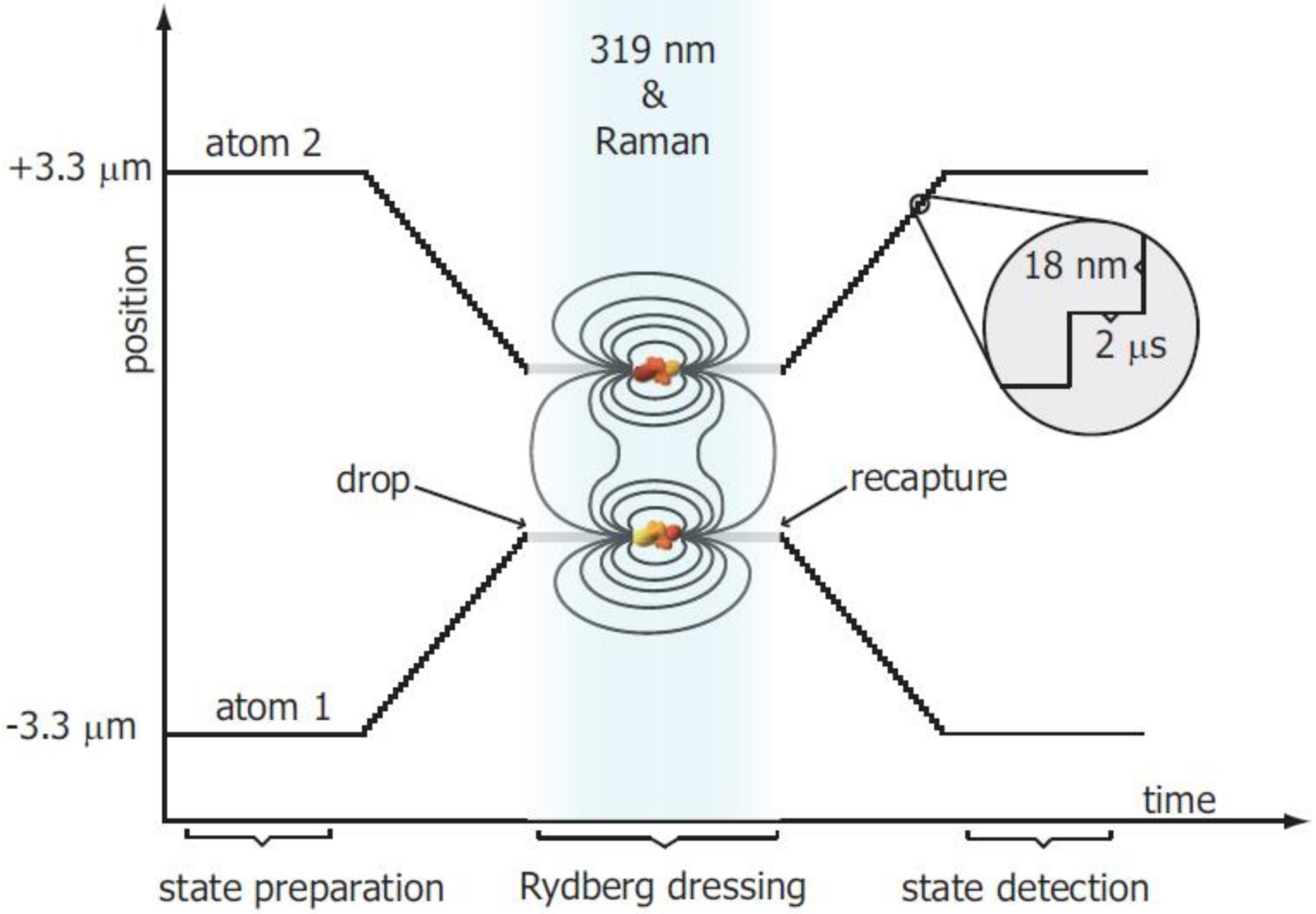
In collaboration with:

UNM

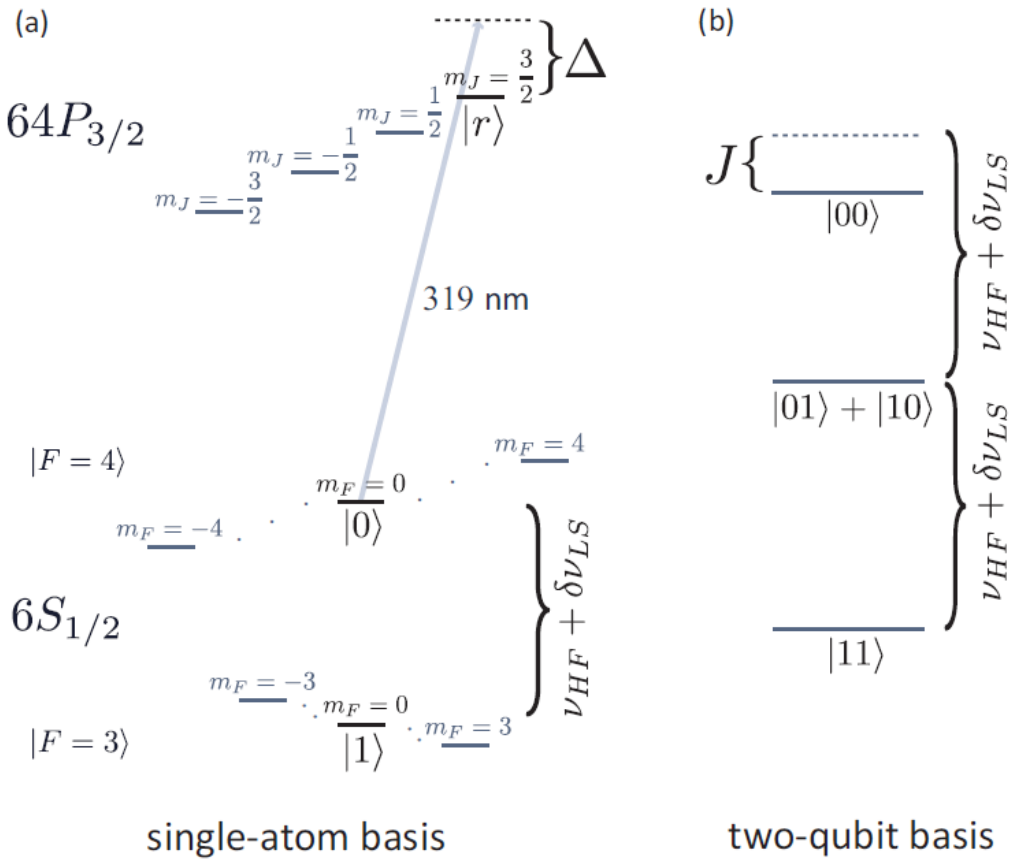
LDRD Laboratory Directed Research & Development

Y.-Y. Jau, A. Hankin, T. Keating, I. Deutsch, and G. Biedermann, *manuscript submitted* (2014)

Dynamic atom spacing



Rydberg-dressed ground state interaction



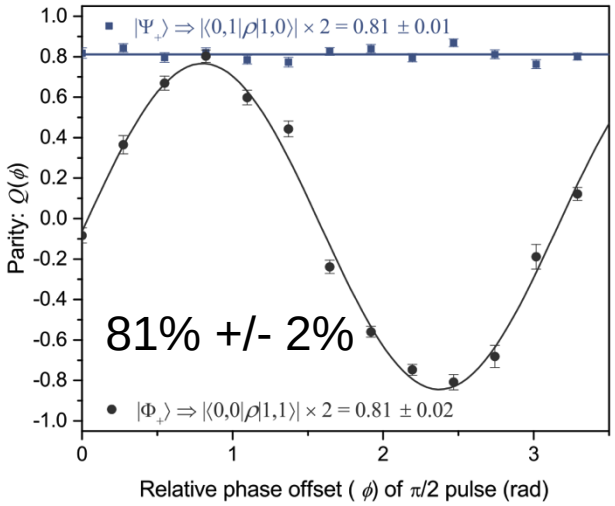
single-atom basis

two-qubit basis

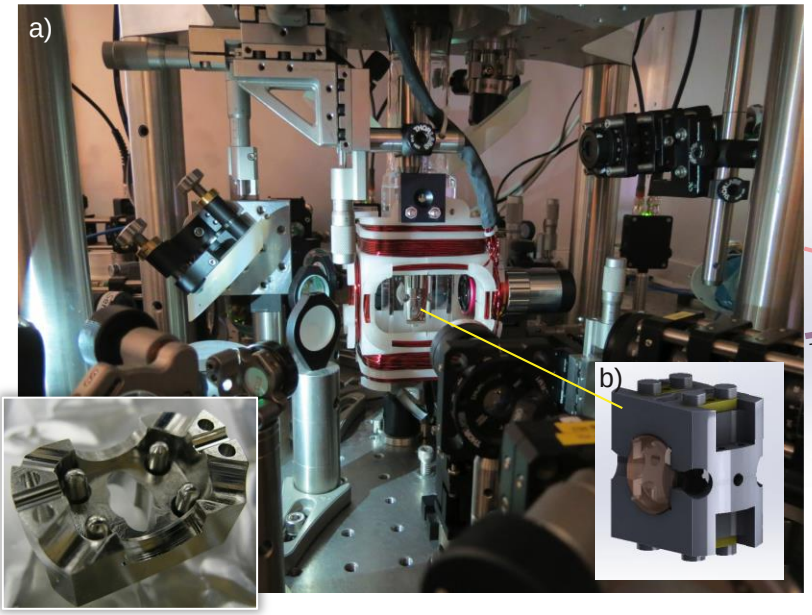
Entangled atom experiment—recent progress

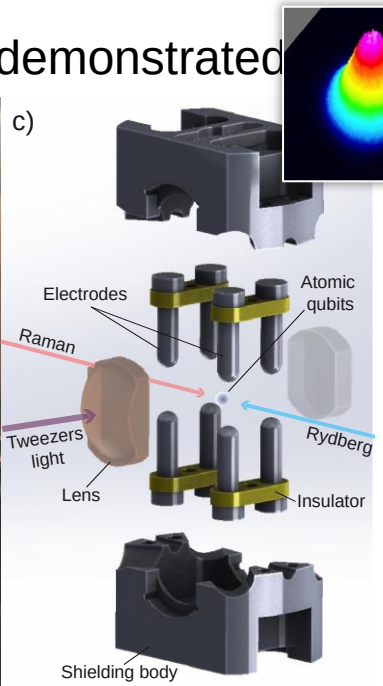
Sandia National Laboratories

Nature Physics, 2015



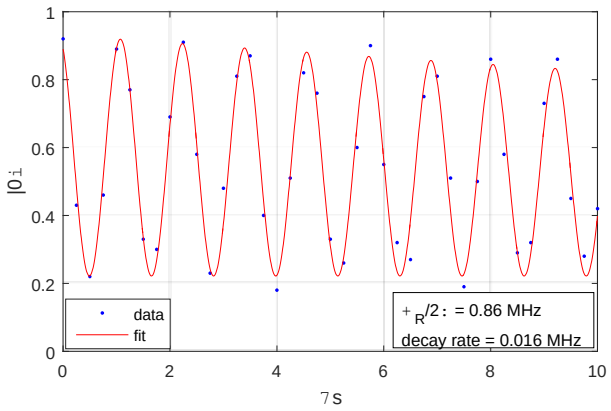
Upgraded apparatus: installed and demonstrated

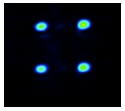




Rabi oscillations to Rydberg: 7x improvement

Furthermore: Virtually eliminated Rydberg state loss channel



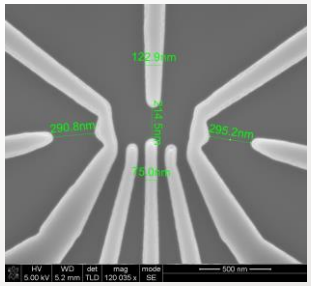


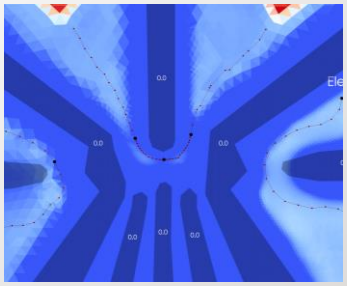
Next up

- 4-atom entanglement
- New Rydberg state longevity has allowed demonstration of mapping to Jaynes-Cummings model for cavity QED

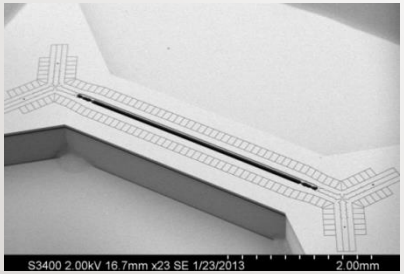
Sandia QIS Modeling

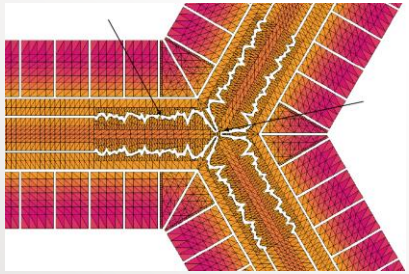
QCAD: Quantum device modeling for semiconductors. Thomas-Fermi, Schrodinger Poisson, Configuration Interaction



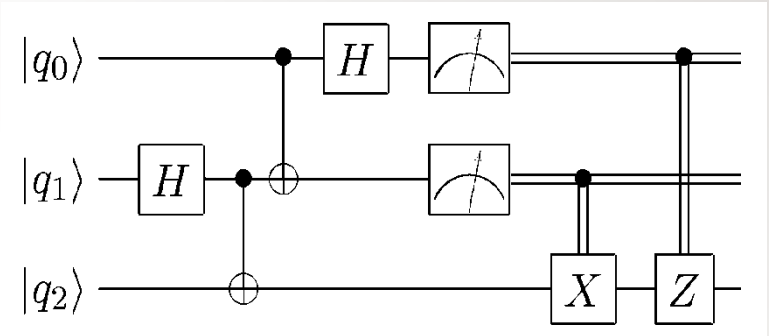


TRAPSIM: electrostatic modeling intended for RF trapped ion device design

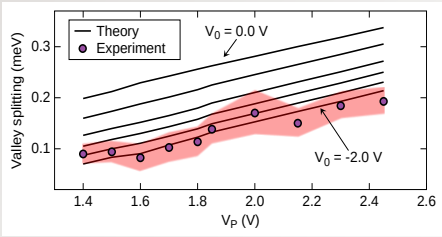


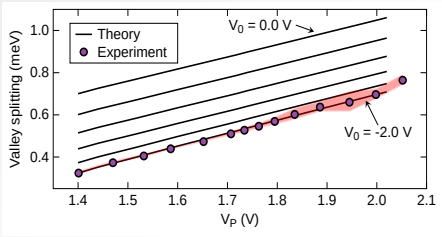


Circuit Simulators: Use vector states, density matrices, or Monte Carlo methods to compute outcomes and thresholds of quantum circuits

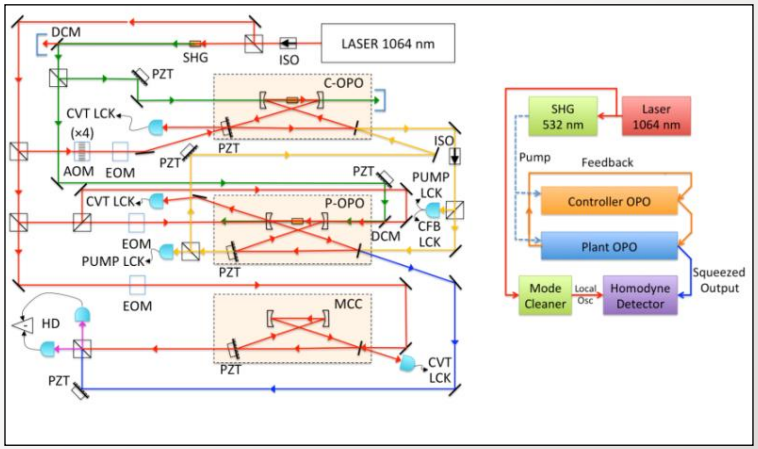


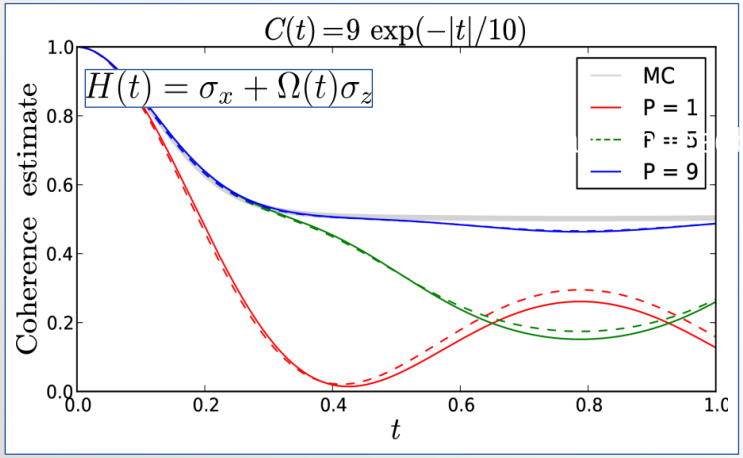
Effective Mass Theory: "Valley-aware" with exceptional computational efficiency.





Sandia QIS Modeling





Qubit coupled to fluctuating dephasing process

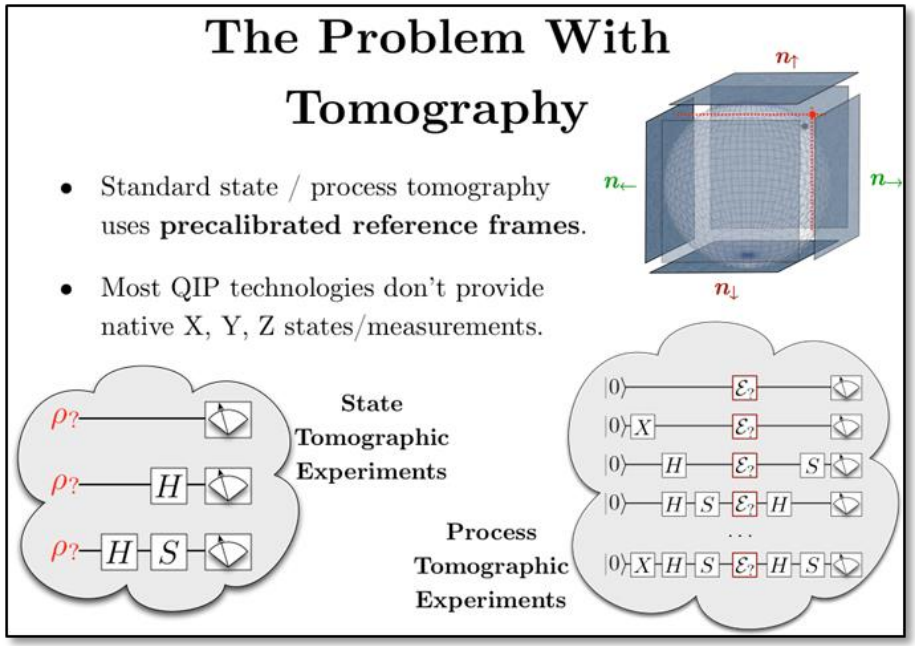
Modeling of complex quantum networks

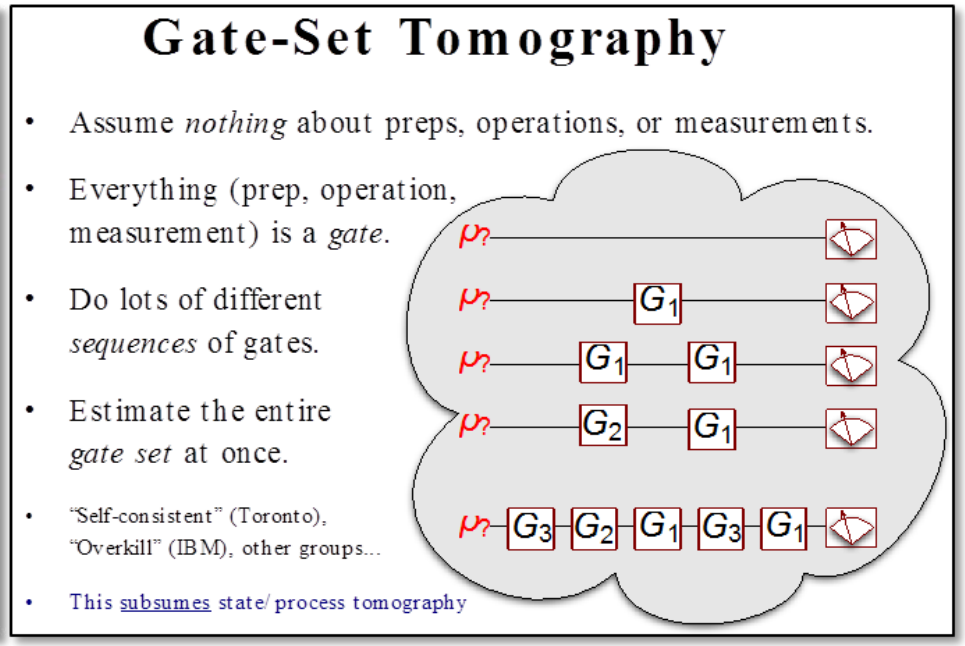
- SLH formalism capable of modeling network of components connected by quantum fields in a modular manner
- Modeling of quantum optical networks for generating squeezed light

Simulation of stochastic quantum systems

- Hierarchical equations of motion
- Polynomial chaos expansions

Gate set tomography





- Robustly diagnoses faulty operations without precalibrated gates

Gate Set Tomography

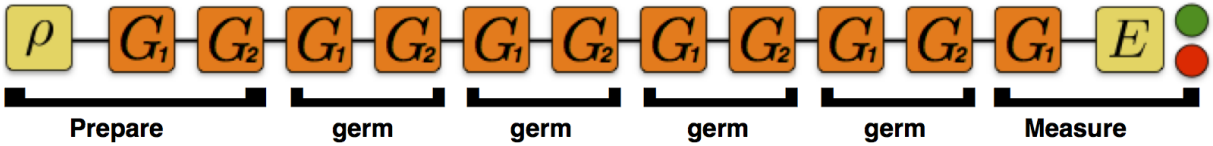
Sandia National Laboratories

We developed GST to fill two needs: *debgugging* and *certifying* as-built qubits

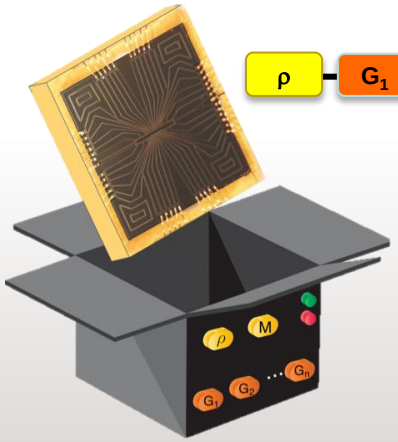
Capabilities vs Protocols	No Calibration Required	Detailed Debug Info	Efficiently Certifies ◇-norm	Detects Non-Markovian noise
Randomized Benchmarking	✔	✘	✘	✔
Process Tomography	✘	✔	✘	✘
Gate Set Tomography	✔	✔	✔	✔

GST characterizes *all* the logic gates at once (like RB)...
...but reports full process matrices for them (like process tomography).

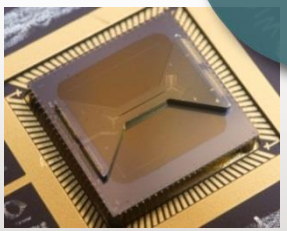
GST uses data from *gate sequences* (like RB), but these sequences are *structured* and *periodic*. Small errors get amplified and are measured precisely.

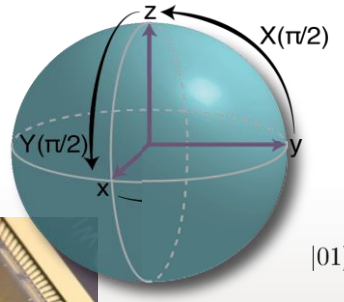


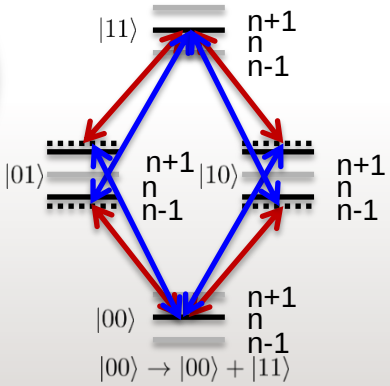
Gate Set Tomography



$$G_I$$
$$G_{XX} = G_X \otimes G_X$$
$$G_{YY} = G_Y \otimes G_Y$$
$$G_{MS}$$

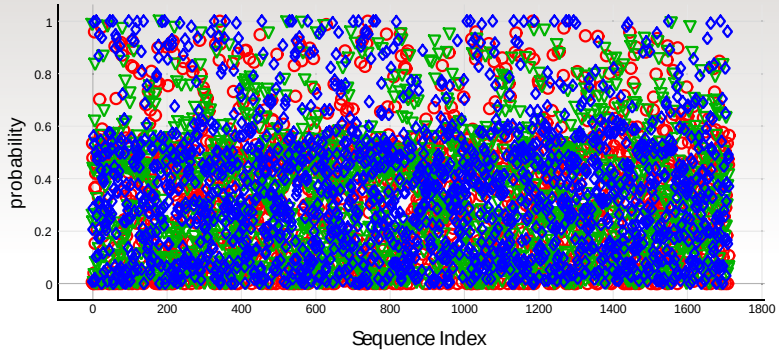




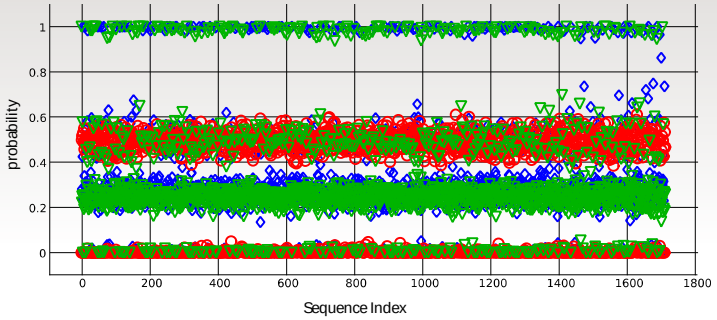


Process fidelity of two-qubit Mølmer-Sørensen gate > 99.5%

GST; poor gate performance



GST; good gate performance

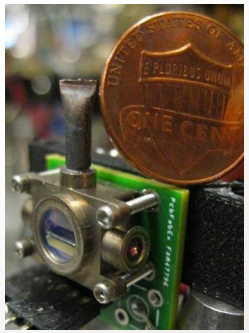


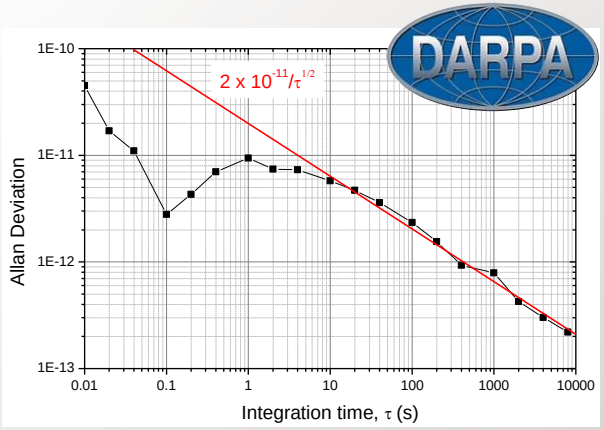
The best characterized two qubit gate in a microfabricated surface trap.

Quantum Sensing

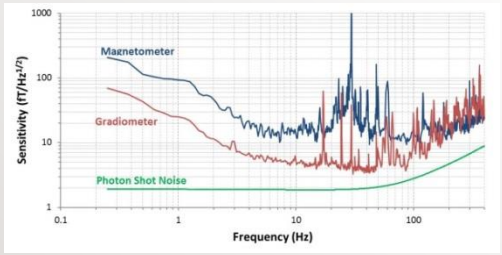
Atomic Clocks

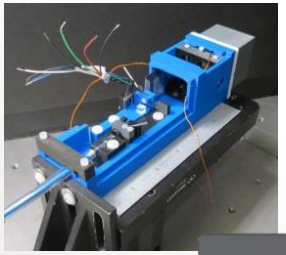
Maximized Precision and Stability
Minimized Volume and Power

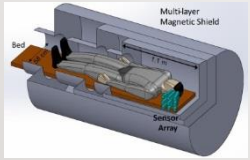




Atomic Magnetometry for Magnetoencephalography

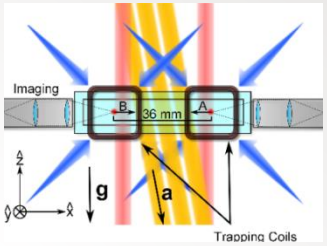


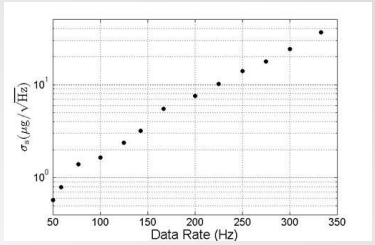


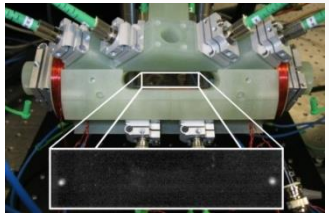


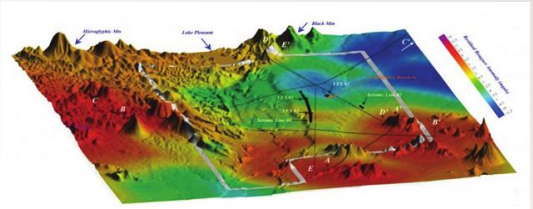
NIH

Atom Interferometry



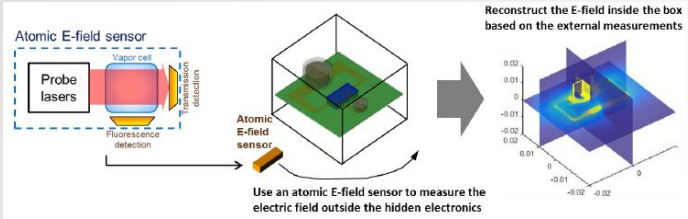


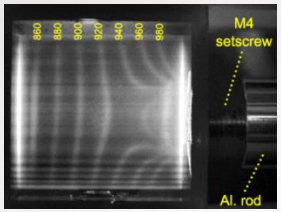




Field Sensing

Rydberg atom based electric field sensing

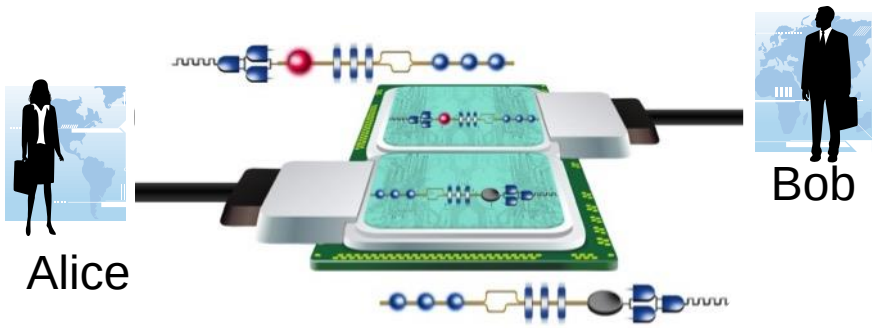


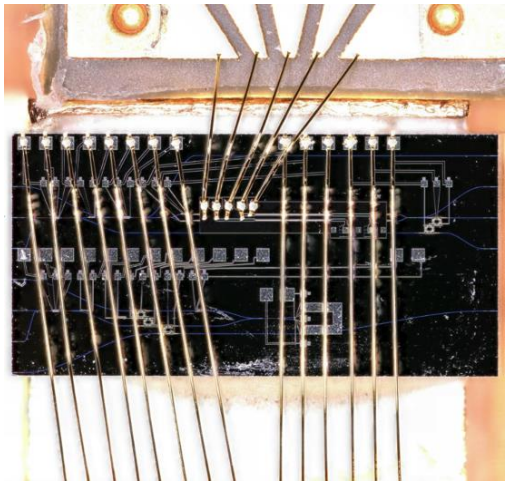


Passive magnetic field sensing

Fescenko, I., Weis, A. "Imaging magnetic scalar potentials by laser-induced fluorescence from bright and dark atoms," *Journal of Physics D*, **47**, 235001, (2014).

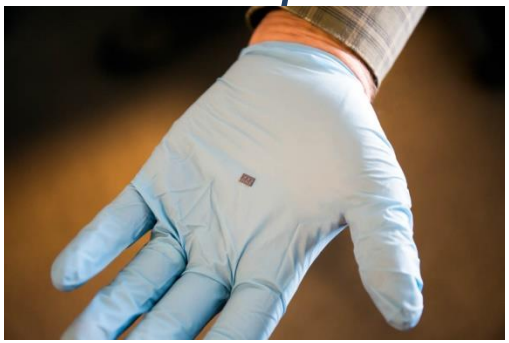
Quantum Communication





Wirebonded QKD chip

- World's first on-chip CV and DV QKD transceivers
- Free space and dark fiber QComms test beds
- World's most sensitive on-chip (CMOS compatible) detectors (1550 nm)
- Patented Self-Referencing (NOLO) protocol achieves increased security



QKD Chip

Sandia's Quantum Information program is rooted in collaborations

Sandia National Laboratories

Backup slides

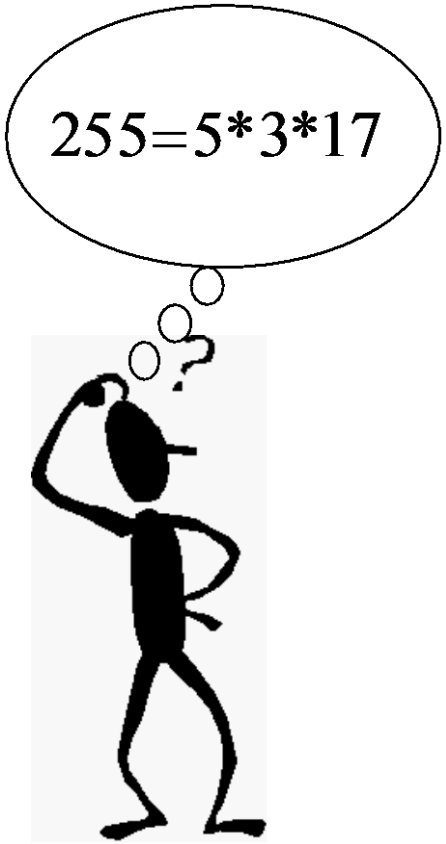
Sandia National Laboratories

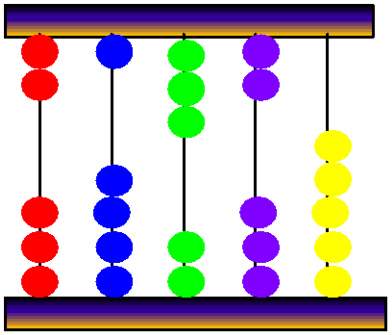
Introduction to QIS

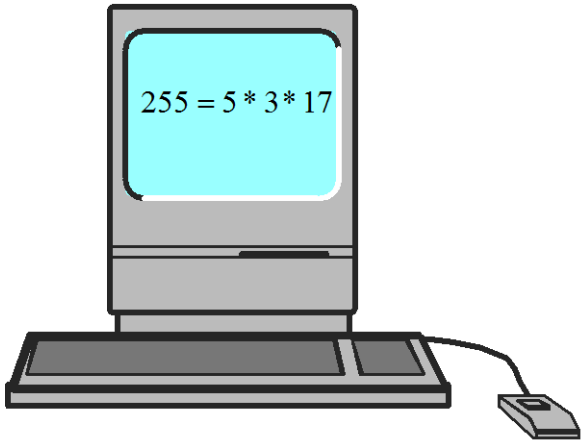
Sandia National Laboratories

"Information is physical"

- Rolf Landauer

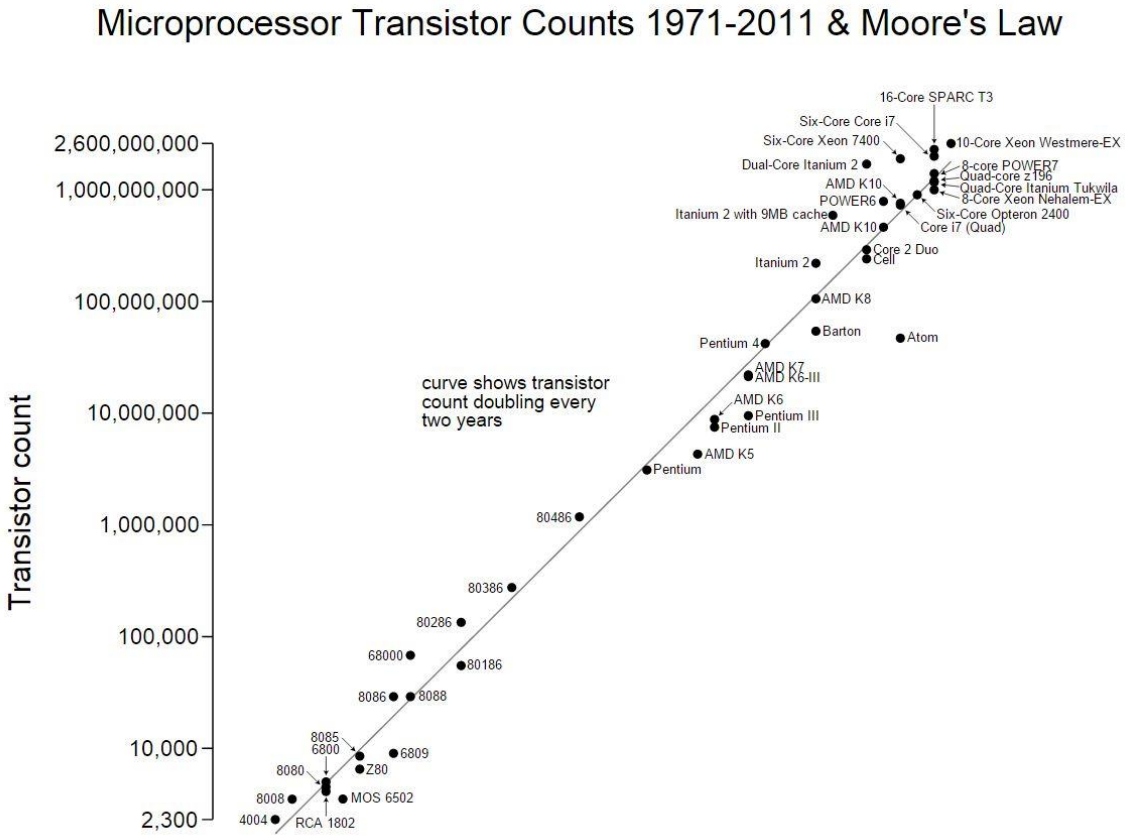


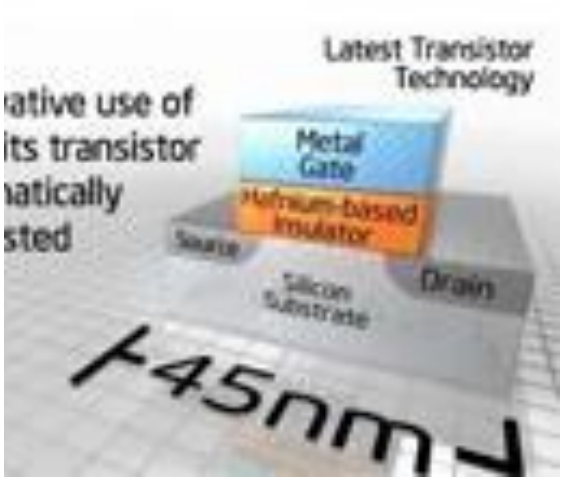




Any computation is constrained by the physical laws governing the "machine" that carries out the operations.

The quantum problem





www.intel.com

QIS origins

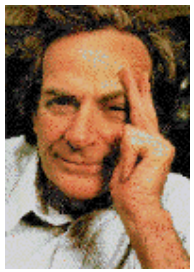
Landauer (1961)

Bennett (1982)

Benioff (1985)

Thermodynamics/reversible computing

Quantum Simulations

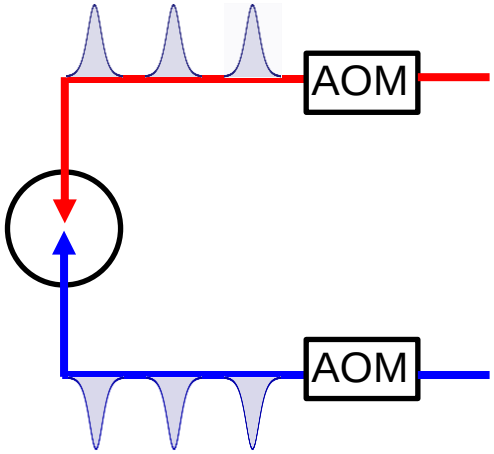


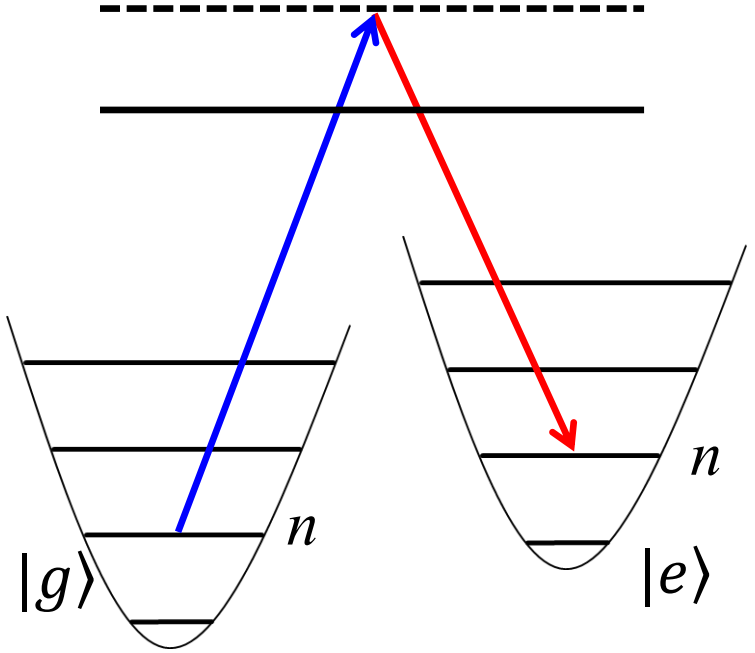
Feyman
(1982)

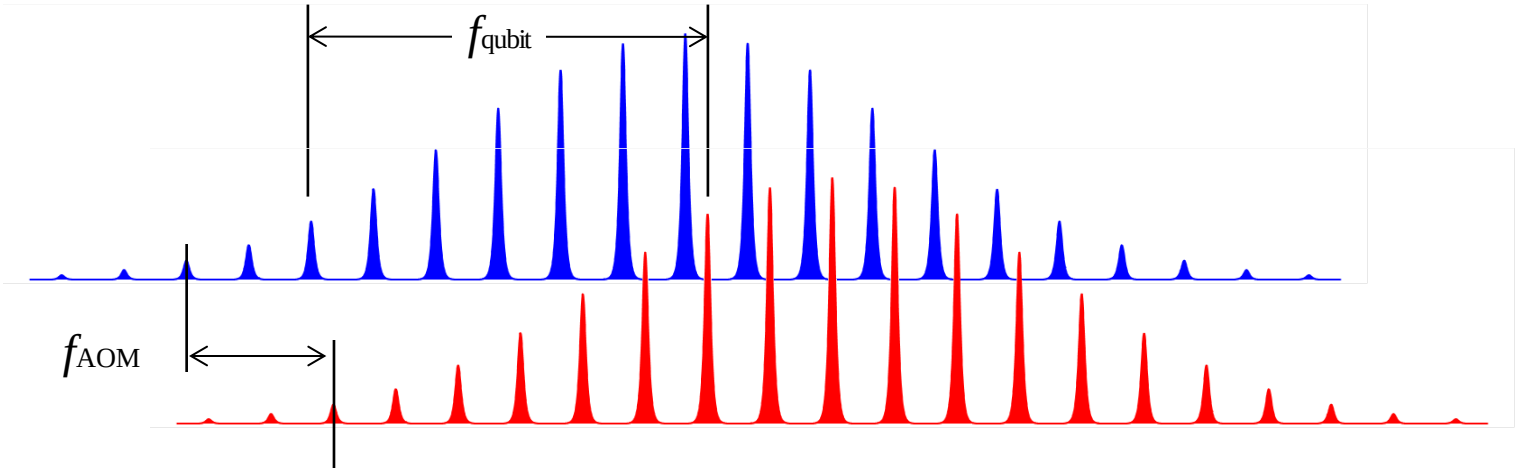
Universal quantum circuit model

Deutsch
(1985)

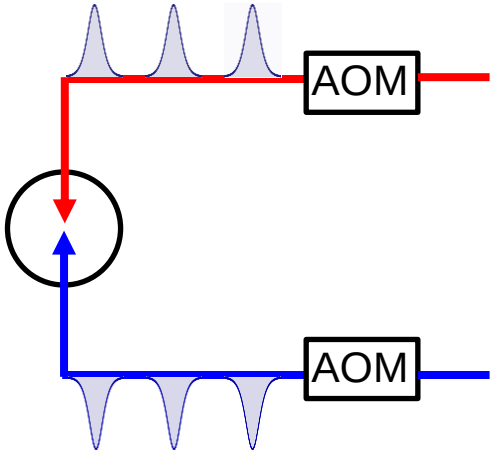
Pulsed laser Raman transitions

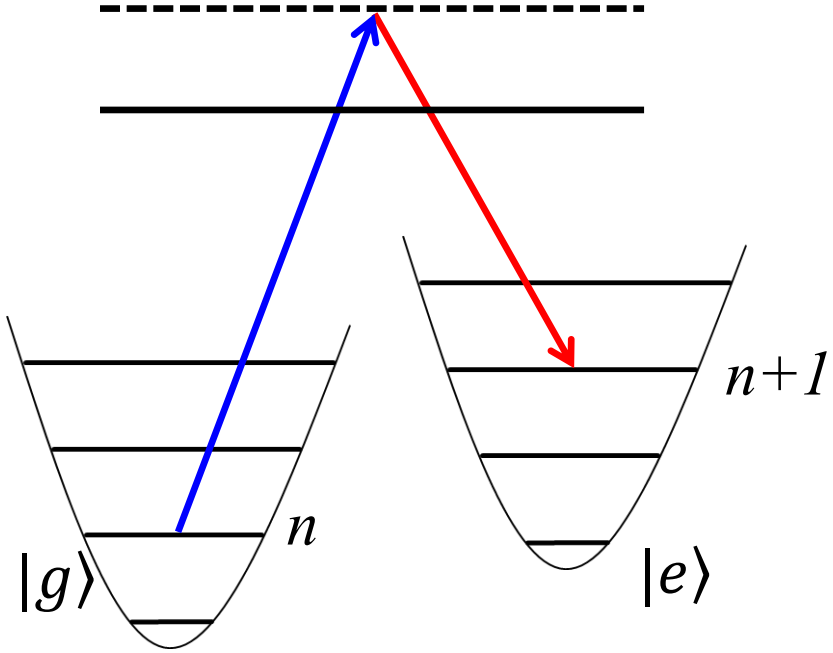


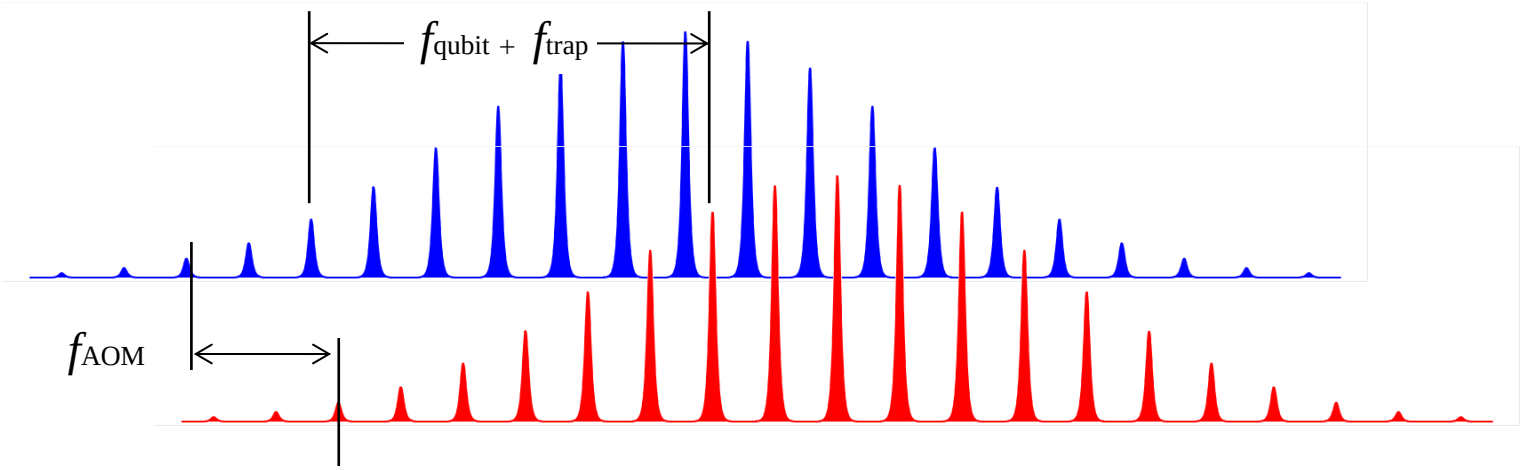




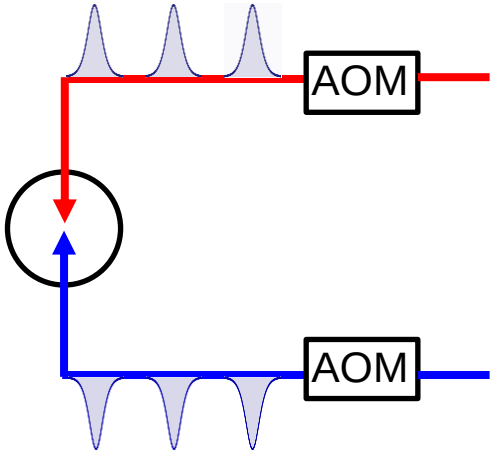
Pulsed laser Raman transitions

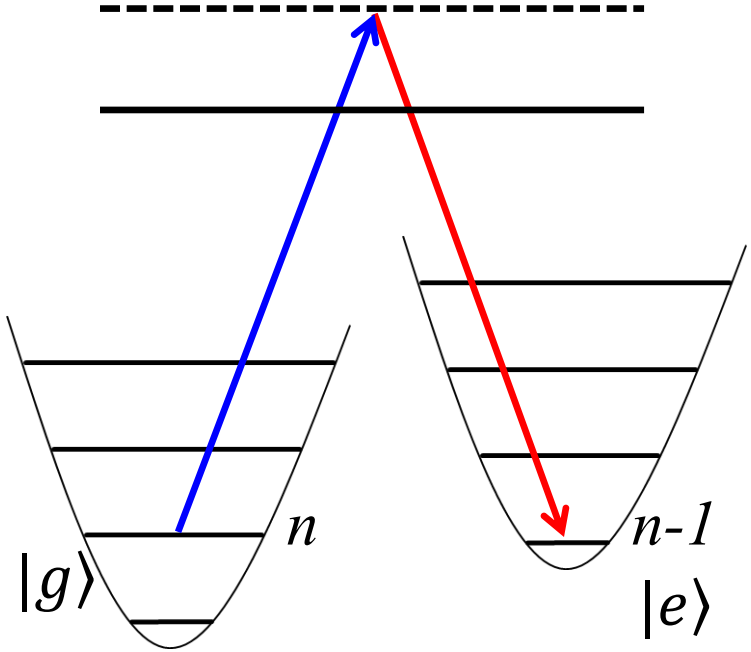


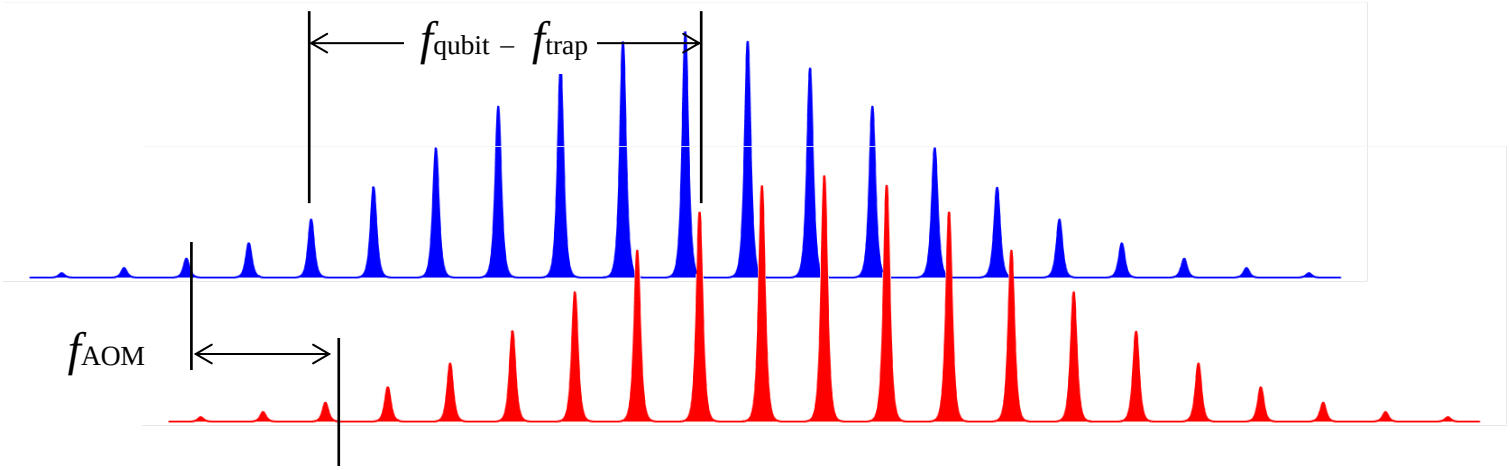




Pulsed laser Raman transitions

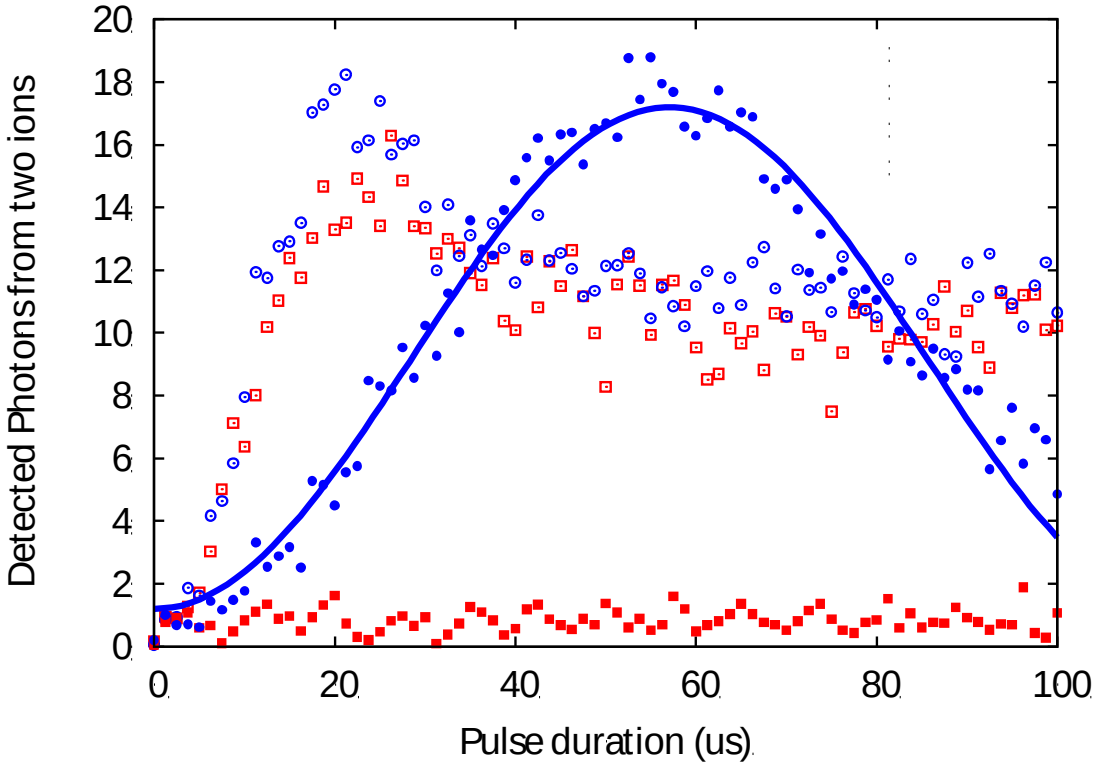


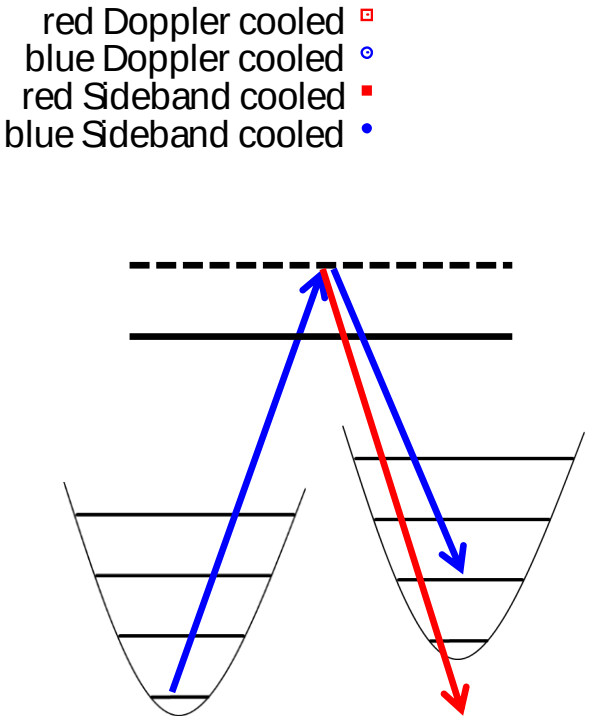




Sideband cooling

- Ground state cooling evident when red sideband cannot be driven
- Data shows ground state cooling of two ion radial tilt mode, $\bar{n} \ll 1$



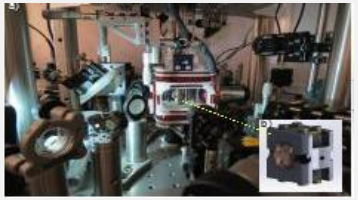
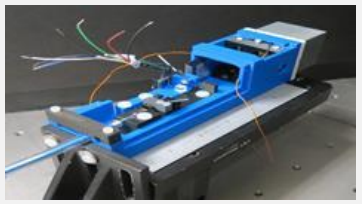
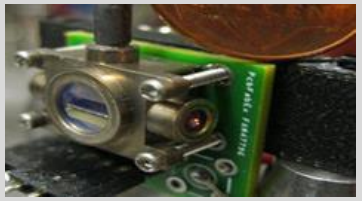


Open source GST software

Send inquiries to **pygsti@sandia.gov**

Import pyGSTi today!

Quantum Sensing Advantages

Measurand	Current SOA	Potential	Approach
Electric Field	4 mV/m√Hz (FET based)	1 nV/m√Hz (Rydberg atoms)	
Rotation	100 nrad/s√Hz (FOG)	1 nrad/s√Hz	
Magnetic Field	2fT/√Hz (SQUID)	160aT/√Hz (OPM)	
Portable Time	1e-11/√τ w/ 30 kg and 30,000 cc	1e-12/√τ w/ 300 g and 100 cc	

Enabling on-chip implementation

The components developed in the SECANT Grand Challenge LDRD enable *on-chip* implementation of the following :

1. **Quantum Photonics Primitives**
   Sources, detectors, nonlinearities, memories, etc.
2. **Quantum Photonic Measurement**
   Quantum radar, green machine, state discrimination, imaging, quantum metrology
3. **Logic Operations / Computing Primitives**
   Logic gates, coherent quantum feedback
4. **Quantum Photonic Simulations**
   Quantum walks, boson sampling, chemistry, condensed matter, Anderson localization, relativistic particle physics
5. **Foundations/Tests of Quantum Mechanics**
   Uncertainty relations, entanglement bounds, loophole free tests, etc.
6. **Communications Primitives**
   Entanglement distribution, teleportation, QRNG's, synchronization etc.
7. **Other Communications tasks**
   Digital signatures, bit commitment, distributed measurement, auctions, etc.