Quantum Science in Ion Traps
(and why it needs microfabrication)

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Outline

- Trapped ions
- Quantum Simulation
- Quantum Computation
- The need for microfabrication

Quantum Simulation with Cold Atoms (FY05 DR)

Quantum simulation (expt & theory)

Trap design, trap validation

P- 21

Dana Berkeland

John Chiaverini (starting October 05)

Warren Lybarger (UCLA GRA)

Greg Ogin (GRA—departs to CalTech Sep. 05)

Bob Scarlett

Rolando Somma (Director's Postdoc Fellow)

Kendra Vant (Director's Postdoc Fellow)

T-Division

Eddy Timmermans

Juan Pablo Paz

Gerardo Ortiz

Jim Gubernatis

Theory of quantum simulation

MST-11

David Lizon

Trap design, fabrication

Sandia NL

Matthew Blain

Chris Tigges

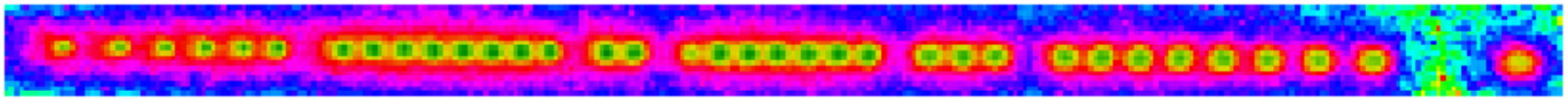
BEC quantum simulation

C-INC

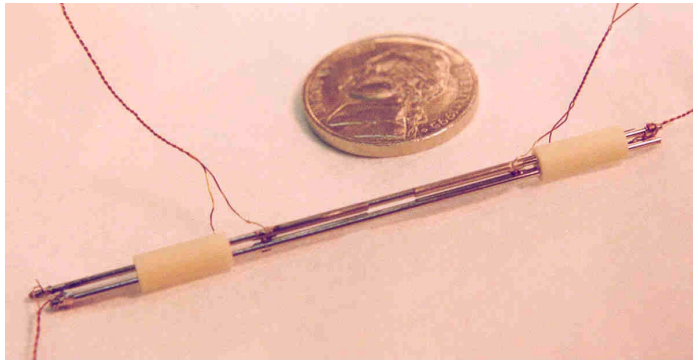
Xin Xin Zhao

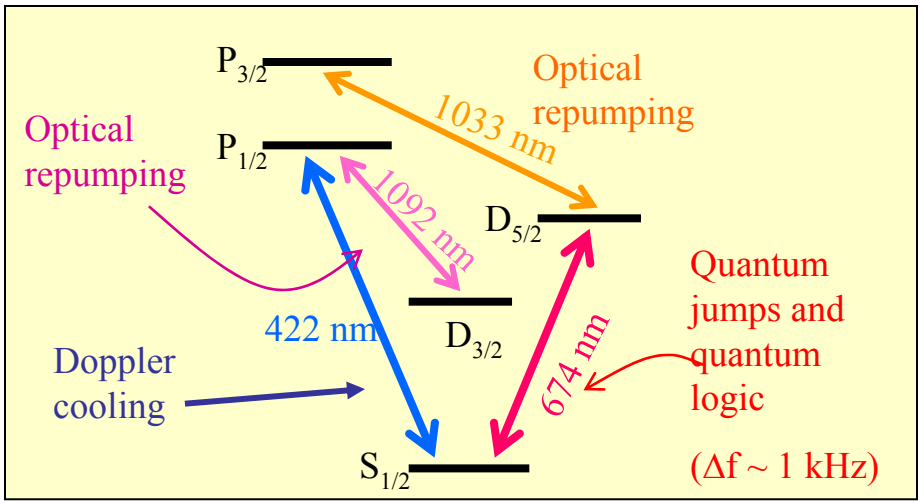
Dave Vieira

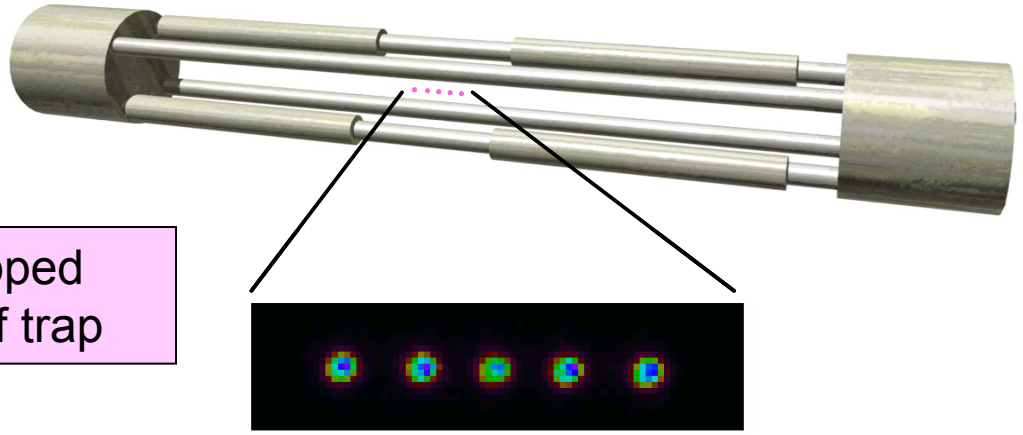
Trapped Strontium Ions



~ 40 ions in our trap







Laser cooled and trapped $^{88}Sr^{+}$ ions in a linear rf trap

Introduction to Quantum Simulations

The Problem (posed by Feynman 1982)

Quantum systems are exponentially complex:

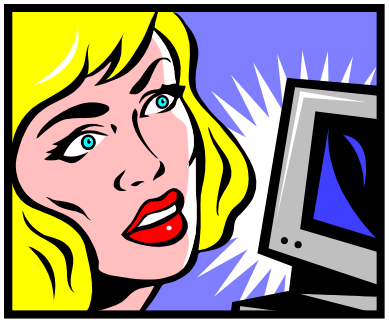
40 spin ½ systems need $2^{40} \times 2^{40} = 10^{24}$ coefficients

Present calculations are limited:

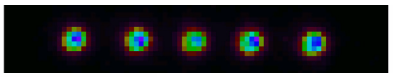
Deterministic algorithms: 32 spins

Non-deterministic algorithms: 100 x 100 spins

Classical computer, distressed physicist



Quantum simulator, happy physicist



The Solution

(proposed by Feynman and revisited by Lloyd 1992)

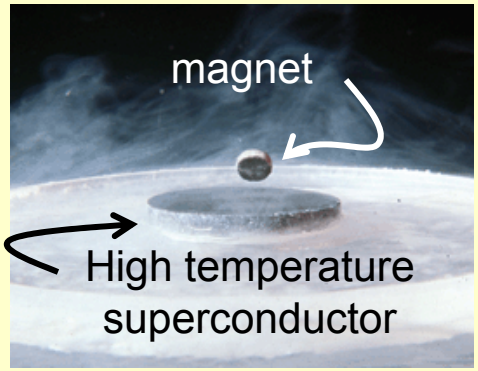
Simulate on another multi-body quantum system

Trapped ions map onto condensed matter paradigms (realized separately by Cirac, Milburn, 2004)

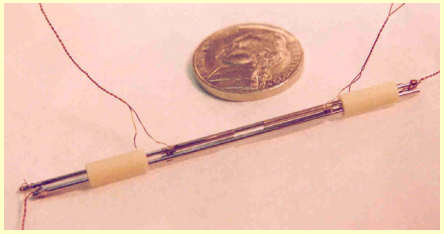
Trapped ions more ideal than real materials

What is a Quantum Simulator?

Real physical system
we don't understand
(e.g. high T_C superconductor)



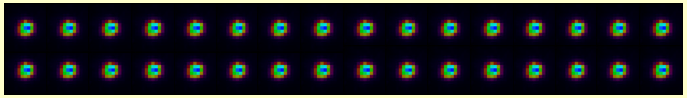
Tightly controlled system



$^{88}Sr^{+}$ ion

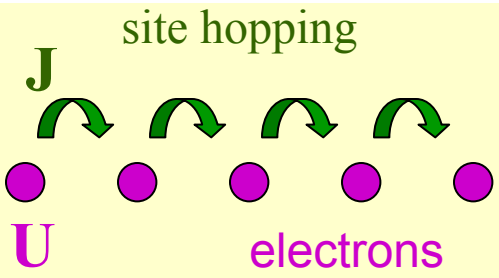
spin-1/2
particle

Proposed
ion array w
laser forces



1 Propose a particle model we can't fully explore

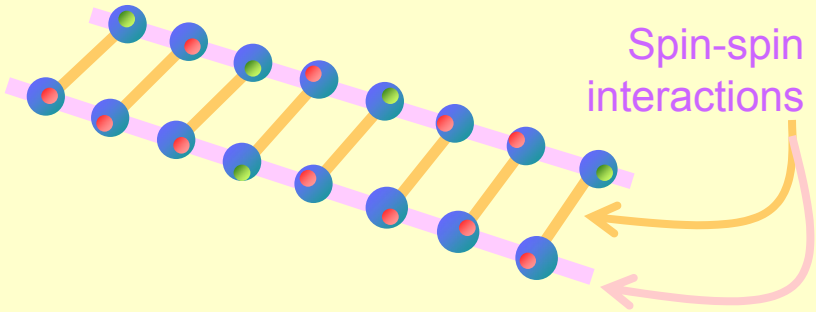
Trapped ions and laser forces simulate a spin model we *can* control 3



Hubbard Model

2

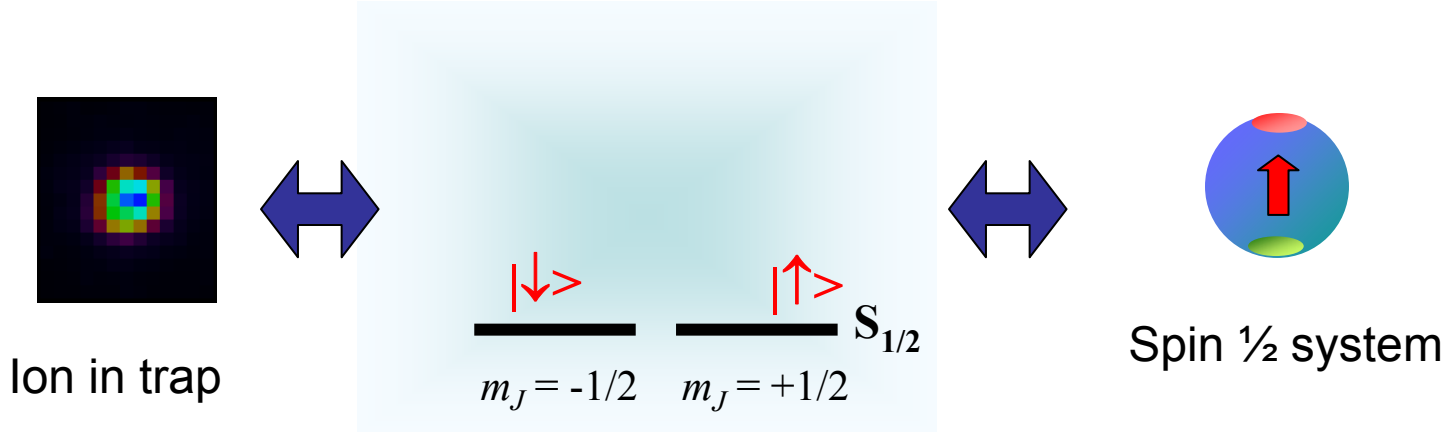
Jordan-Wigner
transformation
to a spin model



Ladder of Interacting Spin ½ Systems
(Ortiz & Batista, 2004)

Physics of Ion Trap Quantum Simulators

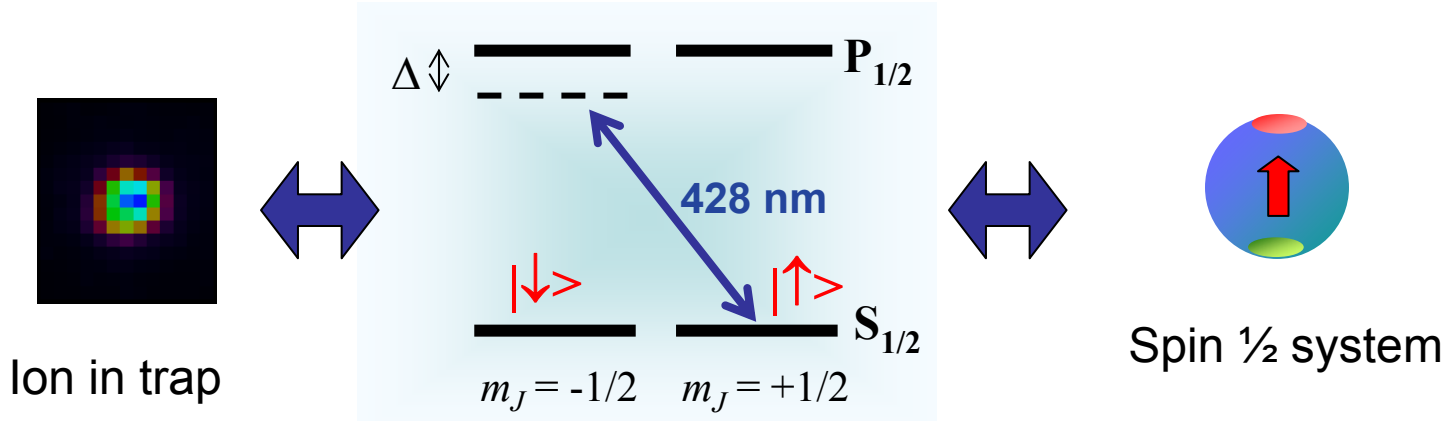
(Porras & Cirac 2004)



Internal states of ion simulate a spin system

Physics of Ion Trap Quantum Simulators

(Porras & Cirac 2004)



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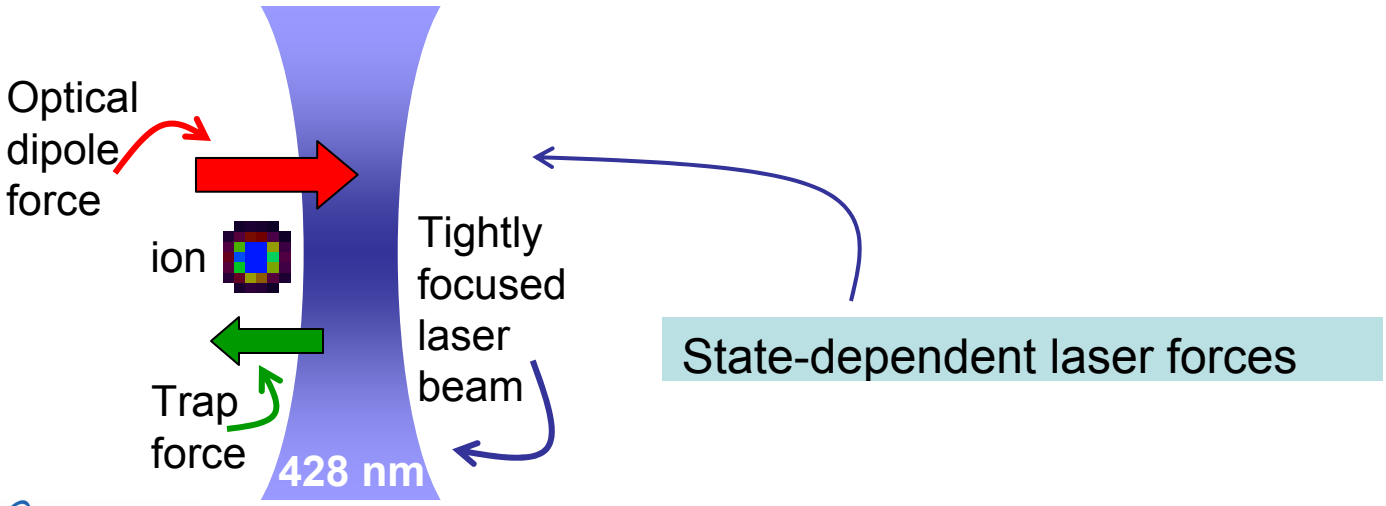

Physics of Ion Trap Quantum Simulators

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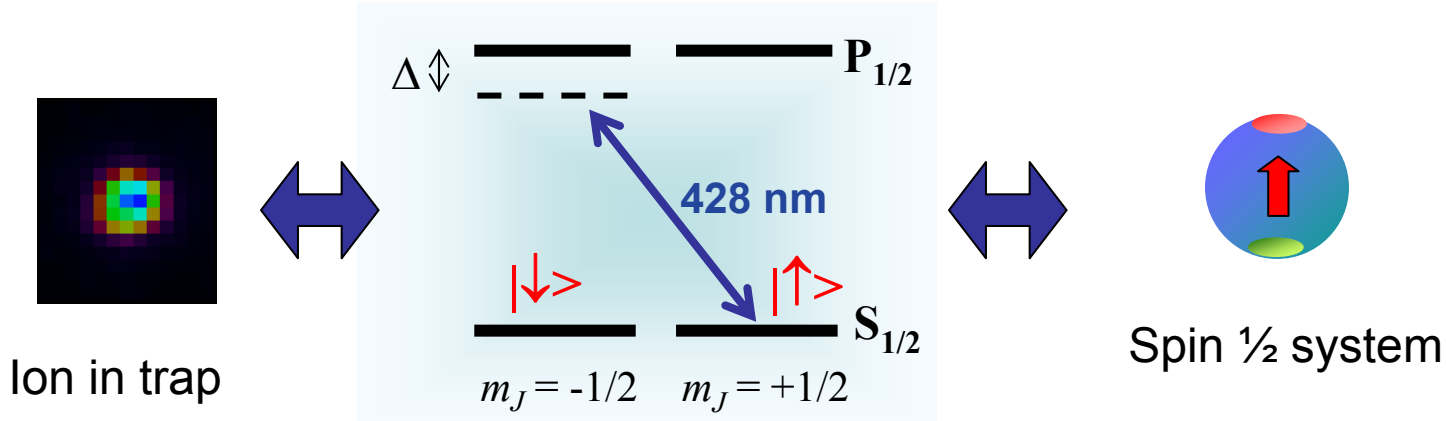
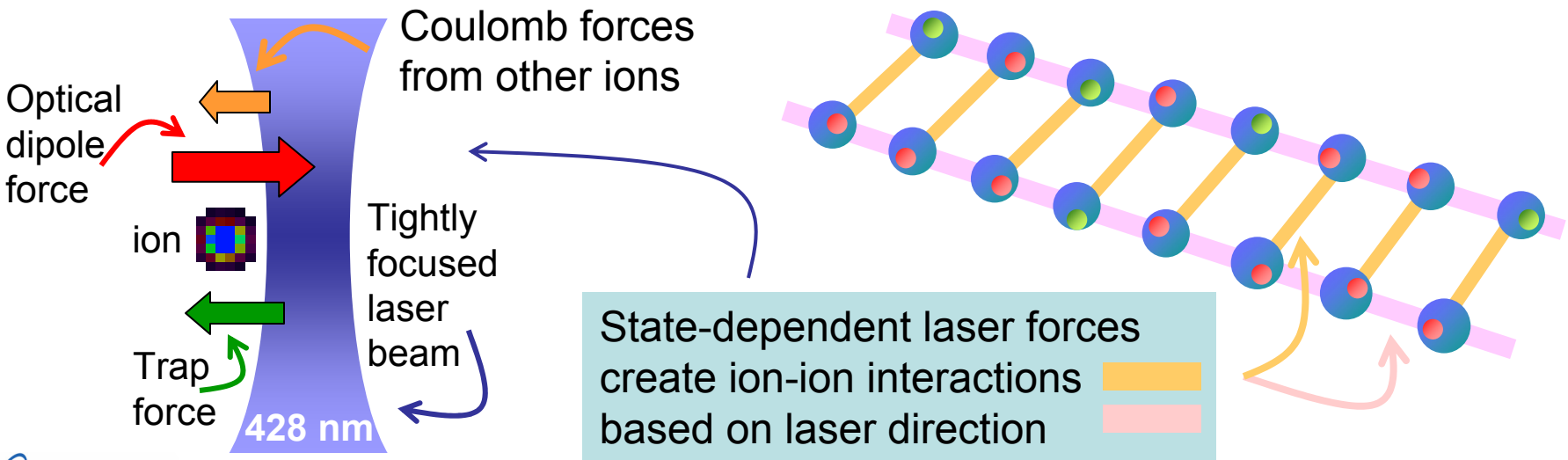
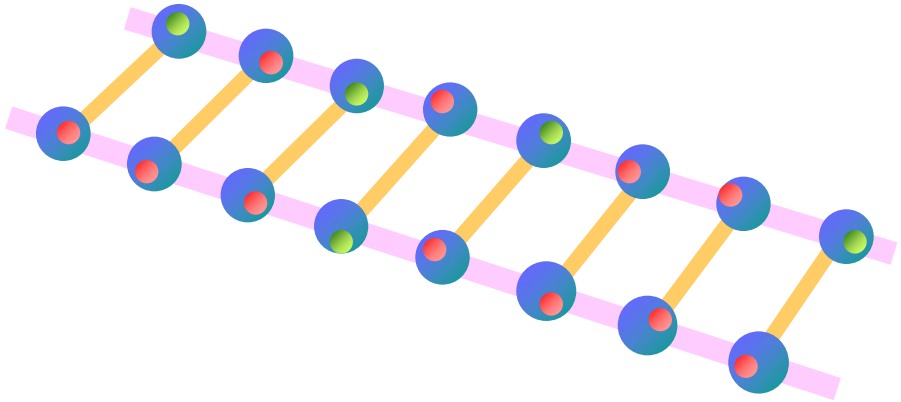


Internal states of ion simulate a spin system



Simulations Microfab Needs

To make and control large arrays of ions like this:



We need traps that:

Have 10s of separate potentials for each ion

Assemble precisely

Are compatible with dense electrical and optical I/O

UHV (10^{-11} Torr) compatible

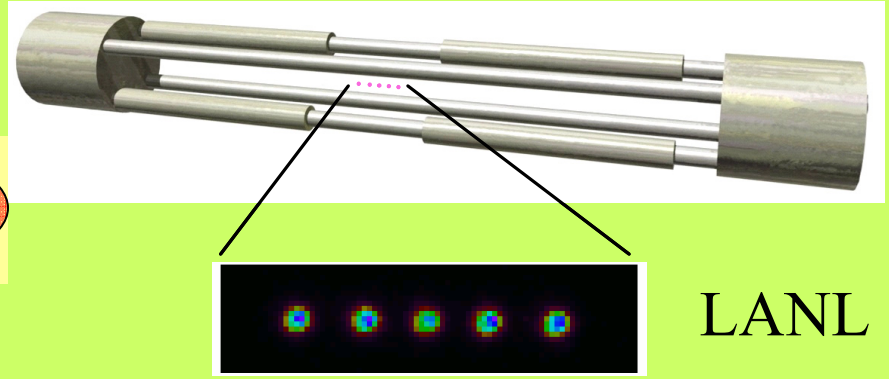
Relation to Quantum Computing

Quantum Computer	**Quantum Simulator**
Universal	Configured for one particular problem (use Ising and Heisenberg XYZ models for material science problems)
Must solve all DiVincenzo commandments *I. Scalable set of qubits* *II. Easy initialization* *III. Universal operations* *IV. Long decoherence time* *V. Easy final readout*	Meets only some DiVincenzo commandments *I. Scalable set of qubits* *II. Easy initialization* *III. Universal operations* *IV. Long decoherence time* *V. Easy final readout*
Need error correction	No error correction for 30-50 spins
State of the art is 4 ions	Work with 30-50 ions
Heavy engineering requirements eventually	Forced to solve engineering requirements - trap fabrication - electrical and optical I/O - micro-optics

Mechanical traps

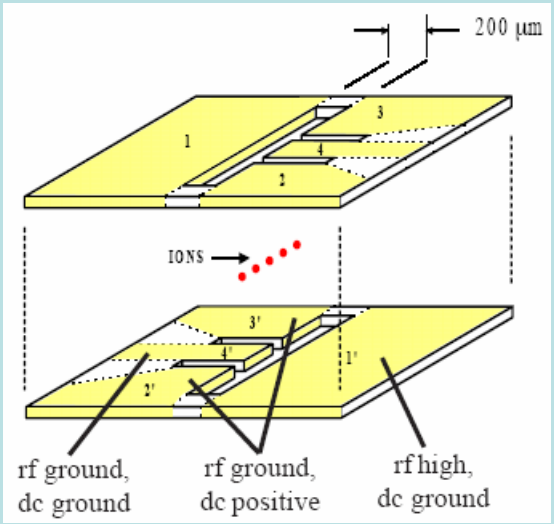
Hard to align electrodes
Rough surfaces
High heating rates

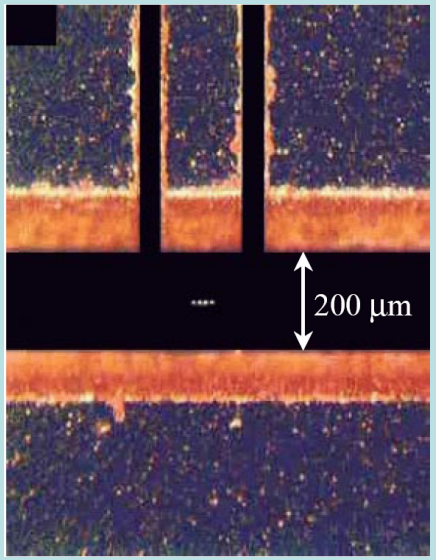
So: Practical quantum computation
Large quantum simulations

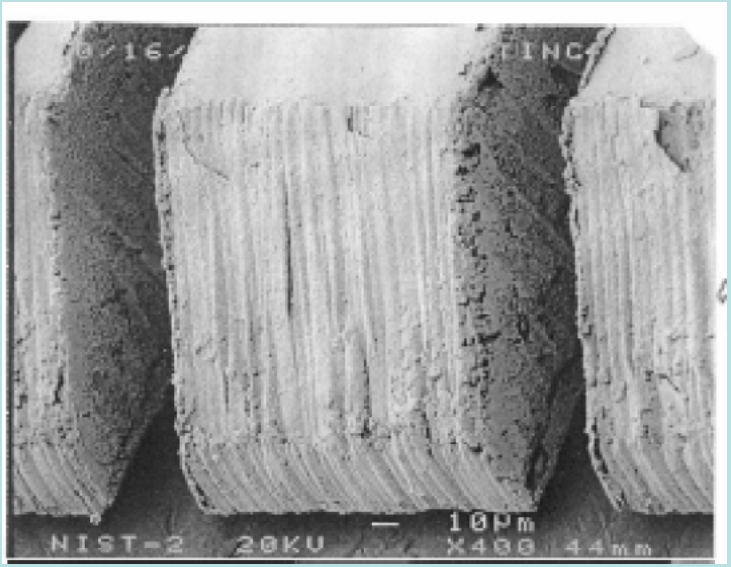


LANL

NIST

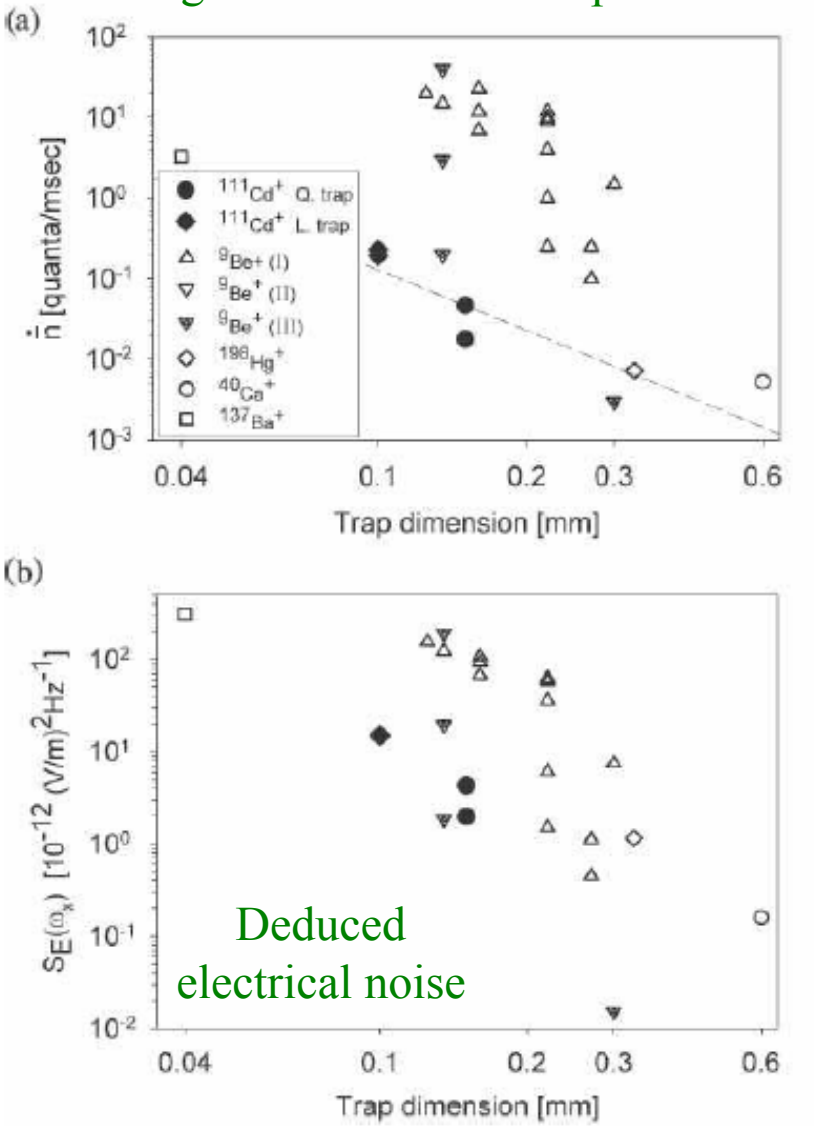




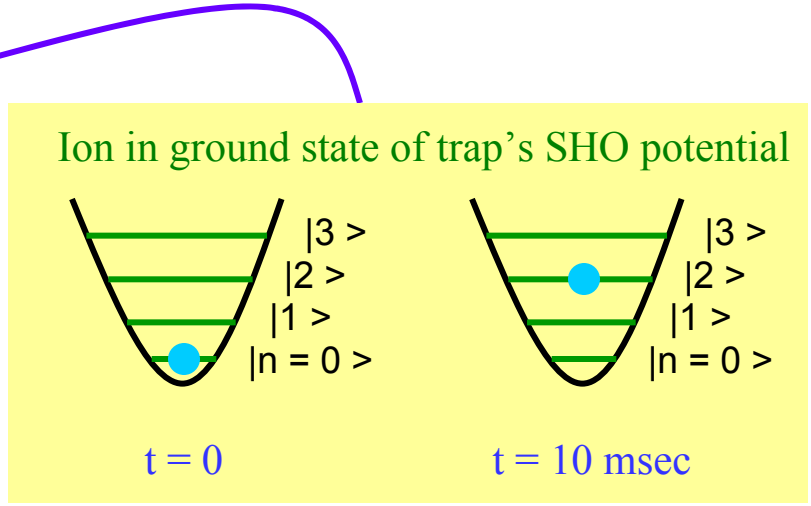


Decoherence: NOT understood or controlled

Heating rate for different experiments



From Deslauriers quant-ph/0404142



Need more data points, with different traps and different ions.

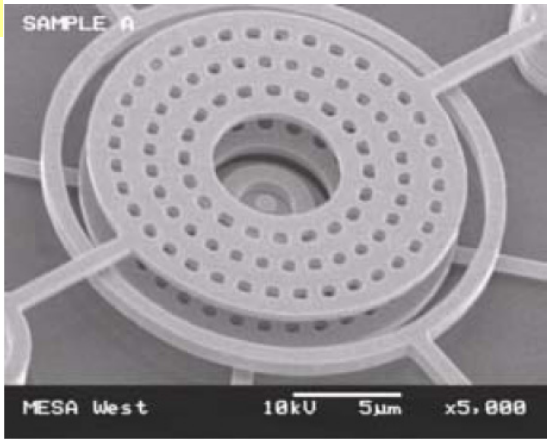
Would help to have a device to measure electric field noise without trapping ions.

Microfabricated ion traps

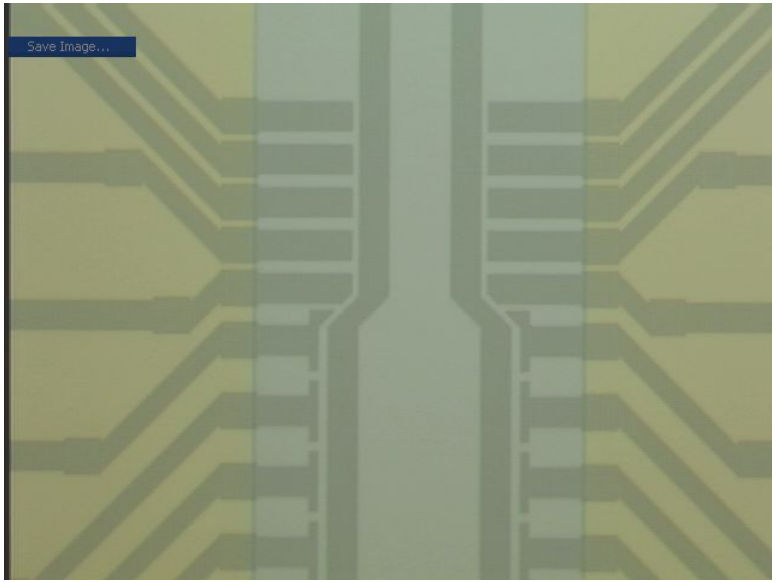
Sandia National Laboratories

Ion trapping (LANL) + microfabrication (SNL) = effective collaboration

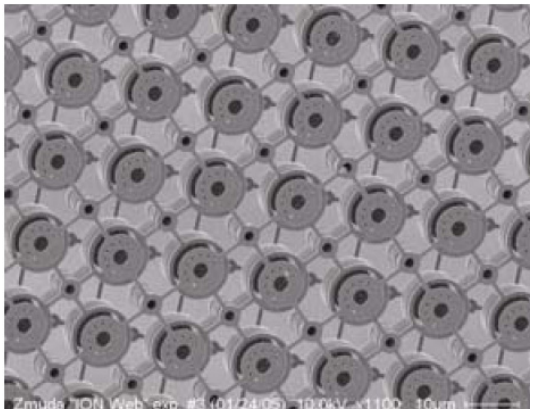
- SNL tungsten deposition process
- Creates large, monolithic arrays of small ion traps
- Extremely clean and smooth electrode surfaces
- Larger, more complex quasi-3-D traps for simulations



Single cylindrical rf ion trap



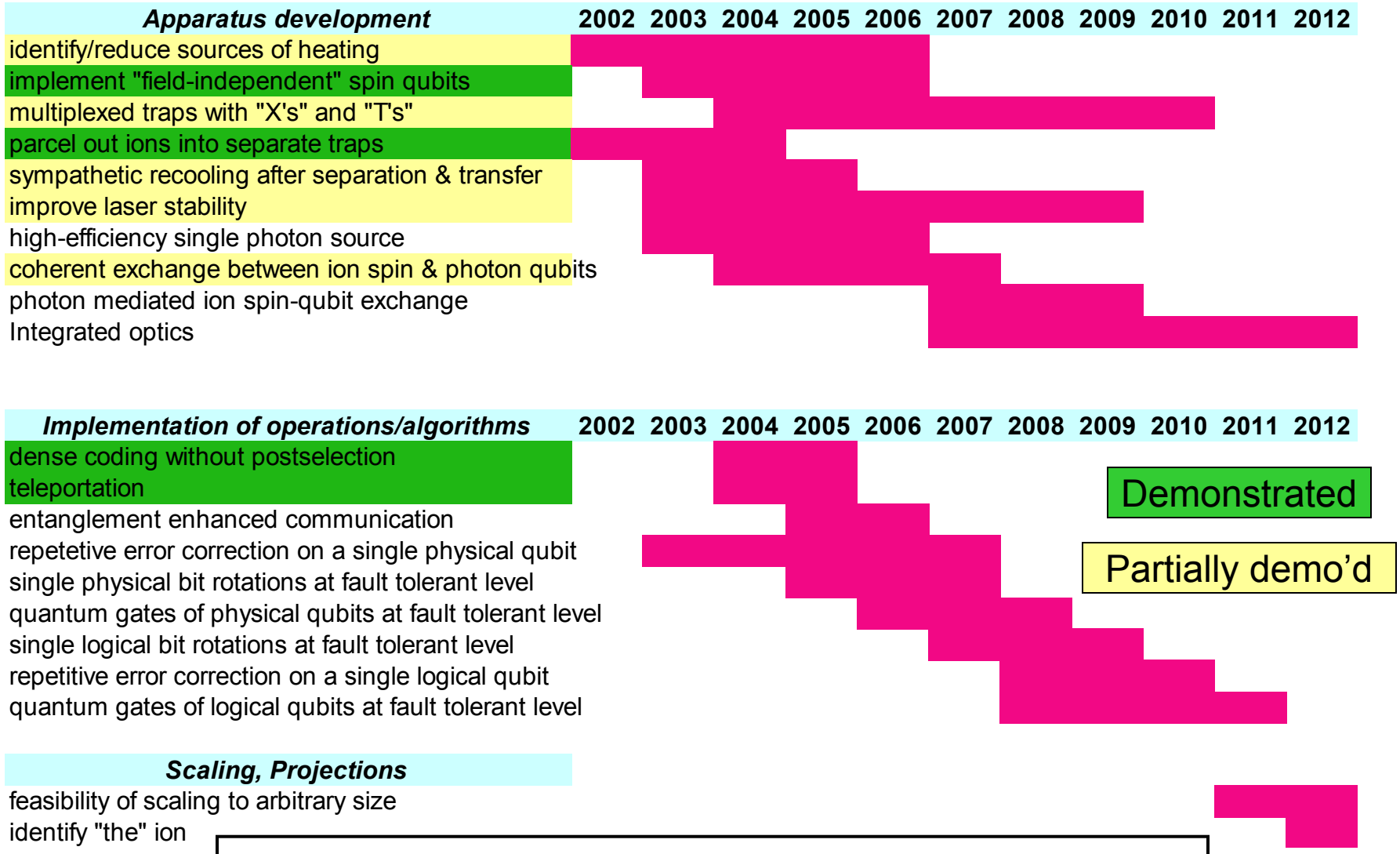
New LANL/SNL segmented linear rf trap



Section of ion trap array

World-wide progress on Ion Trap QC

Time-line from ARDA Roadmap



2007 goals ~met
2012 goals looking feasible

QC *will* happen, microfab can help

Some Microfabrication Wishes

Pristine electrodes that are precisely aligned

Complex traps

(many separately controlled potentials and junctions)

Micro-sensor to monitor electric field noise

Micro-optics for individual ion readout

more more more….