Quantum Simulations with Ion Traps

Dana Berkeland, Malcolm Boshier, John Chiaverini,
David Lizon, Warren Lybarger, Bob Scarlett,
Rolando Somma and Kendra Vant

Los Alamos National Laboratory

Matt Blain, Bernie Jokiel, and Chris Tigges

Sandia National Laboratories

Introduction to Quantum Simulations

<u>**The Problem (posed by Feynman 1982)**</u>

Quantum systems are exponentially complex:

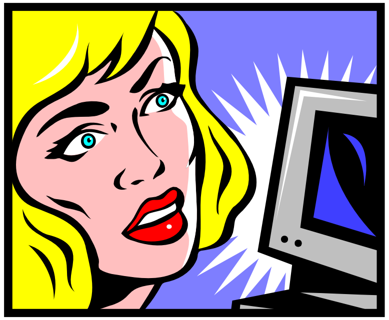
40 spin ½ systems need $2^{40} \times 2^{40} = 10^{24}$ coefficients

Present calculations are limited:

Deterministic algorithms: 32 spins

Non-deterministic algorithms: 100 x 100 spins

Classical computer, distressed physicist



Quantum simulator, happy physicist

<u>**The Solution**</u>

(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)

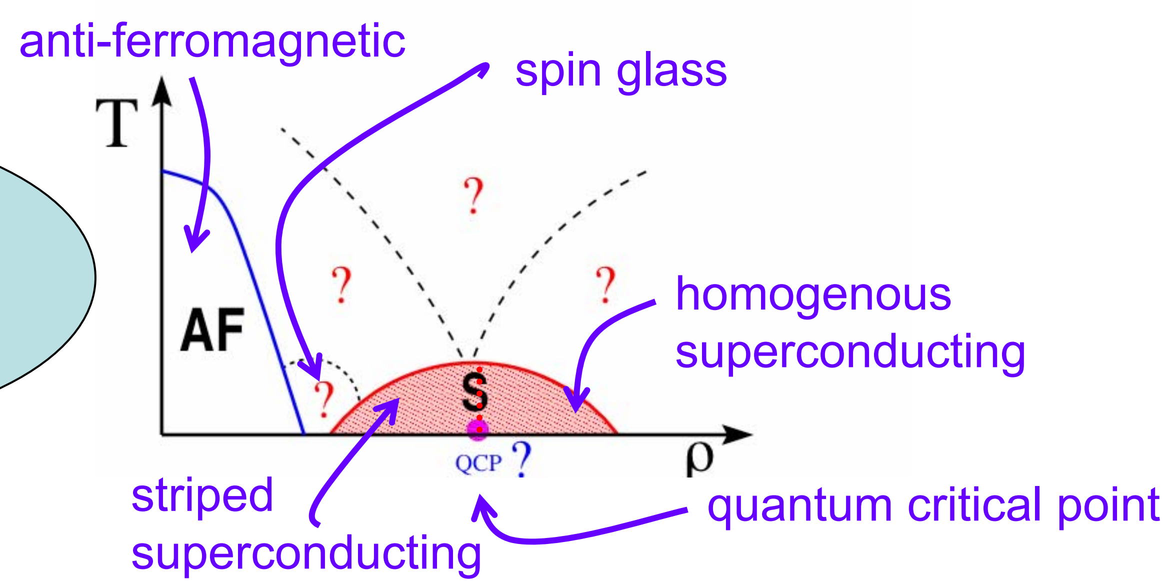
Trapped ions more ideal than real materials

No, really, it's a problem

Current computational capabilities limit understanding of many systems

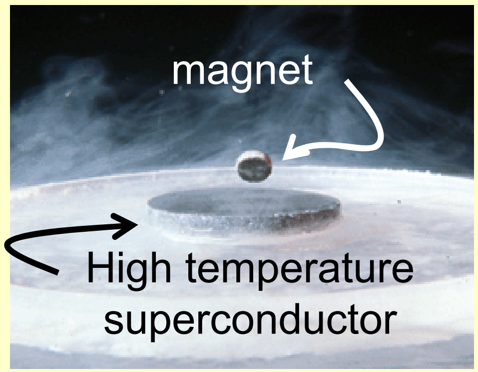
- Understanding and designing new materials with unprecedented properties
  - High T_c superconductivity, cuprates
  - Superconducting Pu compounds, heavy fermions
  - …
- Finite Density QCD: what is the proton size, etc.?
- Large-N nuclei: for N > 12 approximations become unreliable
- Large molecules

Complex, uncertain phase diagram of a new material

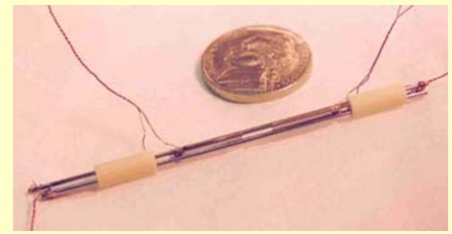


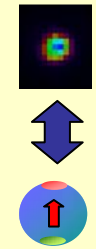
What is a Quantum Simulator?

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



Tightly controlled system

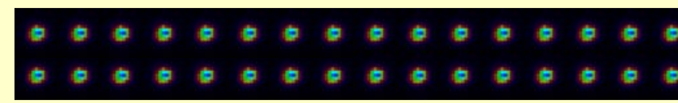




$^{88}Sr^{+}$ ion

spin-1/2
particle

Proposed
ion array w
laser forces

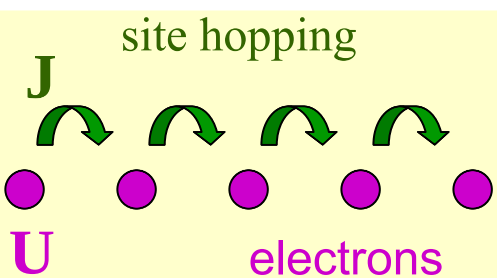


1

Propose a particle model
we can't fully explore

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

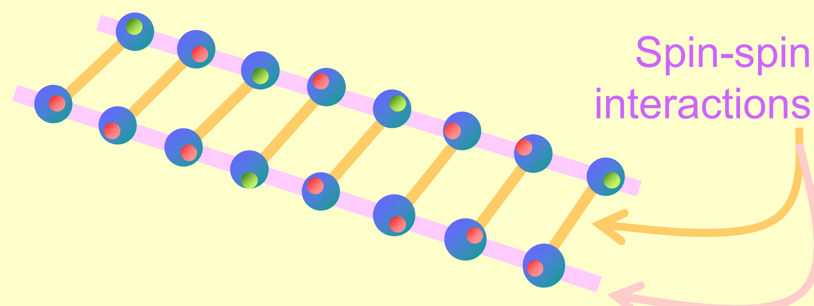
3



Hubbard Model

2

Jordan-Wigner
transformation
to a spin model



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

Relation to Quantum Computing

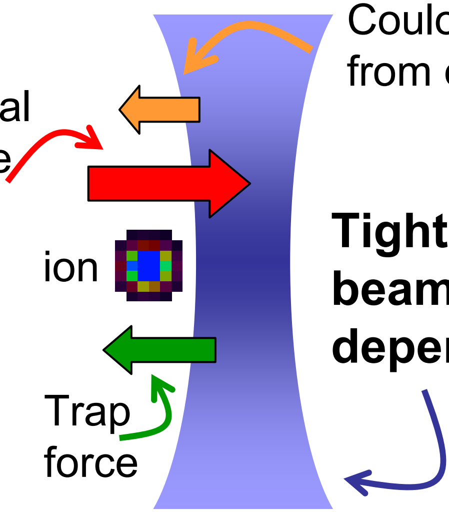
Both need:

Good state initialization
Long decoherence times
Good final state readout
Serious engineering capabilities

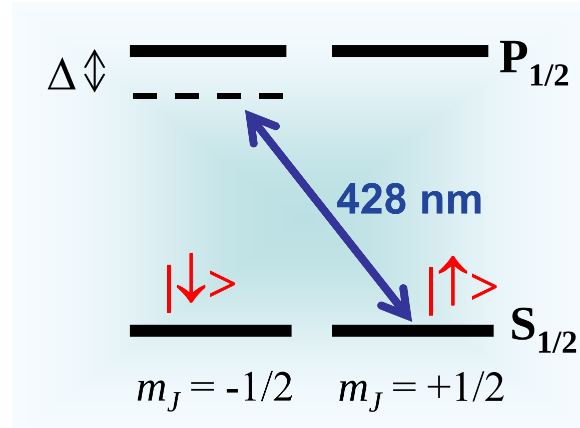
BUT they are different:

Quantum Computer	**Quantum Simulator**
Universal	Configured for one particular problem (we will do materials science problems)
Need universal gates	Don’t need universal gates
Scaleable set of individually addressed qubits	Don’t need individual addressing
Stringent timing requirements	Continuous interactions

Physics of Ion Trap Quantum Simulators

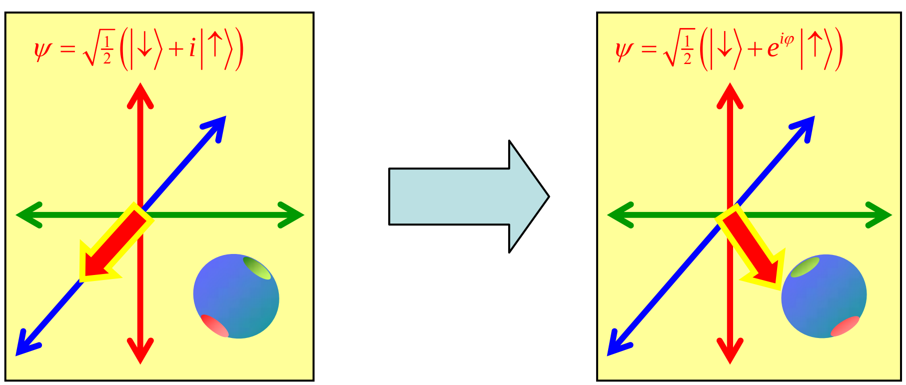


Tightly focused laser beam makes state-dependent laser force



Ion moves through potential due to trap fields and *other moving ions*

$|\uparrow>$ state accumulates phase



Bloch vector

State-dependent,
neighbor-dependent
rotation of Bloch vector

Expect spin-spin interactions

Transformation to Heisenberg Model

Porras & Cirac, PRL 2004

Lab Hamiltonian

State-selective optical dipole force along α

Real or simulated magnetic field

$$H = \sum \hbar\omega_n a^\dagger_{n,\alpha} a_{n,\alpha} + F^\alpha q_\alpha \left|\uparrow\right\rangle\left\langle\uparrow\right|^\alpha_i + B^\alpha \sigma^\alpha_i$$

Trap and ion potential

$q_\alpha \propto (a^\dagger_{n,\alpha} + a_{n,\alpha})$

Transform Lab Hamiltonian into Simulated Hamiltonian

$H' = e^{-S} H\, e^{S}$ *where* $S = \sum \eta^\alpha_{n,i} (1+\sigma^\alpha_i)(a^\dagger_{n,\alpha} - a_{n,\alpha})$

Simulated Hamiltonian (terms up to η²)

Small if $\eta \sim F\sqrt{1/\hbar m\omega^3} \ll 1$

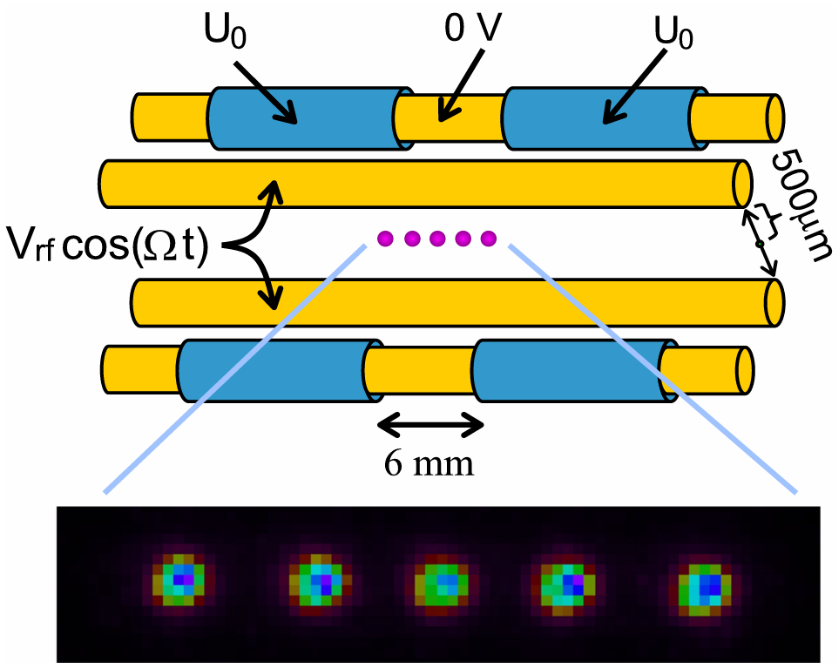
$$H' = \sum \hbar\omega_n a^\dagger_{n,\alpha} a_{n,\alpha} - J^\alpha_{i,j}\, \sigma^\alpha_i \sigma^\alpha_j + B'^\alpha\, \sigma^\alpha_i + \varepsilon$$

Exchange interaction $J_{i,i+1} \propto F^2$

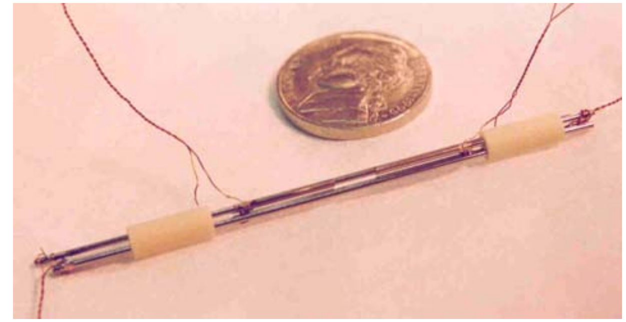
Old B plus *effective* field

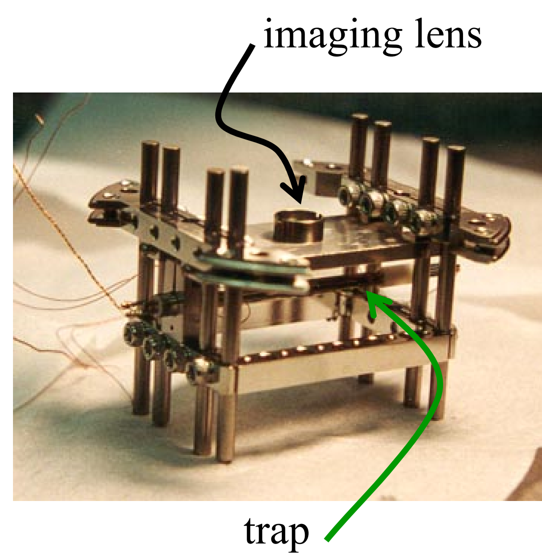
Macroscopic Linear rf Trap

Confine ions radially in a time-averaged potential and axially with a static potential:



(resonant 422-nm light scattered from 5 ions)



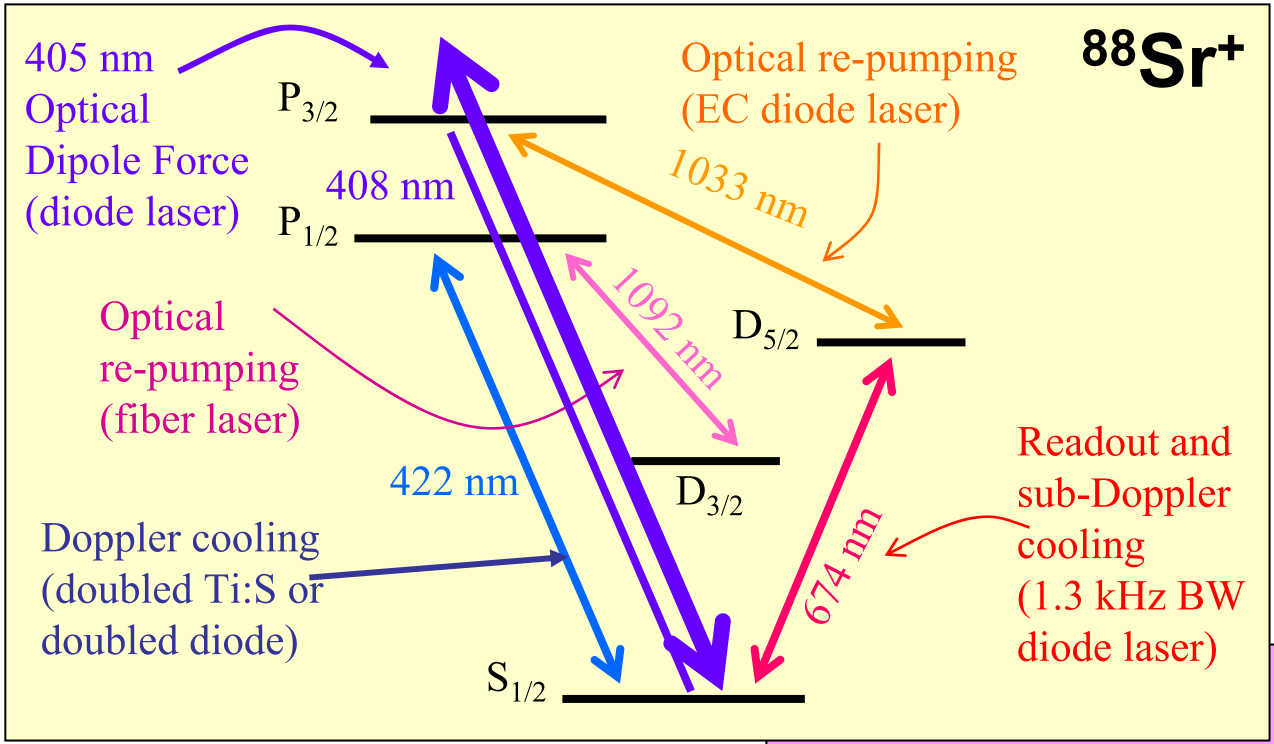


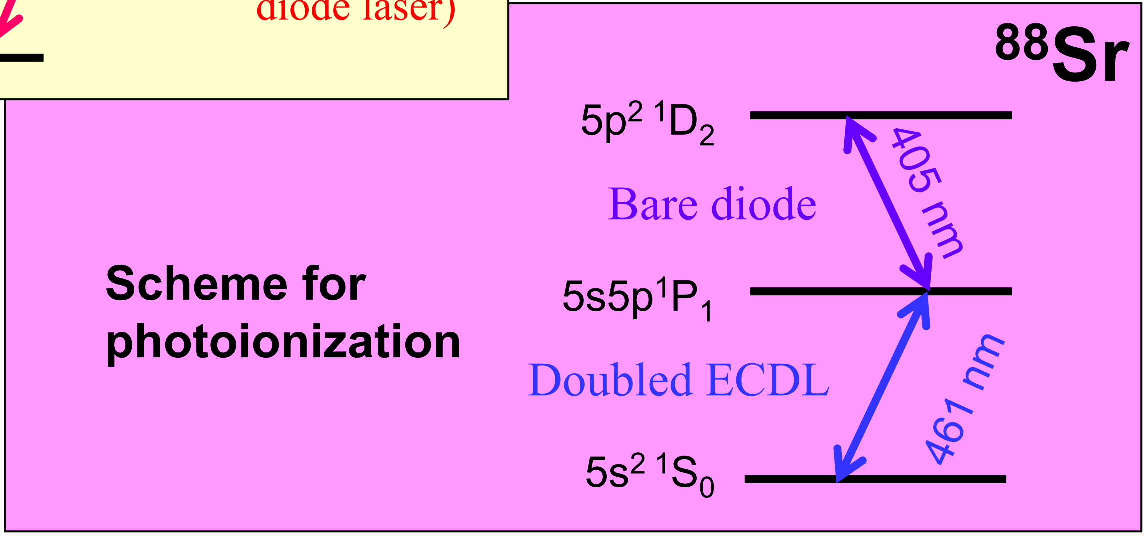
Trap depth ~ 25 eV

(ω_{radial} ~ 2 π 2 MHz, ω_{axial} ~ 2 π 400 kHz)

Ion lifetime > 1 day

Strontium 88

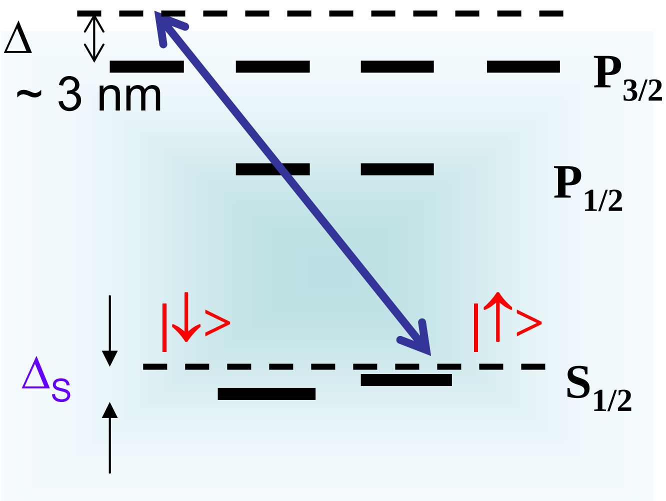


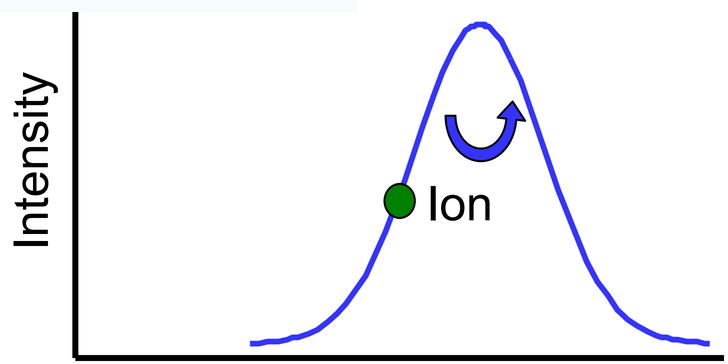


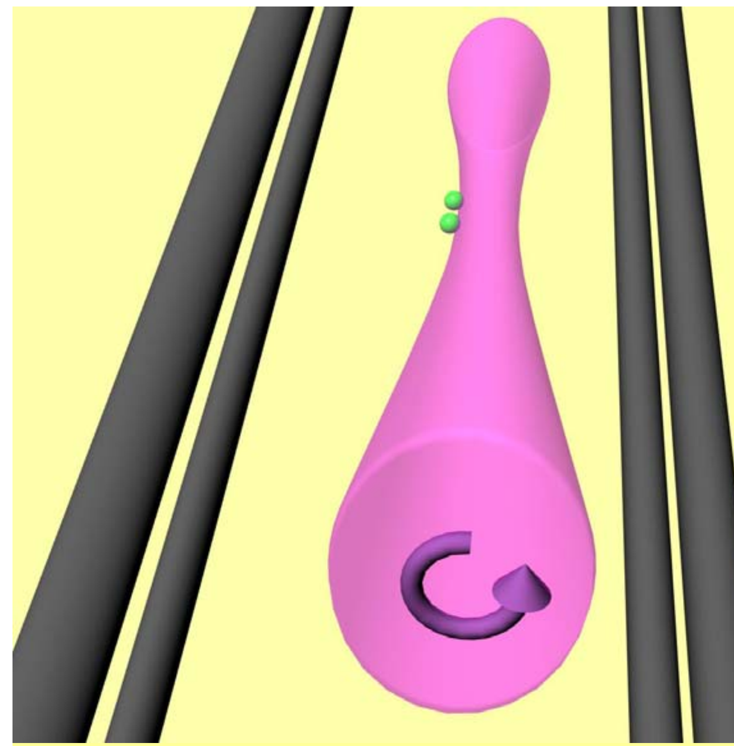
Balancing AC Stark Shifts

AC Stark shifts Δ_S are HUGE (~MHz)!

Acts like a giant B-field







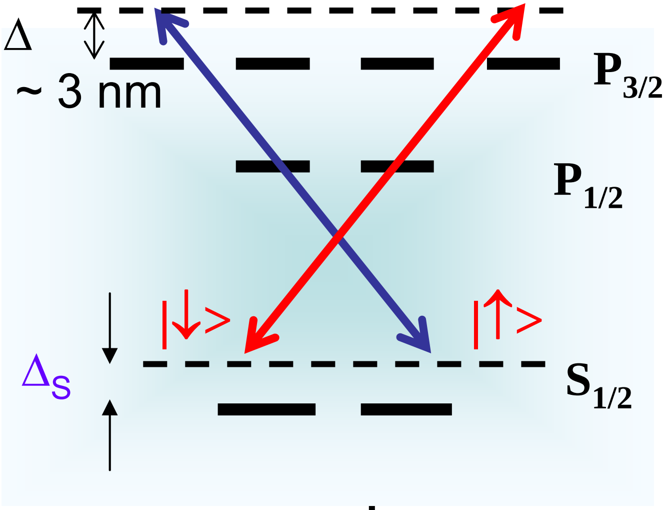
405nm, 10 mW, w ~ 5 um

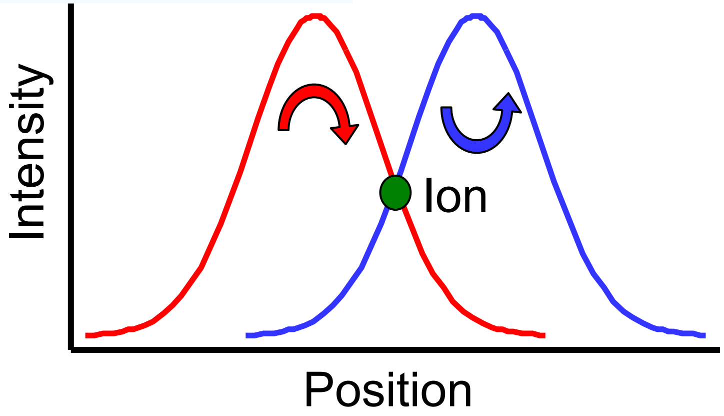
Balancing AC Stark Shifts

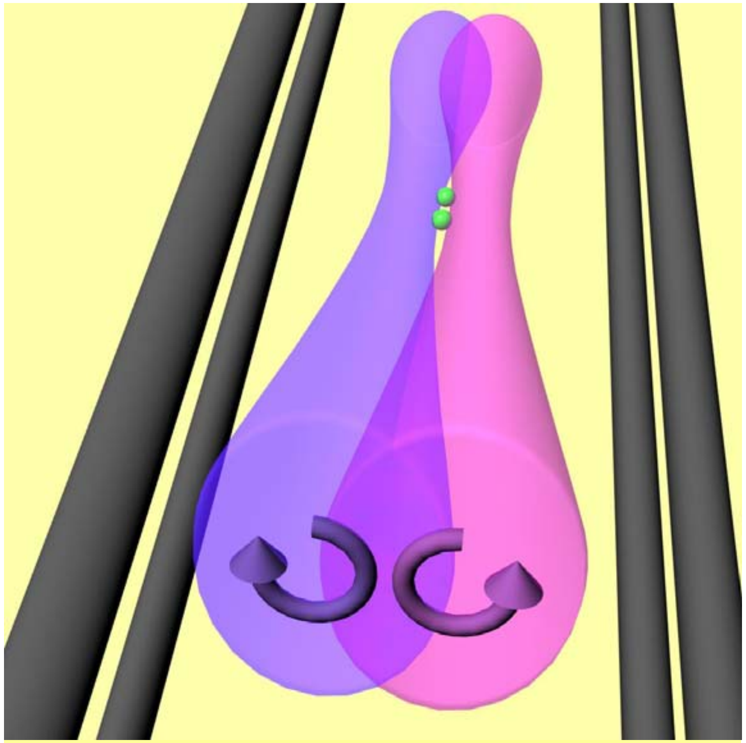
AC Stark shifts Δ_S are HUGE (~MHz)!

Acts like a giant B-field

Solution: equal (but large) shifts for ↑ and ↓







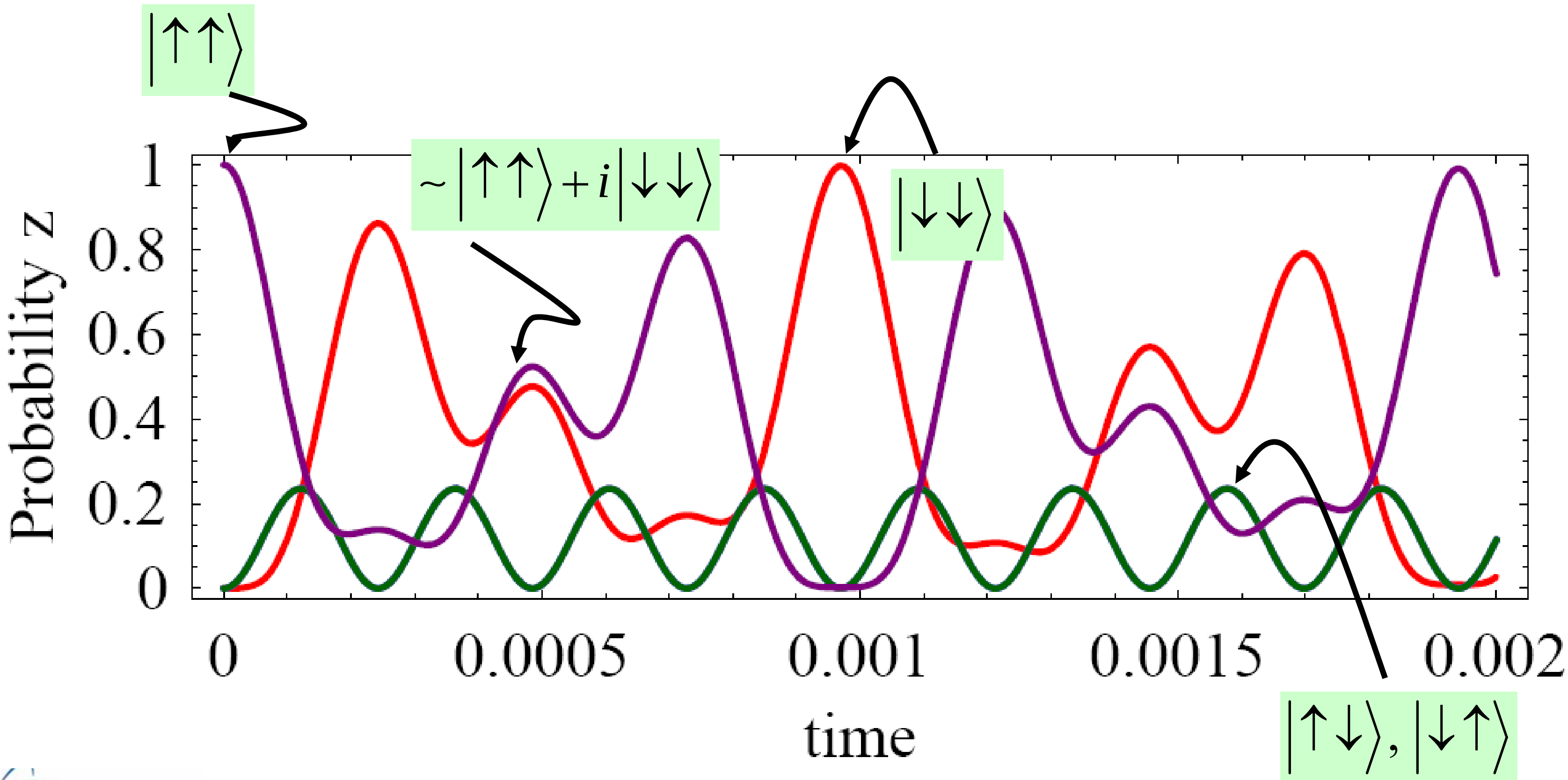
405nm, 10 mW, w ~ 5 um

Expected Behavior

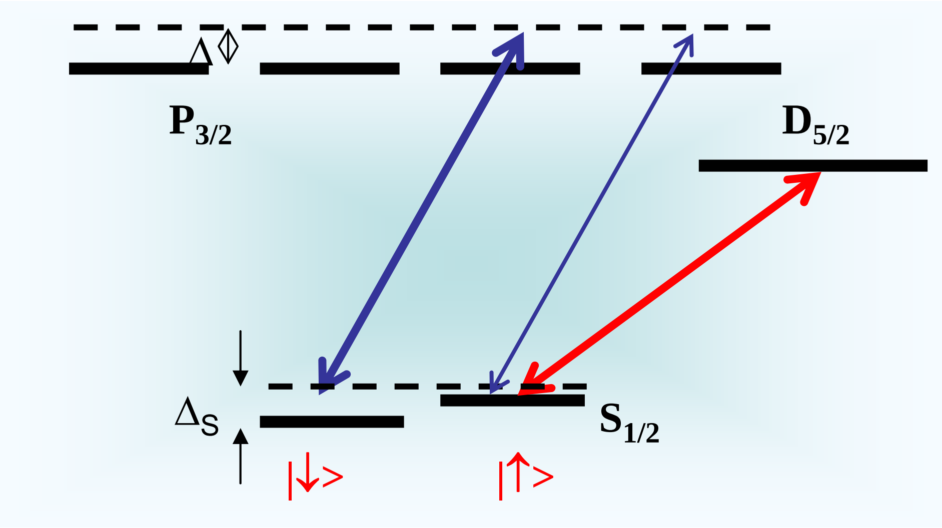
Expected results for 2-spin Ising model

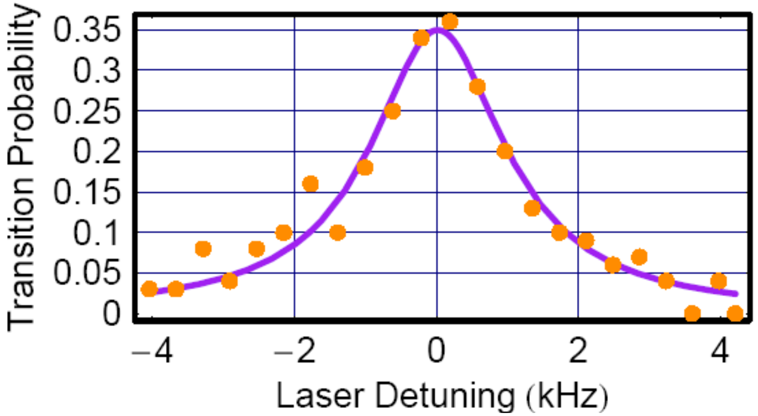
Optical dipole force along one direction and equal for both ions

$J_z/2\pi$ = 1000 Hz; $B_x/2\pi$ = 1 kHz



State Measurement

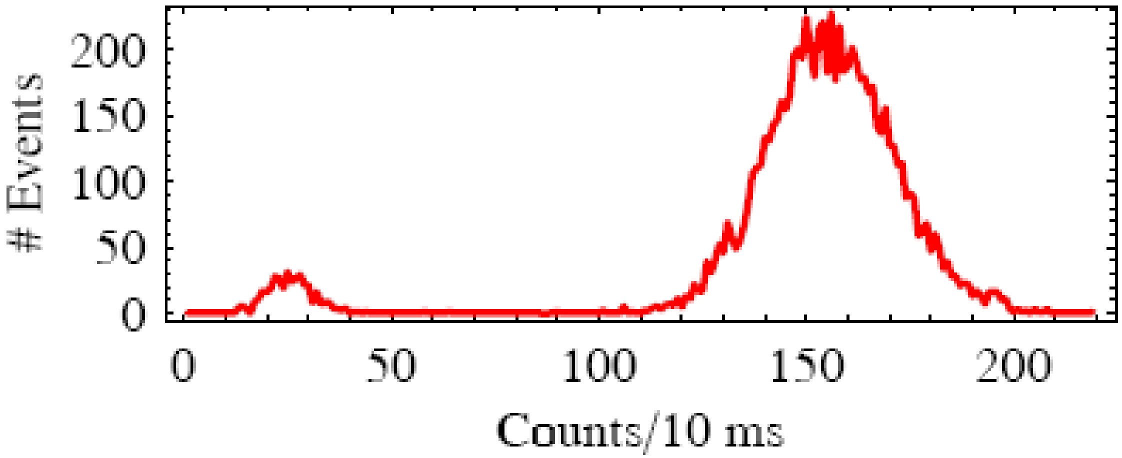




Leave on only one dipole force beam to break ↓ ↑ degeneracy

Shelve ↑ state into "dark" state with precisely tuned red laser

No scattered blue light if ion is in D state



Ions v Ising model (single well)

Calculate 2-ion state for

- Laser forces along axial direction
- Total of 7 phonon states in each mode

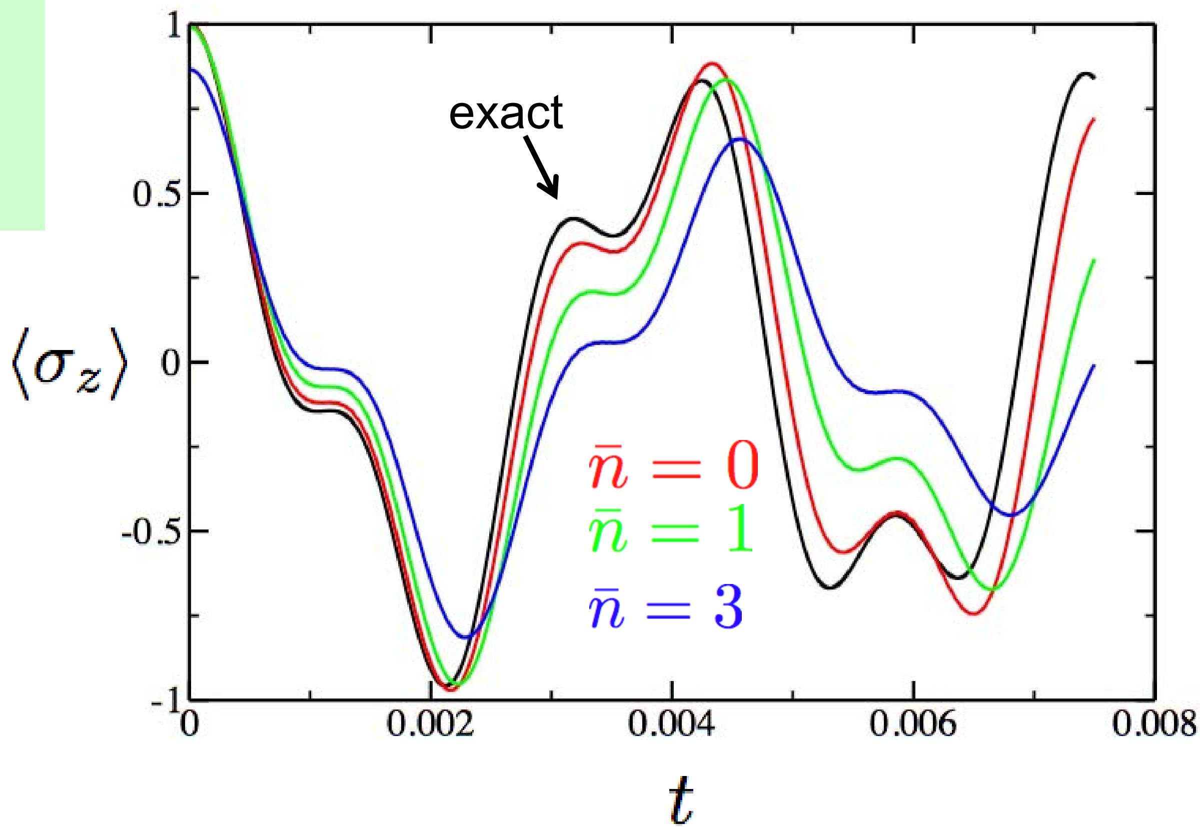
Plot P↑↑ - P↓↓ v time

η~ displacement / |n = 0> width

η = 0.06

$$\omega_{cm} = 100KHz$$
$$F = 25 \times 10^{-24} N$$

$$B \approx -J \approx 1.3KHz$$



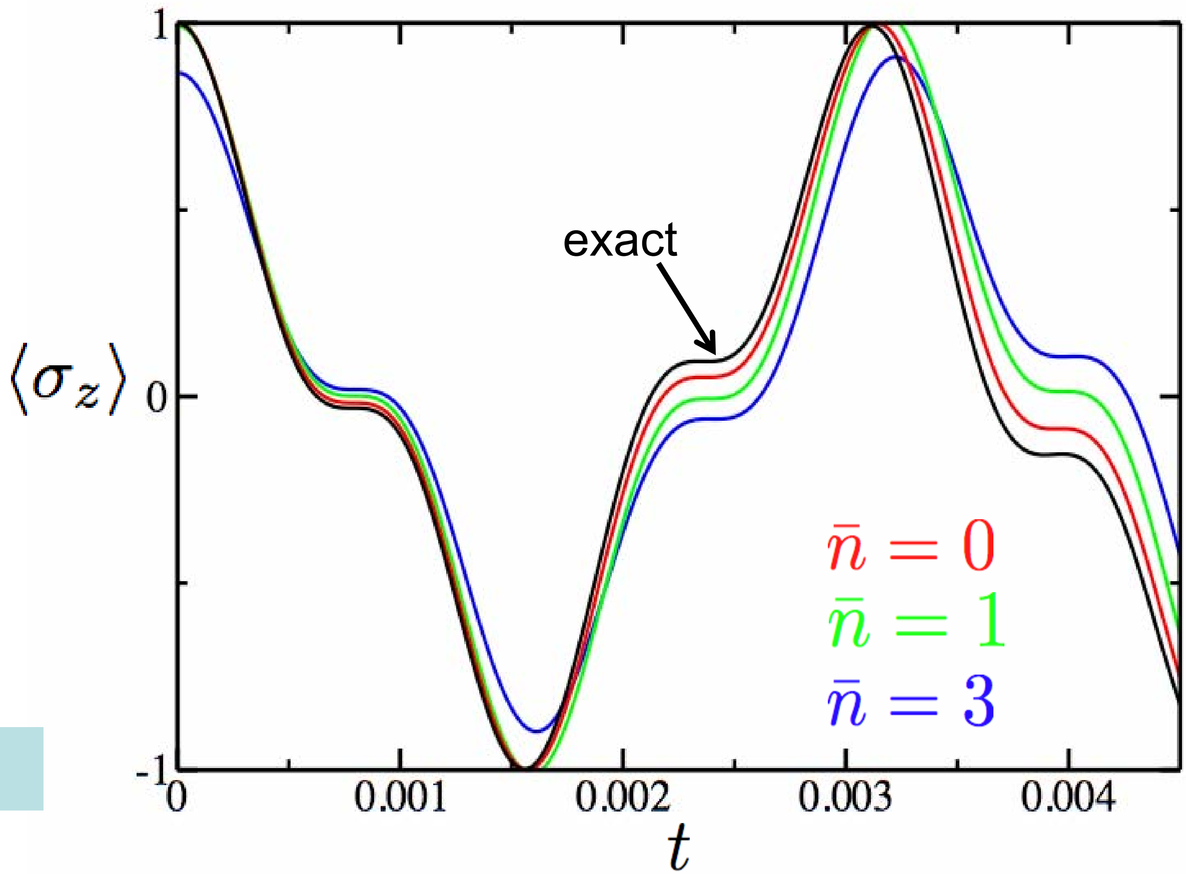
Need to cool ions to near ground state of motion

Ions v Ising model (double well)

$$\omega_{cm} = 100KHz \qquad F = 25 \times 10^{-23} N$$

$$\omega_{br} = 128KHz \qquad B \approx -J \approx 1.8KHz$$

$$d \approx 20\mu m$$

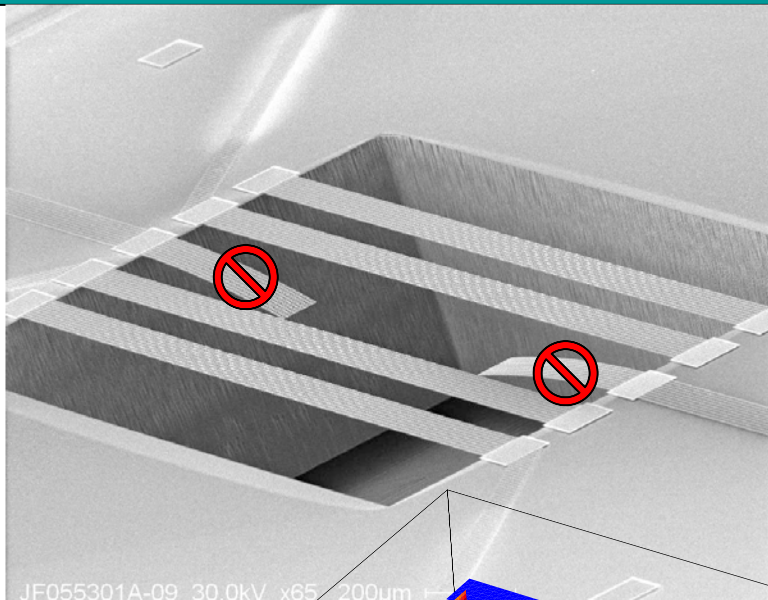


η = 0.06

Reduced error for double well with closely-spaced ions

First microfabricated trap

Sandia National Laboratories

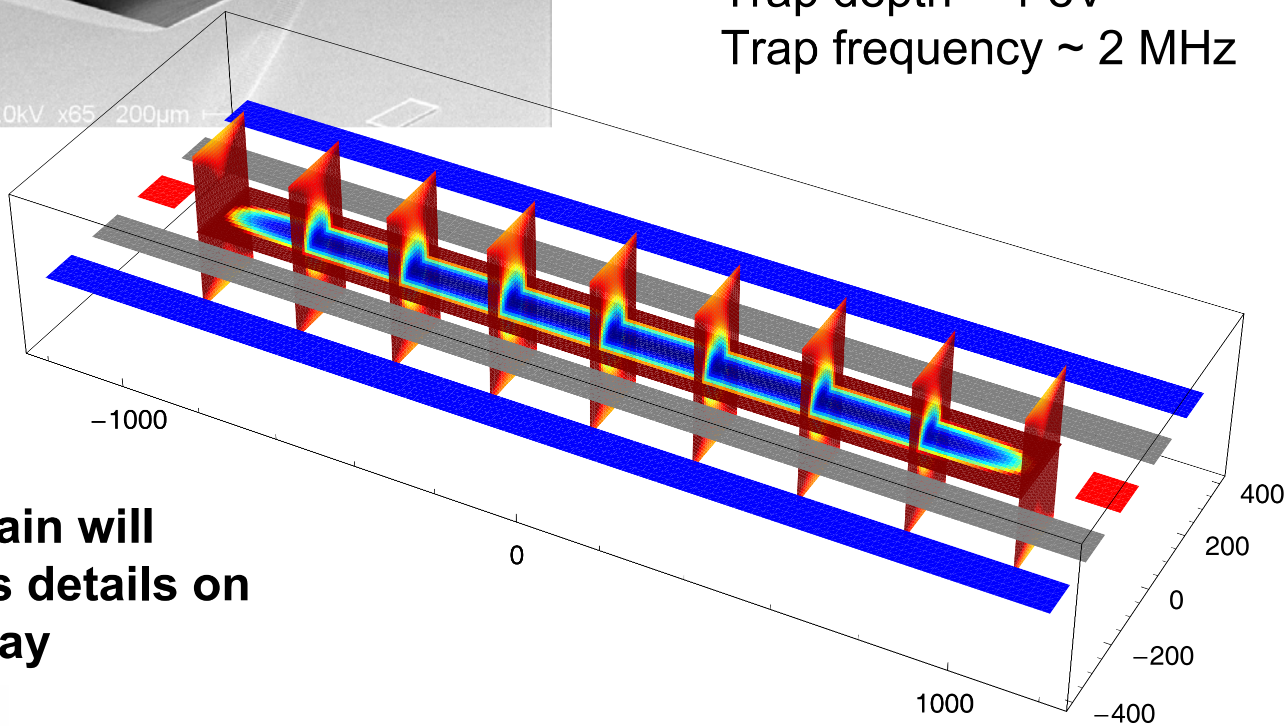


Electrode thickness ~ 3 microns
width ~ 80 microns
length ~ 2 mm

Au-coated on top and bottom

For 200V, 20 MHz drive, 1V on endcaps:

Trap depth ~ 1 eV
Trap frequency ~ 2 MHz



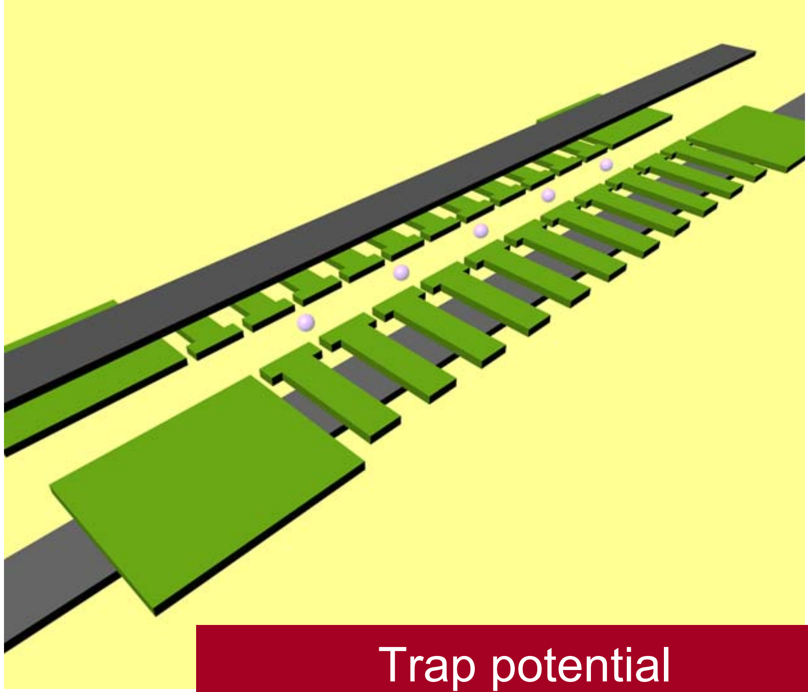
Matt Blain will discuss details on Thursday

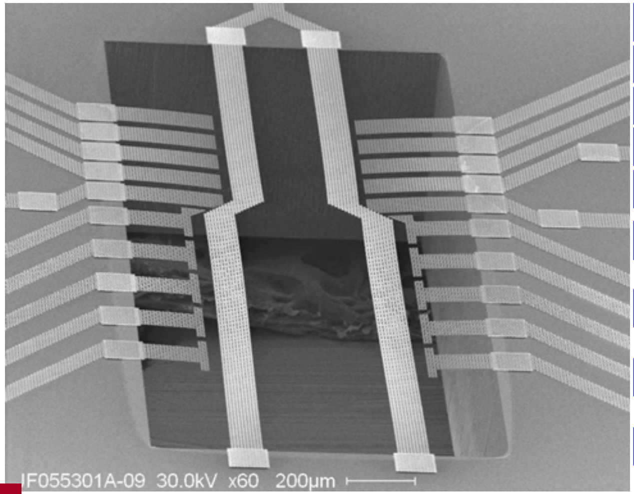
Next traps

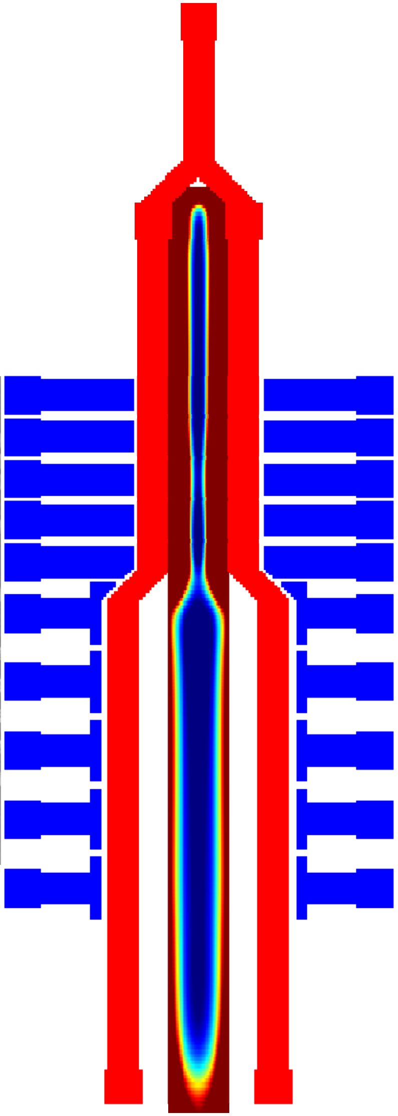
Need segmented traps with 10um DC electrode spacing

Correspondingly small rf electrode spacing

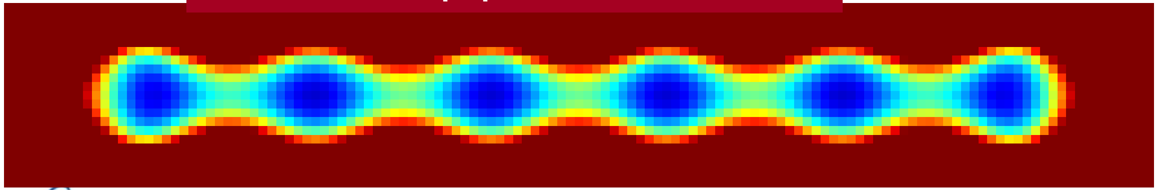
First test with dual zone trap (larger loading zone)







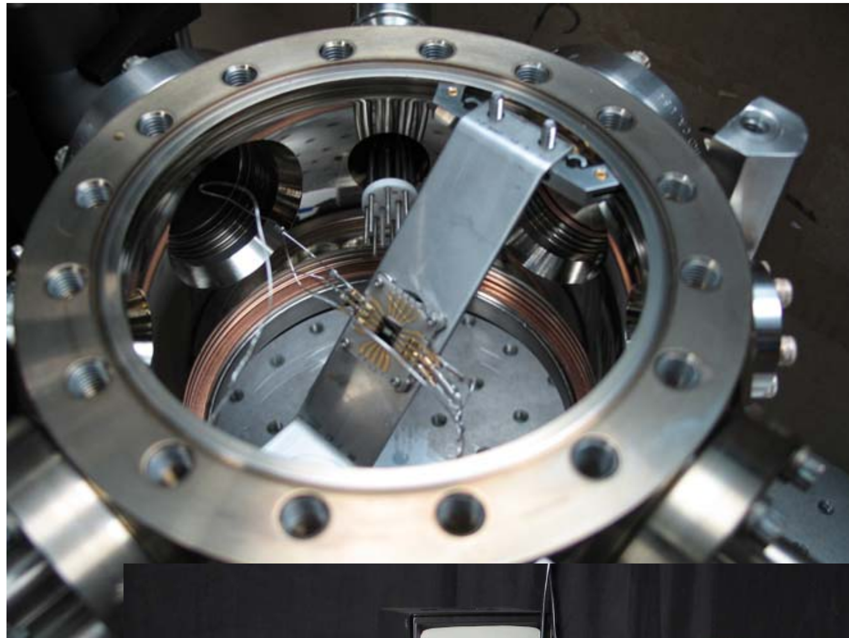
Trap potential

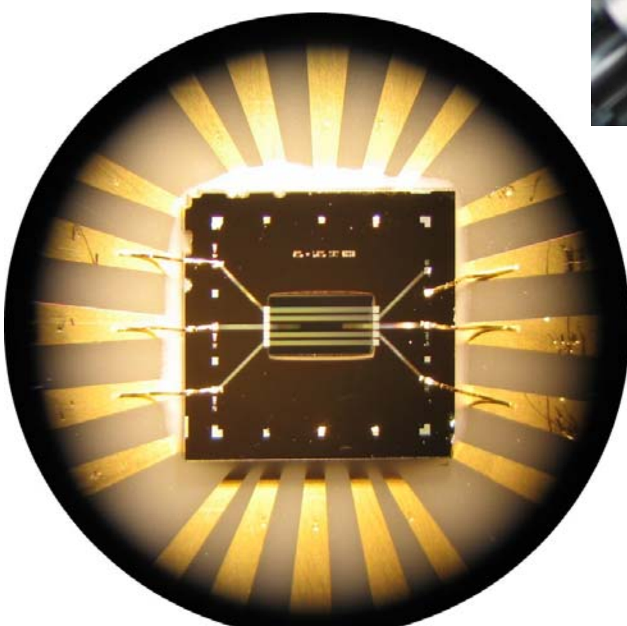


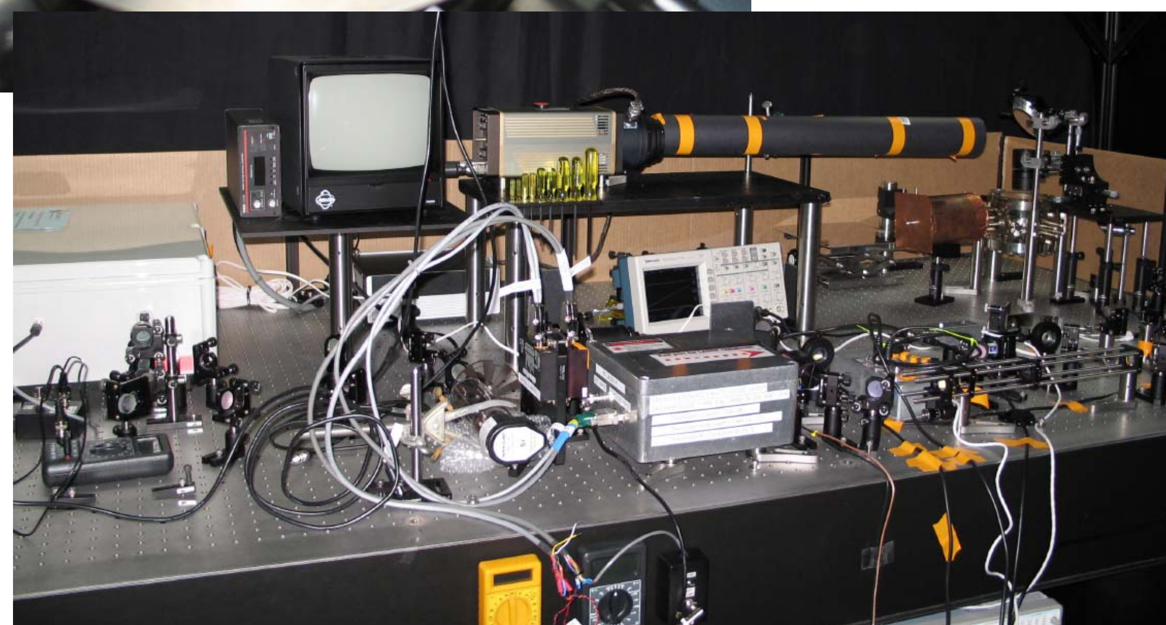
Microfabricated ion traps in the (2nd) lab

Have set up:

Cooling lasers
Imaging system
Vacuum system
RF system
etc.







Summary

Trapped ions can simulate quantum condensed matter systems

Quantum simulators are sort of like analog quantum computers

Have the basic building blocks for small simulations
- optics that reduce AC Stark shifts
- laser systems for sub-Doppler cooling

Building with Sandia advanced, scaleable traps for large simulations

See also posters by Kendra Vant and Rolando Somma