Simulating quantum systems with trapped ions

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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

The Solution

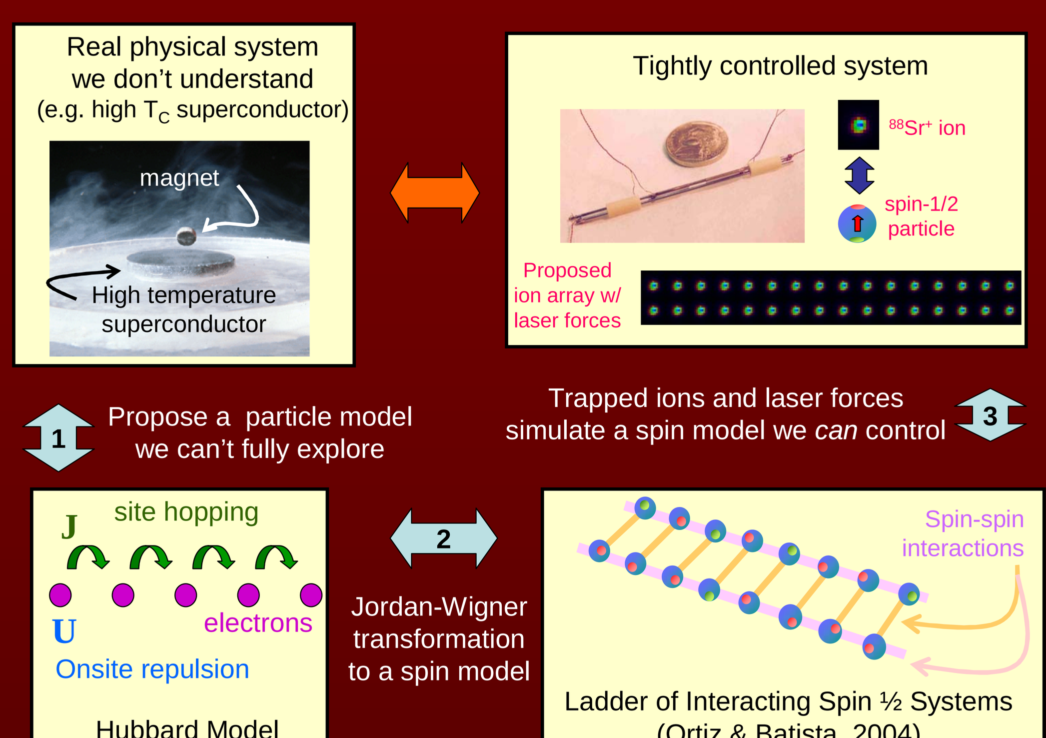
(proposed by Feynman and revisited by Lloyd 1992)

Simulate on another multi-body quantum system

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

Trapped ion systems can be more ideal than real materials

What is a quantum simulator?



Similar to a quantum computer …

Both require:

- Good state initialization
- Long decoherence times relative to operation times
- Good final state readout

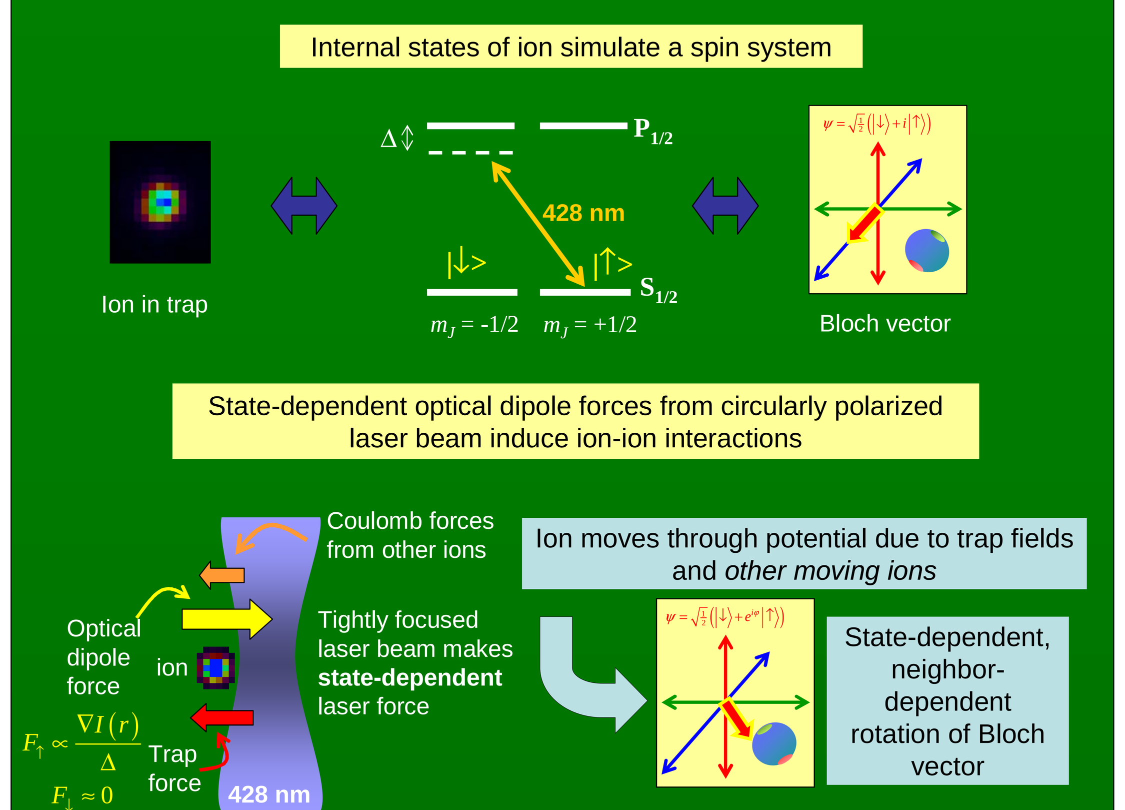
Trapped ions naturally meet these requirements

… BUT different

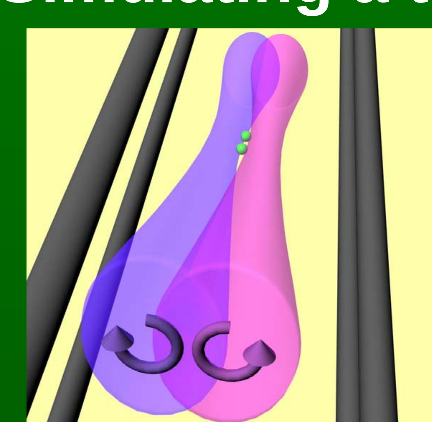
QC	QS
Universal	Configured for one particular problem (e.g. materials science problems)
Scalable set of individually addressable qubits	Qubits need not be accessed individually
Need universal gate operations	Universal gate operations not required
Stringent timing requirements	Continuous interaction without timing issues
Heavy engineering and requirements.	Similar requirements, though simplified since individual access not required. Engineering problems solved for QS will contribute to a toolbox for QC.

Physics of the LANL trapped ion quantum simulator

(Porras & Cirac 2004)



Simulating a two-ion Ising model



- Use two oppositely circularly polarized laser beams.
- Same AC Stark shift for $|\uparrow\rangle$ and $|\downarrow\rangle$
- Each ion sees ~ same laser field.
- Total force is along radial direction.

Lab Hamiltonian

State-selective optical dipole force along x — Real or simulated magnetic field

$$H=\sum_{n=0}^{\infty}\hbar\omega_n a^{\dagger}_{n,x}a_{n,x}+\sum_{i=1}^{2}Fx|\uparrow\rangle\langle\uparrow|_i^x+B^z\sigma_i^z$$

Trap and ion potential — $x \propto (a^{\dagger}_{n,x}+a_{n,x})$

This Lab Hamiltonian is related to the Ising Hamiltonian by a canonical transformation

Simulated (Ising) Hamiltonian

$$H'=\sum\hbar\omega_n a^{\dagger}_{n,x}a_{n,x}-\sum_{i,j=1}^{2}J^x_{i,j}\sigma^x_i\sigma^x_j+B^z\sigma^z_i+\varepsilon$$

Old B plus *effective* field

Spin-spin interaction $J_{ij} \propto F^2$

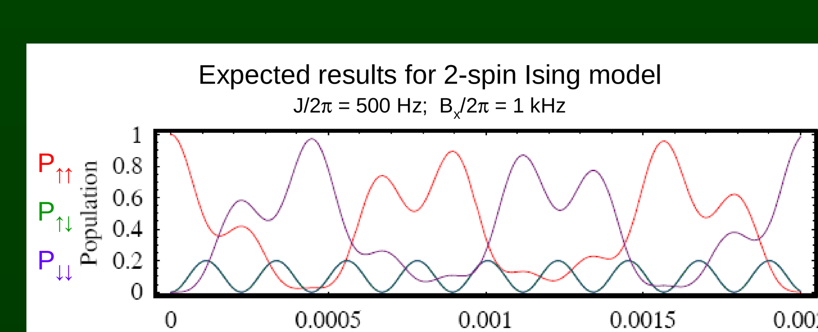
Initial experiment:

Cool ions to <n> < 1 and prepare ions in state ↑↑.

Allow ions to interact with dipole force lasers and real B field.

For final state readout, use 674nm laser to shelve ↑ ions in $D_{5/2}$ states.

Turn on 422nm and 1092nm light to detect only ↓ ions.

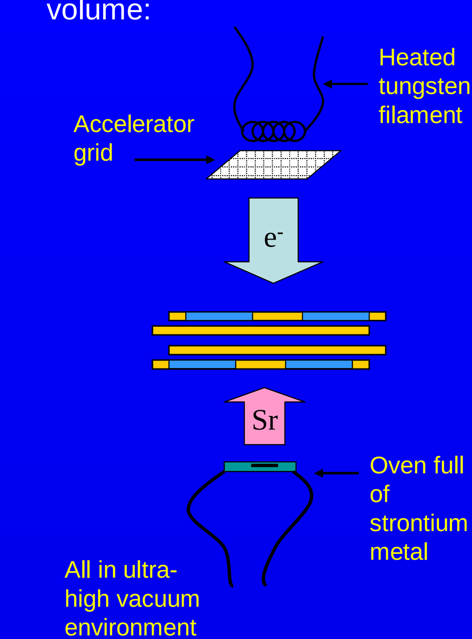


See our theory poster, Quantum simulations of Spin Systems Using Trapped $^{88}Sr^+$ Ions, Rolando Somma et al., for details of transformation and the simulation models

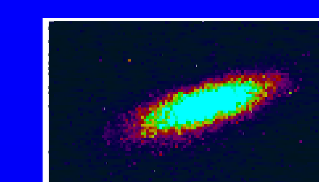
Creating ions inside the trap

Approach #1: Electron gun

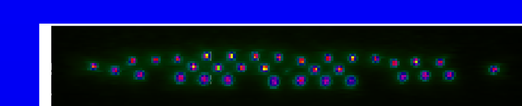
Create ions by colliding neutral Sr with electrons inside the trap volume:



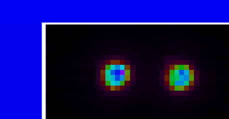
At first, see a fuzzy hot cloud (plasma) of ions:



Lower the trap potential to reduce ion-ion interactions, and continue laser-cooling. See lots of colder ions, but too many:

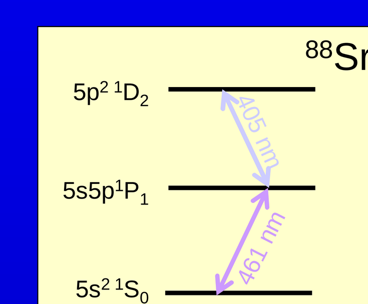


Lower the trap potential to (carefully!) release excess ions:



Only a few ions remain.

Approach #2: Photoionization



461nm light from doubling a grating-stabilized 922nm diode laser.

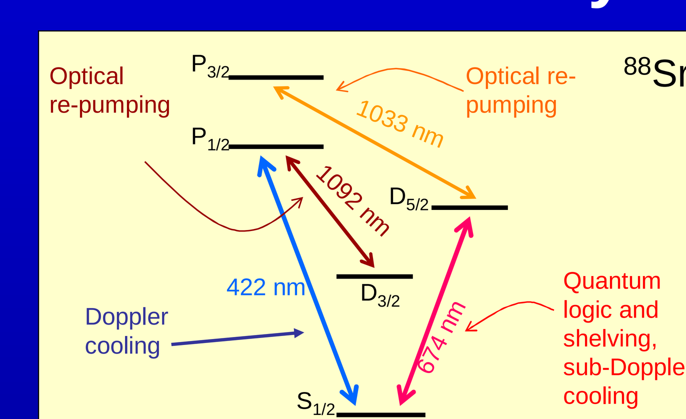
405nm light from free running blue diode laser

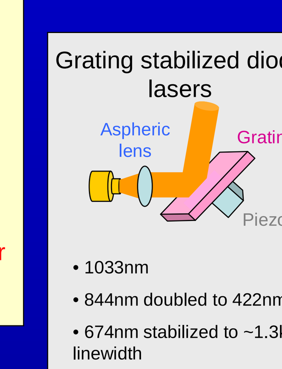
$5p^2\,{}^1D_2$ level is autoionizing

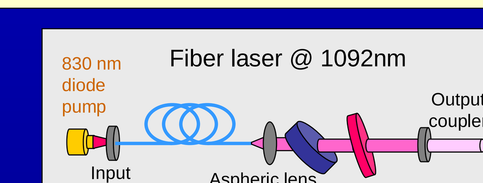
Can load with the camera monitoring the ion cloud. Expect to be able to load a desired number of ions and then switch off the photoionization lasers.

Species selective so eliminates `dark' ions.

Strontium system

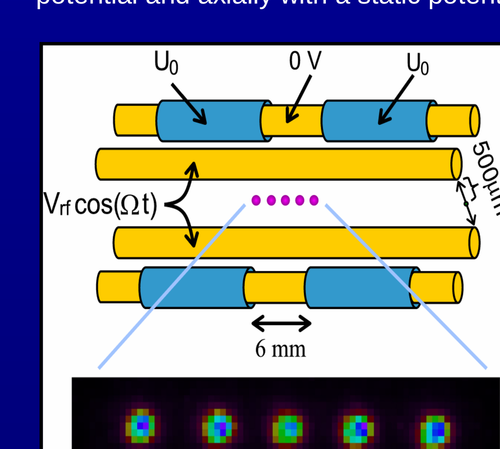




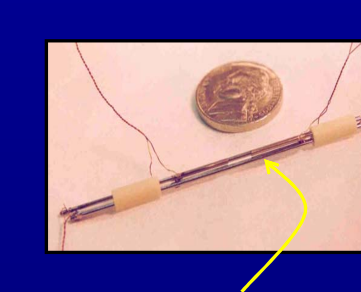


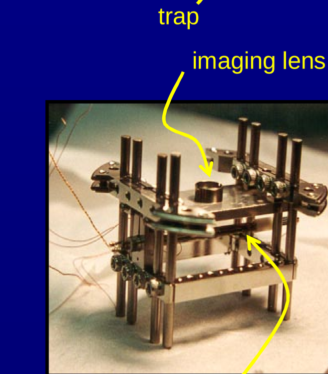
Macro Traps: RF Paul trap

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



(resonant 422-nm light scattered from 5 ions)





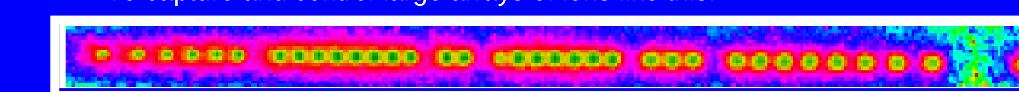
Trap potential ~ $h\,\omega_{-}$

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

Trap depth ~ 25eV, Ion lifetime > 1 day

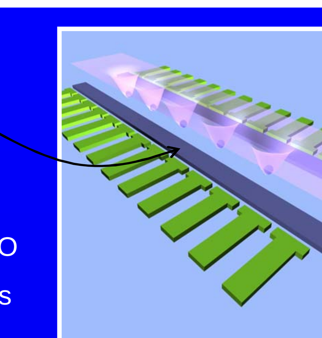
Micro Traps: planar ion traps

To capture and *control* large arrays of ions like this:

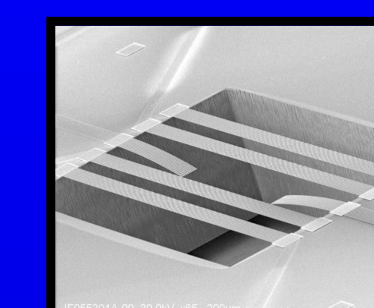


We need traps that:

- Have 10s of separate potentials, one for each ion
- Are made of low-RF-loss materials
- Assemble precisely and have smooth electrodes
- Are compatible with dense electrical and optical I/O
- Have optical access for lasers and detection optics



Almost realized! (see below)



one-zone trap

Electrode thickness ~ 3 microns

width ~ 80 microns

length ~ 2 mm

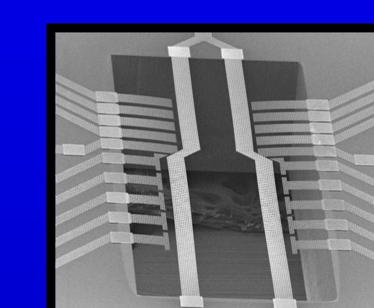
For 200V, 20 MHz drive, 1V on endcaps:

Trap depth ~ 1 eV

Trap frequency ~ 2 MHz

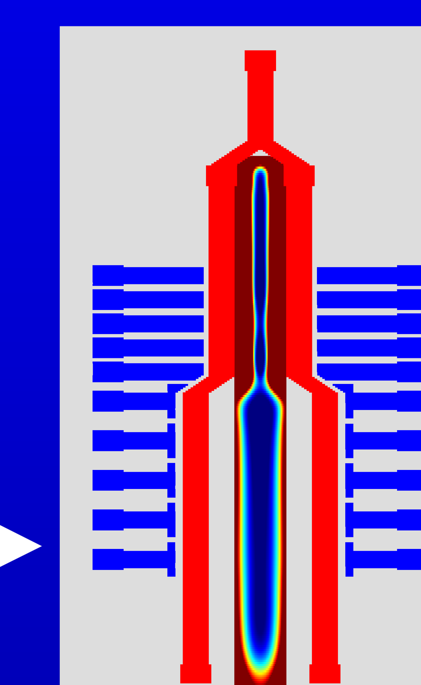
We learned:

- can form optical access holes in Si substrate
- cantilevering has its limits – but sagging endcap electrodes have been snapped off. Trapping will be attempted in these traps soon.



multi-zone trap

Calculated potential



Microfabricated traps to be tested in the lab soon

- Good RF behavior
- Repumping laser ready
- Imaging system built
- Cooling laser ready