# Quantum Information with Trapped Ions

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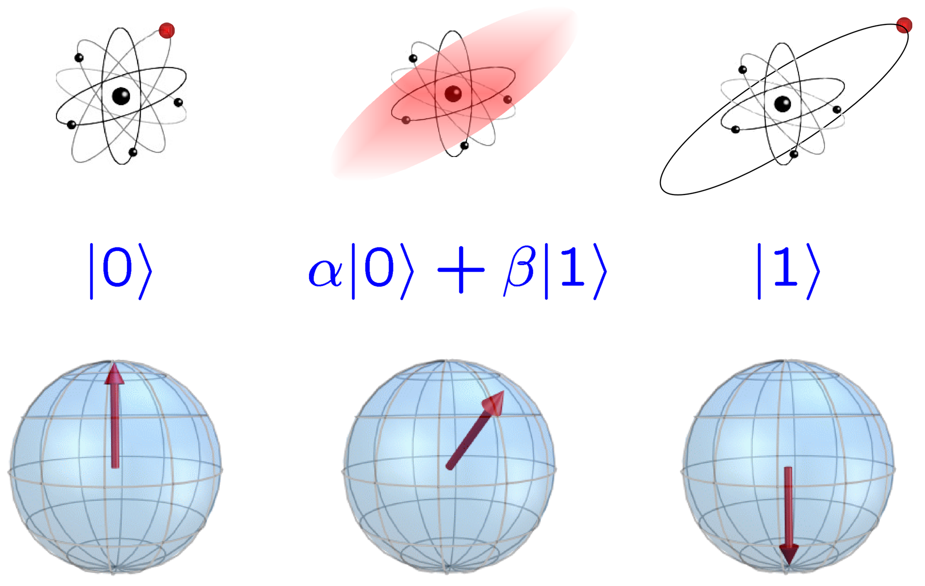
## Quantum Information

**Bits can be in superpositions**

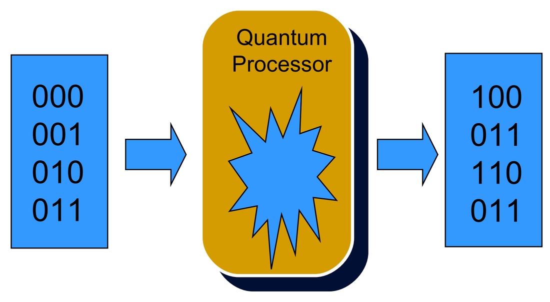


$|0\rangle$ $\alpha|0\rangle + \beta|1\rangle$ $|1\rangle$

Why Quantum information?

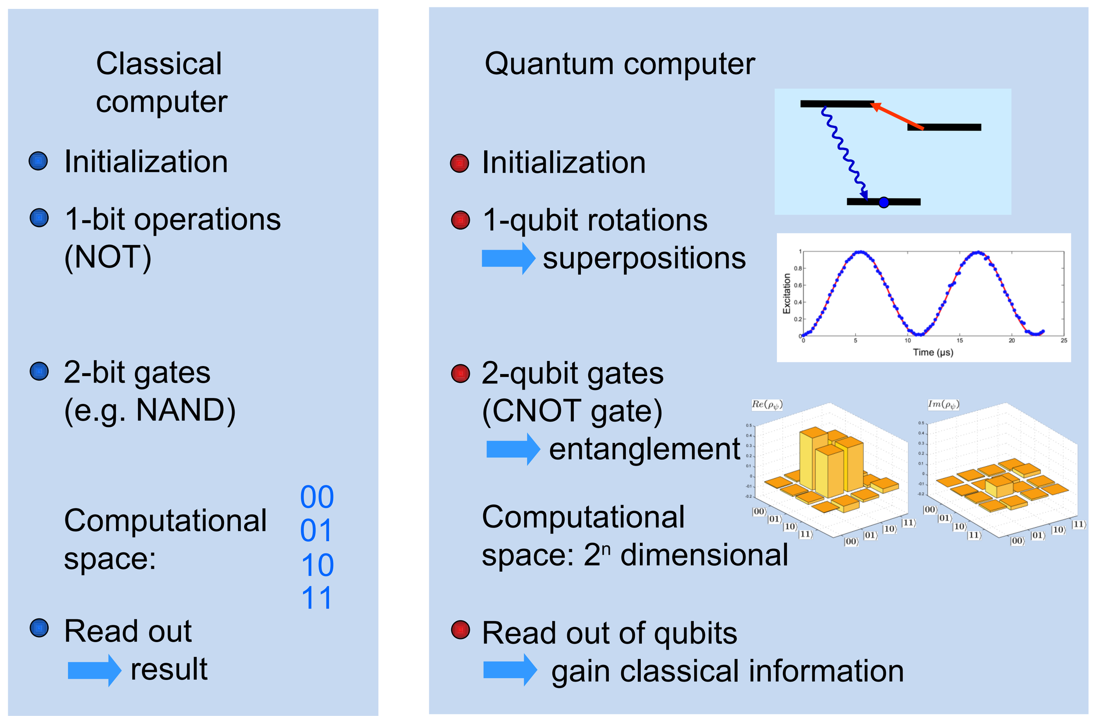
- do fancy computation
- "understand" quantum mechanics
- apply quantum mechanics
- where does quantum mechanics fail?

## Quantum Computing

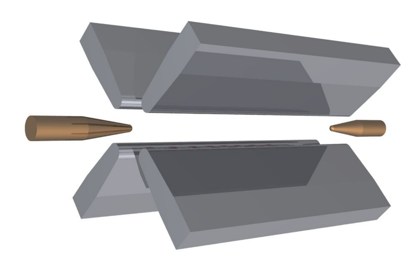


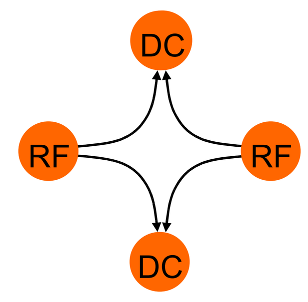

Landmarks with trapped ions:

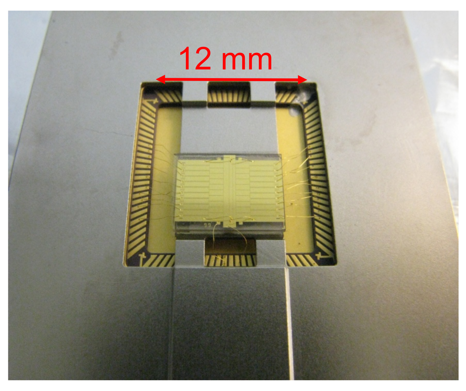
- Deutsch-Josza
- Teleportation
- Quantum error correction




## Ion Trapping

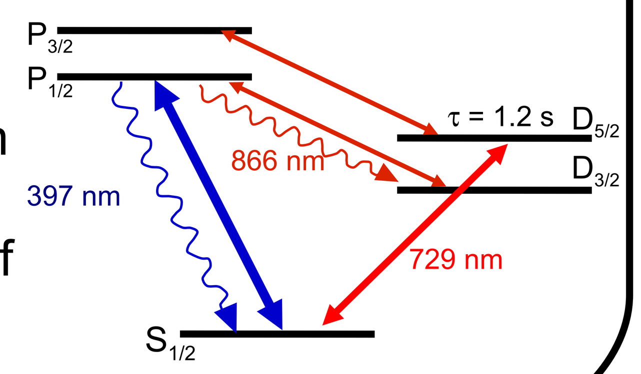




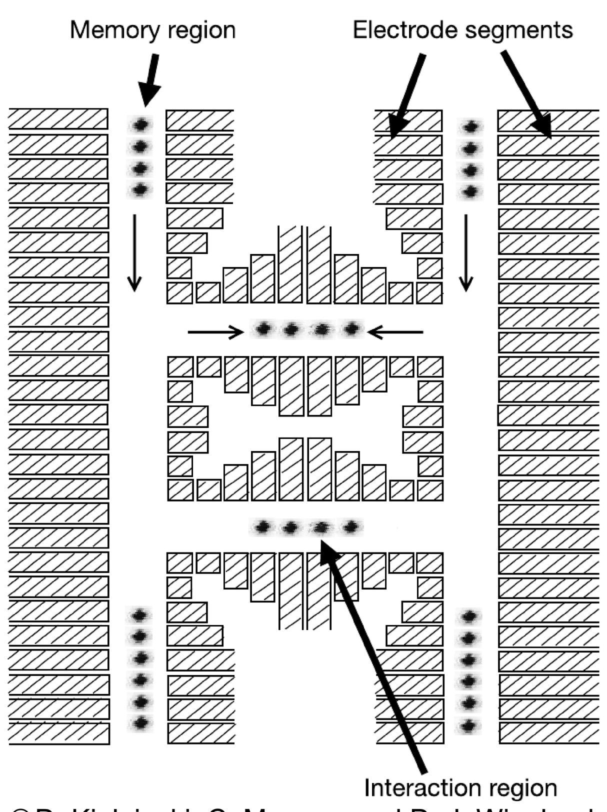




Our planar RF traps are mounted on CPGAs. For operation they reside in a vacuum vessel at approx. $10^{-11}$ mbar

The level structure of $^{40}Ca^+$. Only the 397 nm and 866 nm lasers are needed for detection of ions.




## Scalable QIP

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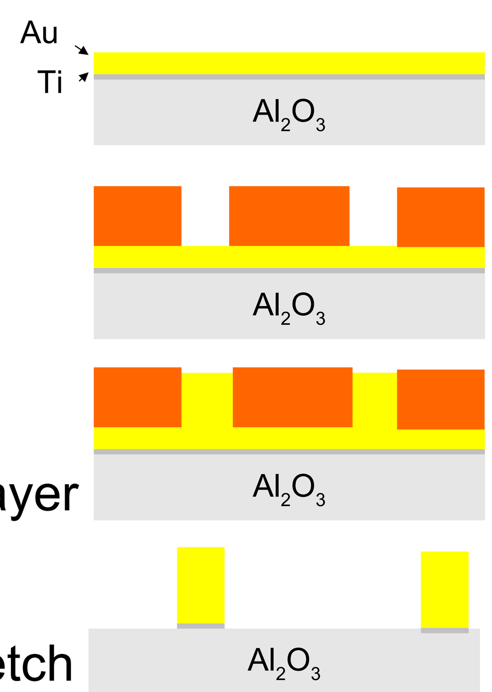
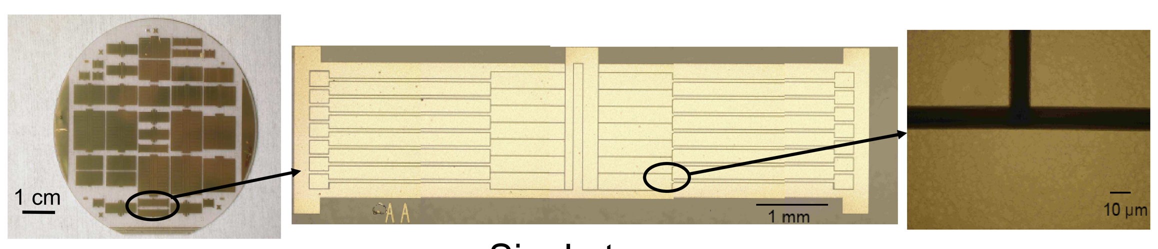
Scaling of trapped ion quantum computing:

- Segmented trap architecture has been proposed [1]
- Planar traps are relatively easy to produce.

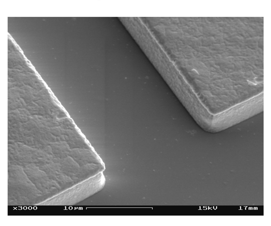
## Trap fabrication

1. Evaporation
   i. 5 nm Ti adhesion layer
   ii. 100 nm Au seed layer
2. Lithography
   ~5 µm thick photoresist
3. Electroplating
   4-5 µm thick Au plated layer
4. Cleaning / Etching
   Resist removal / Au&Ti etch




Complete wafer Single trap Trap details



Electrode spacing: 10 µm

Surface RMS roughness: 20 nm

Crystallite size: 20 nm

[1] D. Kielpinski, C. Monroe, and D. J. Wineland, Nature **417**, 709–711 (2002).

## Quantum Simulations

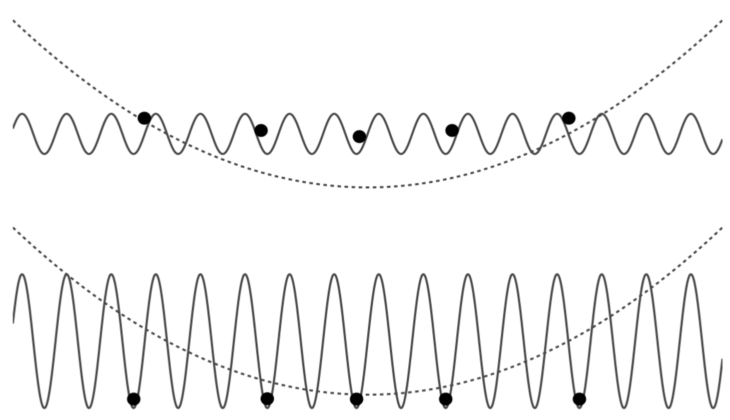
**Frenkel-Kontorova Model:**

Many solid-state physics applications:
dry friction, crystal dislocations, epitaxial growth.

$$\mathcal{H}=\sum_{i=1}^{N}\left(\frac{P_i^2}{2}+\frac{\omega^2}{2}x_i^2-K\cos x_i\right)+\sum_{i>j}\frac{1}{|x_i-x_j|}$$

$K$ is the strength of the optical lattice.
$\omega$ is the frequency of the ion trap potential.

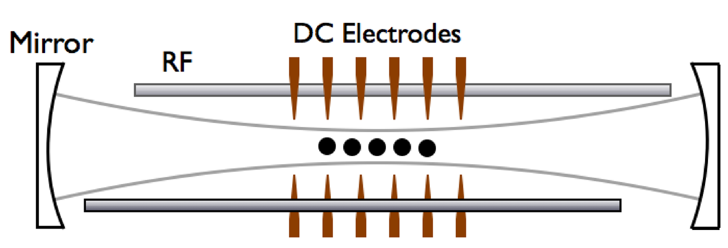
Both parameters can be tuned experimentally to observe different phases of the ion string. Quantum phase transition happens at a specific value of $K$ [2].



Weak lattice Confinement

Strong lattice confinement

**Setup Parameters:**




- $f_{ion} = 1Mhz$
- $f_{lattice} = 1Mhz$
- $\lambda_{lattice} = 405nm$
- $\mathrm{waist} = 10\ \mu m$
- $\mathrm{trap\ height} = 350\ \mu m$

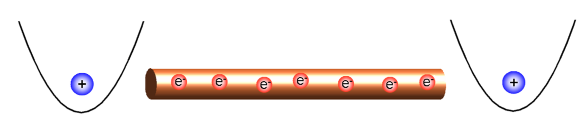
**Goal**

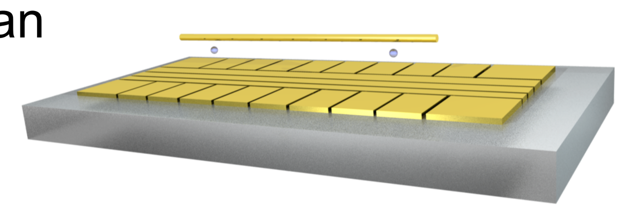
To observe quantum phase transition by varying the value of $K$ and measure the phonon excitation frequency by shaking the ion chain.

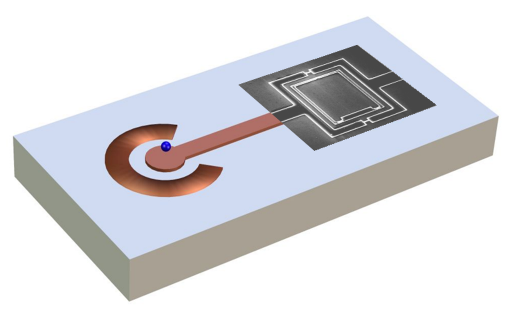
[2] Garcia-Mata *et al.*, Eur.Phys. J. D **41**, 325-330 (2007).

## "Wiring up" Ions

The motion of a trapped ion induces an image current in the wire, which influences the motion of a second trapped ion. This interaction extends over a distance greater than that of pure Coulomb coupling [3].

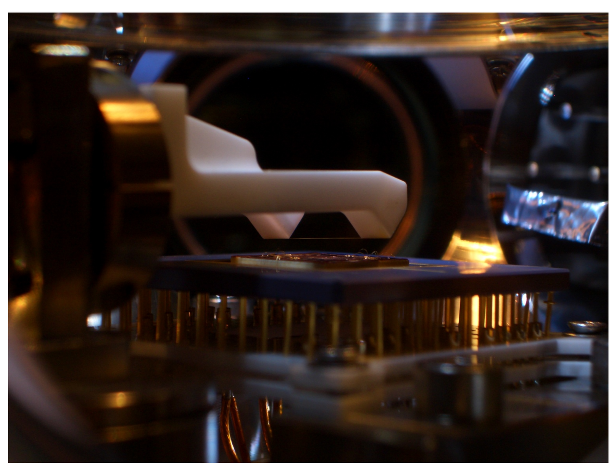






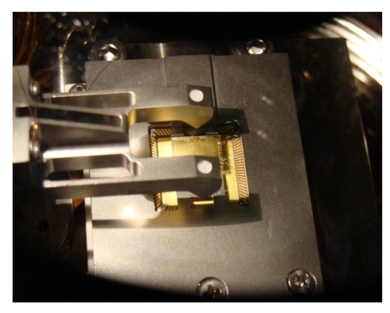
**Possible applications:**

- Quantum information processing
- Sympathetic cooling of ion species inaccessible by laser cooling
- Coupling ions to superconducting qubits / mesoscopic resonators
- Coulomb force electrometer

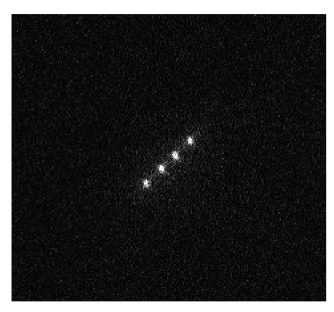


**Current status:**

- Preliminary experiments with room temperature apparatus in progress at IQOQI



- Ions have been observed, trap model tested, and the first signals of ion-wire interaction observed



- Move on to cryogenic temperatures

[3] D.J. Heinzen and D.J. Wineland, PRA **42**, 2977 (1990).