Quantum simulation with 2D ion crystals

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Motivation

- **Scalability** of linear chains faces problems such as high axial heating rates and single-ion addressing of outer ions
- **Possibility** to investigate **2D spin models**

Challenges

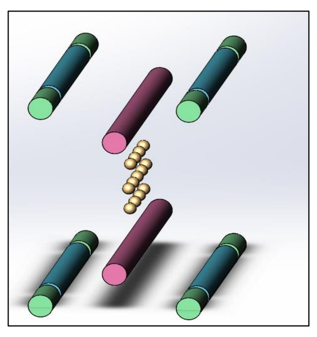
- **Micromotion** in 2D crystals, because some ions are naturally away from the RF null
- **Changes of crystal structure** due to collisions with background gas

Our solution

- **A novel trap design** which allows laser beams to access ions perpendicular to their micromotion
- **Micromotion insensitive** out-of-plane modes are used to provide spin-spin interaction

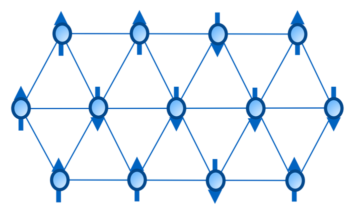
Quantum Simulation

2D Crystals



$^{40}Ca^+$ ions 2D crystal

Model:
2D spin lattice



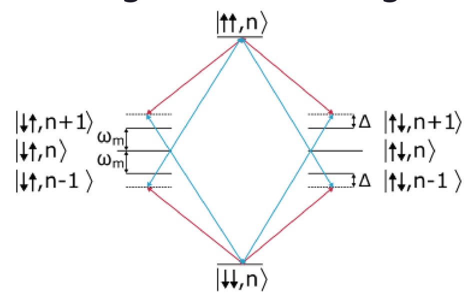
Transverse Ising Hamiltonian

$$H = \sum_{i<j} J_{ij}\sigma_i^x\sigma_j^x + B\sum_i \sigma_i^z$$

$$J_{ij} \propto \frac{1}{|i-j|^\alpha}$$

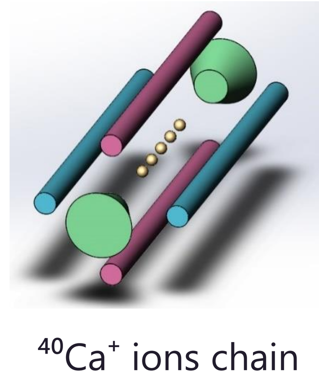
Tunable interaction: $0 < \alpha < 3$ $\quad B = \delta/2$

Tunable long-range spin-spin interaction using bichromatic light fields



Linear Chains

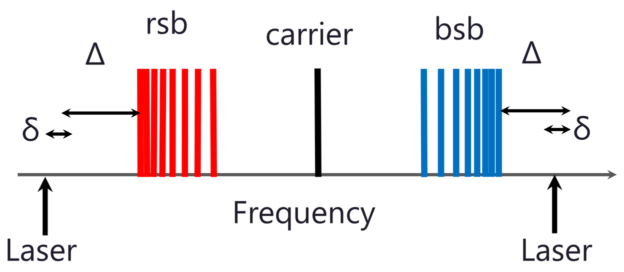
Model:
Large number of interacting spins



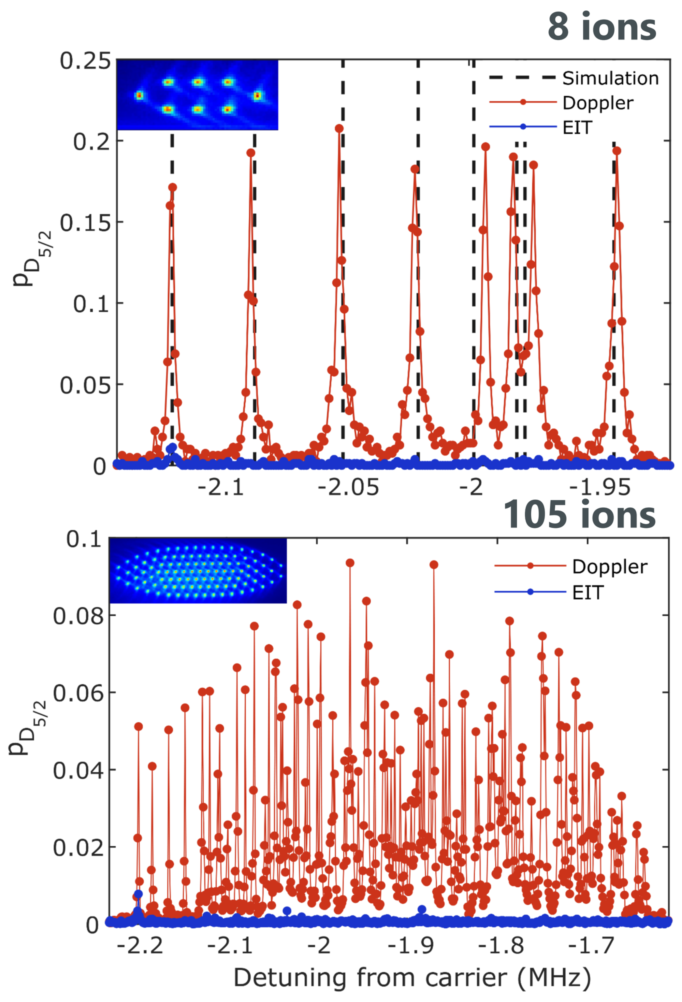
$^{40}Ca^+$ ions chain trapped in a RF Linear Paul Trap

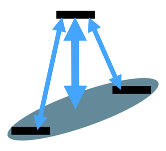
Mapping to trapped ions

- Spin-1/2 particles are encoded into the $4S_{1/2}$ ground state manifold
- Manipulation via Raman transition
- Coupling to radial motional modes (**1D**)/ out-of-plane modes (**2D**)

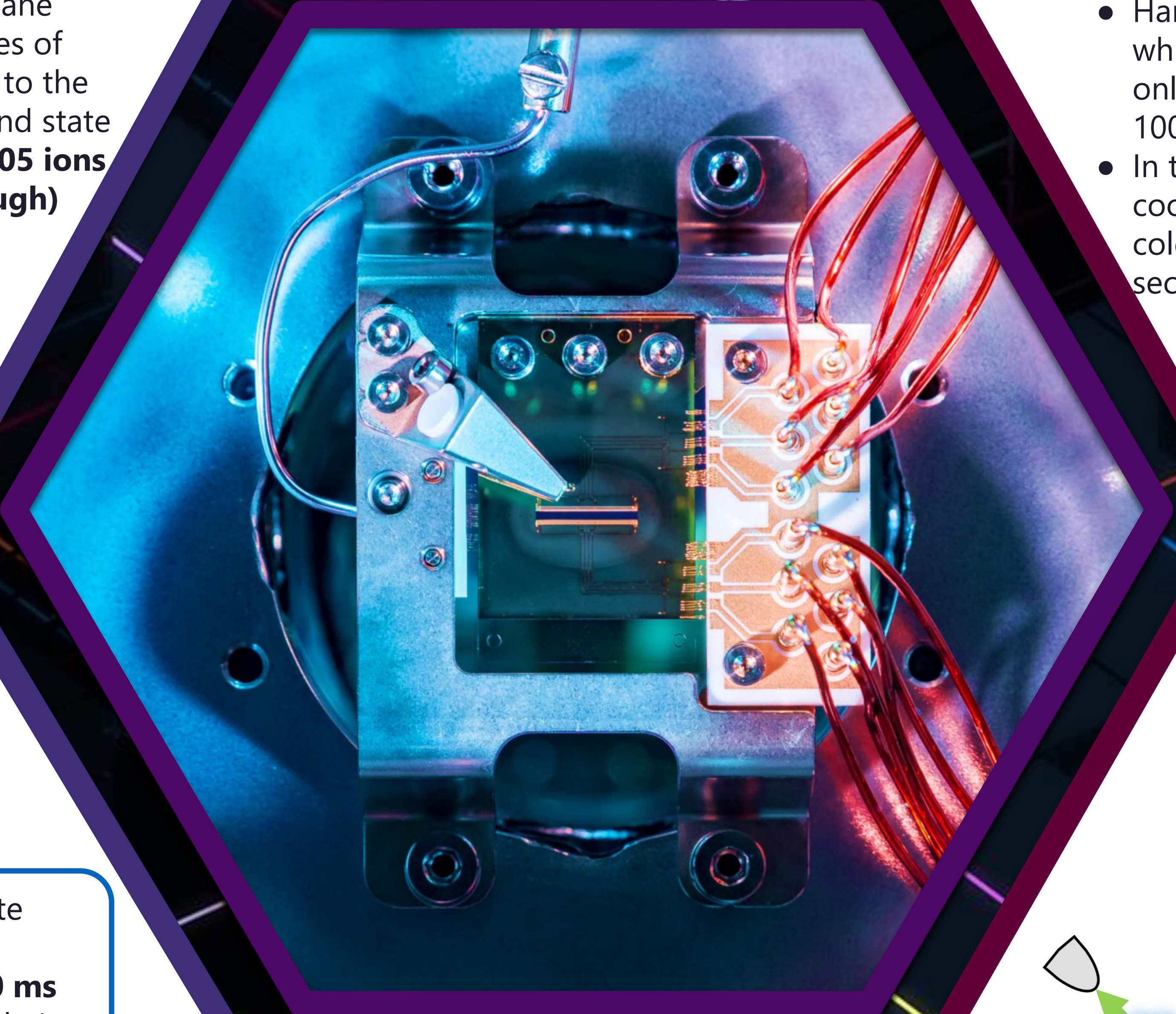


Cooling

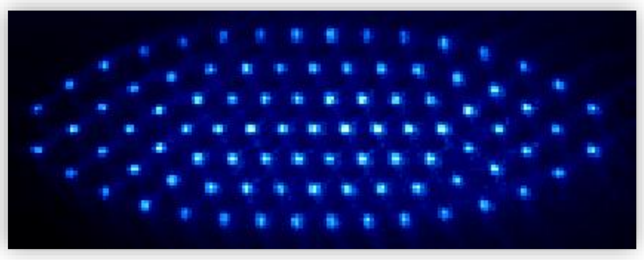


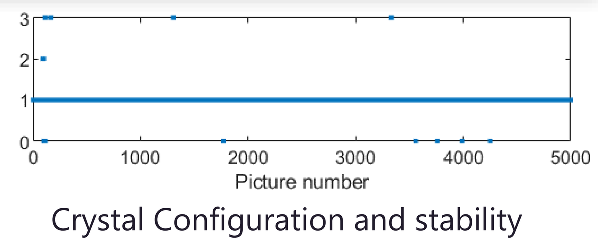


- **Doppler cooling** allows to freeze crystal in a stable state
- **EIT cooling** allows fast simultaneous cooling of all out-of-plane motional modes of planar crystals to the motional ground state **(~400μs for 105 ions crystal is enough)**



Stability

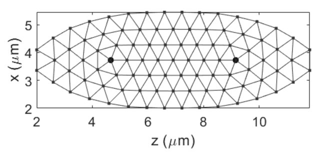




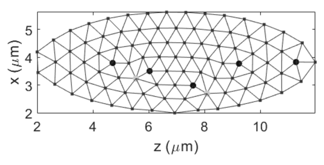
Crystal Configuration and stability

- Stable crystals up to **105 ions**
- For certain numbers of ions and voltage sets we achieve **>99% in the symmetric main configuration**
- Harmful collisions which cause melting only occur once in 1000 seconds
- In the absence of cooling crystals stay cold for several seconds

Simulated annealing

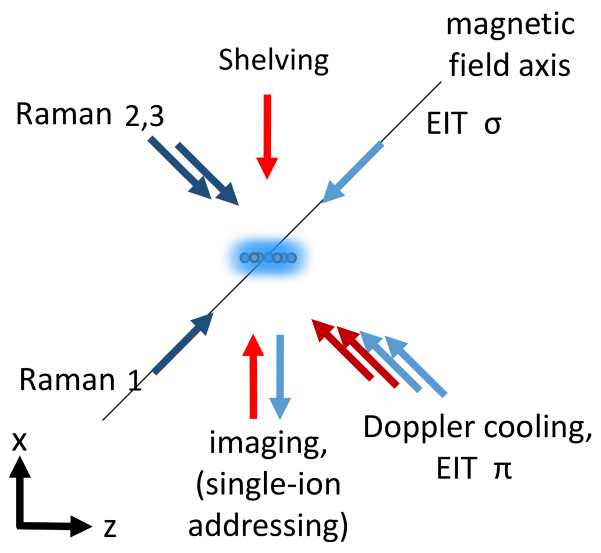


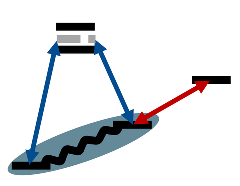
91 ions symmetric main configuration



Metastable configuration

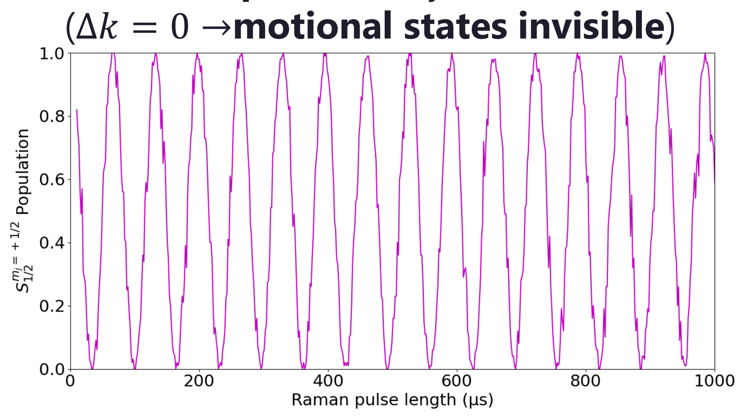
Qubit Control



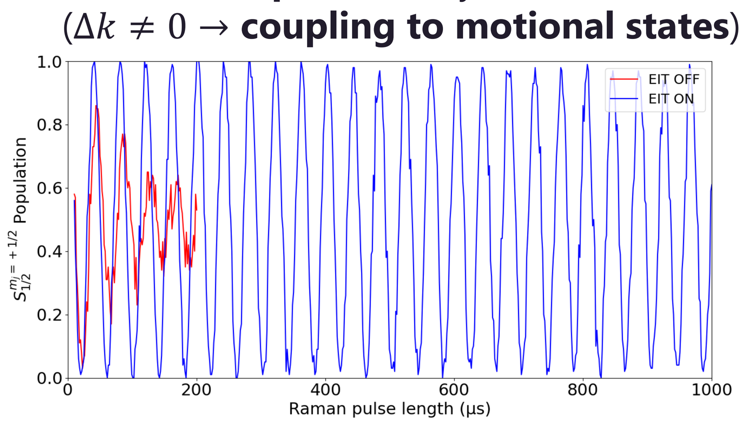


11 MHz Ground State Qubit
Coherence time: **130 ms** (**370 ms** with spin echo)

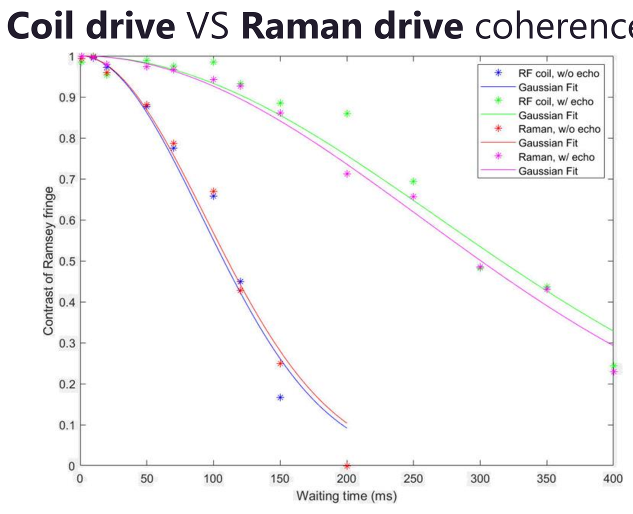
Rabi Flops driven by Beams 2+3 ($\Delta k = 0 \rightarrow$**motional states invisible**)



Rabi Flops driven by Beams 1+2 ($\Delta k \neq 0 \rightarrow$ **coupling to motional states**)

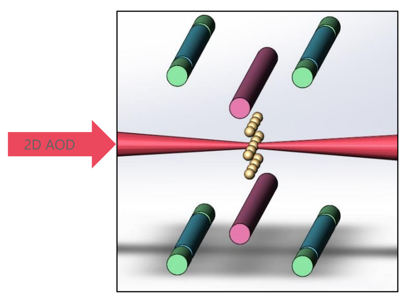


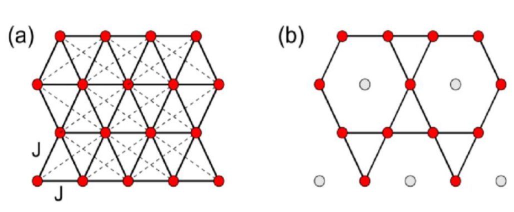
Coil drive VS **Raman drive** coherence



- High-power laser light at 396 nm creates **Raman interaction** to induce **qubit entanglement** via out-of-plane crystal modes
  Rabi Frequency up to $\frac{\Omega}{2\pi}$ ~1MHz
- RF coil **drives all ions** $4S_{1/2}$ state simultaneously

To be implemented

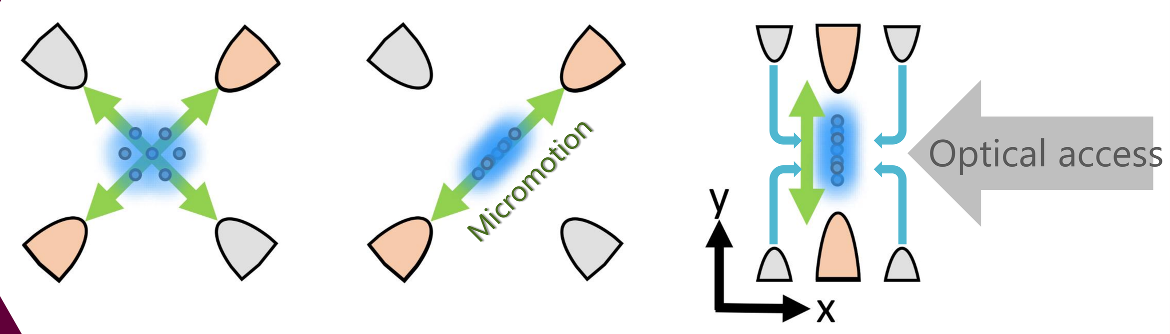




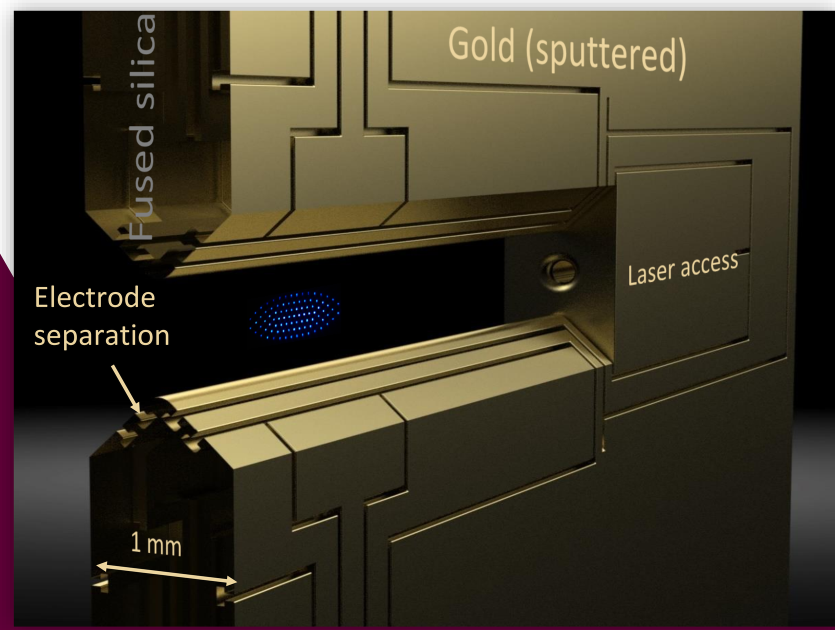
- Addressed with 2D AOD 729 nm laser light induces **phase shifts on individual ground state qubits** and shelves ions to $3D_{5/2}$ state for lattice structuring

Trap design

- Optical access from many directions perpendicular to micromotion. For imaging and laser addressing perpendicular to crystal plane
- Macroscopic linear Paul trap (0.4 mm electrode-ion distance)



- Trap frequencies: 2.2 MHz at 43 MHz drive
  Heating Rate at 2.2 MHz: 13 ph/s
- Subtractive 3D print (fused silica wafer)



Achievements

- Trapping stable 2D ion crystals with **up to 105 ions**
- **Fast cooling** of all out-of-plane modes close to motional ground state
- **130 ms** ground state qubit coherence time (**330 ms** with spin echo)
- **Raman interaction** with up to **1MHz** Rabi Frequency

Upcoming Goals

- **Spin-spin entangling interactions** via Raman transitions coupling to the out-of-plane motional modes
- **Individual qubit control** with 2D-addressed 729nm laser beam
- **Quantum Simulations of 2D Spin Models**

Want to know more?