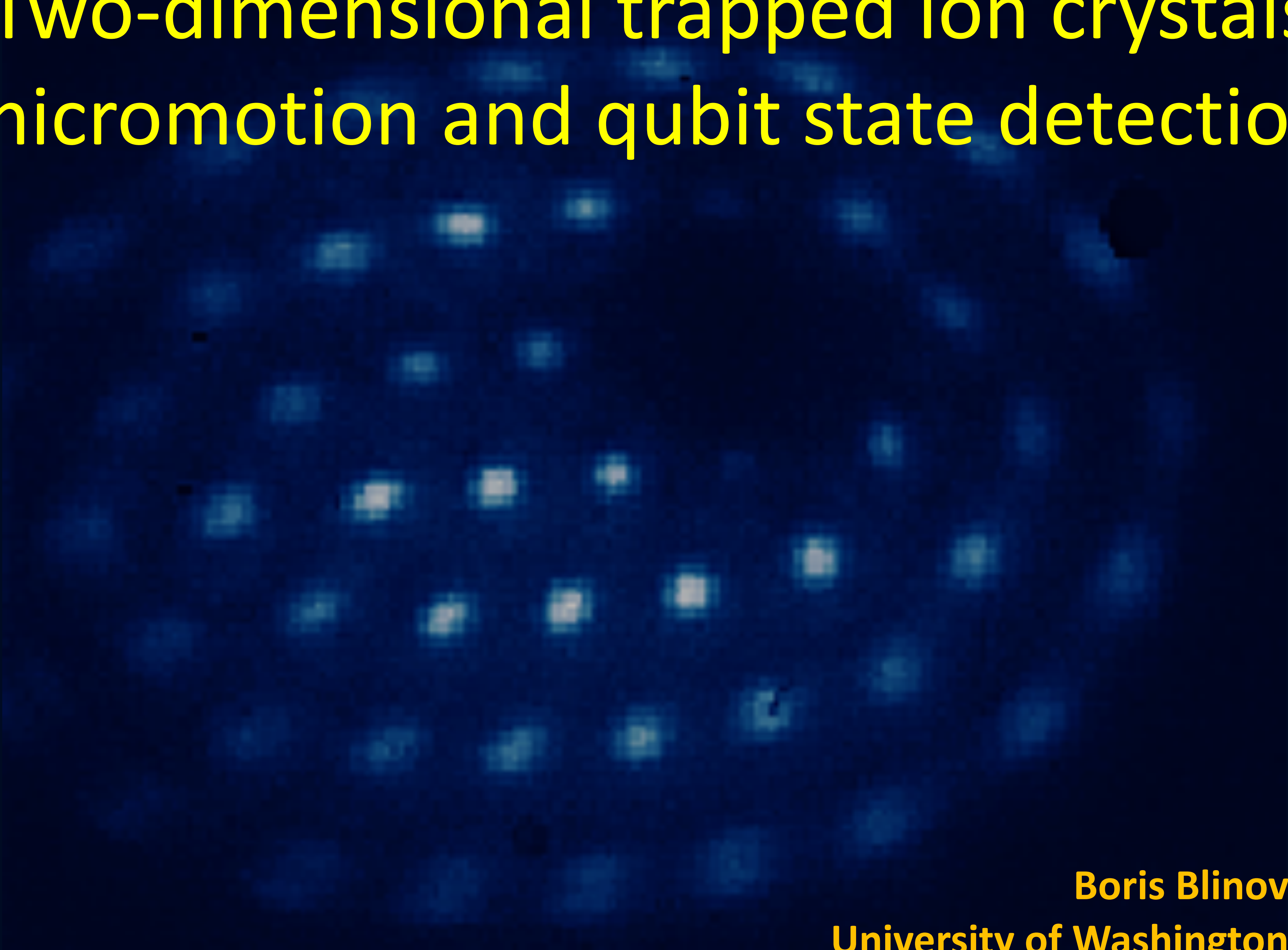
Two-dimensional trapped ion crystals, micromotion and qubit state detection

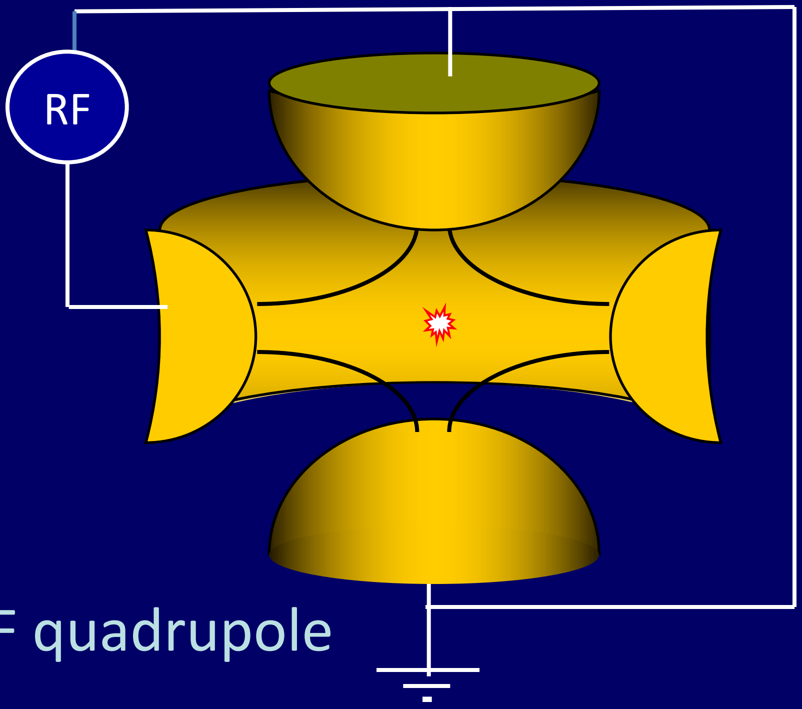


Boris Blinov

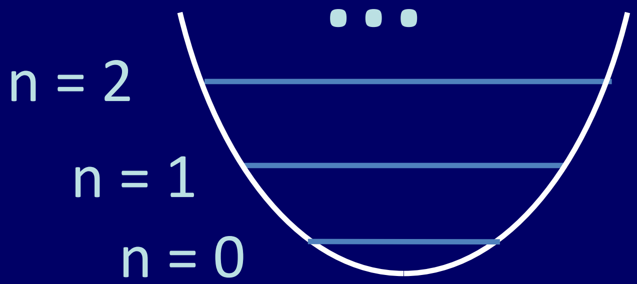
University of Washington

Ion traps

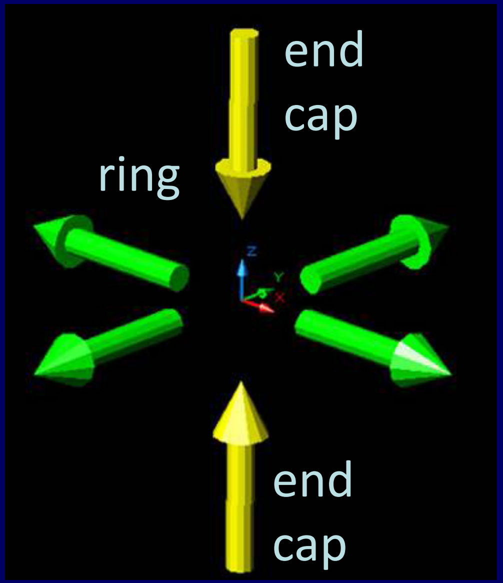
RF (Paul) ion trap

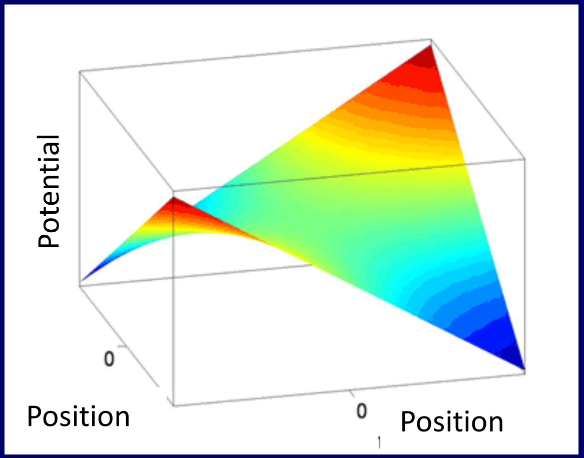


3-d RF quadrupole



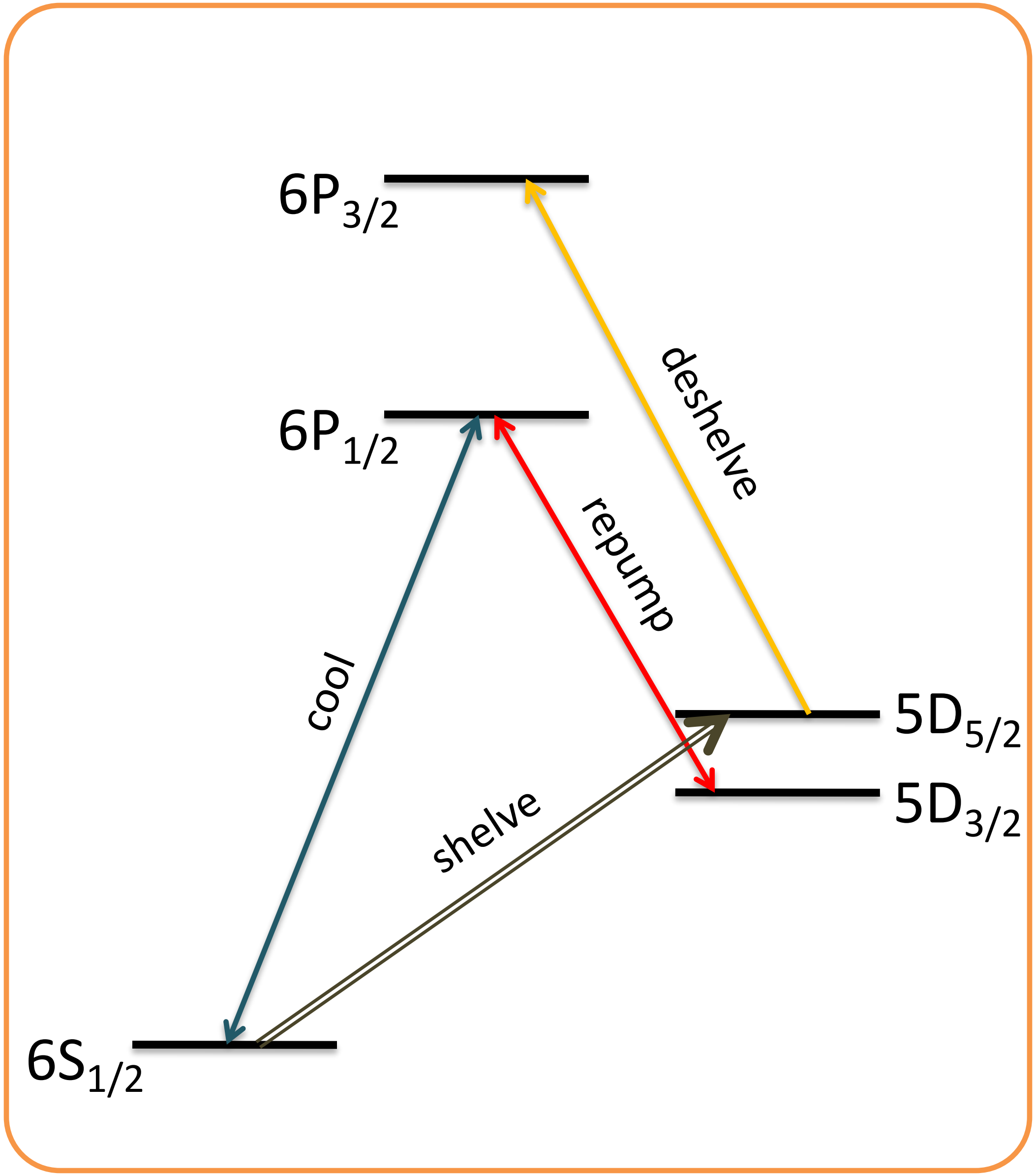
harmonic potential





Barium ion qubits

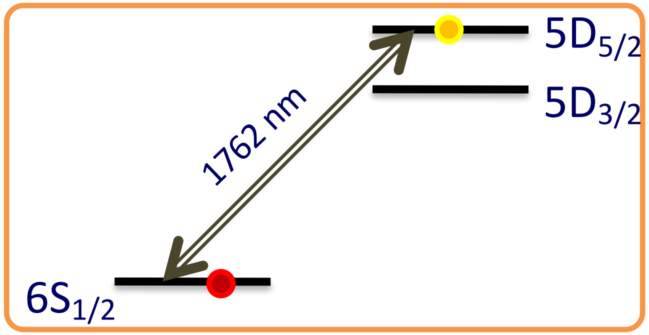
Ba+ ion, a very good qubit ion



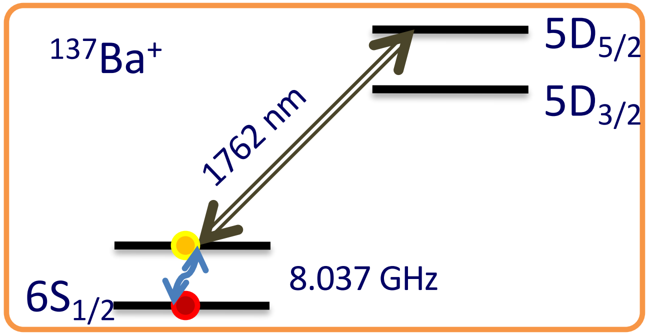
- optical, hyperfine and Zeeman qubits (and qudits)
- laser cooling: 493 nm and 650 nm
- qubit initialization: optical pumping
- qubit control: some form of EM waves
- qubit detection: state-dependent fluorescence

The qubits

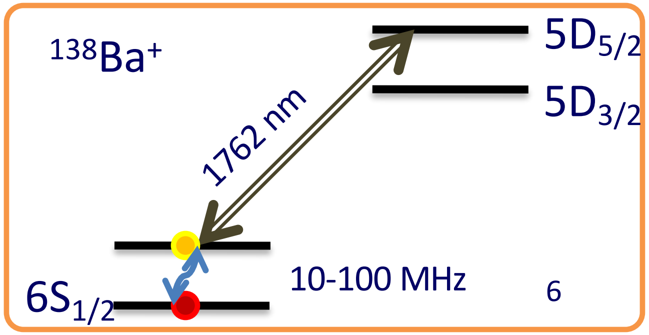
- optical: S-D transition



- hyperfine: ground state "clock" states

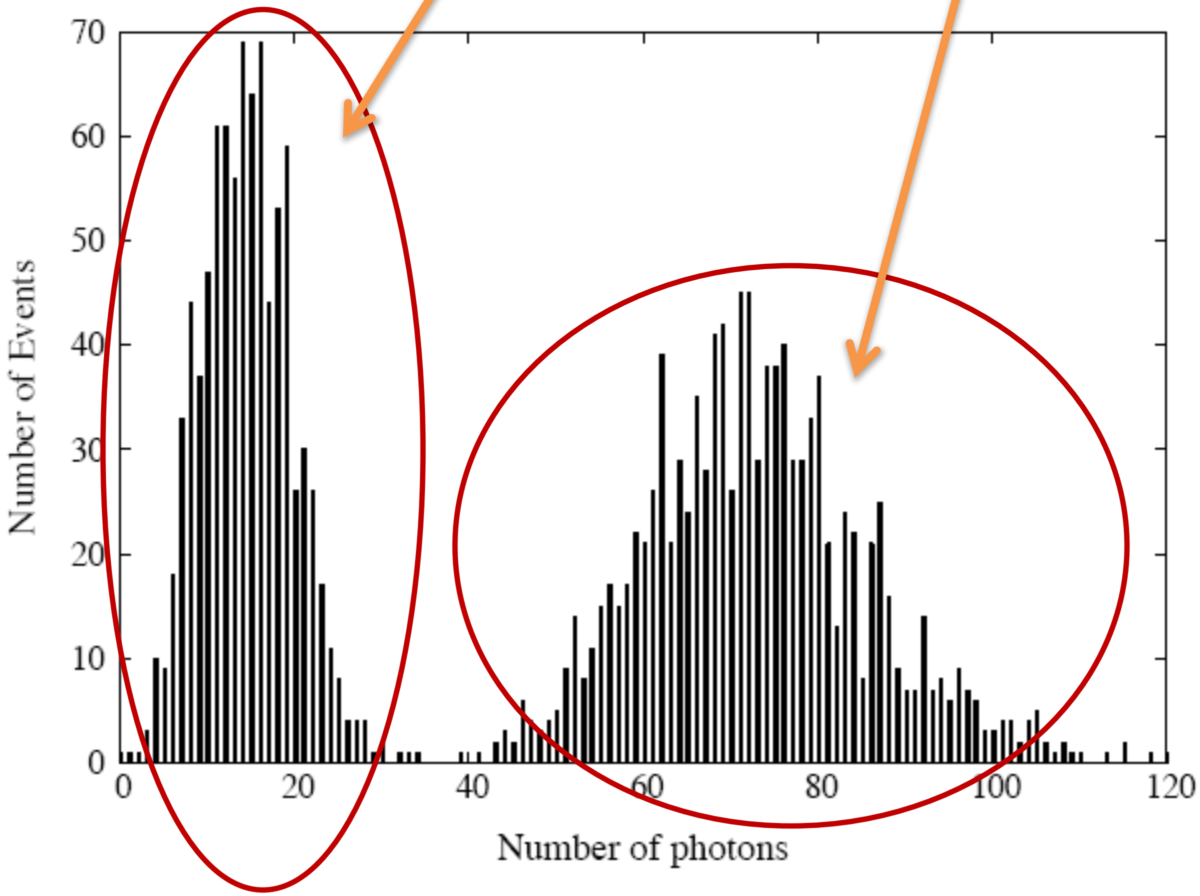


- Zeeman: ground state Zeeman states

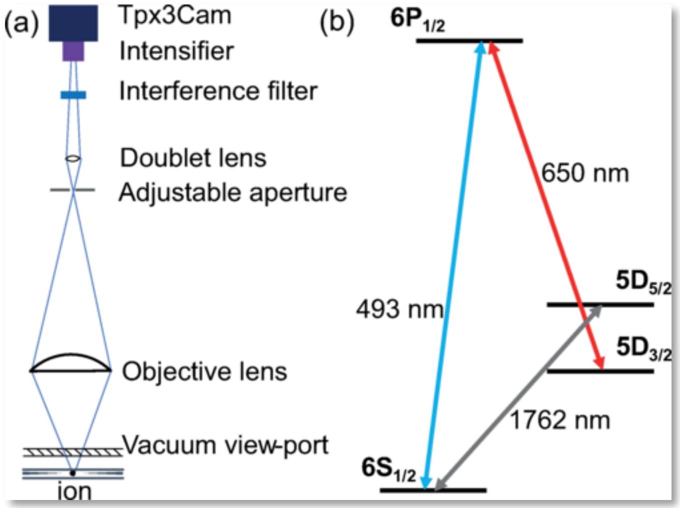


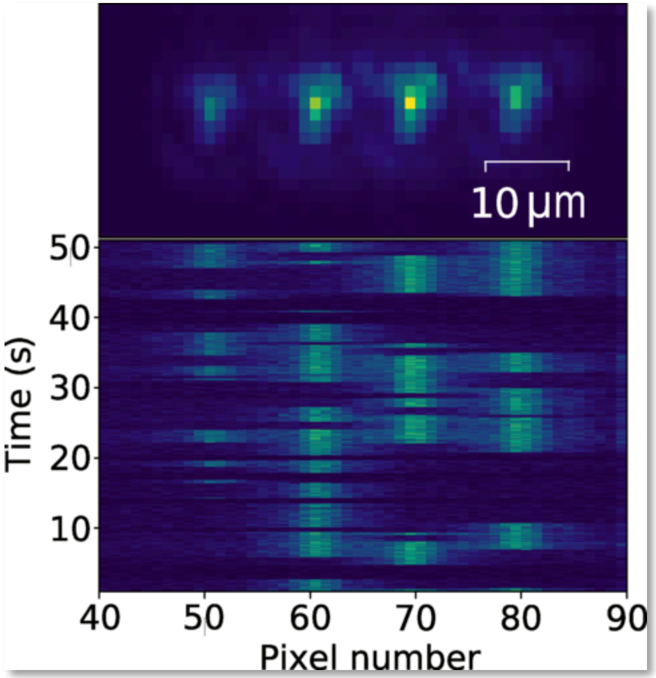
Whatever qubit, detection is the same

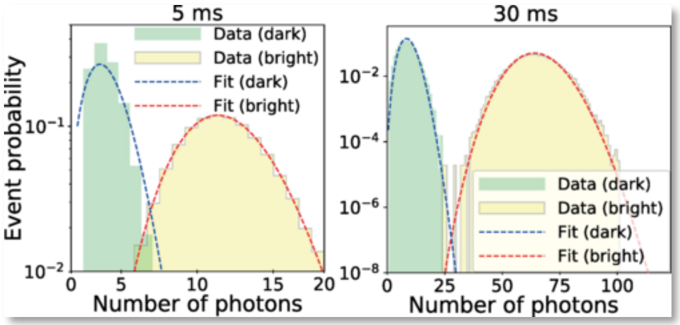
One state “dark”, the other “bright”



Qubit state detection: fluorescence





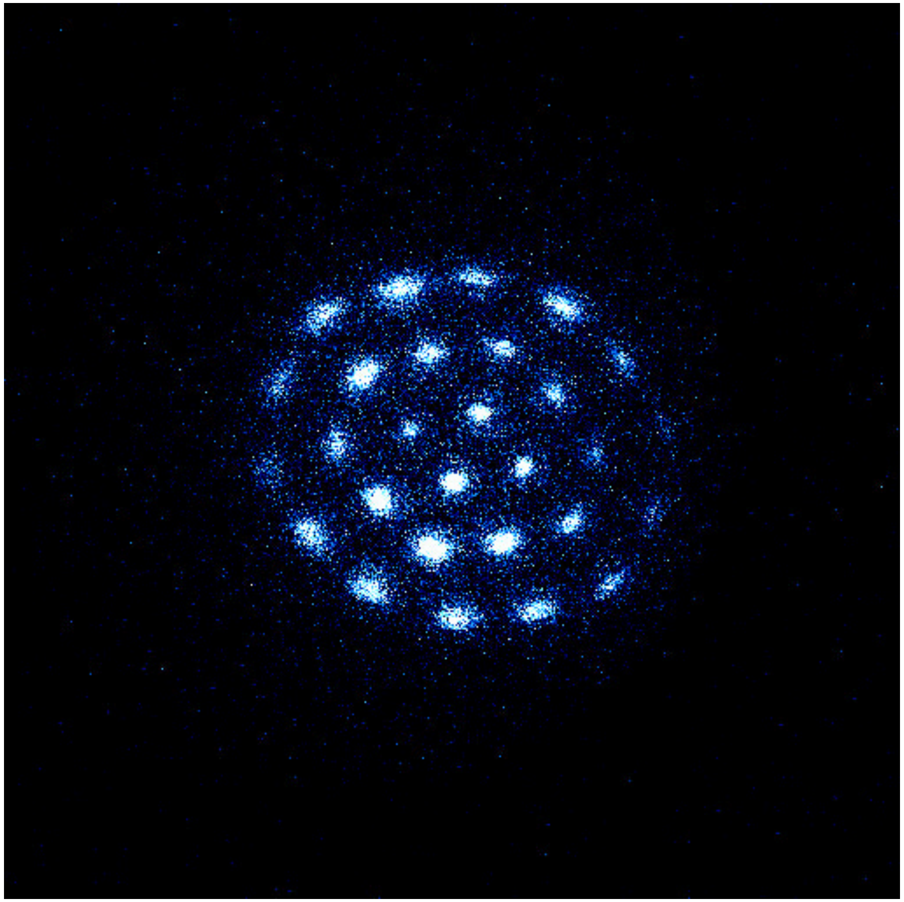


- Under detection laser light, one qubit state is “bright” (detect many photons/s from single ion), the other qubit state is “dark” (few to no photons/s detected).
- >99.9995% fidelity demonstrated

High-fidelity simultaneous detection of a trapped-ion qubit register
Liudmila A. Zhukas, Peter Svihra, Andrei Nomerotski, and Boris B. Blinov
Phys. Rev. A 103, 062614 2021

2-d traps

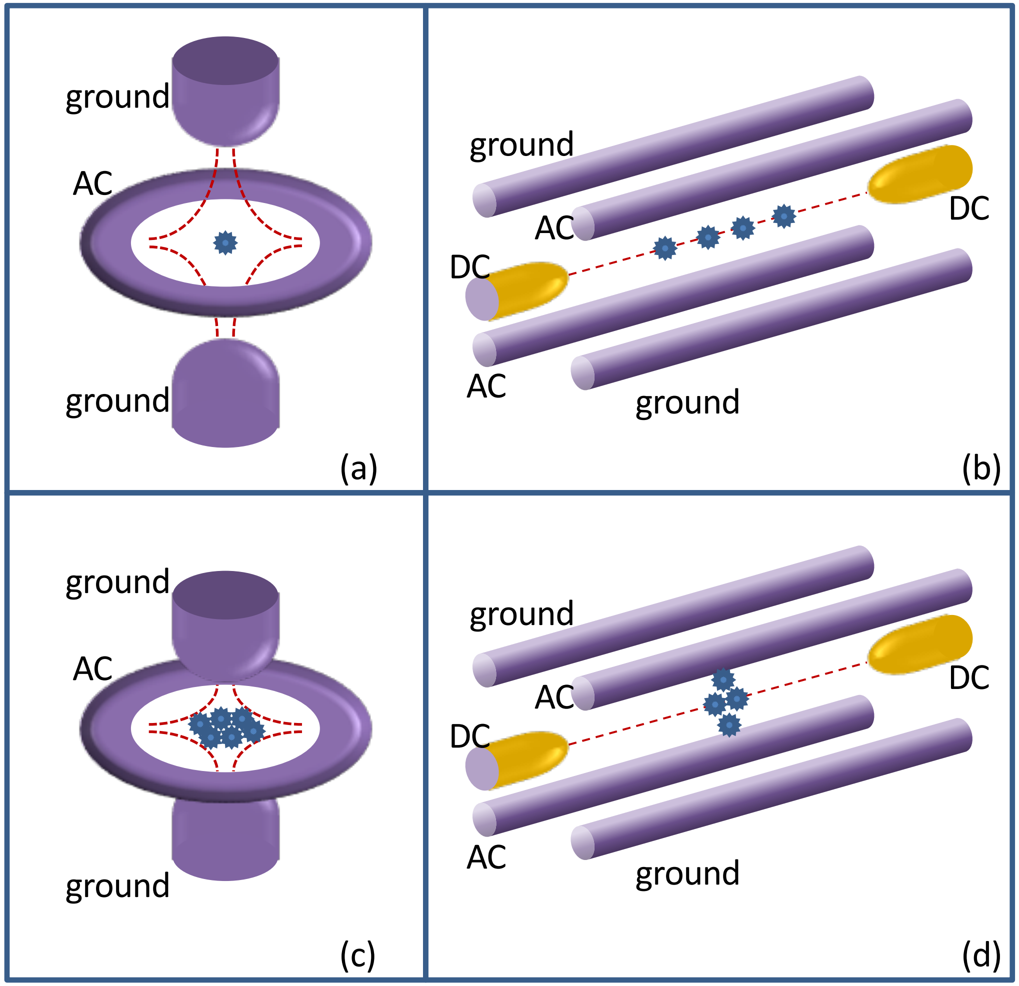
Scaling up: 2-d



Planar crystals of 28 Ba^+ ions

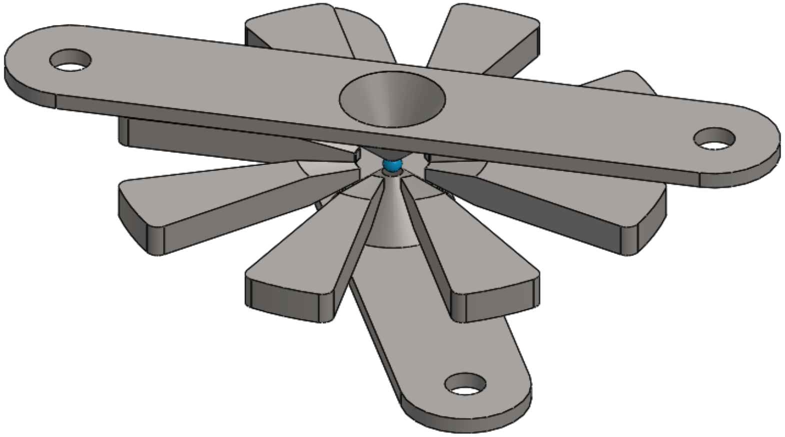
- More qubits per trap with Individual addressing
- Micromotion is inevitable, but show up as AM of laser, so effects can be corrected

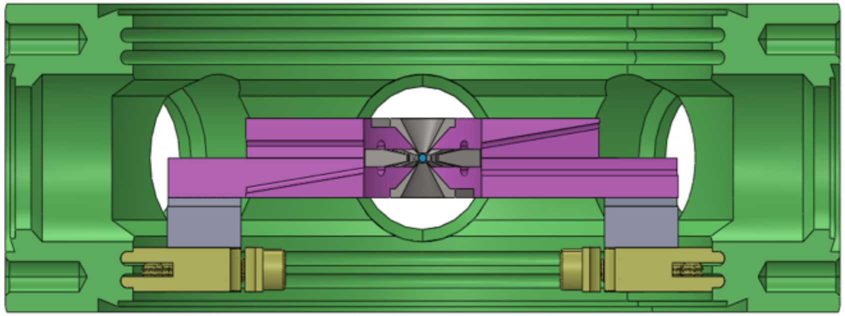
How to trap ions in 2 dimensions?

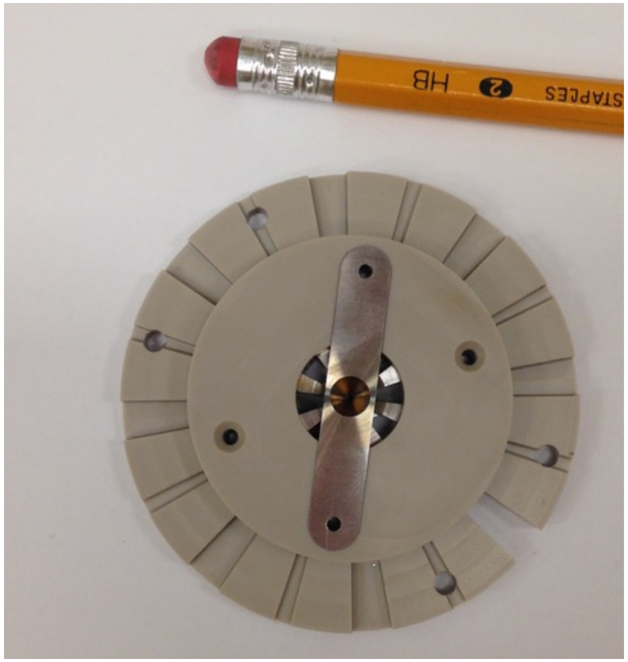


- The original Paul trap was designed to be spherically symmetric.
- It is relatively easy to break the symmetry and create the linear trap, where one principal axis is significantly weaker than the other two.
- Linear traps are the workhorses of quantum computing research due to simplicity.
- If we make one axis significantly stronger than the other two, we have a planar trap.

Oblate trap for large 2-d crystals

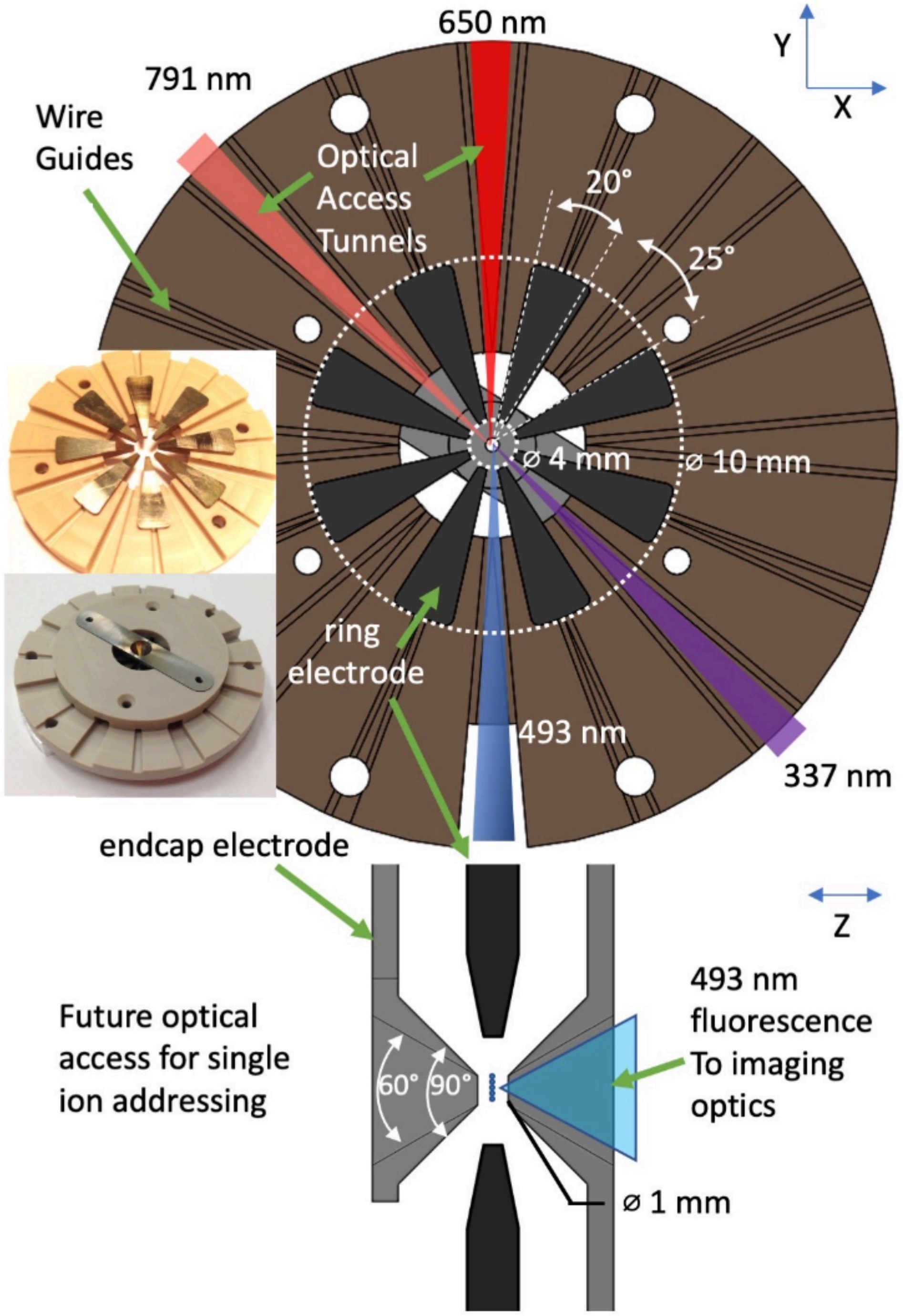






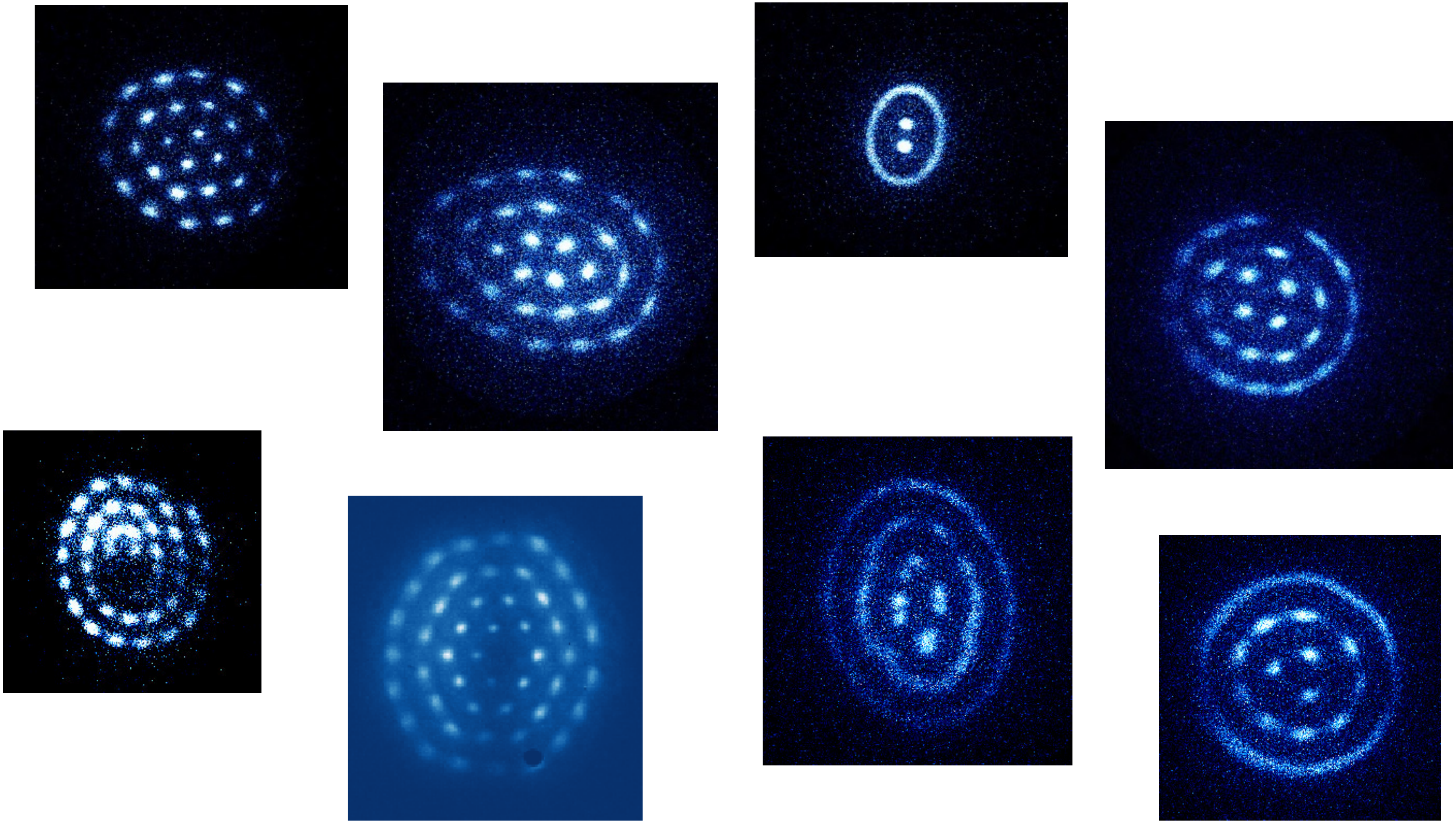
We designed and built a version of Paul trap with segmented ring electrode and hollow cone-shaped endcap electrodes for producing 2-dimensional ion crystals.

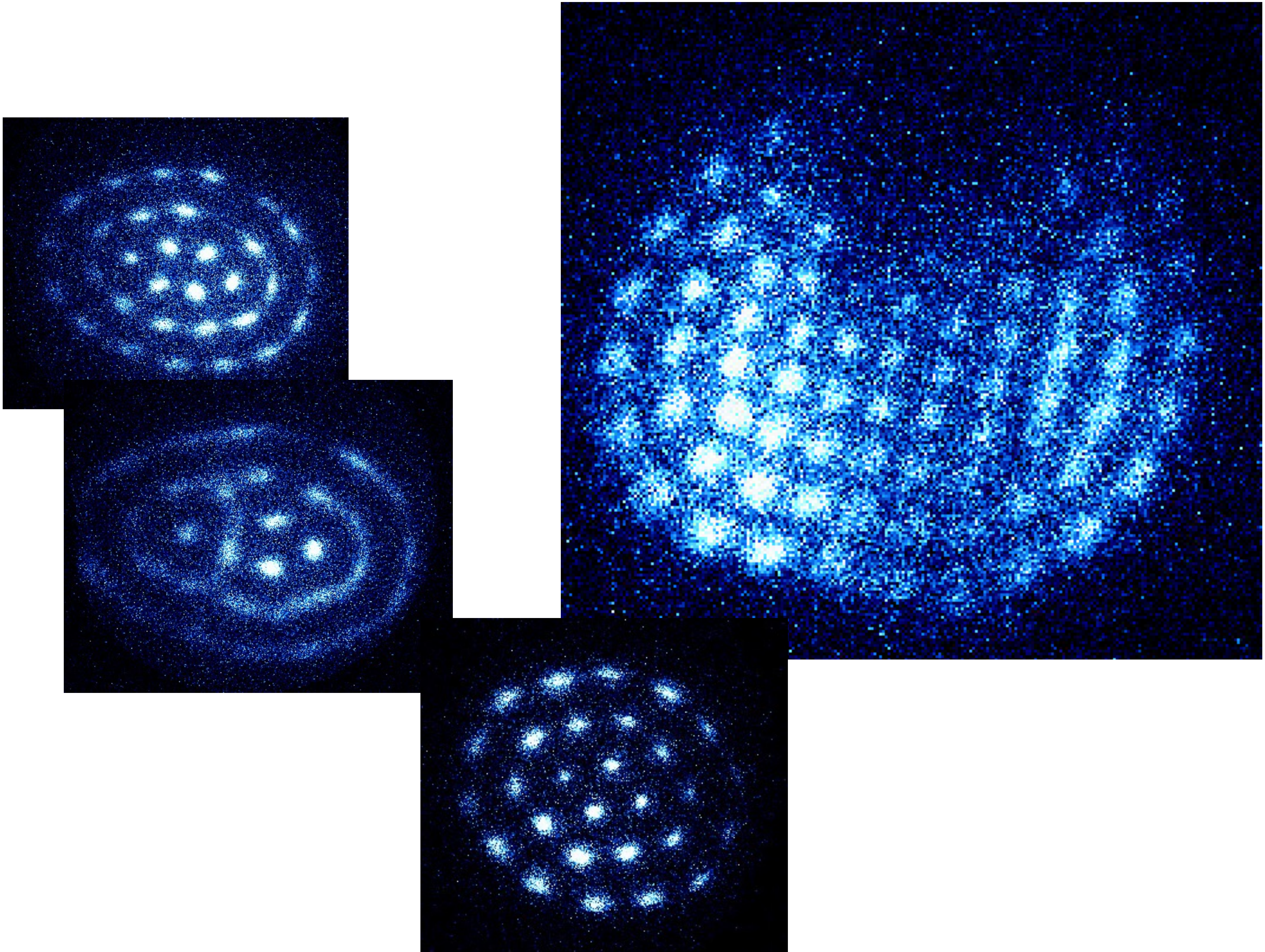
2-d trap details



- Segmented ring electrode for more control of potential shape and for micromotion compensation
- Channels for laser and atomic beam access
- High N.A. optical access through holes in the endcaps for ion imaging and individual ion addressing.
- Typical RF frequency 10 MHz at 800-1000 V amplitude to achieve crystallization in this large trap.

2-d ion crystals observed in our trap

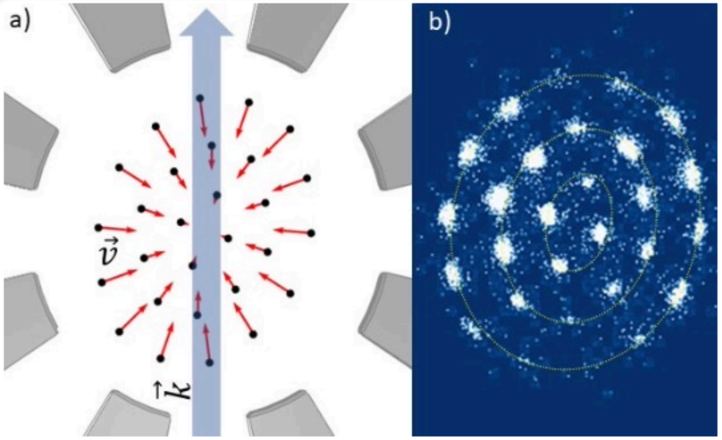




Micromotion

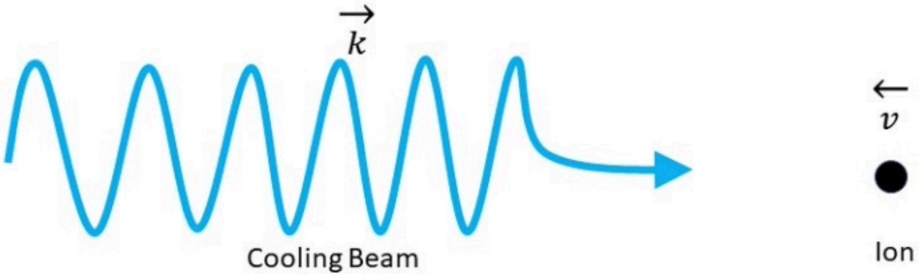
Micromotion effect on cooling

Micromotion and Doppler Cooling

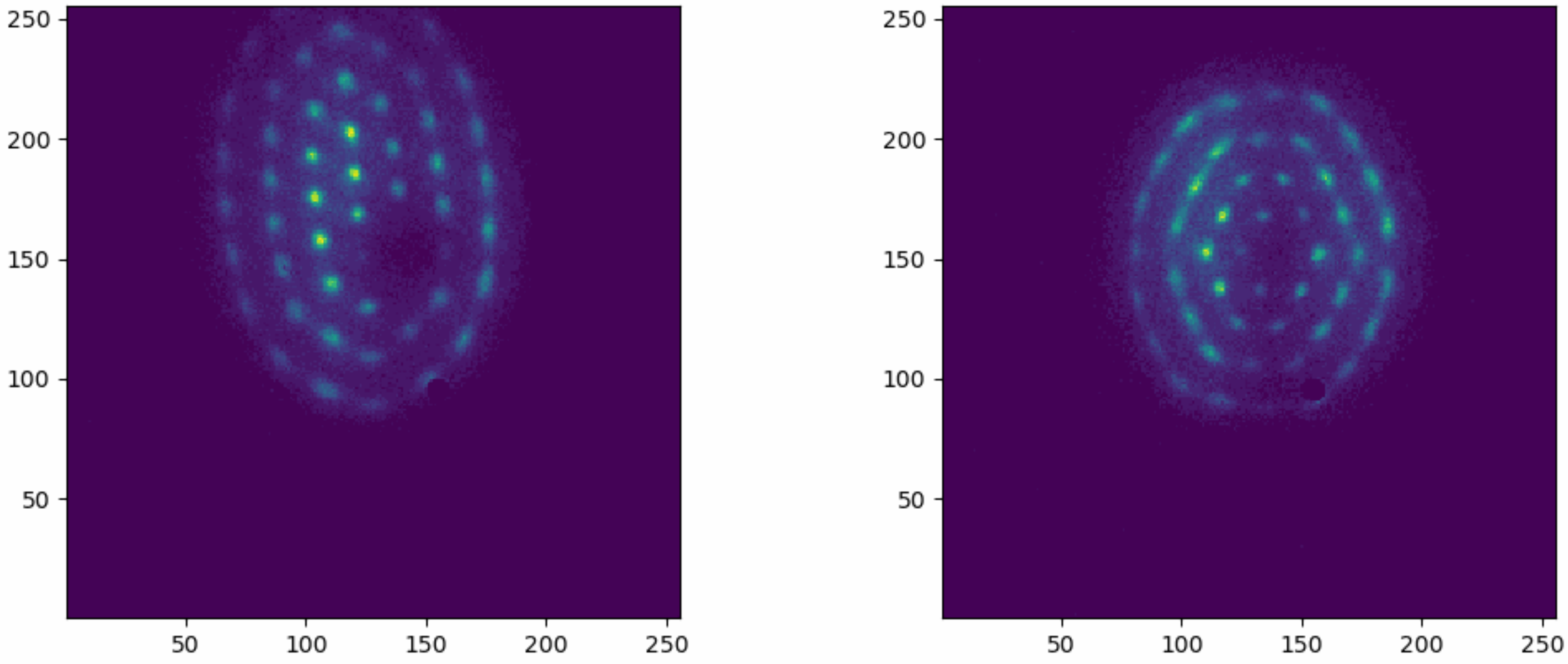


Cooling may be less good, and fluorescence across ion crystals becomes less even

Micromotion in trapped ions effects light-matter interactions due to a time-dependent Doppler shift



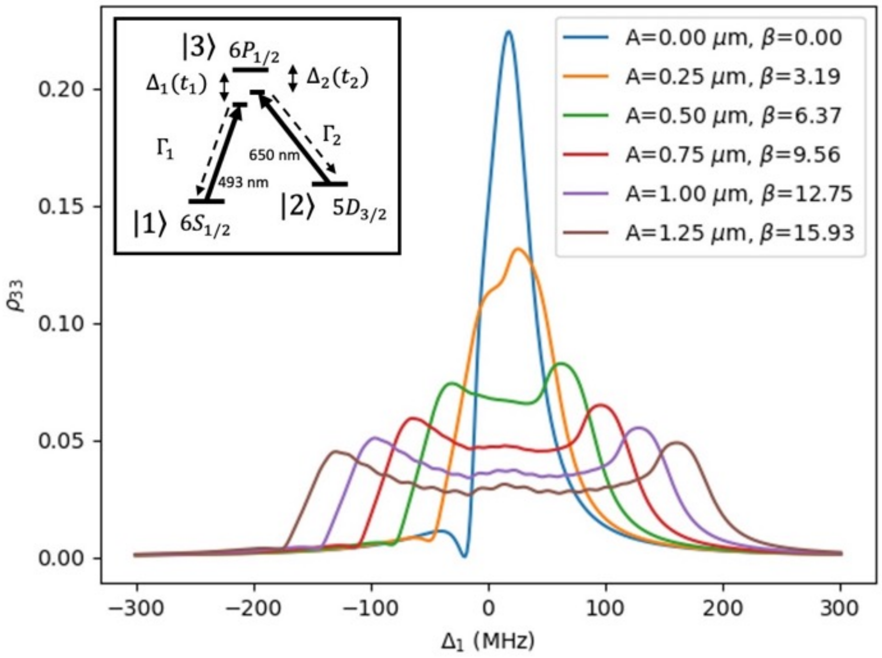
Micromotion in two dimensions



Depending on their position in the crystal, ions experience different amplitude of micromotion (proportional to the distance from the trap center). Their velocities and thus Doppler shifts are thus also different.

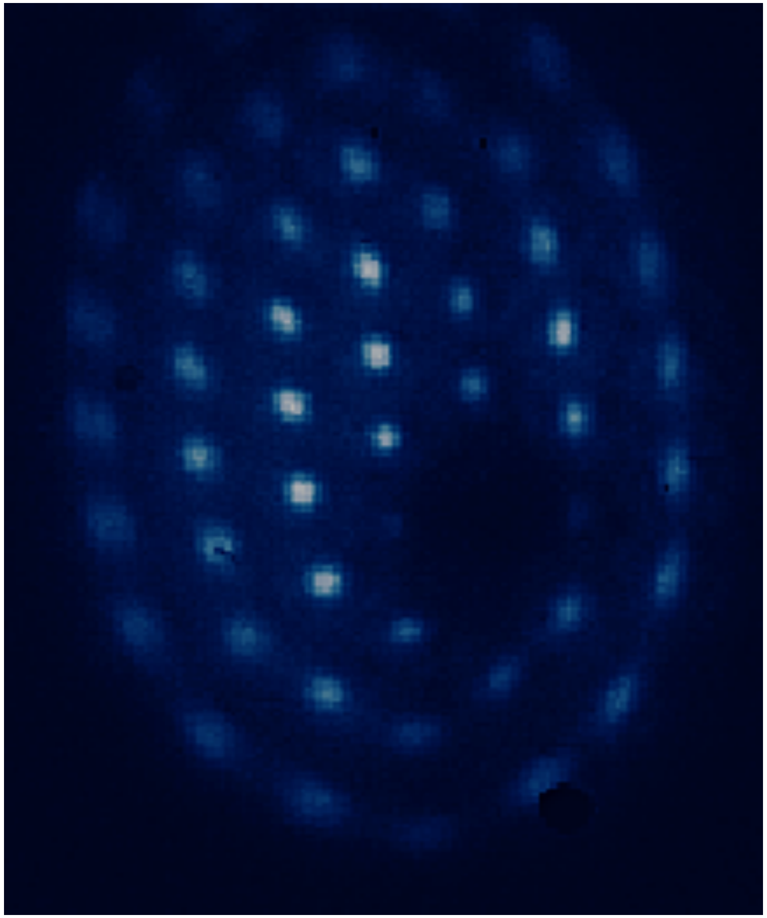
Laser cooling in presence of micromotion

Two-tone laser cooling

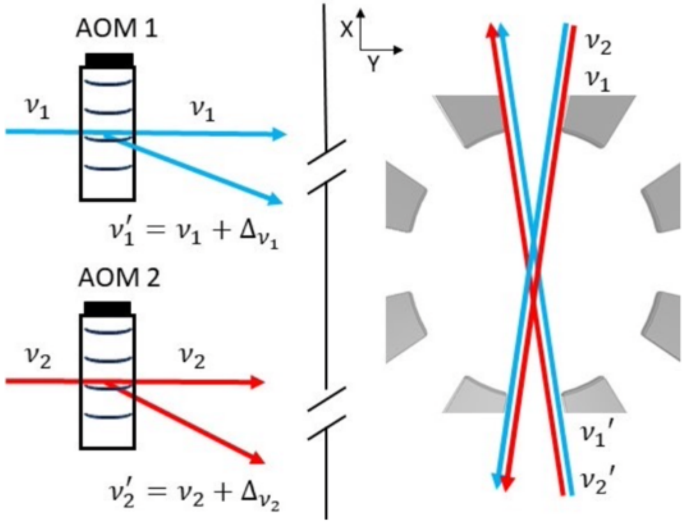


Micromotion modulates the frequency of the Doppler-cooling laser and makes the cooling process less efficient – or not a cooling process at all! This limits the size of the 2-d ion crystal that can be cooled

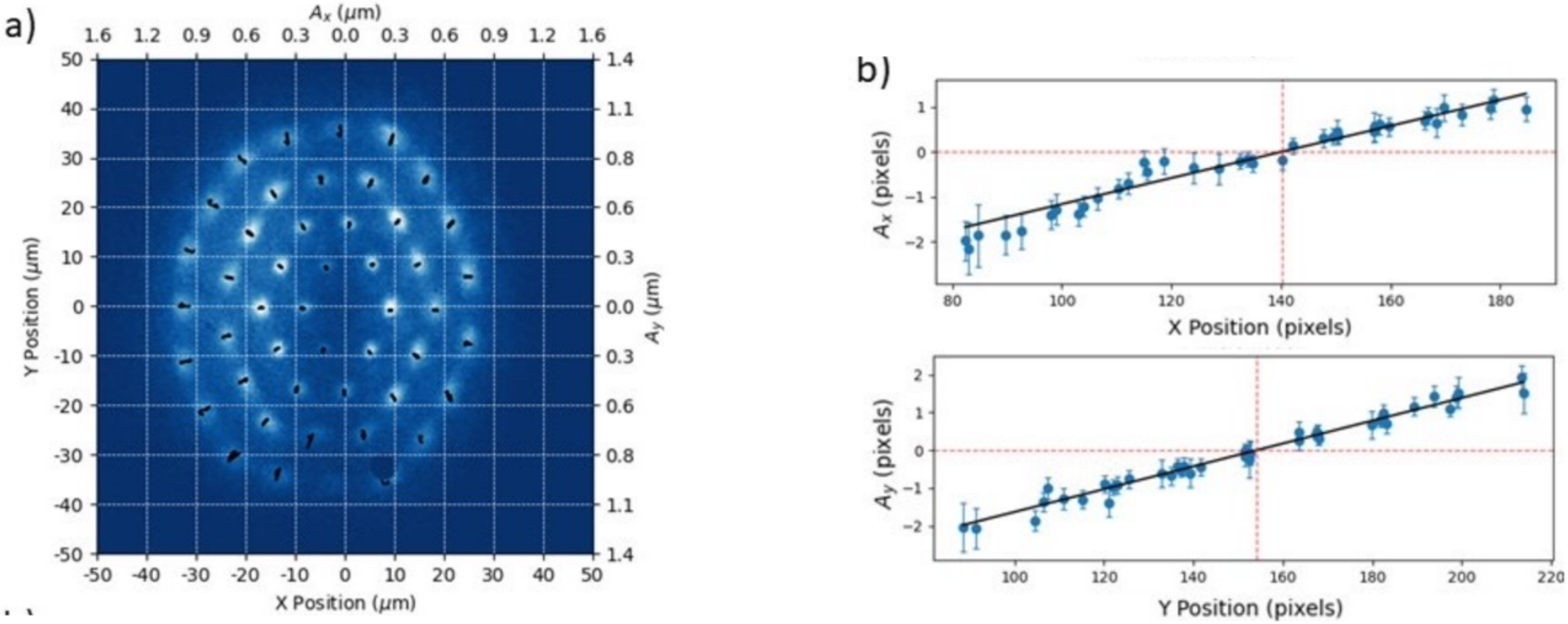
We use two tones of the Doppler-cooling laser to more efficiently cool ions in 2-d, and stabilize a 54-ion crystal



Two-tone laser cooling



Two laser tones separated by up to 80-150 MHz are derived by sending the light through an acousto-optic modulator. The undeflected beam and the 1st order diffracted beam are combined and sent to the trap.



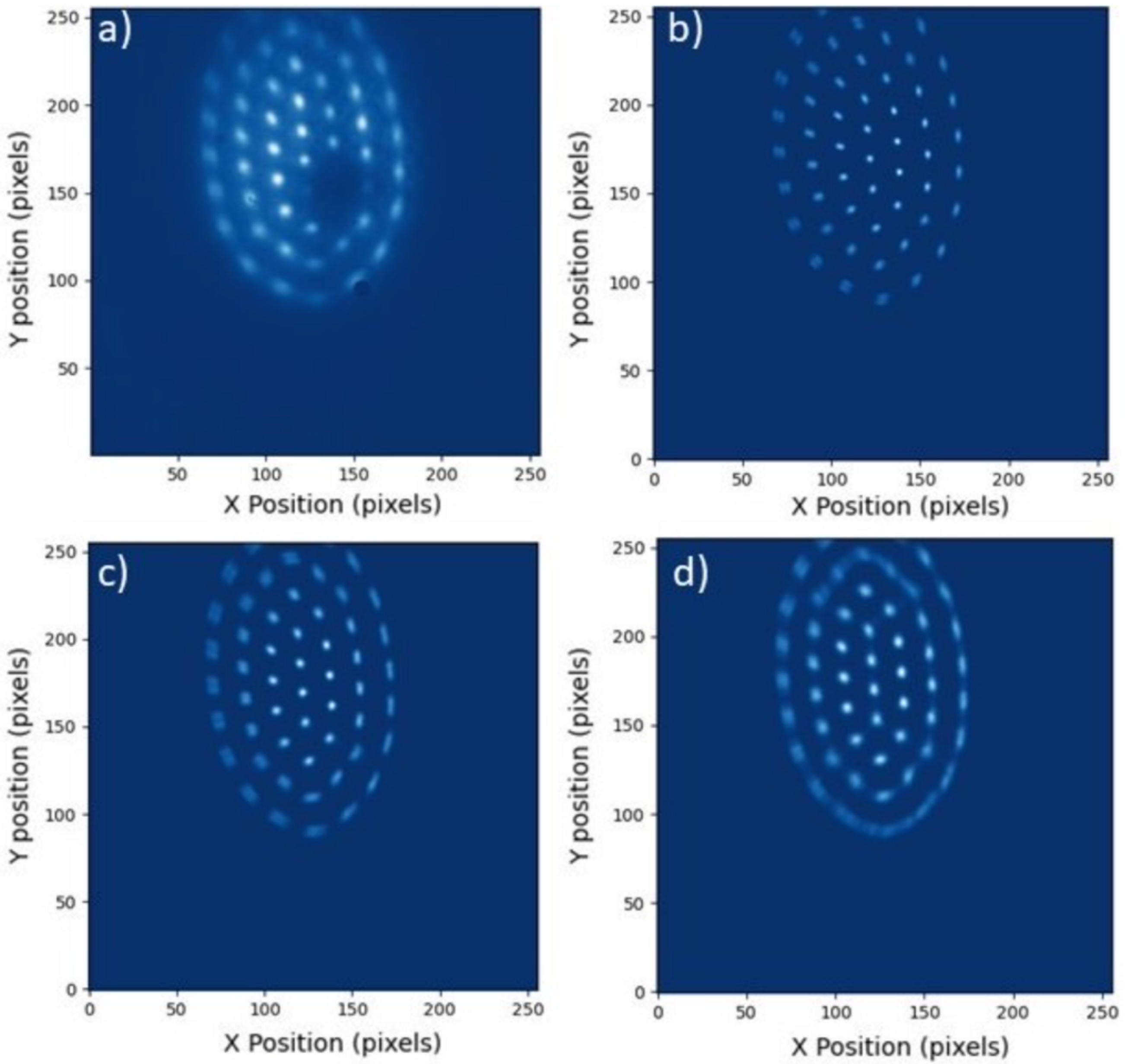
Two-tone laser cooling results and simulations

Panel (a): our best result with a 54-ion crystal.

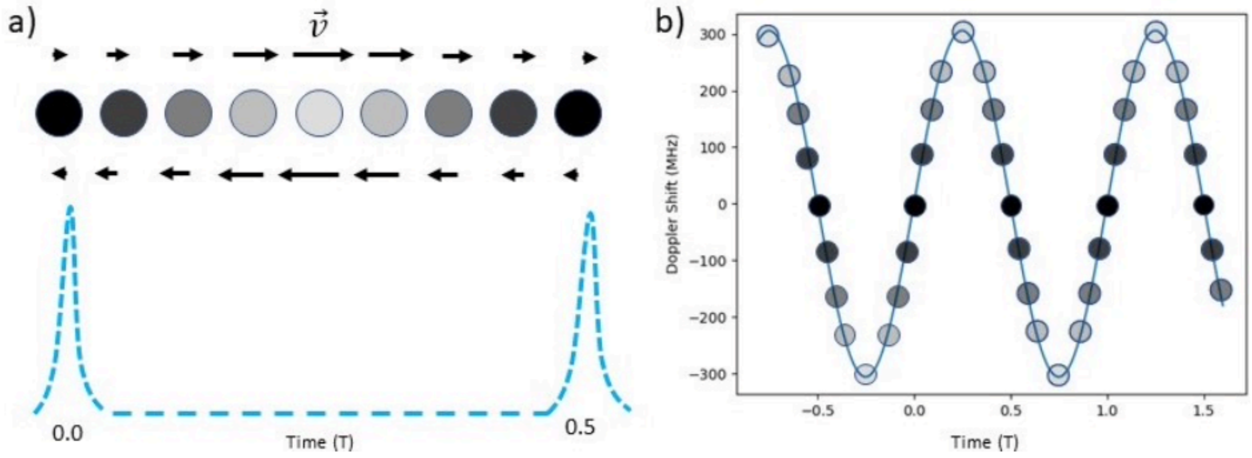
Panels (b-d): numerical simulations of a 54-ion crystal at different temperatures.

We do not have a good thermometer for this system experimentally, so the temperature estimate of ~22 mK is based on the simulations.

This temperature is about 10 times the doppler cooling limit for a single ion.

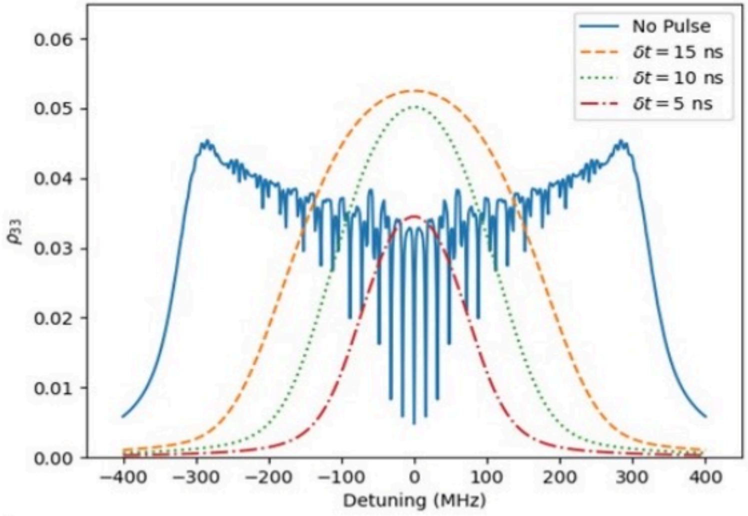


Micromotion-synchronized cooling



What if we only illuminate the ions while the micromotion velocity is near 0?

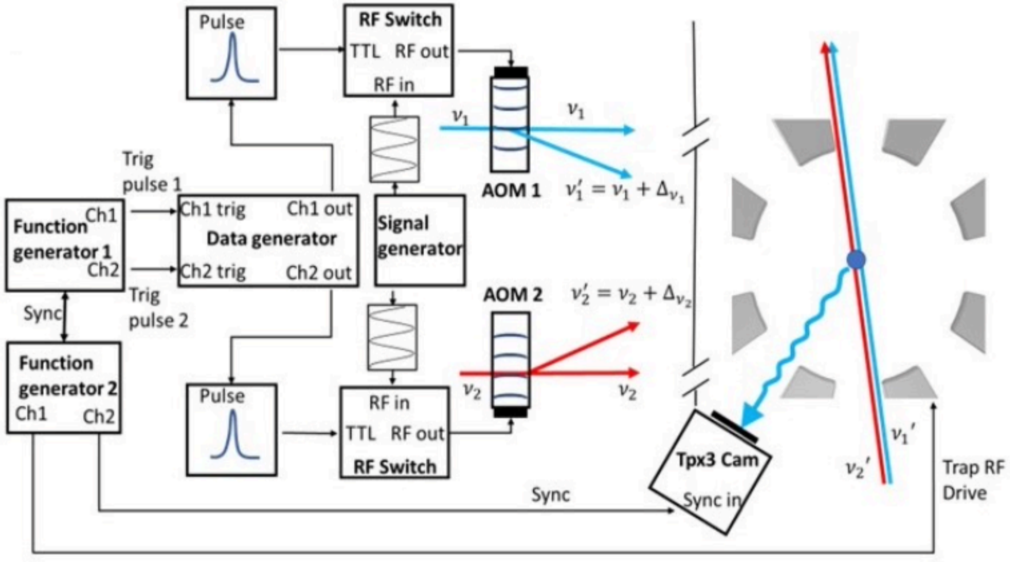
Fixed amplitude of micromotion



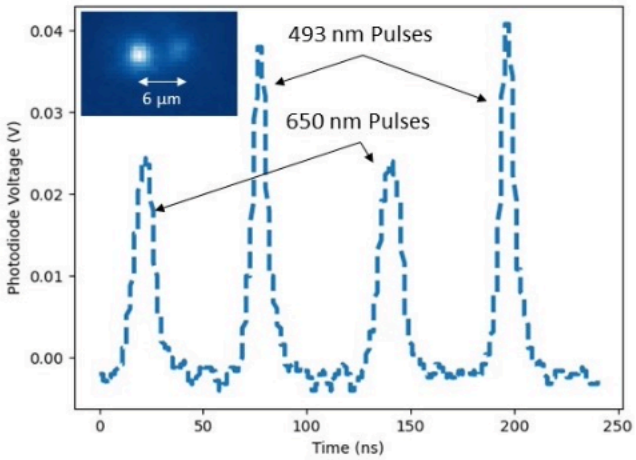
Theoretical absorption spectra for an ion having a fixed (and very large) micromotion amplitude for the CW cooling (blue) and various pulse durations. Eventually, as pulses get too fast, the line widths becomes broadened due to the pulse bandwidth.

Micromotion-synchronized cooling

Schematic of the pulsed-cooling experiment

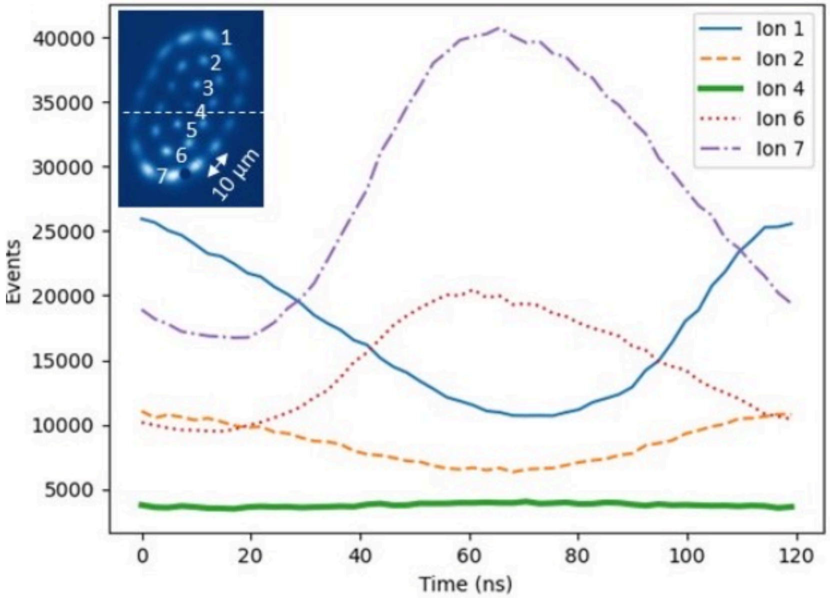


Characterization of the laser pulses



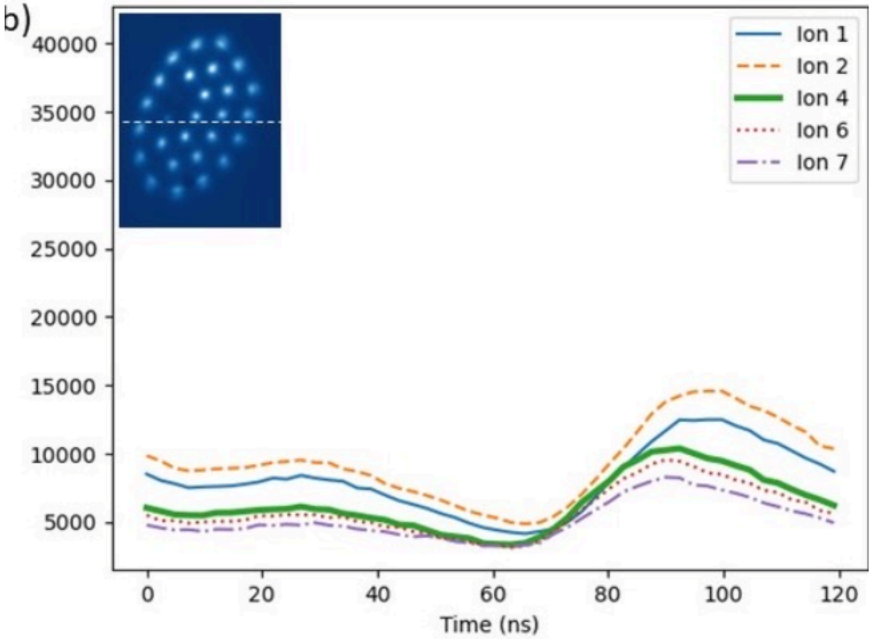
The pulses are generated by fast AOMs separately for the blue and the red lasers.
The two pulse trains are shifted by 1/2 trap RF period, and their arrival time at the ions is synchronized with the RF so that they illuminate the ions when their velocity is near zero.
This reduces the overall scatter rate, but improves the cooling.

Fluorescence profile of ions across the crystal with varying amounts of micromotion



The fluorescence profile can vary significantly with the micromotion amplitude, leading to inefficient cooling in some ions, or even heating.

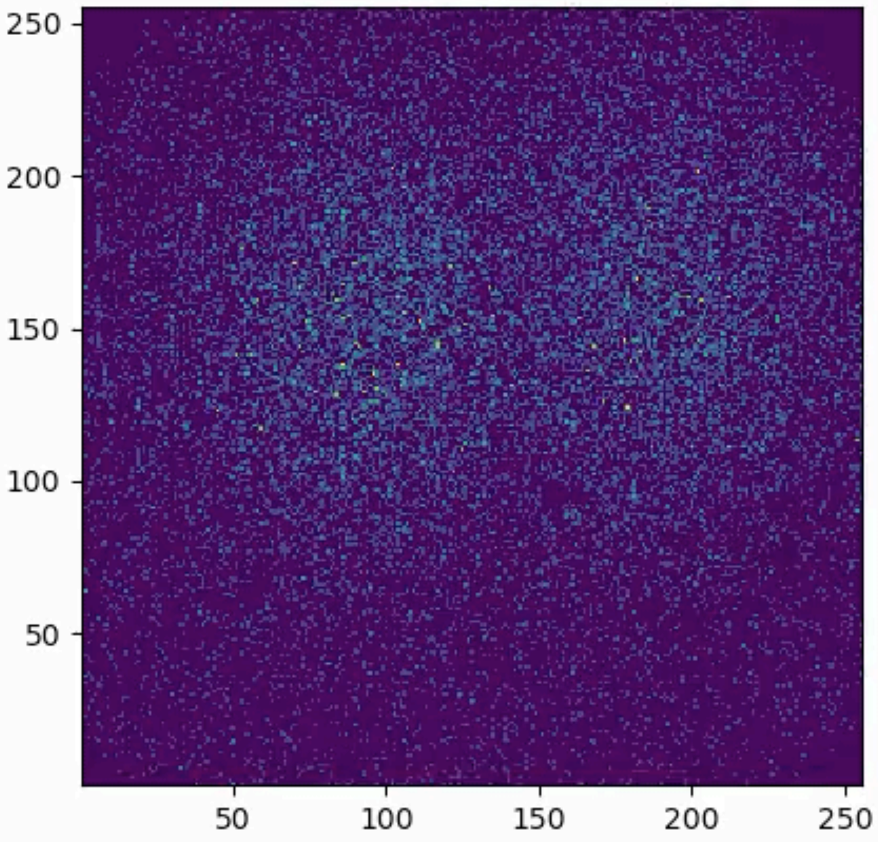
Fluorescence profile of ions across the crystal with varying amounts of micromotion, using pulsed cooling

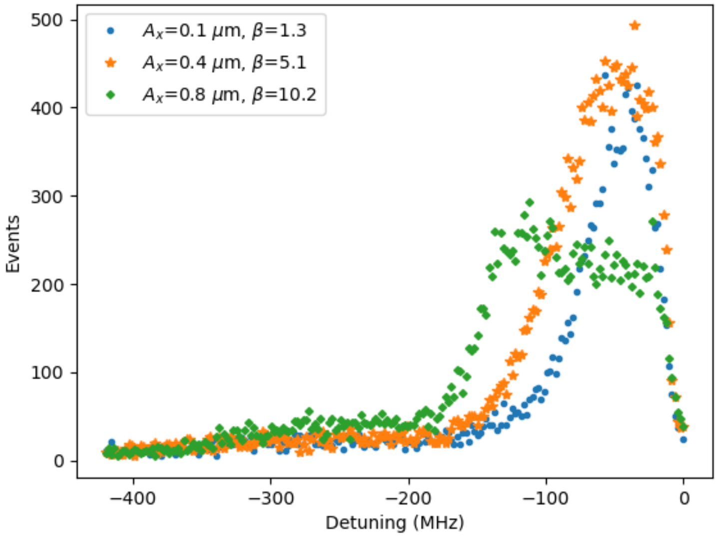


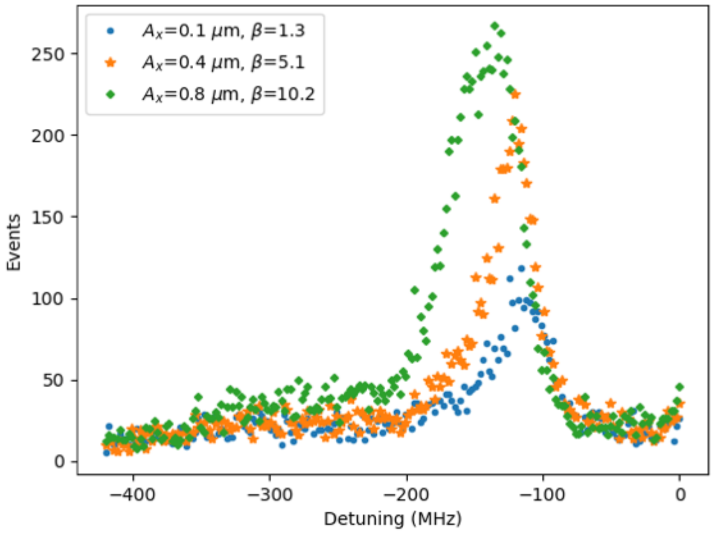
Using pulsed cooling, the fluorescence profile becomes much more even across the crystal. We can use this technique to get even cooling rates for each ion with a single beam

Time permitting…

2-d crystal melting and freezing







By scanning the Doppler-laser frequency, we observe melting and re-freezing of a 2-d ion crystal. Here, the laser frequency is tuned from above the atomic resonance to below, then back again.

Quantum jump study: history and motivation

- Quantum jumps: a 2-level quantum system which is being driven (levels are coupled) while being constantly measured. Theorized by Bohr in 1913, first observed by Dehmelt in 1986 in a single Ba+ ion.

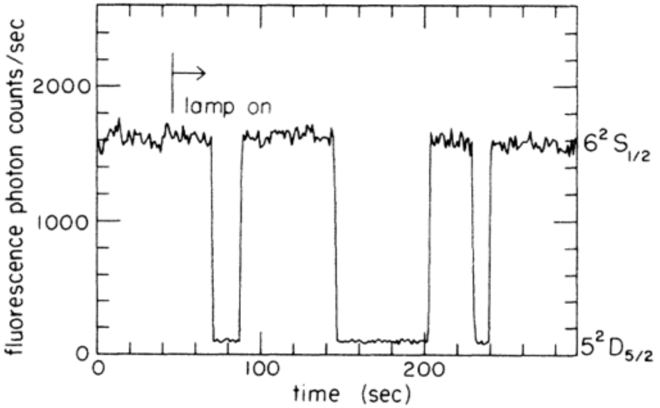
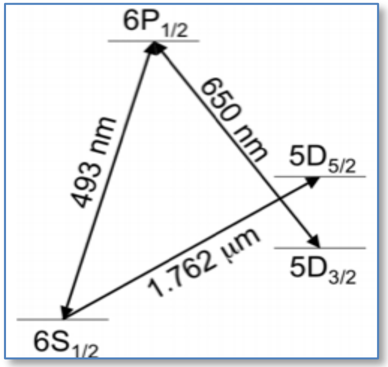
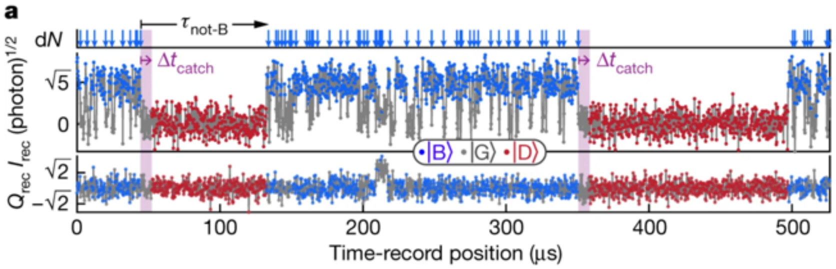


FIG. 2. A typical trace of the 493-nm fluorescence from the $6^2P_{1/2}$ level showing the quantum jumps after the hollow cathode lamp is turned on. The atom is definitely known to be in the shelf level during the low fluorescence periods.



Shelved optical electron amplifier: Observation of quantum jumps, Nagourney, Sandberg, and Dehmelt, Phys. Rev. Lett. 56, 2797 (1986)



Minev, Z., Mundhada, S., Shankar, S. et al. To catch and reverse a quantum jump mid-flight. Nature 570, 200–204 (2019).

- Yale group (Devoret, superconducting transmon qubits) in 2019 found that they can predict, and thus intercept and even reverse quantum jumps.
- We want to study this in a pristine 2-level quantum system: a single trapped ion

Quantum jump study: design considerations

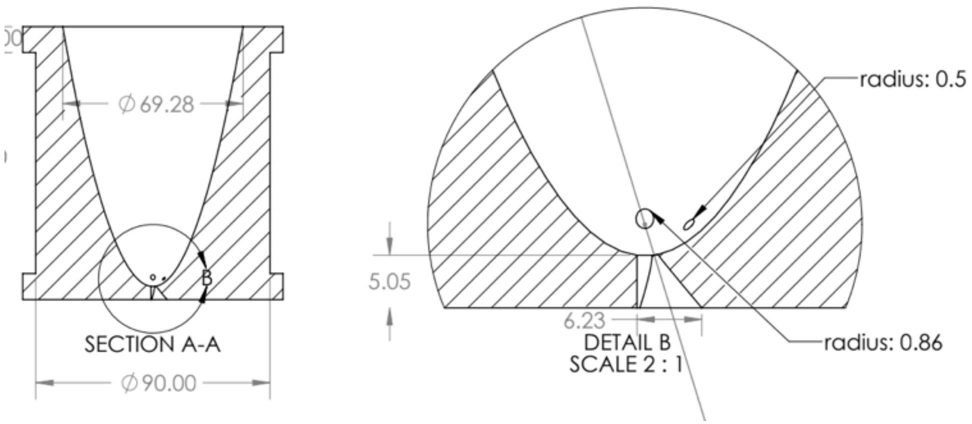
- A quantum jump in our experiment is detected as an abrupt change in ion’s fluorescence. We detect 493 nm and 650 nm photons emitted by the ion in the “bright” state, which are emitted at a rate of ~10^7 s^{-1}.

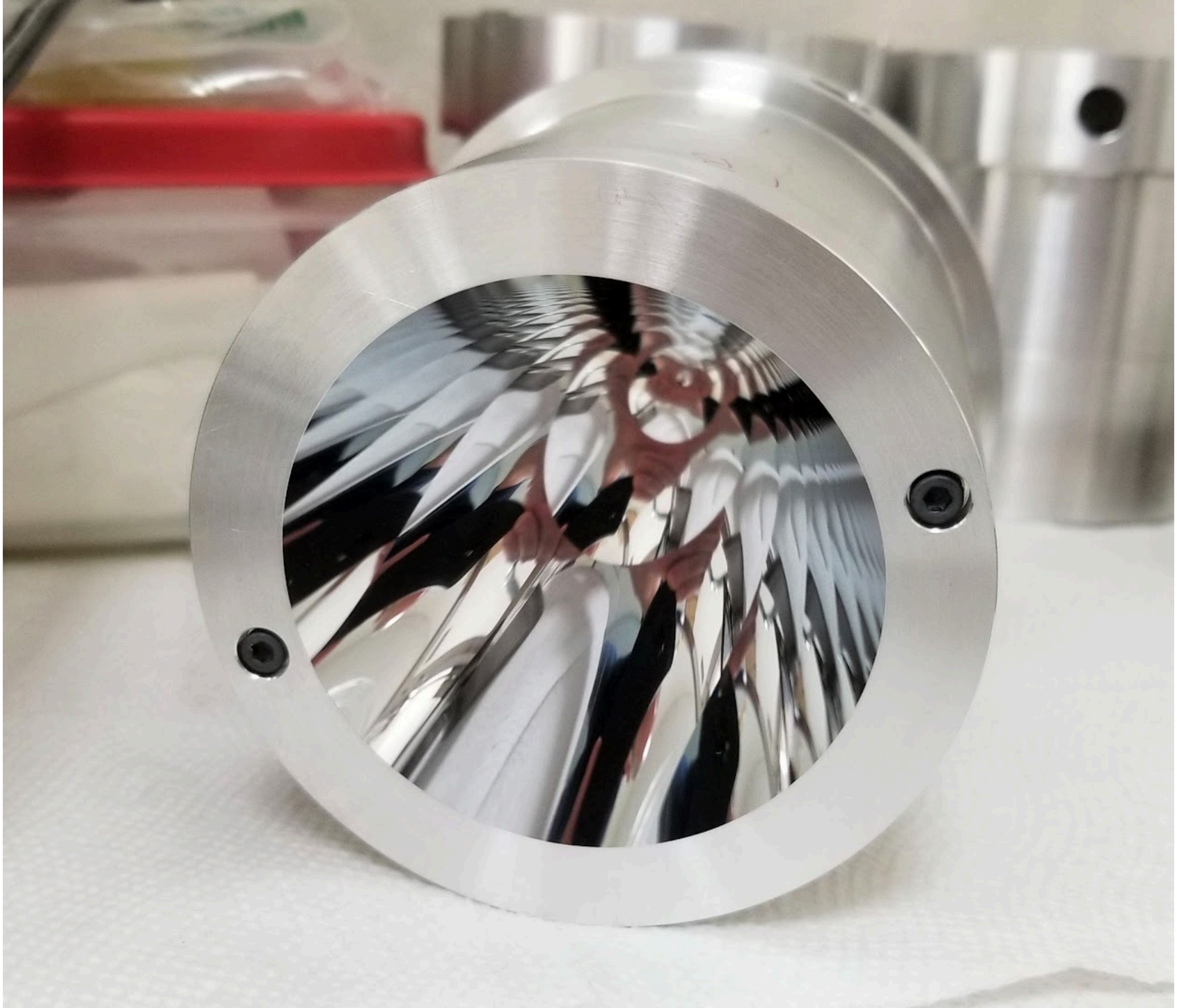
- To repeat the “catch-and-release” experiment, we need to detect at least 80% of these photons.

- Spontaneous emission is isotropic, thus we design an optical element that can intercept most of it: a deep parabolic mirror.

- Current designs promise >95% solid angle coverage. Reflectivity of the material is about 92% at these wavelengths, so >87% of the photons will be directed to a single photon detector.

- Detector: initially, APD (QE > 50%), later SNSPD (QE > 95%).





UW ion trappers

Thank you!