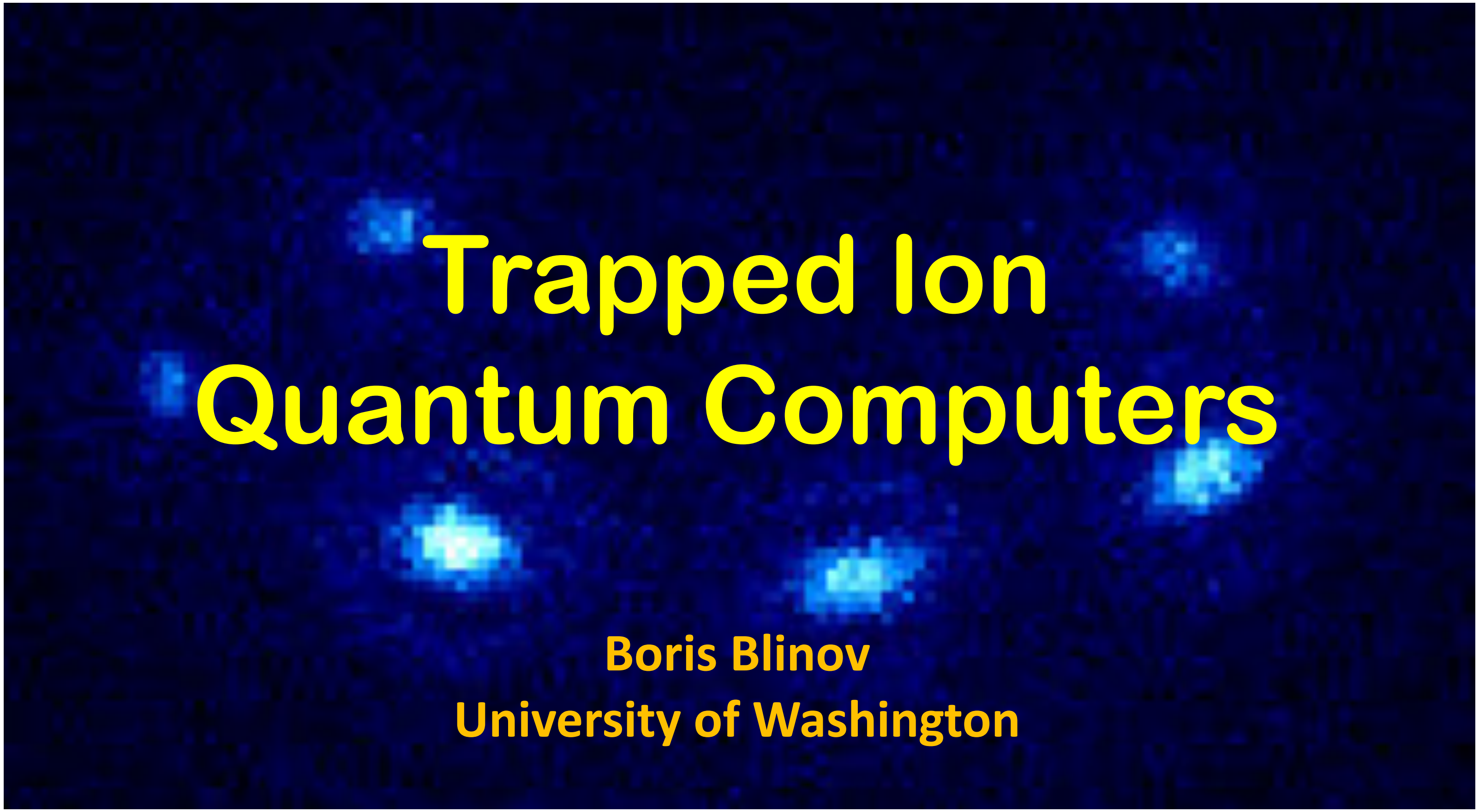
MUSIQC



Trapped Ion Quantum Computers

Boris Blinov
University of Washington

IARPA

Outline

- Qubits and quantum computing
- Ion qubits, ion traps and architectures
- Ion-photon and remote-ion quantum gates
- MUSIQC architecture: ELU modules with photonic quantum link
- Interfacing trapped ion and solid state qubits
- 2-dimensional ion crystals for simulations

“There's Plenty of Room at the Bottom”
(1959 APS annual meeting)

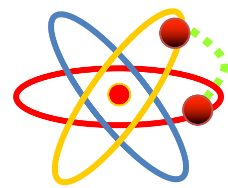
Richard Feynman

“When we get to the very, very small world – say circuits of seven atoms - we have a lot of new things that would happen that represent completely new opportunities for design. **Atoms on a small scale behave like nothing on a large scale, for they satisfy the laws of quantum mechanics…**”

THE GOLDEN RULES OF QUANTUM MECHANICS

1. Quantum objects are waves and can be in states of superposition……

"quantum bit": $\alpha|\mathbf{0}\rangle + \beta|\mathbf{1}\rangle$



2. …… as long as you don't look!

$\alpha|\mathbf{0}\rangle + \beta|\mathbf{1}\rangle$ → $|\mathbf{0}\rangle$ or $|\mathbf{1}\rangle$

Massive storage and parallelism

- One qubit: $|\psi\rangle = (1/2)^{1/2} (|0\rangle + |1\rangle)$
- Two qubits: $|\psi\rangle = (1/2) (|0\rangle + |1\rangle)\times(|0\rangle + |1\rangle) =$

  $$(1/2) (|00\rangle + |01\rangle + |10\rangle + |11\rangle)$$

  $$(1/2) (\text{“0”} + \text{“1”} + \text{“2”} + \text{“3”})$$

- ……………..
- N qubits: $|\psi\rangle = (1/2)^{N/2} (|0\rangle + |1\rangle)\times(|0\rangle + |1\rangle)\times\ldots =$

  $$(1/2)^{N/2} (|00..0\rangle + |0..01\rangle + |0..10\rangle \ldots + |11..1\rangle)$$

  $$(1/2)^{N/2} (\text{“0”} + \text{“1”} + \text{“2”} +\ldots+ \text{“}2^N\text{-1”})$$

- Mere 1000 qubits can store **all numbers** between 0 and $2^{1000}-1 \approx 10^{301}$ >> number of atoms in Universe!

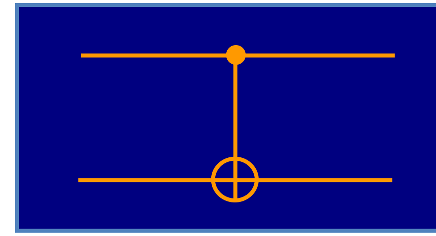
The Entanglement

- A particular superposition state of a complex quantum system which cannot be reduced to a product state of the components of the system. Simplest case: two qubits:

$$|\psi\rangle = |0\rangle|0\rangle + |1\rangle|1\rangle$$

- One consequence: measurement of one part of the system yields information about other part(s) of the system without directly measuring those.

Quantum CNOT gate

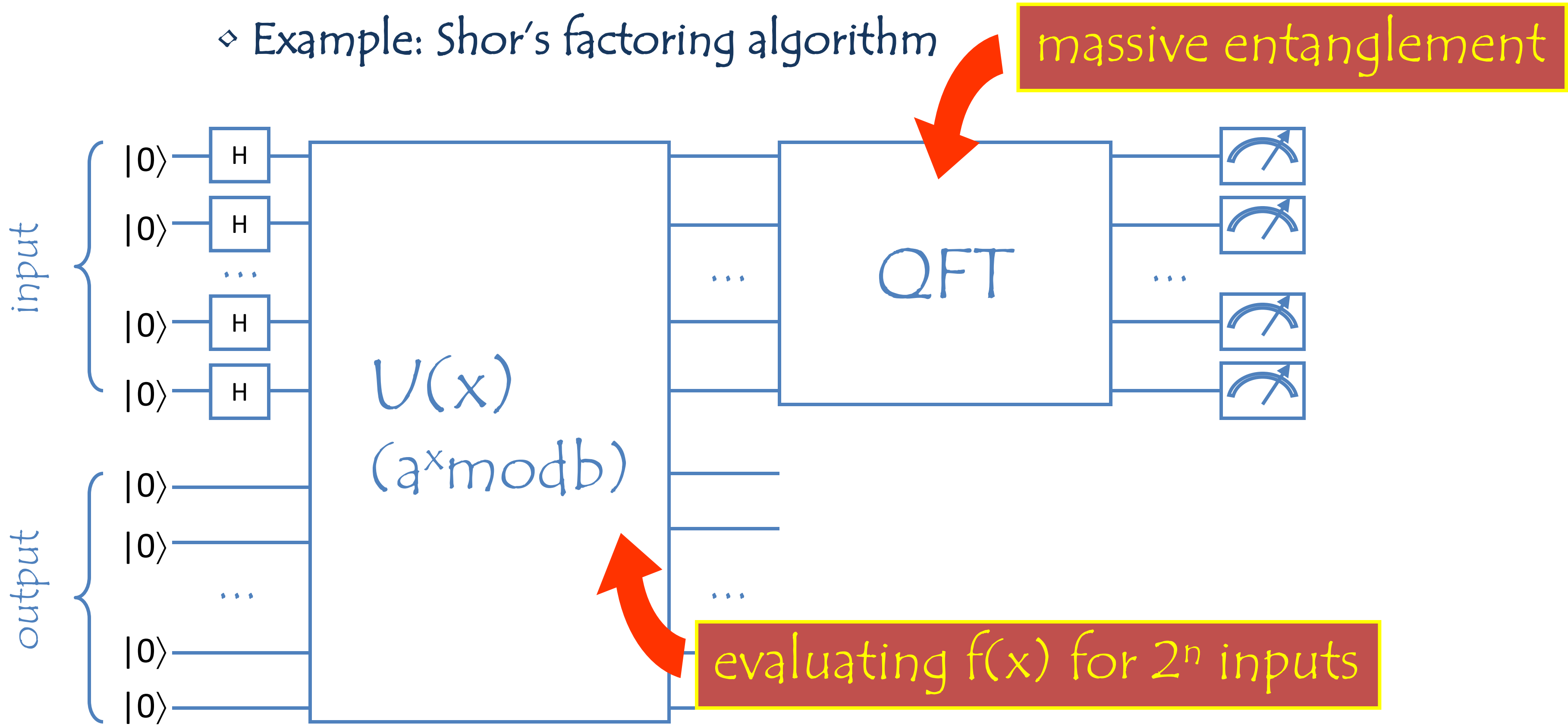


control qubit	target qubit	result
$\|0\rangle$	$\|0\rangle$	$\|0\rangle\ \|0\rangle$
$\|0\rangle$	$\|1\rangle$	$\|0\rangle\ \|1\rangle$
$\|1\rangle$	$\|0\rangle$	$\|1\rangle\ \|1\rangle$
$\|1\rangle$	$\|1\rangle$	$\|1\rangle\ \|0\rangle$
$\alpha\|0\rangle + \beta\|1\rangle$	$\|0\rangle$	$\alpha\|0\rangle\|0\rangle + \beta\|1\rangle\|1\rangle$

Entangled state!

Quantum computing in nutshell

- The power of quantum computing is twofold:
  - parallelism and
  - entanglement
- Example: Shor's factoring algorithm



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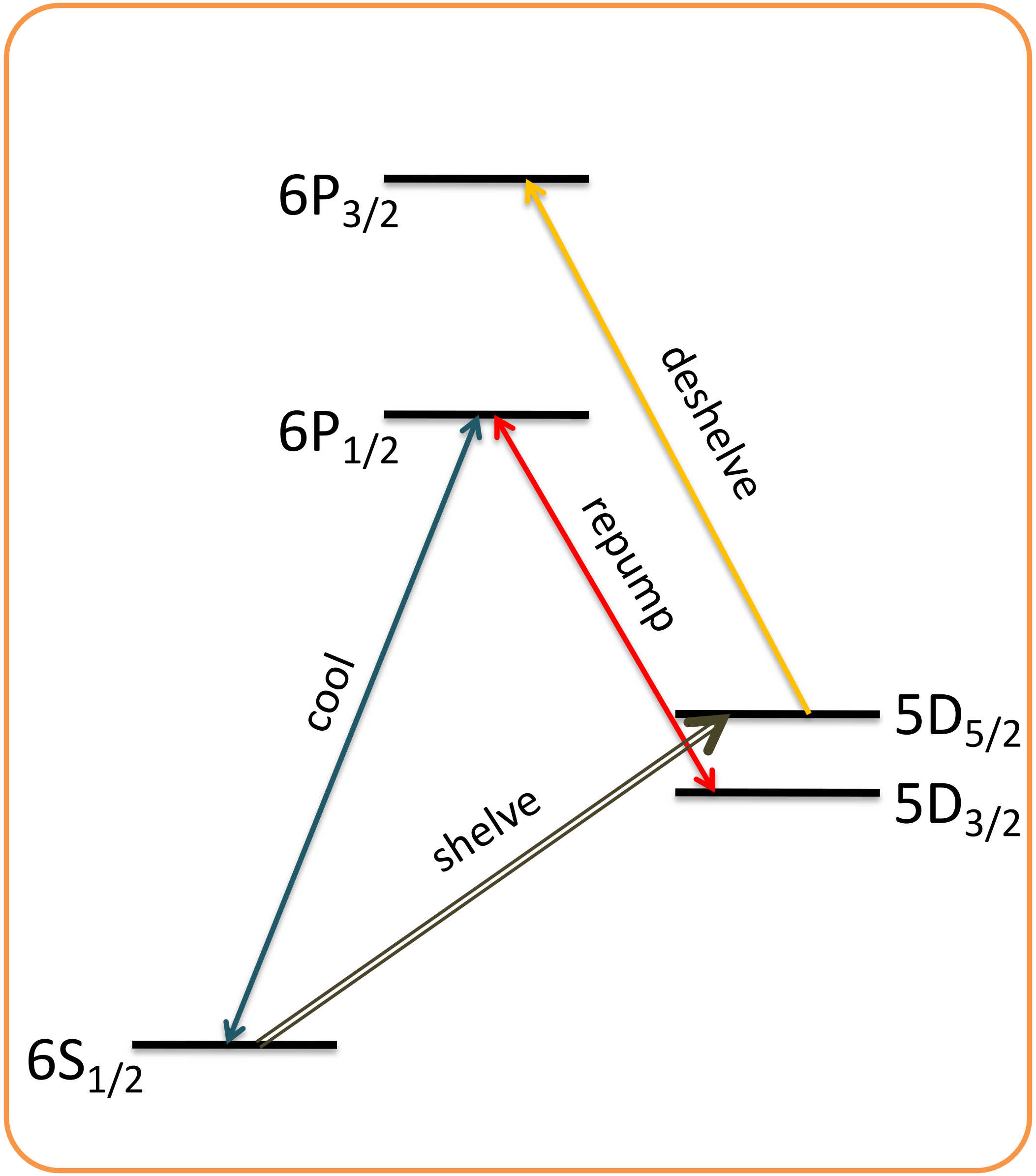
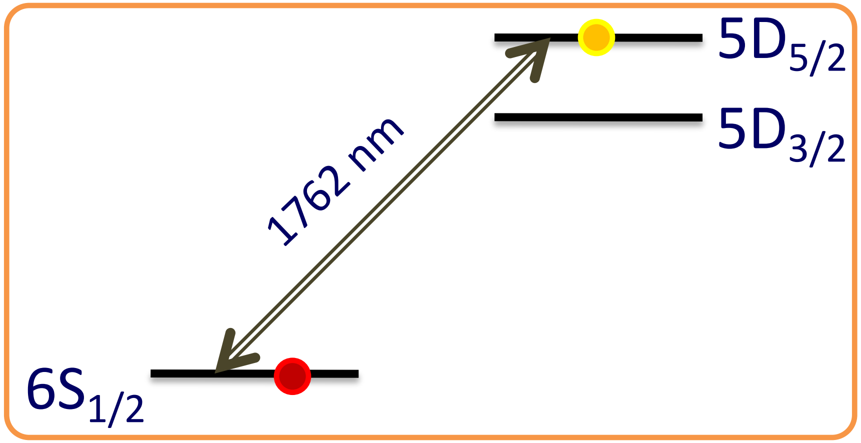
Ba ion



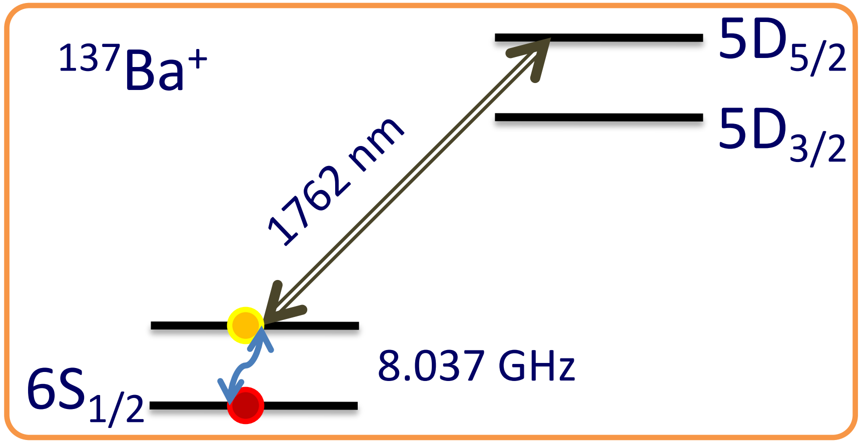
- laser cooling: 493 nm and 650 nm
- qubit initialization: optical pumping
- qubit control: some form of EM waves
- qubit detection: state-dependent fluorescence

Now, the qubits

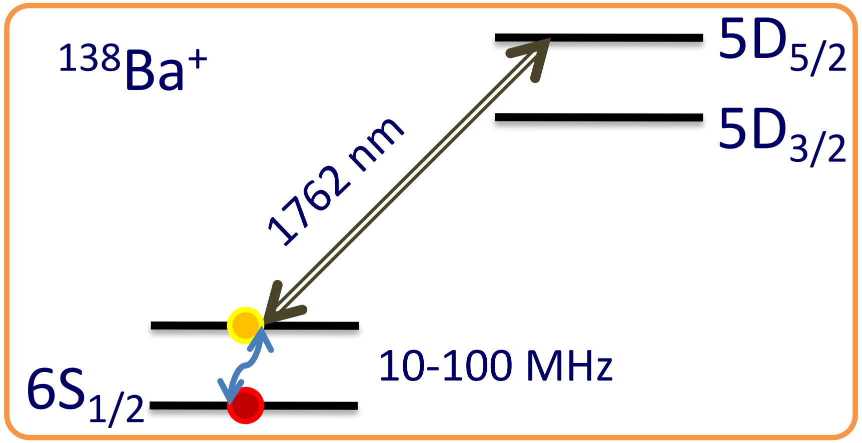
- optical: S-D transition



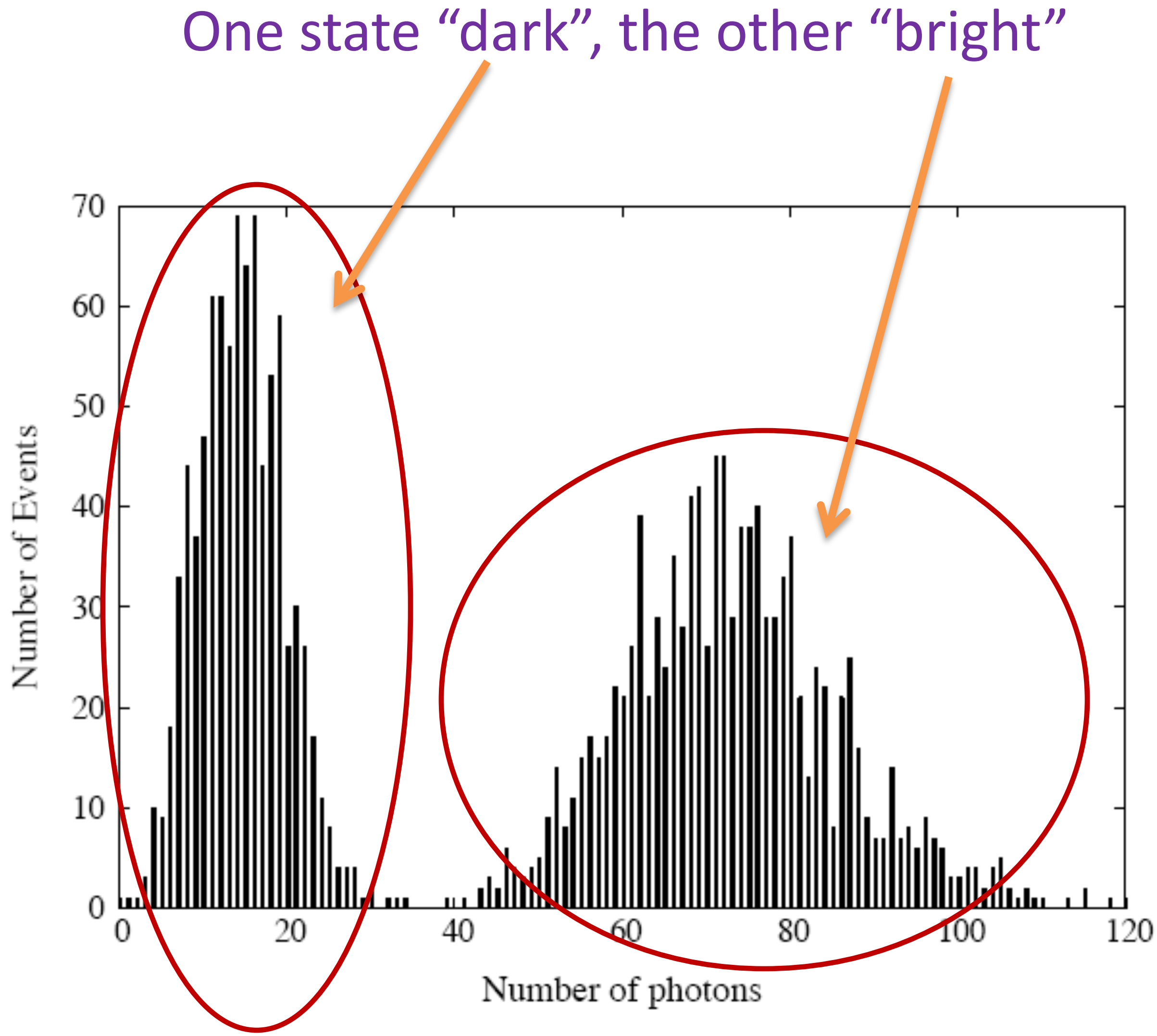
- hyperfine: ground state "clock" states



- Zeeman: ground state Zeeman states

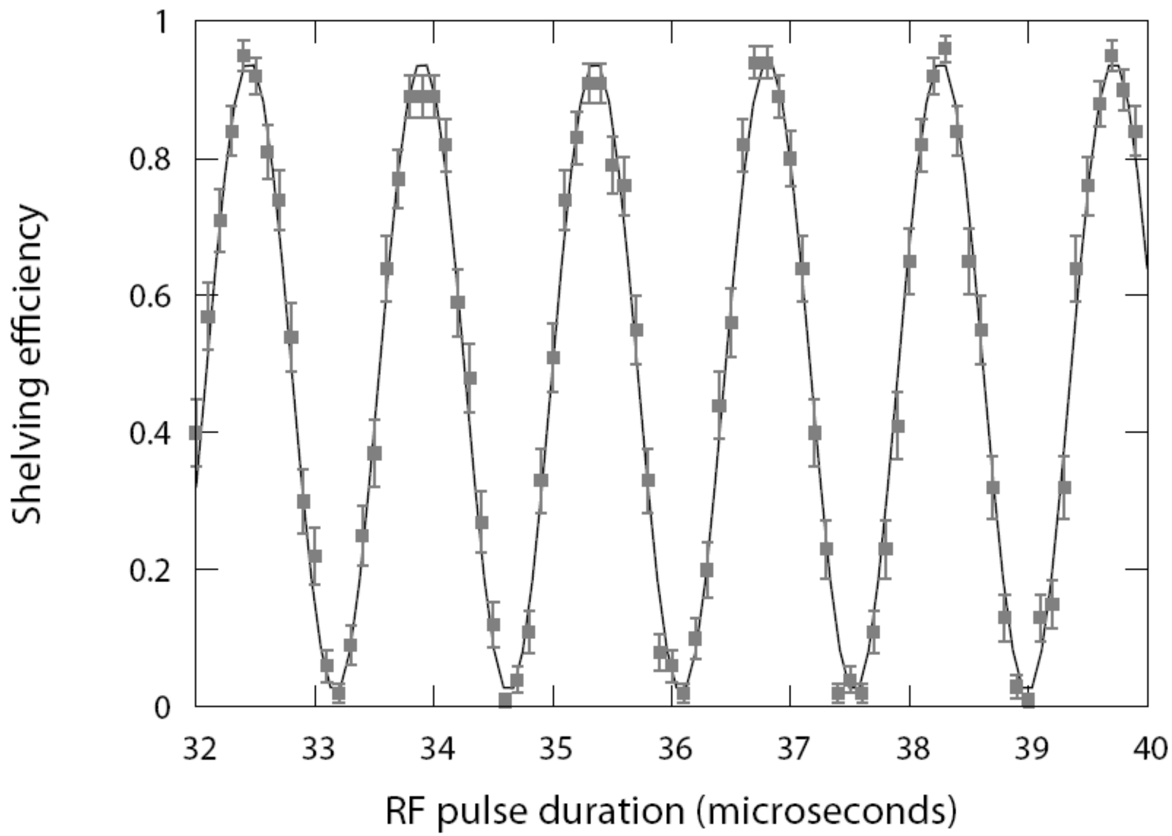


Whatever qubit, detection is the same

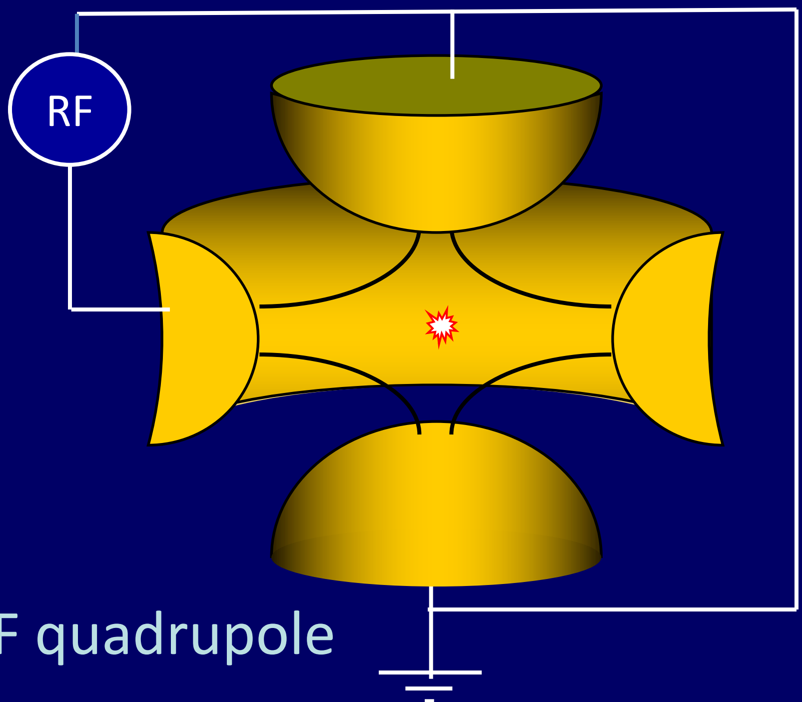


Single qubit control

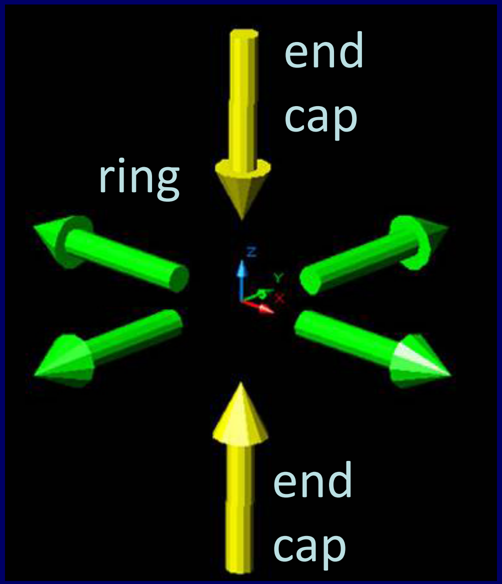
We observe Zeeman qubit coherence times of a few milliseconds, sufficient for >1000 Rabi flops in our present system. This is without any magnetic shielding or active error correction.

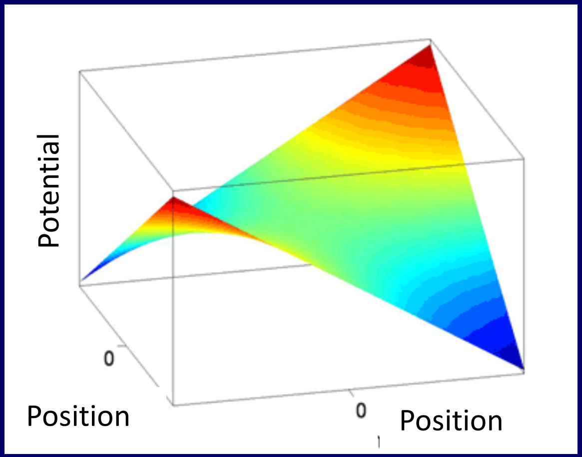


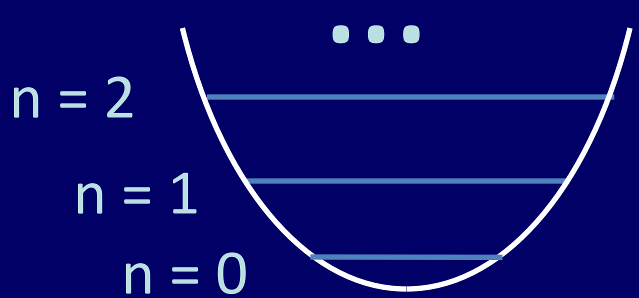
RF (Paul) ion trap



3-d RF quadrupole



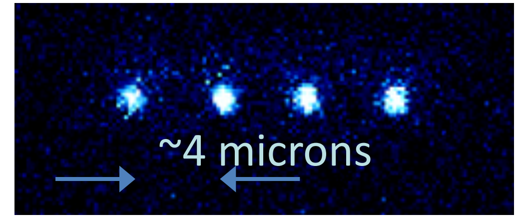




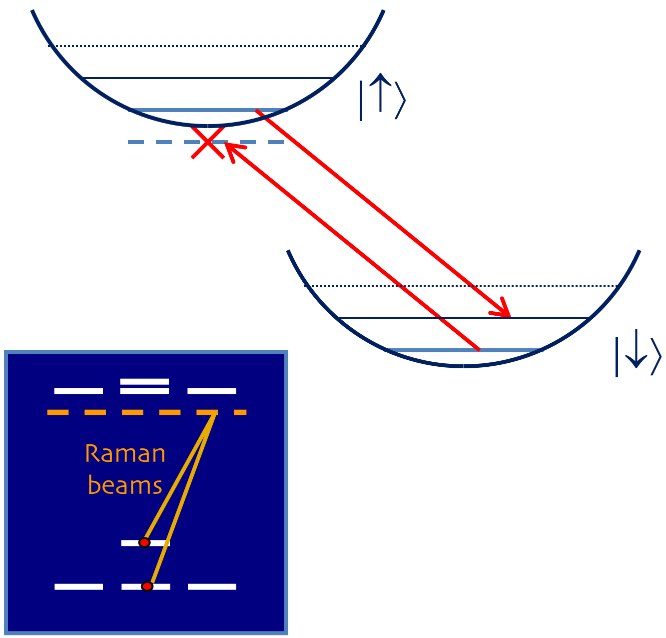
harmonic potential

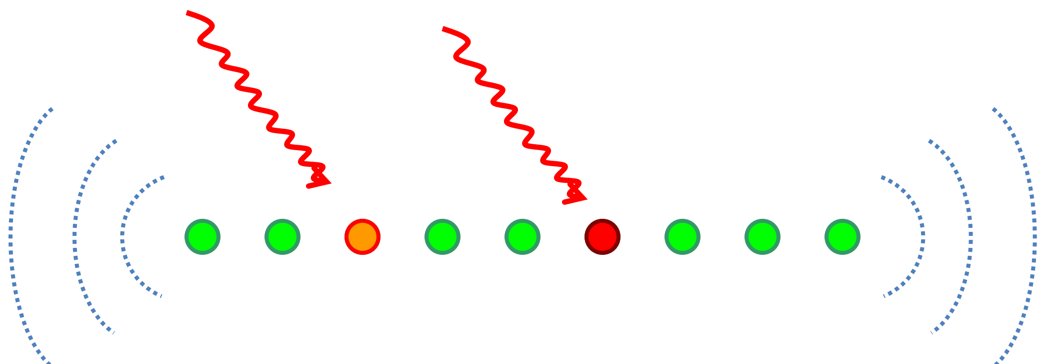
Cirac-Zoller architecture

Ions are too far apart, so their spins do not talk to each other directly.



To create an effective spin-spin coupling, “control” spin state is mapped on to the motional “bus” state, the target spin is flipped according to its motion state, then motion is remapped onto the control qubit.





Cirac and Zoller, *Phys. Rev. Lett.* **74**, 4091 (1995)

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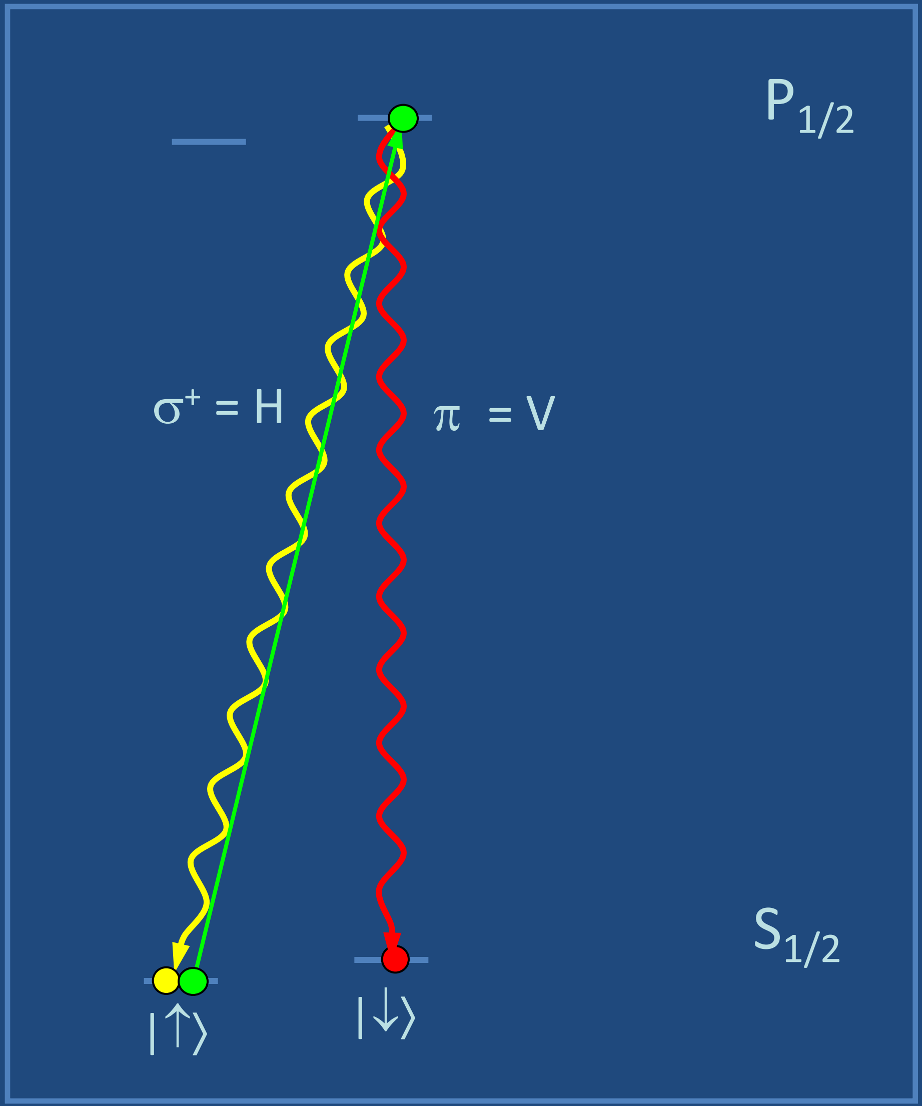
Ion-photon entanglement via spontaneous emission

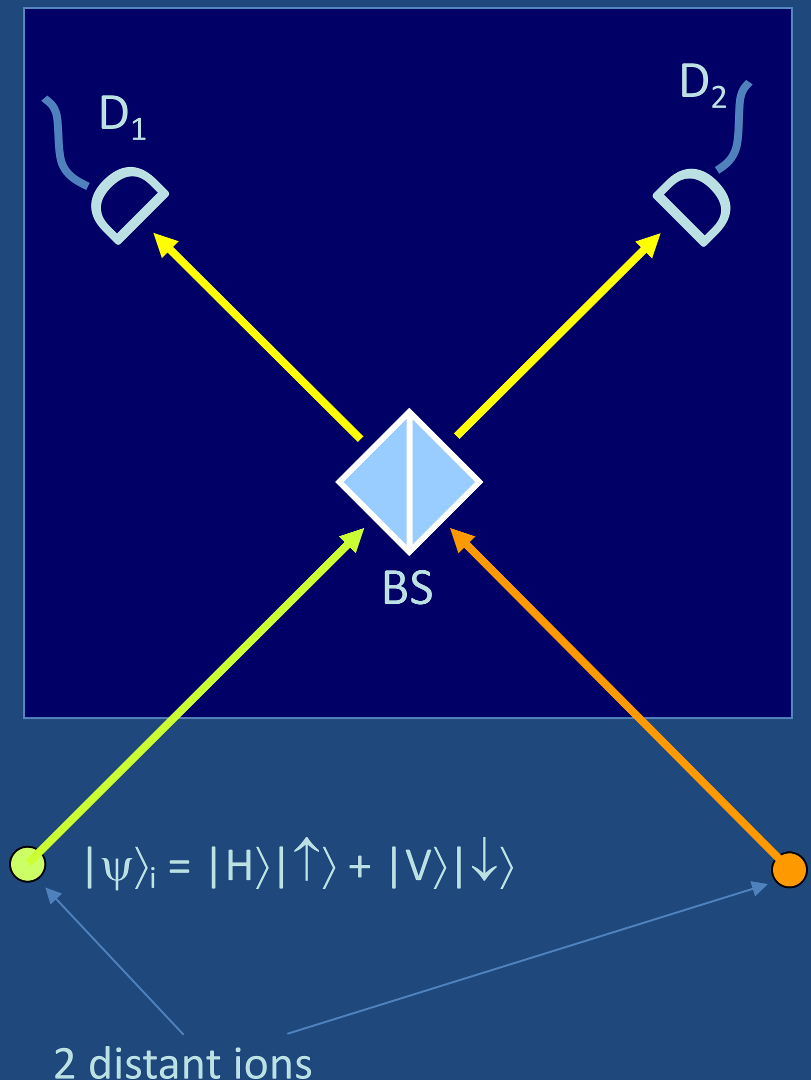


$$|\psi\rangle = |H\rangle|\uparrow\rangle + |V\rangle|\downarrow\rangle$$

- This process is probabilistic – success occurs only when the photon is collected (solid angle small) and detected (detection efficiency small, too)
- But a heralded entanglement of ions is possible using this probabilistic process!

Remote Ion Entanglement

using entangled ion-photon pairs



Coincidence only if photons in state:

$$|\Psi^-\rangle = |H\rangle_1 |V\rangle_2 - |V\rangle_1 |H\rangle_2$$

This projects the ions into …

$$|\uparrow\rangle_1 |\downarrow\rangle_2 - |\downarrow\rangle_1 |\uparrow\rangle_2 = |\Psi^-\rangle_{ions}$$

The ions are now entangled!

Simon and Irvine, *PRL*, 91, 110405 (2003)

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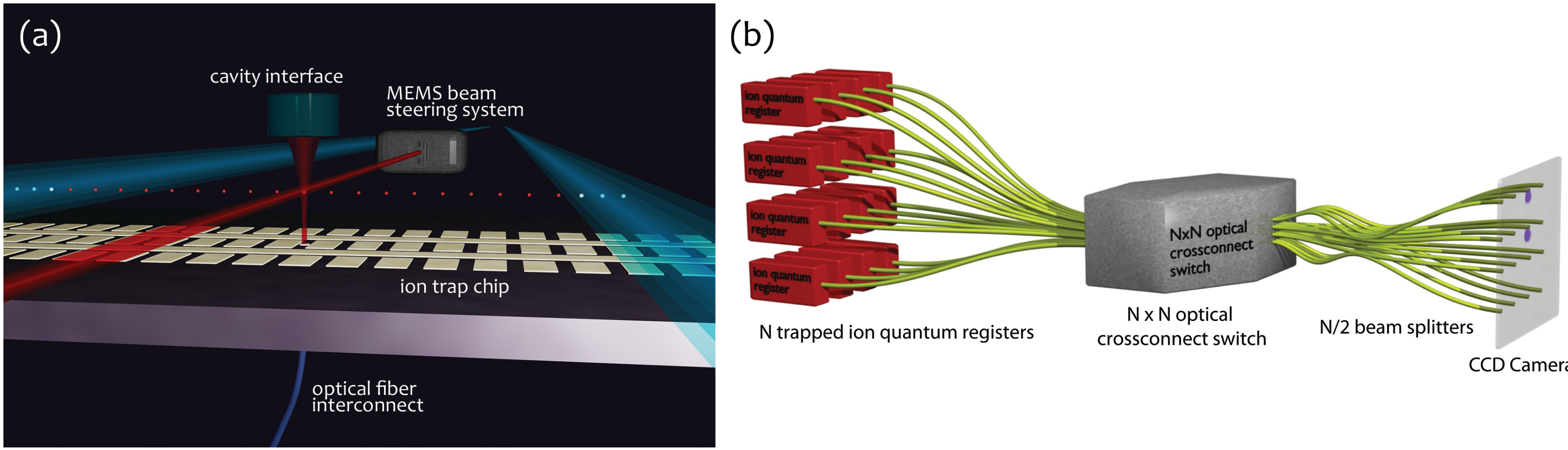
MUSIQC collaboration

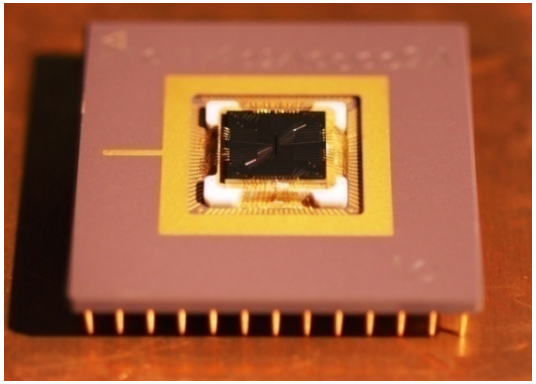
“Hybrid” System:
Small(ish) Ion Trap and Optical Interconnects

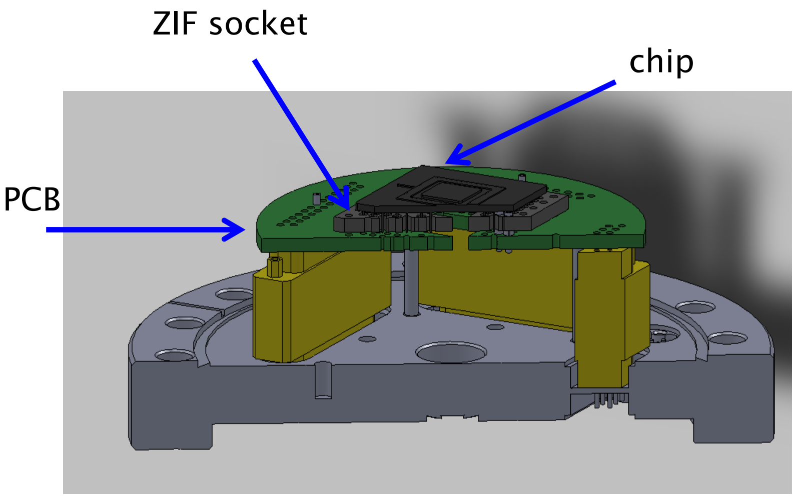


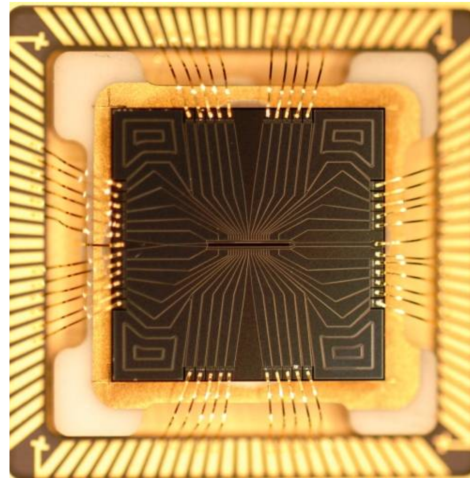
We want to combine a number of “small” (10 – 100 qubits) ion traps in a network trough ion-photon entanglement interface.

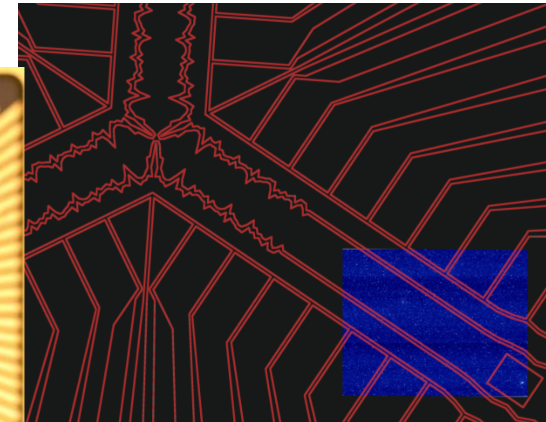
- novel trap designs (anharmonic, ring, …)
- use of multiple ion species
- fast optical switching

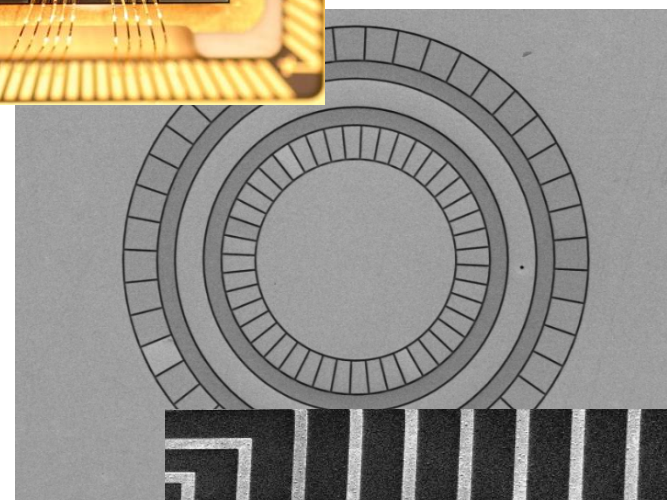
Zoo of Microtraps

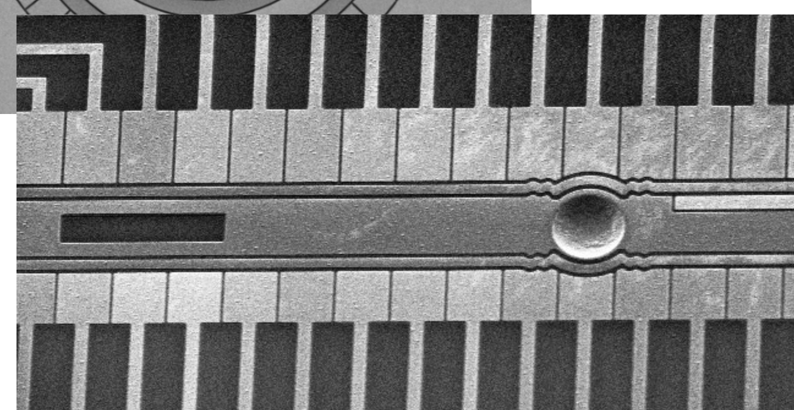








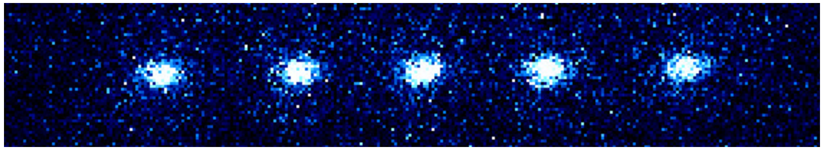




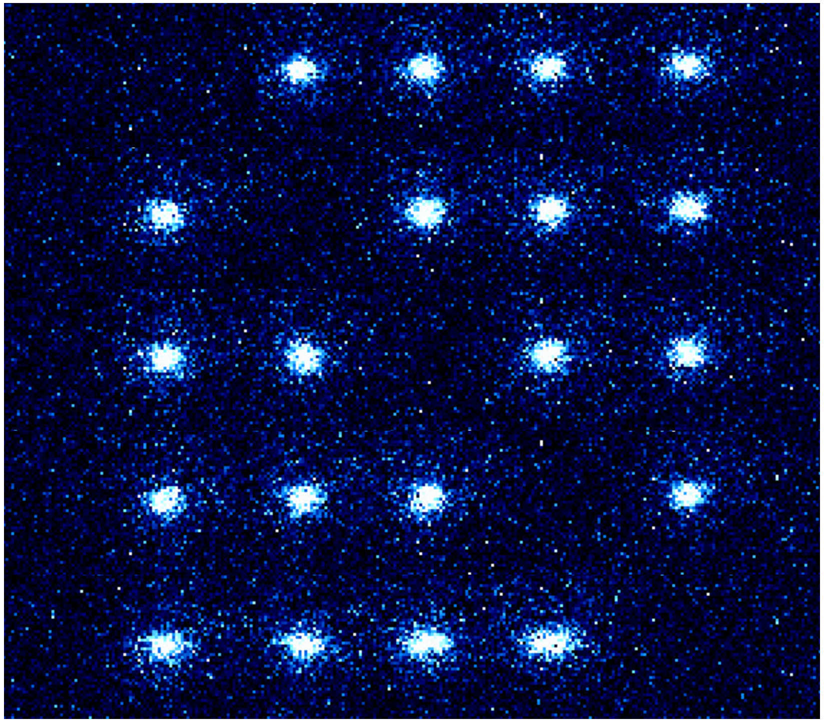
- Traps mounted in a UHV-compatible PCB system with in-vacuum RF filtering
- ZIF-socket to prevent solder joint cracking
- Laser-cooled lifetimes of order 1 hour or more

Hybrid Ba-Yb ion chains in linear trap

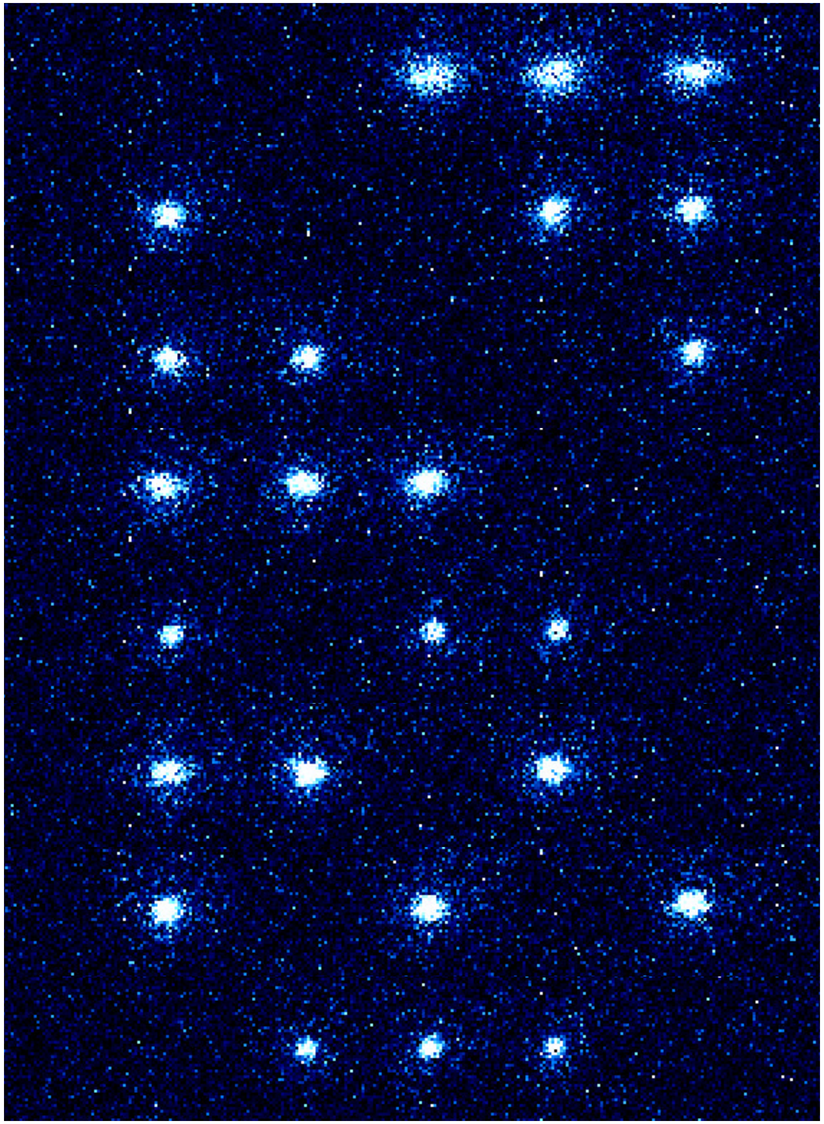
Ba ions are Doppler-cooled, and are visible; Yb ions are dark gaps.



Chain of 5 Ba ions

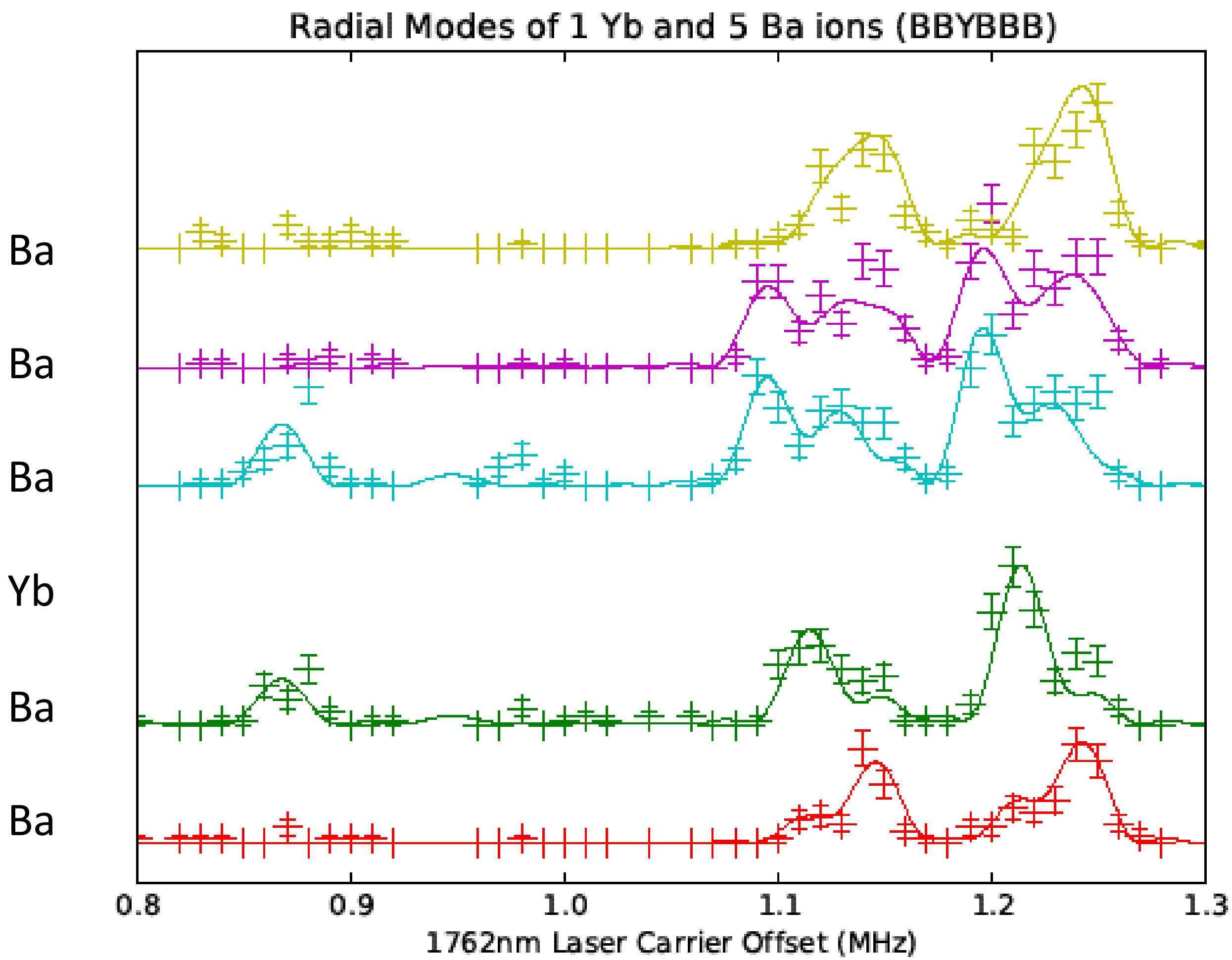


Chain of 4 Ba and 1 Yb ions



Chain of 3 Ba and 2 Yb ions

Radial sidebands for 5 Ba ions + 1 Yb ion



We see that Ba ions that are next to the Yb ion have higher strength for the lower frequency sidebands.

Simulations predict that Yb should couple very strongly to the lowest frequency radial modes; it is probably not well cooled for those modes.

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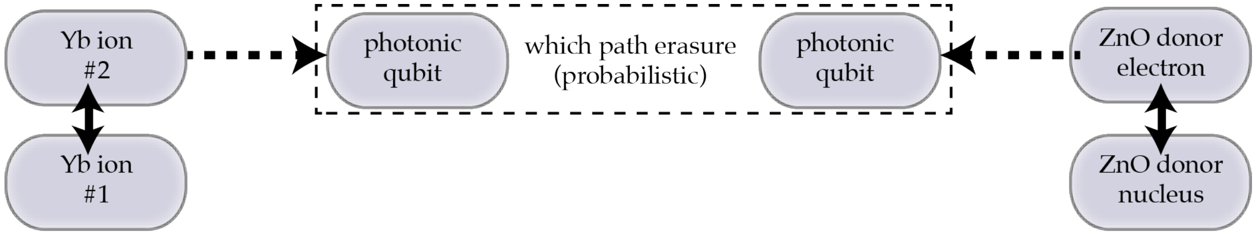
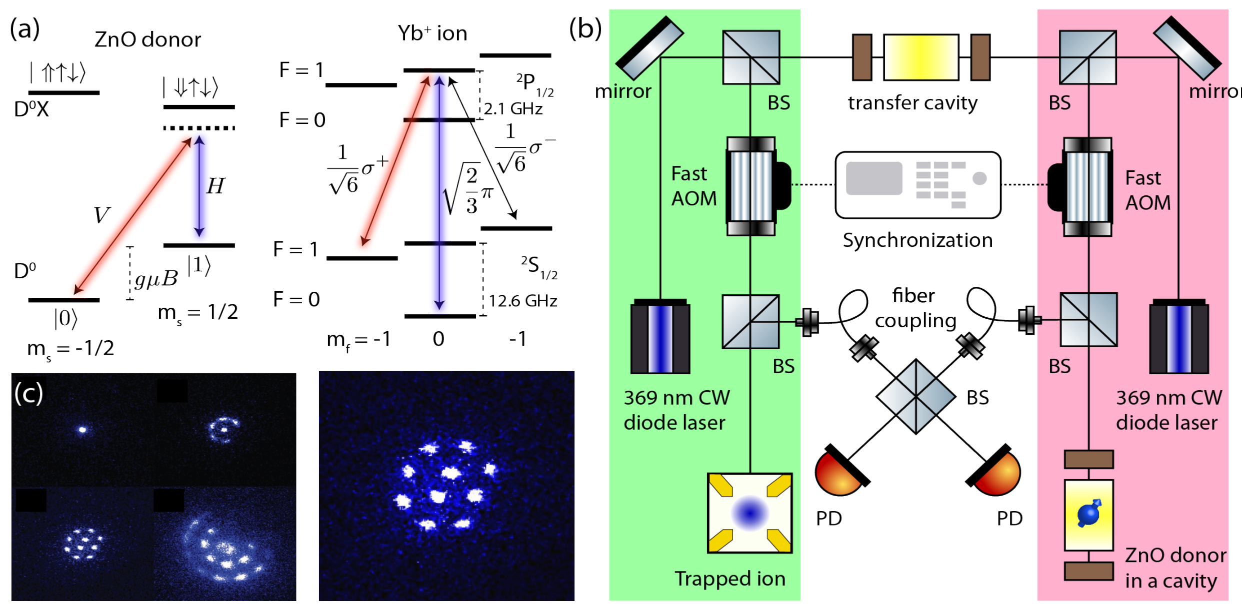
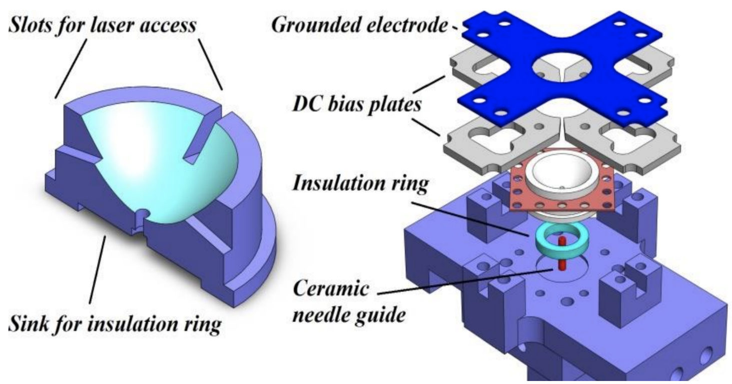
QUANTUM ENTANGLEMENT BETWEEN A SOLID-STATE SPIN AND A TRAPPED ION VIA A PHOTONIC LINK

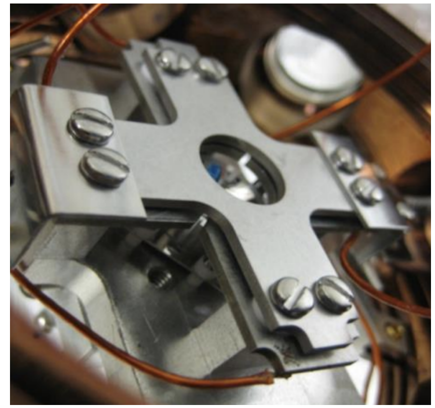


Yb ions and quantum defects in zinc oxide (ZnO) have very similar (but not quite) transition frequencies, so their emitted photons can be made identical. “Which-path erasure” is performed by interfering the two photons on a beam splitter. Long-term quantum information storage is accomplished by local quantum gates.



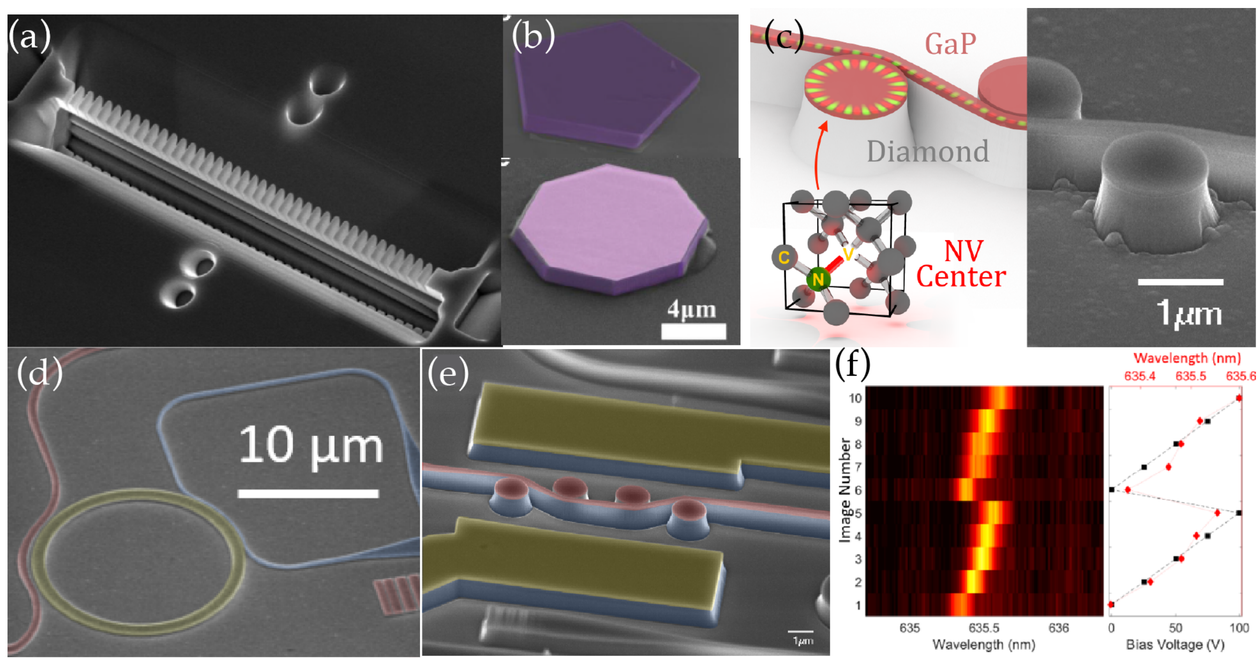
Parabolic mirror trap and photonic cavities



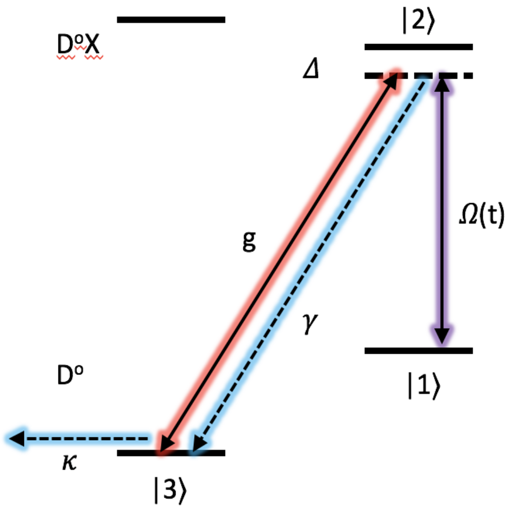


Parabolic mirror trap that collects 40% of a trapped ion fluorescence, built in our group at UW.

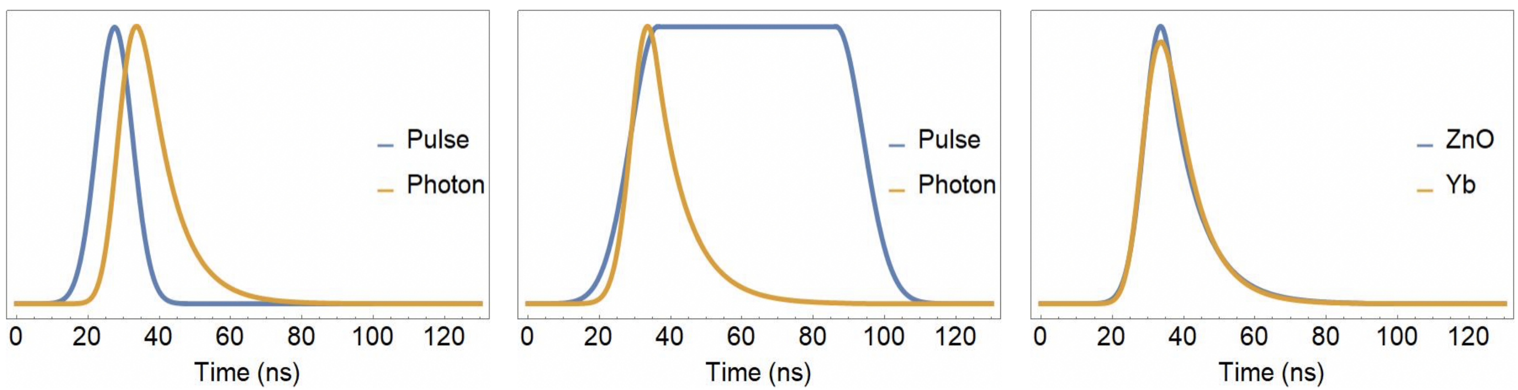
High-finesse, small mode volume optical cavities (photonic crystal; whispering gallery mode) developed by Prof. Kai-Mei Fu's group at UW.



Shaping single photons with optical cavities



- Excited state life time for Yb ion 7P state is about 8 ns, while the D^0X excited state on ZnO donor impurities is of order 1 ns. Transition frequencies are also off by at least 340 GHz.
- Coupling a single donor to a high-finesse, small mode volume optical cavity allows tuning both the pulse shape and the frequency of emitted photons, thus making them identical to Yb photons.



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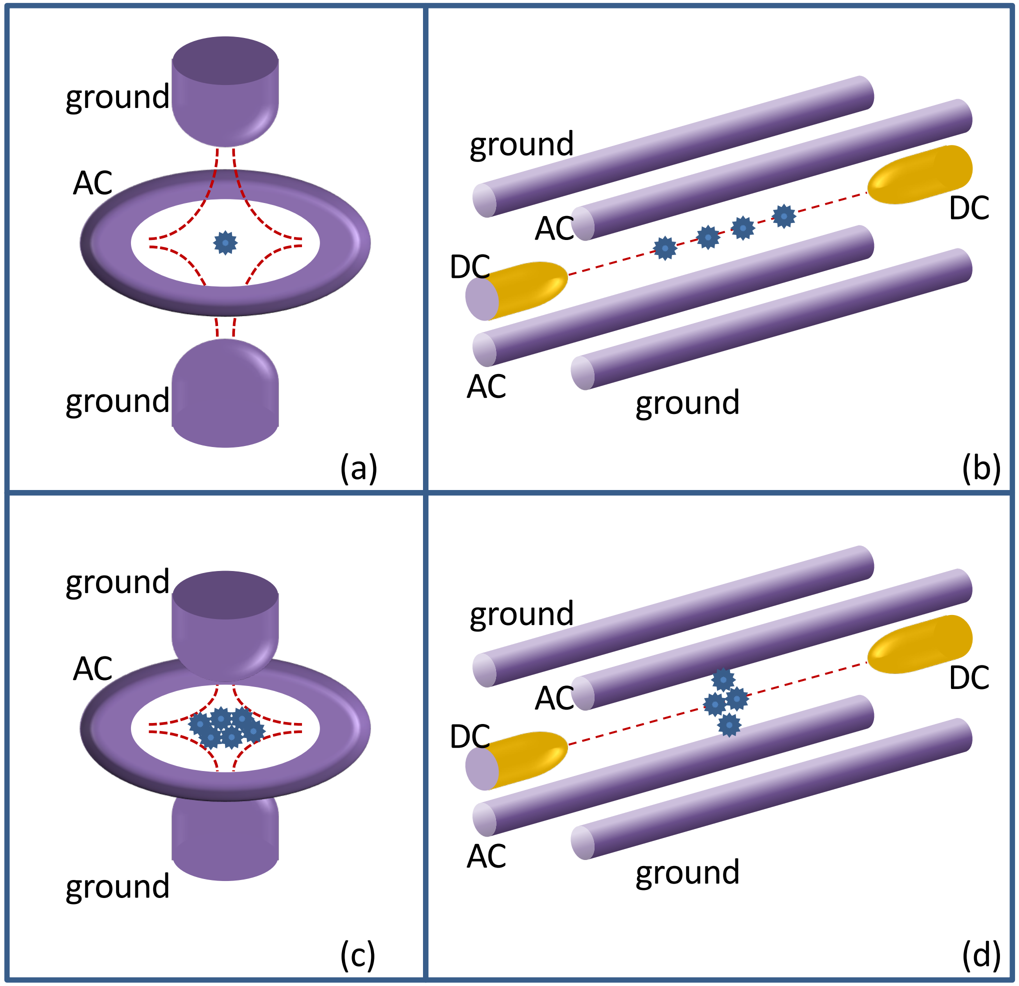
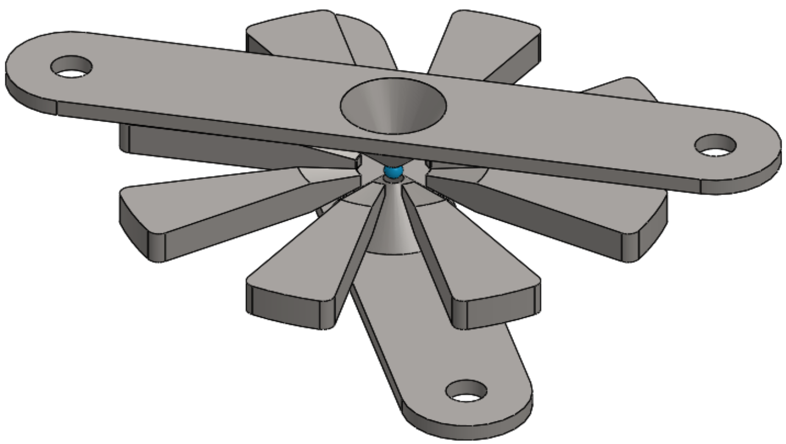
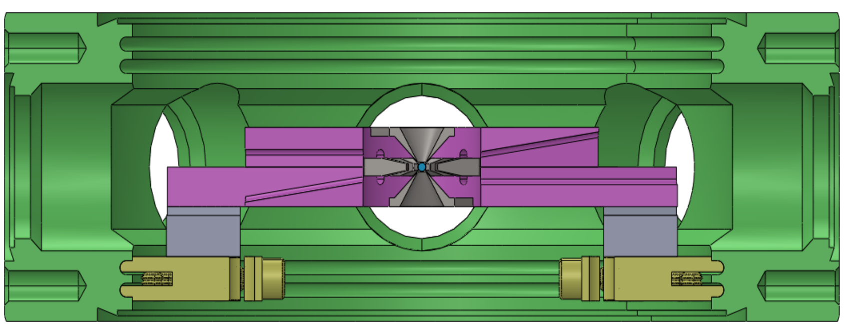
Linear ion trap evolution into a planar trap

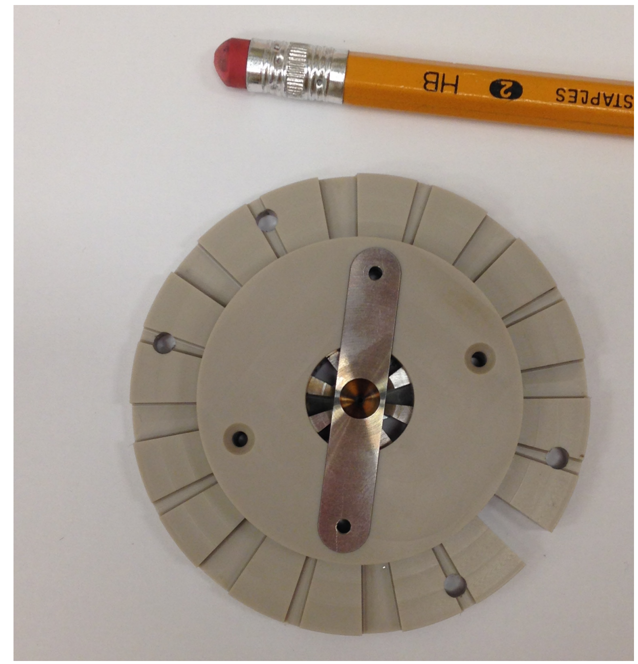


- The original Paul trap was designed to be perfectly spherically symmetric.
- It is relatively easy to break the symmetry and create the linear trap, where one principal axis is significantly weaker than the other two.
- Linear traps are the workhorses of quantum computing research due to simplicity.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

Oblong trap for large 2-d crystals

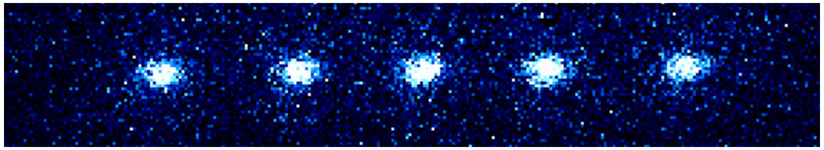






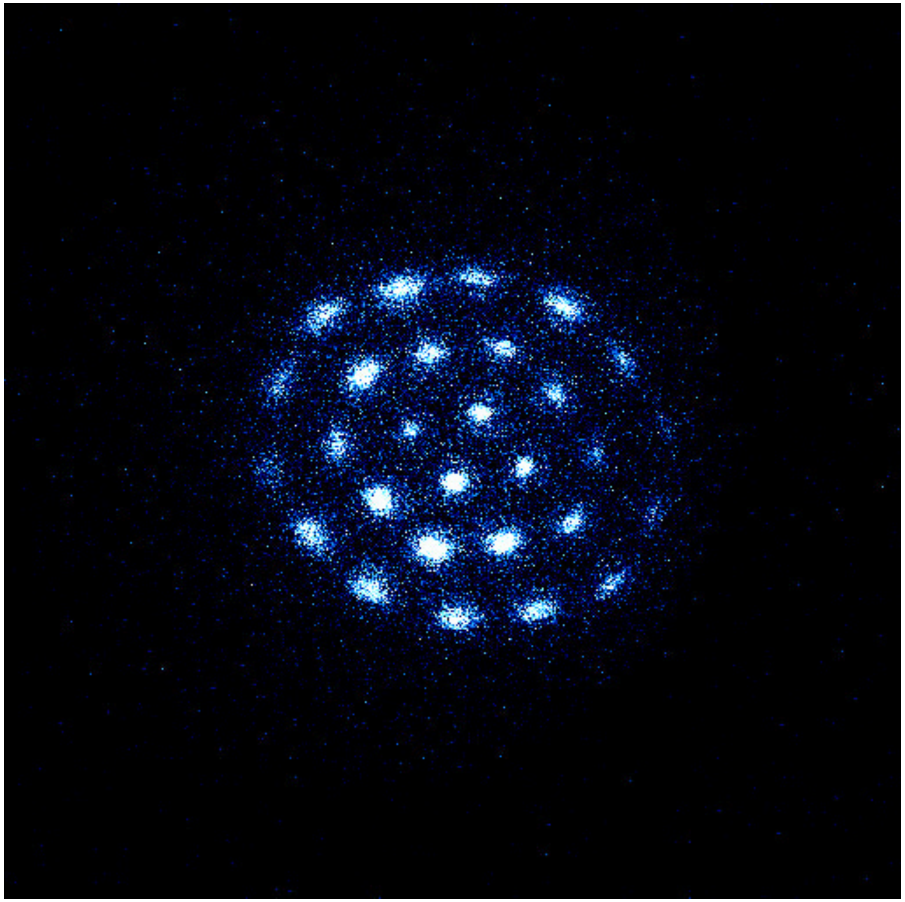
We designed and built a version of Paul trap with segmented ring electrode and hollow cone-shaped endcap electrodes for producing 2-dimensional ion crystals.

Ba ion chain in linear trap
and pancakes in planar trap



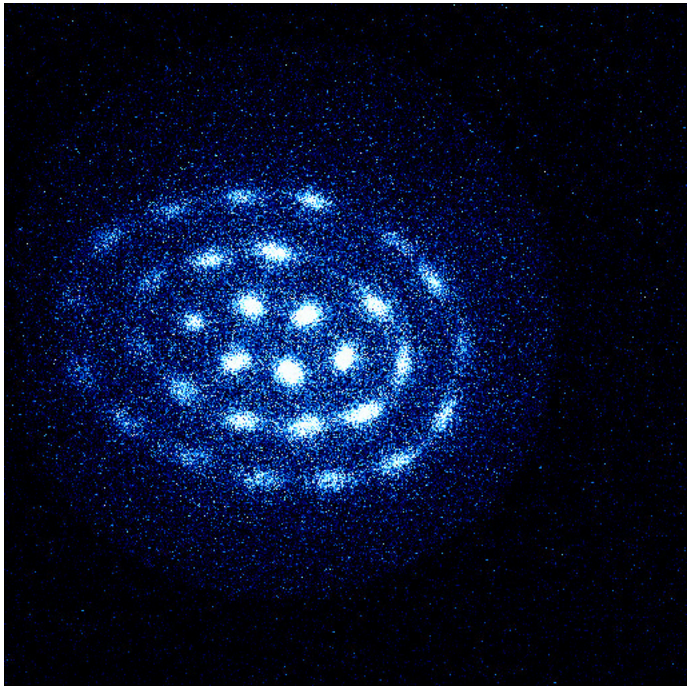
Chain of 5 Ba ions

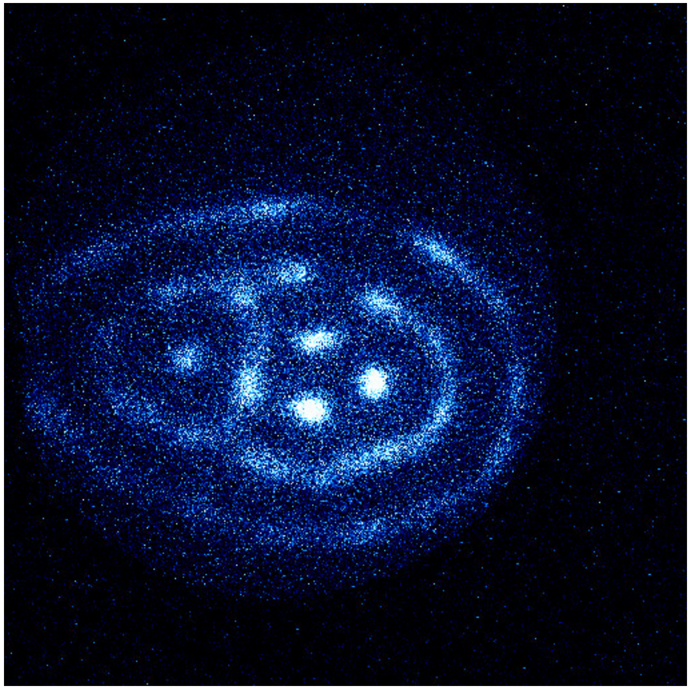
Ba ions are Doppler-cooled, and are visible on an intensified CCD.



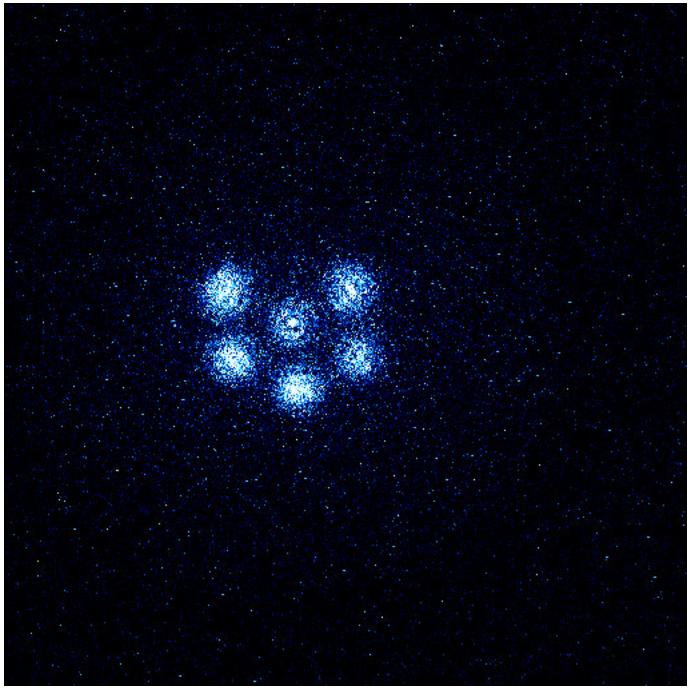
Planar crystals of 28 Ba ions

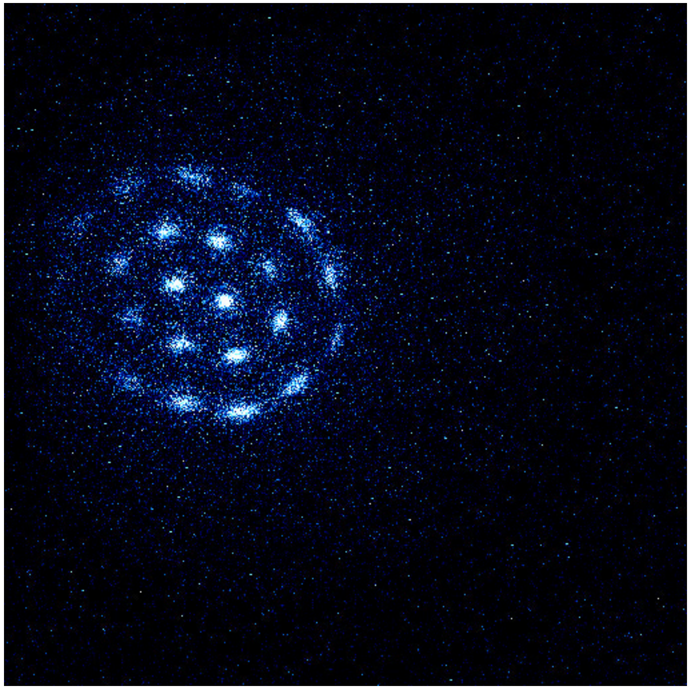
More crystals





Even more crystals…





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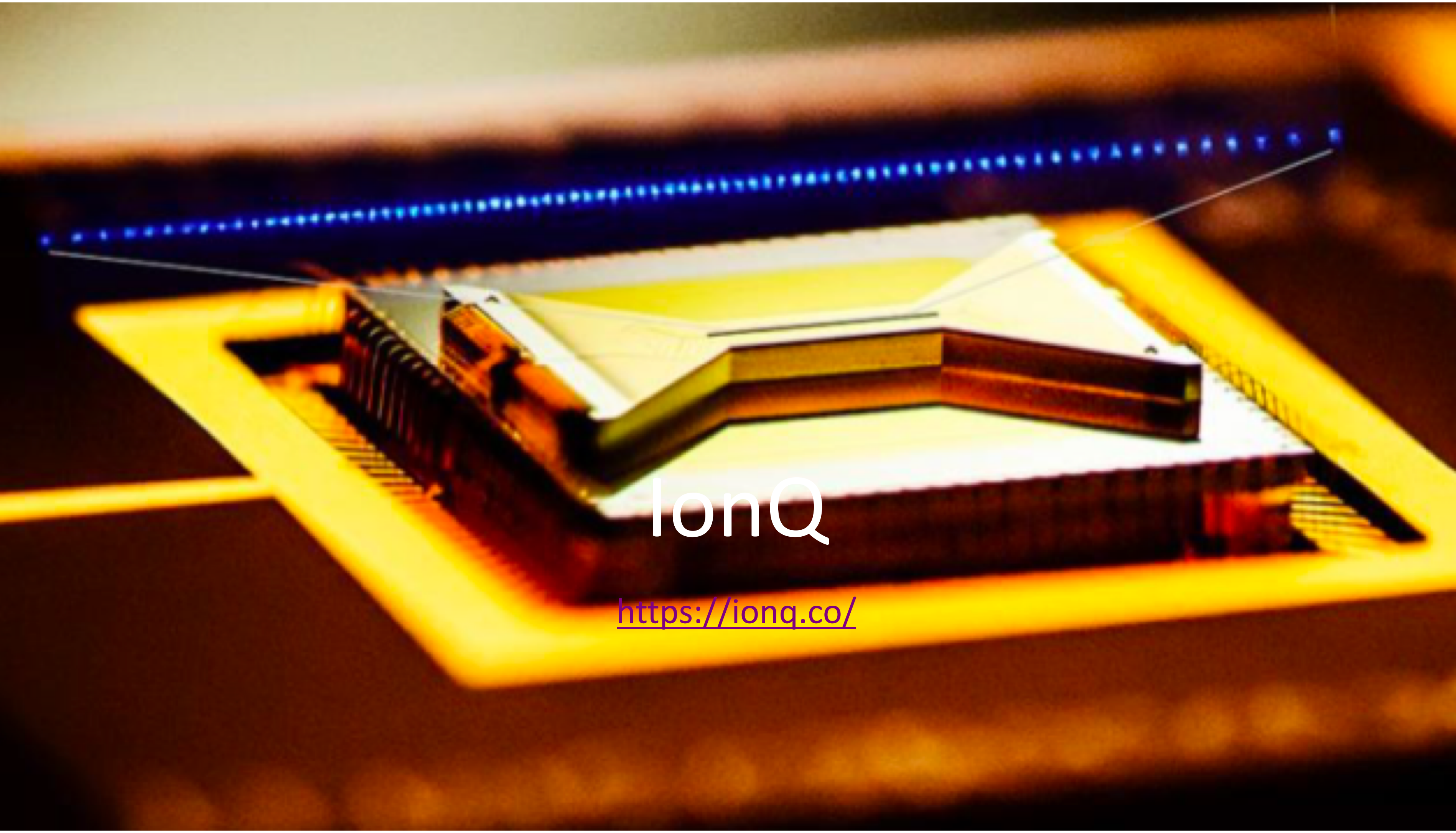
No longer just university research



UW trapped ion group (Aug 2019)

Ali Hasanzadeh Gabriel Moreau Jennifer Lilieholm Alex Kato BB

Yana Lozina Liudmila Zhukas Elizabeth Bernbaum Walker Steere