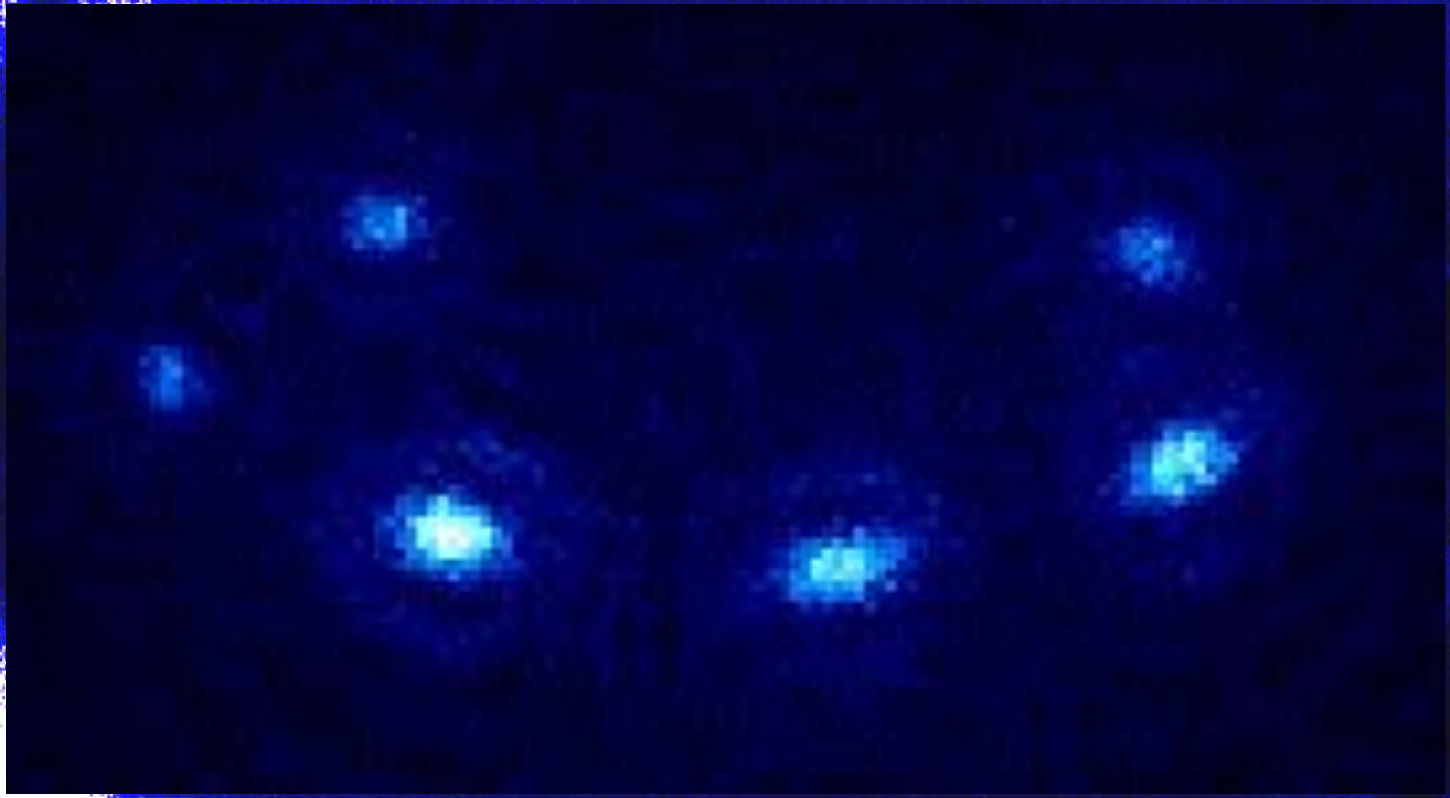
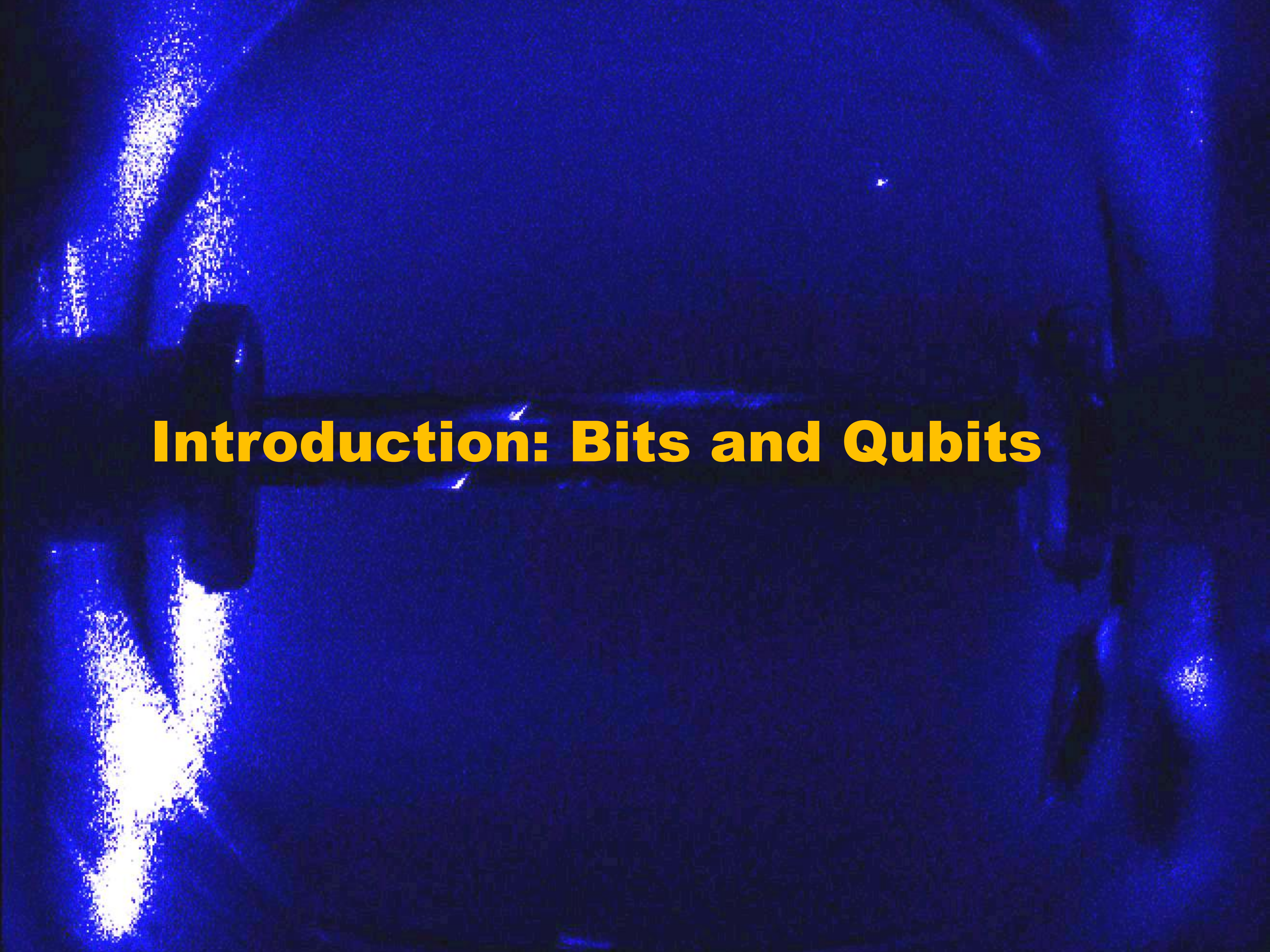
Quantum Computing with Trapped Ions



Boris Blinov
University of Washington
http://depts.washington.edu/qcomp/

Introduction: Bits and Qubits



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

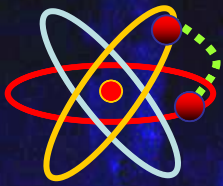

Richard Feynman

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



2. …… as long as you don't look!

$$\alpha|0\rangle + \beta|1\rangle \rightarrow |0\rangle \text{ or } |1\rangle$$

Massive storage and parallelism

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

$$(1/2)^{-1} (|00\rangle + |01\rangle + |10\rangle + |11\rangle)$$

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

- ……………….
- 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!

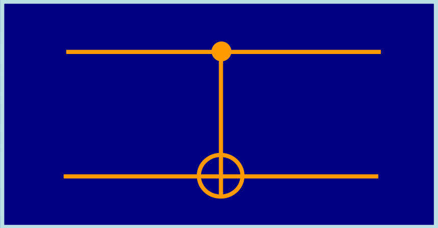
The Entanglement

- 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

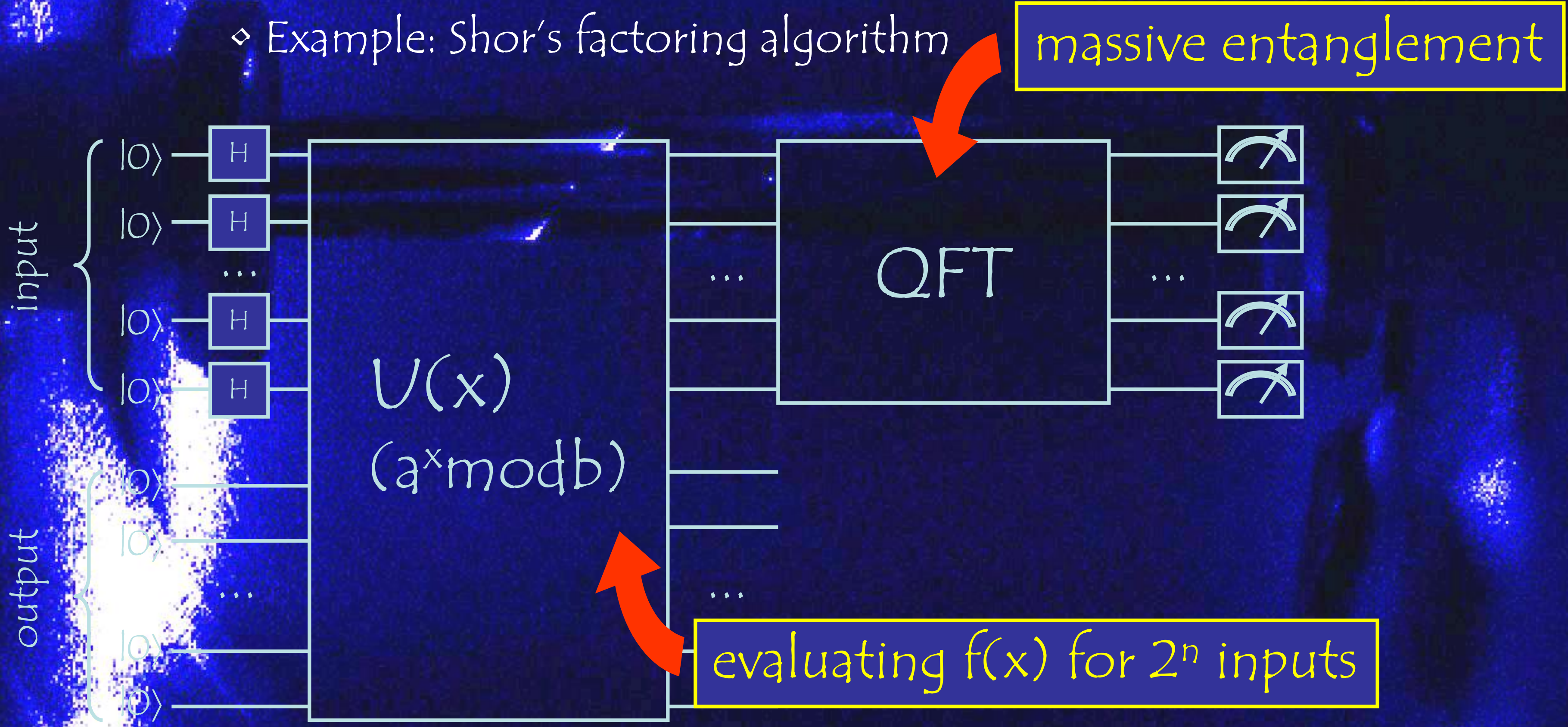


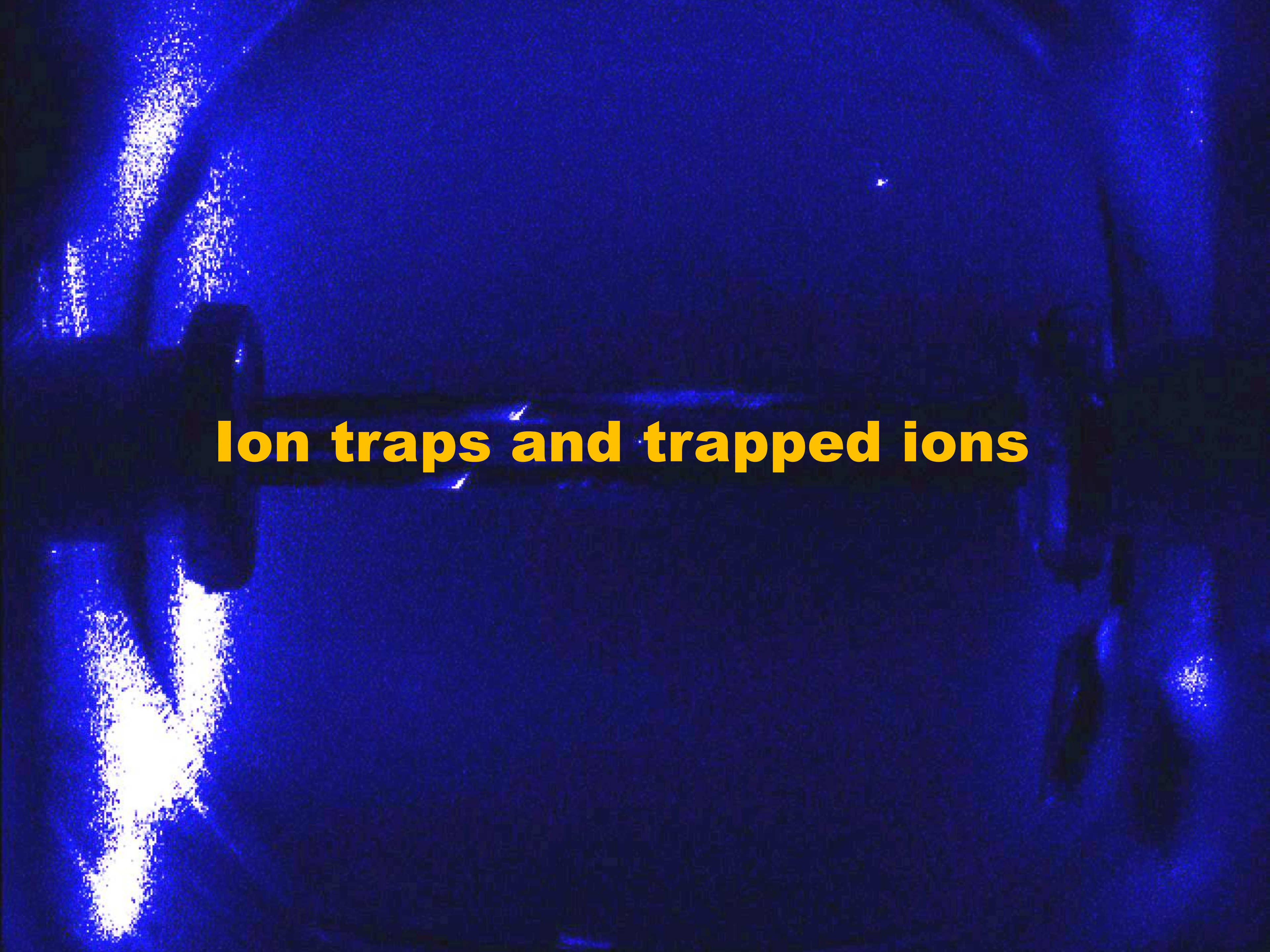
control qubit	target qubit	result
$\|0\rangle$	$\|0\rangle$	$\|0\rangle\,\|0\rangle$
$\|0\rangle$	$\|1\rangle$	$\|0\rangle\,\|1\rangle$
$\|1\rangle$	$\|0\rangle$	$\|1\rangle\,\|1\rangle$
$\|1\rangle$	$\|1\rangle$	$\|1\rangle\,\|0\rangle$
$\alpha\|0\rangle + \beta\|1\rangle$	$\|0\rangle$	$\alpha\|0\rangle\|0\rangle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

Entangled state!

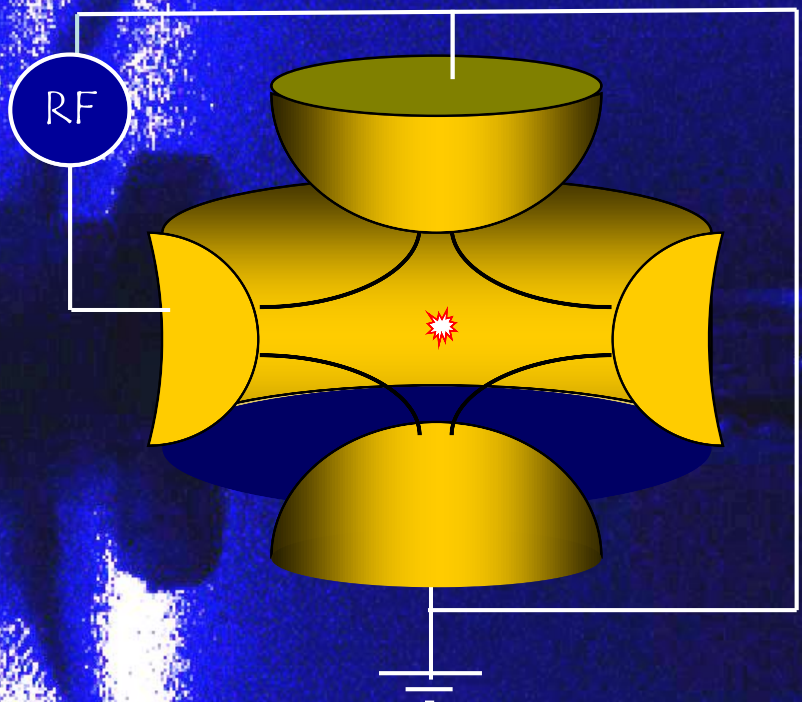
Quantum computing revealed

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

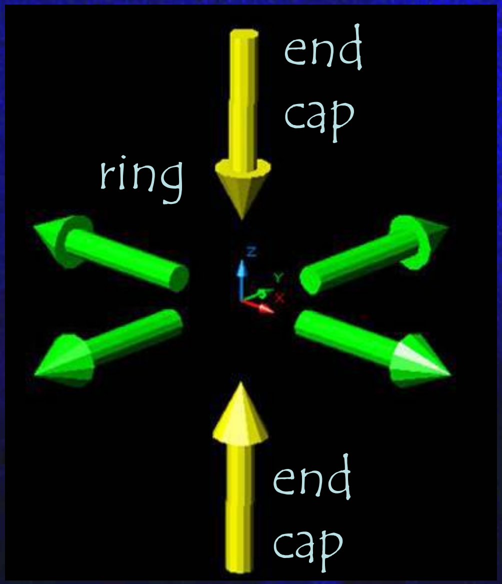


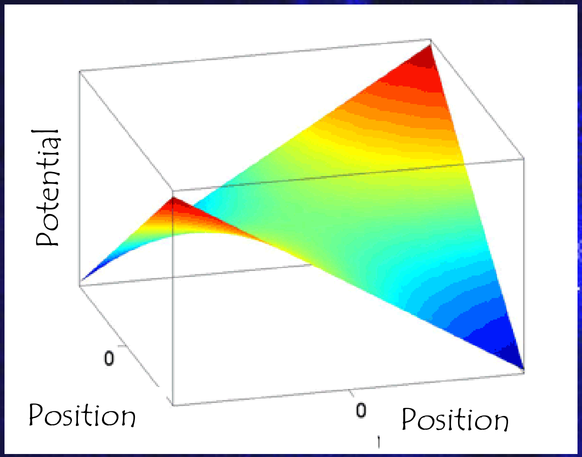

Ion traps and trapped ions

RF (Paul) ion trap

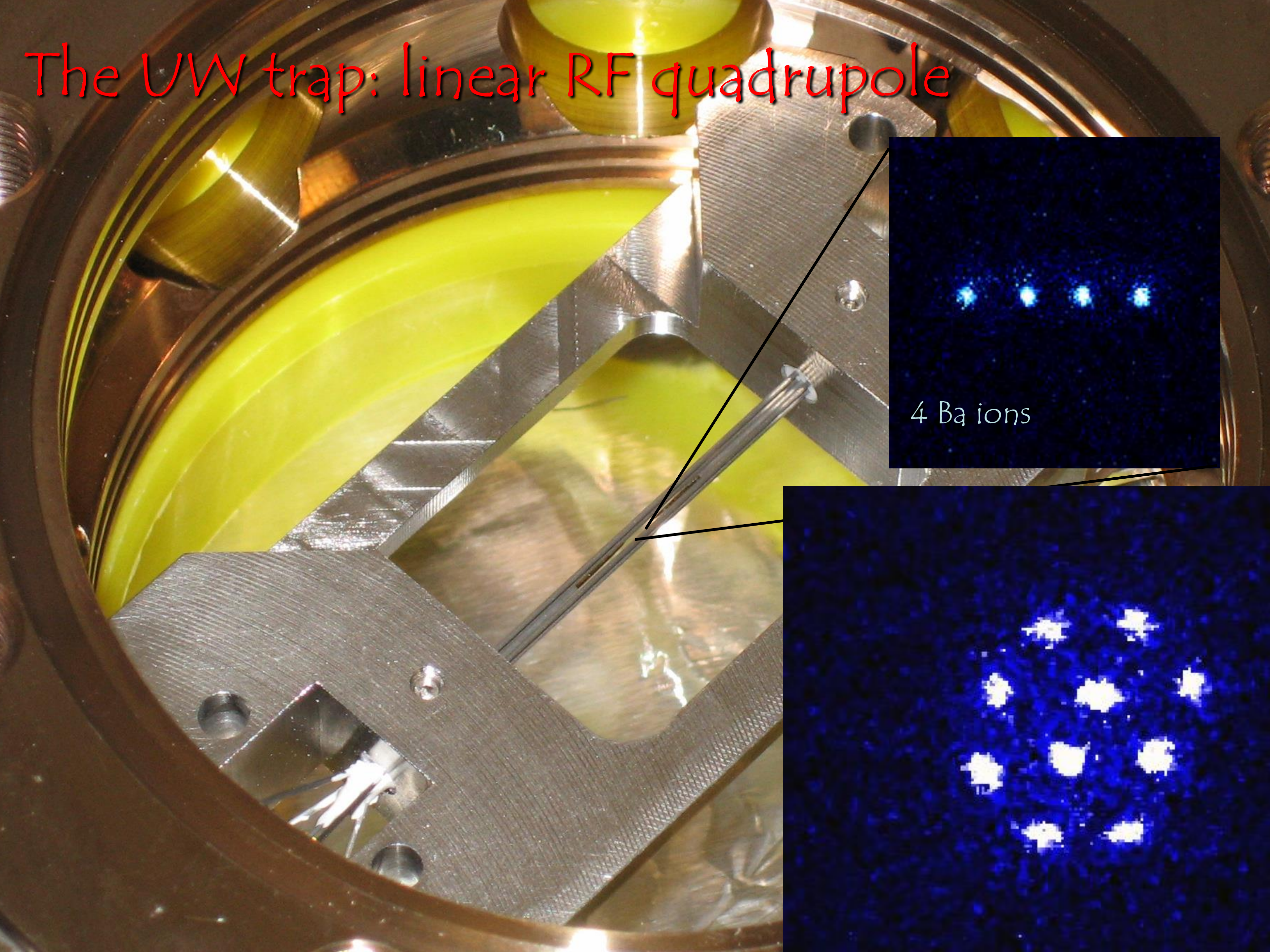


"RF quadrupole"

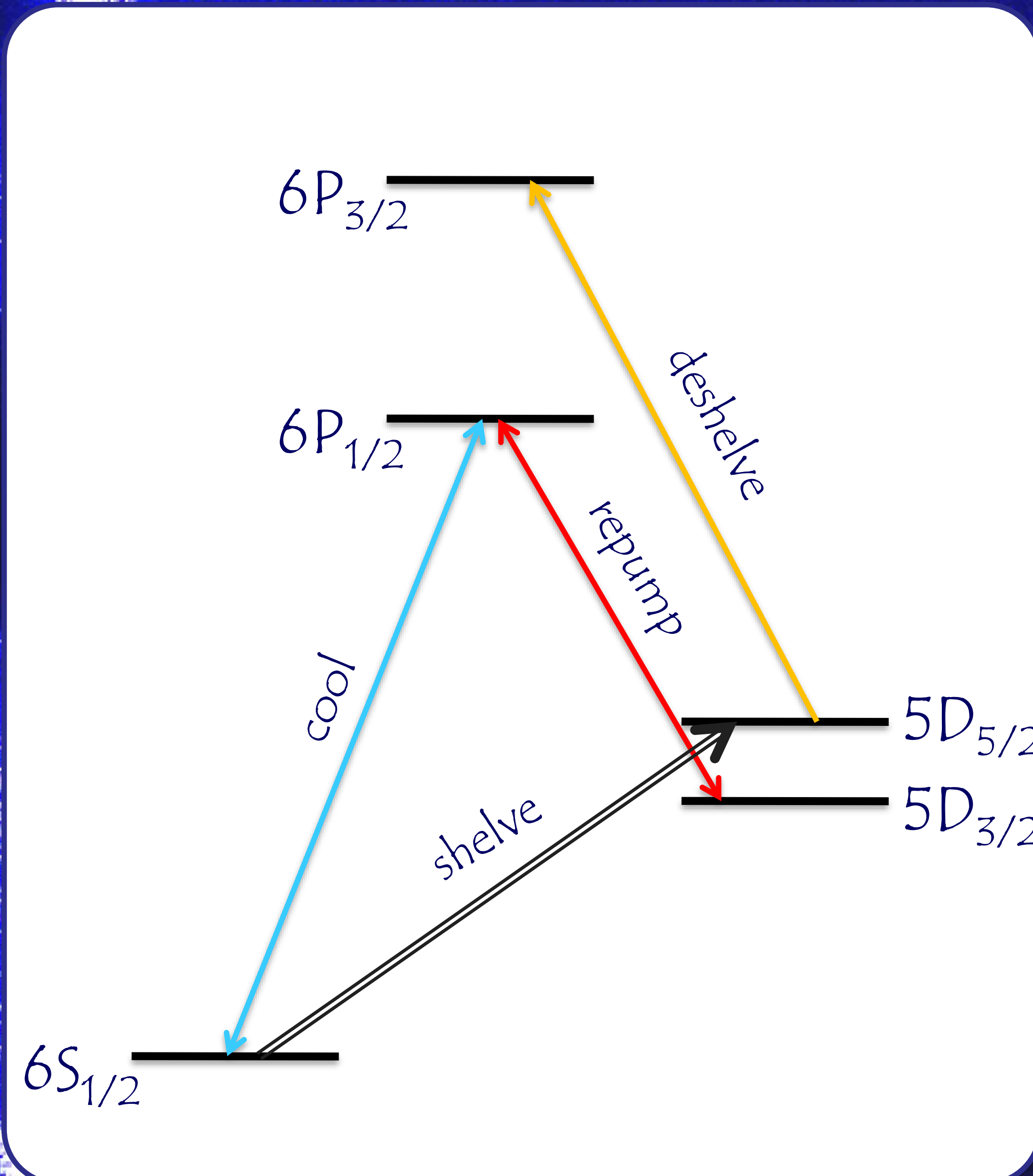




The UW trap: linear RF quadrupole



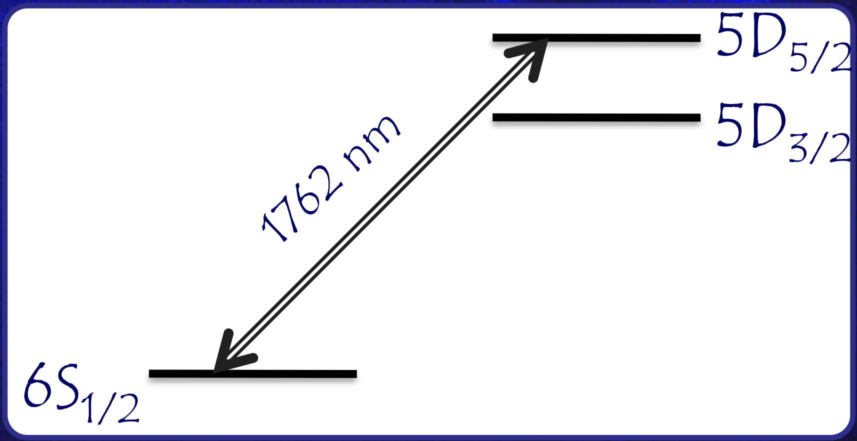
Ba ion laser cooling, etc.



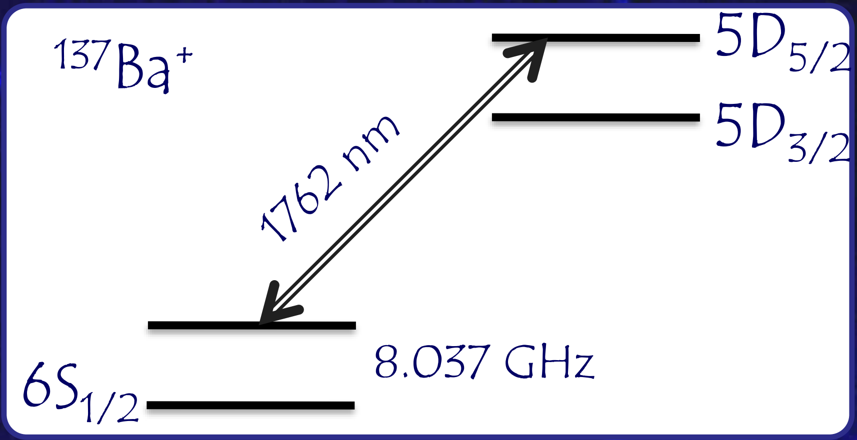
- laser cooling: 493 nm and 650 nm
- qubit initialization: optical pumping
- qubit control: some form of EM waves
- qubit detection: state-dependent fluorescence

Now, the qubits

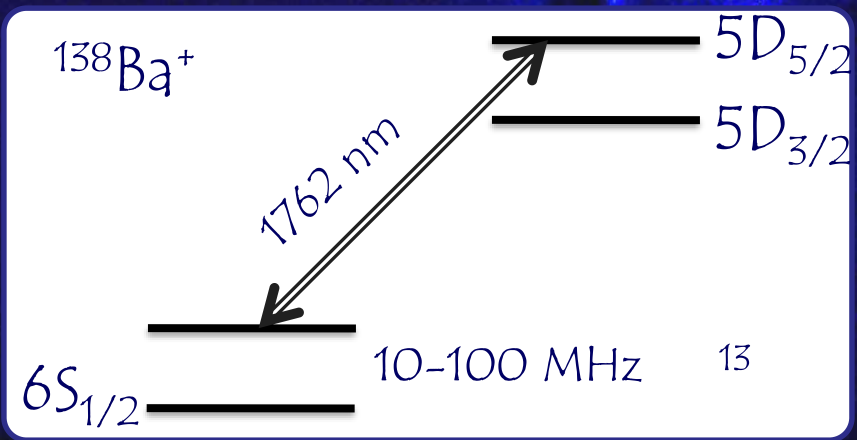
- optical: S-D transition



- hyperfine: ground state "clock" states

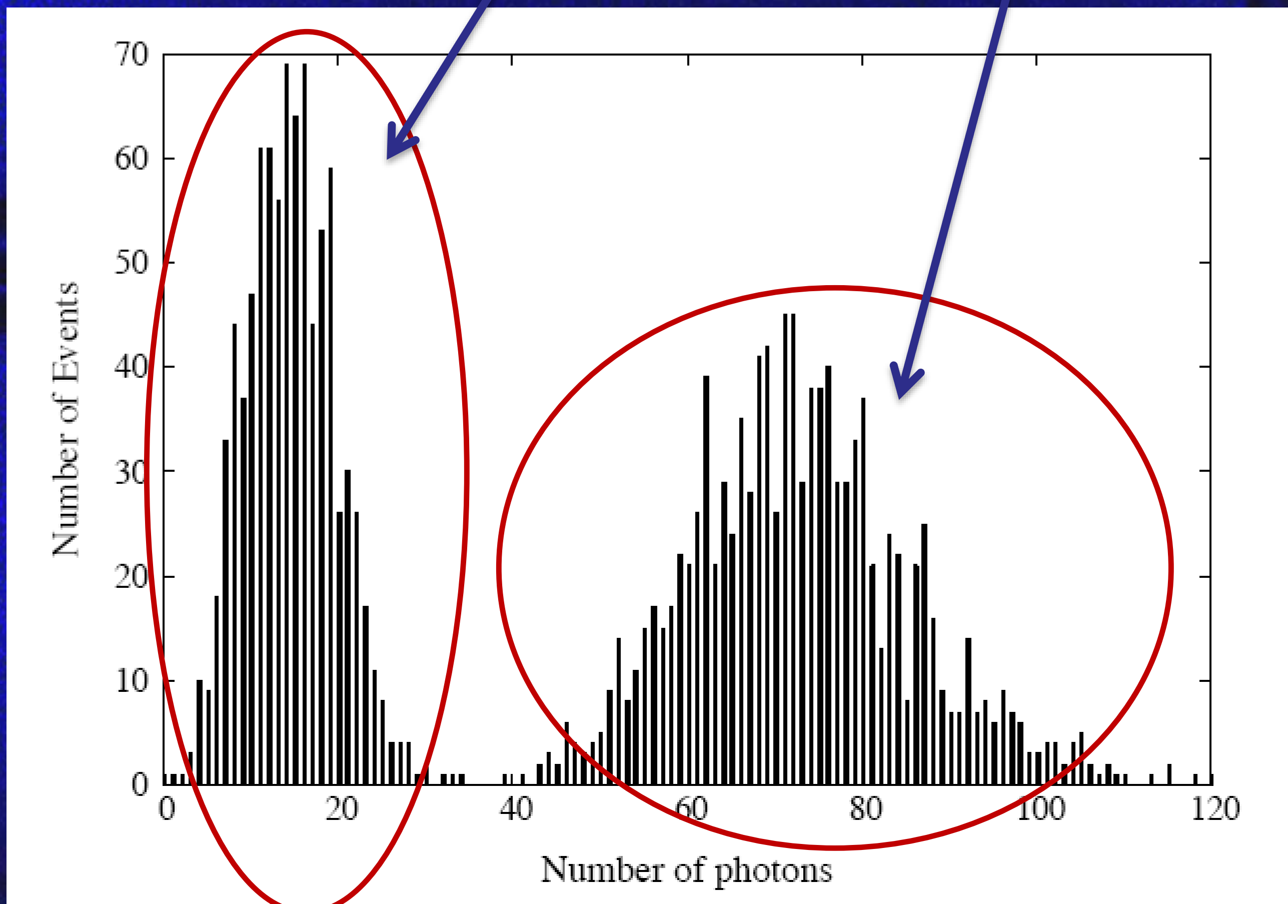


- Zeeman: ground state Zeeman states

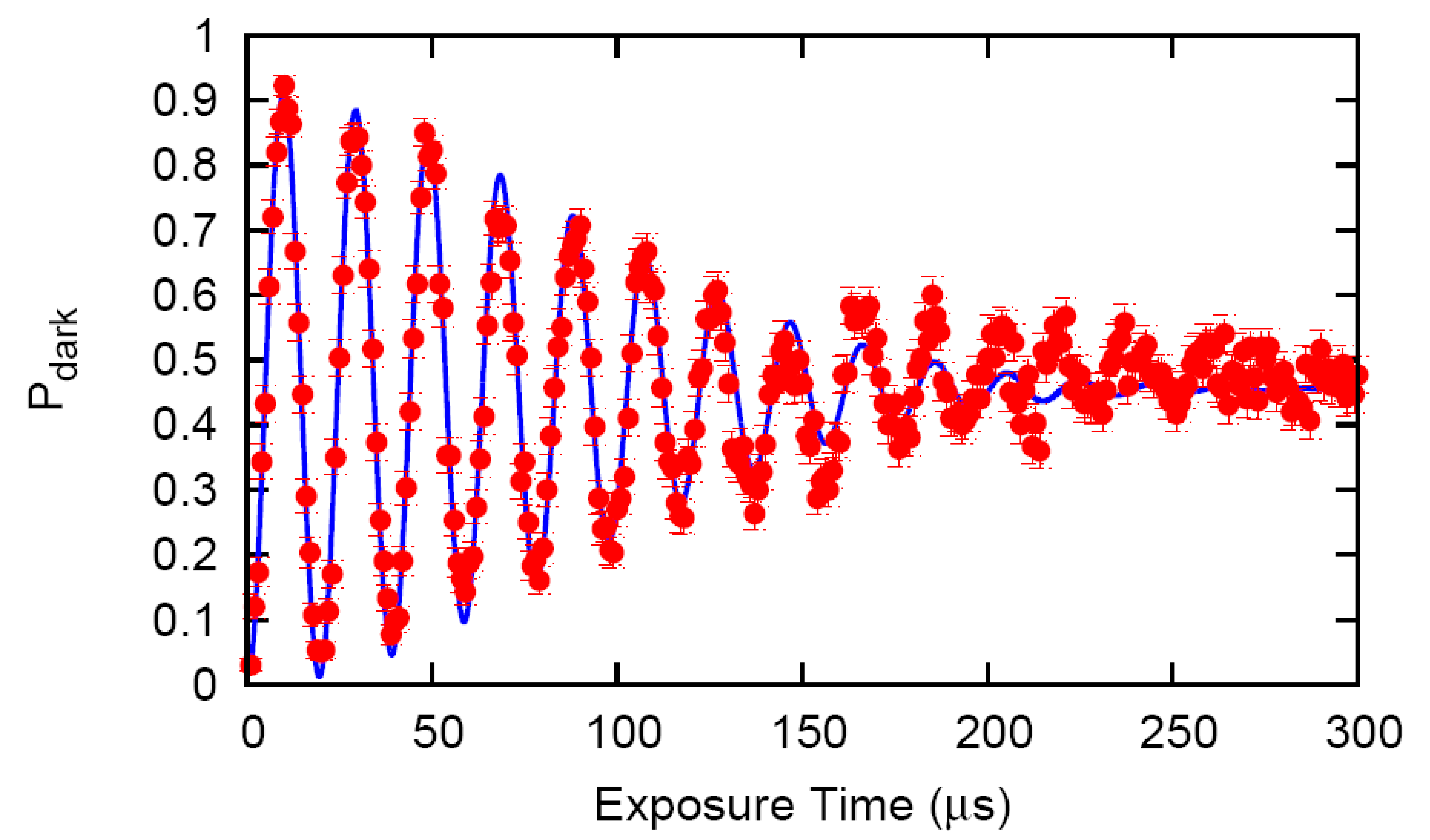


Whatever qubit, same detection

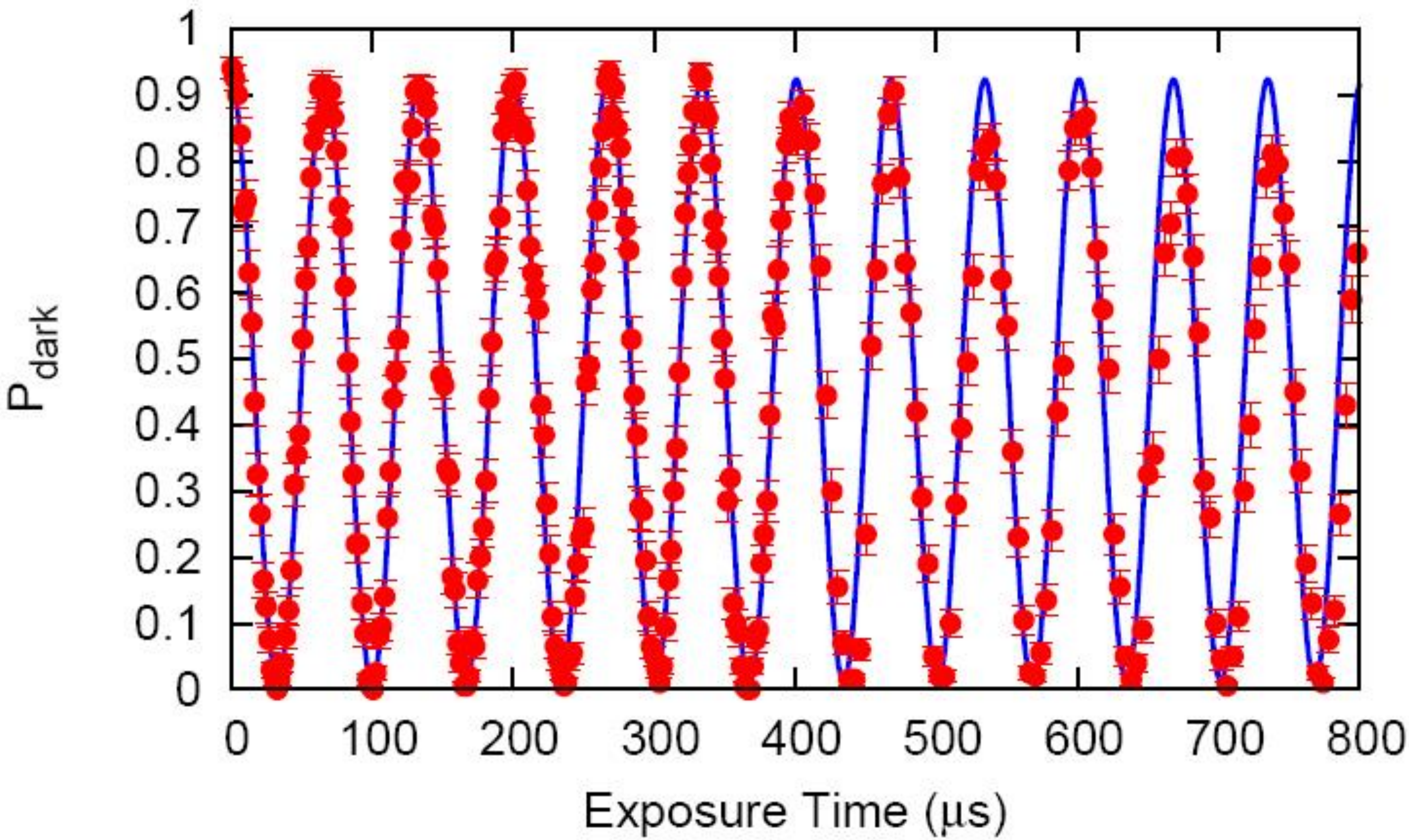
One state "dark", the other "bright"

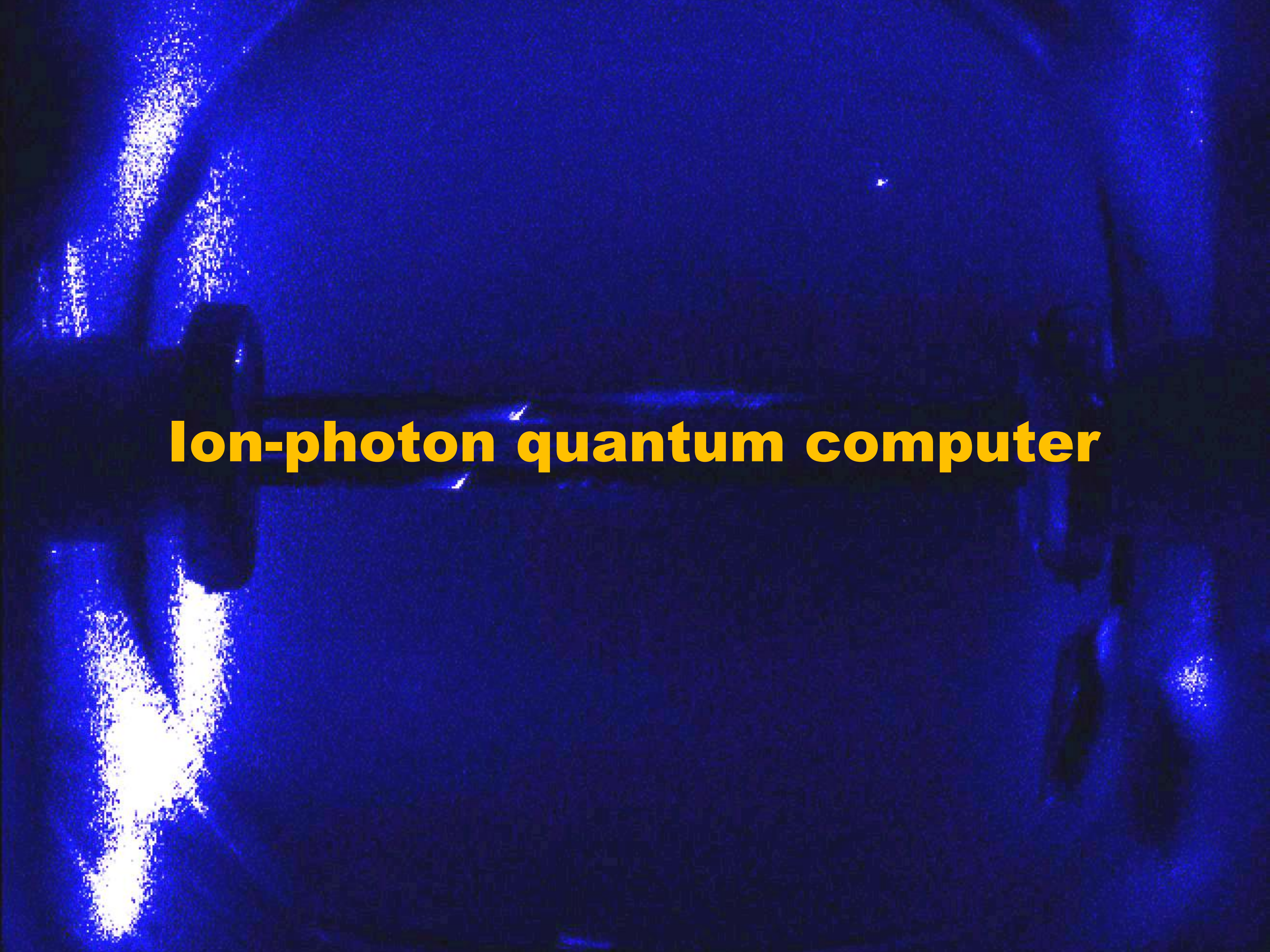


Optical qubit: the Rabi flops

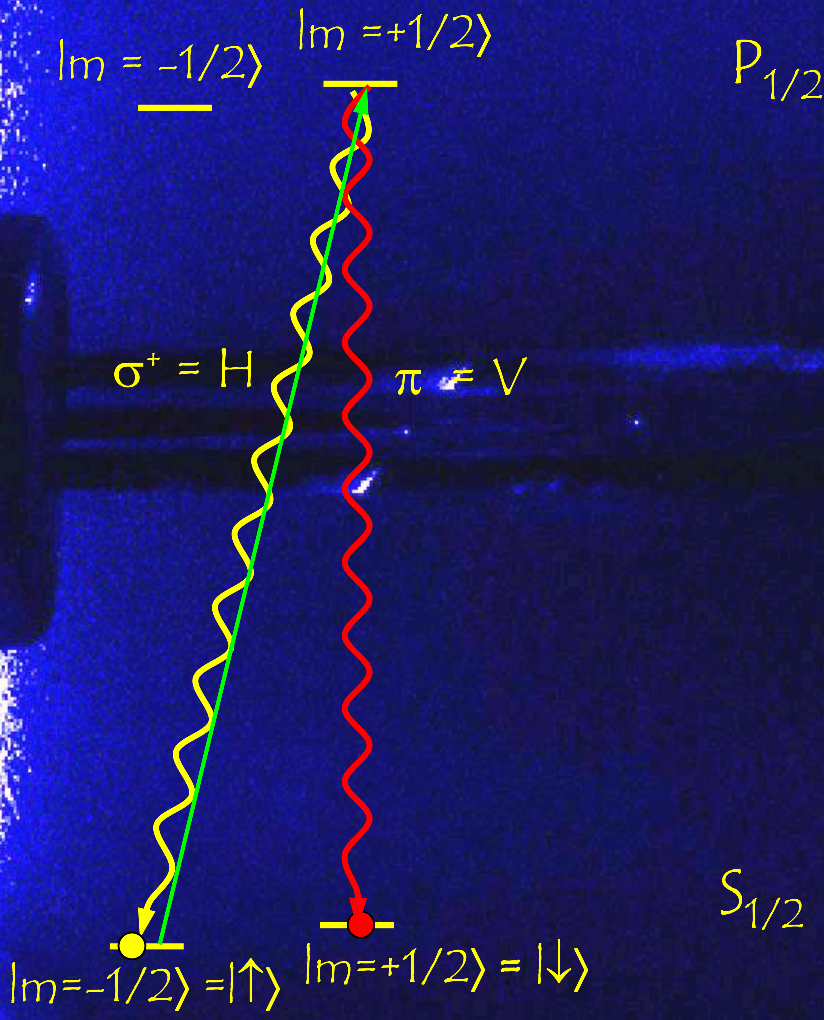


Hyperfine qubit: the Rabi flops




Ion-photon quantum computer

Ion-photon entanglement

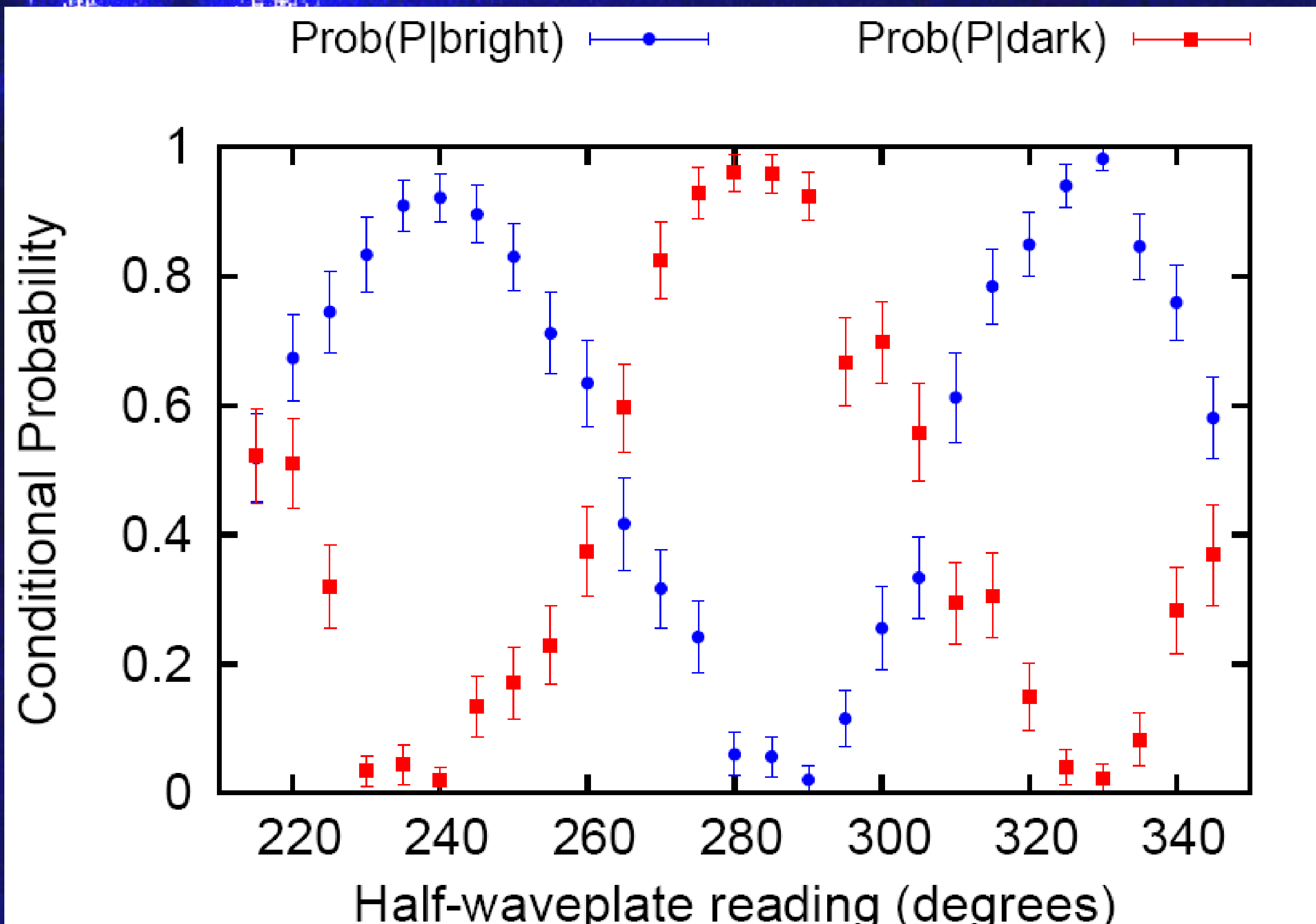


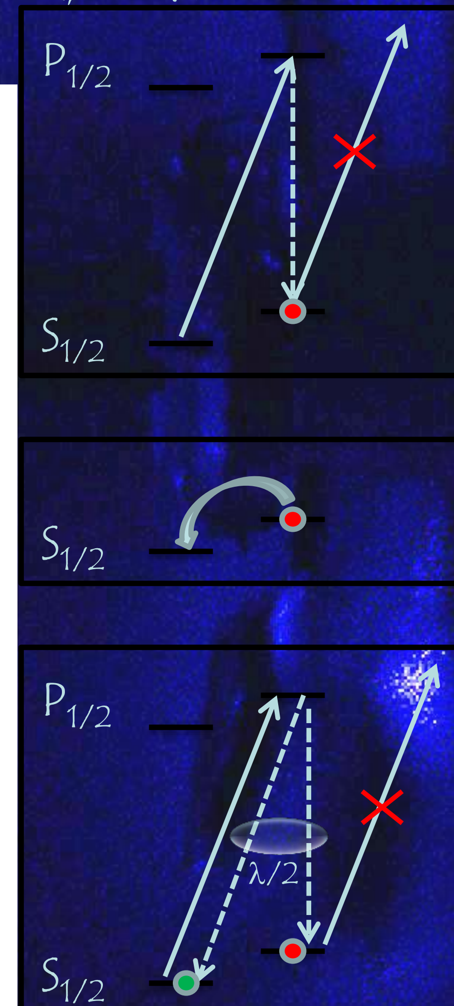
$|\psi\rangle = |H\rangle|\uparrow\rangle + |V\rangle|\downarrow\rangle$

- 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!

Ba ion-photon entanglement

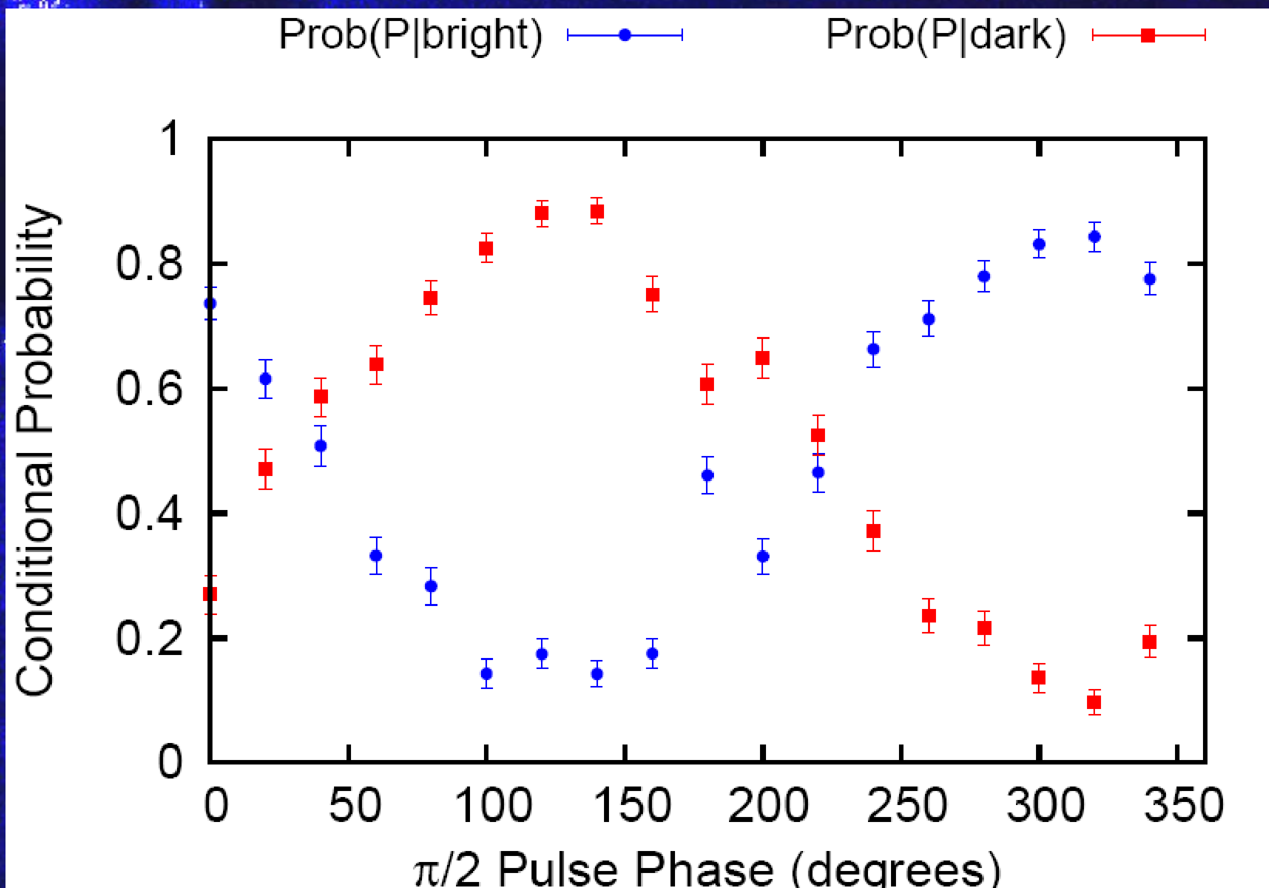
Ba-138 Zeeman sublevels are entangled with the emitted photon polarization. The ion is weakly excited by a short CW laser pulse. Double excitations are suppressed by optical pumping. Repetition rate ~ few tens of KHz, event rate ~ few Hz.

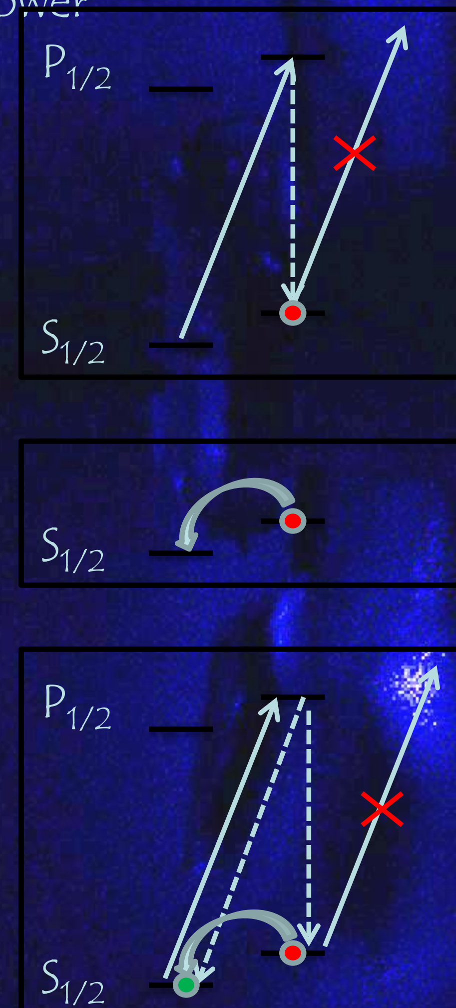




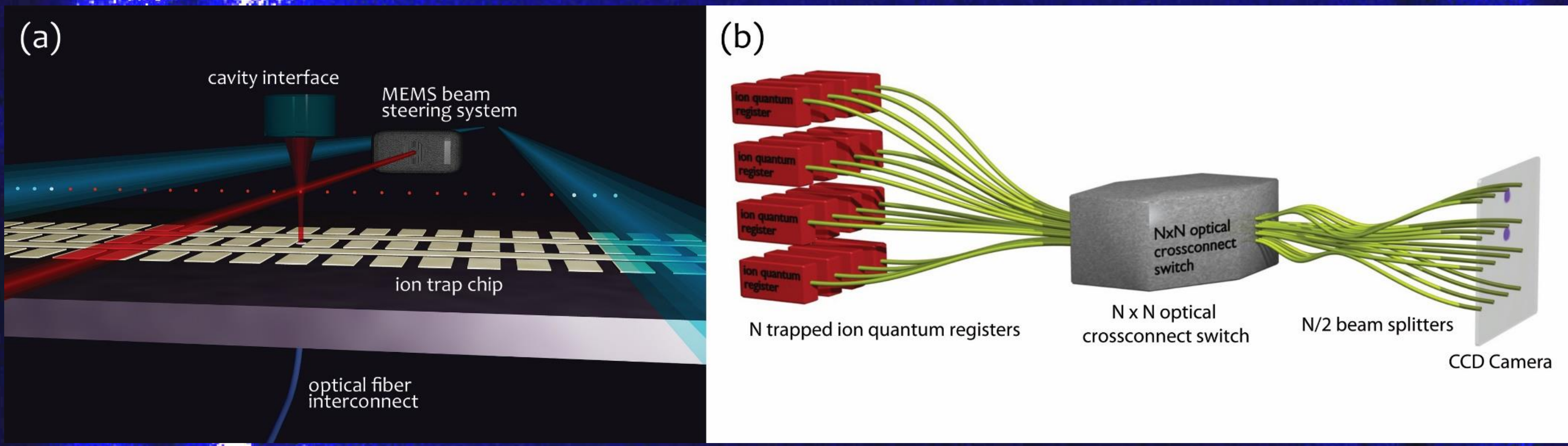
Ba ion-photon entanglement verification

Rotate both the photon qubit and the ion qubit; vary ion qubit rotation phase to observe fringes. Found out that ion heating caused by the RF pulse in the fast loop caused lower contrast (ion not cooled, therefore dark). Lower RF power allowed for much better contrast.

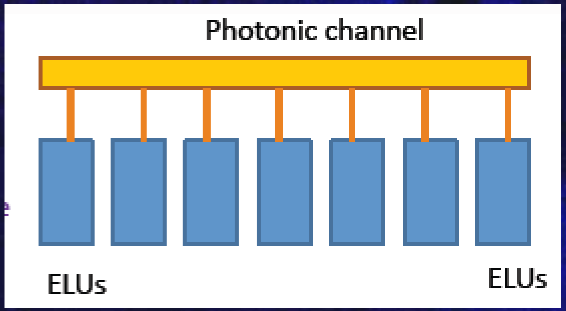




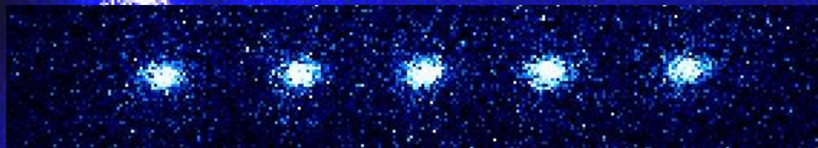
Ion-photon CQ: the basic idea



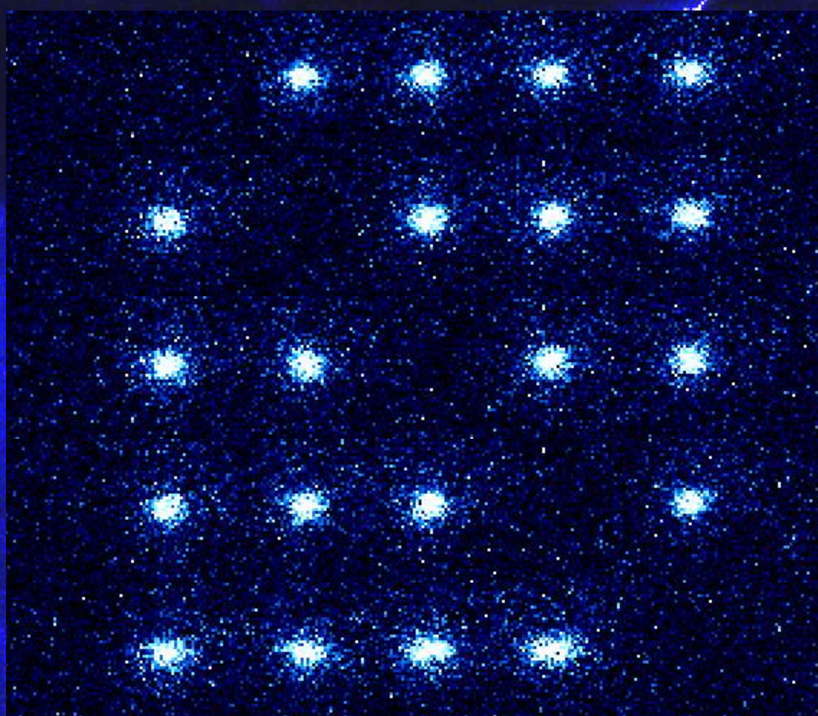
We want to combine a number of “small” (10 – 100 qubits) ion traps in a network through ion-photon entanglement interface.



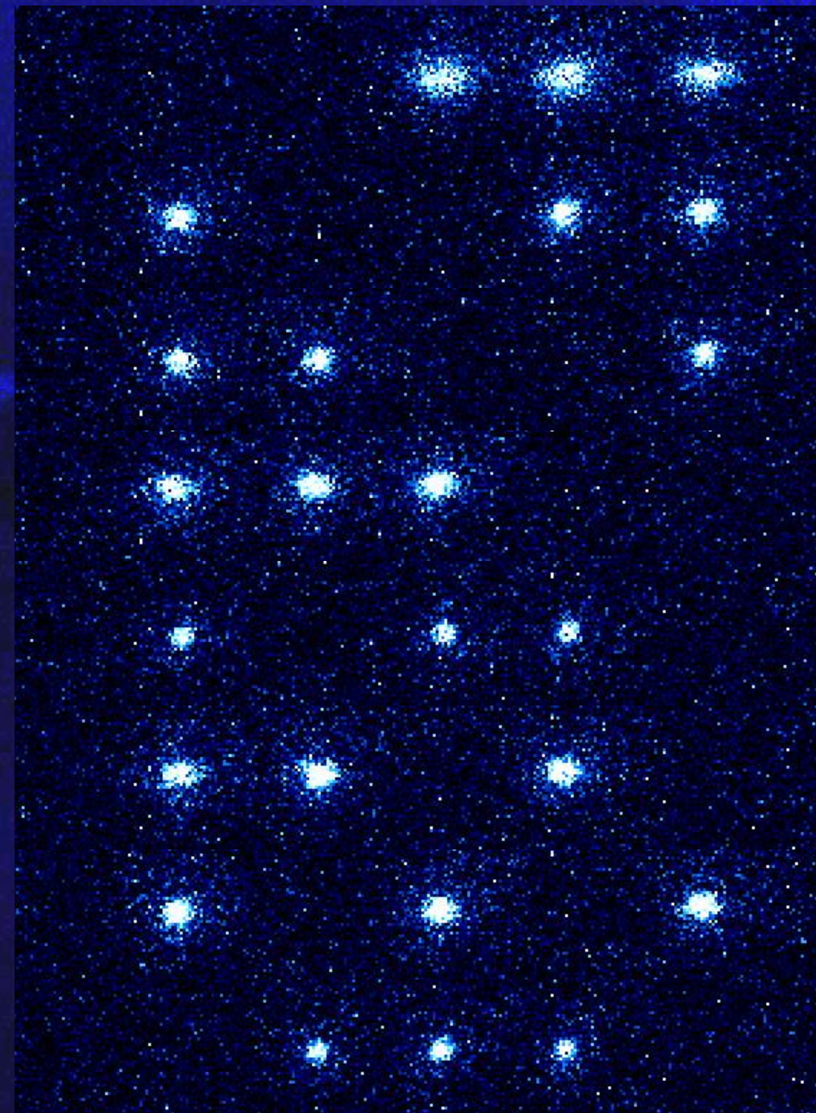
Hybrid Ba-Yb ion chains



Chain of 5 Ba ions

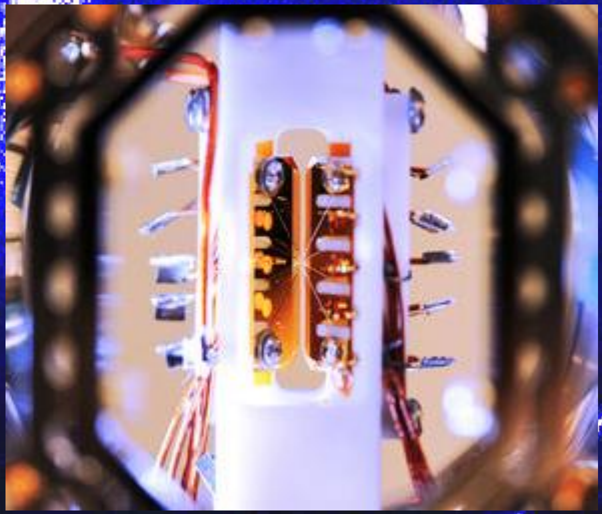


Chain of 4 Ba and 1 Yb ions

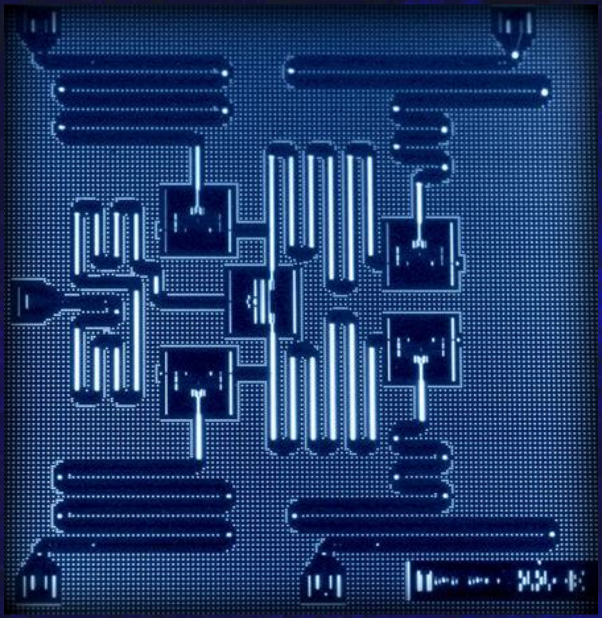


Chain of 3 Ba and 2 Yb ions

Ions vs. Superconductors

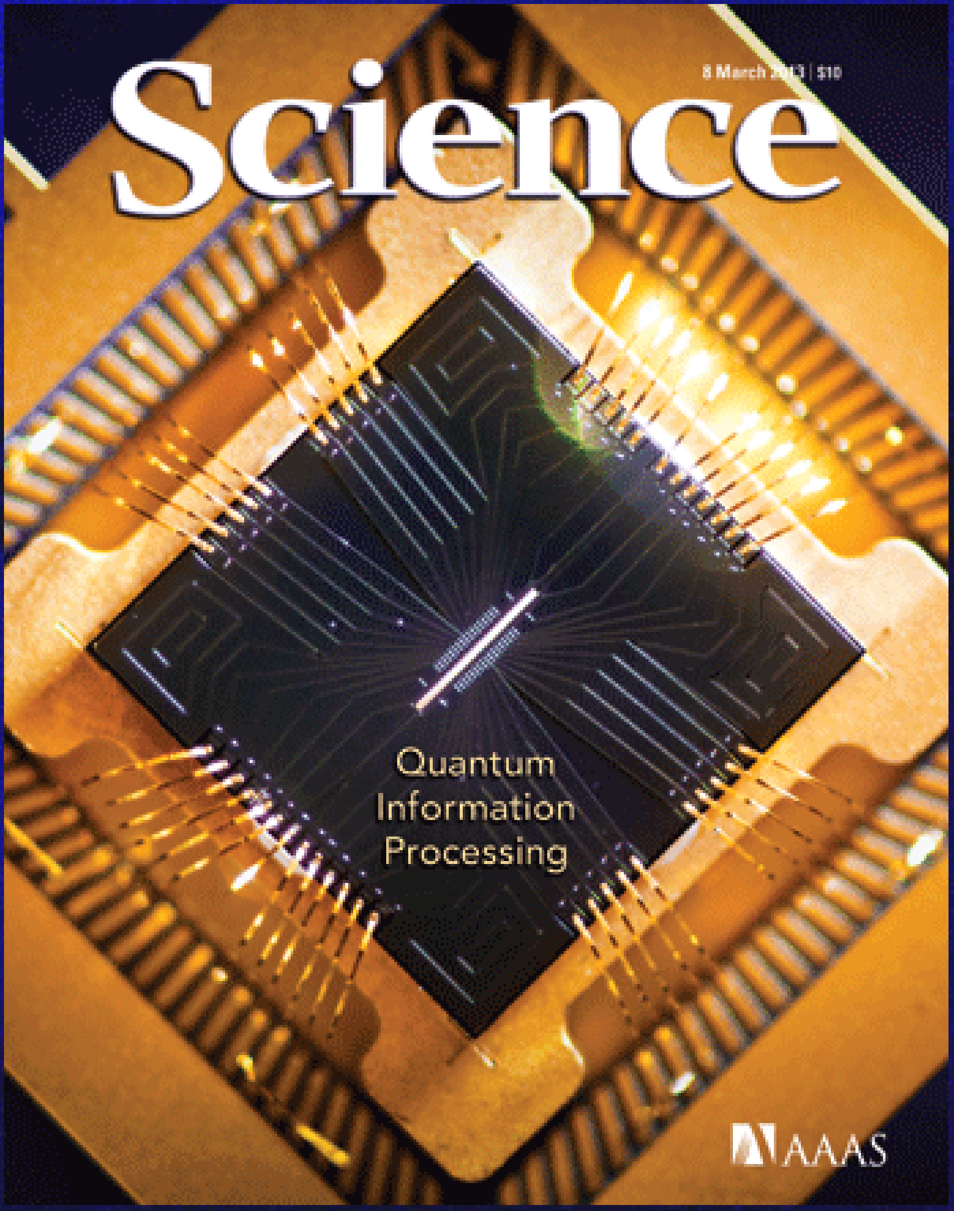


In the left corner, 5-qubit fully interconnected trapped ion quantum processor (UMD/JQI)



In the right corner, 5-qubit cross-connected transmon device (IBM)

The future is here: chip traps



Modern integrated circuits

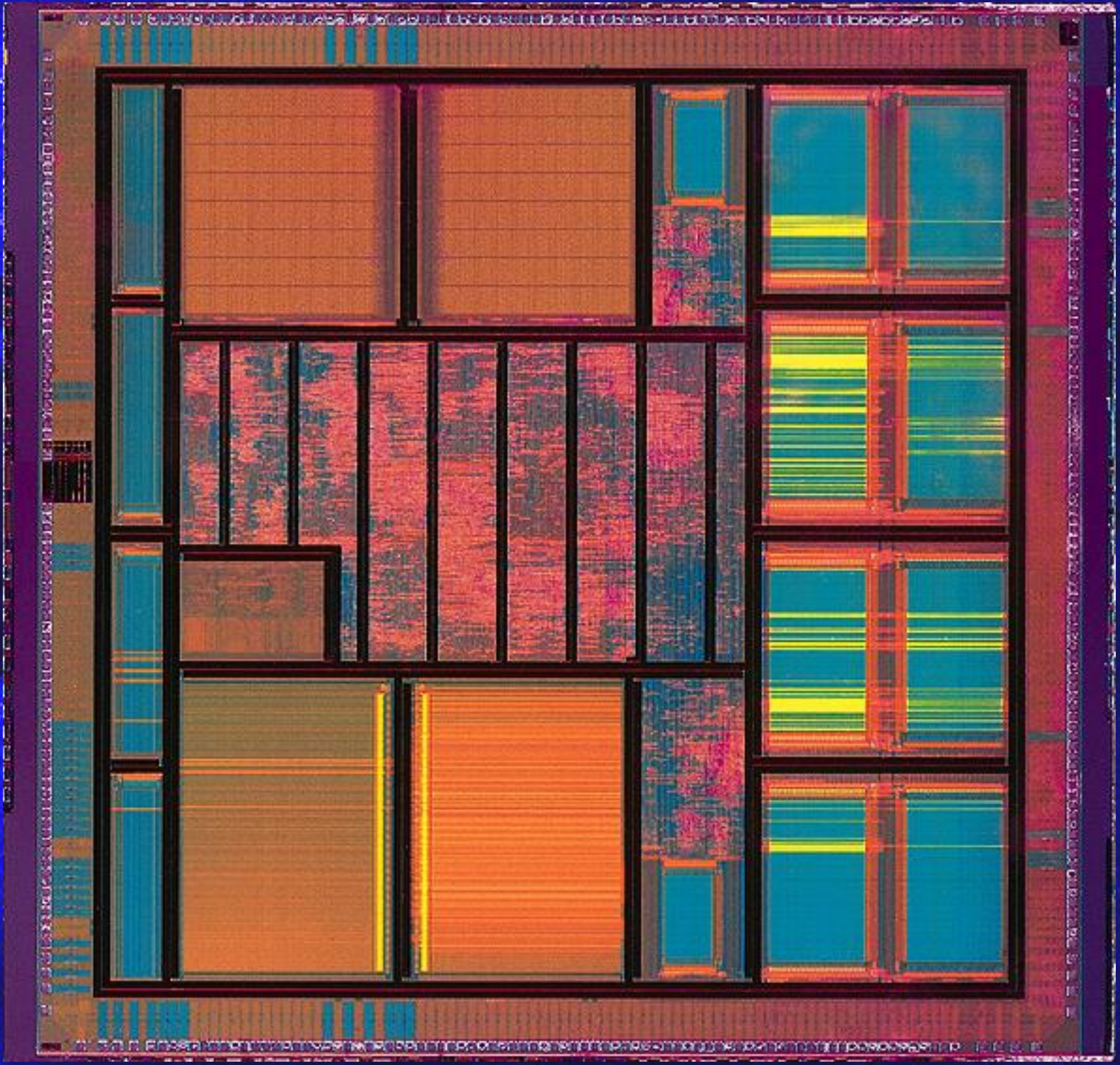
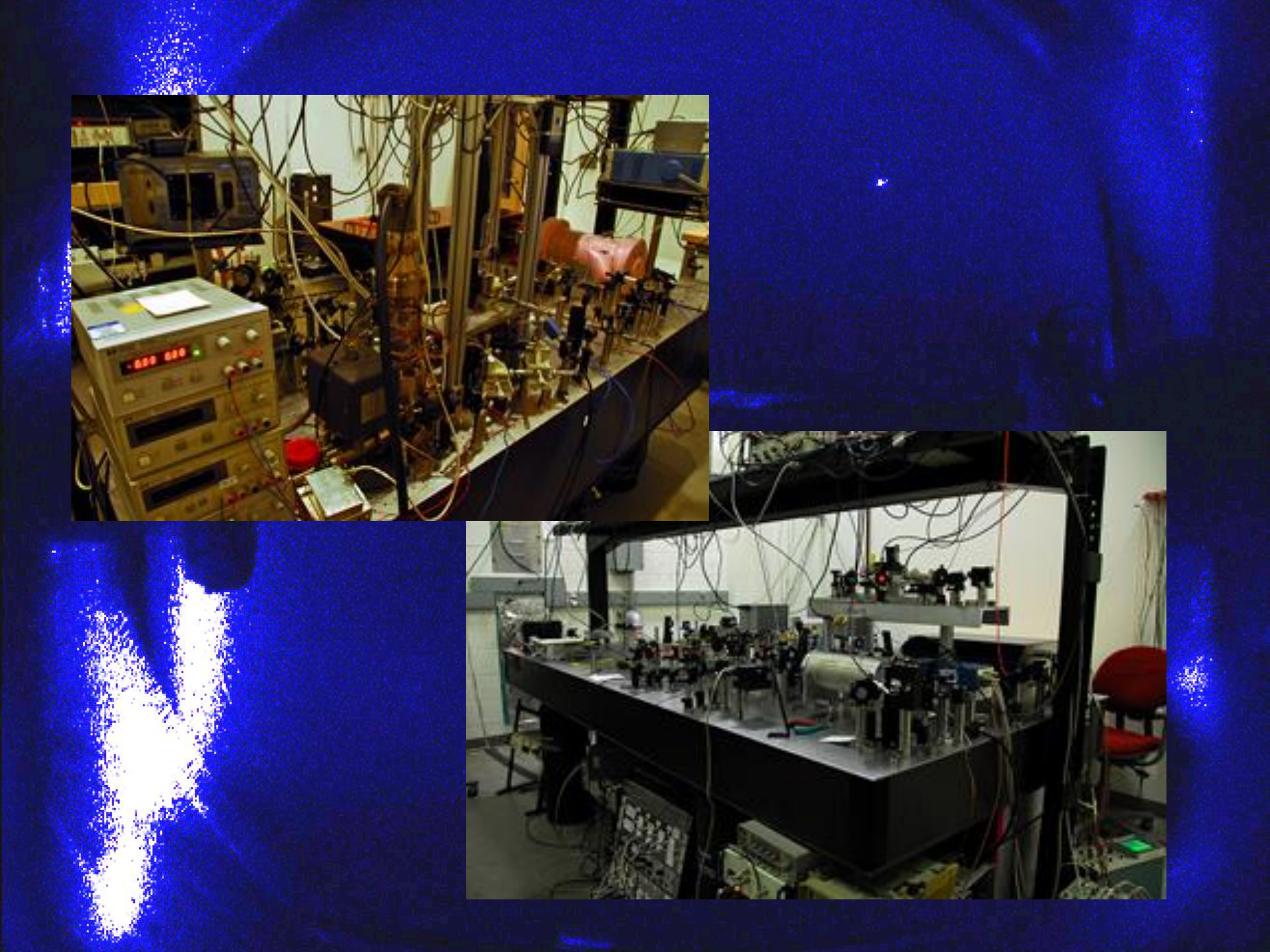
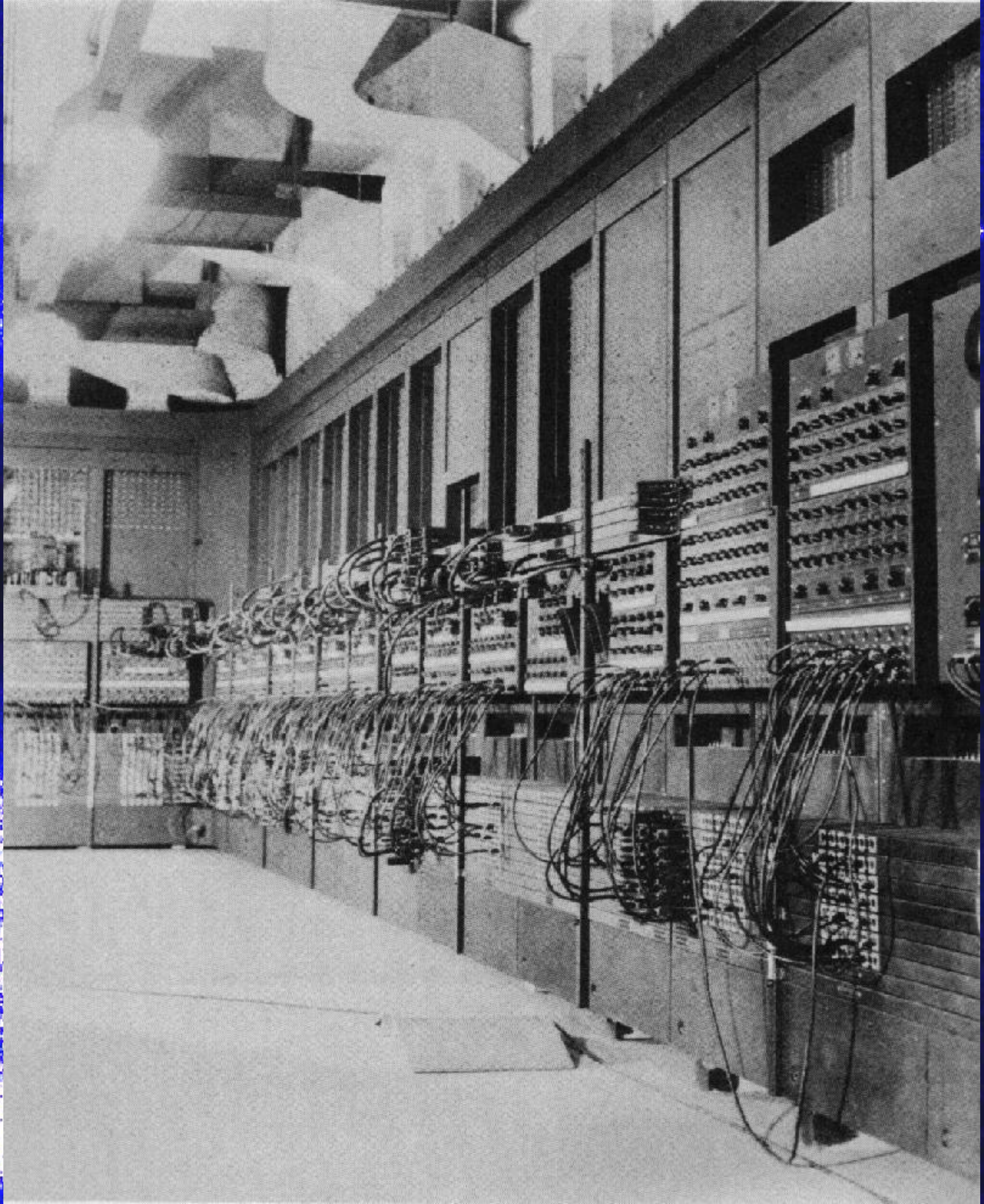


Image courtesy of Wikipedia





ENIAC
(1946)

Final remarks…

Quantum

"Computers in the future may weigh no more than 1.5 tons."

- Popular Mechanics (1949)

Quantum

"I think there is a world market for maybe five computers."

\- Thomas Watson, chairman of IBM (1943)