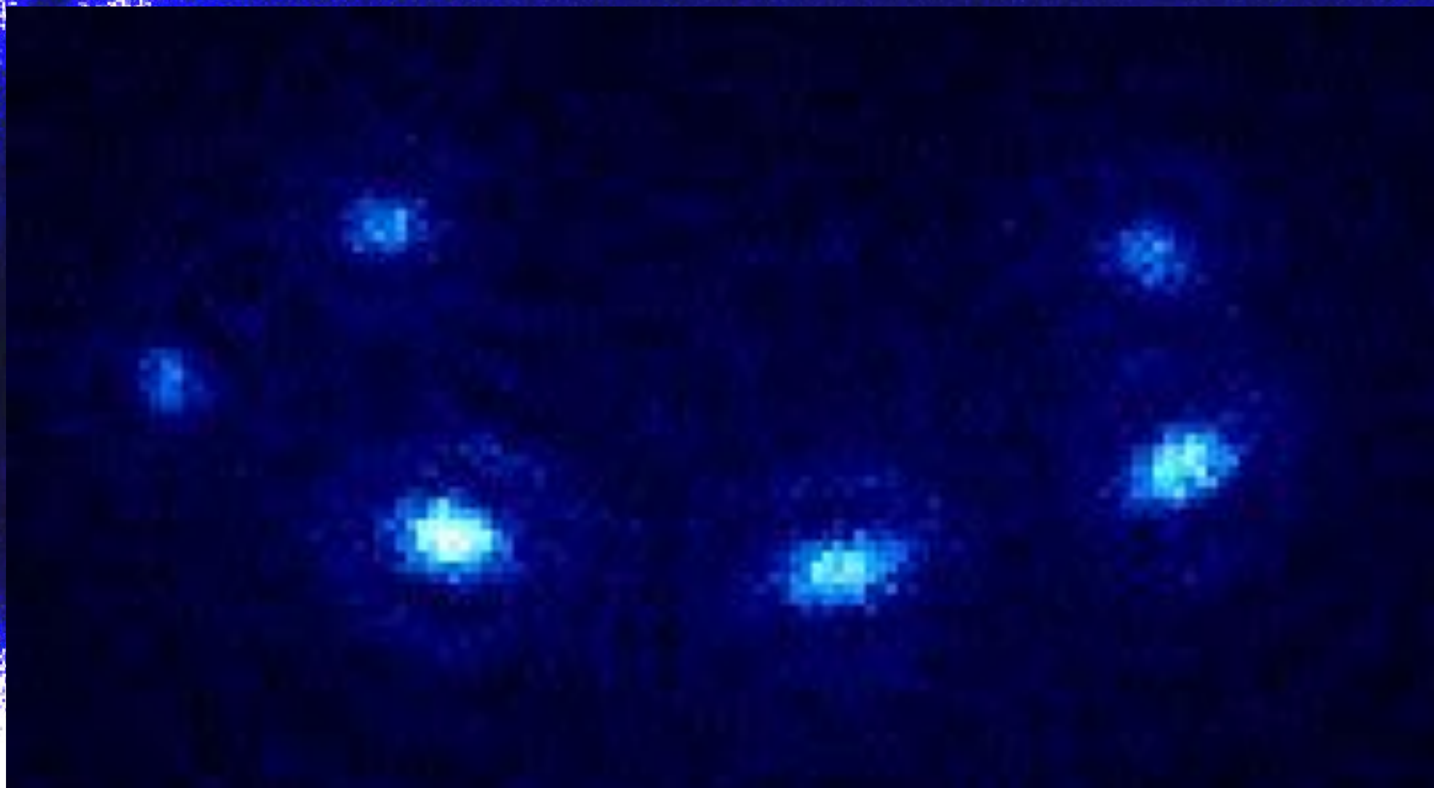
Quantum Computing with Atoms and Photons



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Introduction: of Bits and Qubits

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

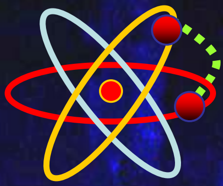
Richard Feynman

"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: $|\psi\rangle = (1/2)^{-1} (|0\rangle + |1\rangle)\times(|0\rangle + |1\rangle) =$

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

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

- ……………..

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

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

  $(1/2)^{-N/2}$ (“0” + “1” + “2” +…+ “2^N-1”)

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

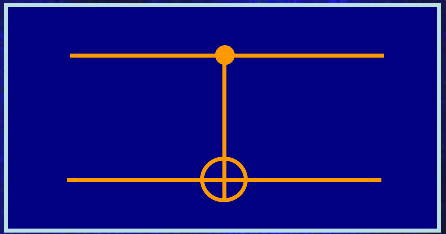
The Entanglement

- 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

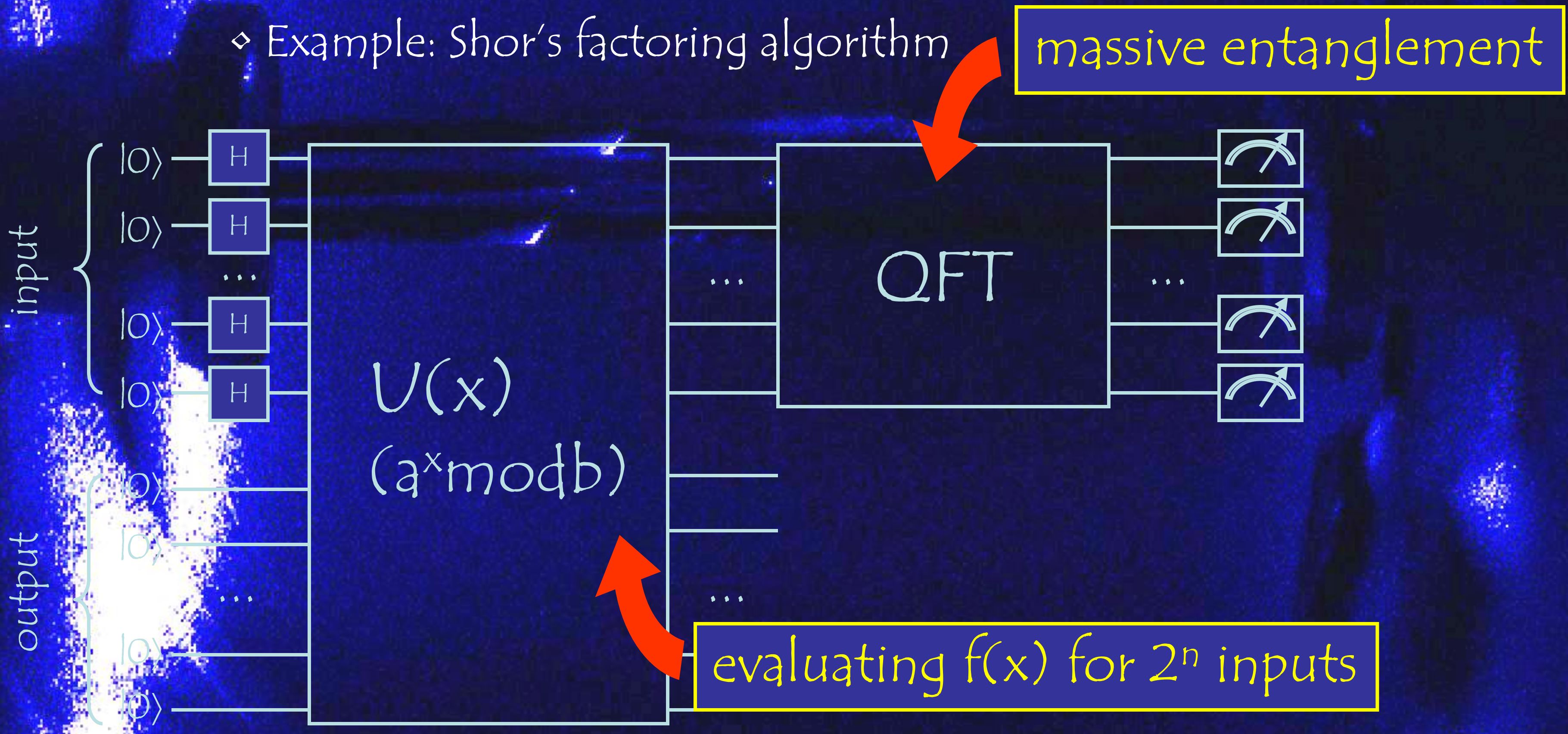


control qubit	target qubit	result
$\|0\rangle$	$\|0\rangle$	$\|0\rangle\,\|0\rangle$
$\|0\rangle$	$\|1\rangle$	$\|0\rangle\,\|1\rangle$
$\|1\rangle$	$\|0\rangle$	$\|1\rangle\,\|1\rangle$
$\|1\rangle$	$\|1\rangle$	$\|1\rangle\,\|0\rangle$
$\alpha\|0\rangle + \beta\|1\rangle$	$\|0\rangle$	$\alpha\|0\rangle\|0\rangle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

Entangled state!

Quantum computing revealed

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

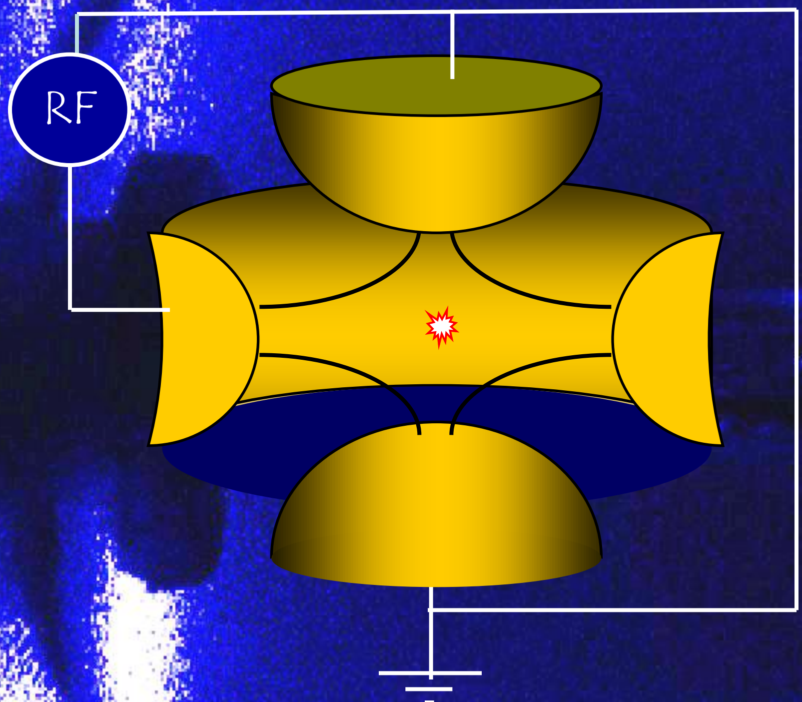


What is it about factoring?

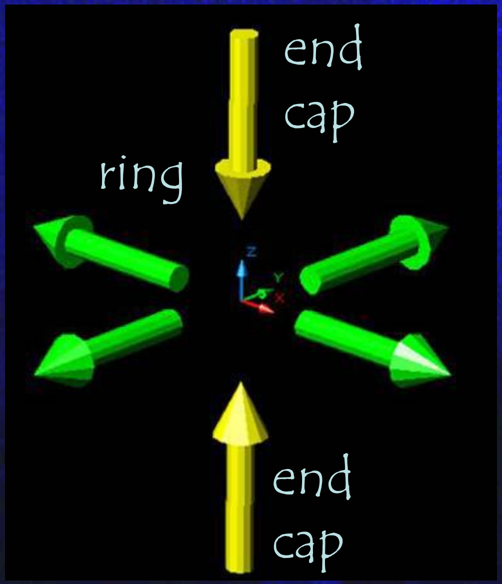
- Let's say I give you two numbers, 577 and 239. What is their product? Trivial: 577 × 239 = 137,903 .
- What if I give you one number, say, 149,797 and ask you to find it's factors? Ha?
- Any takers?
- How would you even approach solving this problem, other than guessing???
- This problem is HARD! Public key encryption is based on this fact. Now, when you see this:  , you know your data is secure!

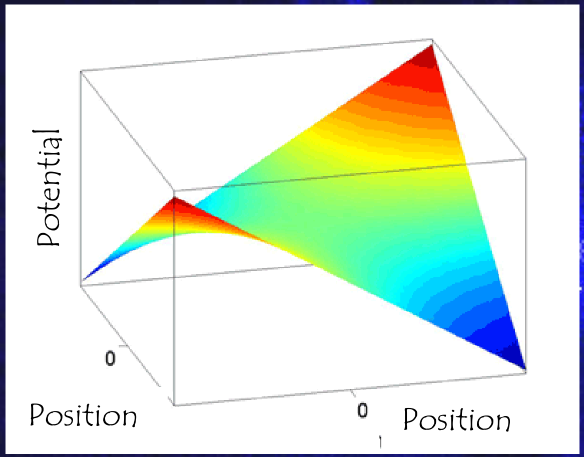
Ion traps and trapped ions

RF (Paul) ion trap

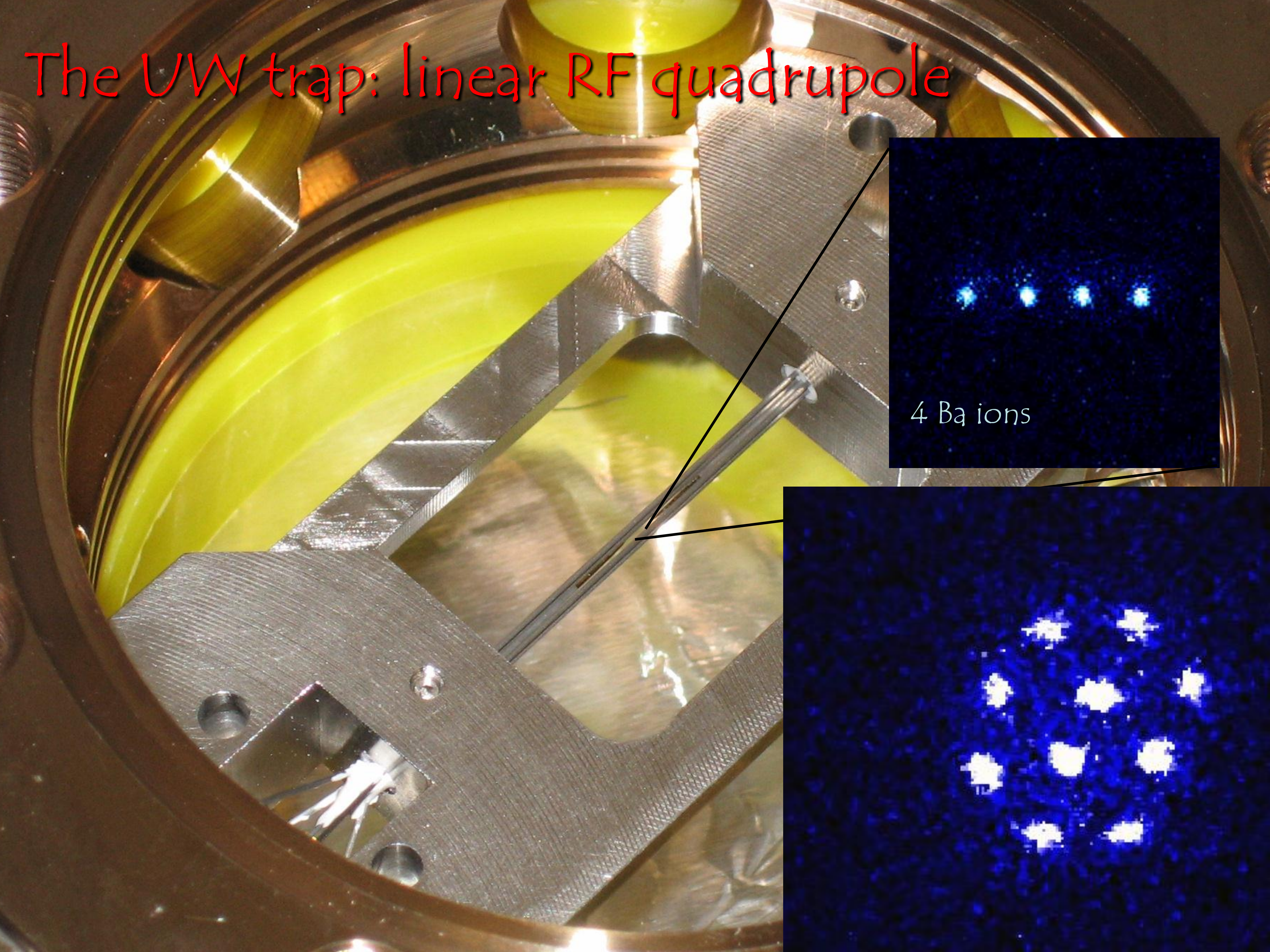


"RF quadrupole"

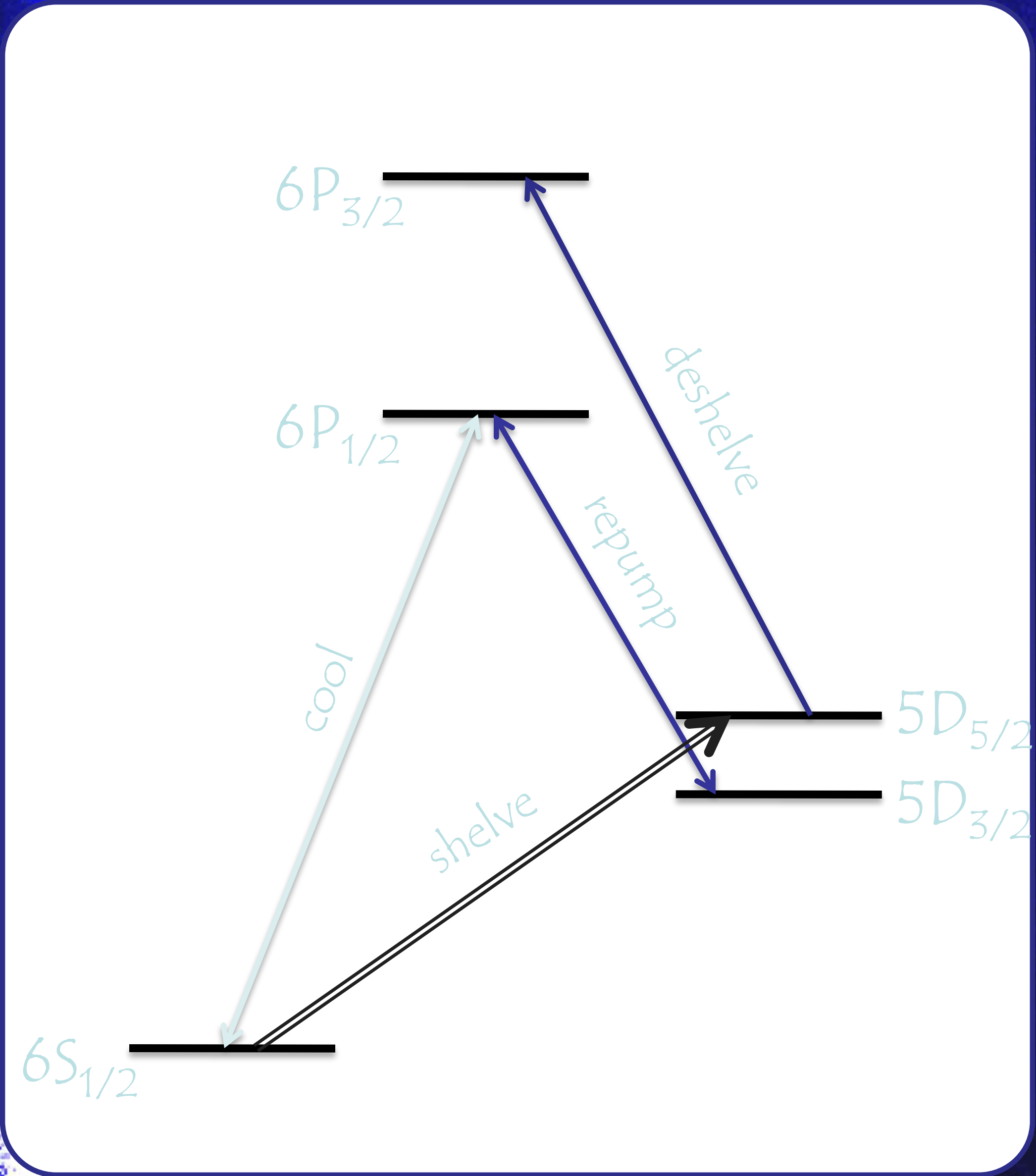




The UW trap: linear RF quadrupole



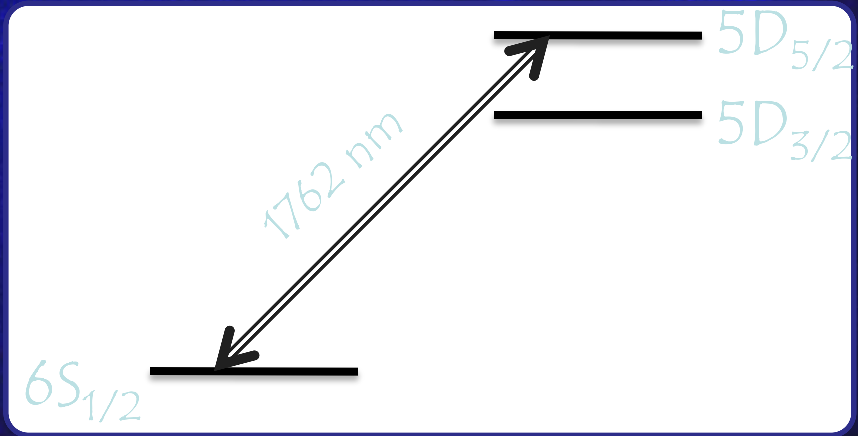
But first: Ba ion qubit(s)



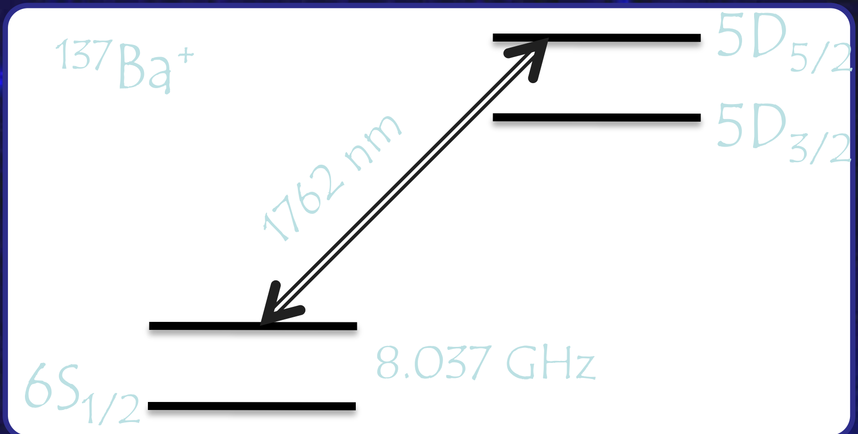
- laser cooling: 493 nm and 650 nm
- qubit initialization: optical pumping
- qubit control: some form of EM waves
- qubit detection: state-dependent fluorescence

Now, the qubits

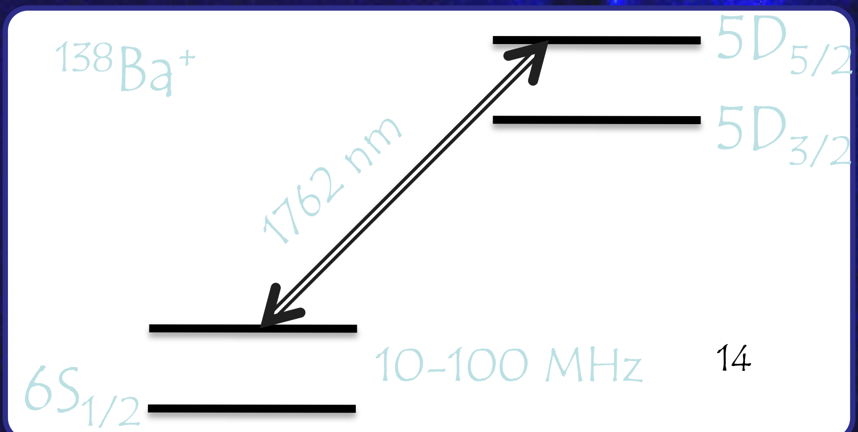
- optical: S-D transition



- hyperfine: ground state "clock" states

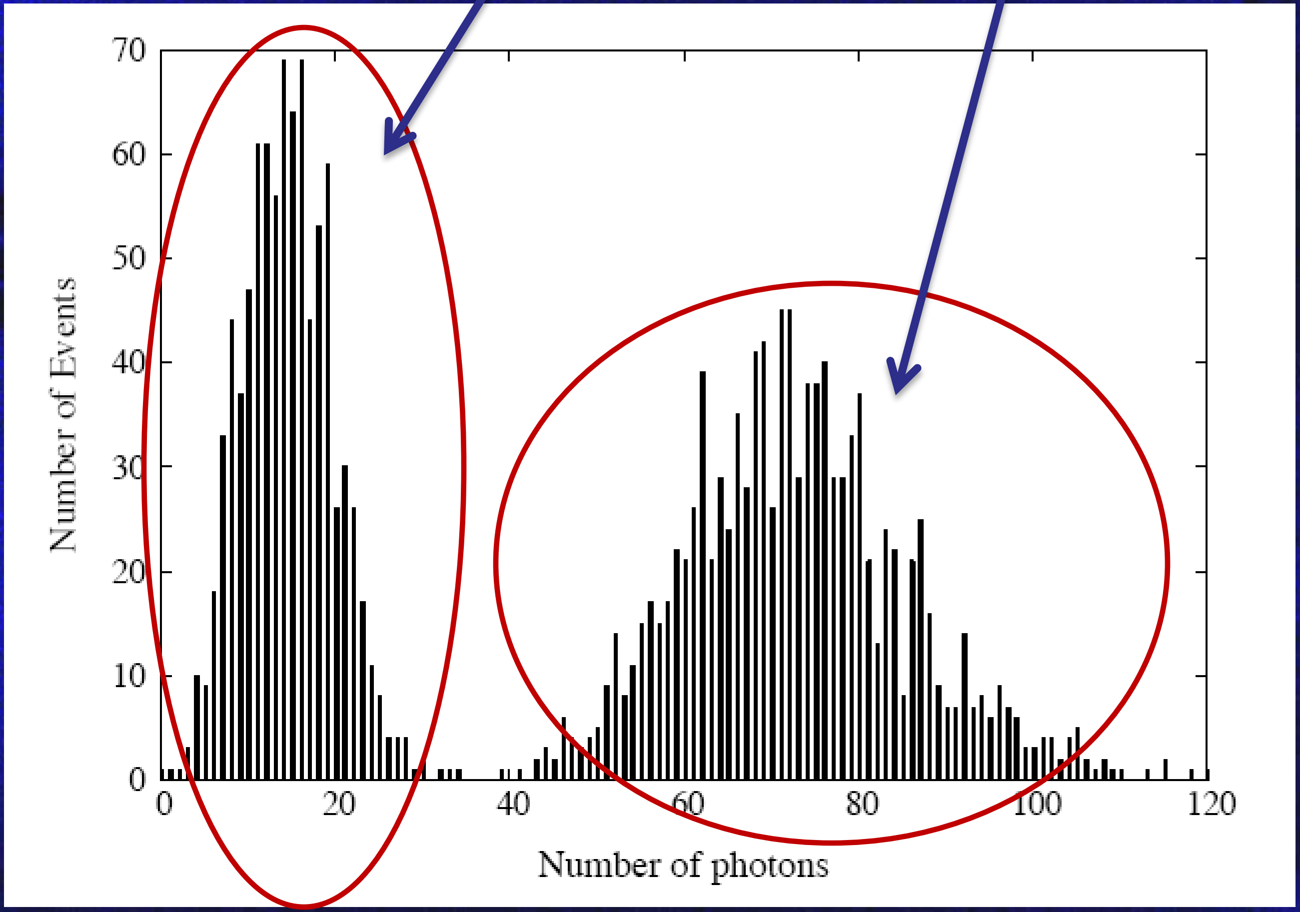


- Zeeman: ground state Zeeman states

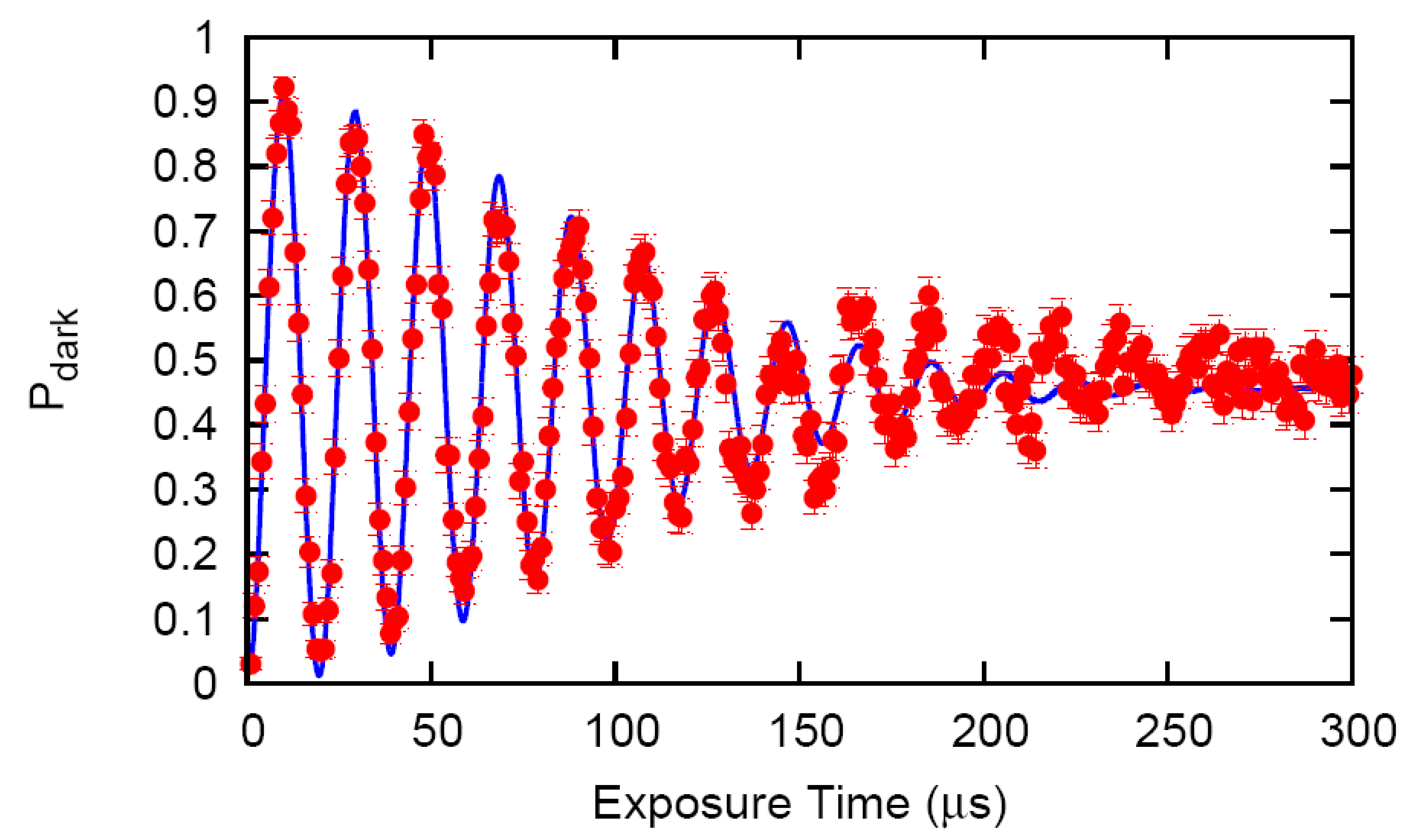


Whatever qubit, detection the same

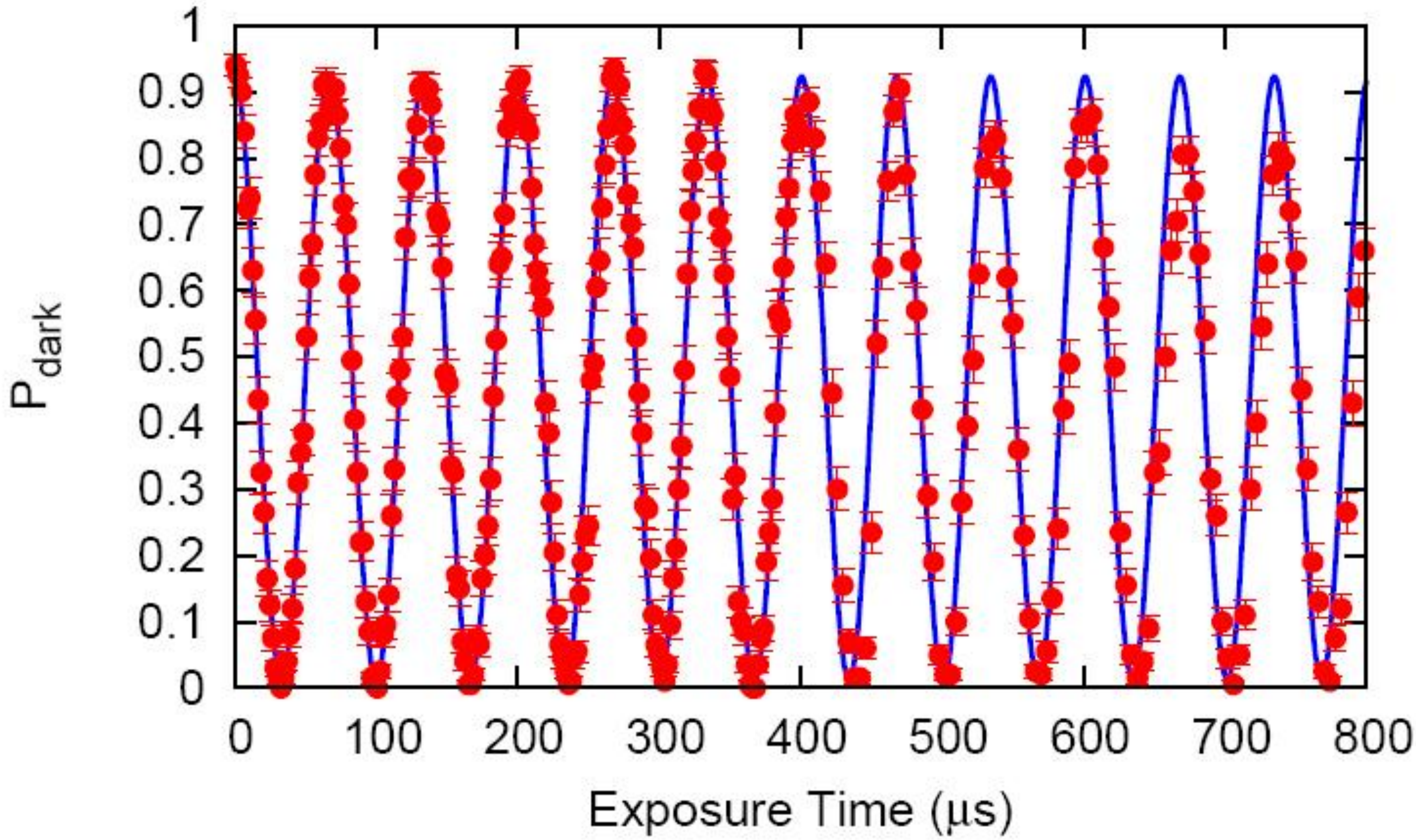
One state "dark", the other "bright"

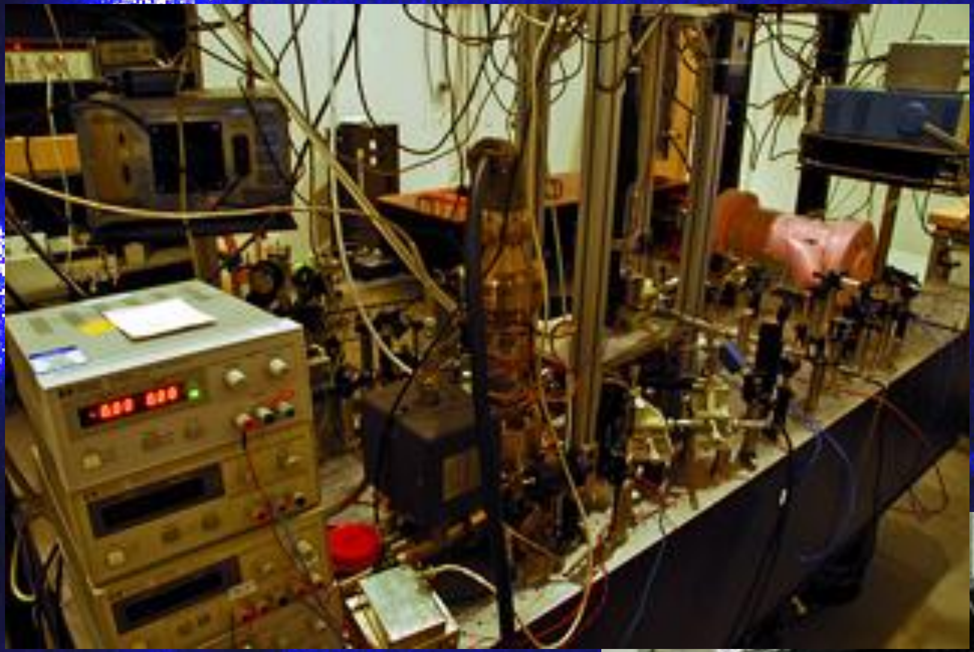


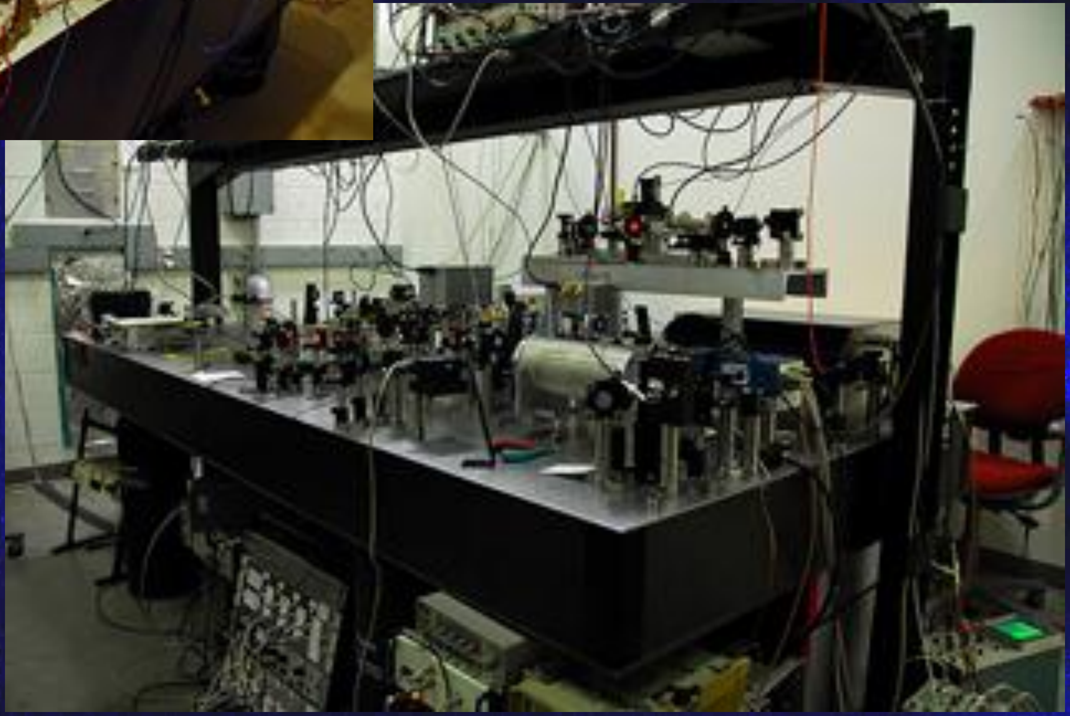
Optical qubit: the Rabi flops

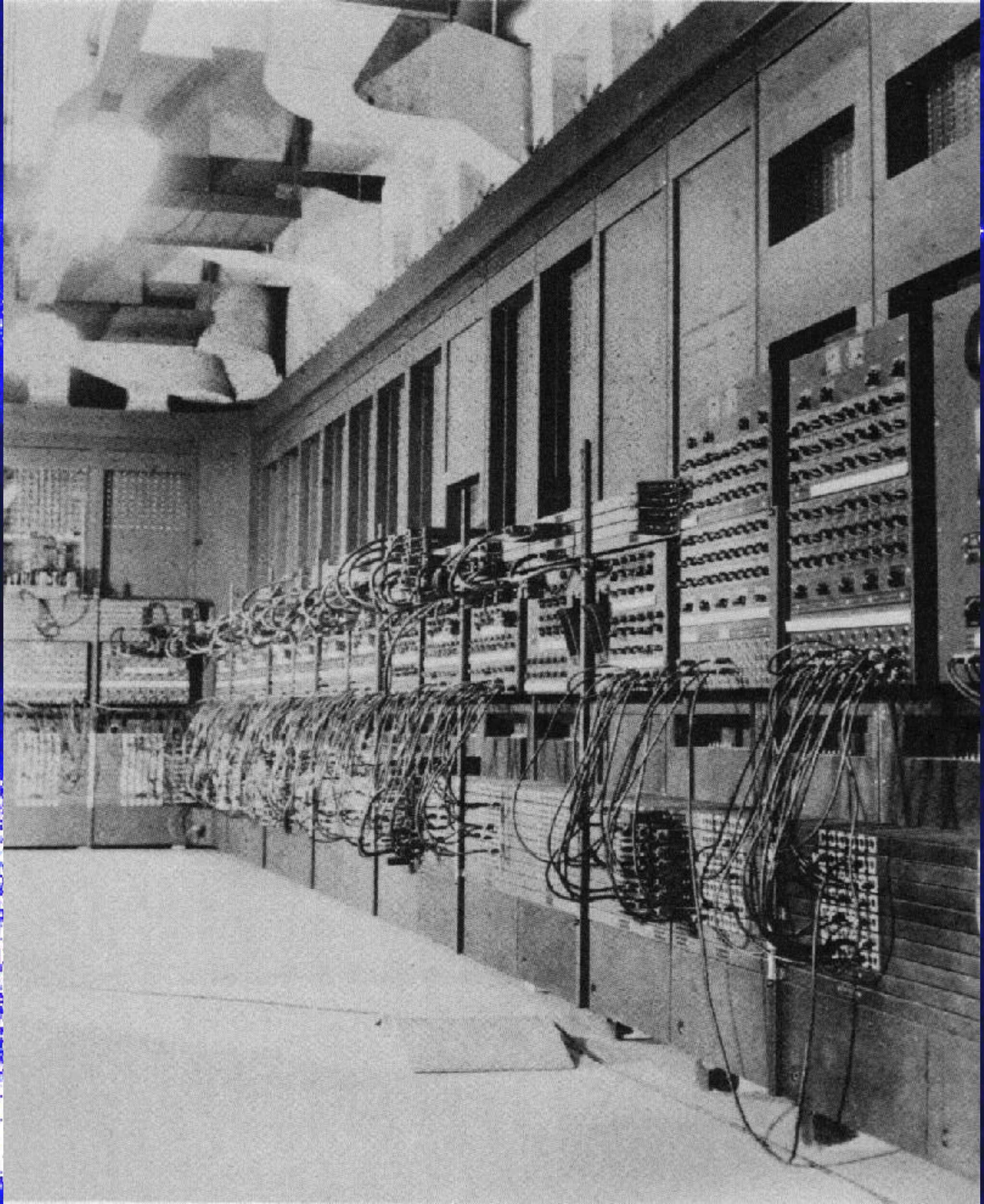


Hyperfine qubit: the Rabi flops

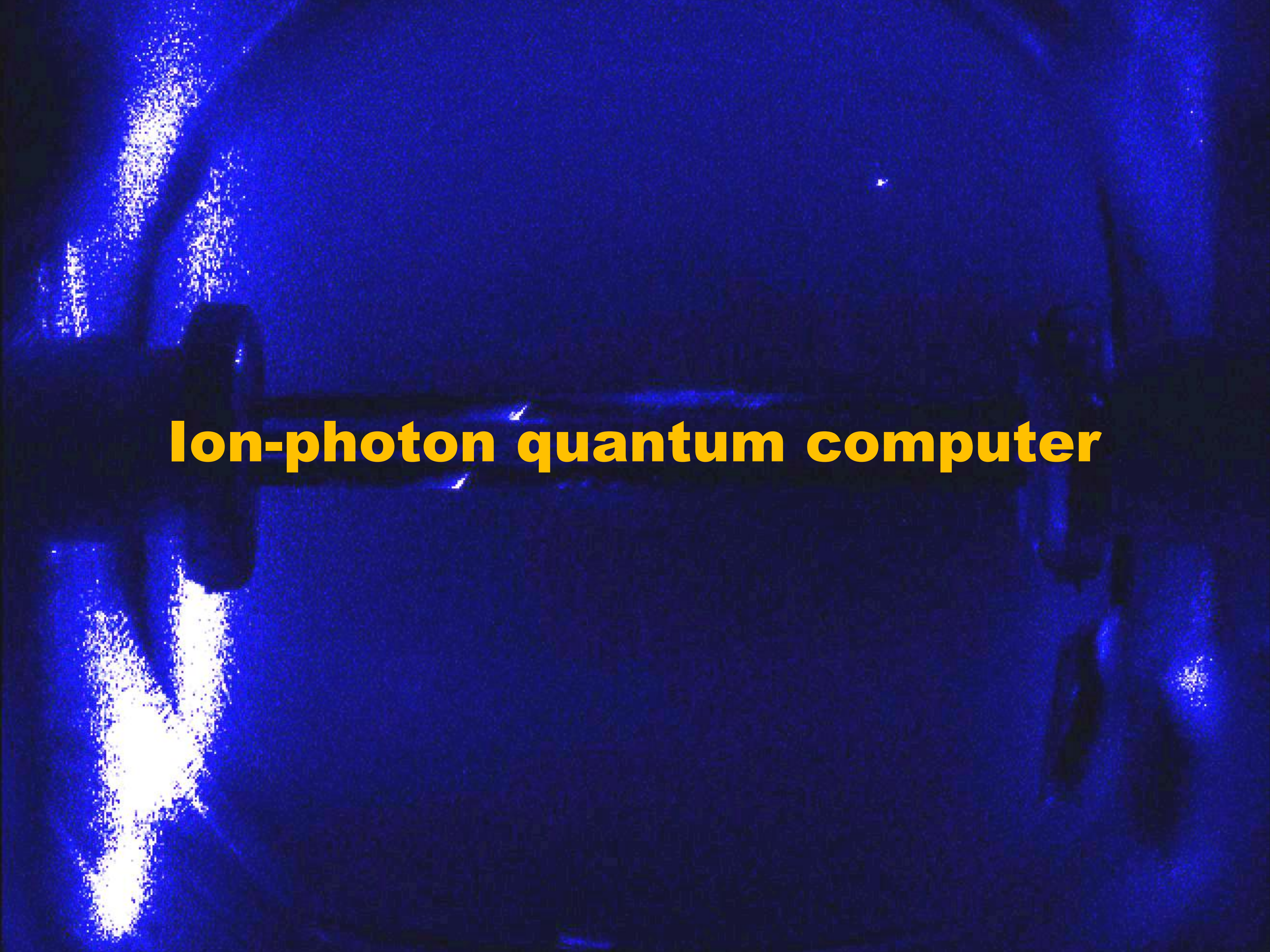




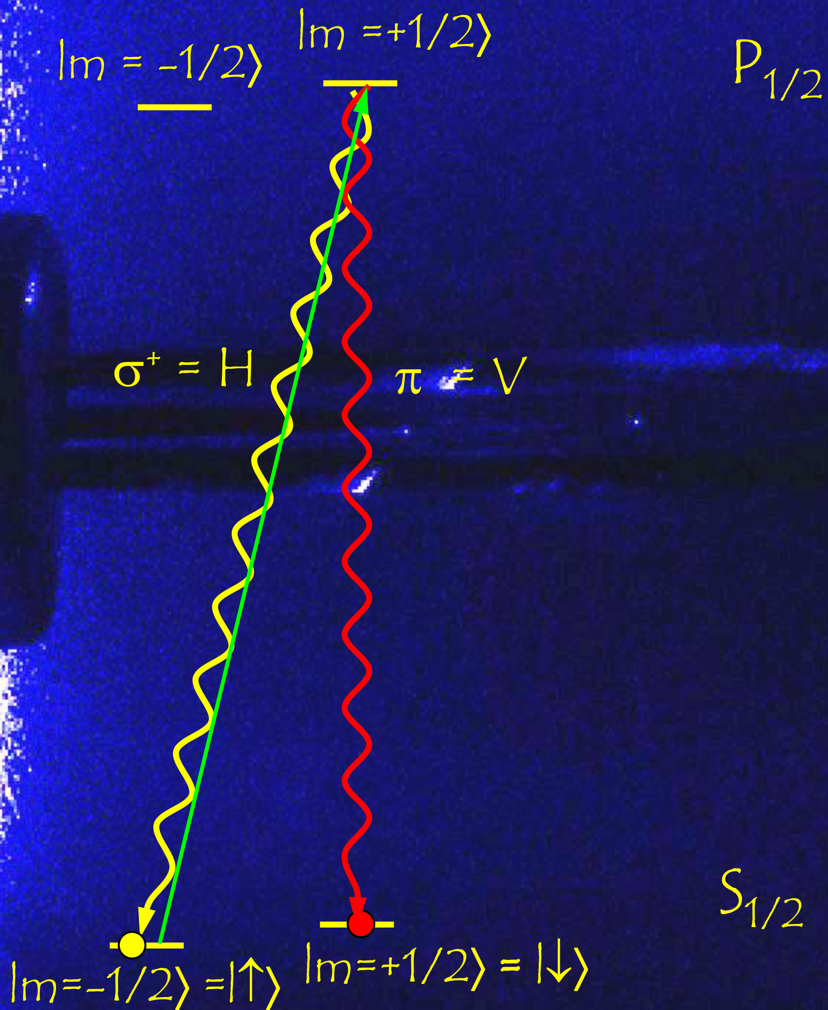




ENIAC
(1946)


Ion-photon quantum computer

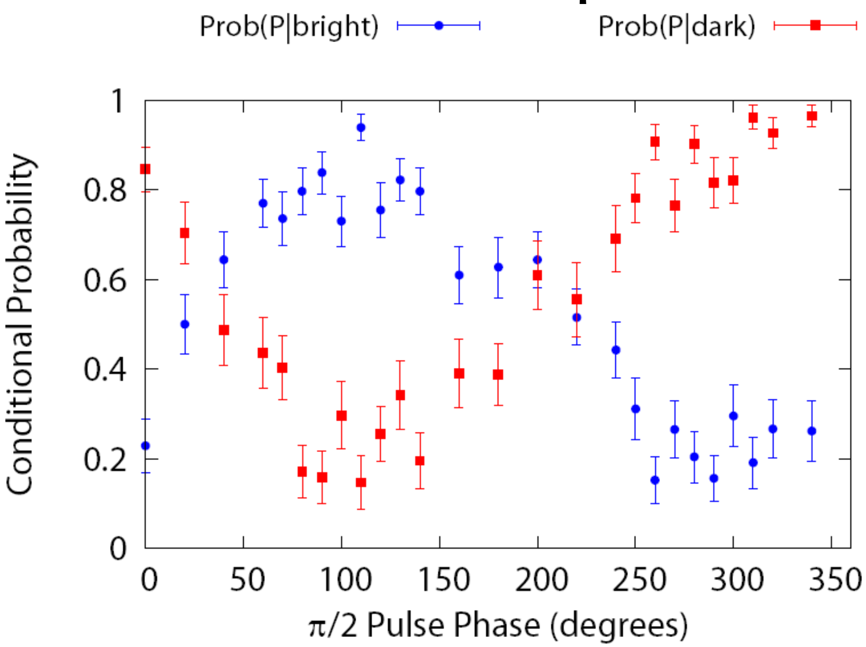
Ion-photon entanglement

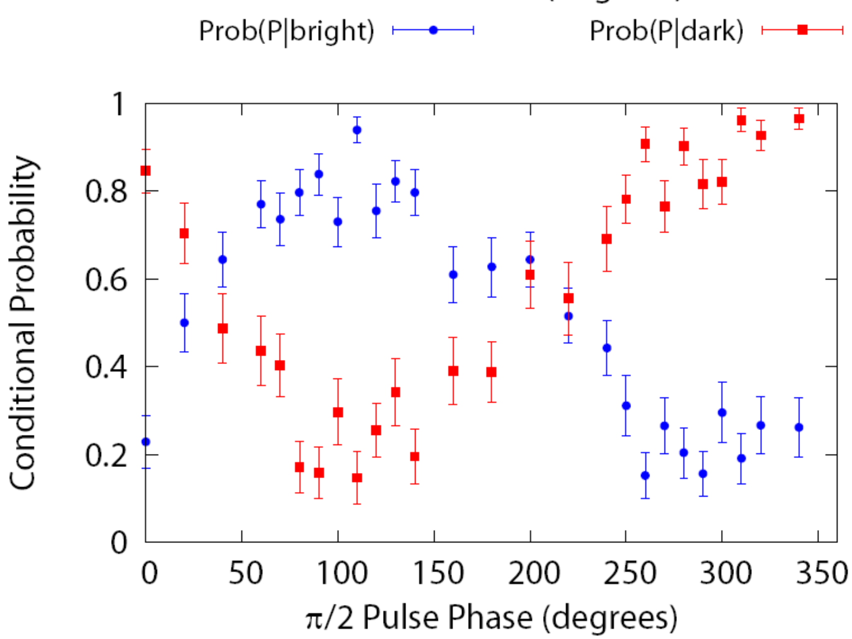


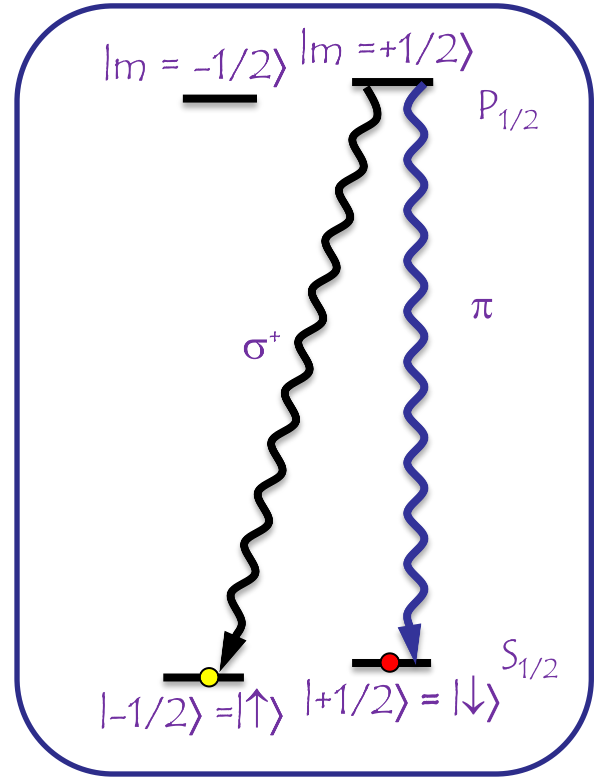
$|\psi\rangle = |H\rangle|\uparrow\rangle + |V\rangle|\downarrow\rangle$

- 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

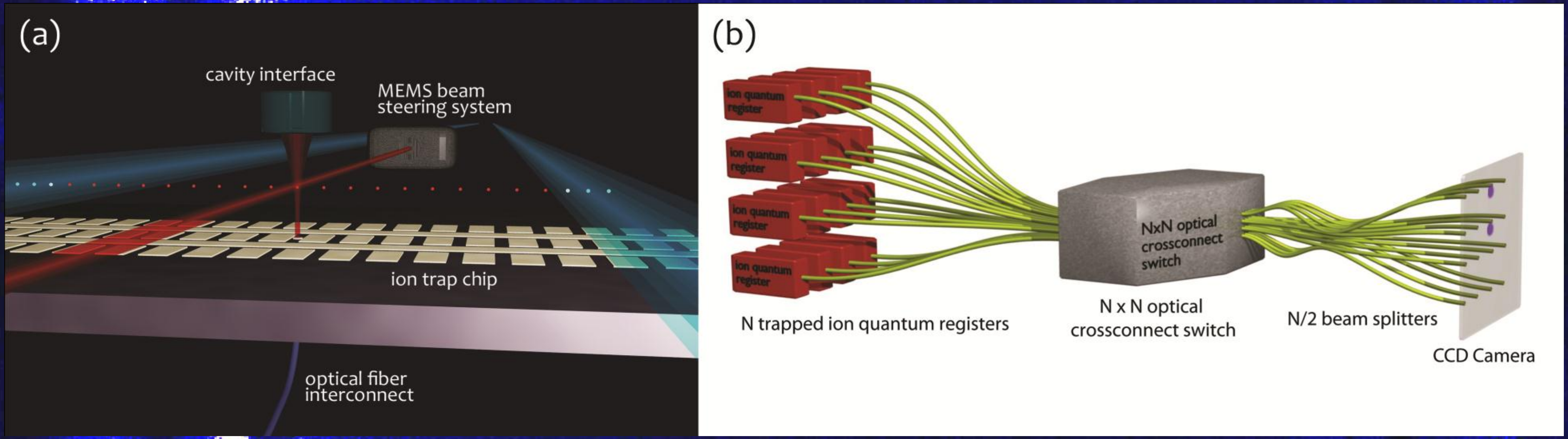




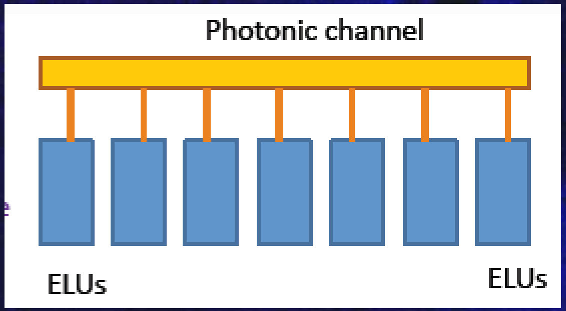


Single photon – ion state correlation. Weak CW pulse excitation at 35 kHz rep rate, ~20% excitation probability; ~1 Hz success rate

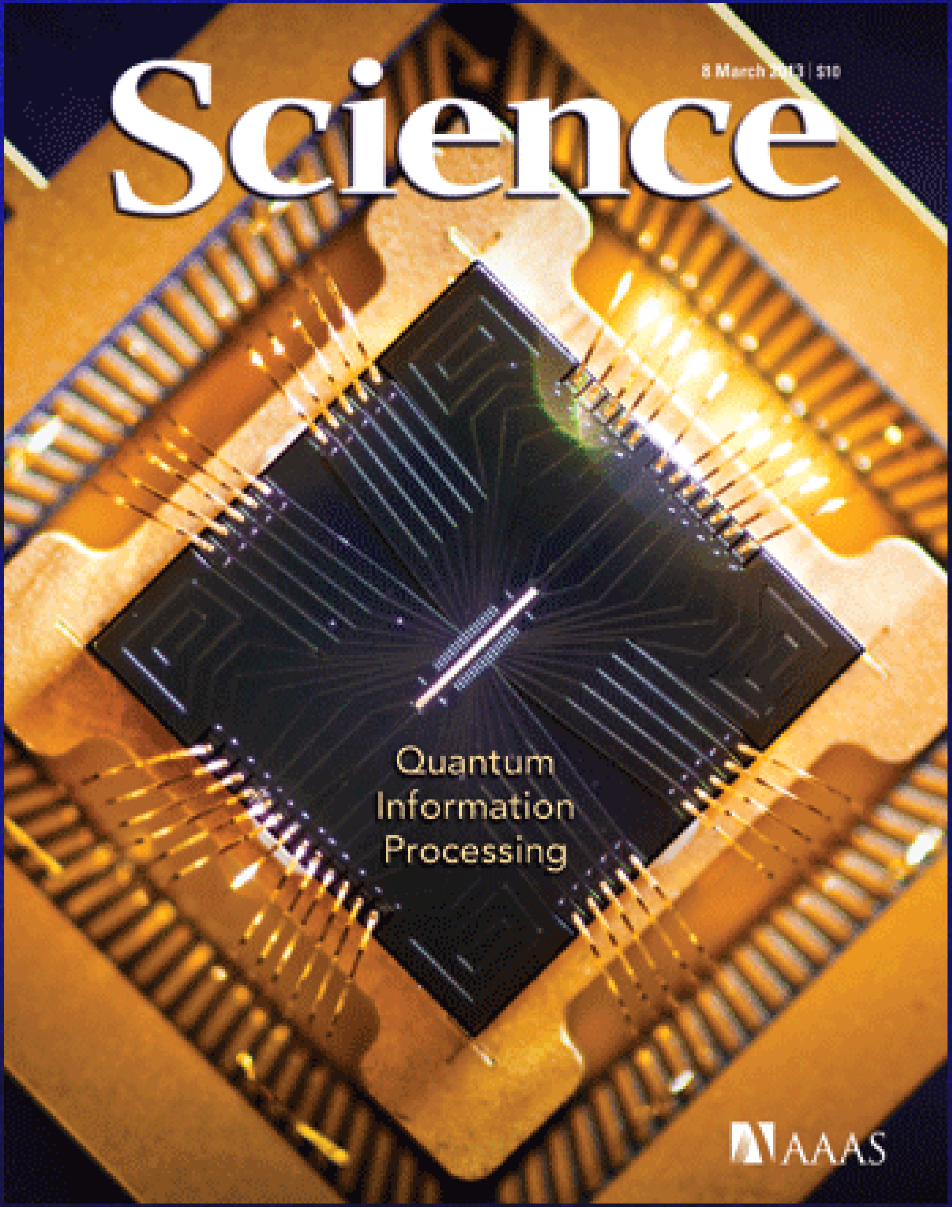
Ion-photon CQ: the basic idea



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



The future is here: chip traps



Modern integrated circuits

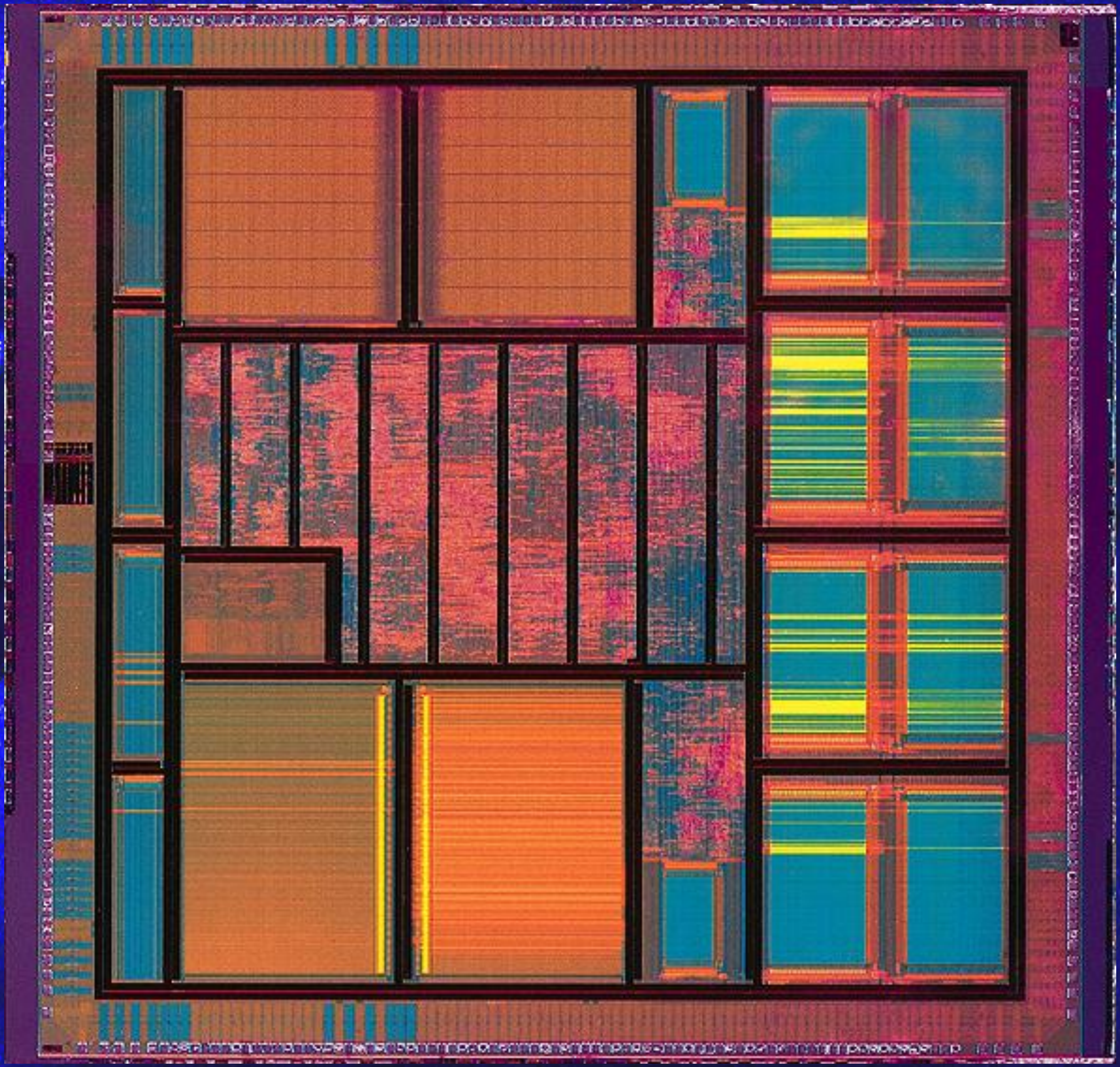
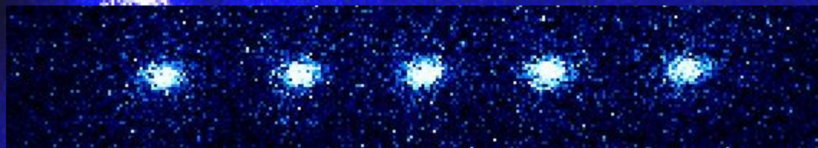
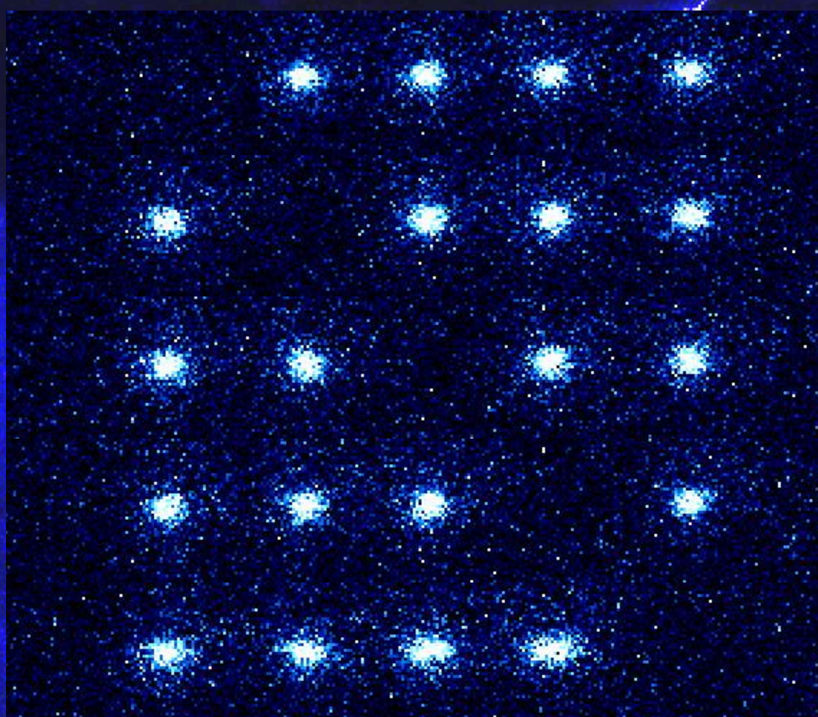


Image courtesy of Wikipedia

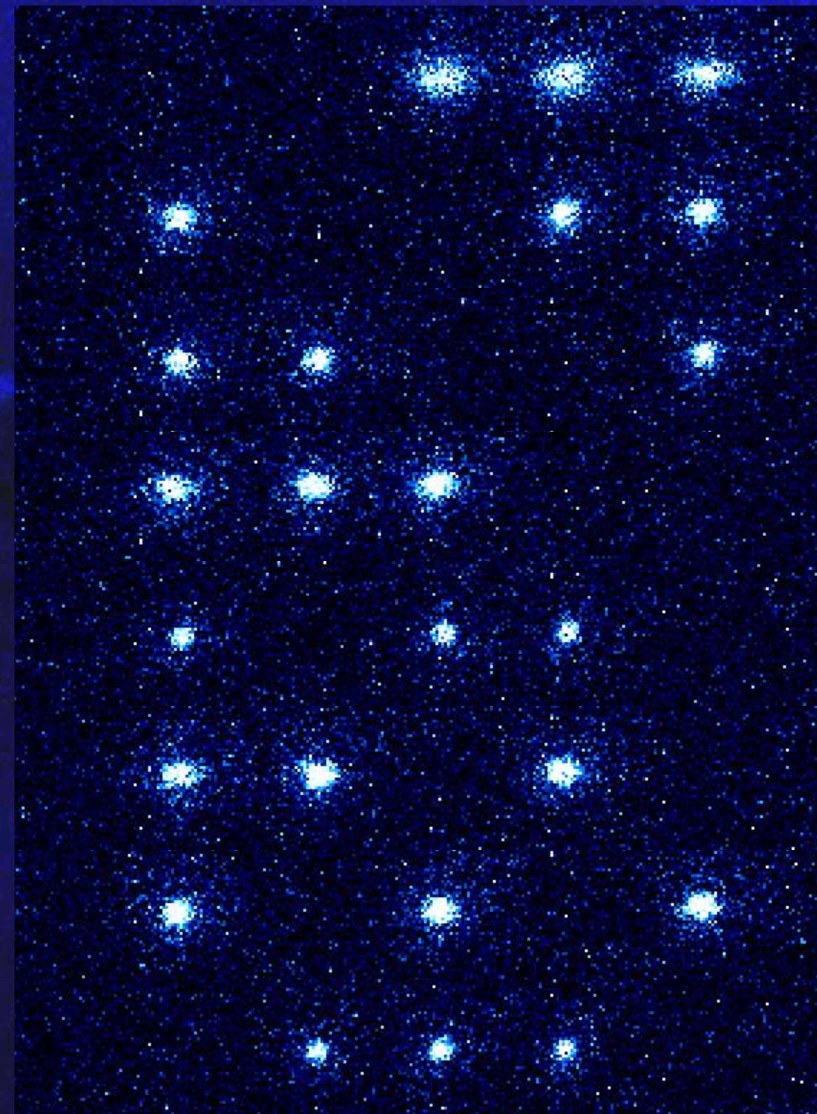
Hybrid Ba-Yb ion chains



Chain of 5 Ba ions

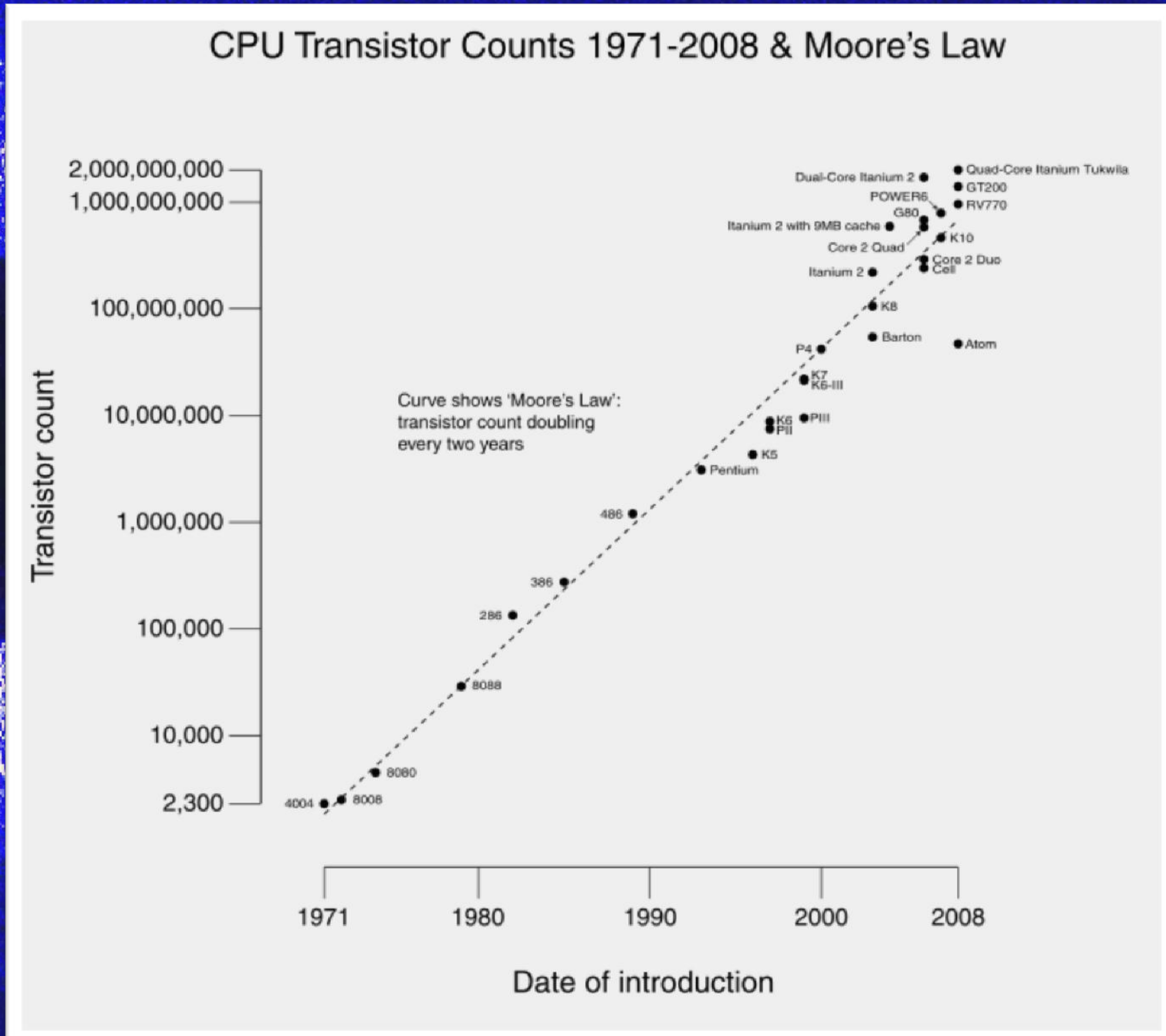


Chain of 4 Ba and 1 Yb ions



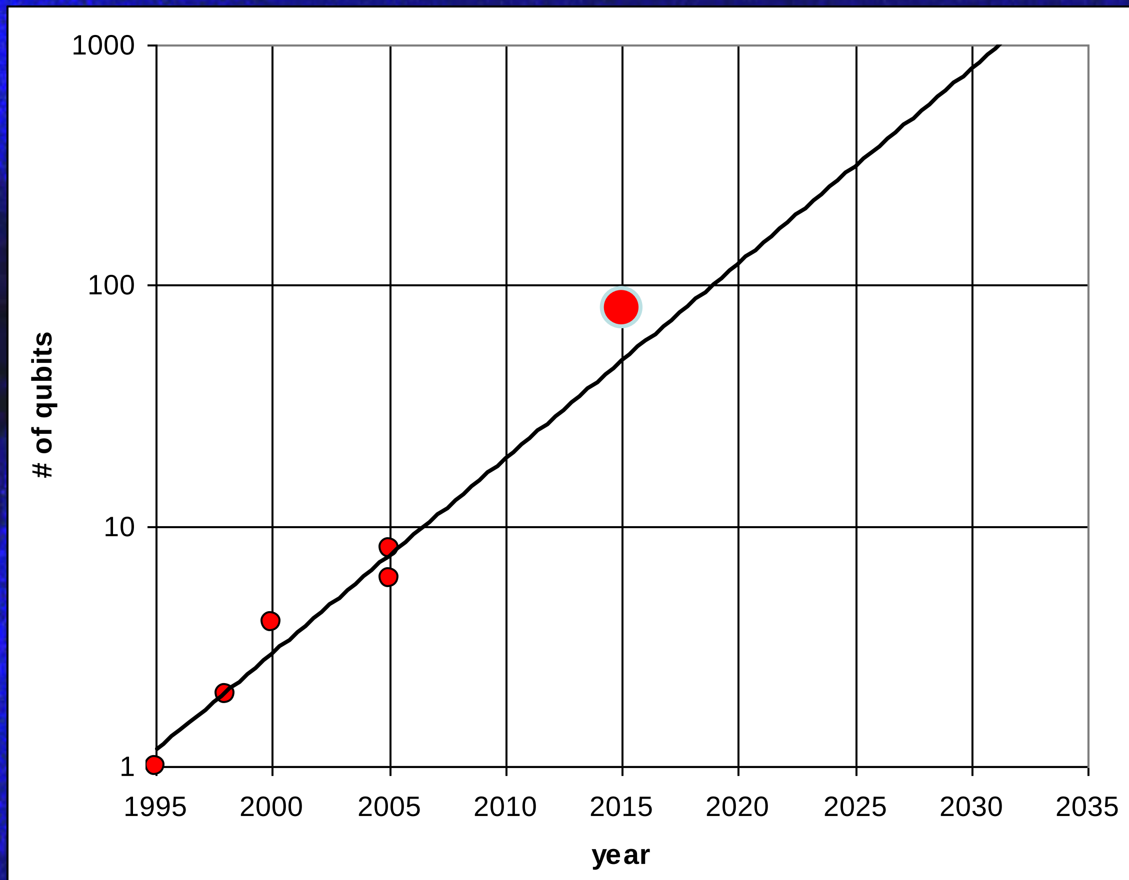
Chain of 3 Ba and 2 Yb ions

Moore’s Law



Graph courtesy of Wikipedia

Moore's Law for trapped ion qubits



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)

BB Mike Cornea Seth Coleman Erik Magnuson Paul Pham Adam Kleczewski Sean Nelson
Gang Shu Bing Chen Kate Mitchell Tom Noel Matt Hoffman
Nathan Kurz Andrea Katz Chen-Kuam Chou