Trapped Ions and Atoms as Qubits

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National Security Agency

NSF tional Science Foundation

Advanced Research
& Development Activity

Frontiers of Optical
Coherent & Ultrafast Science

Army Research Office

Quantum Information and Atomic Physics

$$H = \sum_{i=1}^{N} \frac{1}{2} \omega_i(t) \hat{\vec{\sigma}}^{(i)} + \sum_{i,j=1}^{N} g_{ij}(t) \hat{\vec{\sigma}}^{(i)} \cdot \hat{\vec{\sigma}}^{(j)}$$

N qubits

controlled coupling

… to >99% accuracy*

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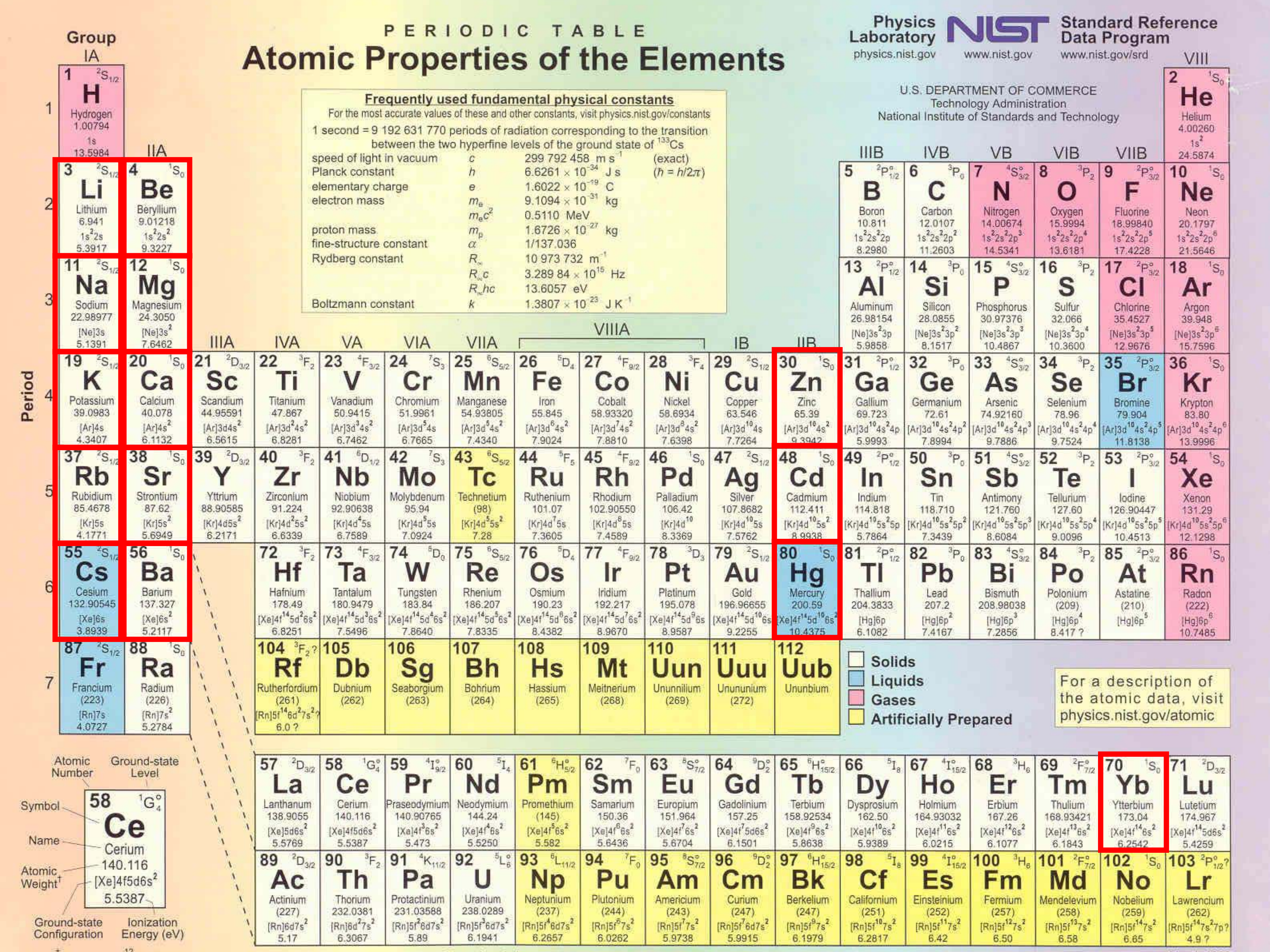
* provided things have been done right



Physics Laboratory
physics.nist.gov

NIST
www.nist.gov

Standard Reference Data Program
www.nist.gov/srd

U.S. DEPARTMENT OF COMMERCE
Technology Administration
National Institute of Standards and Technology

PERIODIC TABLE

Atomic Properties of the Elements

Frequently used fundamental physical constants

For the most accurate values of these and other constants, visit physics.nist.gov/constants

1 second = 9 192 631 770 periods of radiation corresponding to the transition between the two hyperfine levels of the ground state of ^{133}Cs

speed of light in vacuum	c	299 792 458 m s^{-1}	(exact)
Planck constant	h	6.6261×10^{-34} J s	($\hbar = h/2\pi$)
elementary charge	e	1.6022×10^{-19} C	
electron mass	m_e	9.1094×10^{-31} kg	
	m_ec^2	0.5110 MeV	
proton mass	m_p	1.6726×10^{-27} kg	
fine-structure constant	α	1/137.036	
Rydberg constant	R_∞	10 973 732 m^{-1}	
	$R_\infty c$	$3.289\,84 \times 10^{15}$ Hz	
	$R_\infty hc$	13.6057 eV	
Boltzmann constant	k	1.3807×10^{-23} J K^{-1}	

Period	Group IA	IIA	IIIA	IVA	VA	VIA	VIIA	VIIIA	VIIIA	VIIIA	IB	IIB	IIIB	IVB	VB	VIB	VIIB	VIII
1	1 $^2S_{1/2}$ **H** Hydrogen 1.00794 $1s$ 13.5984																	2 $^1S_0$ **He** Helium 4.00260 $1s^2$ 24.5874
2	3 $^2S_{1/2}$ **Li** Lithium 6.941 $1s^2 2s$ 5.3917	4 $^1S_0$ **Be** Beryllium 9.01218 $1s^2 2s^2$ 9.3227											5 $^2P^\circ_{1/2}$ **B** Boron 10.811 $1s^2 2s^2 2p$ 8.2980	6 $^3P_0$ **C** Carbon 12.0107 $1s^2 2s^2 2p^2$ 11.2603	7 $^4S^\circ_{3/2}$ **N** Nitrogen 14.00674 $1s^2 2s^2 2p^3$ 14.5341	8 $^3P_2$ **O** Oxygen 15.9994 $1s^2 2s^2 2p^4$ 13.6181	9 $^2P^\circ_{3/2}$ **F** Fluorine 18.99840 $1s^2 2s^2 2p^5$ 17.4228	10 $^1S_0$ **Ne** Neon 20.1797 $1s^2 2s^2 2p^6$ 21.5646
3	11 $^2S_{1/2}$ **Na** Sodium 22.98977 [Ne]$3s$ 5.1391	12 $^1S_0$ **Mg** Magnesium 24.3050 [Ne]$3s^2$ 7.6462											13 $^2P^\circ_{1/2}$ **Al** Aluminum 26.98154 [Ne]$3s^2 3p$ 5.9858	14 $^3P_0$ **Si** Silicon 28.0855 [Ne]$3s^2 3p^2$ 8.1517	15 $^4S^\circ_{3/2}$ **P** Phosphorus 30.97376 [Ne]$3s^2 3p^3$ 10.4867	16 $^3P_2$ **S** Sulfur 32.066 [Ne]$3s^2 3p^4$ 10.3600	17 $^2P^\circ_{3/2}$ **Cl** Chlorine 35.4527 [Ne]$3s^2 3p^5$ 12.9676	18 $^1S_0$ **Ar** Argon 39.948 [Ne]$3s^2 3p^6$ 15.7596
4	19 $^2S_{1/2}$ **K** Potassium 39.0983 [Ar]$4s$ 4.3407	20 $^1S_0$ **Ca** Calcium 40.078 [Ar]$4s^2$ 6.1132	21 $^2D_{3/2}$ **Sc** Scandium 44.95591 [Ar]$3d4s^2$ 6.5615	22 $^3F_2$ **Ti** Titanium 47.867 [Ar]$3d^2 4s^2$ 6.8281	23 $^4F_{3/2}$ **V** Vanadium 50.9415 [Ar]$3d^3 4s^2$ 6.7462	24 $^7S_3$ **Cr** Chromium 51.9961 [Ar]$3d^5 4s$ 6.7665	25 $^6S_{5/2}$ **Mn** Manganese 54.93805 [Ar]$3d^5 4s^2$ 7.4340	26 $^5D_4$ **Fe** Iron 55.845 [Ar]$3d^6 4s^2$ 7.9024	27 $^4F_{9/2}$ **Co** Cobalt 58.93320 [Ar]$3d^7 4s^2$ 7.8810	28 $^3F_4$ **Ni** Nickel 58.6934 [Ar]$3d^8 4s^2$ 7.6398	29 $^2S_{1/2}$ **Cu** Copper 63.546 [Ar]$3d^{10} 4s$ 7.7264	30 $^1S_0$ **Zn** Zinc 65.39 [Ar]$3d^{10} 4s^2$ 9.3942	31 $^2P^\circ_{1/2}$ **Ga** Gallium 69.723 [Ar]$3d^{10} 4s^2 4p$ 5.9993	32 $^3P_0$ **Ge** Germanium 72.61 [Ar]$3d^{10} 4s^2 4p^2$ 7.8994	33 $^4S^\circ_{3/2}$ **As** Arsenic 74.92160 [Ar]$3d^{10} 4s^2 4p^3$ 9.7886	34 $^3P_2$ **Se** Selenium 78.96 [Ar]$3d^{10} 4s^2 4p^4$ 9.7524	35 $^2P^\circ_{3/2}$ **Br** Bromine 79.904 [Ar]$3d^{10} 4s^2 4p^5$ 11.8138	36 $^1S_0$ **Kr** Krypton 83.80 [Ar]$3d^{10} 4s^2 4p^6$ 13.9996
5	37 $^2S_{1/2}$ **Rb** Rubidium 85.4678 [Kr]$5s$ 4.1771	38 $^1S_0$ **Sr** Strontium 87.62 [Kr]$5s^2$ 5.6949	39 $^2D_{3/2}$ **Y** Yttrium 88.90585 [Kr]$4d5s^2$ 6.2171	40 $^3F_2$ **Zr** Zirconium 91.224 [Kr]$4d^2 5s^2$ 6.6339	41 $^6D_{1/2}$ **Nb** Niobium 92.90638 [Kr]$4d^4 5s$ 6.7589	42 $^7S_3$ **Mo** Molybdenum 95.94 [Kr]$4d^5 5s$ 7.0924	43 $^6S_{5/2}$ **Tc** Technetium (98) [Kr]$4d^5 5s^2$ 7.28	44 $^5F_5$ **Ru** Ruthenium 101.07 [Kr]$4d^7 5s$ 7.3605	45 $^4F_{9/2}$ **Rh** Rhodium 102.90550 [Kr]$4d^8 5s$ 7.4589	46 $^1S_0$ **Pd** Palladium 106.42 [Kr]$4d^{10}$ 8.3369	47 $^2S_{1/2}$ **Ag** Silver 107.8682 [Kr]$4d^{10} 5s$ 7.5762	48 $^1S_0$ **Cd** Cadmium 112.411 [Kr]$4d^{10} 5s^2$ 8.9938	49 $^2P^\circ_{1/2}$ **In** Indium 114.818 [Kr]$4d^{10} 5s^2 5p$ 5.7864	50 $^3P_0$ **Sn** Tin 118.710 [Kr]$4d^{10} 5s^2 5p^2$ 7.3439	51 $^4S^\circ_{3/2}$ **Sb** Antimony 121.760 [Kr]$4d^{10} 5s^2 5p^3$ 8.6084	52 $^3P_2$ **Te** Tellurium 127.60 [Kr]$4d^{10} 5s^2 5p^4$ 9.0096	53 $^2P^\circ_{3/2}$ **I** Iodine 126.90447 [Kr]$4d^{10} 5s^2 5p^5$ 10.4513	54 $^1S_0$ **Xe** Xenon 131.29 [Kr]$4d^{10} 5s^2 5p^6$ 12.1298
6	55 $^2S_{1/2}$ **Cs** Cesium 132.90545 [Xe]$6s$ 3.8939	56 $^1S_0$ **Ba** Barium 137.327 [Xe]$6s^2$ 5.2117		72 $^3F_2$ **Hf** Hafnium 178.49 [Xe]$4f^{14} 5d^2 6s^2$ 6.8251	73 $^4F_{3/2}$ **Ta** Tantalum 180.9479 [Xe]$4f^{14} 5d^3 6s^2$ 7.5496	74 $^5D_0$ **W** Tungsten 183.84 [Xe]$4f^{14} 5d^4 6s^2$ 7.8640	75 $^6S_{5/2}$ **Re** Rhenium 186.207 [Xe]$4f^{14} 5d^5 6s^2$ 7.8335	76 $^5D_4$ **Os** Osmium 190.23 [Xe]$4f^{14} 5d^6 6s^2$ 8.4382	77 $^4F_{9/2}$ **Ir** Iridium 192.217 [Xe]$4f^{14} 5d^7 6s^2$ 8.9670	78 $^3D_3$ **Pt** Platinum 195.078 [Xe]$4f^{14} 5d^9 6s$ 8.9587	79 $^2S_{1/2}$ **Au** Gold 196.96655 [Xe]$4f^{14} 5d^{10} 6s$ 9.2255	80 $^1S_0$ **Hg** Mercury 200.59 [Xe]$4f^{14} 5d^{10} 6s^2$ 10.4375	81 $^2P^\circ_{1/2}$ **Tl** Thallium 204.3833 [Hg]$6p$ 6.1082	82 $^3P_0$ **Pb** Lead 207.2 [Hg]$6p^2$ 7.4167	83 $^4S^\circ_{3/2}$ **Bi** Bismuth 208.98038 [Hg]$6p^3$ 7.2856	84 $^3P_2$ **Po** Polonium (209) [Hg]$6p^4$ 8.417 ?	85 $^2P^\circ_{3/2}$ **At** Astatine (210) [Hg]$6p^5$	86 $^1S_0$ **Rn** Radon (222) [Hg]$6p^6$ 10.7485
7	87 $^2S_{1/2}$ **Fr** Francium (223) [Rn]$7s$ 4.0727	88 $^1S_0$ **Ra** Radium (226) [Rn]$7s^2$ 5.2784		104 $^3F_2$? **Rf** Rutherfordium (261) [Rn]$5f^{14} 6d^2 7s^2$? 6.0 ?	105 **Db** Dubnium (262)	106 **Sg** Seaborgium (263)	107 **Bh** Bohrium (264)	108 **Hs** Hassium (265)	109 **Mt** Meitnerium (268)	110 **Uun** Ununnilium (269)	111 **Uuu** Unununium (272)	112 **Uub** Ununbium						

57 $^2D_{3/2}$ **La** Lanthanum 138.9055 [Xe]$5d6s^2$ 5.5769	58 $^1G^\circ_4$ **Ce** Cerium 140.116 [Xe]$4f5d6s^2$ 5.5387	59 $^4I^\circ_{9/2}$ **Pr** Praseodymium 140.90765 [Xe]$4f^3 6s^2$ 5.473	60 $^5I_4$ **Nd** Neodymium 144.24 [Xe]$4f^4 6s^2$ 5.5250	61 $^6H^\circ_{5/2}$ **Pm** Promethium (145) [Xe]$4f^5 6s^2$ 5.582	62 $^7F_0$ **Sm** Samarium 150.36 [Xe]$4f^6 6s^2$ 5.6436	63 $^8S^\circ_{7/2}$ **Eu** Europium 151.964 [Xe]$4f^7 6s^2$ 5.6704	64 $^9D^\circ_2$ **Gd** Gadolinium 157.25 [Xe]$4f^7 5d6s^2$ 6.1501	65 $^6H^\circ_{15/2}$ **Tb** Terbium 158.92534 [Xe]$4f^9 6s^2$ 5.8638	66 $^5I_8$ **Dy** Dysprosium 162.50 [Xe]$4f^{10} 6s^2$ 5.9389	67 $^4I^\circ_{15/2}$ **Ho** Holmium 164.93032 [Xe]$4f^{11} 6s^2$ 6.0215	68 $^3H_6$ **Er** Erbium 167.26 [Xe]$4f^{12} 6s^2$ 6.1077	69 $^2F^\circ_{7/2}$ **Tm** Thulium 168.93421 [Xe]$4f^{13} 6s^2$ 6.1843	70 $^1S_0$ **Yb** Ytterbium 173.04 [Xe]$4f^{14} 6s^2$ 6.2542	71 $^2D_{3/2}$ **Lu** Lutetium 174.967 [Xe]$4f^{14} 5d6s^2$ 5.4259
89 $^2D_{3/2}$ **Ac** Actinium (227) [Rn]$6d7s^2$ 5.17	90 $^3F_2$ **Th** Thorium 232.0381 [Rn]$6d^2 7s^2$ 6.3067	91 $^4K_{11/2}$ **Pa** Protactinium 231.03588 [Rn]$5f^2 6d7s^2$ 5.89	92 $^5L^\circ_6$ **U** Uranium 238.0289 [Rn]$5f^3 6d7s^2$ 6.1941	93 $^6L_{11/2}$ **Np** Neptunium (237) [Rn]$5f^4 6d7s^2$ 6.2657	94 $^7F_0$ **Pu** Plutonium (244) [Rn]$5f^6 7s^2$ 6.0262	95 $^8S^\circ_{7/2}$ **Am** Americium (243) [Rn]$5f^7 7s^2$ 5.9738	96 $^9D^\circ_2$ **Cm** Curium (247) [Rn]$5f^7 6d7s^2$ 5.9915	97 $^6H^\circ_{15/2}$ **Bk** Berkelium (247) [Rn]$5f^9 7s^2$ 6.1979	98 $^5I_8$ **Cf** Californium (251) [Rn]$5f^{10} 7s^2$ 6.2817	99 $^4I^\circ_{15/2}$ **Es** Einsteinium (252) [Rn]$5f^{11} 7s^2$ 6.42	100 $^3H_6$ **Fm** Fermium (257) [Rn]$5f^{12} 7s^2$ 6.50	101 $^2F^\circ_{7/2}$ **Md** Mendelevium (258) [Rn]$5f^{13} 7s^2$ 6.58	102 $^1S_0$ **No** Nobelium (259) [Rn]$5f^{14} 7s^2$ 6.65	103 $^2P^\circ_{1/2}$? **Lr** Lawrencium (262) [Rn]$5f^{14} 7s^2 7p$? 4.9 ?

☐ Solids
🟦 Liquids
🟥 Gases
🟨 Artificially Prepared

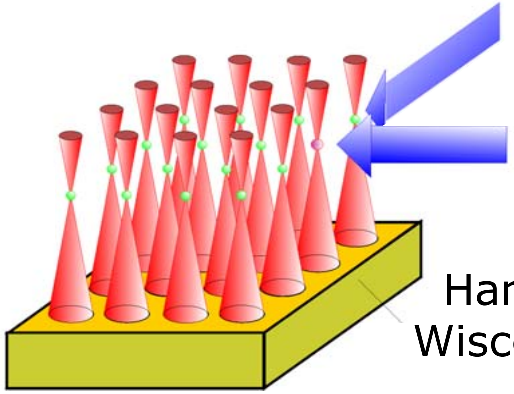
For a description of the atomic data, visit physics.nist.gov/atomic

Atomic Number — 58
Ground-state Level — $^1G^\circ_4$
Symbol — Ce
Name — Cerium
Atomic Weight† — 140.116
Ground-state Configuration — [Xe]$4f5d6s^2$
Ionization Energy (eV) — 5.5387

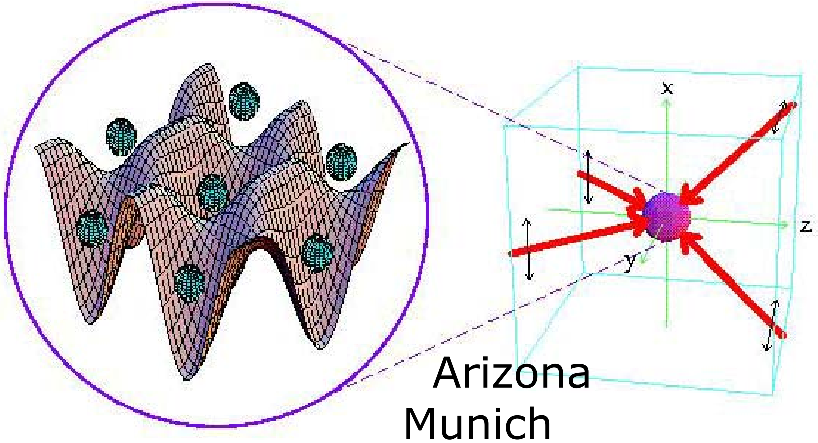
Trapped Neutral Atoms

Atom arrangement/control

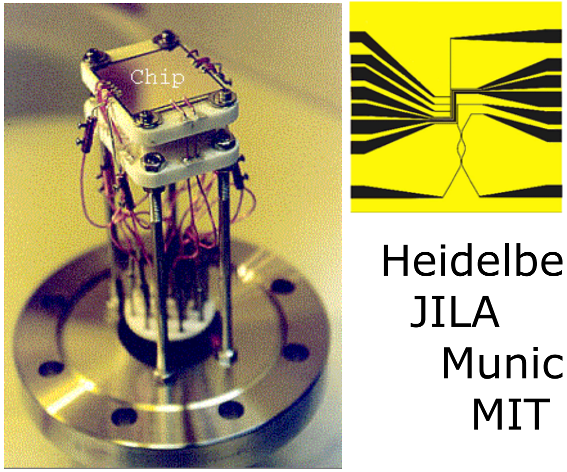
- optical lattices
- micro-magnetic traps
- dipole-trap arrays



Hannover
Wisconsin



Arizona
Munich
NIST-G’burg
Stanford
Yale
…

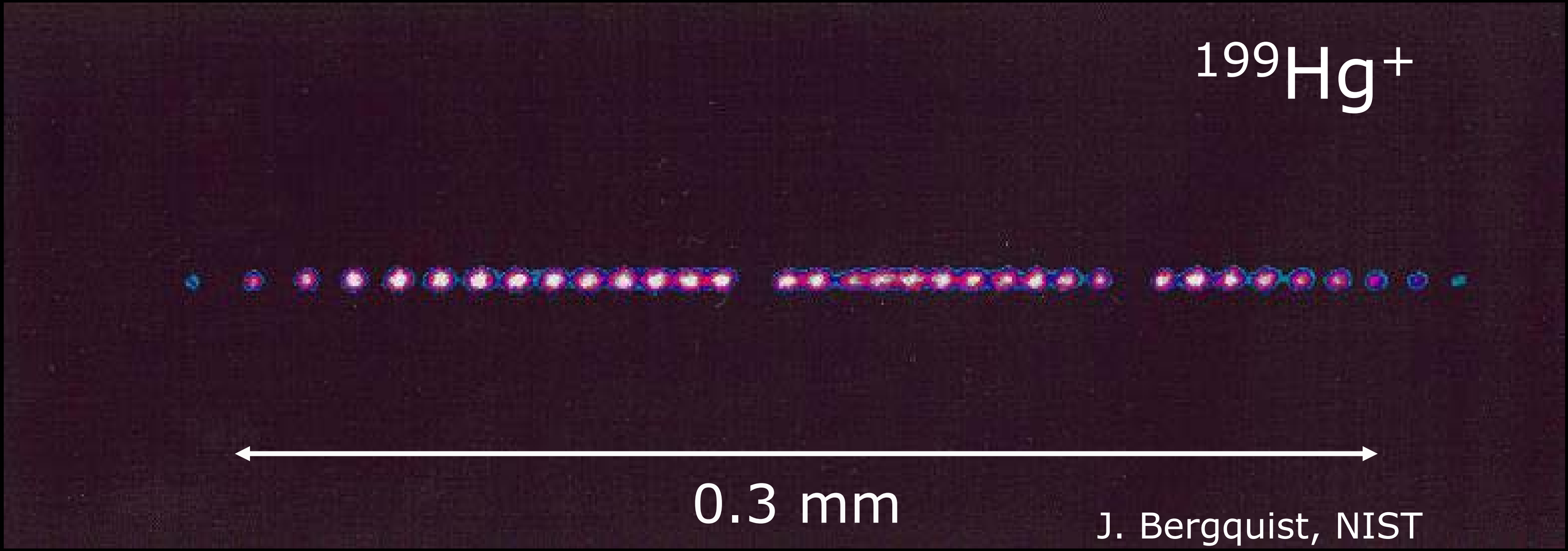


Heidelberg
JILA
Munich
MIT
…

Atom-atom interaction

- dipole-dipole
- s-wave collisions
- Rydberg atoms

Trapped Atomic Ions

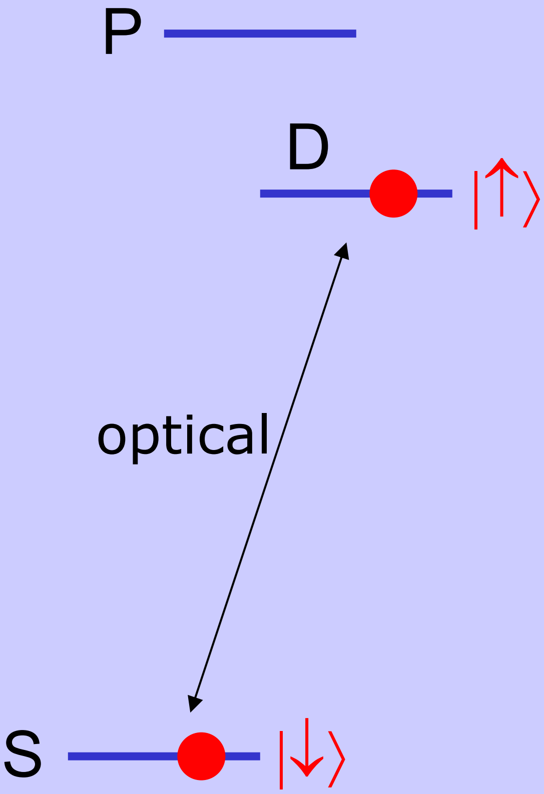


J. Bergquist, NIST

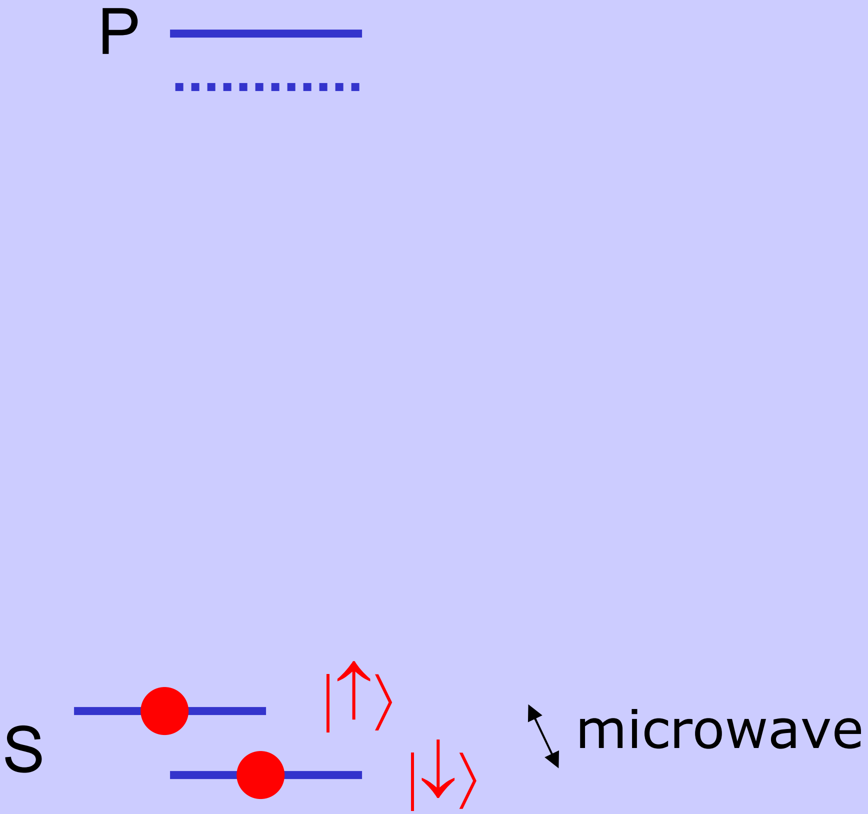
Ion Trap QC Groups:

- Aarhus
- Alamaden (IBM)
- Boulder (NIST)
- Munich (MPQ)
- Hamburg
- Innsbruck
- Los Alamos
- McMaster (Ontario)
- Michigan
- Oxford
- Teddington (NPL)

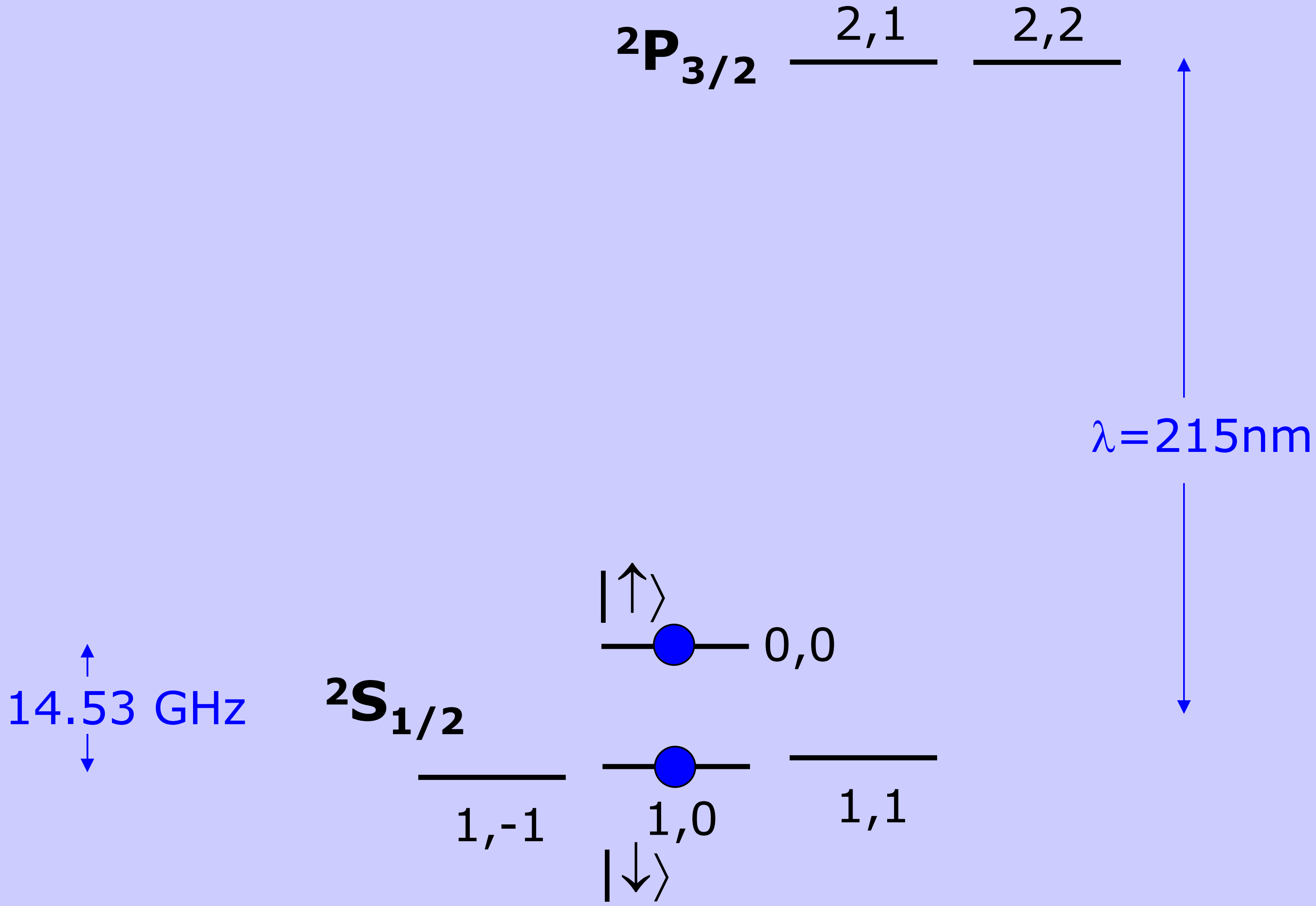
Ca^+, Sr^+, Ba^+, Yb^+



Be^+, Mg^+, Hg^+, Cd^+, Zn^+



^{111}Cd$^+$ atomic structure



$^2P_{3/2}$

2,1

2,2

λ=215nm

$|\uparrow\rangle$

0,0

14.53 GHz

$^2S_{1/2}$

1,-1

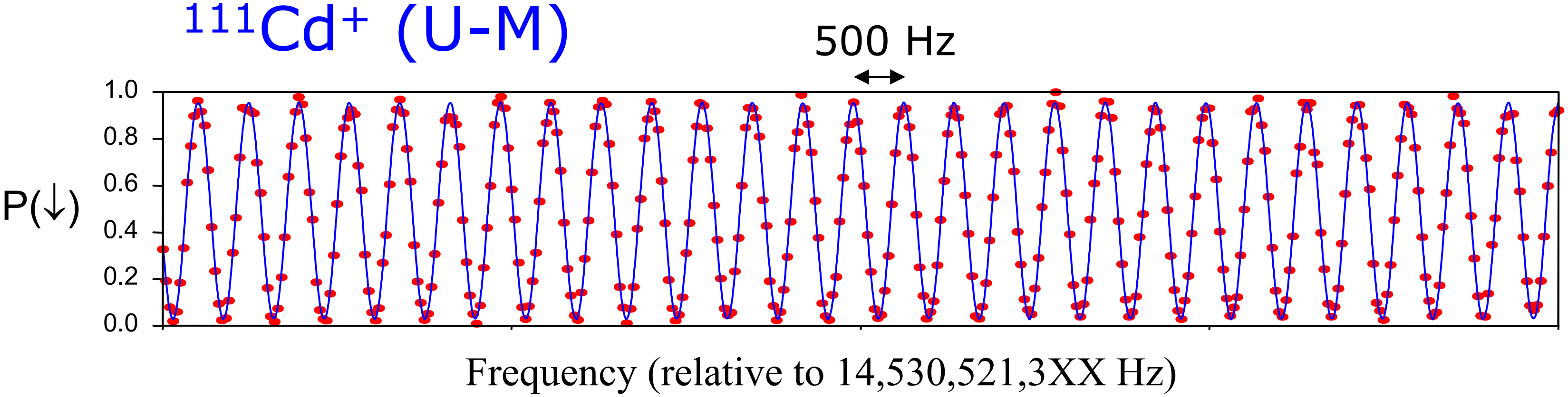
1,0

1,1

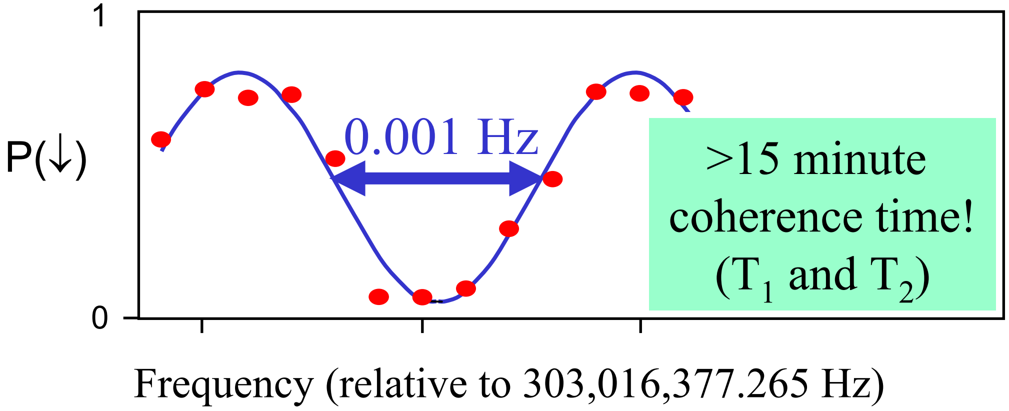
$|\downarrow\rangle$

Ramsey interferometry with a trapped ion HF qubit: atomic clockwork

$^{111}Cd^+$ (U-M)



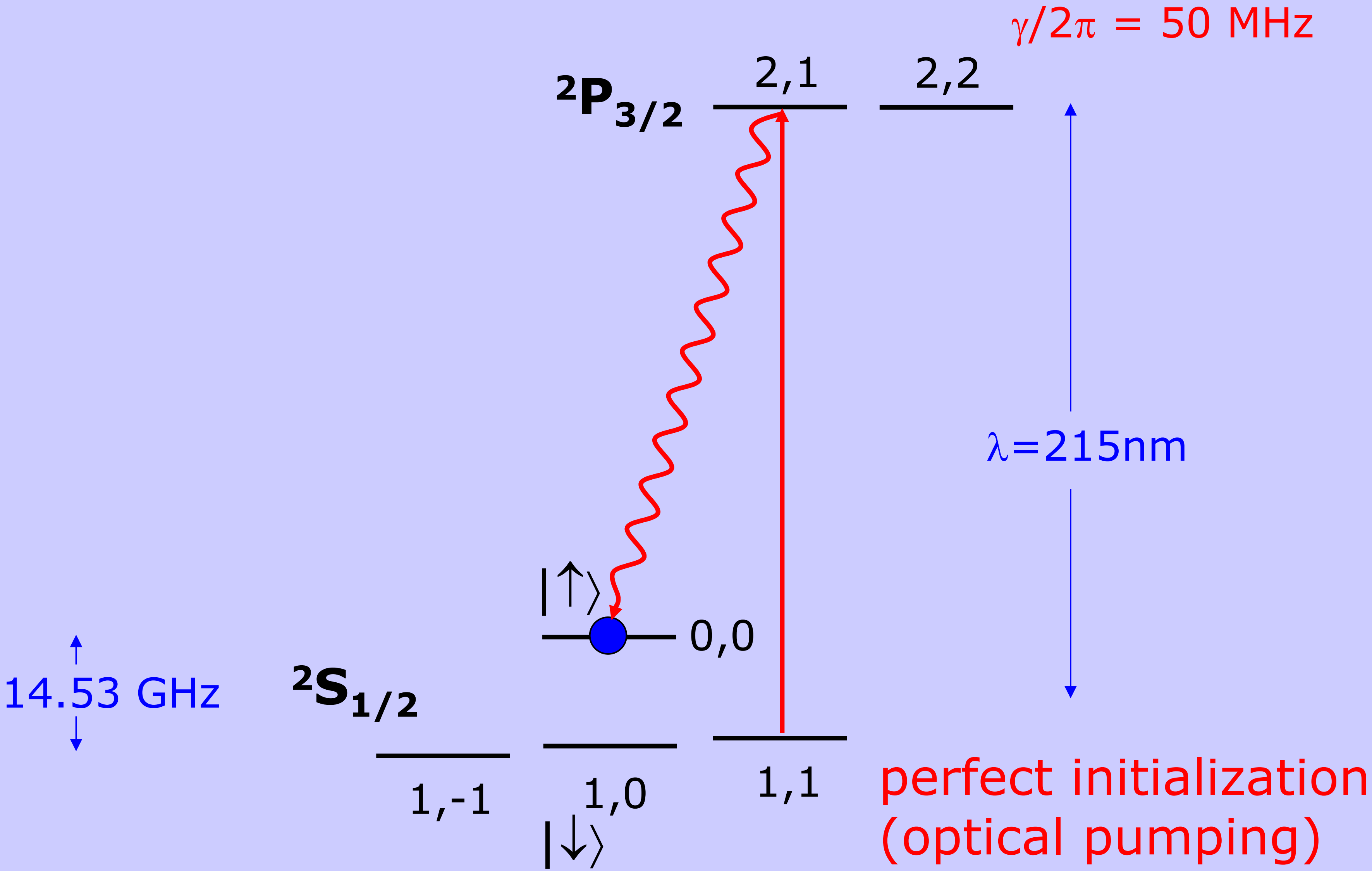
$^{9}Be^+$ (NIST-Boulder)



>15 minute coherence time! (T_1 and T_2)

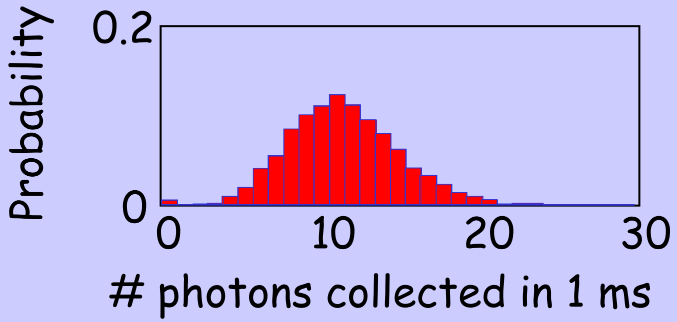
NIST: J. Bollinger, et. al., IEEE Trans. Instrum. Meas. **40**, 126 (1991)

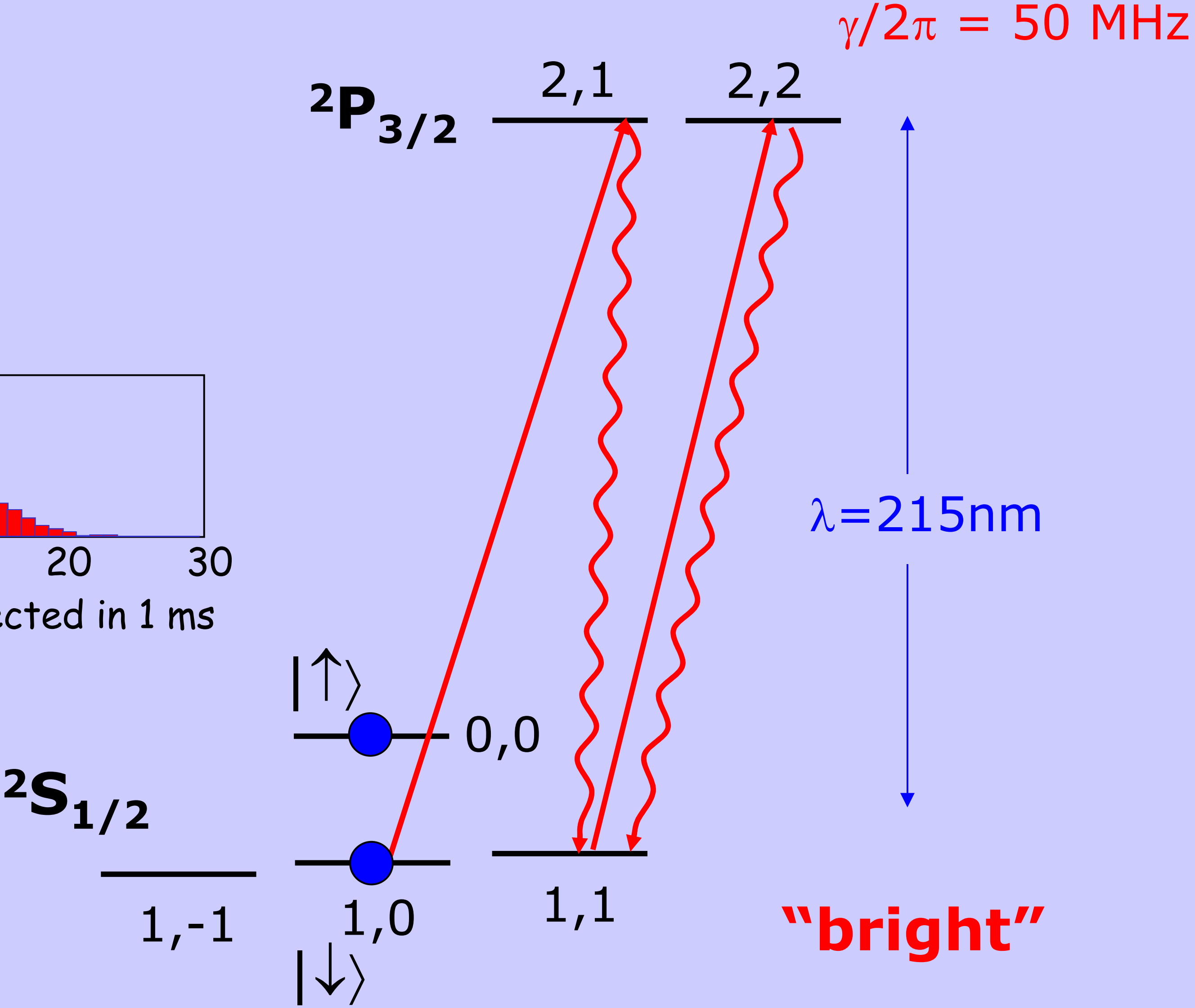
qubit initialization



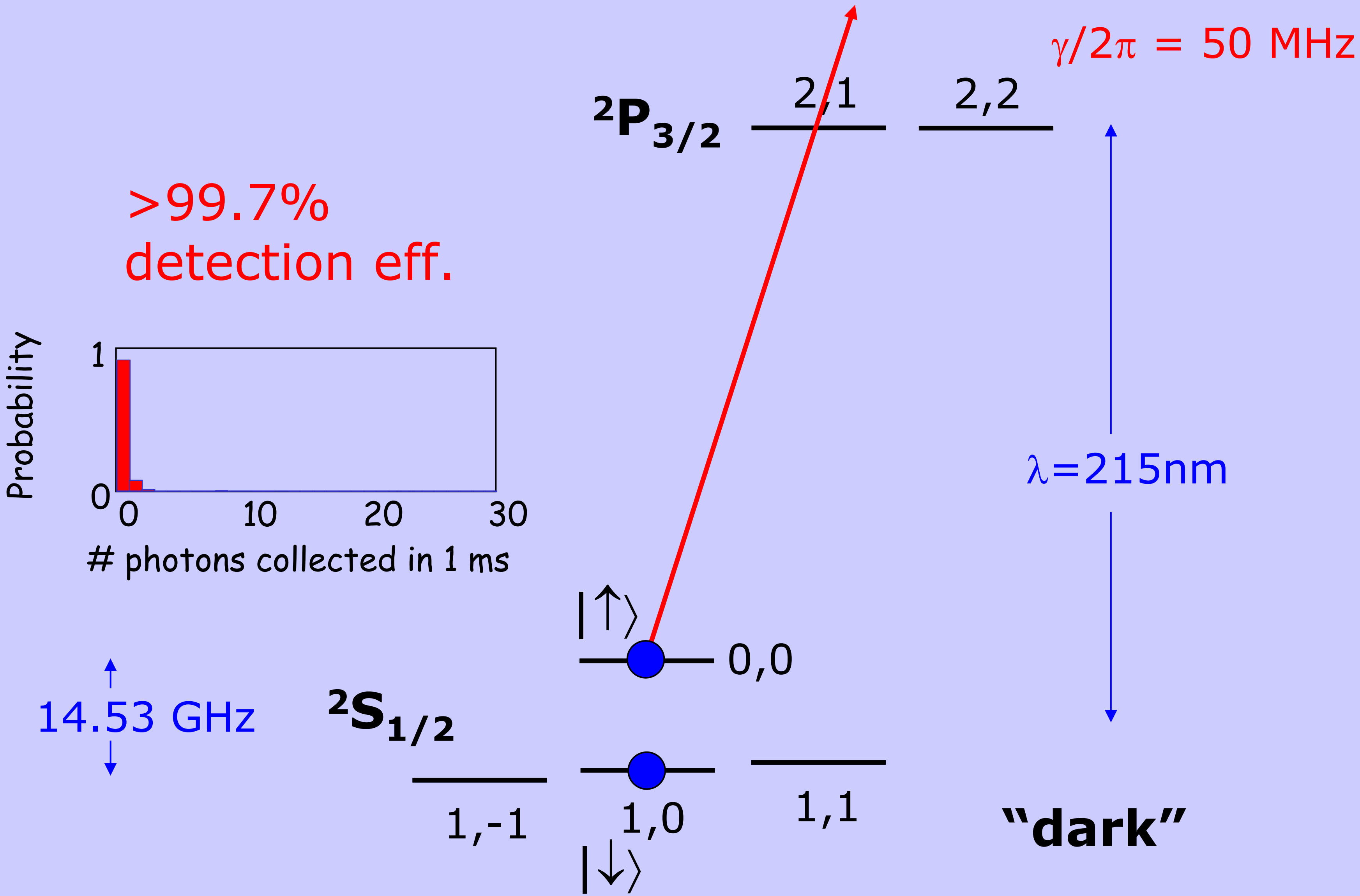
perfect initialization
(optical pumping)

qubit measurement



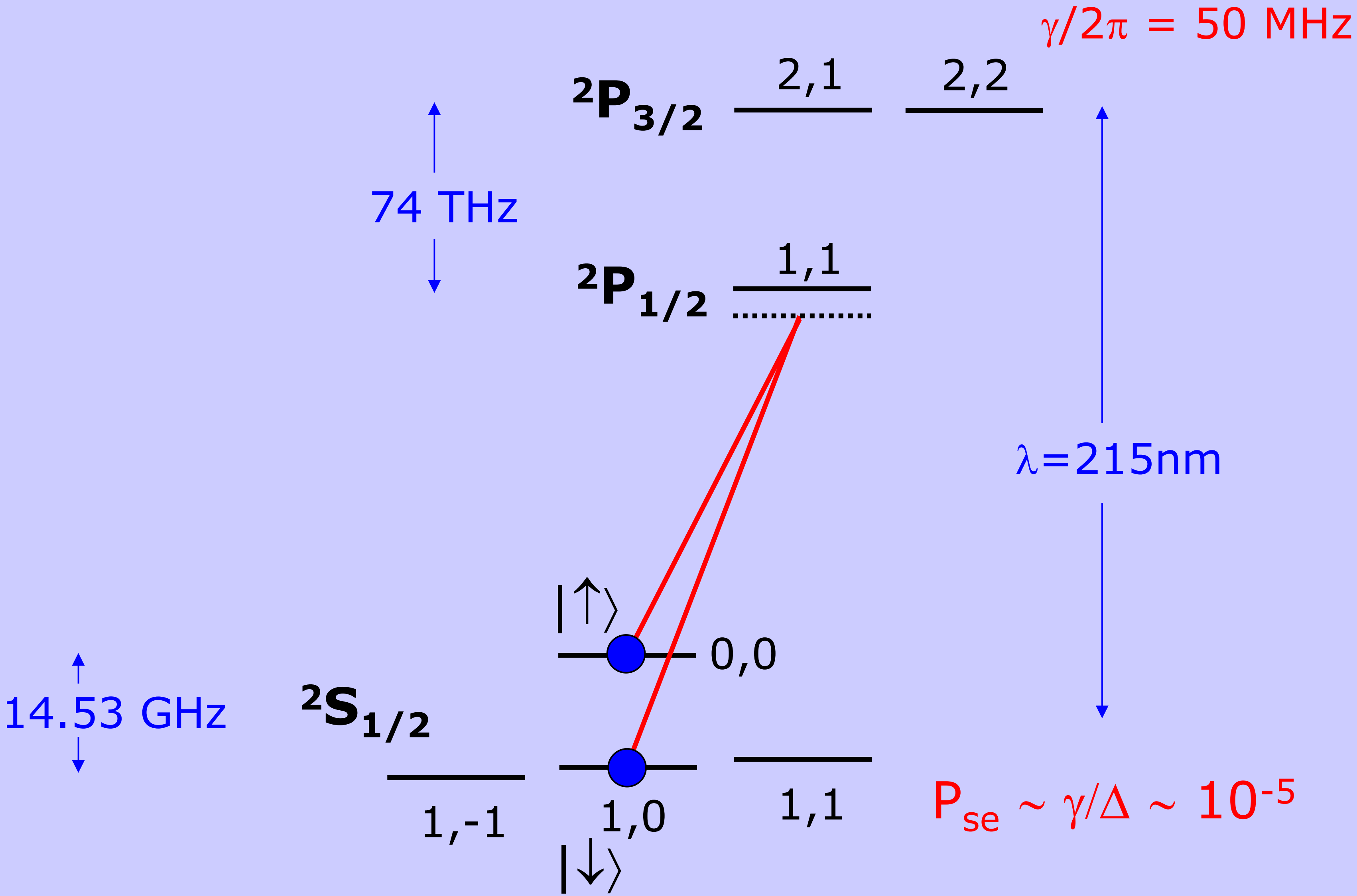


qubit measurement



>99.7% detection eff.

qubit manipulation



$\gamma/2\pi$ = 50 MHz

$^2P_{3/2}$ 2,1 2,2

74 THz

$^2P_{1/2}$ 1,1

λ=215nm

$|\uparrow\rangle$ 0,0

14.53 GHz

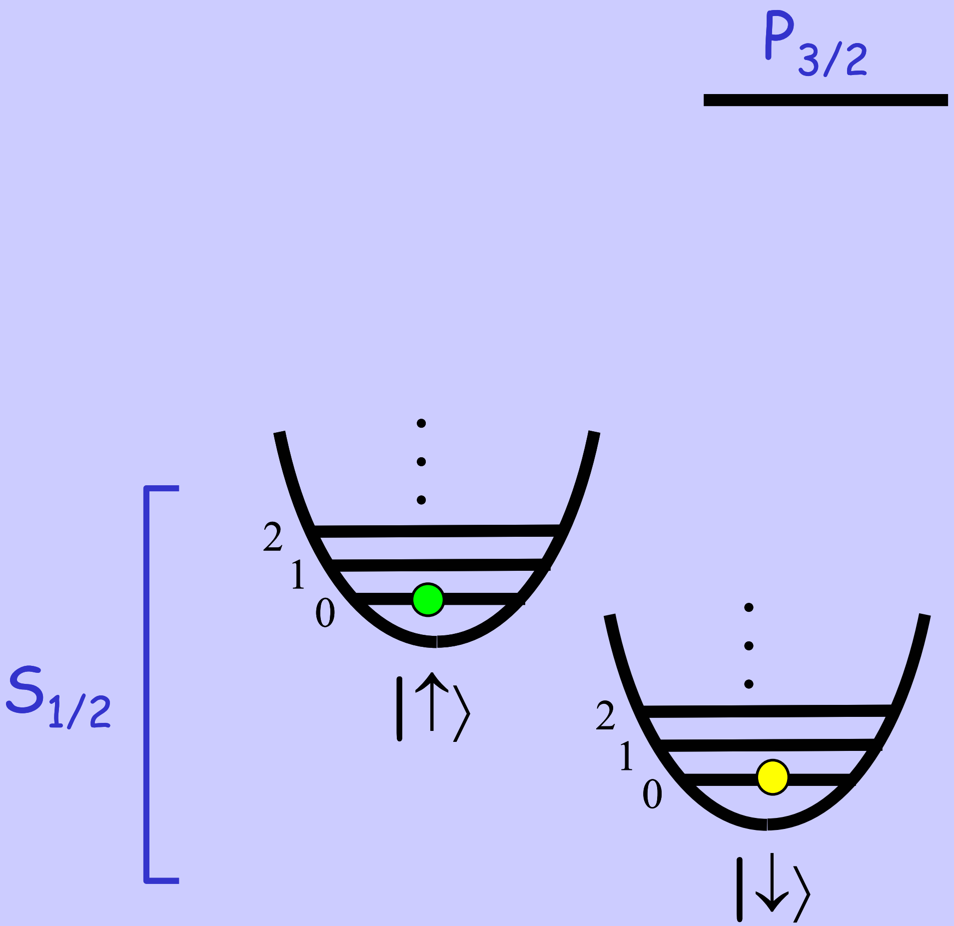
$^2S_{1/2}$

1,-1 1,0 1,1

$|\downarrow\rangle$

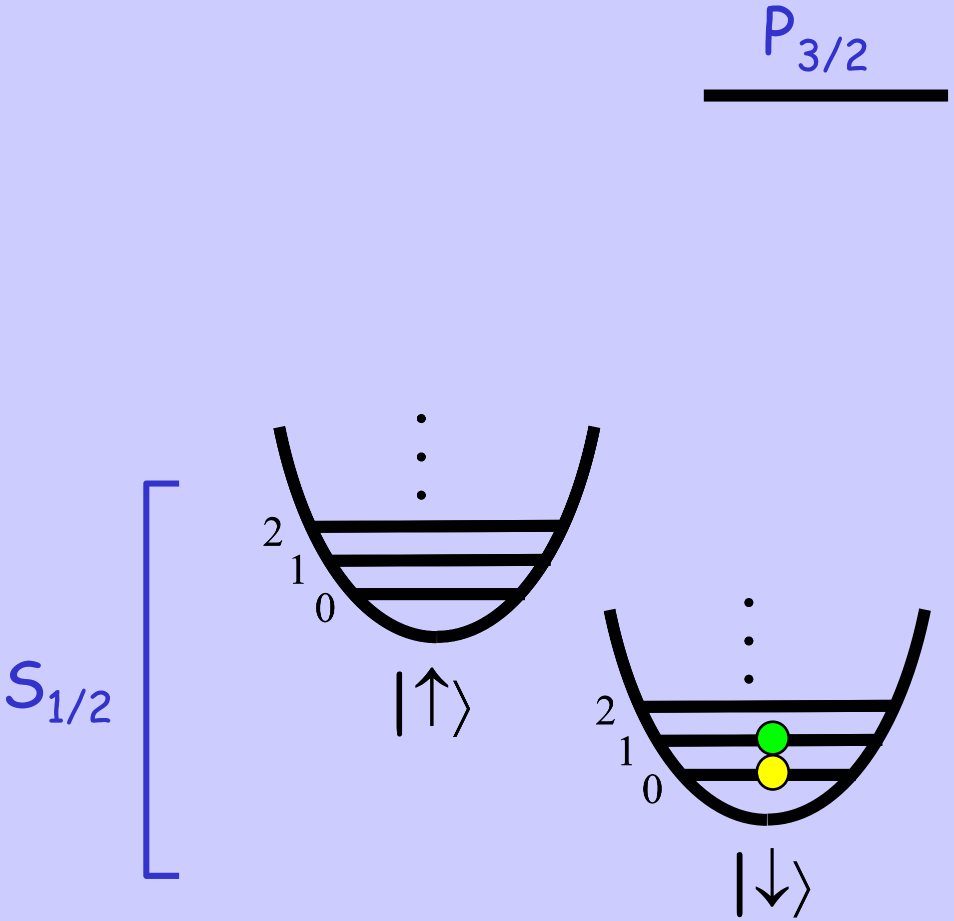
$P_{se} \sim \gamma/\Delta \sim 10^{-5}$

More ions: Use *collective* motion to entangle



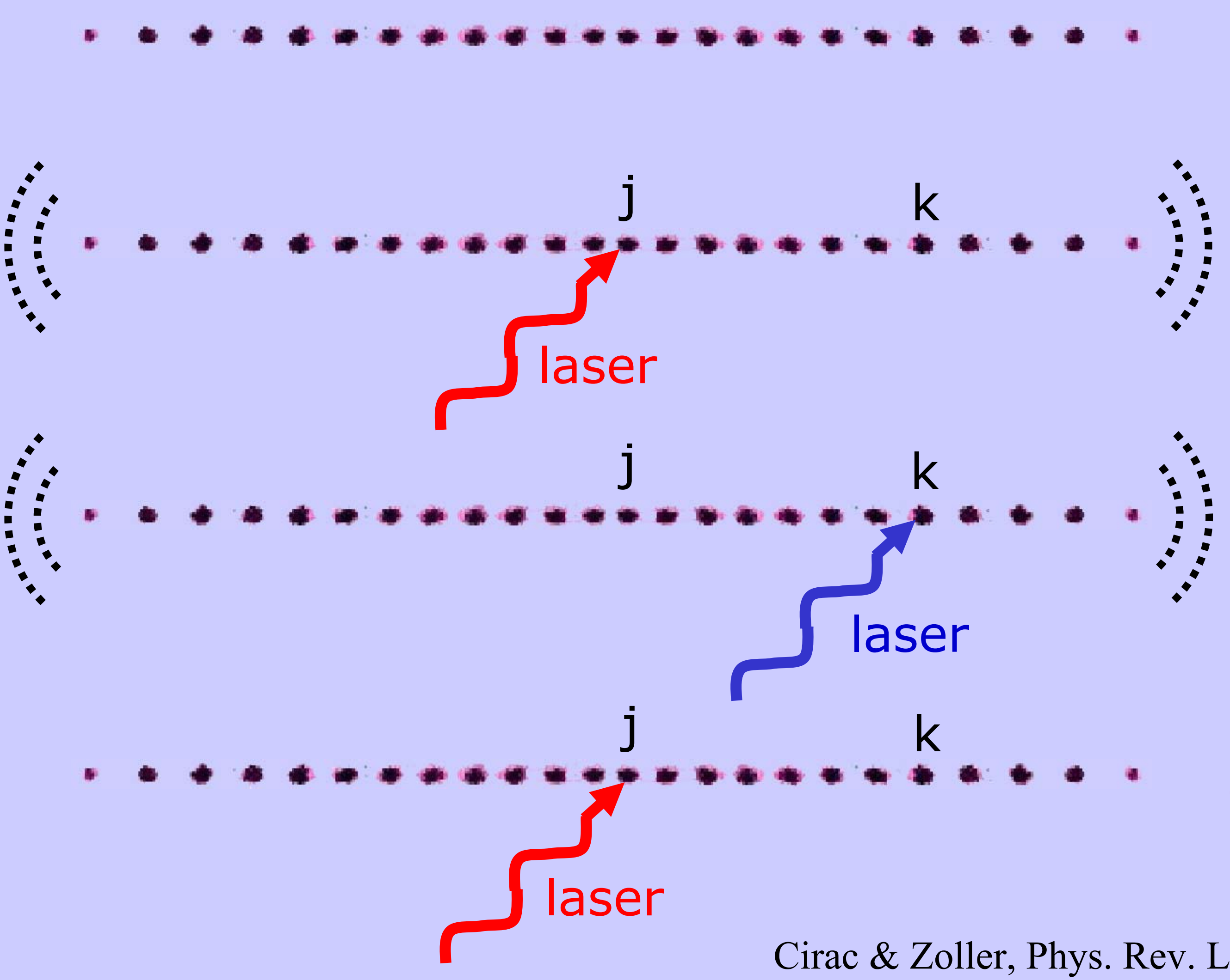
Mapping: $\boxed{(\alpha|\downarrow\rangle + \beta|\uparrow\rangle)}\,|0\rangle_m \rightarrow |\downarrow\rangle\,(\alpha|0\rangle_m + \beta|1\rangle_m)$

More ions: Use *collective* motion to entangle



Mapping: $(\alpha|\downarrow\rangle + \beta|\uparrow\rangle)\,|0\rangle_m \rightarrow |\downarrow\rangle\boxed{(\alpha|0\rangle_m + \beta|1\rangle_m)}$

Entangling Ions with Collective Phonons



laser cool to
rest (n=0)

map j^{th} qubit
to phonon

flip k^{th} qubit
if phonon present

map phonon
to j^{th} qubit

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

Cirac-Zoller Scheme

NIST(1995): N=1 ion, F=85%
Innsbruck (2003): N=2 ions, F=71%

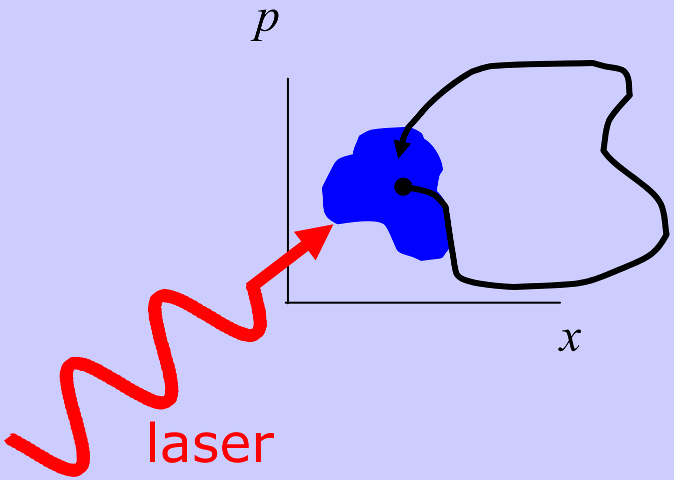
Major improvements:

- Don’t need to individually address ions to entangle them
- Don’t need a “pure” state of motion

Thy: Molmer & Sorensen (1999)
Milburn, Schneider, James (1999)
Exp: NIST (2000): N=4 ions, F=57%
NIST (2003): N=2 ions, F=97%

"State-dependent force" gates

N=1 ion: $\text{Force} = F_0|\uparrow\rangle\langle\uparrow|$

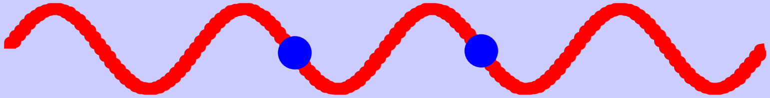


$$\downarrow \;\Rightarrow\; \downarrow$$
$$\uparrow \;\Rightarrow\; e^{i\phi}\uparrow$$

($\phi \propto$ enclosed area)

N=2 ions

e.g., force on stretch mode only



$$\downarrow\downarrow \;\Rightarrow\; \downarrow\downarrow$$
$$\downarrow\uparrow \;\Rightarrow\; e^{i\phi}\downarrow\uparrow$$
$$\uparrow\downarrow \;\Rightarrow\; e^{i\phi}\uparrow\downarrow$$
$$\uparrow\uparrow \;\Rightarrow\; \uparrow\uparrow$$

$\phi = \pi/2$: π-phase gate

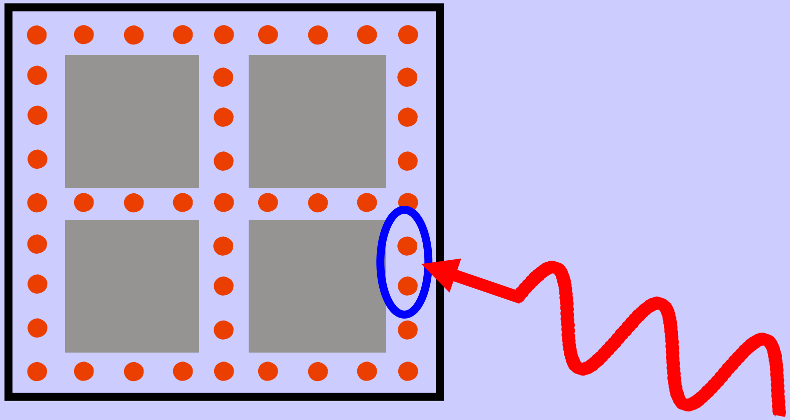
NIST (2003): 97% Fidelity

Ultrafast force gates (theoretical):

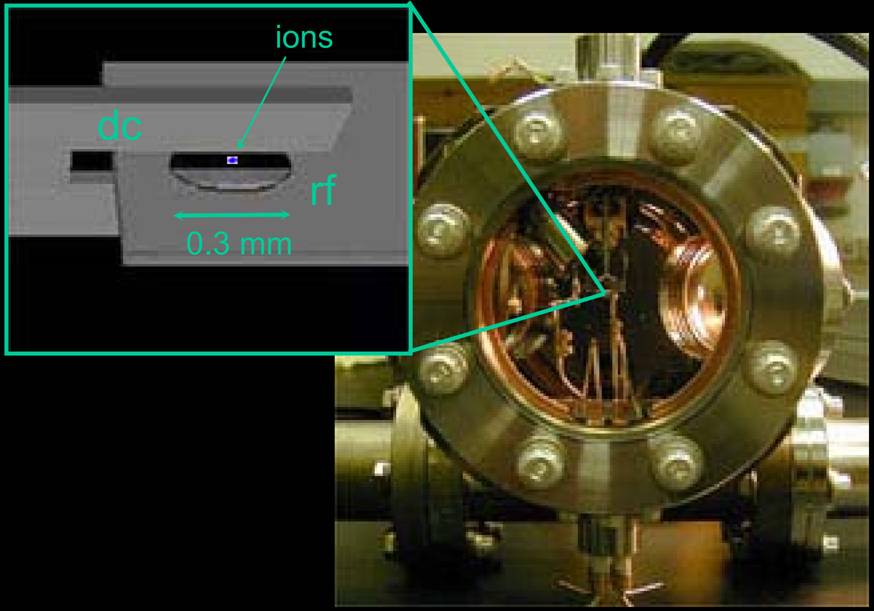
- Don’t need $\Delta x < \lambda$ (Lamb-Dicke confinement not required)
- Not speed-limited by motional trap frequency

  Thy: Garcia-Ripoll, Zoller, Cirac (2003)
- OK in the presence of other ions

  Thy: Duan (2004)

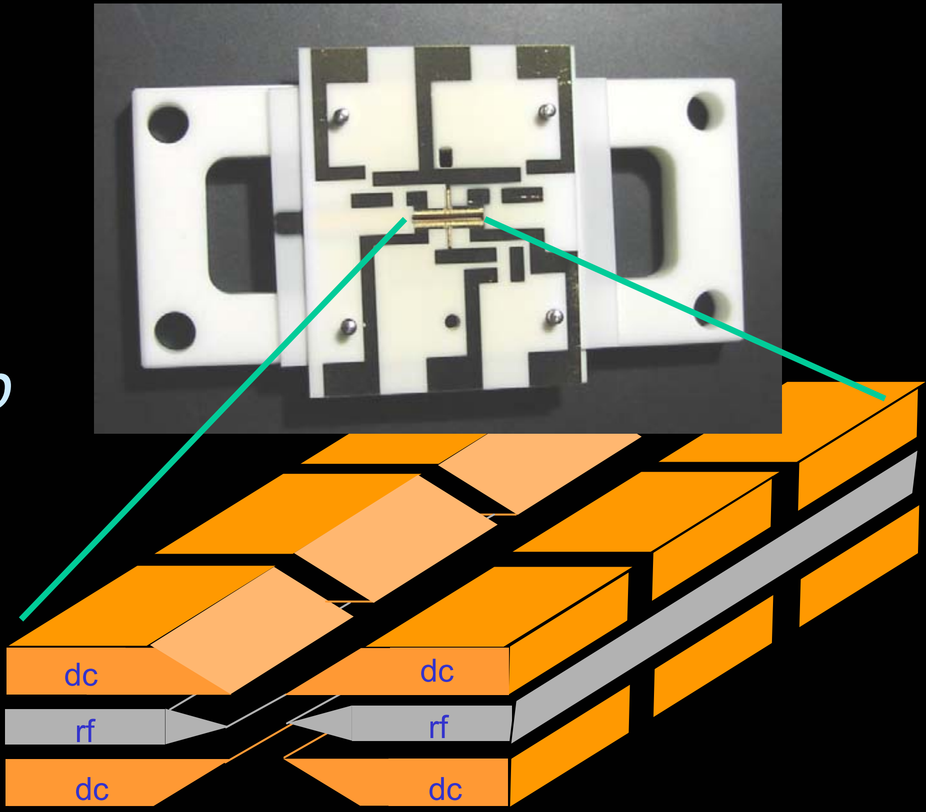


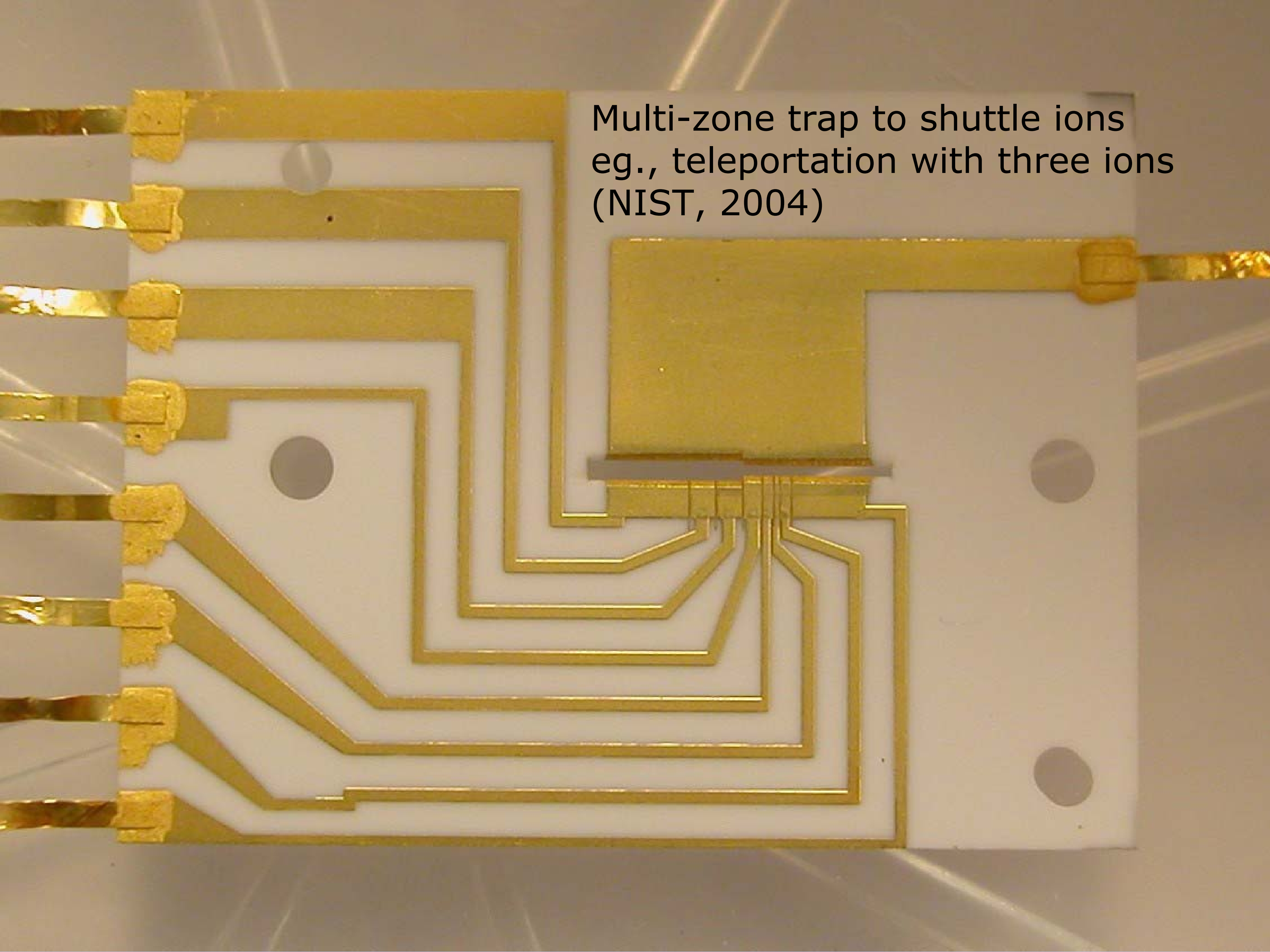
Exp: Need good pulsed lasers!
(eg., 1 GHz rep rate, τ=1 psec)



quadrupole rf trap

linear rf trap

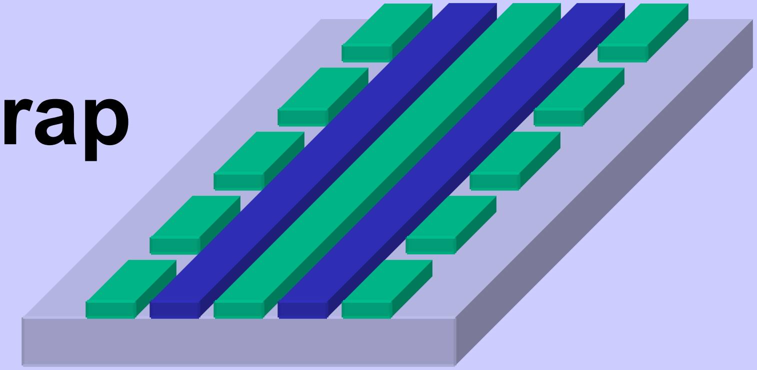




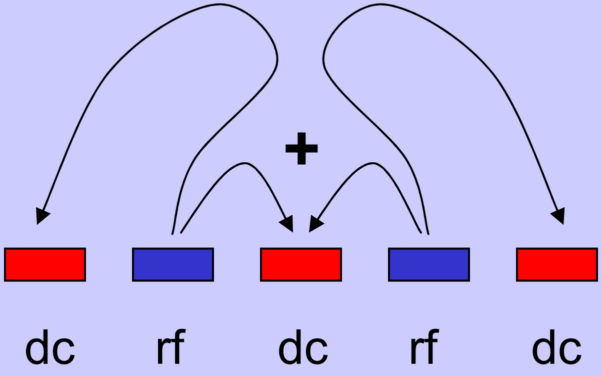
Multi-zone trap to shuttle ions
eg., teleportation with three ions
(NIST, 2004)

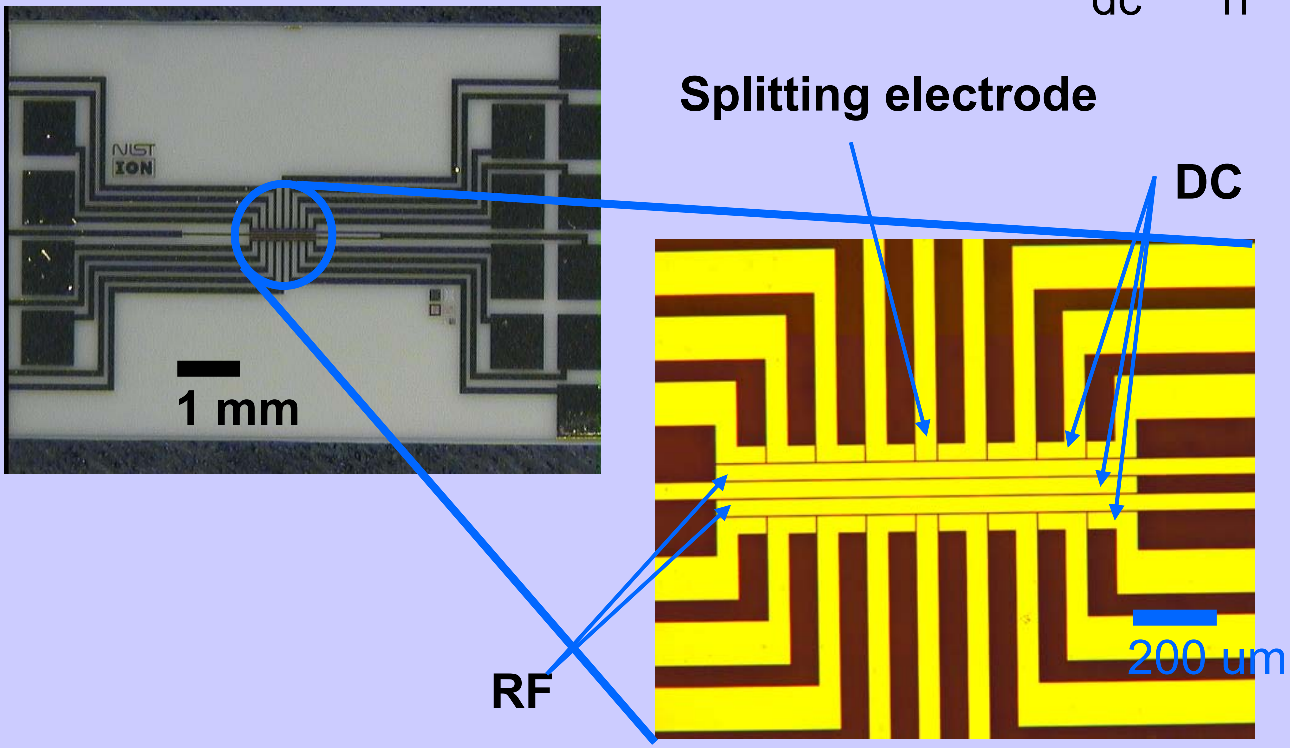
New Trapology (J. Chiaverini, NIST)

Planar trap



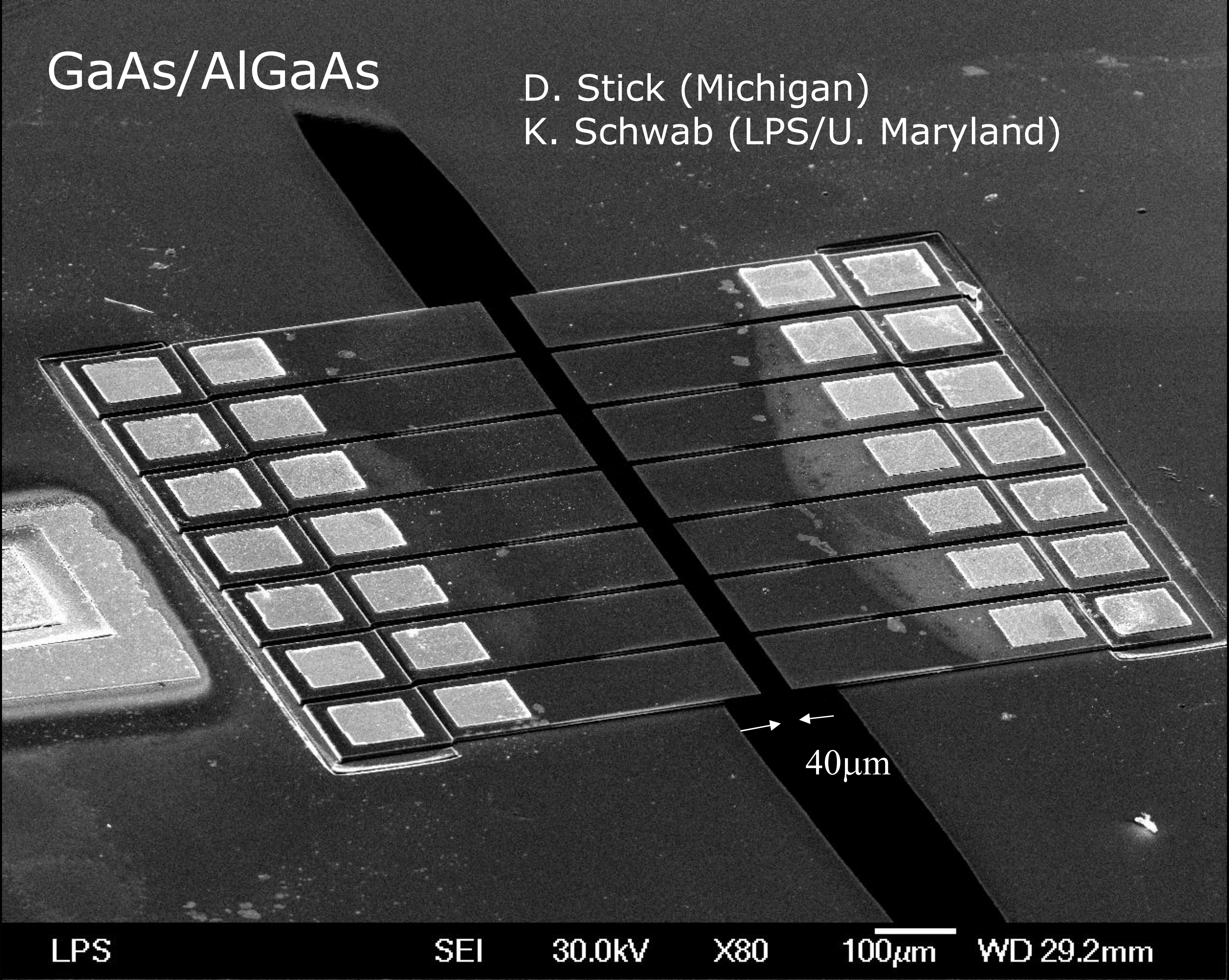
Field lines:

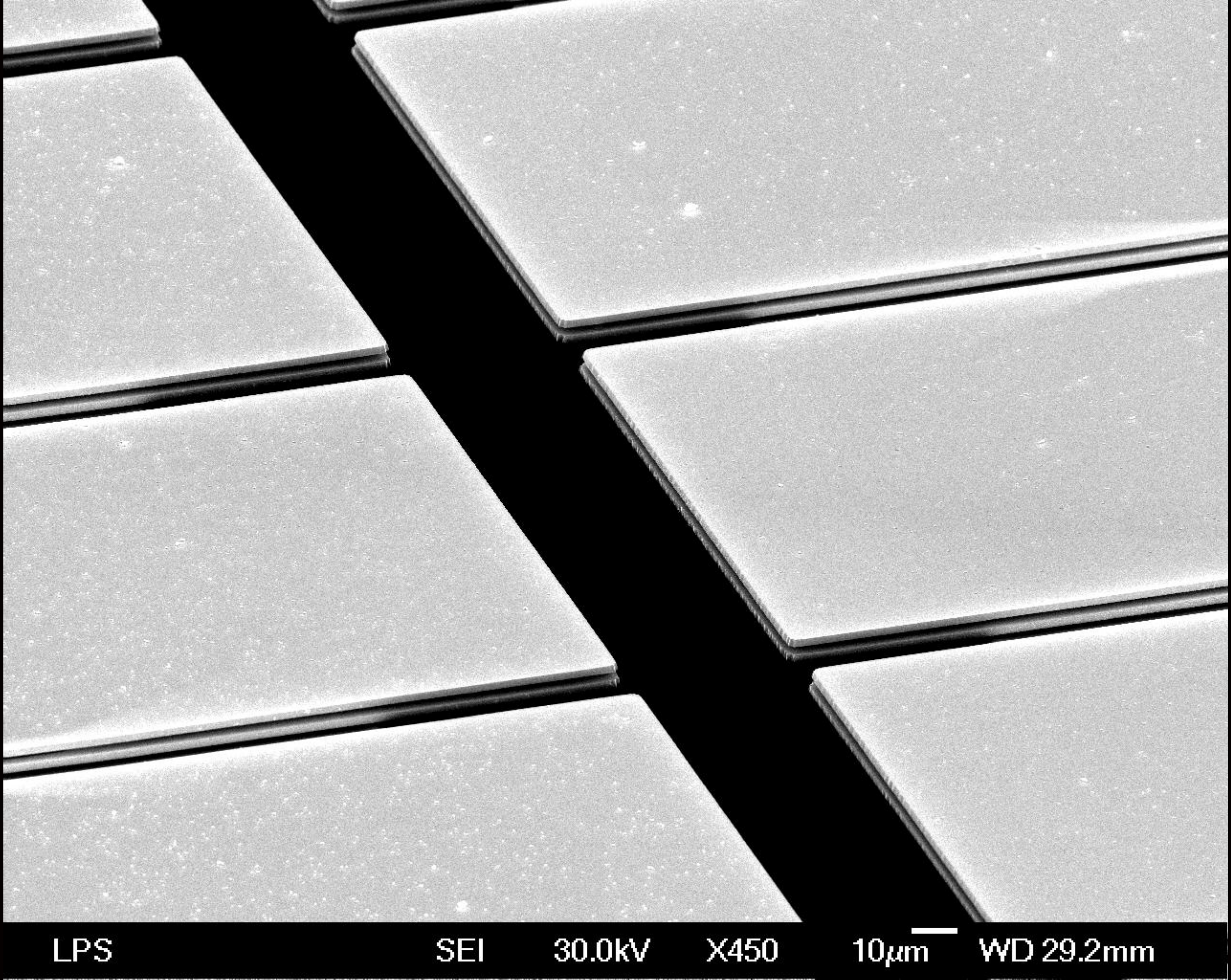


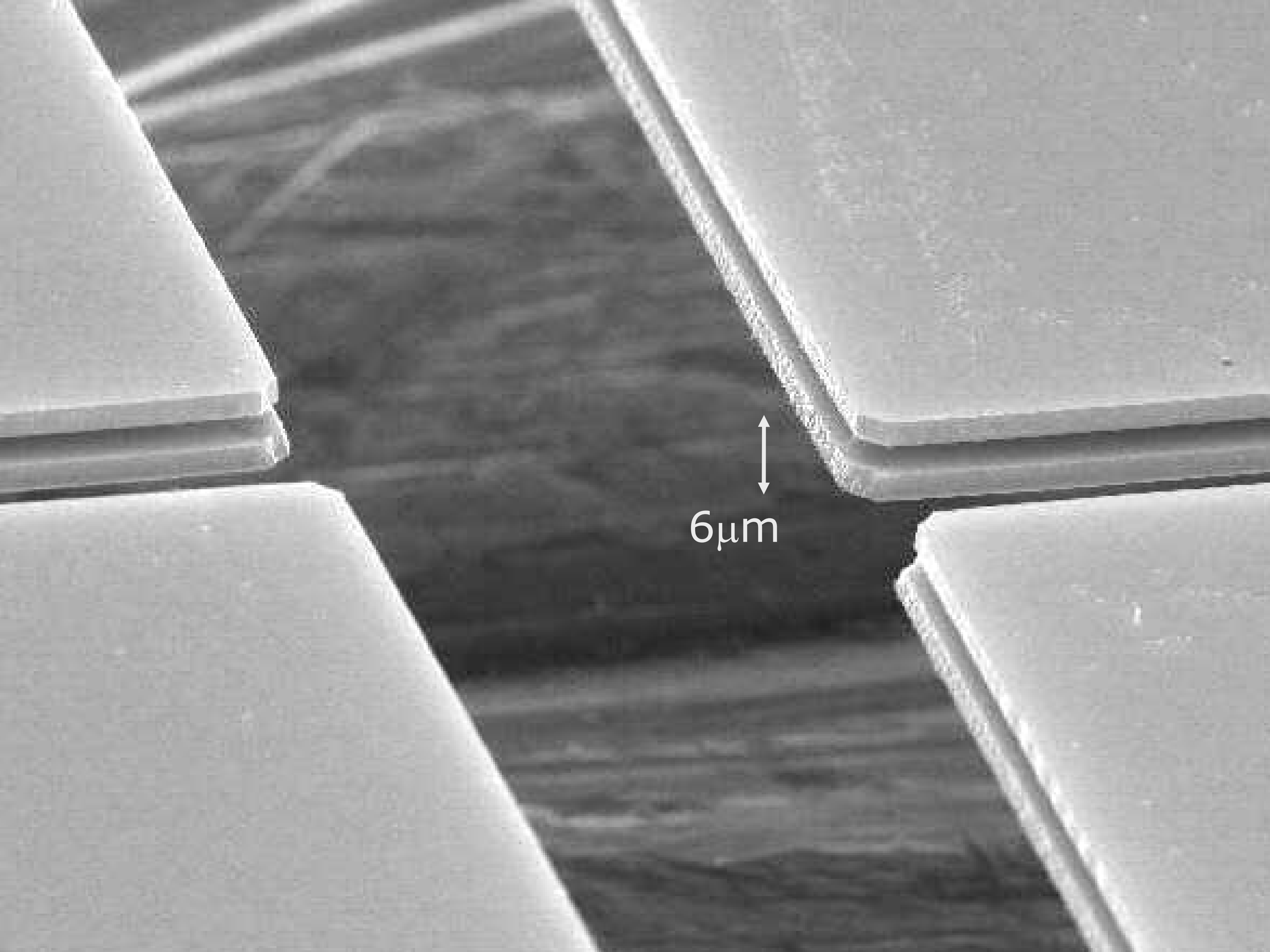


GaAs/AlGaAs

D. Stick (Michigan)
K. Schwab (LPS/U. Maryland)




LPS
SEI
30.0kV
X450
10μm
WD 29.2mm


6μm

Using a photon as the data bus

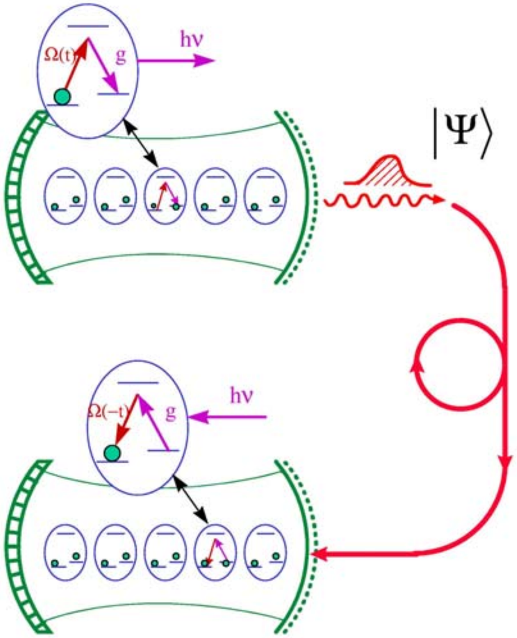
“DiVincenzo 6,7”

cavity-QED (trap the photon too)

- CalTech
- ENS-Paris
- MPQ-Garching
- …

Ensemble spin-squeezing

- Copenhagen
- Rochester
- Harvard
- …



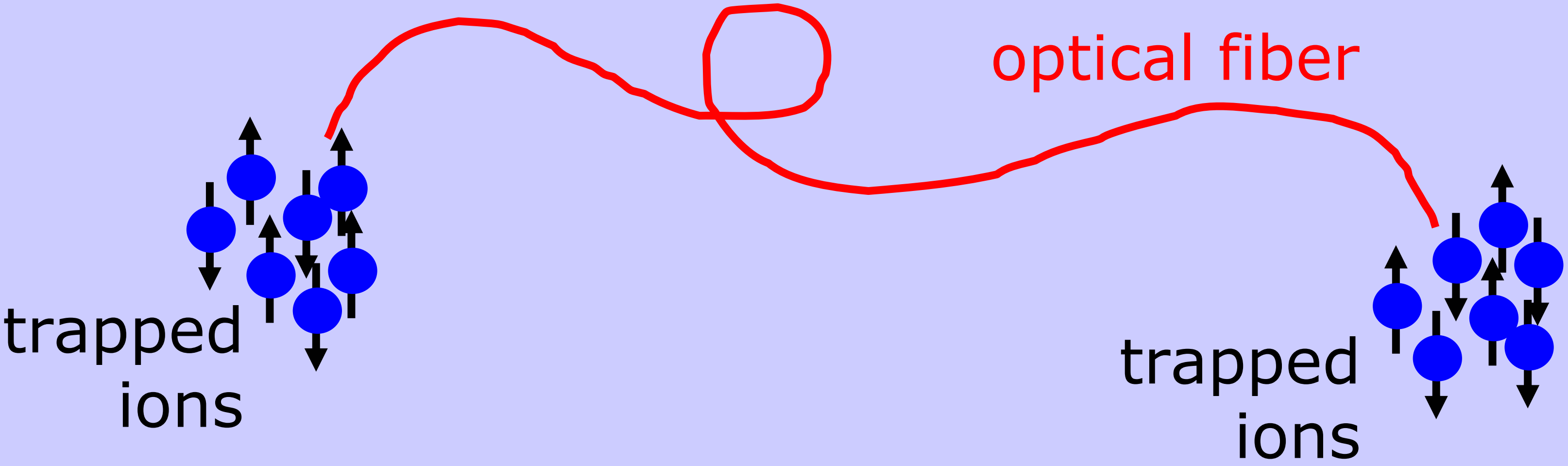
entanglement of atom & photon:
must have excellent control of ***both*** atom and photon

Ideal quantum memory

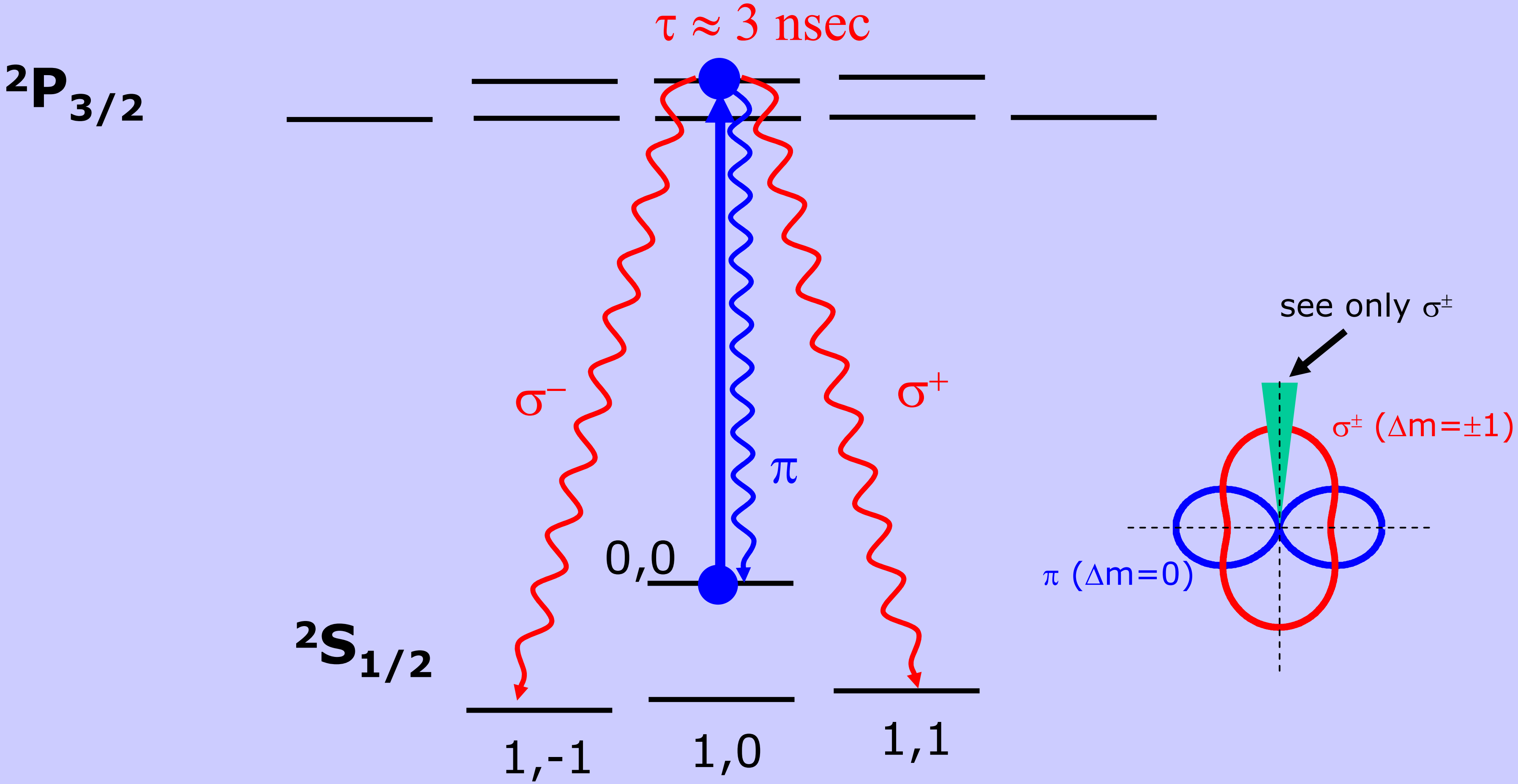
trapped atomic ion

Quantum communication channel

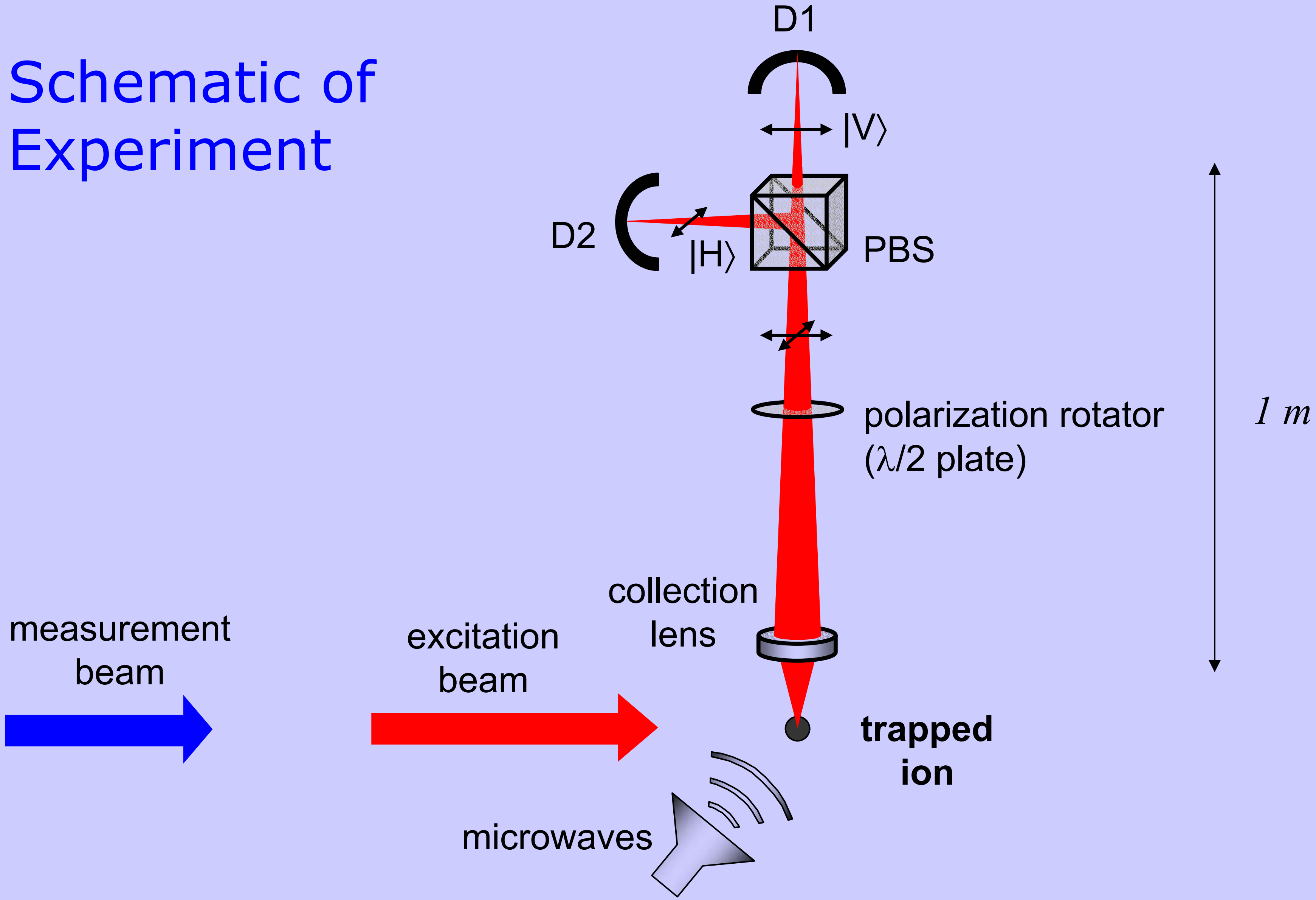
photon: "flying qubit"



Probabalistic entanglement between a single atom and single photon

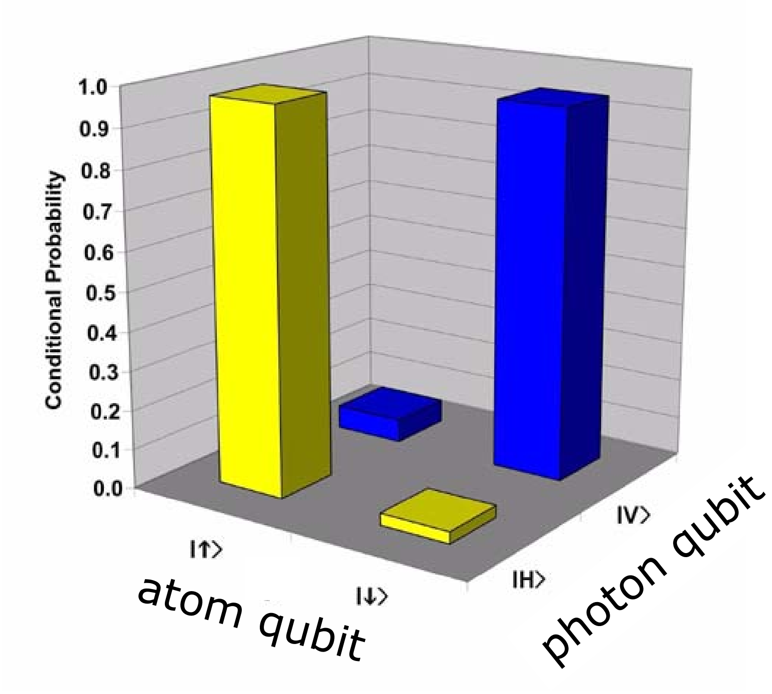


Schematic of Experiment

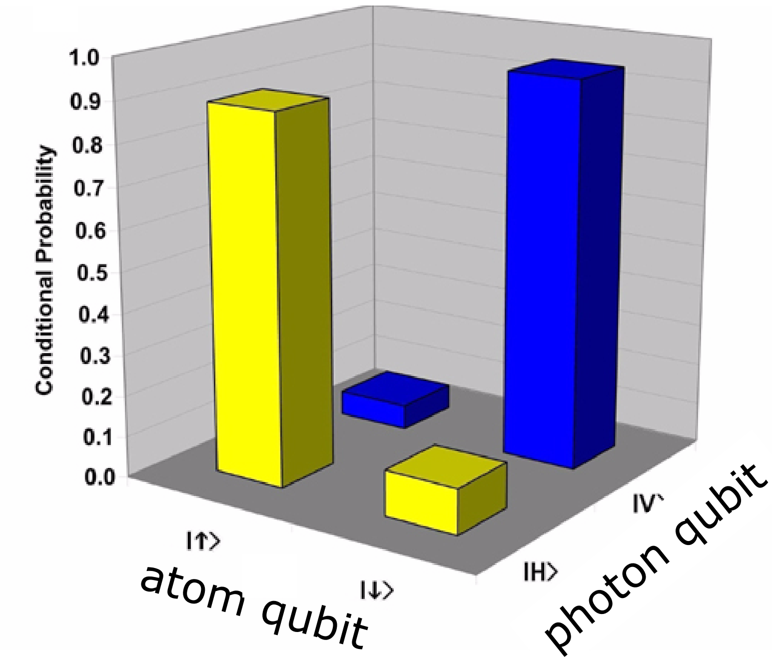


$$|\psi\rangle_{\mathrm{ideal}} = |H\rangle|\uparrow\rangle + |V\rangle|\downarrow\rangle$$

Measured correlation between atomic and photonic qubits…



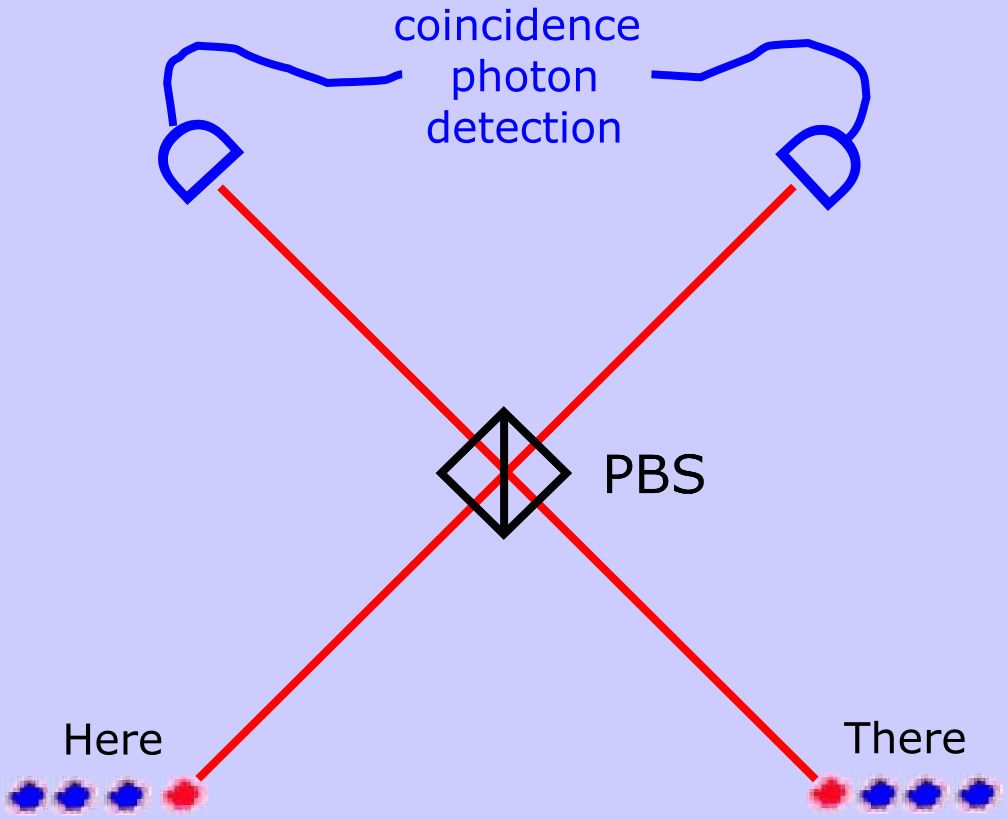
… and after rotation of each qubit by $\pi/2$ before measurement



Entanglement Fidelity: $F = \langle\Psi_{\mathrm{ideal}}|\rho|\Psi_{\mathrm{ideal}}\rangle > 87\%$

Blinov, et. al., *Nature* **428**, 153 (2004)

Can use this technique to seed remote ion-ion entanglement…



Speed of gate:

$R = \Gamma(P_{succ})^2$

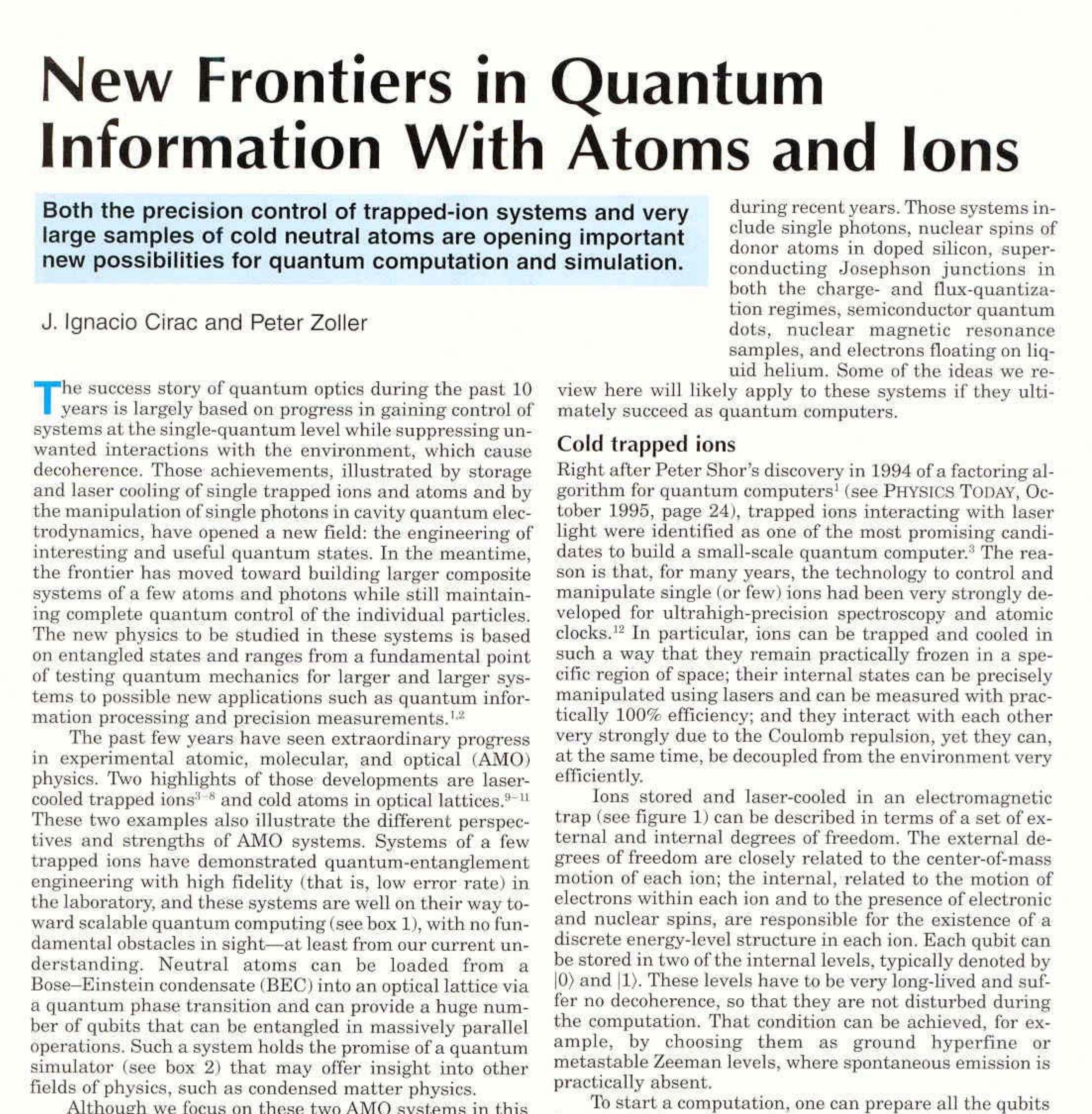
$= 0.01$/sec now

$= 10^6$/sec possible

… and form the basis for ***scalable*** QC

Duan, et. al., *Quantum. Inf. Comp.* (in press), quant-ph/0401020

Physics Today
March, 2004



New Frontiers in Quantum Information With Atoms and Ions

Both the precision control of trapped-ion systems and very large samples of cold neutral atoms are opening important new possibilities for quantum computation and simulation.

J. Ignacio Cirac and Peter Zoller

The success story of quantum optics during the past 10 years is largely based on progress in gaining control of systems at the single-quantum level while suppressing unwanted interactions with the environment, which cause decoherence. Those achievements, illustrated by storage and laser cooling of single trapped ions and atoms and by the manipulation of single photons in cavity quantum electrodynamics, have opened a new field: the engineering of interesting and useful quantum states. In the meantime, the frontier has moved toward building larger composite systems of a few atoms and photons while still maintaining complete quantum control of the individual particles. The new physics to be studied in these systems is based on entangled states and ranges from a fundamental point of testing quantum mechanics for larger and larger systems to possible new applications such as quantum information processing and precision measurements.[1,2]

The past few years have seen extraordinary progress in experimental atomic, molecular, and optical (AMO) physics. Two highlights of those developments are laser-cooled trapped ions[3–8] and cold atoms in optical lattices.[9–11] These two examples also illustrate the different perspectives and strengths of AMO systems. Systems of a few trapped ions have demonstrated quantum-entanglement engineering with high fidelity (that is, low error rate) in the laboratory, and these systems are well on their way toward scalable quantum computing (see box 1), with no fundamental obstacles in sight—at least from our current understanding. Neutral atoms can be loaded from a Bose–Einstein condensate (BEC) into an optical lattice via a quantum phase transition and can provide a huge number of qubits that can be entangled in massively parallel operations. Such a system holds the promise of a quantum simulator (see box 2) that may offer insight into other fields of physics, such as condensed matter physics.

Although we focus on these two AMO systems in this

during recent years. Those systems include single photons, nuclear spins of donor atoms in doped silicon, superconducting Josephson junctions in both the charge- and flux-quantization regimes, semiconductor quantum dots, nuclear magnetic resonance samples, and electrons floating on liquid helium. Some of the ideas we review here will likely apply to these systems if they ultimately succeed as quantum computers.

Cold trapped ions

Right after Peter Shor's discovery in 1994 of a factoring algorithm for quantum computers[1] (see PHYSICS TODAY, October 1995, page 24), trapped ions interacting with laser light were identified as one of the most promising candidates to build a small-scale quantum computer.[3] The reason is that, for many years, the technology to control and manipulate single (or few) ions had been very strongly developed for ultrahigh-precision spectroscopy and atomic clocks.[12] In particular, ions can be trapped and cooled in such a way that they remain practically frozen in a specific region of space; their internal states can be precisely manipulated using lasers and can be measured with practically 100% efficiency; and they interact with each other very strongly due to the Coulomb repulsion, yet they can, at the same time, be decoupled from the environment very efficiently.

Ions stored and laser-cooled in an electromagnetic trap (see figure 1) can be described in terms of a set of external and internal degrees of freedom. The external degrees of freedom are closely related to the center-of-mass motion of each ion; the internal, related to the motion of electrons within each ion and to the presence of electronic and nuclear spins, are responsible for the existence of a discrete energy-level structure in each ion. Each qubit can be stored in two of the internal levels, typically denoted by $|0\rangle$ and $|1\rangle$. These levels have to be very long-lived and suffer no decoherence, so that they are not disturbed during the computation. That condition can be achieved, for example, by choosing them as ground hyperfine or metastable Zeeman levels, where spontaneous emission is practically absent.

To start a computation, one can prepare all the qubits

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Winfried Hensinger (postdoc)
Chitra Rangan (postdoc/theory)

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US National Security Agency
ARDA **US Advanced Research and Development Activity**
US Army Research Office
NSF **National Science Foundation**
FOCUS **FOCUS Center**

http://iontrap.physics.lsa.umich.edu/