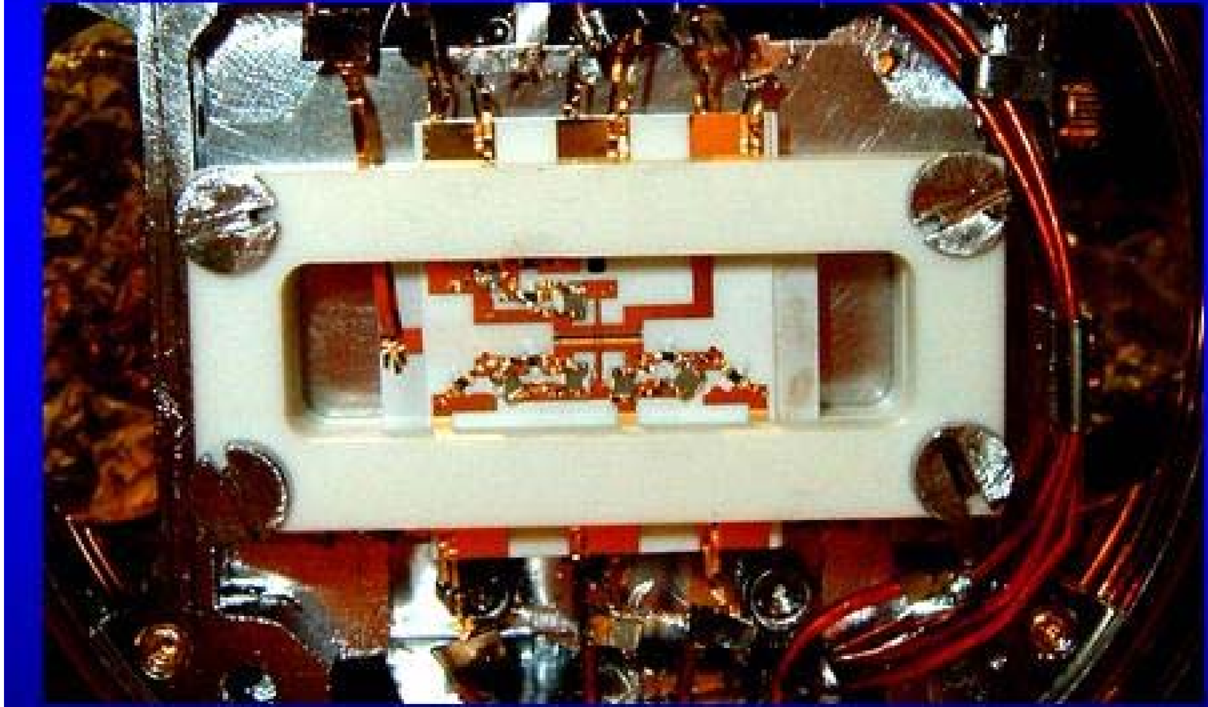
University of Michigan
Trapped Ion Quantum Computing

Implementing quantum computing with trapped ions



Louis Deslauriers

P.I. Chris Monroe

National Science Foundation

US Army Research Office

US National Security Agency

US Advanced Research and Development Activity

Michigan FOCUS Center

Quantum Computers: Physical Implementations

1. Individual atoms and photons
    - a. ion traps
    - b. atoms in optical lattices
    - c. cavity-QED

2. Superconductors
    - a. Cooper-pair boxes (charge qubits)
    - b. rf-SQUIDS (flux qubits)

3. Semiconductors
    - quantum dots

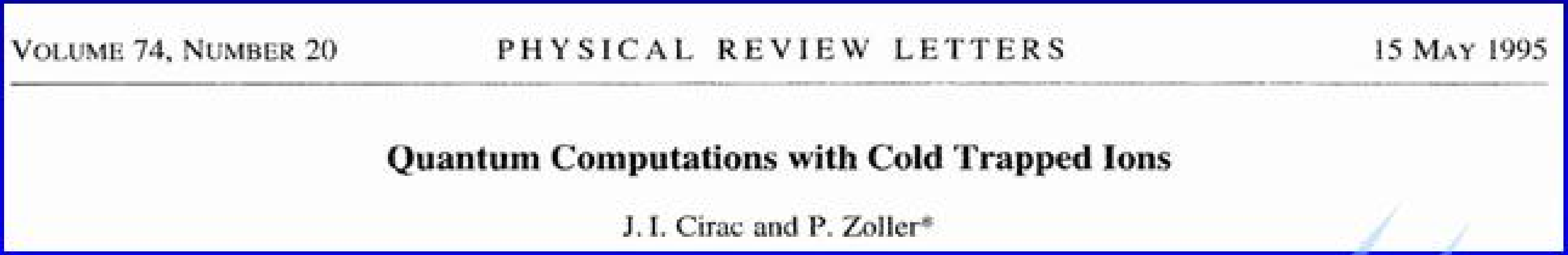
4. Other condensed-matter
    - a. electrons floating on liquid helium
    - b. single phosphorus atoms in silicon

Conflicting requirements

Qubits must interact strongly with one another (on demand)...

... but must interact weakly with the environment

Building a quantum computer "bottom up"

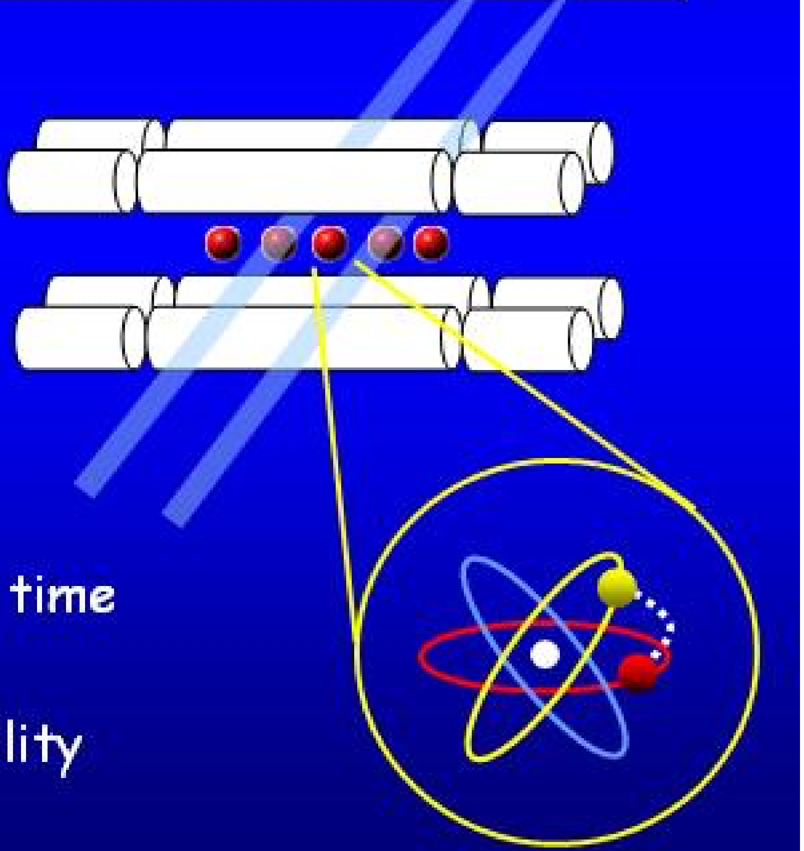


VOLUME 74, NUMBER 20 PHYSICAL REVIEW LETTERS 15 MAY 1995

Quantum Computations with Cold Trapped Ions

J. I. Cirac and P. Zoller*

---- Requirements ----
(David DiVincenzo,IBM)



1) Scalable system of qubits
2) Initialization (i.e. to |000...⟩)
3) Decoherence times >> gate operation time
4) A "universal" set of quantum gates
5) A qubit-specific measurement capability

Two big challenges to tackle:

- ***Robustness***: We need long qubit coherence times and high fidelity operations to reach error correction thresholds for stable quantum computing ($<10^{-4}$ error rate).

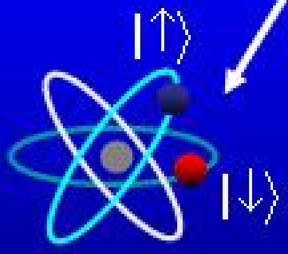
- ***Scalability***: At the same time we need a scalable design to reach a useful number of qubits.

Trapped ions → "No fundamental obstacle in sight toward realizing a scalable quantum information processor"

I. Cirac, P. Zoller, Physics Today, March 2004

Trapped Atomic Ions

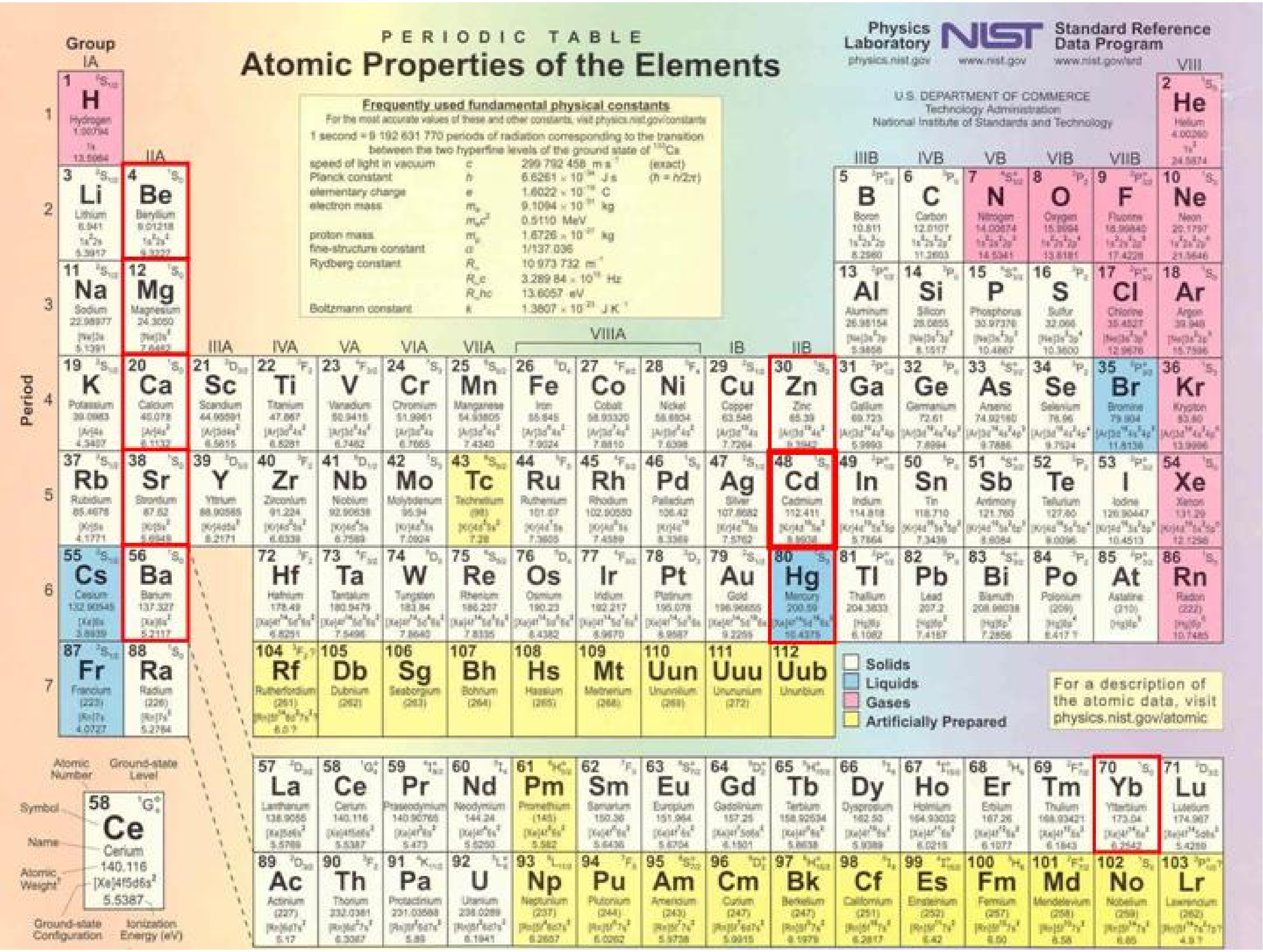
J. Bergquist (NIST)



qubit stored
inside each
trapped ion

Ion Trap QC Groups (worldwide):

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



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 × 10^{15} Hz	
	$R_\infty hc$	13.6057 eV	
Boltzmann constant	k	1.3807 × 10^{-23} J K^{-1}	

Period	IA	IIA	IIIA	IVA	VA	VIA	VIIA	VIIIA			IB	IIB	IIIB	IVB	VB	VIB	VIIB	VIII
1	1 H Hydrogen																	2 He Helium
2	3 Li Lithium	4 Be Beryllium											5 B Boron	6 C Carbon	7 N Nitrogen	8 O Oxygen	9 F Fluorine	10 Ne Neon
3	11 Na Sodium	12 Mg Magnesium											13 Al Aluminum	14 Si Silicon	15 P Phosphorus	16 S Sulfur	17 Cl Chlorine	18 Ar Argon
4	19 K Potassium	20 Ca Calcium	21 Sc Scandium	22 Ti Titanium	23 V Vanadium	24 Cr Chromium	25 Mn Manganese	26 Fe Iron	27 Co Cobalt	28 Ni Nickel	29 Cu Copper	30 Zn Zinc	31 Ga Gallium	32 Ge Germanium	33 As Arsenic	34 Se Selenium	35 Br Bromine	36 Kr Krypton
5	37 Rb Rubidium	38 Sr Strontium	39 Y Yttrium	40 Zr Zirconium	41 Nb Niobium	42 Mo Molybdenum	43 Tc Technetium	44 Ru Ruthenium	45 Rh Rhodium	46 Pd Palladium	47 Ag Silver	48 Cd Cadmium	49 In Indium	50 Sn Tin	51 Sb Antimony	52 Te Tellurium	53 I Iodine	54 Xe Xenon
6	55 Cs Cesium	56 Ba Barium		72 Hf Hafnium	73 Ta Tantalum	74 W Tungsten	75 Re Rhenium	76 Os Osmium	77 Ir Iridium	78 Pt Platinum	79 Au Gold	80 Hg Mercury	81 Tl Thallium	82 Pb Lead	83 Bi Bismuth	84 Po Polonium	85 At Astatine	86 Rn Radon
7	87 Fr Francium	88 Ra Radium		104 Rf Rutherfordium	105 Db Dubnium	106 Sg Seaborgium	107 Bh Bohrium	108 Hs Hassium	109 Mt Meitnerium	110 Uun Ununnilium	111 Uuu Unununium	112 Uub Ununbium						

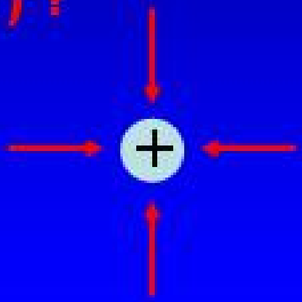
57 La Lanthanum	58 Ce Cerium	59 Pr Praseodymium	60 Nd Neodymium	61 Pm Promethium	62 Sm Samarium	63 Eu Europium	64 Gd Gadolinium	65 Tb Terbium	66 Dy Dysprosium	67 Ho Holmium	68 Er Erbium	69 Tm Thulium	70 Yb Ytterbium	71 Lu Lutetium
89 Ac Actinium	90 Th Thorium	91 Pa Protactinium	92 U Uranium	93 Np Neptunium	94 Pu Plutonium	95 Am Americium	96 Cm Curium	97 Bk Berkelium	98 Cf Californium	99 Es Einsteinium	100 Fm Fermium	101 Md Mendelevium	102 No Nobelium	103 Lr Lawrencium

☐ Solids
🟦 Liquids
🟥 Gases
🟨 Artificially Prepared

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

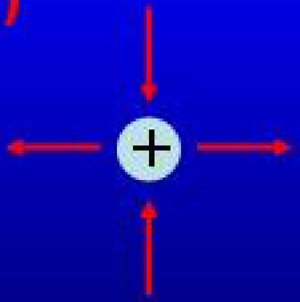
The Paul trap: 3-D rf quadrupole potential

E(r) ?

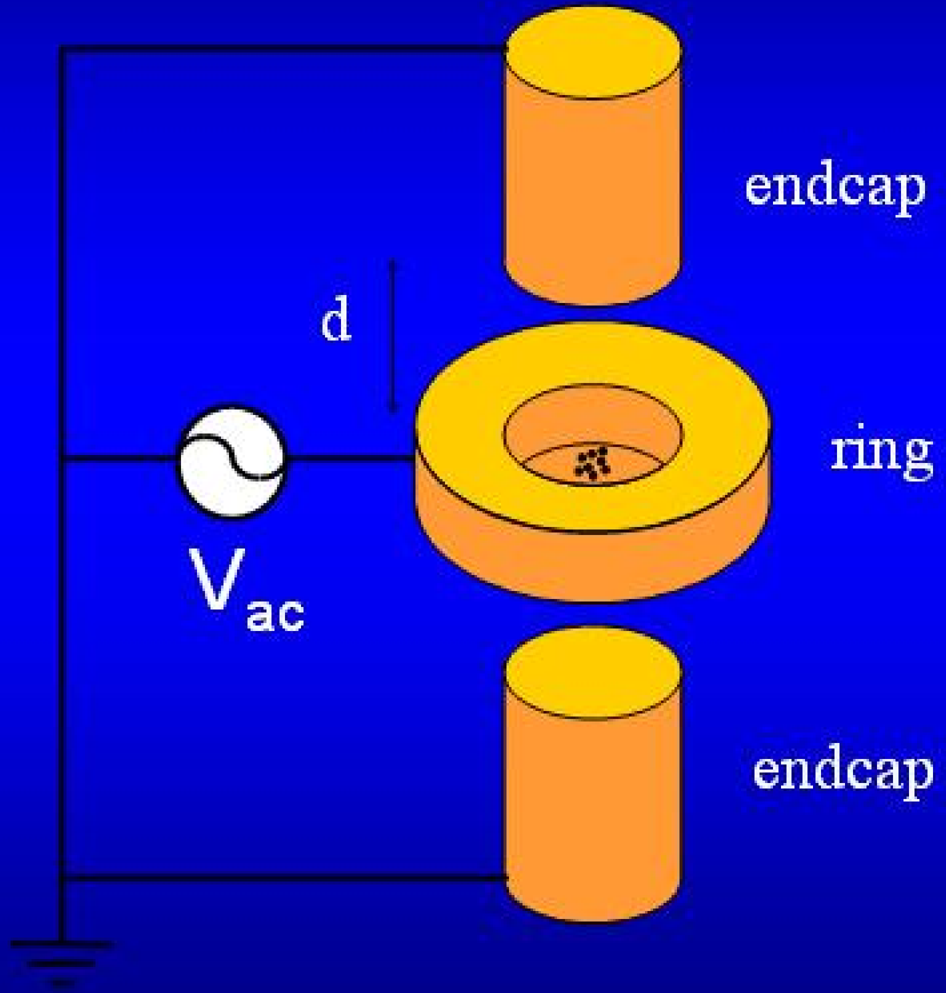


NO! $\nabla\cdot\mathbf{E} = 0$

E(r)



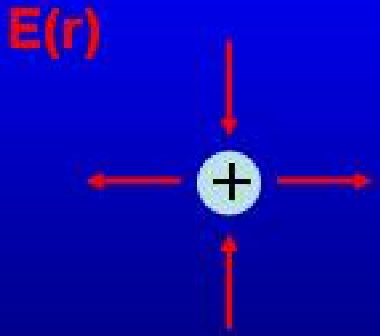
Saddle/quadrupole potential



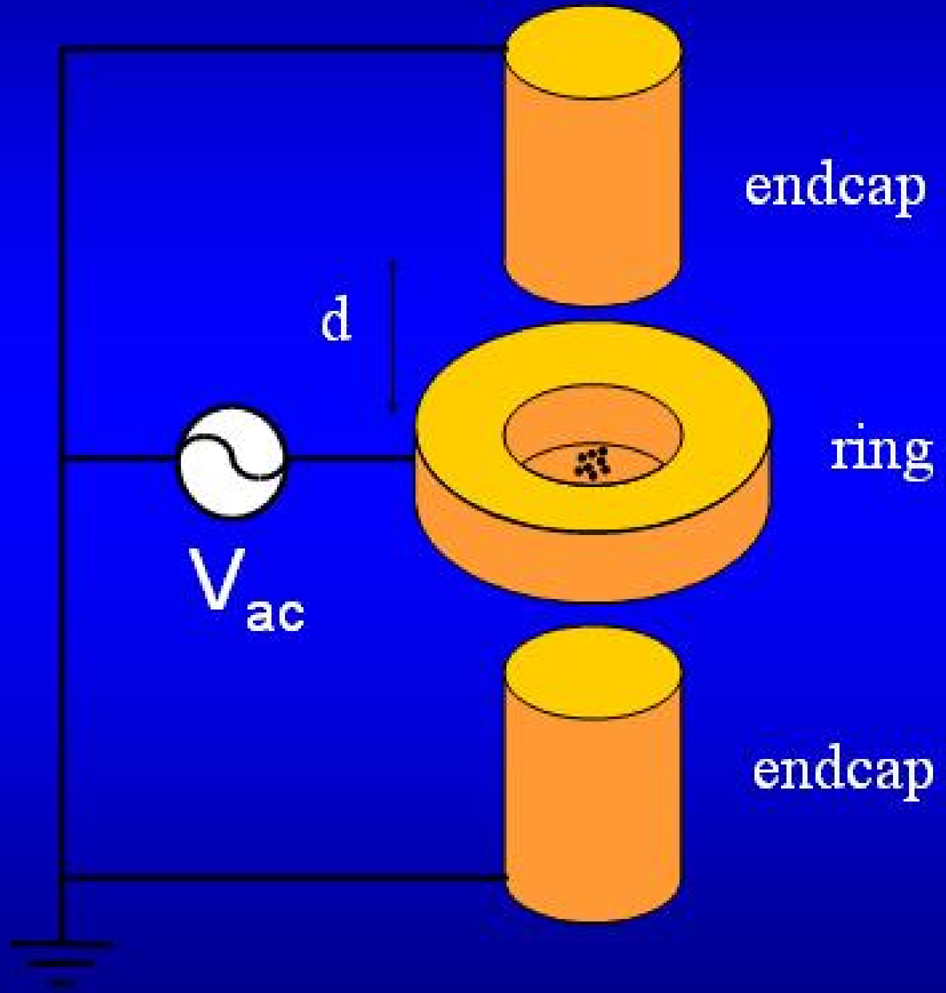
The Paul trap: 3-D rf quadrupole potential

Trick: apply sinusoidal electric field (rotate saddle)

RF (PAUL) TRAP



Saddle/quadrupole potential



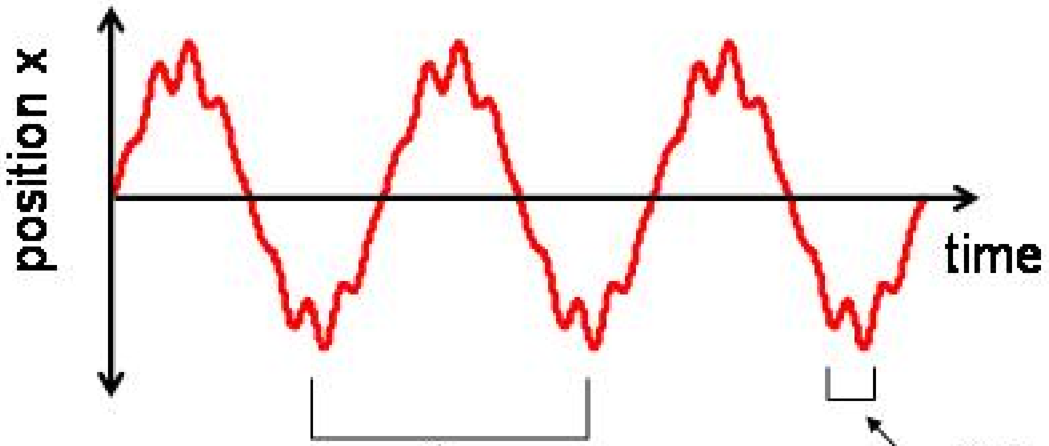
Dynamics of a single ion in a rf trap

$$\ddot{x} + [\kappa^2 \cos\Omega t]x = 0$$

$$\kappa^2 = eV_0/md^2$$

e = ion charge
m = ion mass
V_0 = rf voltage amplitude
d = trapsize

Mathieu Equation: $x(t)$ bounded for $\kappa \ll \Omega$

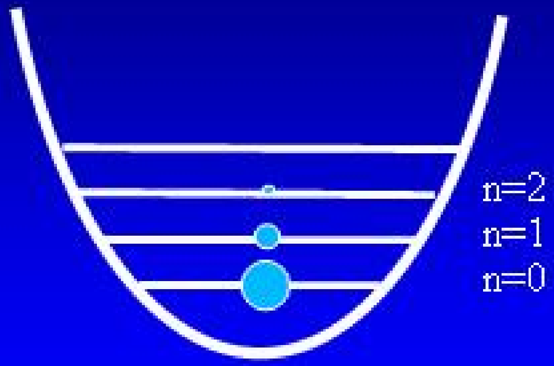


"secular" motion
at frequency $\omega_{trap} \approx \kappa^2/\Omega$ ~ MHz

"micromotion"
at frequency Ω ~ 20-200 MHz

Secular motion → quantum harmonic oscillator:

$$H = \underbrace{\sum_{i=1}^{N} \frac{\hbar\omega_0}{2}\sigma_z^{(i)}}_{\text{N qubits}} + \underbrace{\sum_{\nu=1}^{N} \hbar\omega_\nu a_\nu^\dagger a_\nu}_{\text{N harmonic oscillator modes}}$$



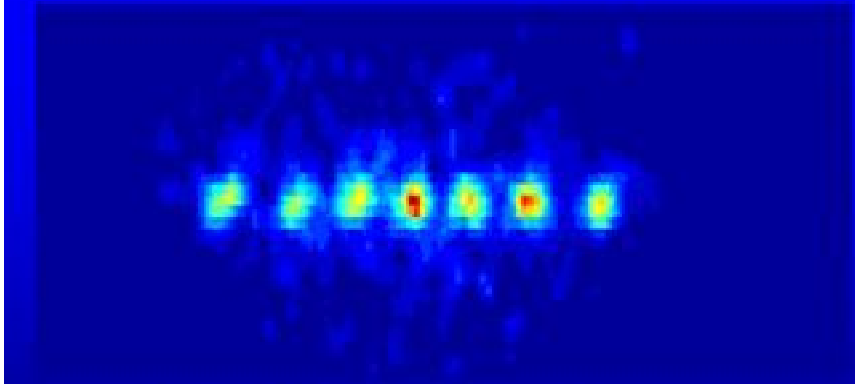
Fock state

if $|\Psi\rangle = |n_x\rangle$

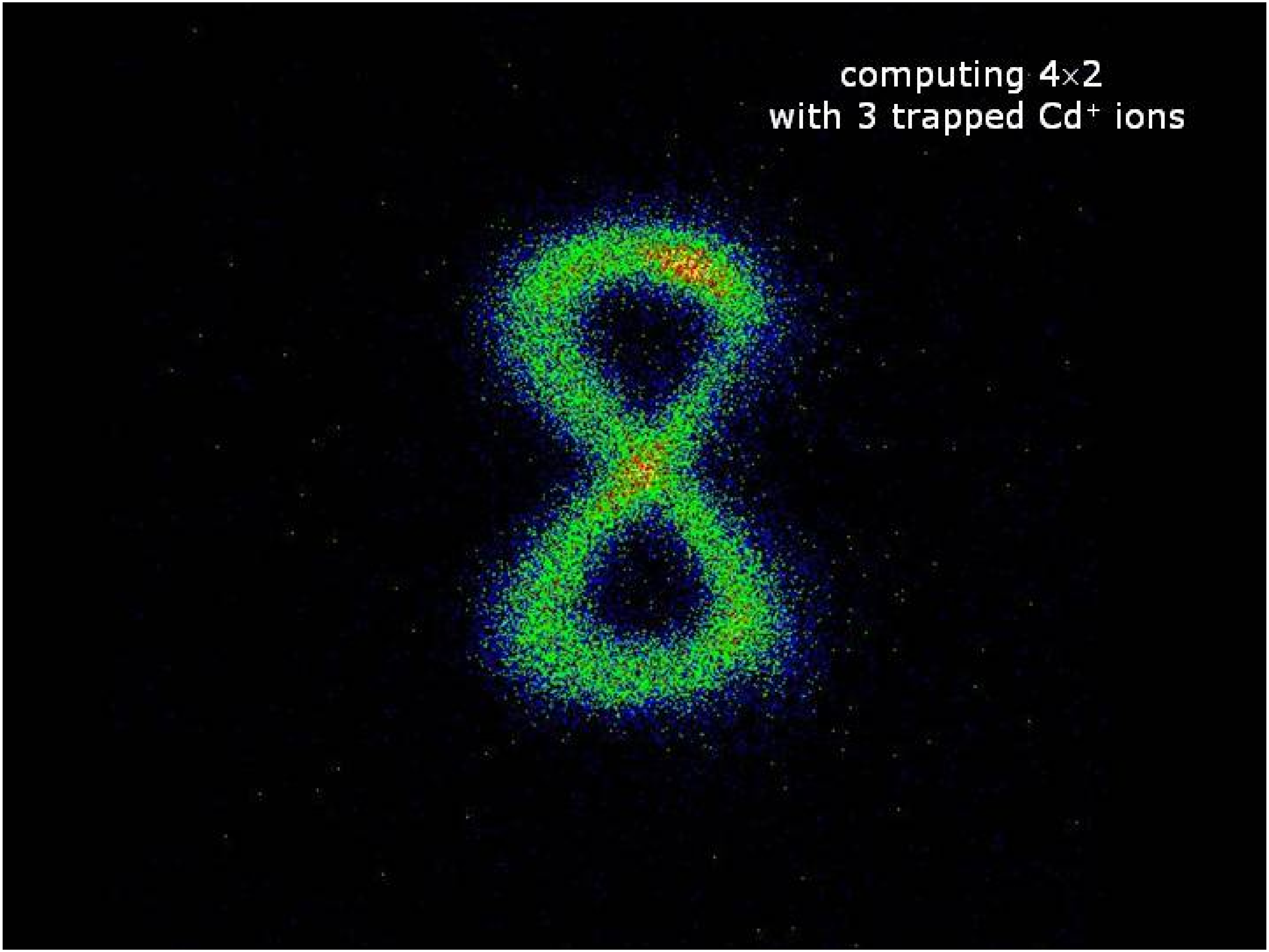
$$\left(\frac{\hat{p}^2}{2m} + \frac{1}{2}m\omega^2\hat{x}^2\right)|\Psi\rangle = \hbar\omega\left(n_x + \frac{1}{2}\right)|\Psi\rangle$$

$$\hat{X} = \hat{X}_0\left(\hat{a} + \hat{a}^\dagger\right)$$

$$\sqrt{\langle n=0|\hat{X}^2|n=0\rangle} \rightarrow X_0 = \sqrt{\frac{\hbar}{2m\omega}} \approx 5nm$$



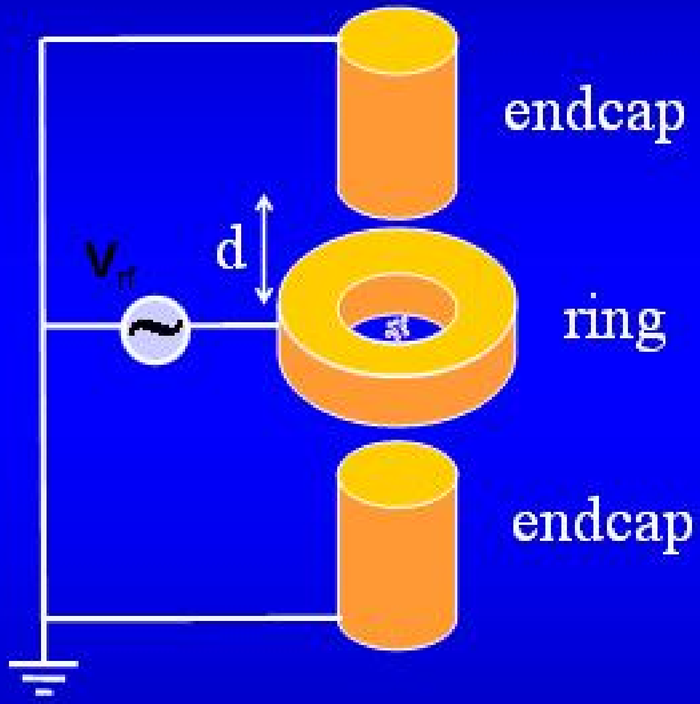
$^{40}Ca^+$ (R. Blatt, Univ. Innsbruck)



computing 4×2
with 3 trapped Cd^+ ions

Generic ion trap hardware

3-D rf Quadrupole Trap

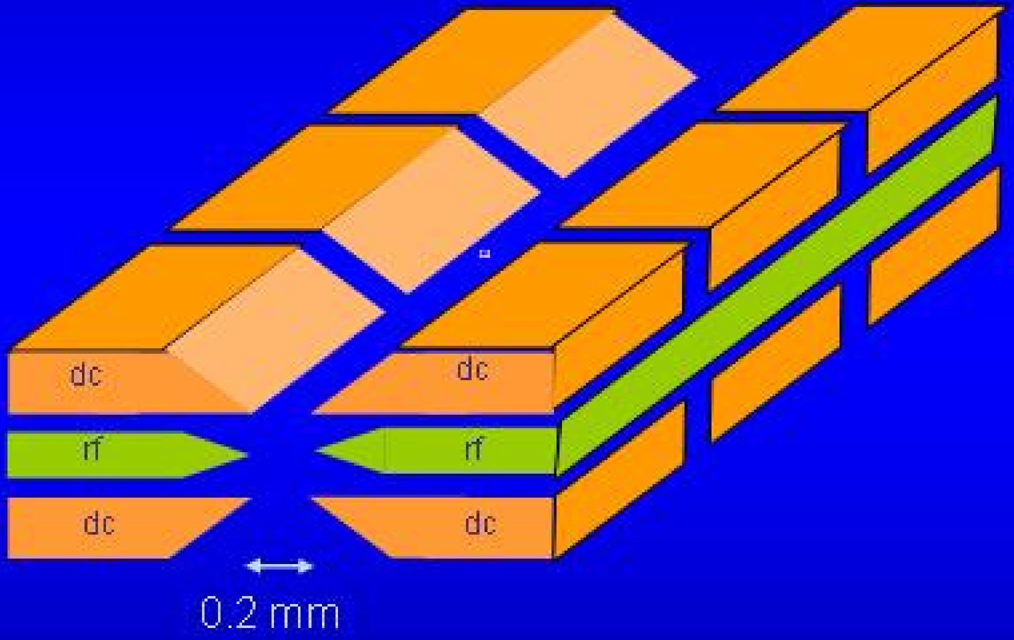


- Trap single ions

d_T = Trap dimension (~200μm)

Ω_T = Rf drive frequency (~50MHz)

2-D rf Quadrupole Trap
"3-Layer design"

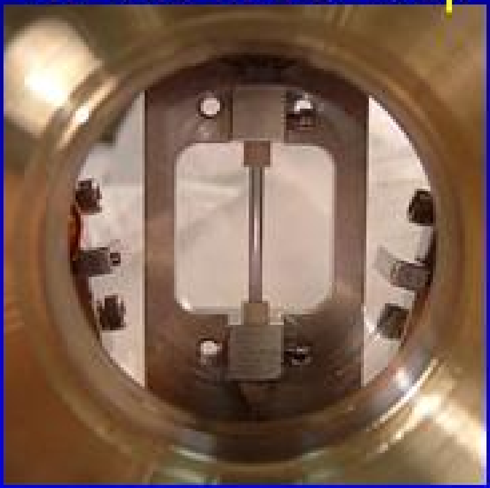


- Trapping strings of ions
- Allows corners, junctions
- Trap frequencies:
  radial 9MHz, axial 3MHz

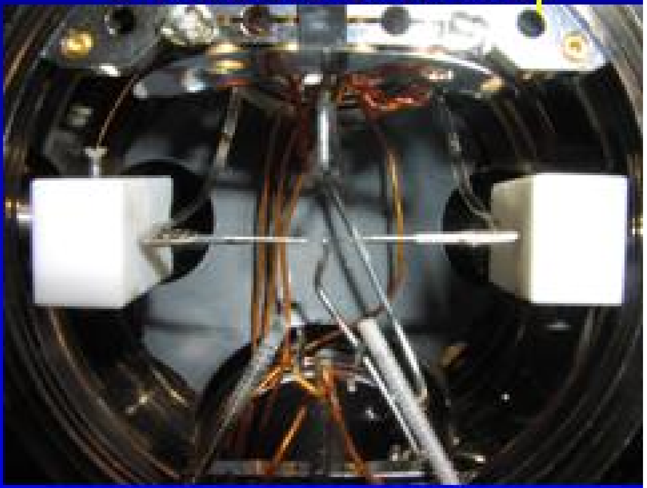
RF Paul Traps in the Monroe Lab

Ring & fork 3-D trap

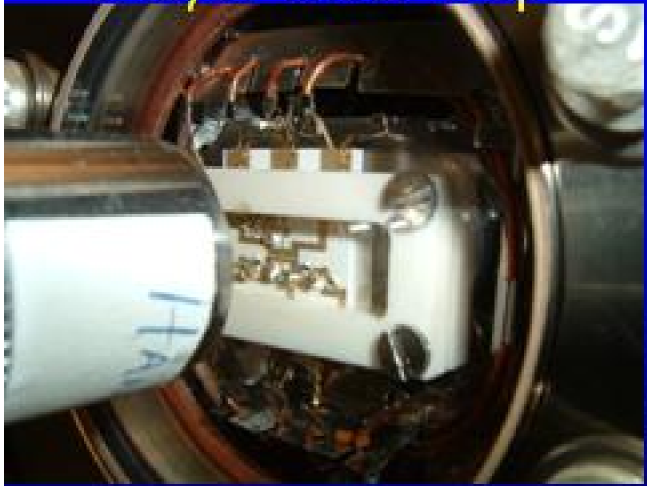
4 rods linear trap



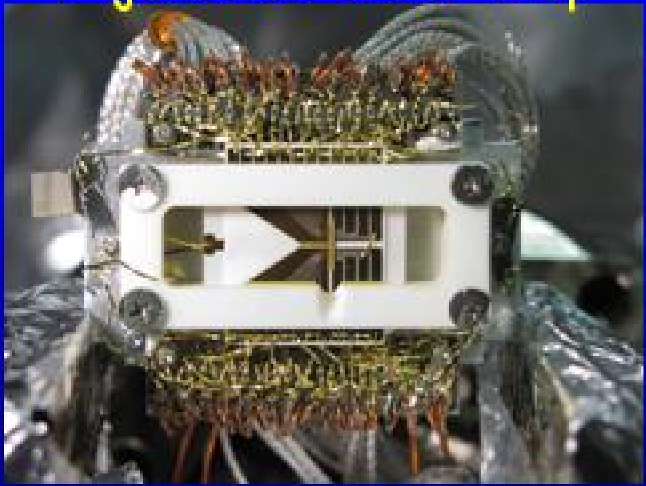
2 Needle 3-D trap



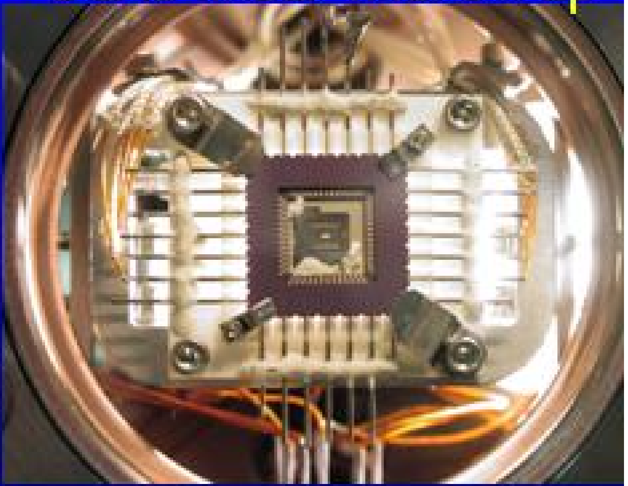
3-layer linear trap



T- junction linear trap

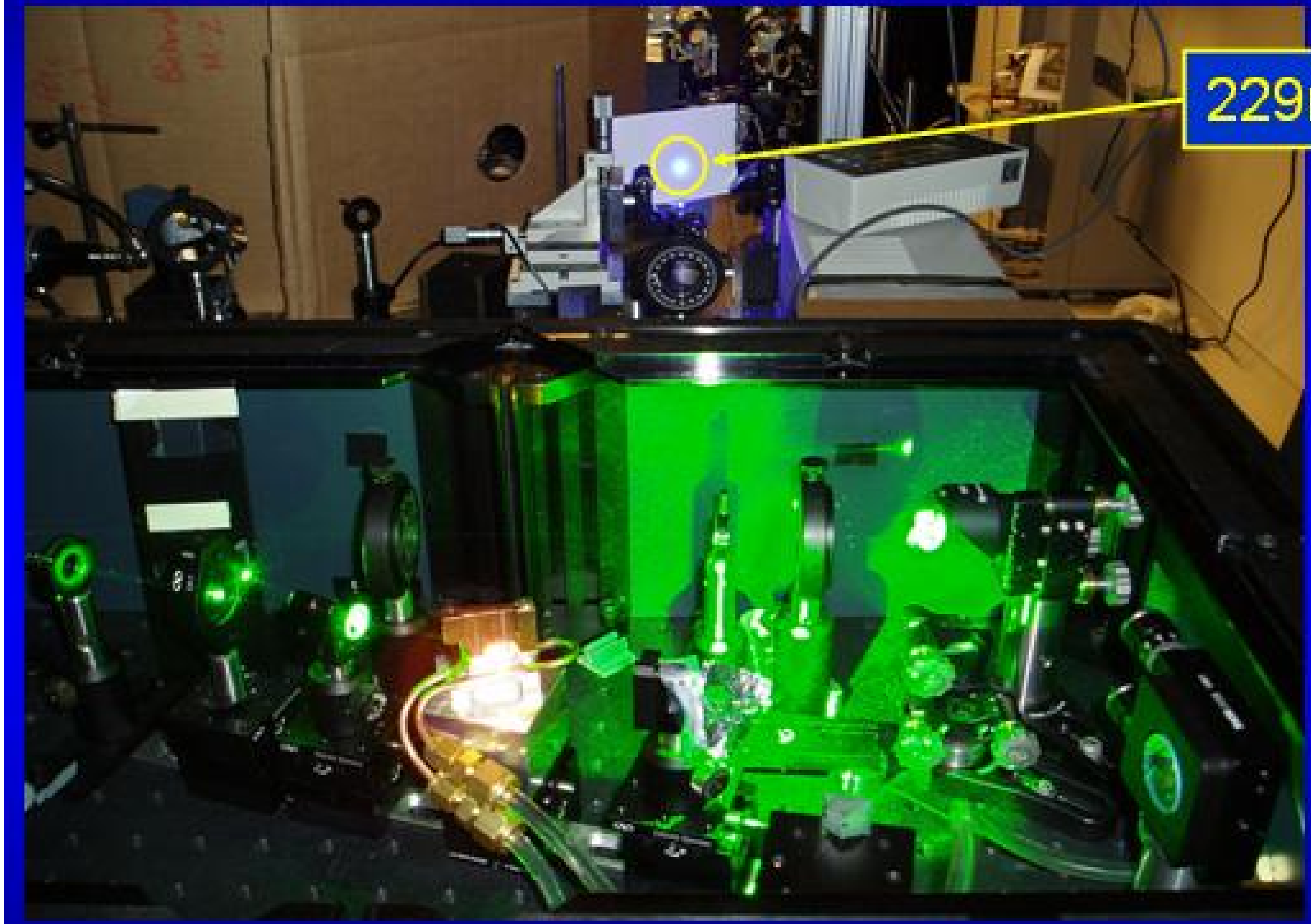


GaAs linear microtrap

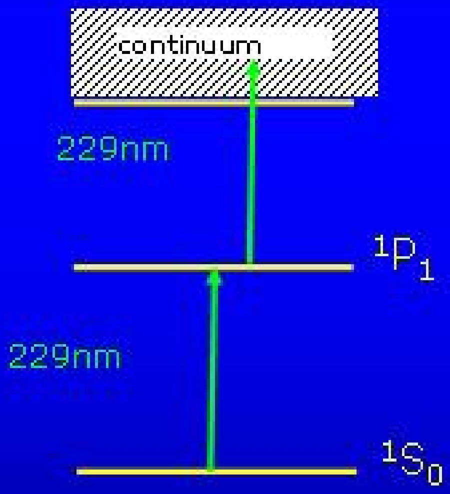


Vacuum Chambers @ $\sim 10^{-11}$ Torr

“Clean” photoionization-loading of Cd^+ into trap

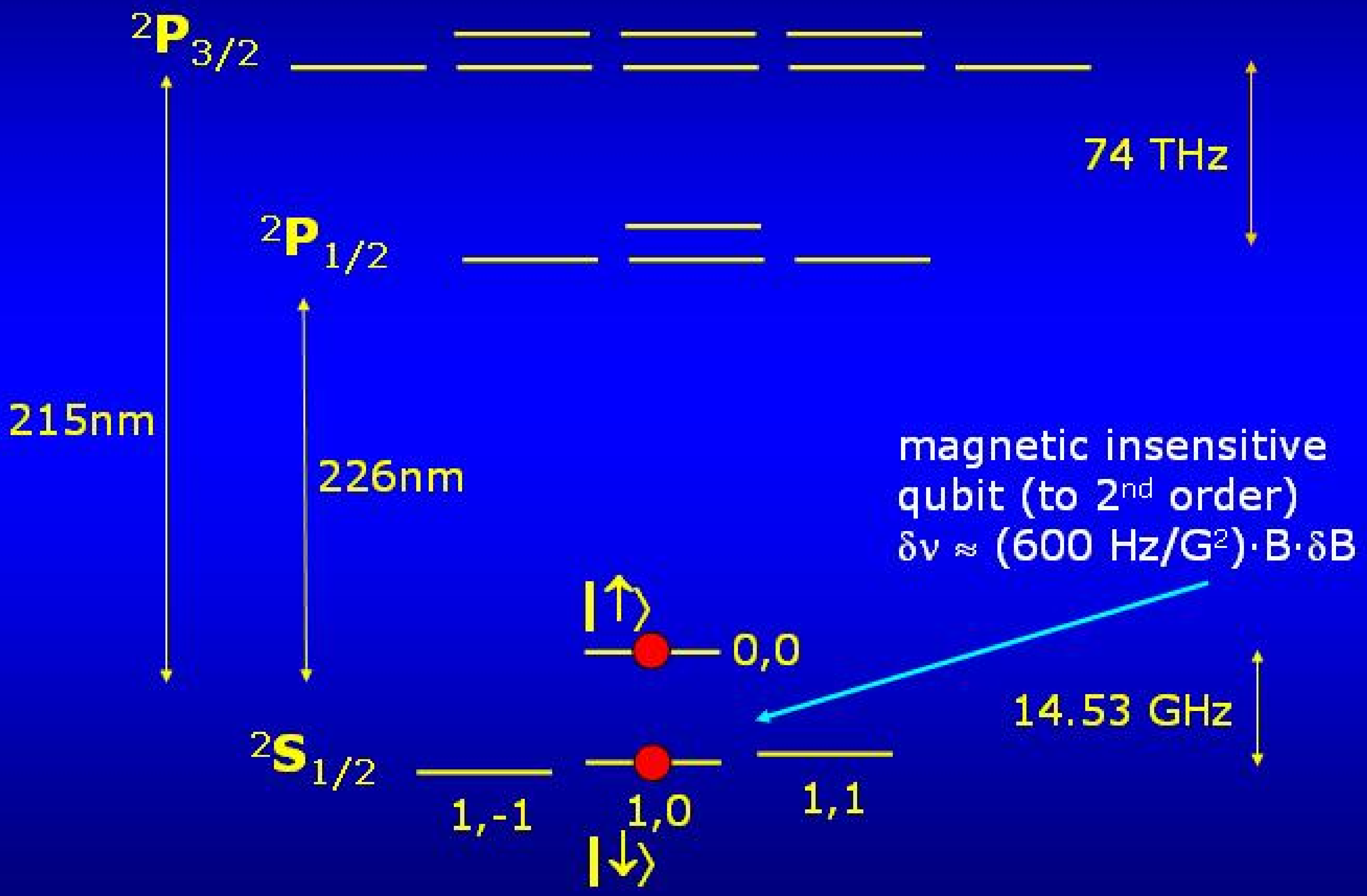


Cd neutral levels



Performance: P_{avg} ~ 600mW (infrared), **P_{avg} ~ 20mW (UV)**
Pulse length (infrared) ~ 30fsec-150fsec

$^{111}Cd^{+}$ atomic structure ($^{113}Cd^{+}$ similar)



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

74 THz

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

215nm

226nm

magnetic insensitive
qubit (to 2nd order)
$\delta\nu \approx (600\ \mathrm{Hz/G^2})\cdot B\cdot\delta B$

$|\uparrow\rangle$

0,0

14.53 GHz

$^{2}S_{1/2}$

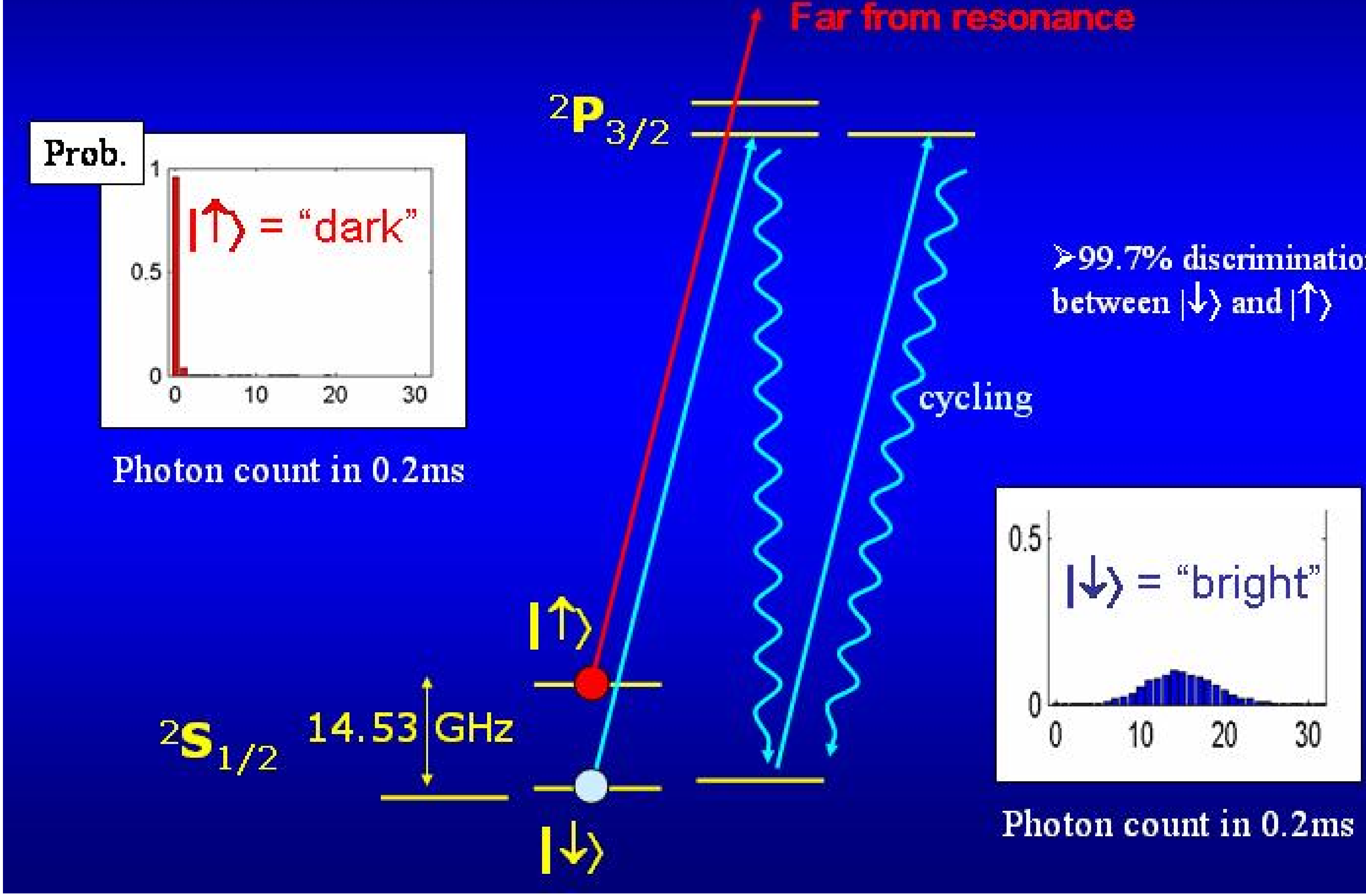
1,-1

1,0

1,1

$|\downarrow\rangle$

Efficient state detection

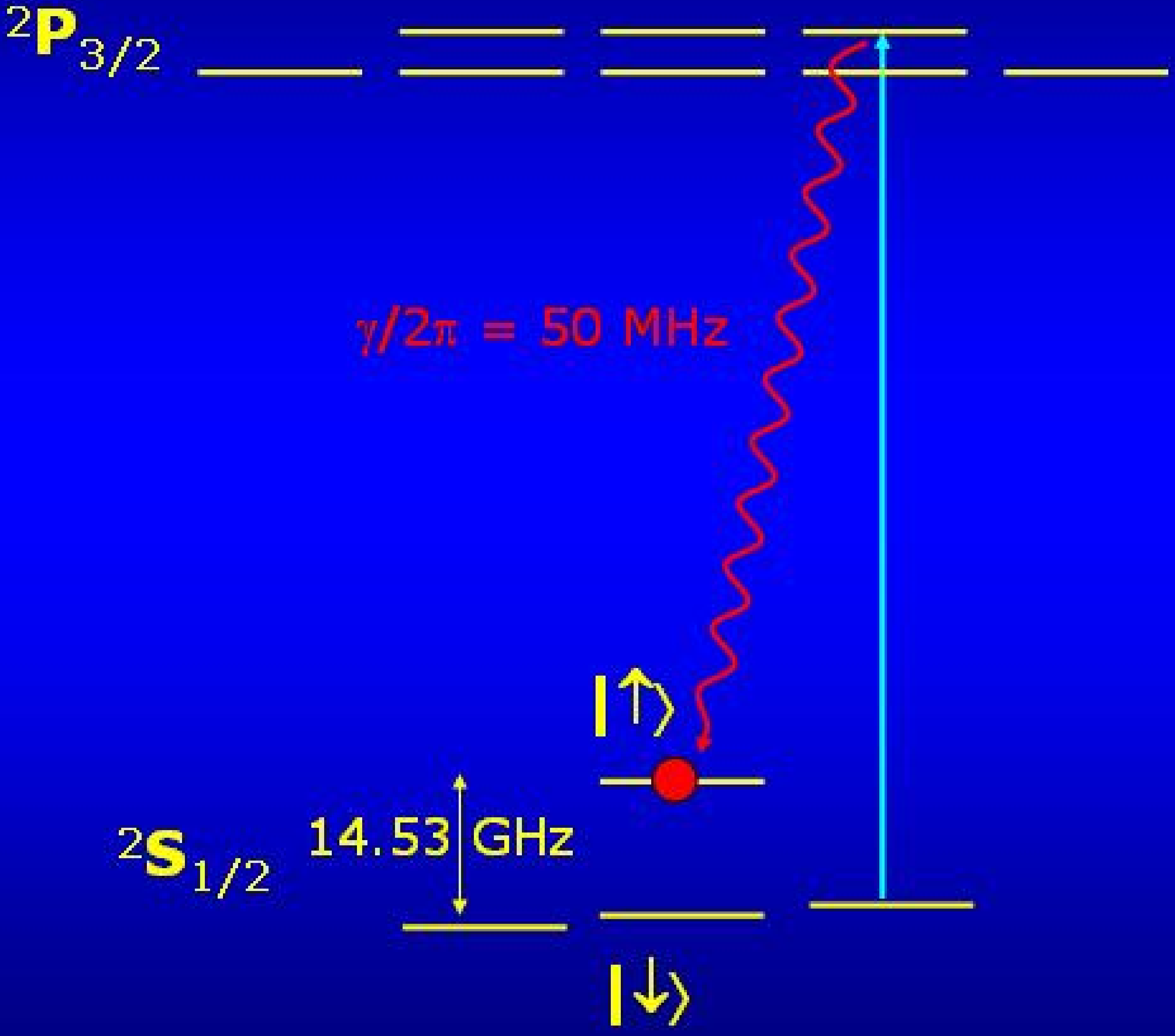


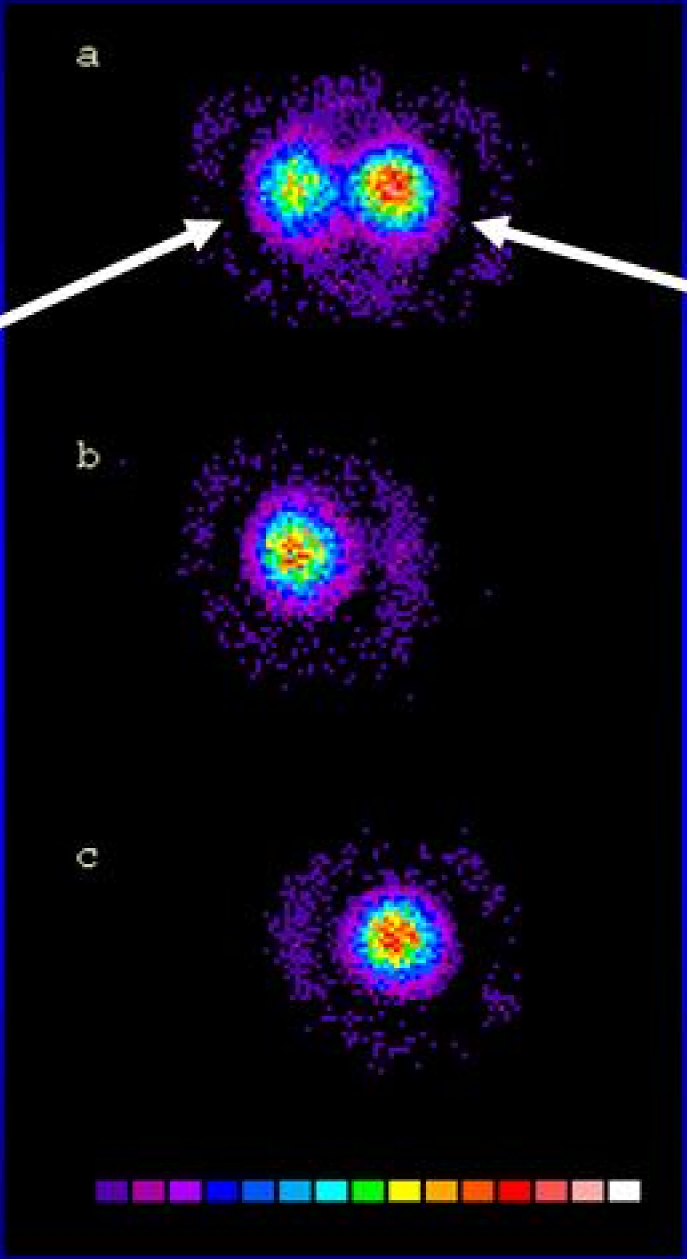
Photon count in 0.2ms

➢99.7% discrimination between |↓⟩ and |↑⟩

Photon count in 0.2ms

Near perfect **initialization** (optical pumping)





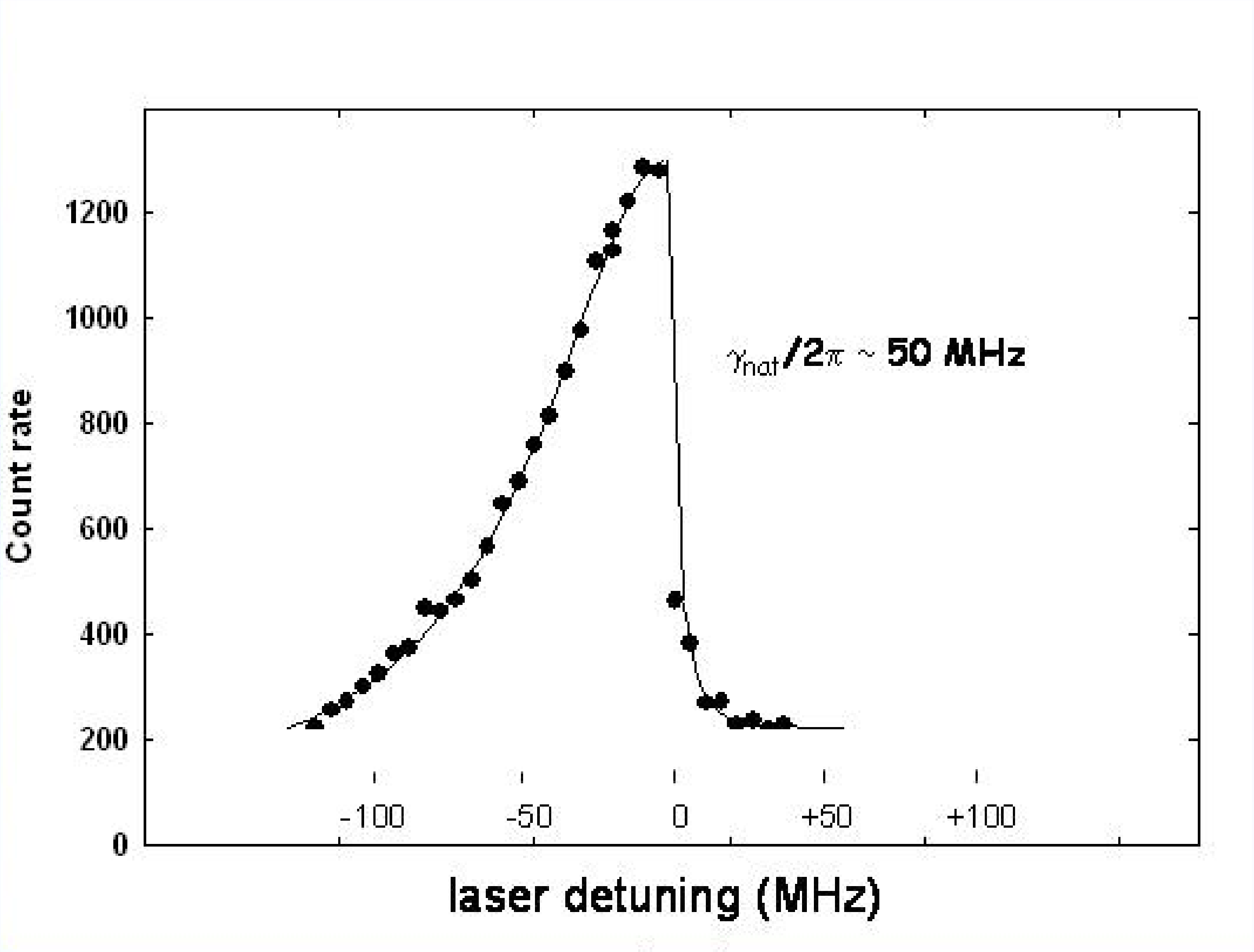
$^{112}Cd^+$

$^{114}Cd^+$

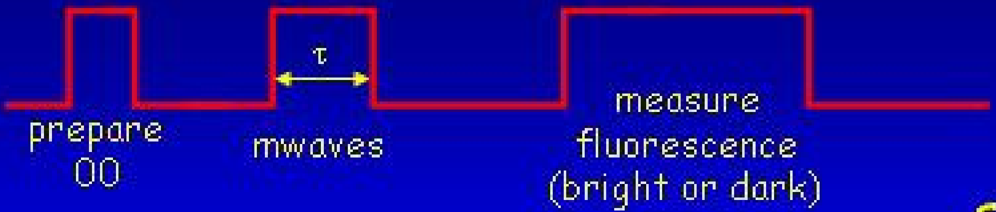
probe ($^{112}Cd^+$)
beam only

cooling ($^{114}Cd^+$)
beam only

Fluorescence scan of *detection/cooling* beam on single $^{112}Cd^{+}$ ion

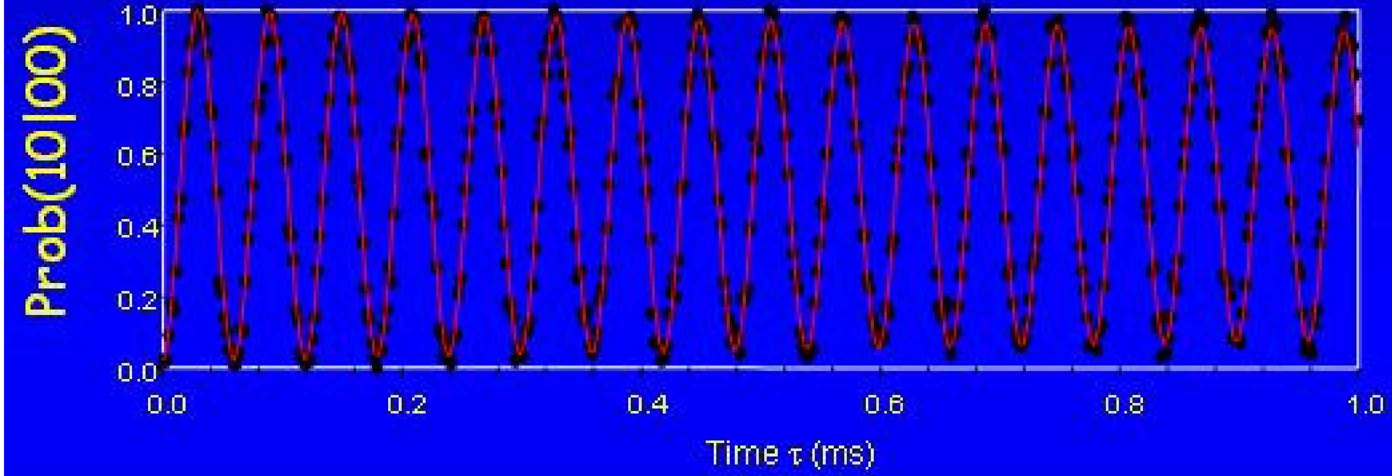


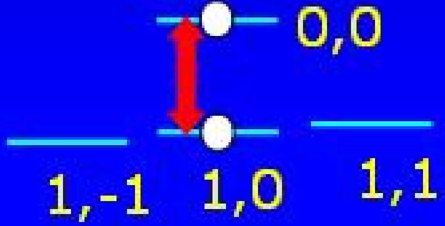
Microwave Rabi Flopping

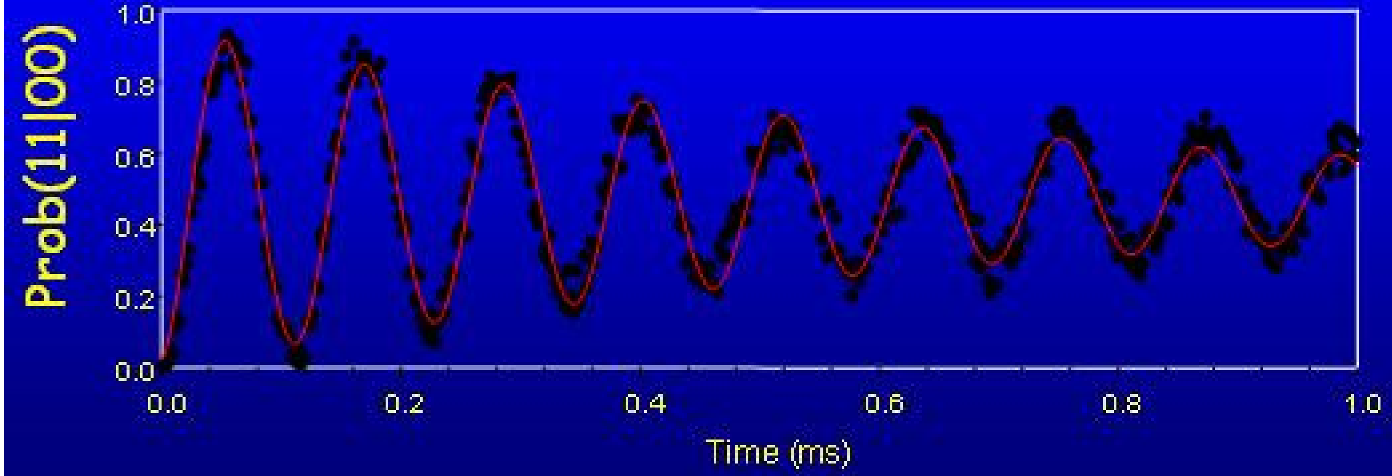


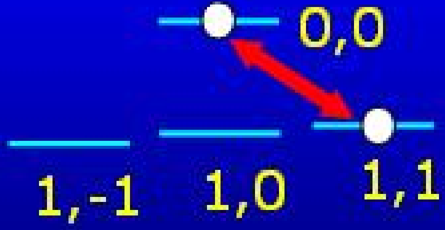
$g_\mu \sim 10\text{–}100\text{kHz}$

sweep t

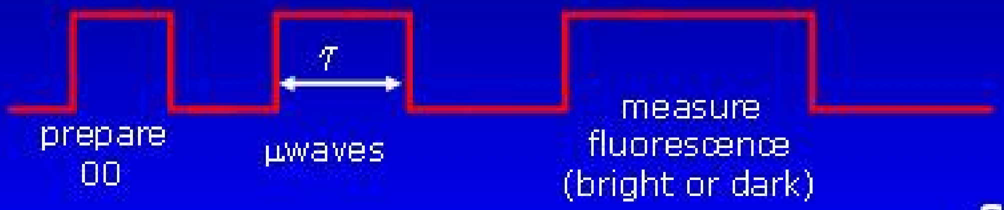




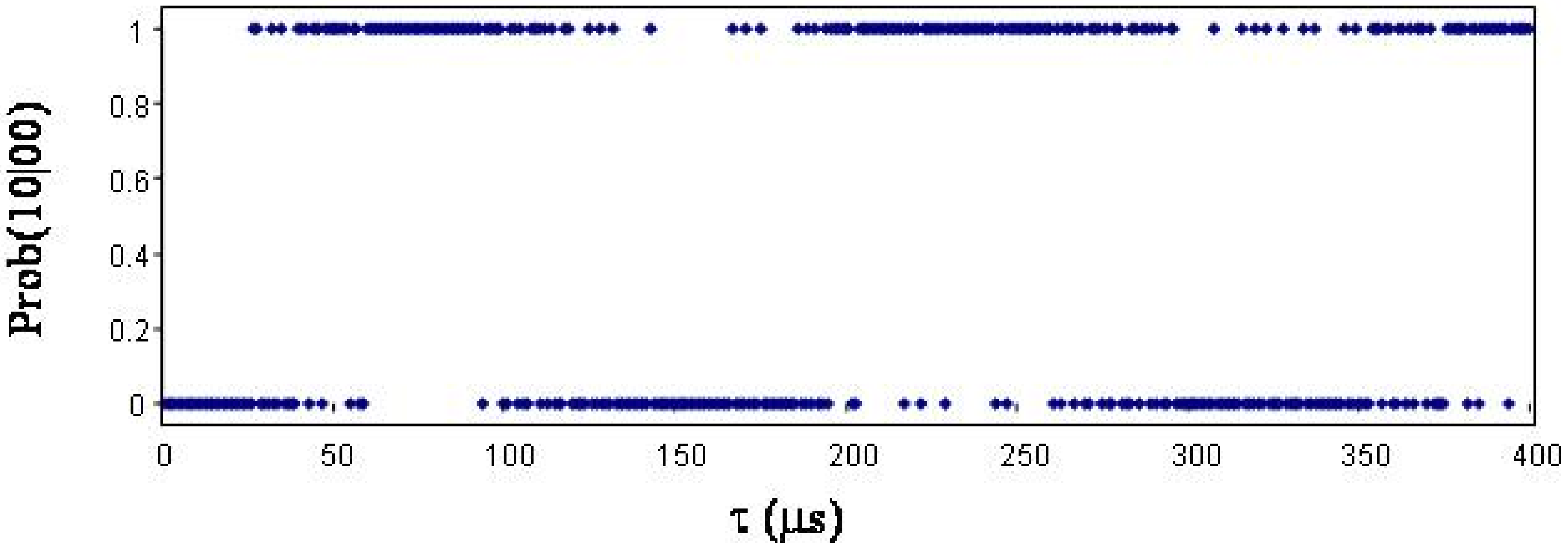




"Single shot" Rabi Flopping

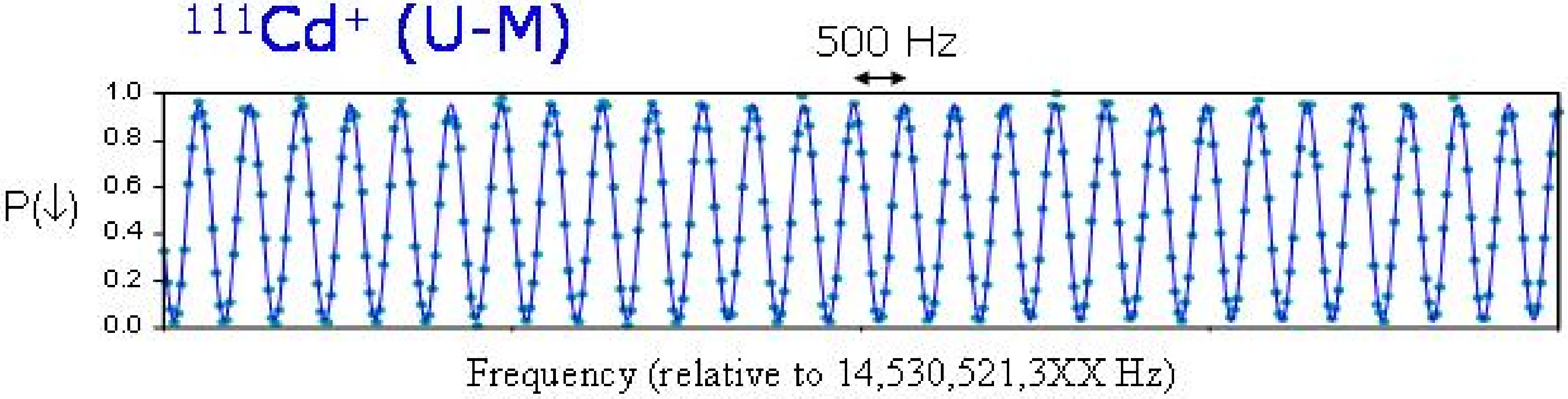


sweep τ

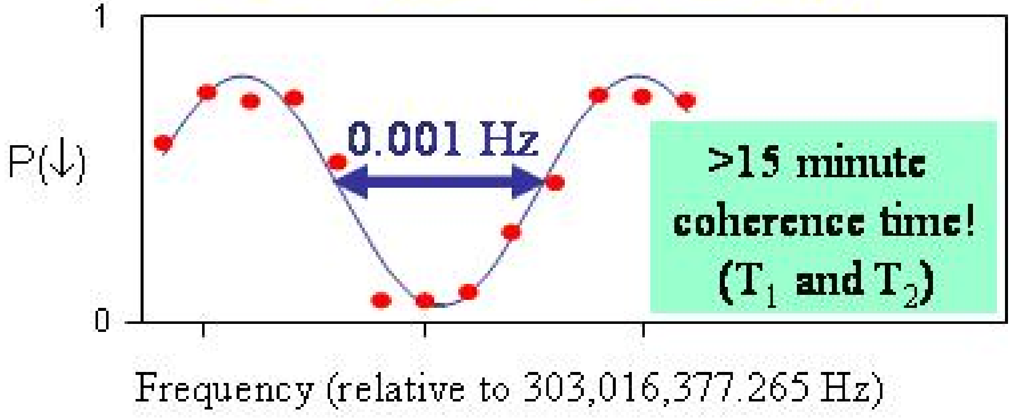


Ramsey interferometry with a trapped ion HF qubit: atomic clockwork

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



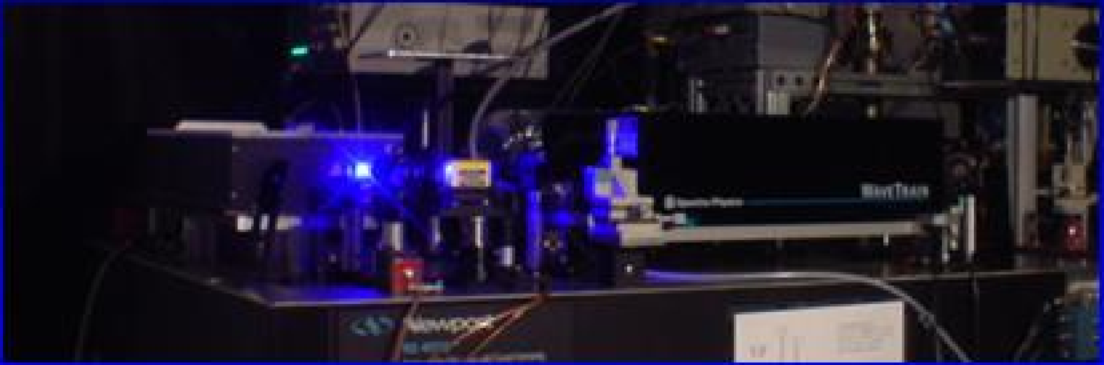
^{9}Be^{+} (NIST-Boulder)

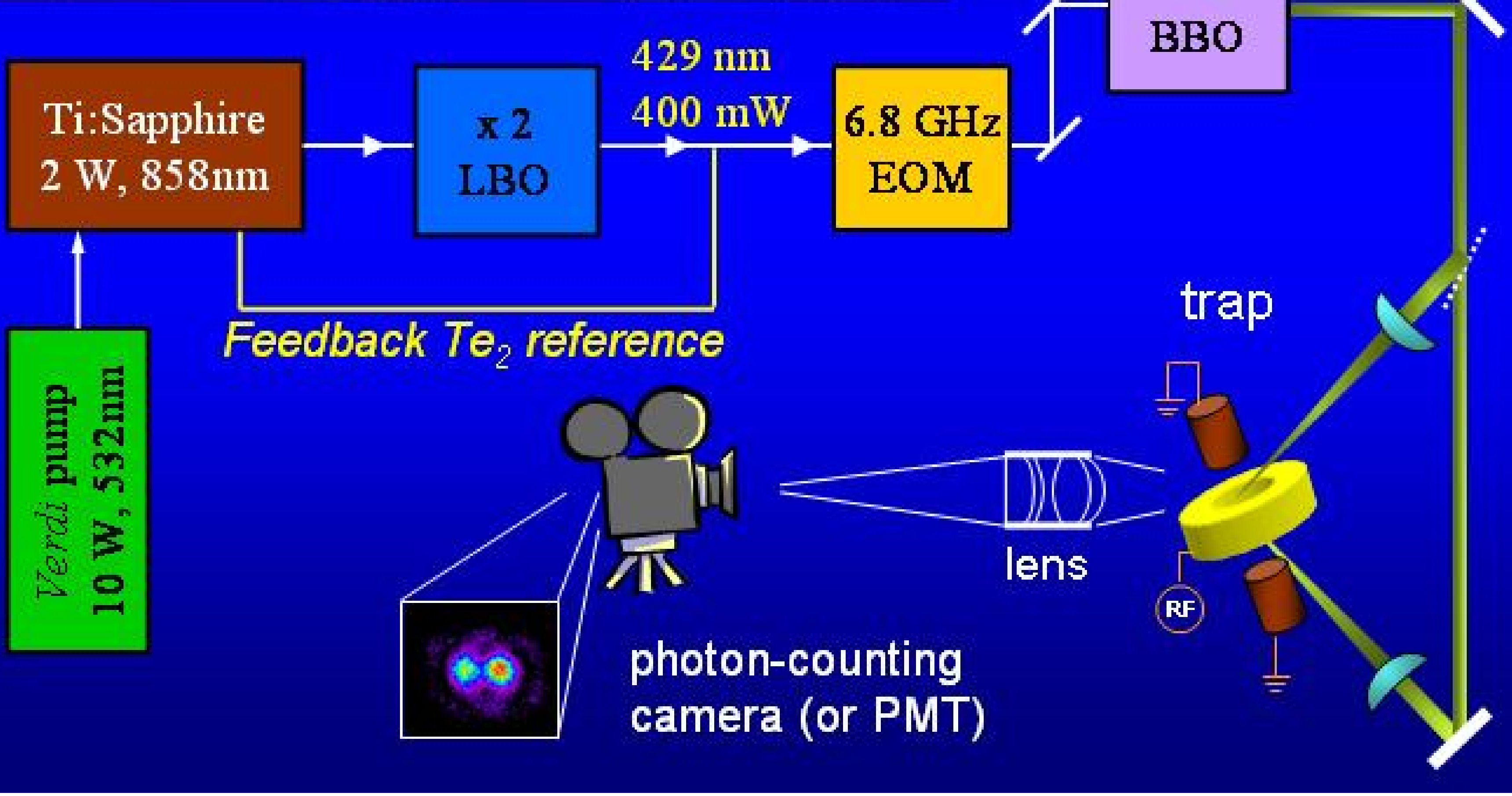


>15 minute coherence time! (T_1 and T_2)

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

Basic setup: seeing trapped ions





Ti:Sapphire
2 W, 858nm

x 2
LBO

429 nm
400 mW

6.8 GHz
EOM

x 2
BBO

214.5 nm
5 mW

Verdi pump
10 W, 532nm

Feedback Te_2 reference

trap

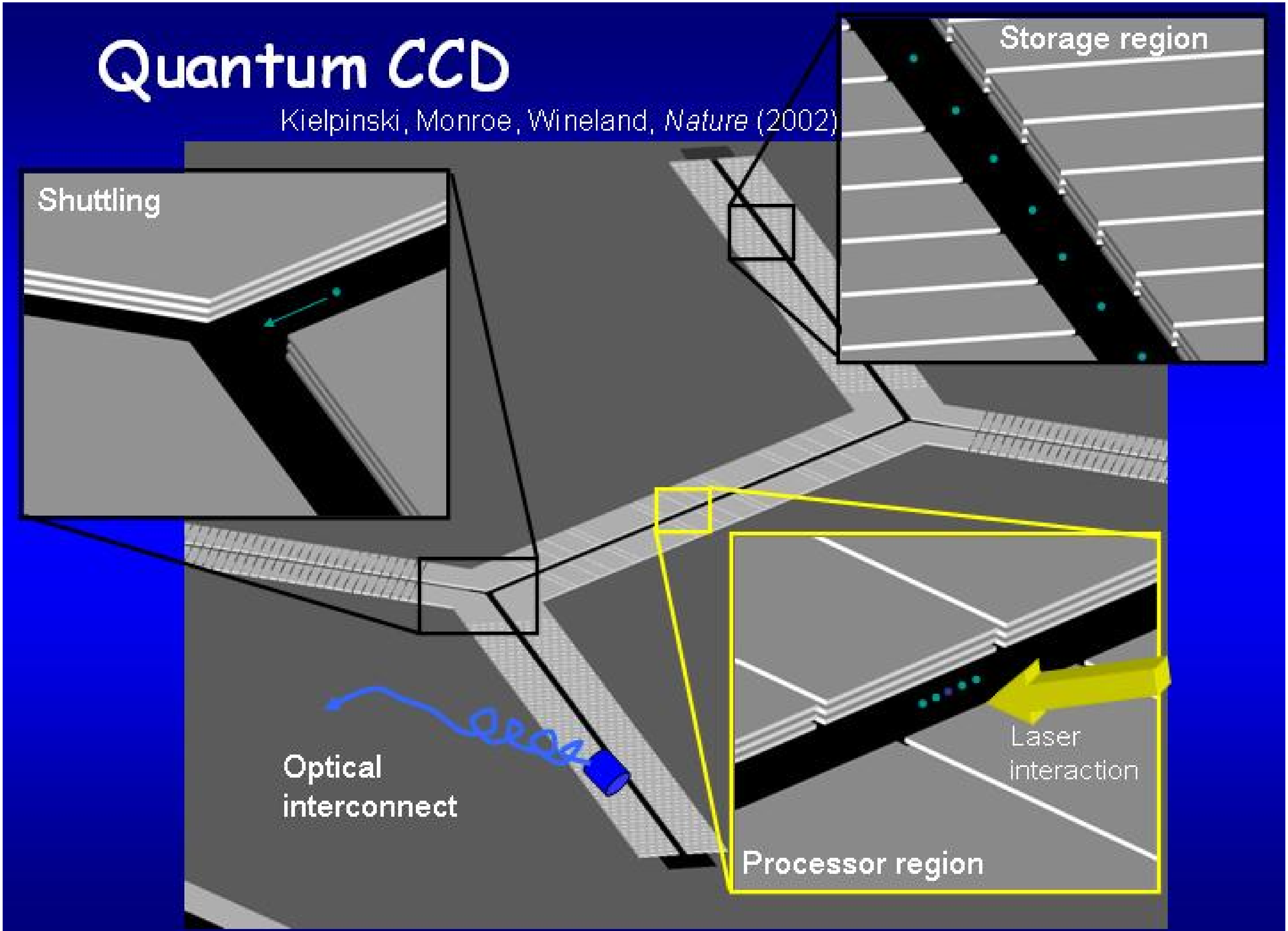
lens

RF

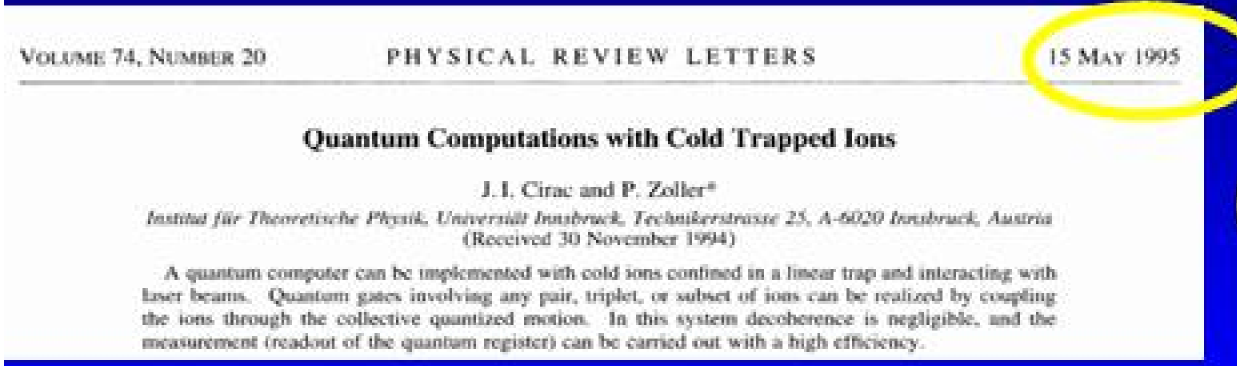
photon-counting
camera (or PMT)

Quantum CCD

Kielpinski, Monroe, Wineland, *Nature* (2002)



Two qubit gates - motional data bus



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Quantum Computations with Cold Trapped Ions

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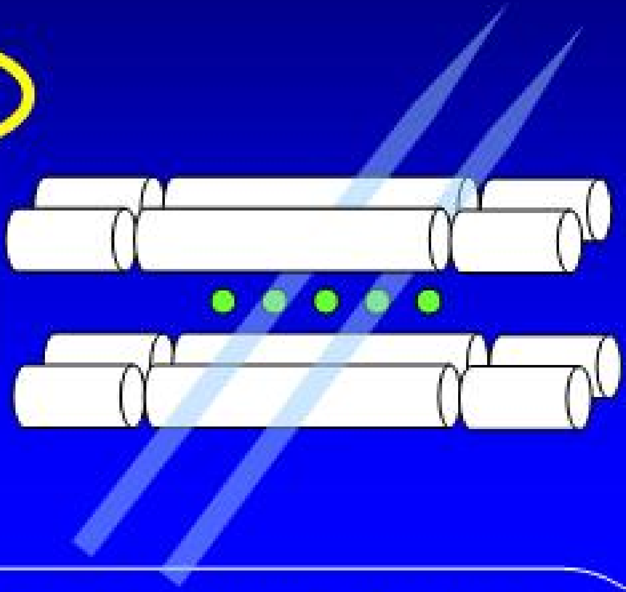
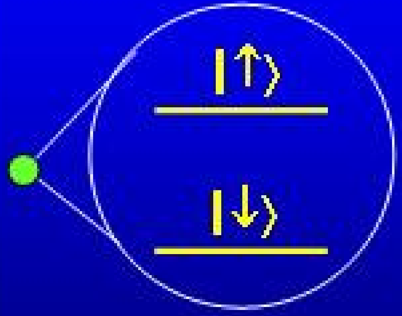
(Received 30 November 1994)

A quantum computer can be implemented with cold ions confined in a linear trap and interacting with laser beams. Quantum gates involving any pair, triplet, or subset of ions can be realized by coupling the ions through the collective quantized motion. In this system decoherence is negligible, and the measurement (readout of the quantum register) can be carried out with a high efficiency.

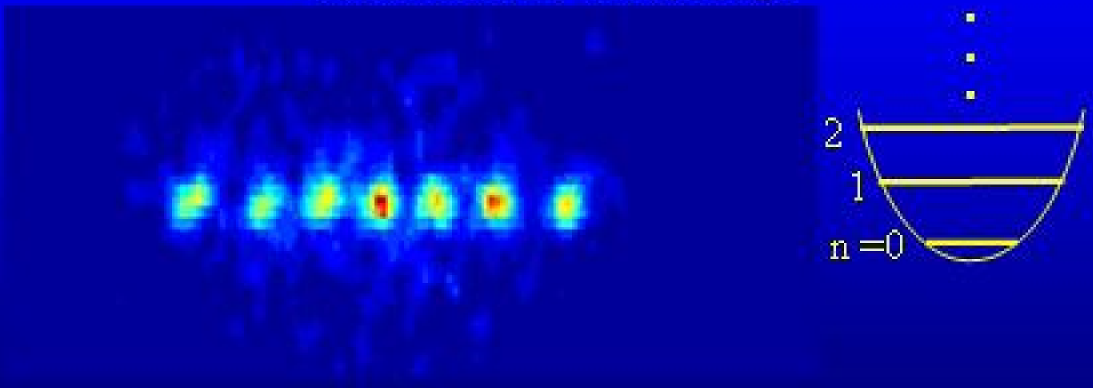


Internal state qubit



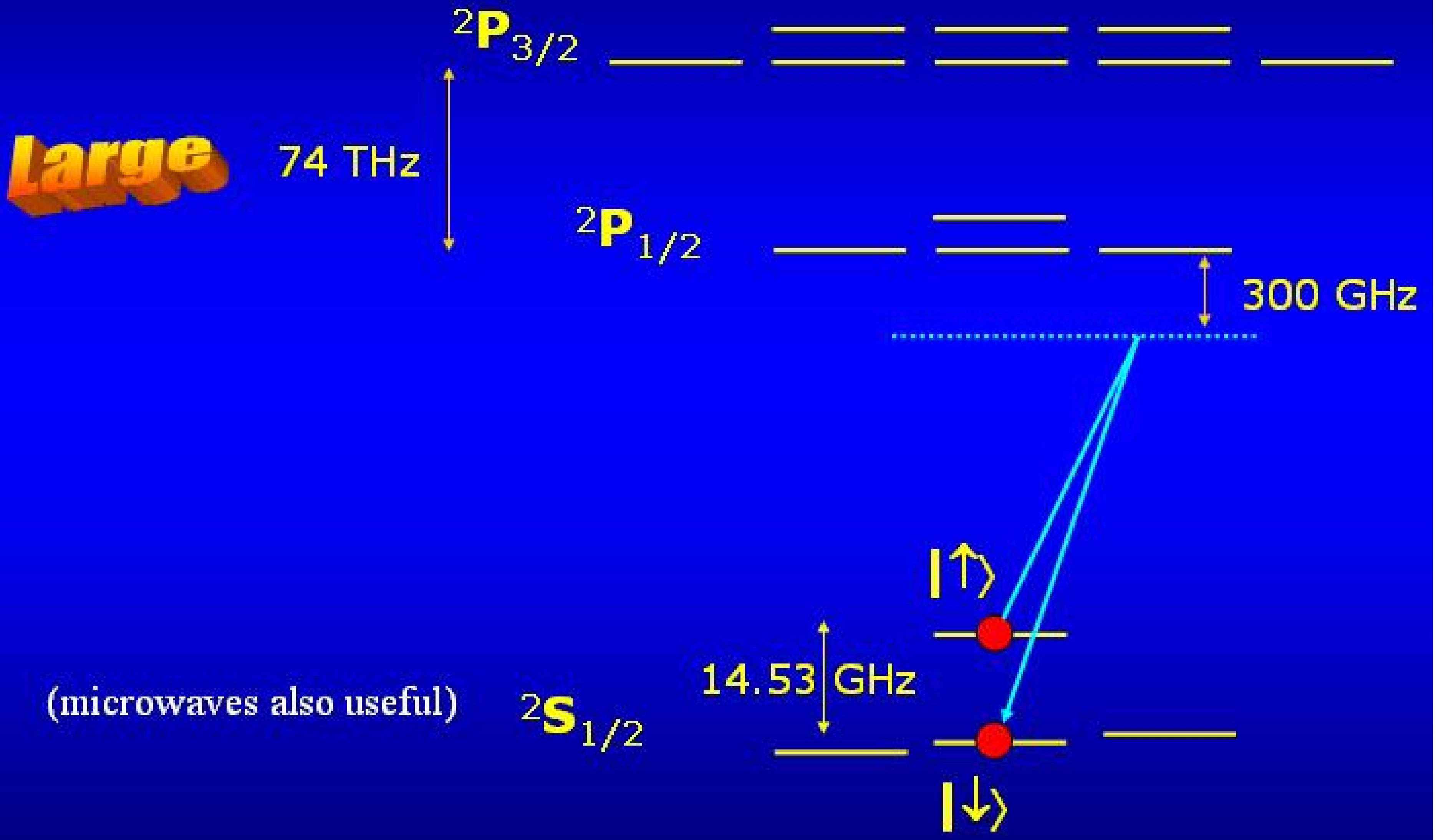
$\otimes$

Collective motion = quantum data bus for information transfer and ion-ion coupling.



$^{40}Ca^+$ (R. Blatt, Univ. Innsbruck)

Qubit operations: optical Raman transitions



$^2P_{3/2}$

Large

74 THz

$^2P_{1/2}$

300 GHz

$|\uparrow\rangle$

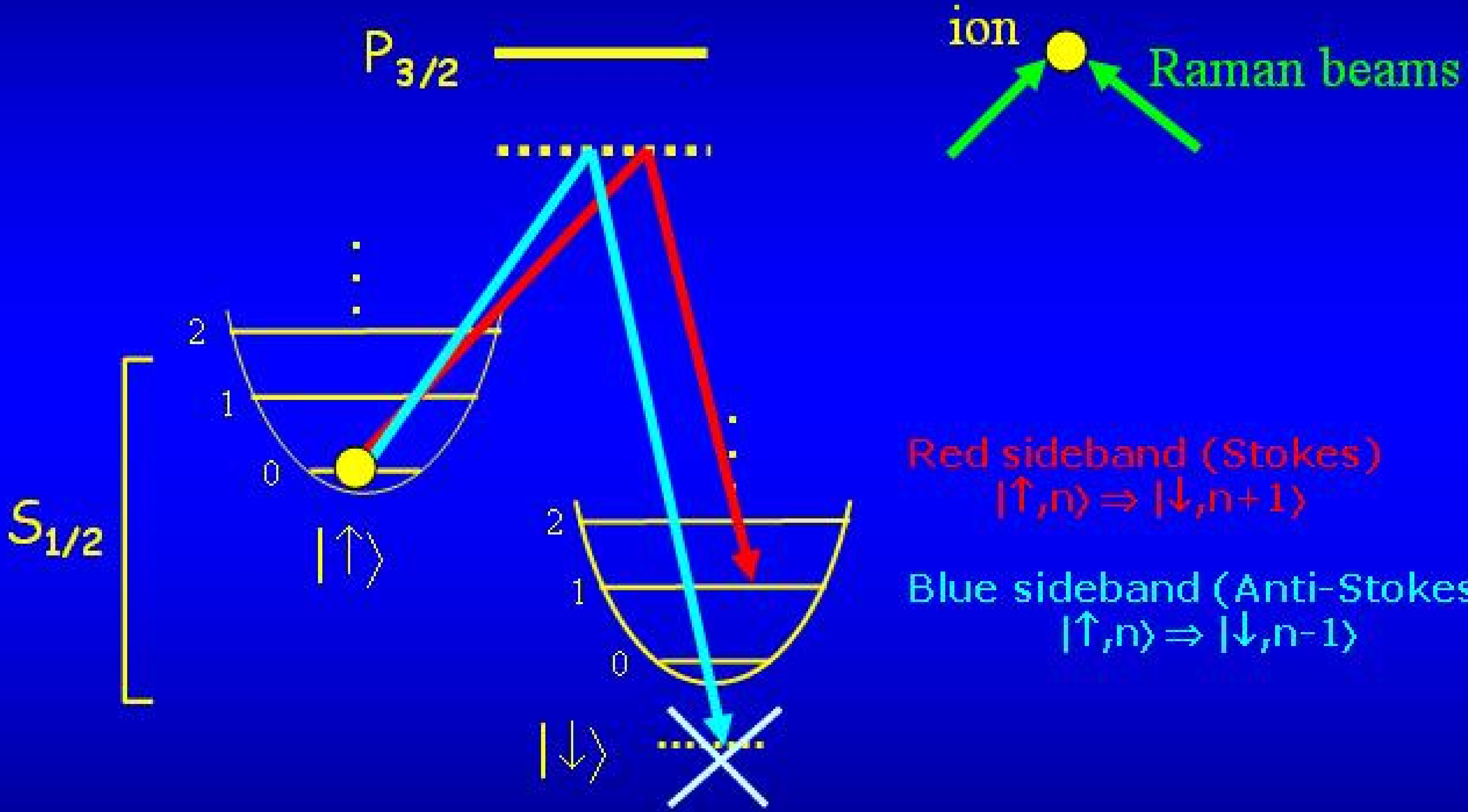
14.53 GHz

(microwaves also useful)

$^2S_{1/2}$

$|\downarrow\rangle$

Motion-sensitive Raman transitions: sideband cooling and phonon mediated entanglement



Red sideband (Stokes)
$|\uparrow,n\rangle \Rightarrow |\downarrow,n+1\rangle$

Blue sideband (Anti-Stokes)
$|\uparrow,n\rangle \Rightarrow |\downarrow,n-1\rangle$

Sideband couplings give (anti) Jaynes Cummings Hamiltonian of cavity QED.

Spin-motion coupling

$$H = \hbar\omega_0\hat{\sigma}_z + \underbrace{\frac{\hat{p}^2}{2m} + \frac{1}{2}m\omega^2\hat{x}^2}_{\hbar\omega(a^+a+1/2)} - \hat{\mu}\cdot E(\hat{x})$$

frequency of applied radiation

$$-\mu_0\cdot\frac{E_0}{2}(\hat{\sigma}_+ + \hat{\sigma}_-)(e^{ik\hat{x}-i\omega_L t} + e^{-ik\hat{x}+i\omega_L t})$$

interaction picture + rotating wave approximation

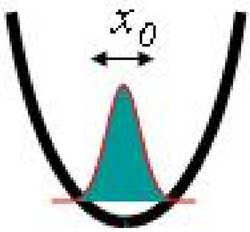
$$\boxed{H = \hbar g(\hat{\sigma}_+ e^{ik\hat{x}-i\delta t} + \hat{\sigma}_- e^{-ik\hat{x}+i\delta t})}$$

$\delta = \omega_L - \omega_0$ = *detuning*

$k = 2\pi/\lambda$ = *wavenumber*

$\hat{x} = x_0(ae^{-i\omega t} + a^+e^{i\omega t})$

$$x_0 = \sqrt{\frac{\hbar}{2m\omega}}$$



$$\boxed{H = \hbar g\left[\hat{\sigma}_+ e^{ikx_0(ae^{-i\omega t}+a^+e^{i\omega t})-i\delta t} + \hat{\sigma}\_e^{-ikx_0(ae^{-i\omega t}+a^+e^{i\omega t})+i\delta t}\right]}$$

stationary terms arise in H at particular values of δ:

$\delta = 0$ $\quad H_0 = \hbar g(\hat{\sigma}_+ + \hat{\sigma}_-) \longrightarrow \langle\downarrow,n|\,H_0\,|\uparrow,n\rangle = \hbar g$

“CARRIER”

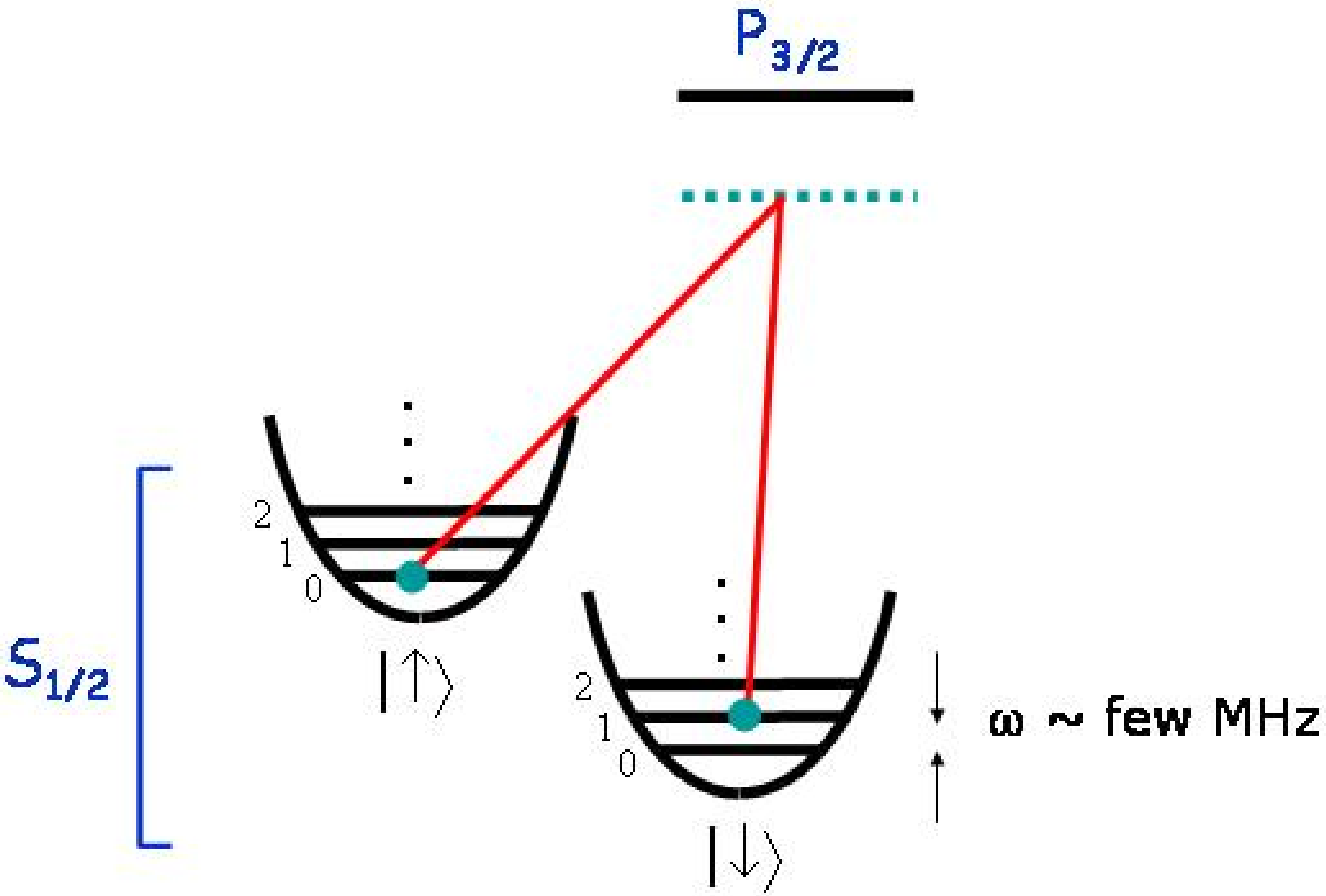
$\delta = +\omega$ $\quad H_{+1} = \hbar g(kx_0)(\hat{\sigma}_+ a^+ + \hat{\sigma}\_a) \longrightarrow \langle\downarrow,n+1|H_{+1}|\uparrow,n\rangle = \hbar g(kx_0)\sqrt{n+1}$

“1ST UPPER SIDEBAND”

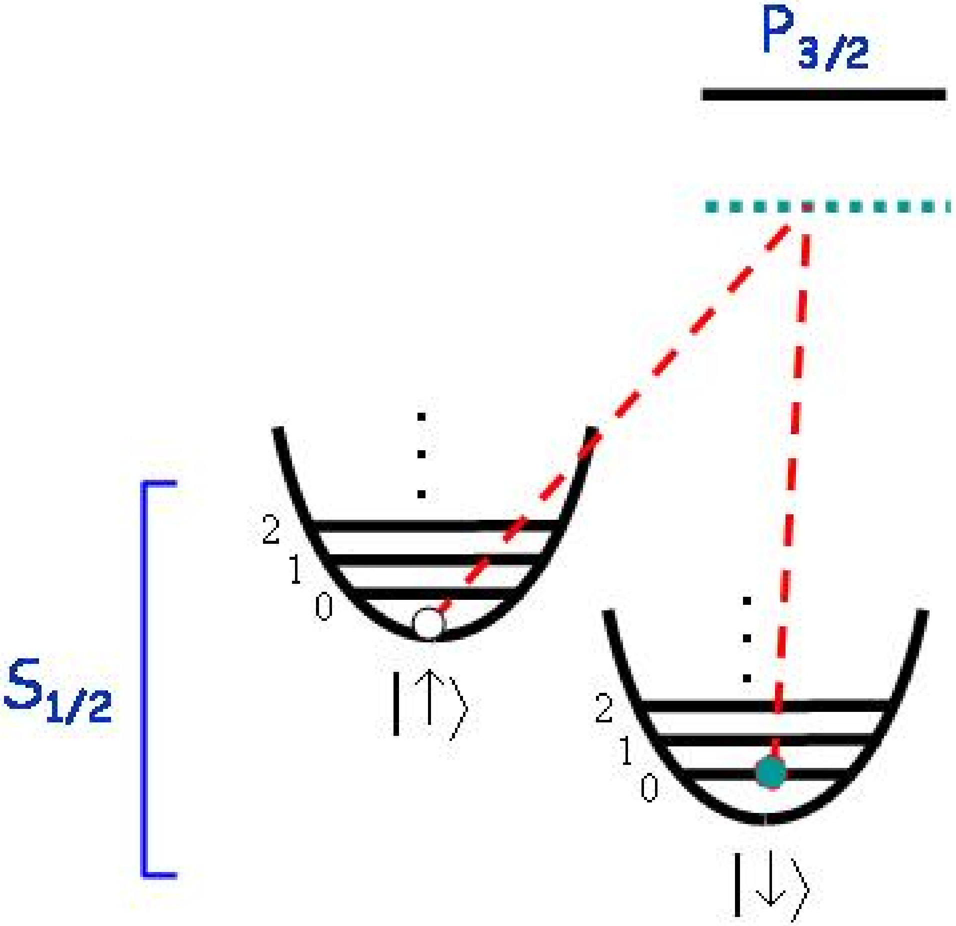
$\delta = -\omega$ $\quad H_{-1} = \hbar g(kx_0)(\hat{\sigma}_+ a + \hat{\sigma}\_a^+) \longrightarrow \langle\downarrow,n-1|H_{-1}|\uparrow,n\rangle = \hbar g(kx_0)\sqrt{n}$

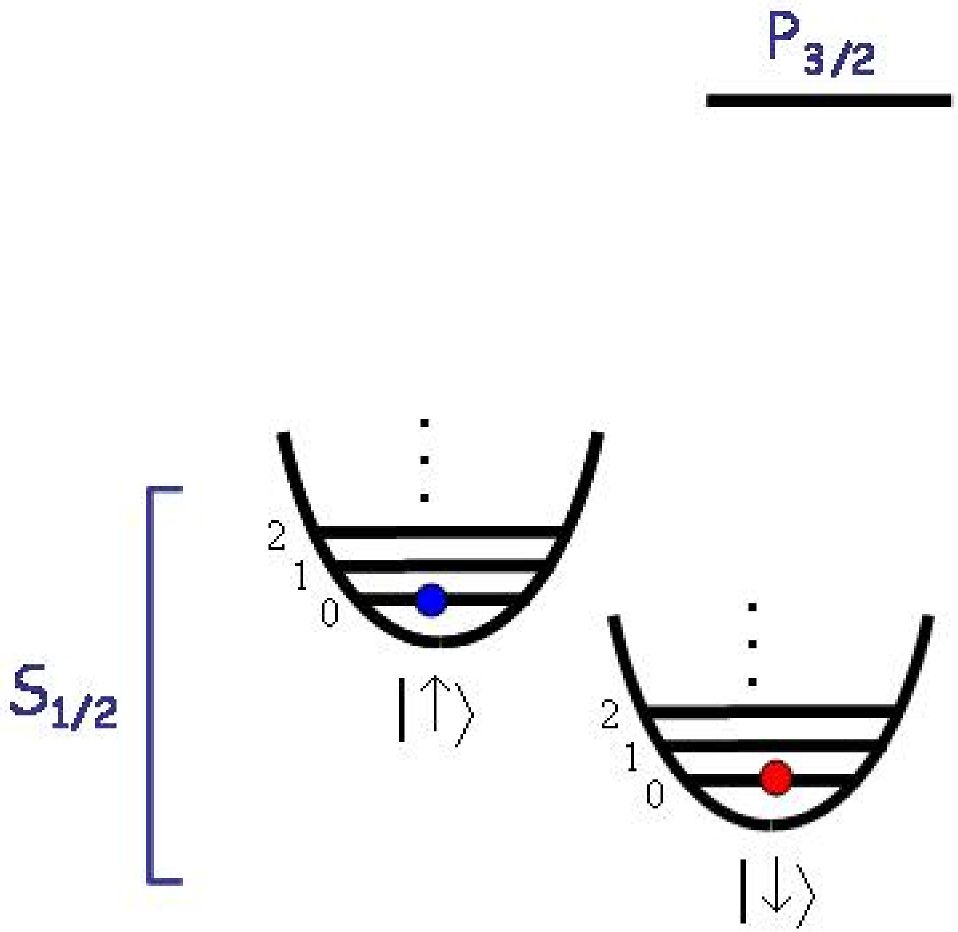
“1ST LOWER SIDEBAND”

excitation on 1st lower ion motional sideband (n=0)

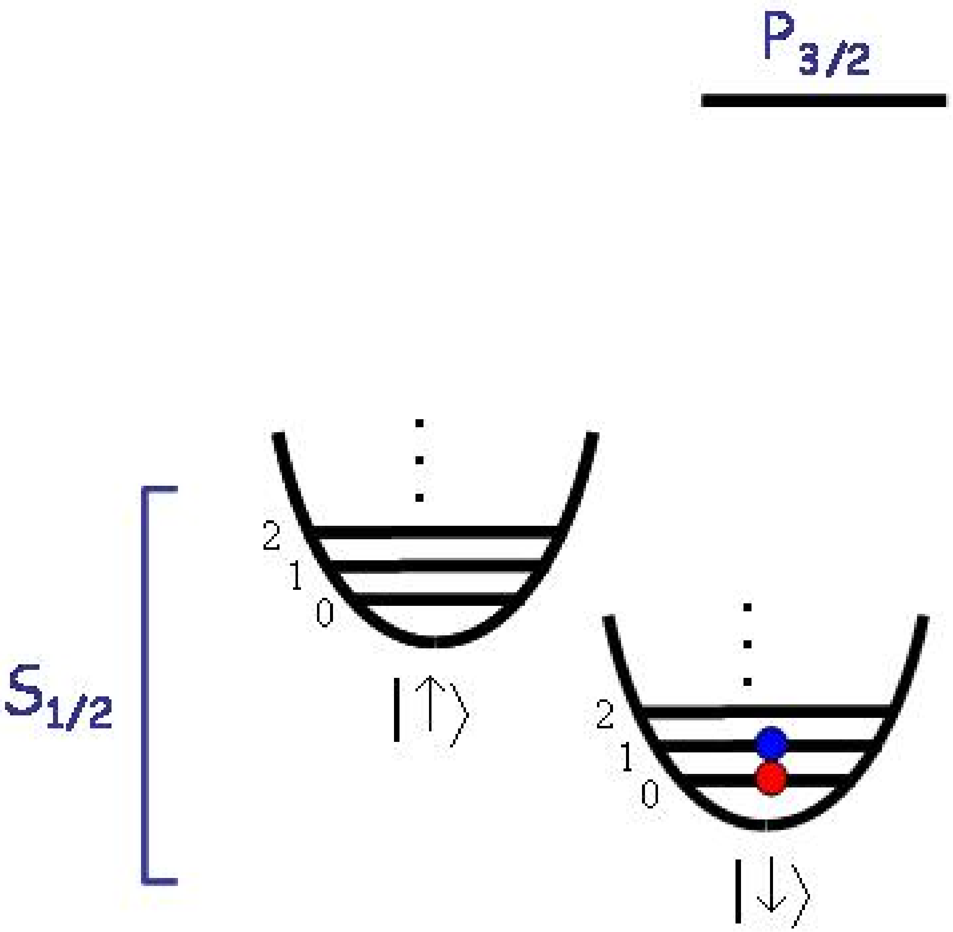


excitation on 1st lower sideband (n=0)





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



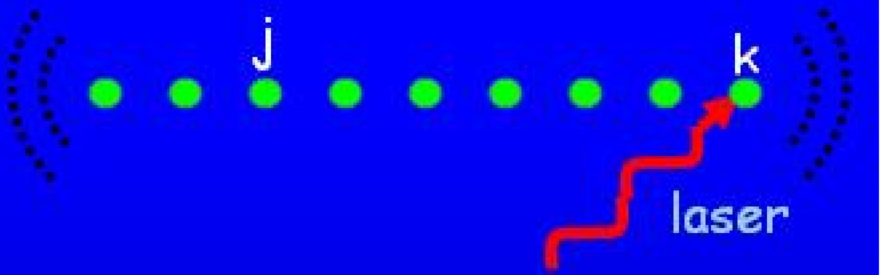
Mapping: $(\alpha|\downarrow\rangle + \beta|\uparrow\rangle)\,|0\rangle_m \rightarrow |\downarrow\rangle \boxed{(\alpha|0\rangle_m + \beta|1\rangle_m)}$

Cirac and Zoller Entangling Gate

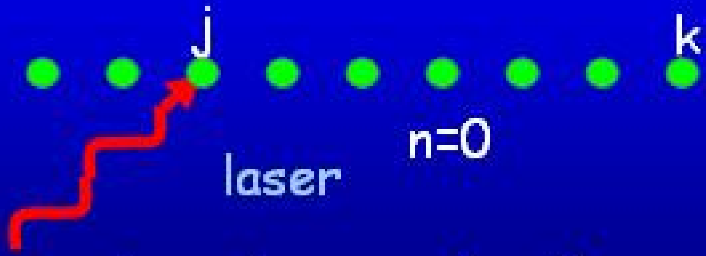
Step 1 Laser cool collective motion to rest

Step 2 Map jth qubit to collective motion

Step 3 Flip kth qubit depending upon motion



Step 4 Remap collective motion to jth qubit (reverse of Step 2)



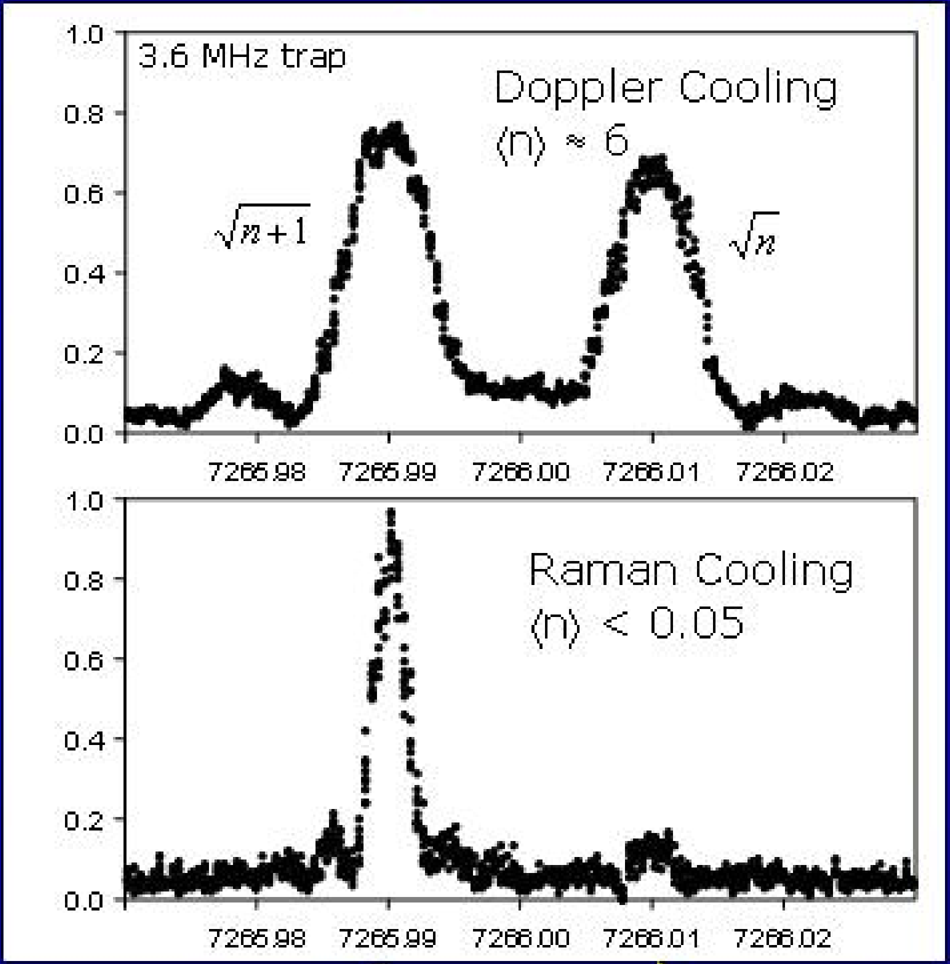
Net result: $[|\downarrow\rangle_j + |\uparrow\rangle_j]\,|\downarrow\rangle_k \rightarrow |\downarrow\rangle_j\,|\downarrow\rangle_k + |\uparrow\rangle_j|\uparrow\rangle_k$

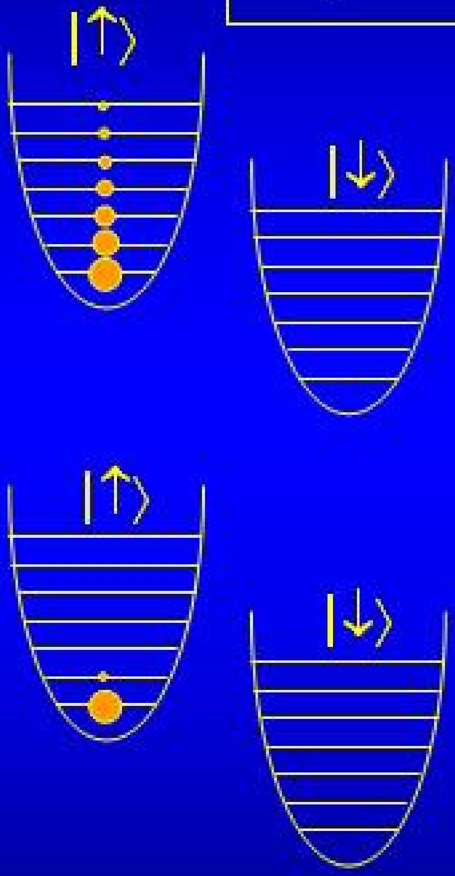
Cirac and Zoller, Phys. Rev. Lett. 74, 4091 (1995) expt: C. Monroe et. al. Phys. Rev. Lett. 75, 4714 (1995), R.Blatt et al, PRA 52, 518, 1995)

Initializing phonon databus: laser-cooling Cd^+ to n=0

Thermometry:

$$\frac{I_{AS}}{I_S} = \frac{\langle n \rangle}{1+\langle n \rangle}$$



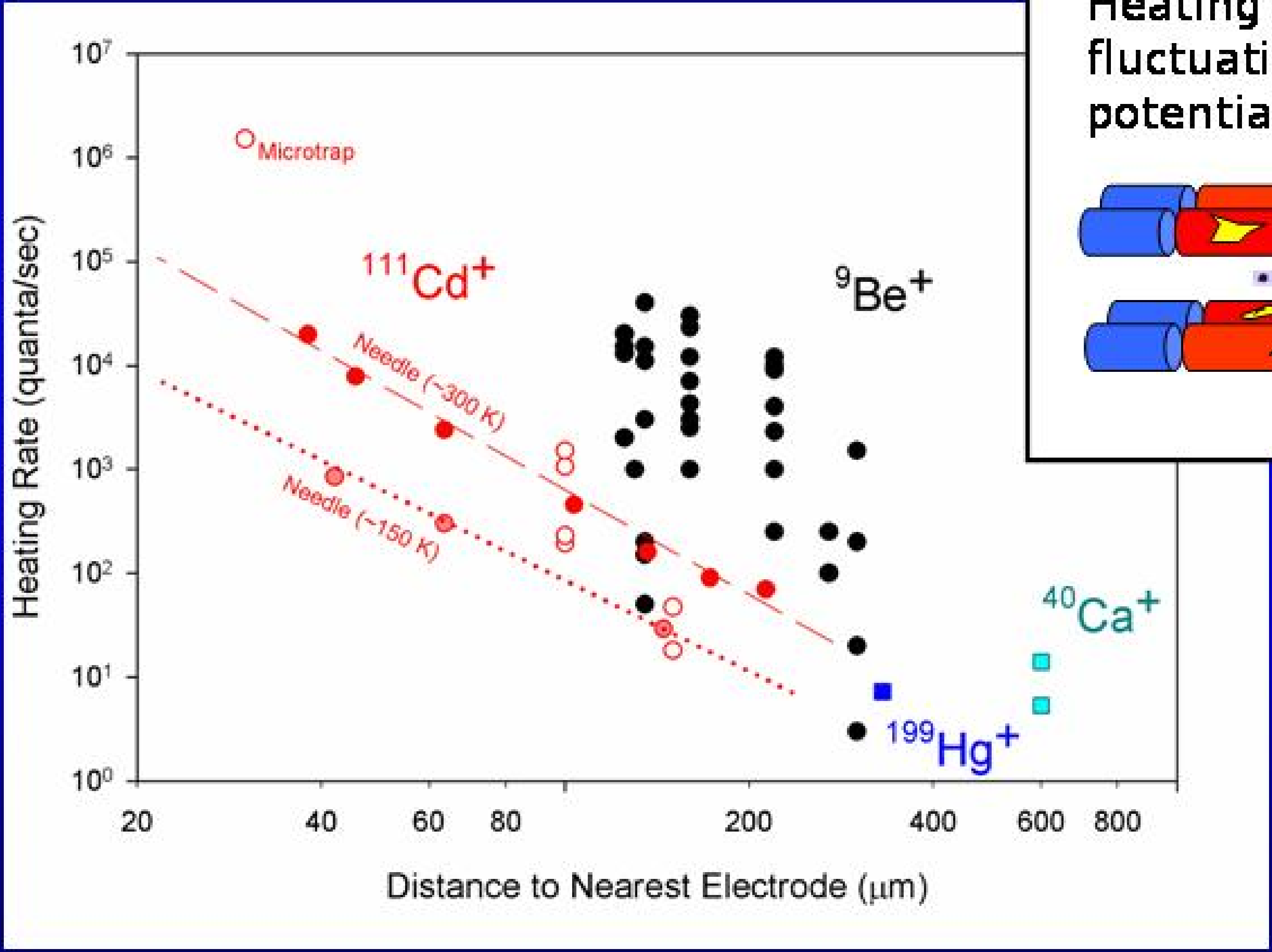


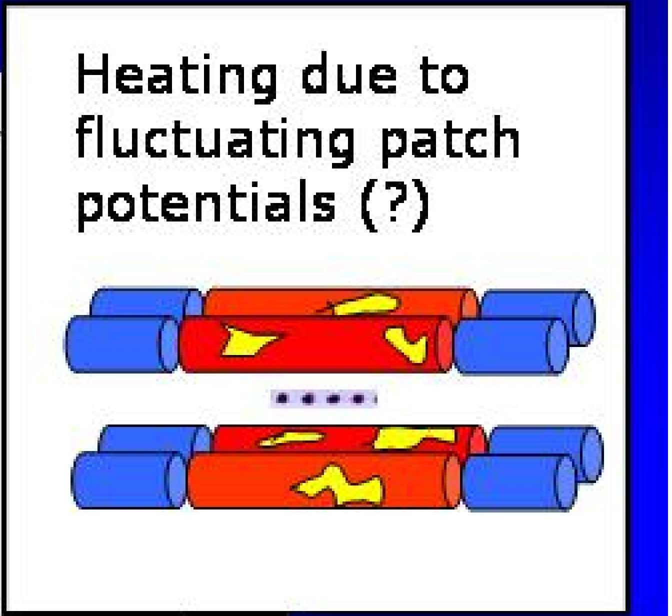
Stokes
$|\uparrow, n\rangle \Rightarrow |\downarrow, n+1\rangle$

Anti-Stokes
$|\uparrow, n\rangle \Rightarrow |\downarrow, n-1\rangle$

Δx_{rms} = 3 nm
"Lamb-Dicke" regime

Measurement *history* of motional heating

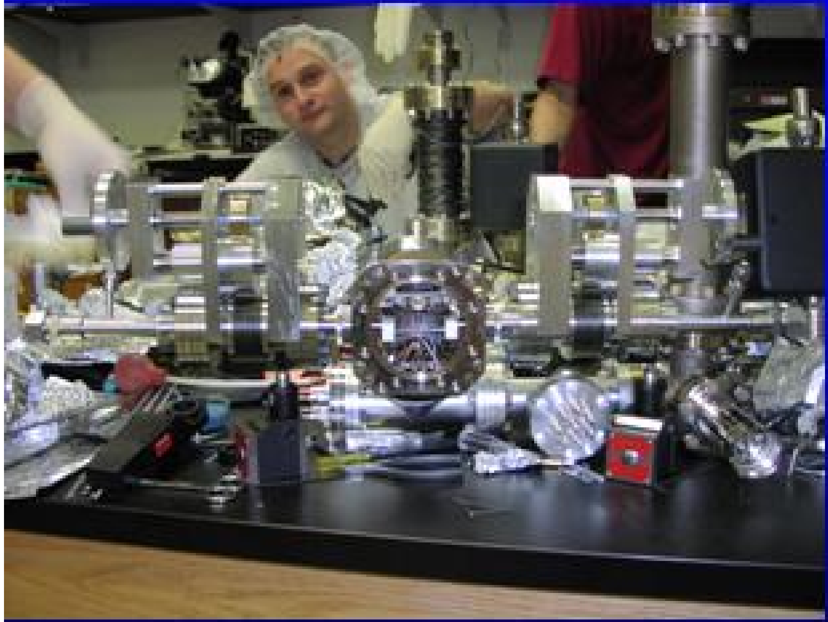


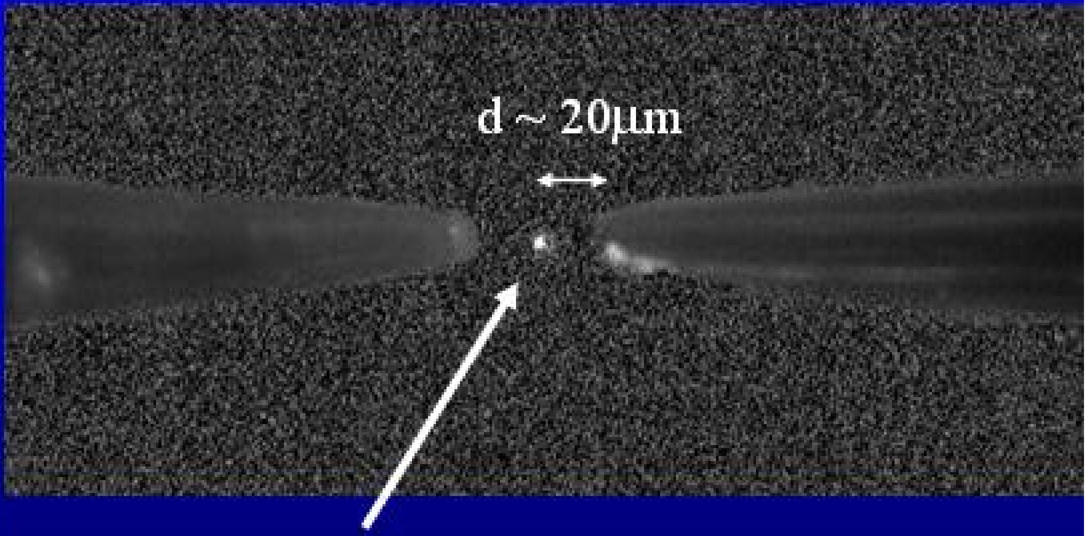

Heating due to fluctuating patch potentials (?)

Systematic study = Variable electrode micron-scale ion trap

Also:

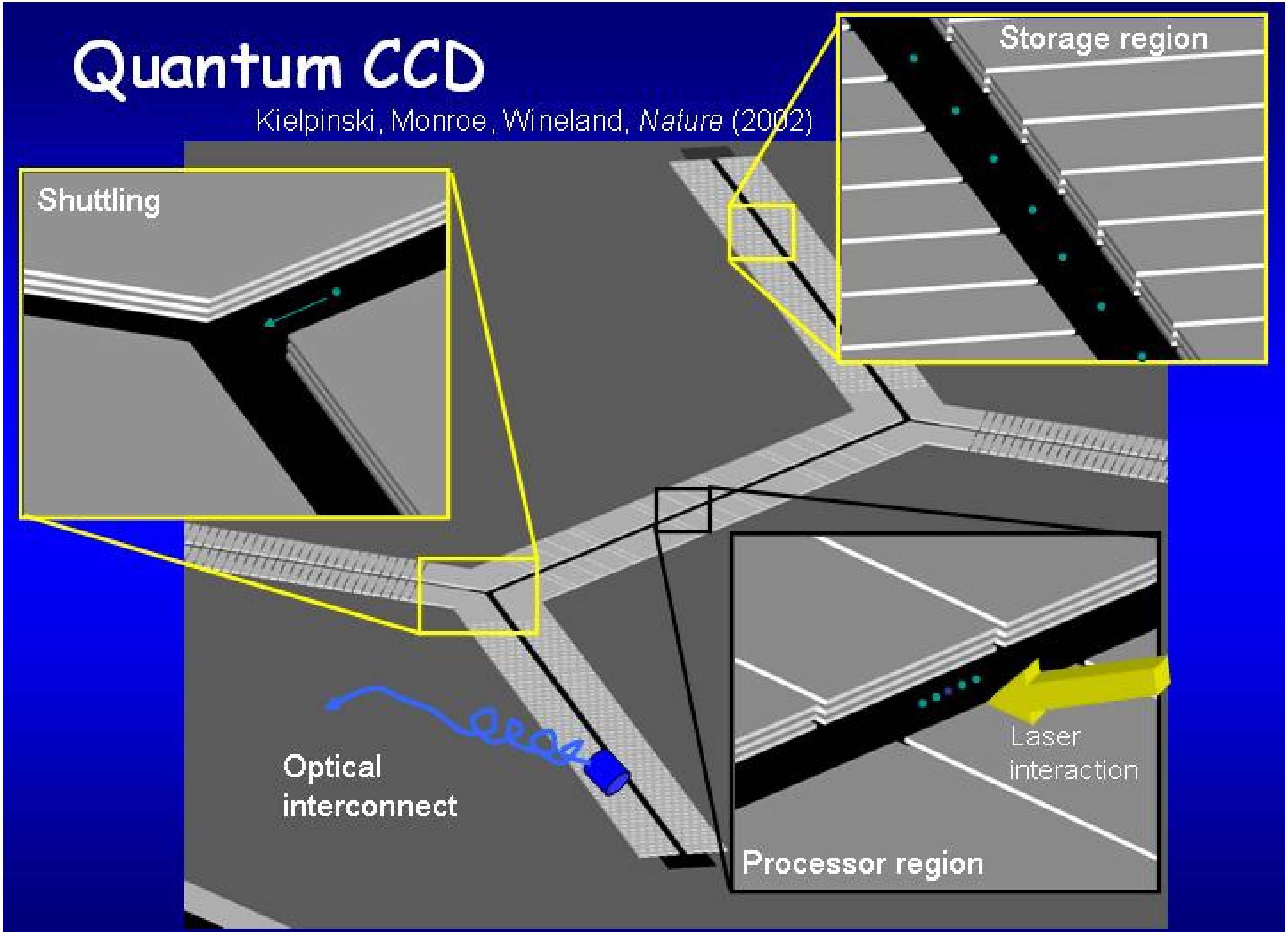
- Investigate limit on “smallness” of ion traps
- Interfacing ion traps with other quantum systems (i.e. CQED)

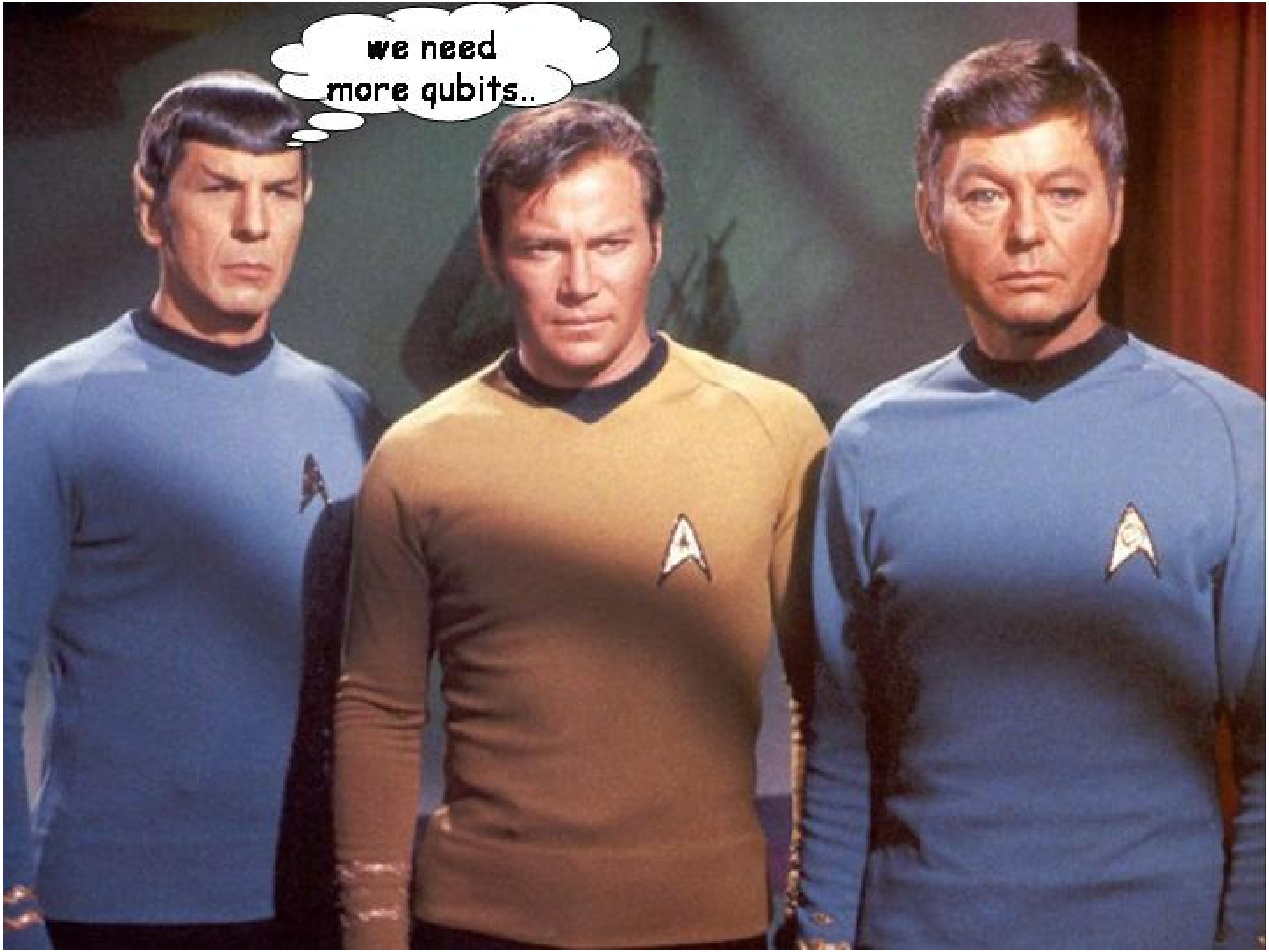


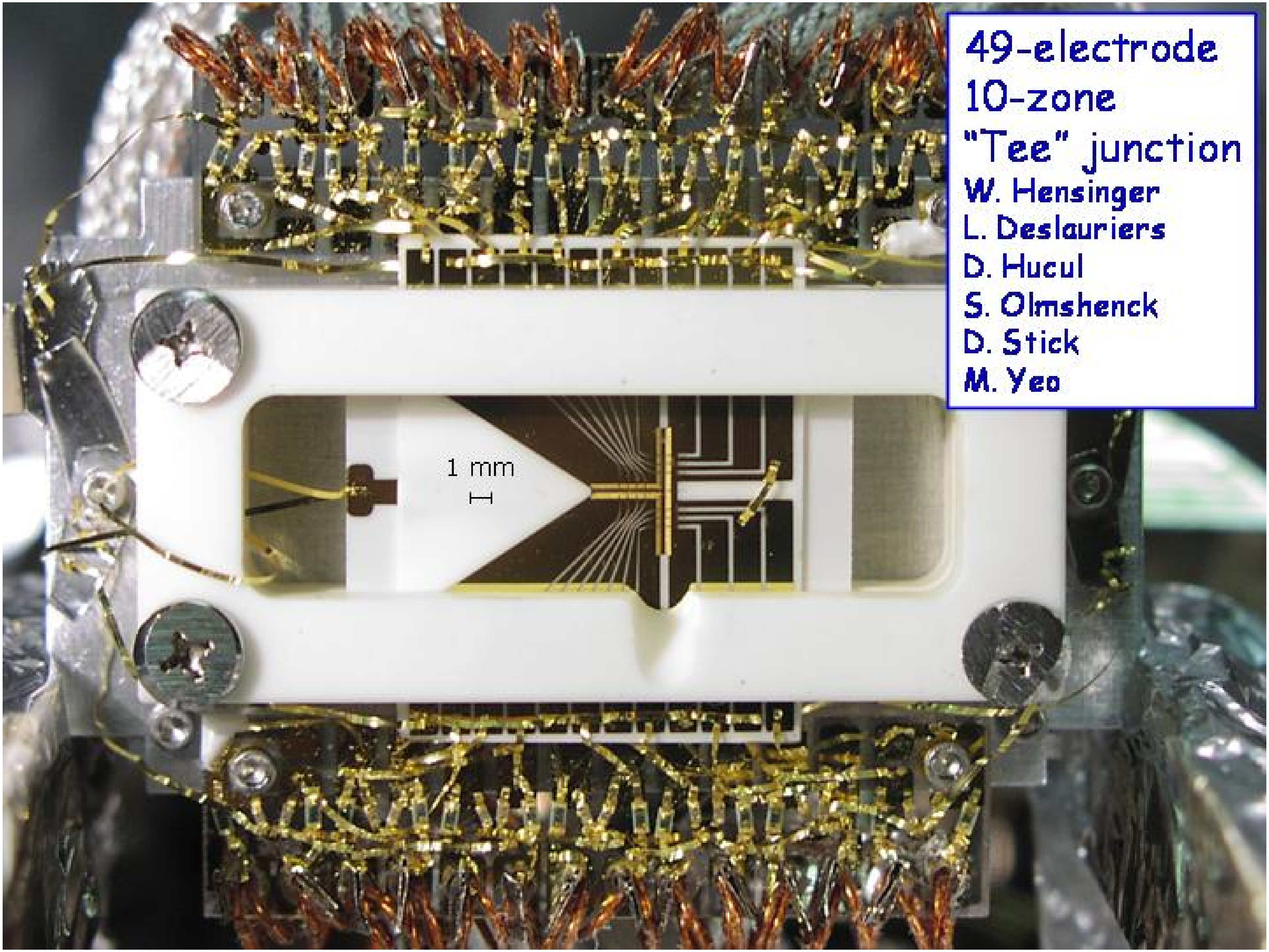


Quantum CCD

Kielpinski, Monroe, Wineland, *Nature* (2002)

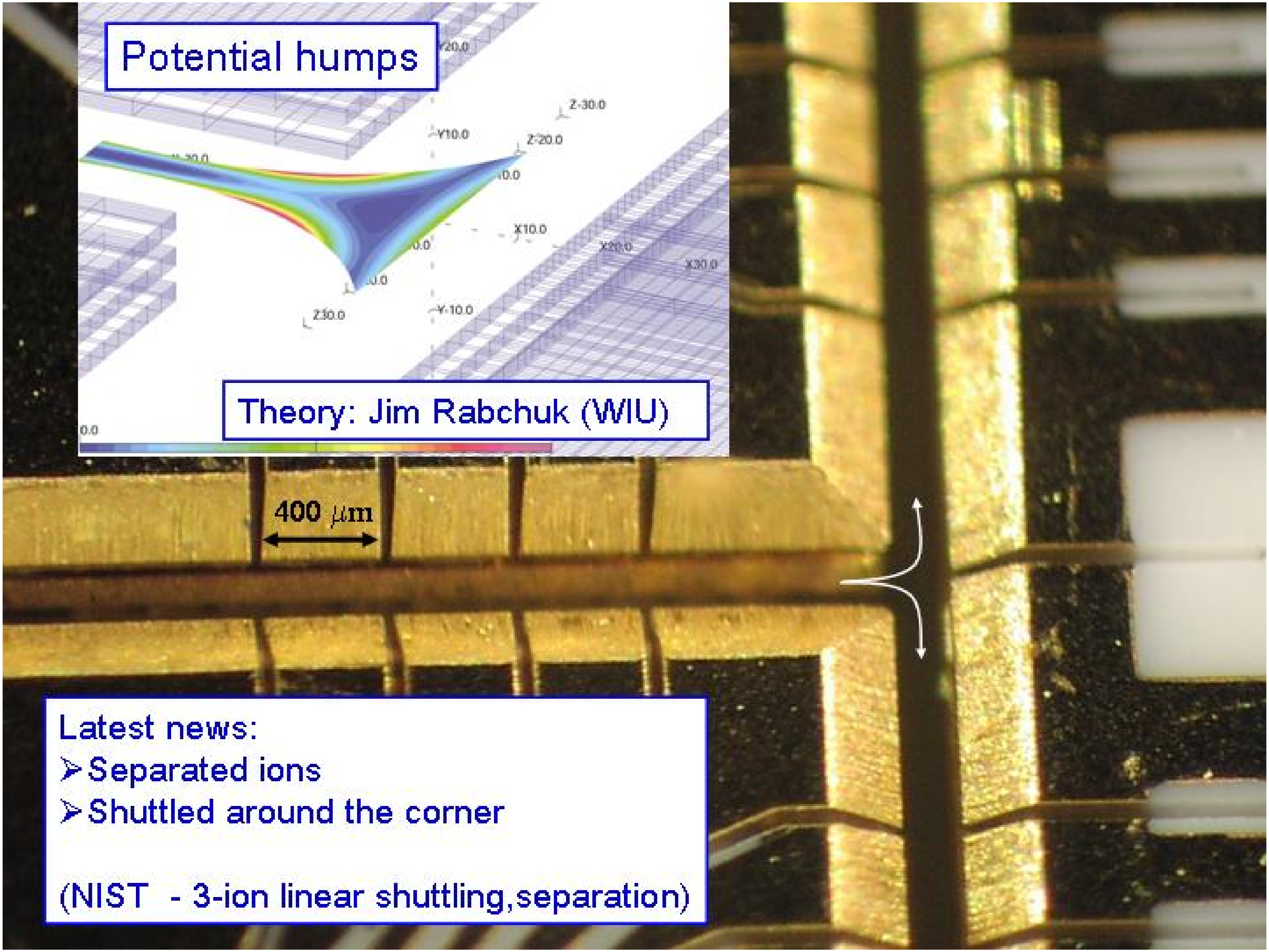



we need more qubits..



49-electrode
10-zone
"Tee" junction

W. Hensinger
L. Deslauriers
D. Hucul
S. Olmshenck
D. Stick
M. Yeo



Potential humps

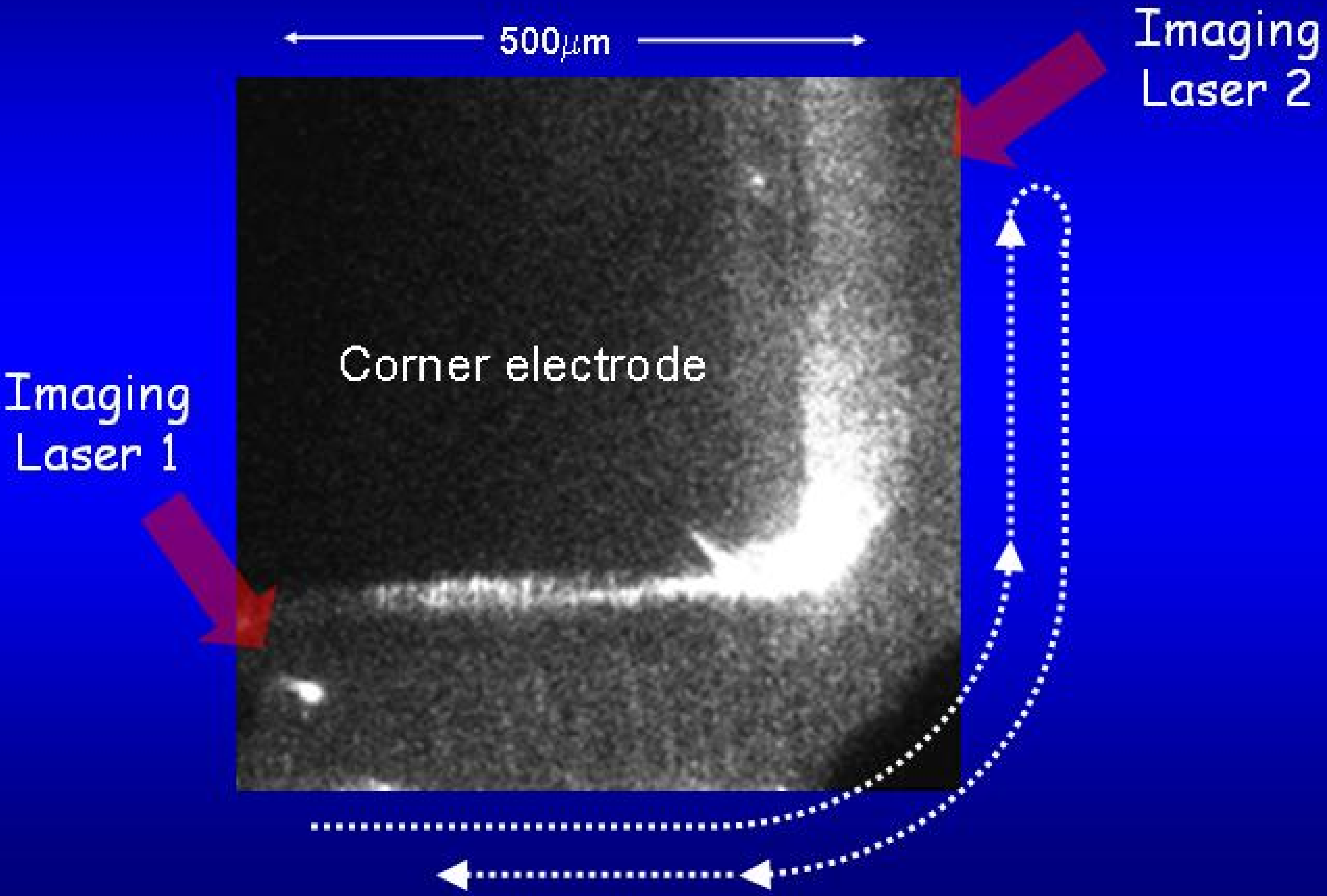
Theory: Jim Rabchuk (WIU)

Latest news:

- Separated ions
- Shuttled around the corner

(NIST - 3-ion linear shuttling,separation)

Making the corner



500μm

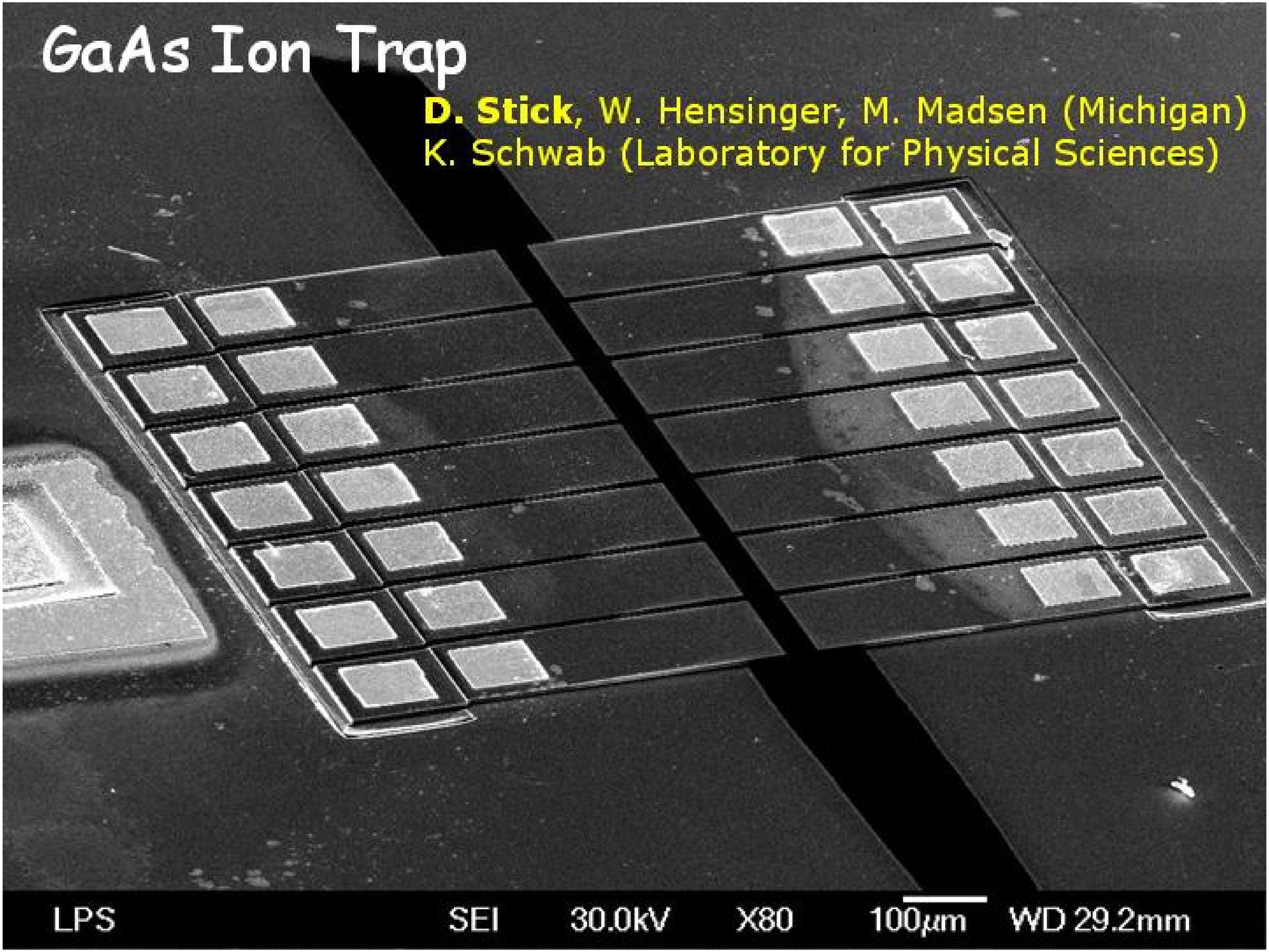
Imaging Laser 2

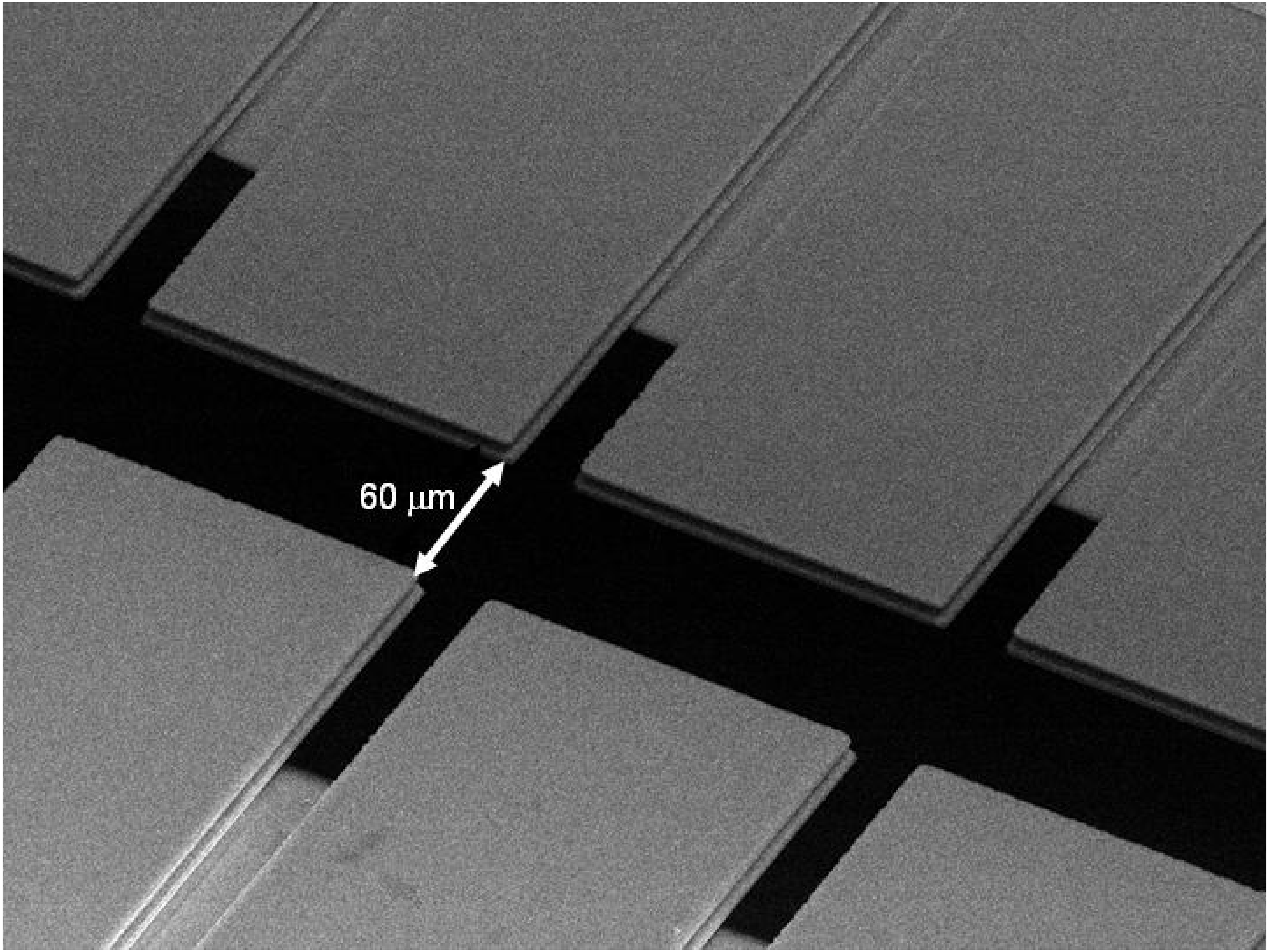
Corner electrode

Imaging Laser 1

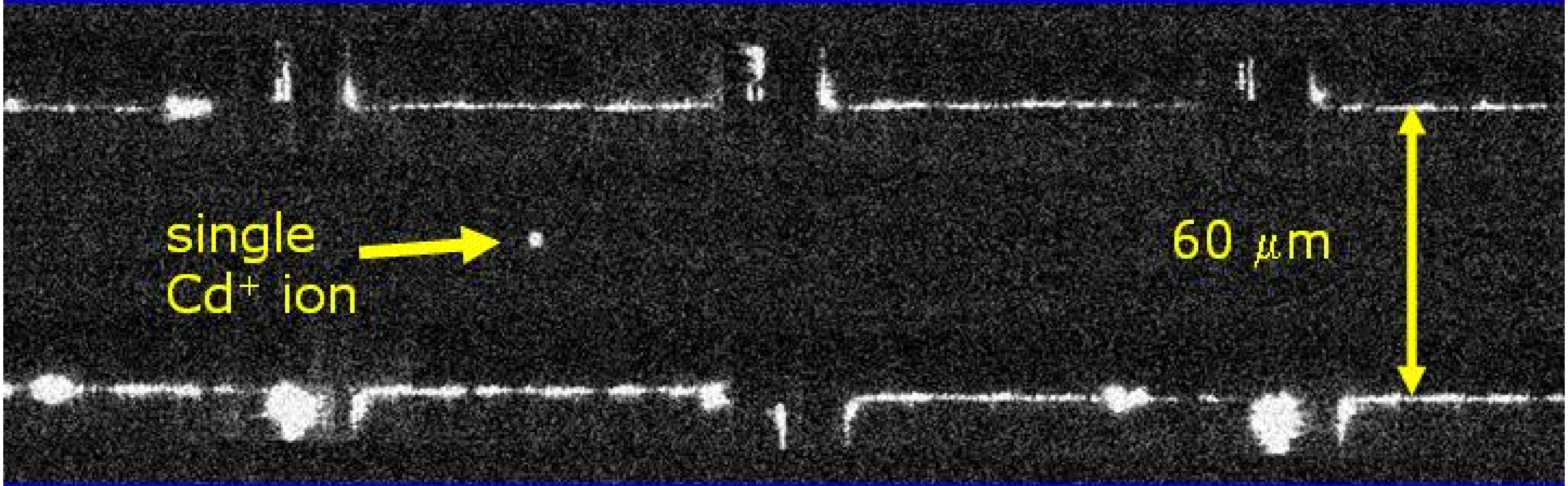
GaAs Ion Trap

D. Stick, W. Hensinger, M. Madsen (Michigan)
K. Schwab (Laboratory for Physical Sciences)




60 μm

Ion Trapped in a Semiconductor Chip

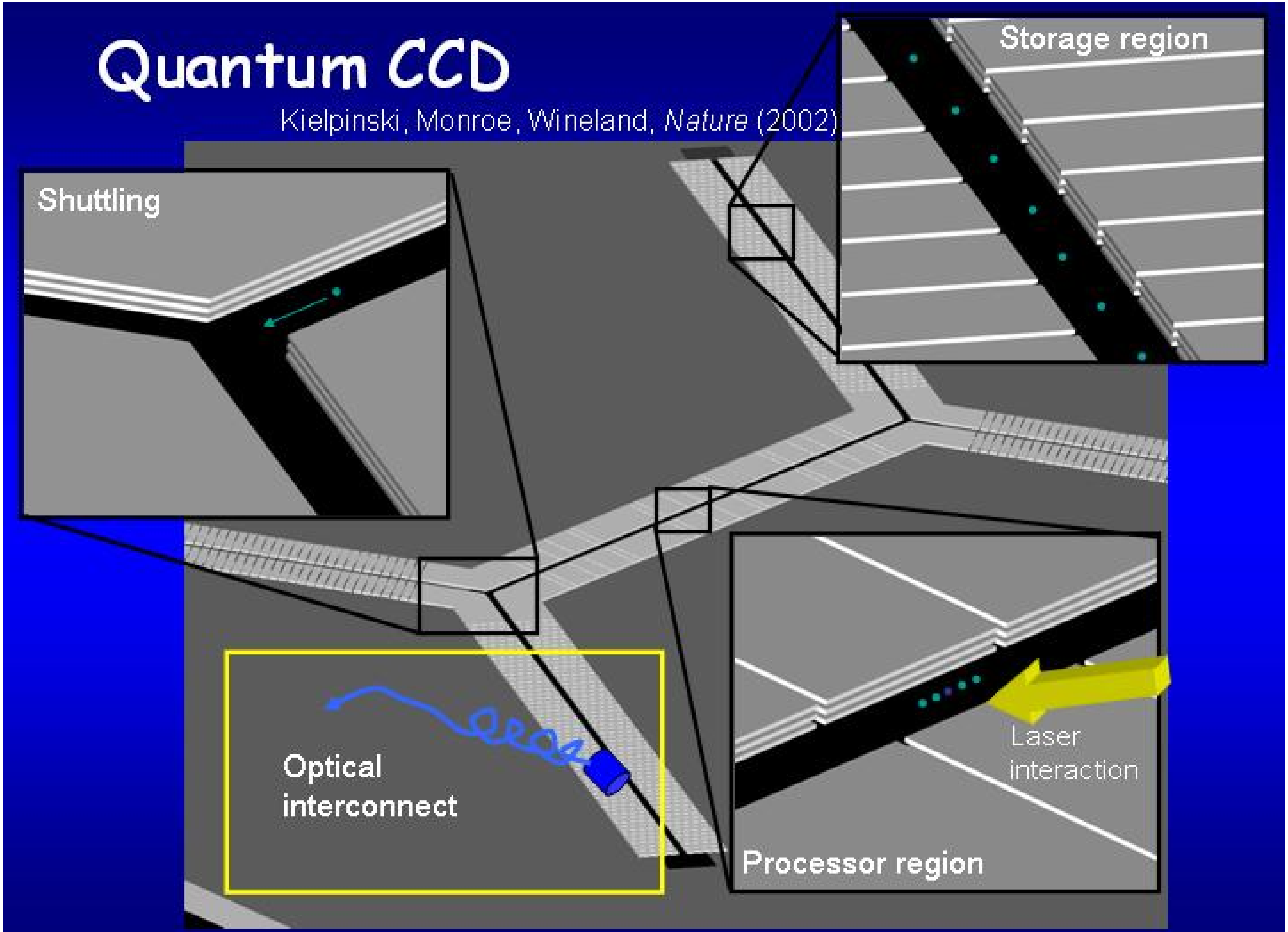


V_{RF} = 8V @ 16 MHz (Q~50)
V_{STATIC} = +1V (endcaps), −0.33V (middles)

Trap frequencies: 1.0 MHz, 3.3 MHz and 4.3 MHz
Trap depth: 0.08 eV
***** Heating rate of 1.0 (± 0.5) × 10^6 quanta/sec *****

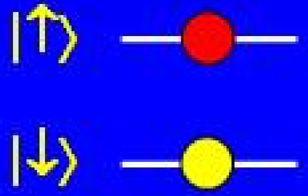
Quantum CCD

Kielpinski, Monroe, Wineland, *Nature* (2002)

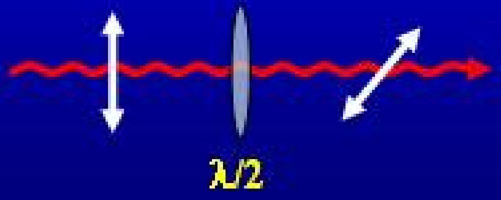


Remote ion-ion entanglement

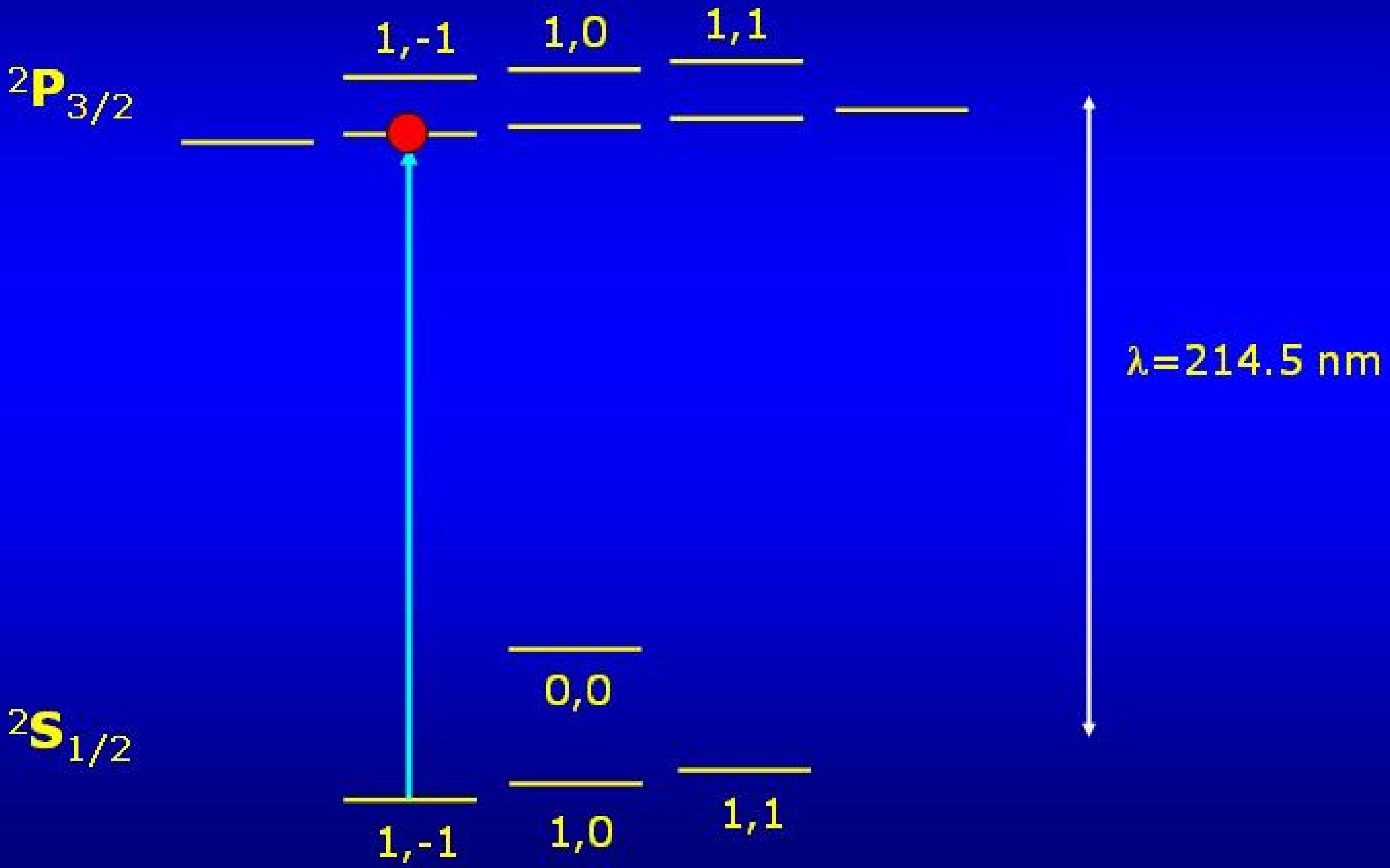
- **Ions**
  - Hyperfine ground states of $^{111}Cd^+$ ($|\uparrow\rangle$ and $|\downarrow\rangle$)
  - Qubit rotations via microwaves or Raman beams
  - Quantum memory



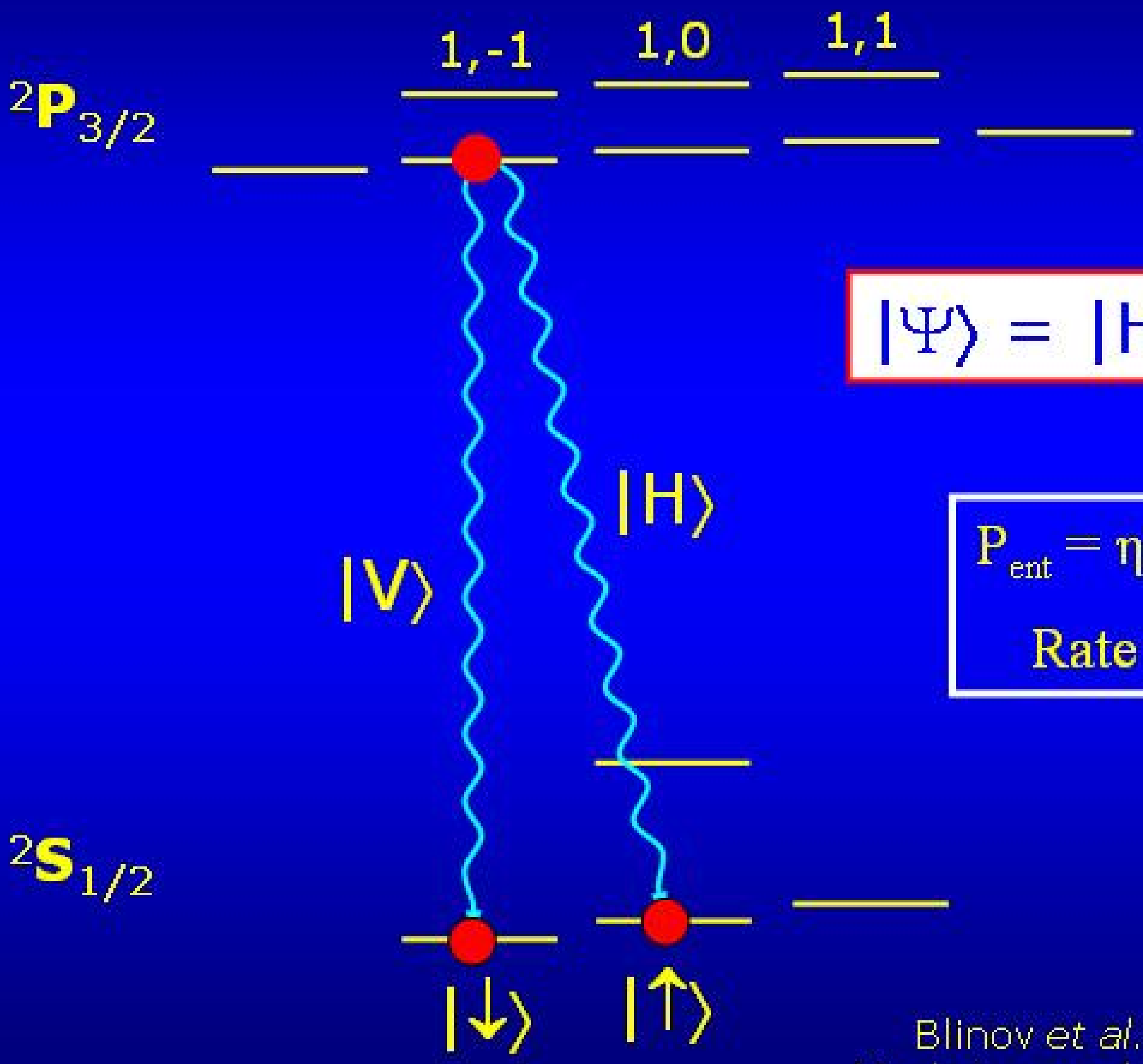
- **Photons**
  - Two orthogonal polarizations ($|H\rangle$ and $|V\rangle$)
  - Qubit rotations with waveplates
  - Quantum communication
    - "Flying Qubit"



Probabilistic Ion-Photon Entanglement



Probabilistic Ion-Photon Entanglement



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

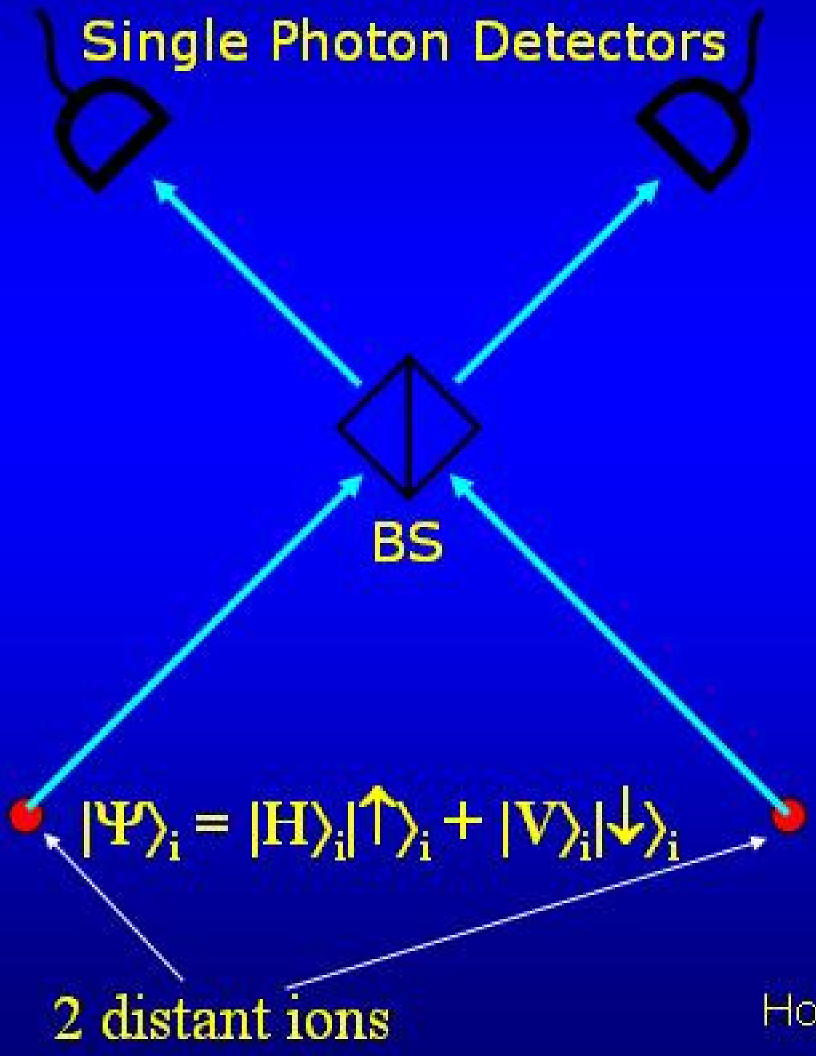
$$P_{ent} = \eta T P_{exc}(\Delta\Omega/4\pi) \sim 10^{-4}$$

$$\text{Rate} = P_{ent}\, R \sim 100\ \text{Hz}$$

Blinov *et al.*, *Nature* **428**, 153 (2004)
Moehring *et al.*, *PRL*, **93**, 090410 (2004)

Probabilistic Remote Ion Entanglement

Using entangled ion-photon pairs



$$|\Psi\rangle = (|H\rangle_1|\uparrow\rangle_1 + |V\rangle_1|\downarrow\rangle_1) \otimes (|H\rangle_2|\uparrow\rangle_2 + |V\rangle_2|\downarrow\rangle_2)$$

When mode matched on the BS, coincident detection only if:

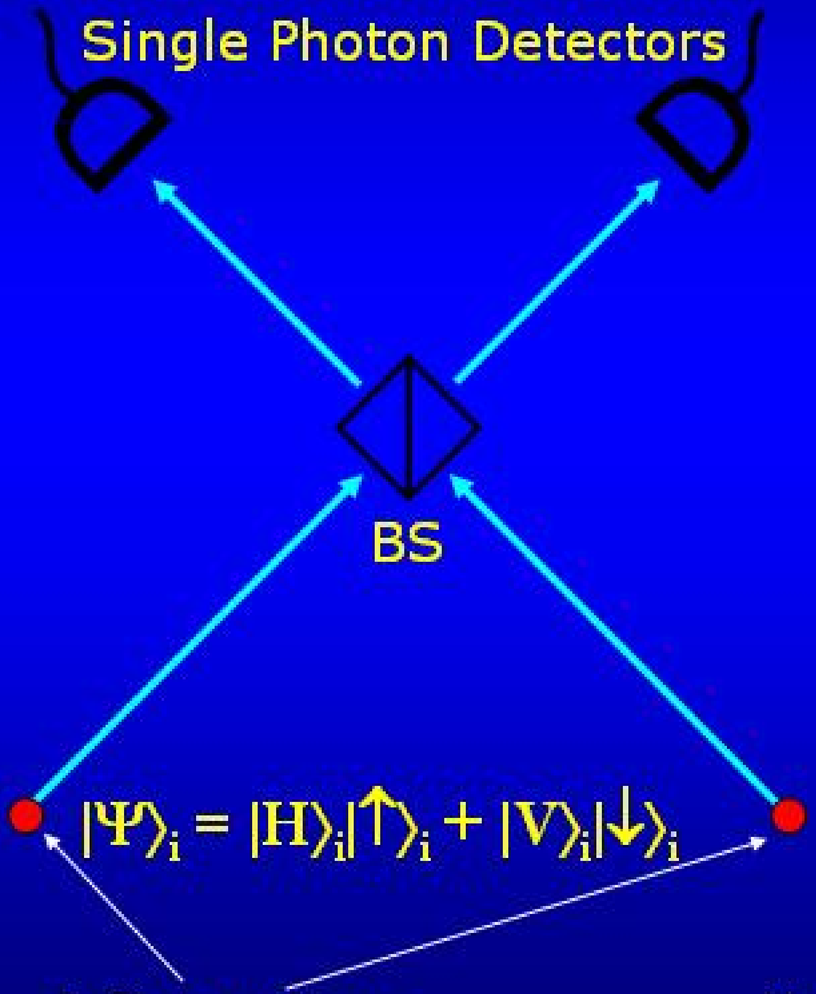
$$|\Psi^-\rangle_{\mathbf{photons}} = |H\rangle_1|V\rangle_2 - |V\rangle_1|H\rangle_2$$

This projects the ions into
$|\Psi^-\rangle_{\mathbf{ions}} = |\uparrow\rangle_1|\downarrow\rangle_2 - |\downarrow\rangle_1|\uparrow\rangle_2$

Hong, Ou, and Mandel, *PRL*, **59**, 2044 (1997);
Simon and Irvine, *PRL*, **91**, 110405 (2003)

Probabilistic Remote Ion Entanglement

Using entangled ion-photon pairs



Single Photon Detectors

BS

$|\Psi\rangle_i = |H\rangle_i|\uparrow\rangle_i + |V\rangle_i|\downarrow\rangle_i$

2 distant ions

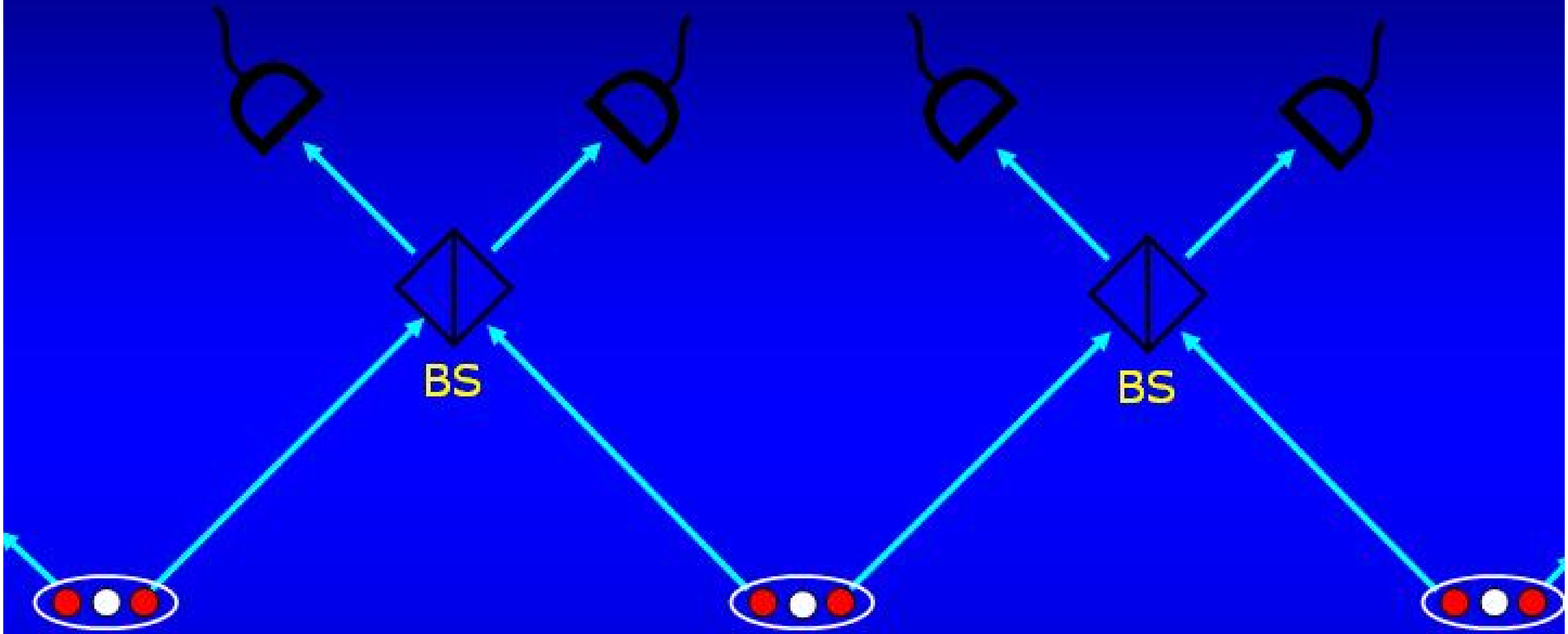
$$|\Psi\rangle = (|H\rangle_1|\uparrow\rangle_1 + |V\rangle_1|\downarrow\rangle_1) \otimes (|H\rangle_2|\uparrow\rangle_2 + |V\rangle_2|\downarrow\rangle_2)$$

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

$$\boxed{\begin{array}{c} P_{\text{ent}} = \eta T P_{\text{exc}}(\Delta\Omega/4\pi) \sim 10^{-3} \\ \text{Rate} = (P_{\text{ent}})^2 R \sim 1\ \text{Hz} \end{array}}$$

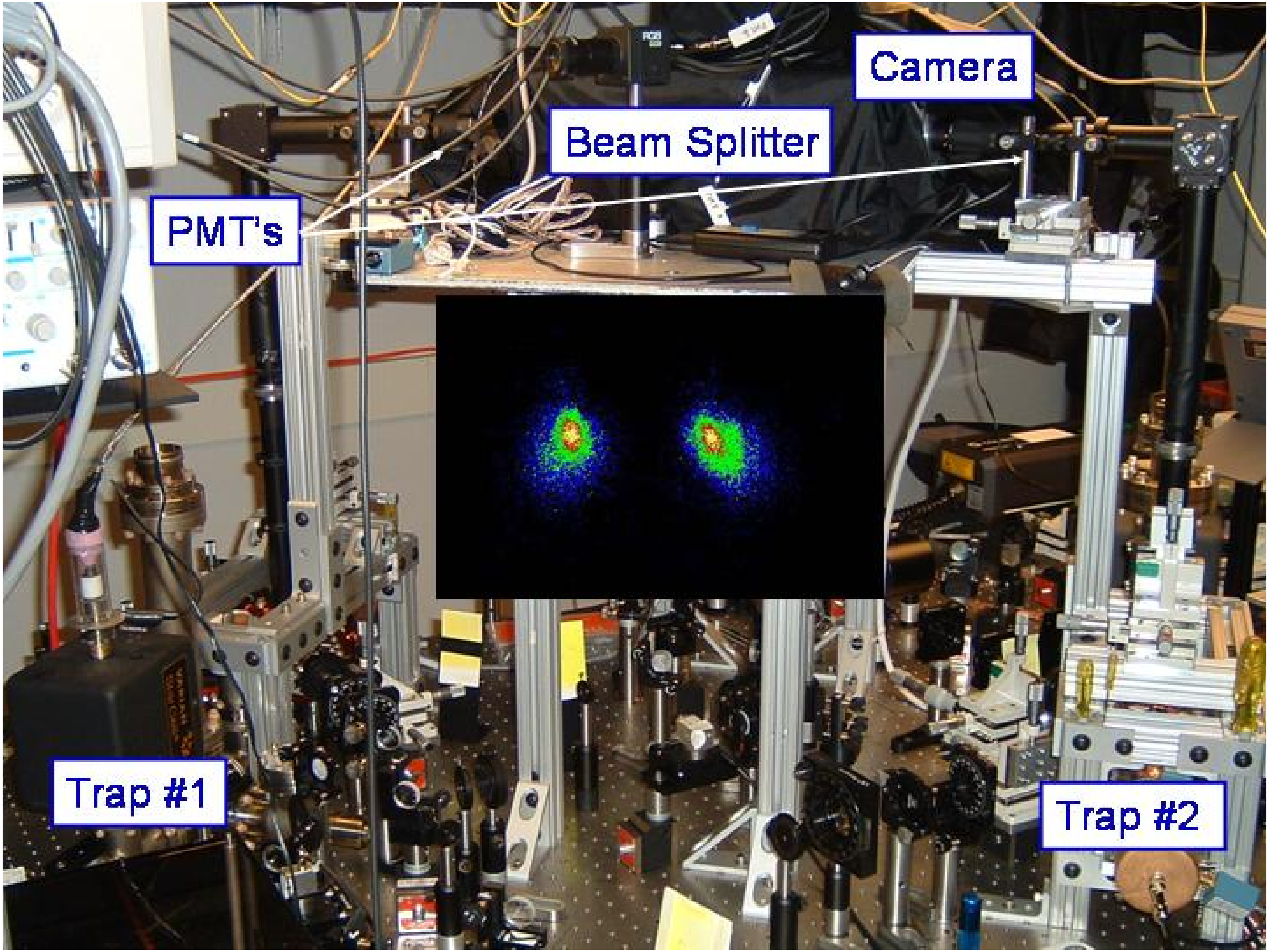
Hong, Ou, and Mandel, *PRL*, **59**, 2044 (1997);
Simon and Irvine, *PRL*, **91**, 110405 (2003)

Deterministic Remote Ion Entanglement



When combined with local deterministic quantum gates, this provides a possible method for scalable quantum computation.

Duan, Blinov, Moehring, and Monroe, *QIC* **4**, 165 (2004)


Camera
Beam Splitter
PMT's
Trap #1
Trap #2

University of Michigan

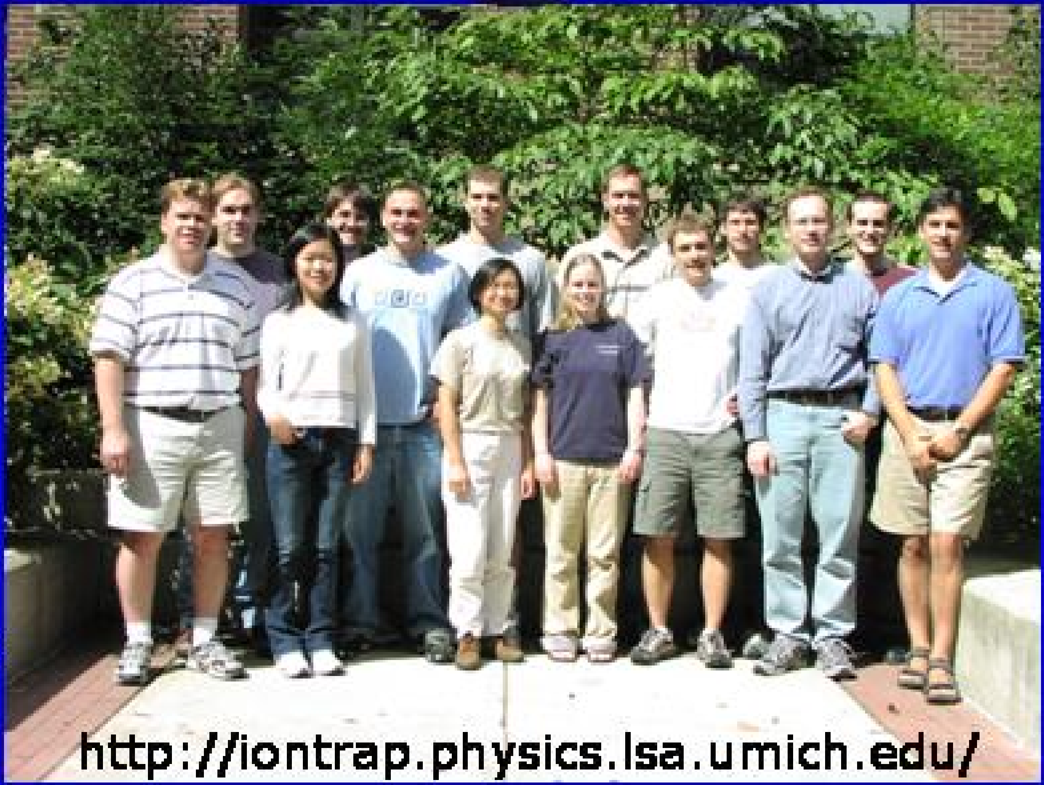
Trapped Ion Quantum Computing

Grad Students

Mark Acton
Kathy-Anne Brickman
Louis Deslauriers
Patricia Lee
Martin Madsen
David Moehring
Steven Olmschenk
Jon Sterk
Daniel Stick
Kelly Younge

Collaborators

Luming Duan (Michigan)
Jim Rabchuk (W. Illinois)
Keith Schwab (LPS)



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

Postdocs

Boris Blinov
Paul Haljan
Winfried Hensinger
Peter Maunz

Undergrads

Jacob Burress
David Hucul
Rudy Kohn
Elizabeth Otto
Mark Yeo

ARDA **US Advanced Research and Development Activity**

US Army Research Office

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NSF **National Science Foundation**