SAND2007-4863C

Fabrication and applications of ion traps

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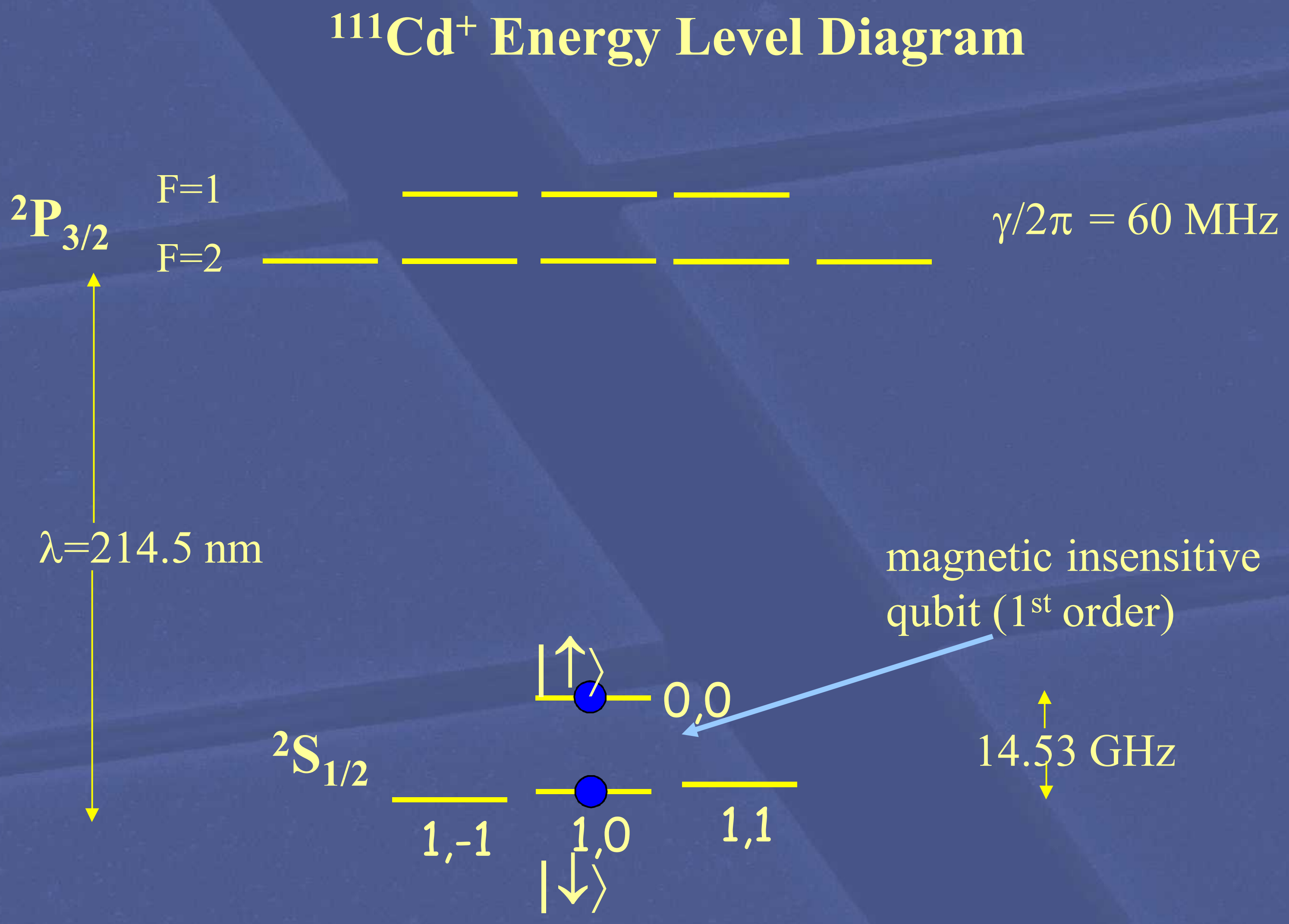
Sandia National Laboratories

Overview

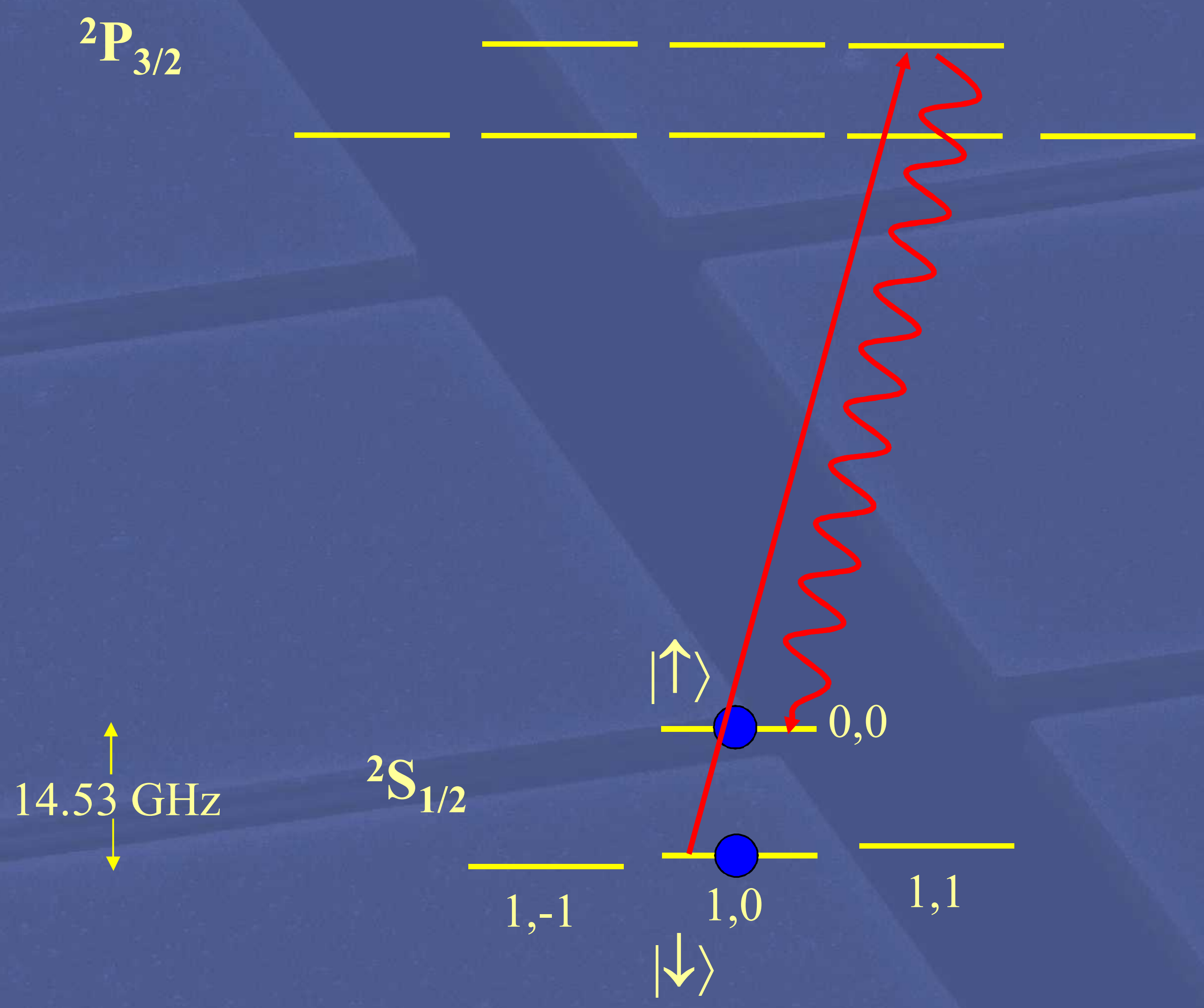
1. Ion qubit
   a. Cadmium: hyperfine qubit
   b. Ytterbium: ion-photon entanglement
   c. Cadmium MOT: combining neutrals and ions

2. Trap development
   a. General requirements/hurdles of microfabricated traps
   b. Anomalous heating
   c. Specific fabrication examples

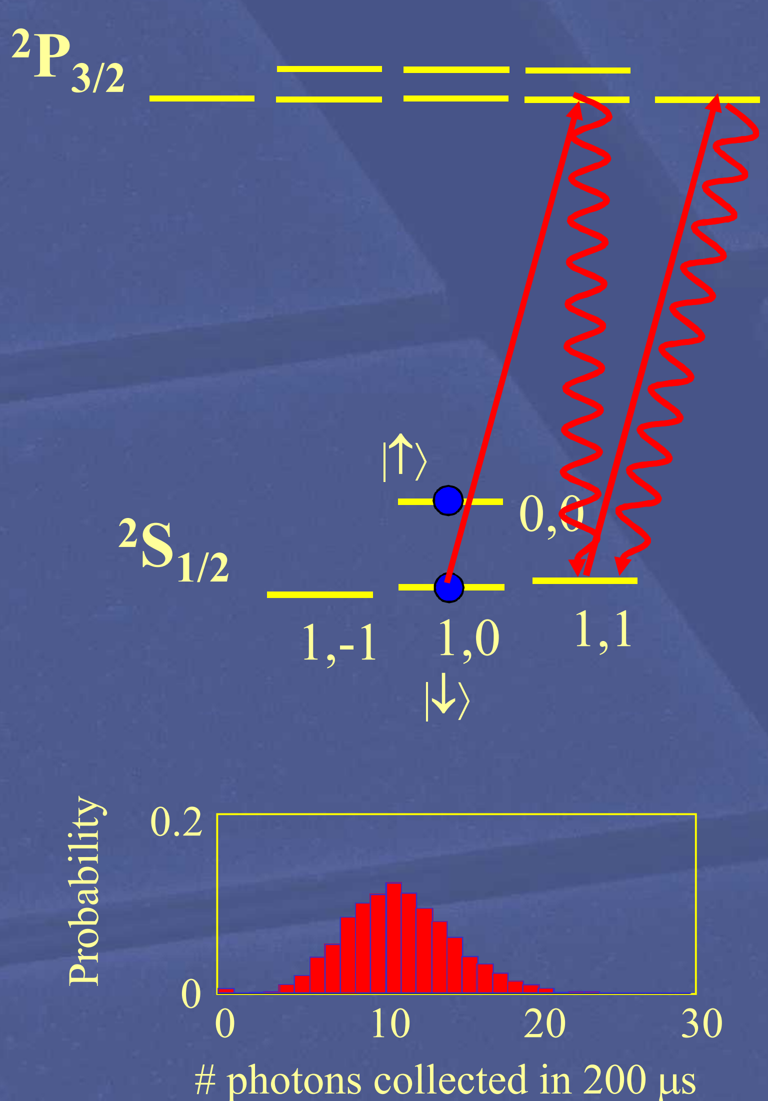
1a. Cadmium qubit



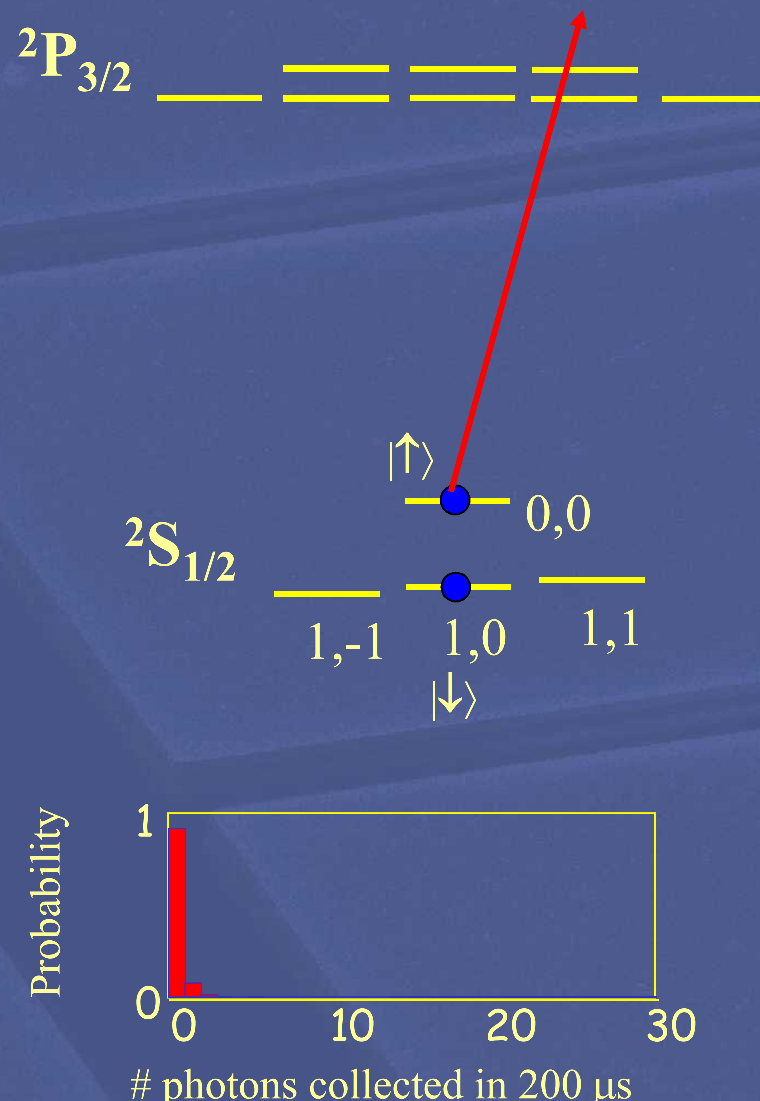
Initialization



Detection



$^2P_{3/2}$
|↑⟩
0,0
$^2S_{1/2}$
1,-1
1,0
1,1
|↓⟩
Probability
0.2
0
0
10
20
30
photons collected in 200 μs



$^2P_{3/2}$
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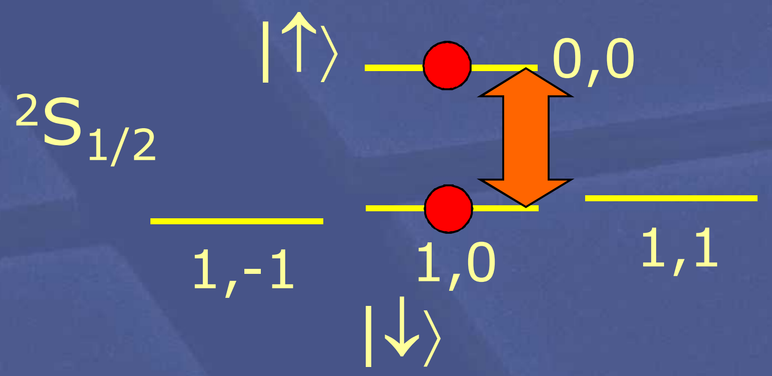
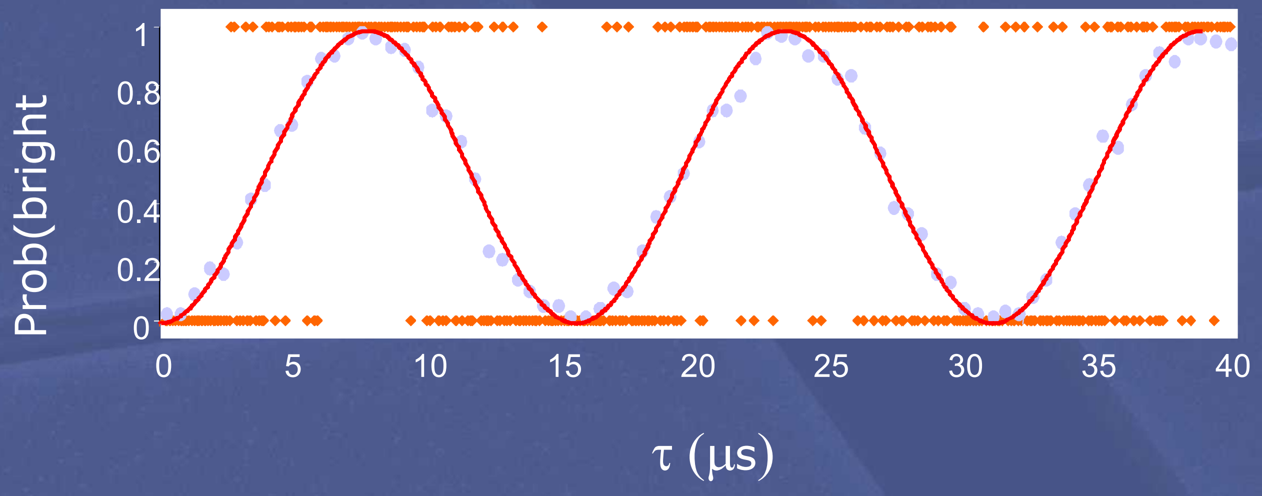
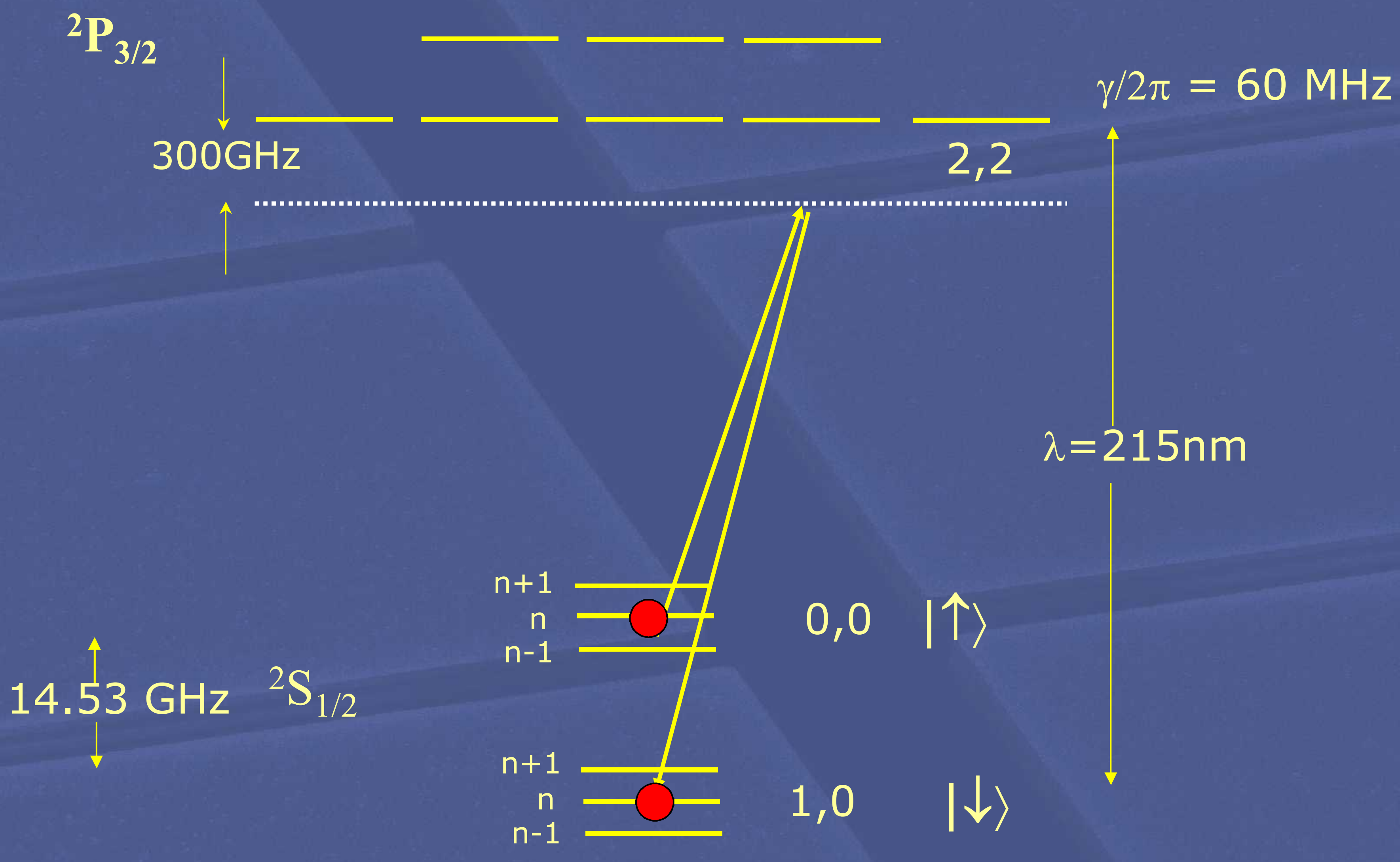
1,-1
1,0
1,1
|↓⟩
Probability
1
0
0
10
20
30
photons collected in 200 μs

Qubit rotations: microwaves

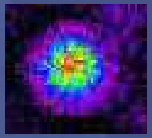




Raman transitions: motional sidebands



Cadmium vs. Ytterbium

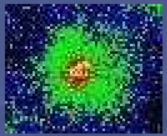
<u>Cadmium</u> 

Pros:

- simple atomic structure

Cons:

- difficult wavelength
  - quadrupled diode-laser (complex, expensive)
  - low power
  - always free space

<u>Ytterbium</u> 

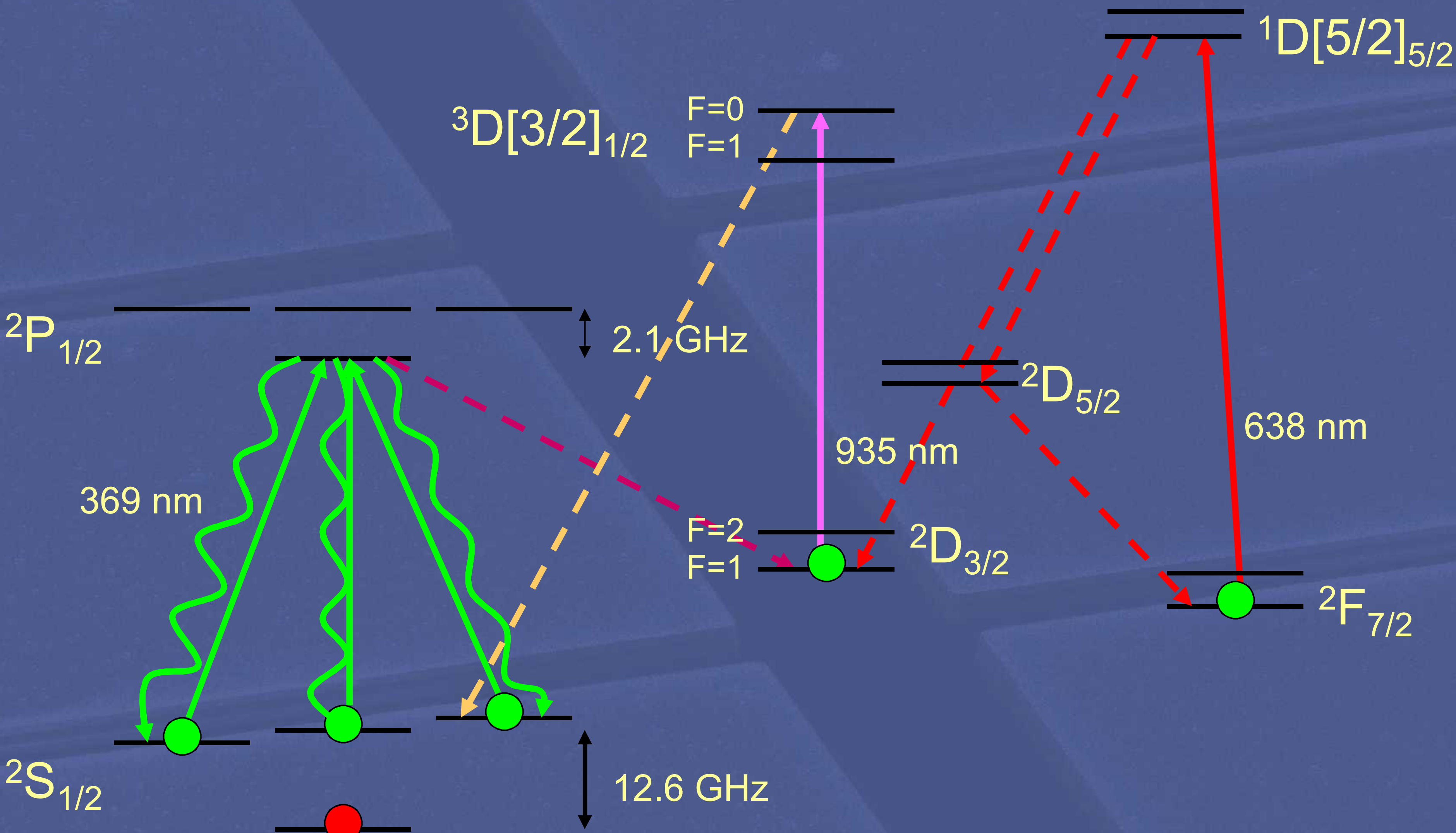
Cons:

- more complicated atomic structure
- more lasers

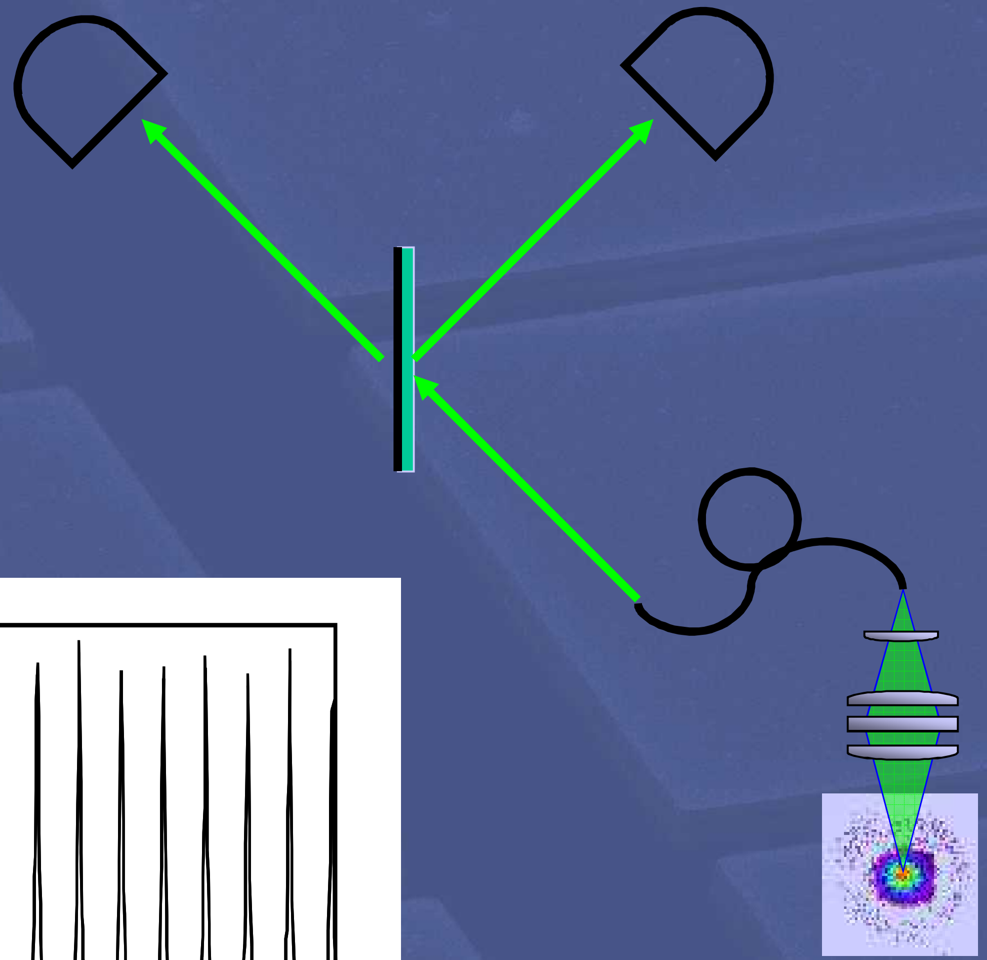
Pros:

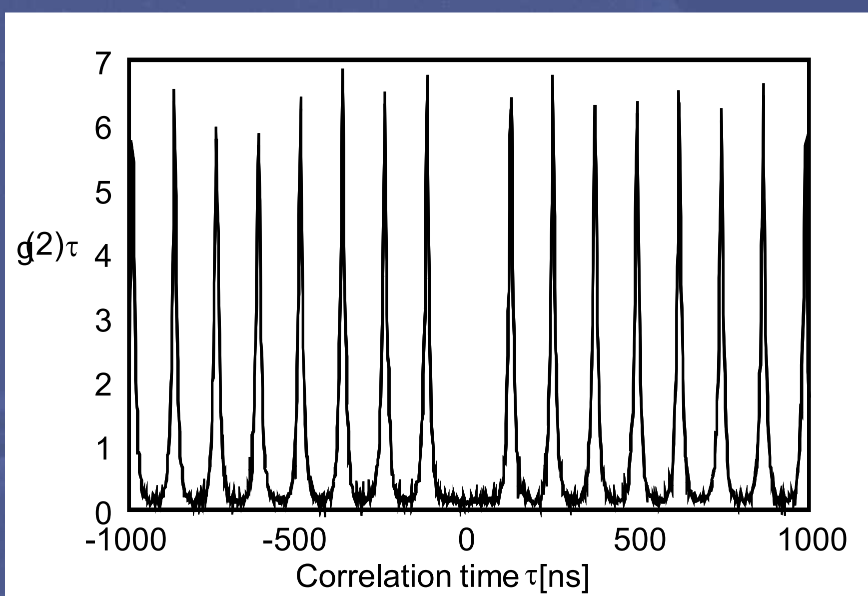
- nice wavelengths
  - direct diode lasers (simple, cheap)
  - more power
  - *fibers*

The Ytterbium ($^{171}Yb^+$) Ion

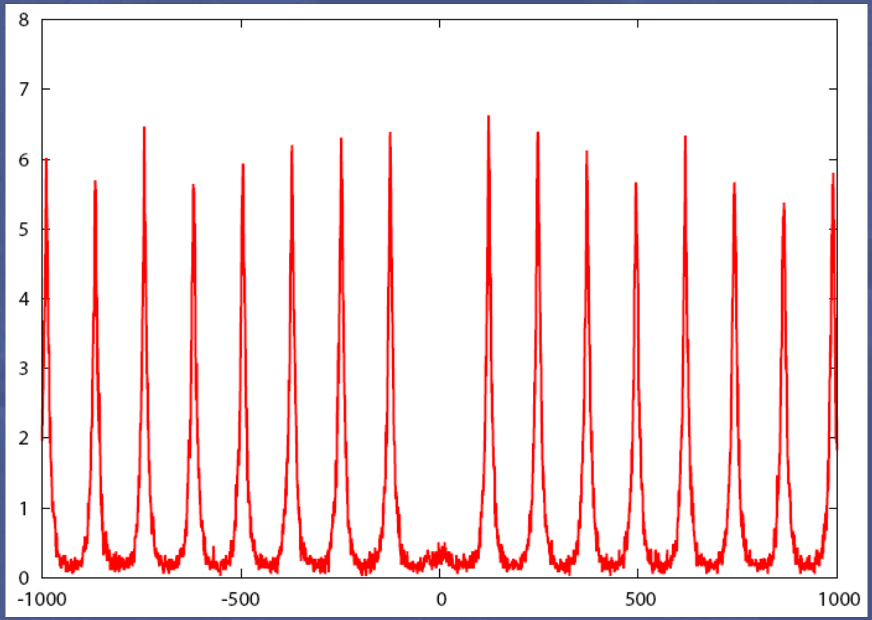


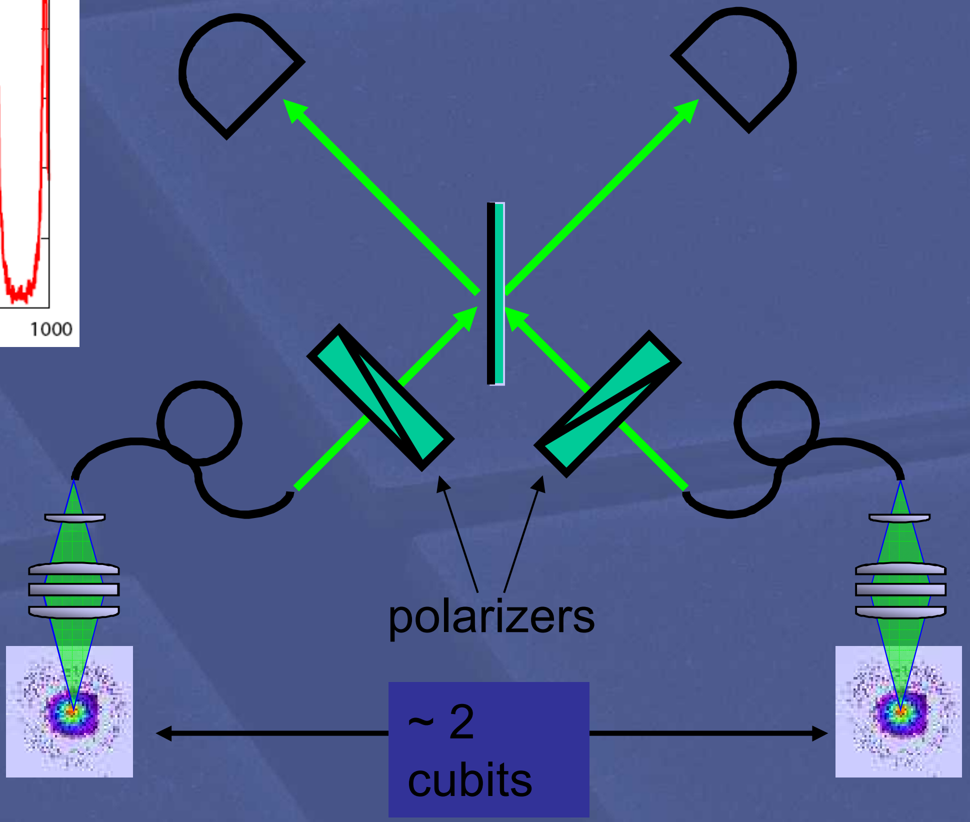
Single Photon Source



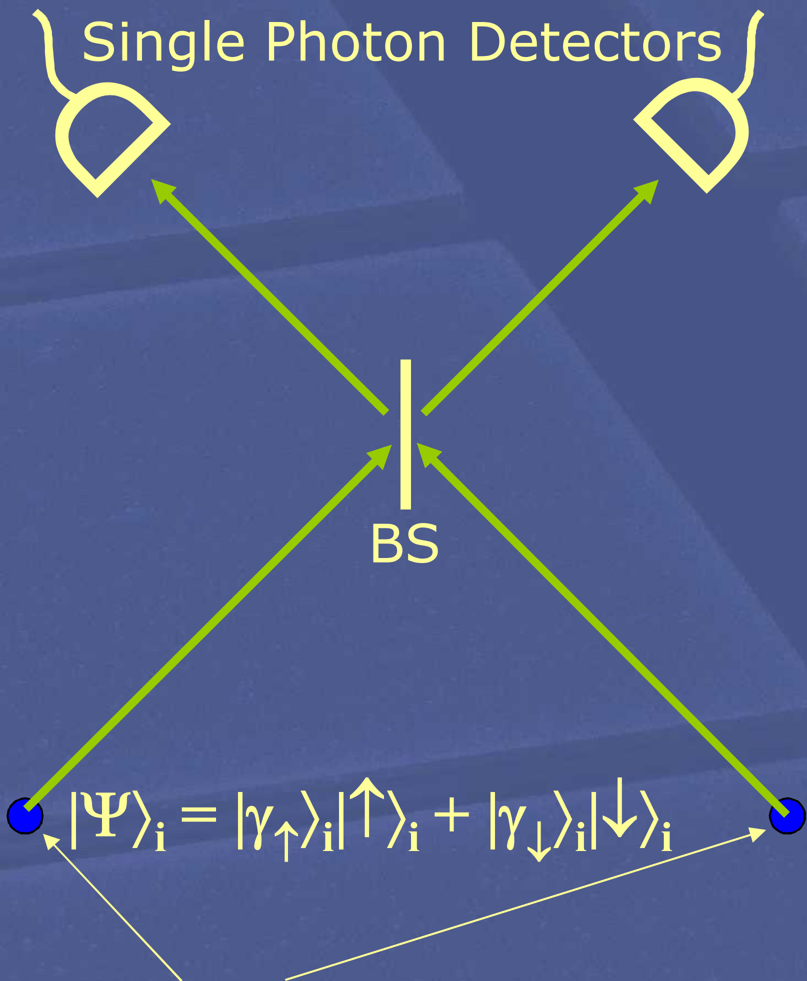


Two Photon Interference





Remote Ion Entanglement

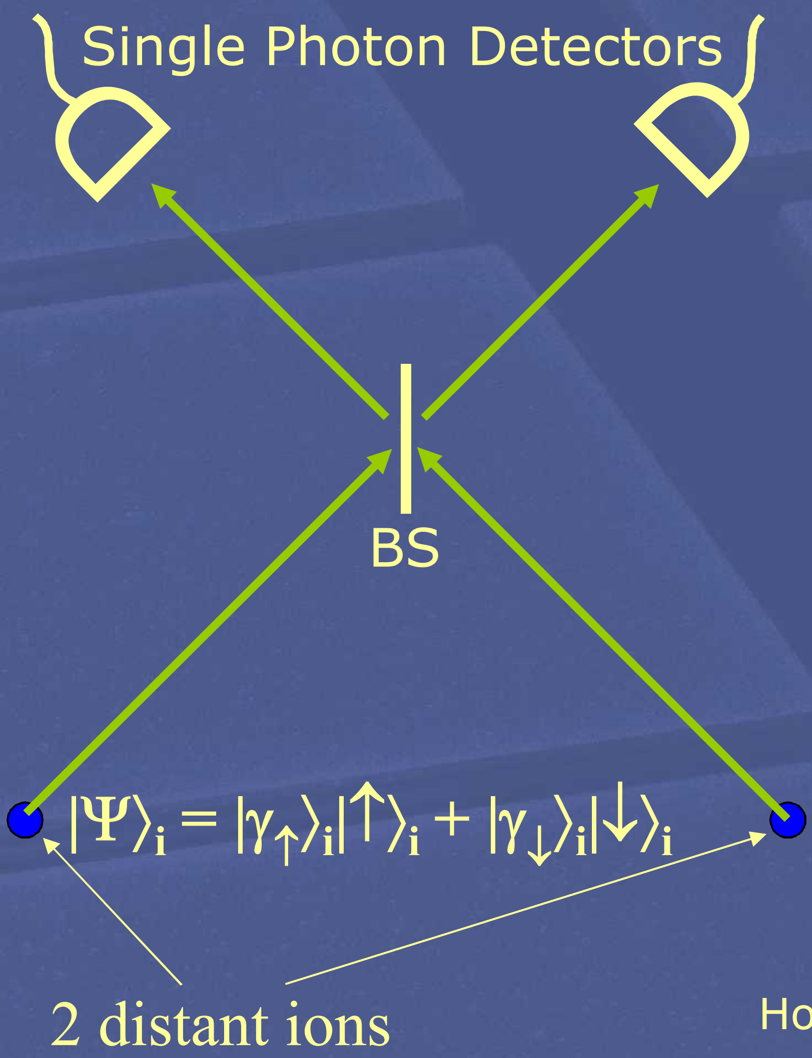


$$|\Psi\rangle_i = |\gamma_\uparrow\rangle_i|\uparrow\rangle_i + |\gamma_\downarrow\rangle_i|\downarrow\rangle_i$$

2 distant ions

$$|\Psi\rangle = (|\gamma_\uparrow\rangle_a|\uparrow\rangle_a + |\gamma_\downarrow\rangle_a|\downarrow\rangle_a) \otimes (|\gamma_\uparrow\rangle_b|\uparrow\rangle_b + |\gamma_\downarrow\rangle_b|\downarrow\rangle_b)$$

Remote Ion Entanglement



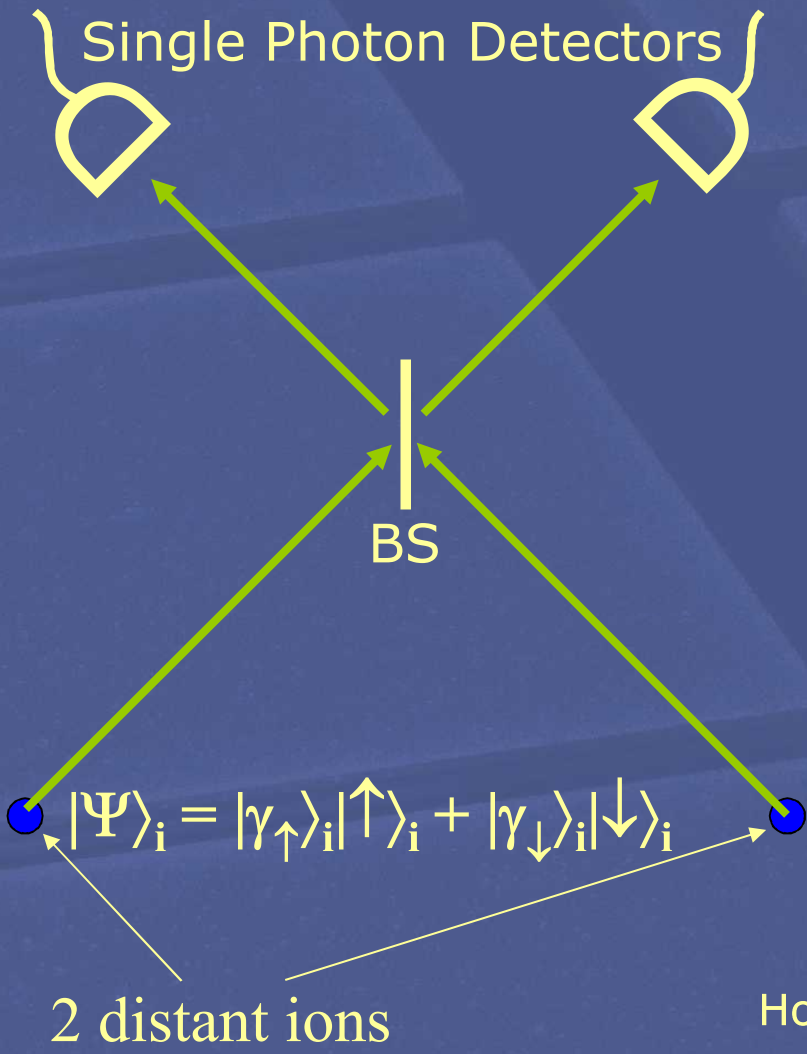
$$|\Psi\rangle = (|\gamma_\uparrow\rangle_a|\uparrow\rangle_a + |\gamma_\downarrow\rangle_a|\downarrow\rangle_a) \otimes (|\gamma_\uparrow\rangle_b|\uparrow\rangle_b + |\gamma_\downarrow\rangle_b|\downarrow\rangle_b)$$

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

$$|\Psi^-\rangle_{photons} = |\gamma_\uparrow\rangle_a |\gamma_\downarrow\rangle_b - |\gamma_\downarrow\rangle_a|\gamma_\uparrow\rangle_b$$

Hong, Ou, and Mandel, *PRL*, **59**, 2044 (1997);

Remote Ion Entanglement



$$|\Psi\rangle = (|\gamma_\uparrow\rangle_a|\uparrow\rangle_a + |\gamma_\downarrow\rangle_a|\downarrow\rangle_a) \otimes (|\gamma_\uparrow\rangle_b|\uparrow\rangle_b + |\gamma_\downarrow\rangle_b|\downarrow\rangle_b)$$

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

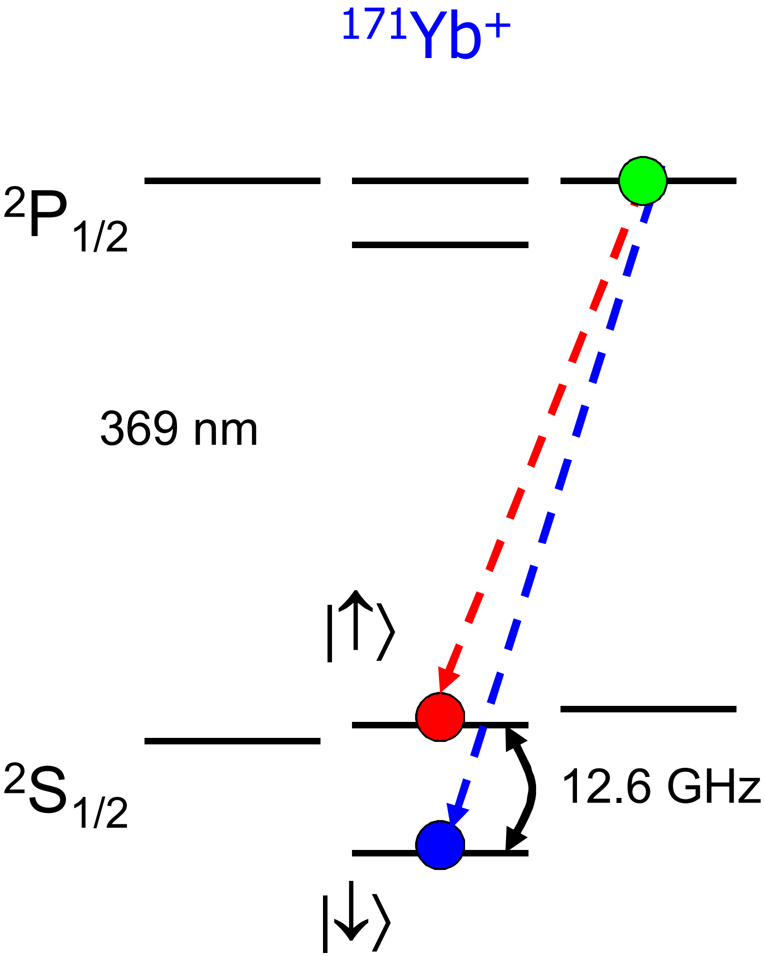
$$|\Psi^-\rangle_{photons} = |\gamma_\uparrow\rangle_a |\gamma_\downarrow\rangle_b - |\gamma_\downarrow\rangle_a|\gamma_\uparrow\rangle_b$$

This projects the ions into
$|\Psi^-\rangle_{ions} = |\uparrow\rangle_a|\downarrow\rangle_b - |\downarrow\rangle_a|\uparrow\rangle_b$

Coincidence “heralds” the entanglement preparation.

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

Remote Ion Entanglement



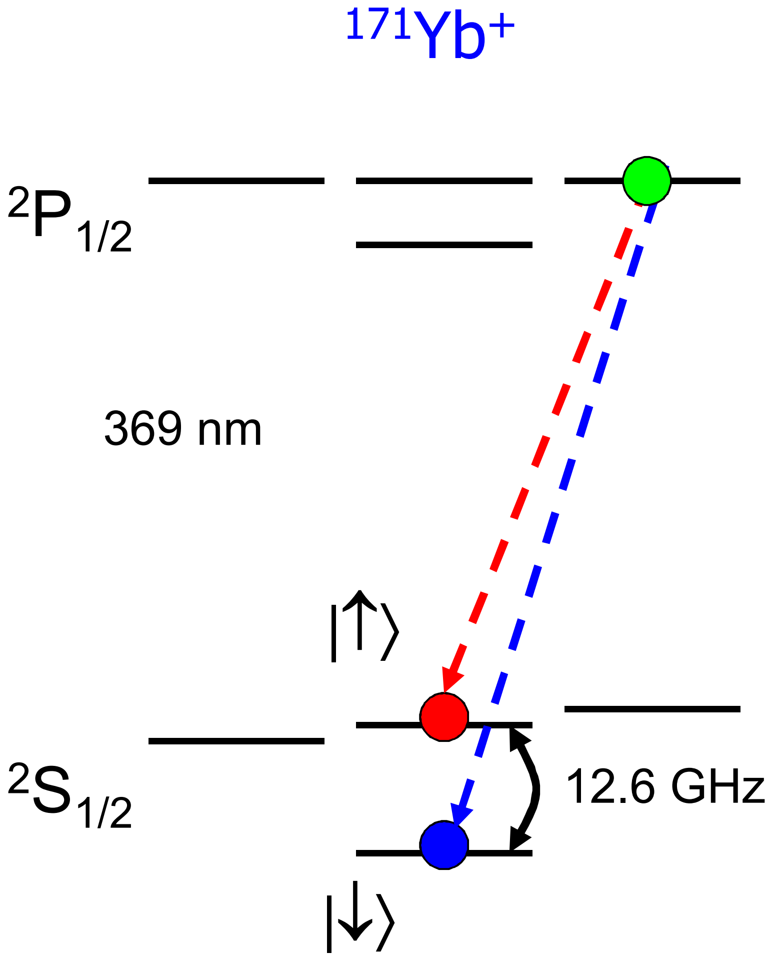
Ion

Hyperfine ground states
|↑⟩ state is F=1, m=0
|↓⟩ state is F=0, m=0

Photon

Two different light frequencies |R⟩ and |B⟩

Remote Ion Entanglement



Ion

Hyperfine ground states
|↑⟩ state is F=1, m=0
|↓⟩ state is F=0, m=0

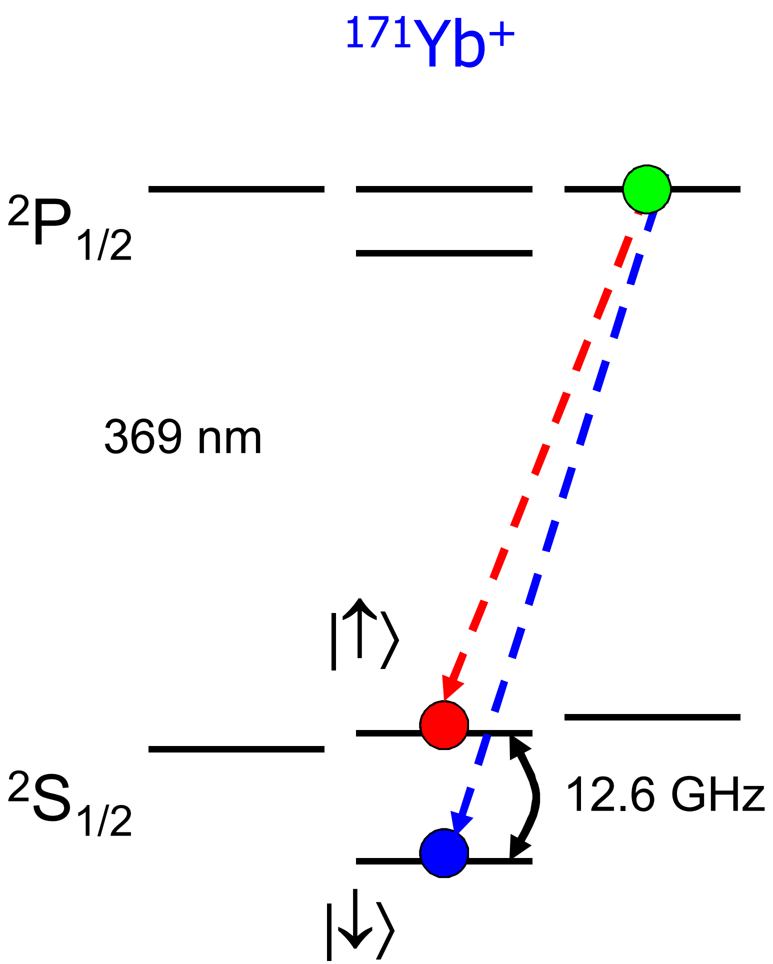
Photon

Two different light frequencies |R⟩ and |B⟩

Ion-Photon Entanglement

|↑⟩|**R**⟩ - |↓⟩|**B**⟩

Remote Ion Entanglement



Ion

Hyperfine ground states

$|\uparrow\rangle$ state is F=1, m=0

$|\downarrow\rangle$ state is F=0, m=0

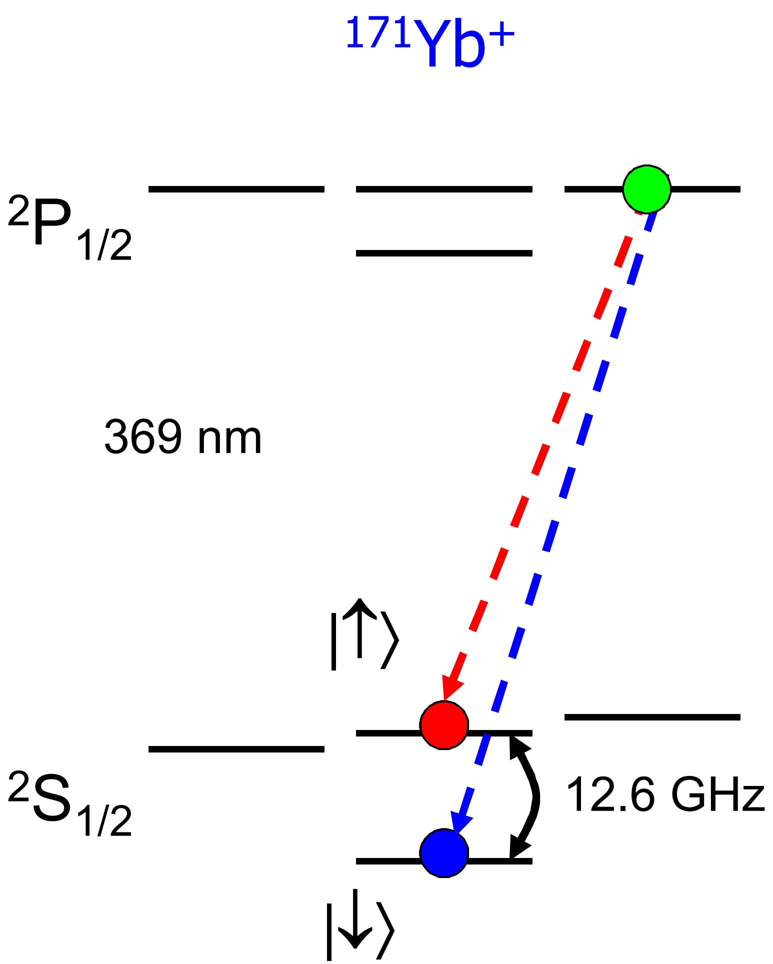
Photon

Two different light frequencies $|R\rangle$ and $|B\rangle$

Ion-Photon Entanglement

$$(|\uparrow\rangle|R\rangle - |\downarrow\rangle|B\rangle)_a \otimes (|\uparrow\rangle|R\rangle - |\downarrow\rangle|B\rangle)_b$$

Remote Ion Entanglement



Ion

Hyperfine ground states

|↑⟩ state is F=1, m=0

|↓⟩ state is F=0, m=0

Photon

Two different light frequencies |R⟩ and |B⟩

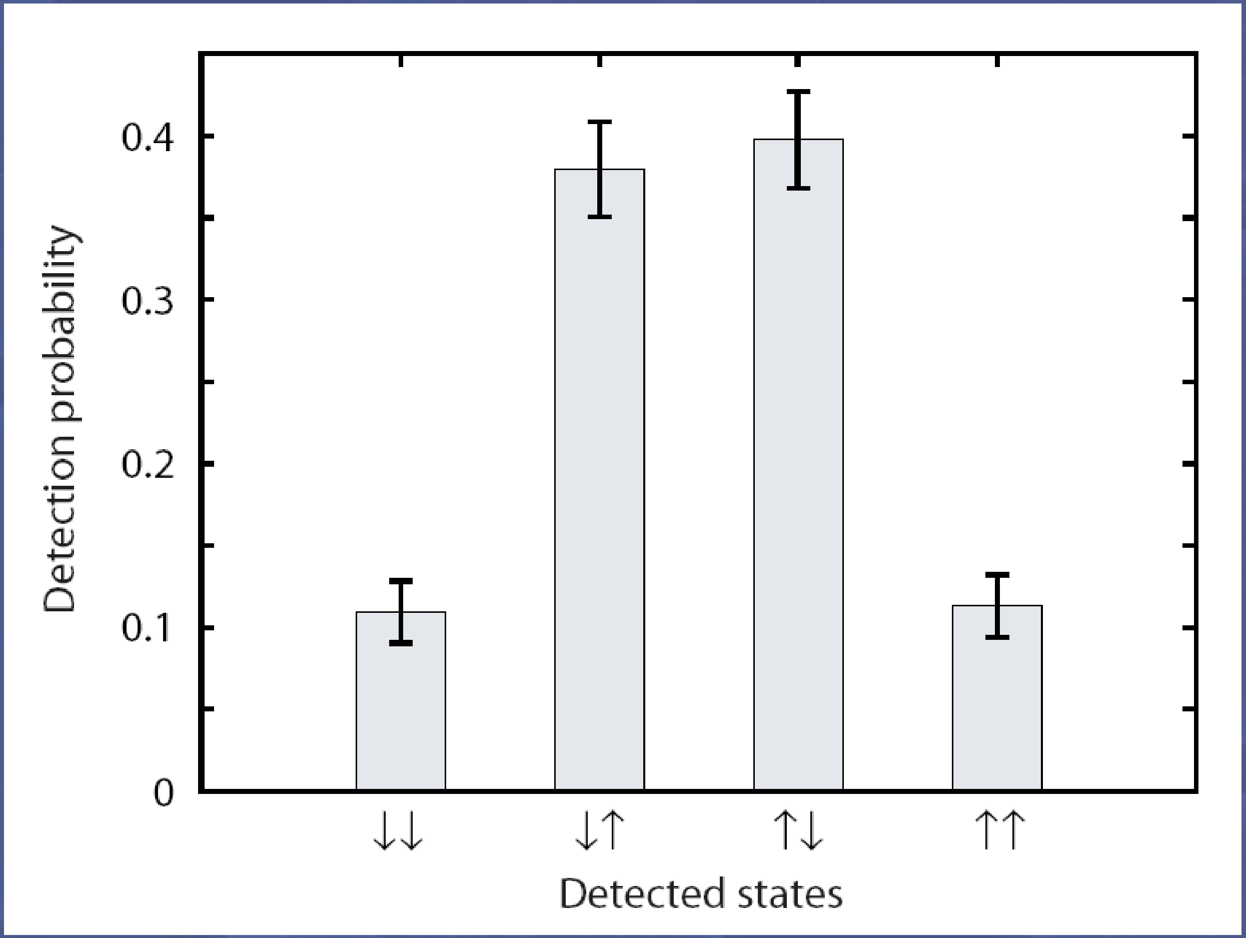
Ion-Photon Entanglement

$(|\uparrow\rangle|R\rangle - |\downarrow\rangle|B\rangle)_a \otimes (|\uparrow\rangle|R\rangle - |\downarrow\rangle|B\rangle)_b$

Coincidence projects ions onto:

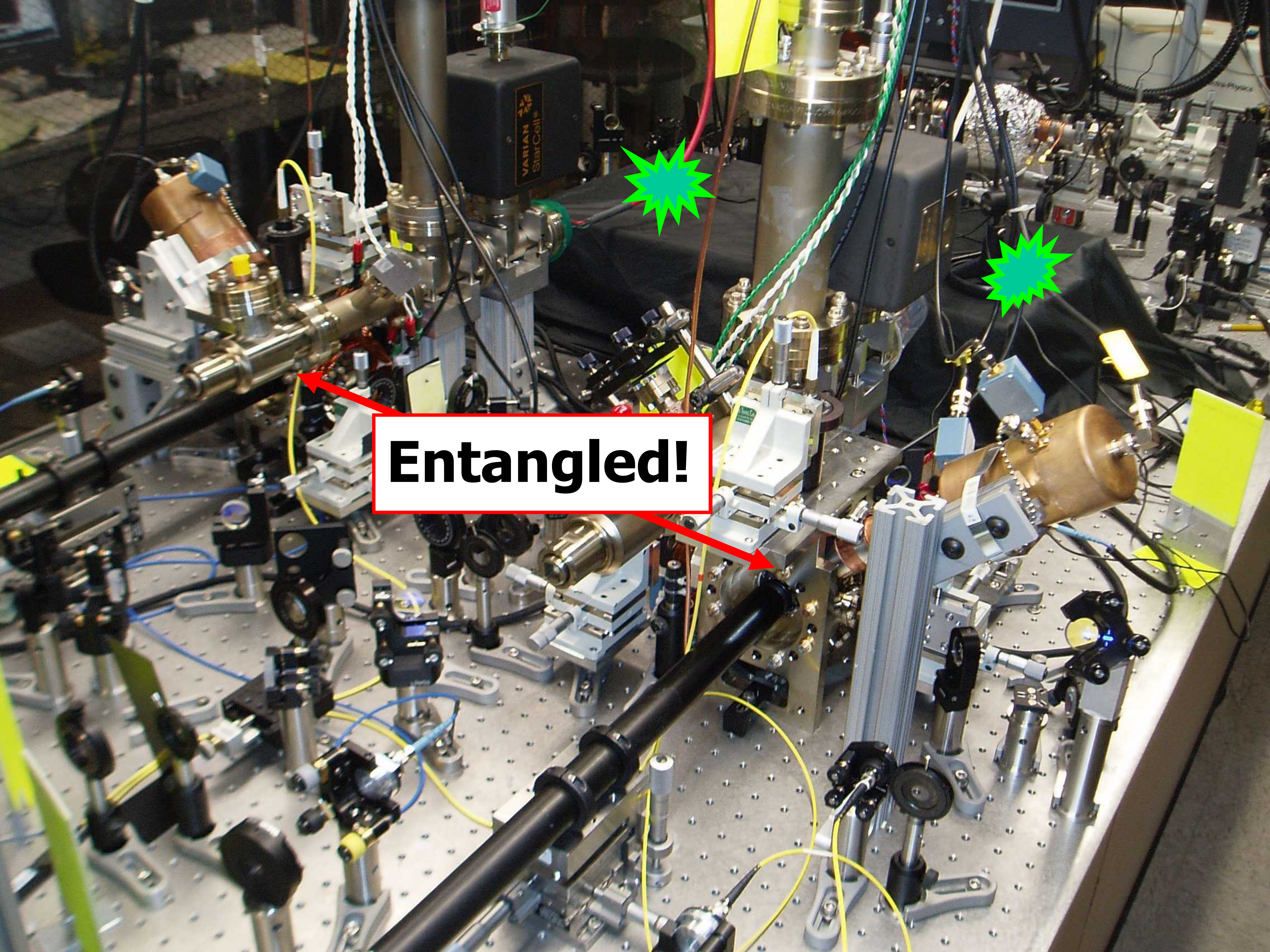
$|\Psi^-\rangle_{ions} = |\uparrow\rangle_a|\downarrow\rangle_b - |\downarrow\rangle_a|\uparrow\rangle_b$

Qubit state measurements

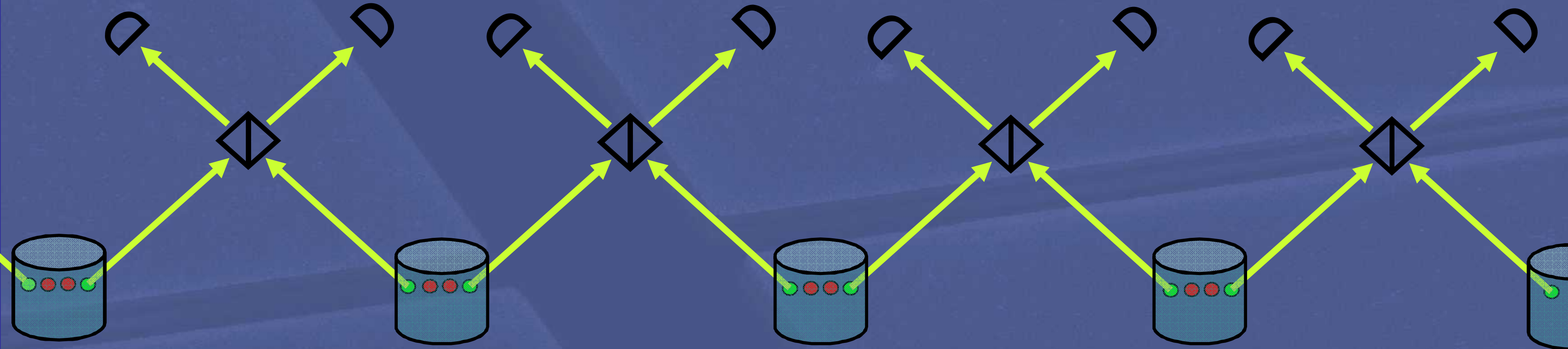


Expected ion state is: $|\Psi^{-}\rangle_{ions} = |\uparrow\rangle_a|\downarrow\rangle_b - |\downarrow\rangle_a|\uparrow\rangle_b$

Success probability per trial $P = \frac{1}{4}[\frac{1}{2}\eta\zeta T\beta P_{exc}(\Delta\Omega/4\pi)] = 3 \times 10\text{-}9$

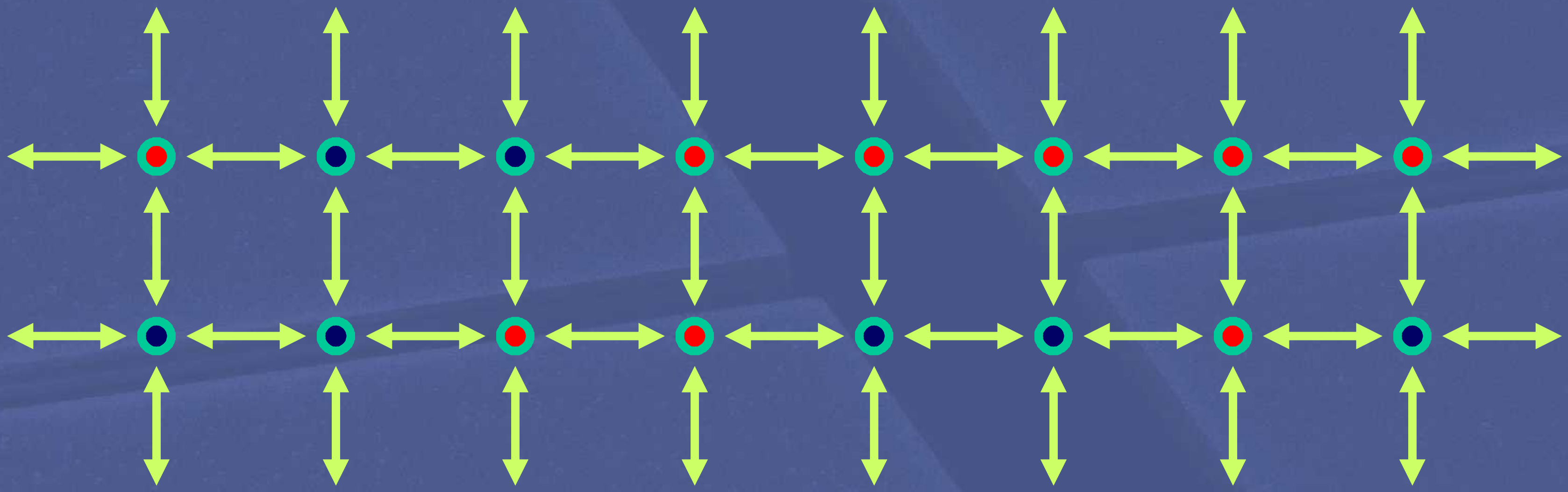

Entangled!
VARIAN
StarCell

Scalable even though *probabilistic*



Quantum Repeater Network

Duan et. al., *Quan. Inf. Comp.* **4**, 165 (2004)

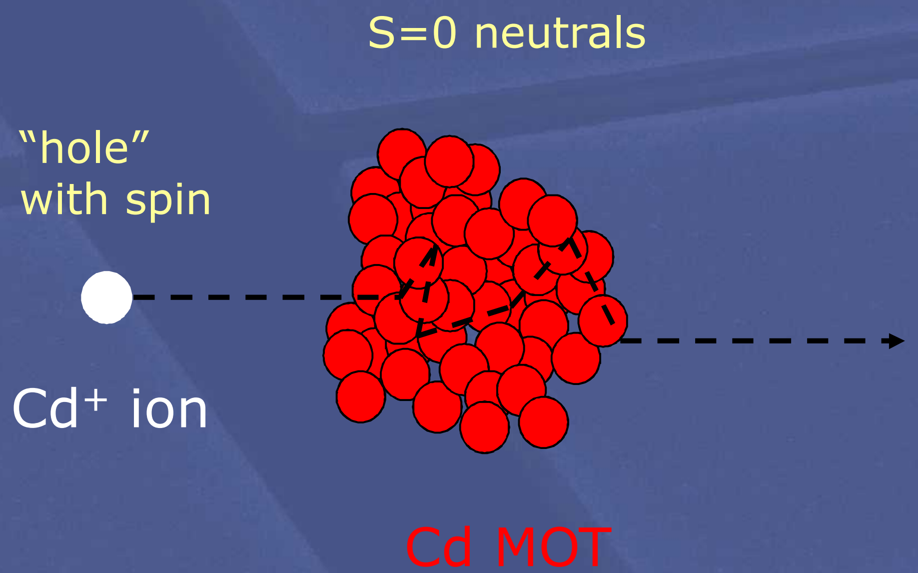


Cluster State Quantum Computing

Raussendorf and Briegel, *PRL* **86**, 910 (2001)
Duan and Raussendorf, *PRL* 95, 080503 (2005)

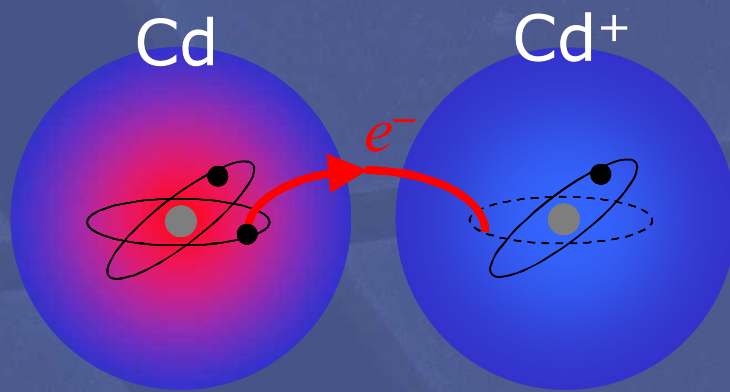
Combining ions and neutrals

Single ion and a magneto-optical trap



Combining ions and neutrals

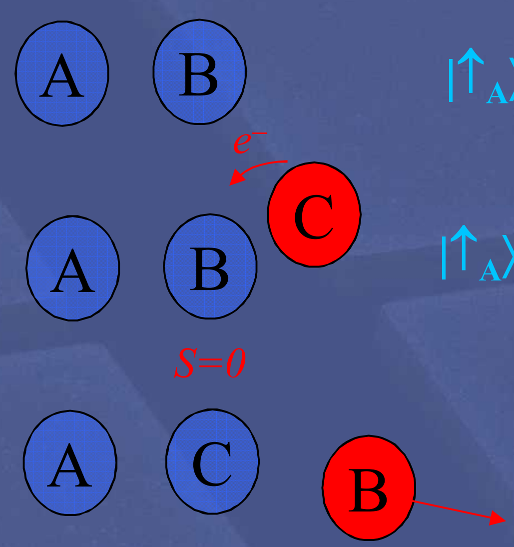
Single ion and a single neutral atom



(i) ions entangled

(ii) add e- to ion B

(iii) move B with protected qubit in nucleus

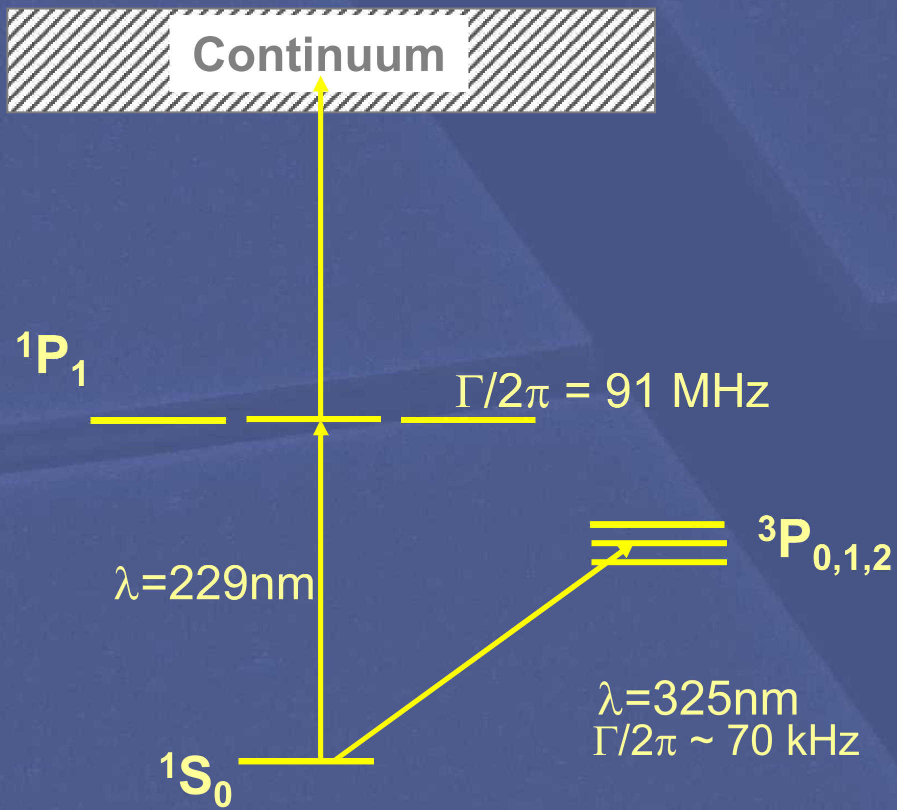


$|\uparrow_A\rangle|\downarrow_B\rangle+|\downarrow_A\rangle|\uparrow_B\rangle$

$|\uparrow_A\rangle|\downarrow_B\rangle+|\downarrow_A\rangle|\uparrow_B\rangle$??

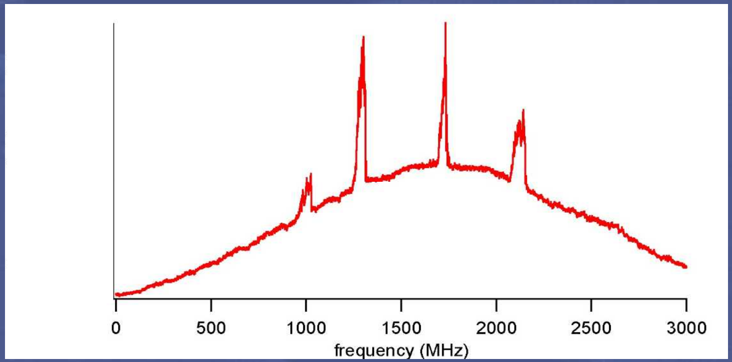
Cadmium Energy Level Diagram

Even Isotopes; I=0



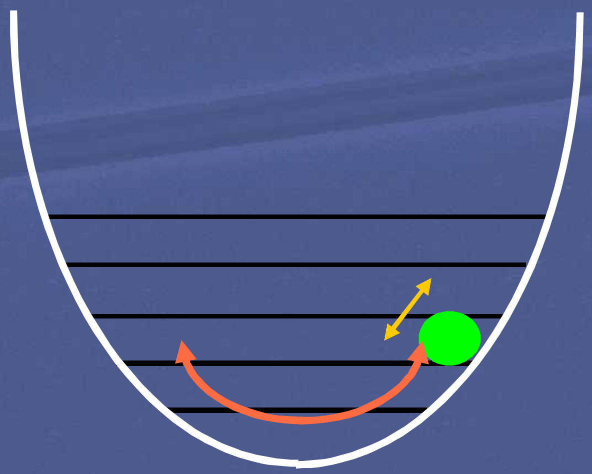
Pros:
- simple structure
- good vapor pressure at room temperature
- triplet manifold useful for optical clock studies

Cons:
- Low power! (few mW) (I_{sat}=1W/cm^2)
- Small beams (few mm)
- Large excited state linewidth requires large B-field gradient (500G/cm)



2a. Microfabricated traps

$$\Psi_{RF} \propto \left|\nabla V(x,y,z)\right|^2$$



Equation of motion: $$z(t) = \left[1 + \frac{\sqrt{2}\omega}{\Omega}\cos(\Omega t)\right] z_0 \cos(\omega t)$$

Micromotion

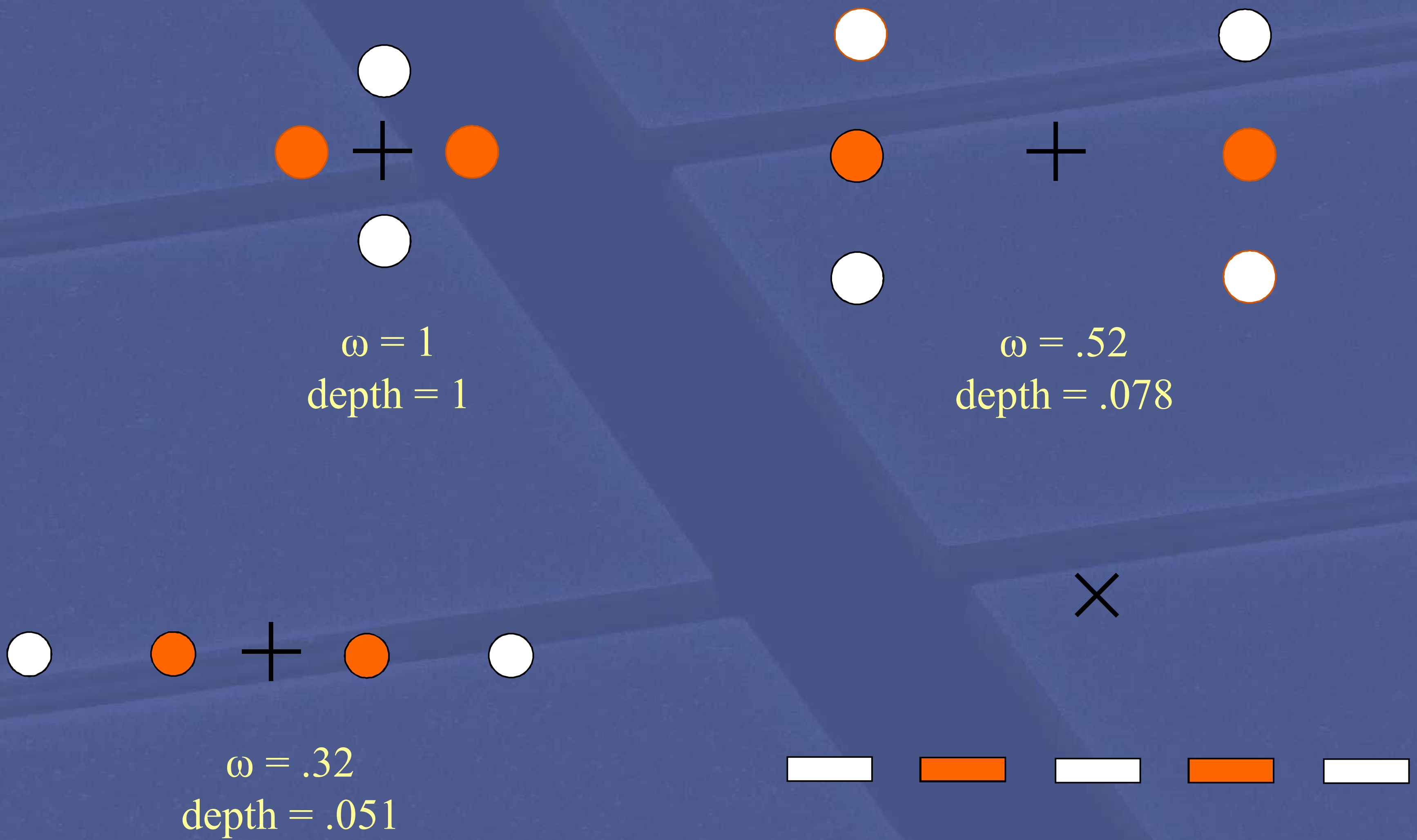
Secular motion

Ω= RF drive frequency

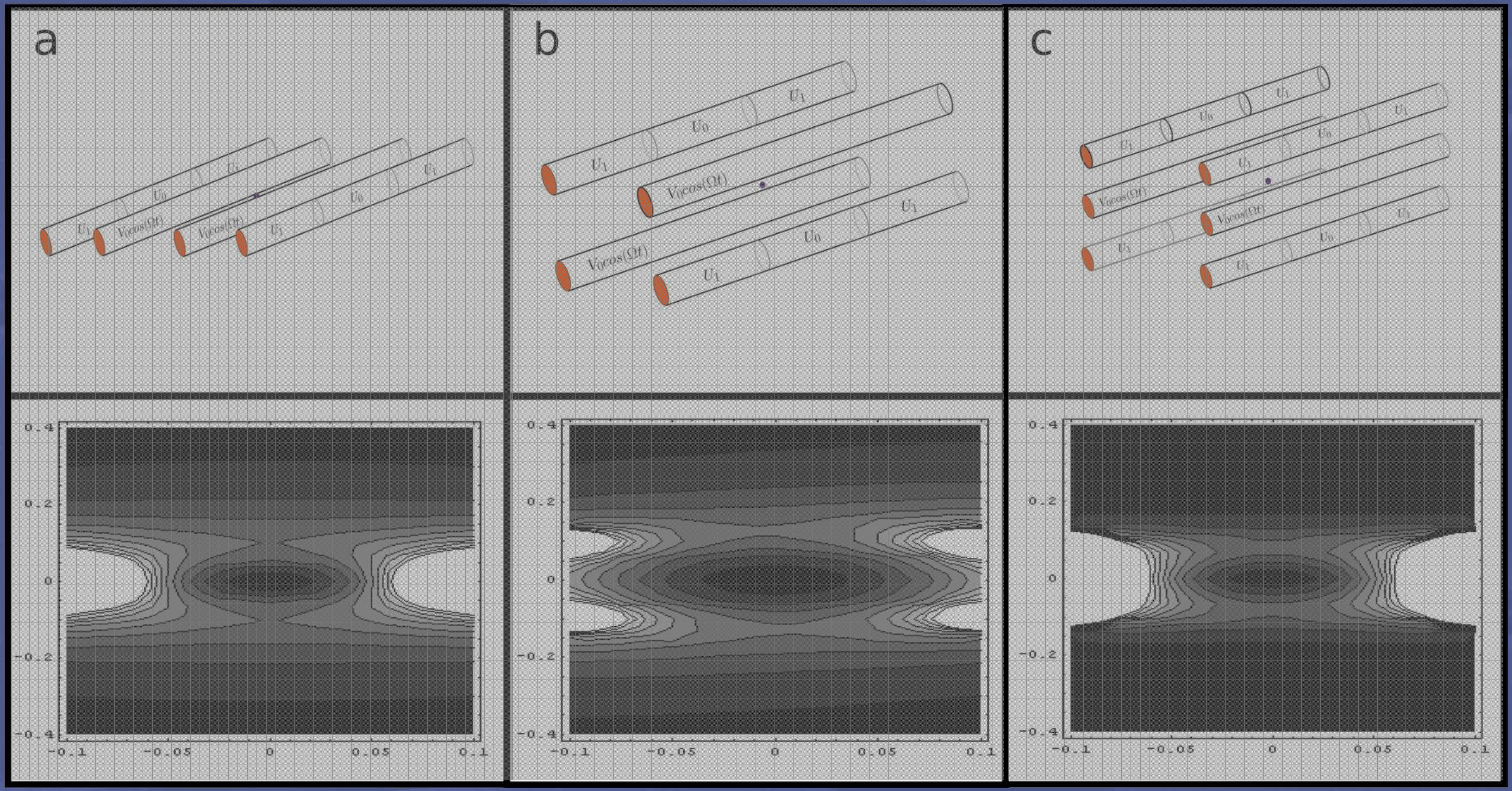
ω = secular frequency

RF DC

Trap geometries



Comparative geometries



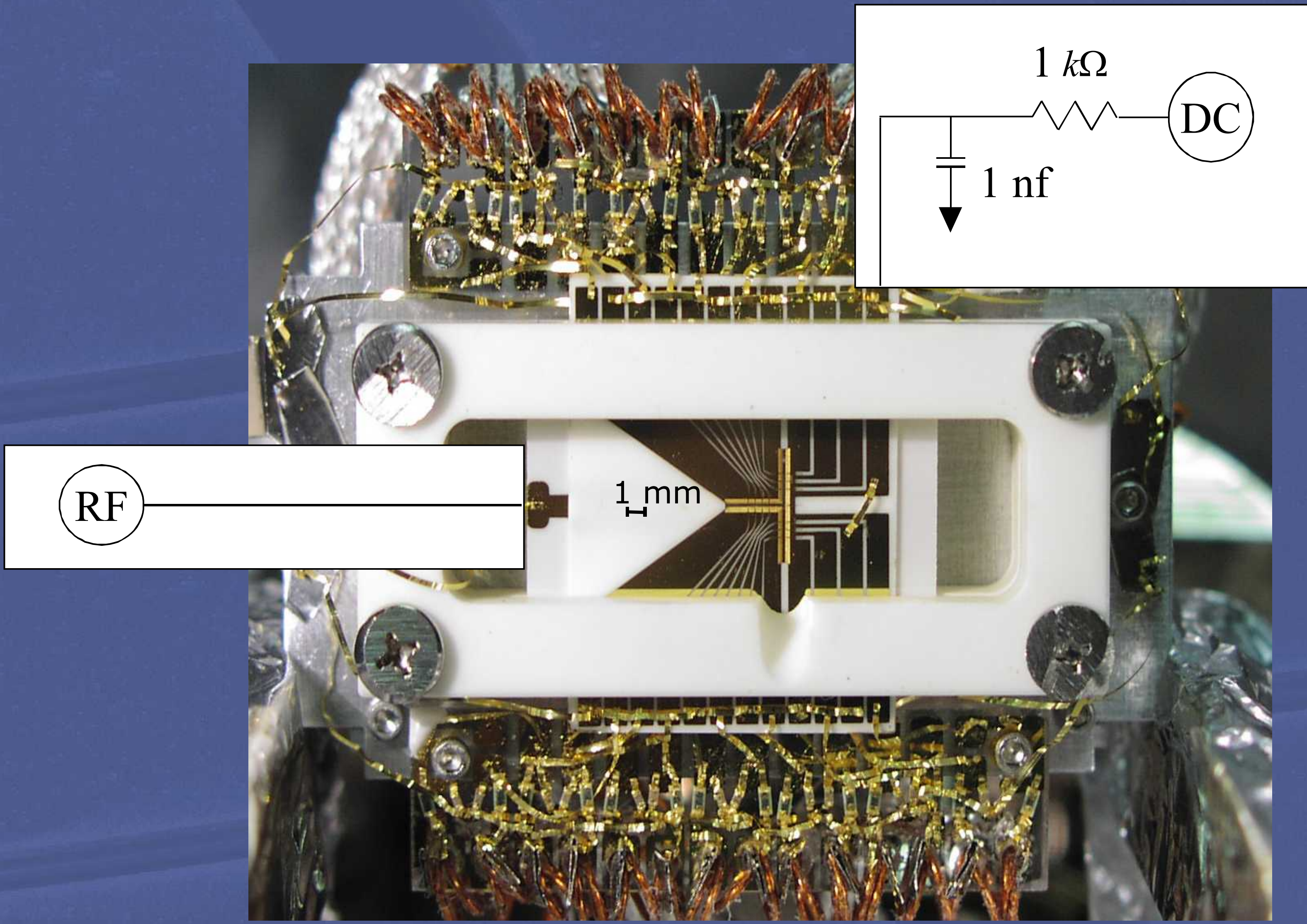
ω = .32
depth = .051

ω = 1
depth = 1

ω = .52
depth = .078

Chiaverini, et al. QIC **5** (2005)

T junction trap

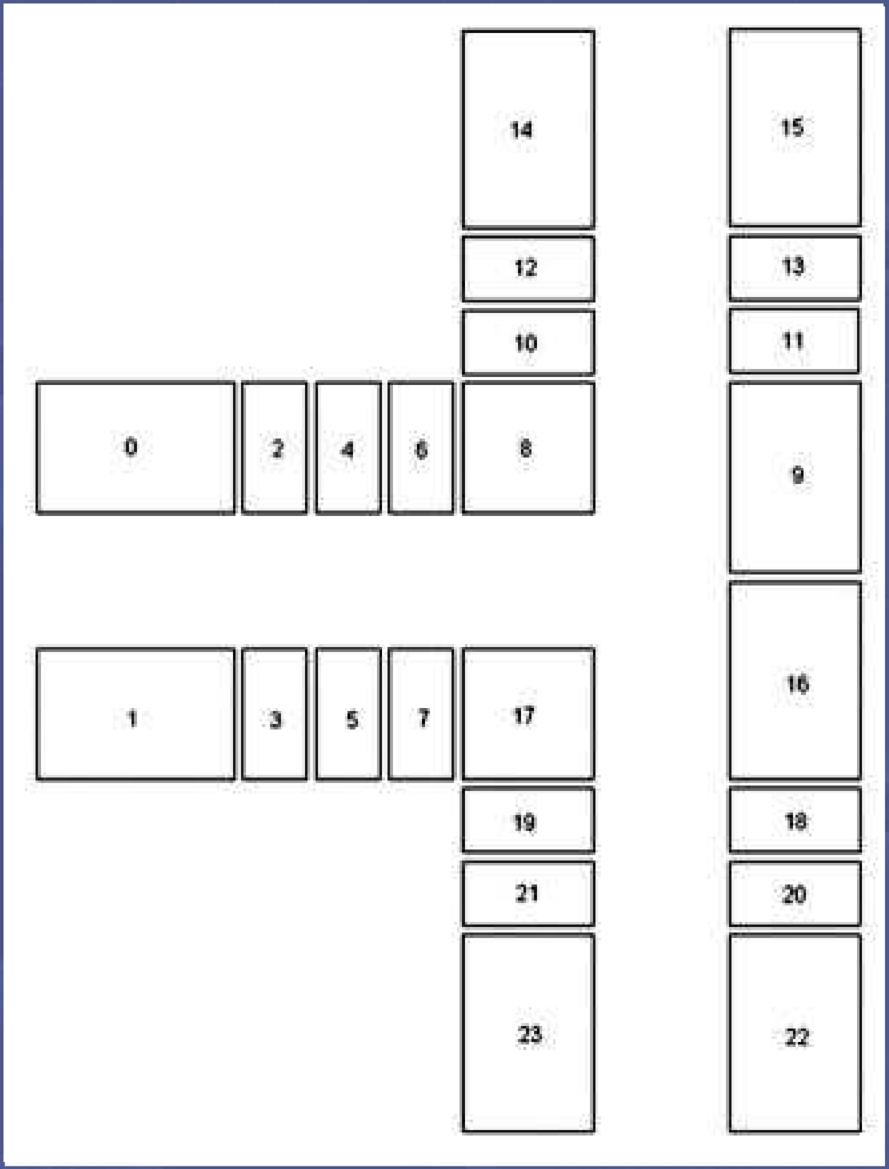


Hensinger, W.K., Appl. Physics Lett. **88**, 034101

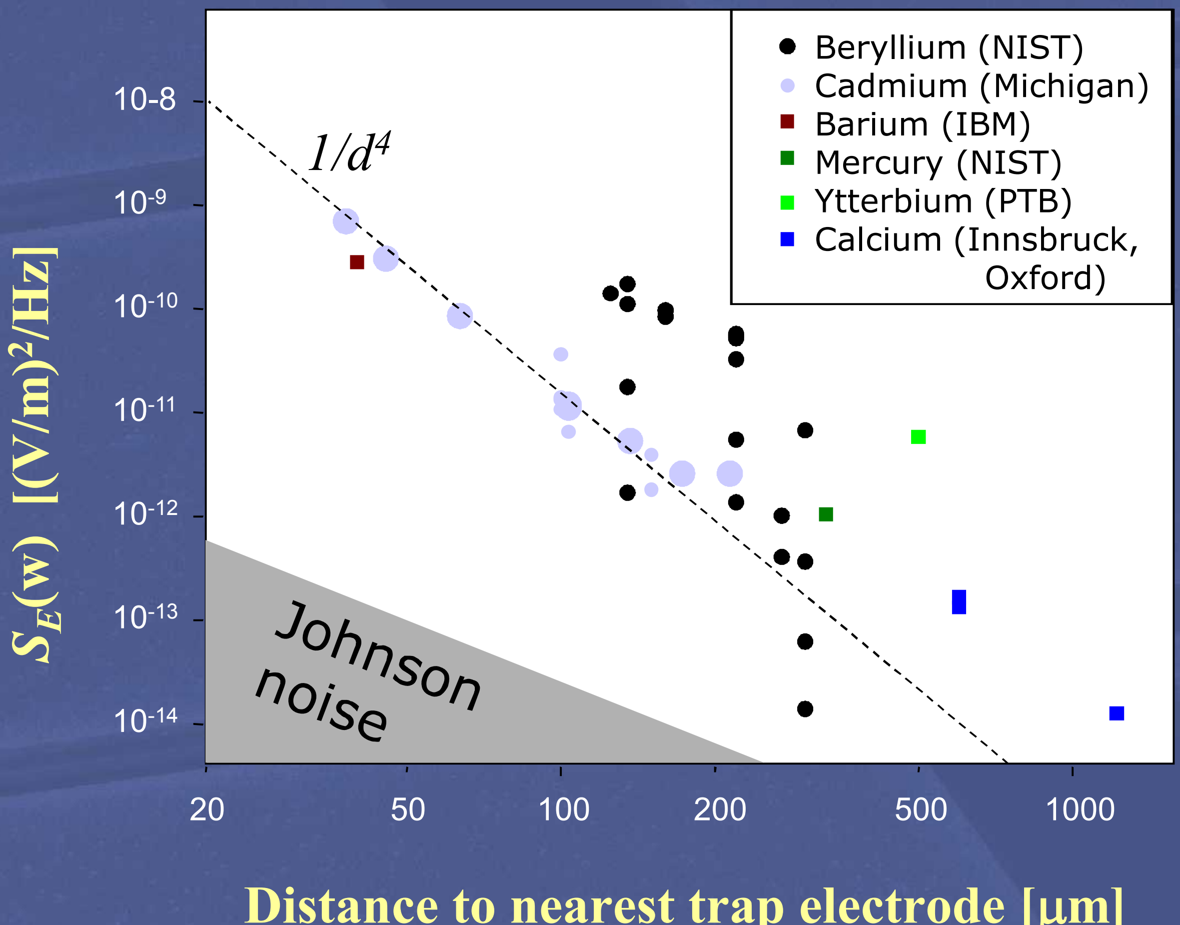
Results: Shuttling

Probability of successfully:

1. Turning the corner, from electrode 8 to 10:
   - 881/882 ~ 100%
2. Returning, from electrode 10 to 8:
   - 116/118 ~ 98%
3. Separation
   - 37/64 ~ 58%
4. Total success rate:
   - 12/51 ~ 24%

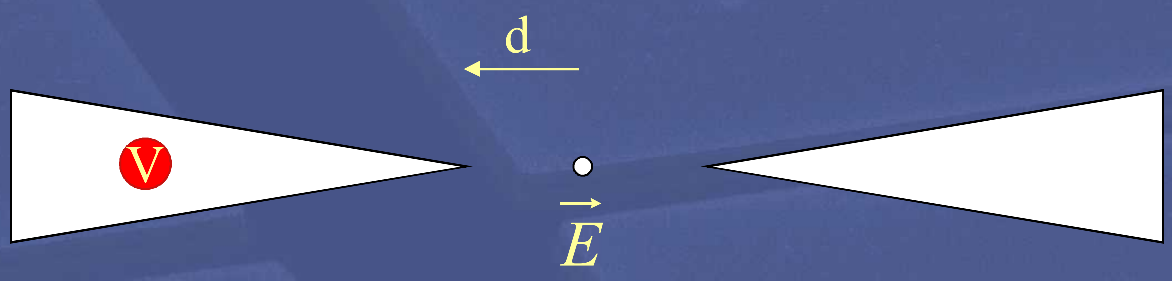


2b. Motional heating vs. ion-electrode distance



$$\dot{n} = \frac{e^2}{4m\hbar\omega} S_E(\omega)$$

Characterizing anomalous 'patch potential' heating



Find ground state heating rate given spectral density of electric field noise.

$$\Gamma_{0\to1} = \frac{1}{\hbar^2}\int_{-\infty}^{\infty} d\tau \cdot e^{i\omega_z\tau}\left\langle E(t)E(t+\tau)\right\rangle \left|\left\langle 0\,|\,qz\,|\,1\right\rangle\right|^2$$

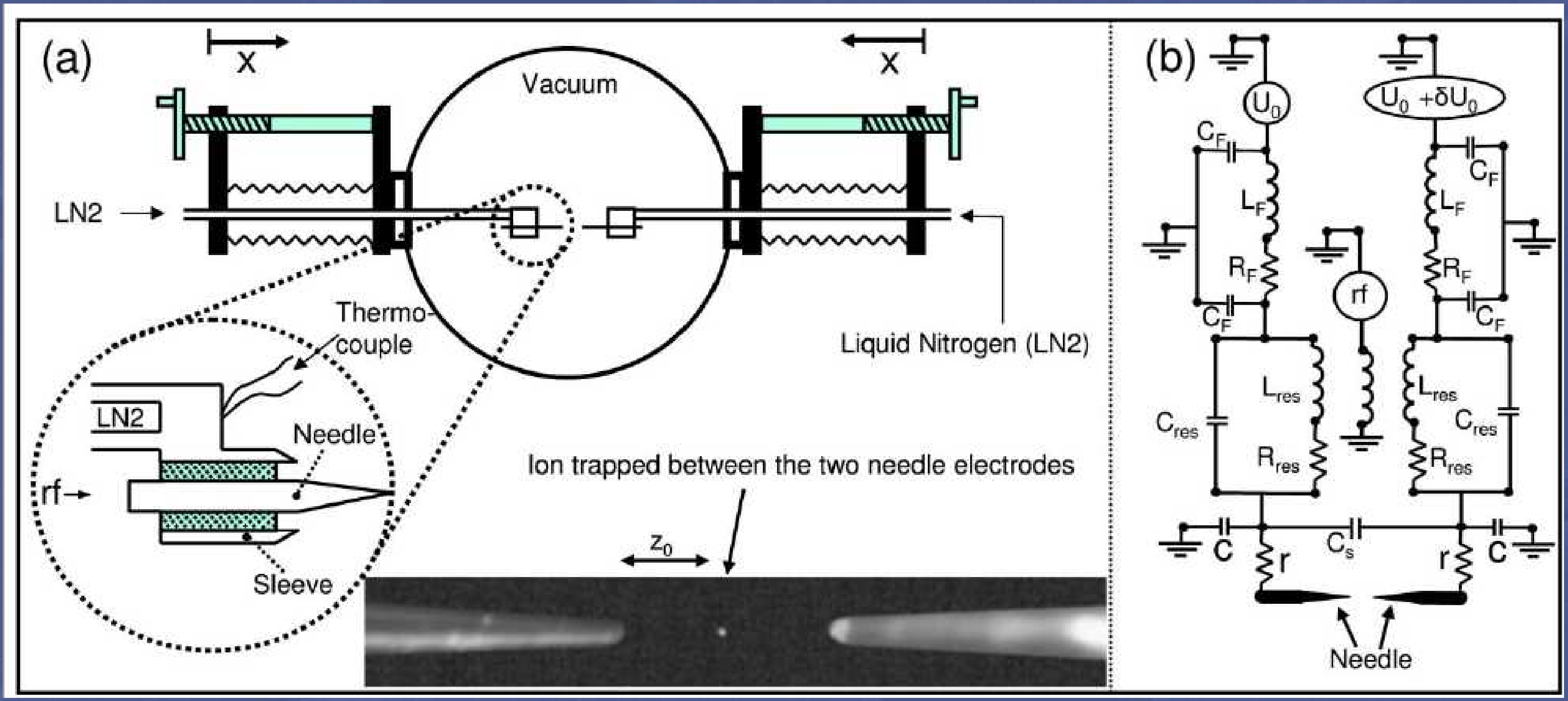
$$= \frac{e^2}{4m\hbar\omega_z} S_E(\omega_z)$$

Find the electric field noise given the ion-electrode distance d, patch size s, and summed over n patches.

$$E_z = V_n \xi_{n,s,d}$$

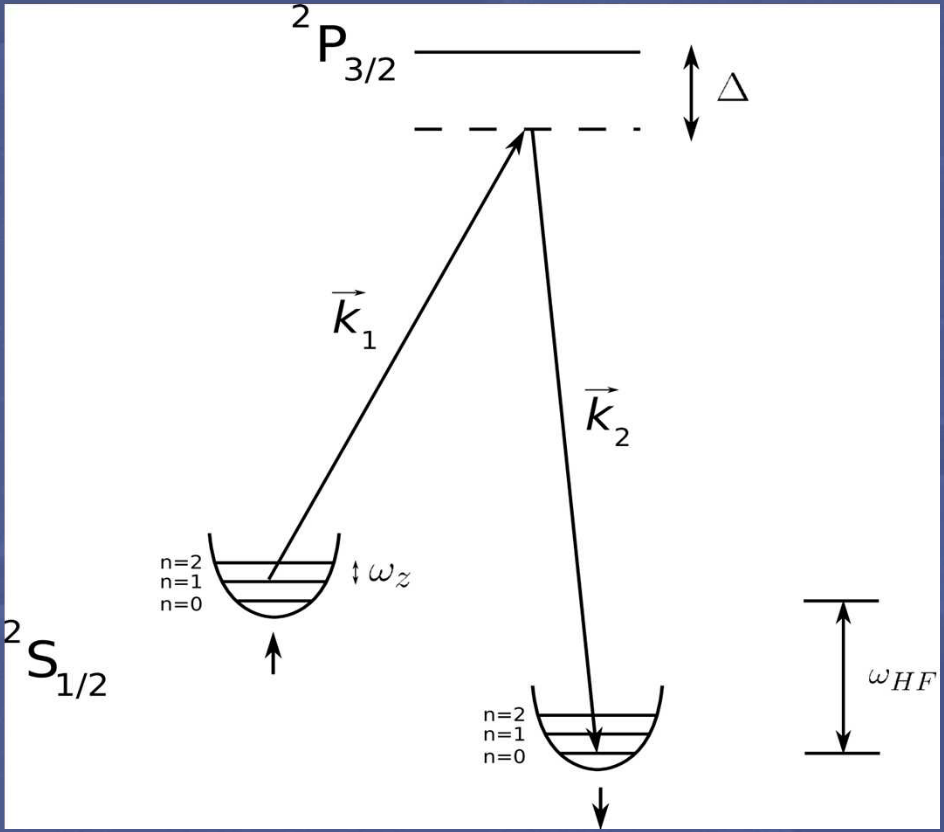
$$S_E(\omega_z) = 2\Big(\sum_n \xi_{n,s,d}^2\Big) S_V(\omega_z)$$

Needle trap



Deslauriers, L., PRL **97** 103007

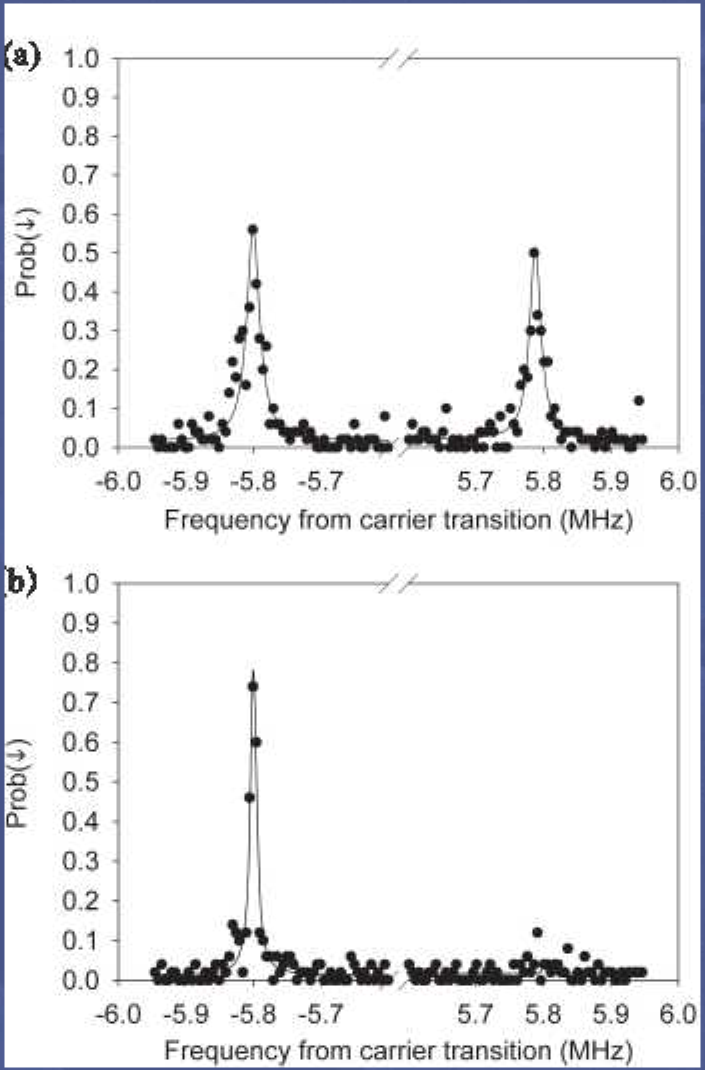
Sideband thermometry



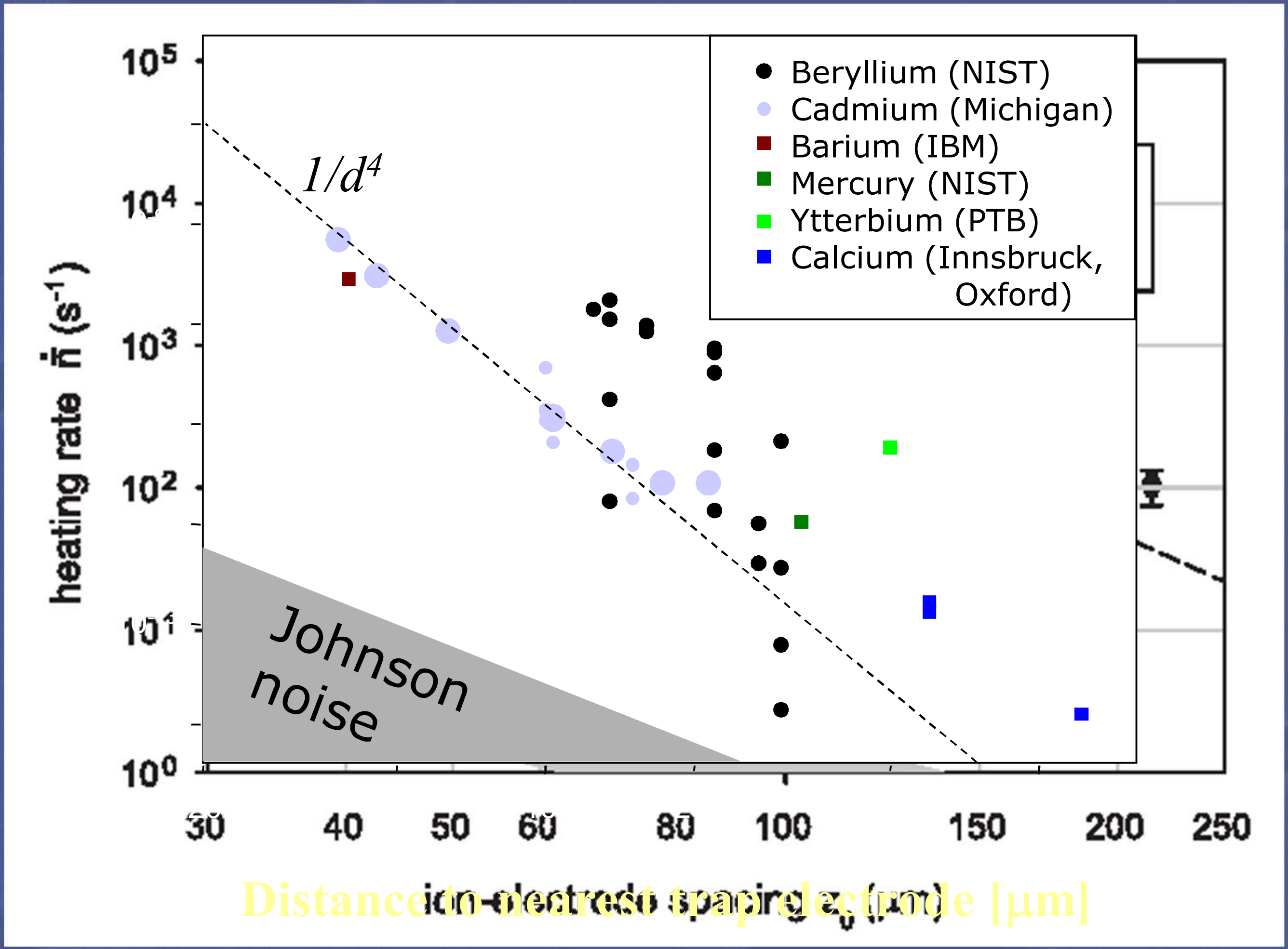
$$\Omega_{n,n} = \Omega_0$$

$$\Omega_{n,n-1} = \Omega_0 \eta \sqrt{n}$$

$$\Omega_{n,n+1} = \Omega_0 \eta \sqrt{n+1}$$

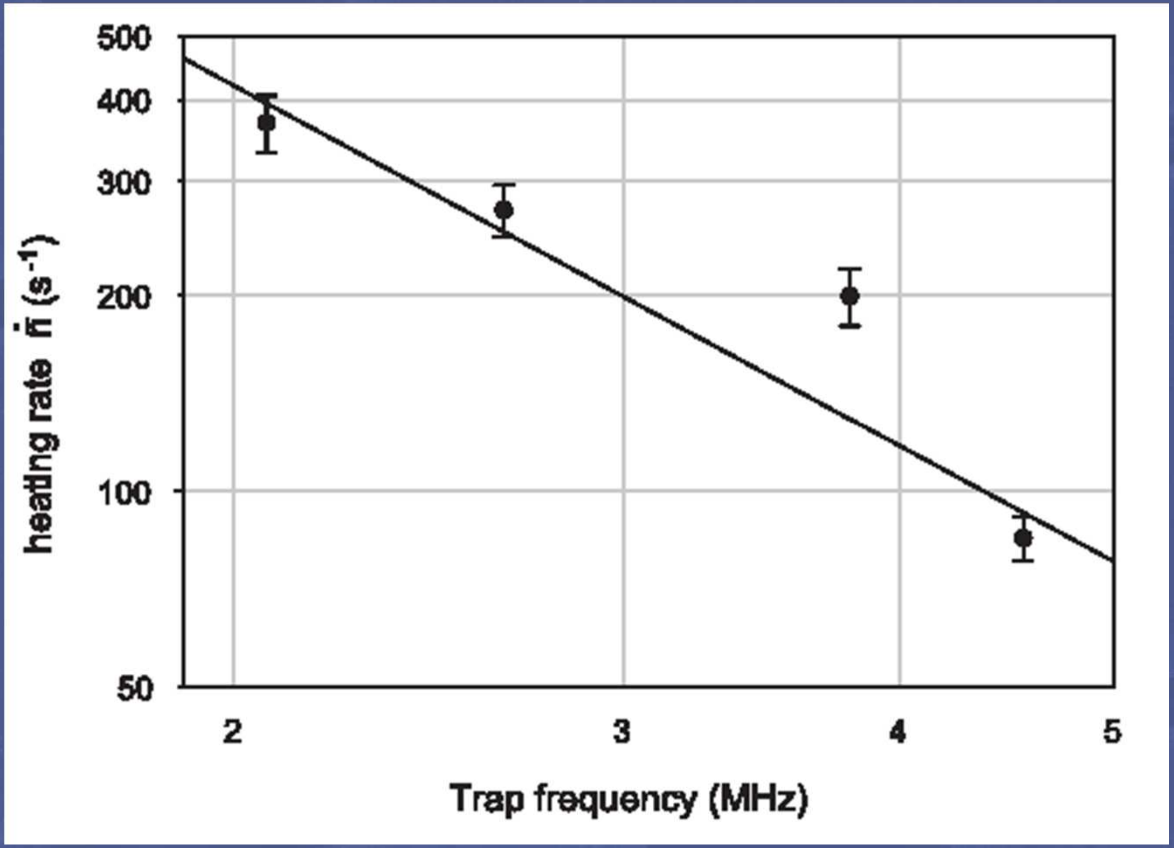


Results: Heating vs. distance



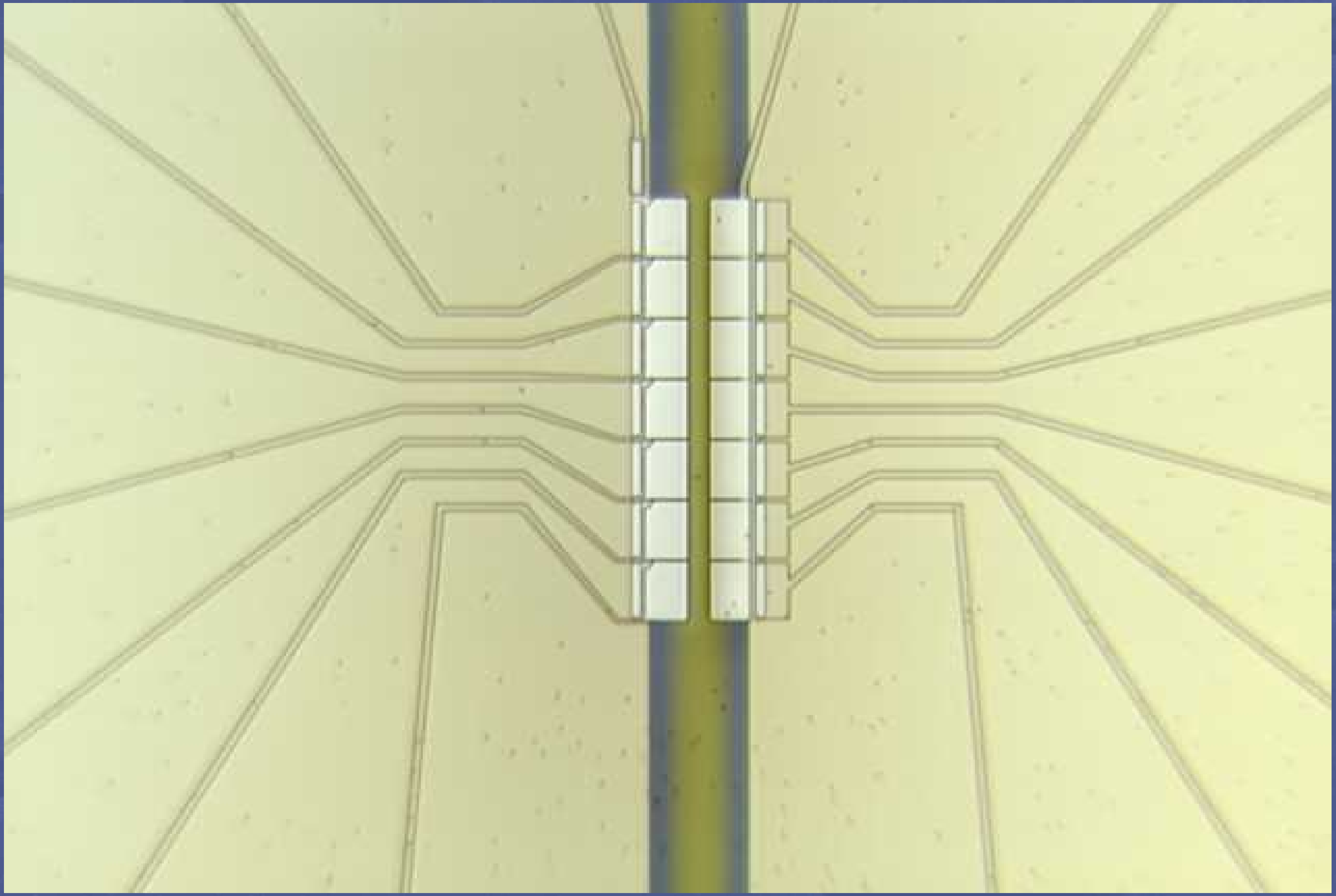
$$S_E(\omega) \propto d^{-3.5\pm.1}$$

Results: Heating vs Frequency



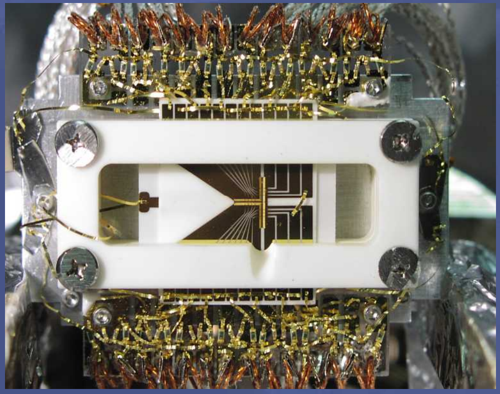
$$S_E(\omega) \propto \omega^{-.8\pm.2}$$

2c. Examples of microfabricated traps



Advantages of microfabricated traps

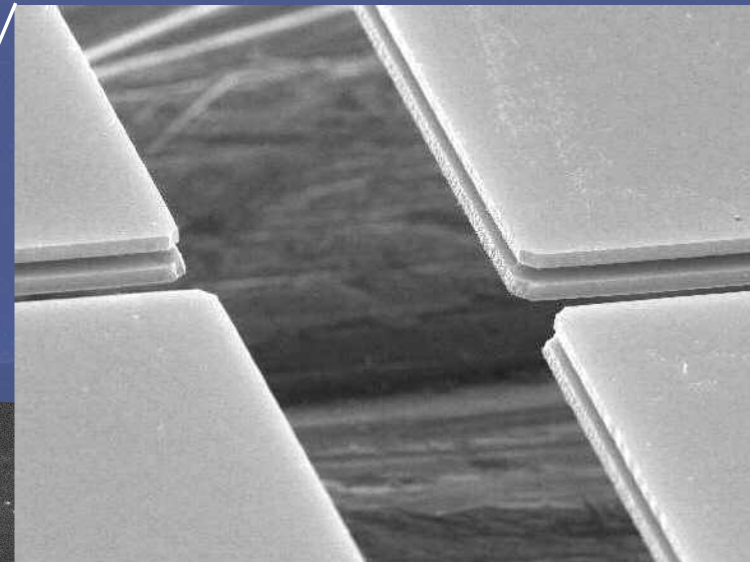
- No assembly (except wire bonding)
  - No alignment
- Small electrodes
- Scalable – change photolithographic mask
  - Easy to change design
- On board filters for DC electrodes, control electronics integration

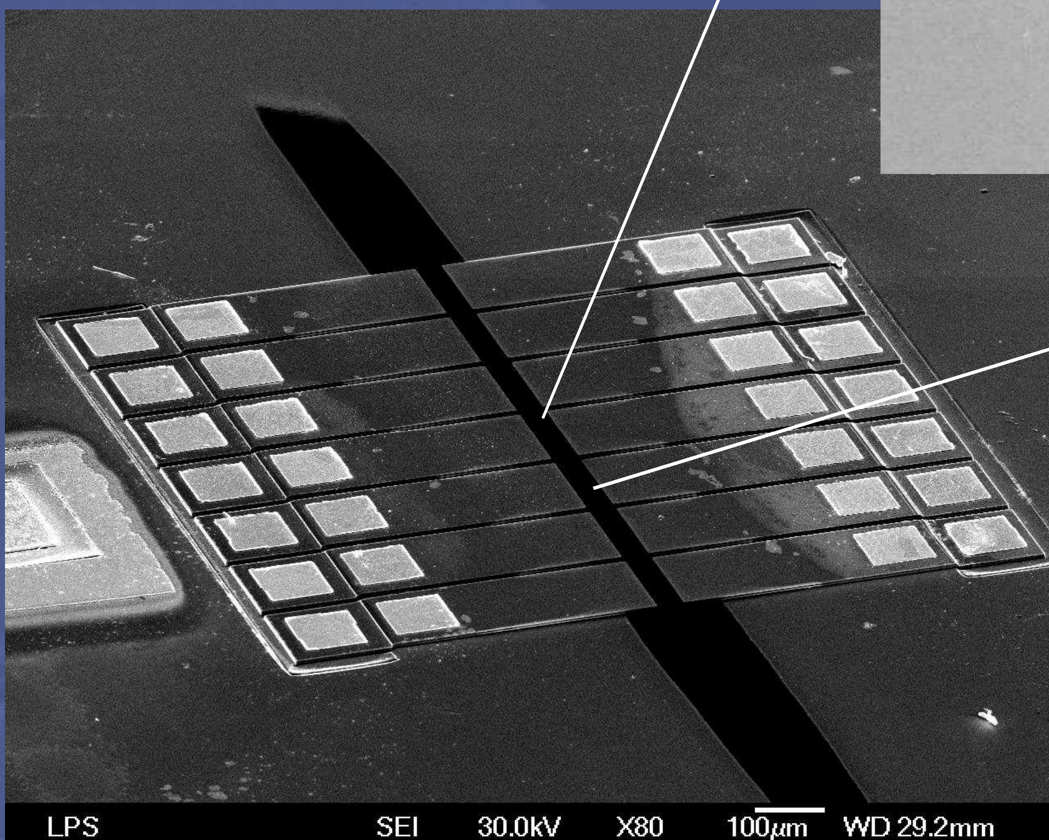


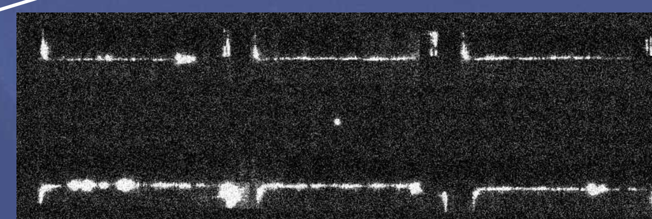
Disadvantages of microfabricated traps

- Material properties
  - Lossy conductors, high parasitic capacitance, low breakdown insulators
  - Power dissipation: $V^2 \Omega C (R C \Omega + \tan\delta)$
- Restricted physical dimensions
  - Limited vertical thicknesses
- Small size drastically increases heating

Trapping Parameters





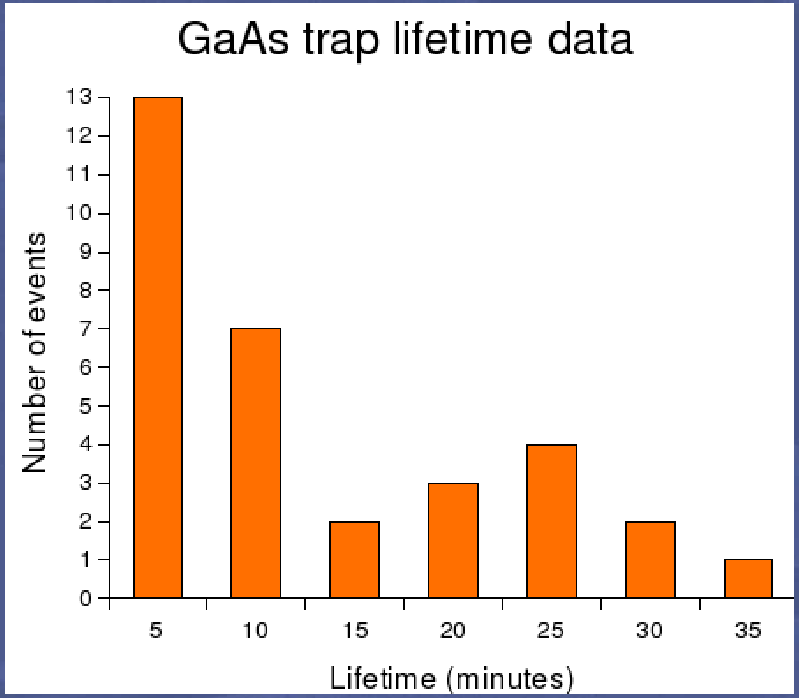


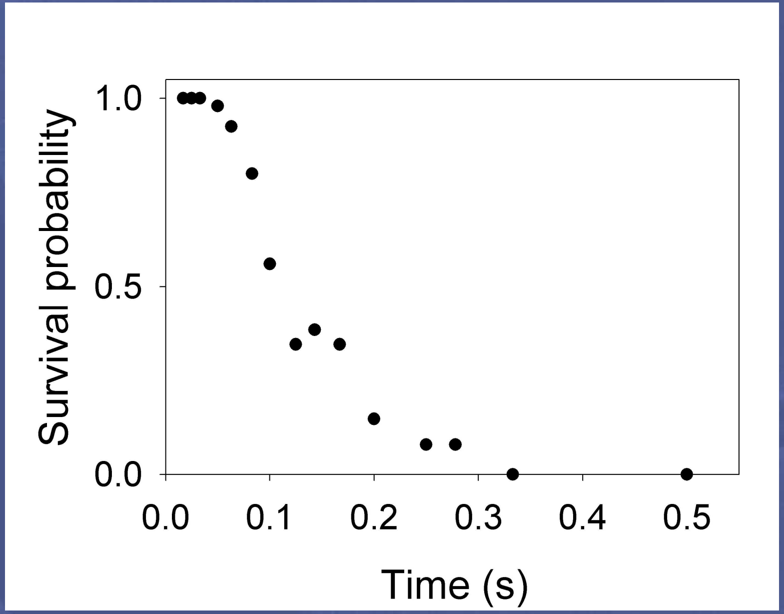
Depth = 3 x room temperature

$\omega/2\pi$ = 1 MHz

Stick, D., Nature Physics **2**, 36-39

Results: lifetime with and without cooling



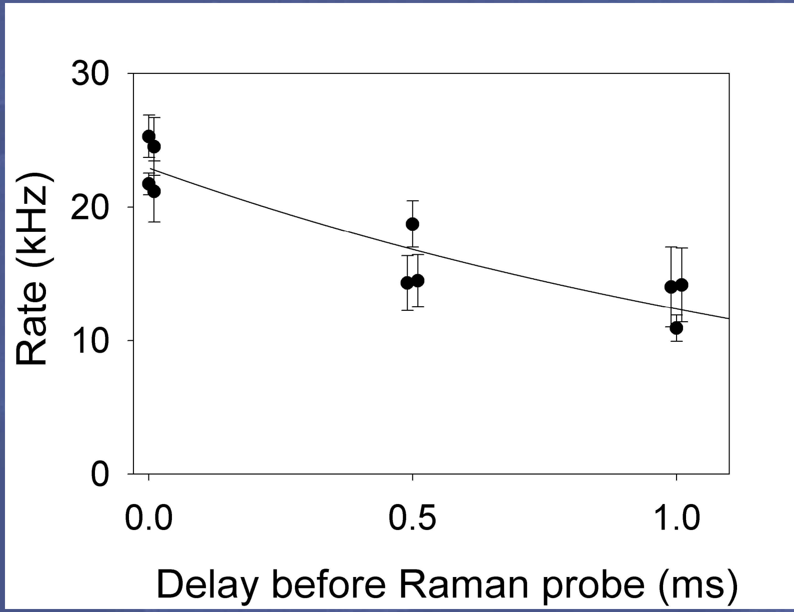


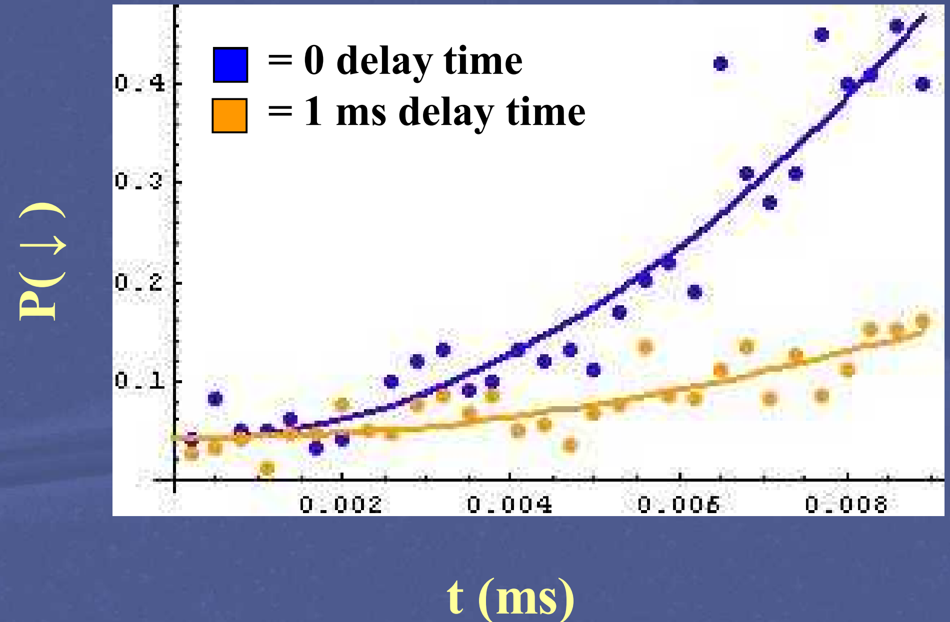
Results: heating rate

$$\Omega_{n,n} = \Omega_0 e^{-\eta^2/2} L_n^2(\eta^2)$$

$$S(t) = \sin^2(\Omega_{n,n} t/2)$$

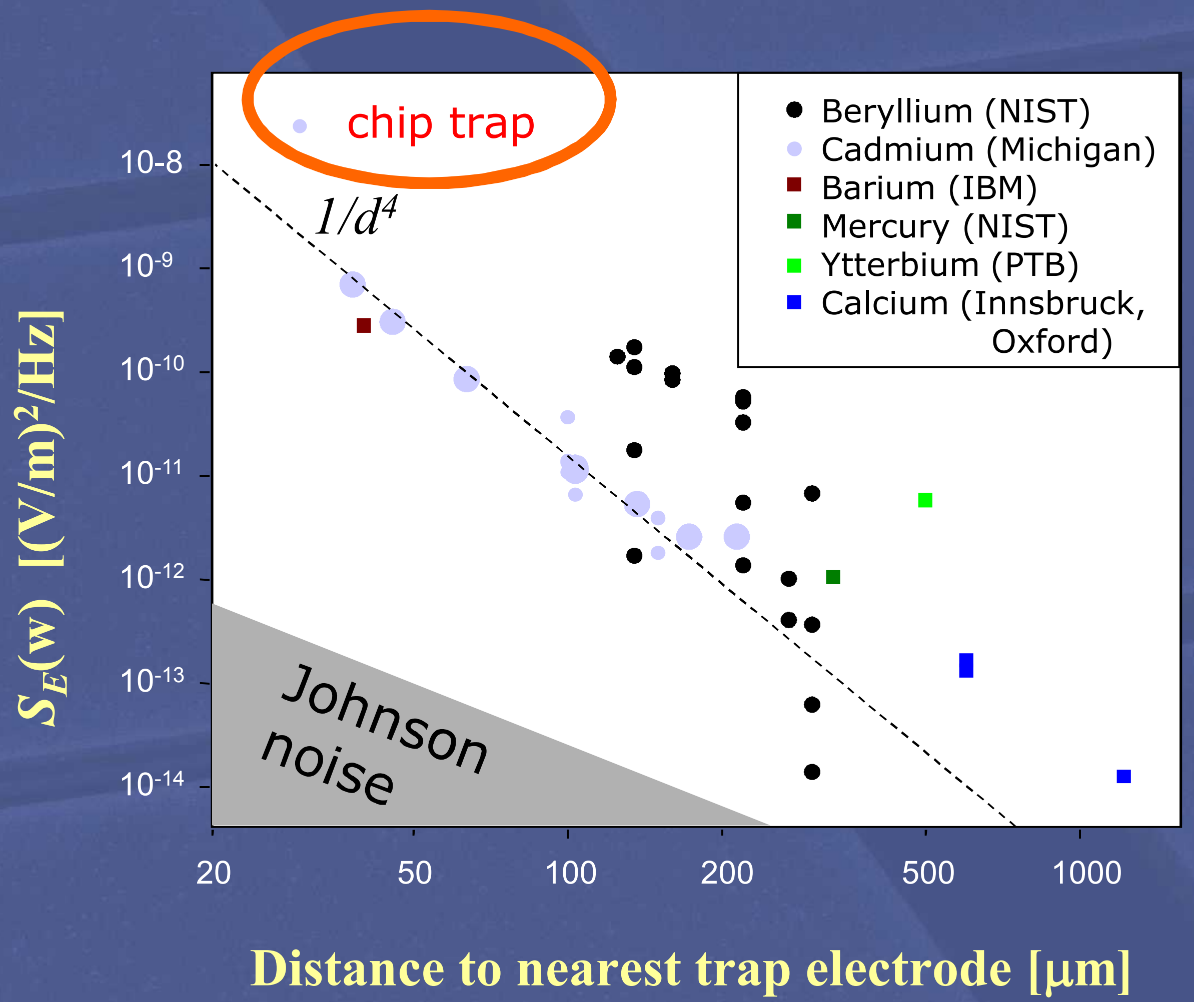
$$= \frac{\Omega_0 t^2}{4}(1 - 2\eta^2 \Gamma T)$$



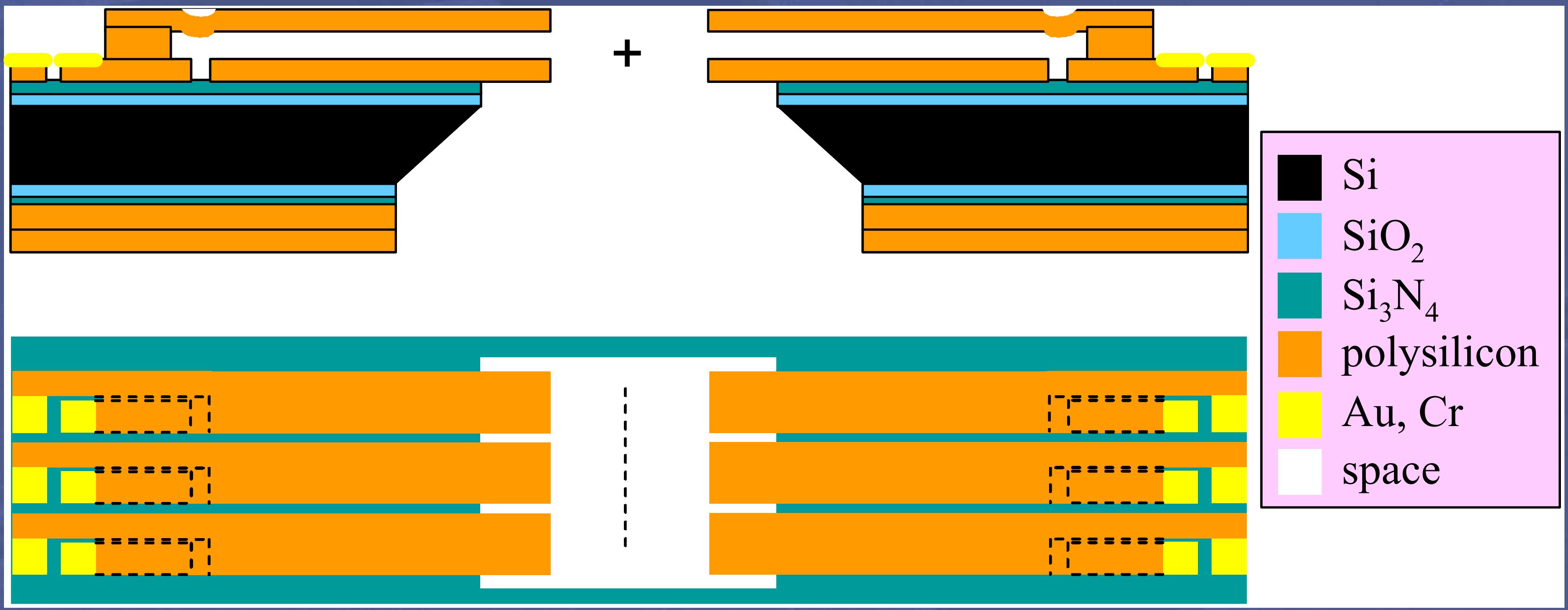


Heating rate:
1±.5 quanta/microsecond

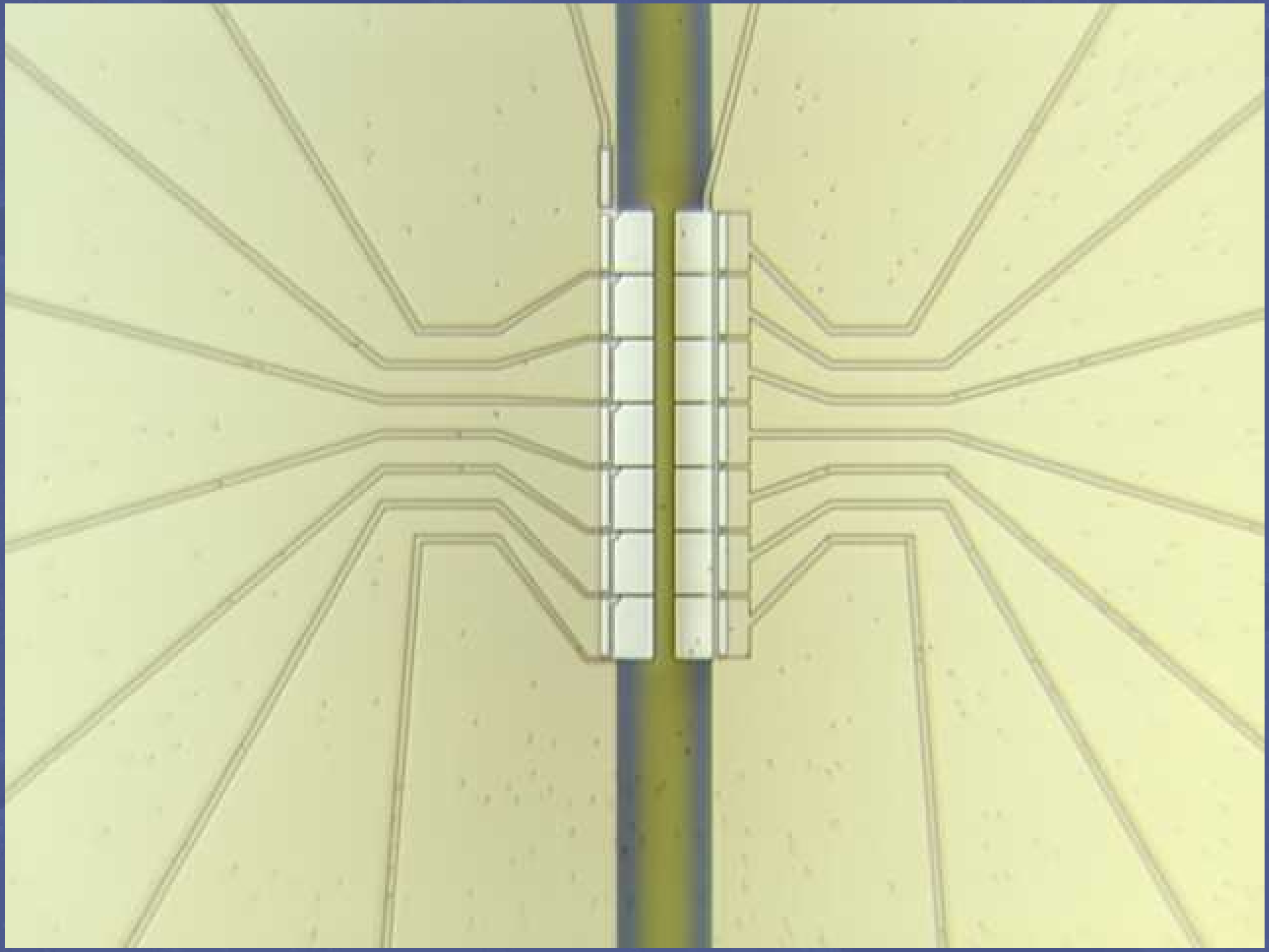
Heating rate relative to other traps



Polysilicon MEMS trap



Polysilicon MEMS trap

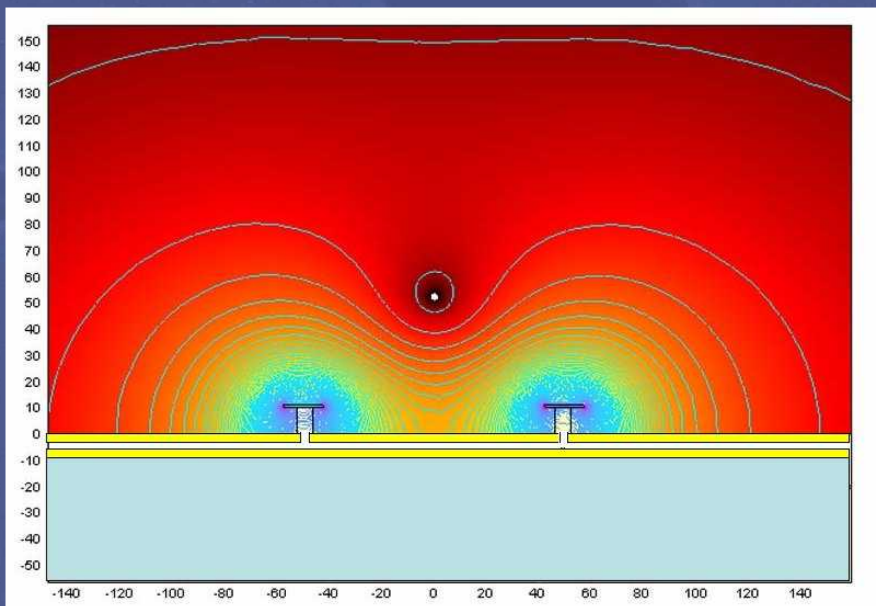


Si/SiO$_2$ “surface” trap

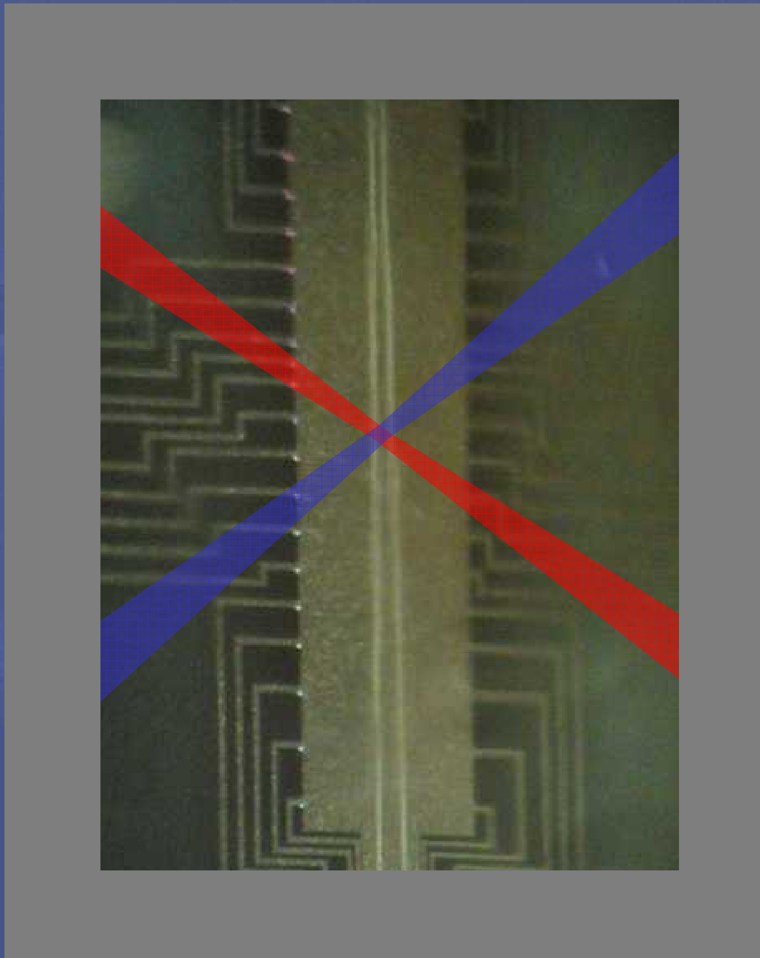
R. Slusher, Lucent

Ponderomotive potential

Vertical distance (μm)

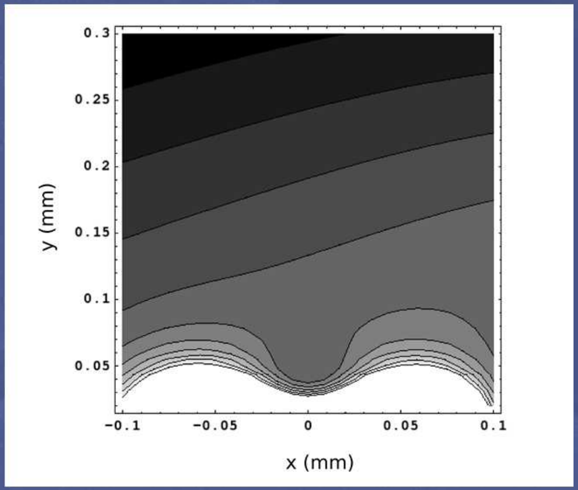


Horizontal distance (μm)

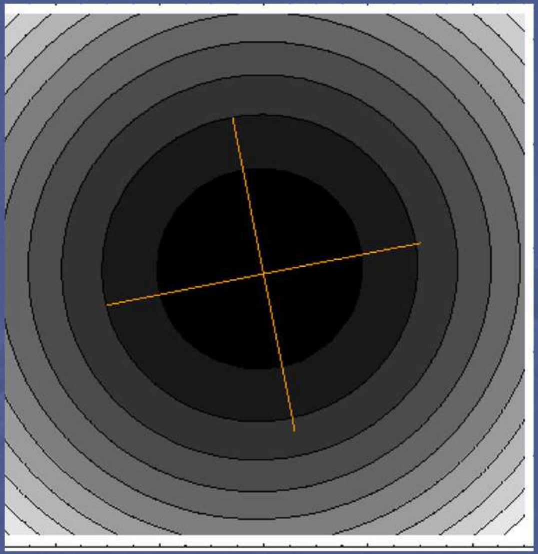


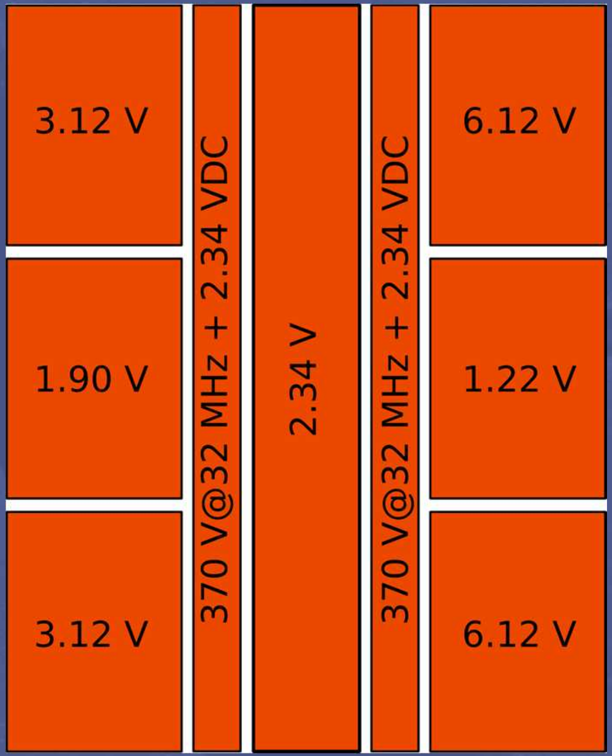
S. Seidelin, et al. Phys. Rev. Lett. **96**, 253003 (2006)

Results: Tilting the principal axes



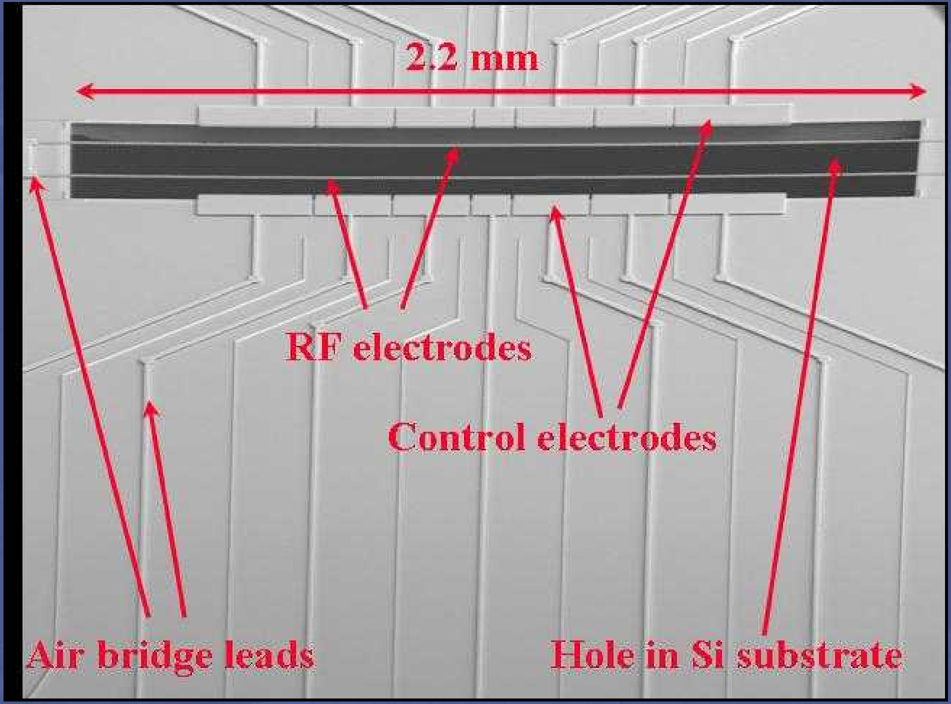
The principal axes are the directions in which the ion's motion is uncoupled from the other directions. The laser cannot cool the ion's motion if it is perpendicular to one of the principal axes.

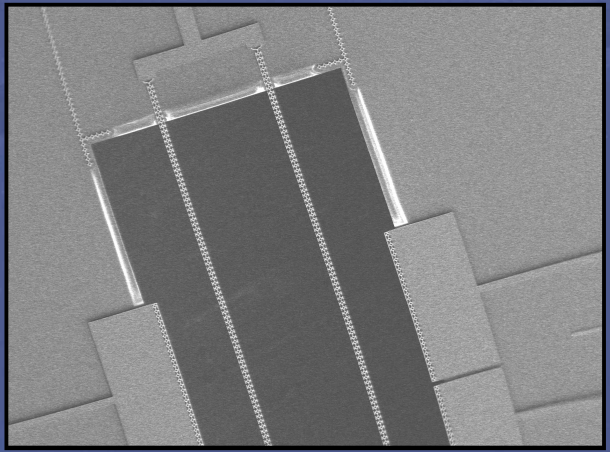


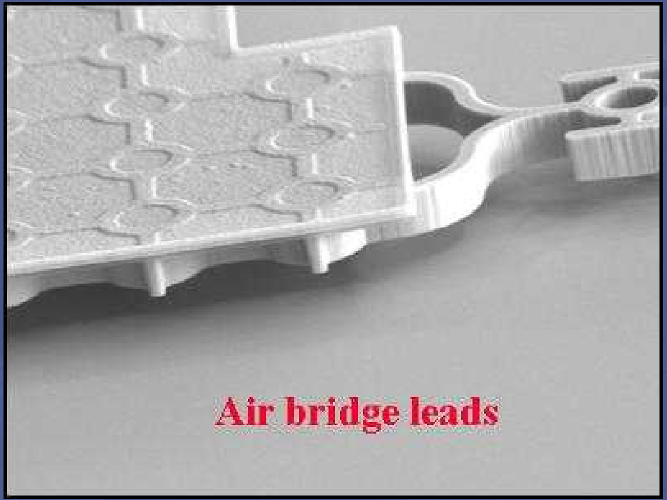


Tungsten traps

M. Blain, C. Tigges, J. Hudgens, Sandia







Summary

University of Michigan
Trapped Ion Quantum Computing

Grad Students
Mark Acton
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to Stanford
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to NIST-G'burg
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David Moehring
Steven Olmschenk
Jon Sterk
Yisa Rumala
Daniel Stick
Kelly Younge

Collaborators
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Jim Rabchuk (W. Illinois)
Keith Schwab (Cornell)

Postdocs
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to U. Washington
Paul Haljan
to Simon Fraser U.
Winfried Hensinger
to U. Sussex
Peter Maunz
Ming-Shien Chang
Dzmitry Matsukevich

Undergrads
Jacob Burress
Dan Cook
David Hucul
Rudy Kohn
Elizabeth Otto
Mark Yeo

US National Security Agency

NSF **National Science Foundation**

DARPA **US Defense Advanced Research Projects Agency**

DTO **Disruptive Technology Office**

FOCUS **Michigan FOCUS Center**

US Army Research Office