University of Michigan
Trapped Ion Quantum Computing

Grad Students
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Kathy-Anne Brickman
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to Stanford
Patricia Lee
to NIST-G'burg
Martin Madsen
David Moehring
Steven Olmschenk
Jon Sterk
Daniel Stick
Kelly Younge

Postdocs
Boris Blinov
to U. Washington
Paul Haljan
to Simon Fraser U.
Winfried Hensinger
to U. Sussex
Peter Maunz

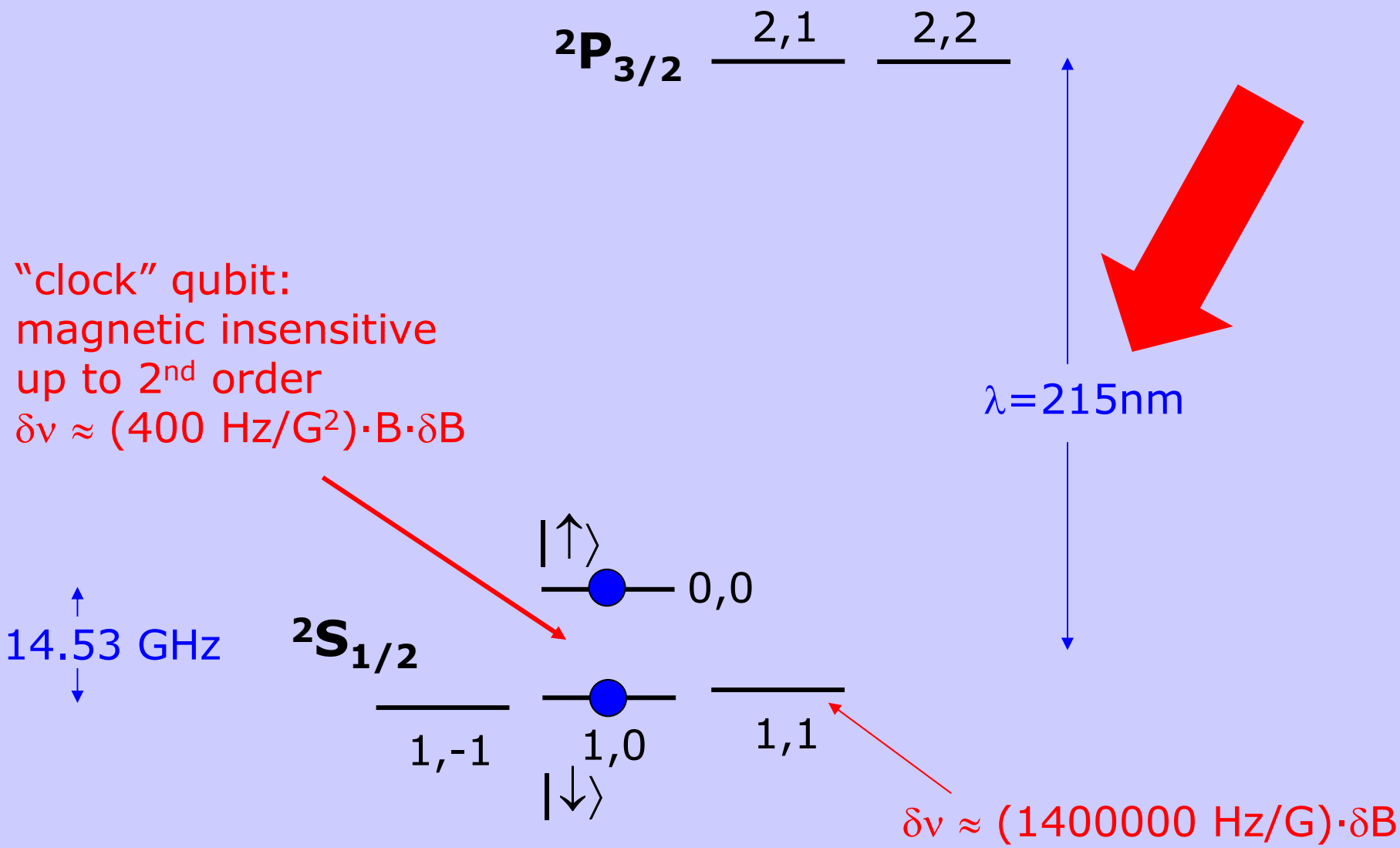
Undergrads
David Hucul
Rudy Kohn
Elizabeth Otto
Mark Yeo

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

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

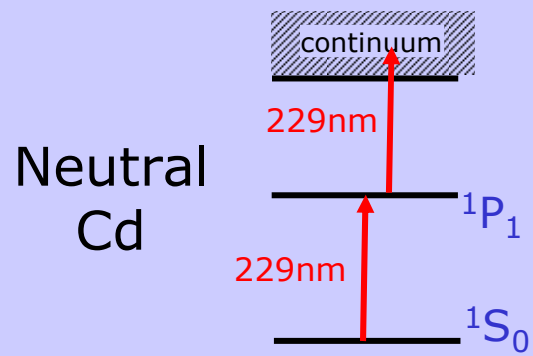
DTO — **US Disruptive Technology Office**
US Army Research Office
FOCUS — **NSF FOCUS Center**
US National Security Agency
NSF — **National Science Foundation**
DARPA — **US Defense Advanced Research Projects Agency**

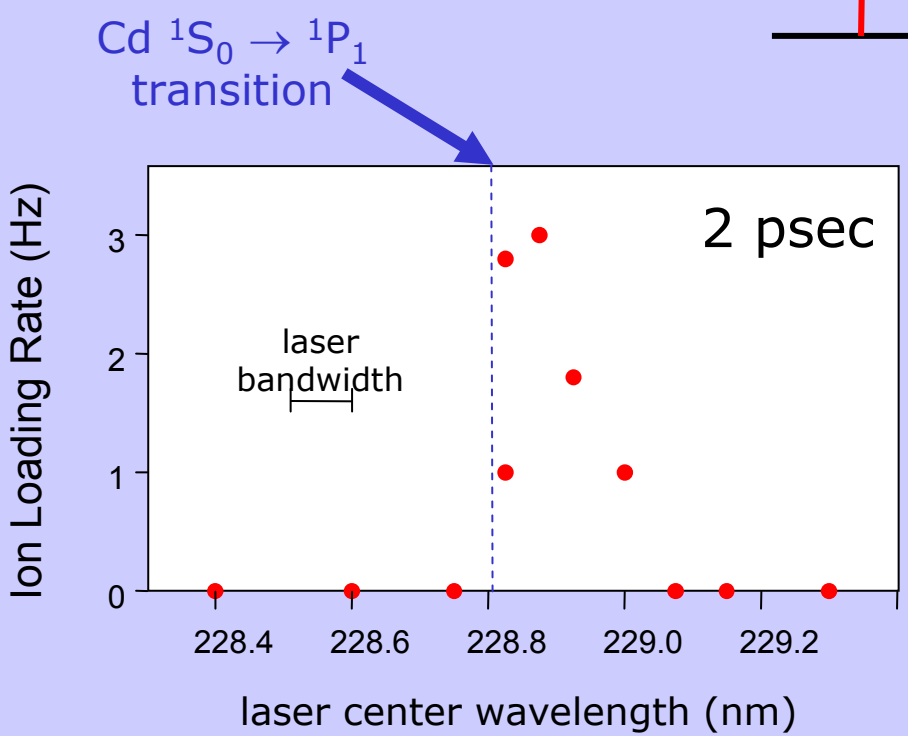
$^{111}Cd^{+}$ atomic structure

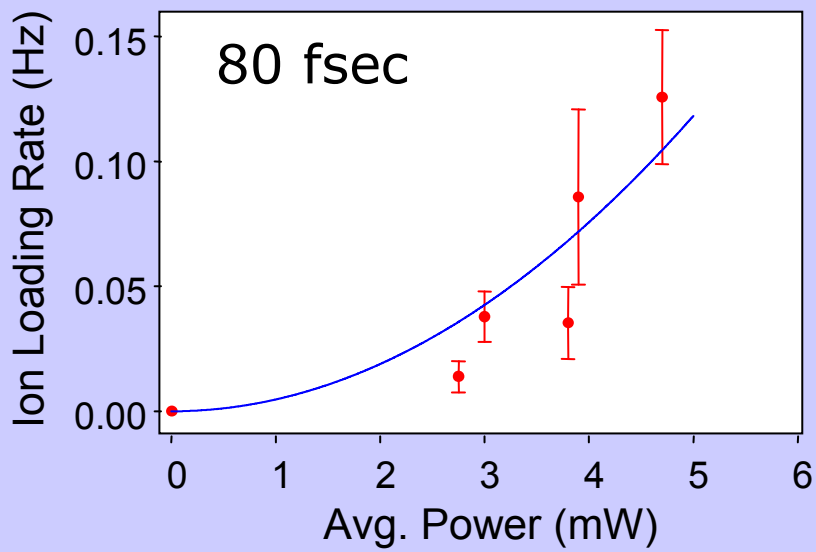


Broadband photoionization of neutral Cd

- 80 MHz pulsed laser capable of loading 100% of atoms
- Cd vapor pressure at room temperature: 10^{-11} torr
  VERY CLEAN (little risk of elecrode shorting)

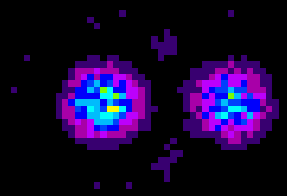






Michigan Ion Trap Projects

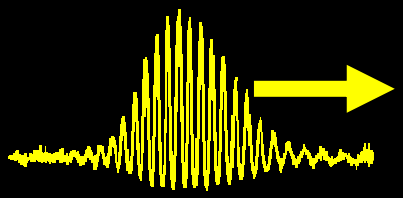
- Local entanglement through the Coulomb interaction (phonons)



- Advanced trap structures

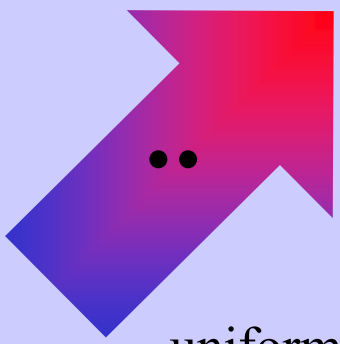
- Entanglement though atomic spontaneous emission (photons)

- Ultrafast laser-ion interactions

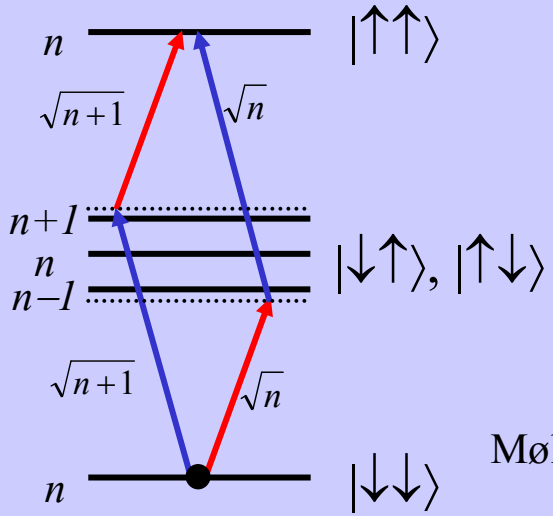


Entanglement of "Clock state" qubits

x-basis spin-dependent force (Mølmer/Sørensen)



uniform illumination



$$|\downarrow\downarrow\rangle \Rightarrow |\downarrow\downarrow\rangle + e^{i\phi}|\uparrow\uparrow\rangle$$
$$|\uparrow\uparrow\rangle \Rightarrow |\uparrow\uparrow\rangle - e^{-i\phi}|\downarrow\downarrow\rangle$$
$$|\downarrow\uparrow\rangle \Rightarrow |\downarrow\uparrow\rangle + i|\uparrow\downarrow\rangle$$
$$|\uparrow\downarrow\rangle \Rightarrow |\uparrow\downarrow\rangle + i|\downarrow\uparrow\rangle$$

Mølmer/Sørensen, *Phys. Rev. Lett.* **82,**1835 (1999)
Sackett, et. al. *Nature* **404**, 256 (2000)

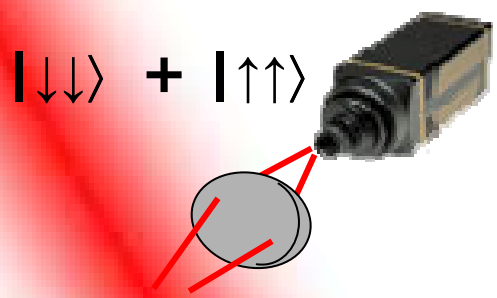
$$H = \hbar\Omega\hat{\sigma}_x^{(1)} \otimes \hat{\sigma}_x^{(2)}$$

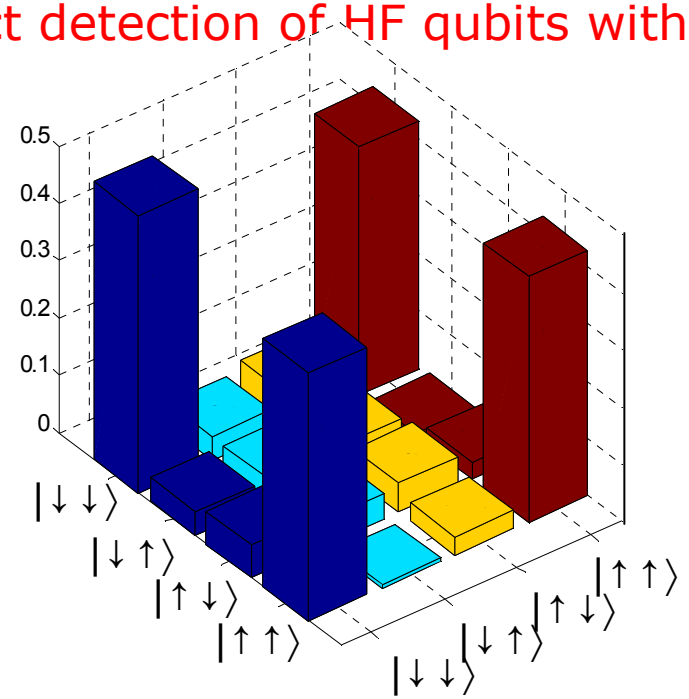
removing sensitivity to absolute optical phase ϕ:
P.C. Haljan, et al., PRL **94** 153602 (2005)
P.J. Lee, et al., J. Opt. B **7**, S371 (2005)
P.C. Haljan, et al., PRA (2005)

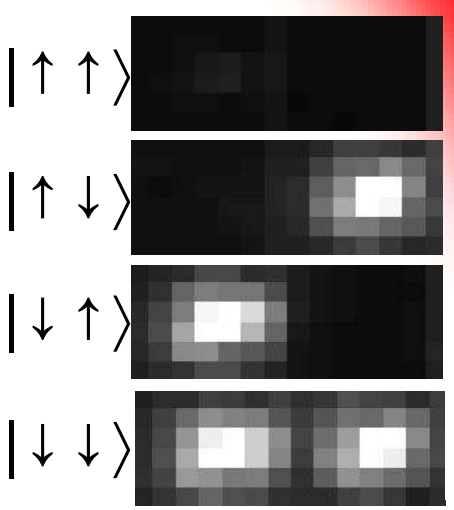
P. Haljan
POSTER M21

sity Matrix Reconstruction of Entangled State

- The Molmer/Sorensen gate
- Uses B-insensitive HF "clock" qubits
- Composite single-bit rotations from μwaves & focused Stark-shift beam
- Simultaneous near-perfect detection of HF qubits with CCD







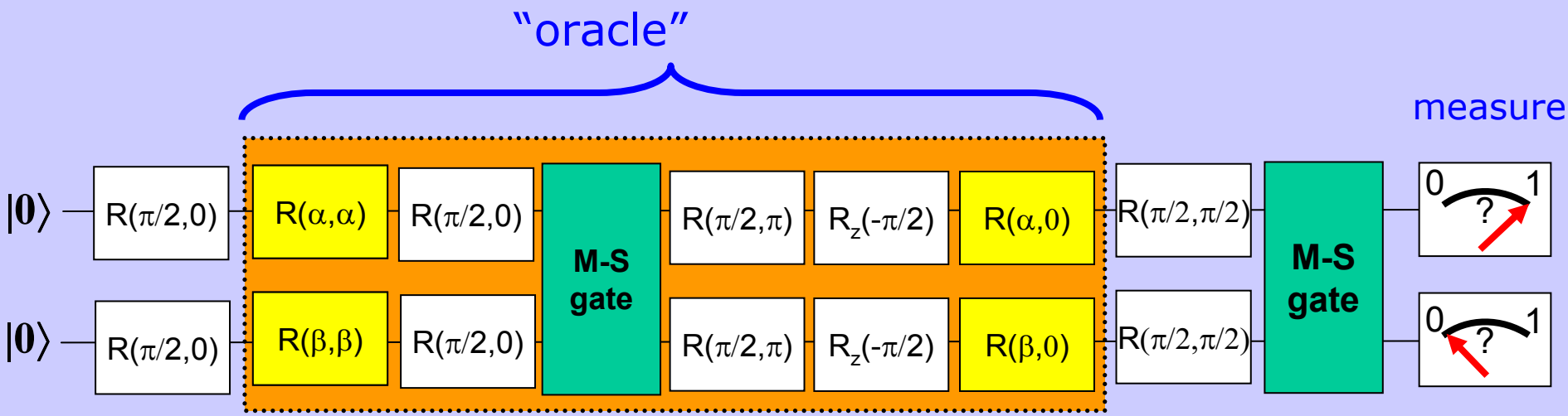
Entanglement Fidelity ~ 80-90%

P. C. Haljan, et al., PRA **72**, 062316 (2005)
D. James *et al.*, PRA **64**, 052312 (2001)

limited by spont. em. and fluctuating Stark shifts (NEED MORE LASER POWER!)

Implementation of Grover's Search Algorithm

on N=2 ions (4-element database)



mark state with Bloch-sphere rotation angles

	α	β
$\|00\rangle$	π	π
$\|01\rangle$	π	0
$\|10\rangle$	0	π
$\|11\rangle$	0	0

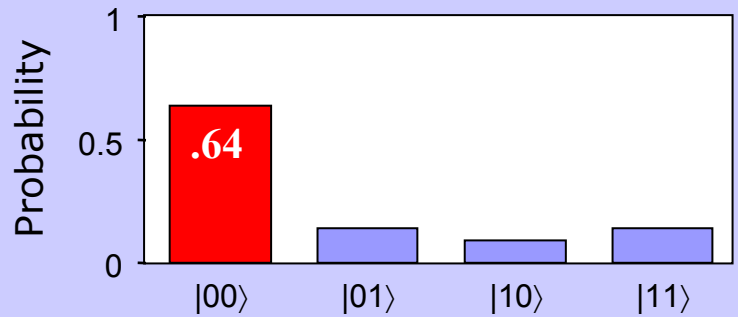
K.-A. Brickman, et al., PRA **72,** 050306 (2005)

Single query of quantum database

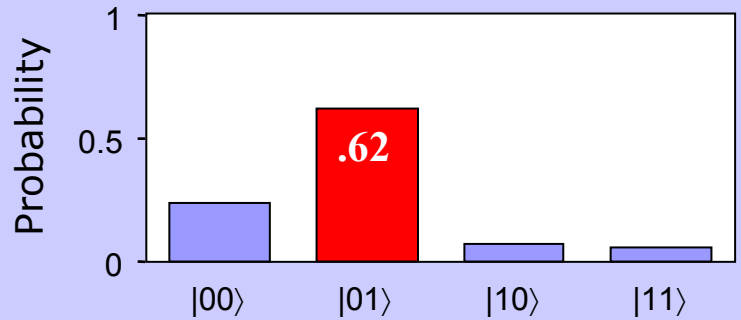
single query of 4-element classical database:

$\langle$**Prob**$\rangle \leq$ **0.50**

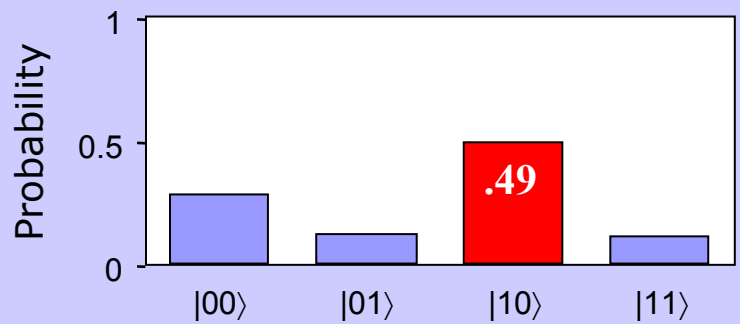
$|00\rangle$ marked



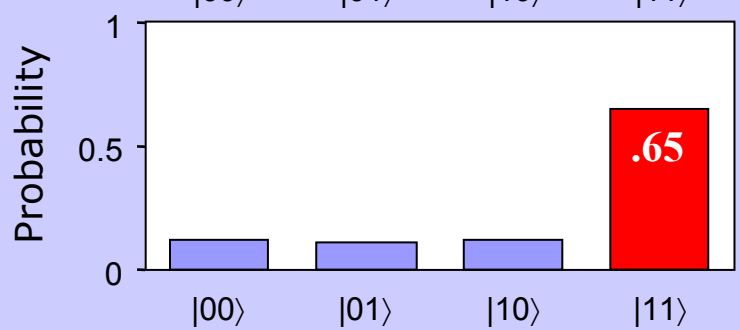
$|01\rangle$ marked



$|10\rangle$ marked



$|11\rangle$ marked



P. Haljan
POSTER M21

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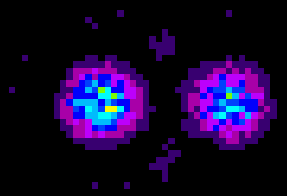

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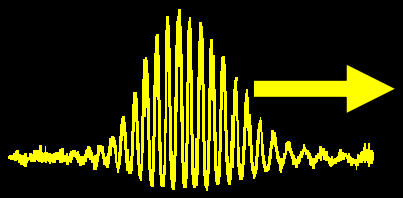
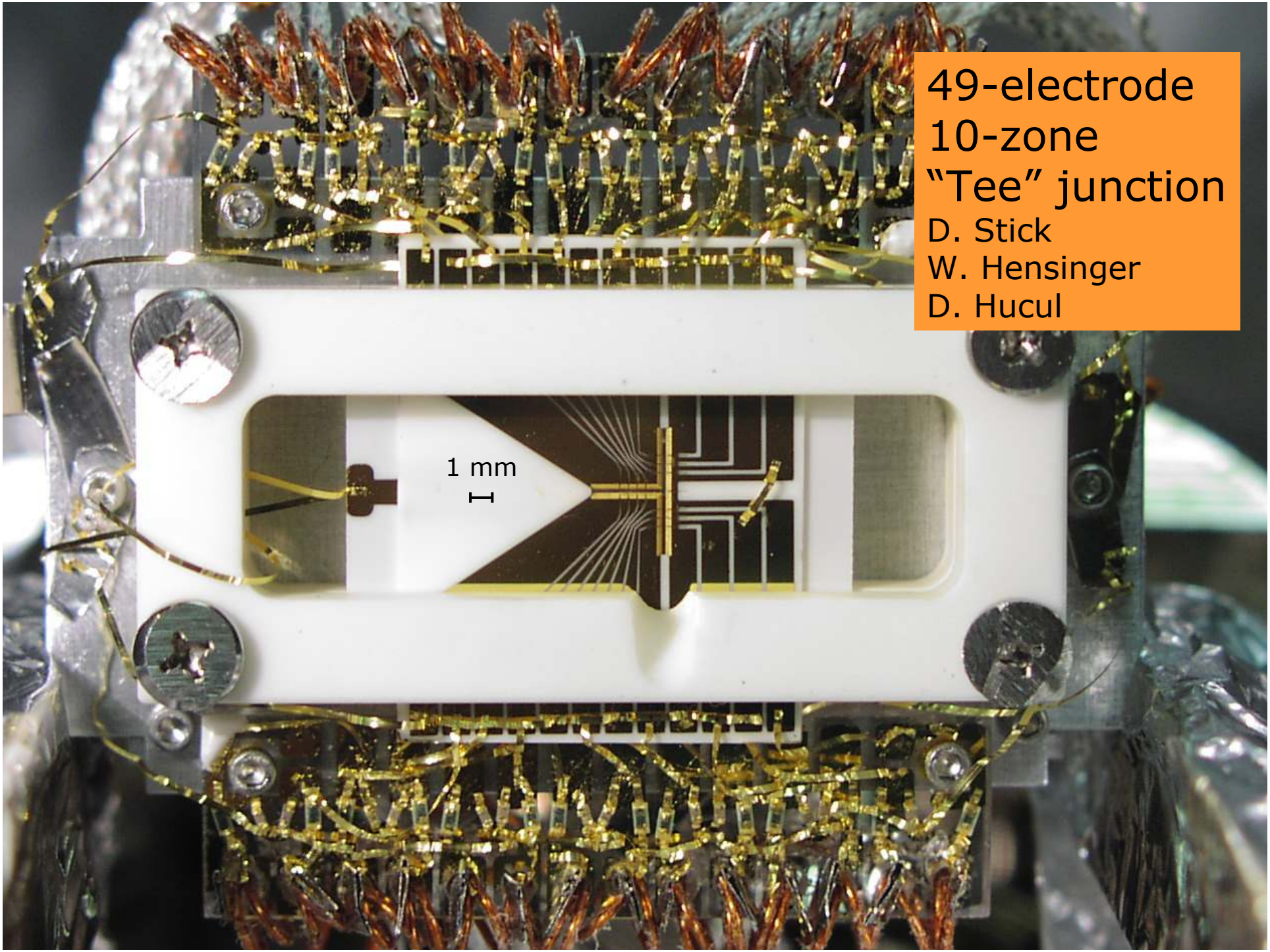
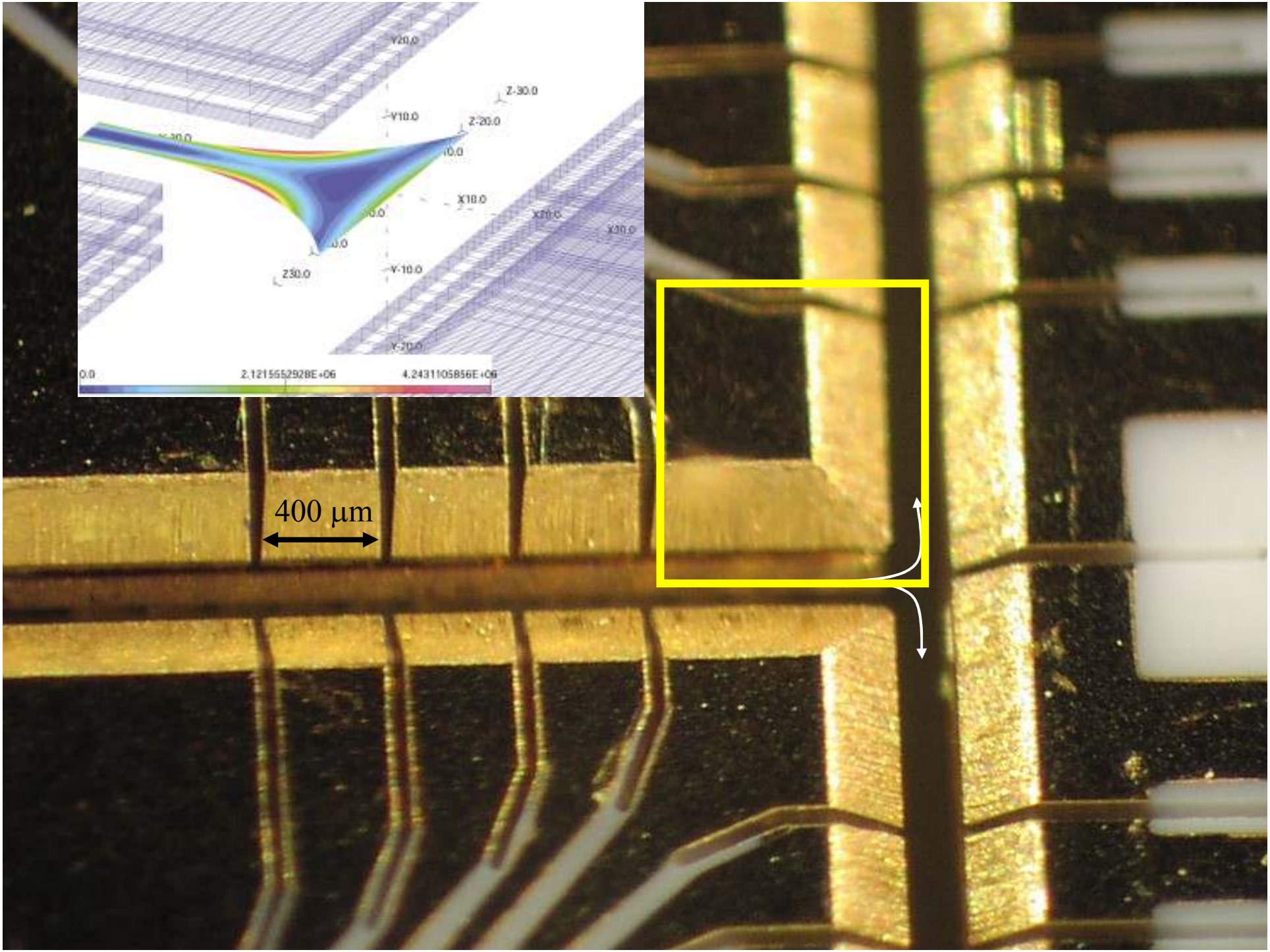
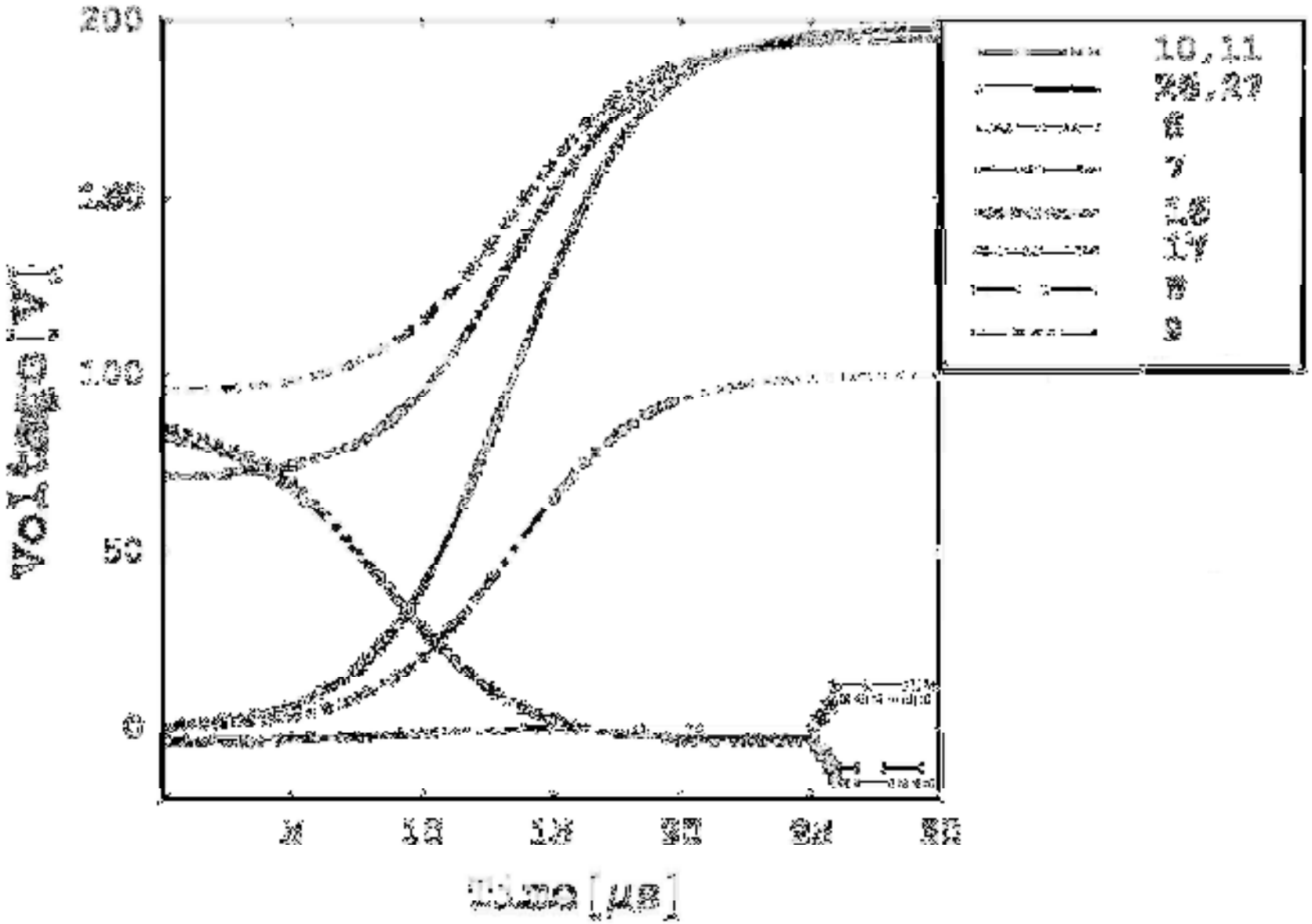




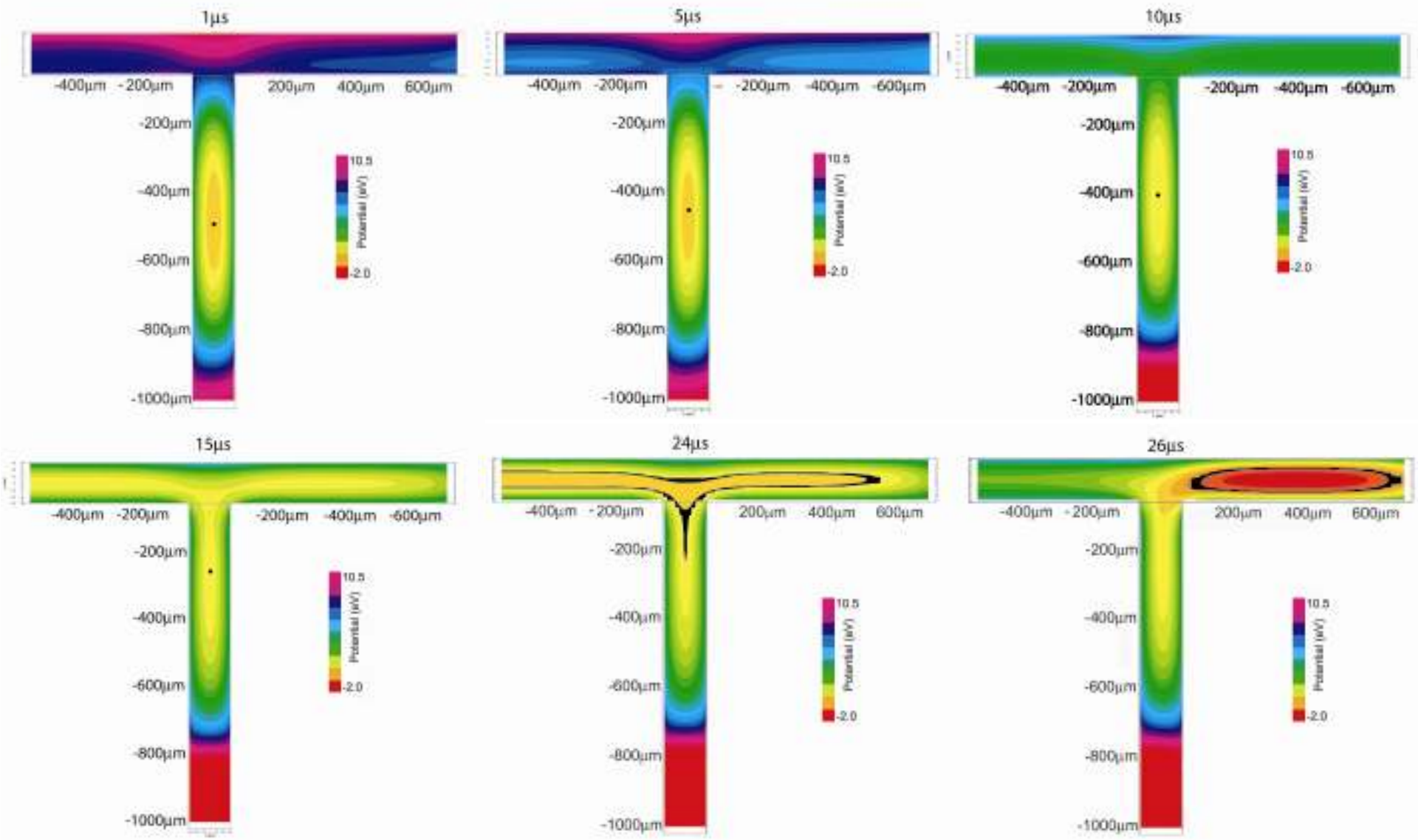
49-electrode
10-zone
"Tee" junction

D. Stick
W. Hensinger
D. Hucul

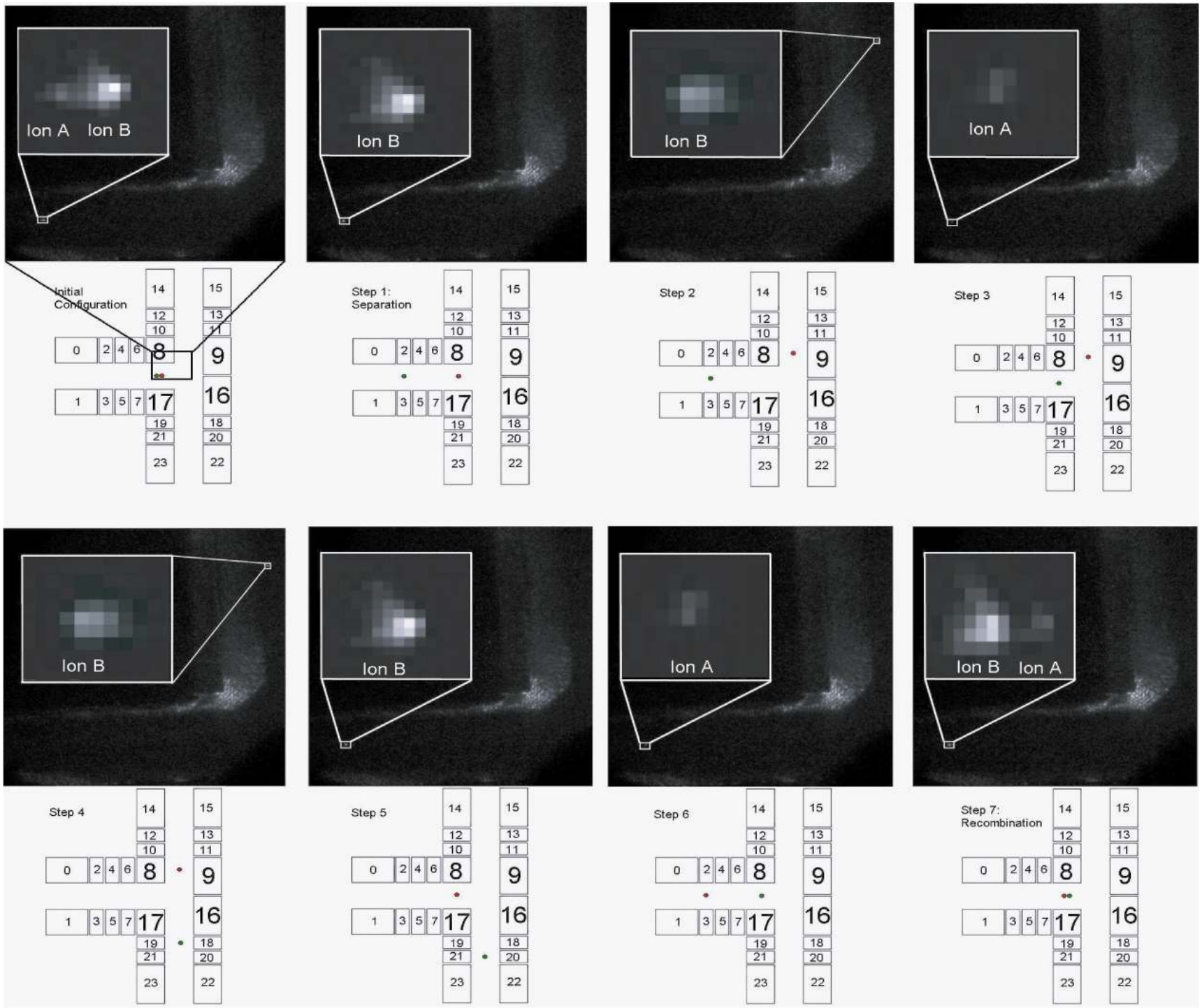

400 µm
0.0
2.1215552928E+06
4.2431105856E+06



200
150
100
50
0
Voltage [V]
10,11
26,27
6
7
16
17
8
9
Time [μs]

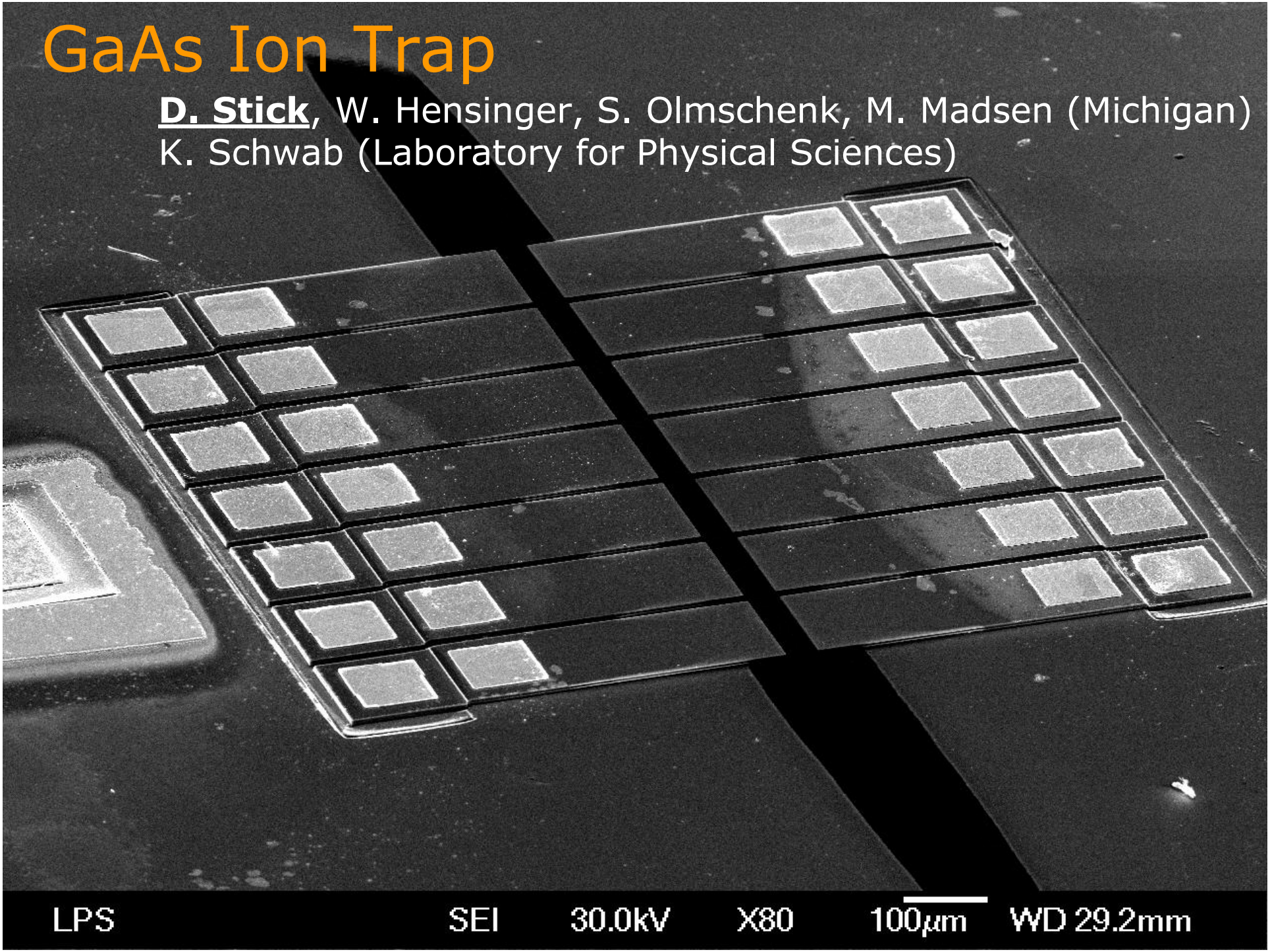


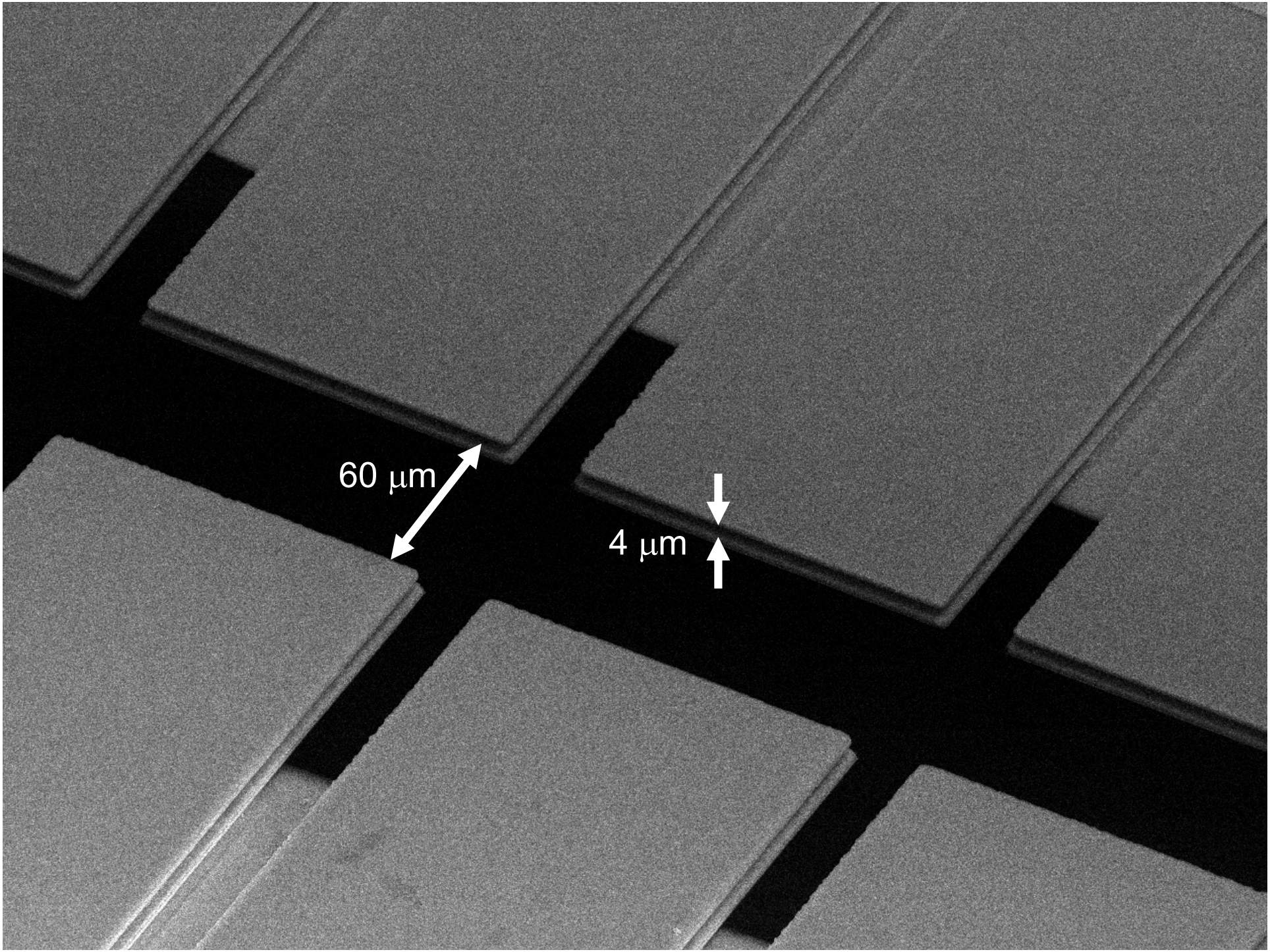
D. Hucul
POSTER T09

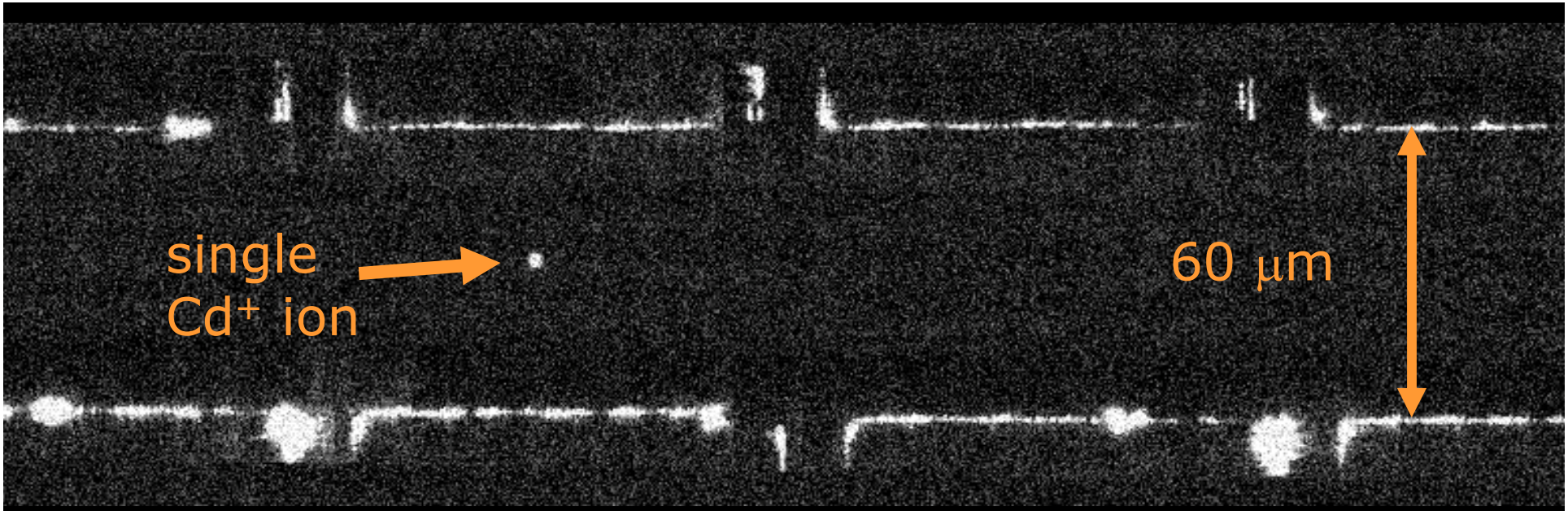

Ion A Ion B
Initial Configuration
Ion B
Step 1: Separation
Ion B
Step 2
Ion A
Step 3
Ion B
Step 4
Ion B
Step 5
Ion A
Step 6
Ion B Ion A
Step 7: Recombination
0 2 4 6 8 9
1 3 5 7 17 16
14 12 10 19 21 23
15 13 11 18 20 22

GaAs Ion Trap

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




60 μm
4 μm



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

Power ~ $V_{RF}^2\Omega^2$ ~ V_{RF}^3
~ 1mW

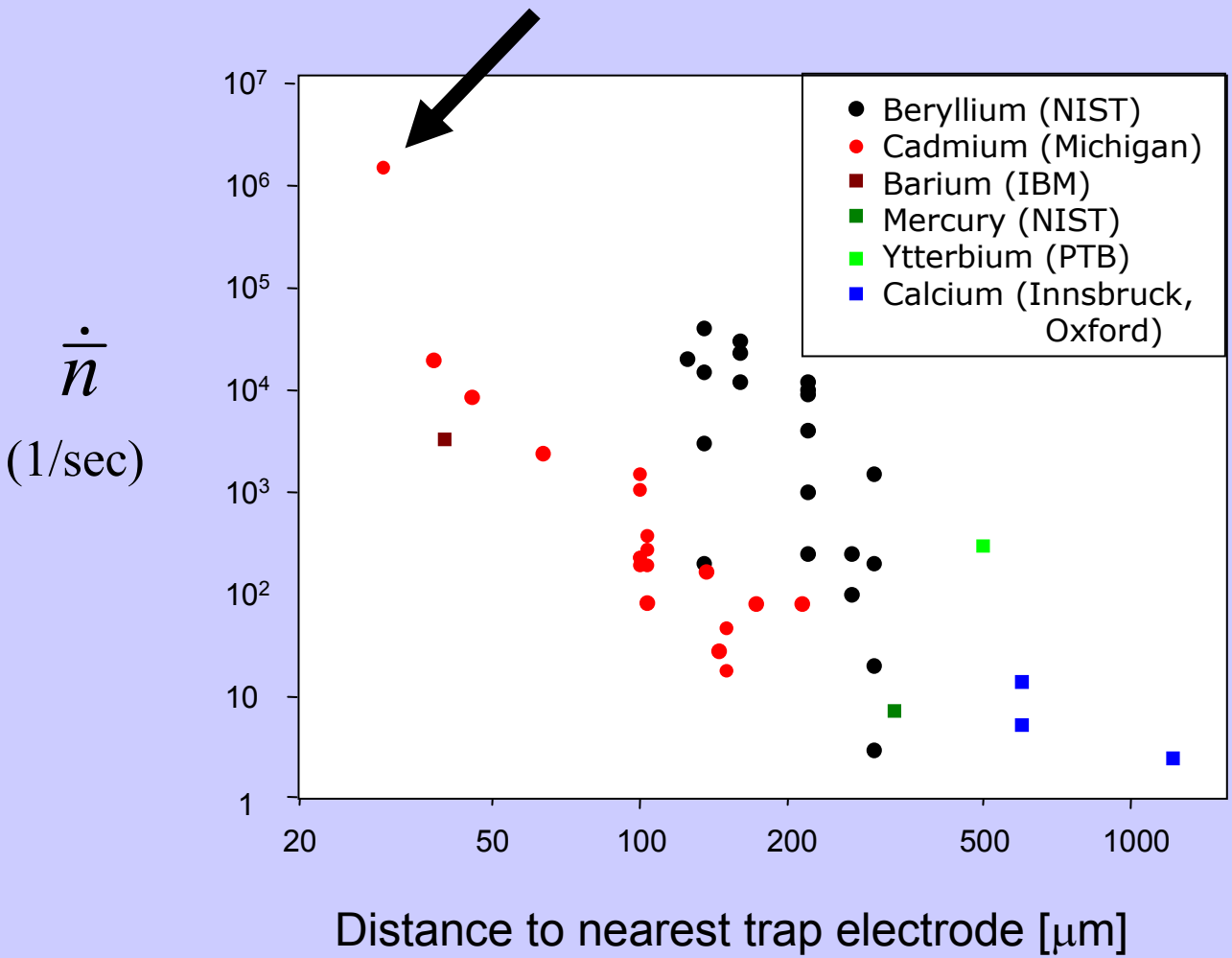
Trap frequencies: 1.0 MHz, 3.3 MHz and 4.3 MHz

Trap depth: 0.08 eV

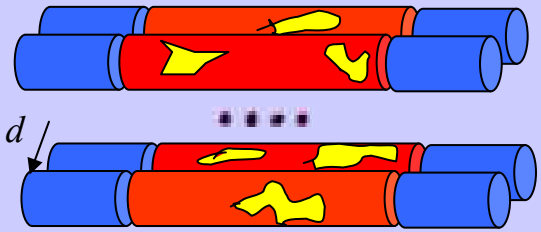
Next: 10 μm cantilever gap
(Thanks: Greg Peake, Matt Blain,… Sandia)

D. Stick
POSTER T05

Heating history in 0.6-6.0 MHz traps



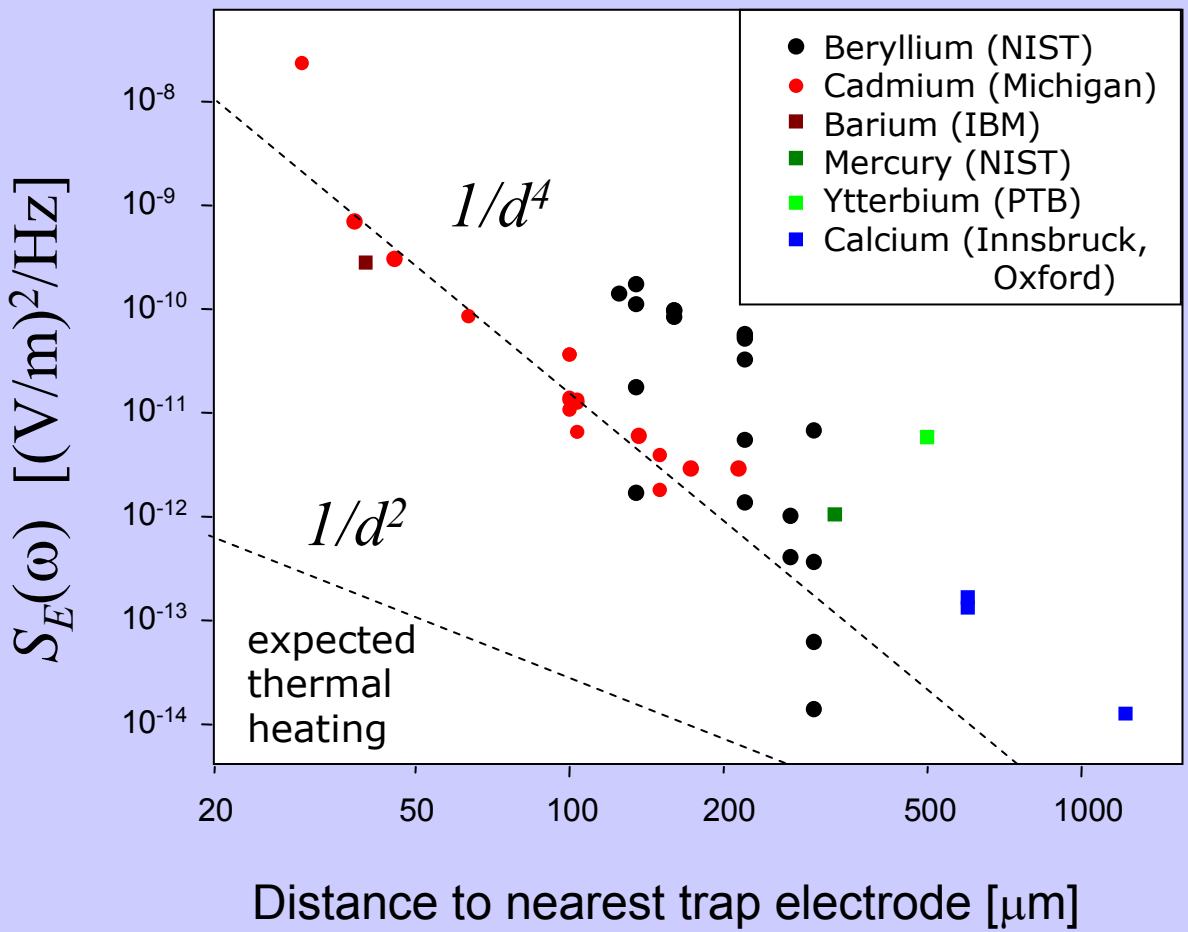
Heating due to fluctuating patch potentials (?)



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

$$\sim 1/d^4$$

Electric Field Noise History in 0.6-6.0 MHz traps



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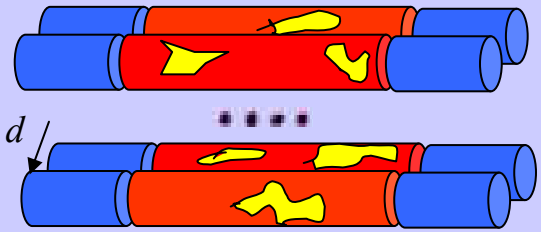
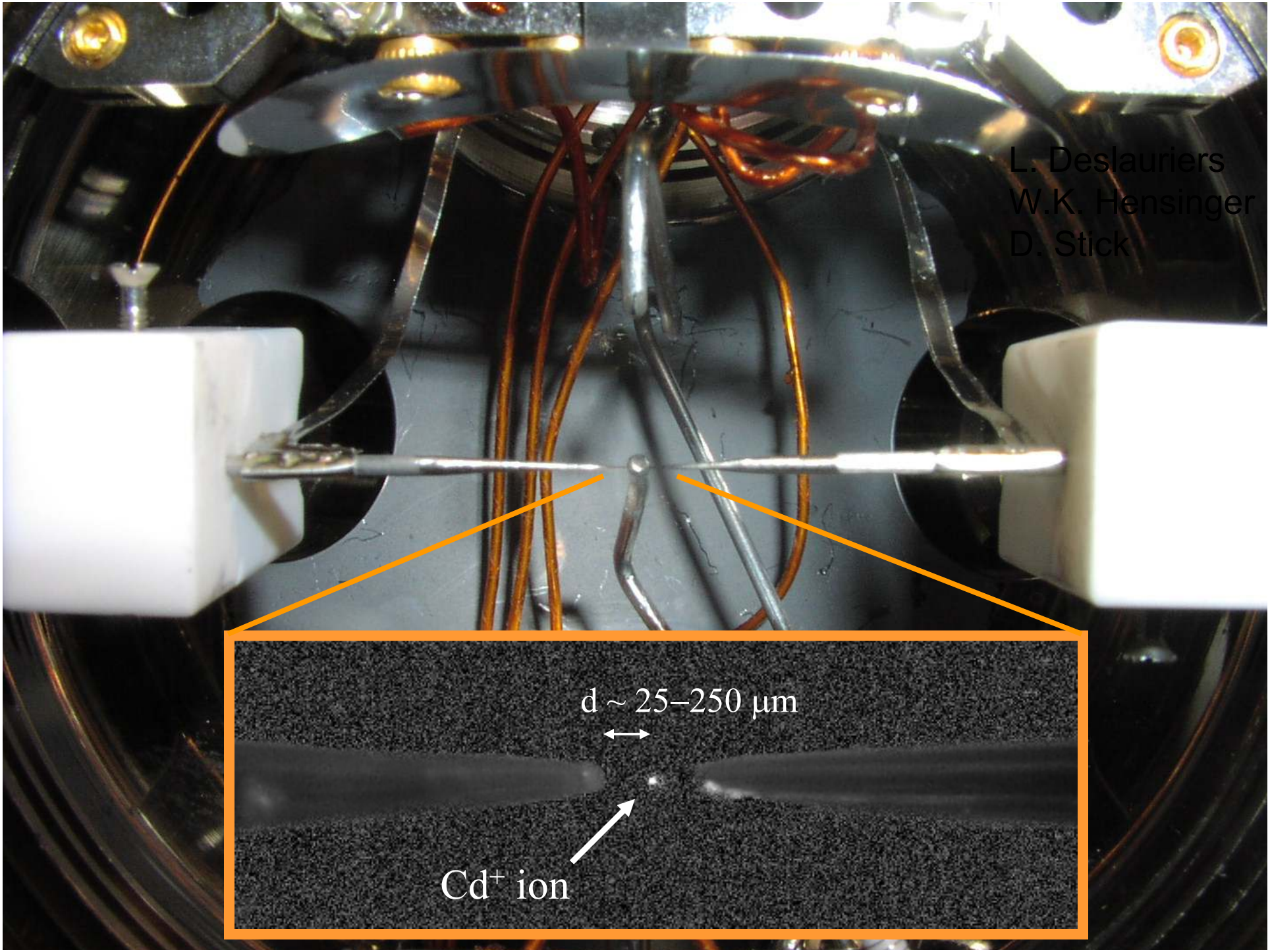


$$\dot{\bar{n}} = \frac{e^2}{4m\hbar\omega} S_E(\omega)$$

$$\sim 1/d^4$$

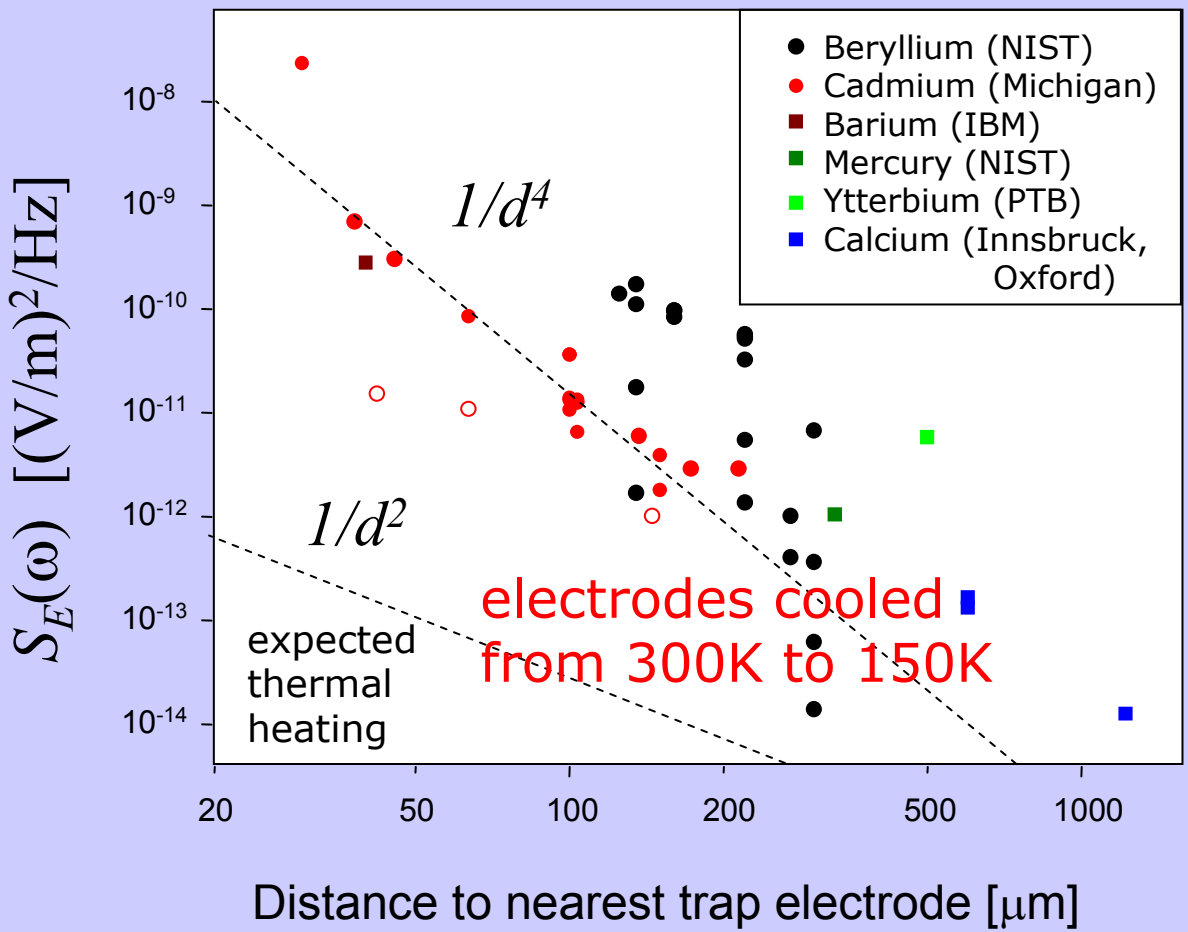
“double needle” trap

- 15 μm diameter W tips
- adjustable separation
- cooling to 150K


L. Deslauriers
W.K. Hensinger
D. Stick
d ~ 25–250 μm
Cd+ ion

Measurements of Heating vs. Trap Size at 2 MHz

Electric Field Noise History in 0.6-6.0 MHz traps



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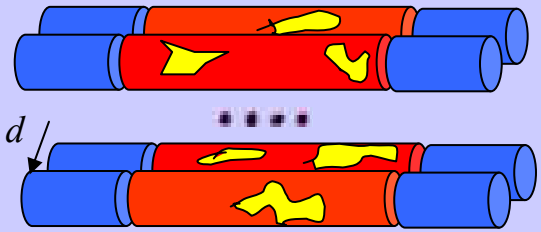


$$\dot{\bar{n}} = \frac{e^2}{4m\hbar\omega} S_E(\omega)$$

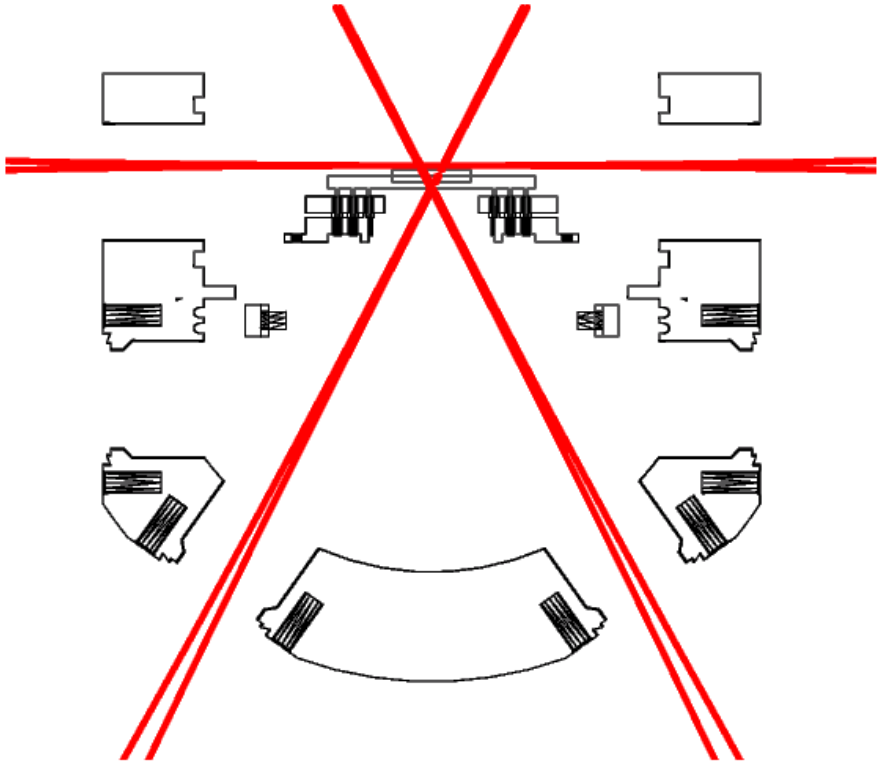
$$\sim 1/d^4$$

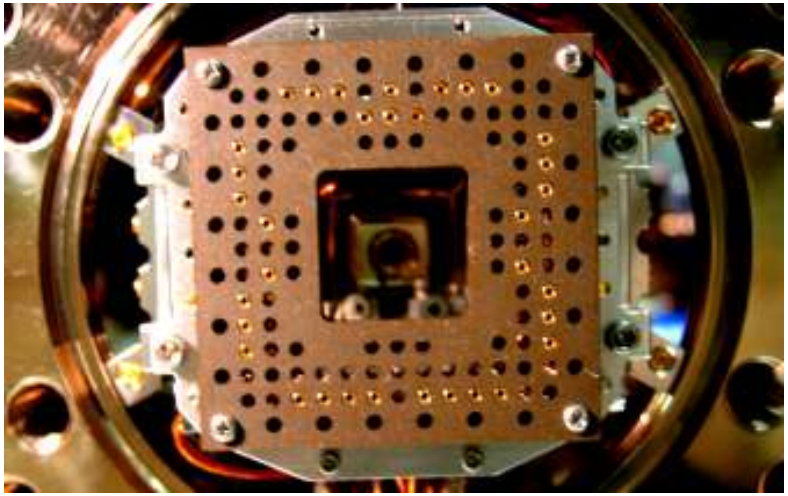
L. Deslauriers, et al., quant-ph/0602003 (2006)

W. Hensinger
POSTER M11

Universal Chip-trap vacuum chamber

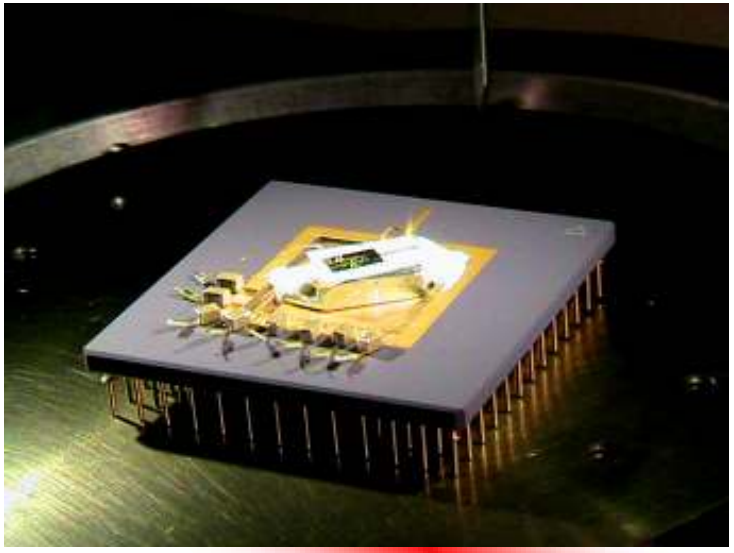
J. Sterk
POSTER T03

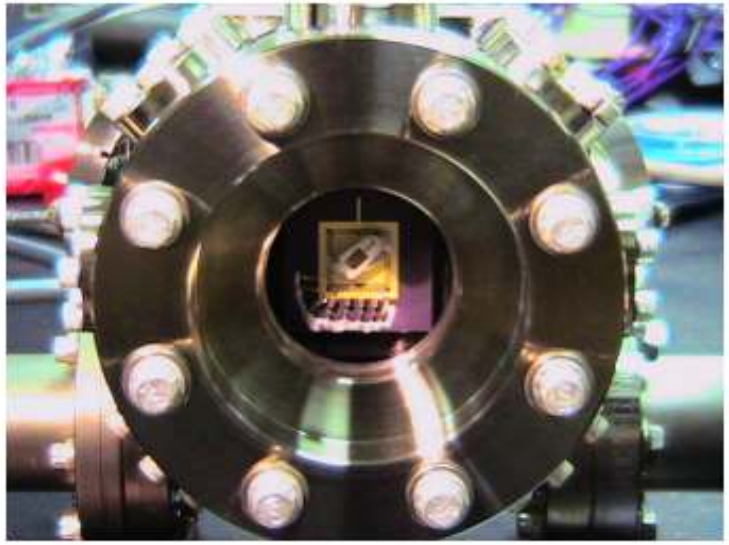


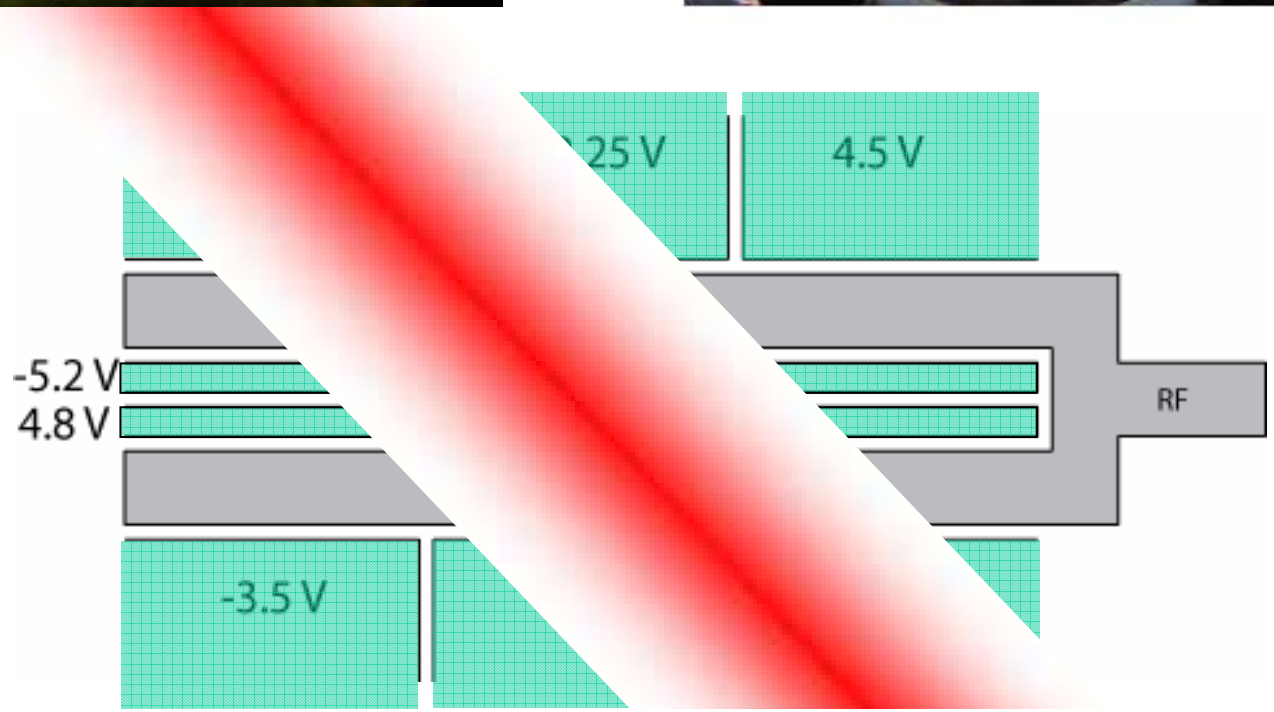


UHV high temperature chip socket

Surface Trap Guinea Pig

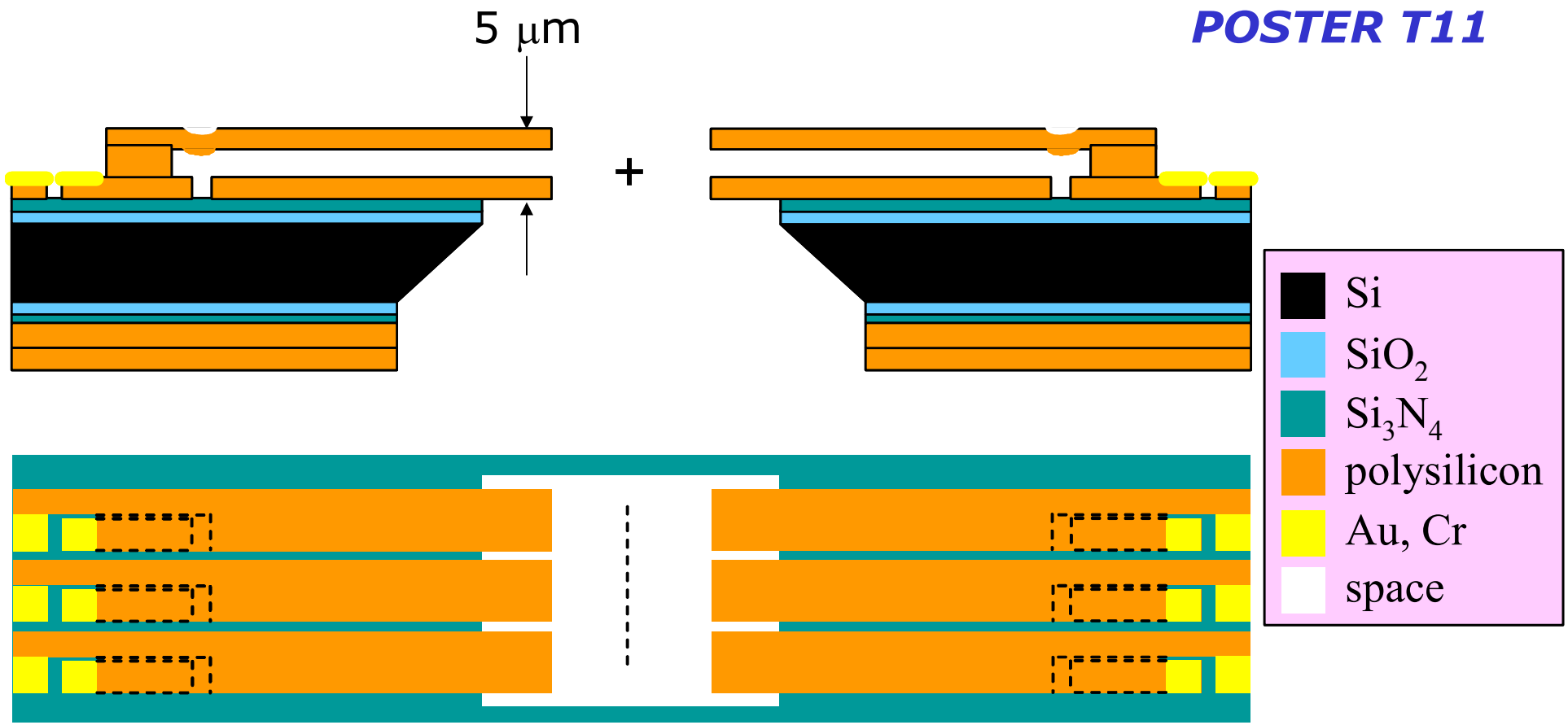






Polysilicon MEMS trap

W. Hensinger
POSTER T11



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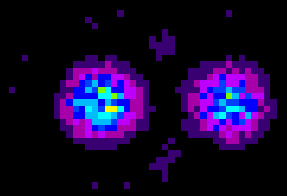

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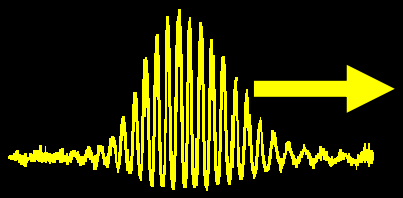
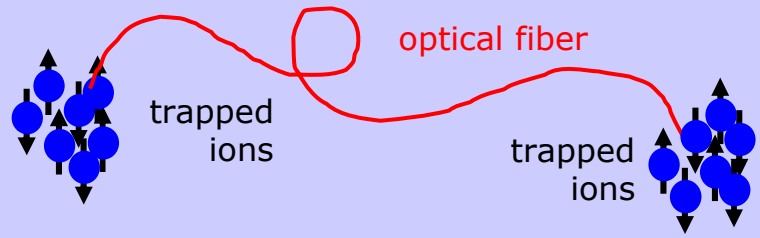
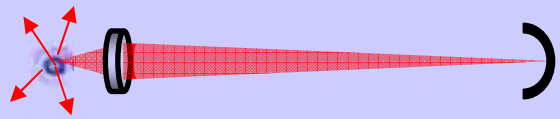


Interfacing Trapped Ions and Photons



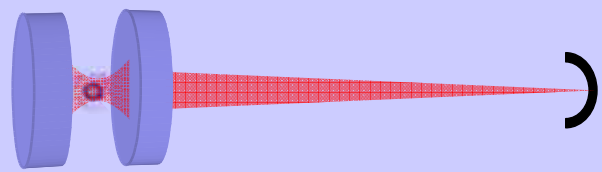
- Free space (probabilistic $p<<1$)



$$p = \eta\, d\Omega \sim 10^{-3}$$

- "Bad" cavities (probabilistic $p\sim 0.3$)

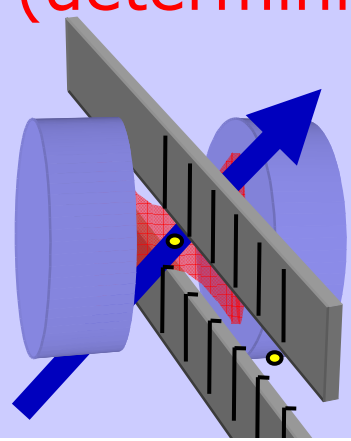
$$C = \frac{g^2}{\kappa\gamma} \approx 1$$



$$p = \eta\left(\frac{C}{C+1}\right) \approx 0.1 - 0.3$$

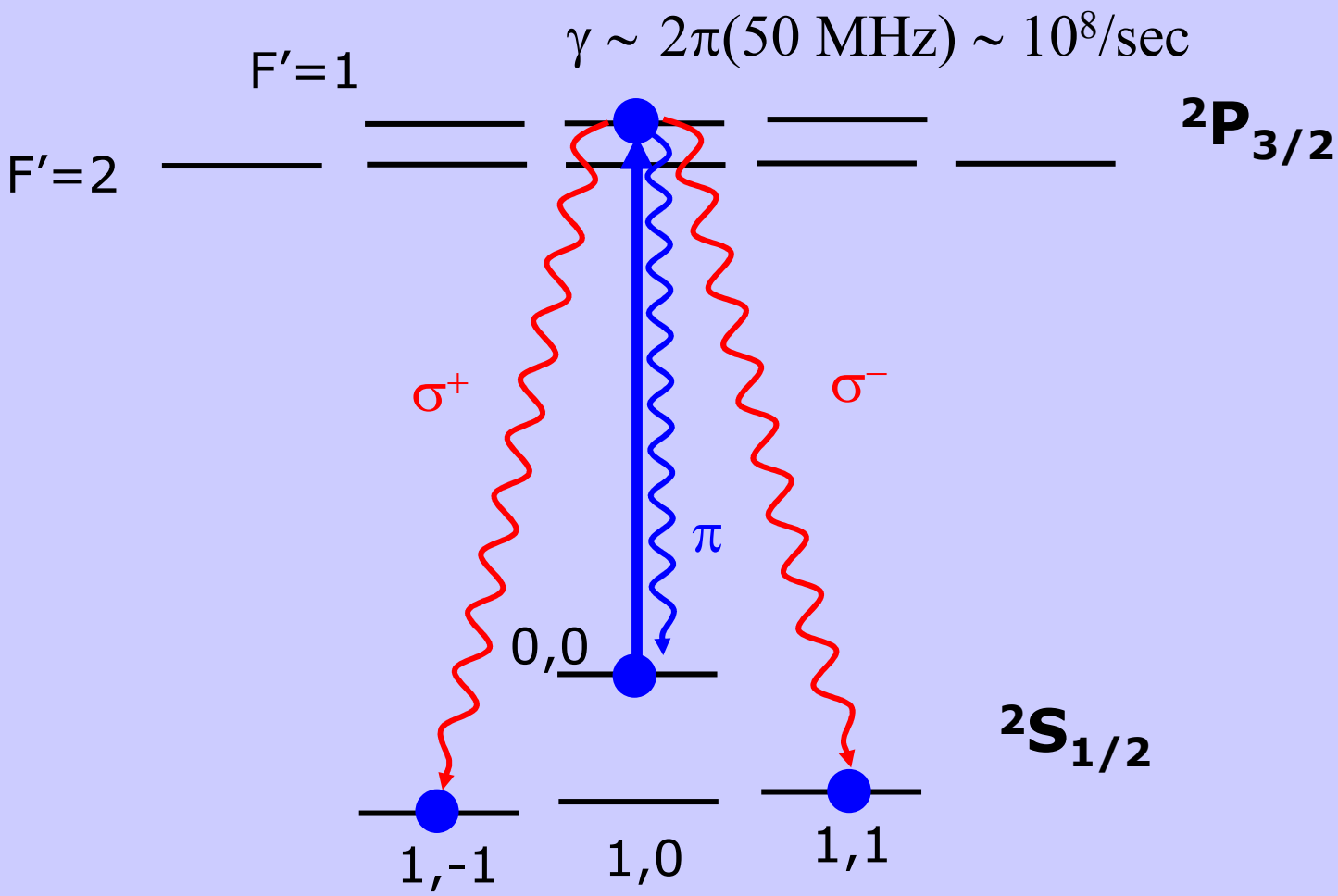
- Strong coupling (deterministic cavity-QED)

$$C = \frac{g^2}{\kappa\gamma} >> 1$$



Spontaneous (probabalistic) entanglement between a single atom and single photon

Polarization Qubit

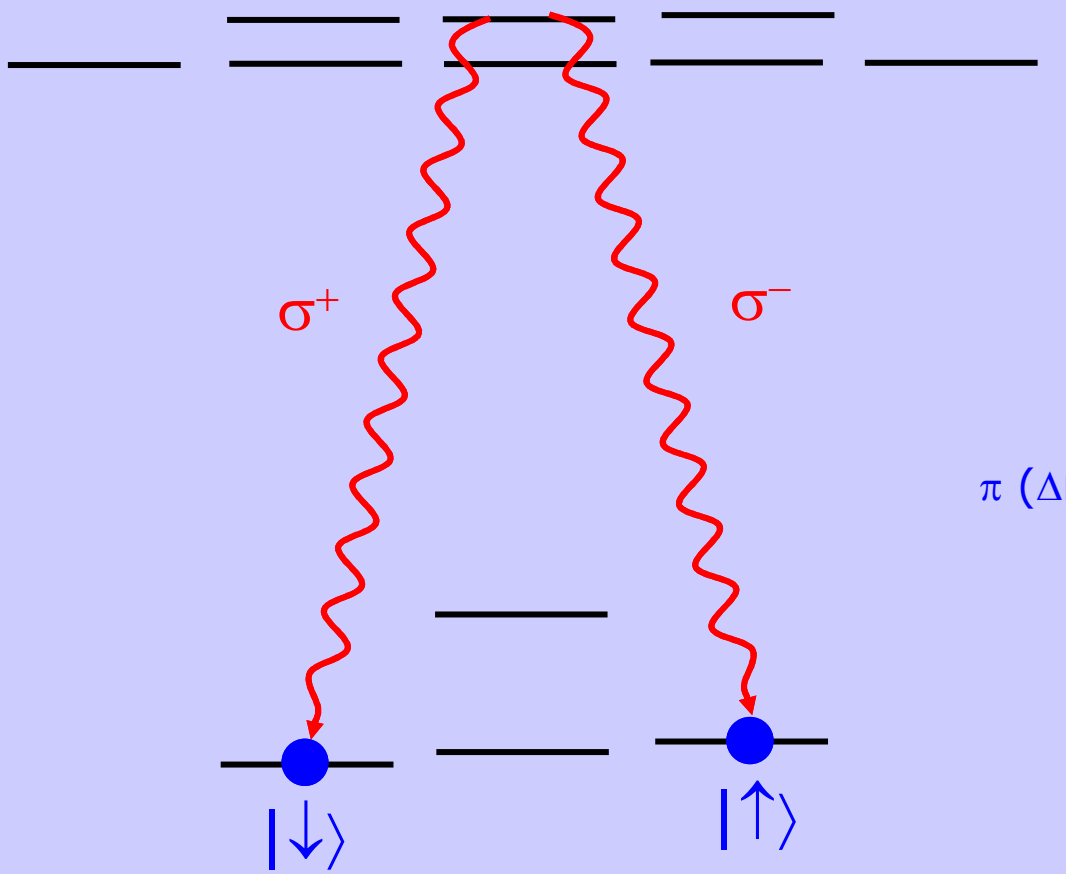


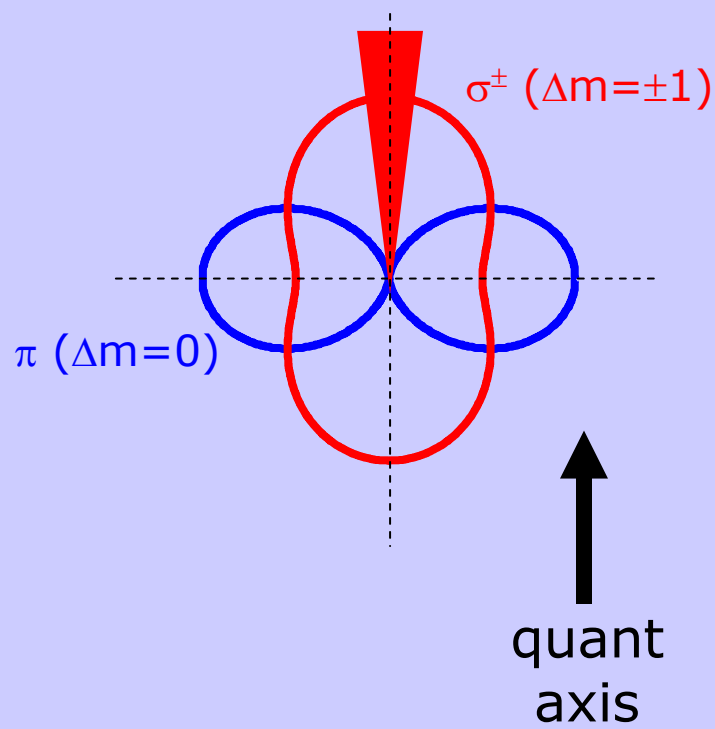
Given photon is emitted along quantization-axis:

$|\psi\rangle = |\downarrow\rangle|\sigma^+\rangle + |\uparrow\rangle|\sigma^-\rangle$ (postselected)

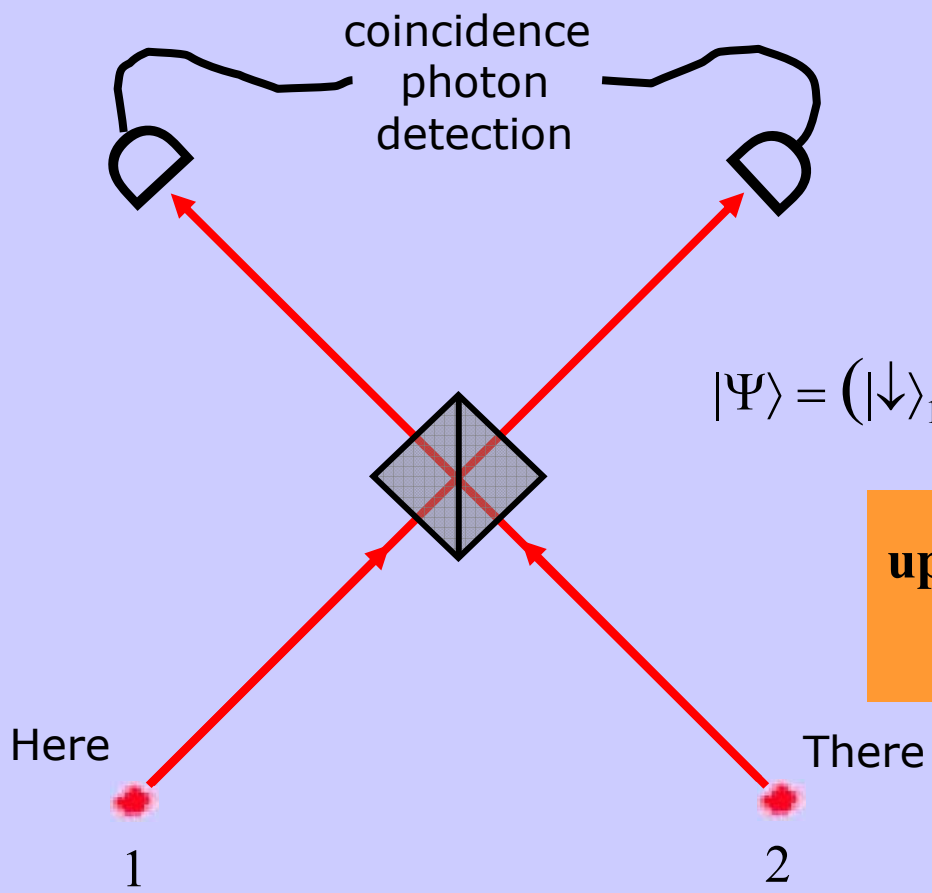
$P_{ent} = \eta\, d\Omega \sim 10^{-3}$

$Rate = P_{ent}\, R \sim 1\ kHz$





Networking distant ions



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

upon coincidence photon detection

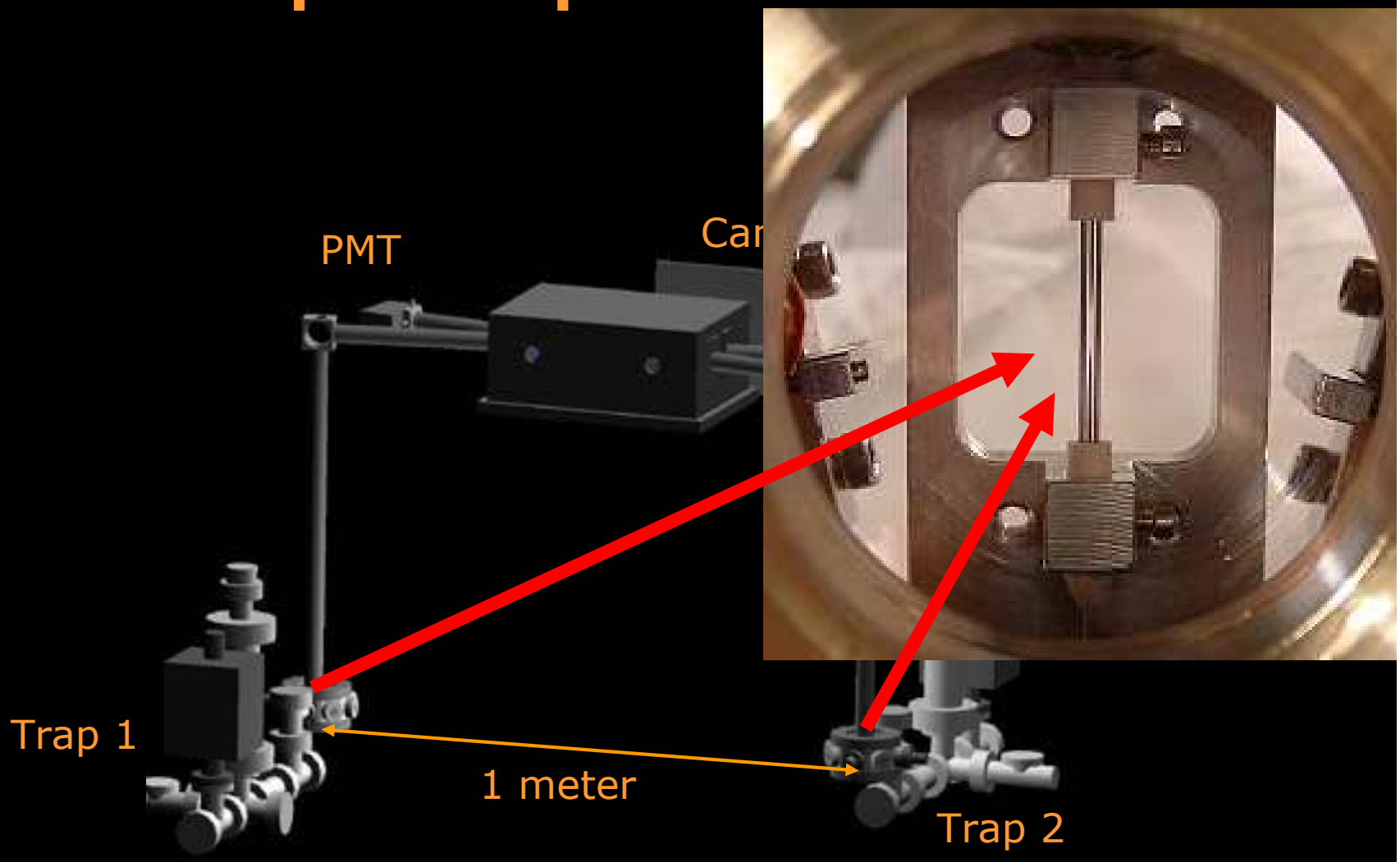
$$|\Psi\rangle \Rightarrow |\downarrow\rangle_1|\uparrow\rangle_2 - |\uparrow\rangle_2|\downarrow\rangle_2$$

insensitive to interferometric phase noise
insensitive to ion motion

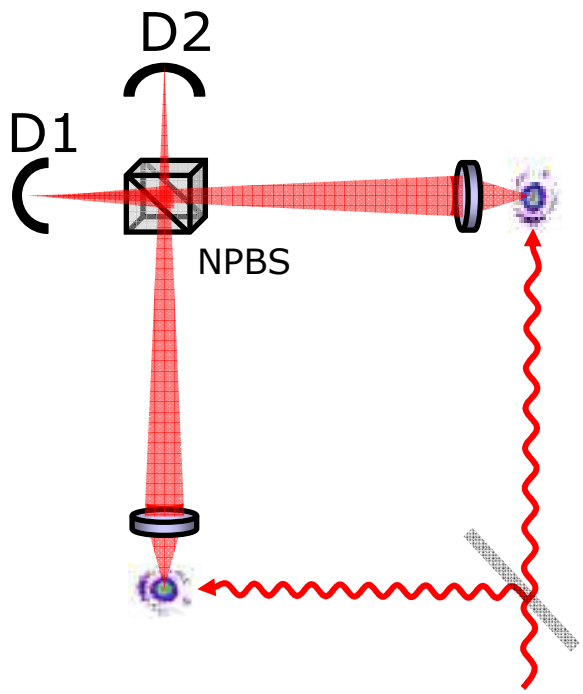
C. Simon and W. Irvine,
PRL **91**, 110405 (2003)

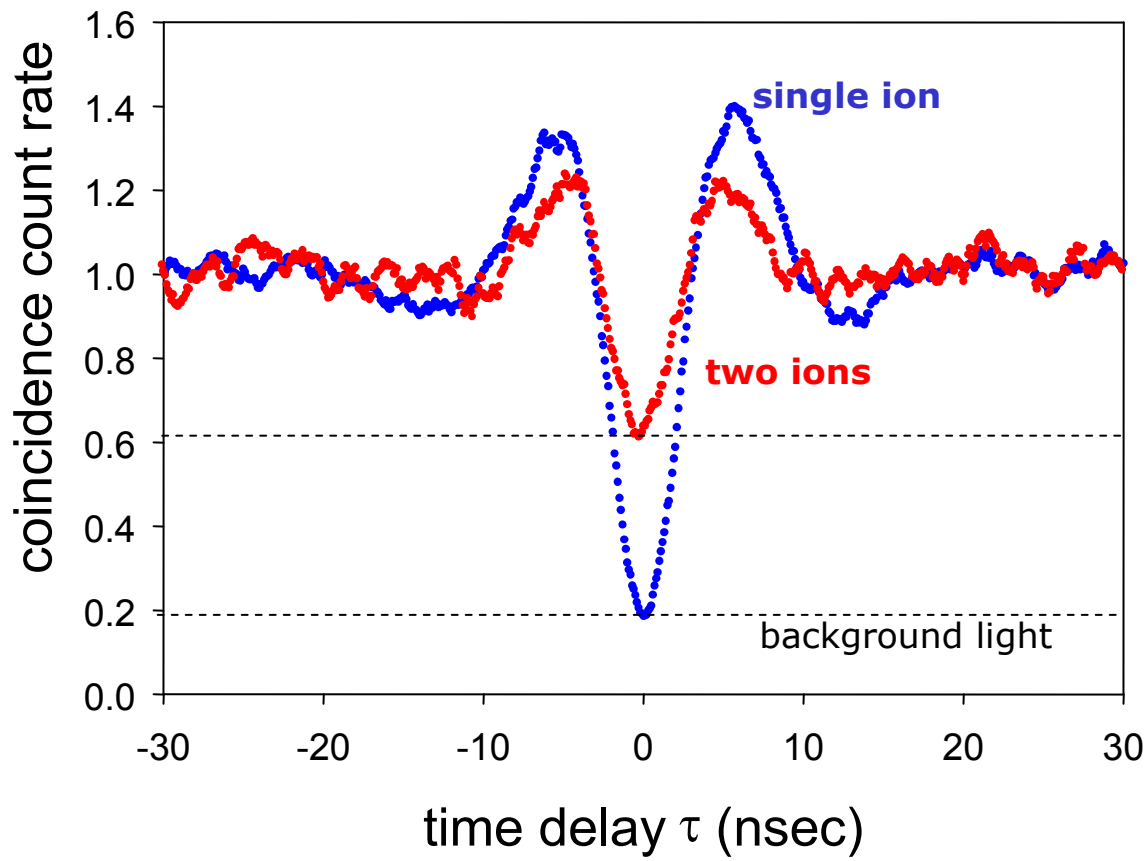
L.-M. Duan, et. al.,
Quant. Inf. Comp. **4**, 165 (2004)

Free space experiments

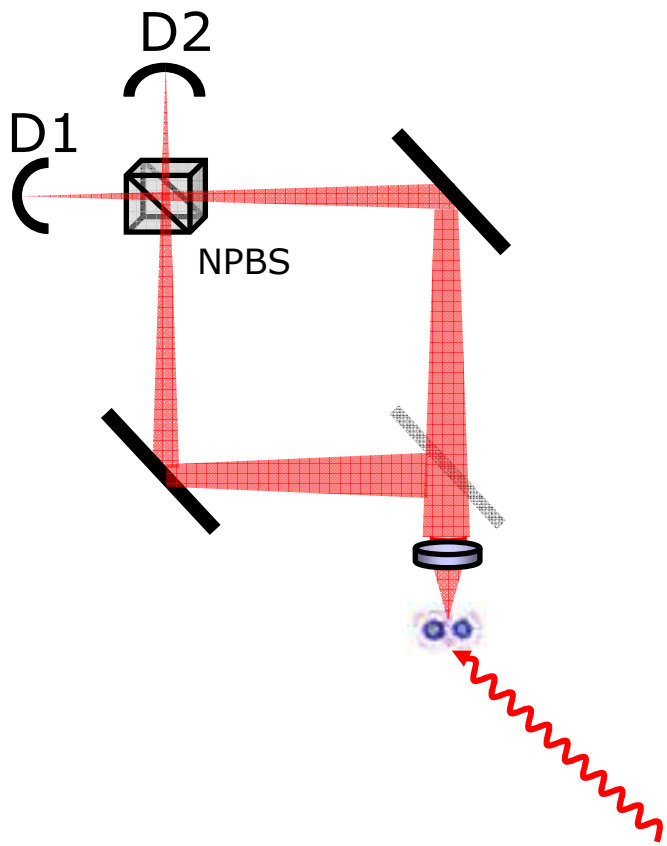


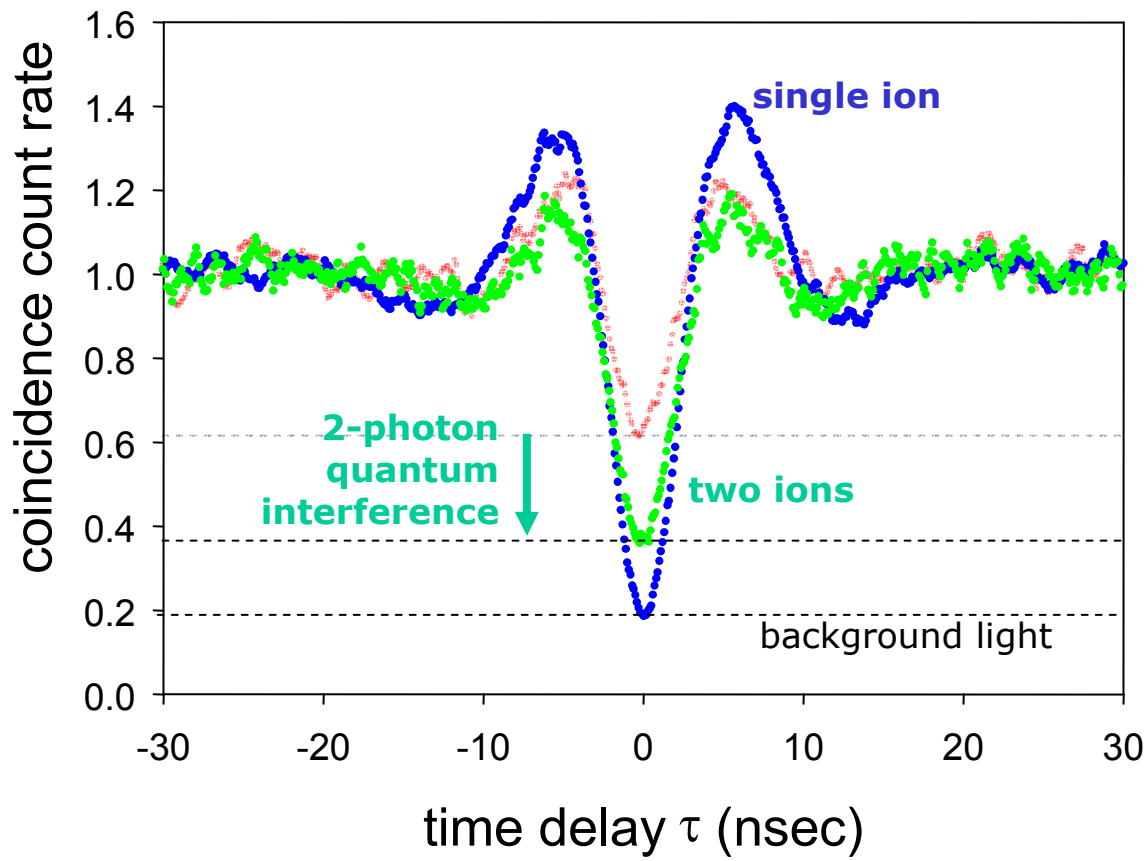
Continuous-wave excitation of a pair of ions separated by 1 meter





Continuous-wave excitation of a pair of ions in the same trap





P. Maunz
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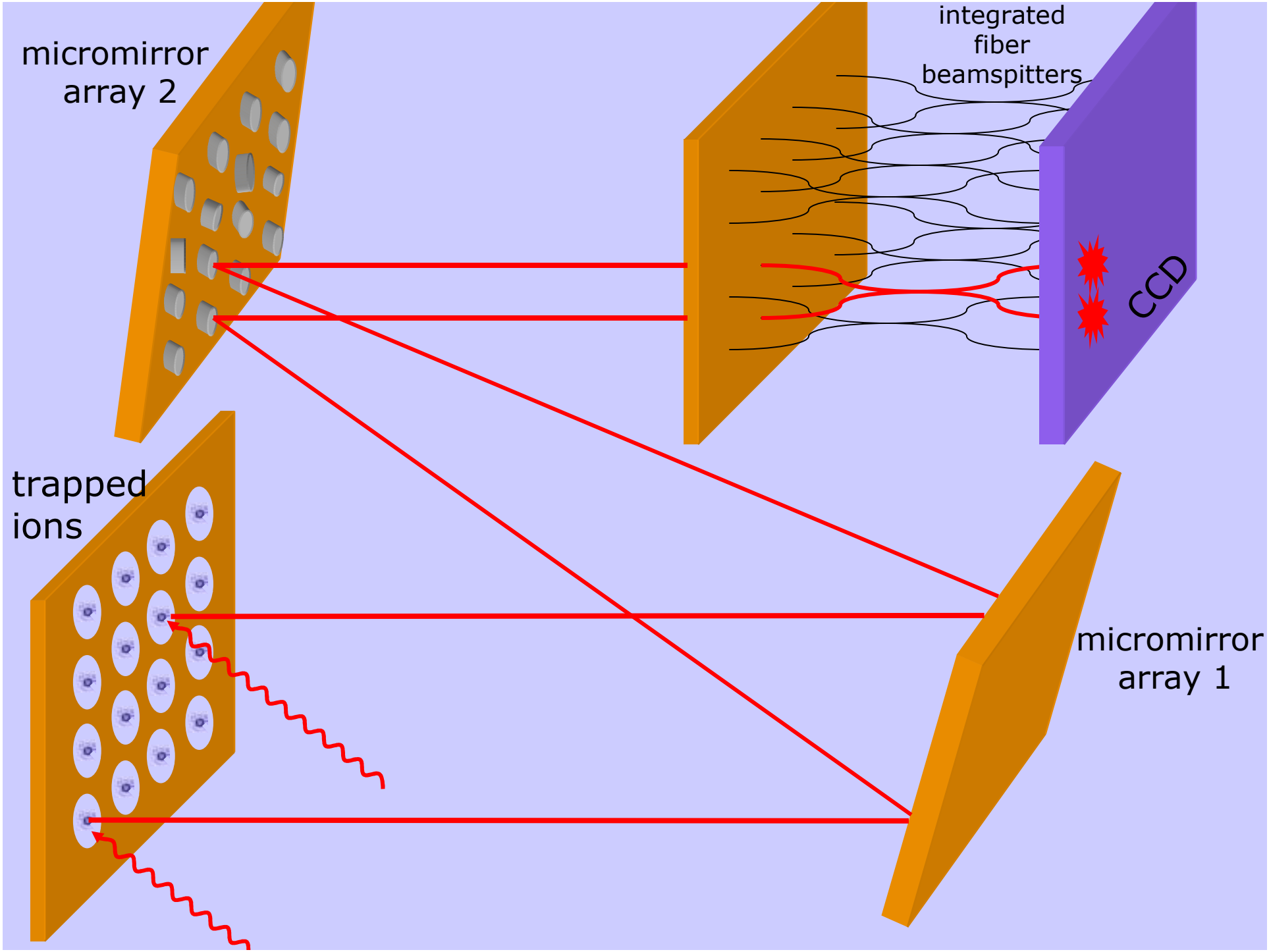
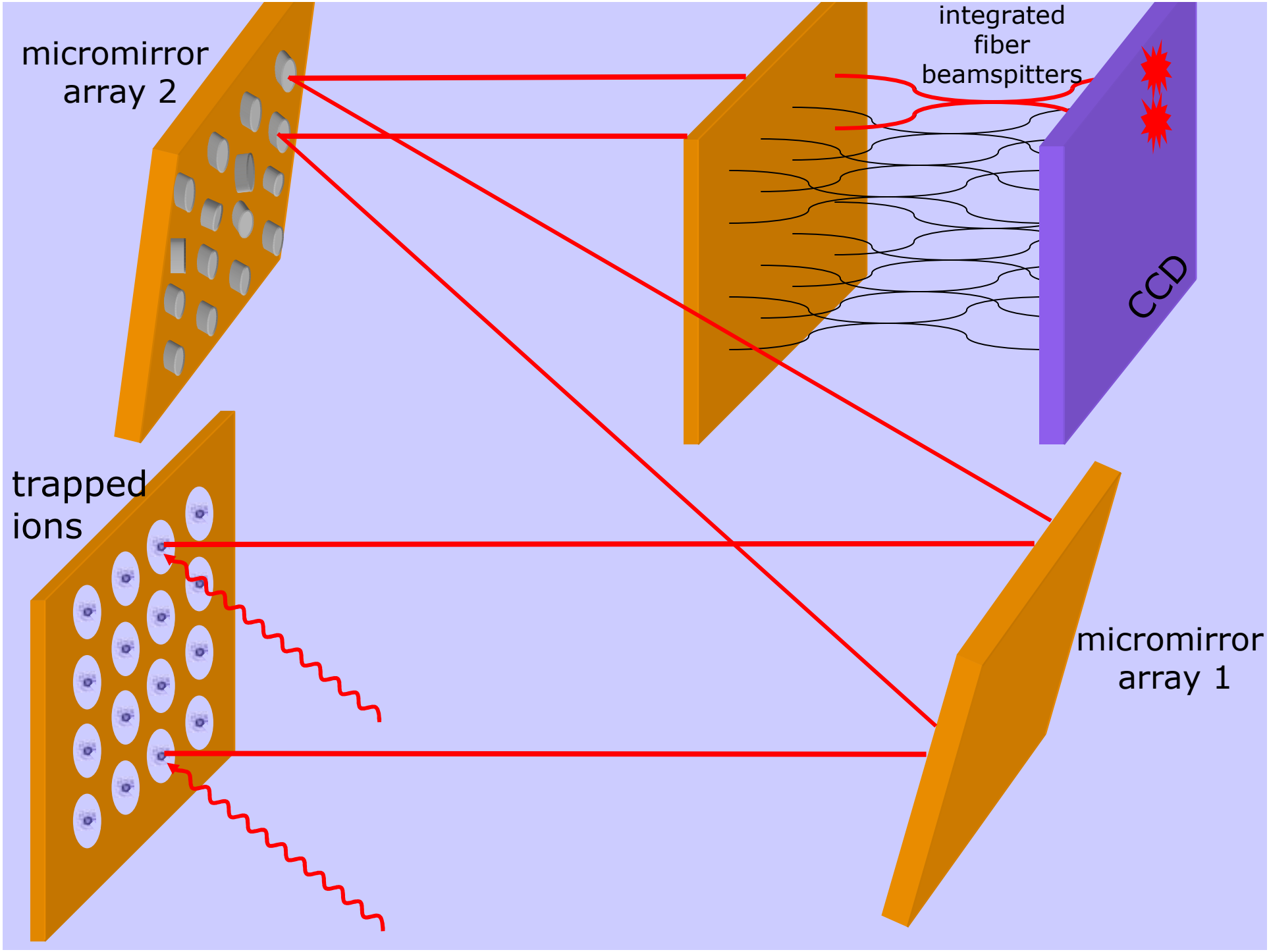
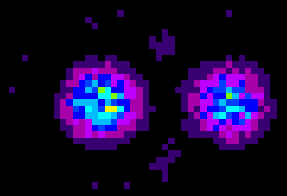

micromirror
array 2
integrated
fiber
beamspitters
CCD
trapped
ions
micromirror
array 1


micromirror
array 2
integrated
fiber
beamspitters
CCD
trapped
ions
micromirror
array 1

Michigan Ion Trap Projects

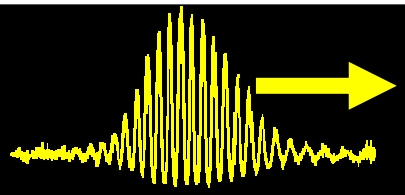
- Local entanglement through the Coulomb interaction (phonons)



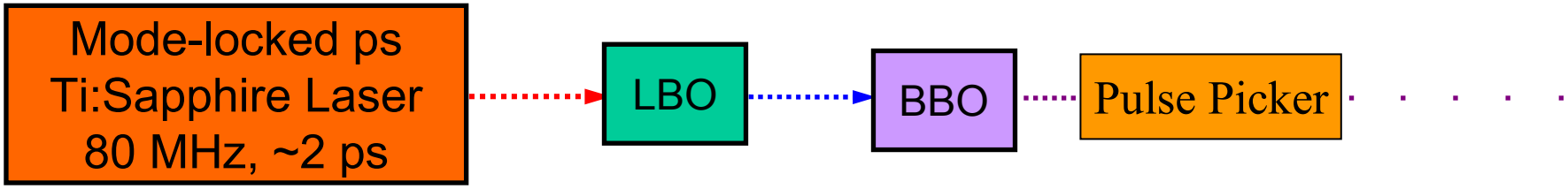
- Advanced trap structures

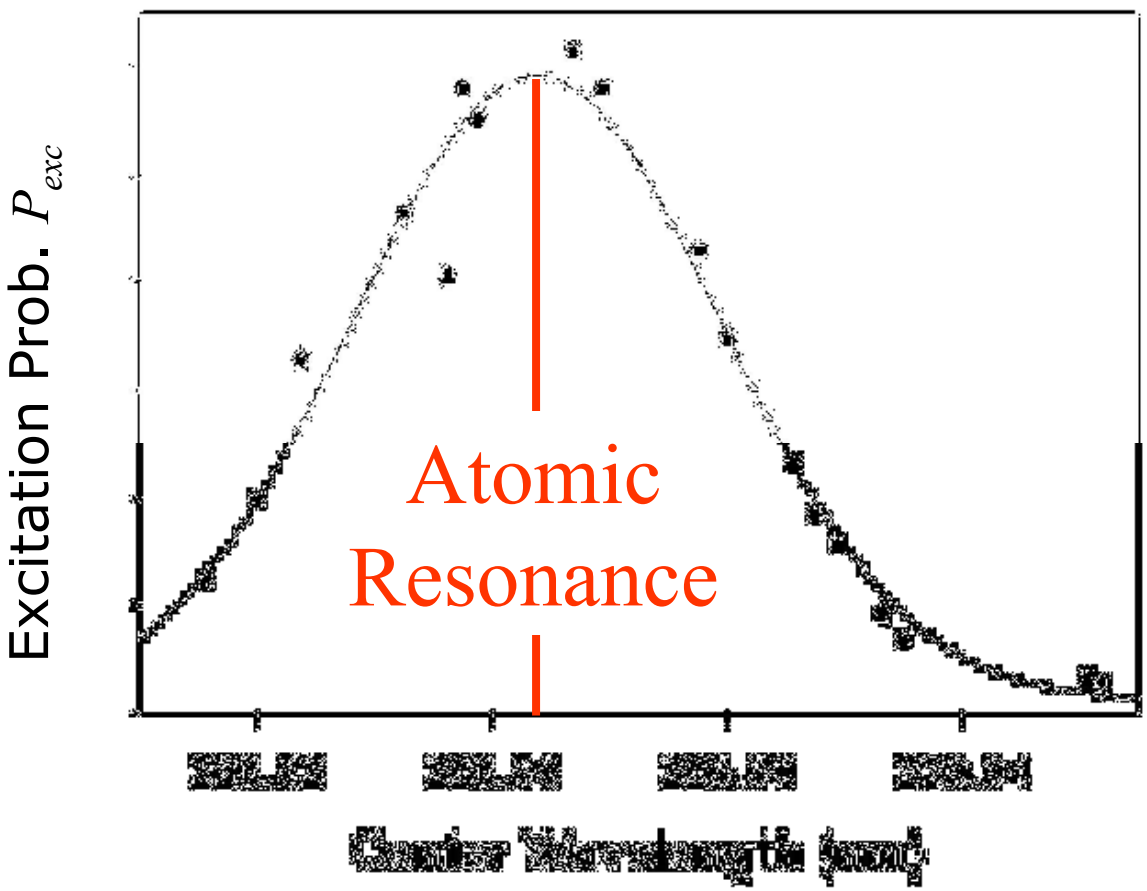
- Entanglement though atomic spontaneous emission (photons)

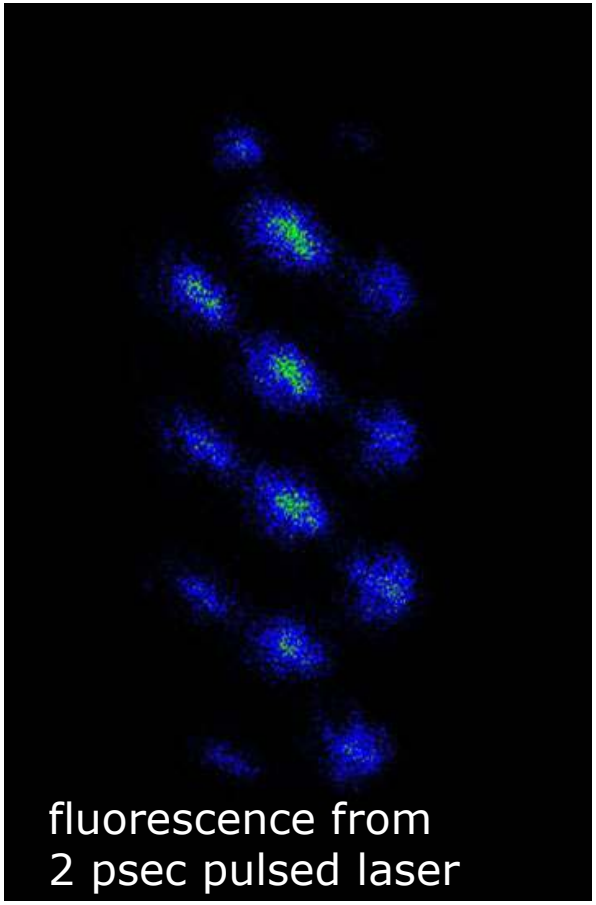
- Ultrafast laser-ion interactions



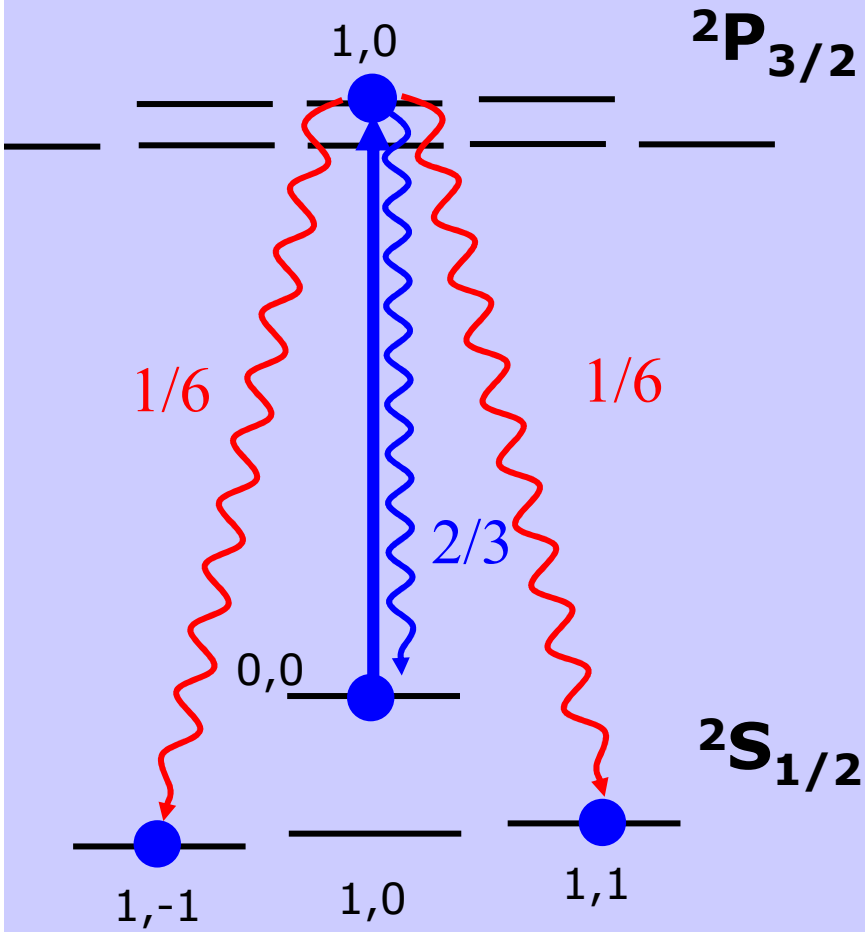
Ultrafast Ion Excitation

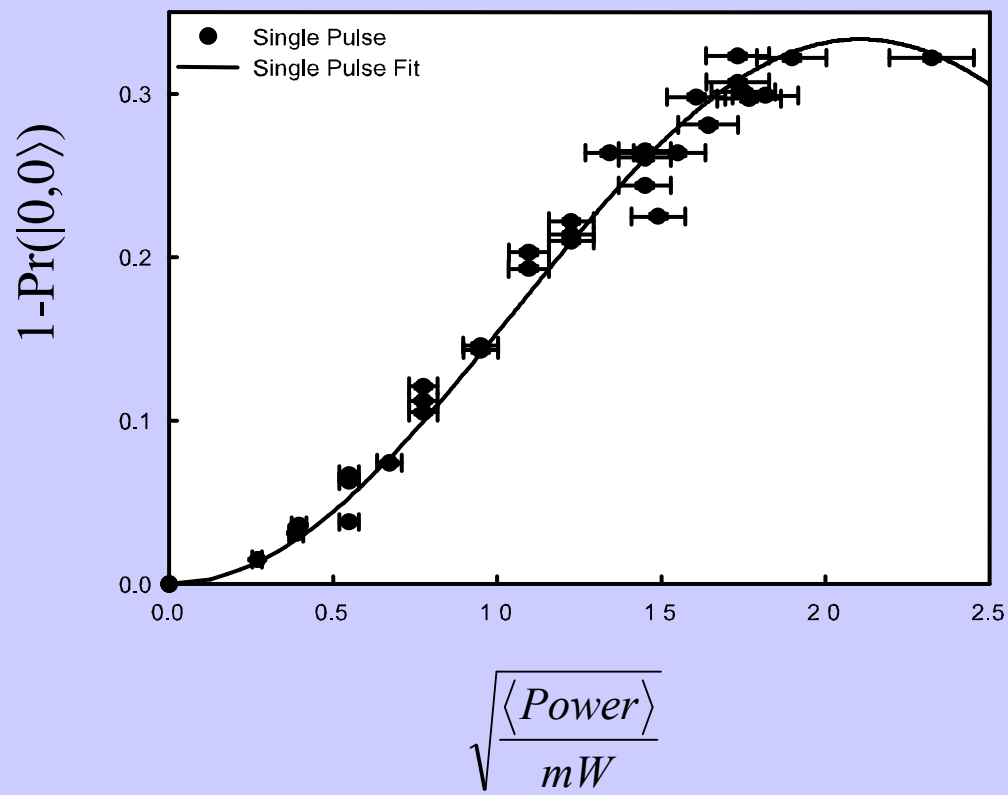






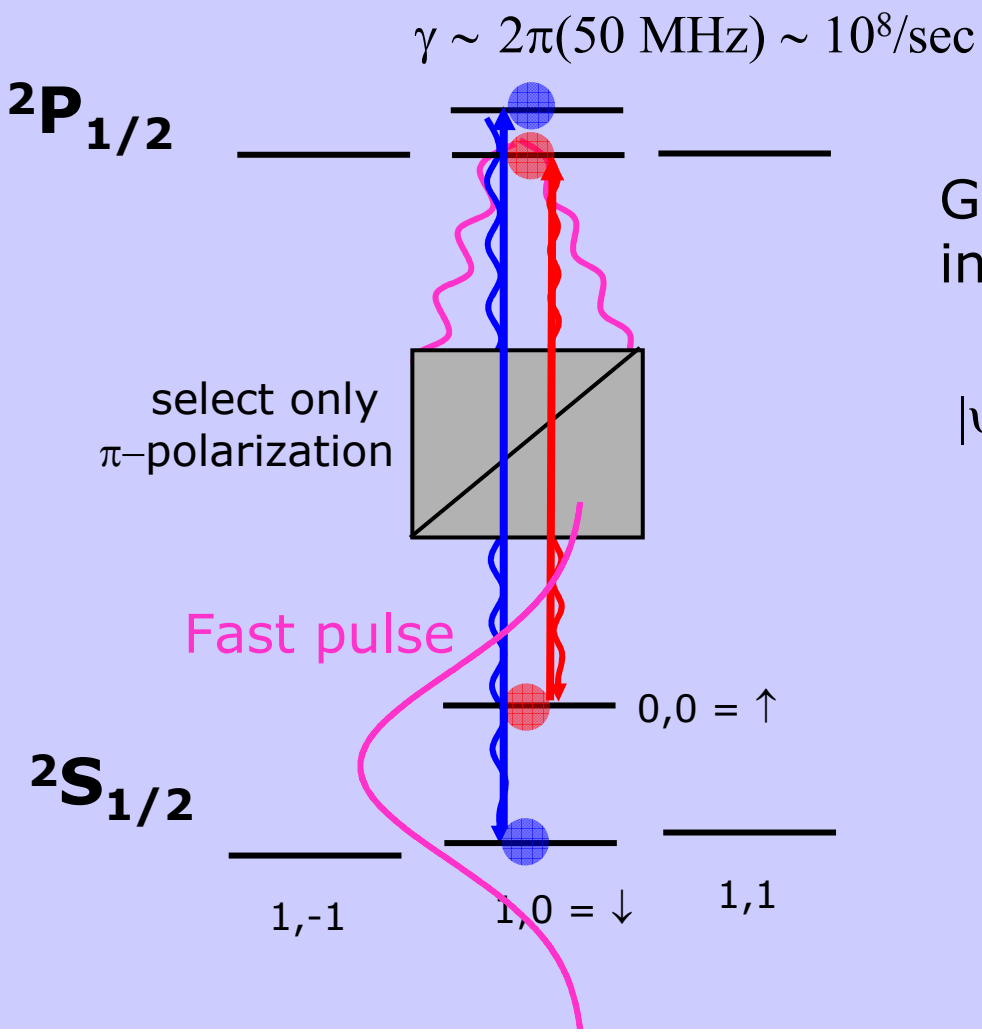
Picosecond Rabi Flopping





Spontaneous (probabalistic) entanglement between a single atom and single photon

Frequency Qubit

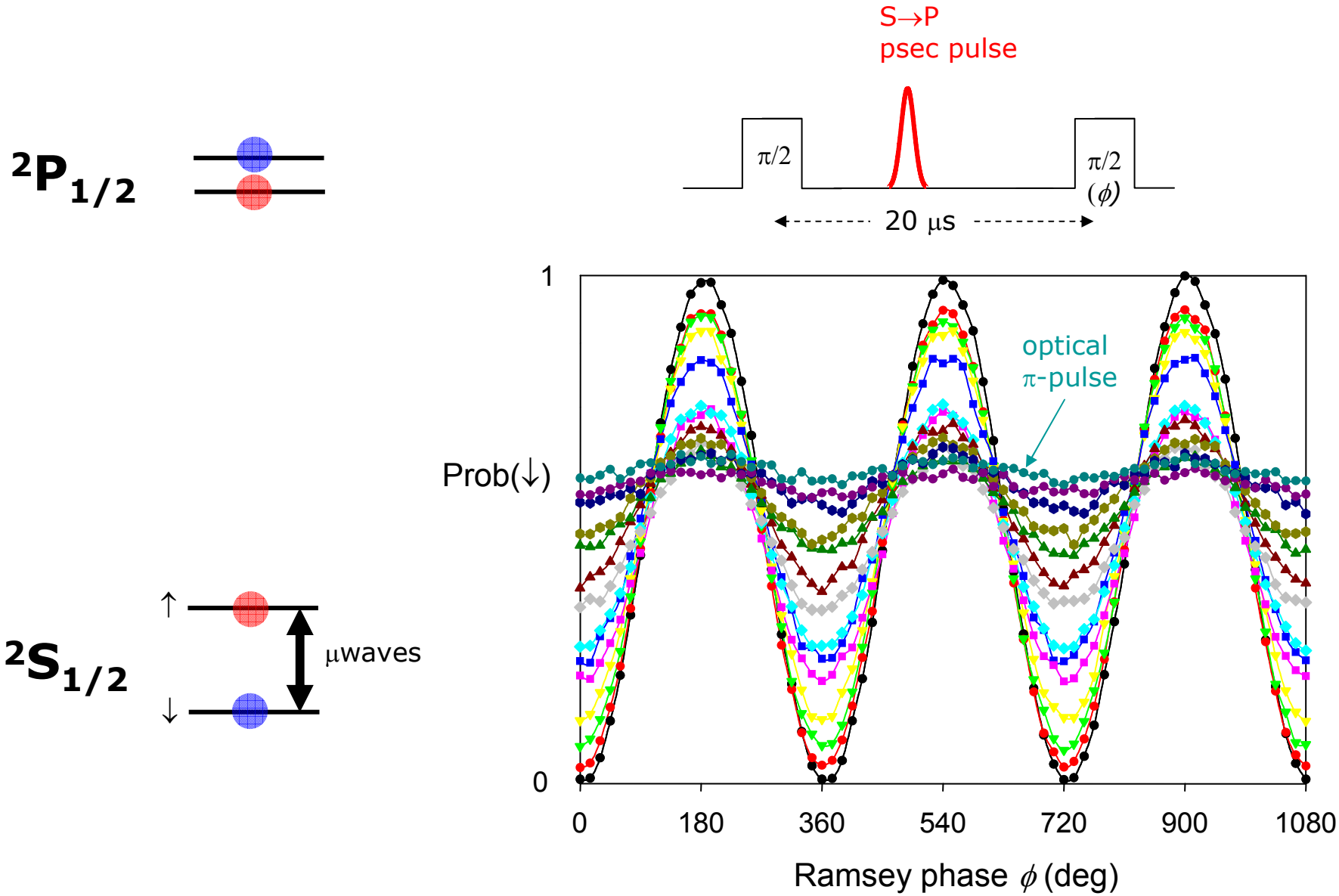


Given photon is emitted into polarizer

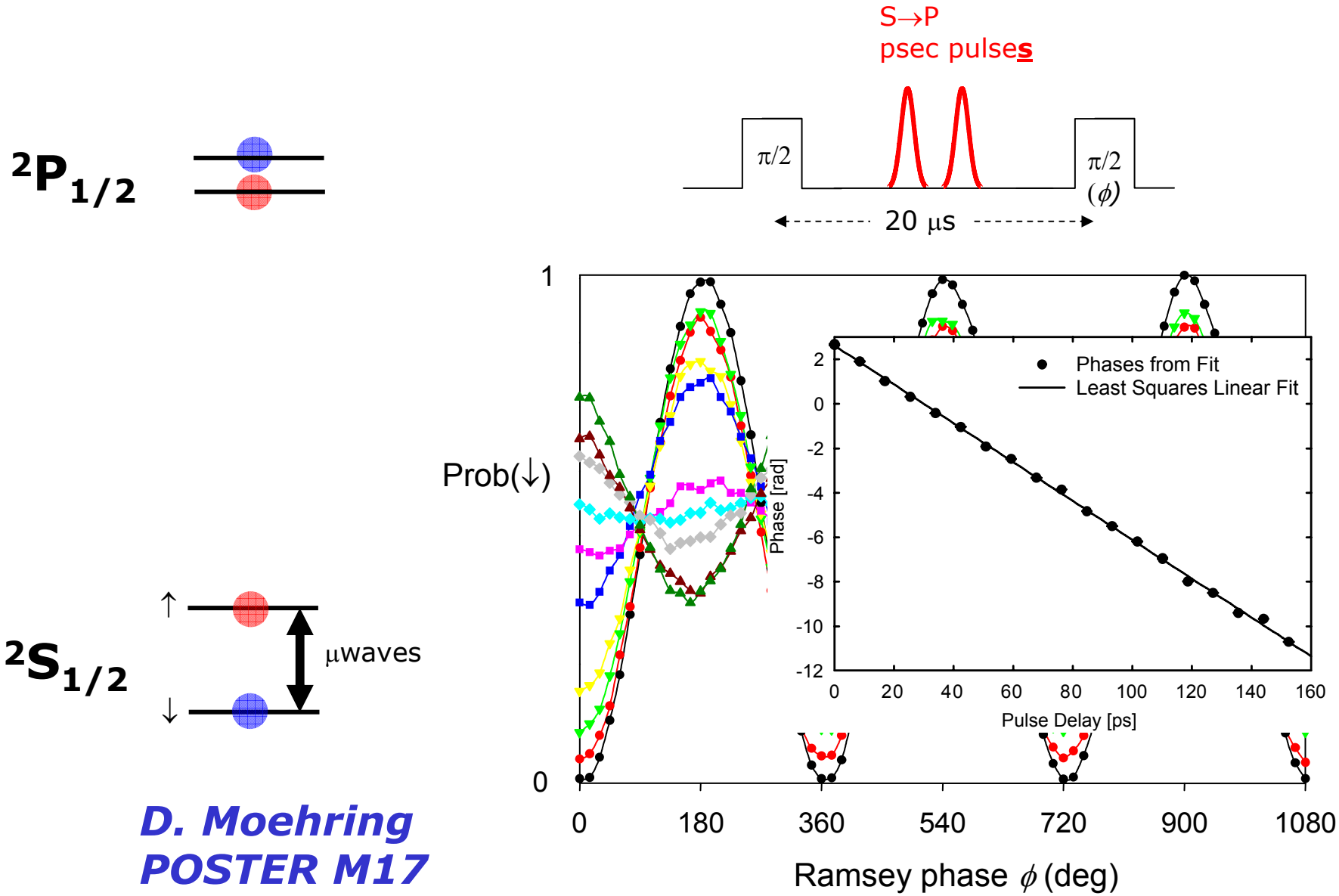
$$|\psi\rangle = |\downarrow\rangle|\mathrm{blue}\rangle + |\uparrow\rangle|\mathrm{red}\rangle$$

(postselected)

Frequency qubit decoherence



Frequency qubit coherence returned



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