Title: Errors in the Trapped Ion Quantum Computer

Date: Jun 15, 2007 11:45 AM

URL: http://pirsa.org/07060054

Abstract:

Errors in Trapped Ion Quantum Processing

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

DTO US Disruptive Technology Office

US Army Research Office

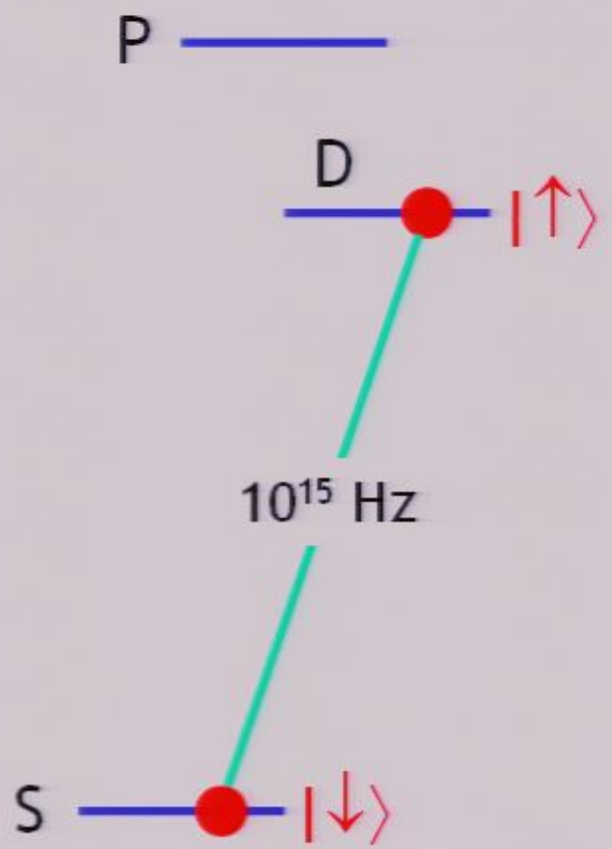
FOCUS NSF FOCUS Center

US National Security Agency

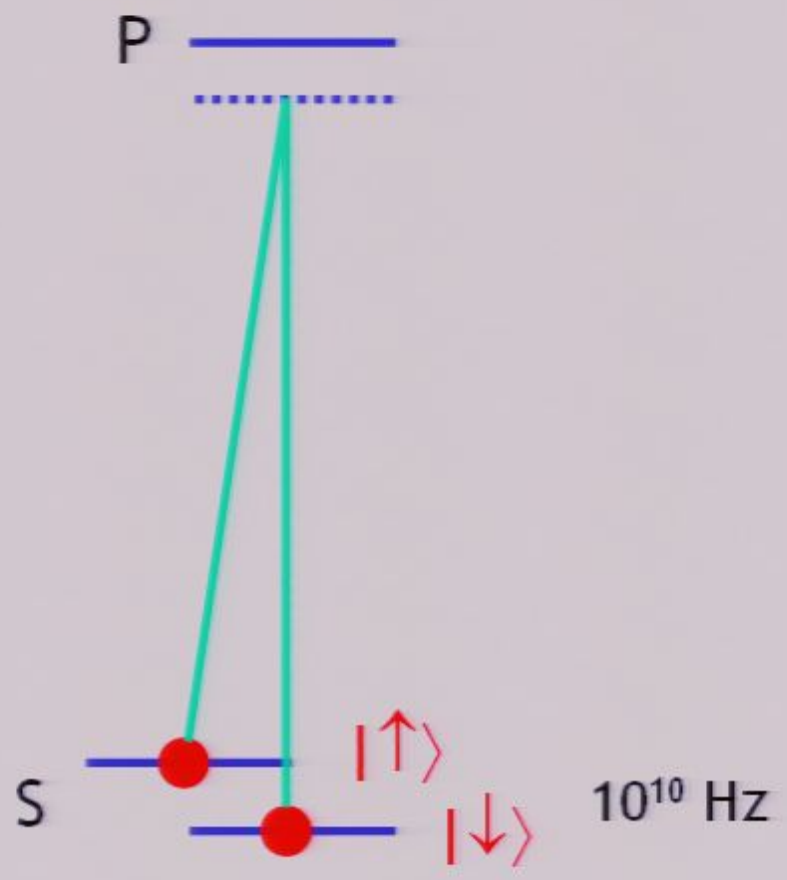
NSF National Science Foundation

DARPA US Defense Advanced Research Projects Agency

Good atomic two-level systems

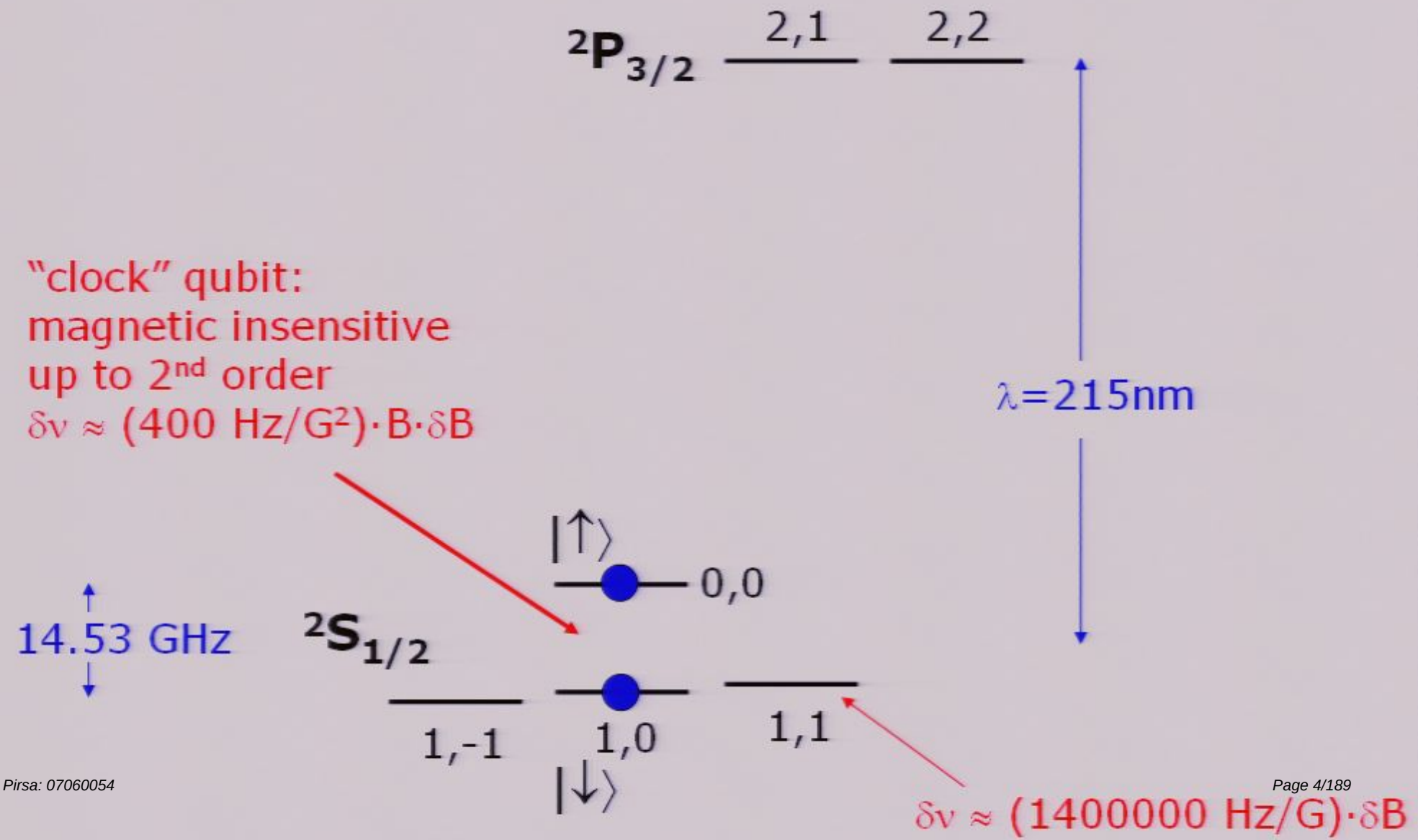


optical



microwave

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



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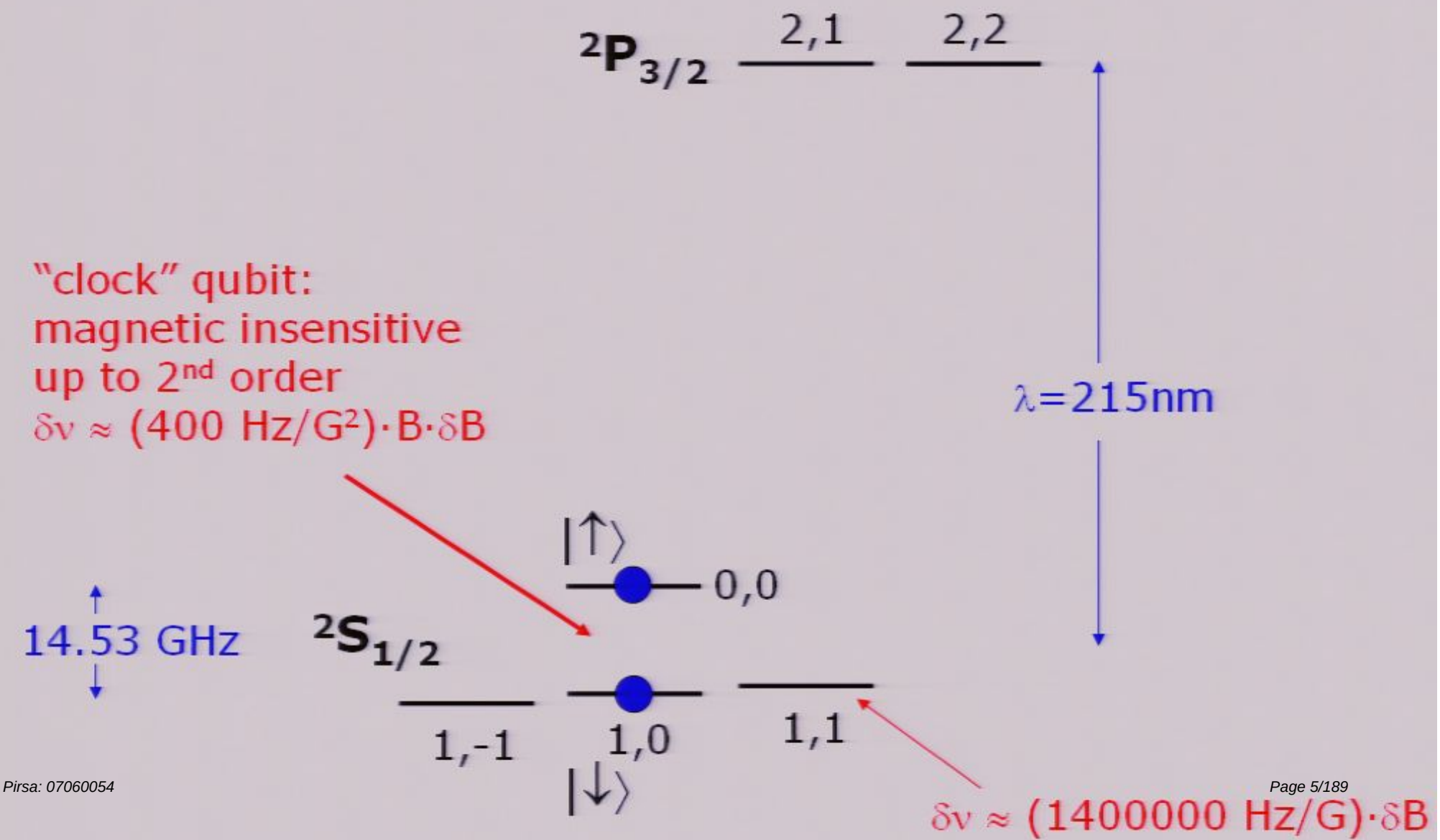


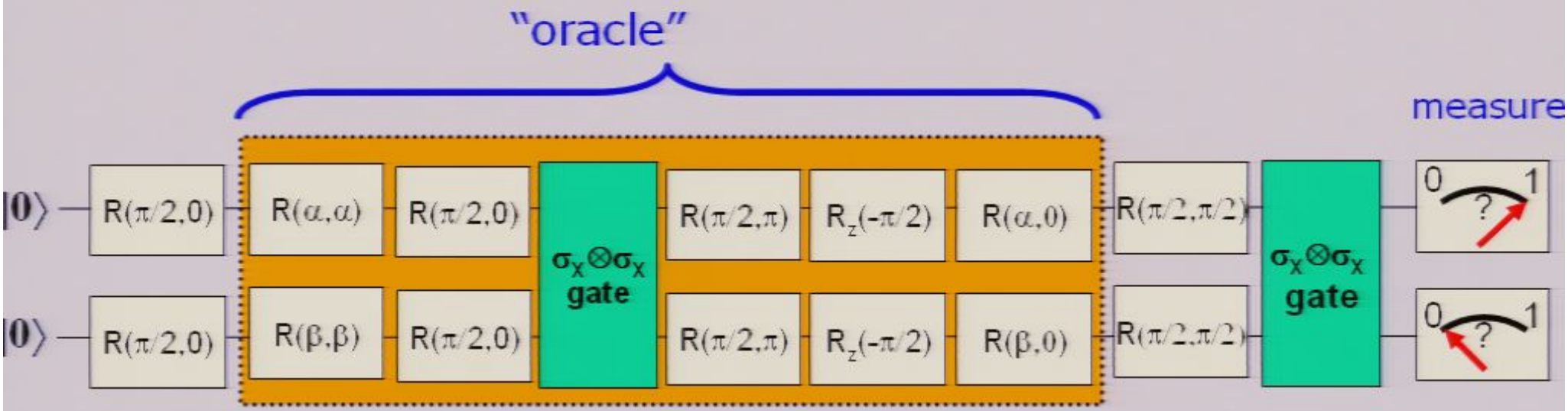
Quantum Algorithms Demonstrated with Ions

* Deutsch-Jozsa (is a function constant or balanced?) 1 qubit
* Dense coding (using one qubit to transmit 2 classical bits)
* Fast Fourier Transform: 3 qubits
* Quantum Teleportation: 3 qubits
* Grover (searching unsorted database): 2 qubits

NIST-Boulder
Innsbruck
Michigan

Implementation of Grover's Search Algorithm

on N=2 ions (4-element database)



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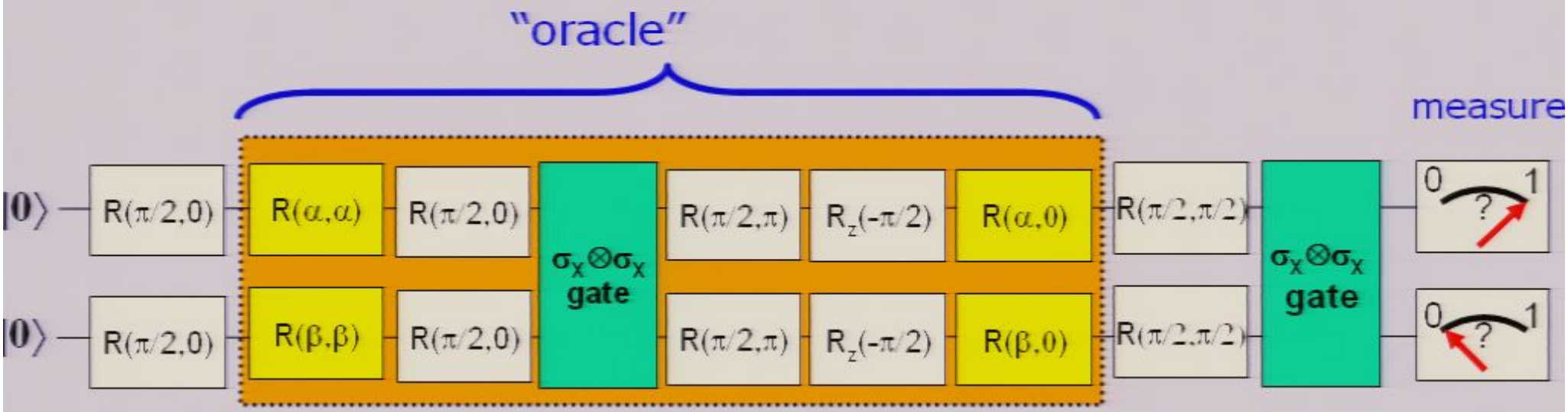
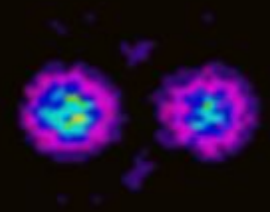


mark state with Bloch-sphere rotation angles

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

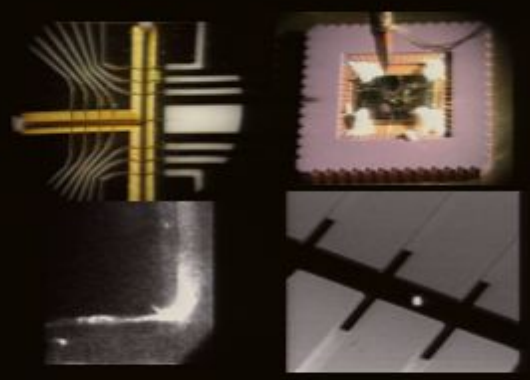
Ion Trap Quantum Networks

- Local entanglement through the Coulomb interaction (phonons)



$\sim 10^{-6}$ m

- Shuttling ions through advanced scalable trap structures



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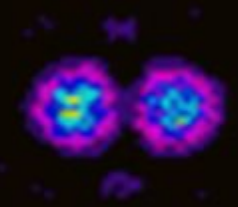

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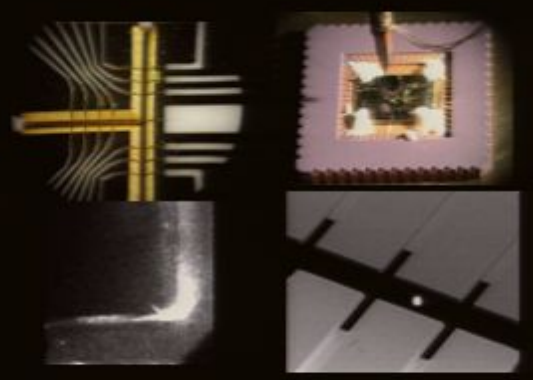

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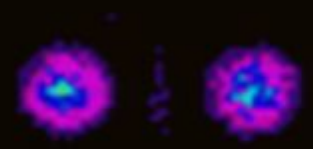

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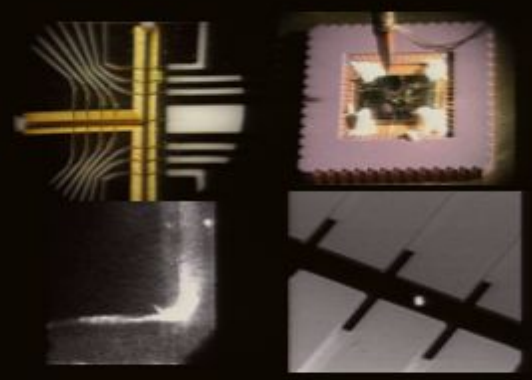

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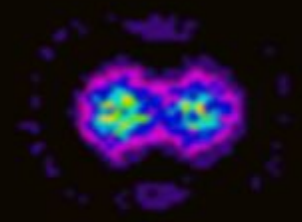

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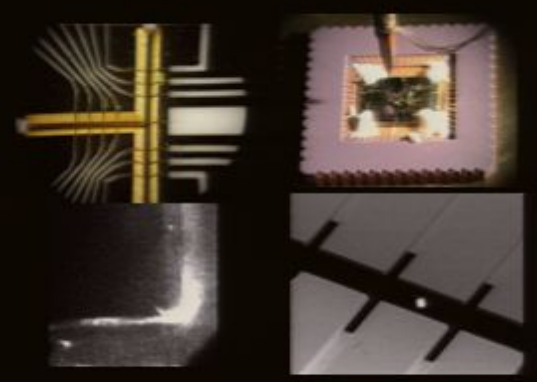

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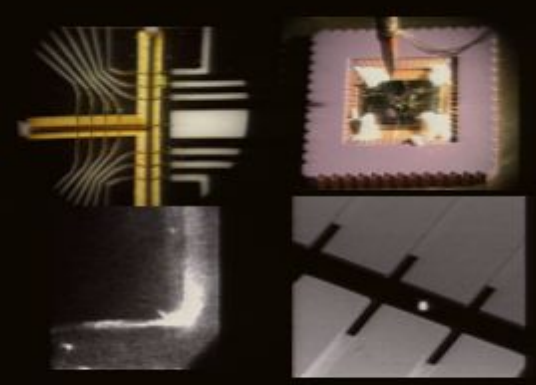

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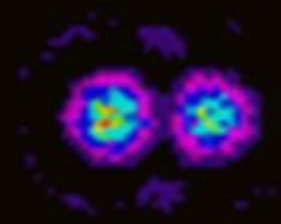

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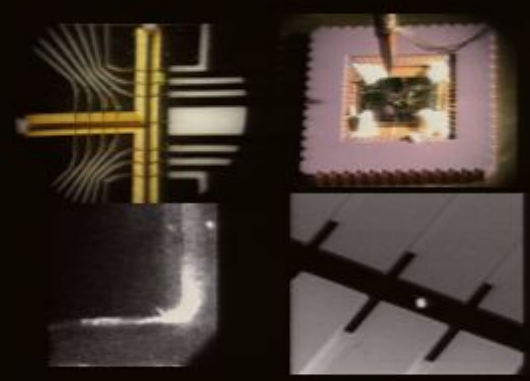

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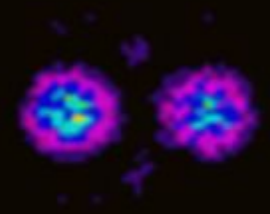

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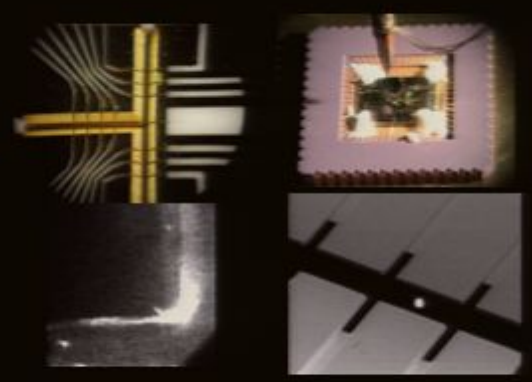

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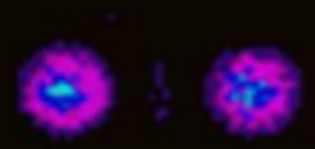

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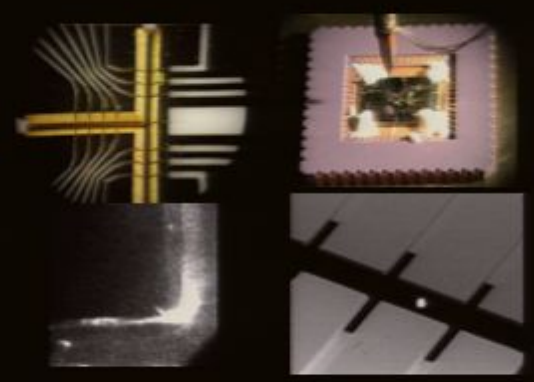

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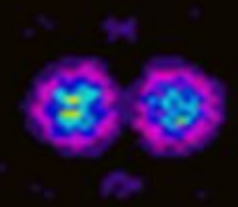

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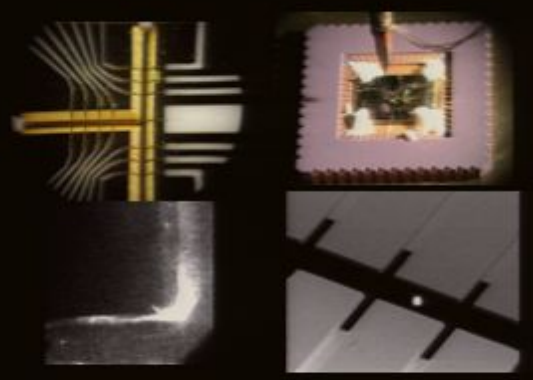

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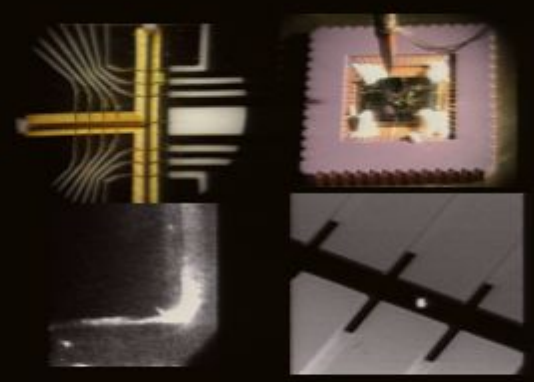

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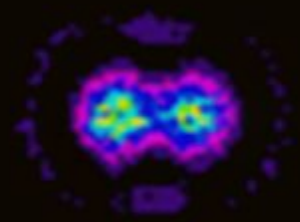

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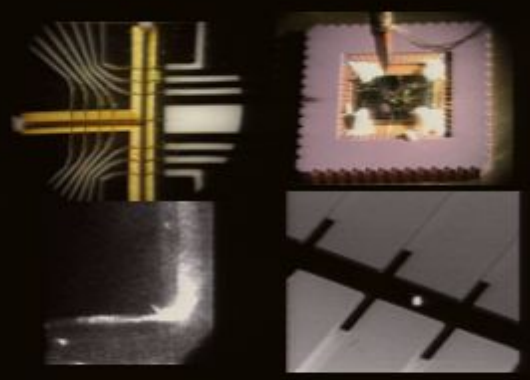

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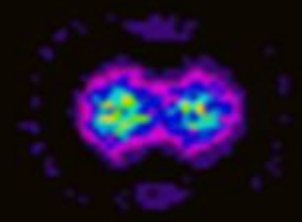

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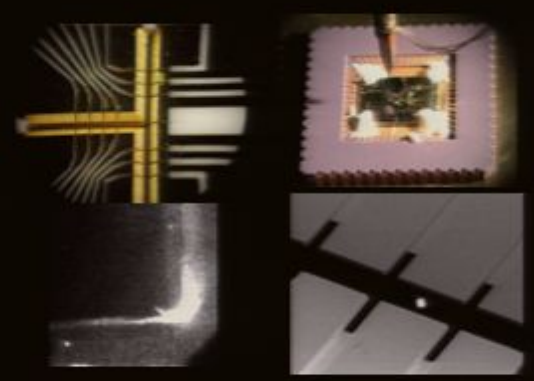

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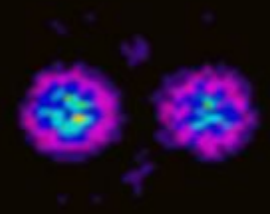

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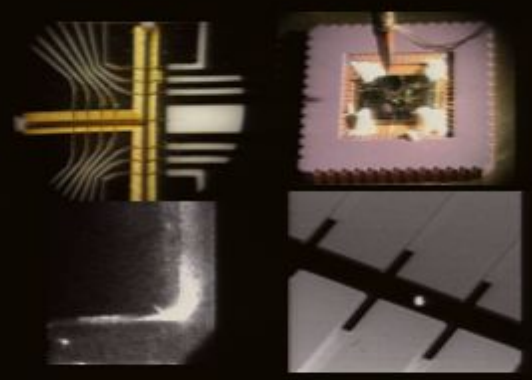

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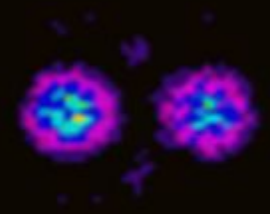

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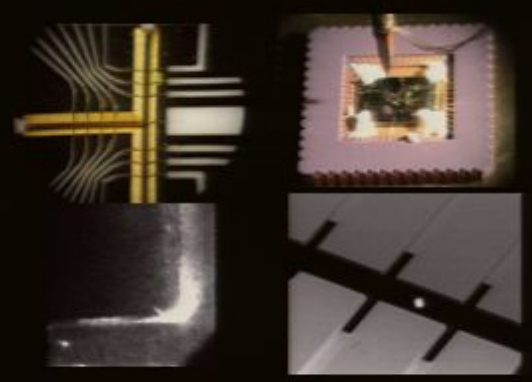

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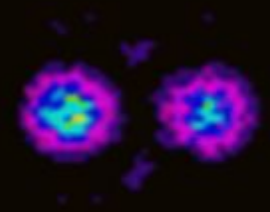

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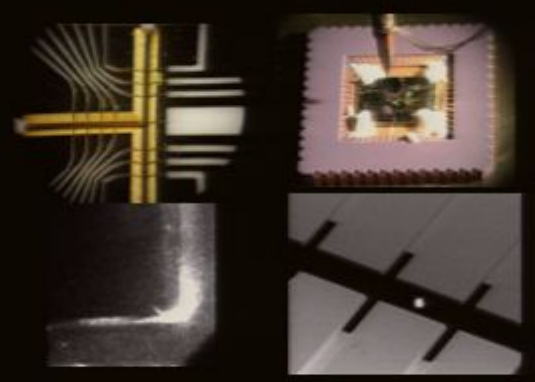

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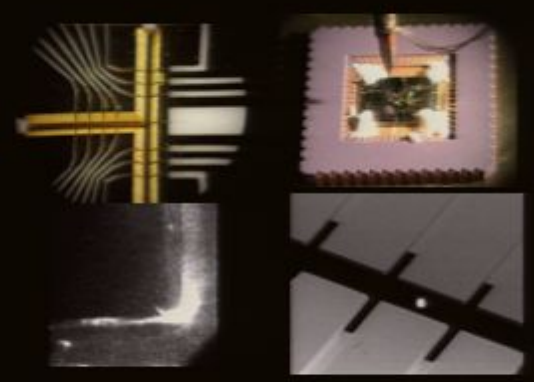

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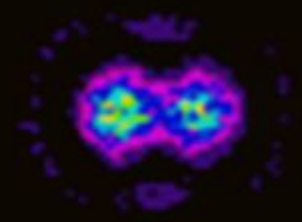

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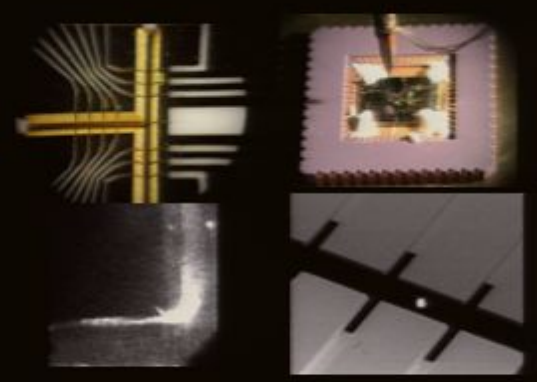

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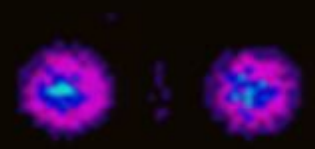

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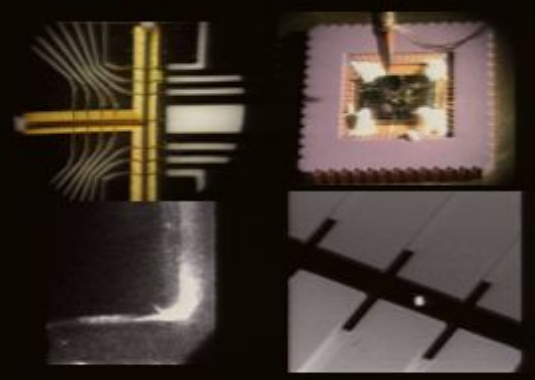

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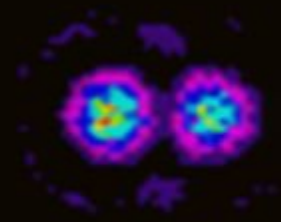

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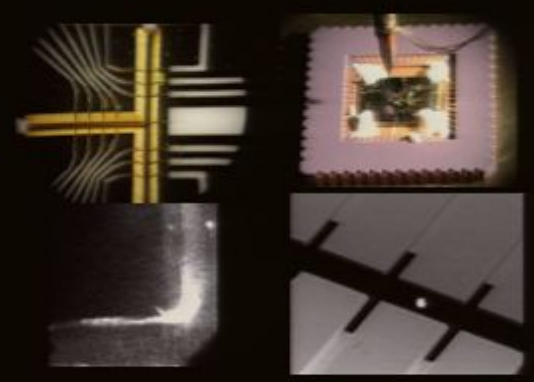

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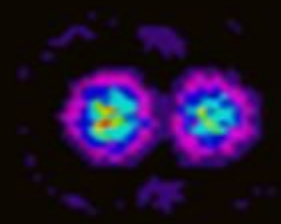

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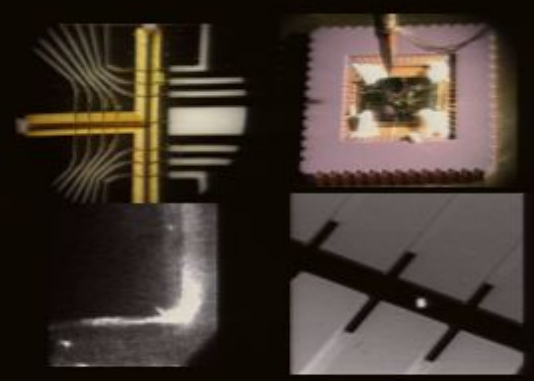

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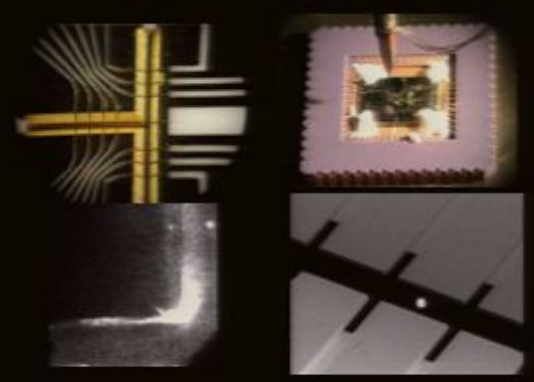

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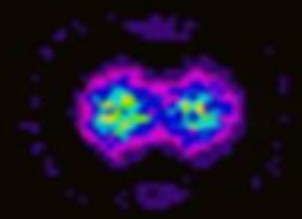

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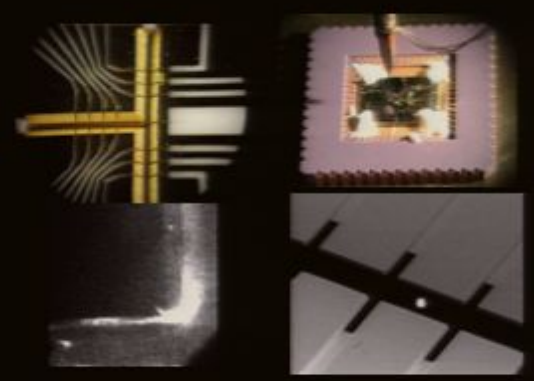

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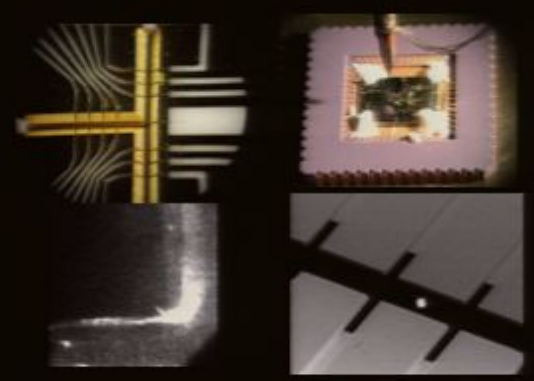

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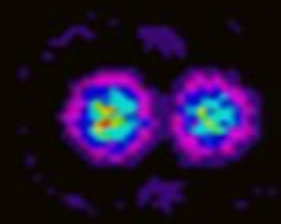

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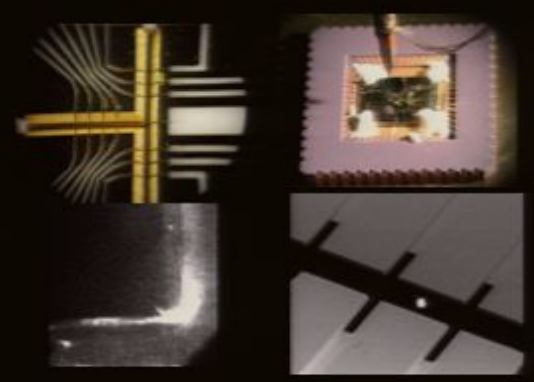

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- Nonlocal entanglement though spontaneous emission (photons)

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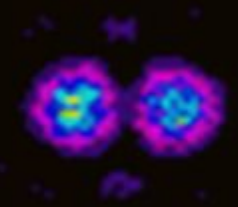
Ion Trap Quantum Networks

- Local entanglement through the Coulomb interaction (phonons)



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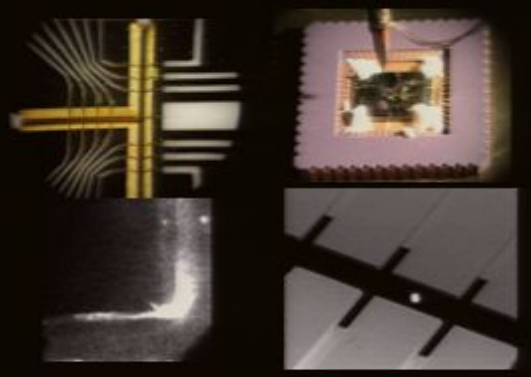

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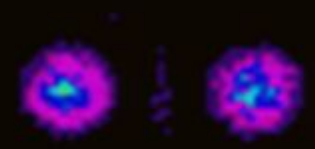

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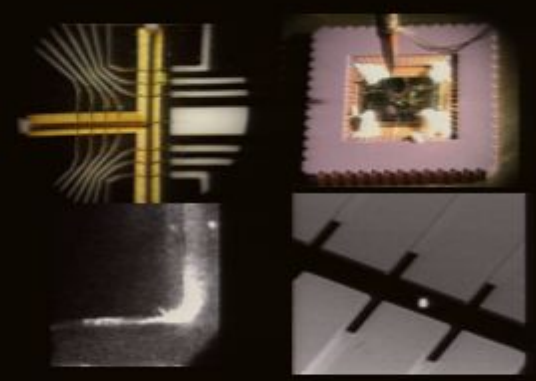

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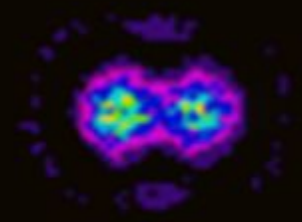

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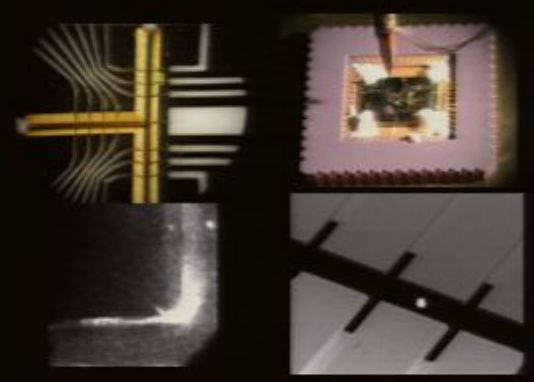

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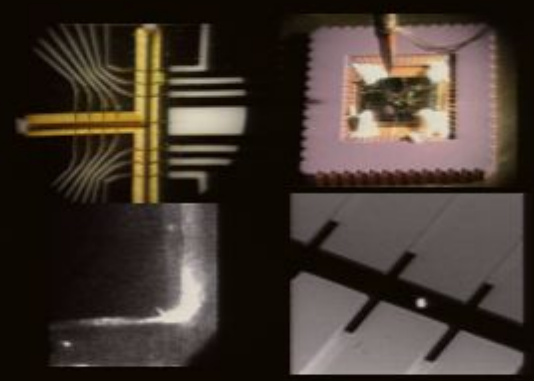

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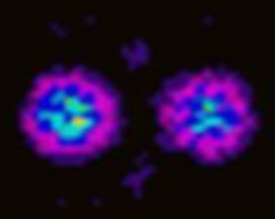

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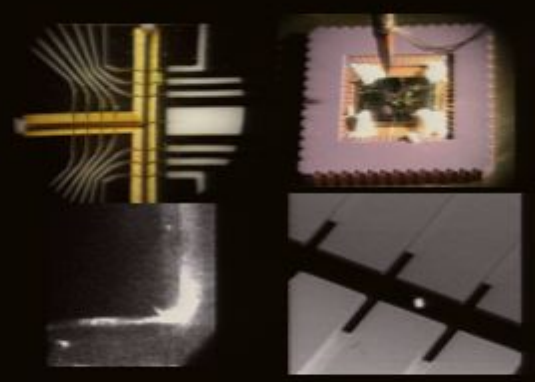

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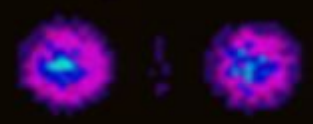

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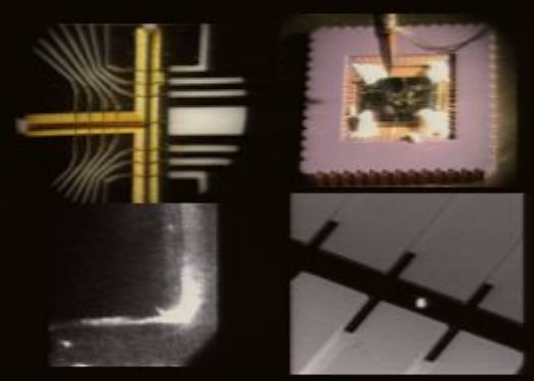

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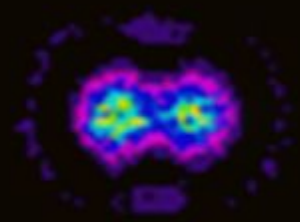

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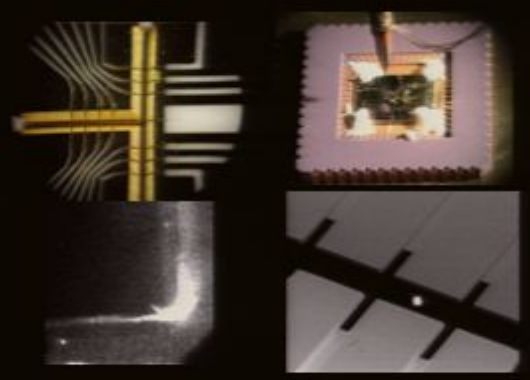

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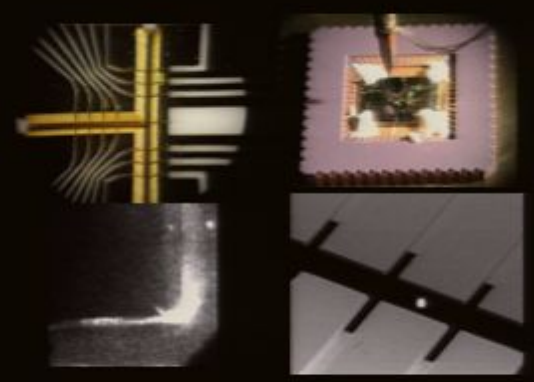

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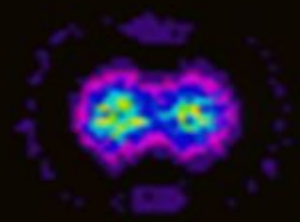

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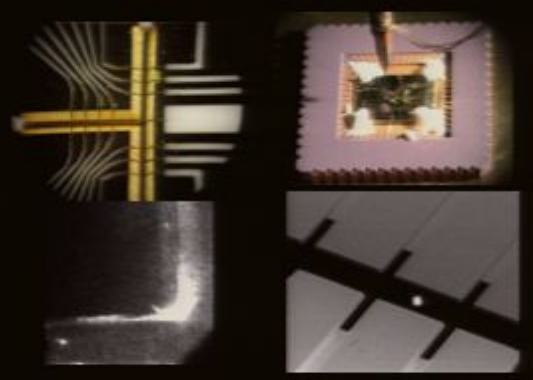

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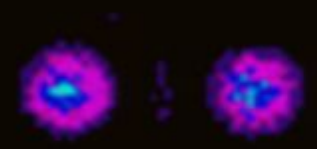

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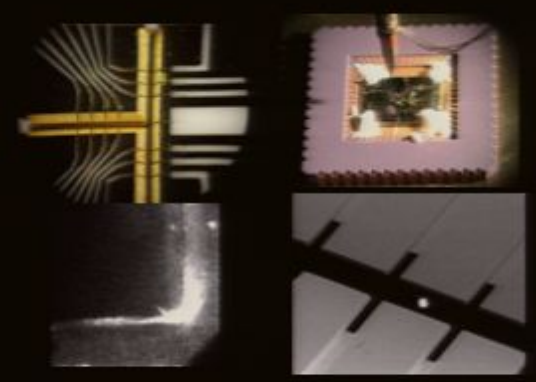

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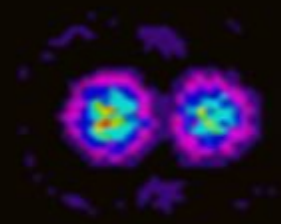

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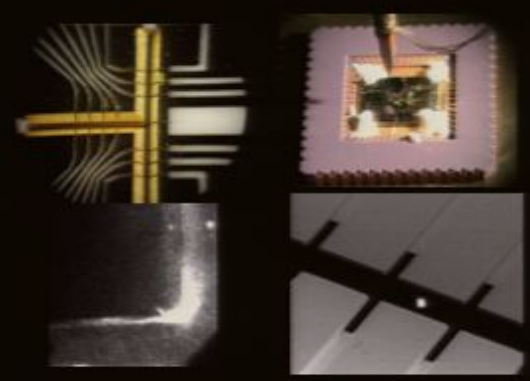

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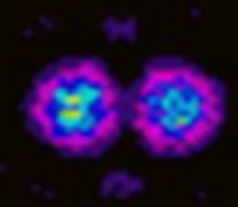

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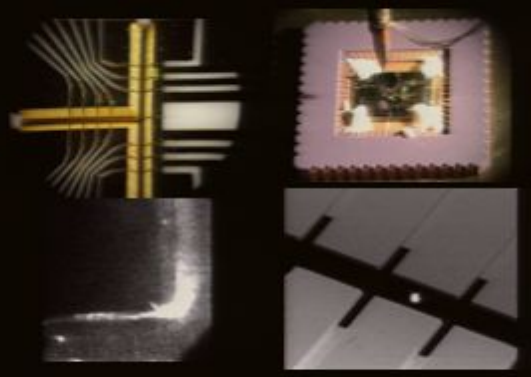

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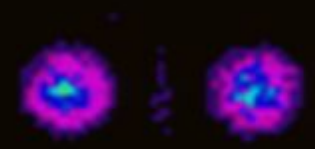

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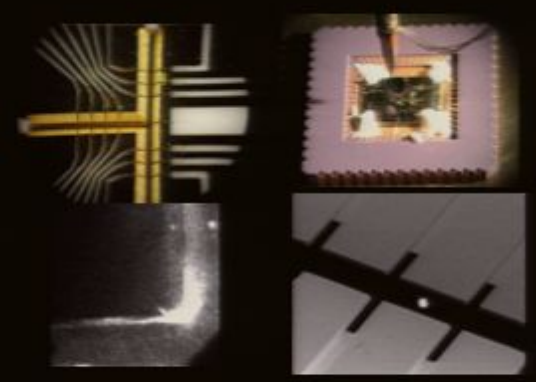

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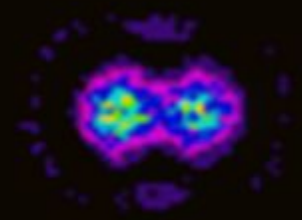

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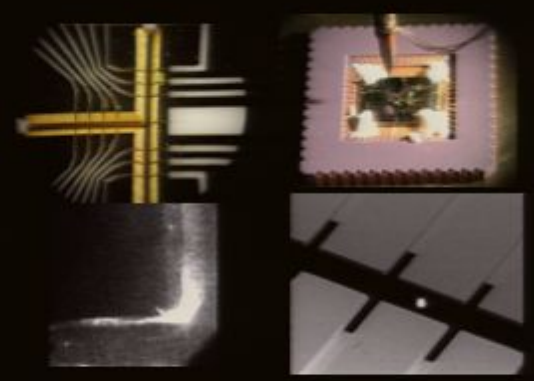

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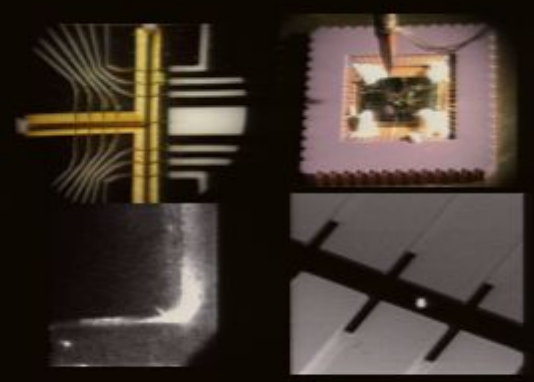

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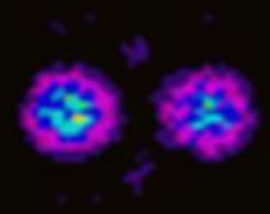

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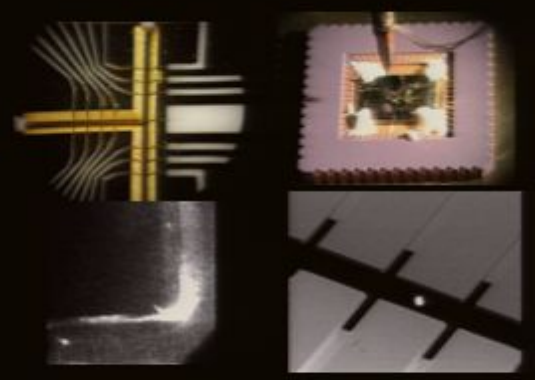

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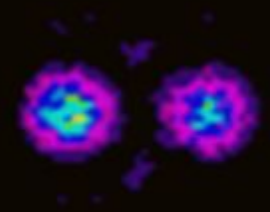

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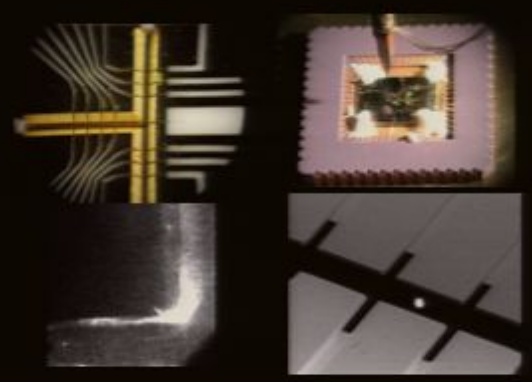

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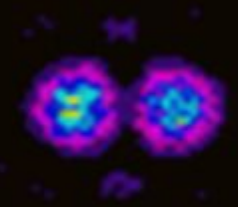

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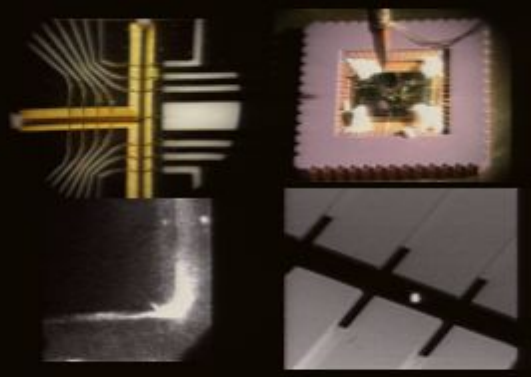

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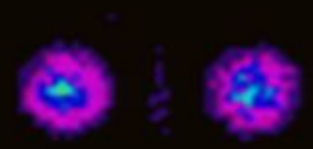

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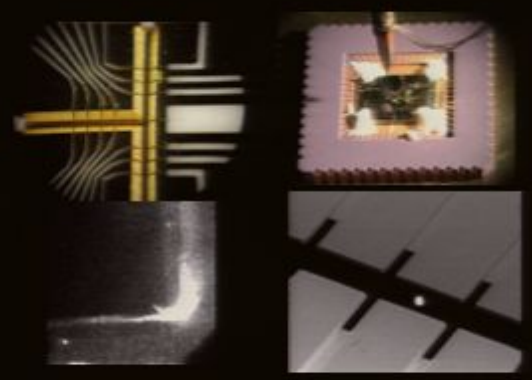

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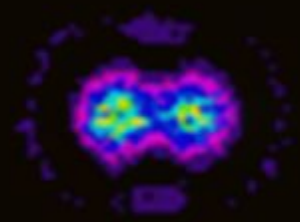

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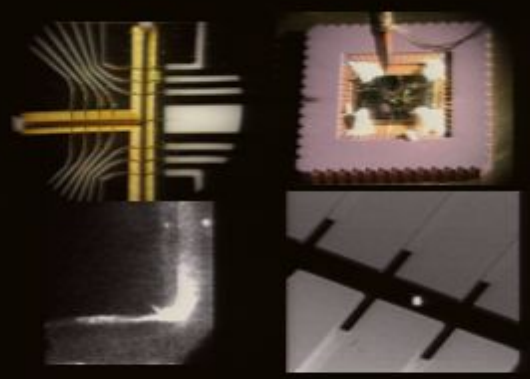

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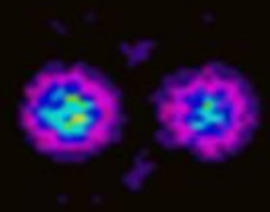

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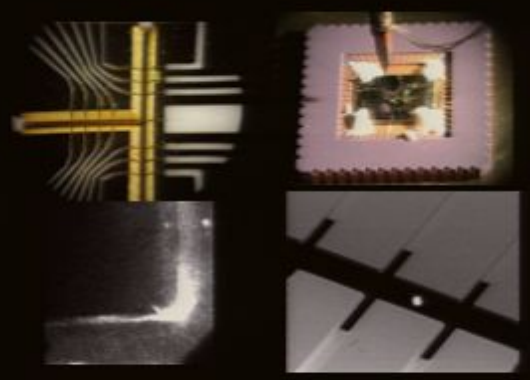

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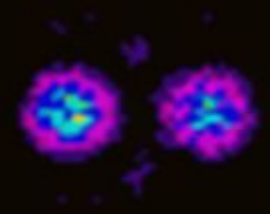

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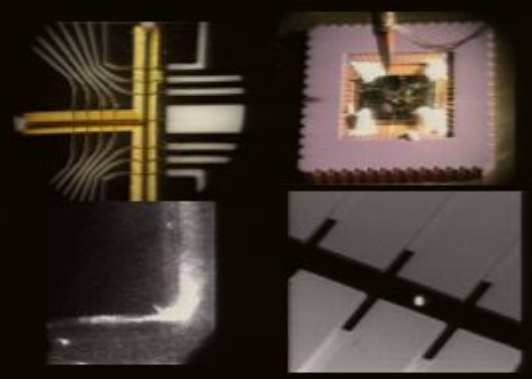

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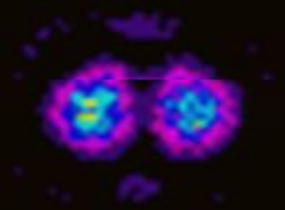

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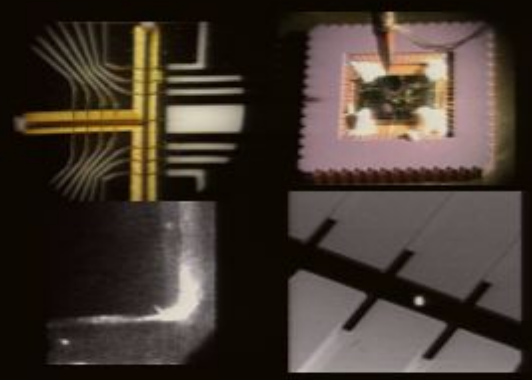

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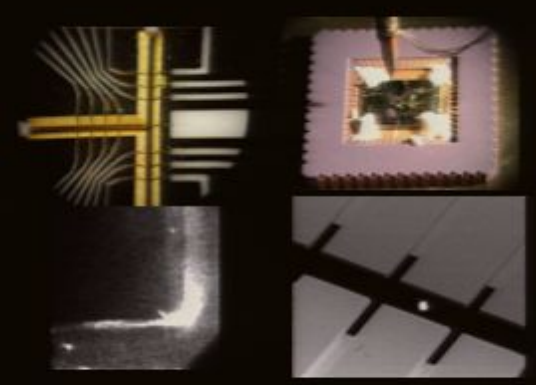

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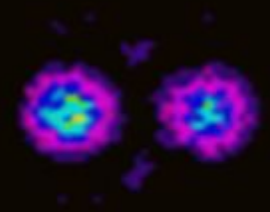

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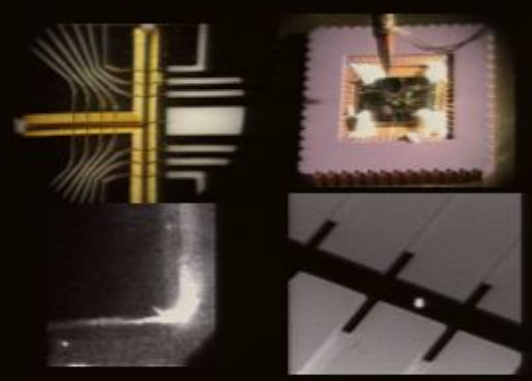

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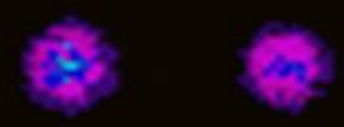

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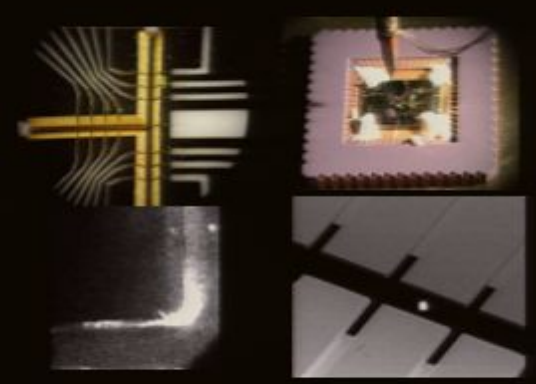

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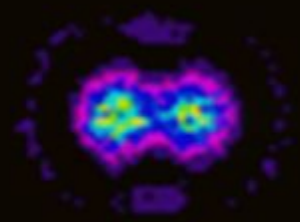
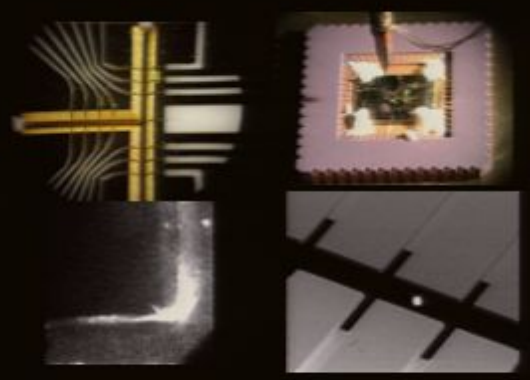


$\sim 10^{-6}$ m

- Shuttling ions through advanced scalable trap structures



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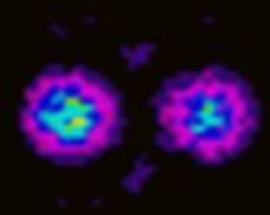

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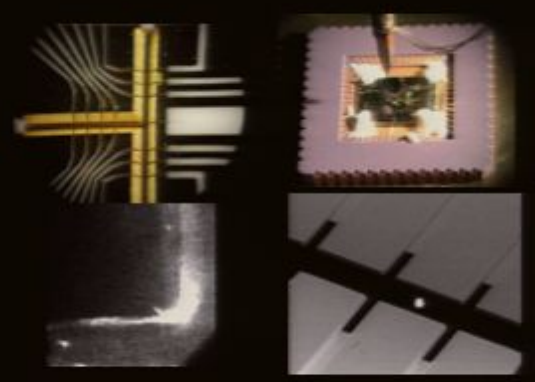

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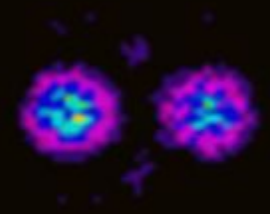

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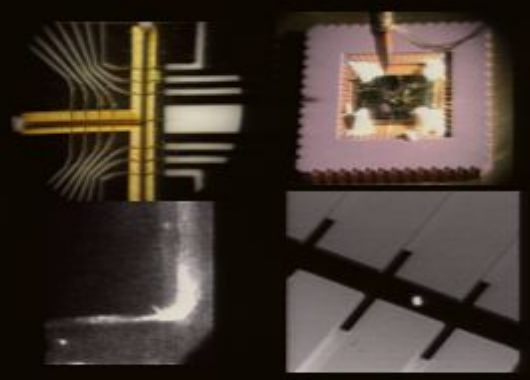

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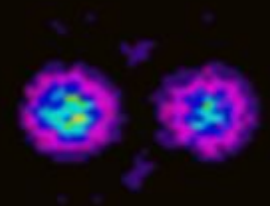

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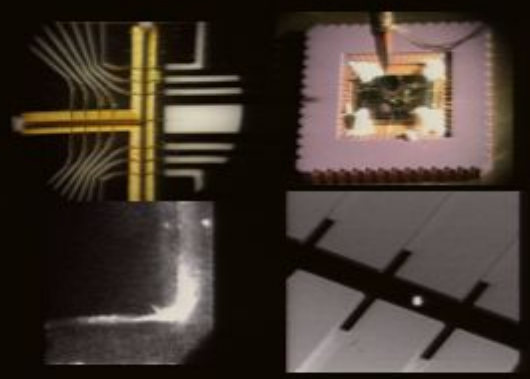

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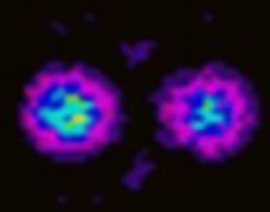

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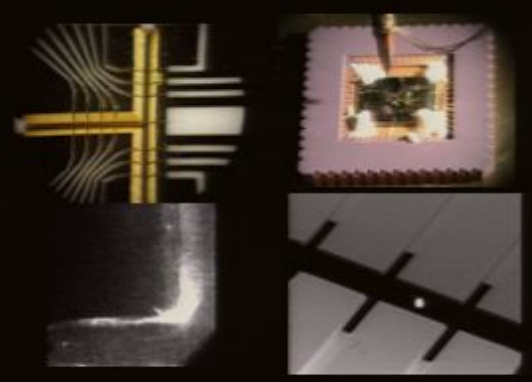

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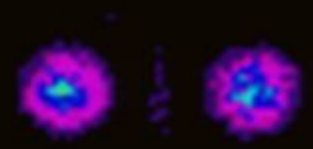

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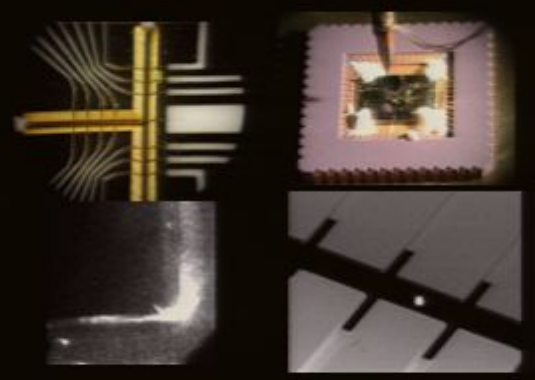

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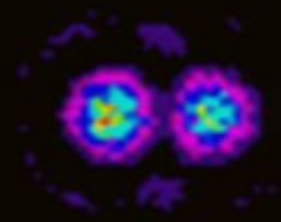

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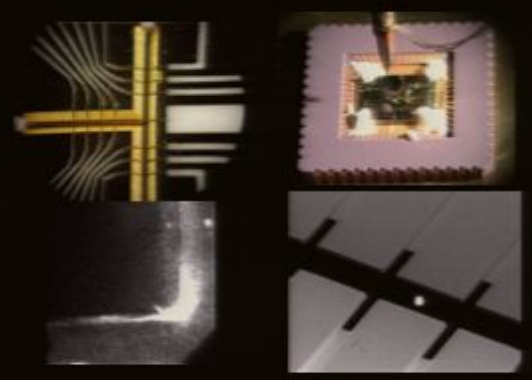

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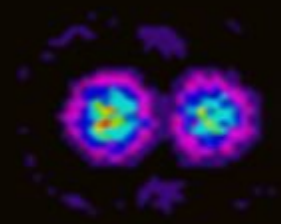

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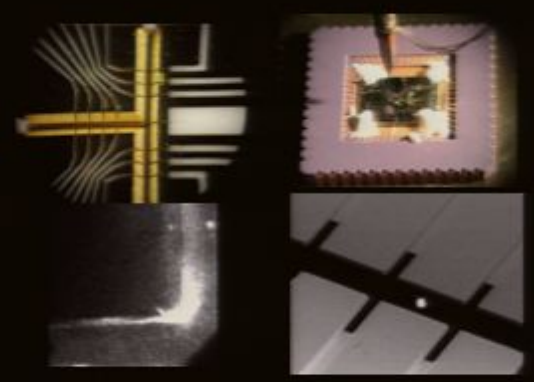

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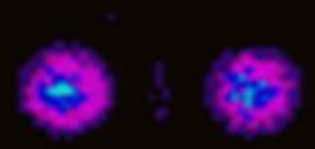

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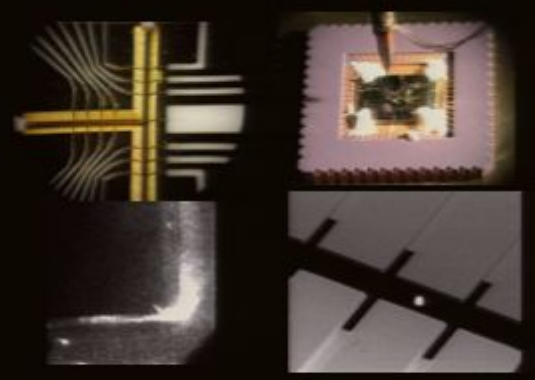

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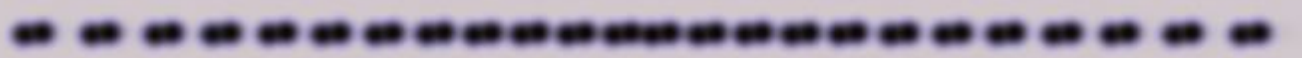

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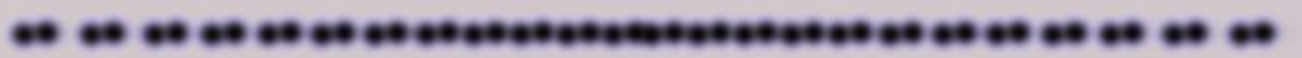

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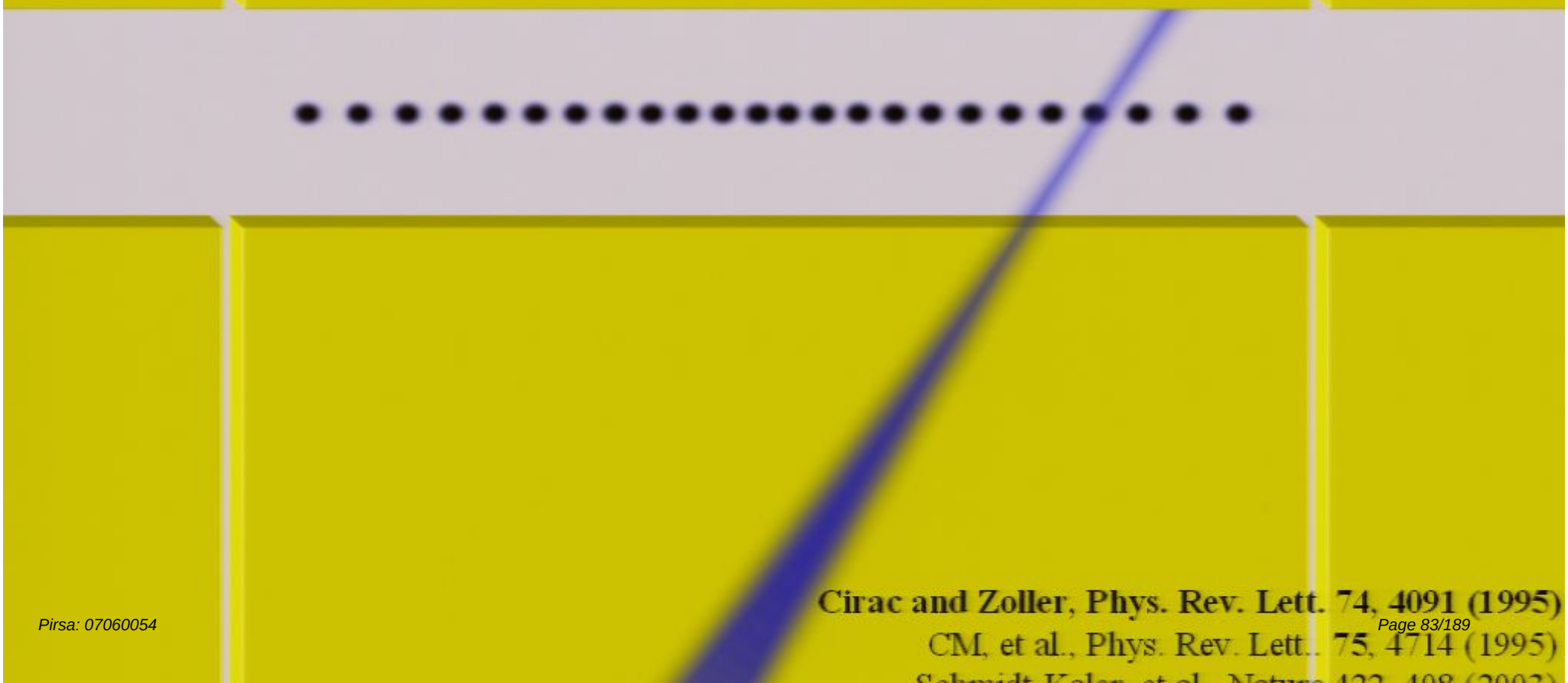

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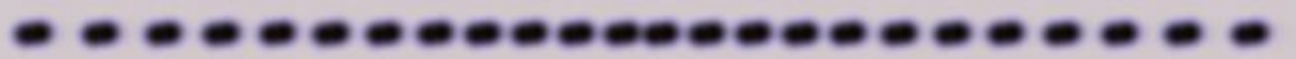

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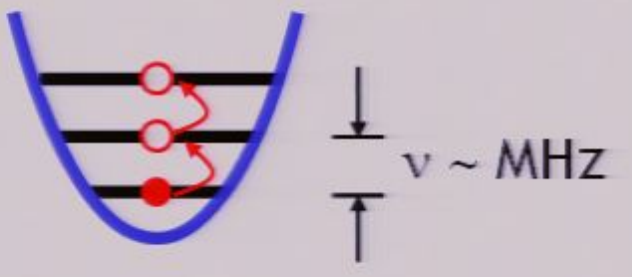
Decoherence of C.O.M. motion



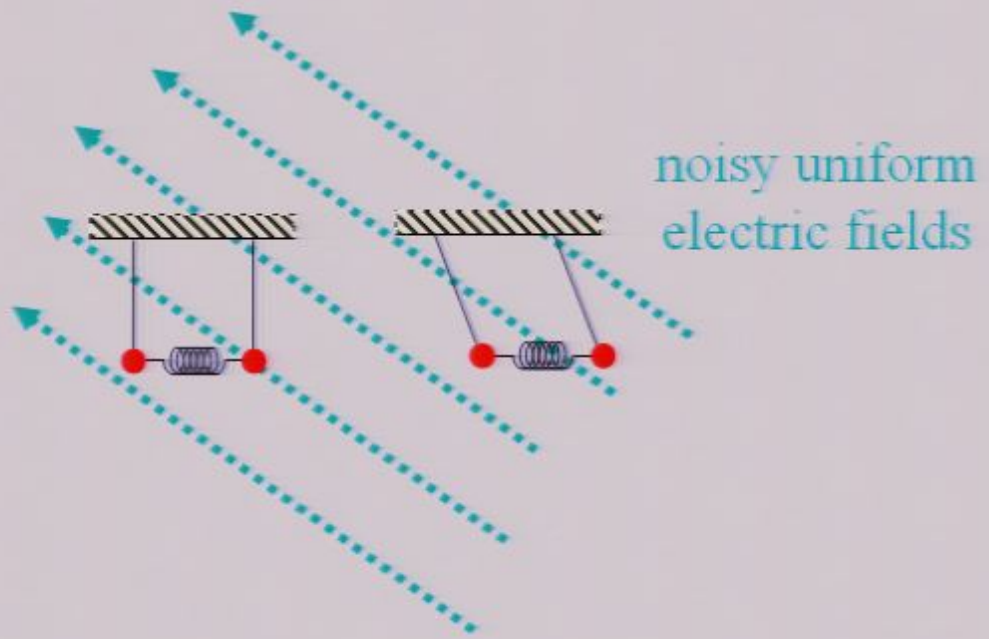
$\gamma = d\langle n \rangle / dt$

expect $\gamma \sim 1\ \mathrm{sec}^{-1}$ (blackbody rad.)

measure $\gamma \sim 10^2 - 10^5\ \mathrm{sec}^{-1}$

COM mode at ω

$x_{COM} = x_1 + x_2$



"Stretch" mode at $\omega\sqrt{3}$

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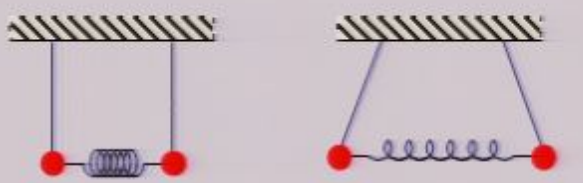
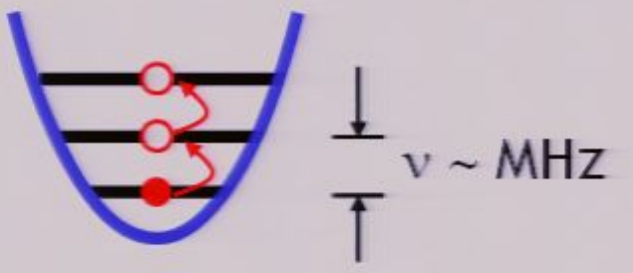


logical 0 logical 1

A decoherence-free subspace!

Decoherence of C.O.M. motion



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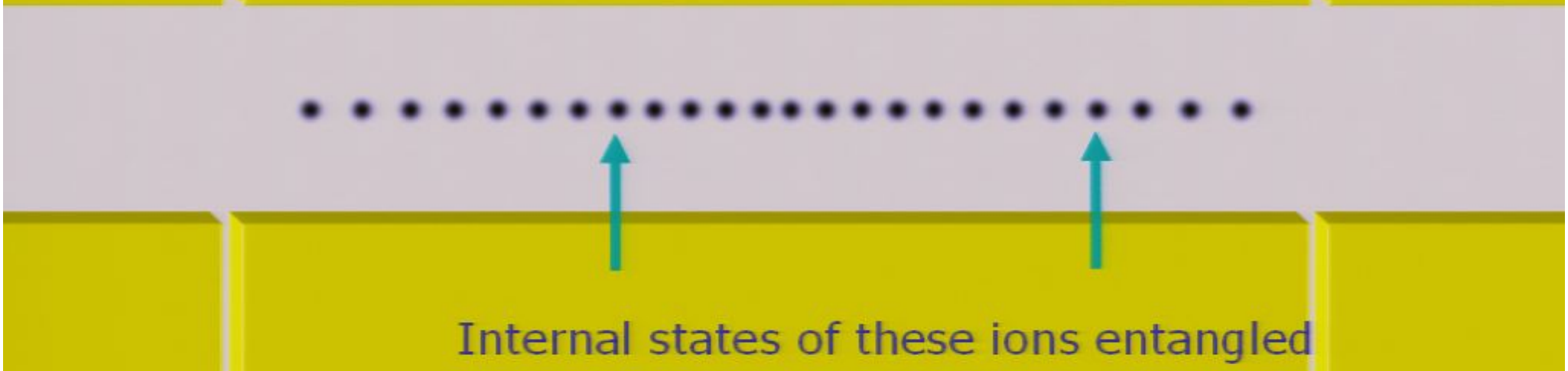

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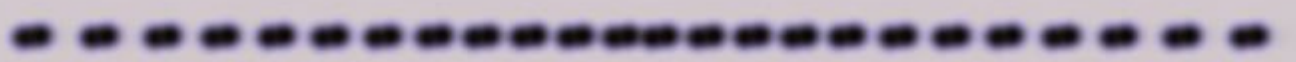

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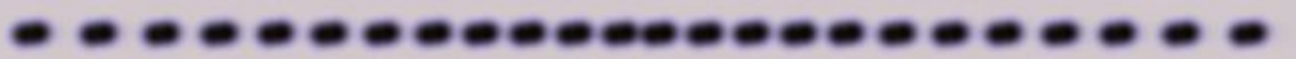

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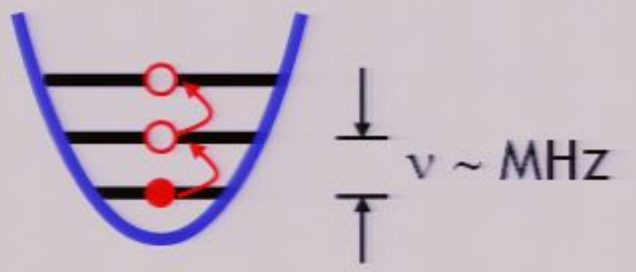

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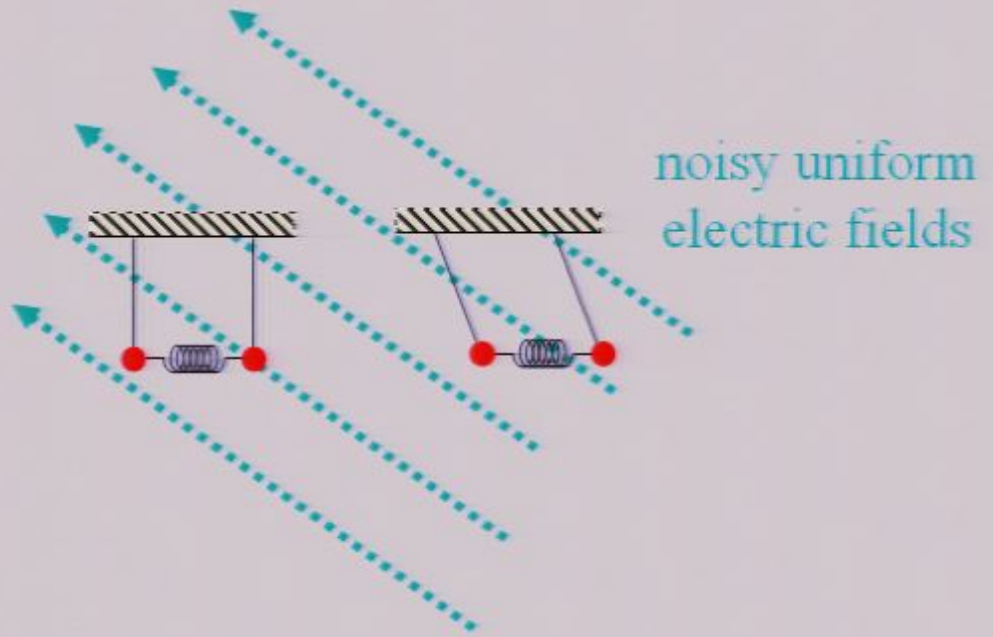

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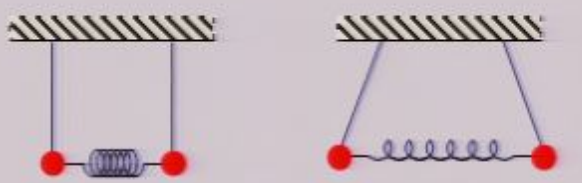

logical 0 logical 1

A decoherence-free subspace!

COM mode at ω

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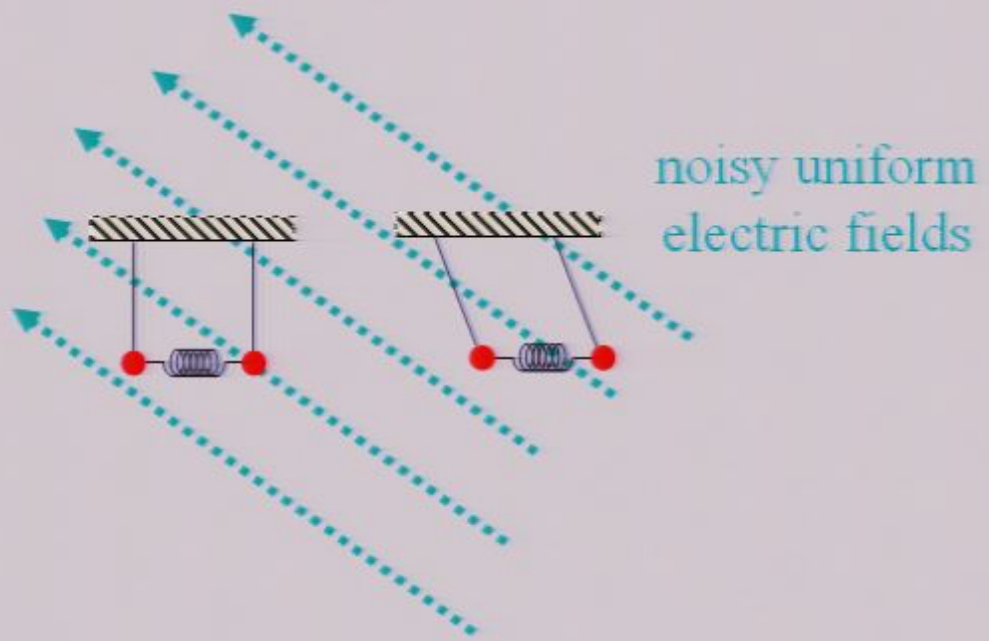

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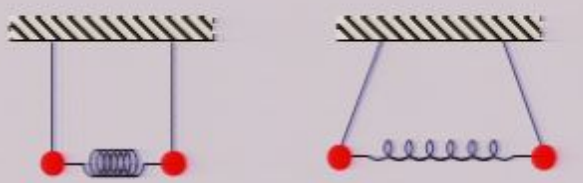
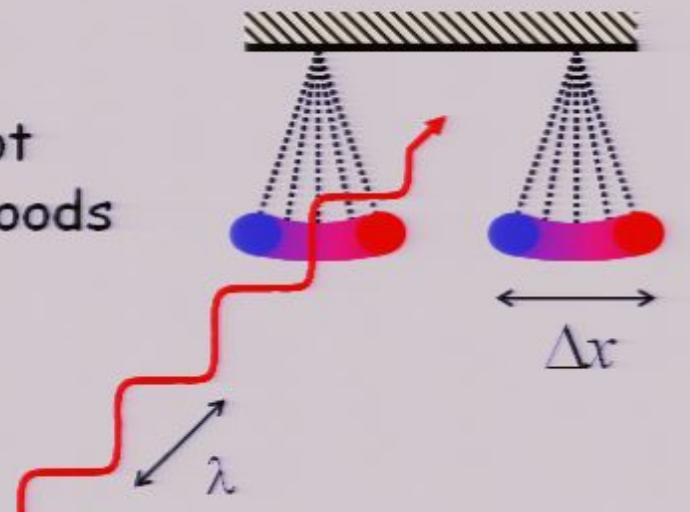


logical 0 logical 1

A decoherence-free subspace!

... but still not out of the woods



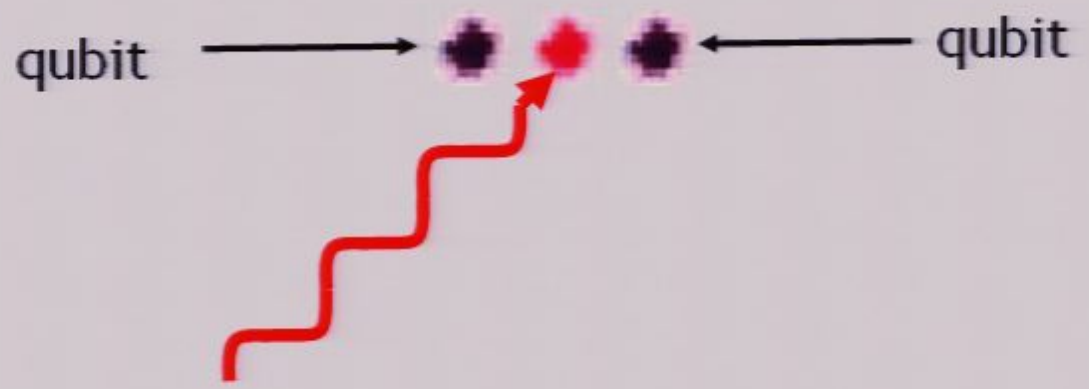
x_{STR} fixed; x_{COM} random

$\Rightarrow e^{-(\Delta x/\lambda)^2}$ gate fidelity

Debye-Waller effect

“ion-in-the-middle” sympathetic laser cooling:

quench heating without disturbing internal state
OR symmetric stretch mode



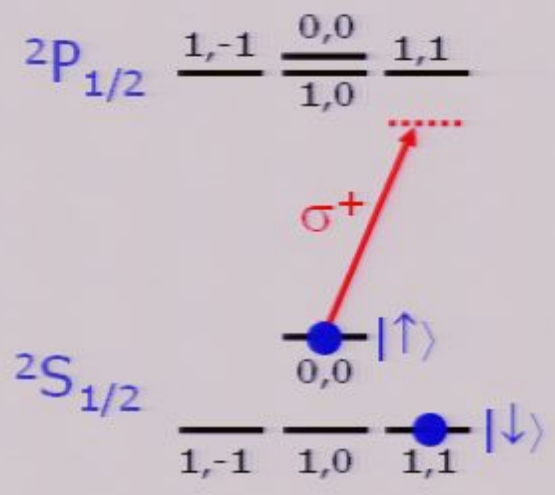
continuous cooling of middle ion
eliminates C.O.M. heating from uniform fields
(tight focusing, or different species)

D. Kielpinski, et. al., Phys. Rev. A **61**, 032310 (2000)

BETTER: Indirect use of motion for quantum gates

spin-dependent force:

$$\text{Force} = F_0 |\uparrow\rangle\langle\uparrow|$$



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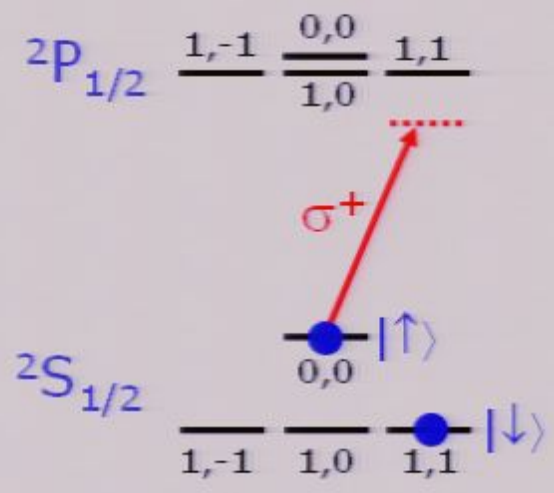
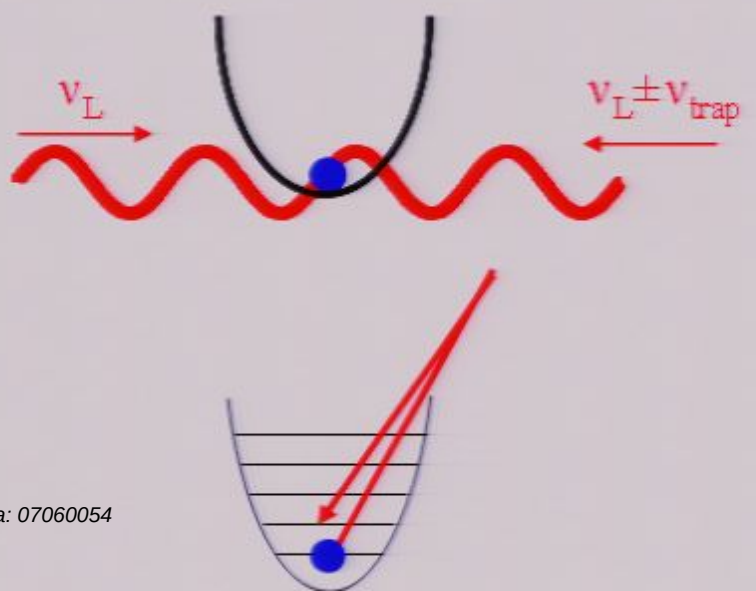
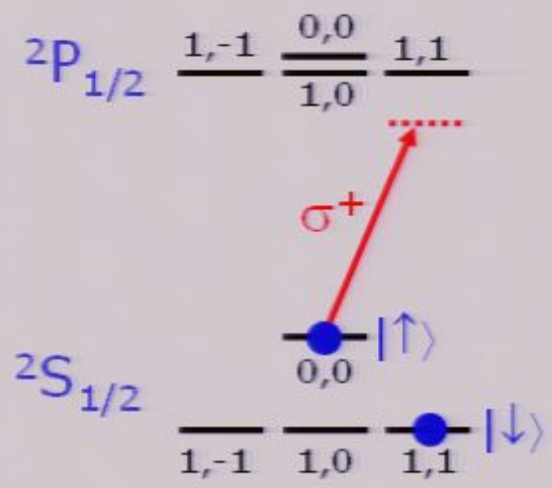


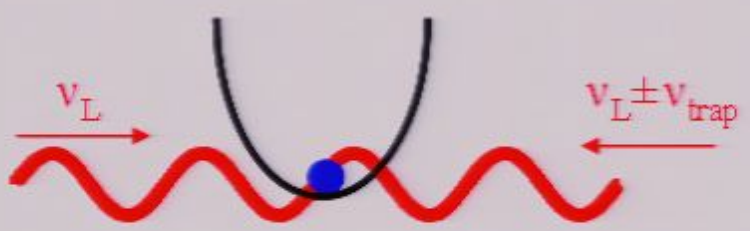


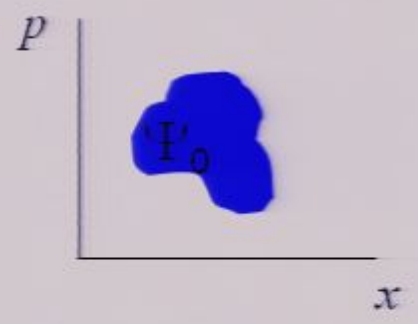
BETTER: Indirect use of motion for quantum gates

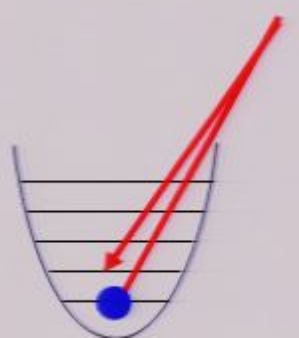
spin-dependent force:

Force = $F_0 |\uparrow\rangle\langle\uparrow|$









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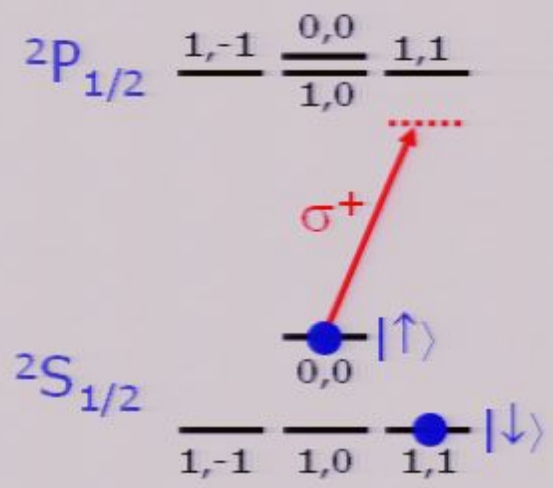

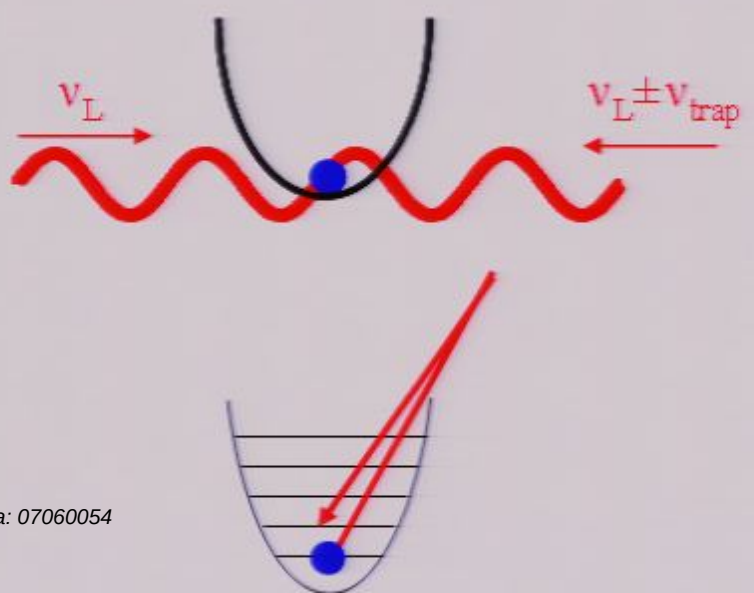

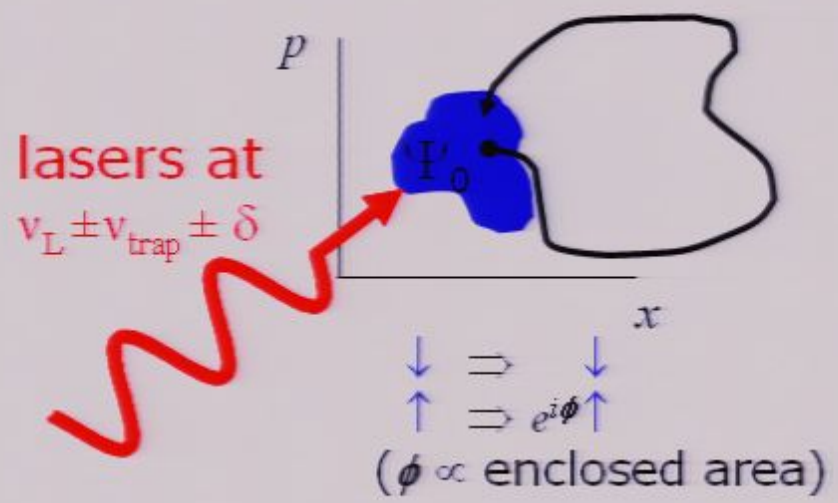

Independent of initial state but requires Lamb-Dicke limit

N=2 ions

e.g., force on stretch mode only

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

$$H = \hbar\Omega\hat{\sigma}_z^2$$

$\phi = \pi/2$: π-phase gate

Mølmer and Sørensen, PRL **82**, 1835 (1999)
Solano, de Matos Filho, Zagury, PRA **59**, R2539 (1999)
Milburn, Schneider, James, Fortschr. Phys. (2000)

Leibfried *et al.*, Nature **422**, 412 (2003) ← F=97%
Lucas, Steane, *et al.* (2005)

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N=6 ions

$$\uparrow\uparrow\uparrow\uparrow\uparrow\uparrow + \downarrow\downarrow\downarrow\downarrow\downarrow\downarrow$$

Leibfried *et al.*, Nature **438**, 639-642 (2005)

Problem with $\sigma_Z \sigma_Z$ gates:

With "clock" state qubits
(no differential Zeeman shift),...

cannot realize a spin-dependent force
(no differential AC Stark shift)

P. J. Lee, et al., Journal of Optics B **7**, S371 (2005).

Solution: do $\sigma_X \sigma_X$ gates instead!

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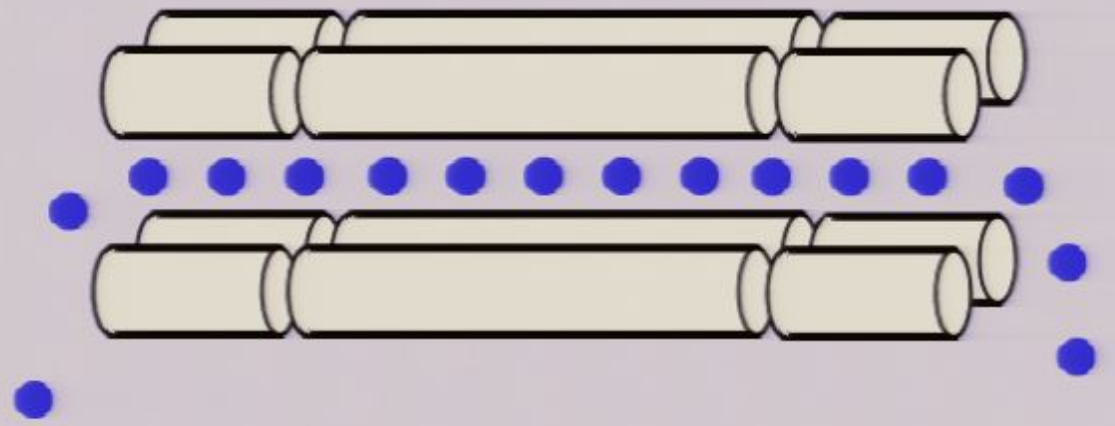
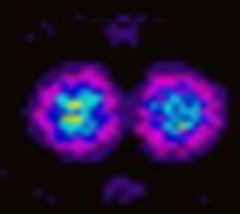
Scale up?



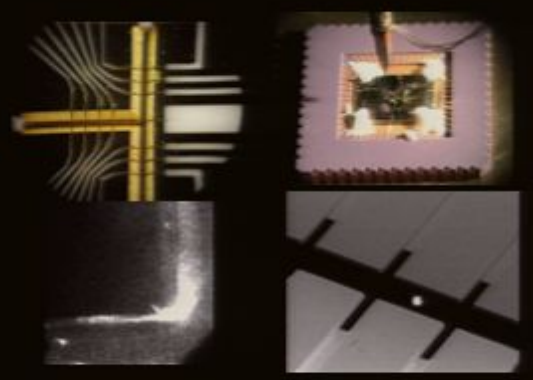
Ion Trap Quantum Networks

- Local entanglement through the Coulomb interaction (phonons)



$\sim 10^{-6}$ m

- Shuttling ions through advanced scalable trap structures



$\sim 10^{-3}$ m

- Nonlocal entanglement though spontaneous emission (photons)

~ 1 m

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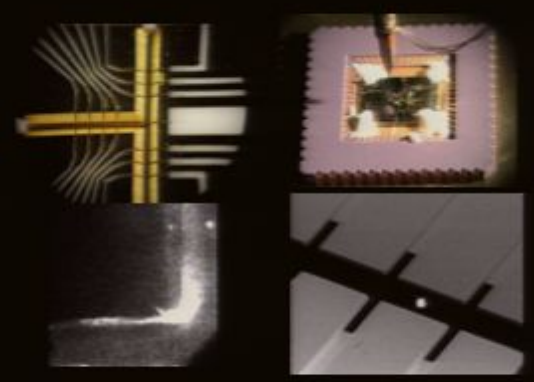

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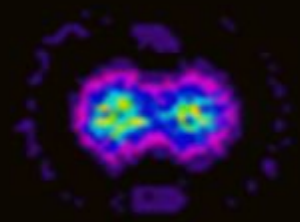

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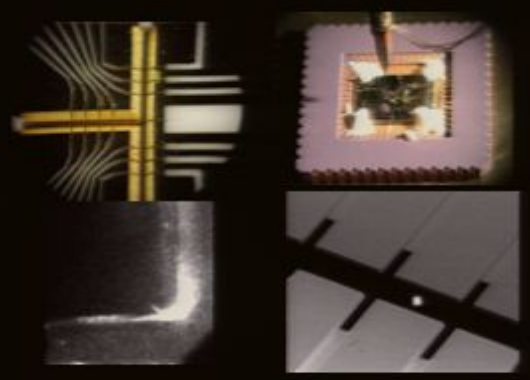

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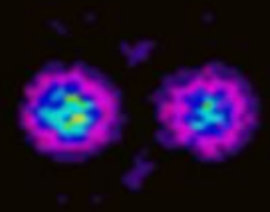

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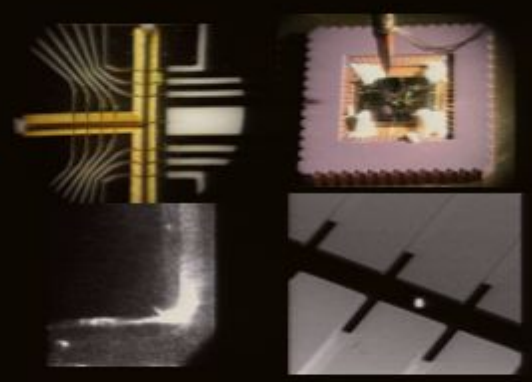

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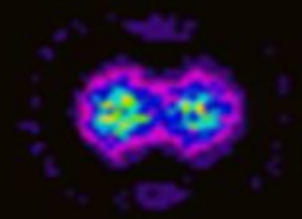

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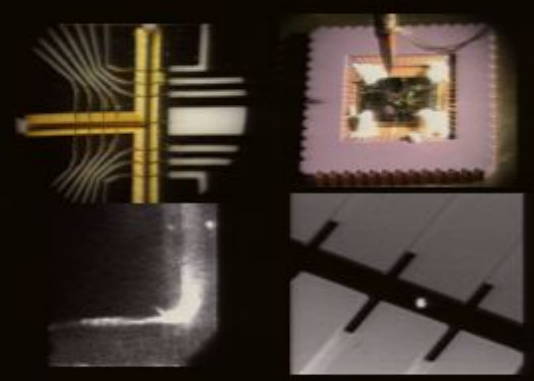

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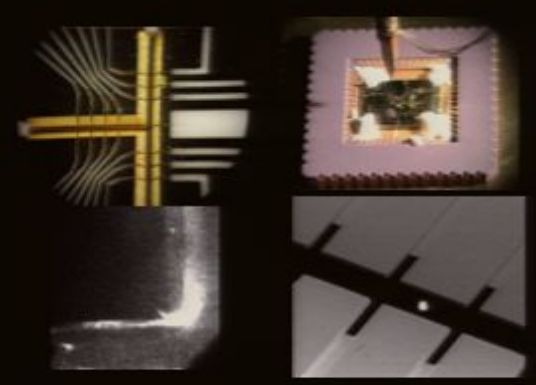

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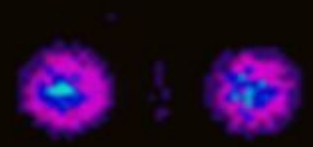

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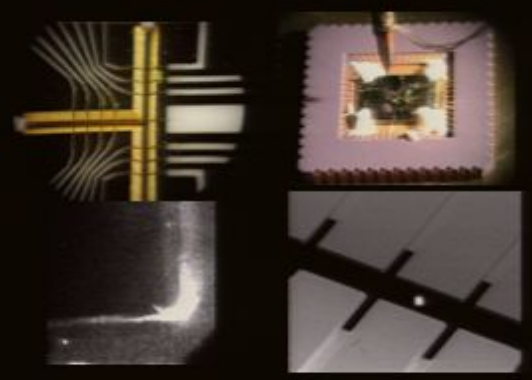

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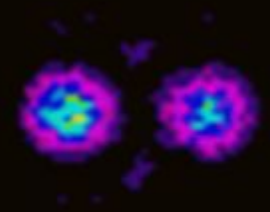

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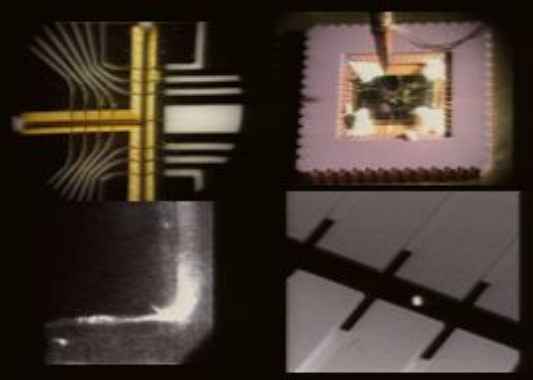

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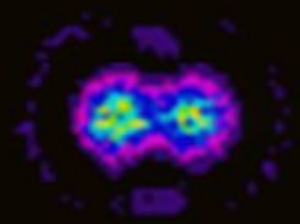

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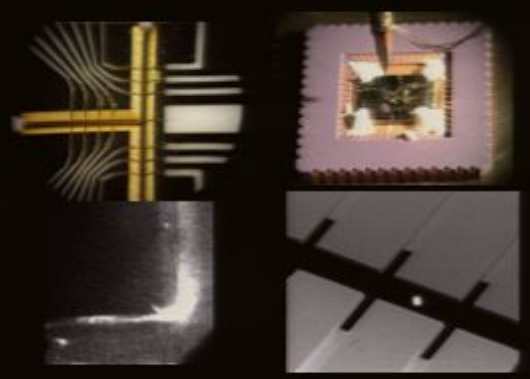

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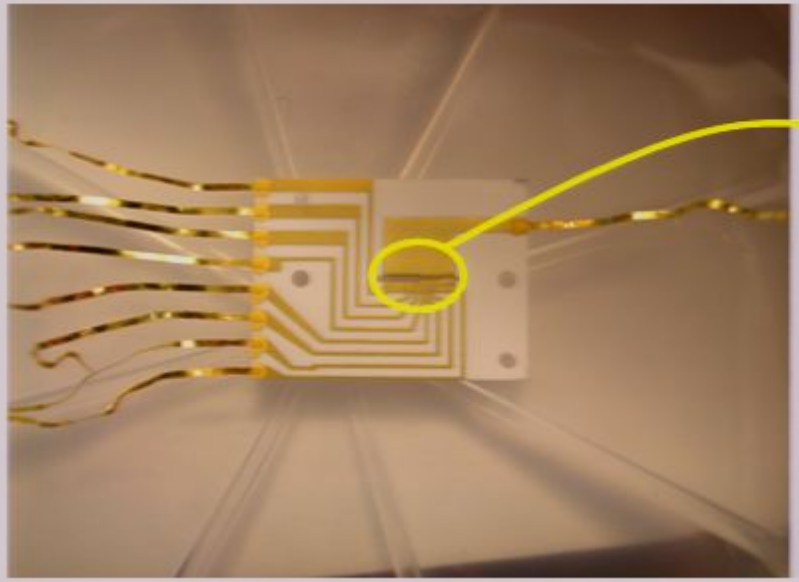
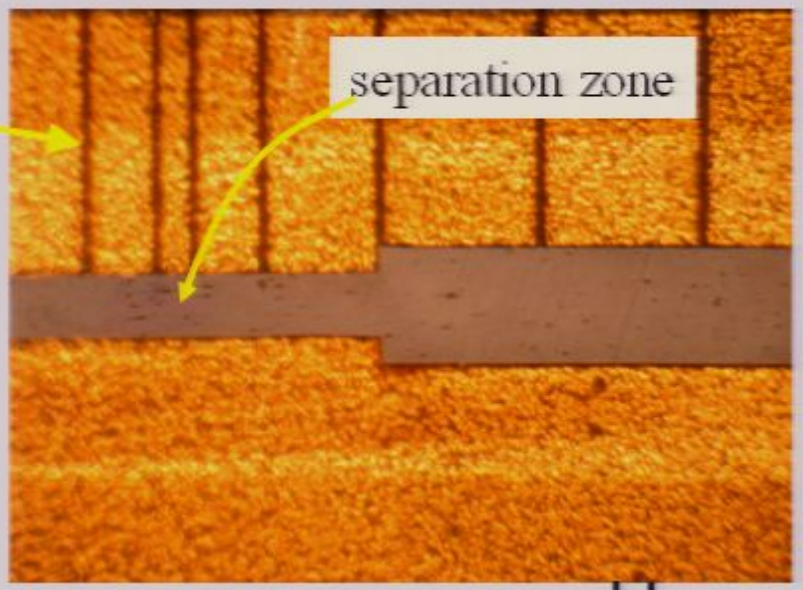
(6-zone) alumina/gold trap

(D. Wineland, et. al., NIST-Boulder)

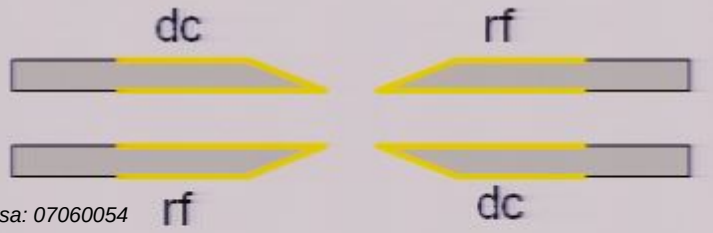




200 μm

100 μm

view along axis:



Multiqubit operations

- teleportation
- 3-qubit phase noise error correction
- FFT
- entanglement purification

Microsoft PowerPoint - [FTQC_Waterloo_Jun07.PPT]

(6-zone) alumina/gold trap

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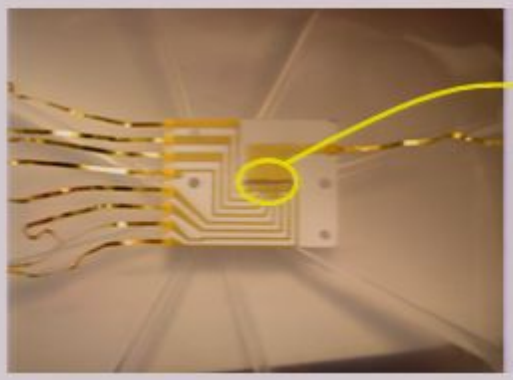

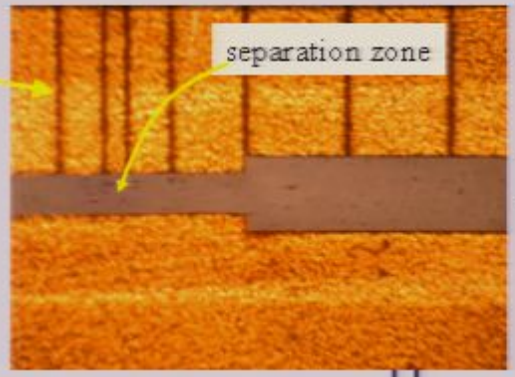

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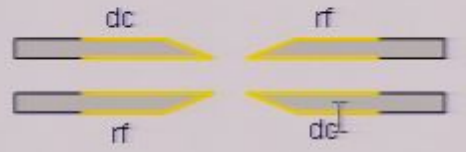

Multiqubit operations

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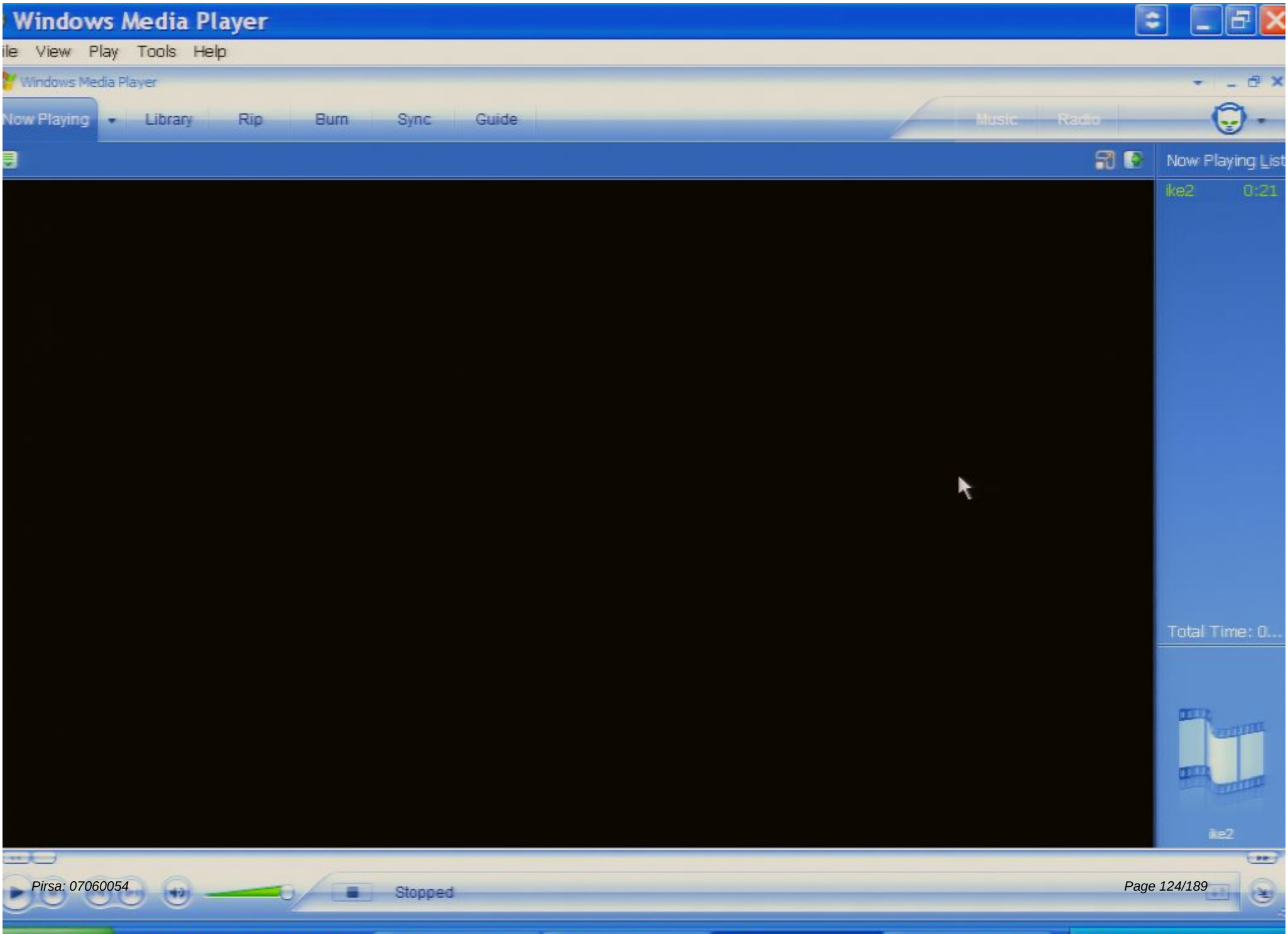
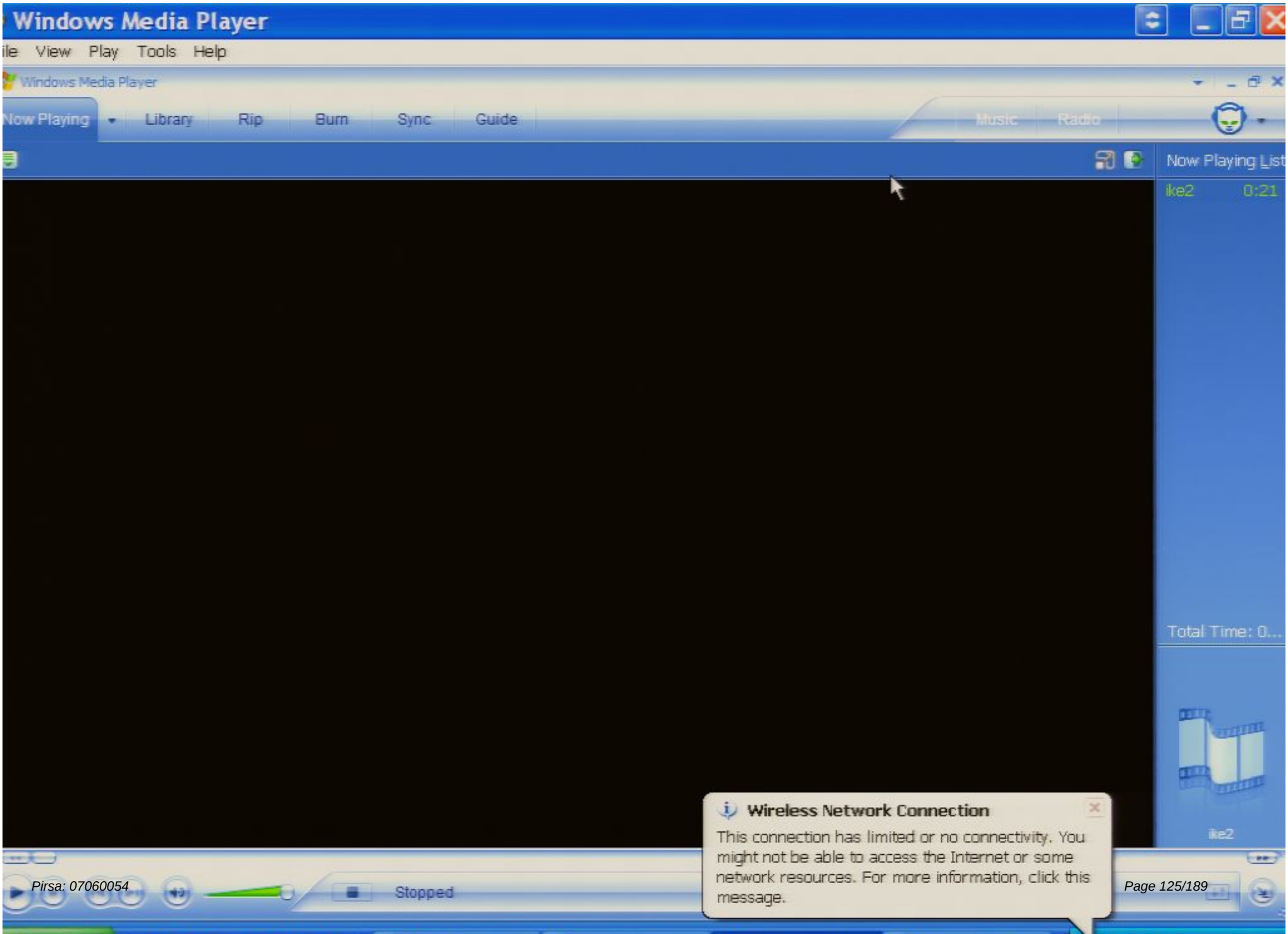
Slide 16 of 44 1_Blank Presentation English (U.S.)


Windows Media Player
ile View Play Tools Help
Windows Media Player
Now Playing
Library
Rip
Burn
Sync
Guide
Music
Radio
Now Playing List
ike2 0:21
Total Time: 0...
ike2
Stopped


Windows Media Player
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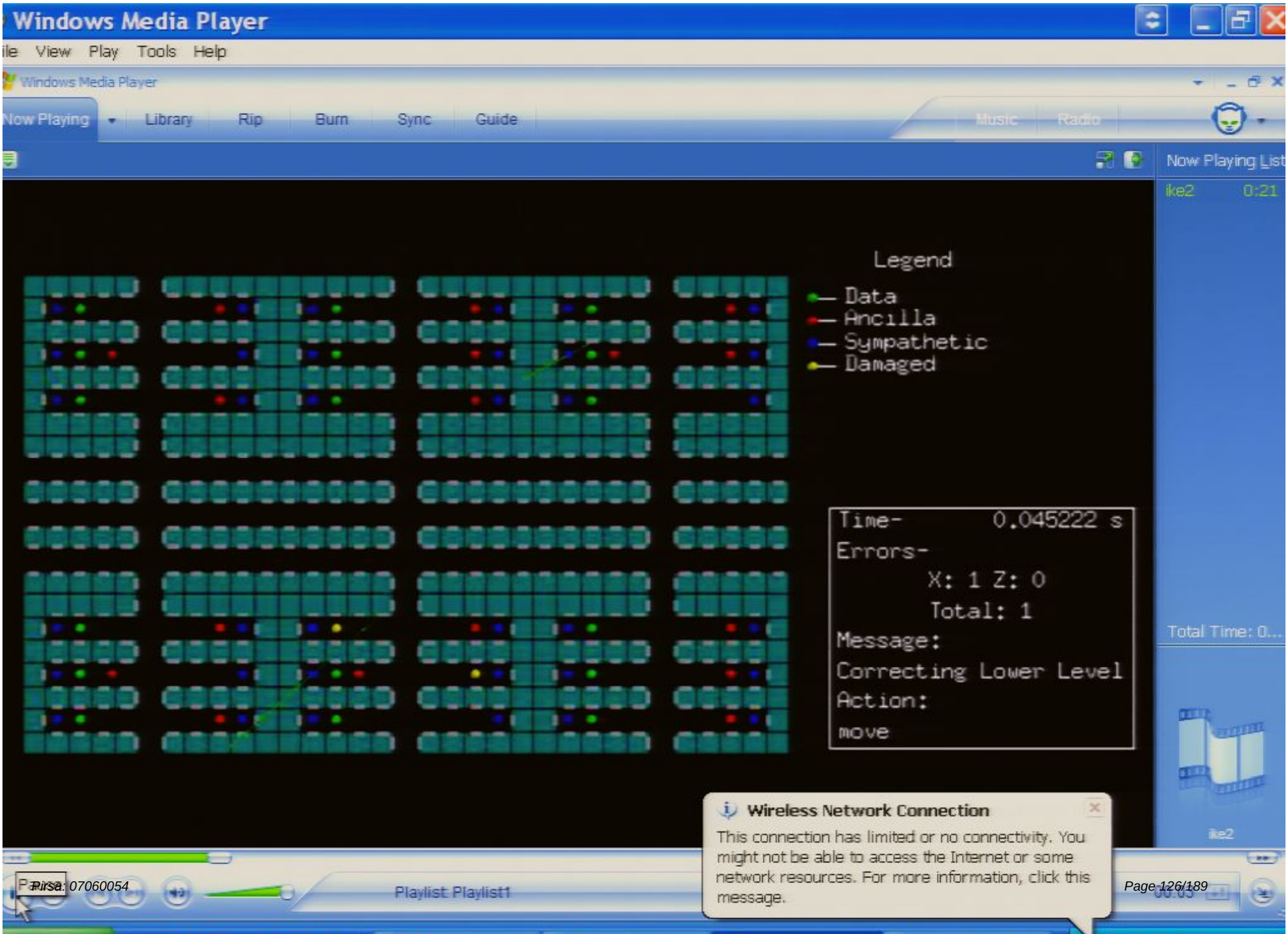
ike2 0:21
Total Time: 0...
ike2
Wireless Network Connection
This connection has limited or no connectivity. You might not be able to access the Internet or some network resources. For more information, click this message.
Stopped


Windows Media Player
File View Play Tools Help
Windows Media Player
Now Playing
Library
Rip
Burn
Sync
Guide
Music
Radio
Now Playing List
ike2 0:21
Legend
Data
Ancilla
Sympathetic
Damaged
Time- 0.045222 s
Errors-
X: 1 Z: 0
Total: 1
Message:
Correcting Lower Level
Action:
move
Total Time: 0...
ike2
Wireless Network Connection
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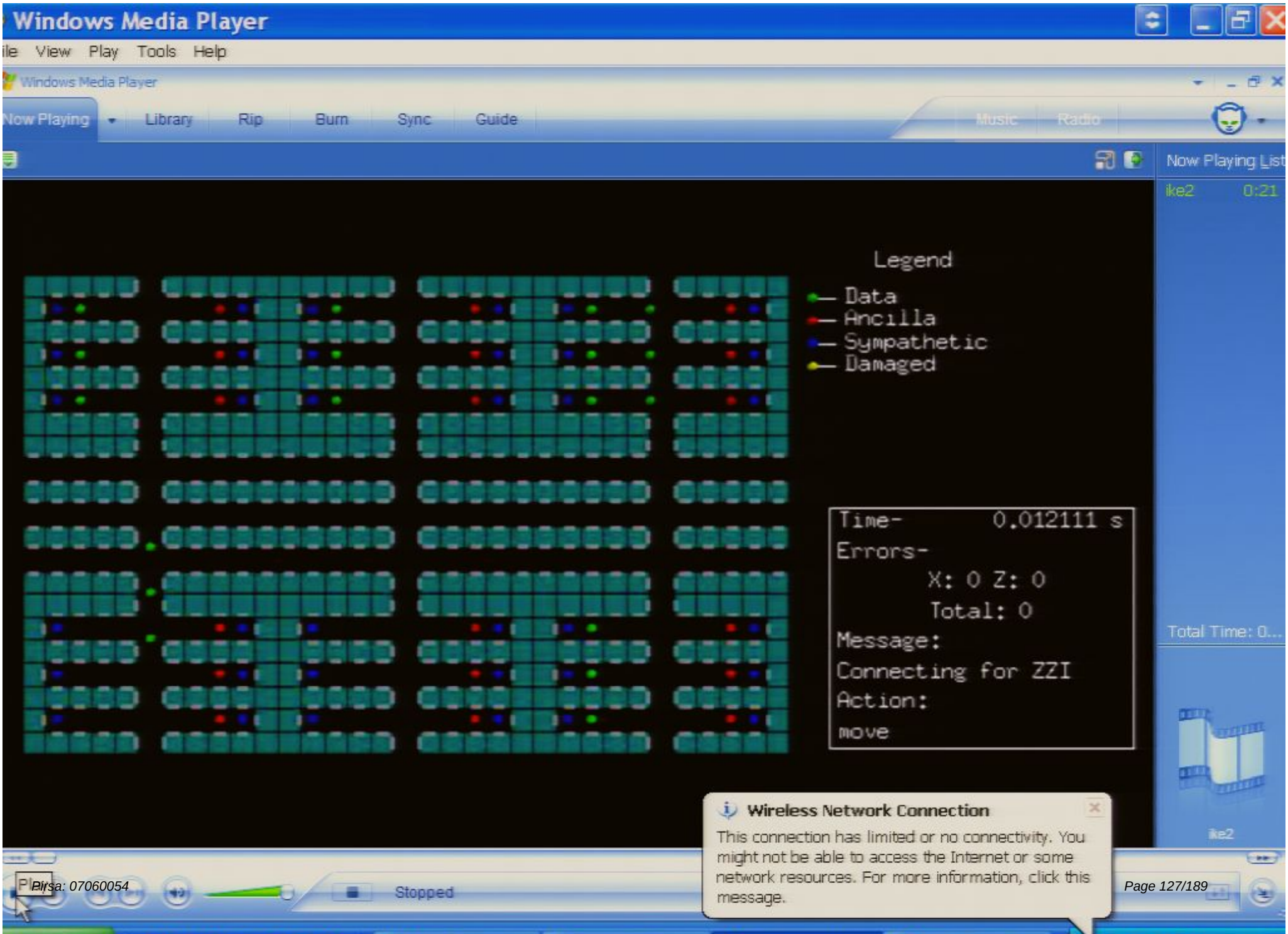
Playlist Playlist1


Windows Media Player
File View Play Tools Help
Windows Media Player
Now Playing
Library
Rip
Burn
Sync
Guide
Music
Radio
Now Playing List
ike2 0:21
Legend
Data
Ancilla
Sympathetic
Damaged
Time- 0.012111 s
Errors-
X: 0 Z: 0
Total: 0
Message:
Connecting for ZZI
Action:
move
Total Time: 0...
ike2
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Stopped

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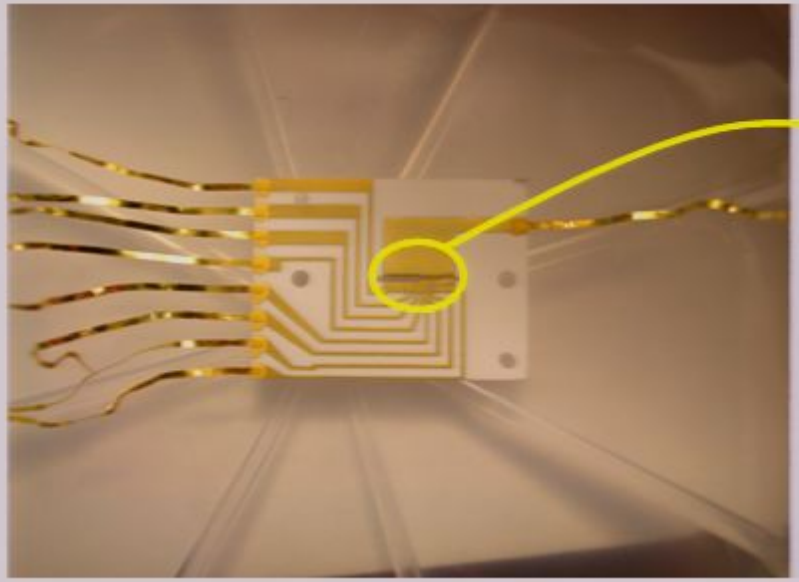
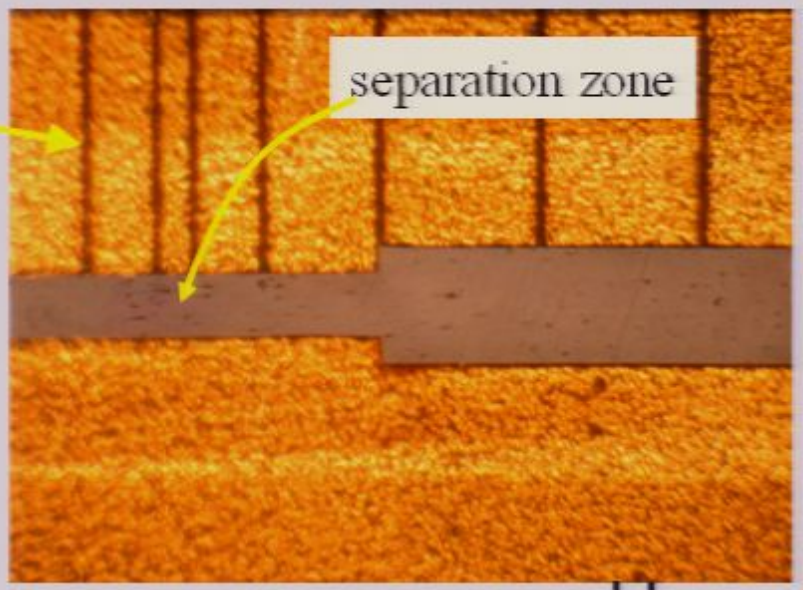
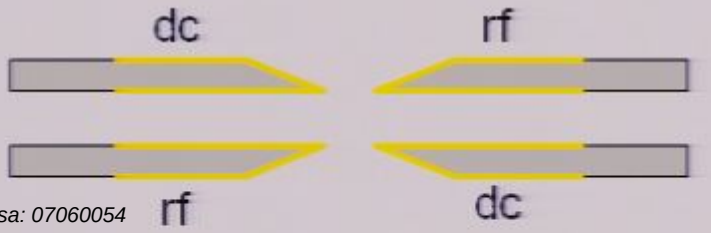




200 μm

100 μm

view along axis:



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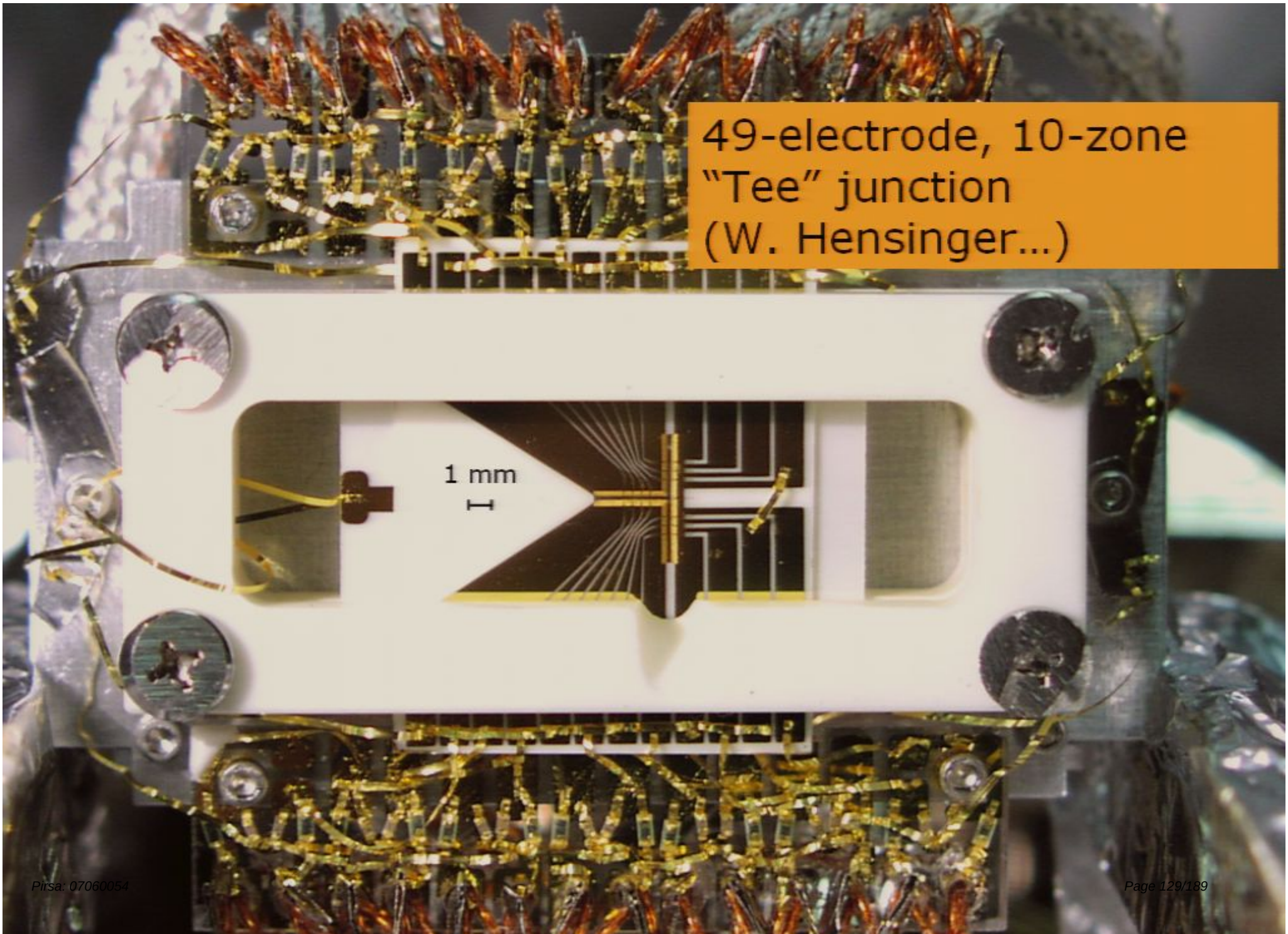
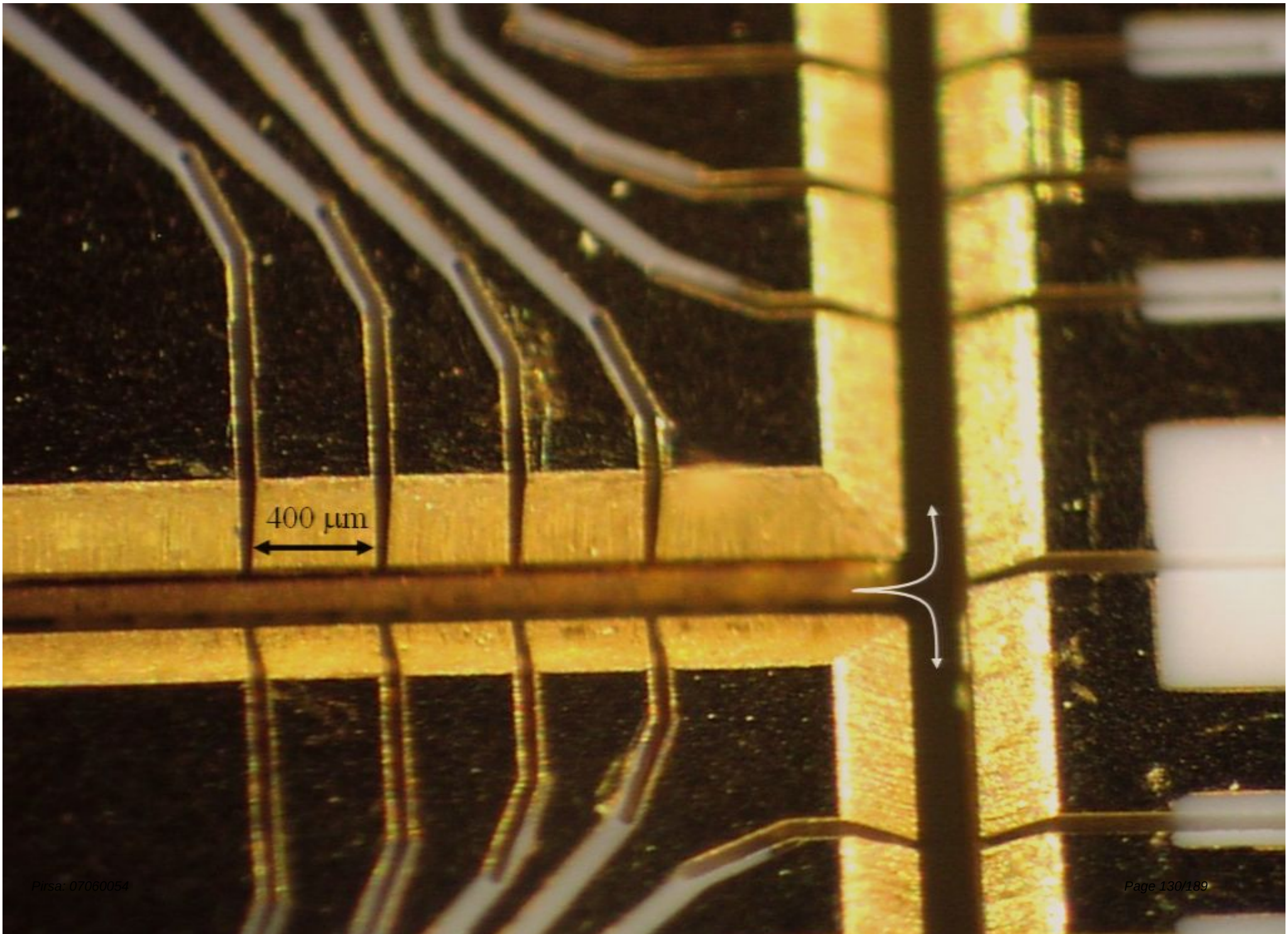
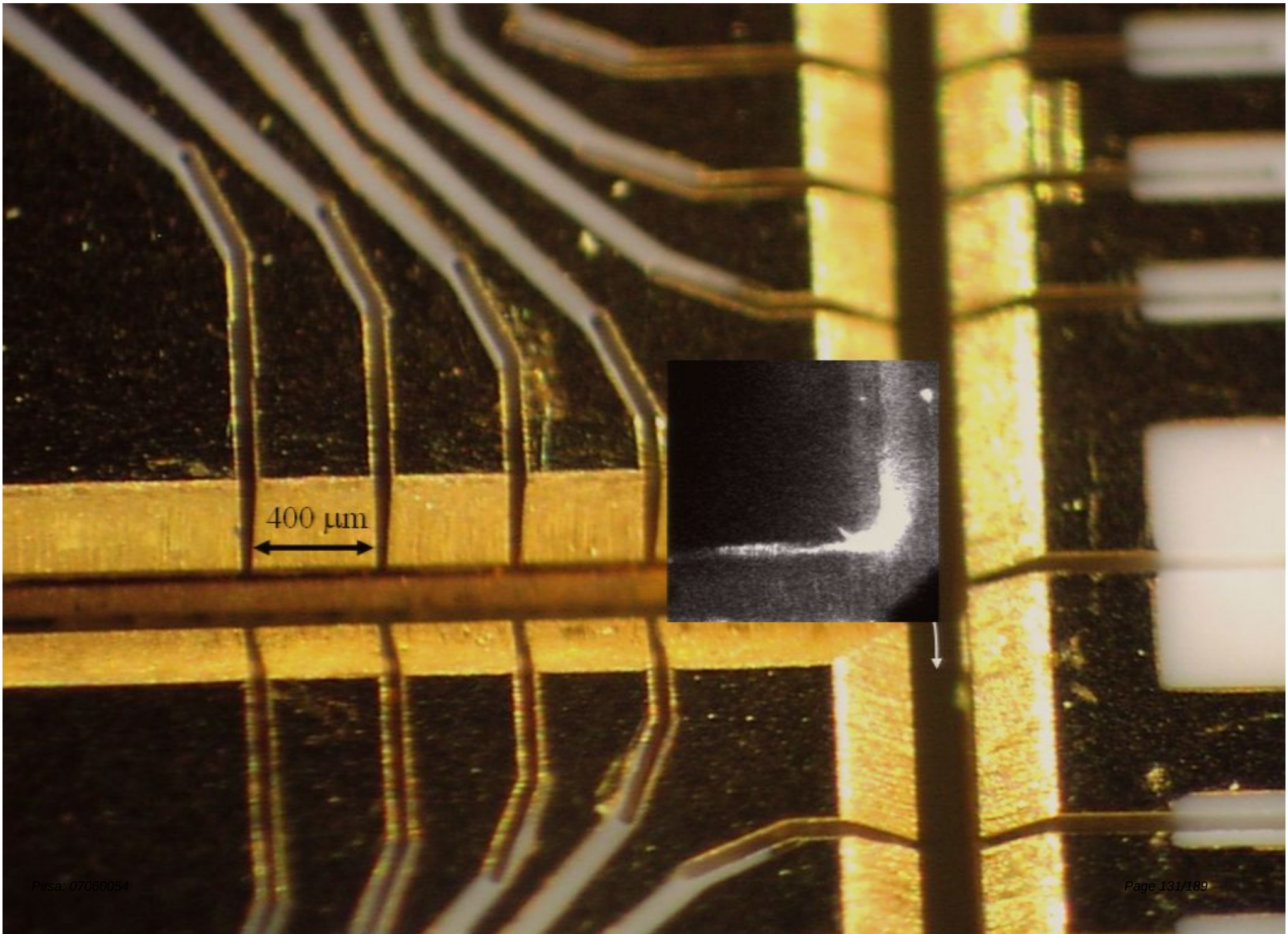
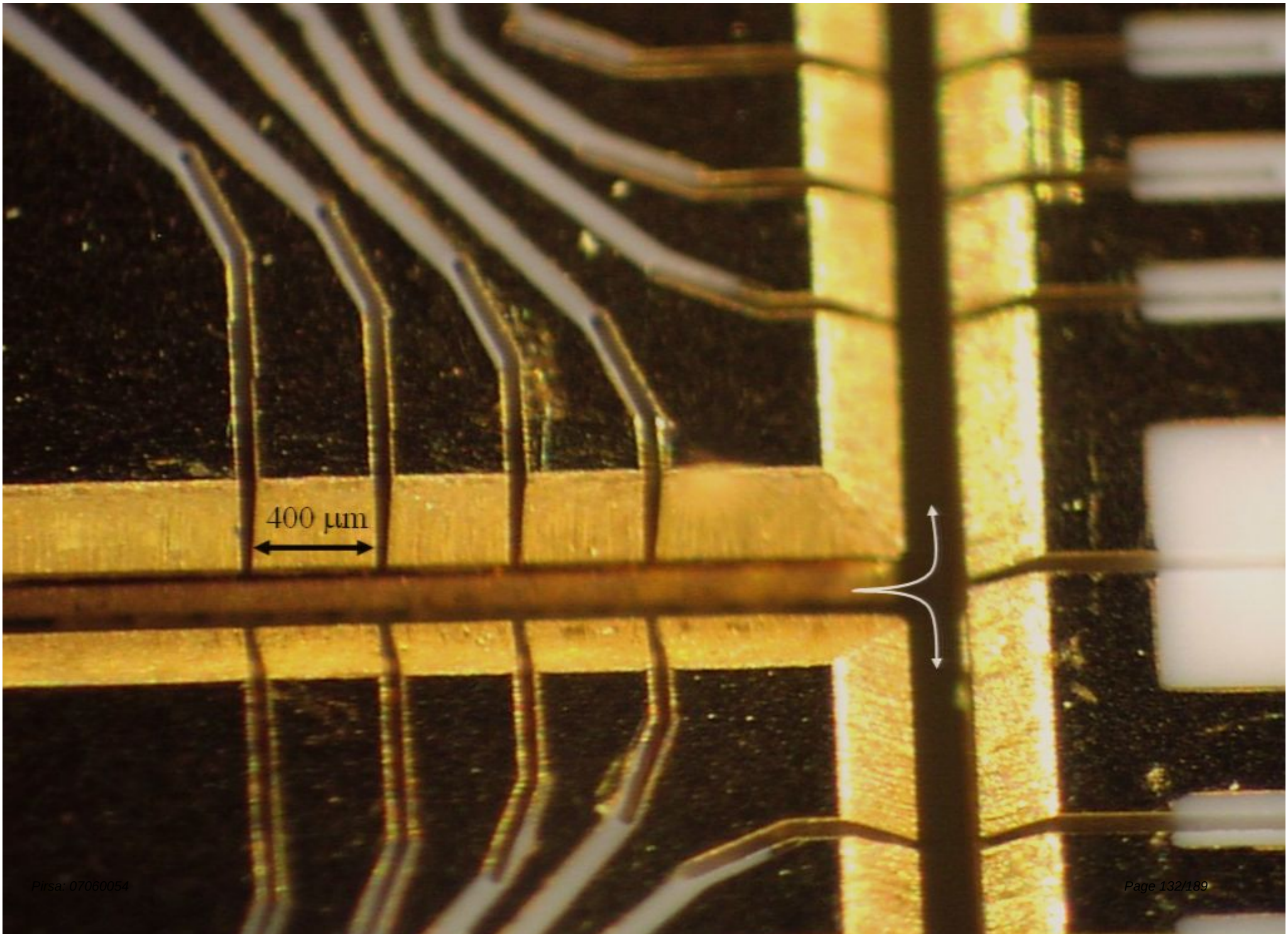
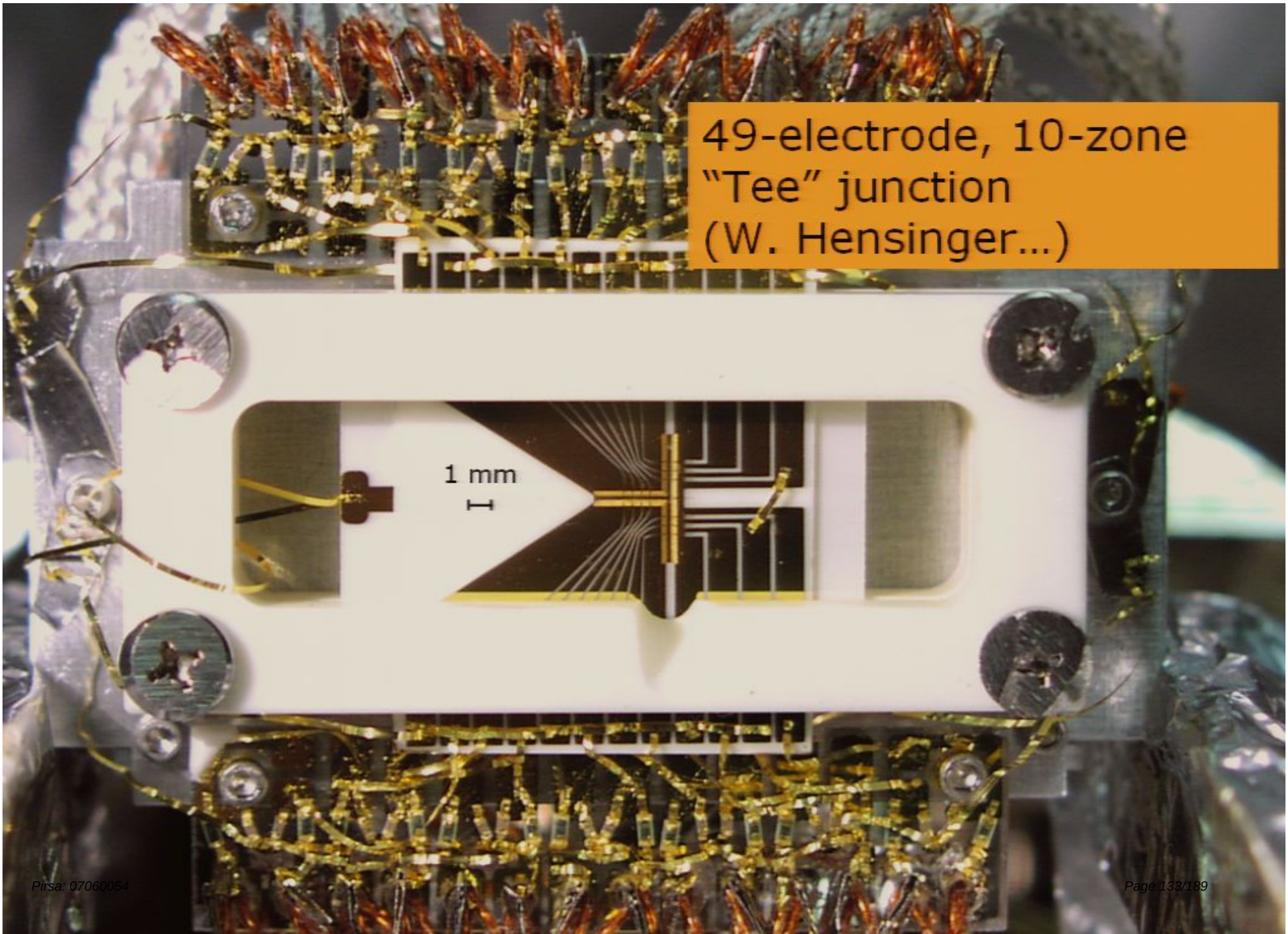
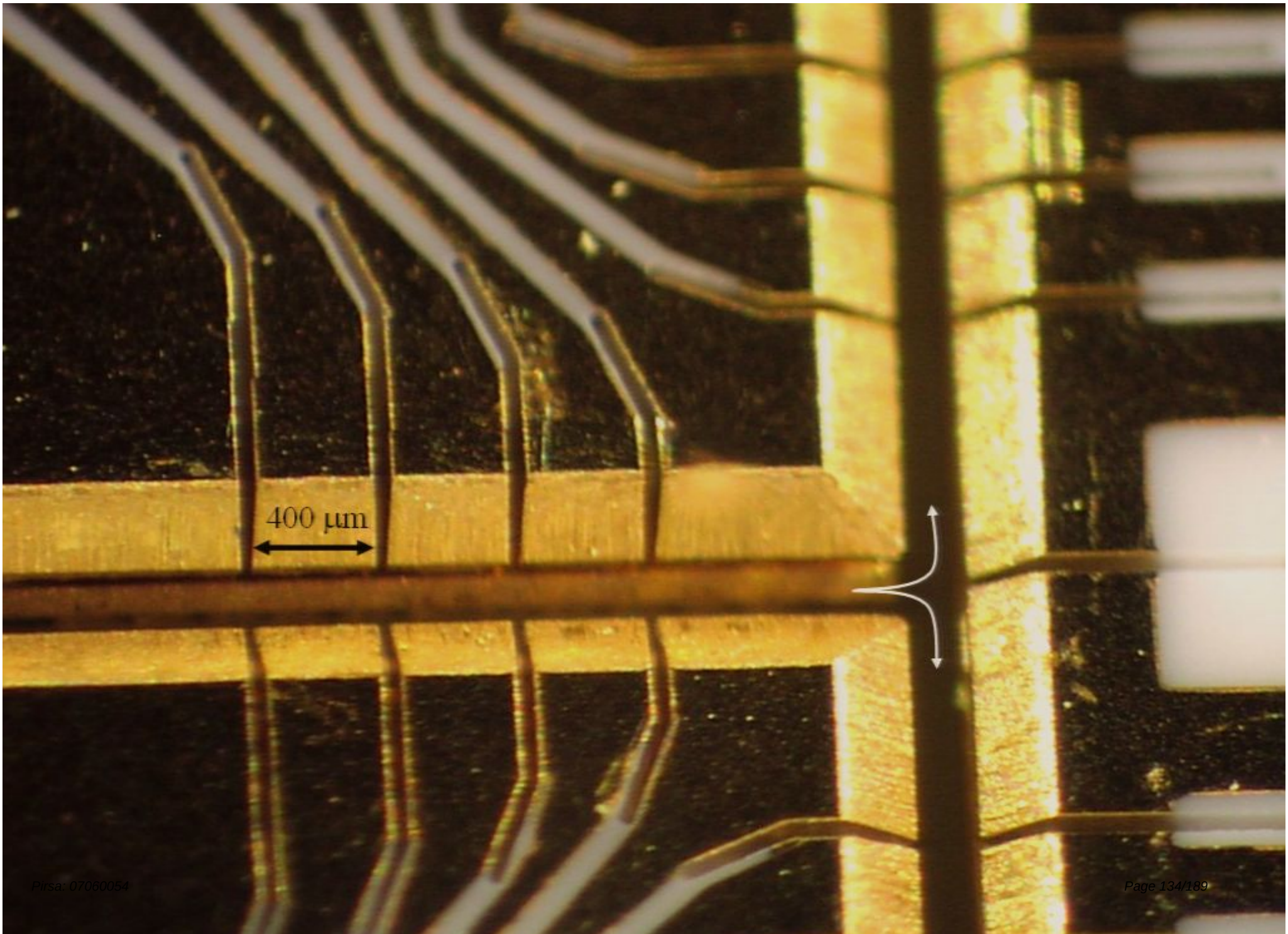

49-electrode, 10-zone
"Tee" junction
(W. Hensinger...)
1 mm

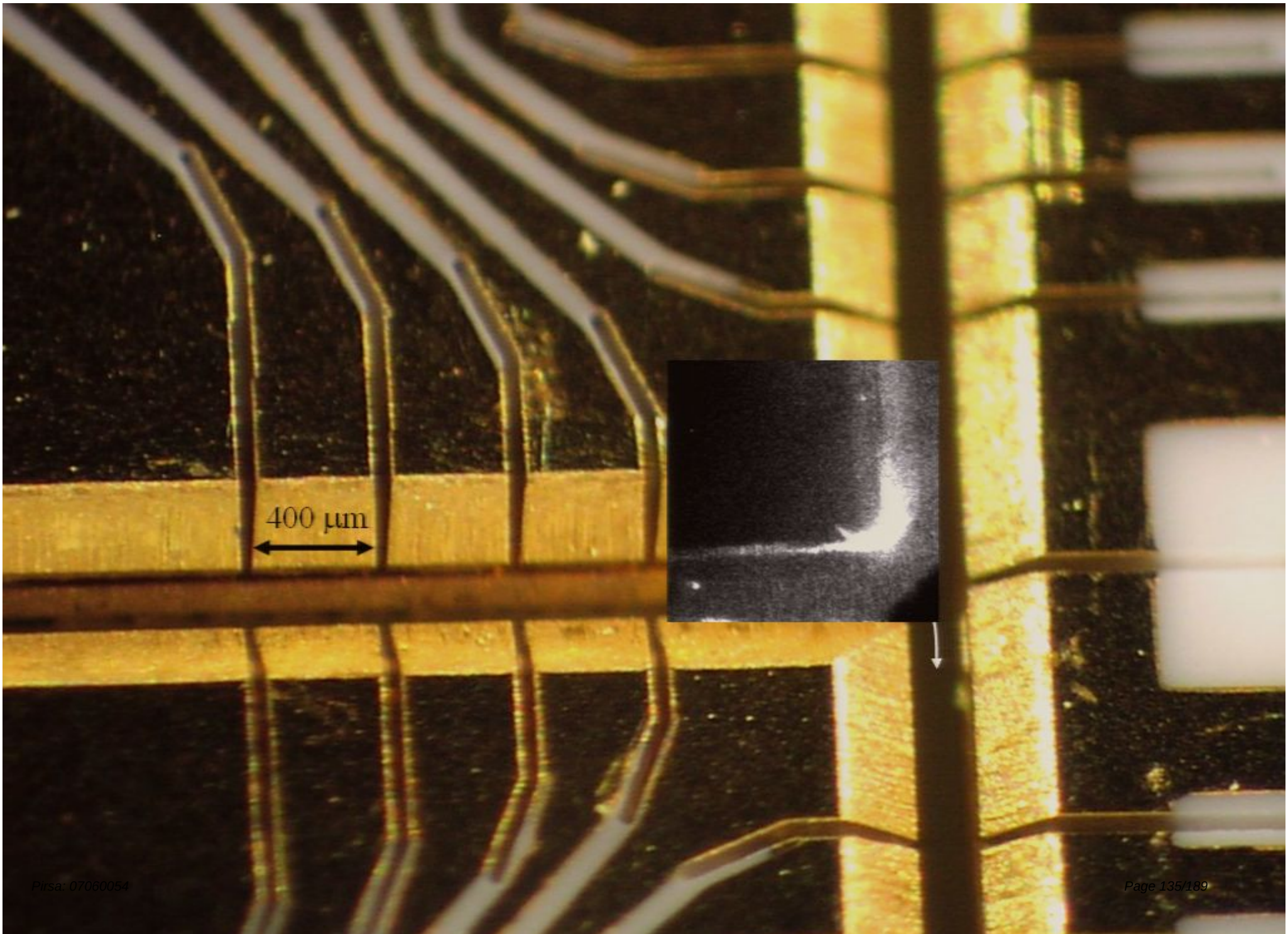

400 μm


400 μm


400 μm

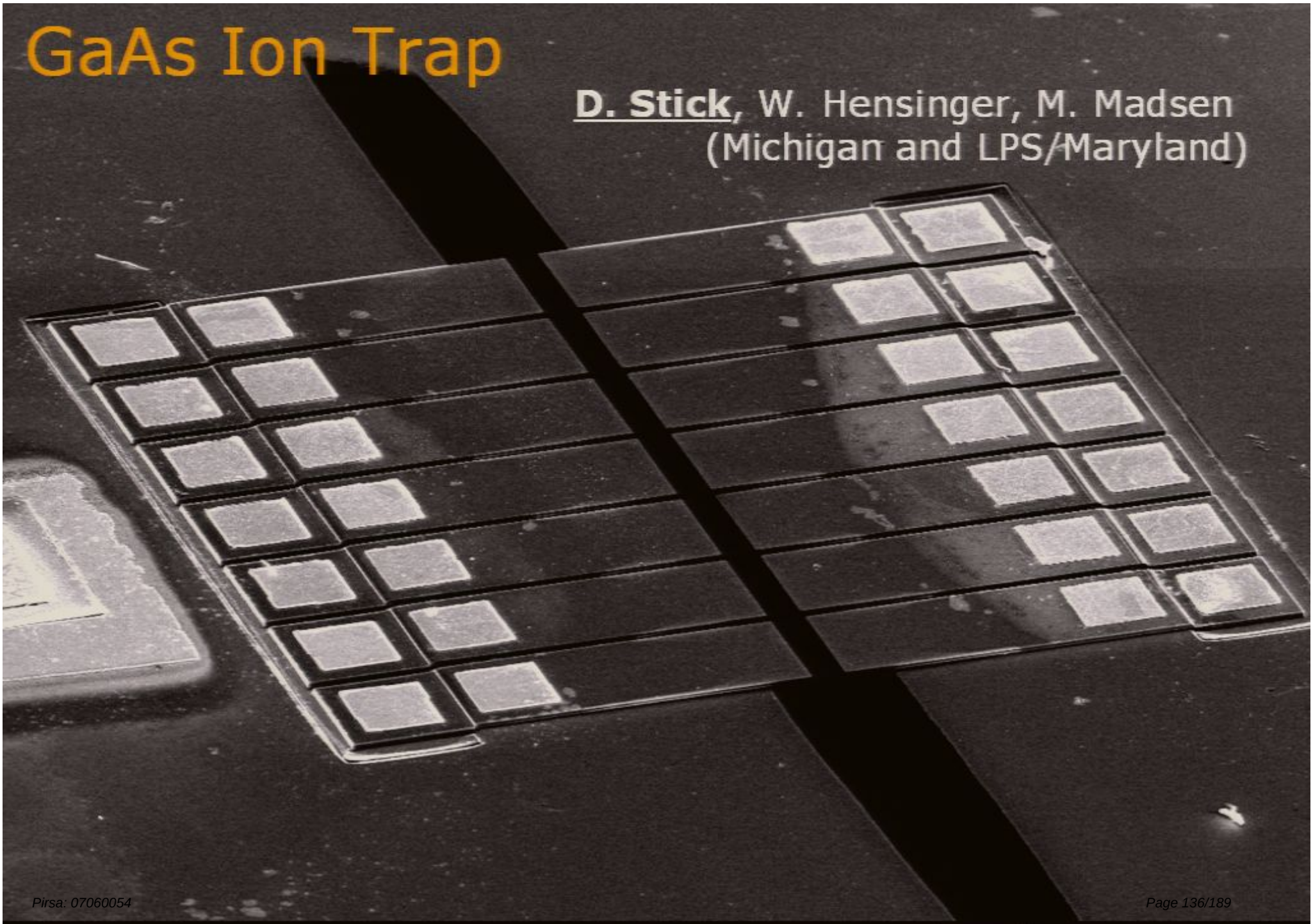

49-electrode, 10-zone
"Tee" junction
(W. Hensinger…)
1 mm

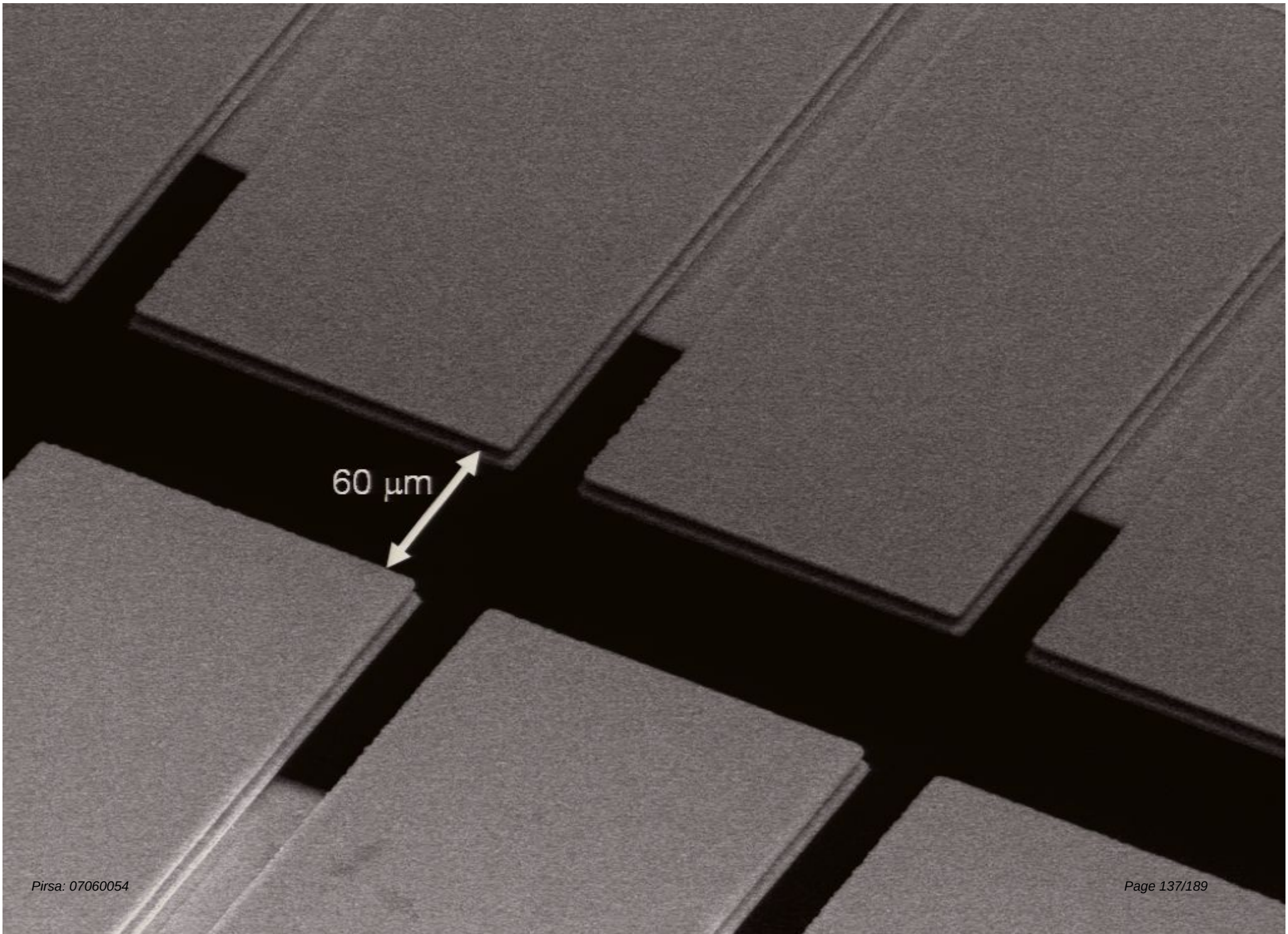

400 μm

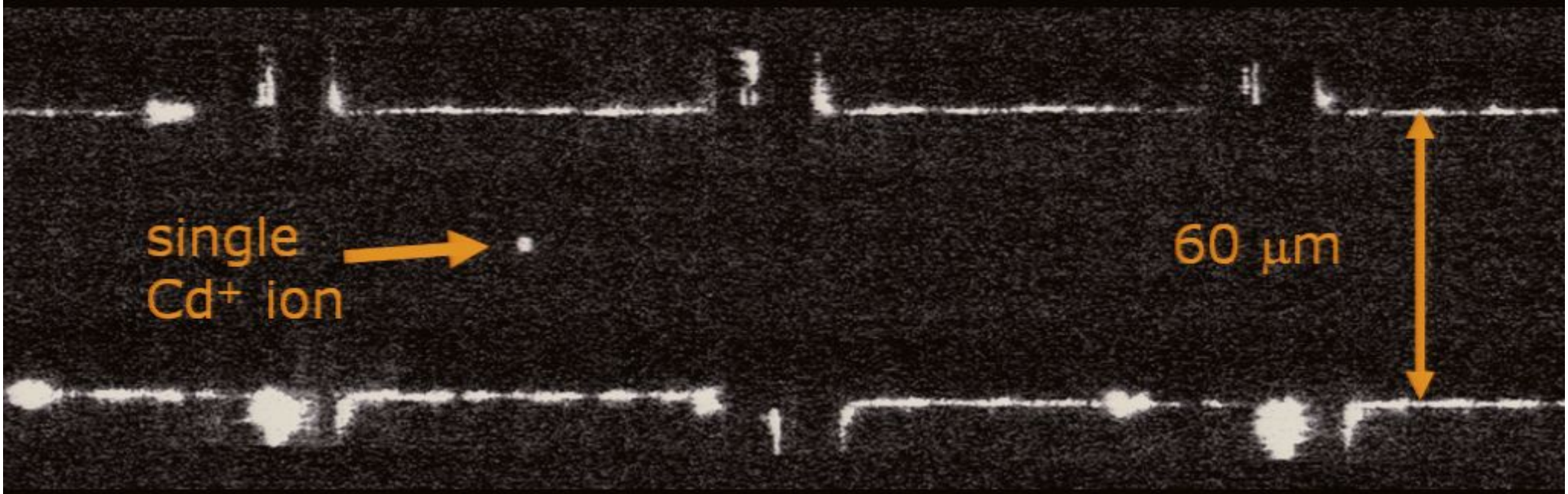

400 μm

GaAs Ion Trap

D. Stick, W. Hensinger, M. Madsen
(Michigan and LPS/Maryland)




60 μm



V_{RF} = 8V @ 16 MHz (Q~50)

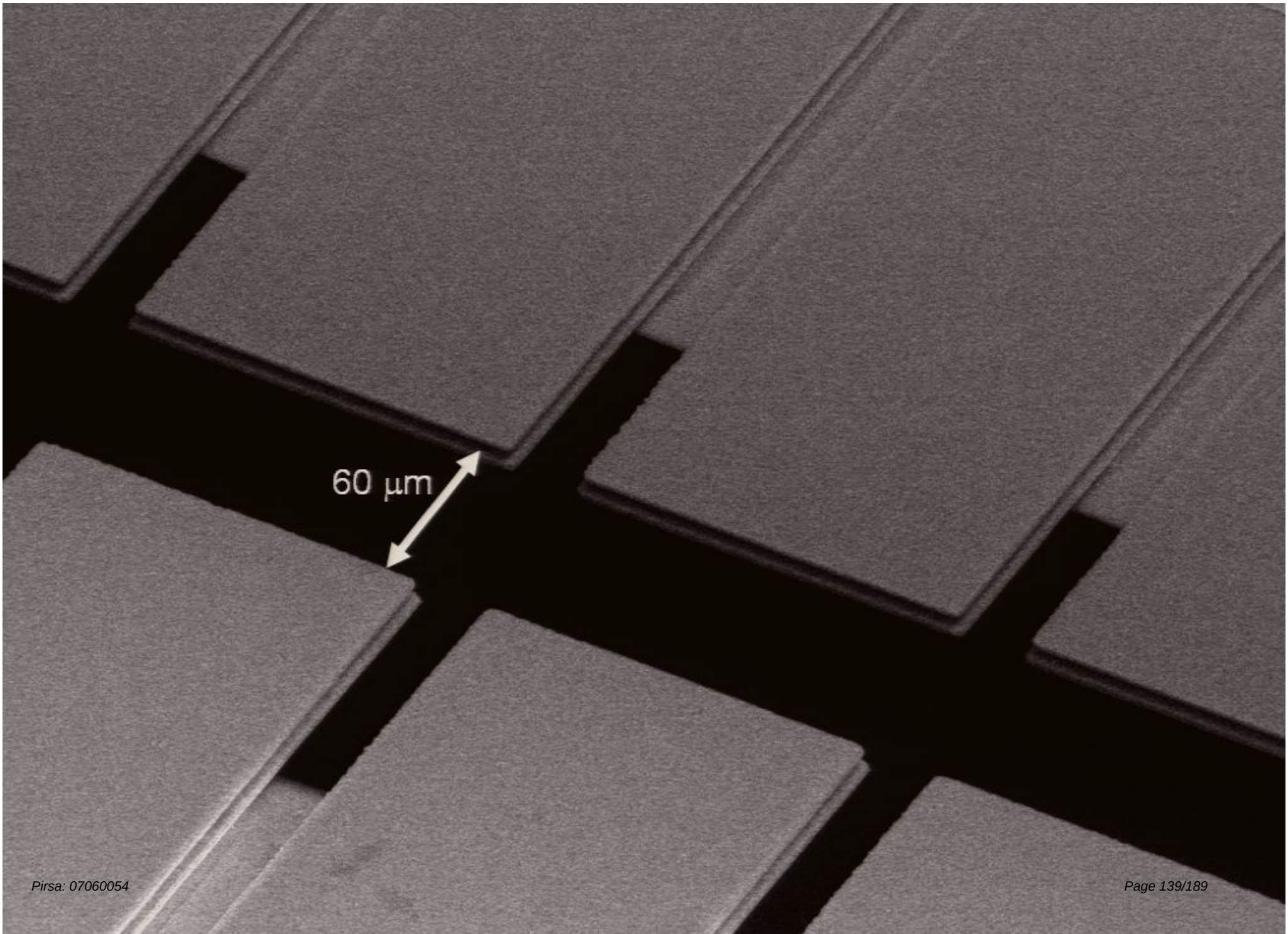
V_{STATIC} = +1V (endcaps), −0.33V (middles)

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

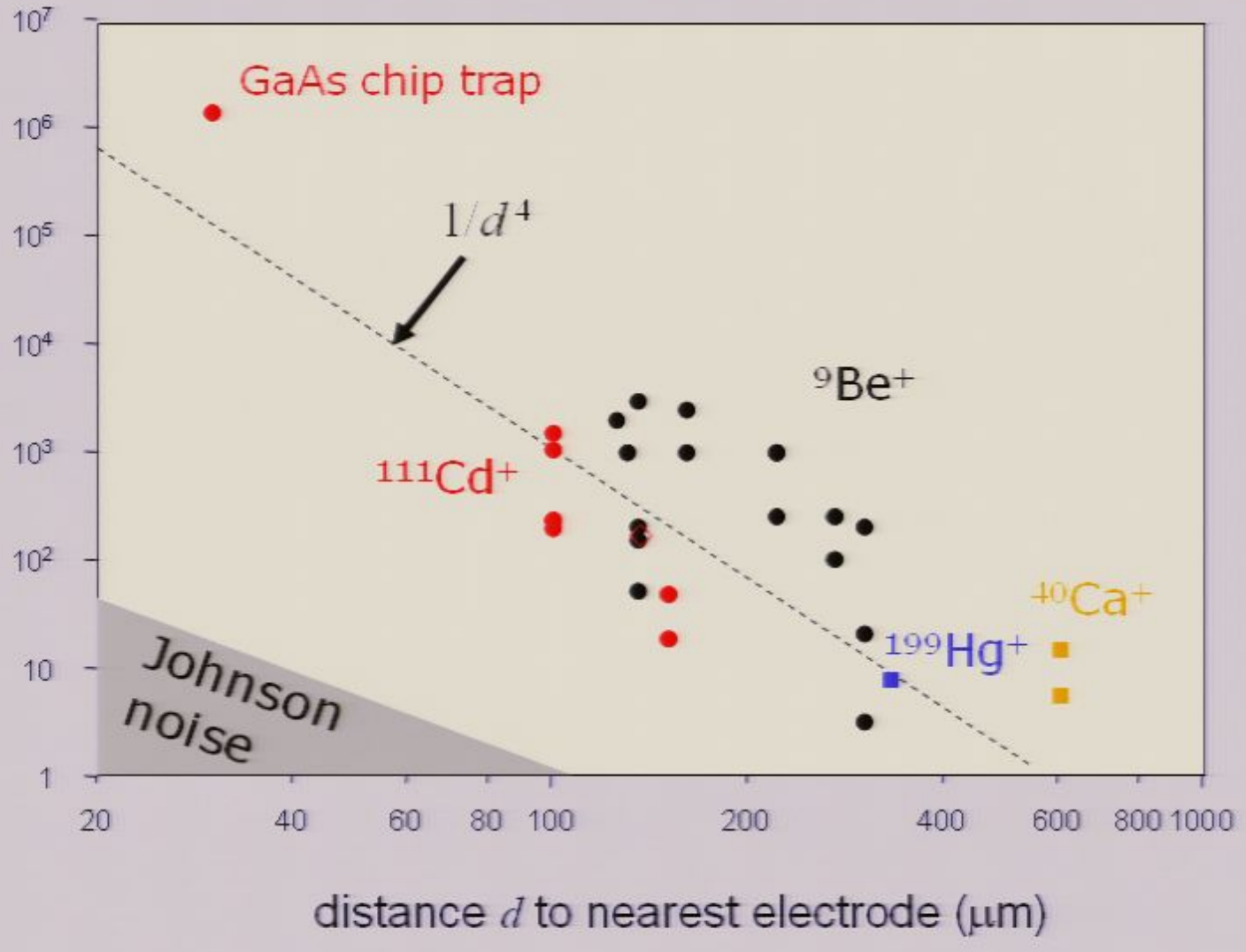
~ 1mW

Trap frequencies: 1.0 MHz, 3.3 MHz and 4.3 MHz

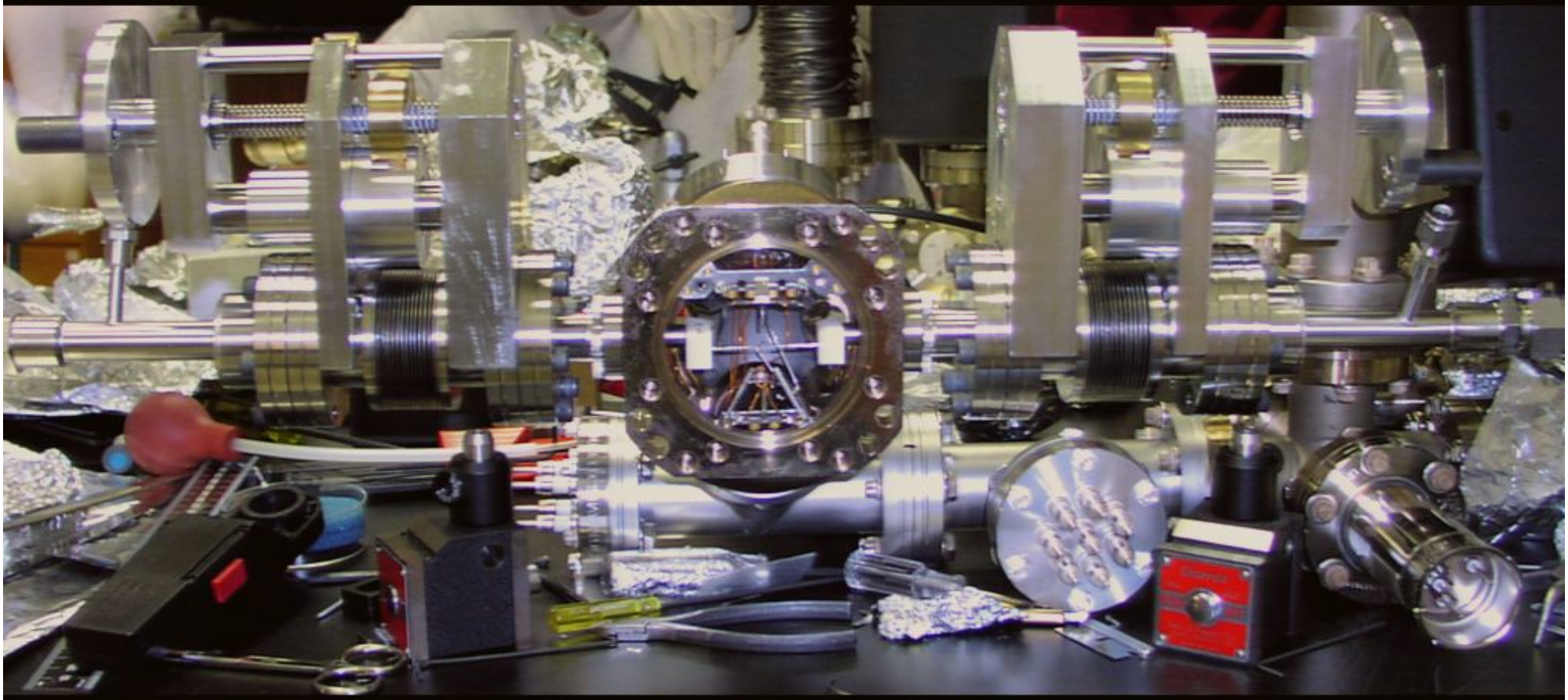
Trap depth: 0.08 eV Lifetime w/o cooling: 0.1sec


60 μm

Heating in Trapped Ions vs. Proximity to Electrodes

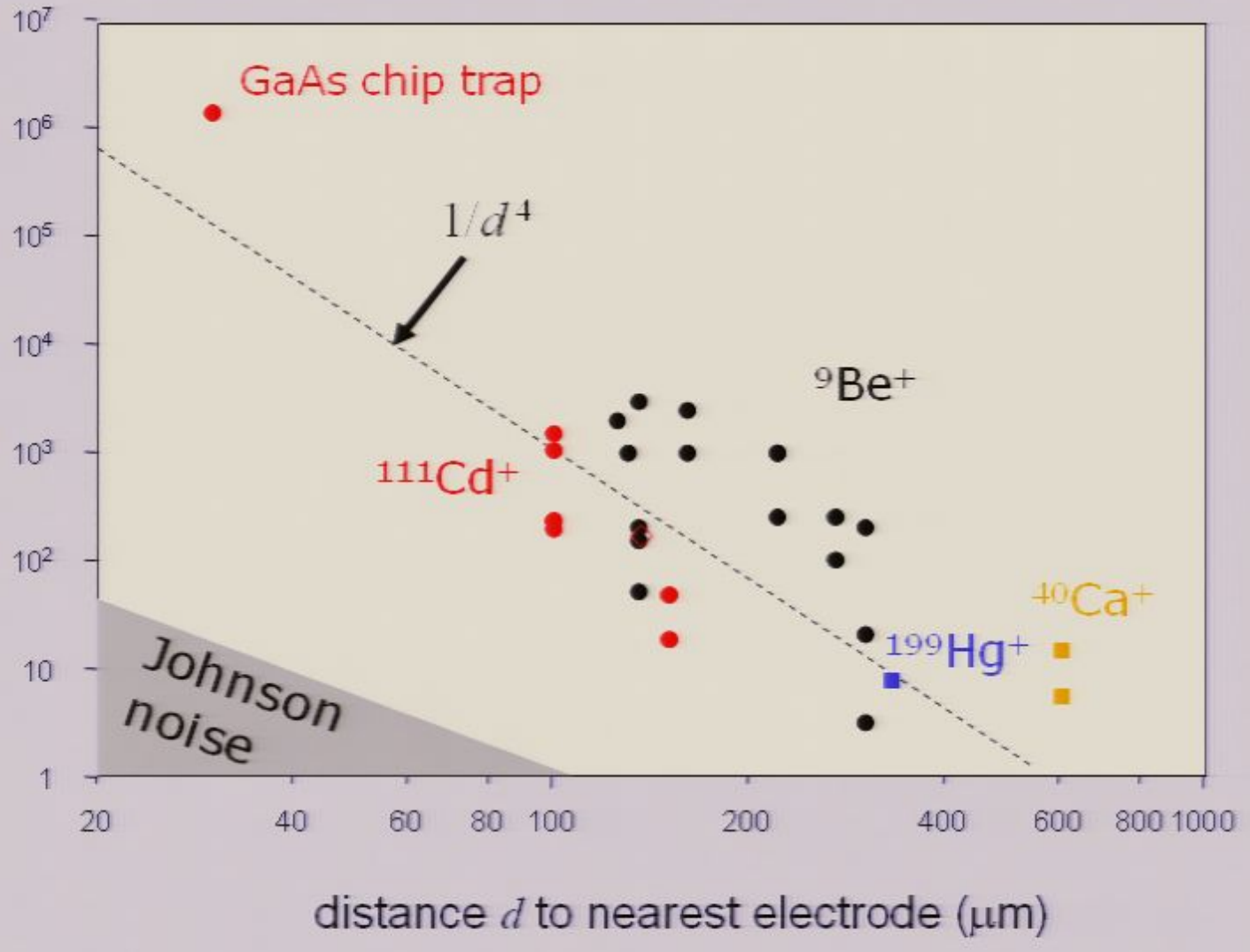


"double needle" trap
(L. Deslauriers)



- 15 μm diameter W tips
- adjustable separation
- cooling to 77K

Heating in Trapped Ions vs. Proximity to Electrodes



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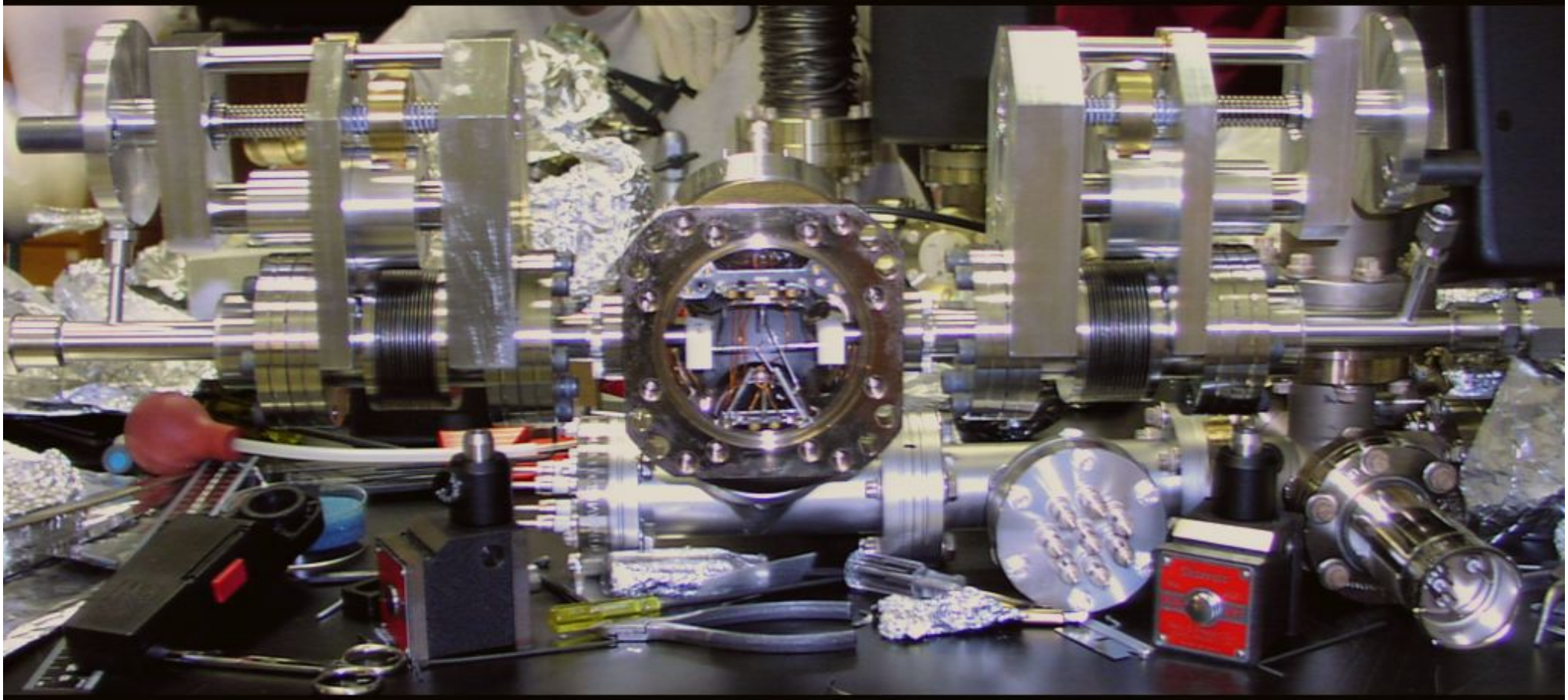

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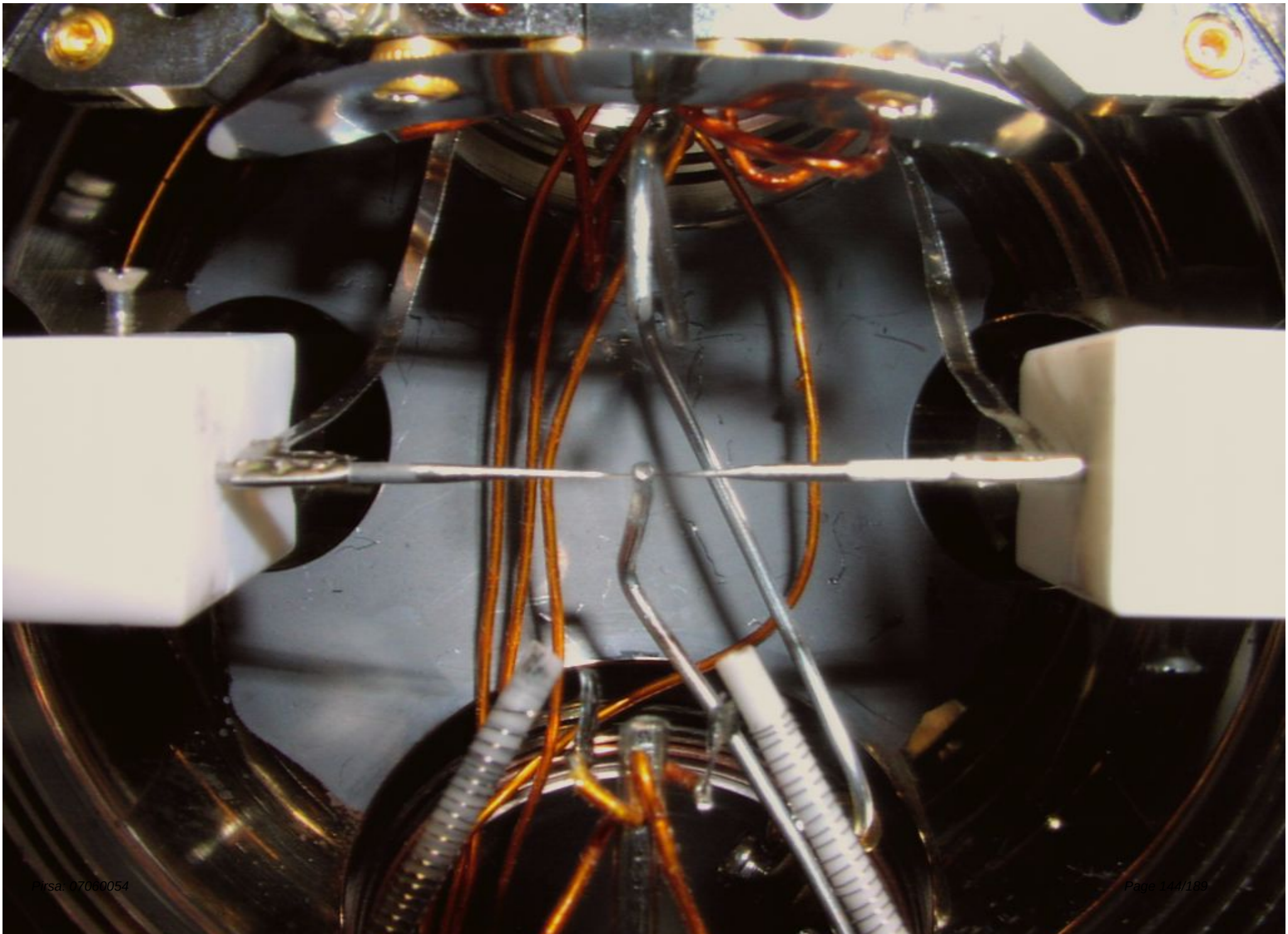
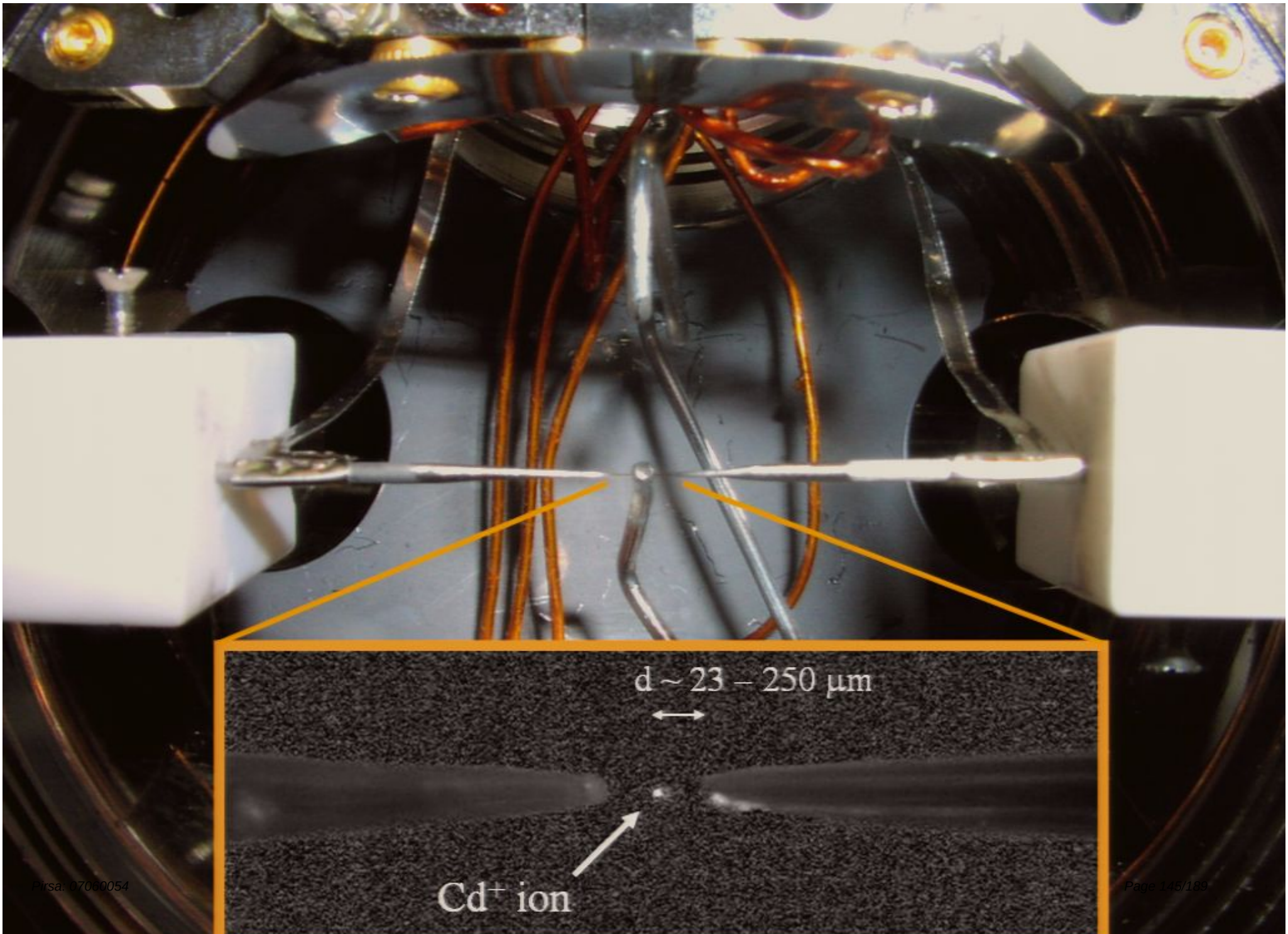
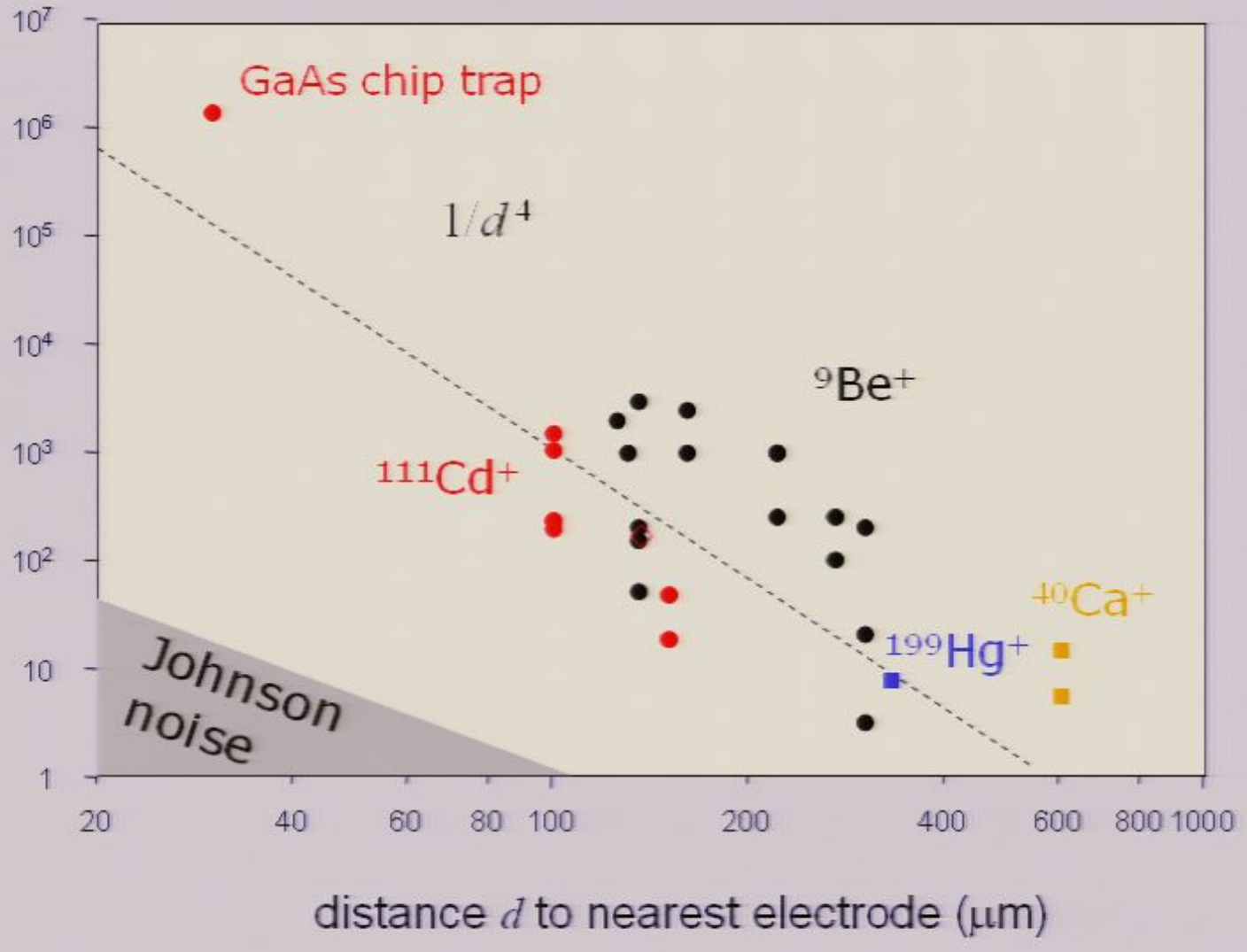
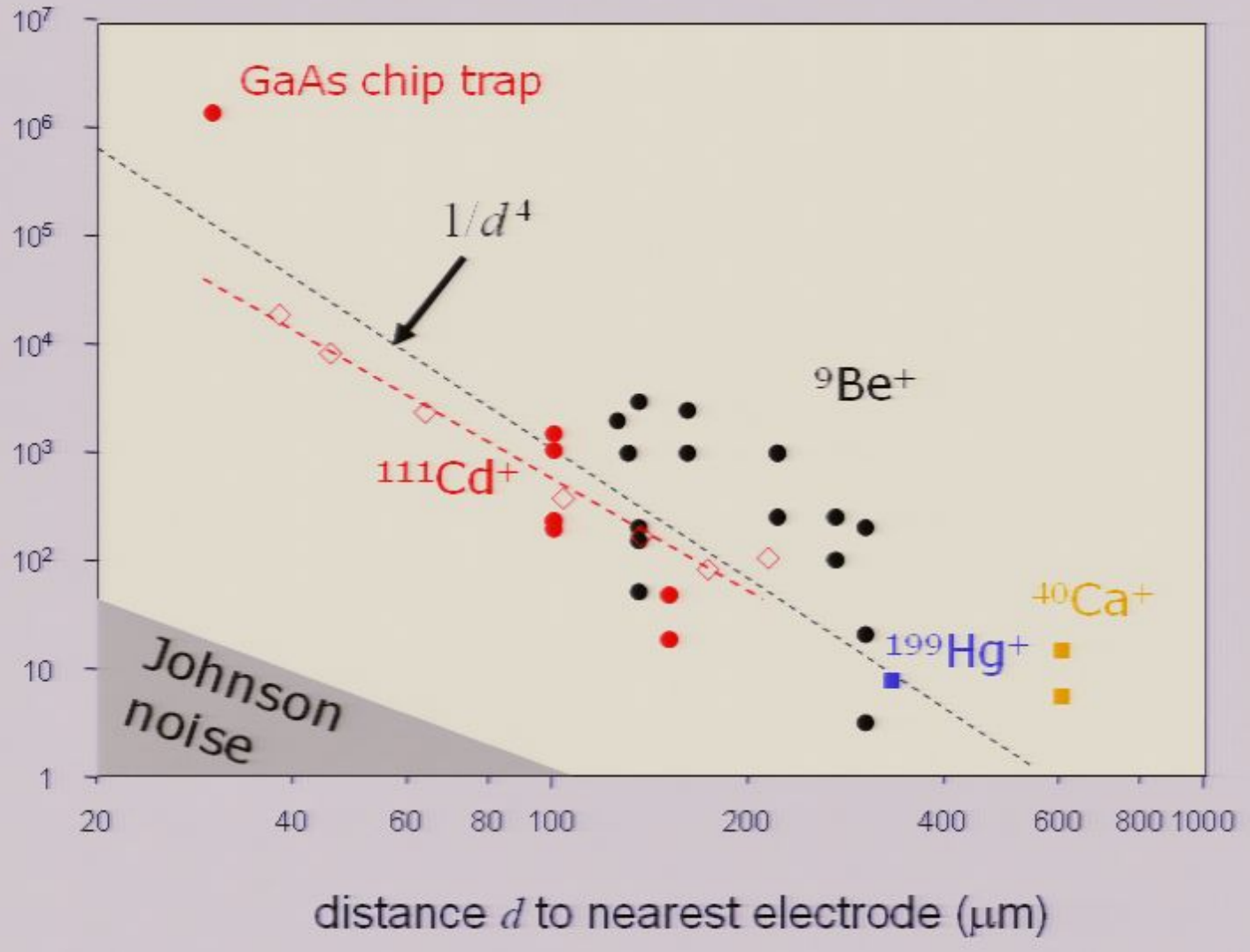



d ~ 23 – 250 μm
Cd+ ion

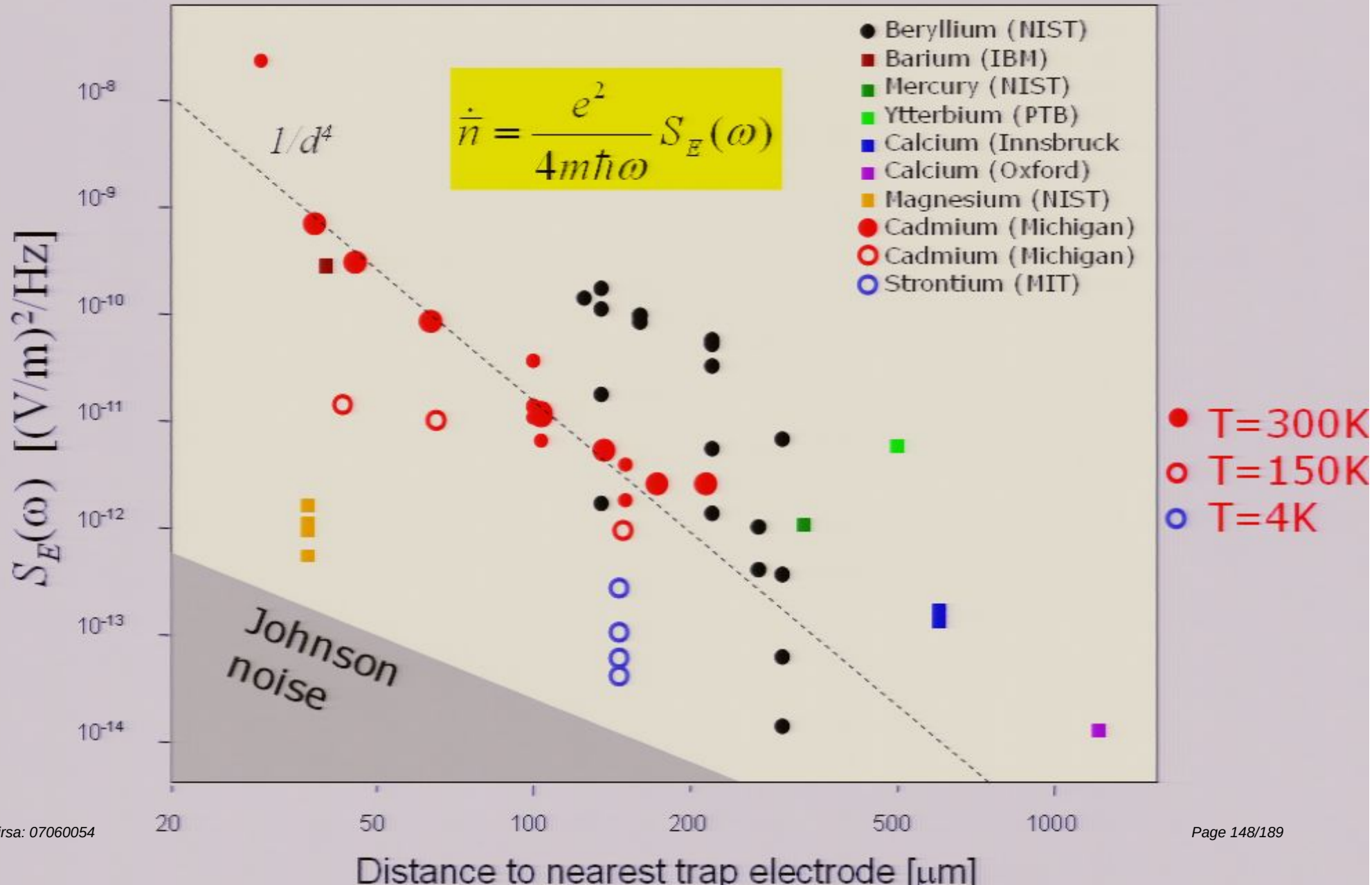
Heating in Trapped Ions vs. Proximity to Electrodes



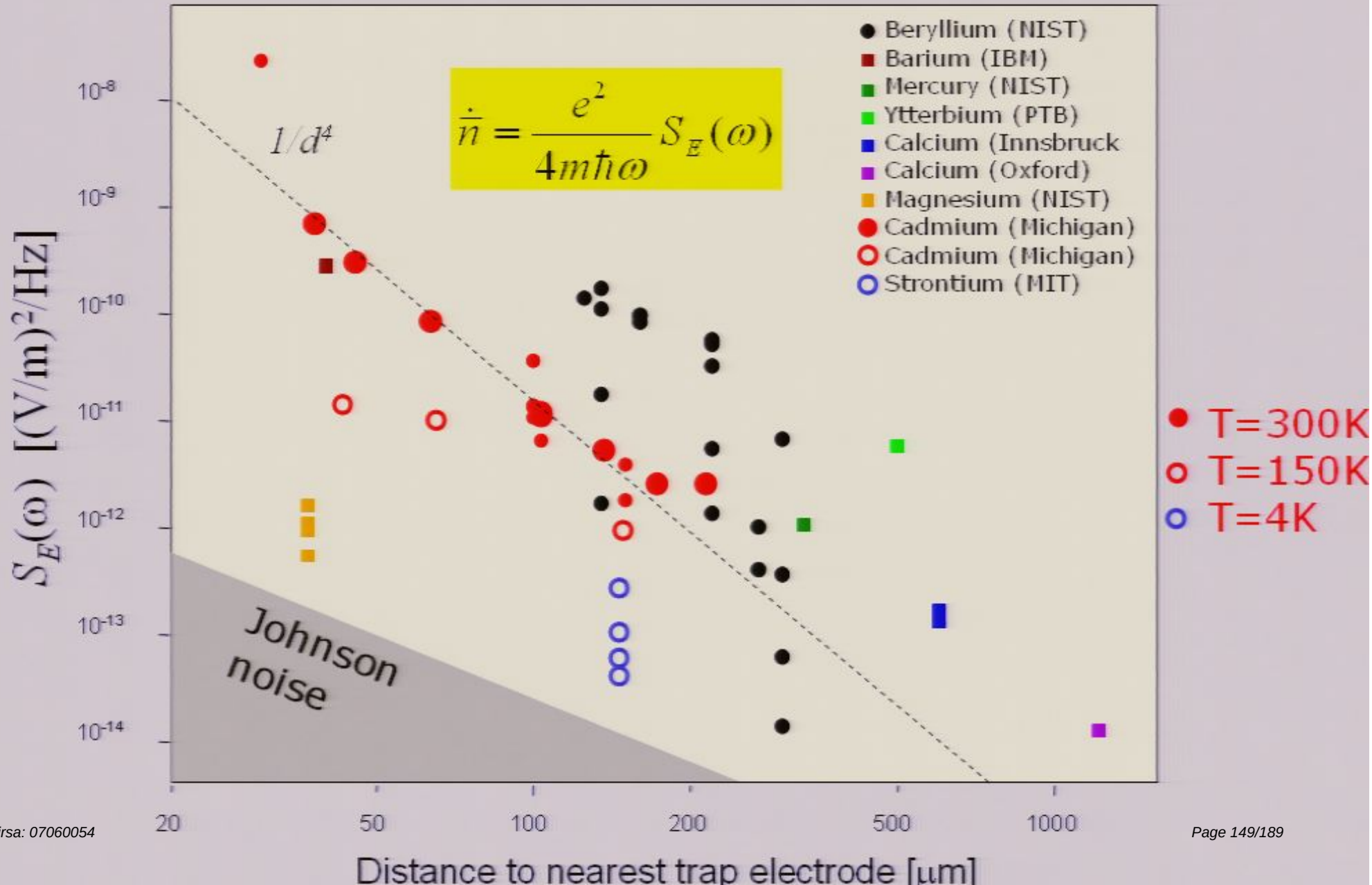
Heating in Trapped Ions vs. Proximity to Electrodes



Inferred Electric Field Noise

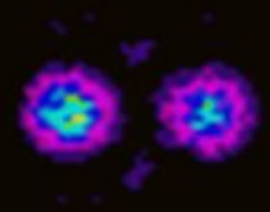


Inferred Electric Field Noise



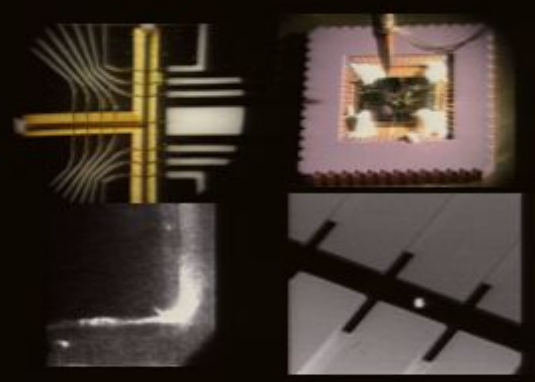
Ion Trap Quantum Networks

- Local entanglement through the Coulomb interaction (phonons)



$\sim 10^{-6}$ m

- Shuttling ions through advanced scalable trap structures



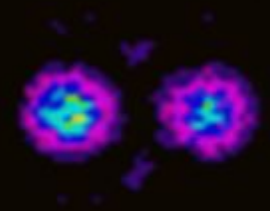
$\sim 10^{-3}$ m

- Nonlocal entanglement though spontaneous emission (photons)

~ 1 m

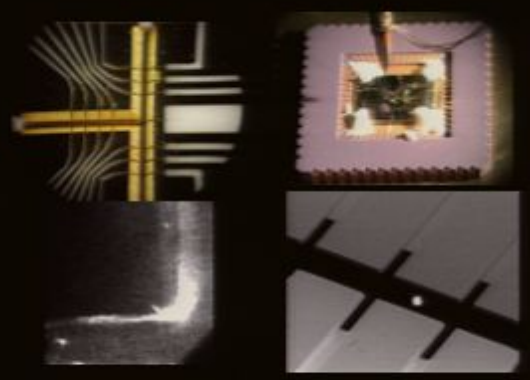
Ion Trap Quantum Networks

- Local entanglement through the Coulomb interaction (phonons)



$\sim 10^{-6}$ m

- Shuttling ions through advanced scalable trap structures



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Ion Trap Quantum Networks

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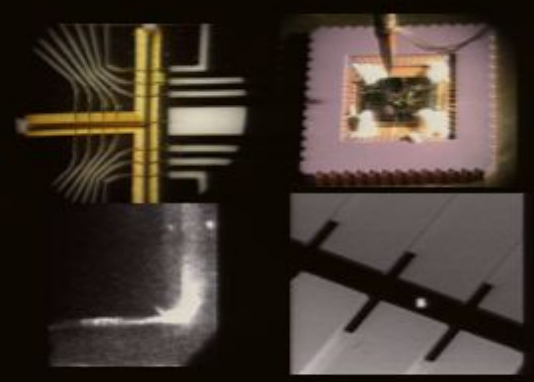

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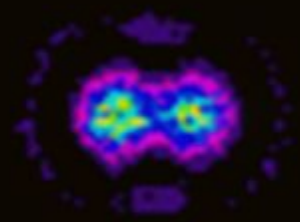
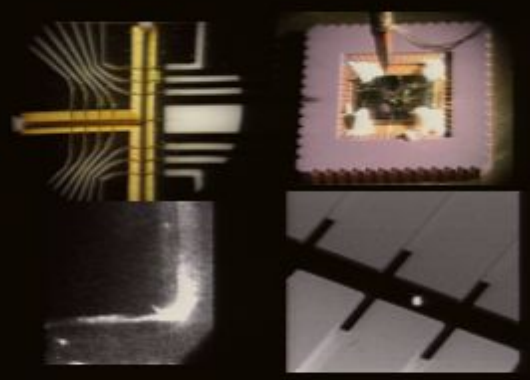


$\sim 10^{-6}$ m

- Shuttling ions through advanced scalable trap structures



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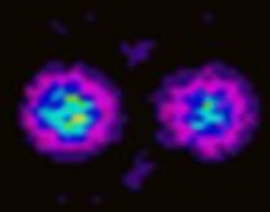
~ 1 m

Ion Trap Quantum Networks

- Local entanglement through the Coulomb interaction (phonons)



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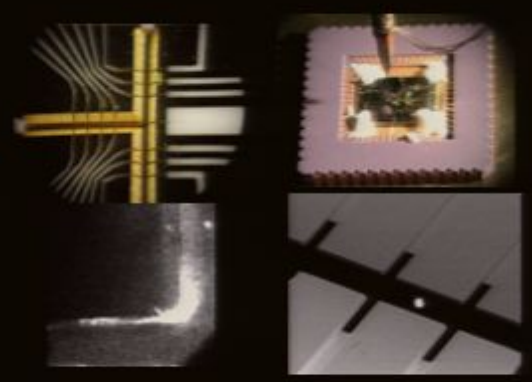


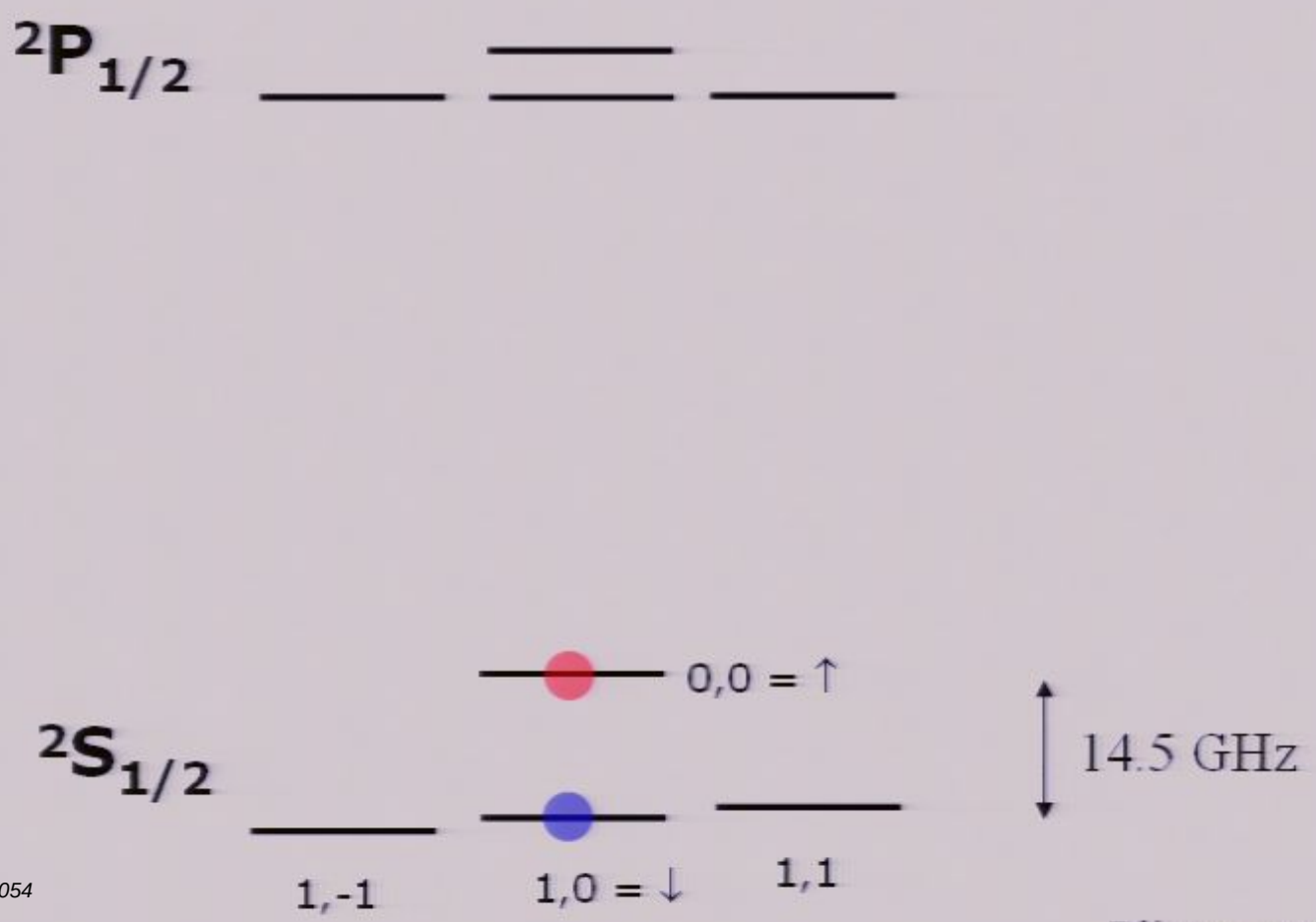
$\sim 10^{-3}$ m

- Nonlocal entanglement though spontaneous emission (photons)

~ 1 m

Linking atoms with ~~phonons~~ photons

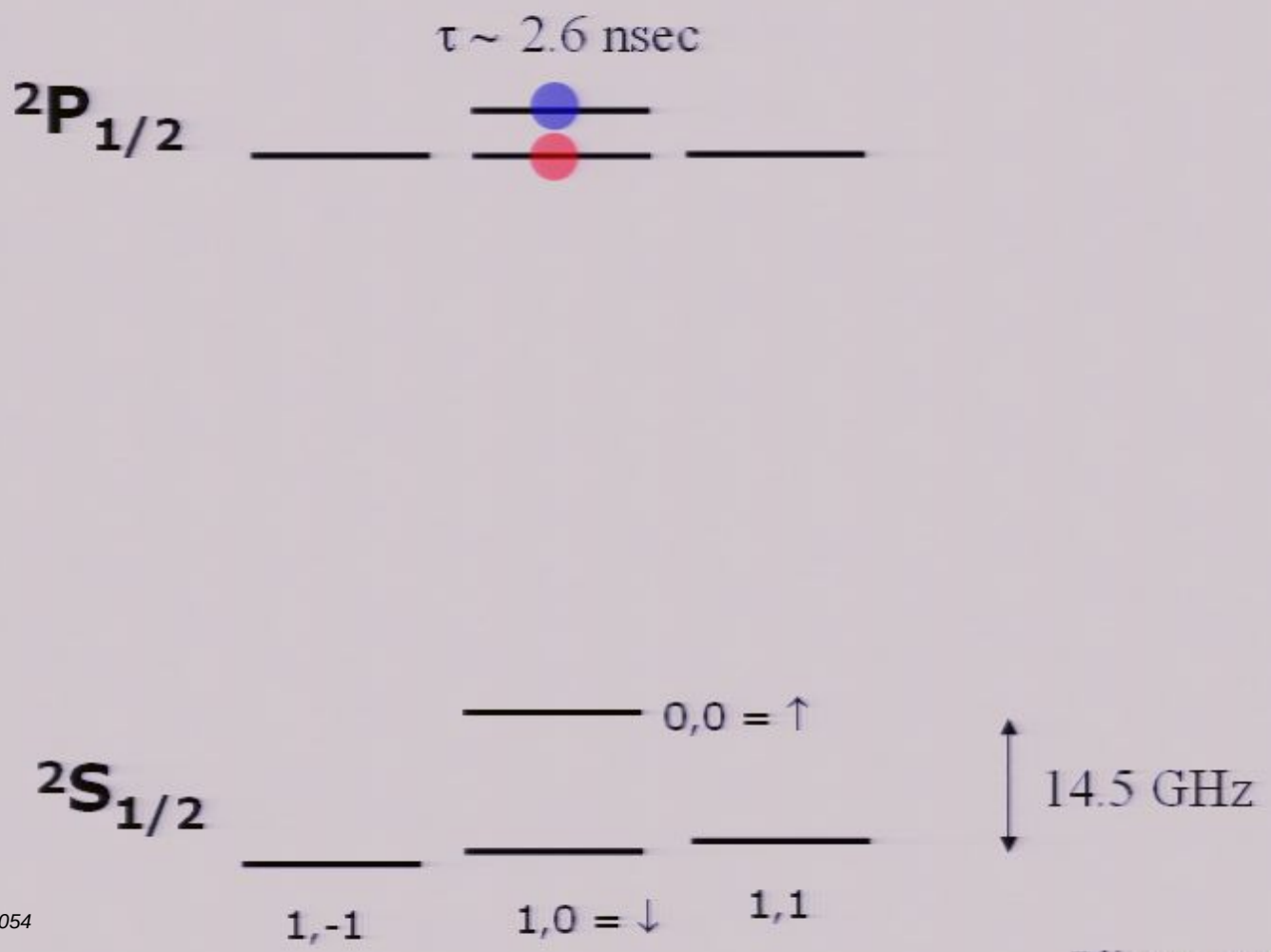
$^{111}Cd^{+}$



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

Linking atoms with ~~phonons~~ photons

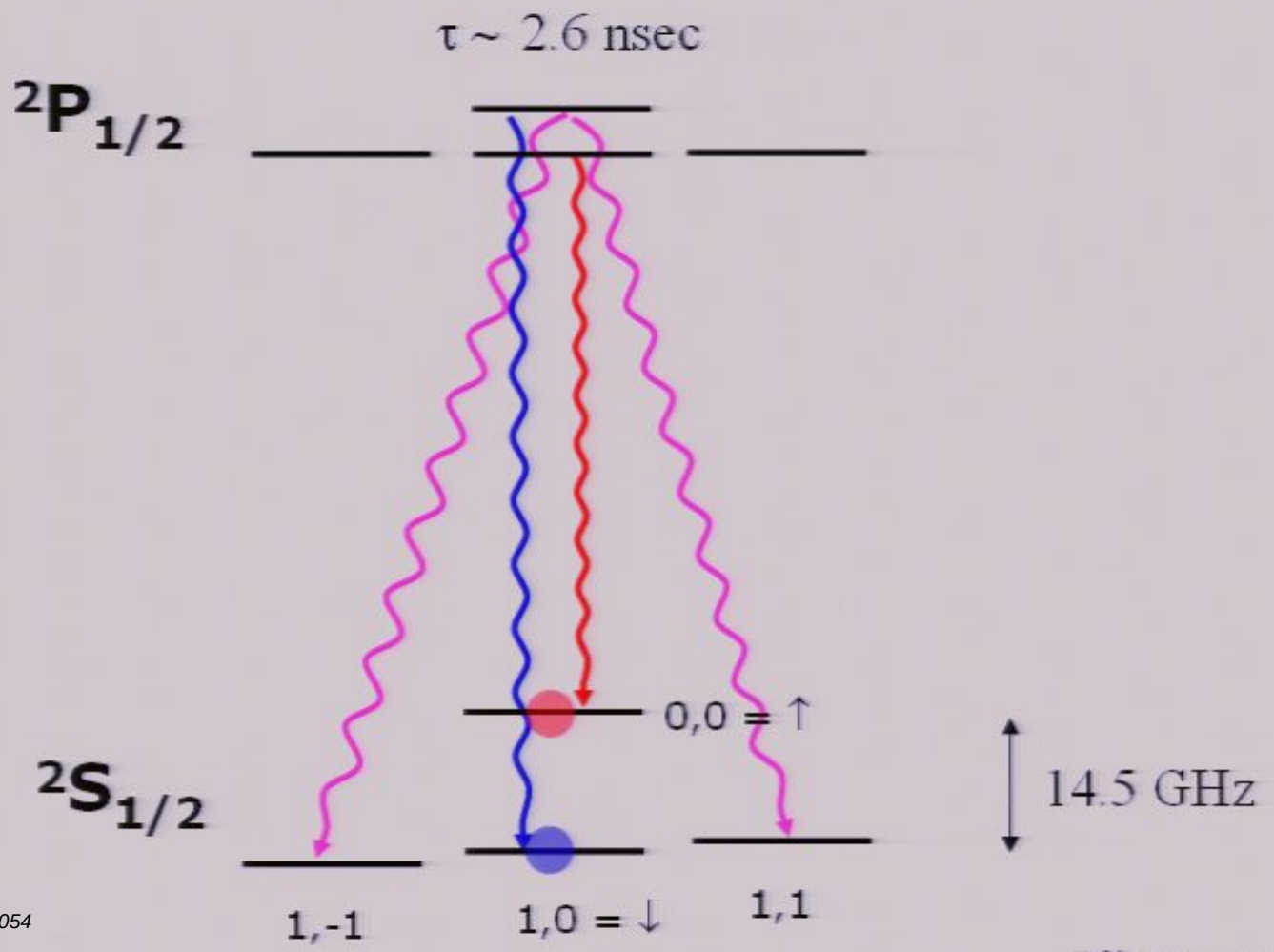
$^{111}Cd^{+}$



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

Linking atoms with ~~phonons~~ photons

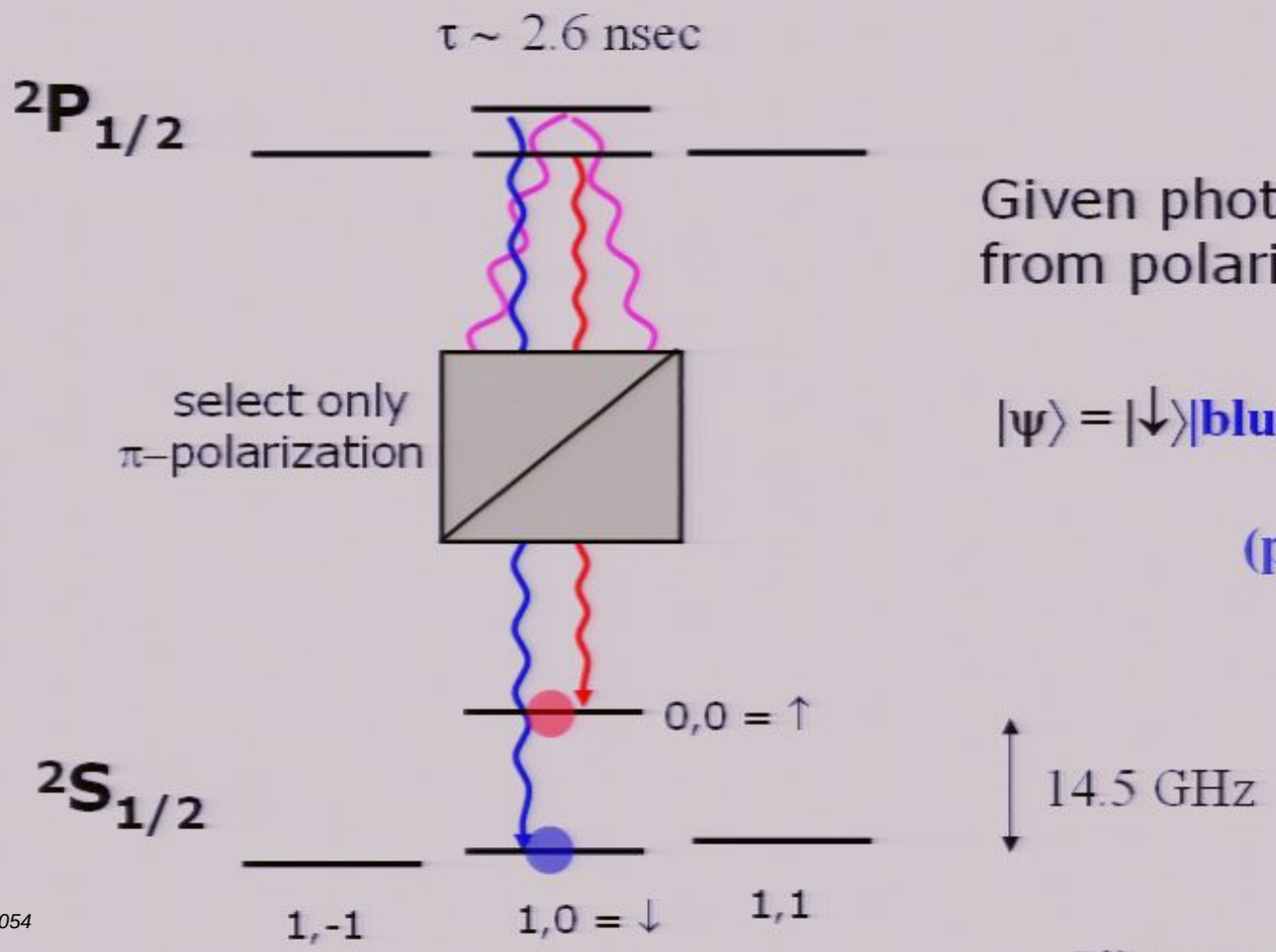
$^{111}Cd^{+}$



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

Linking atoms with ~~phonons~~ photons

$^{111}Cd^{+}$

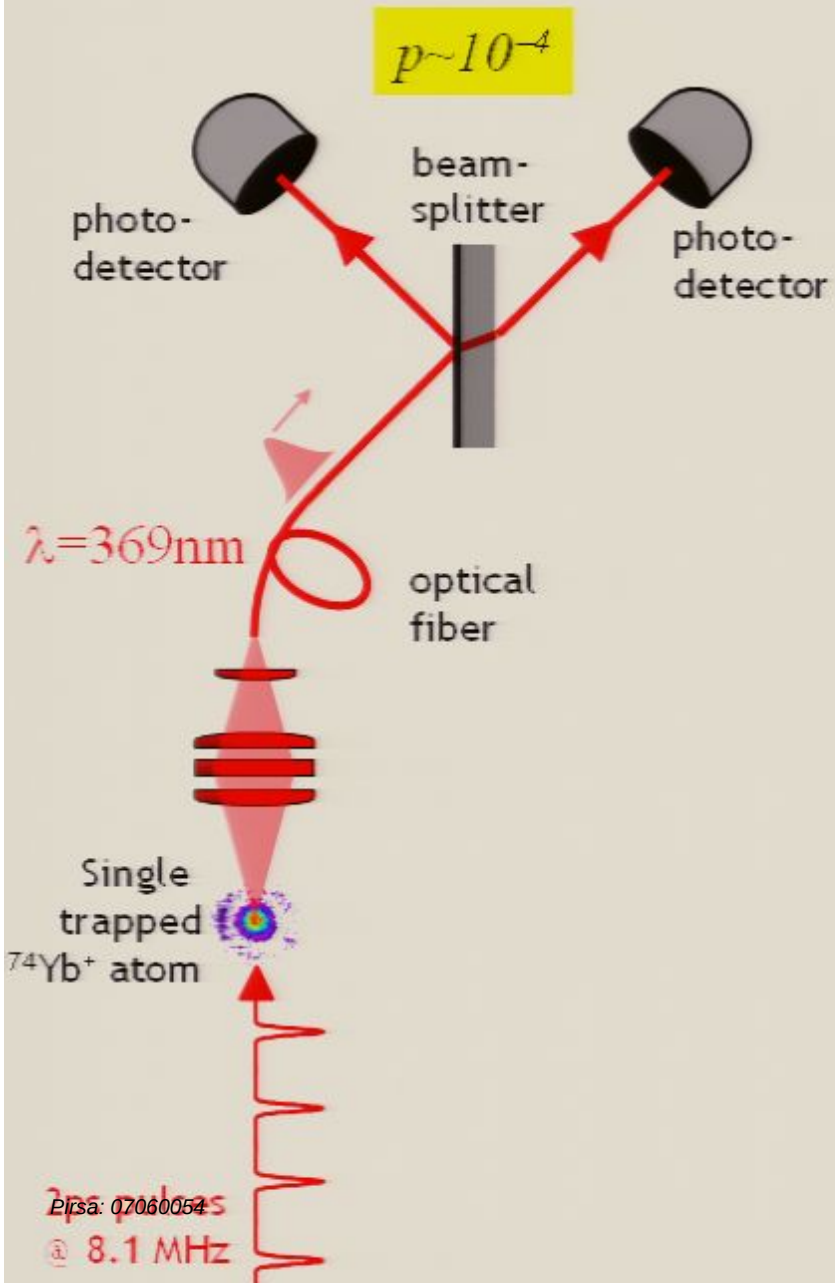


Given photon emerges from polarizer

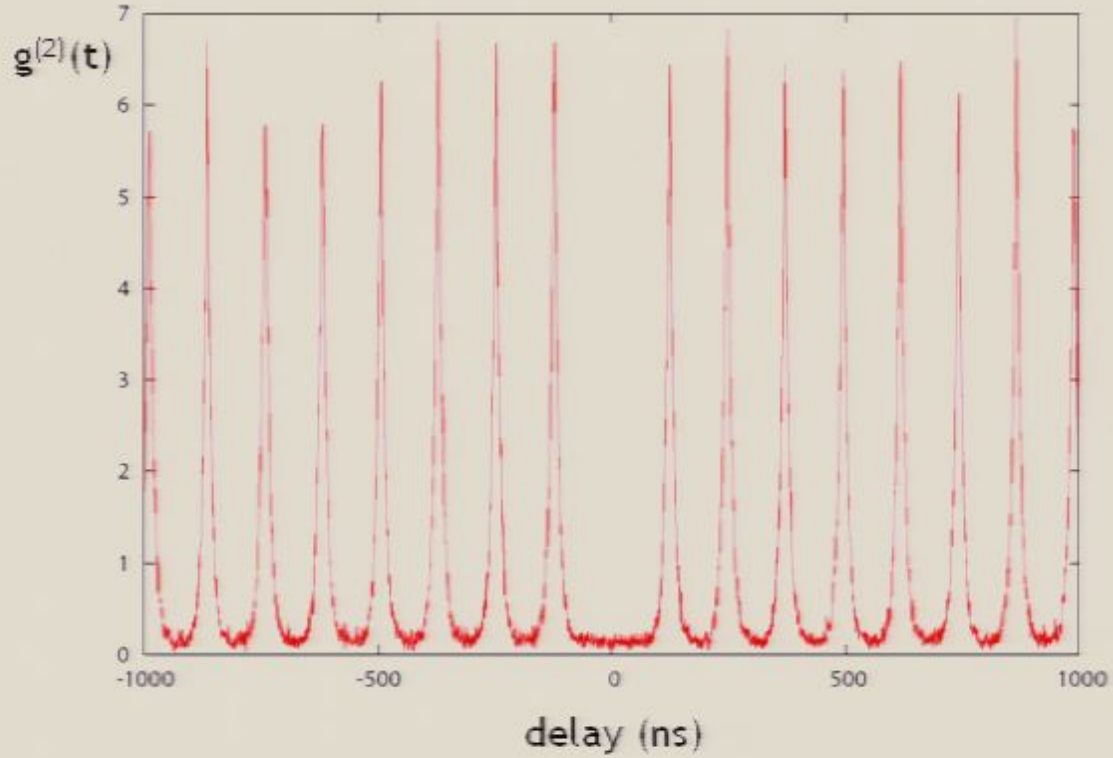
$|\psi\rangle = |\downarrow\rangle|\mathbf{blue}\rangle + |\uparrow\rangle|\mathbf{red}\rangle$

(post-selected)

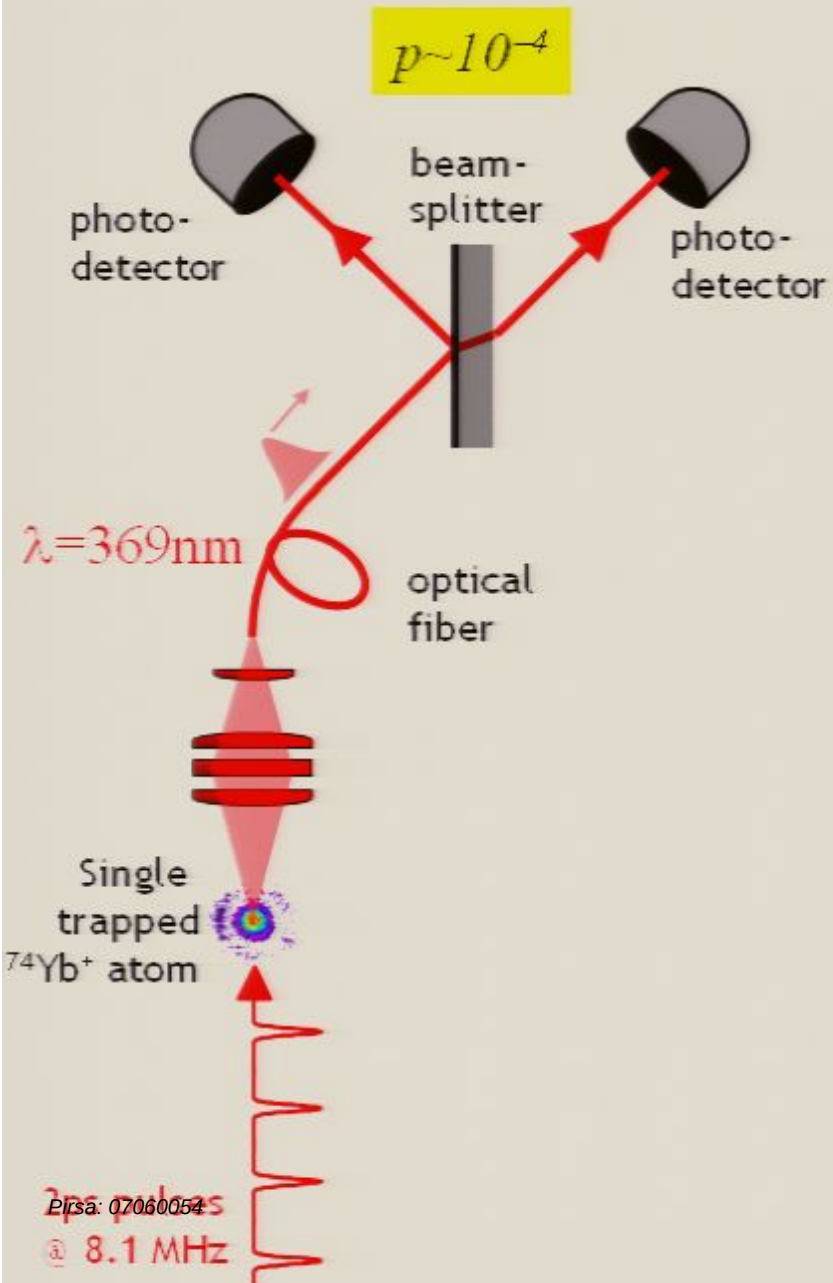
Blinov, et al., *Nature* **428**, 153 (2004)



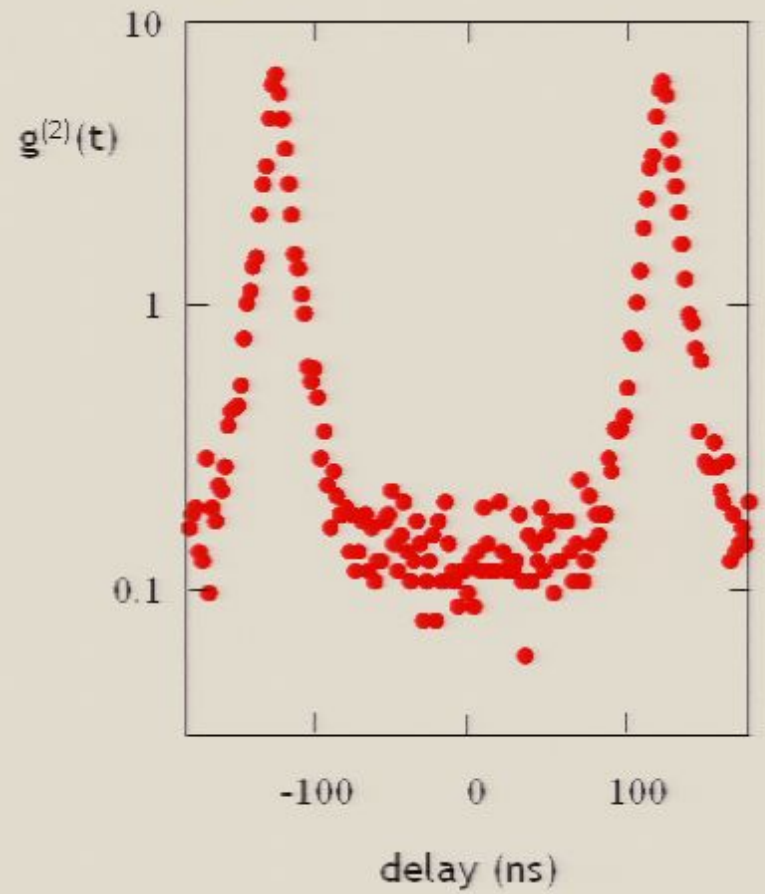
excellent probabilistic
single photon source



P. Maunz, et al., *Nature Physics* (2007)

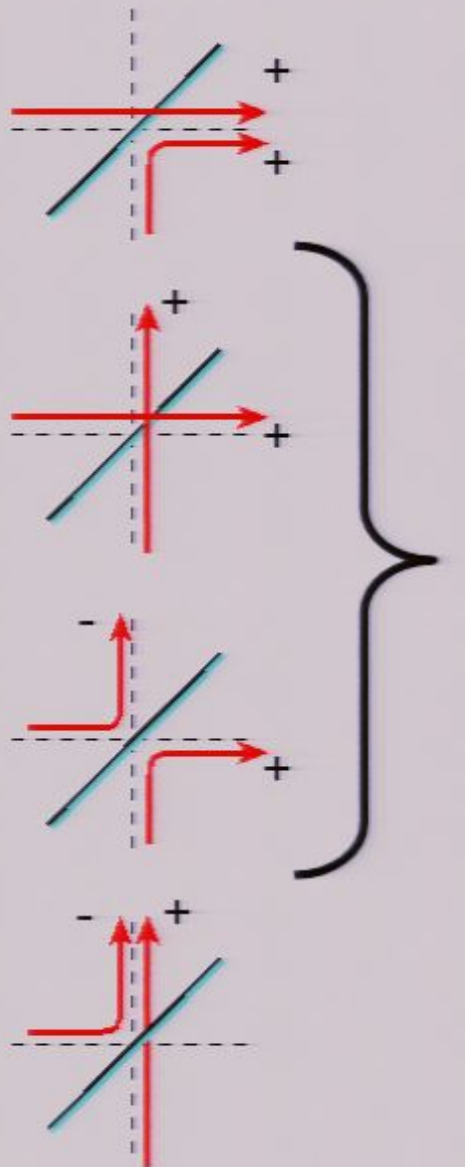


excellent probabilistic
single photon source



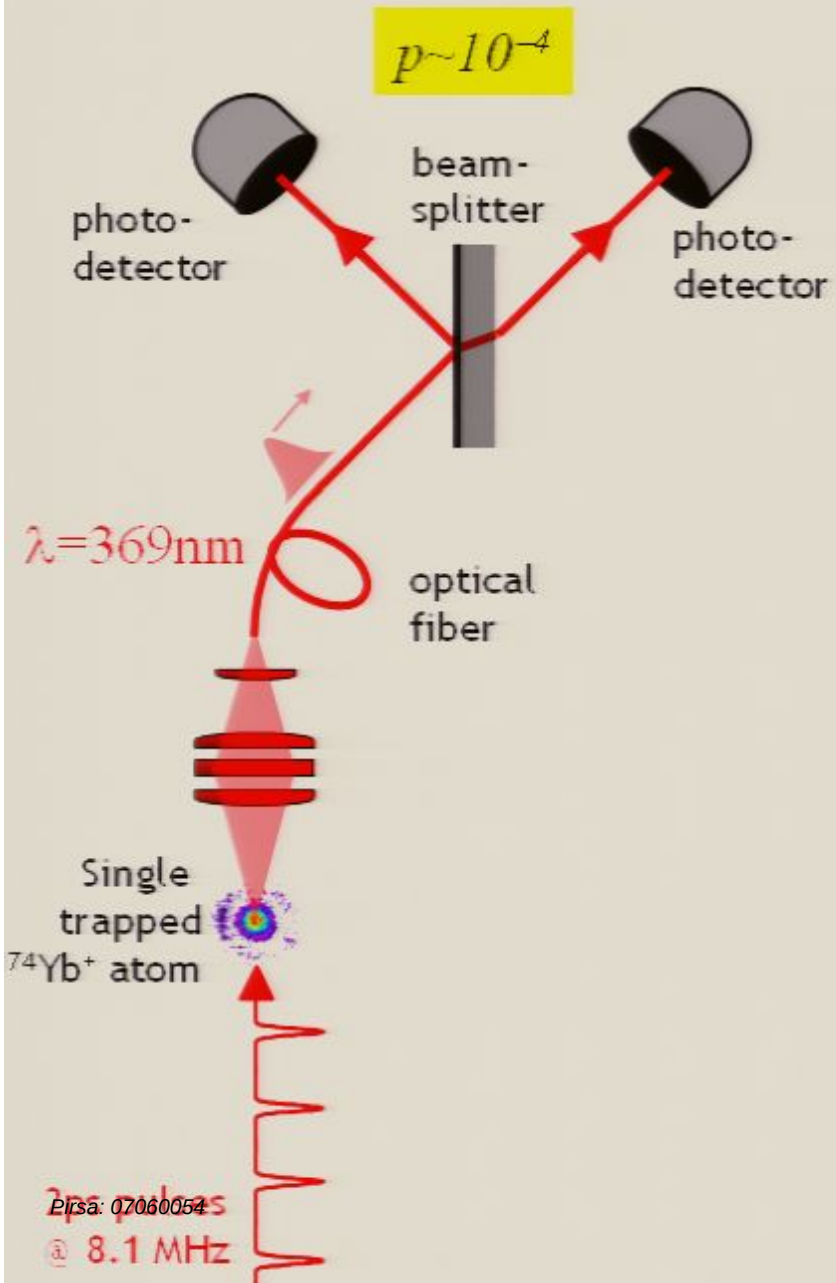
P. Maunz, et al., *Nature Physics* (2007)

Hong-Ou-Mandel Interference



destructive interference of these paths

Hong, Ou, and Mandel, *PRL*, **59**, 2044 (1987)



excellent probabilistic
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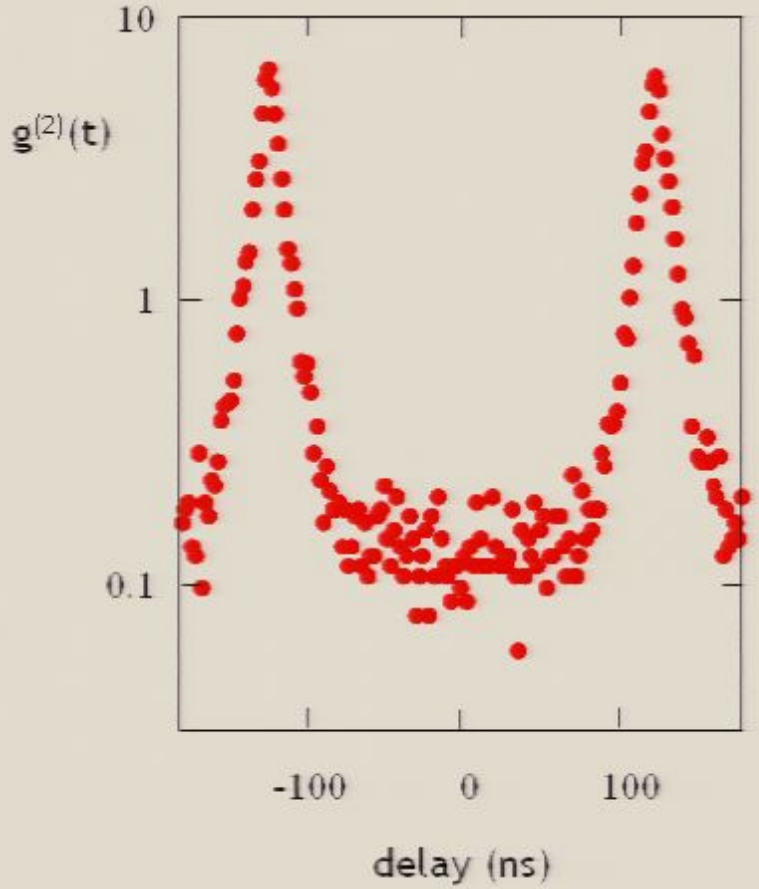
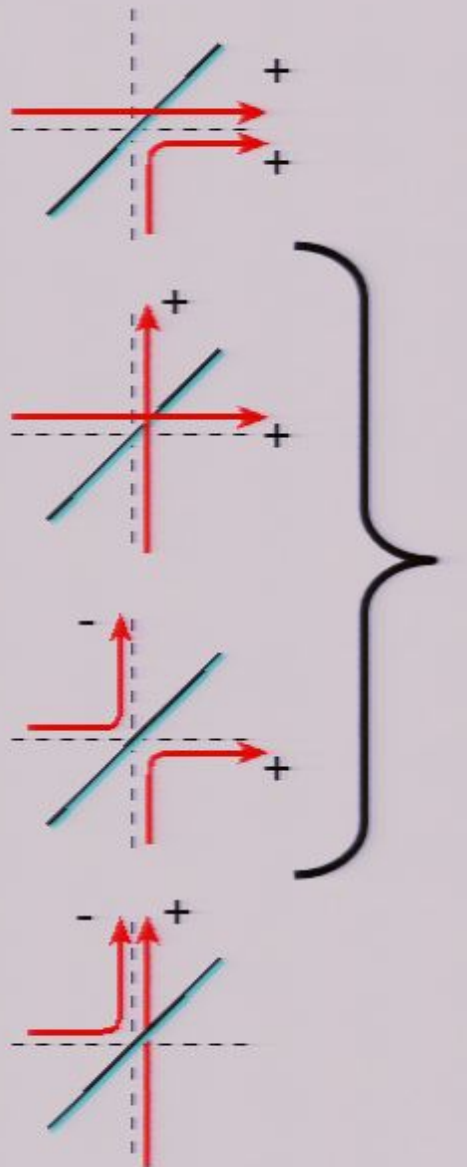


P. Maunz, et al., *Nature Physics* (2007)

Hong-Ou-Mandel Interference



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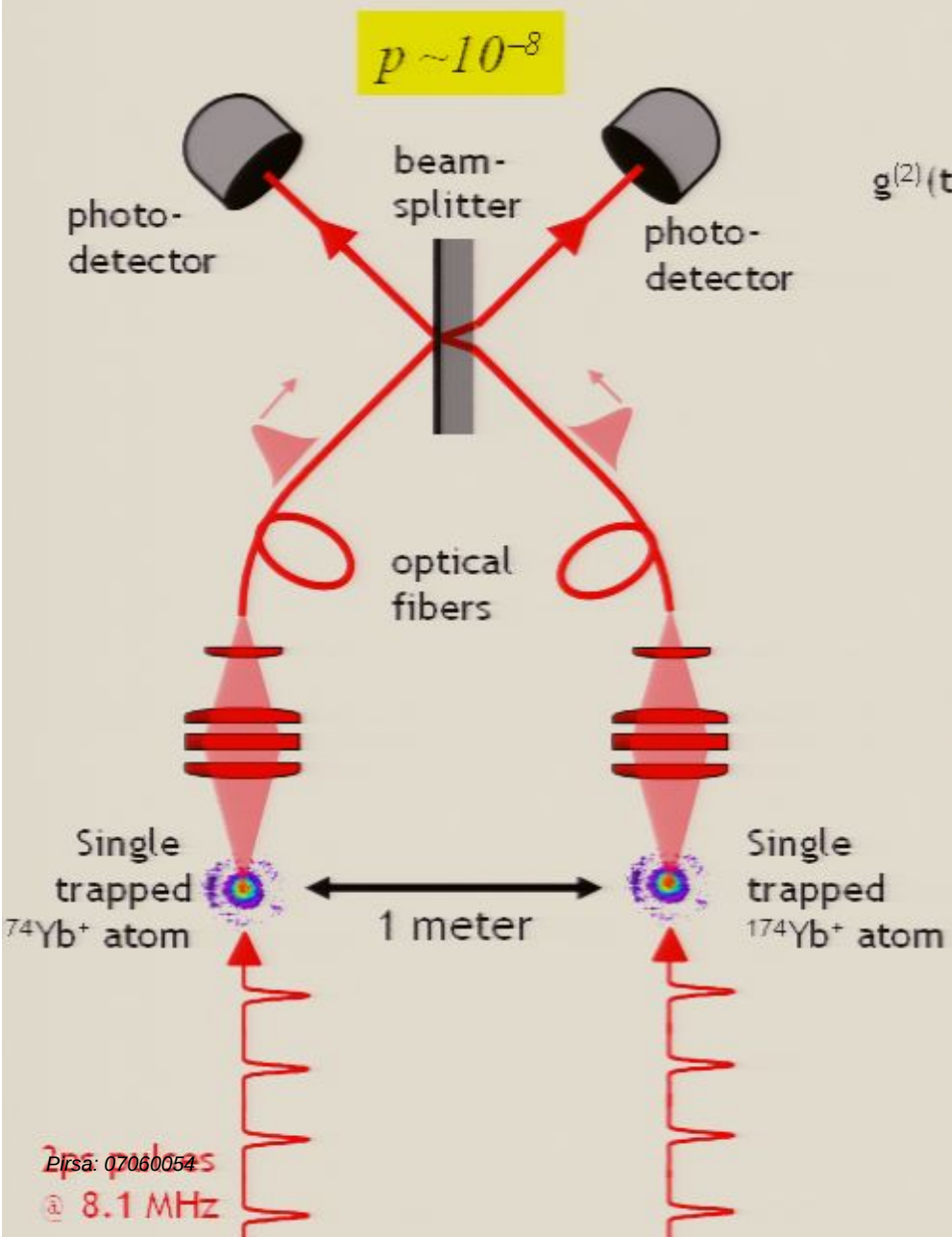
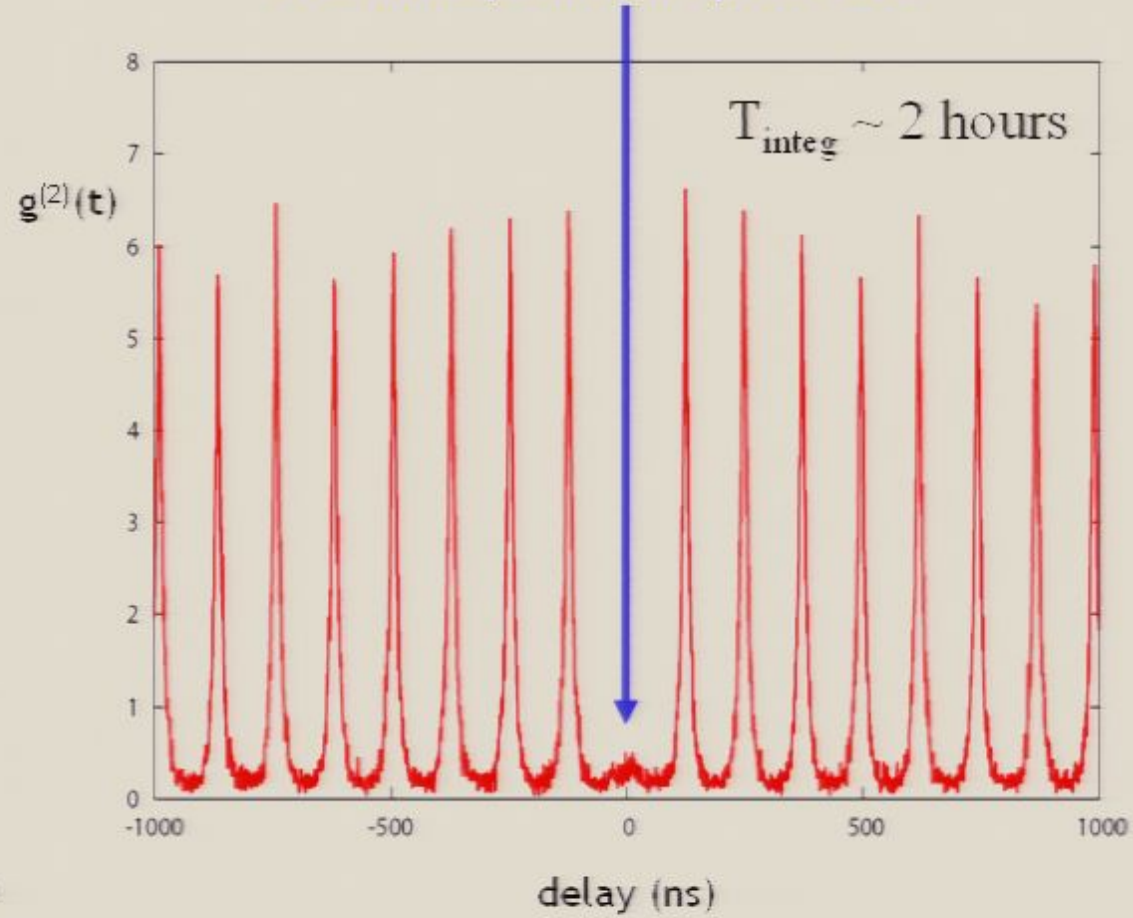
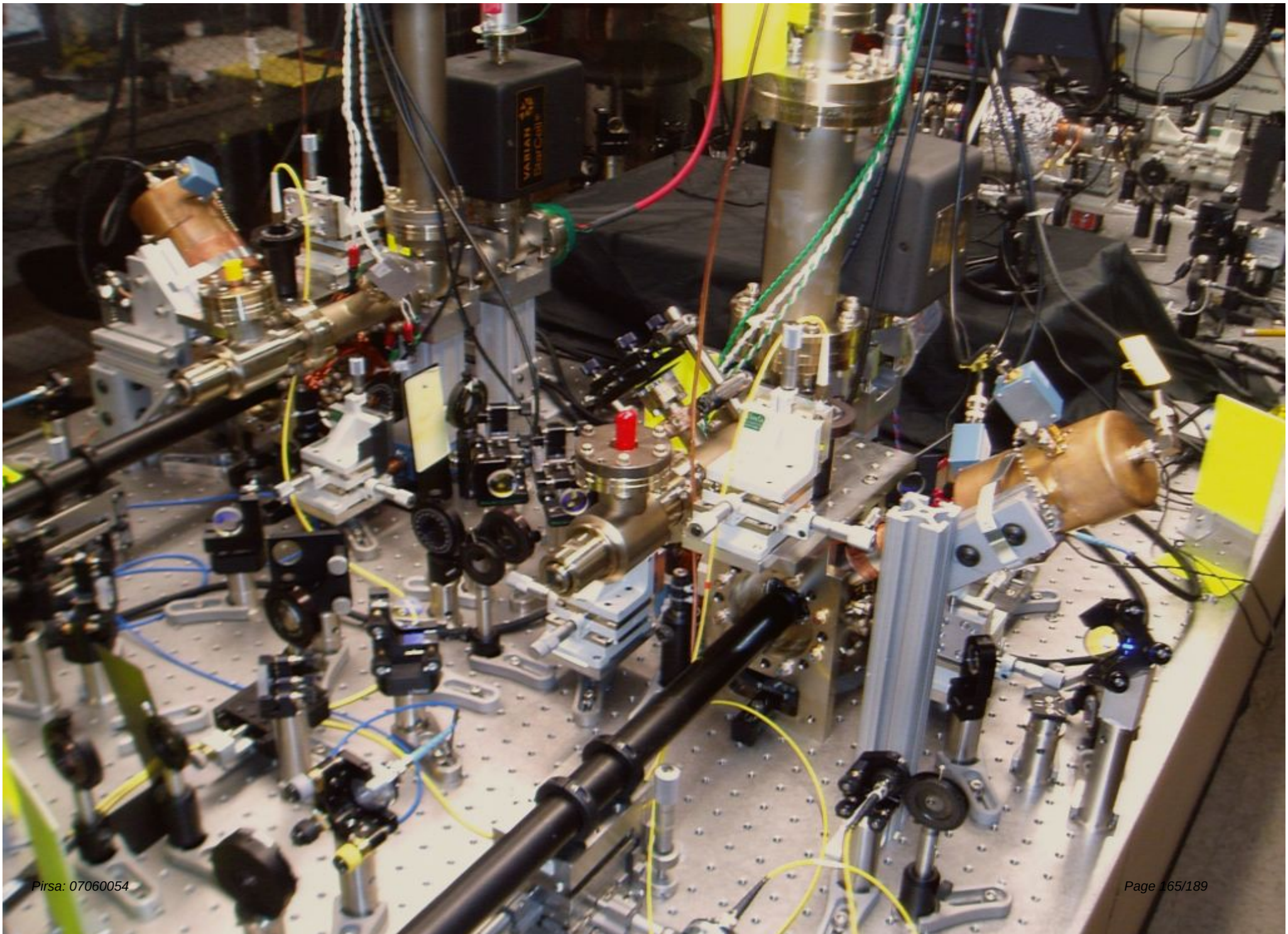


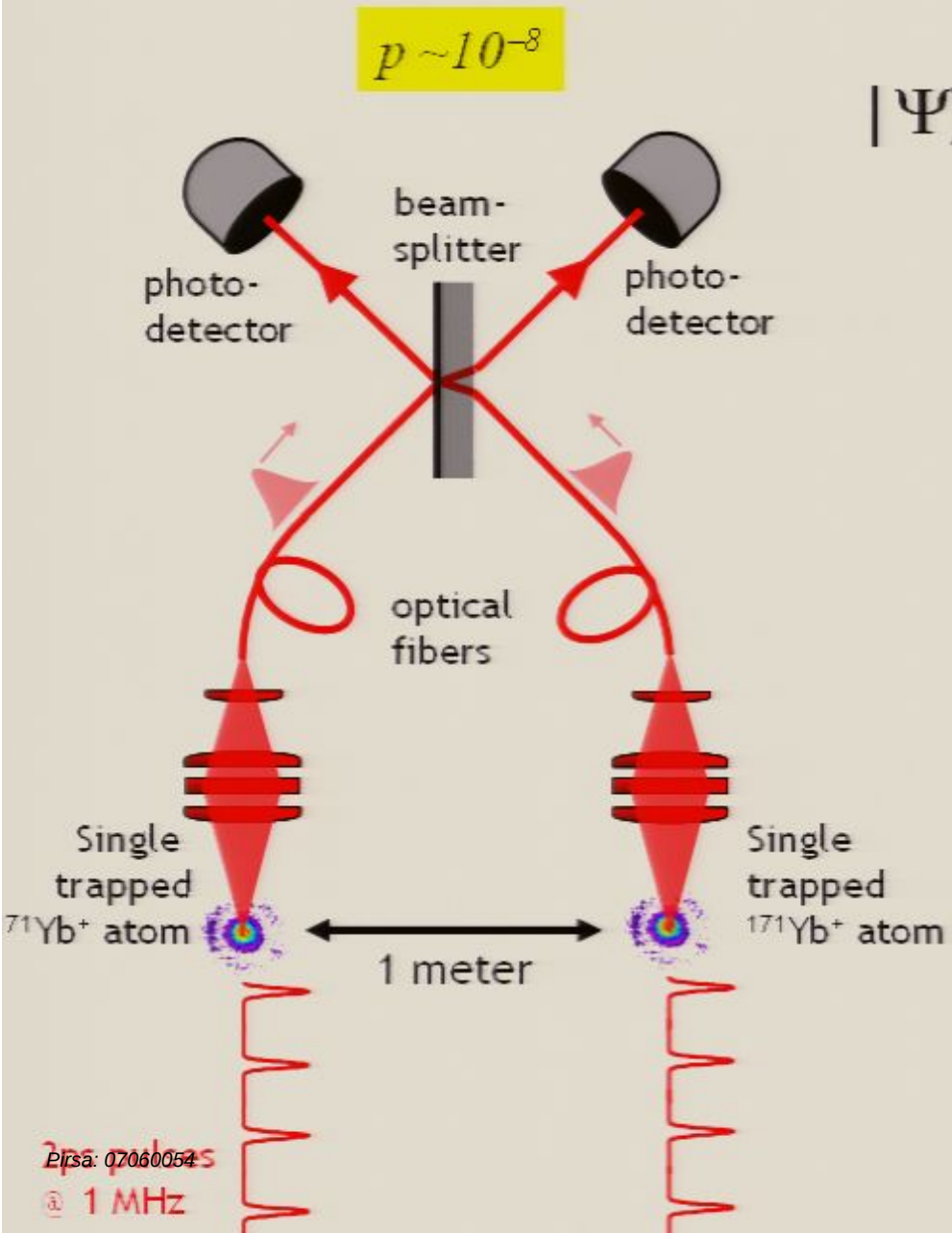
Quantum interference from two independent photons



Hong, Ou, Mandel, PRL 59, 2044 (1987)
Santori, et al., Nature, 419, 594 (2002)
Kaltenbaek, et al, PRL, 96, 240502 (2006)
Legero, et al., PRL, 93, 070503 (2004).
Thompson, et al., Science, 313, 74 (2006).
Felinto, et al. Nature Physics, 2, 844 (2006).
Beugnon, et al. Nature, 440, 779 (2006).


VARIAN

Now with odd isotopes (having nuclear spin)

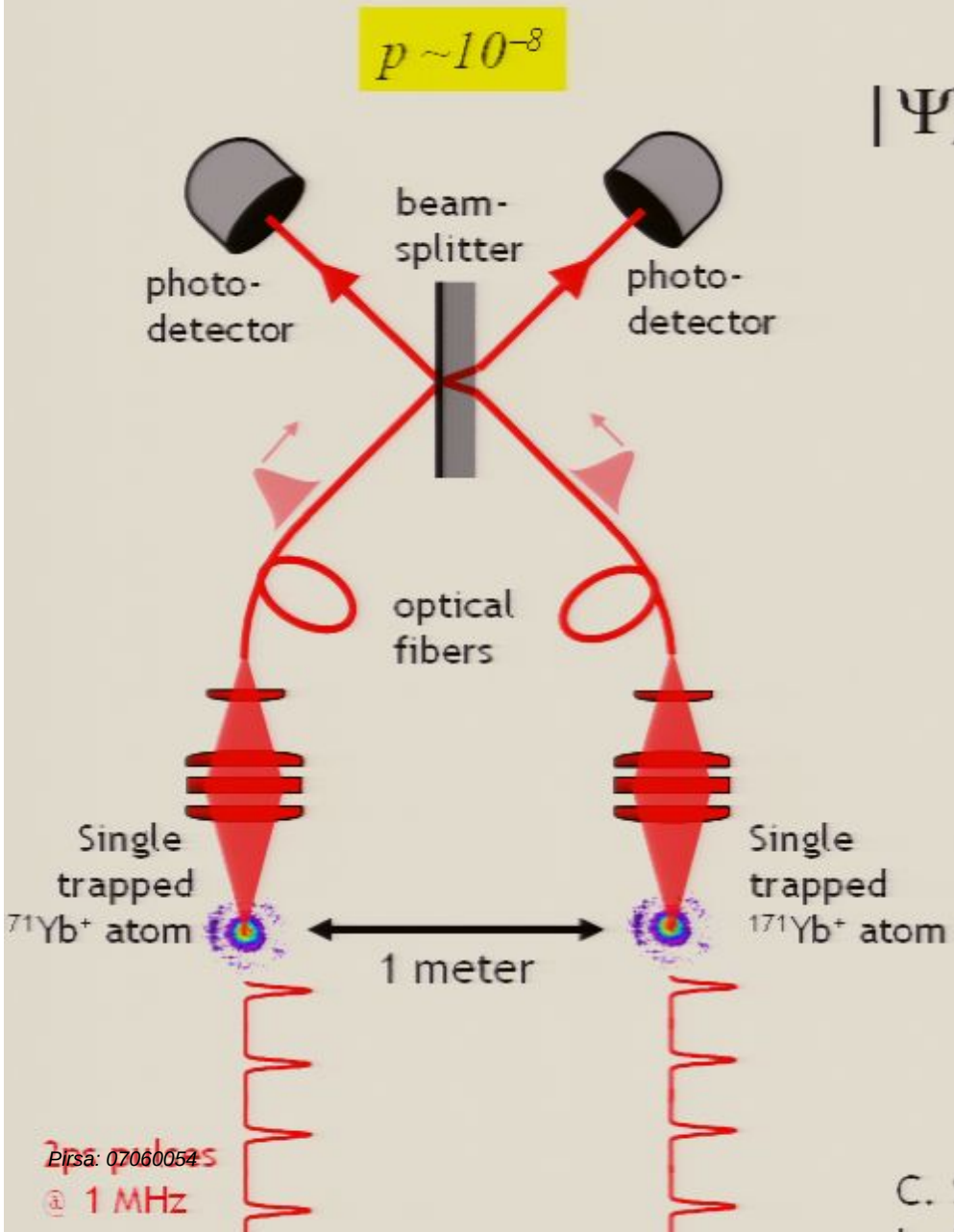


$$|\Psi\rangle = (|\downarrow\rangle_1 |\text{blue}\rangle_1 + |\uparrow\rangle_1 |\text{red}\rangle_1) \otimes (|\downarrow\rangle_2 |\text{blue}\rangle_2 + |\uparrow\rangle_2 |\text{red}\rangle_2)$$

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

...upon coincidence photon detection

Now with odd isotopes (having nuclear spin)



$$|\Psi\rangle = (|\downarrow\rangle_1 |\text{blue}\rangle_1 + |\uparrow\rangle_1 |\text{red}\rangle_1) \otimes (|\downarrow\rangle_2 |\text{blue}\rangle_2 + |\uparrow\rangle_2 |\text{red}\rangle_2)$$

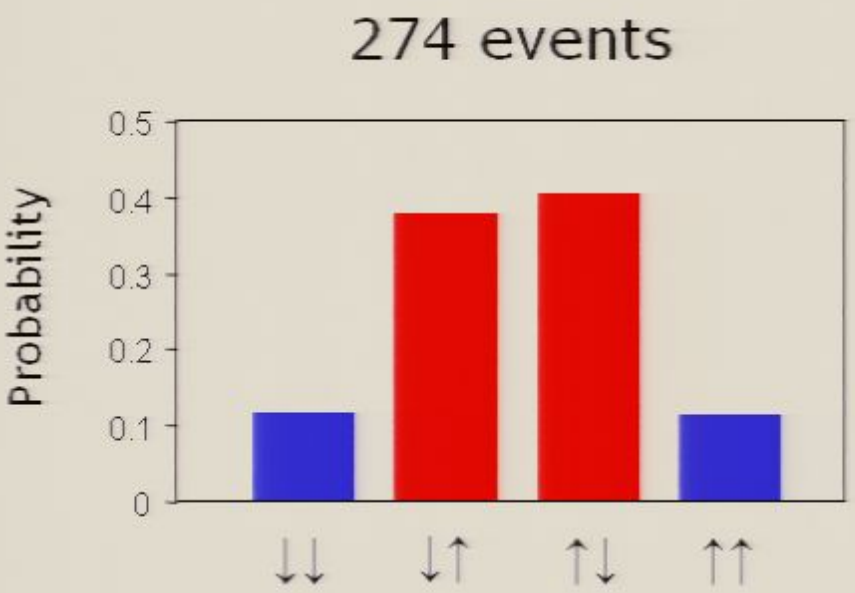
$$\Rightarrow |\downarrow\rangle_1 |\uparrow\rangle_2 - |\uparrow\rangle_2 |\downarrow\rangle_2$$

...upon coincidence photon detection

insensitive to
- interferometric phase noise
- ion motion

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

Measured ion correlations given coincidence photons

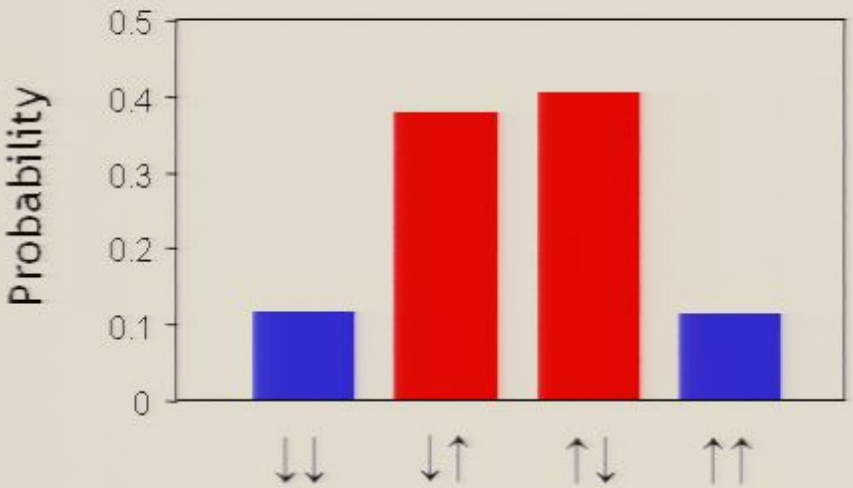


Measured ion correlations given coincidence photons

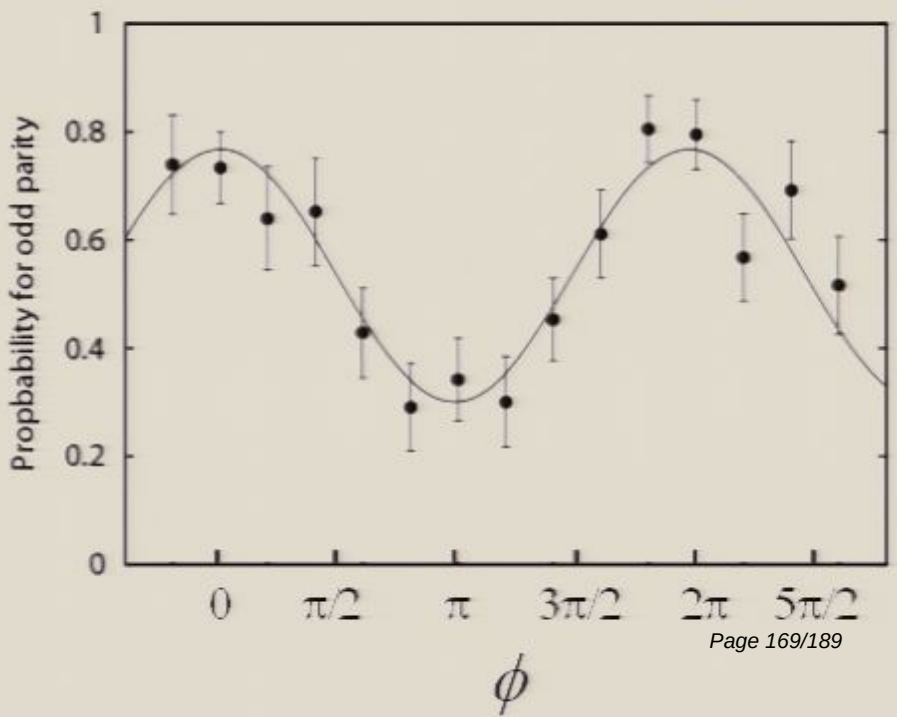
Rotate both qubits by $\theta=\pi/2$, with phase difference ϕ

$$|\downarrow\rangle_1|\uparrow\rangle_2 - |\uparrow\rangle_1|\downarrow\rangle_2 \Rightarrow$$
$$\cos(\phi/2)\left(|\downarrow\rangle_1|\uparrow\rangle_2 - |\uparrow\rangle_1|\downarrow\rangle_2\right)$$
$$+\ \sin(\phi/2)\left(|\uparrow\rangle_1|\uparrow\rangle_2 - |\downarrow\rangle_1|\downarrow\rangle_2\right)$$

274 events



502 events



Measured density matrix:

$$\rho = \begin{array}{c} \begin{array}{cccc} \downarrow\downarrow & \downarrow\uparrow & \uparrow\downarrow & \uparrow\uparrow \end{array} \\ \begin{pmatrix} 0.11 & ? & ? & ? \\ ? & 0.38 & -0.24 & ? \\ ? & -0.24 & 0.40 & ? \\ ? & ? & ? & 0.11 \end{pmatrix} \end{array} \begin{array}{c} \\ \downarrow\downarrow \\ \downarrow\uparrow \\ \uparrow\downarrow \\ \uparrow\uparrow \end{array}$$

Fidelity F $= \langle \Psi^- | \rho | \Psi^- \rangle$

$= \frac{1}{2}(\rho_{\downarrow\uparrow,\downarrow\uparrow} + \rho_{\uparrow\downarrow,\uparrow\downarrow}) + |\rho_{\downarrow\uparrow,\uparrow\downarrow}|$

$= 0.63(3)$

Concurrence C = 0.25(5)

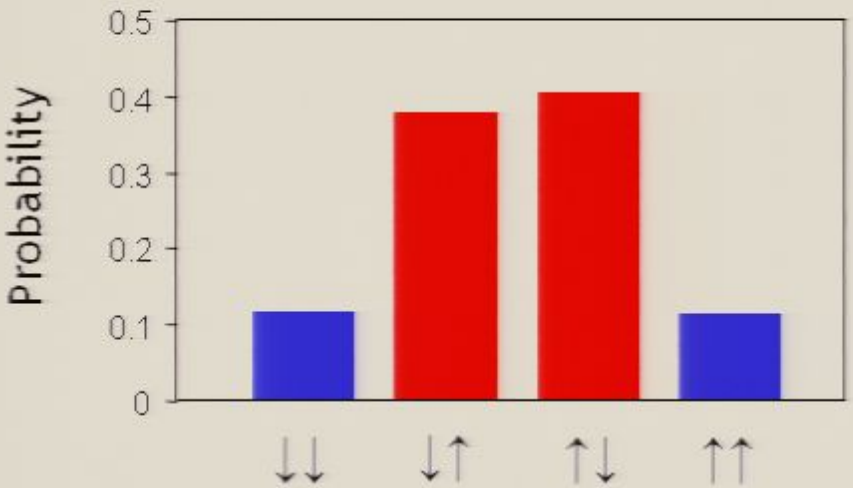
Entanglement of Formation E = 0.13(3)

Measured ion correlations given coincidence photons

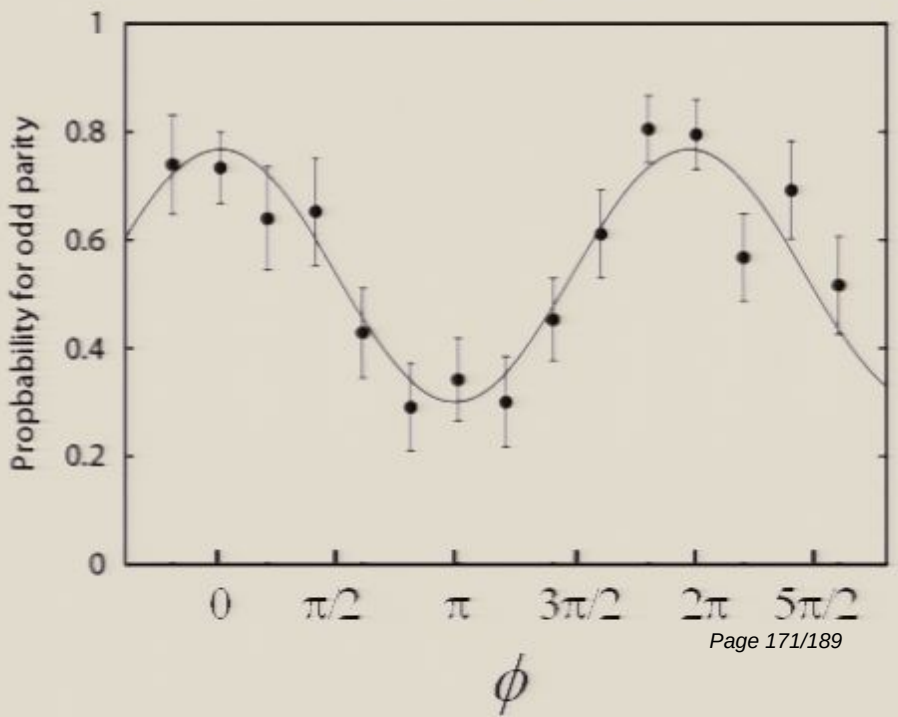
Rotate both qubits by $\theta=\pi/2$, with phase difference ϕ

$$|\downarrow\rangle_1|\uparrow\rangle_2 - |\uparrow\rangle_1|\downarrow\rangle_2 \Rightarrow$$
$$\cos(\phi/2)\left(|\downarrow\rangle_1|\uparrow\rangle_2 - |\uparrow\rangle_1|\downarrow\rangle_2\right)$$
$$+\ \sin(\phi/2)\left(|\uparrow\rangle_1|\uparrow\rangle_2 - |\downarrow\rangle_1|\downarrow\rangle_2\right)$$

274 events



502 events



Probability of heralding per attempt

$$p = \frac{1}{4}\left[\overbrace{\frac{1}{2}(0.995)(0.8)(0.5)(0.2)(0.15)(0.02)}^{\text{probability of 1 photon emitted and detected}}\right]^2 = 3\times 10^{-9}$$

Prob. of having singlet Bell state

radiation pattern

branching to $^2D_{3/2}$ state

losses

excitation probability

fiber coupling efficiency

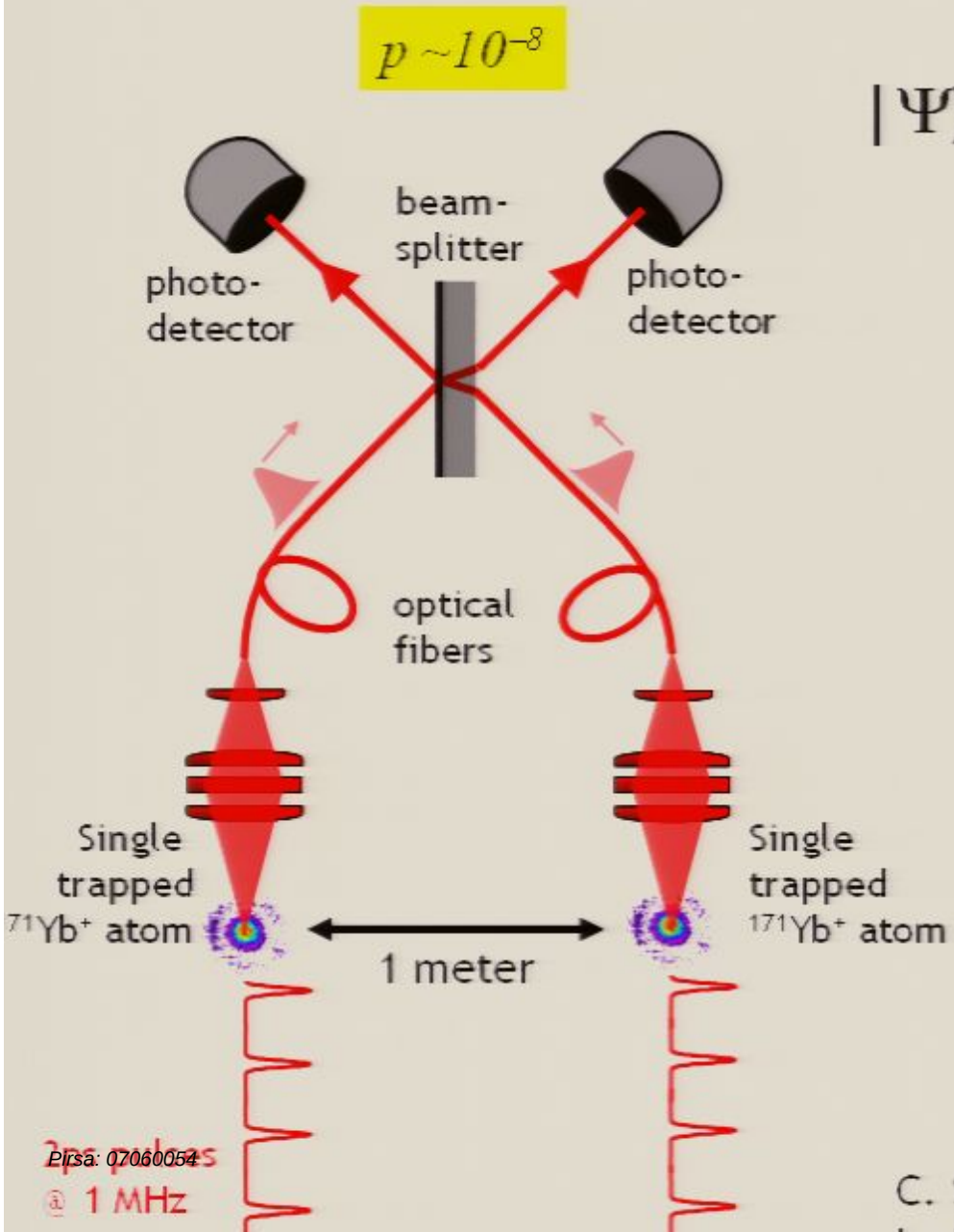
detector efficiency

solid angle

Rate of heralded entanglement

$$R = \Gamma p = 0.002/sec$$

Now with odd isotopes (having nuclear spin)



$$|\Psi\rangle = (|\downarrow\rangle_1 |\text{blue}\rangle_1 + |\uparrow\rangle_1 |\text{red}\rangle_1) \otimes (|\downarrow\rangle_2 |\text{blue}\rangle_2 + |\uparrow\rangle_2 |\text{red}\rangle_2)$$

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

...upon coincidence photon detection

insensitive to
- interferometric phase noise
- ion motion

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

Probability of heralding per attempt

$$p = \frac{1}{4}\left[\overbrace{\frac{1}{2}(0.995)(0.8)(0.5)(0.2)(0.15)(0.02)}^{\text{probability of 1 photon emitted and detected}}\right]^2 = 3\times 10^{-9}$$

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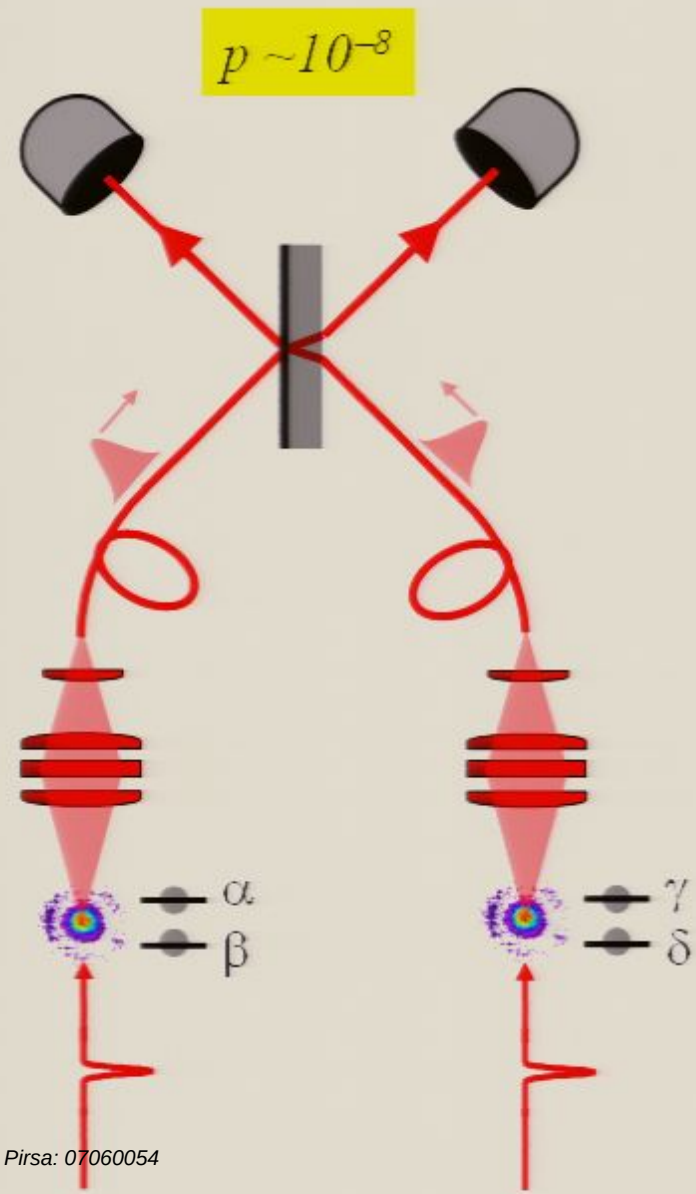
But there's more: Remote Gates

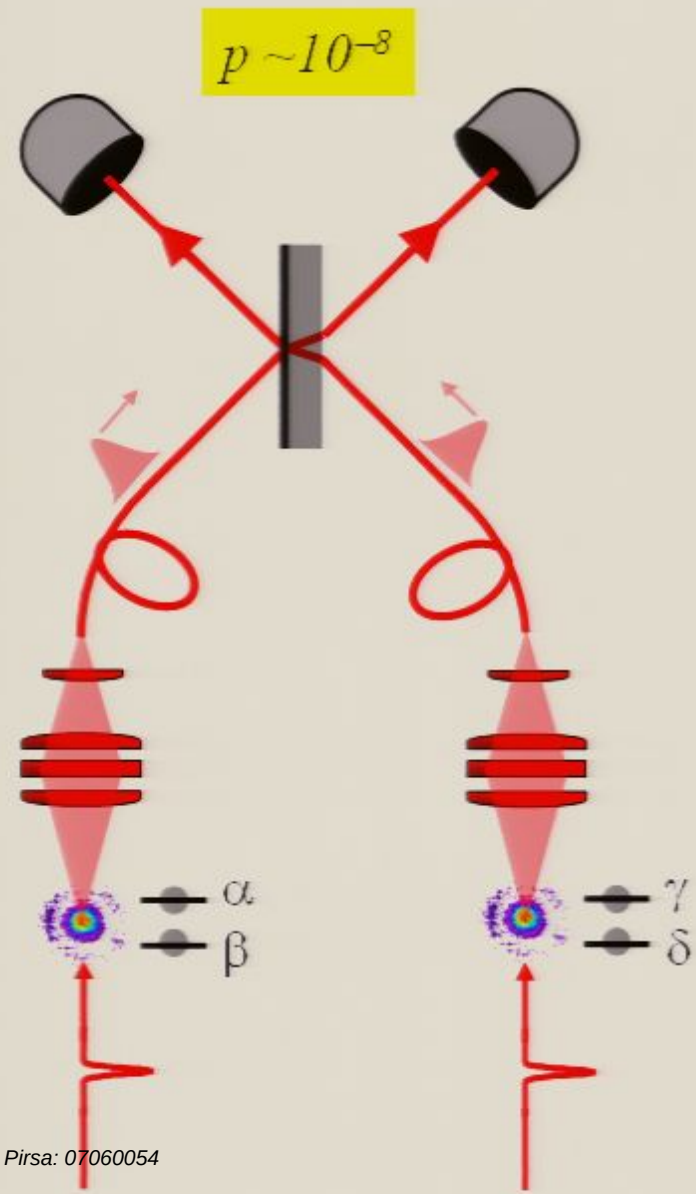


$$|\Psi\rangle = (\alpha|\downarrow\rangle_1 + \beta|\uparrow\rangle_1)\otimes(\gamma|\downarrow\rangle_2 + \delta|\uparrow\rangle_2)$$

$$\Rightarrow \alpha\delta|\downarrow\rangle_1|\uparrow\rangle_2 - \beta\gamma|\uparrow\rangle_1|\downarrow\rangle_2$$

L.-M. Duan, et al., PRA **73**, 062324 (2006)

But there's more: Remote Gates



$$|\Psi\rangle = (\alpha|\downarrow\rangle_1 + \beta|\uparrow\rangle_1)\otimes(\gamma|\downarrow\rangle_2 + \delta|\uparrow\rangle_2)$$

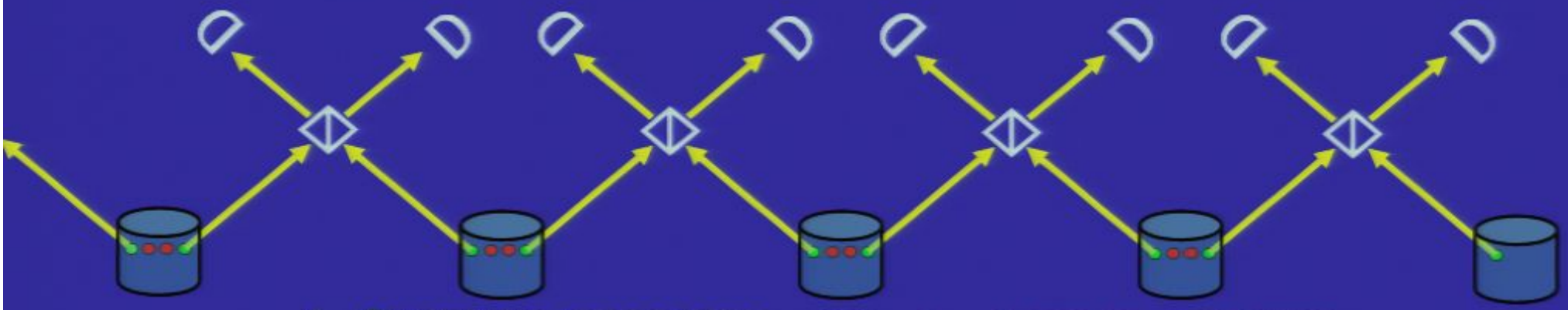
$$\Rightarrow \alpha\delta|\downarrow\rangle_1|\uparrow\rangle_2 - \beta\gamma|\uparrow\rangle_1|\downarrow\rangle_2$$

or equivalently,

$$|\Psi\rangle \Rightarrow (I - ZZ)|\Psi\rangle$$

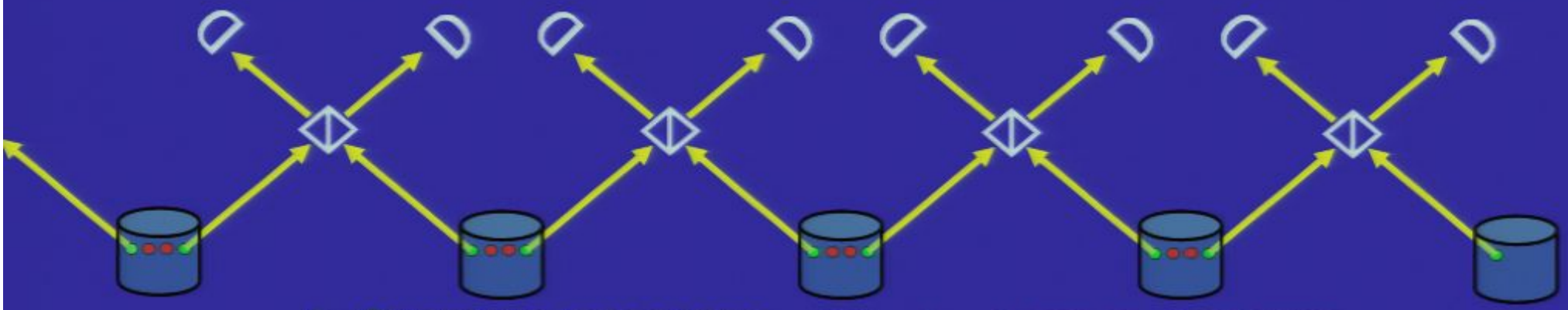
L.-M. Duan, et al., PRA **73**, 062324 (2006)

Quantum networking with probabalistic entanglement



1. Quantum repeaters Briegel *et al.*, PRL **81**, 5932 (1998)

Quantum networking with probabalistic entanglement



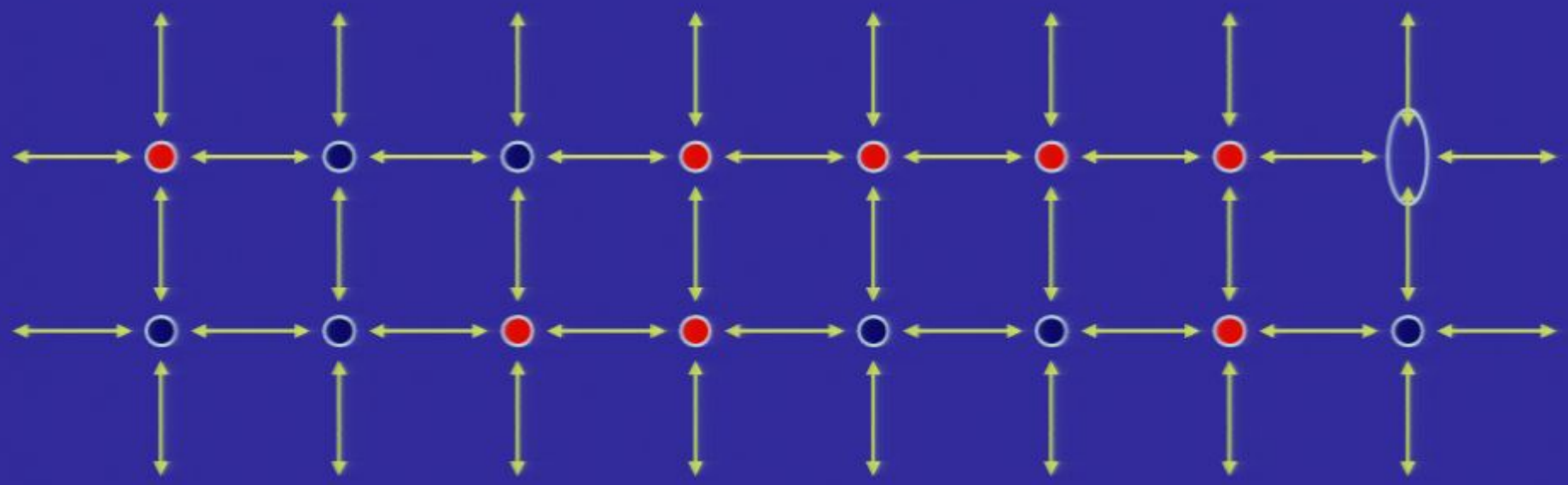
1. Quantum repeaters Briegel *et al.*, PRL **81**, 5932 (1998)

2. Distributed quantum computing with hybrid gates

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

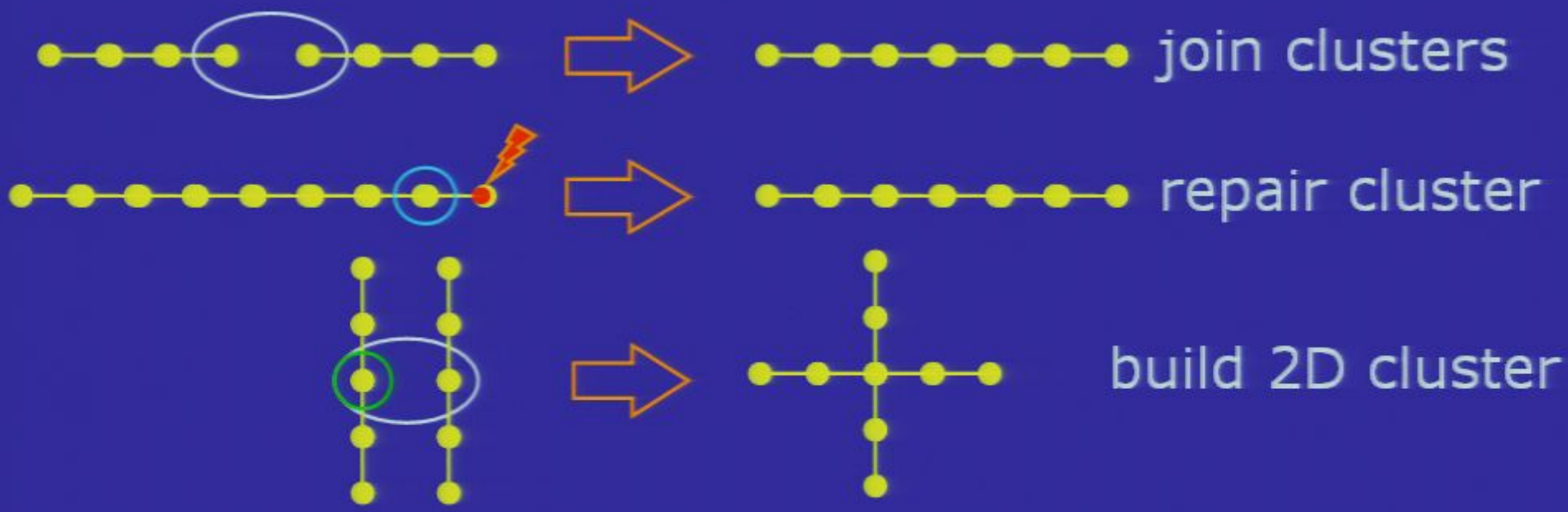
Quantum computing exclusively with probabalistic entanglement

KLM 409, 46, Nature (2001)



Cluster state quantum computing Raussendorf and Briegel, PRL **86**, 910 (2001)

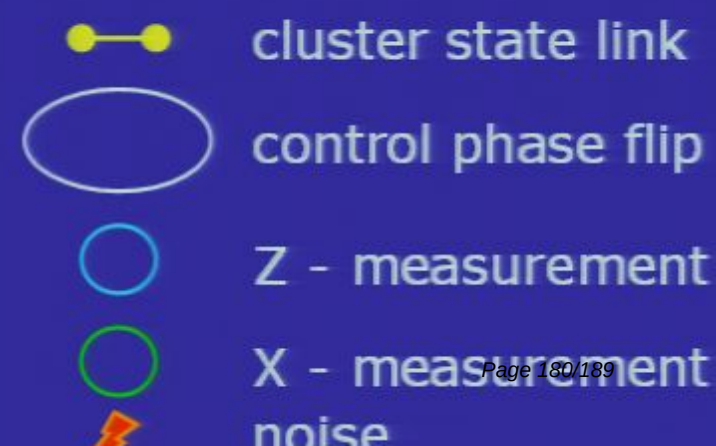
Quantum computing using probabilistic gates

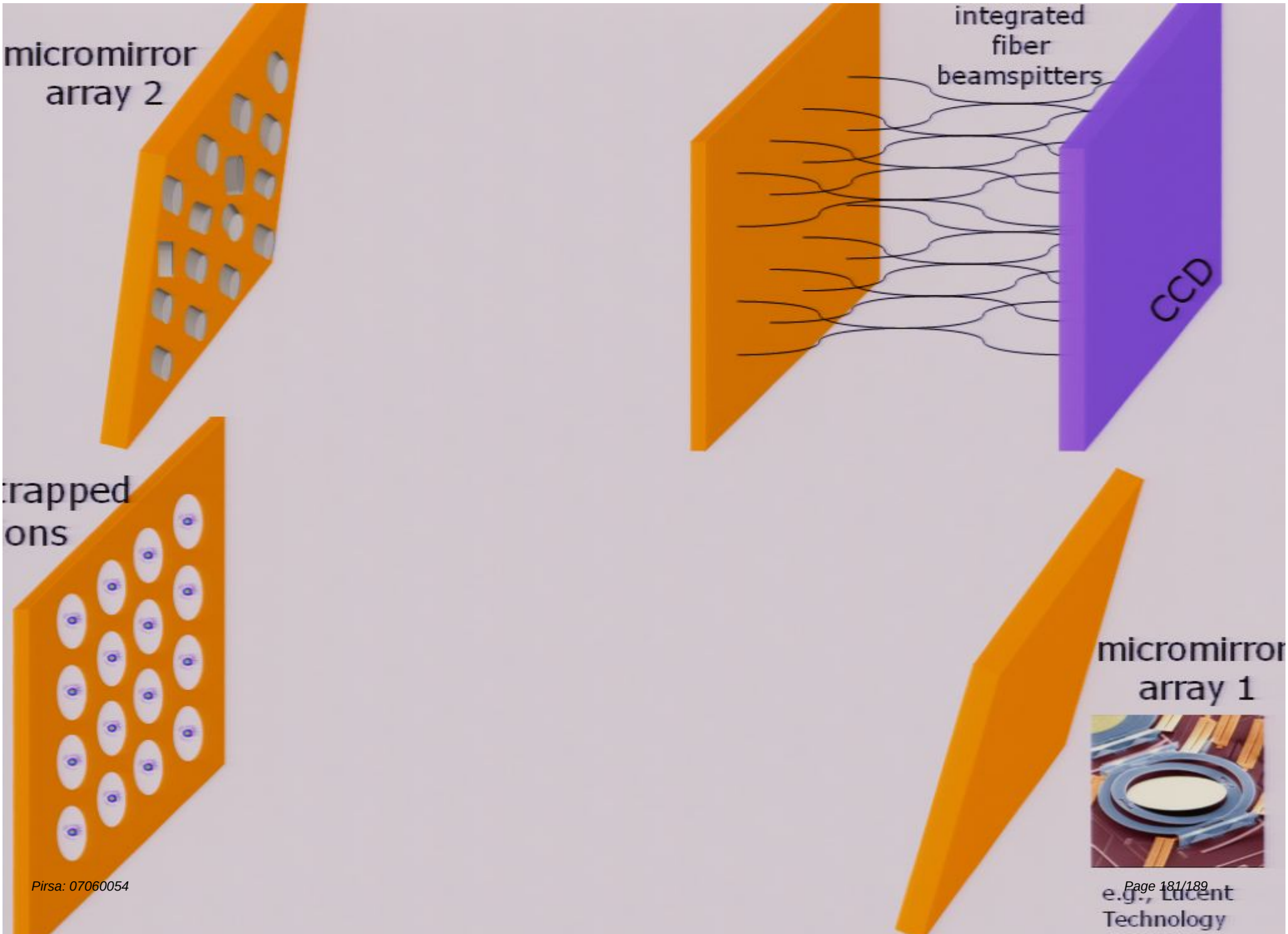


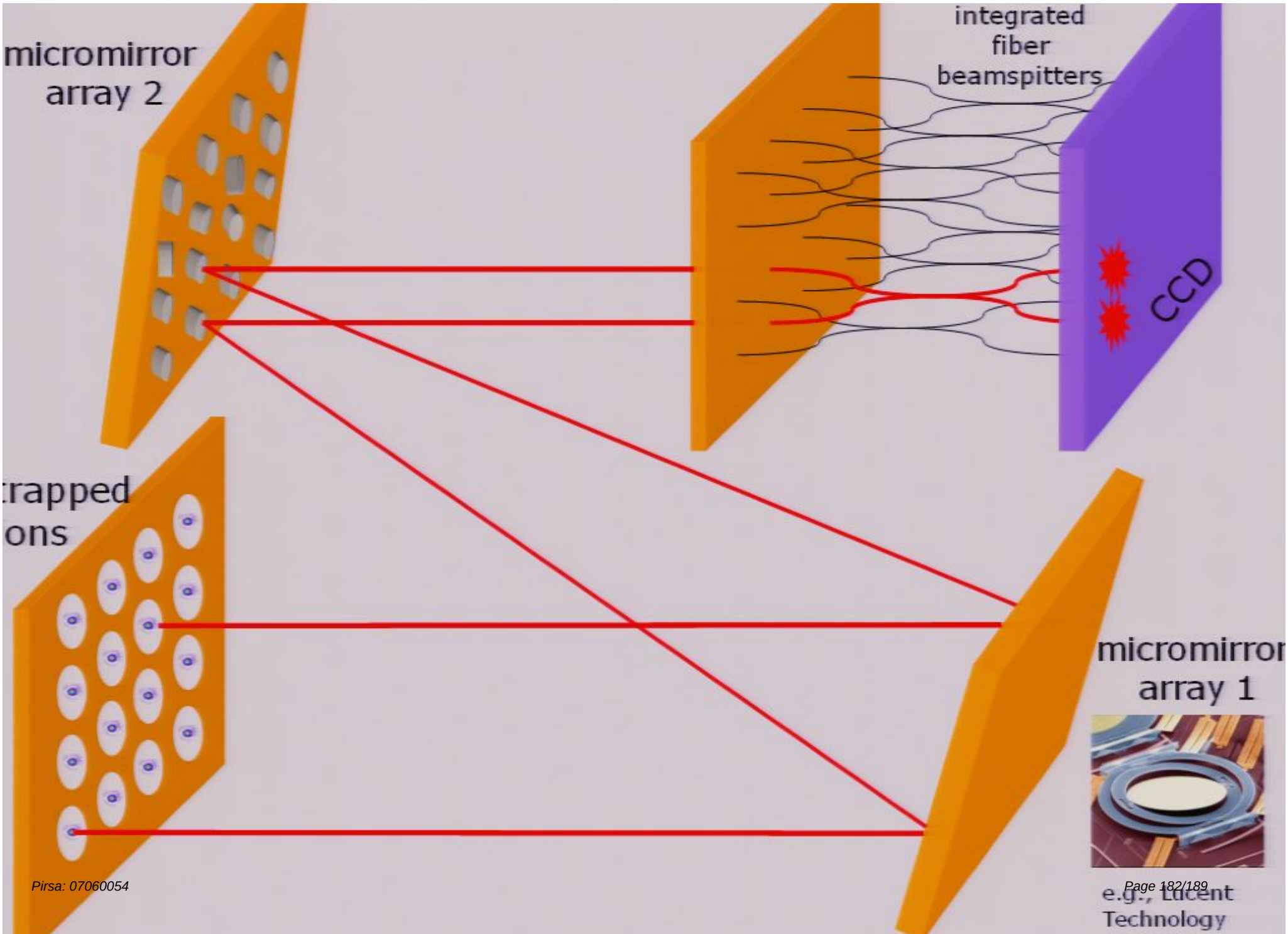
- Efficient computation is possible no matter how small p
- Overhead scales efficiently both with $1/p$ and n

time $\approx (1/p)^{\log(4/p)}$

Duan and Raussendorf, PRL 95, 080503 (2005)




micromirror
array 2
integrated
fiber
beamspitters
CCD
trapped
ons
micromirror
array 1
e.g., Lucent
Technology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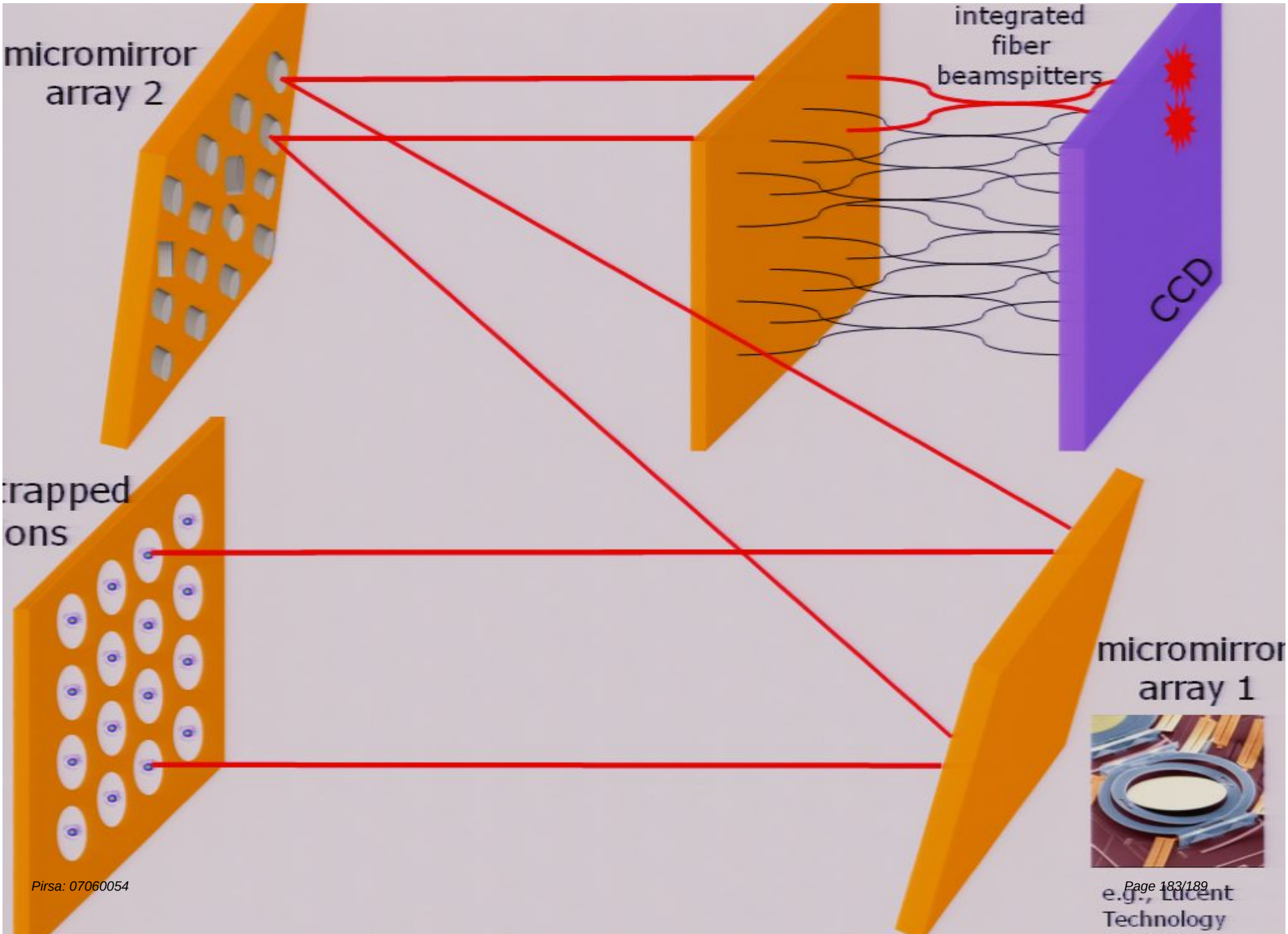
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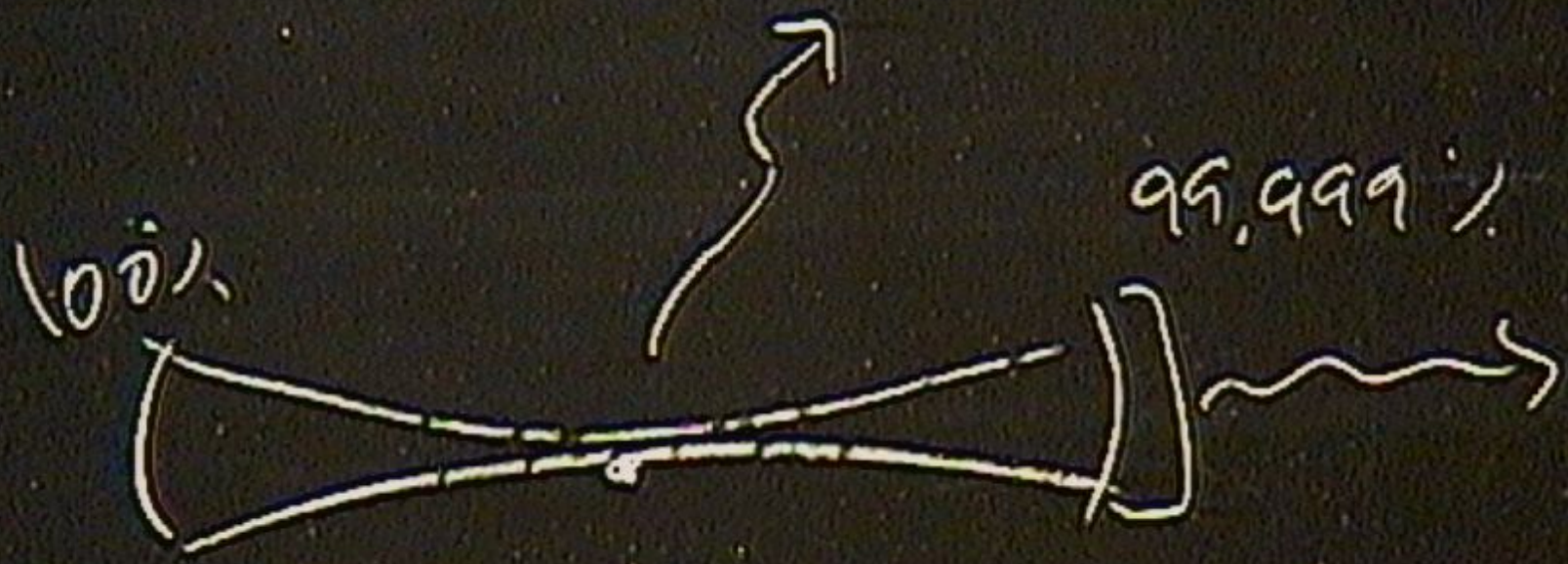
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