Wiring up ion traps for quantum information

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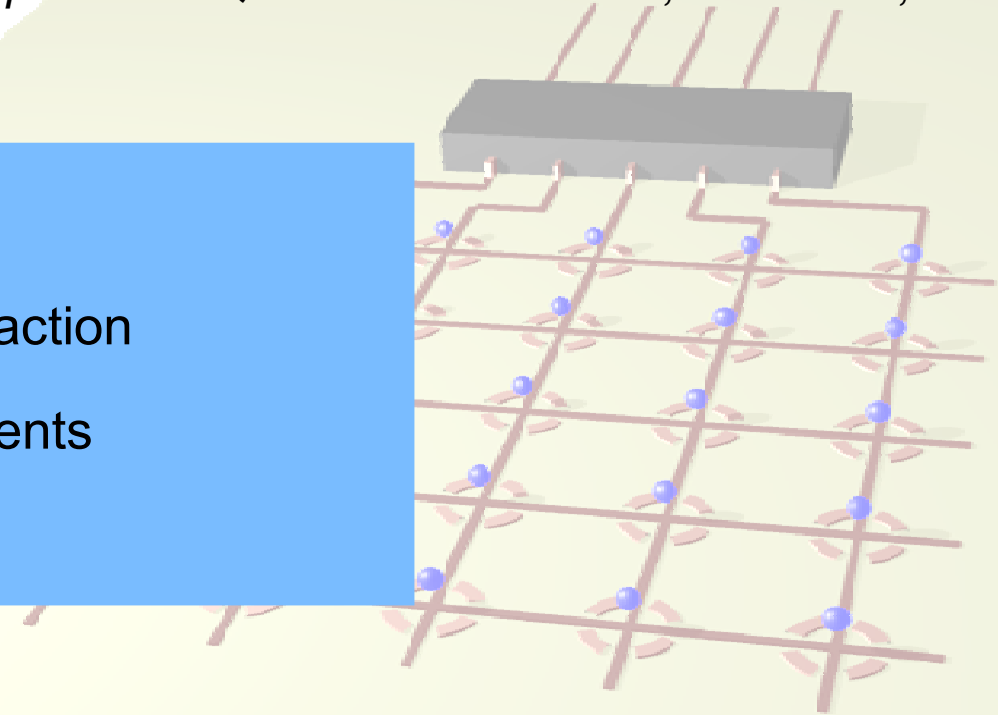
- Motivation
- Ion-wire interaction
- First experiments
- Summary

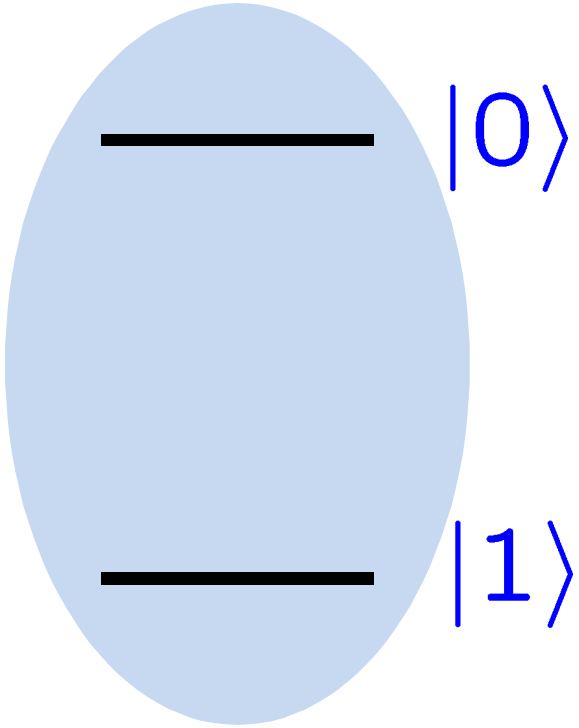


FWF bm:bwk

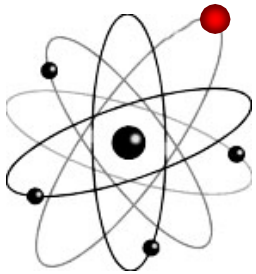
Berkeley, 23th Jan 2009

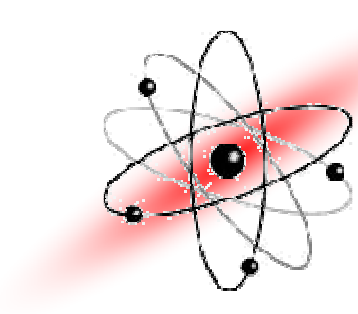
Quantum bits

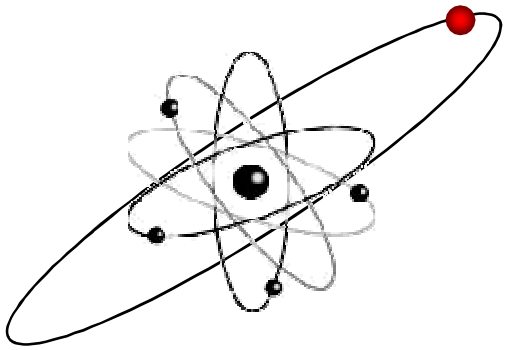
Two level system:



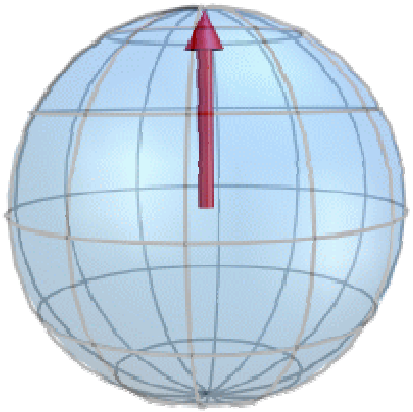
Quantum bits

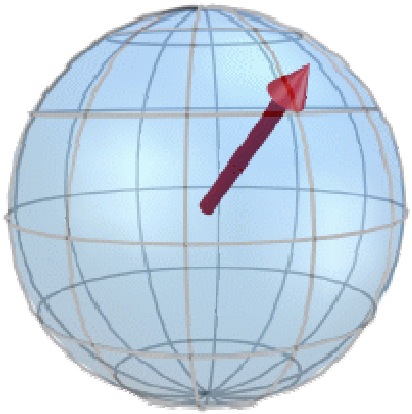


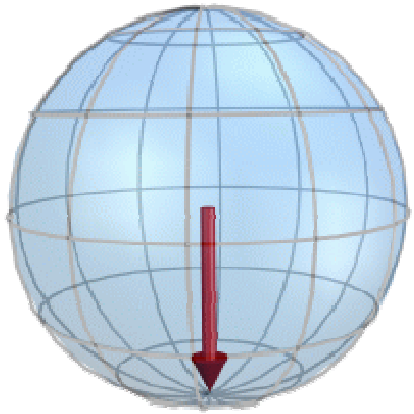




$|0\rangle$ $\alpha|0\rangle + \beta|1\rangle$ $|1\rangle$







Why quantum information ?

Schrödinger equation for 300 interacting spins.

Classical computation needs more bits than there are atoms in the universe.

➡ Quantum computers can solve certain tasks much more efficiently than classical computers.

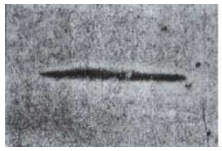
Allows a new view on nature: reduction to information

physics ⟷ computer science

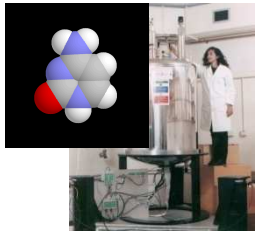
Experimental challenges

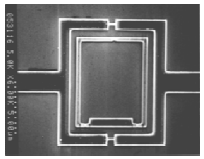
Some examples of quantum control:

- Stern-Gerlach experiment



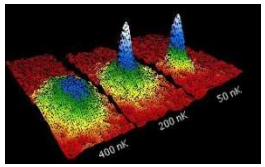
- NMR





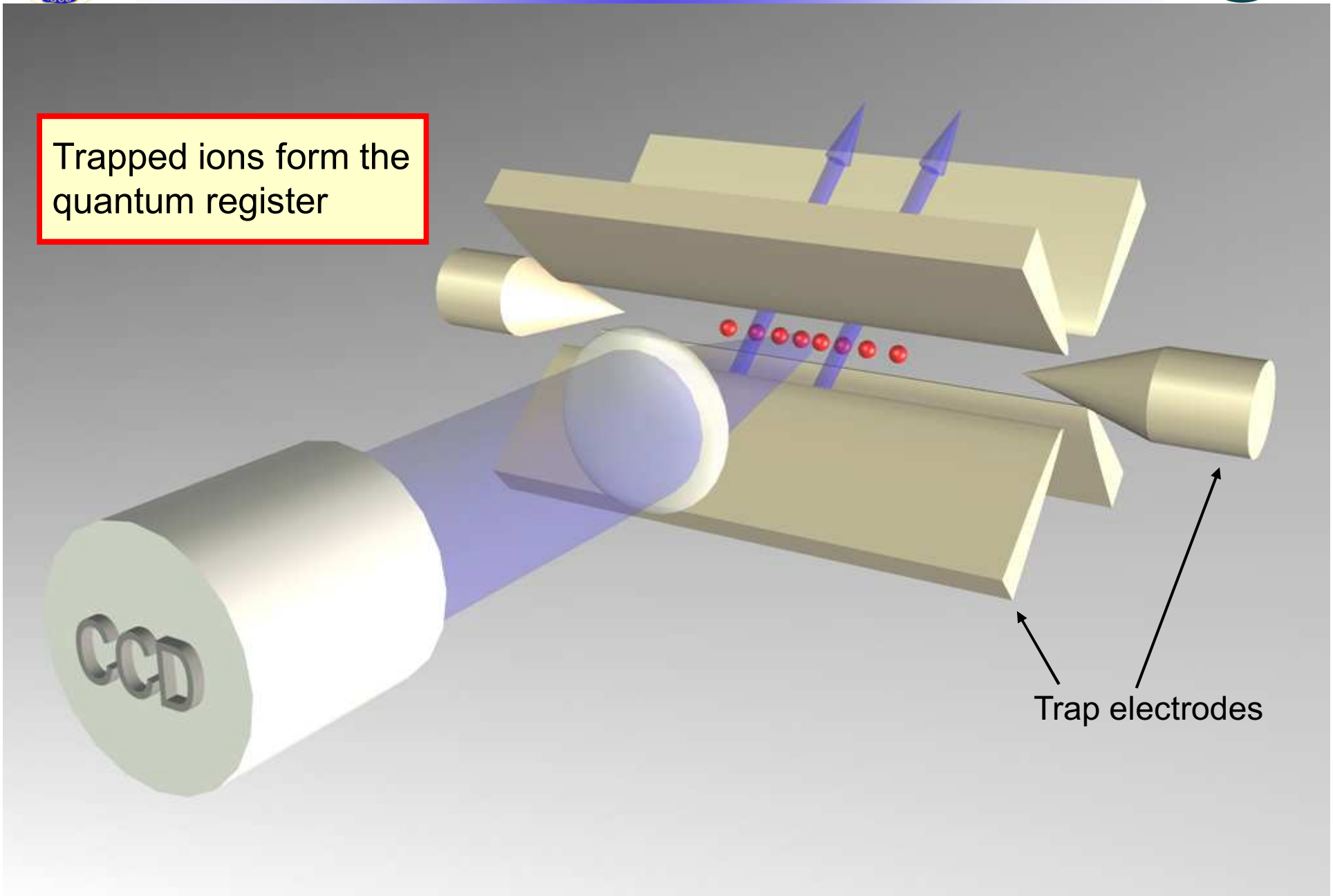
- SQUIDs

- Bose-Einstein condensates

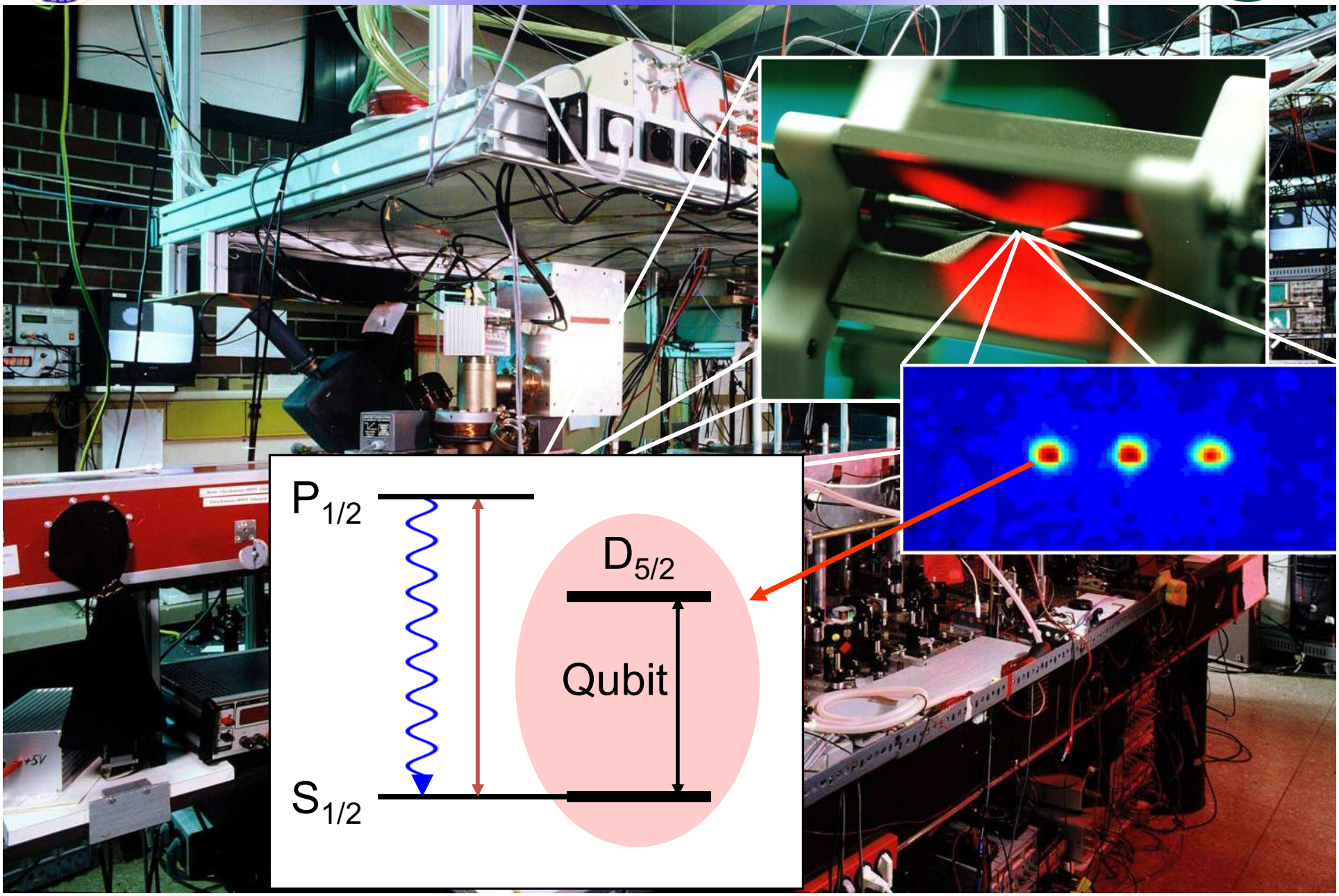


Full control of complex quantum systems is quite difficult.

Ion trap quantum computing

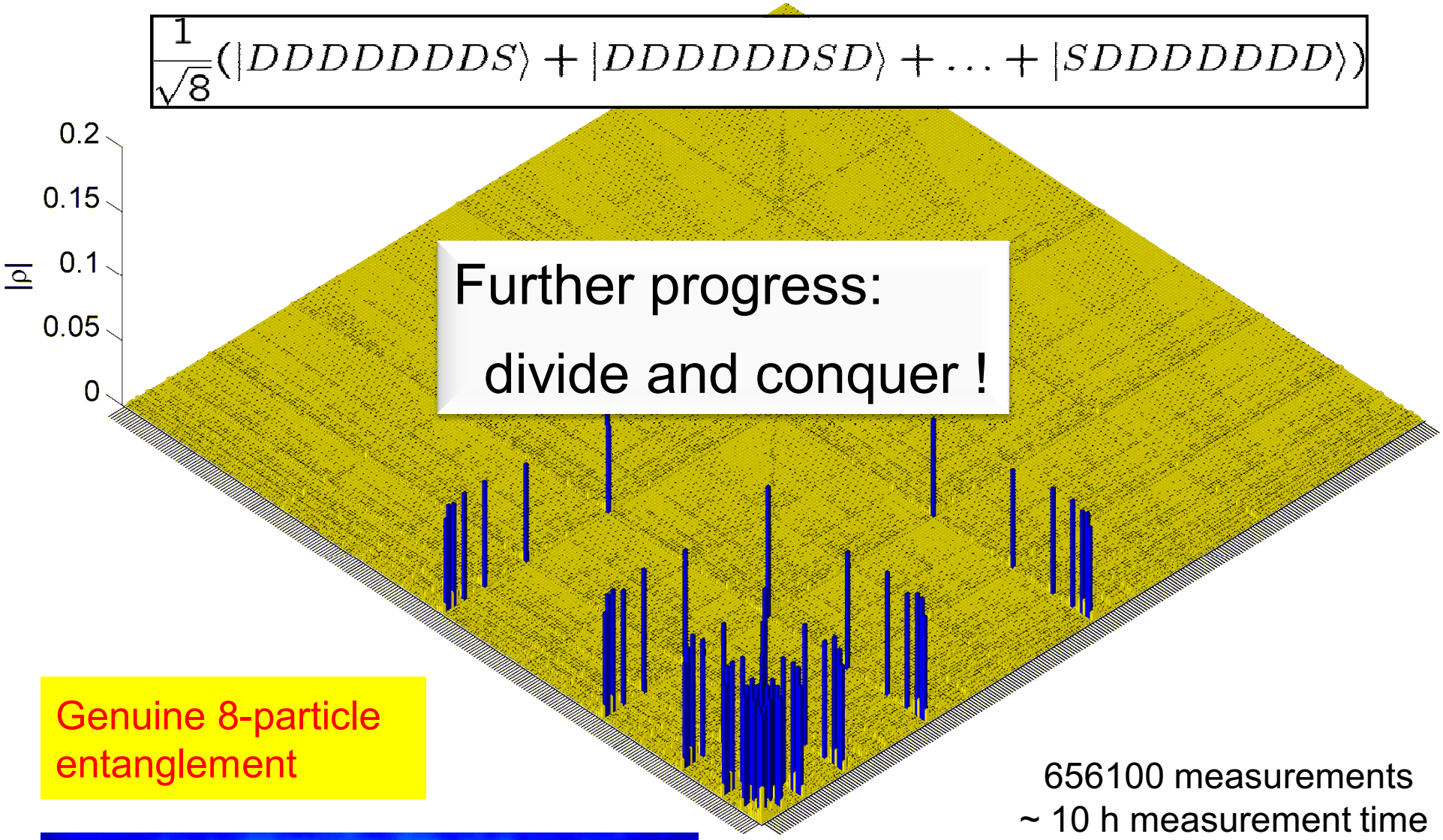


Ion trap quantum computing



Eight particle entanglement

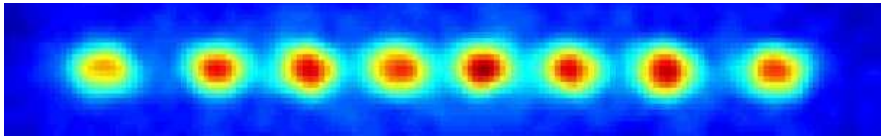
$$\frac{1}{\sqrt{8}}(|DDDDDDDS\rangle + |DDDDDDSD\rangle + \ldots + |SDDDDDDD\rangle)$$



Further progress:

divide and conquer !

Genuine 8-particle entanglement

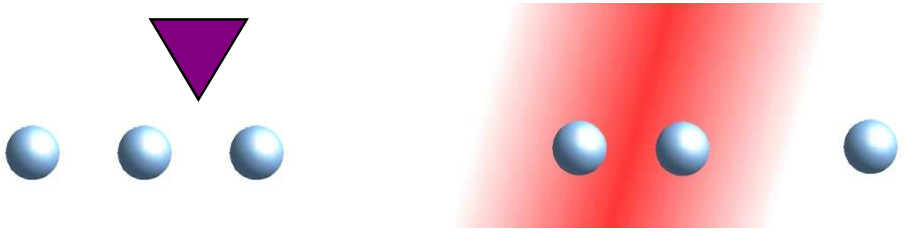


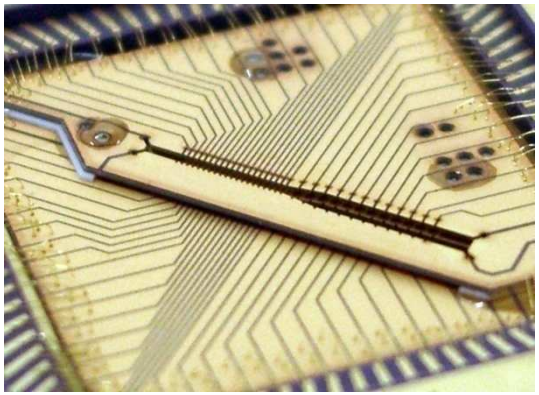
656100 measurements
~ 10 h measurement time

Häffner et al., Nature **438**, 643 (2005)

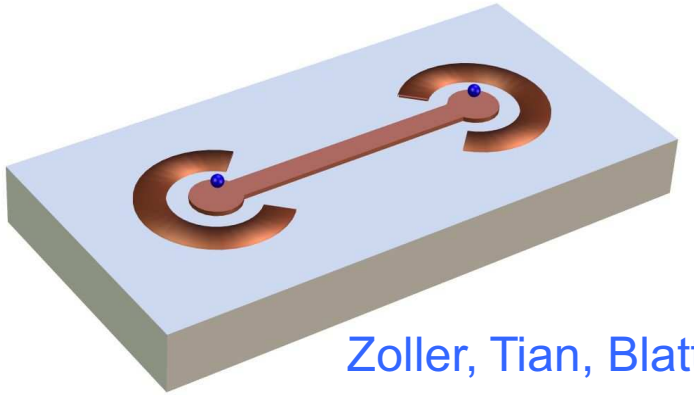
Scaling of ion trap quantum computers

Kielpinski, Monroe, Wineland



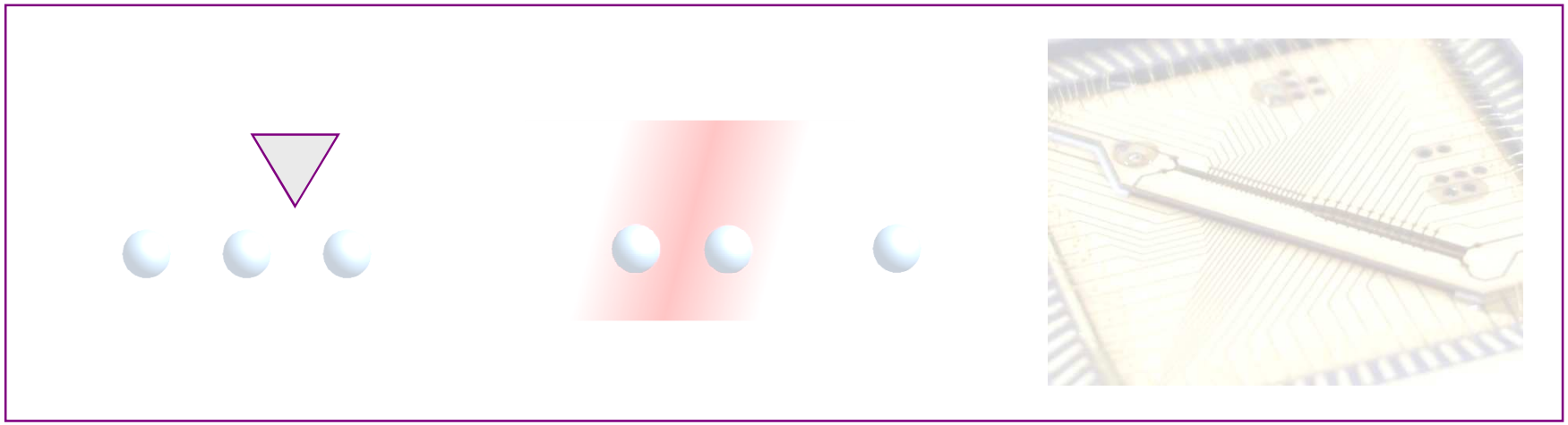


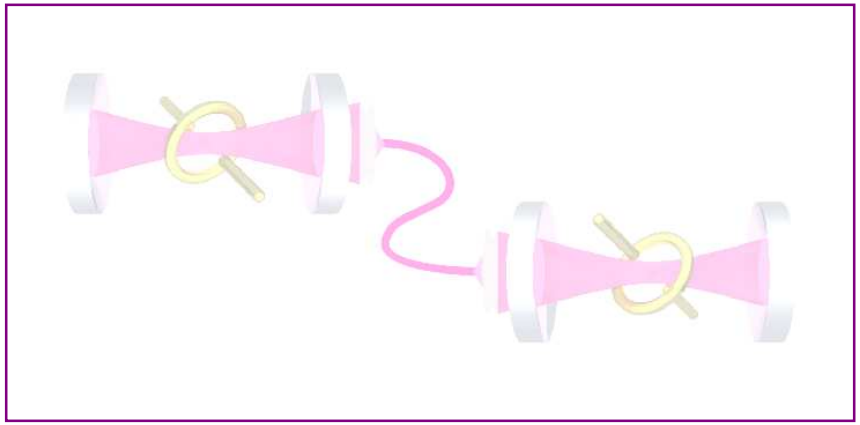
Cirac, Zoller, Kimble, Mabuchi

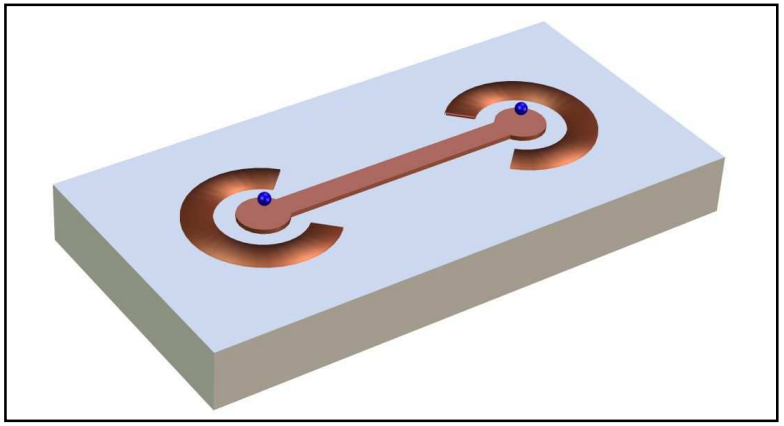


Zoller, Tian, Blatt

Scaling of ion trap quantum computers

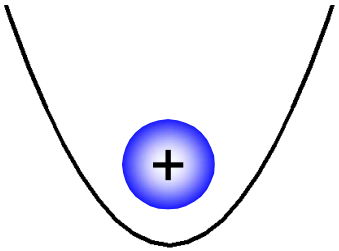


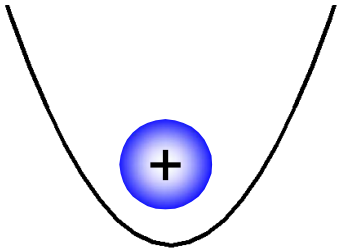




Wiring up trapped ions

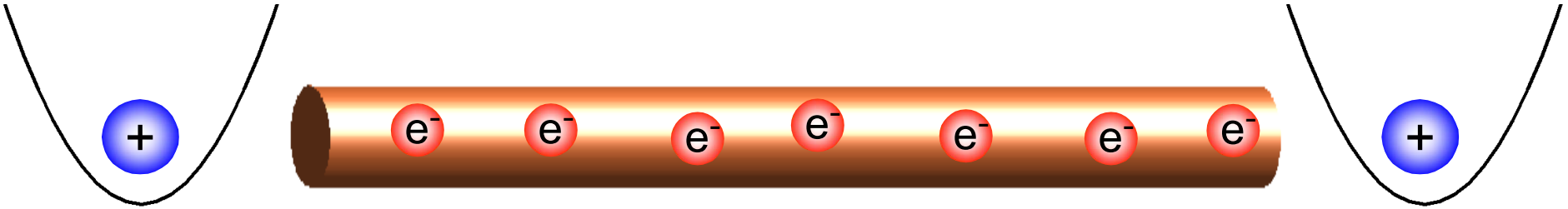
Two trapped ions …



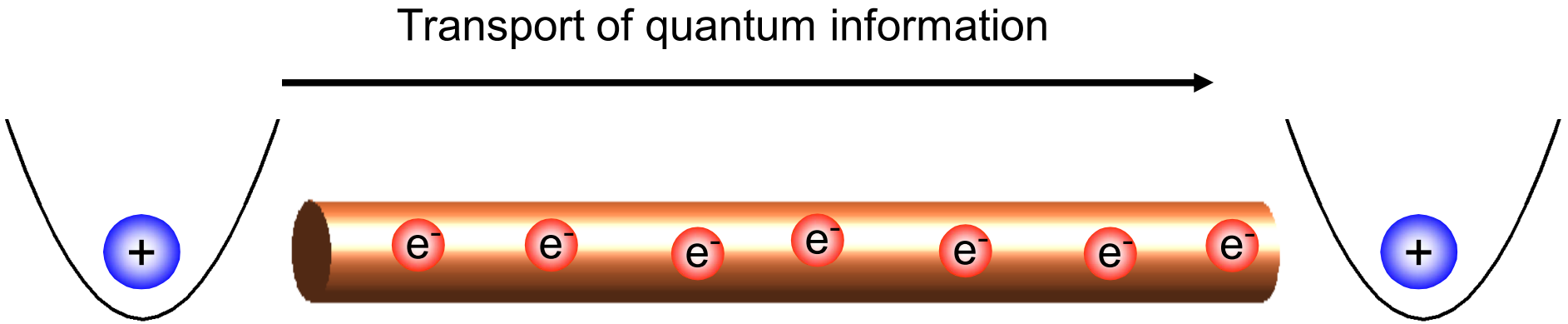


Wiring up trapped ions

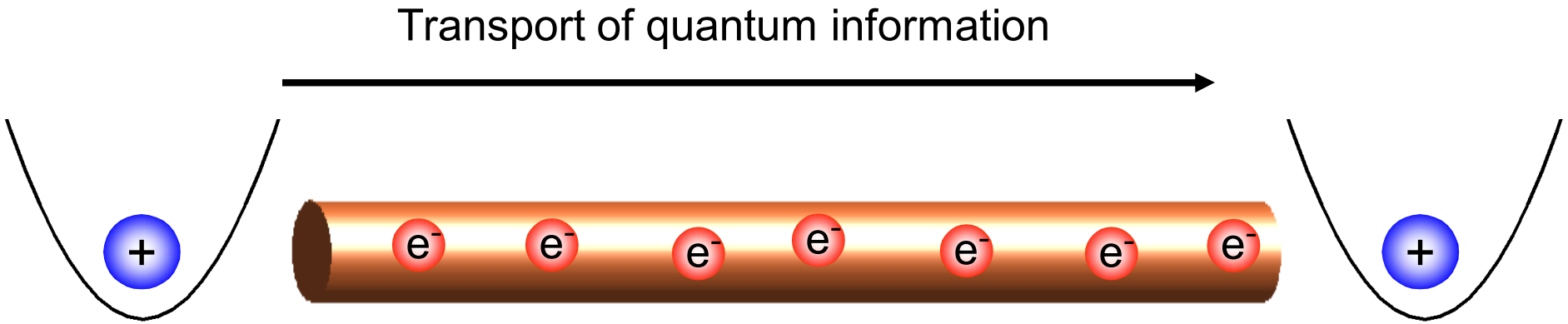
Two trapped ions + a wire



Wiring up trapped ions



Wiring up trapped ions



No trace of the quantum information should remain in the wire

➡ ~~super conducting~~ wire

Physics with this set-up

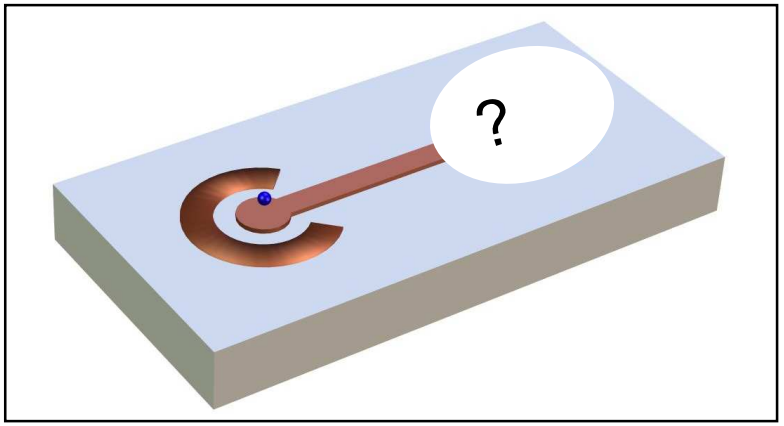
Physics:

- Decoherence in charge transport
- Wire mediated laser cooling to a few μK
- Cooling of LC resonators

Heinzen and Wineland, PRA PRA **47**, 2977 (1990).

Technology:

- Scalable quantum computing with trapped ions/electrons
- Hybrid quantum computing
- Quantum detectors



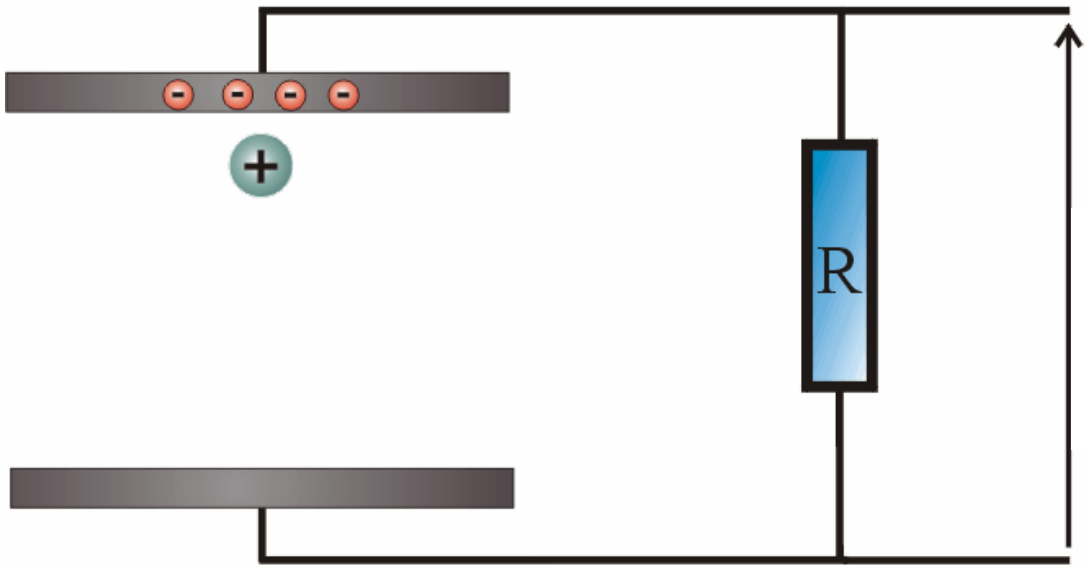
Quantum control

Ion-wire interaction

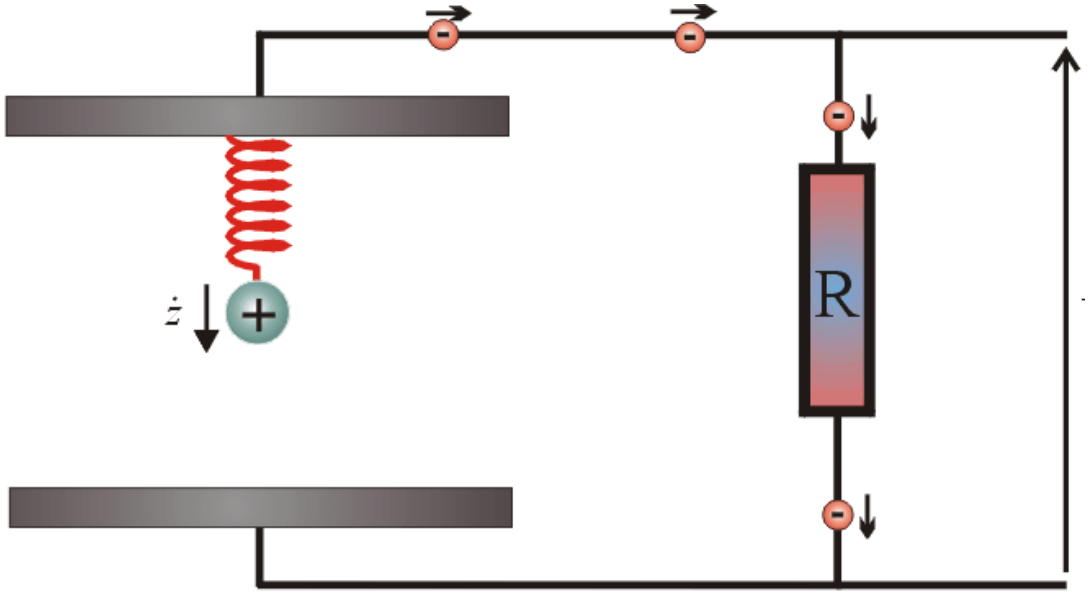
Experiments

Summary

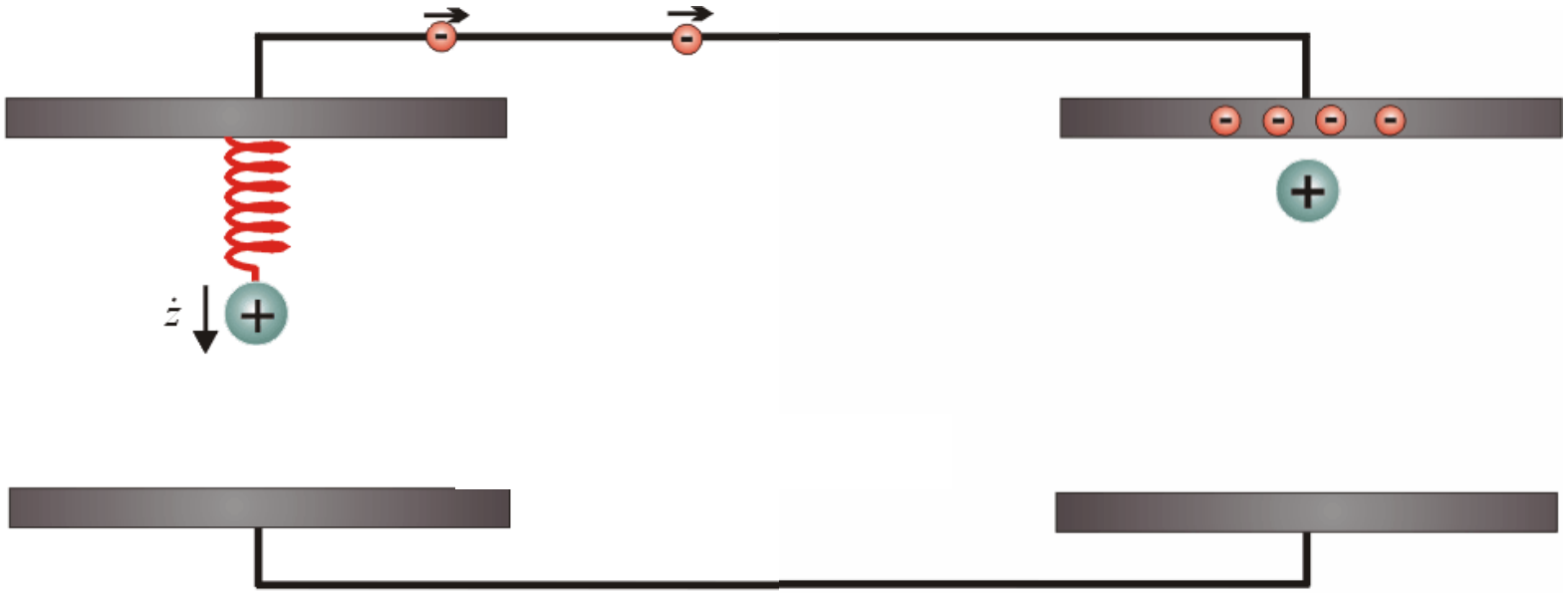
Ion-resistor interaction



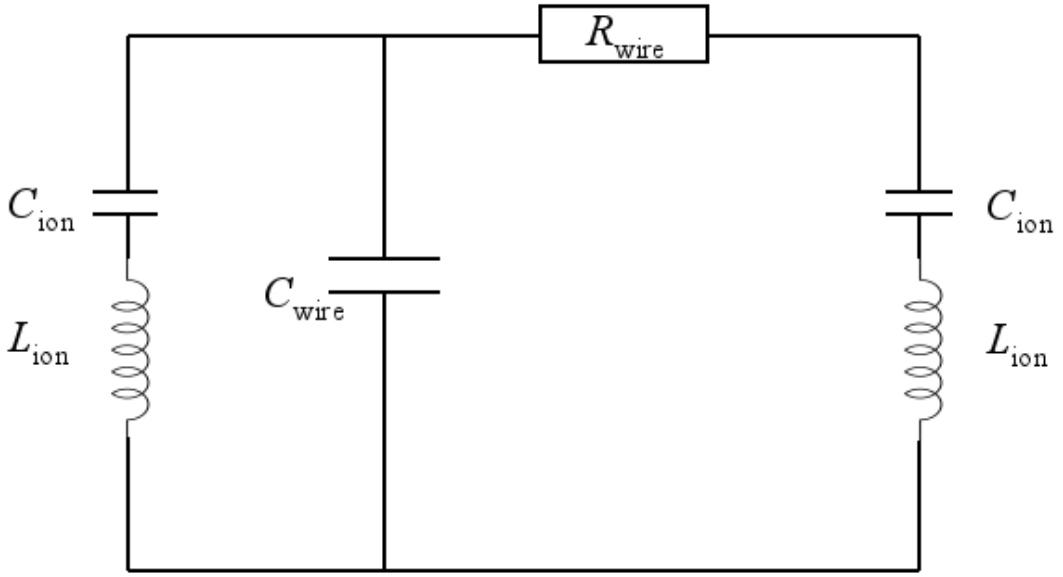
Ion-resistor interaction



Ion-resistor interaction



Coupling



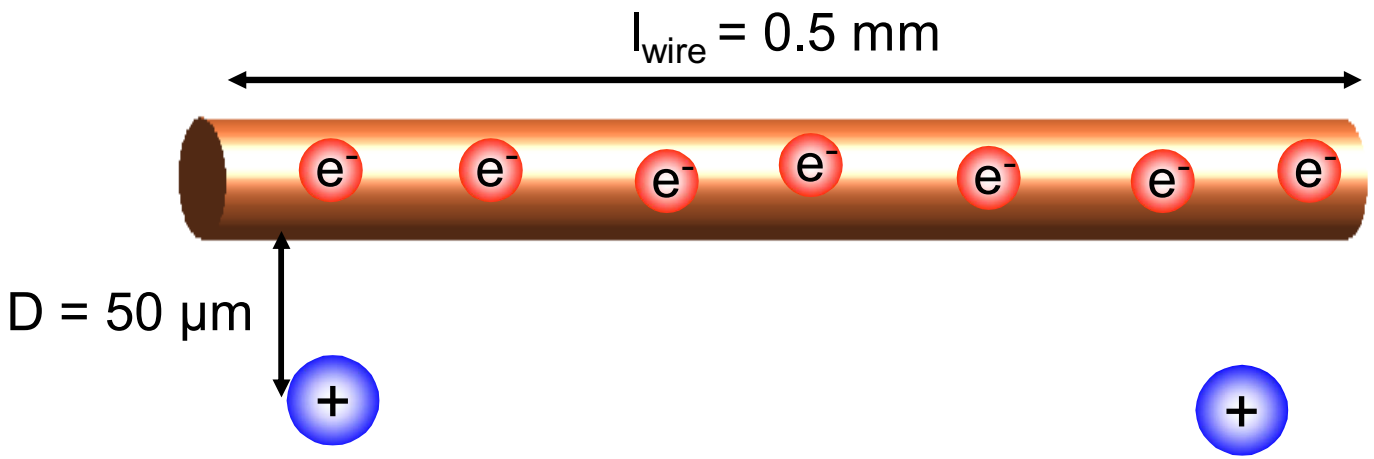
with $I = \frac{q}{D}\dot{x}, \quad L_{\text{ion}} = \frac{mD^2}{q^2}, \quad C_{\text{ion}} = \frac{1}{\omega^2 L_{\text{ion}}}$

Energy exchange rate: $\frac{1}{T} = \frac{1}{2\pi}\frac{q^2}{mD^2}\frac{1}{\omega}\frac{1}{C_{\text{wire}}}$

D.J. Wineland and H.G. Dehmelt, J. Appl. Phys **46**, 919 (1975).

D.J. Heinzen and D.J. Wineland, PRA **47**, 2977 (1990).

Coupling



Projected numbers:

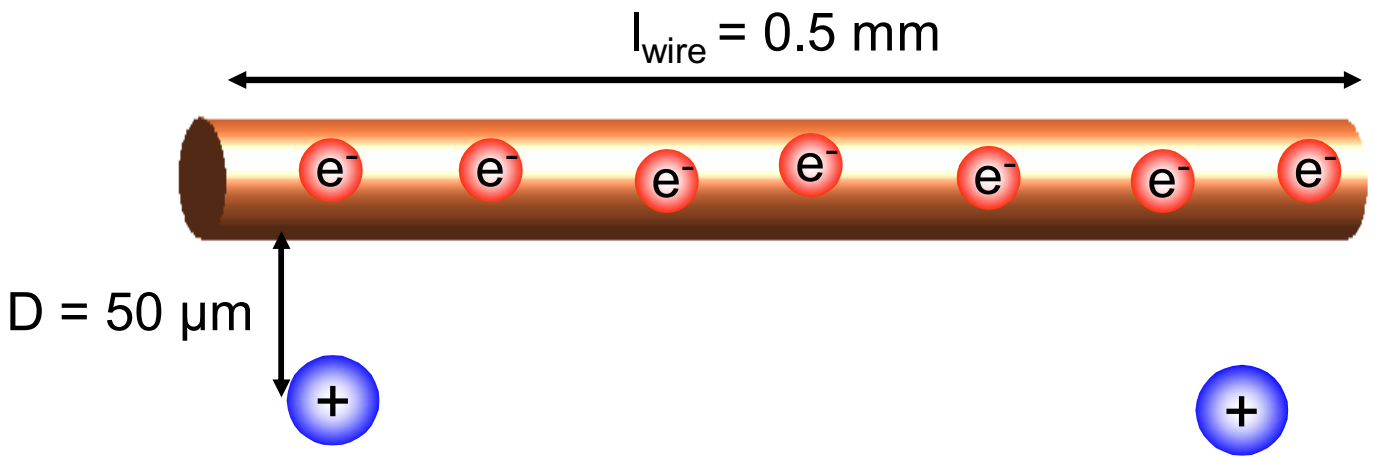
D_{eff} = 3.6 X 50 μm

$\omega = 2\pi$ X 500 kHz

C_{wire} = 6 fF (l_{wire} = 0.5mm)

$\gamma = 2\pi$ X 100 Hz

Coupling



Current numbers:

D_{eff} = 3.6 X 300 μm

ω =2π X 500 kHz

C_{wire} = 120 fF (l_{wire} = 1cm)

γ would be 2π X 0.14 Hz

Projected numbers:

D_{eff} = 3.6 X 50 μm

ω =2π X 500 kHz

C_{wire} = 6 fF (l_{wire} = 0.5mm)

γ = 2π X 100 Hz

Decoherence

Dissipation in the wire

Trap parameters: $\omega = 2\pi \cdot 500\ kHz$, $D = 3.6 \cdot 50\ \mu m$, $R = 0.1\ \Omega$

Induced current: $$I = \frac{q}{D}\dot{x} = \frac{q}{D}\sqrt{\frac{\hbar\omega}{m}} \approx 10^{-16}\ A$$

Dissipation rate for motional quantum: $$\gamma = \frac{I^2 R}{\hbar\omega} \approx 10^{-6}\ \frac{1}{s}$$

But what about Johnson noise?

Decoherence

Dissipation in the wire

Trap parameters: $\omega = 2\pi \cdot 500\ kHz$, $D = 3.6 \cdot 50\ \mu m$, $R = 0.1\ \Omega$

Induced current: $$I = \frac{q}{D}\dot{x} = \frac{q}{D}\sqrt{\frac{\hbar\omega}{m}} \approx 10^{-16}\ A$$

Dissipation rate for motional quantum: $$\gamma = \frac{I^2 R}{\hbar\omega} \approx 10^{-6}\,\frac{1}{s}$$

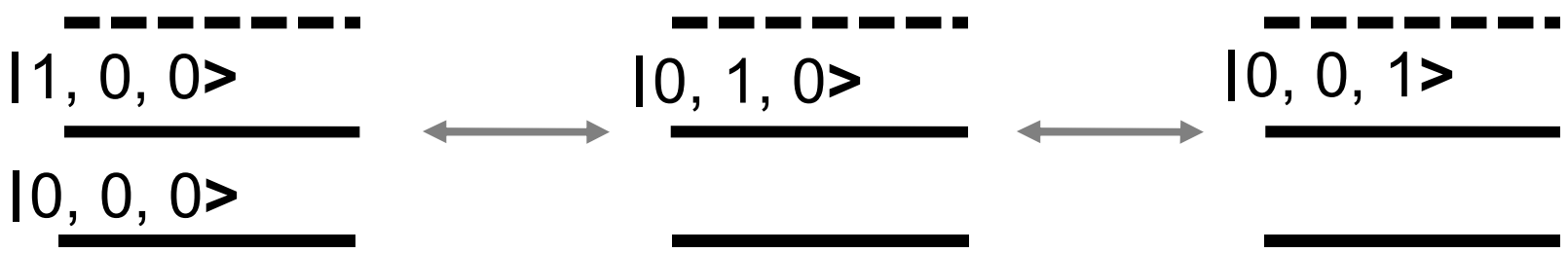
Johnson noise heating

Heating rate : $$\gamma_J = \frac{P_J}{\hbar\omega} = \frac{k_B T\gamma}{\hbar\omega} \approx 14\frac{1}{s}$$

Expected coupling over 0.5 mm: 2π X 100 1/s

Decoherence

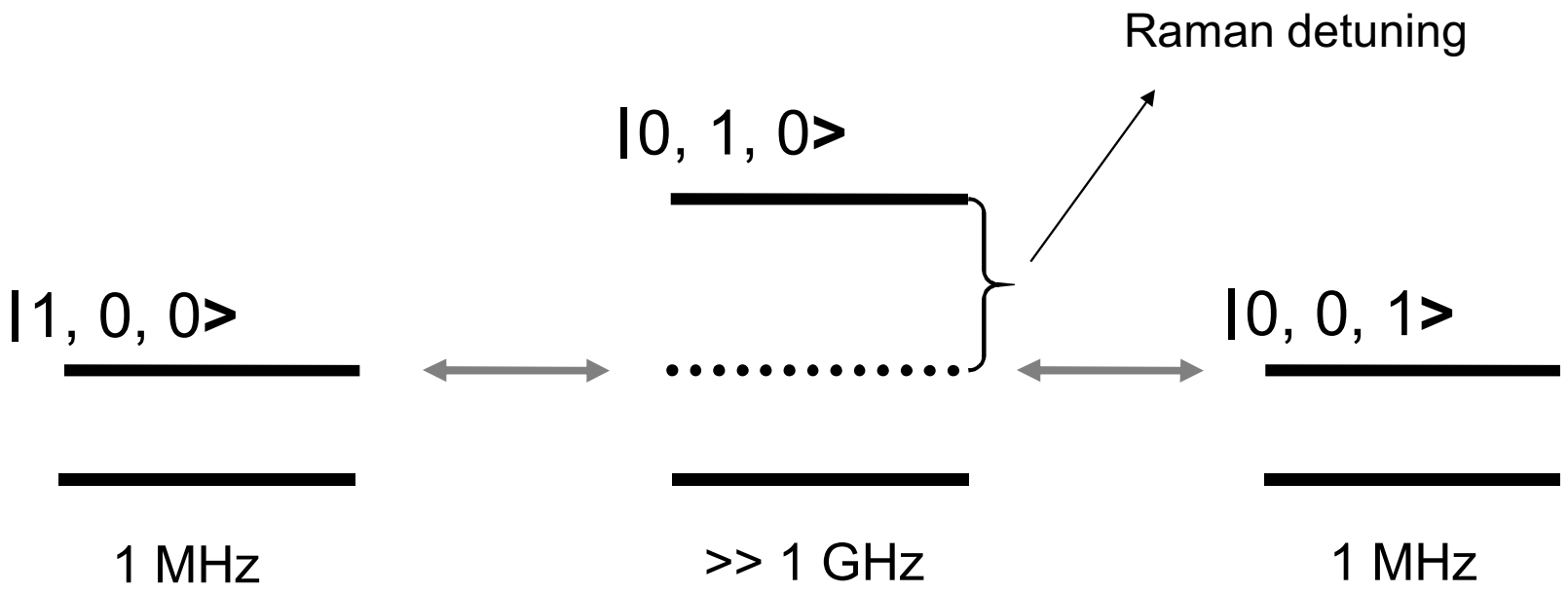
Three coupled harmonic oscillators:



$|\text{ion}_1, \text{wire}, \text{ion}_1\rangle$

Decoherence

Three coupled harmonic oscillators:



$|\text{ion}_1, \text{wire}, \text{ion}_1\rangle$

Decoherence

Anything else ?

See: J.R. Zurita-Sánchez and C. Henkel, submitted to New J. Phys. (2008).

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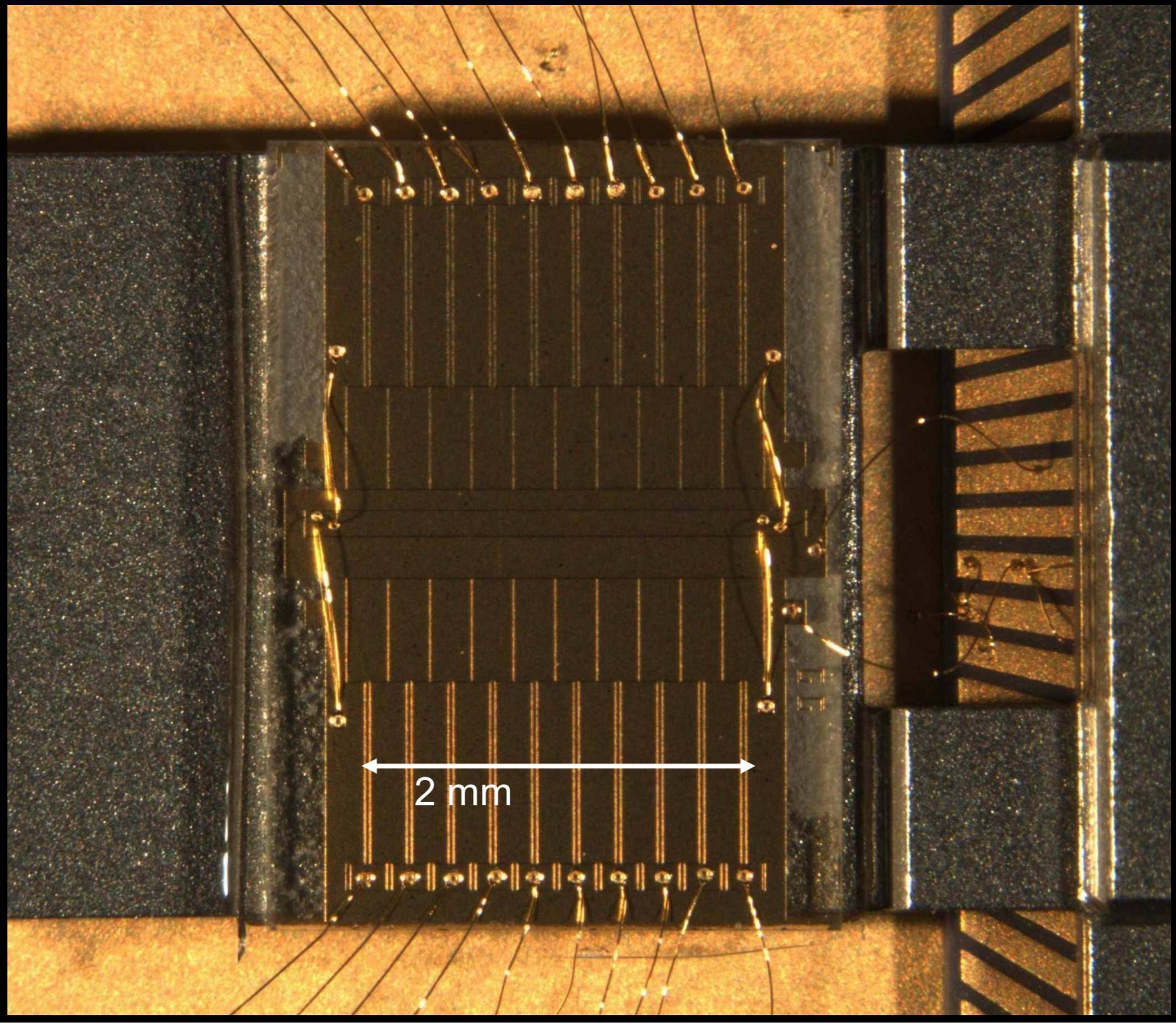
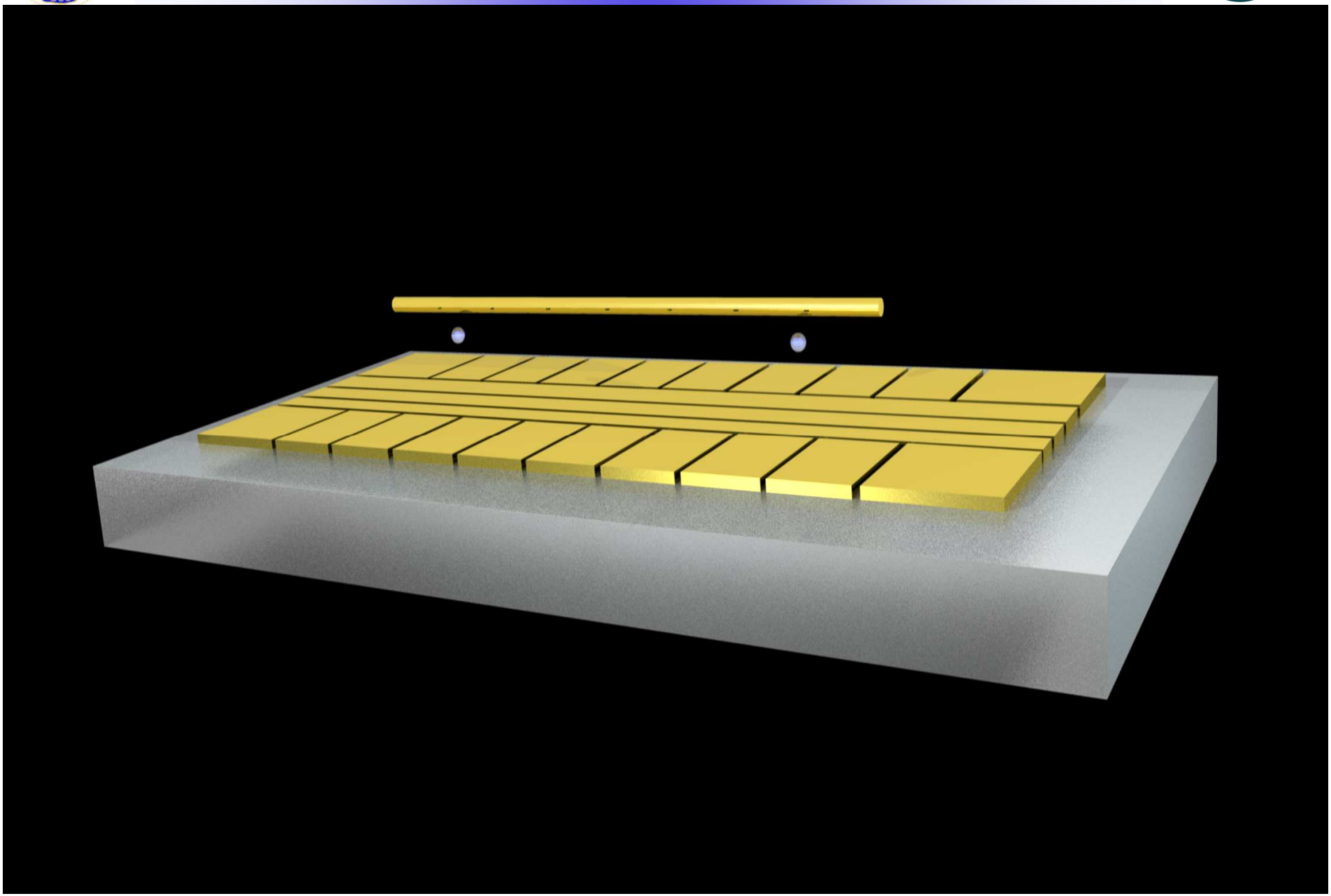
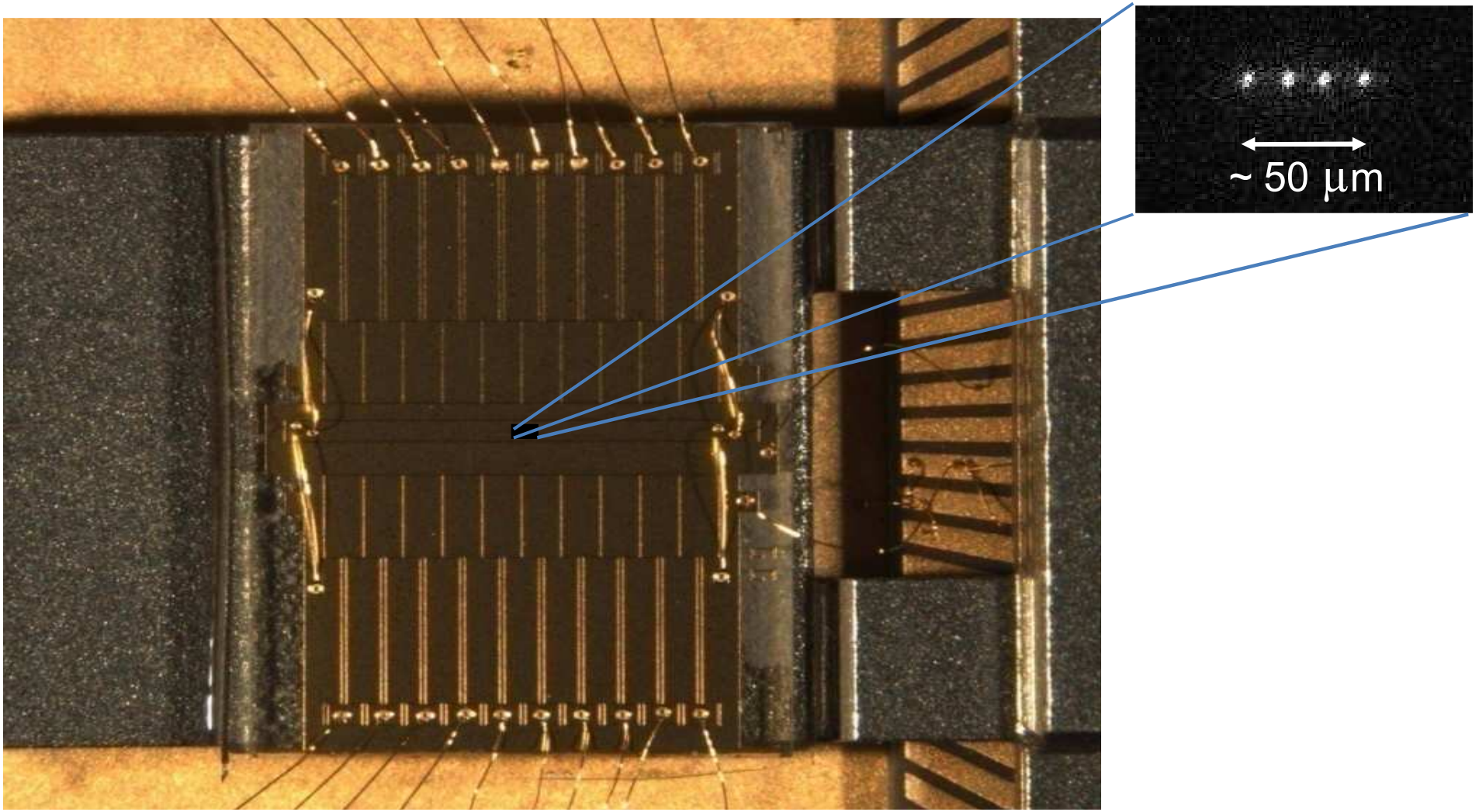
A segmented trap



Experimental set-up

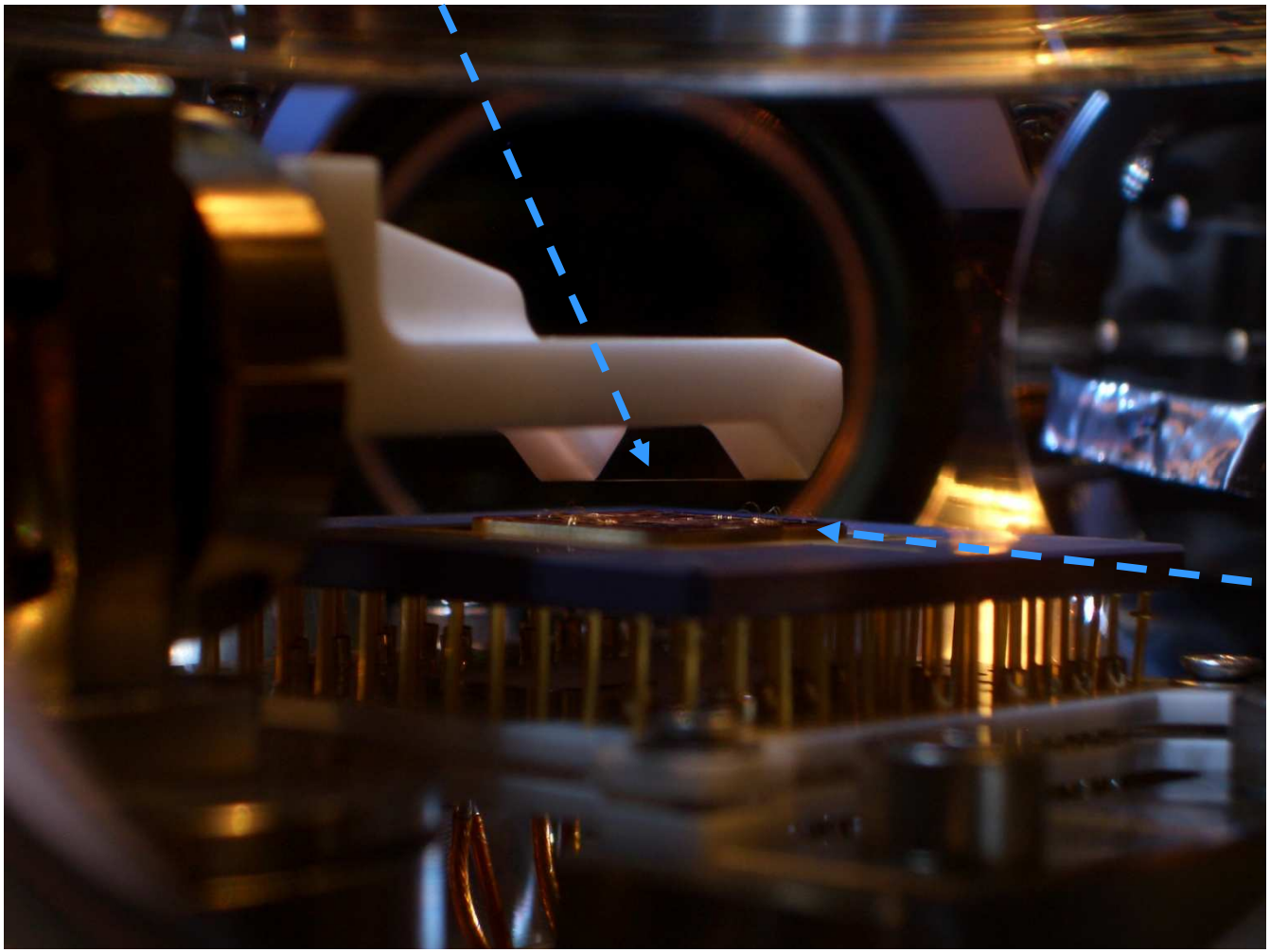


Experimental set-up

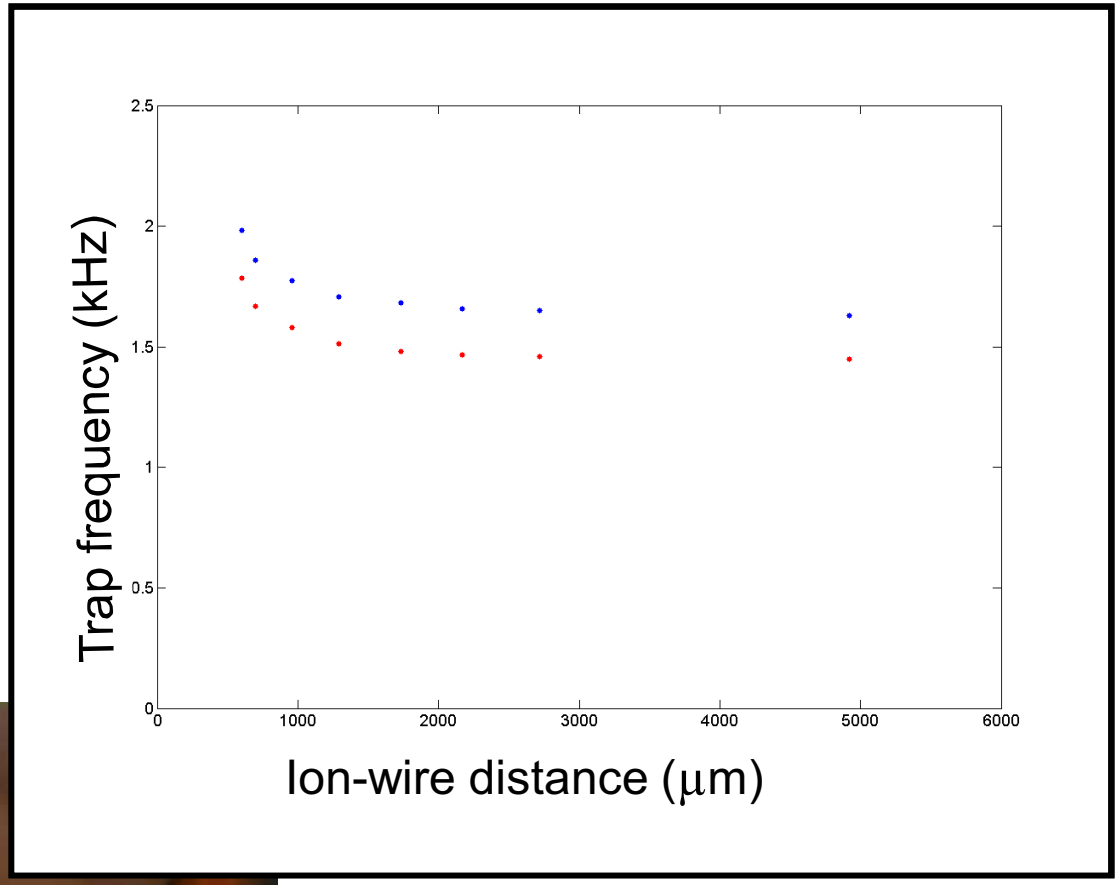


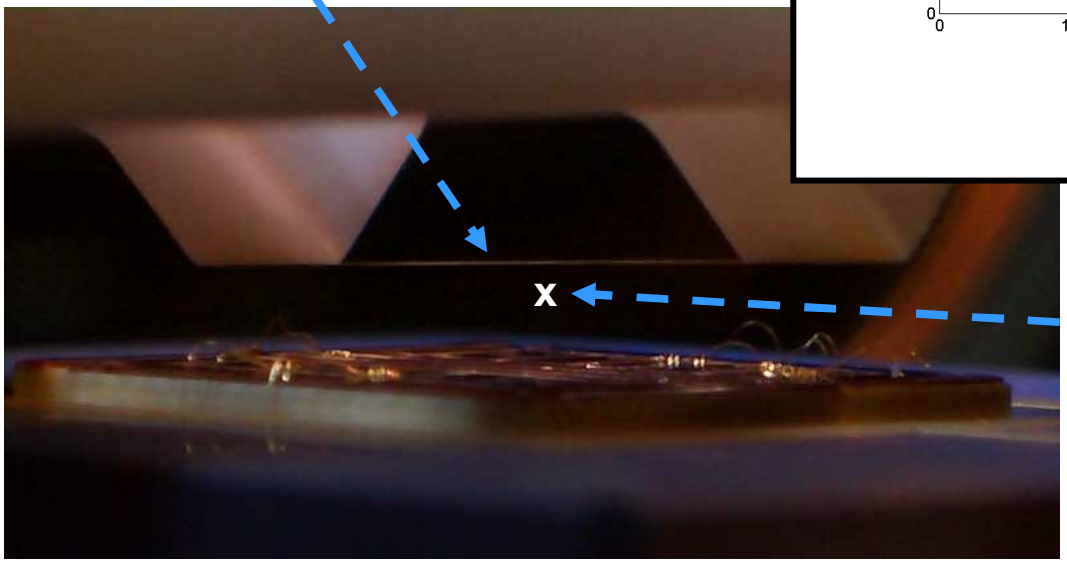
Experimental set-up

Separation of trapping and coupling

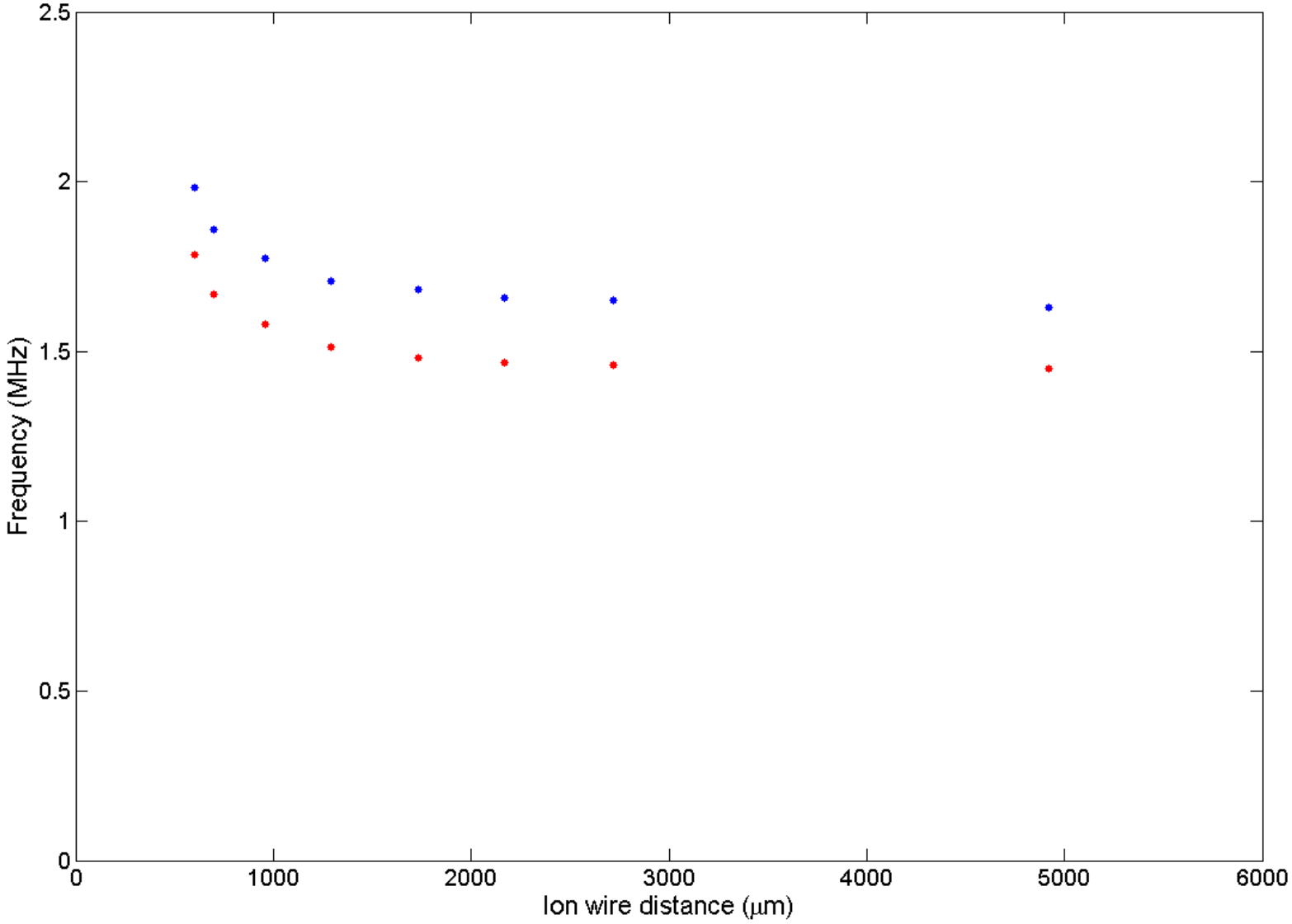


Ion-wire interaction





Ion-wire interaction



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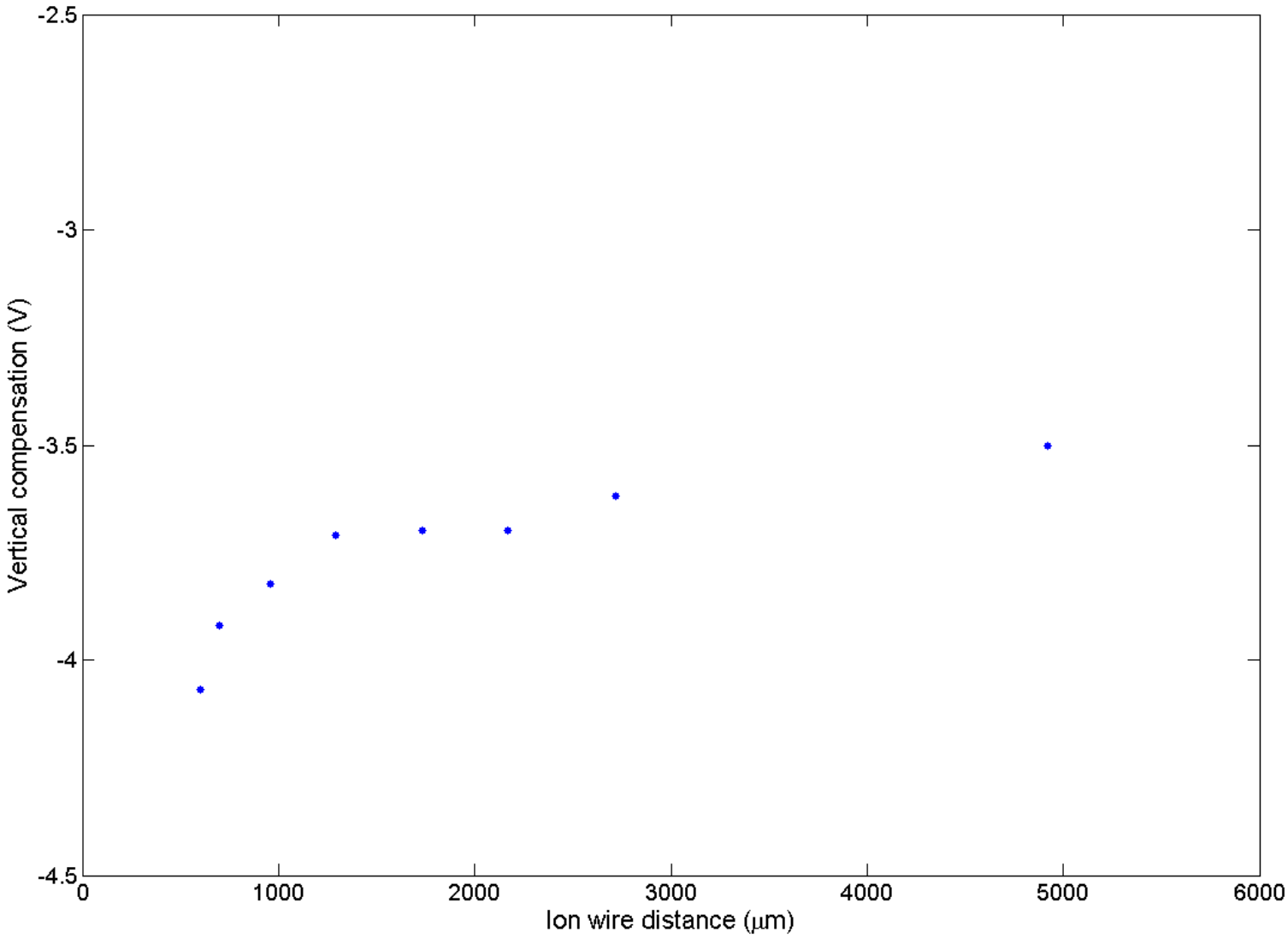
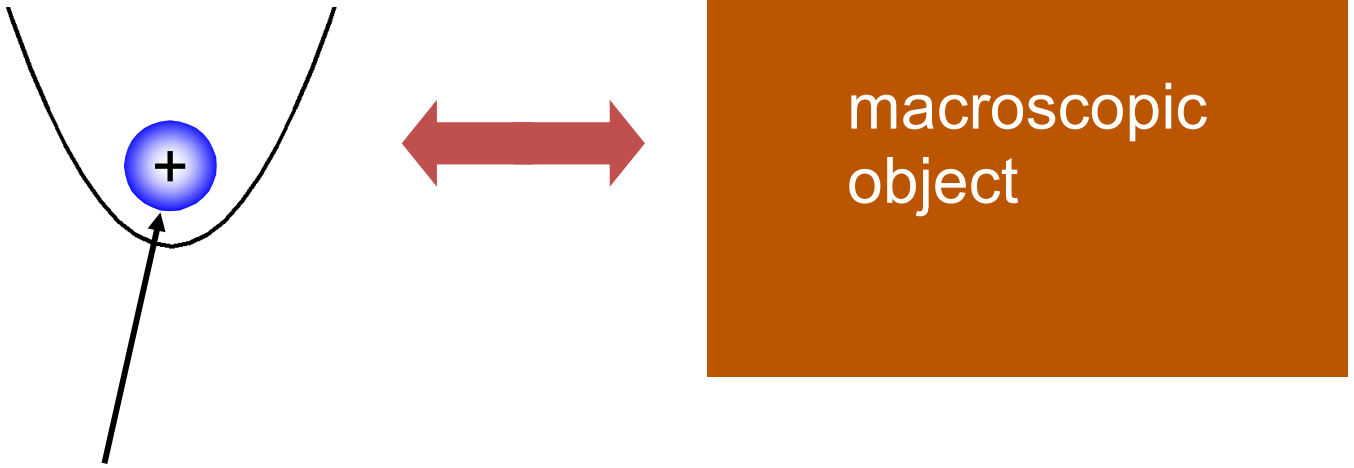


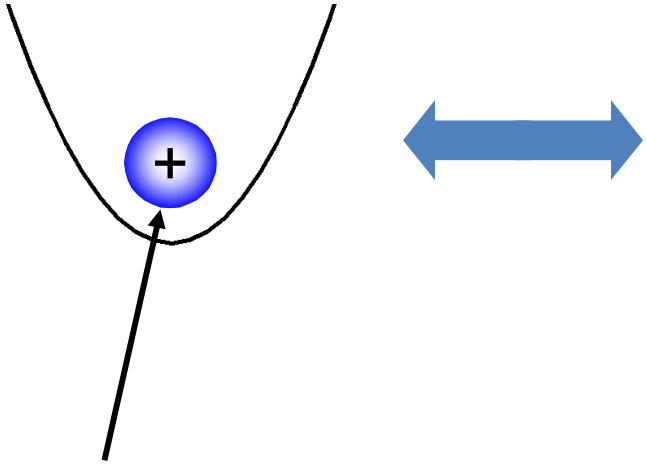
Quantum sensors

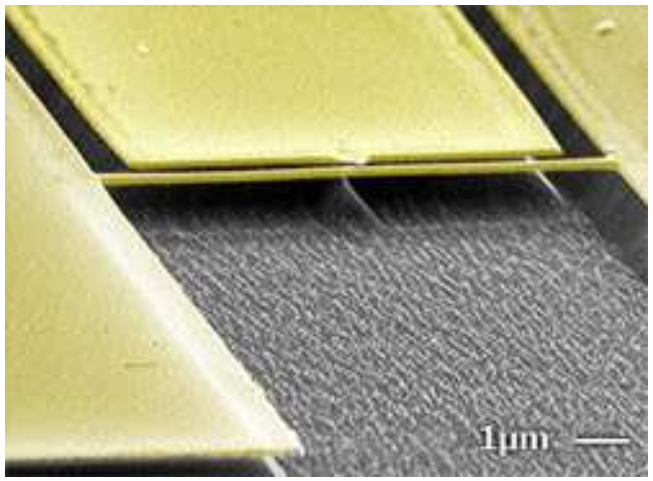


Quantum sensor

Ultimate control and detection

Quantum sensors





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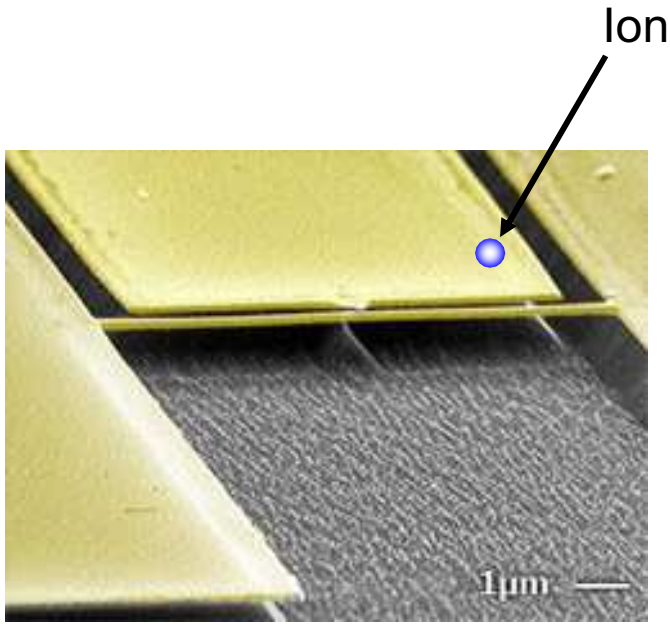
Quantum sensor

Ultimate control and detection

Quantum sensors



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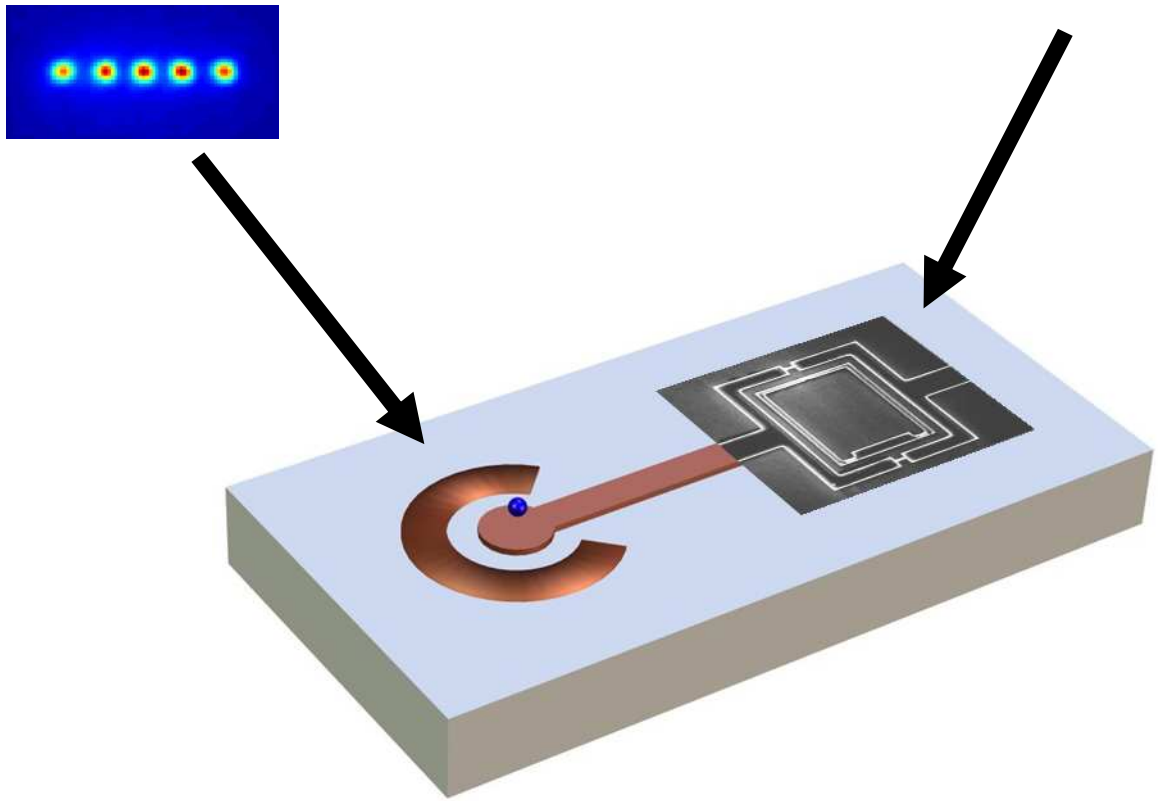
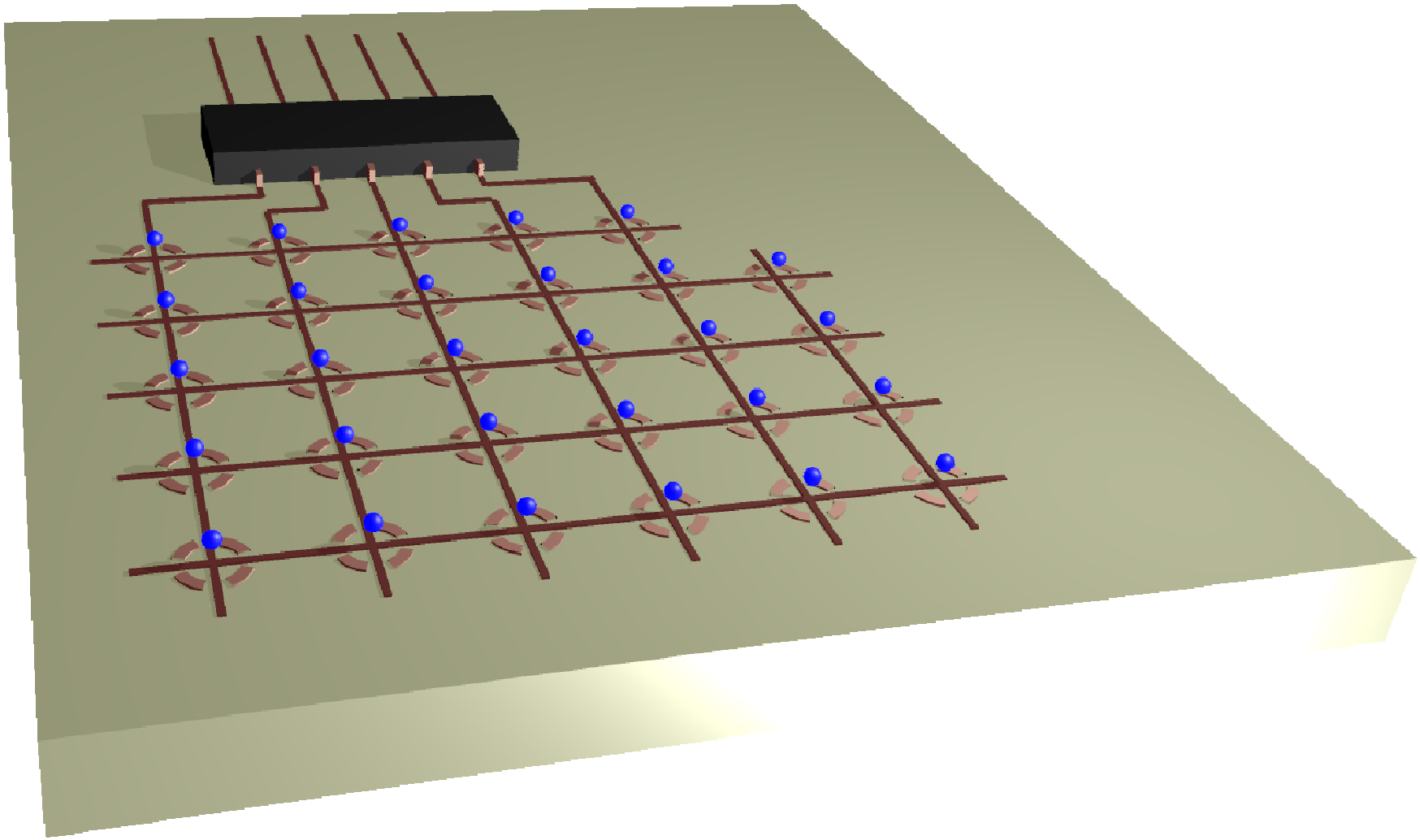
Hybrid quantum devices

Trapped ions

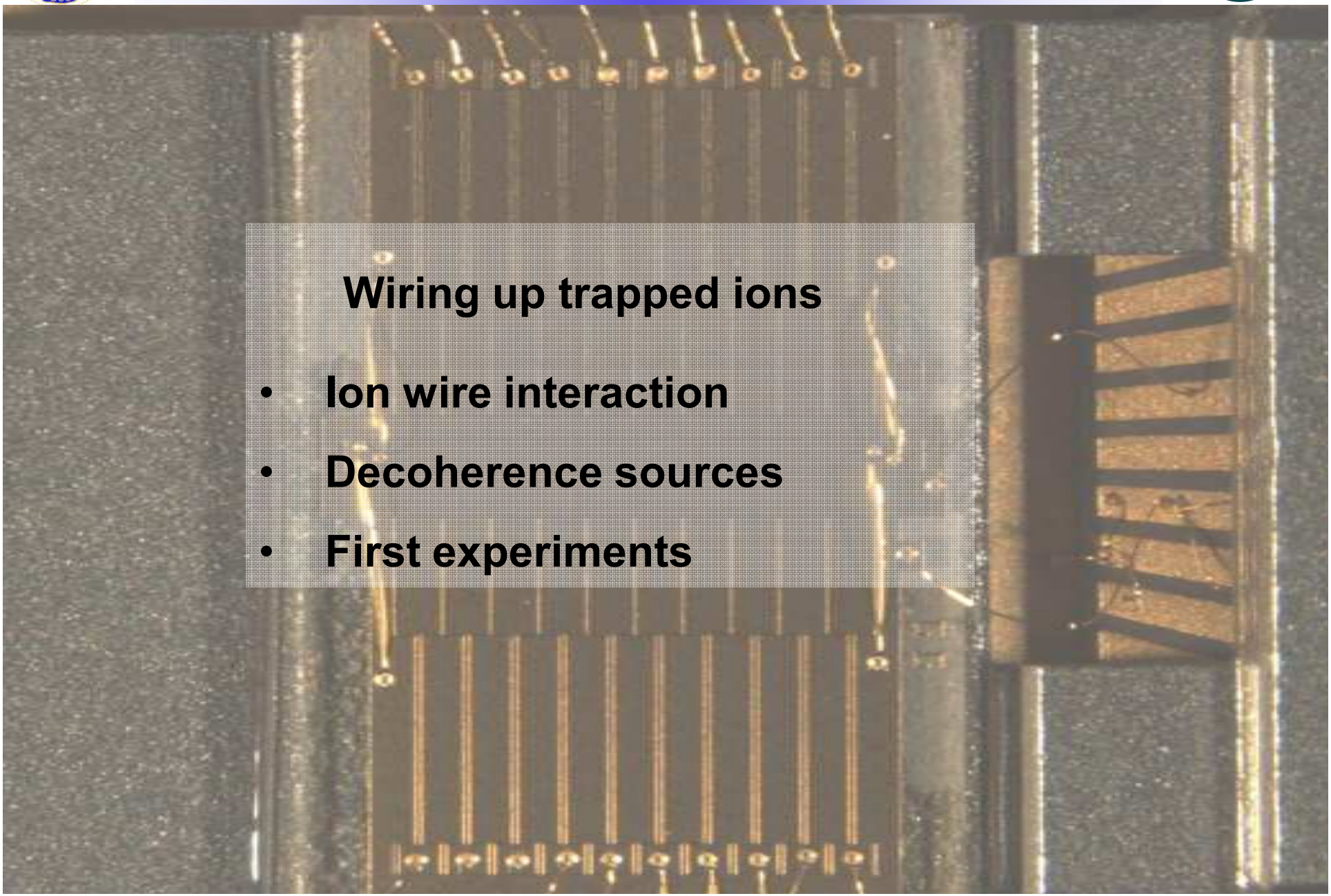
Josephson qubits



A vision



Summary



Wiring up trapped ions

- **Ion wire interaction**
- **Decoherence sources**
- **First experiments**