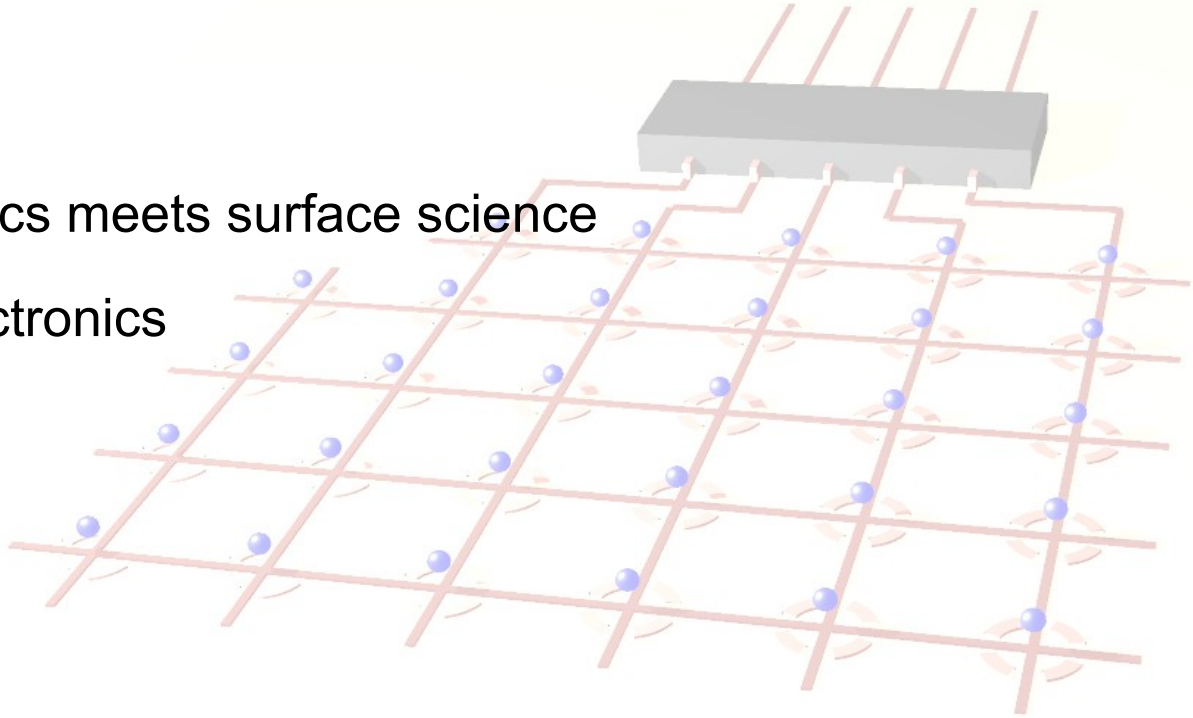
Towards electronics with single charge carriers

Hartmut Häffner

Department of Physics, University of California, Berkeley, USA

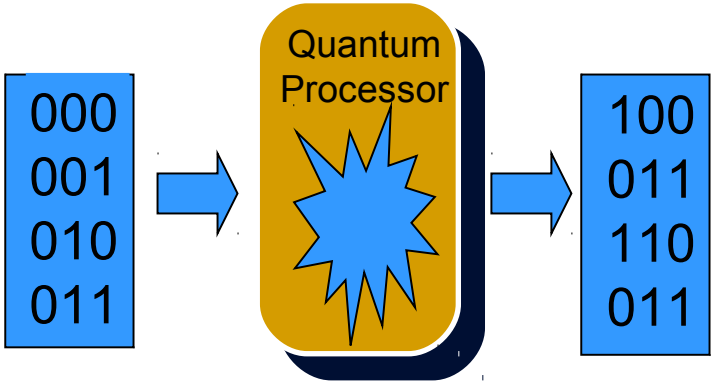
- Introduction
- Quantum optics meets surface science
- Quantum electronics
- Conclusions



IARPA DARPA U.S. AIR FORCE

Quantum information

Long term goal: A universal quantum computer



Fault tolerancy

→ control a huge amounts of qubits on the 10^{-4} level

Key challenges in quantum information

Carriers of quantum information need to be

- isolated perfectly from the environment

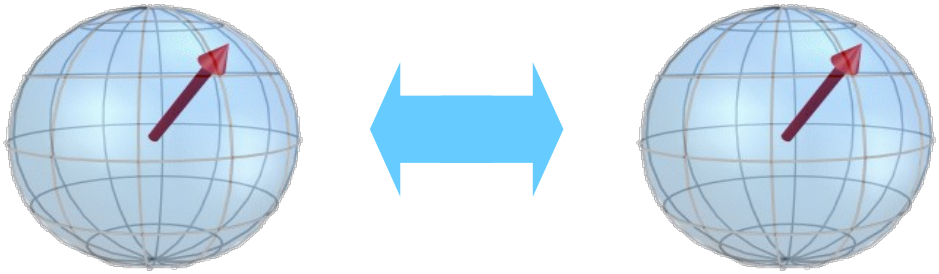
$$\alpha|0\rangle + \beta|1\rangle$$

Key challenges in quantum information

Carriers of quantum information need to be

- isolated perfectly from the environment
- interacting strongly among each other

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



Key challenges in quantum information

Carriers of quantum information need to be

- isolated perfectly from the environment
- interacting strongly among each other
- controlled by external parameters

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

Read out

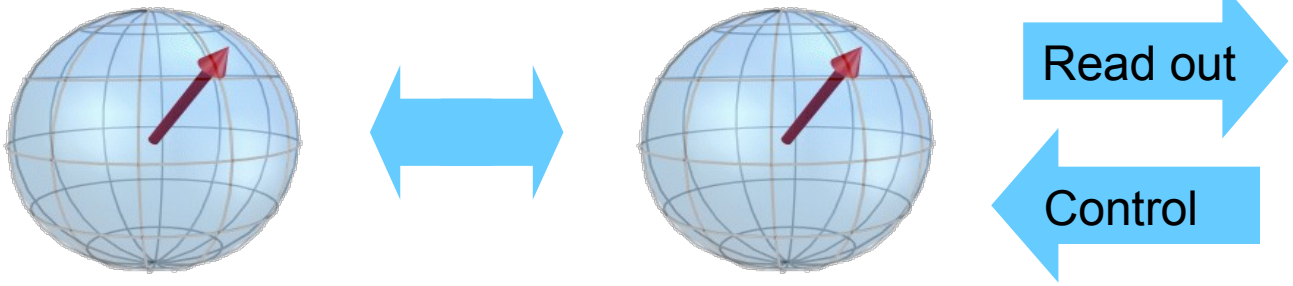
Control

Key challenges in quantum information

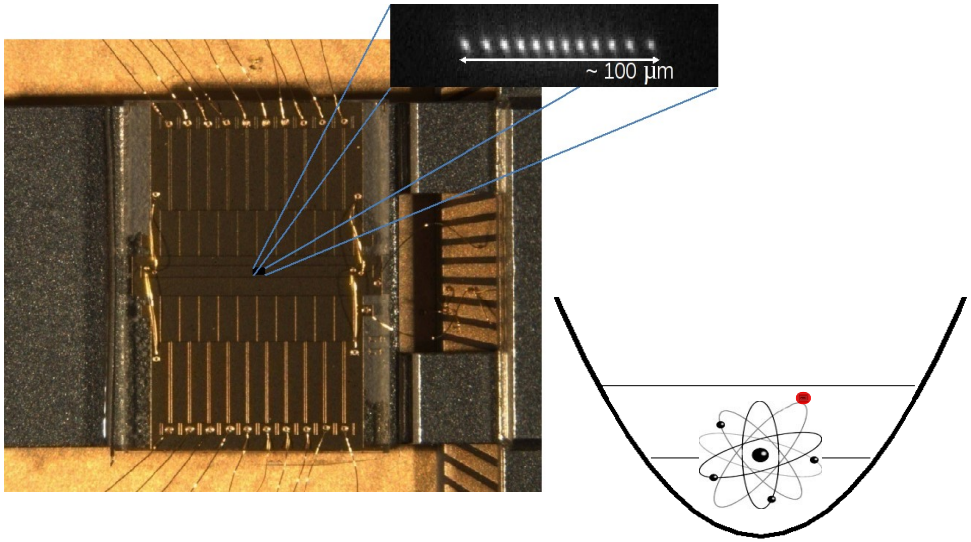
Carriers of quantum information need to be

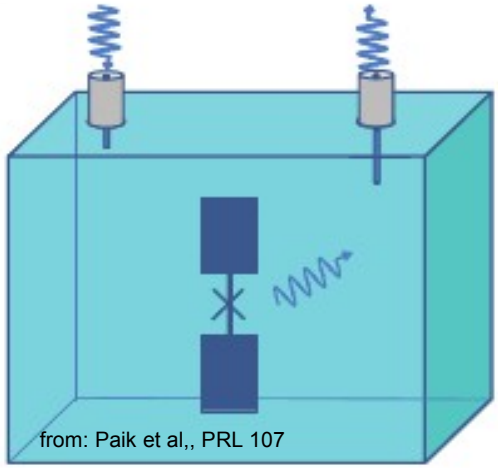
- isolated perfectly from the environment
- interacting strongly among each other
- controlled by external parameters
- scalable

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



Two QIP approaches





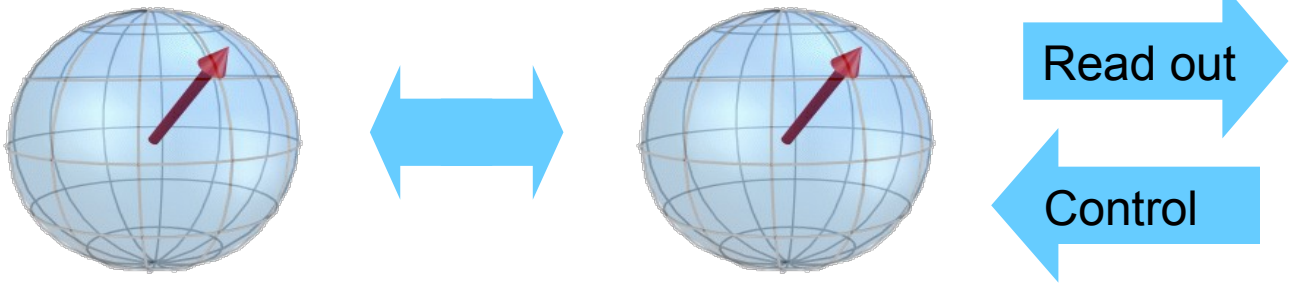
	Trapped ions	Josephson junction / cavity
Coherence time	10^{2} s	10^{-4} s
Gate speed	10^{-4} s	10^{-7} s

Key challenges in quantum information

Carriers of quantum information need to be

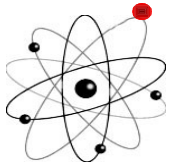
- isolated perfectly from the environment
- interacting strongly among each other
- controlled by external parameters
- scalable

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

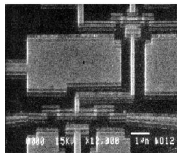


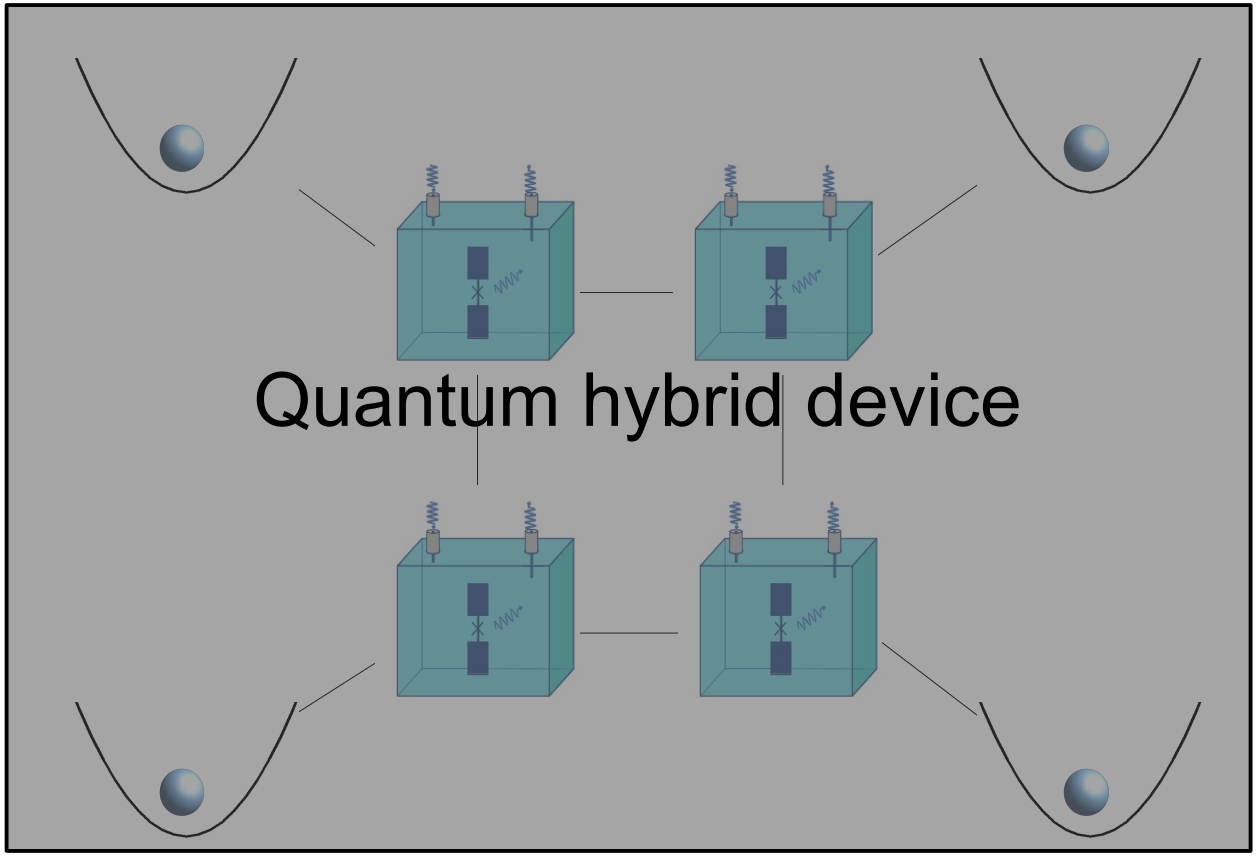
Quantum hybrid devices

Quantum memory



Quantum processor

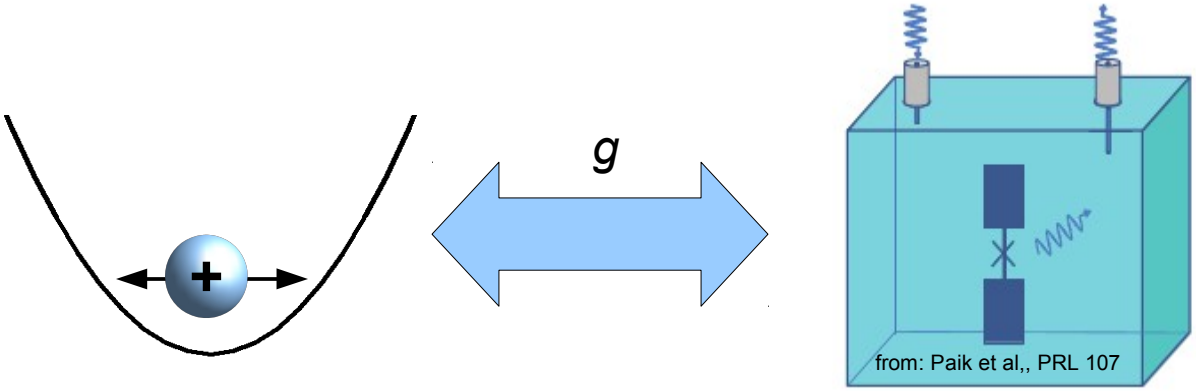




Coherent coupling

Quantum memory

Quantum processor

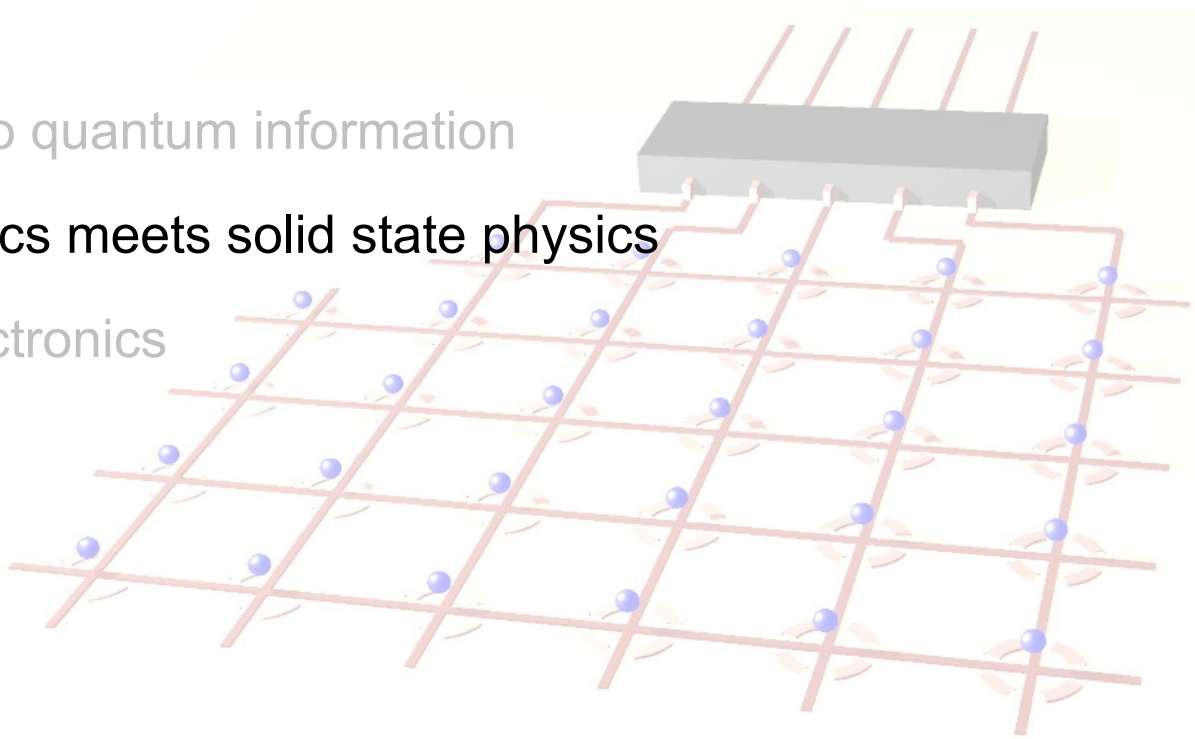


$g >> \{\tau_{ion}, \tau_S\}$

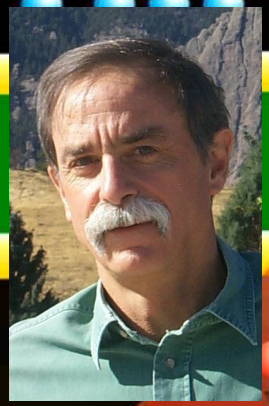
This implies: the solid state qubit must couple much stronger to the ion than to the sum of all other degrees-of-freedom

→ Need to bring the ion very close to the circuit

- Introduction to quantum information
- Quantum optics meets solid state physics
- Quantum electronics
- Conclusions

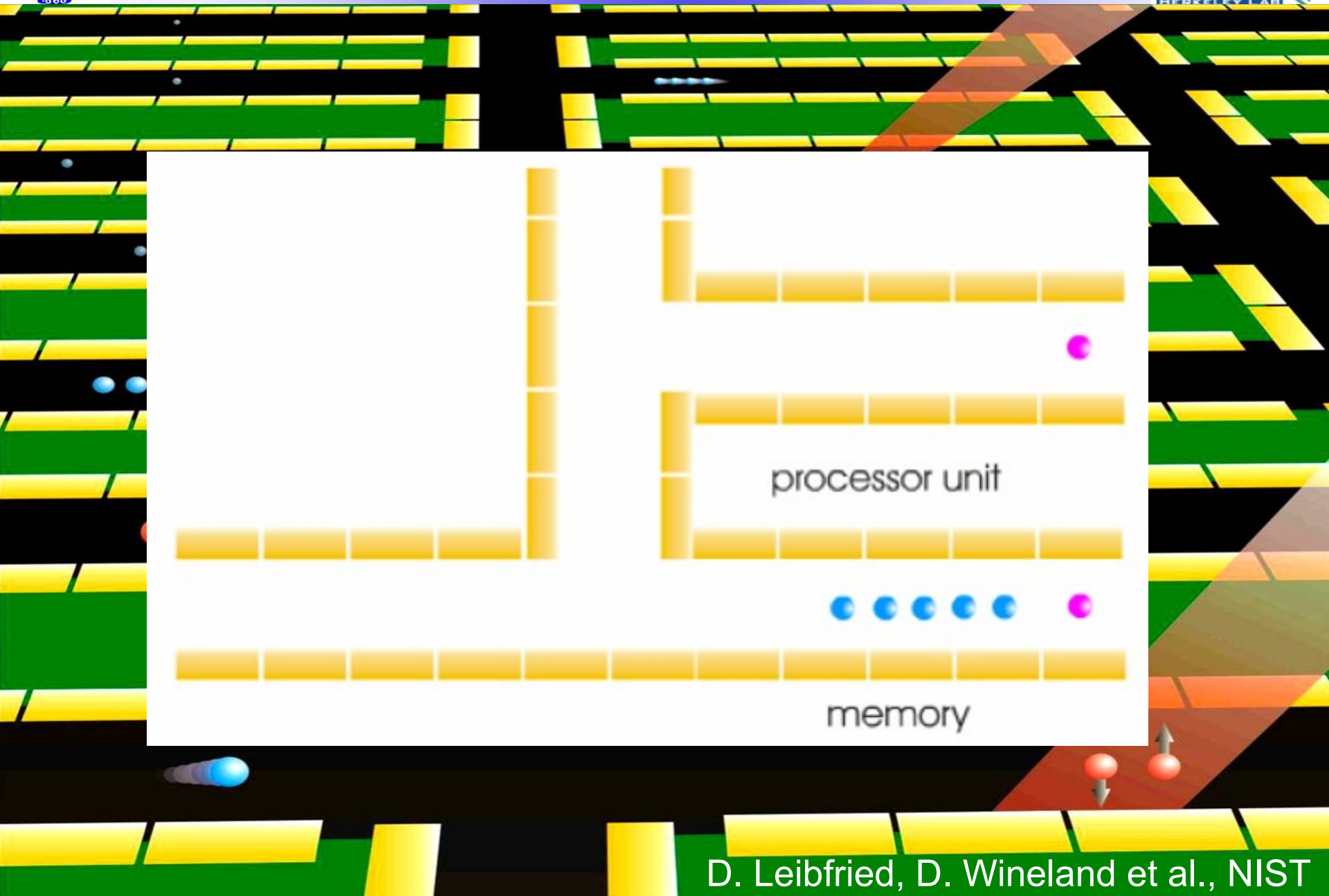


Scalable ion trap quantum computers



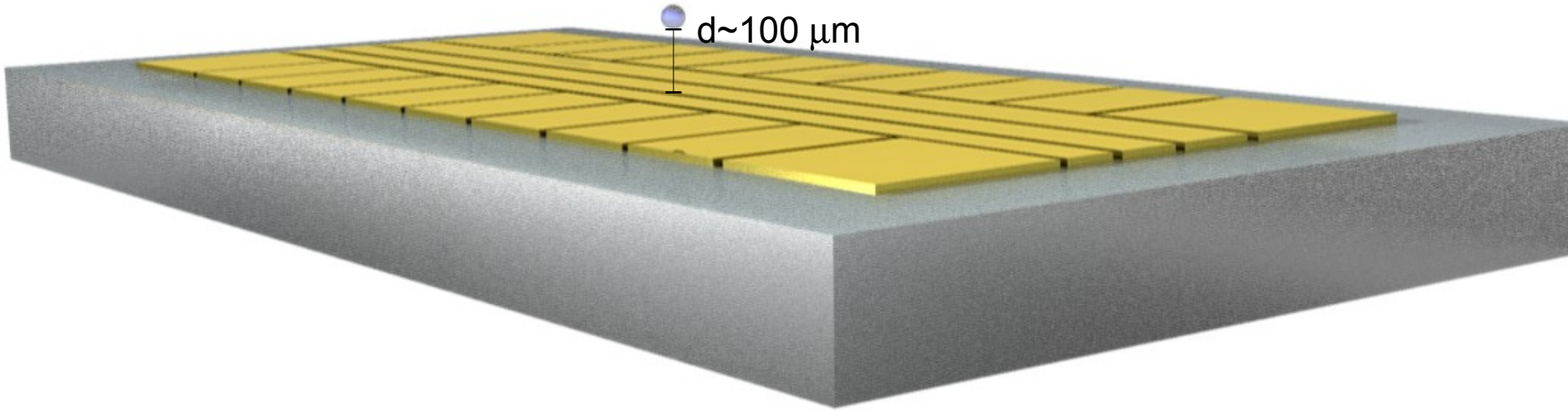
D. Leibfried, D. Wineland et al., NIST

Scalable ion trap quantum computers

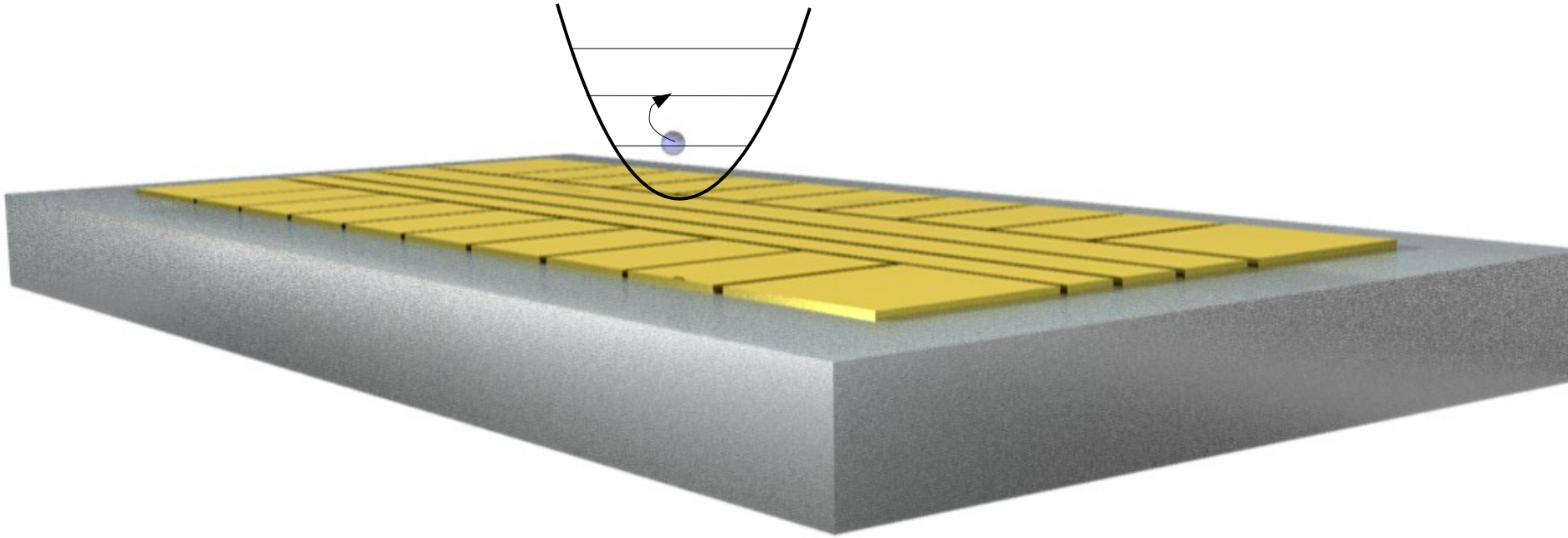


D. Leibfried, D. Wineland et al., NIST

Anomalous heating



Anomalous heating

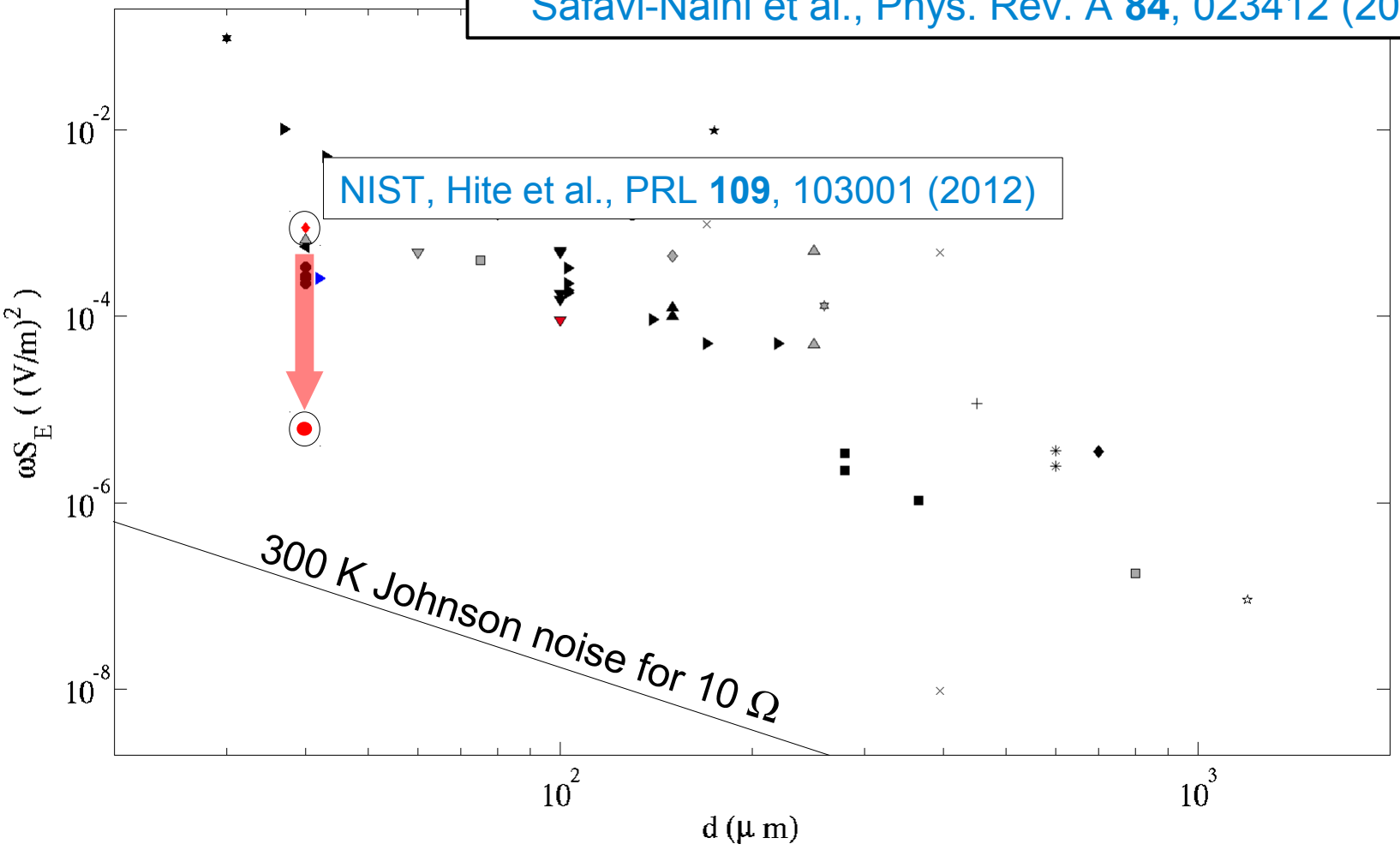


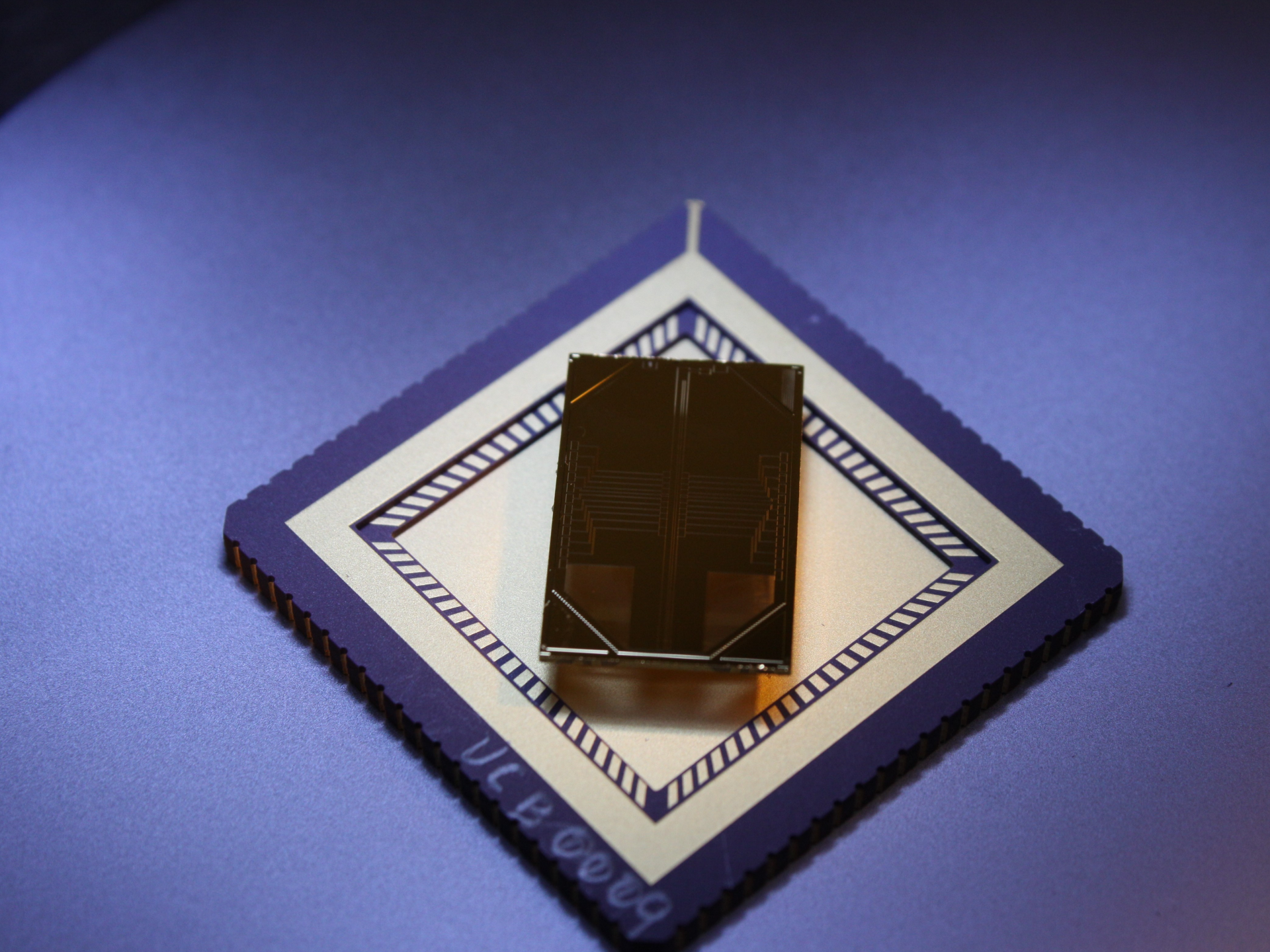
Anomalous heating

Surface contamination?

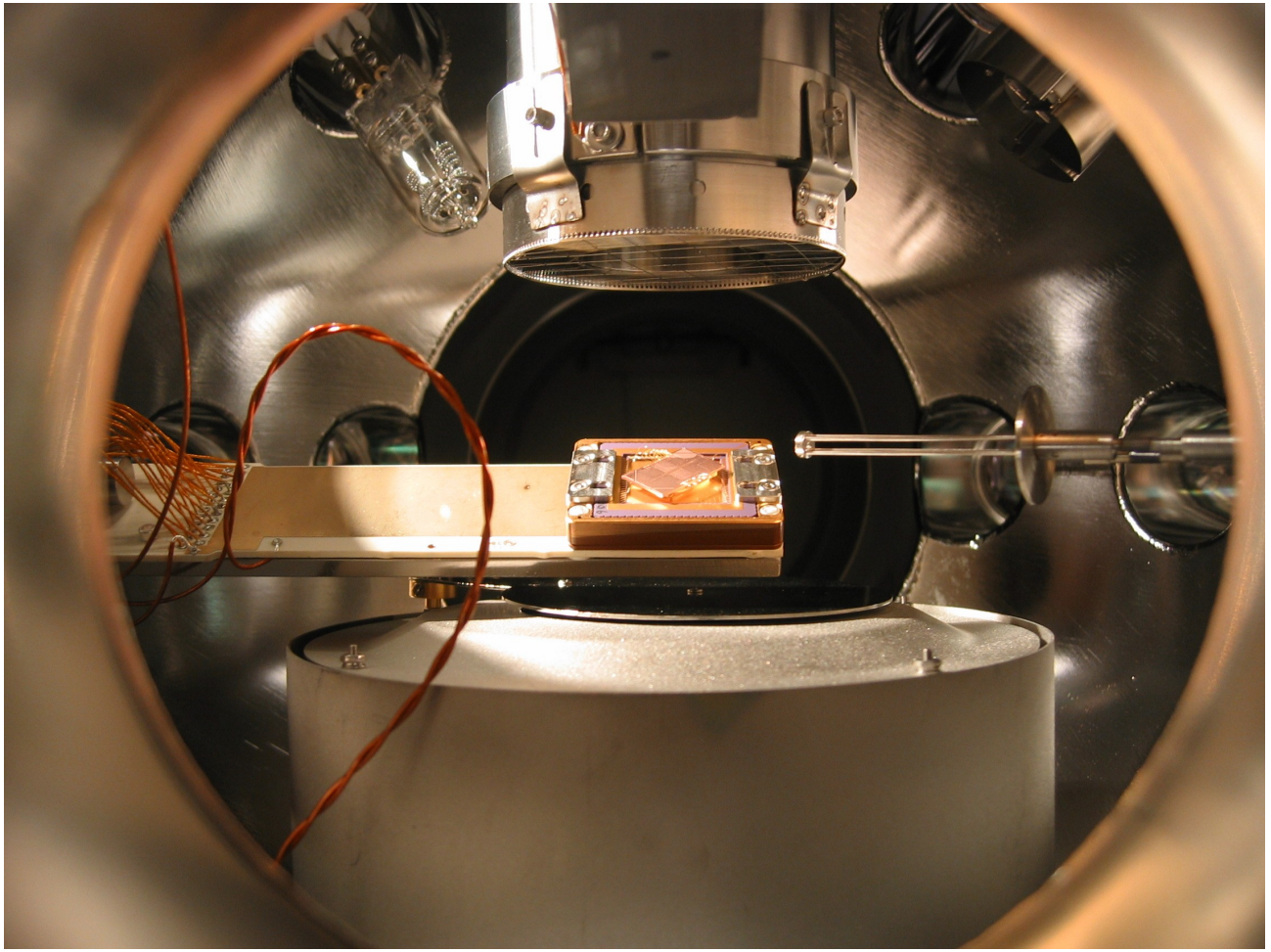
Daniilidis et al., New J. Phys. **13**, 013032 (2011).

Safavi-Naini et al., Phys. Rev. A **84**, 023412 (2011).

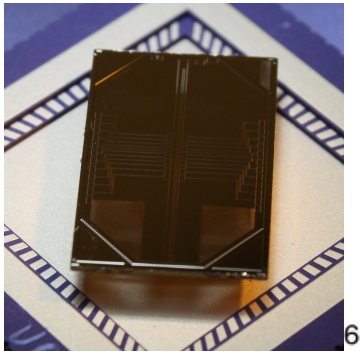




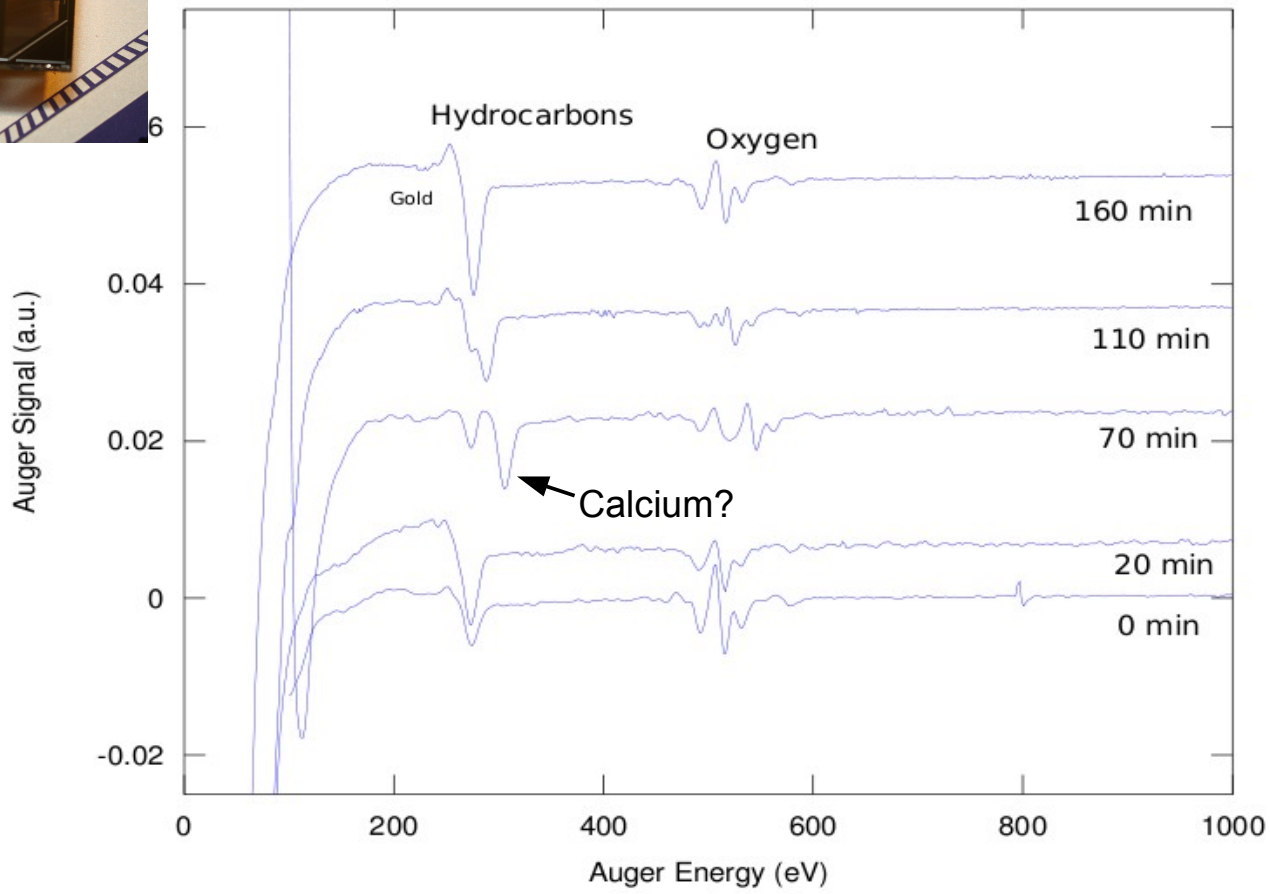
Surface science chamber



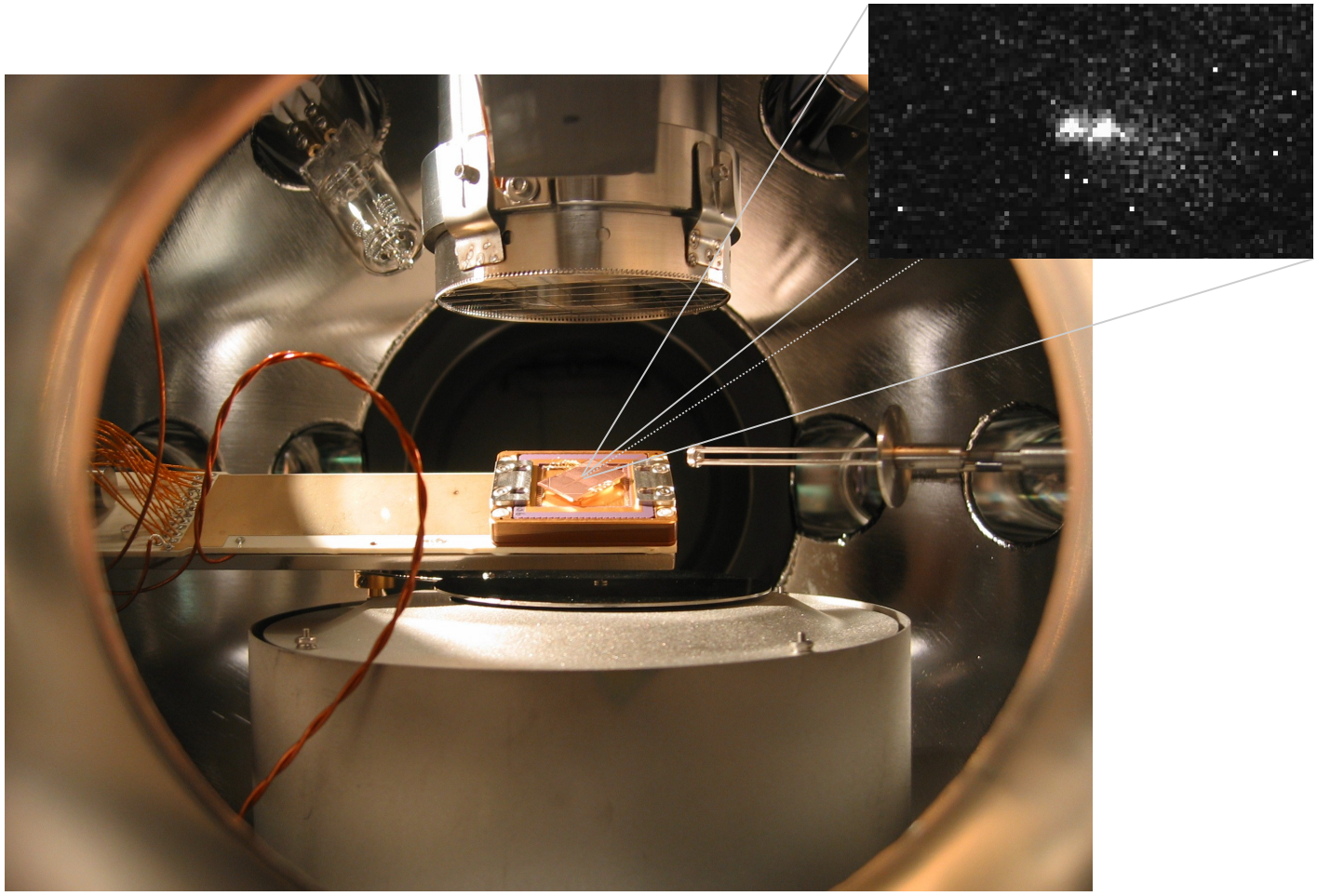
UV induced surface dynamics



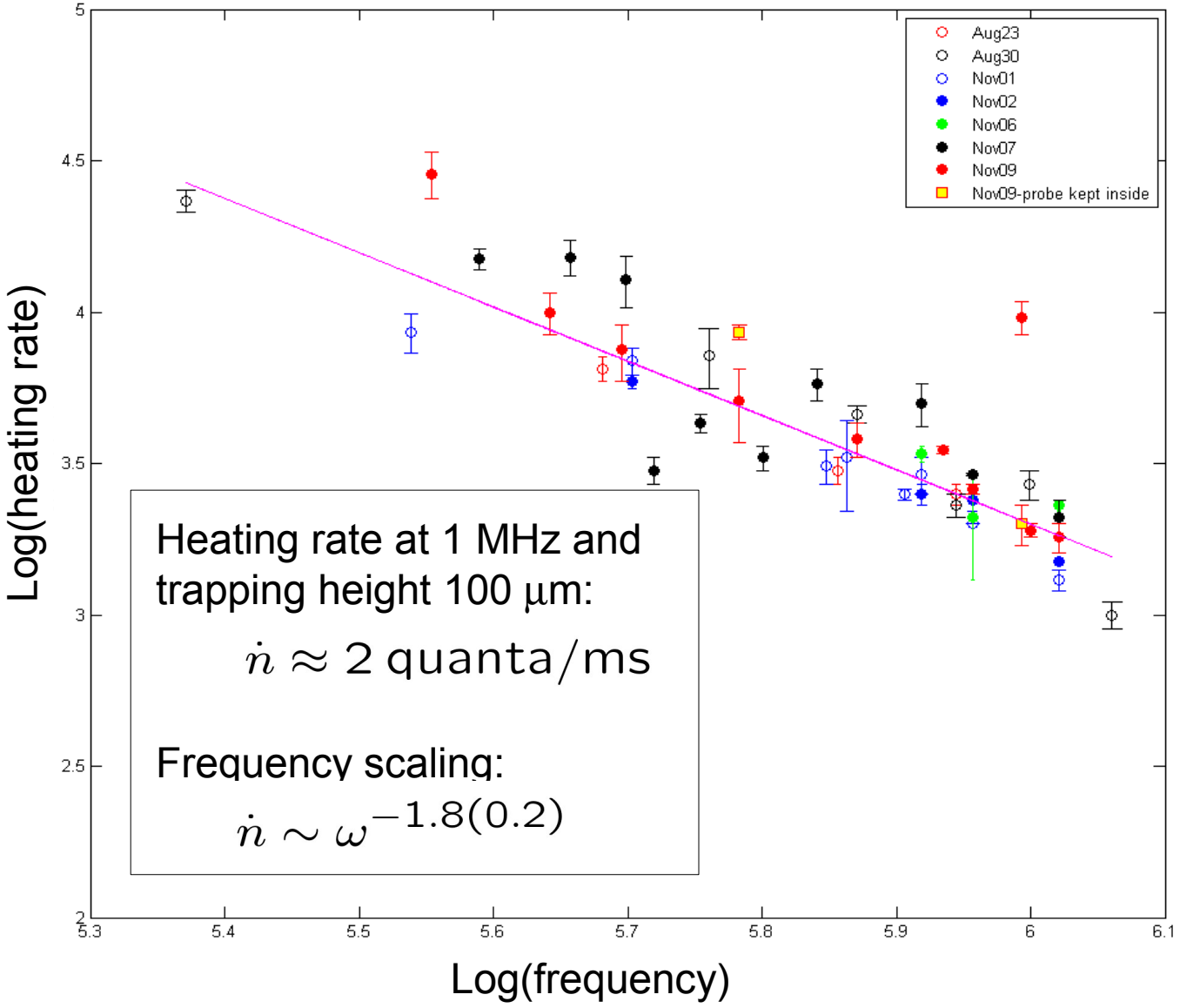
UV light dose (172 nm)



Ions in a surface science chamber



Heating rate scaling with frequency



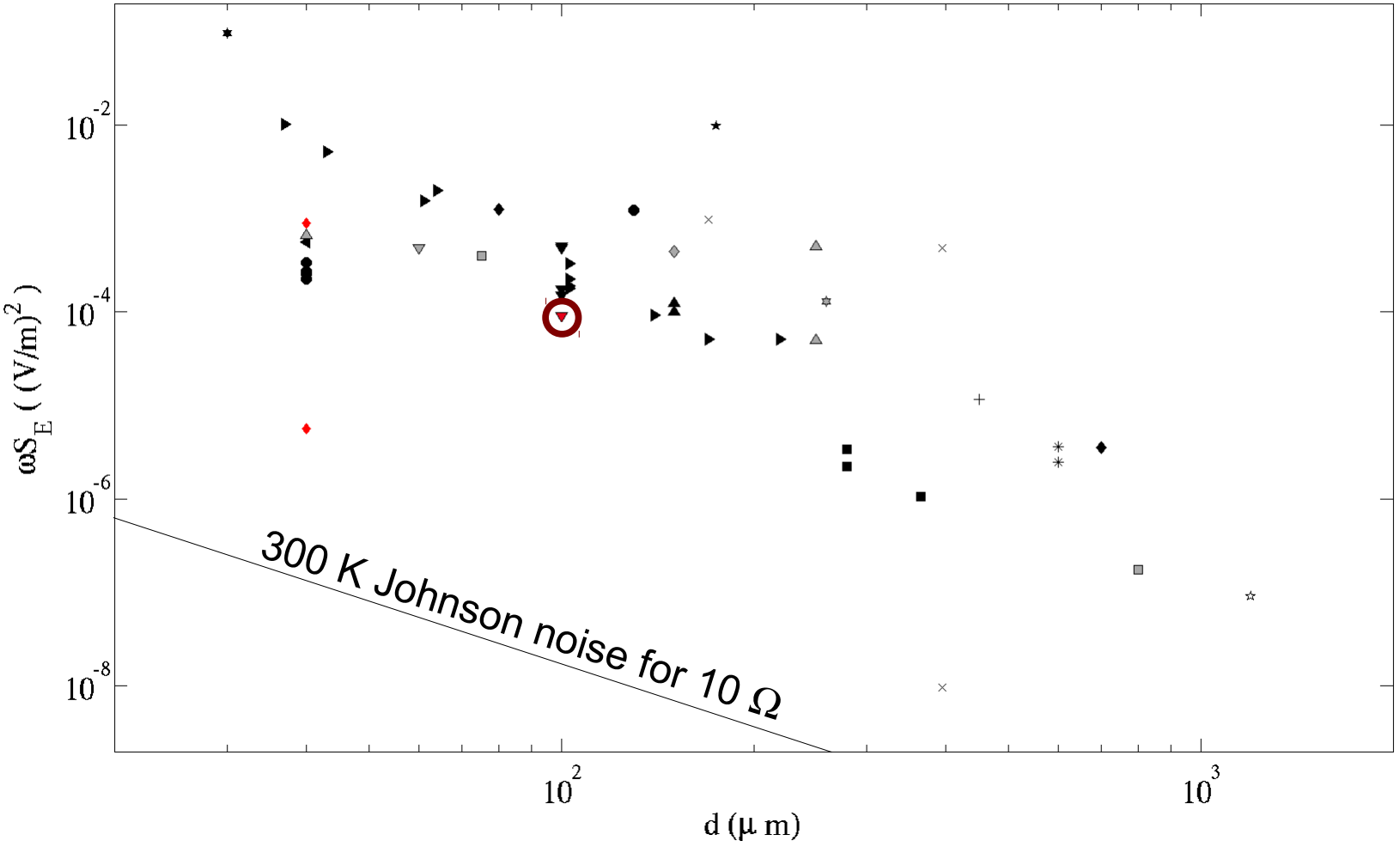
Heating rate at 1 MHz and trapping height 100 μm:

$$\dot{n} \approx 2\,\mathrm{quanta/ms}$$

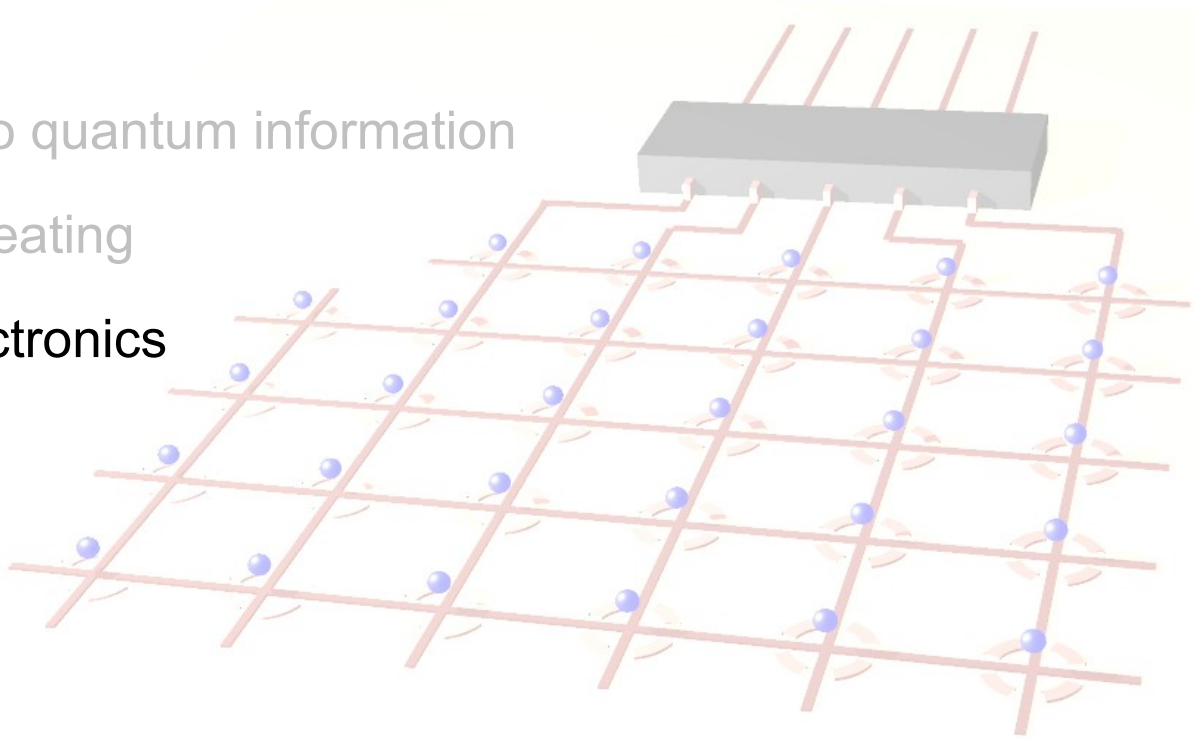
Frequency scaling:

$$\dot{n} \sim \omega^{-1.8(0.2)}$$

Heating rates



- Introduction to quantum information
- Anomalous heating
- Quantum electronics
- Conclusions



Key challenges

Carriers of quantum information need to be

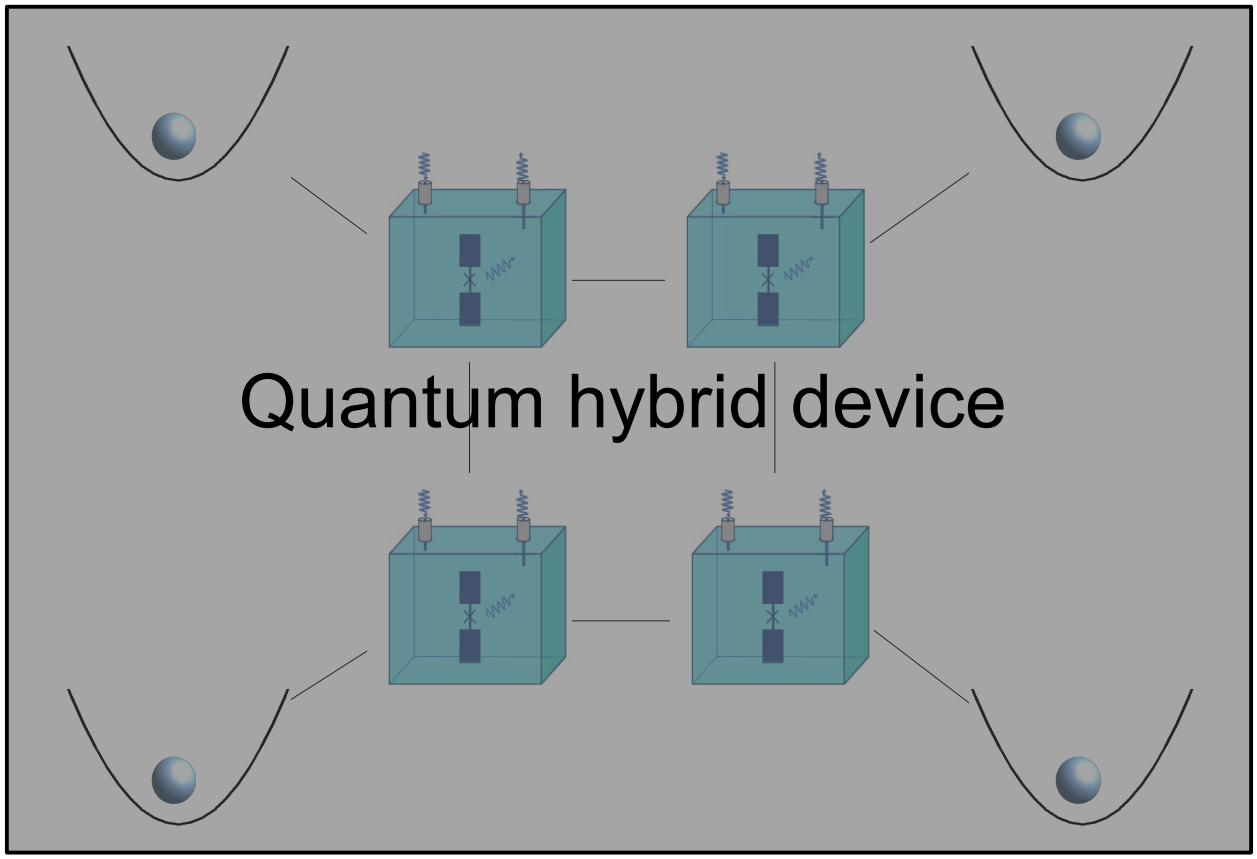
- isolated perfectly from the environment.
- interacting strongly among each other.
- controlled by external parameters.
- scalable

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

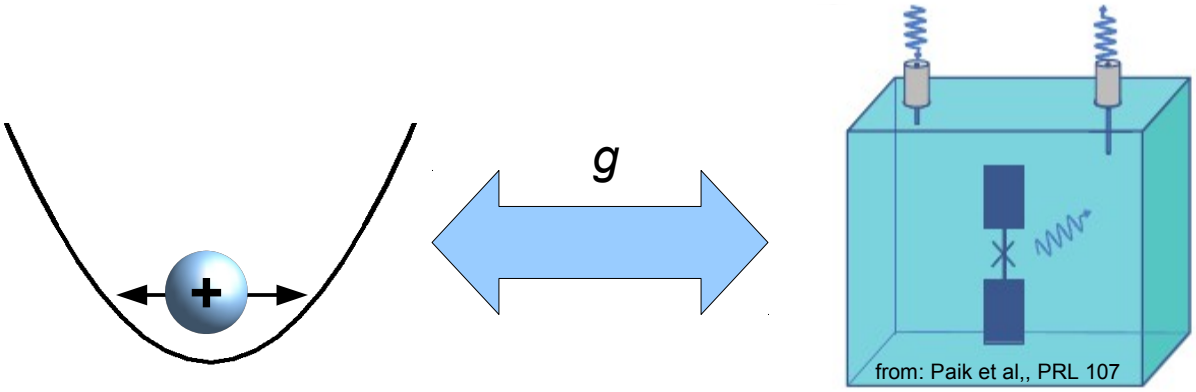
Read out

Control

Quantum hybrids



Coherent coupling

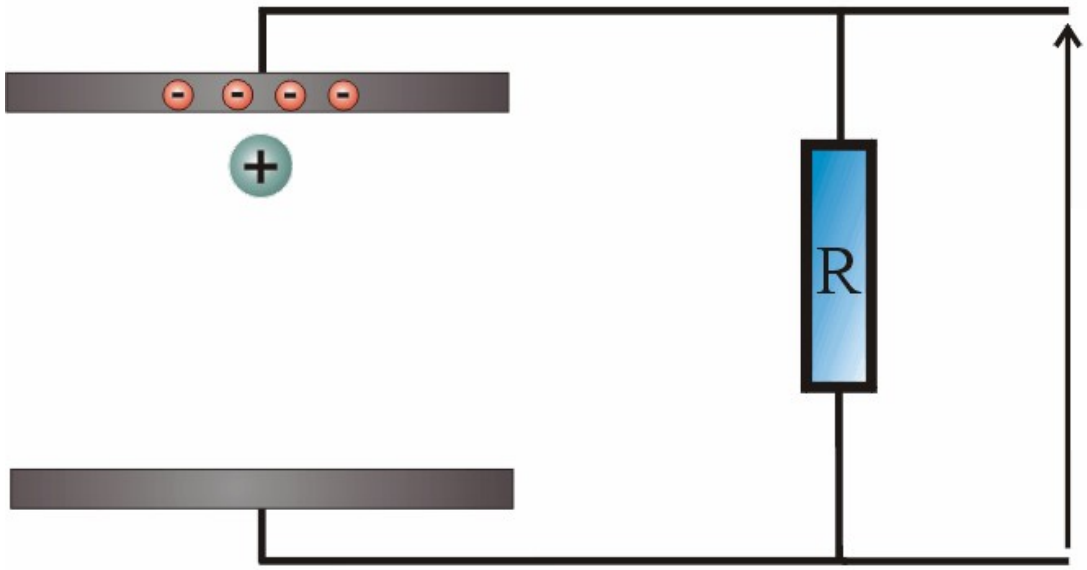


$g >> \{\tau_{ion}, \tau_S\}$

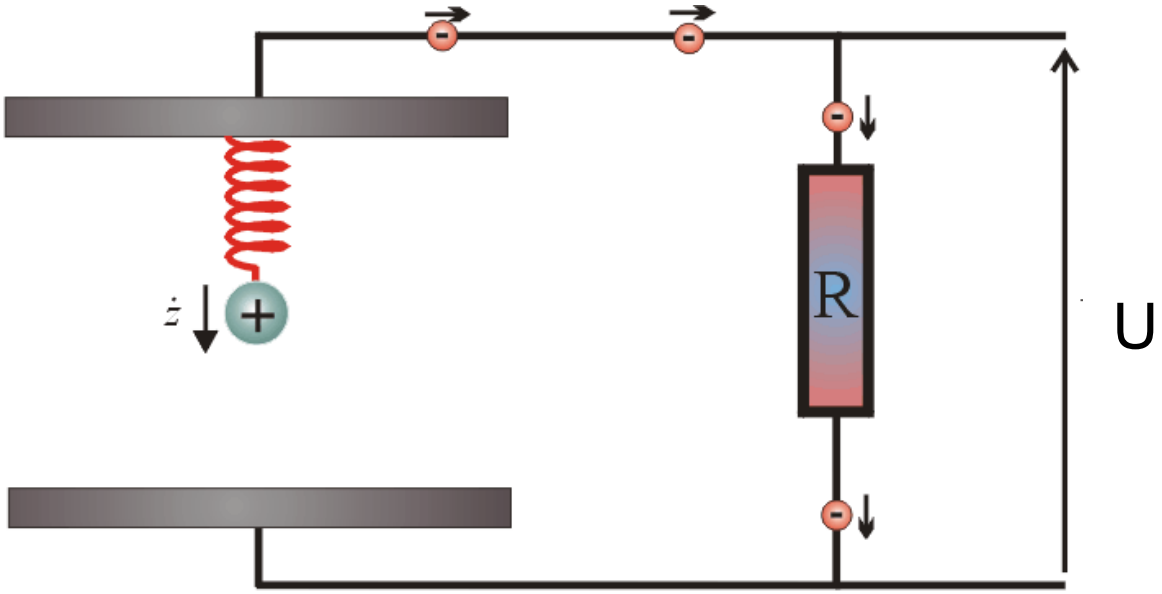
This implies: the solid state qubit must couple much stronger to the ion than to the sum of all other degrees-of-freedom

→ Need a coherent coupling mechanism

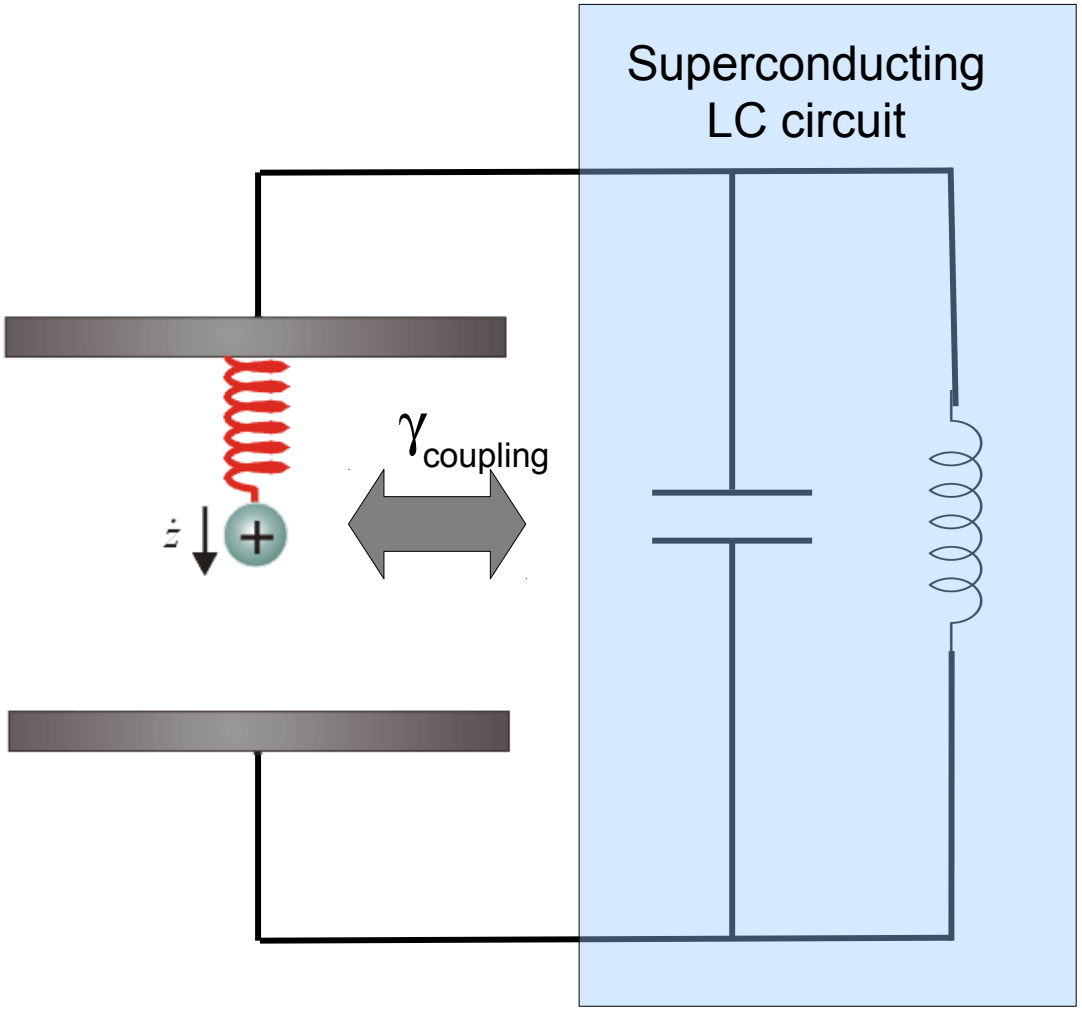
Ion-electronics



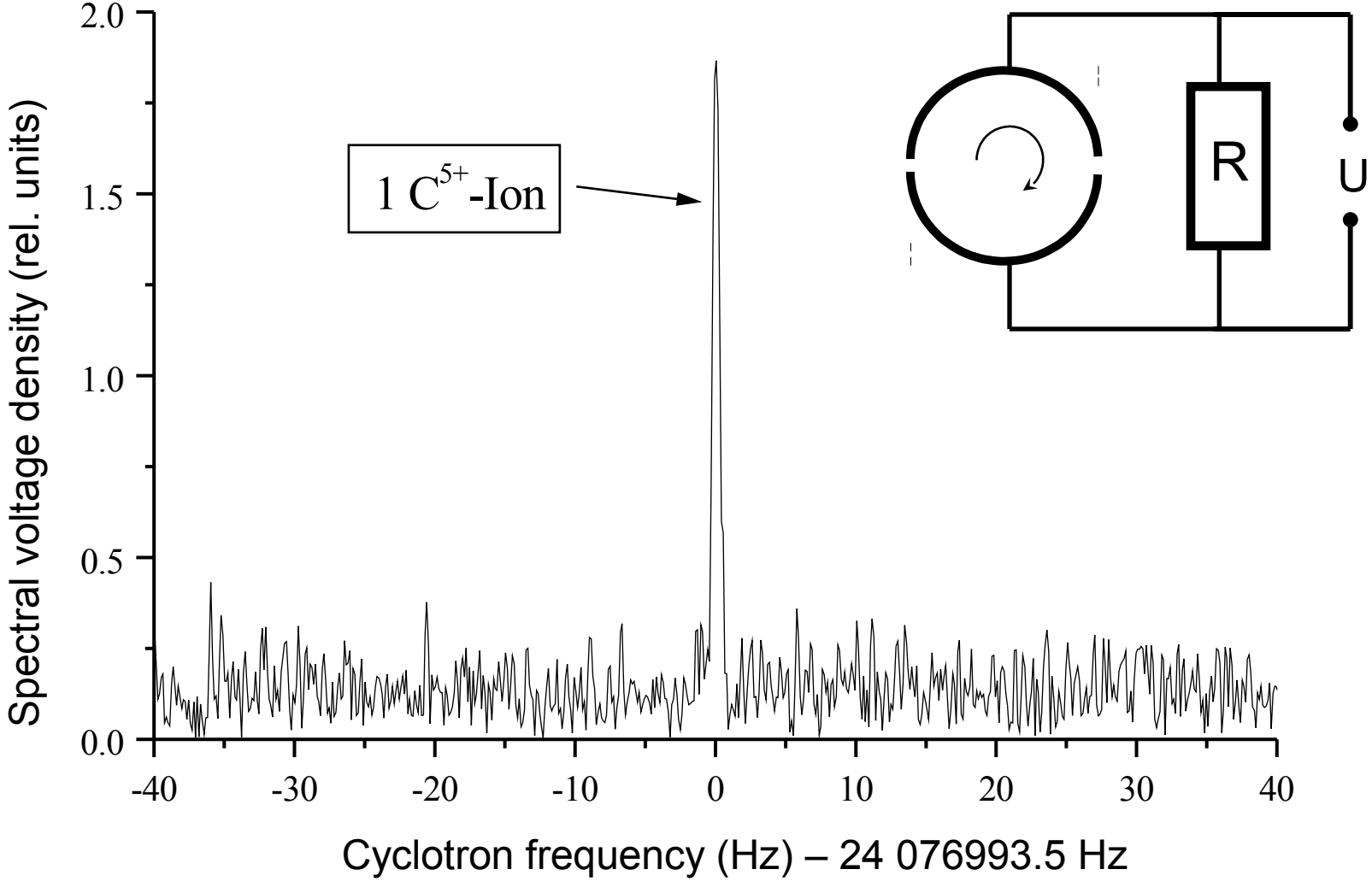
Ion-electronics



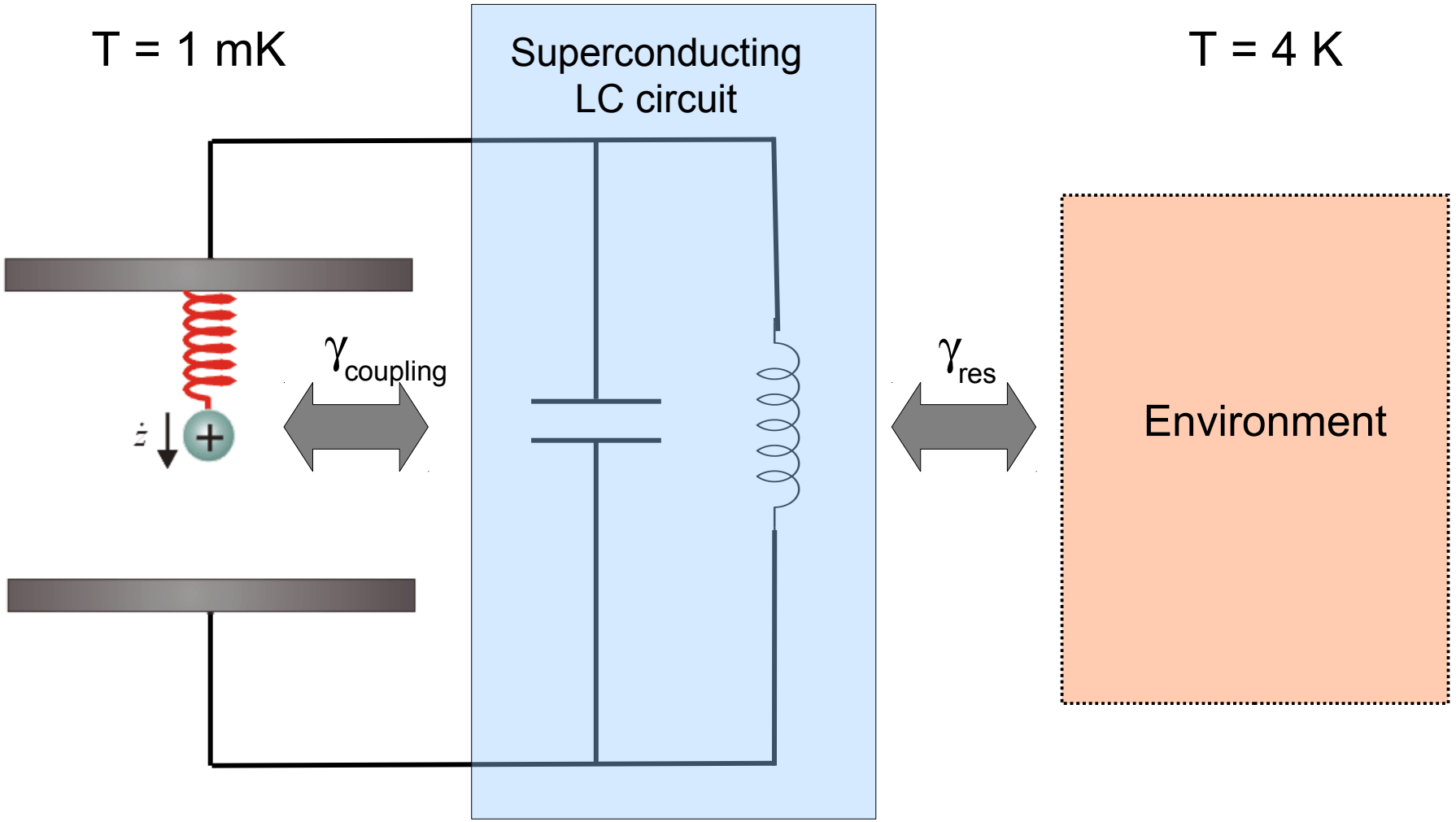
Coupling an ion to a resonator mode



Ion-electronics

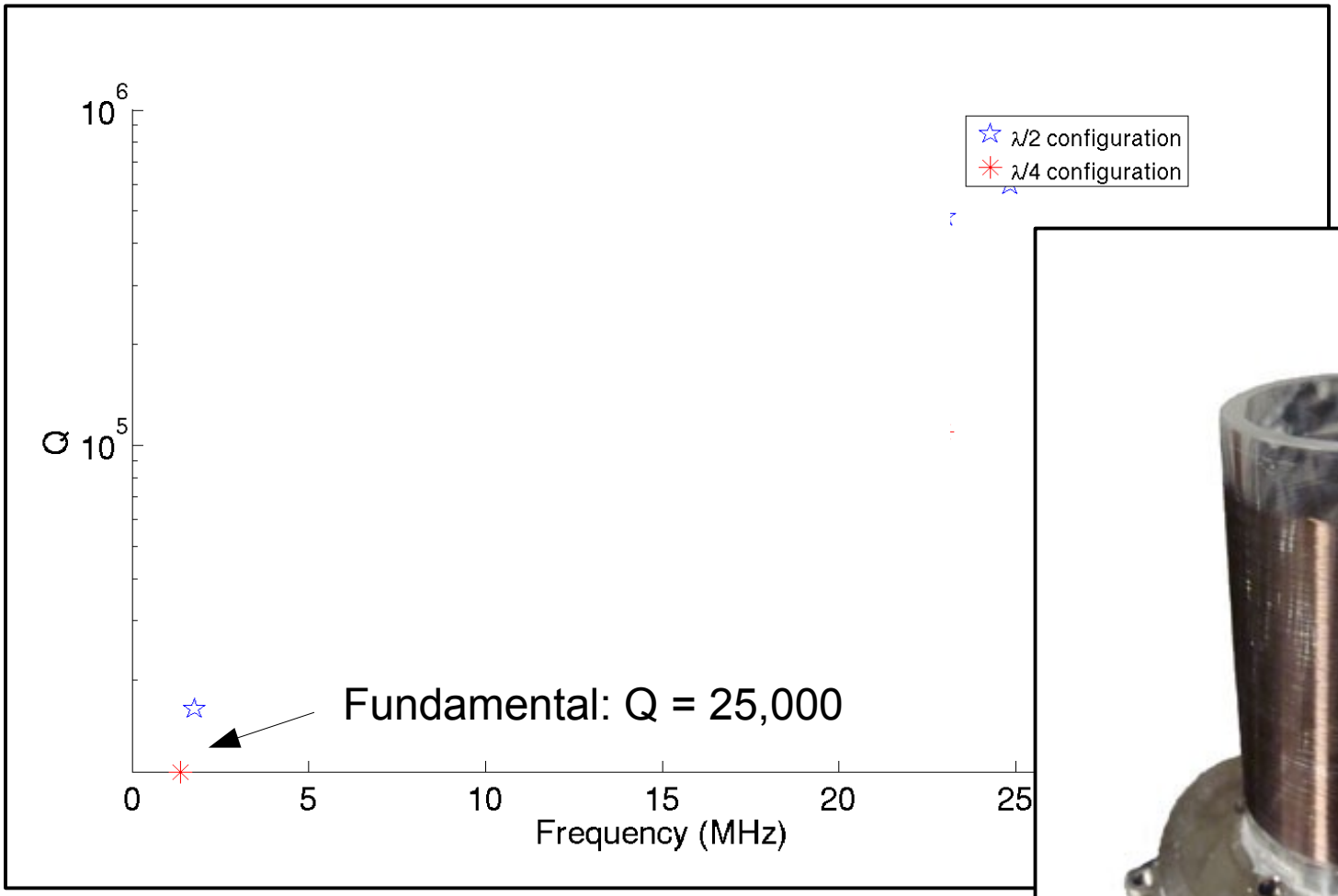


Cooling a resonator mode with a single ion

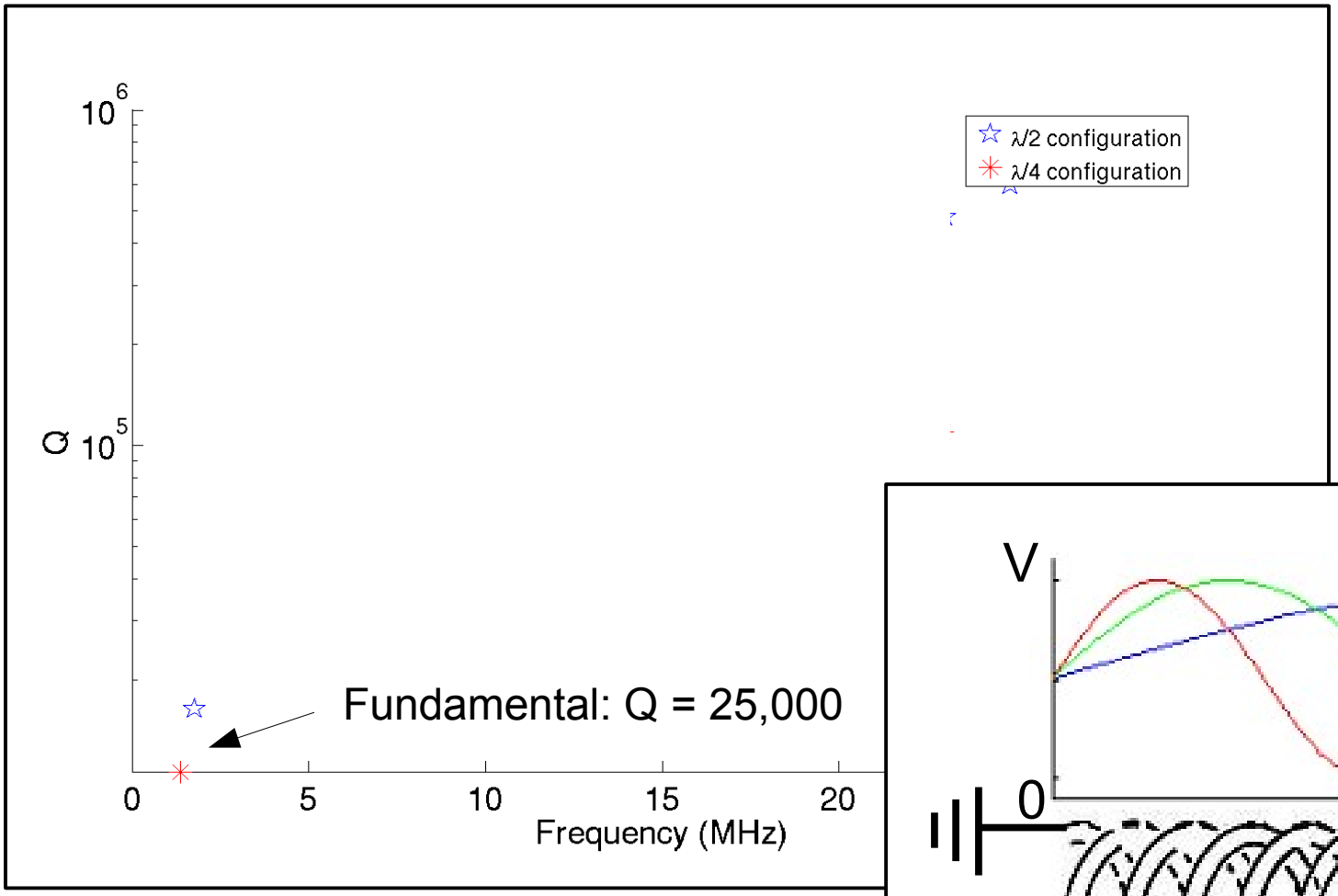


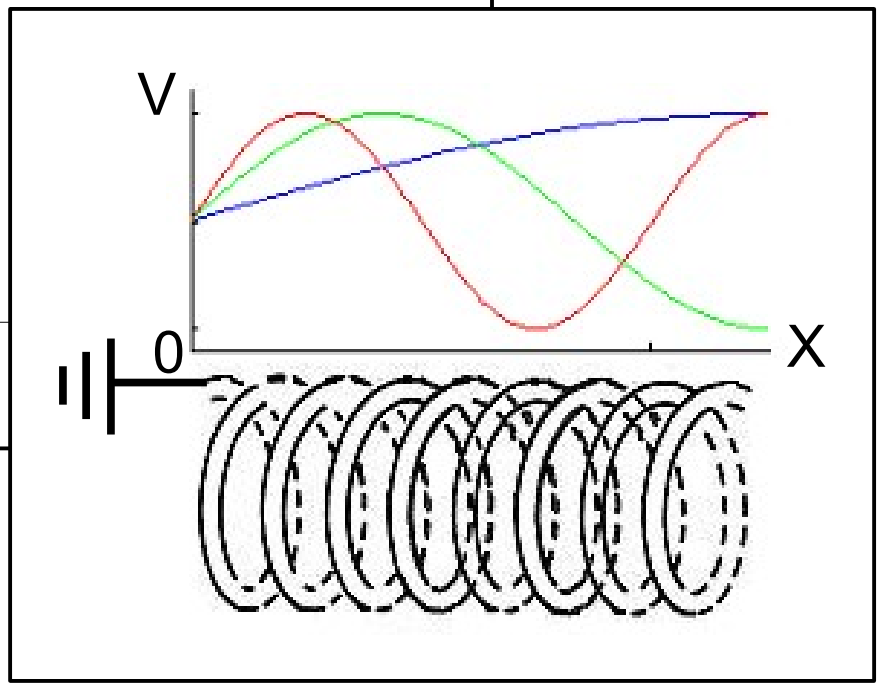
Heinzen and Wineland, PRA **47**, 2977 (1990).

Quality factor of the resonator

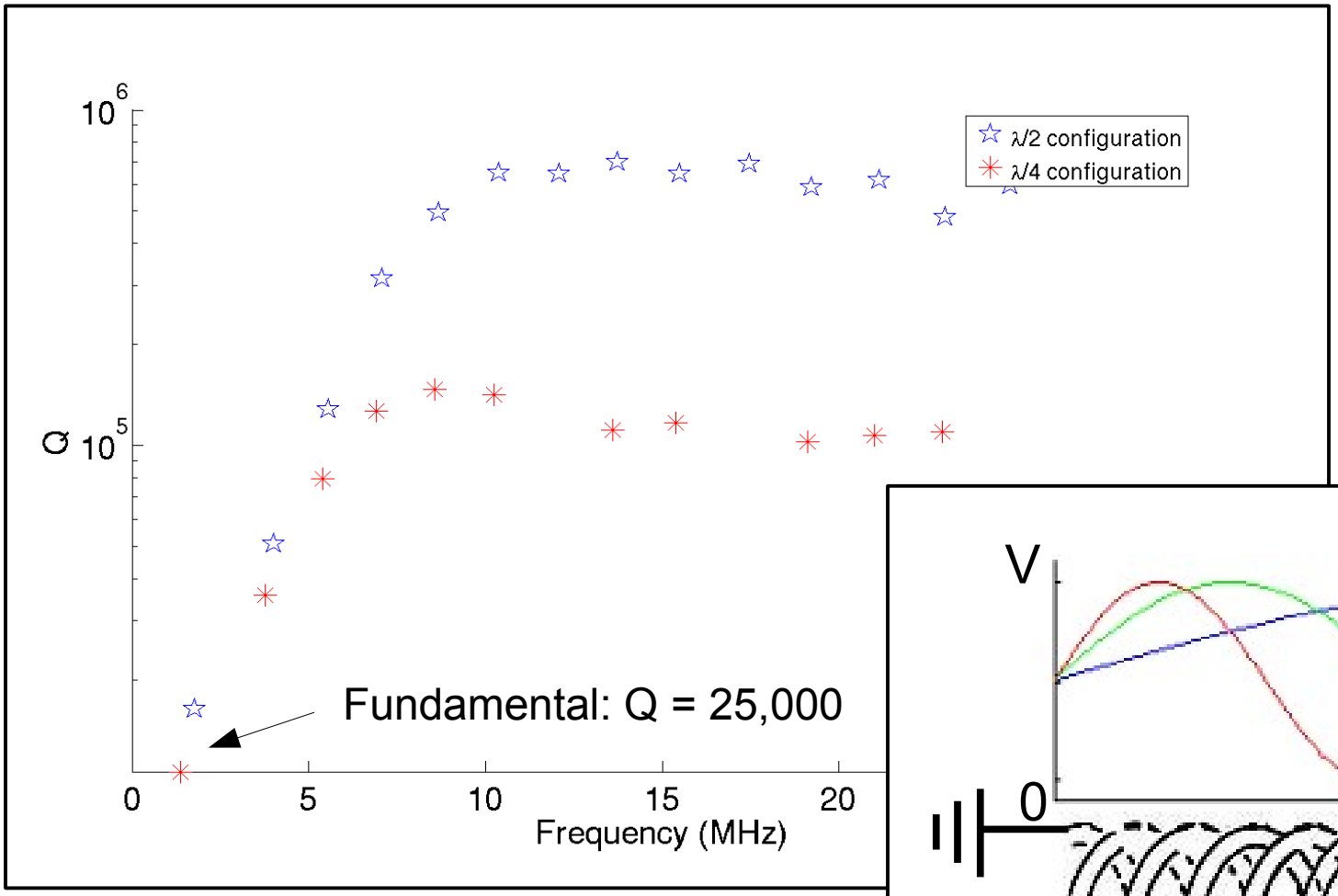


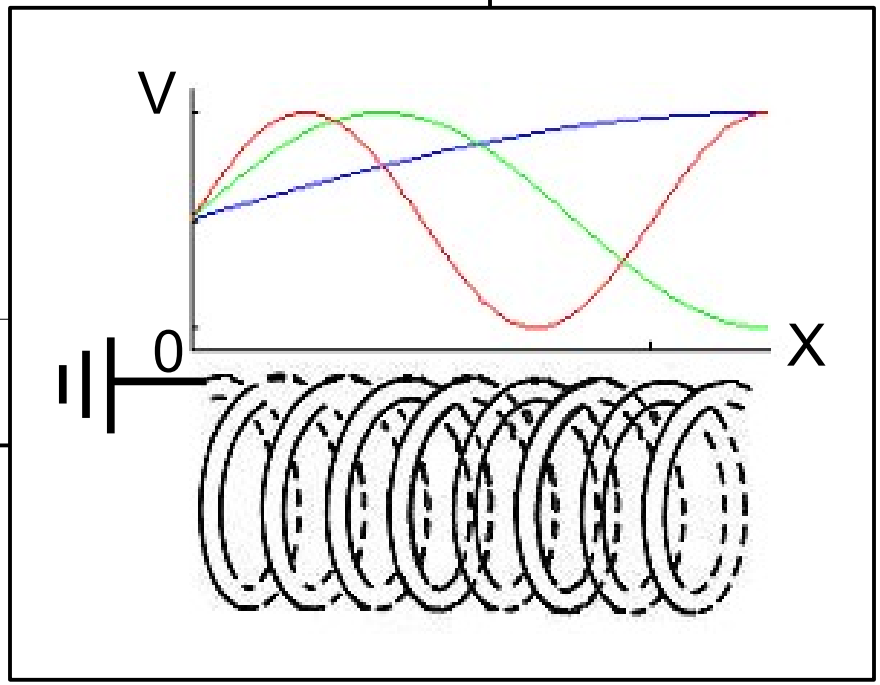
Quality factor of the resonator





Quality factor of the resonator





Coupling an ion to a resonator mode

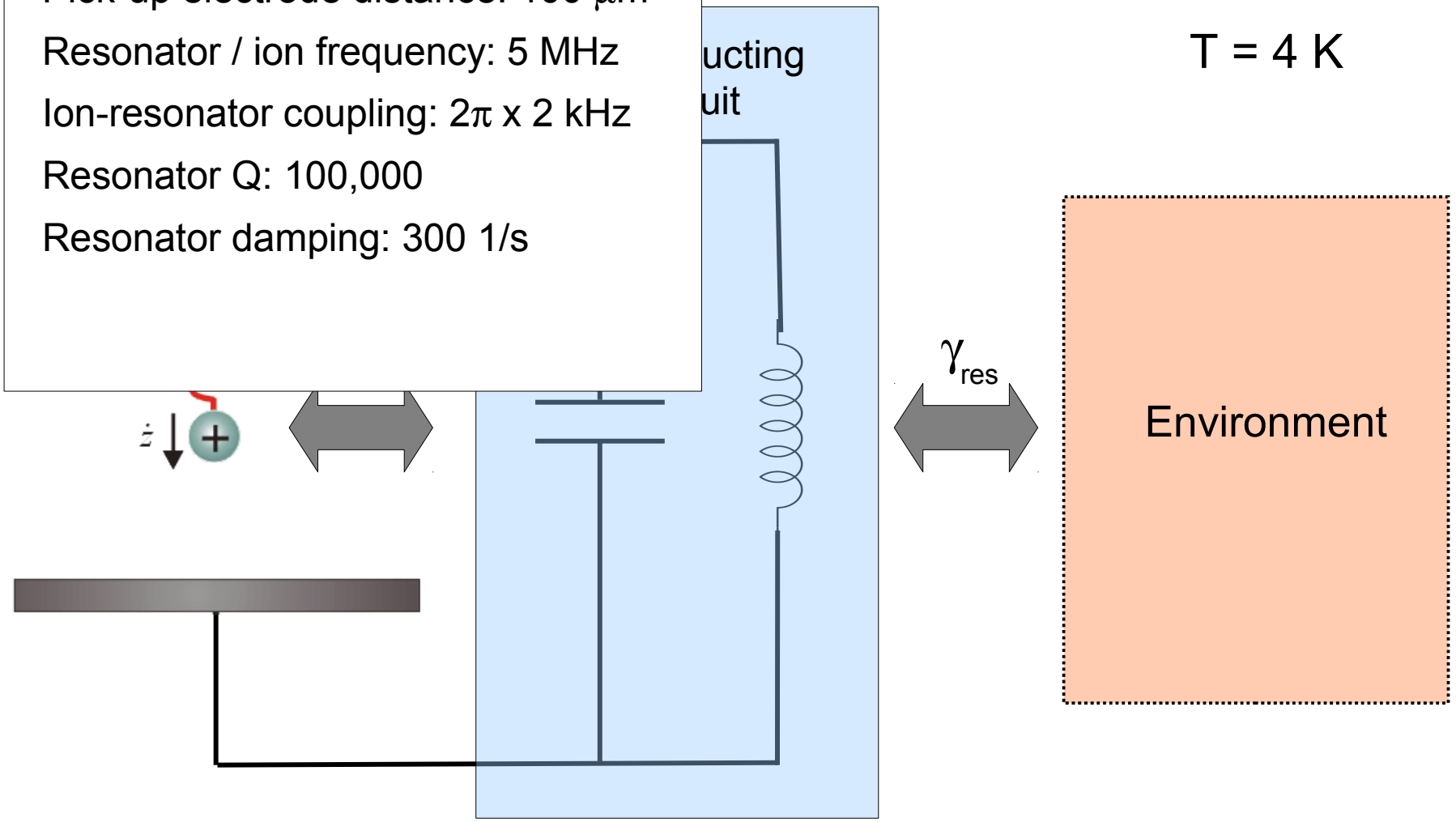
Pick-up electrode distance: 100 μm

Resonator / ion frequency: 5 MHz

Ion-resonator coupling: 2π x 2 kHz

Resonator Q: 100,000

Resonator damping: 300 1/s



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

Coupling an ion to a resonator mode

Pick-up electrode distance: 100 μm

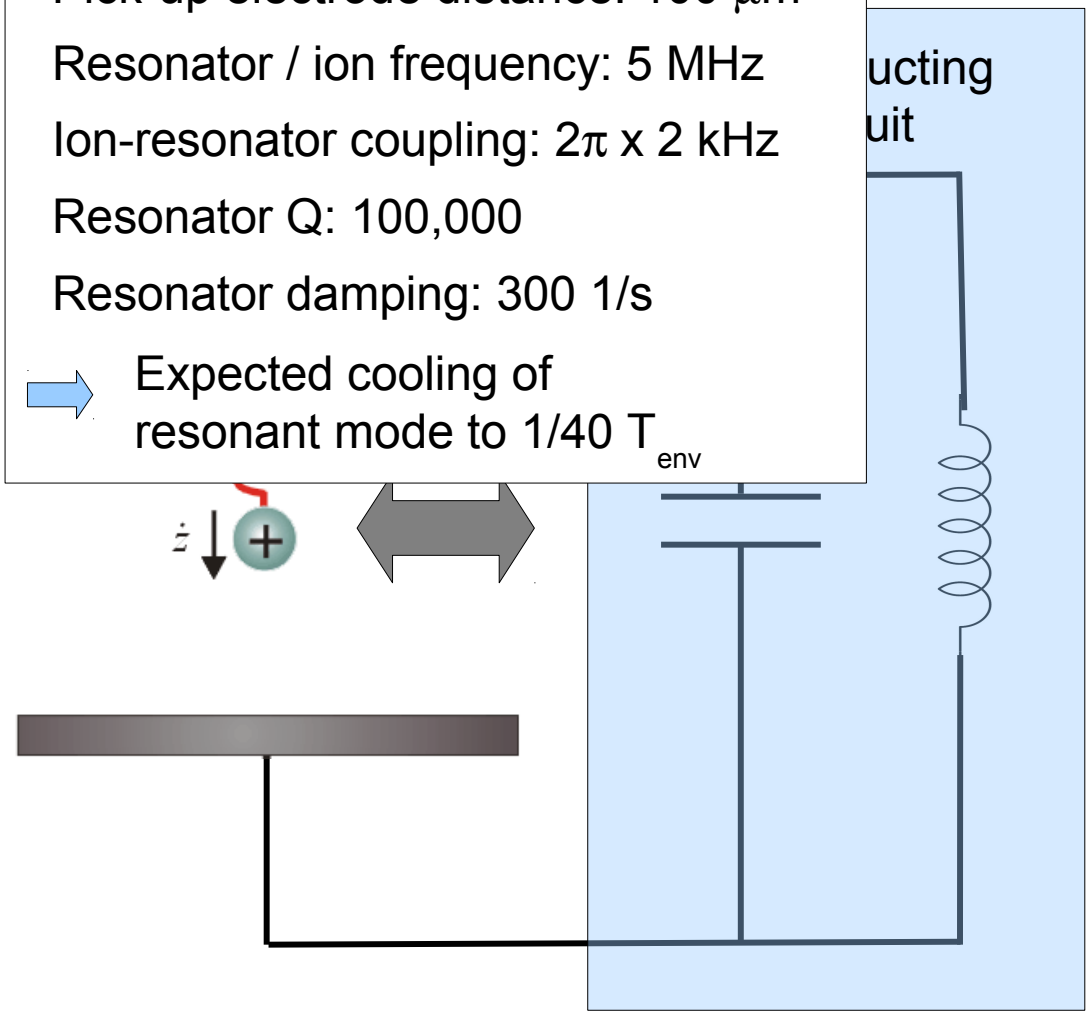
Resonator / ion frequency: 5 MHz

Ion-resonator coupling: 2π x 2 kHz

Resonator Q: 100,000

Resonator damping: 300 1/s

⇒ Expected cooling of resonant mode to 1/40 T_{env}



T = 4 K

γ_{res}

Environment

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

Coupling an ion to a resonator mode

Pick-up electrode distance: 100 μm

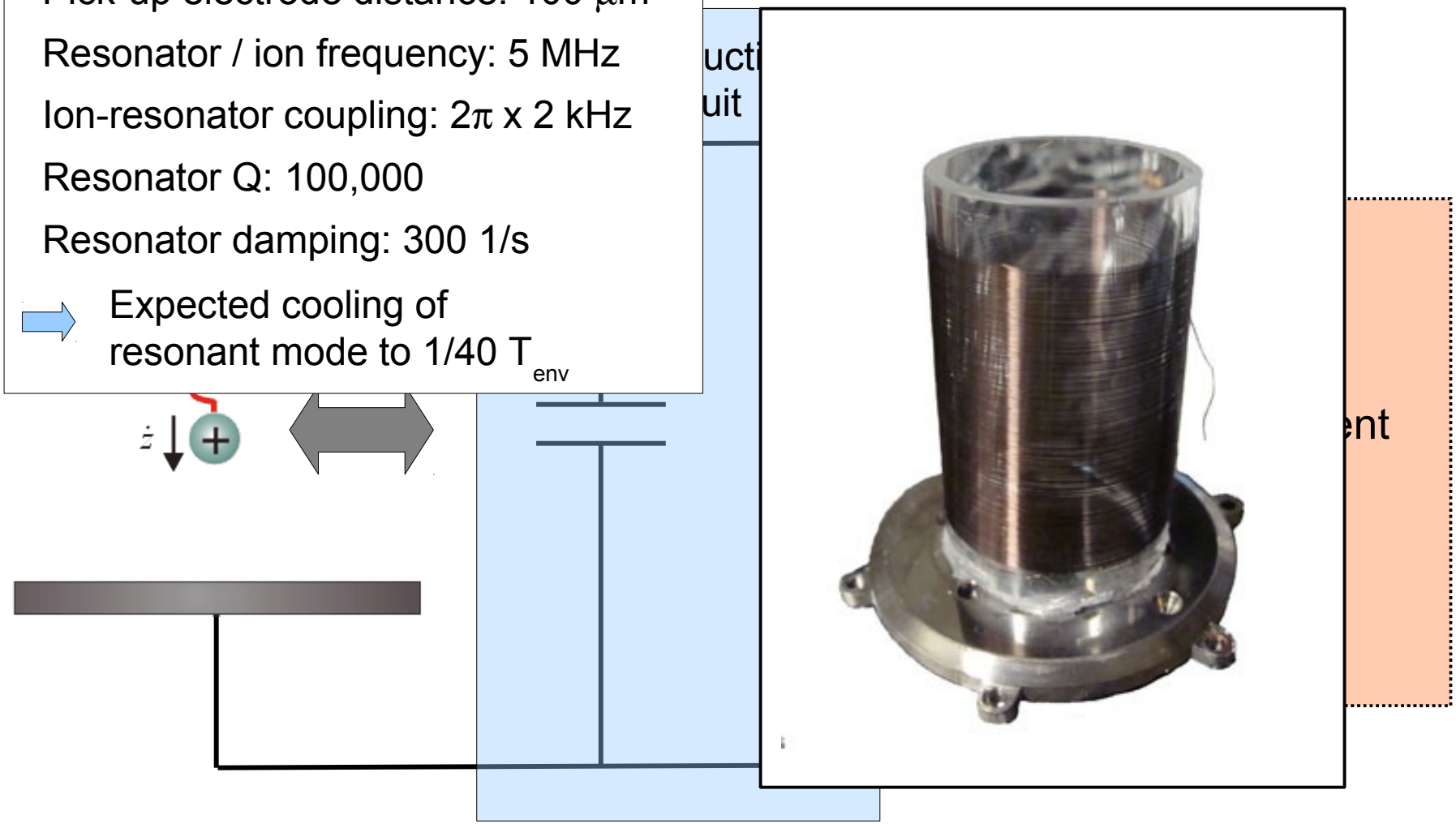
Resonator / ion frequency: 5 MHz

Ion-resonator coupling: 2π x 2 kHz

Resonator Q: 100,000

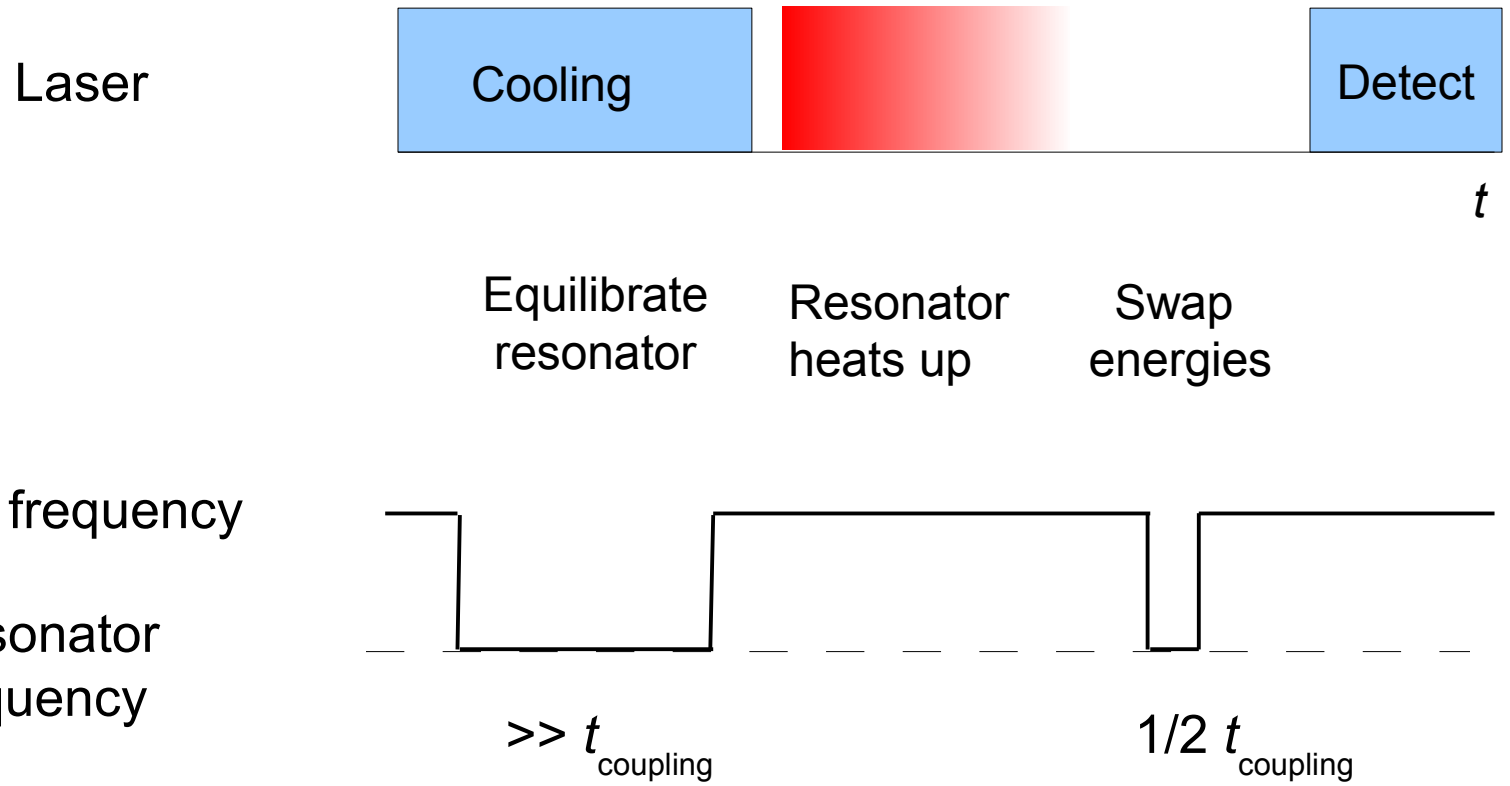
Resonator damping: 300 1/s

⇒ Expected cooling of resonant mode to 1/40 T_{env}

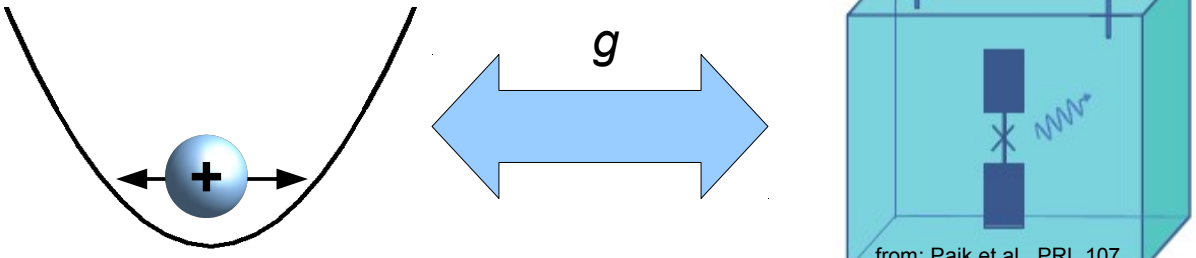


Heinzen and Wineland, PRA **47**, 2977 (1990).

Experimental procedure



Coherent coupling



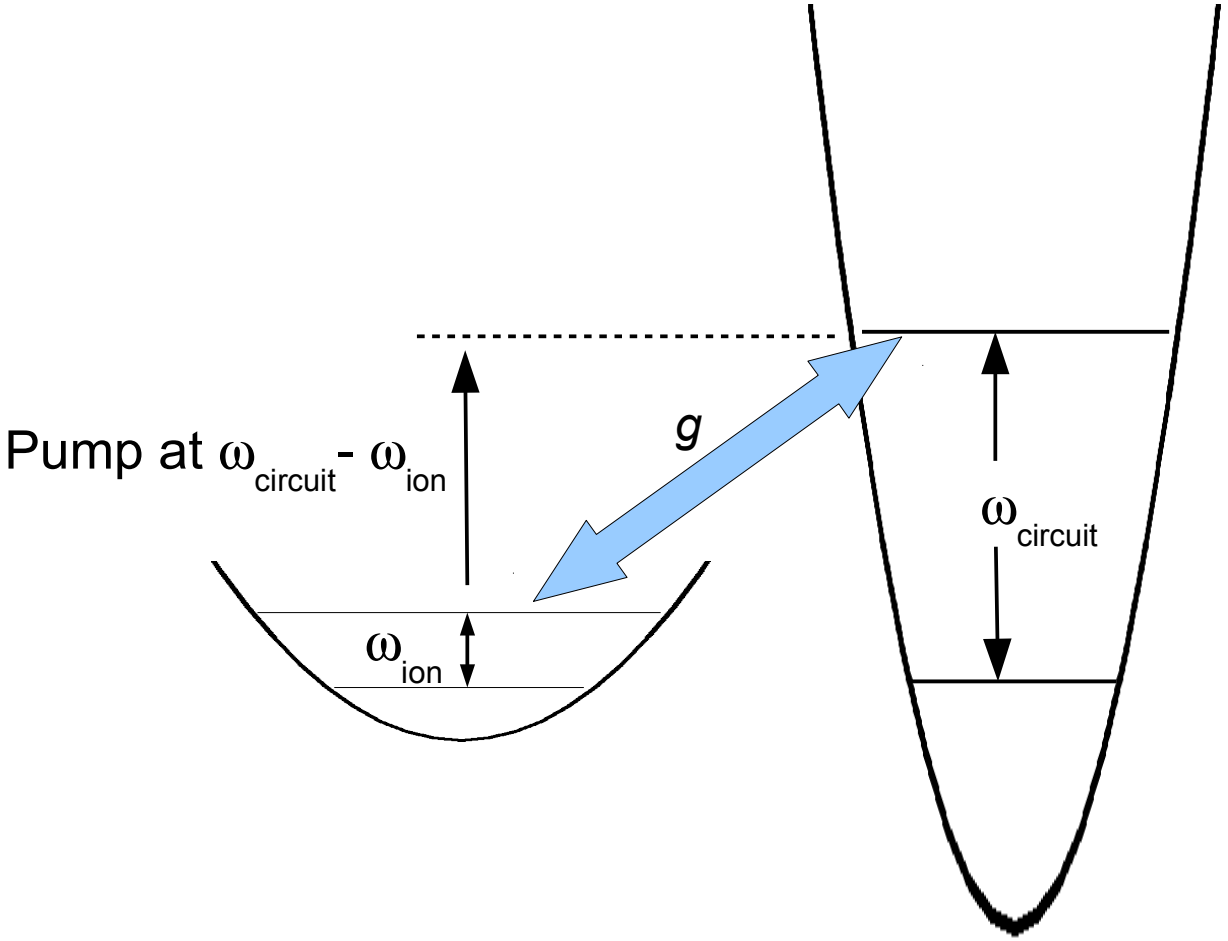
5 MHz

7 GHz

Challenges: - Impedance mismatch
- Frequency mismatch

Quantum mixing

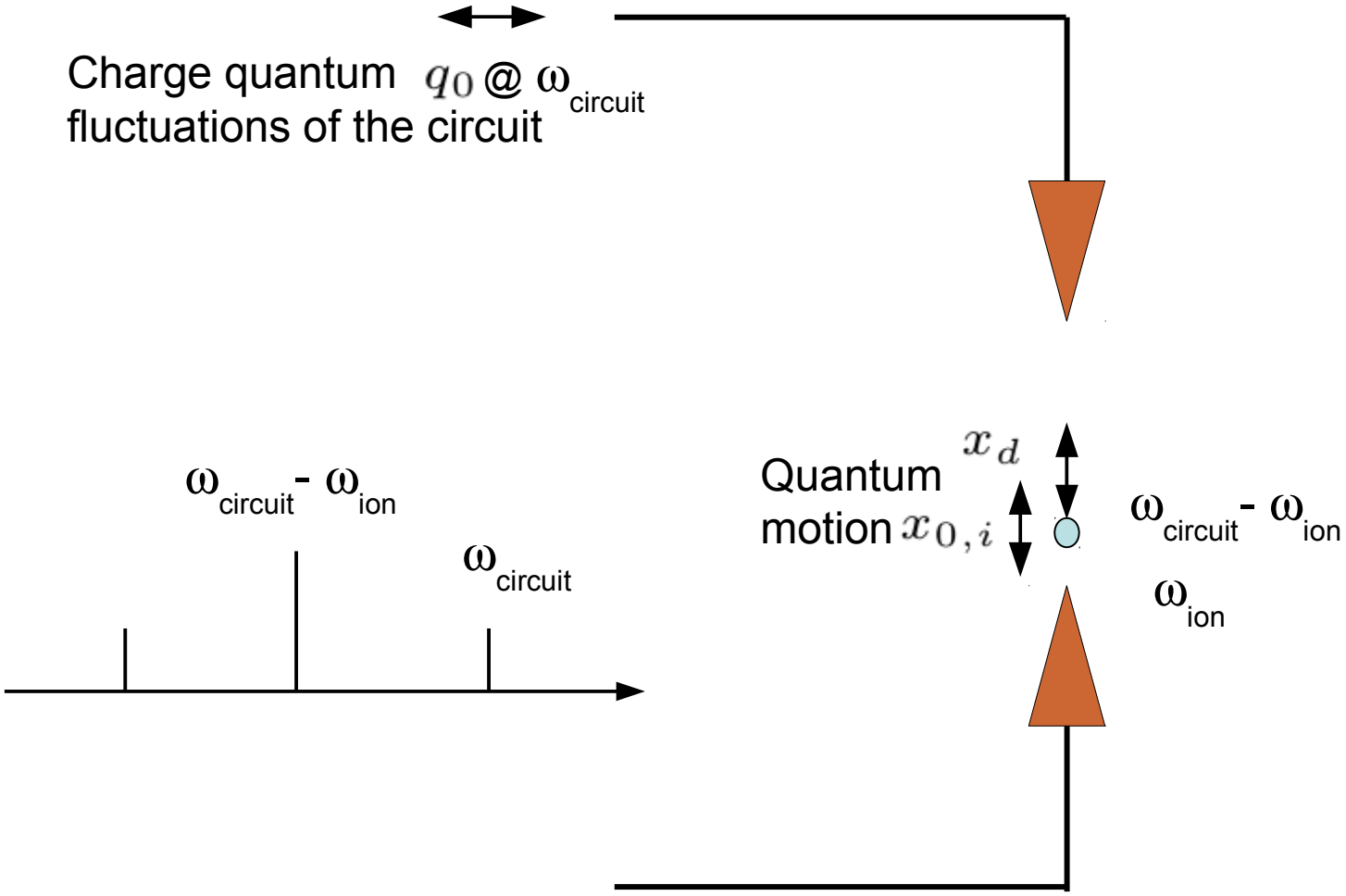
Parametric upconversion



Quantum mixing

Parametric upconversion using a nonlinear induced current

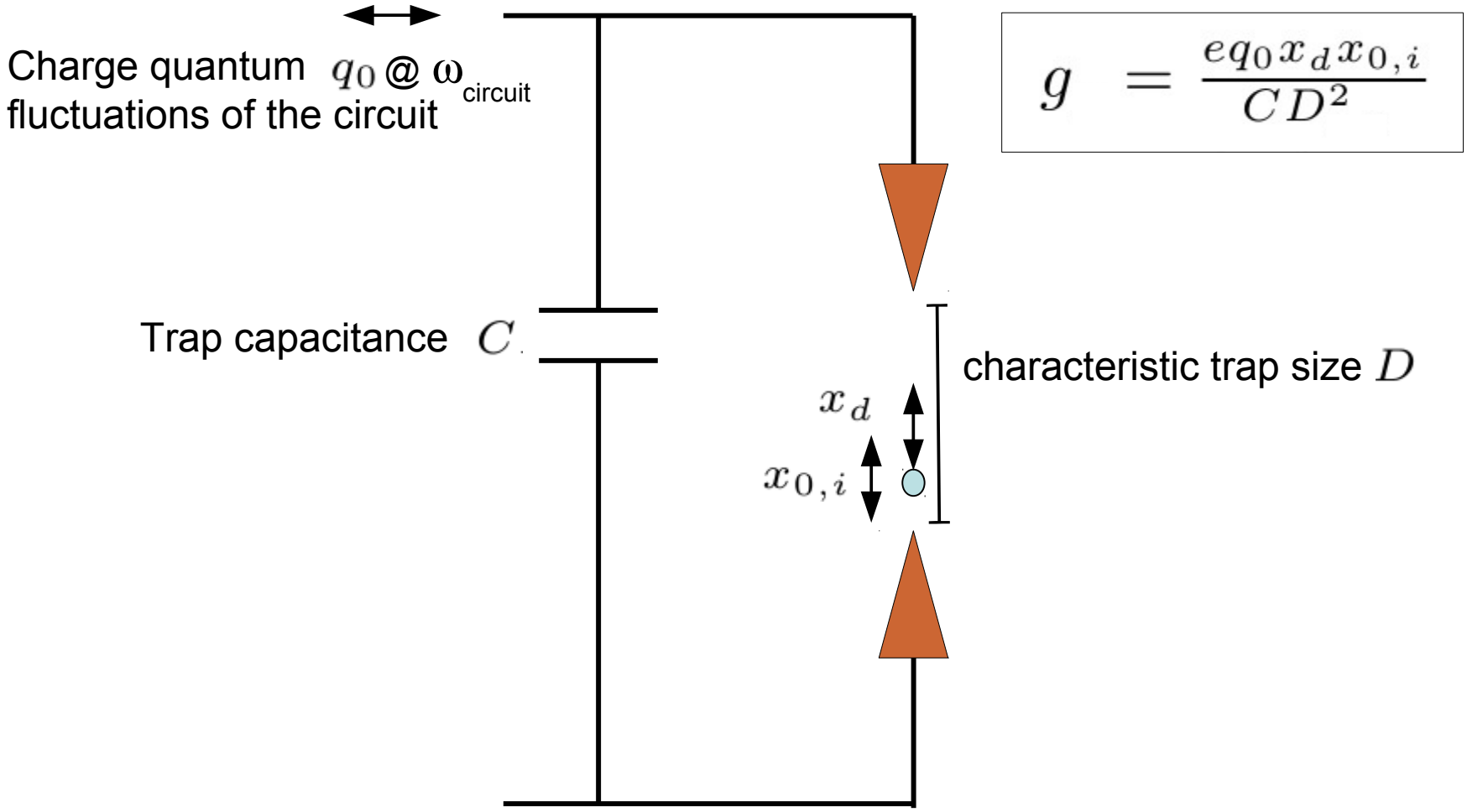
⇒ sidebands of the quantum motion on the pump field



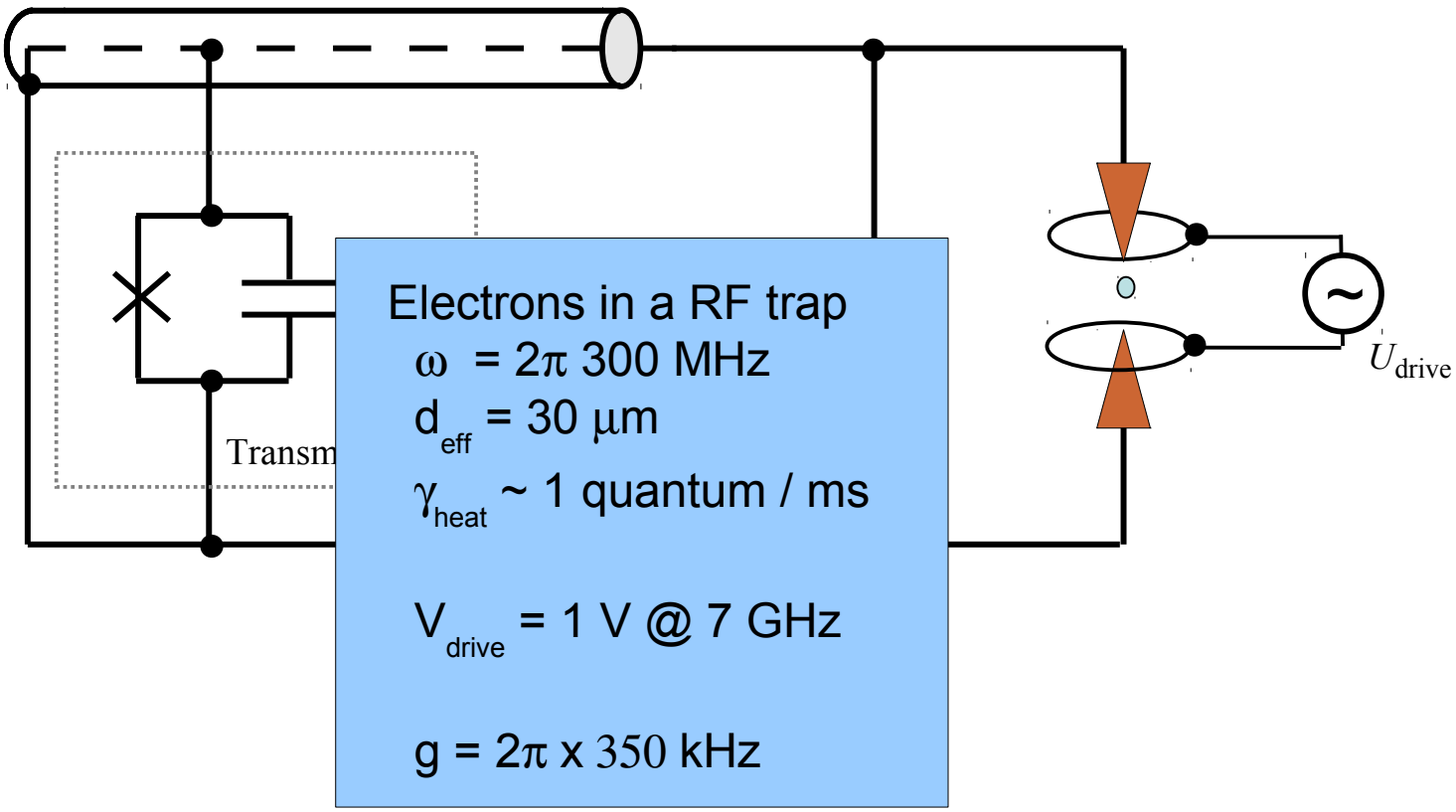
Quantum mixing

Parametric upconversion using a nonlinear induced current

⇒ sidebands of the quantum motion on the pump field



Quantum mixing



Electrons in a RF trap

$\omega = 2\pi$ 300 MHz

d_{eff} = 30 μm

γ_{heat} ~ 1 quantum / ms

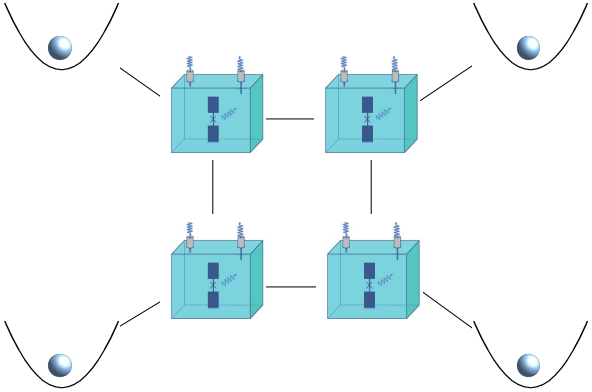
V_{drive} = 1 V @ 7 GHz

g = 2π x 350 kHz

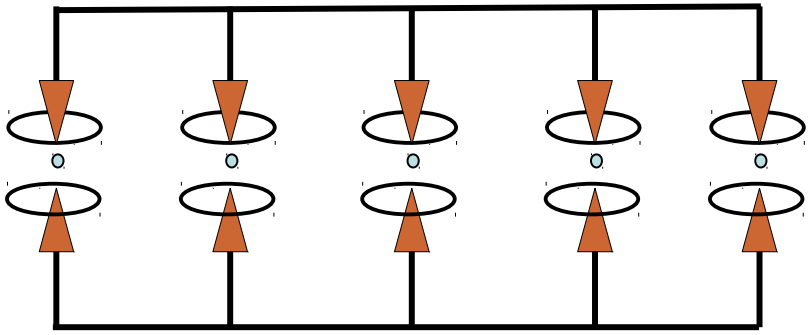
Daniilidis *et al*., in preparation

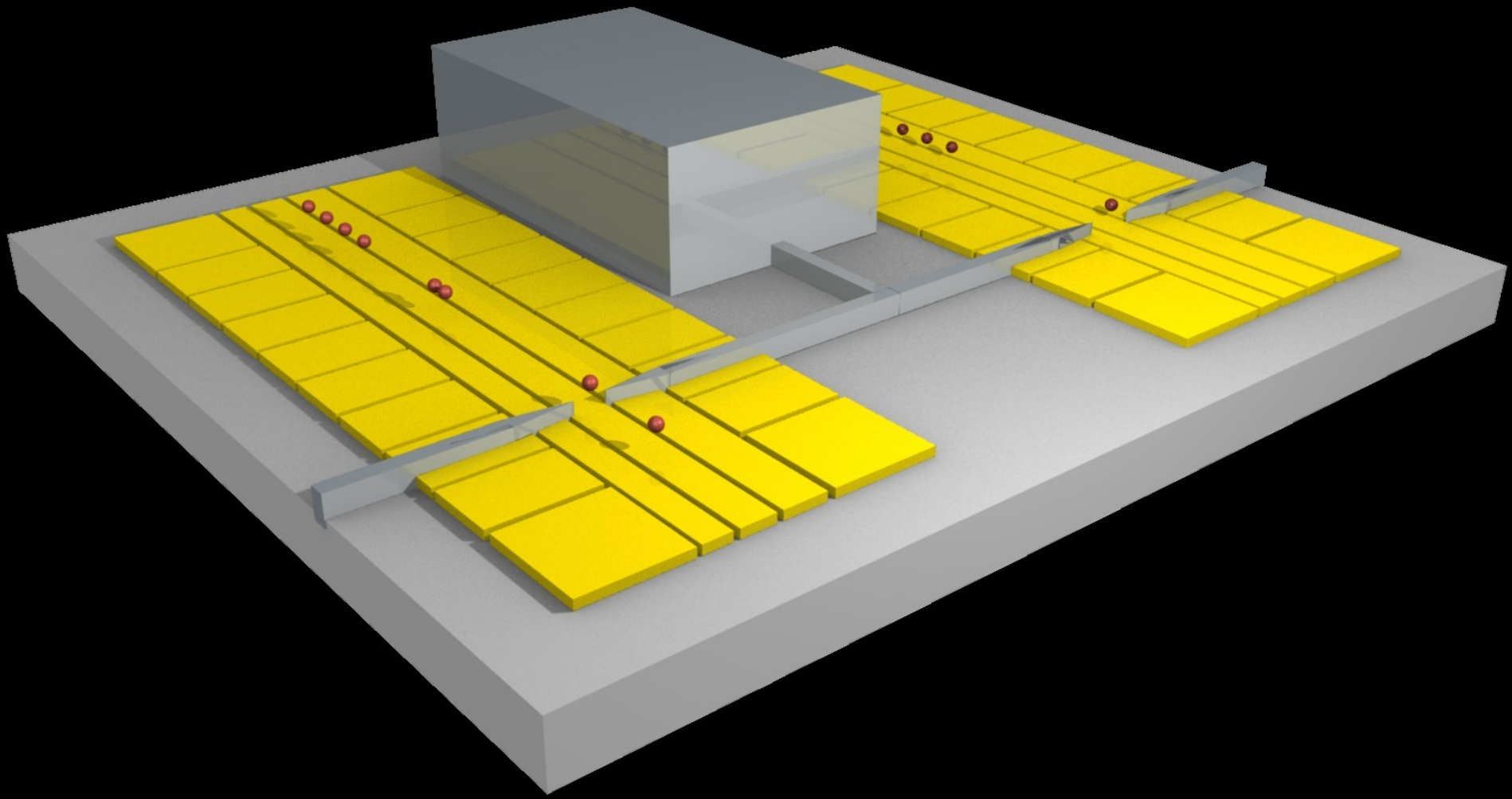
Some perspectives

1) quantum memory for JJ-qubits of seconds in the electron spin



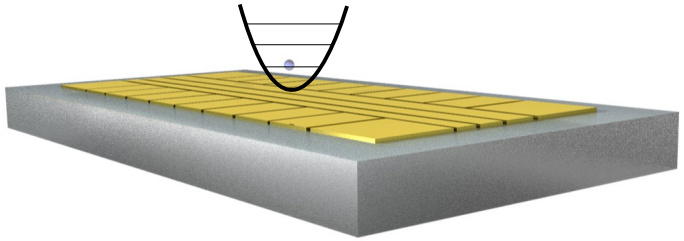
2) electron quantum computer





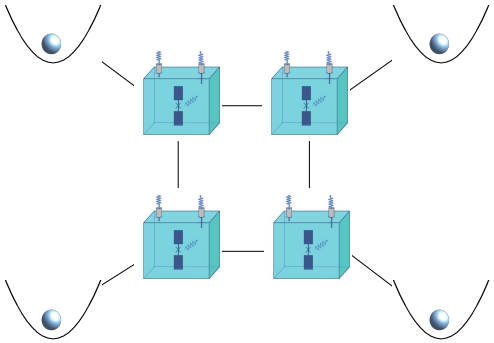
Summary

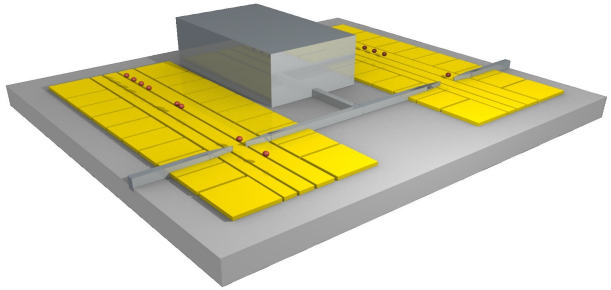
- Anomalous electric field noise



- Towards laser cooling a coil

- Novel quantum computing approaches





The group

- Greg Bolloton
- Nikos Daniliidis
- Dylan Gorman
- Sebastian Gerber
- Sönke Möller
- Sankara Narayanan
- Thaned (Hong) Pruttivarasin
- Michael Ramm
- Ishan Talukdar