# Coupling trapped ions via transmission lines

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*IESL-FORTH 29.09.09*

FWF Der Wissenschaftsfonds.

START project

MARIE CURIE ACTIONS

# Outline

- Quantum information with trapped ions
- Why wire-up trapped ions
- Coupling mechanism
- Experimental status

  -microfabricated traps

  -trap characterization

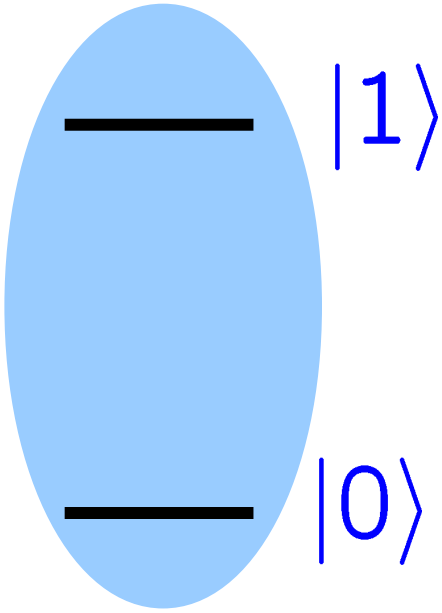
  -influence of coupling wire
- Outlook

# Why quantum information?

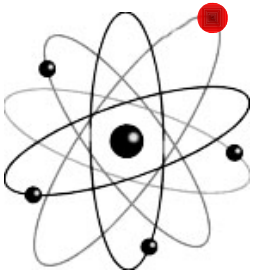
- Several known efficient quantum algorithms
- Quantum simulations
- Information is physical!

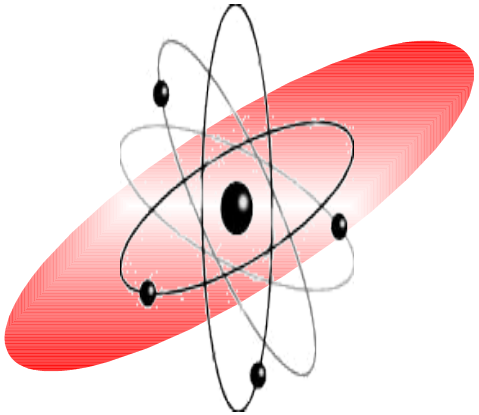
Qubit: two level system

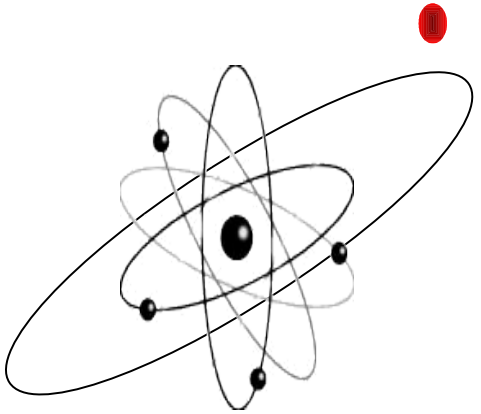
(photon, spin, atom, …)



# The atomic qubit

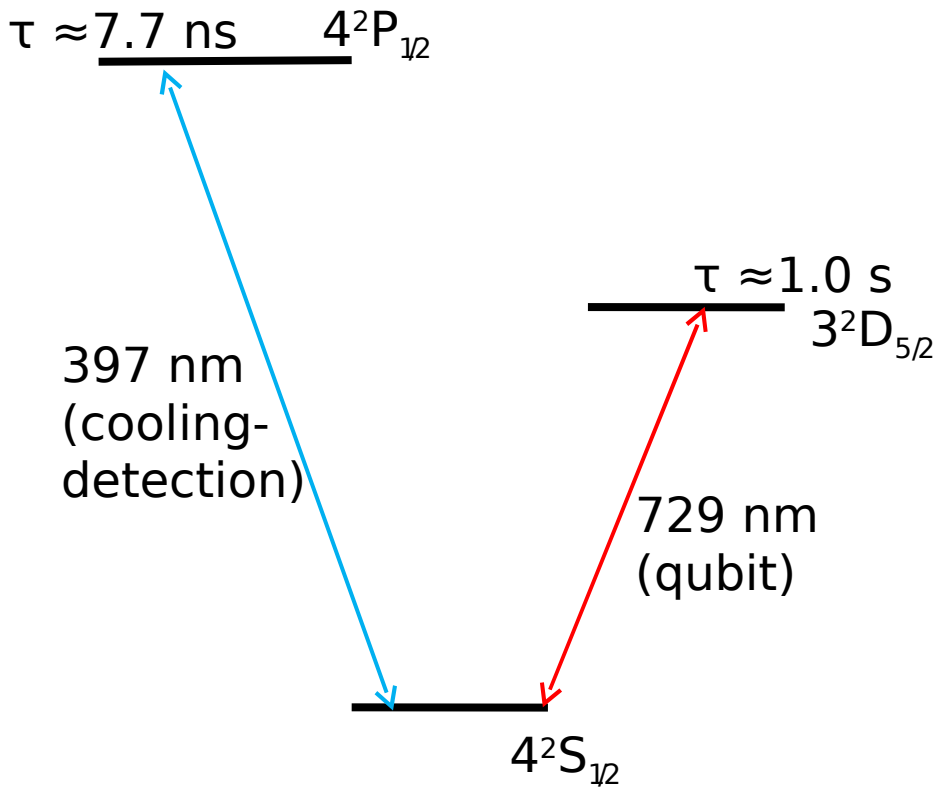




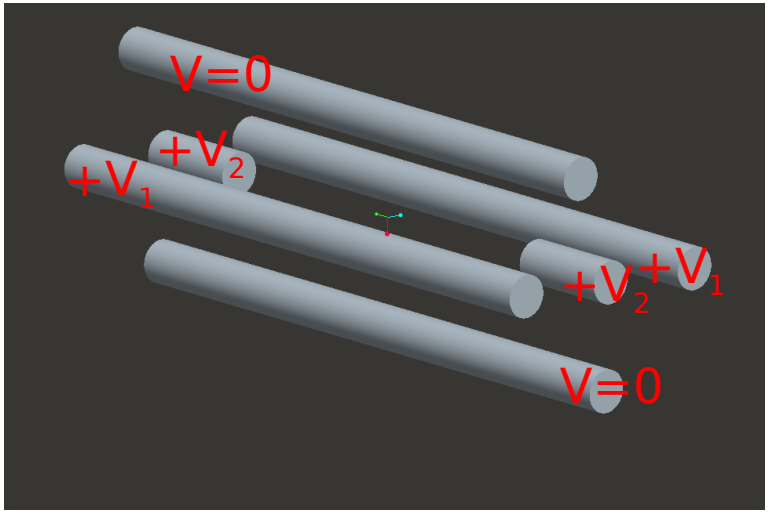


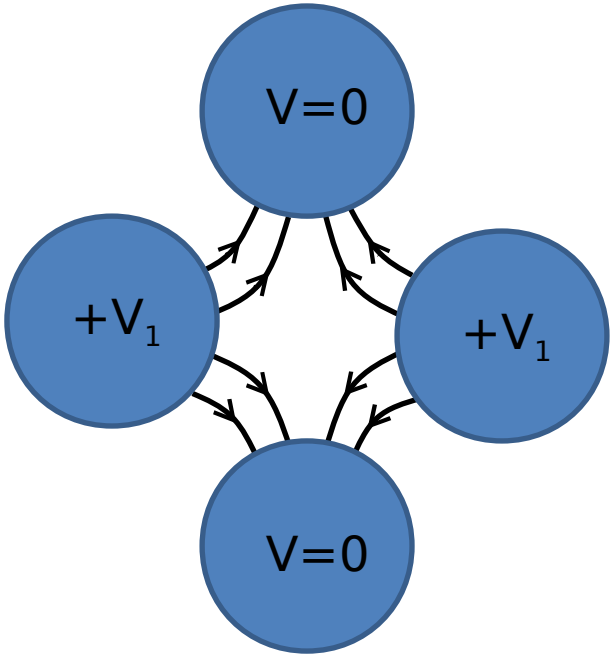
$|0\rangle$ $\alpha|0\rangle + \beta|1\rangle$ $|1\rangle$

# The $^{40}Ca^{+}$ ion


τ ≈7.7 ns
4²P1/2
τ ≈1.0 s
3²D5/2
397 nm
(cooling-
detection)
729 nm
(qubit)
4²S1/2

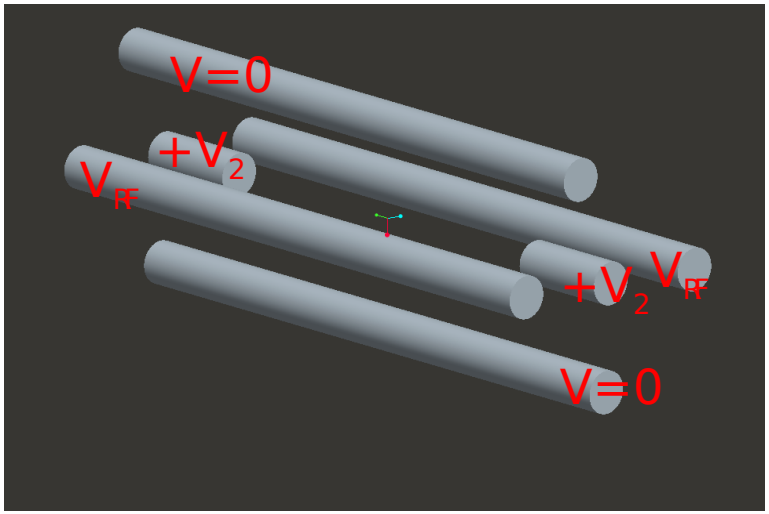
# Ion trap electrodynamics

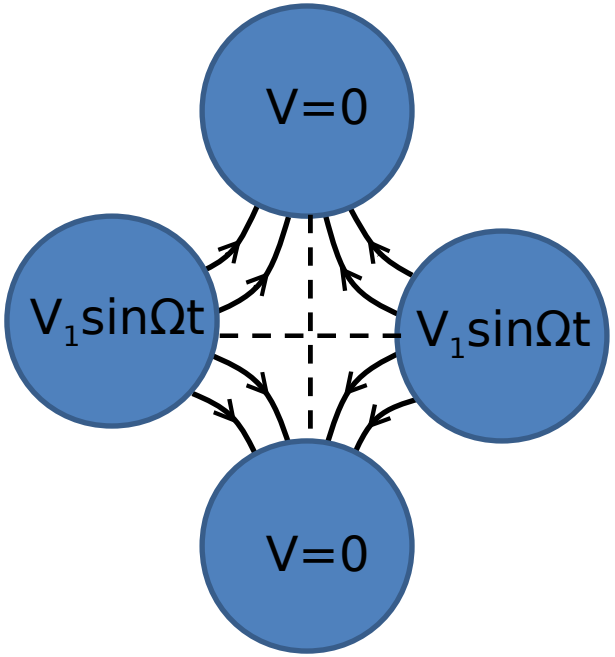



Unstable!

# Ion trap electrodynamics



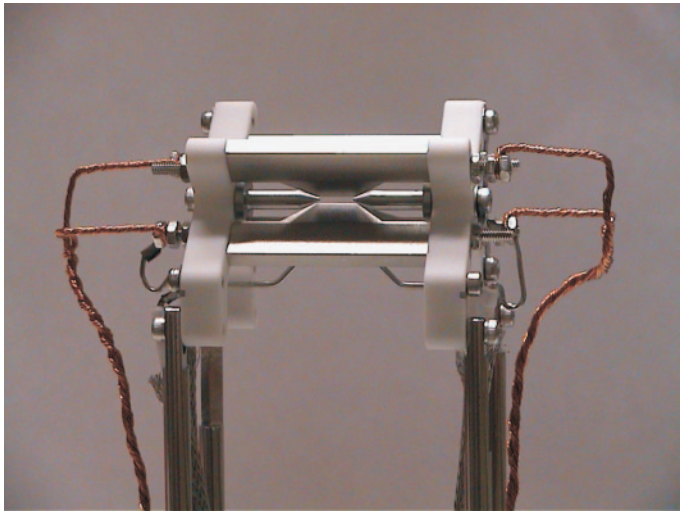



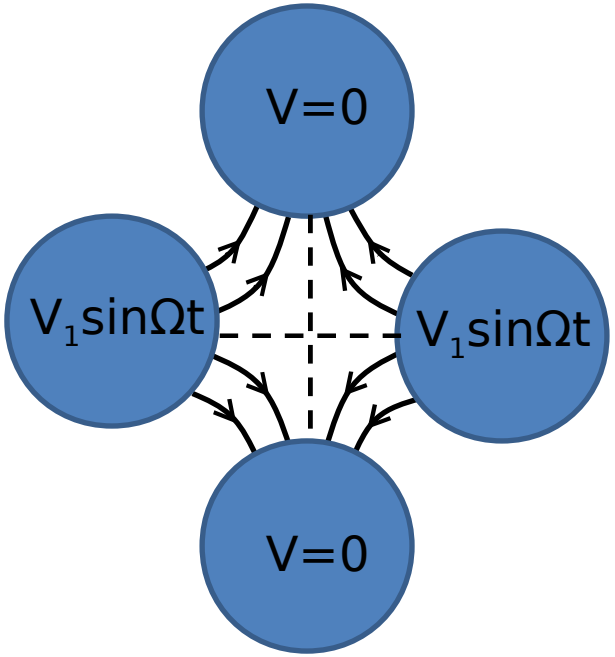

Dynamically trapped

$$\Phi_{eff} \propto \left(\nabla V\right)^2$$

$$H_{eff} = \frac{p^2}{2m} + \frac{1}{2} m \left(\omega_x^2 x^2 + \omega_y^2 y^2 + \omega_z^2 z^2\right)$$

# Ion trap electrodynamics



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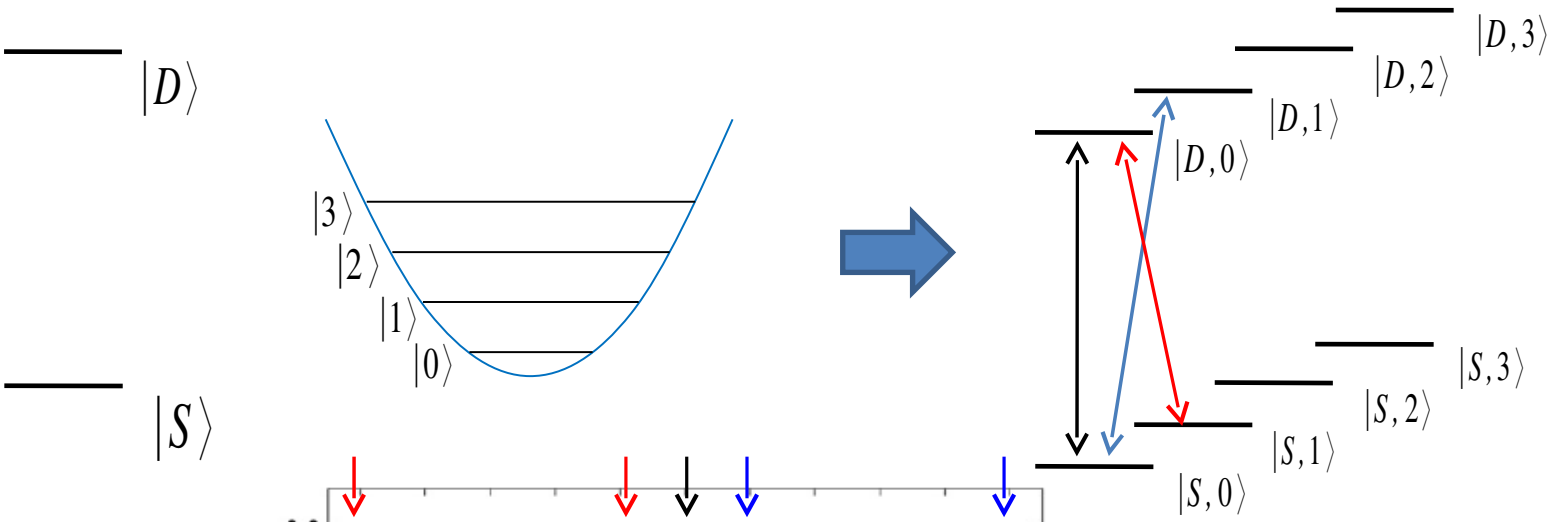
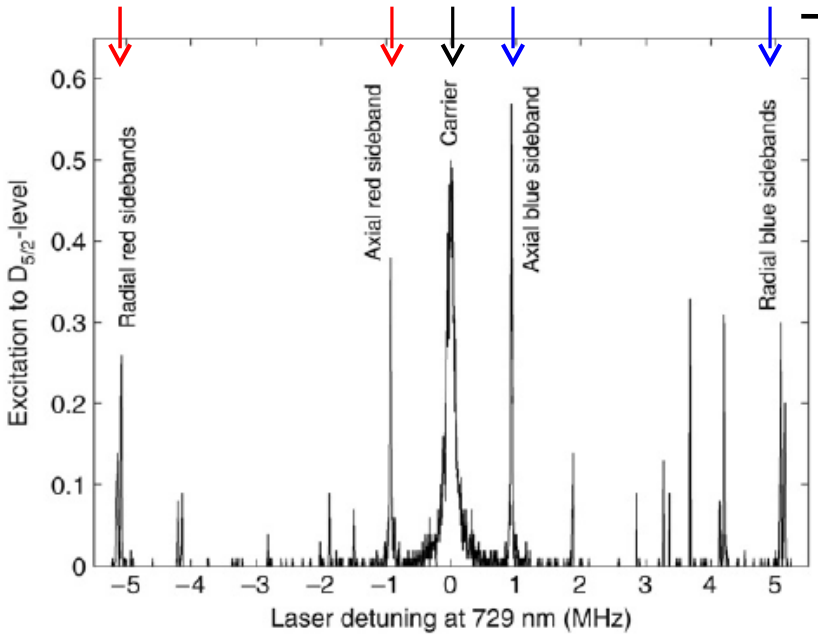
# Hilbert space

Two-level system ⊗ Motional state ladder

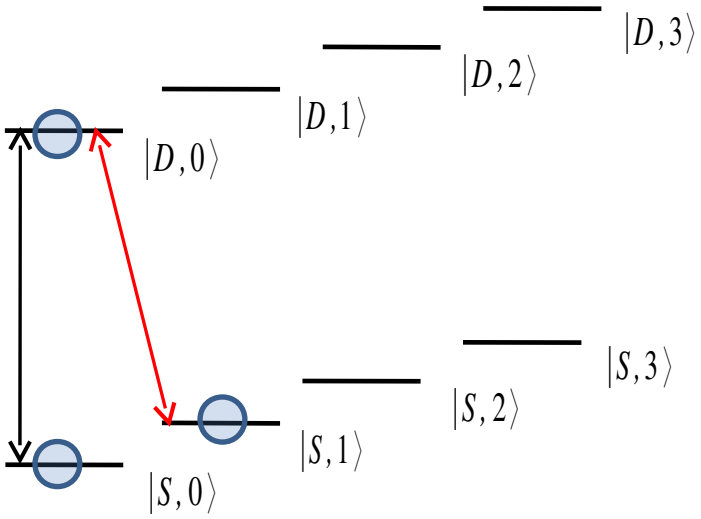



Graph from H. Häffner *et al.*

Phys. Rep. **469** 155 (2008)

# Map qubit onto motional state




0.Initialize

$$|S,0\rangle$$

1. Carrier pulse

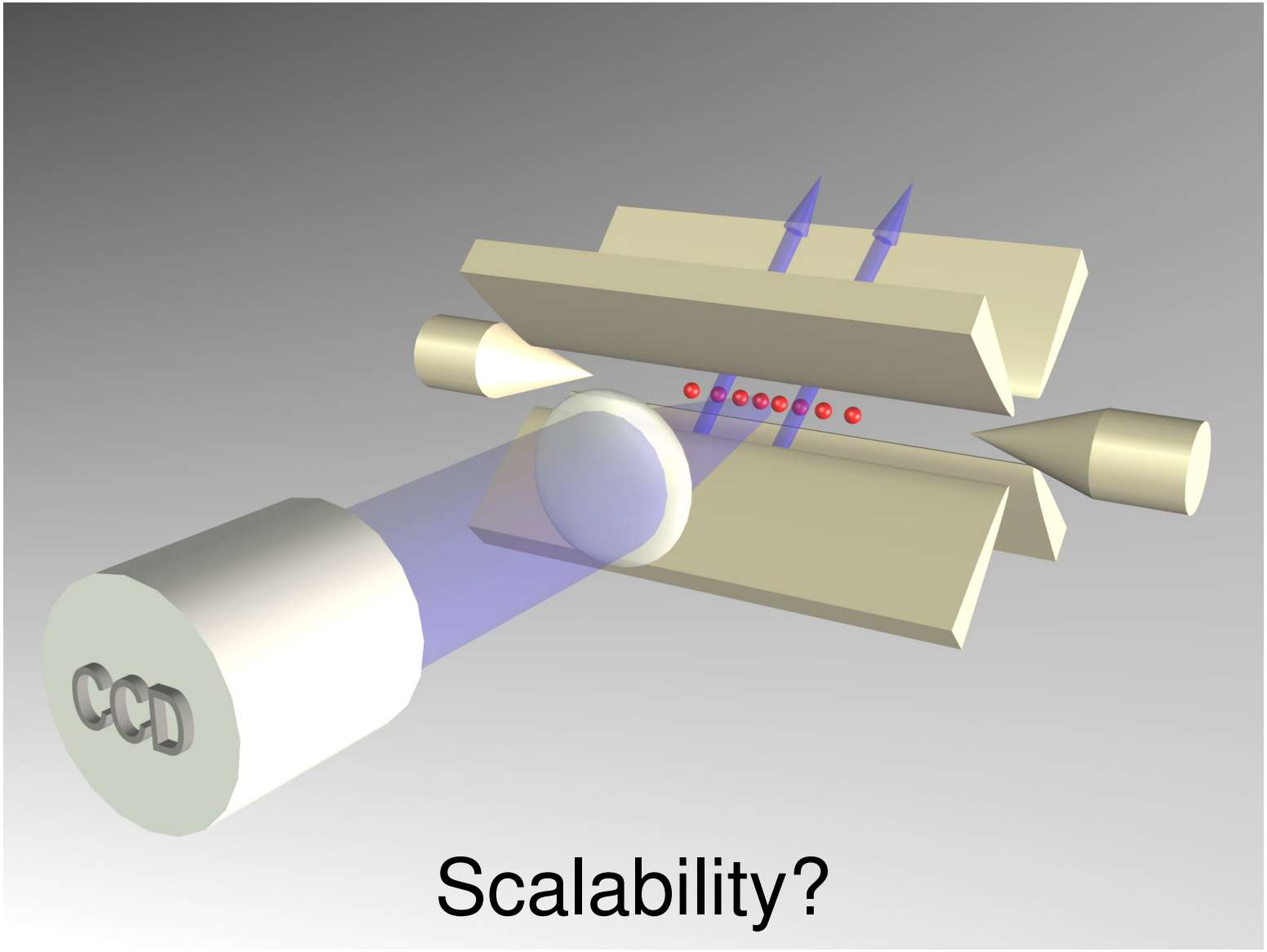
$$\alpha|S,0\rangle+\beta|D,0\rangle$$

2. Red sideband pulse

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

*I. Cirac, P. Zoller, PRL **74**, 4091 (1995)*

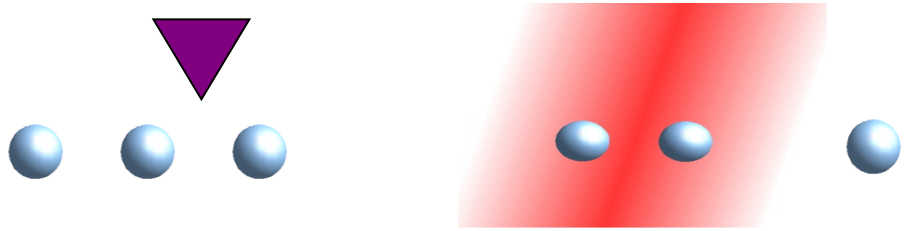
# The linear trap approach

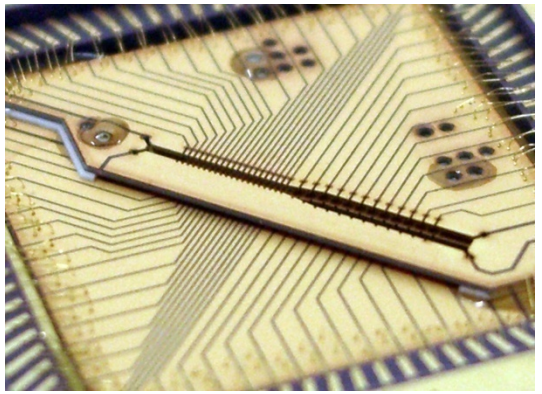


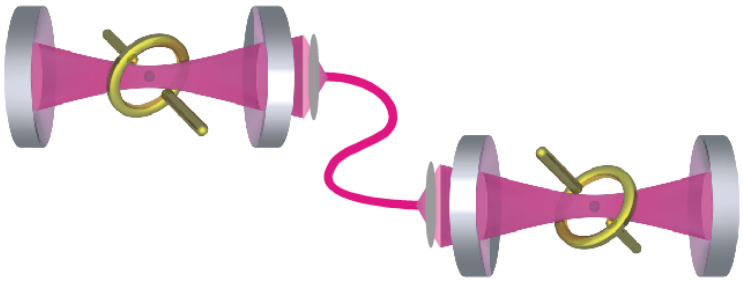

Scalability?

# Scaling approaches

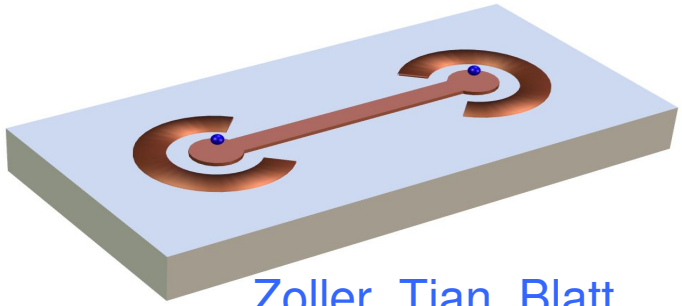
Kielpinski, Monroe, Wineland





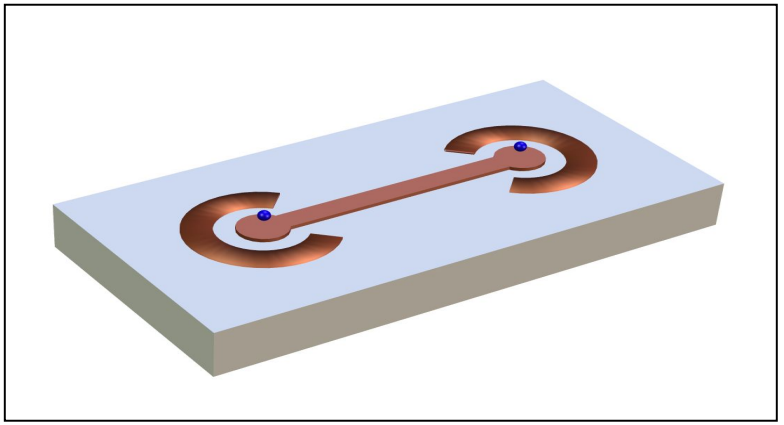


Cirac, Zoller, Kimble, Mabuchi



Zoller, Tian, Blatt

# Scaling approaches

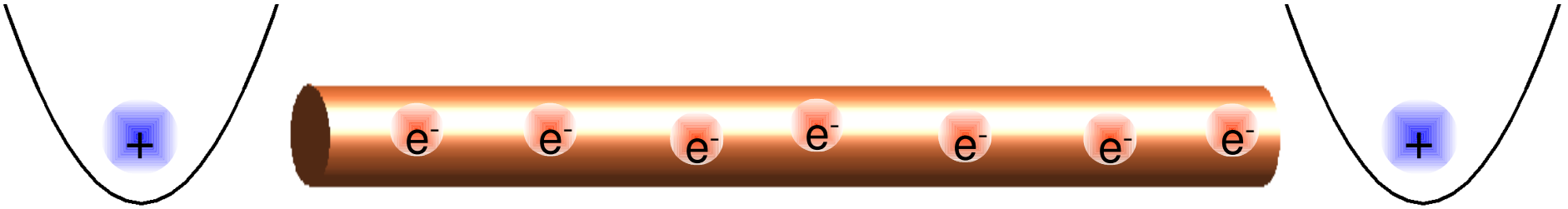


# Wiring-up trapped ions

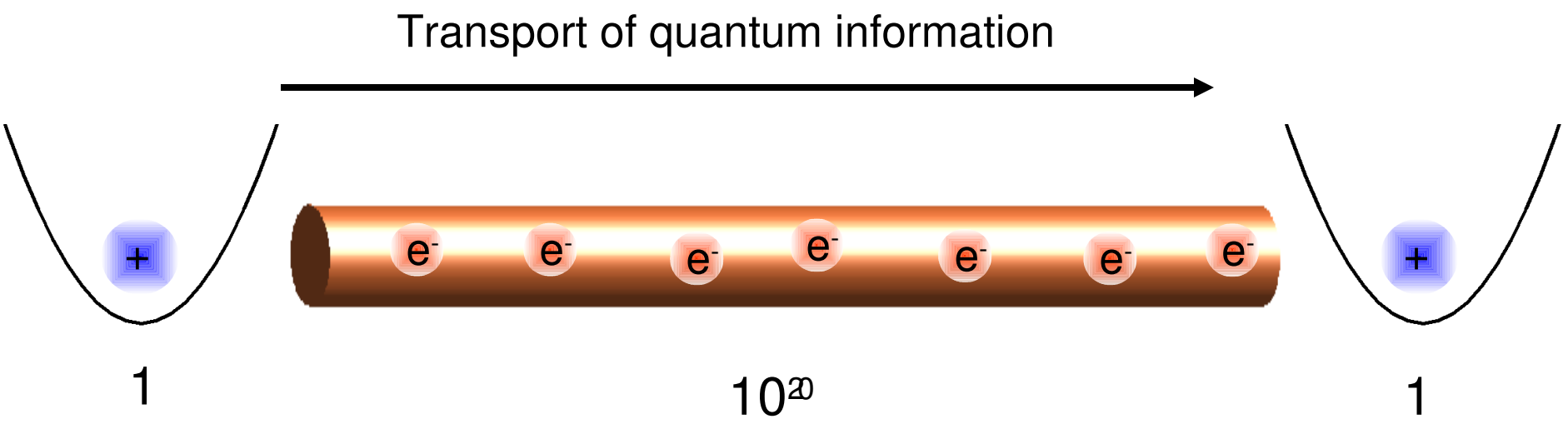
Two trapped ions …

# Wiring-up trapped ions

Two trapped ions + a wire



# Wiring-up trapped ions



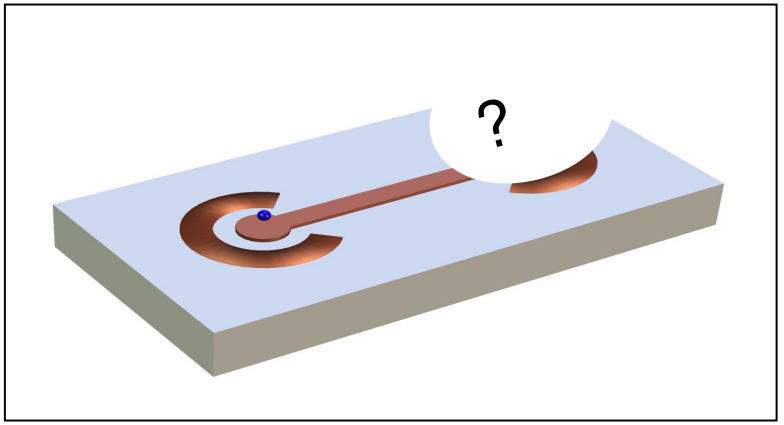

Quantum coherence in the wire?

Nature can be generous!

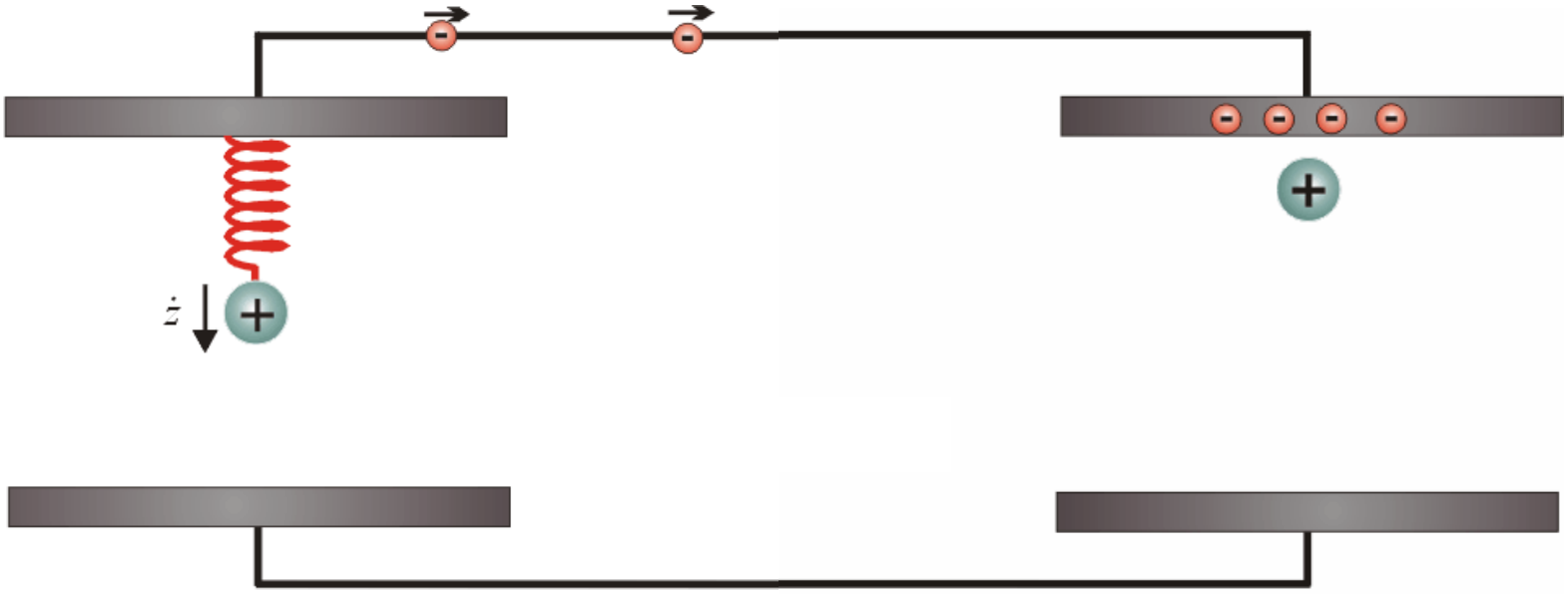
# Wiring-up trapped ions

# Applications

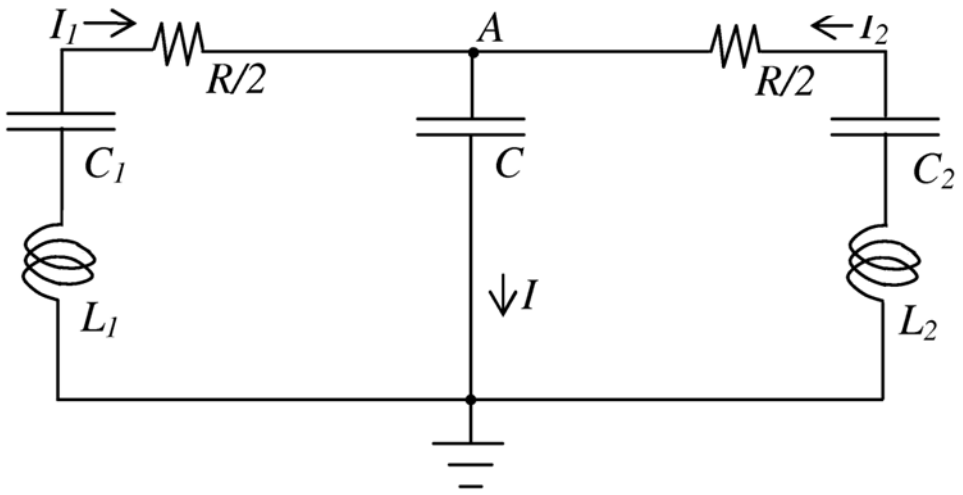
- Scalable quantum computing with trapped ions/electrons
- Decoherence in charge transport
- Wire-mediated laser cooling of “exotic” ion species

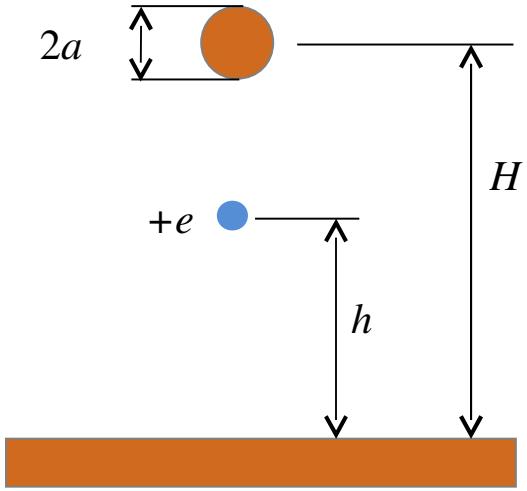


# Coupling mechanism



# Coupling mechanism




$$H = \frac{p_1^2}{2m} + \frac{1}{2}m\omega_1^2 y_1^2 + \frac{p_2^2}{2m} + \frac{1}{2}m\omega_2^2 y_2^2 + \gamma y_1 y_2$$

$$t_{ex} \sim \omega \cdot L \cdot (H-h)^2$$

Expected $t_{ex} \approx 100$ ms $(h = 200\ \mu\text{m})$

Projected $t_{ex} \approx 1$ ms $(h = 50\ \mu\text{m})$


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

D.J. Heinzen and D.J. Wineland, PRA **47**, 2977 (1990), N. Daniilidis *et al.* J Phys. B, **42**, 154012

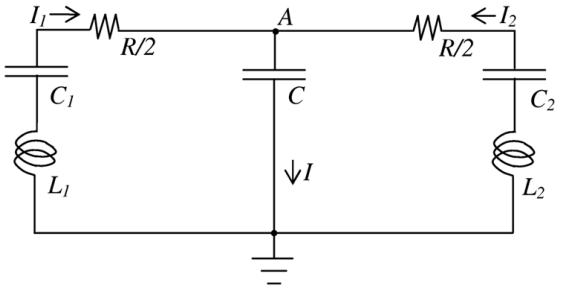
# Decoherence

## Dissipation in the wire

$(\omega = 2\pi \cdot 1\,\mathrm{MHz},\ D \approx 3.6 \cdot 50\,\mu m,\ R = 0.5\,\Omega)$

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

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



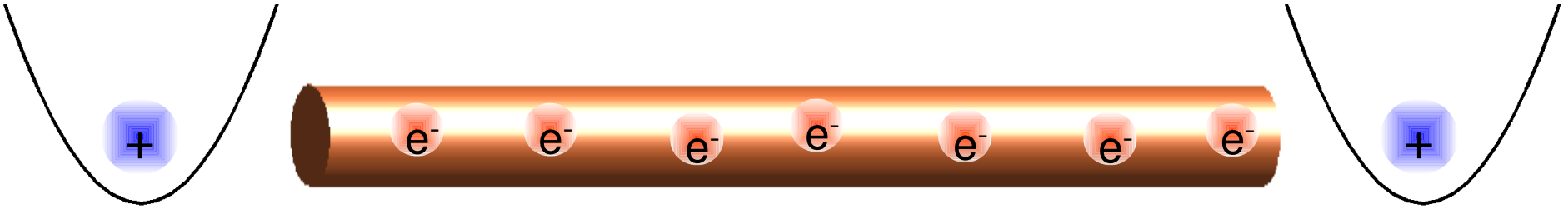

## Johnson noise heating

$\gamma_J = \frac{k_B T \Delta f}{\hbar\omega} = \frac{2\pi k_B T}{\hbar Q} \approx 3 \cdot 10^{-3}\,\frac{1}{s}$

**Cool apparatus to cryogenic temperatures**

N. Daniilidis *et al.* J Phys. B, **42**, 154012 (2009)

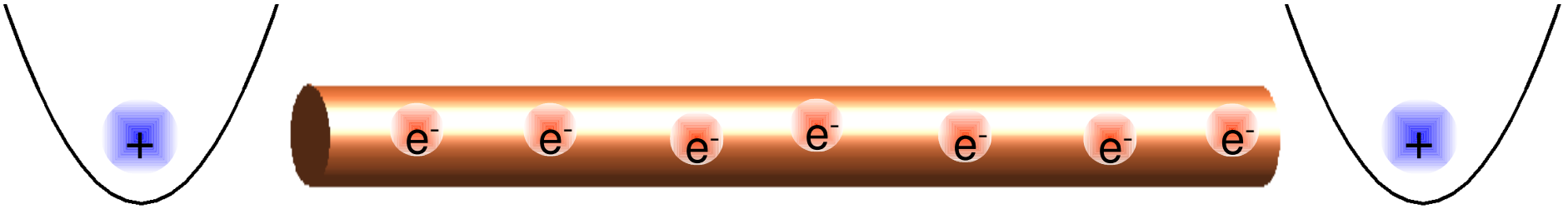
# State transfer




$|0\rangle$

$$\frac{|0\rangle + |n\rangle}{\sqrt{2}}$$

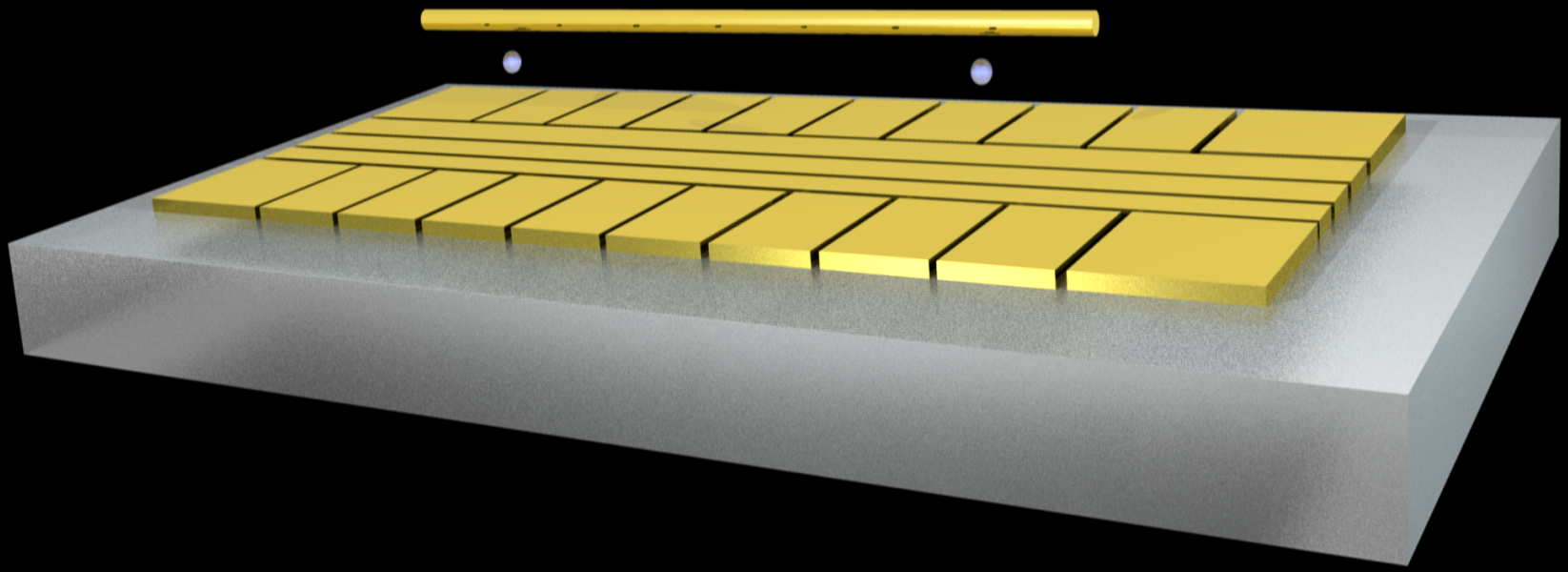
# State transfer



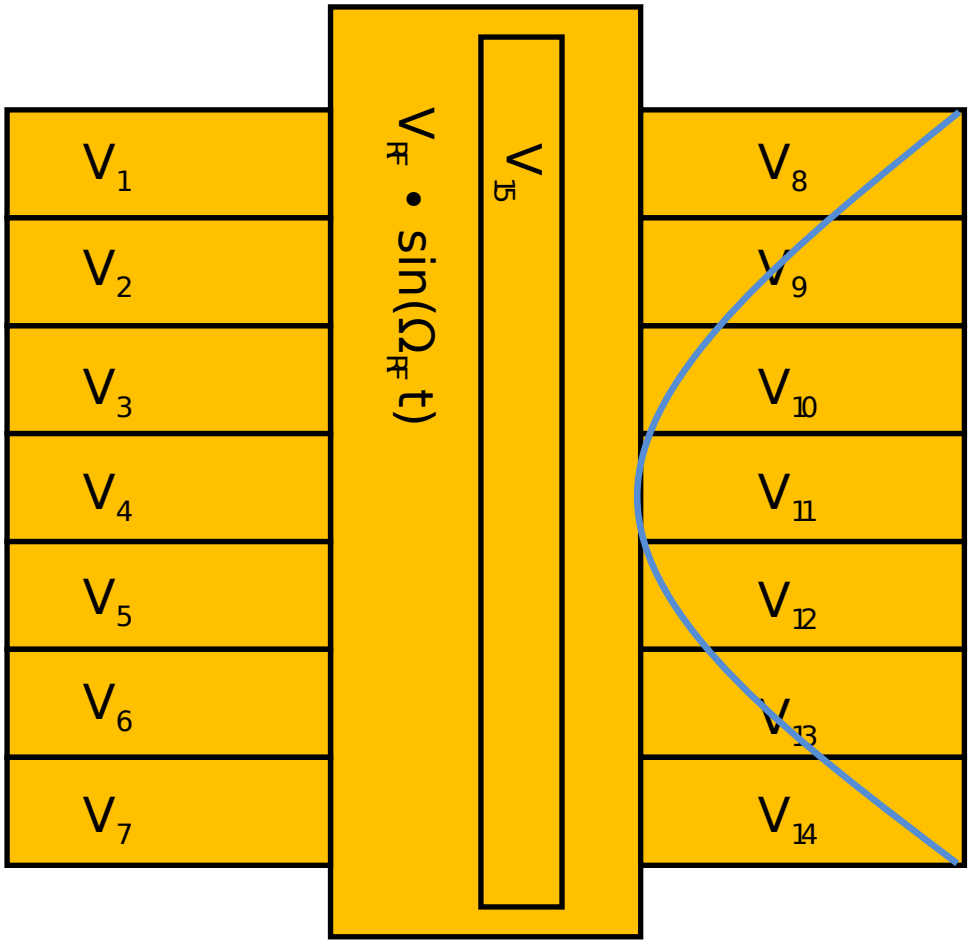

$$\frac{|0\rangle + e^{-in\Theta}|n\rangle}{\sqrt{2}}$$

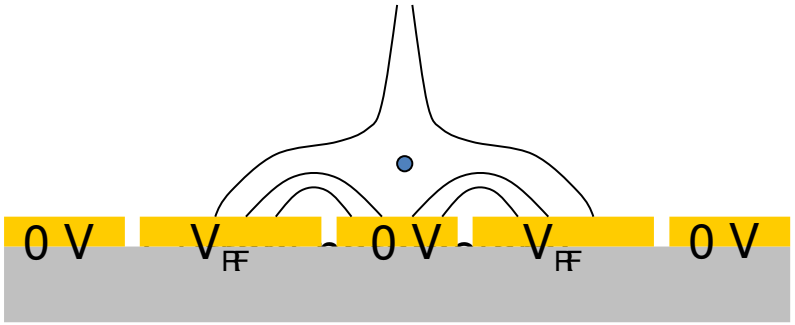
$$|0\rangle$$

# Experimental approach



# Planar ion traps




Ion height ≈ 220 μm

$\Omega_{RF}/2\pi$ = 10-15 MHz

$V_{RF} \approx 100$ V

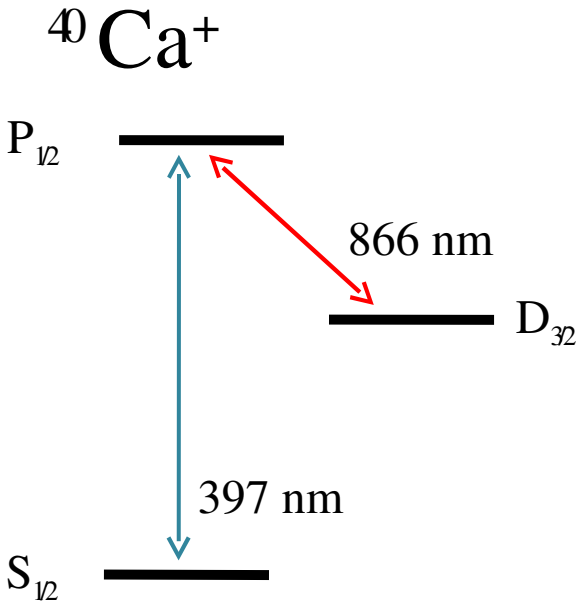
$V_{DC} < 10$ V

$\omega_H \approx 2\pi \cdot 1.3$ MHz

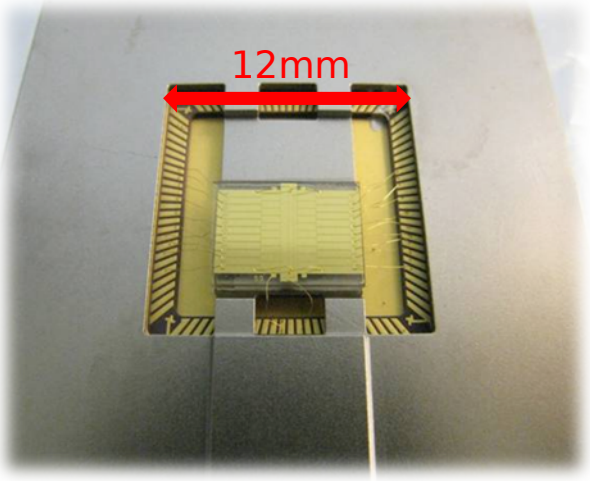
$\omega_V \approx 2\pi \cdot 1.5$ MHz

$\omega_A \approx 2\pi \cdot 300$ kHz

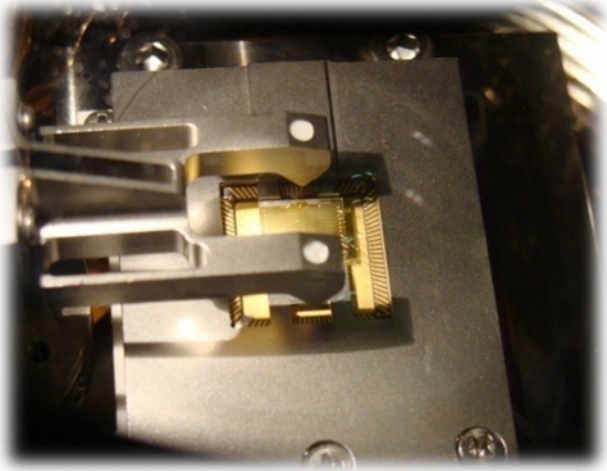
# Experimental system




Laser cooling and detection:
397nm and 866nm laser



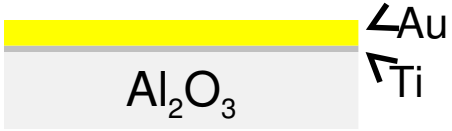

Gold on sapphire microfabricated trap



Wire on translation stage

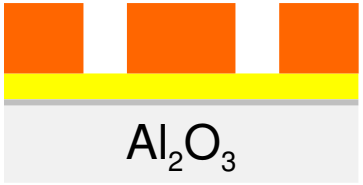
# Trap fabrication

1. Evaporation



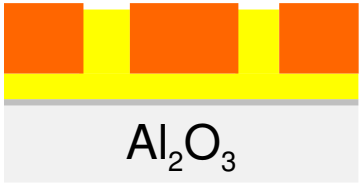

i. 5 nm Ti adhesion layer
ii. 100 nm Au seed layer

2. Lithography



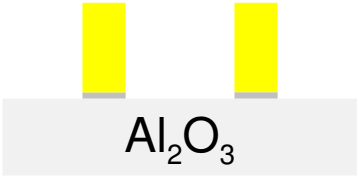

5 µm thick photoresist

3. Electroplating




4-5 µm thick Au plated layer

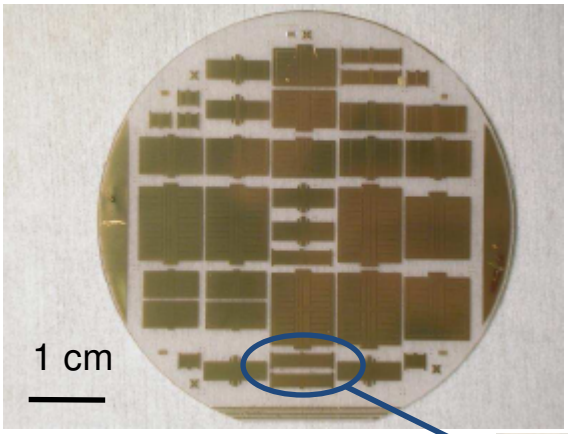
4. Cleaning/Etching



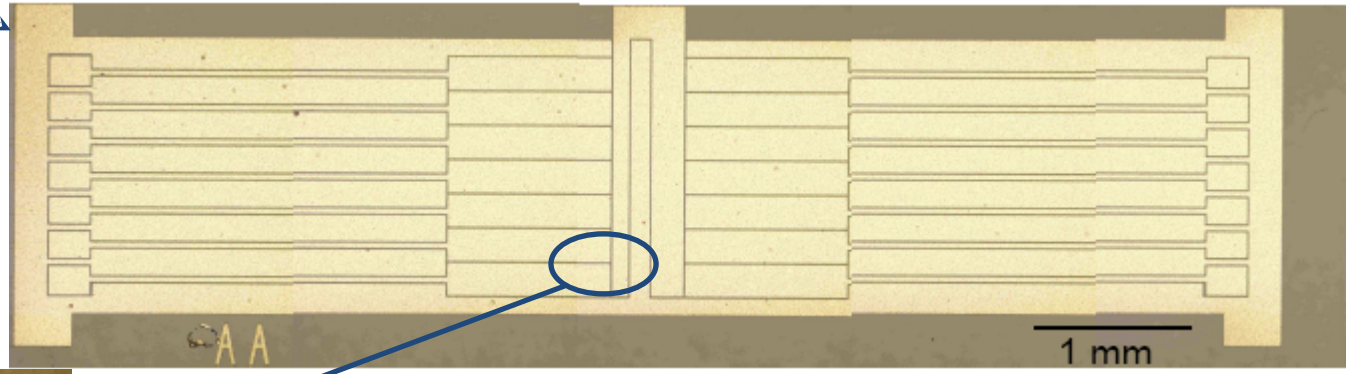

i. Resist removal
ii. Au etch
iii. Ti etch

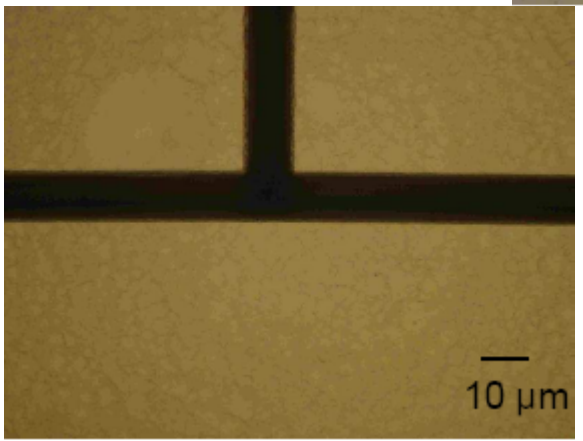
N. Daniilidis *et.al.* in preparation,
*Collaboration with A. Wallraff, ETH, Zürich*

# Fabrication results



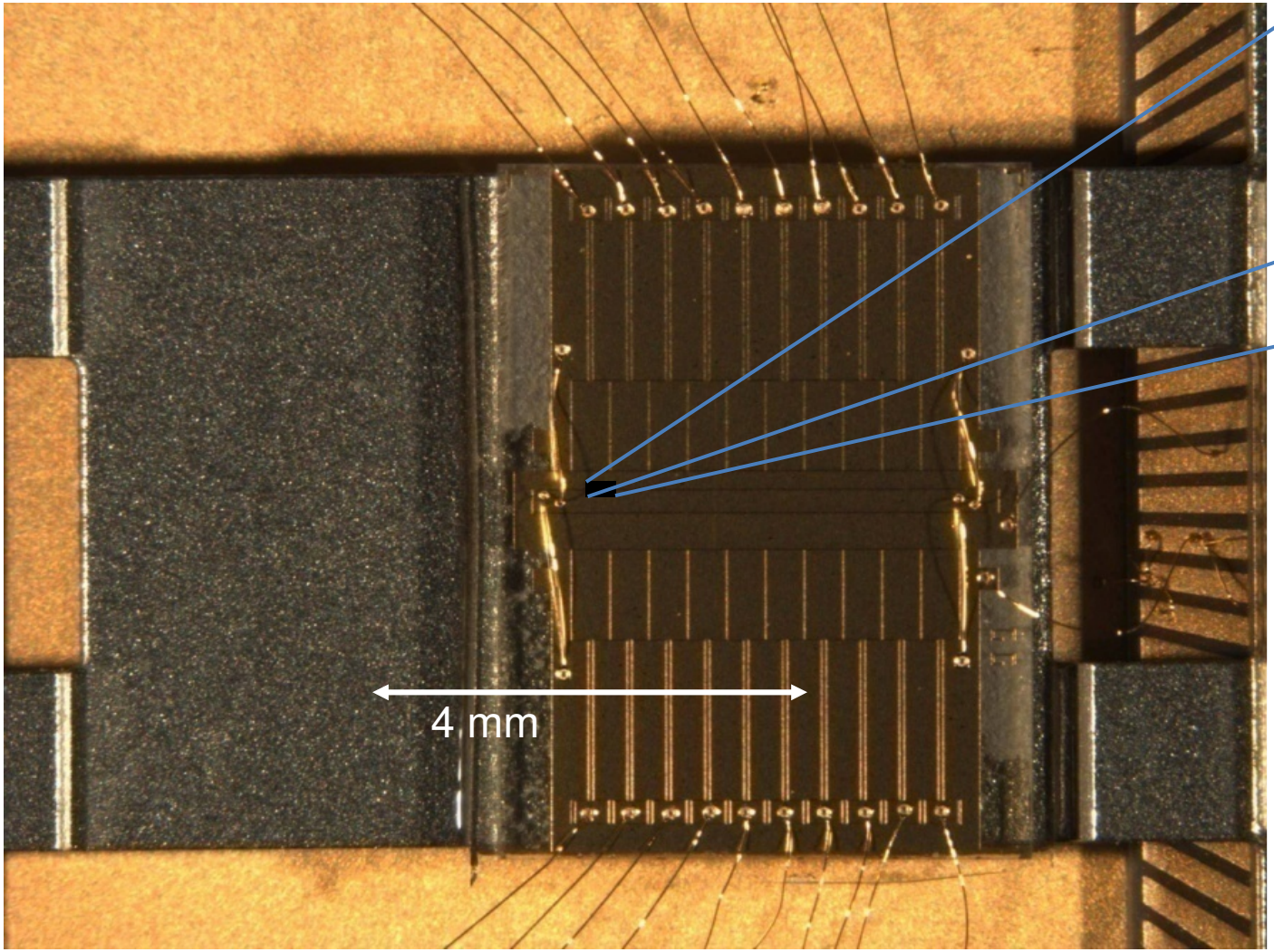

Au layer thickness 5 µm, rms roughness 20 nm

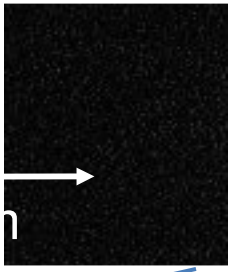



Feature size: 10 µm

# Ions!



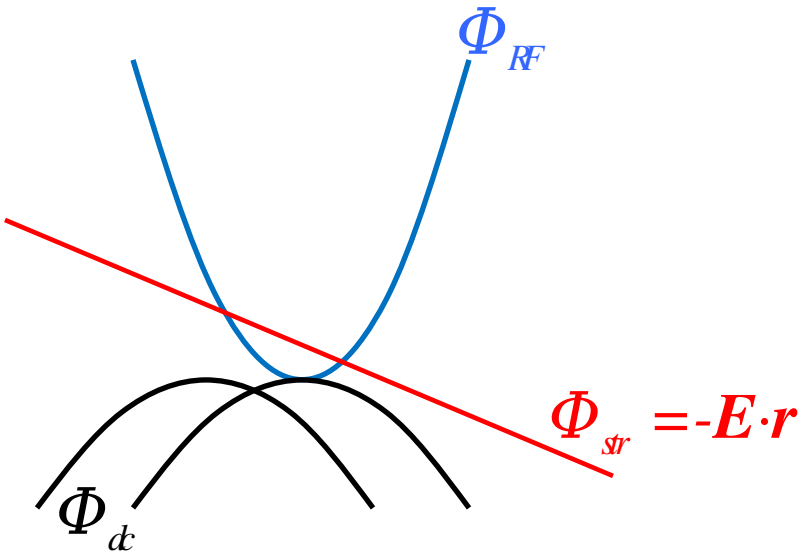



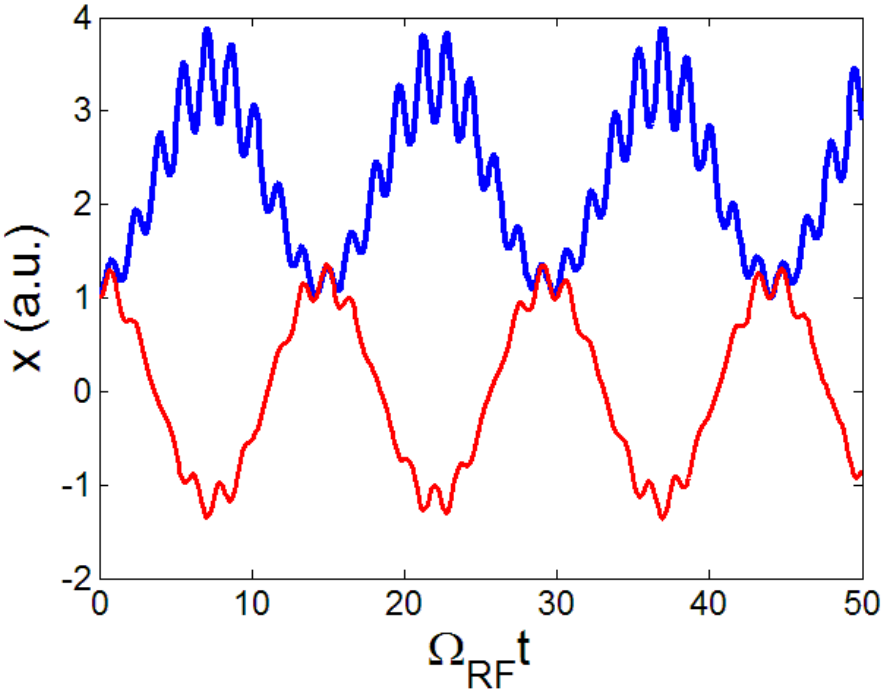
But

-Stray charges

-Ion heating

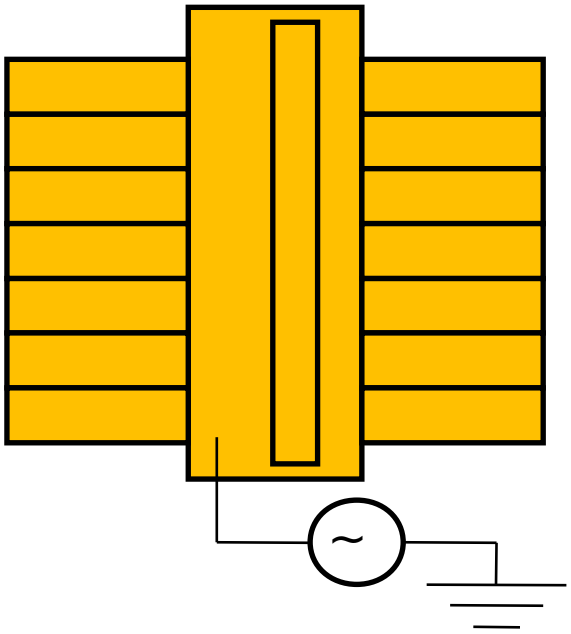
# Effect of stray fields



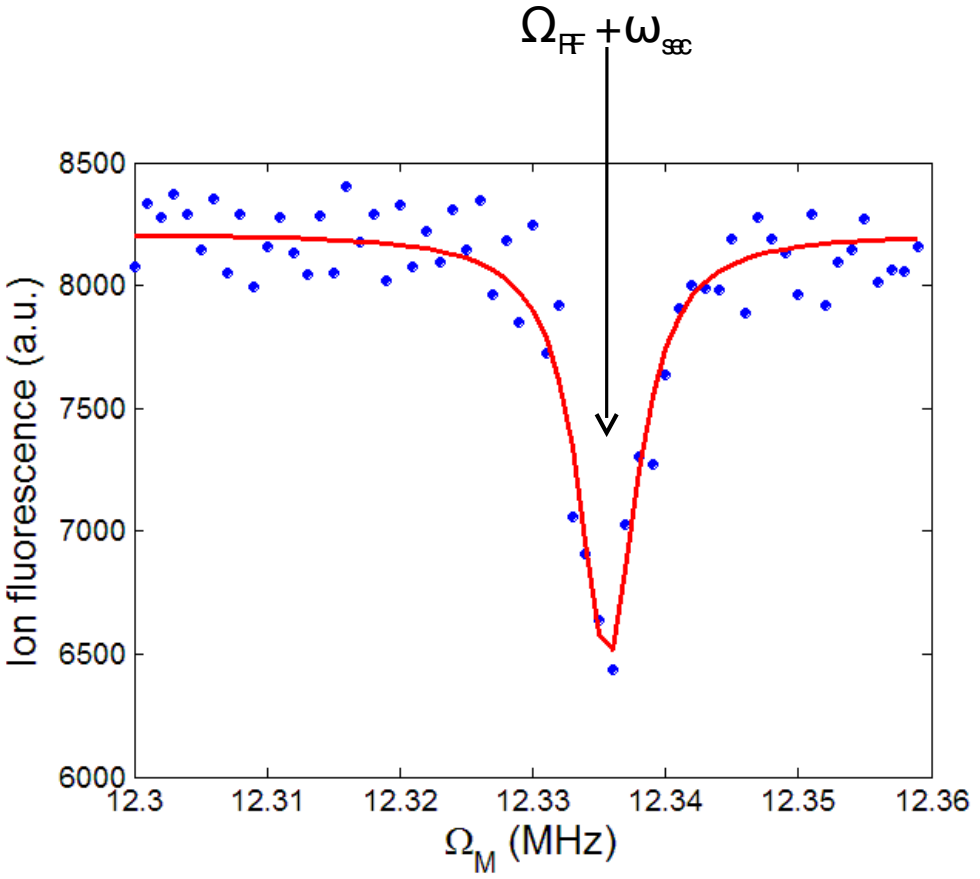




Stray fields lead to increased “micromotion”

# Detection of “micromotion”

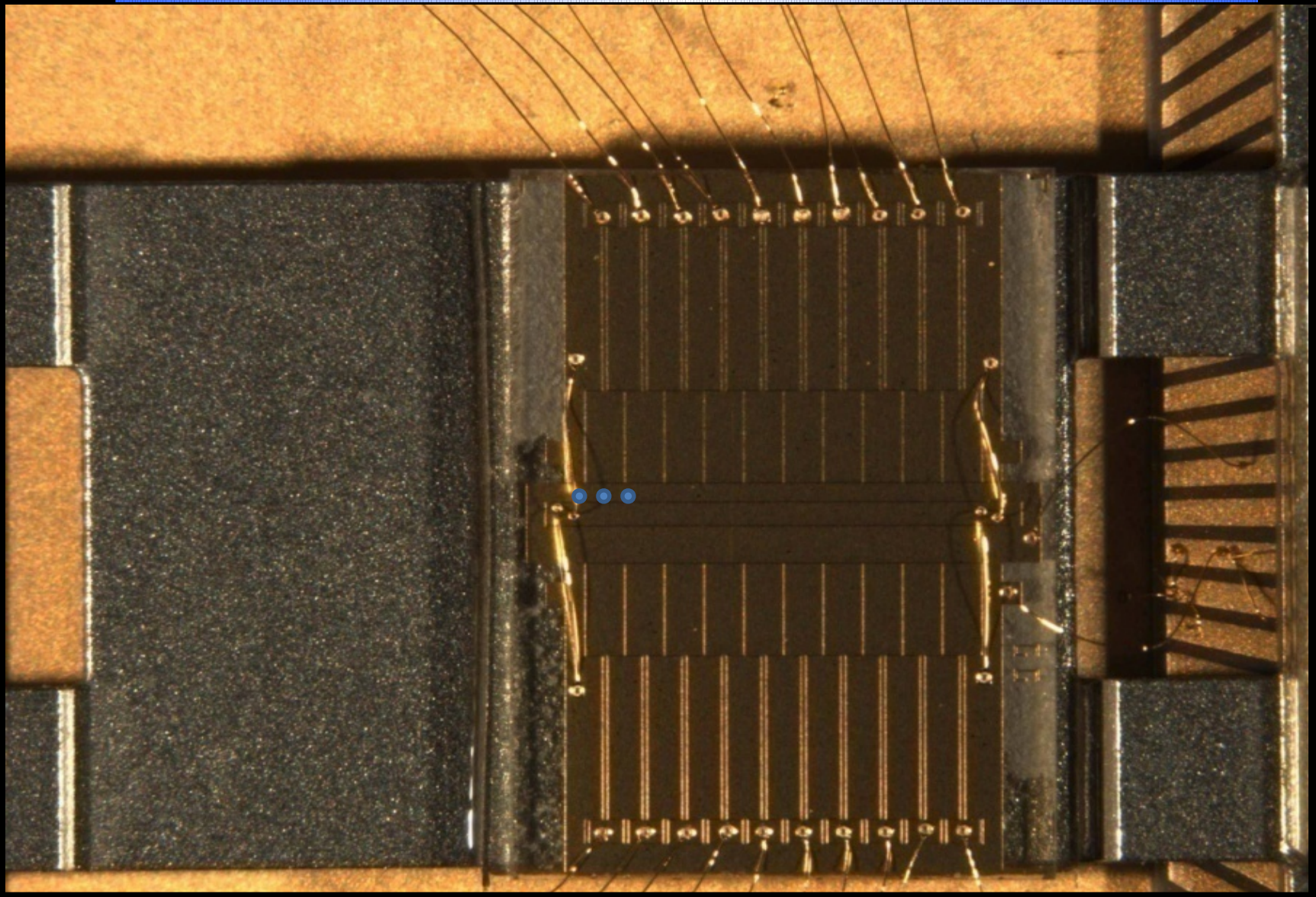



$$V_{RF} \cdot \sin(\Omega_{RF} t) + V_a \cdot \sin(\Omega_M t))$$



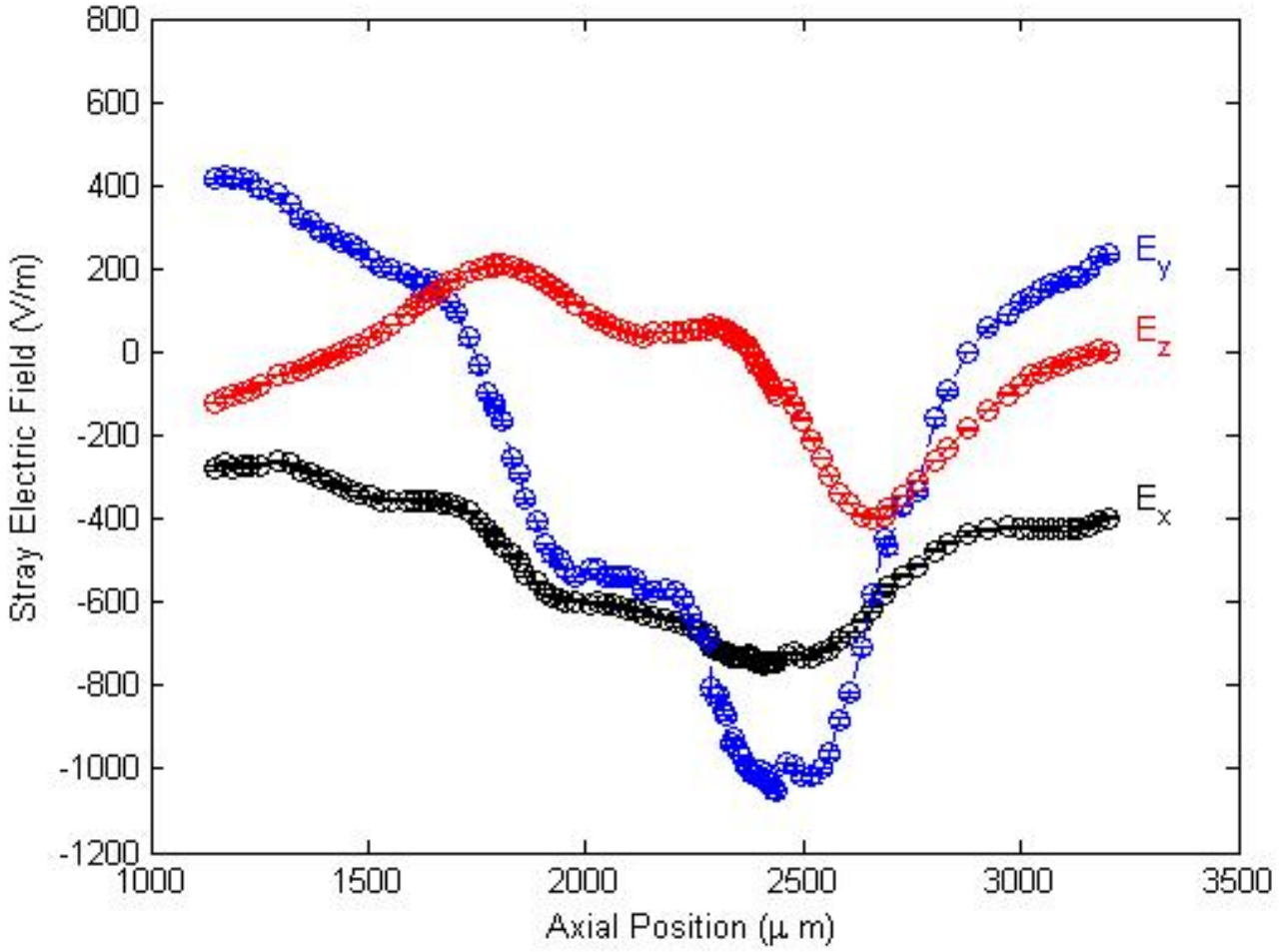

Compensate micromotion ↔ Find stray electrostatic field

# Mapping electrostatic field



Collaboration with F. Schmidt-Kaler, Univ. Ulm

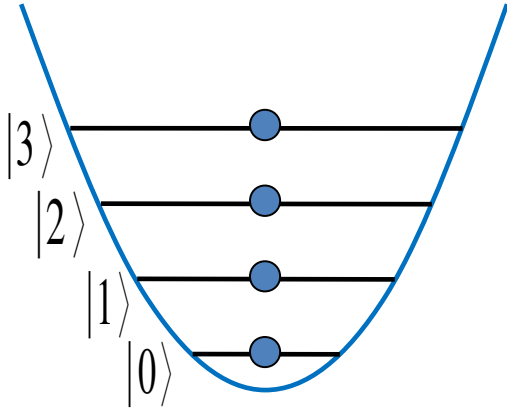
# Mapping electrostatic field



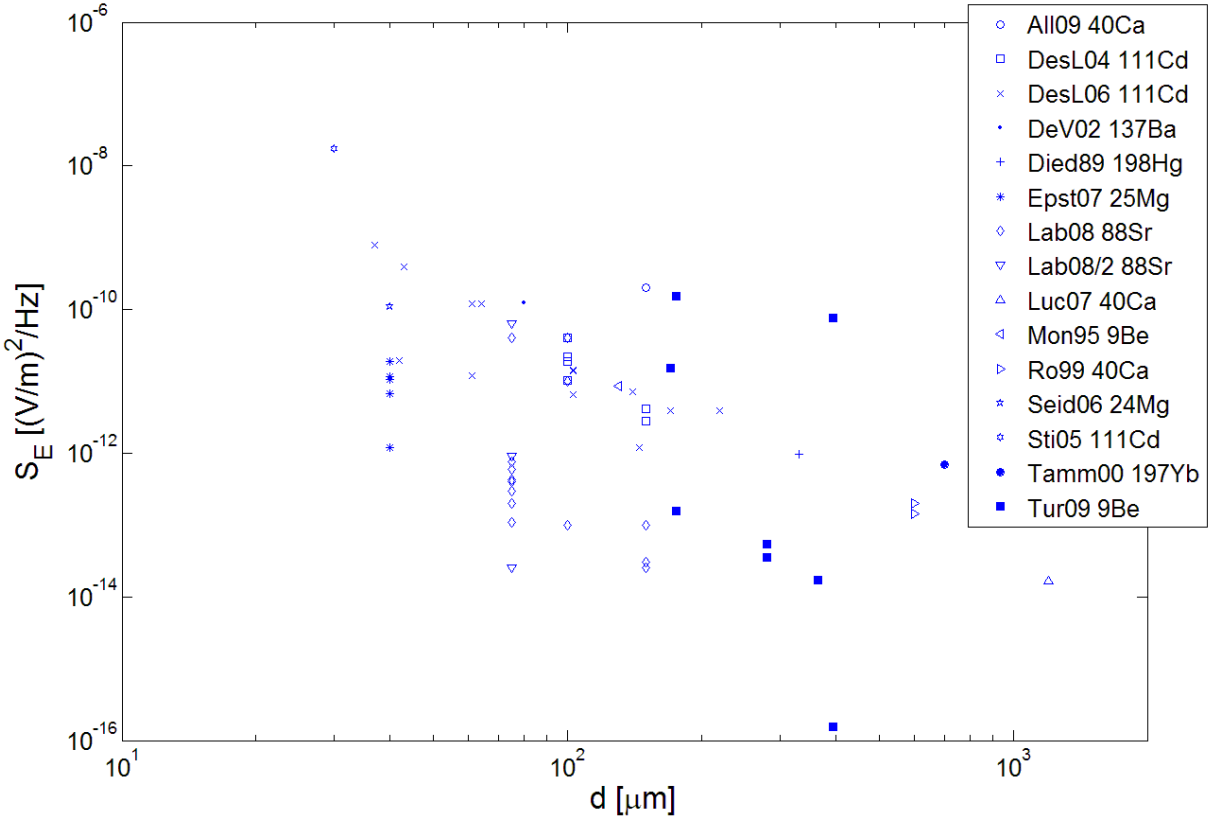

Long term (~month) stability of the stray fields!

S. Narayanan *et. al.* in preparation

# Ion heating



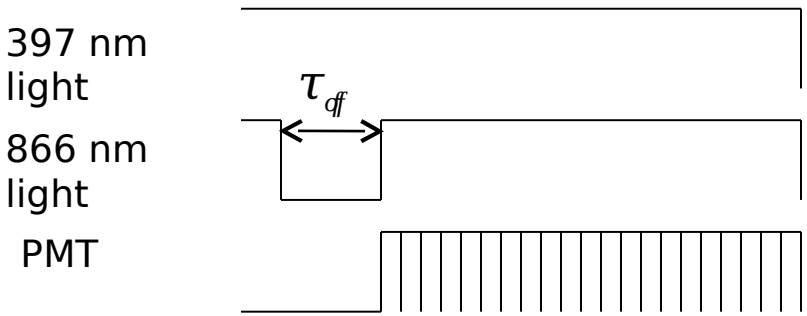

$$\frac{d\langle n\rangle}{dt} \approx \frac{e^2}{4m\hbar\omega} S_E(\omega)$$

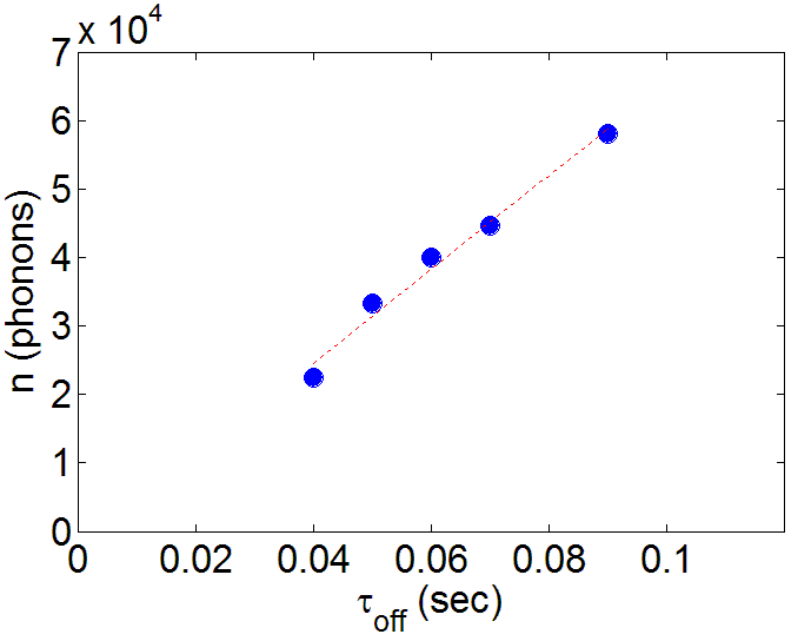


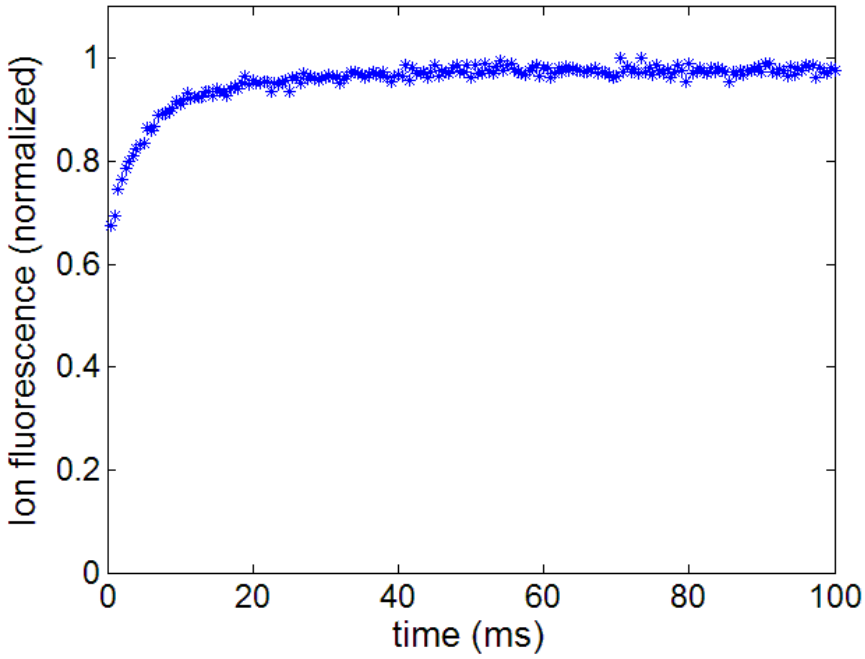


Q. A. Turchette *et. al.* PRA **61** 063418 (2006)
R. J. Epstein *et.al.* PRA **76** 033411 (2007)

# Heating rate measurement



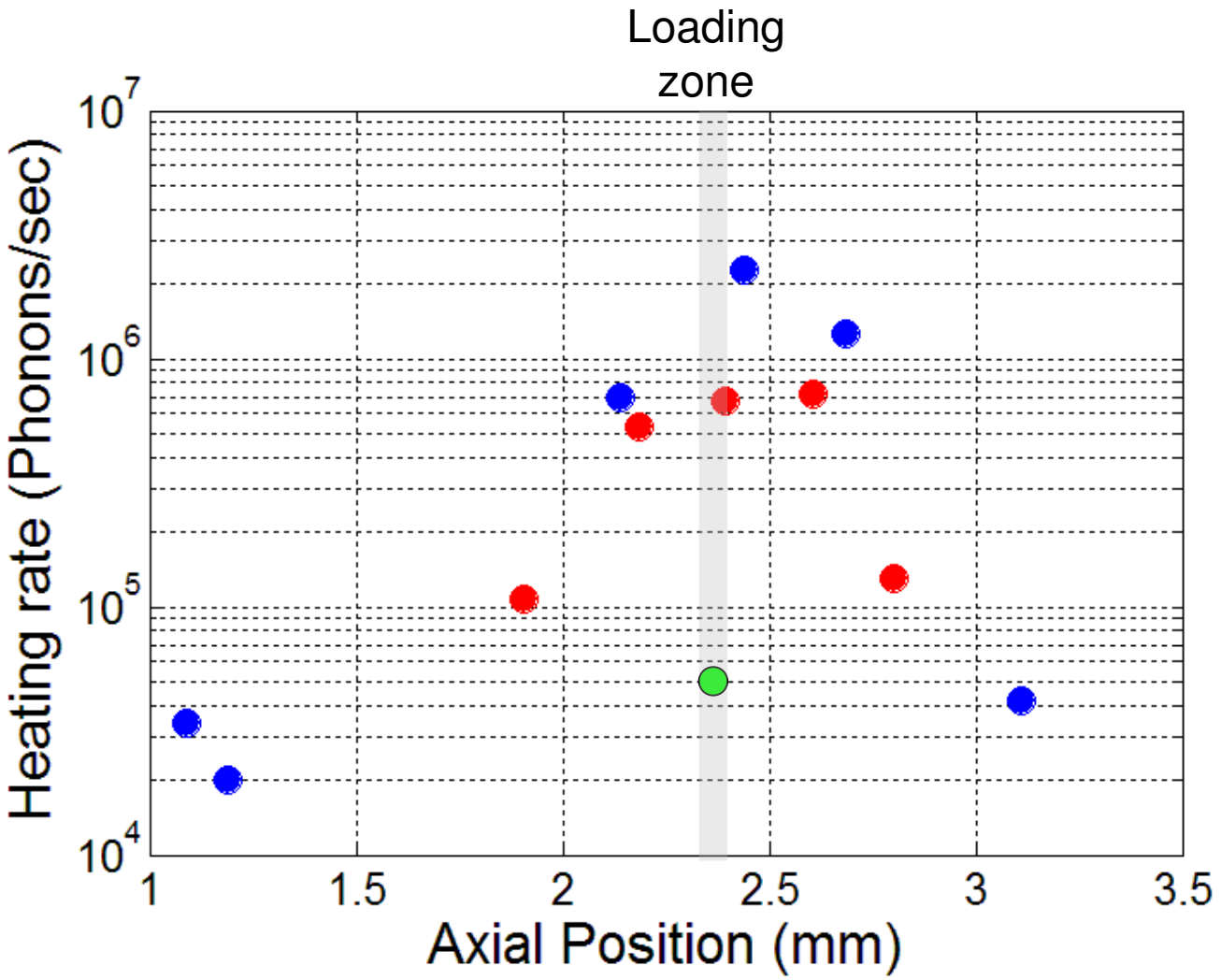




S. Narayanan *et. al.* in preparation

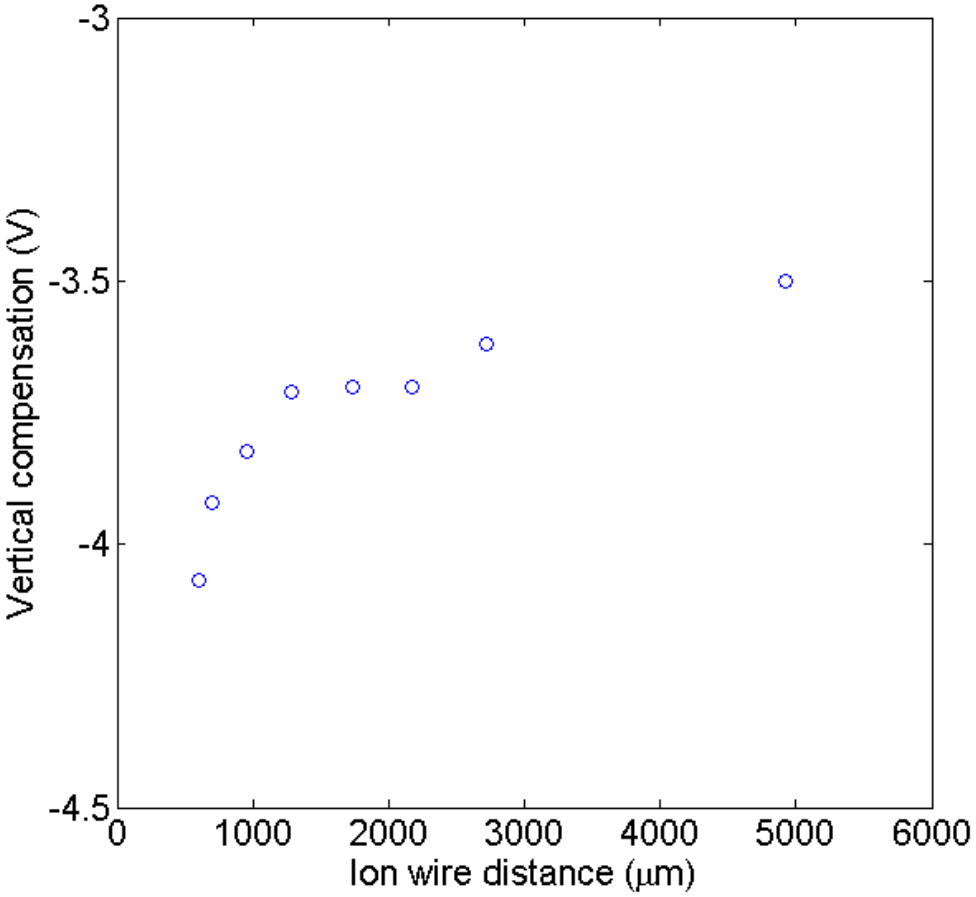
Theory: J.H. Wesenberg et al, PRA **76**, 053416 (2007)

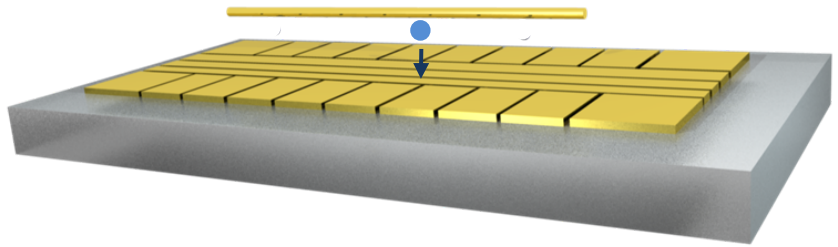
# Heating rate along the trap




Increased heating in loading region

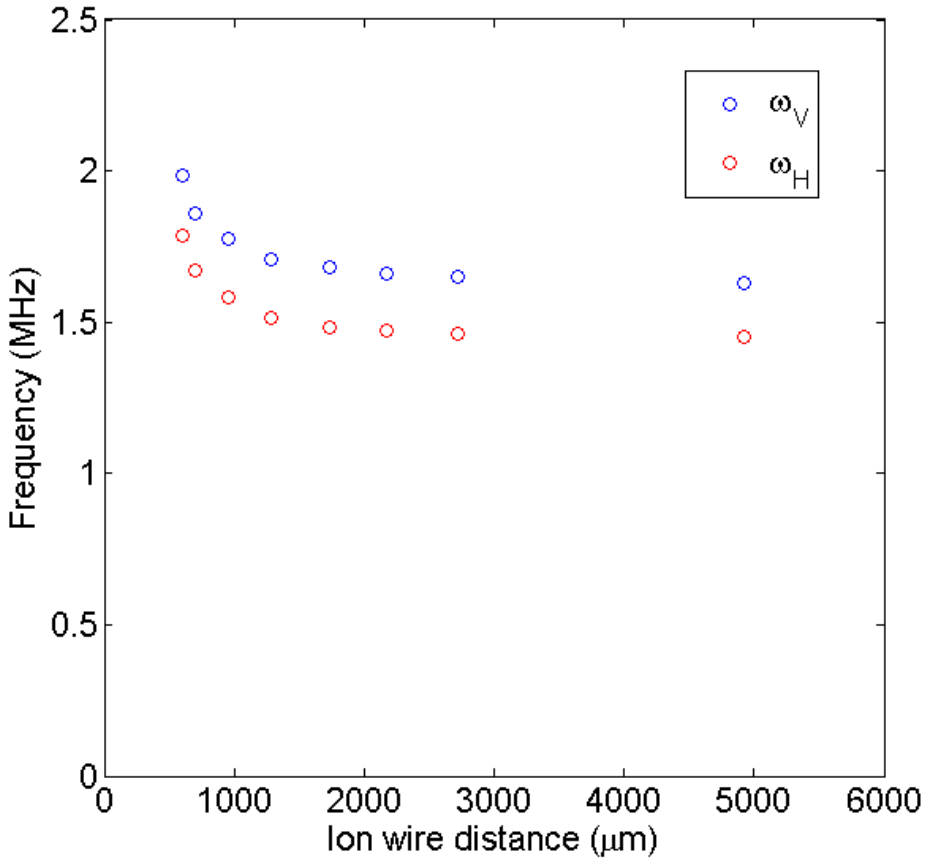
# Influence of the wire

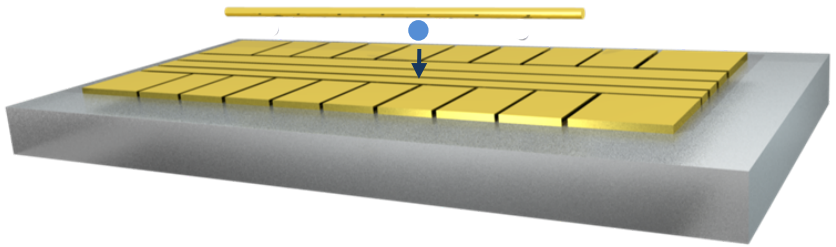


Ion pushed down as wire approaches

# Influence of the wire



Wire acts as an additional electrode!

# Outlook

- Fabricate new traps
- Characterize new traps
- Trap in cryostat
- Enter coherent regime
- Coupling: metallic/superconducting wire
- Couple to solid-state systems

# People

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