Towards wiring-up trapped ions

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SQuInT

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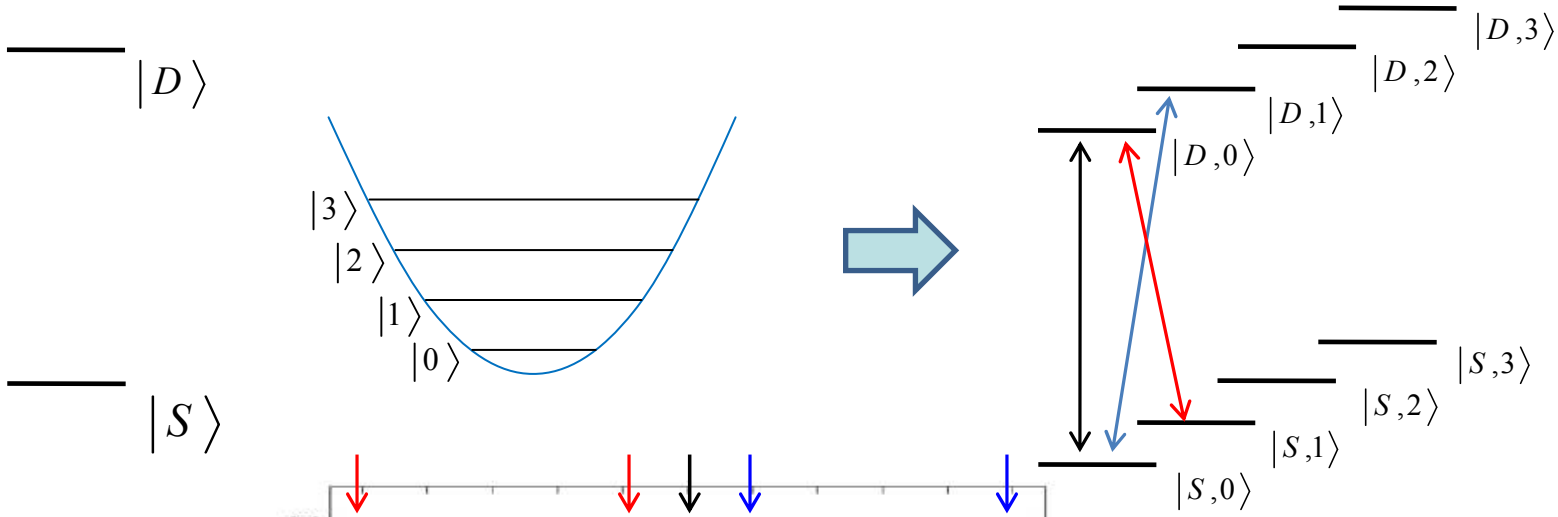
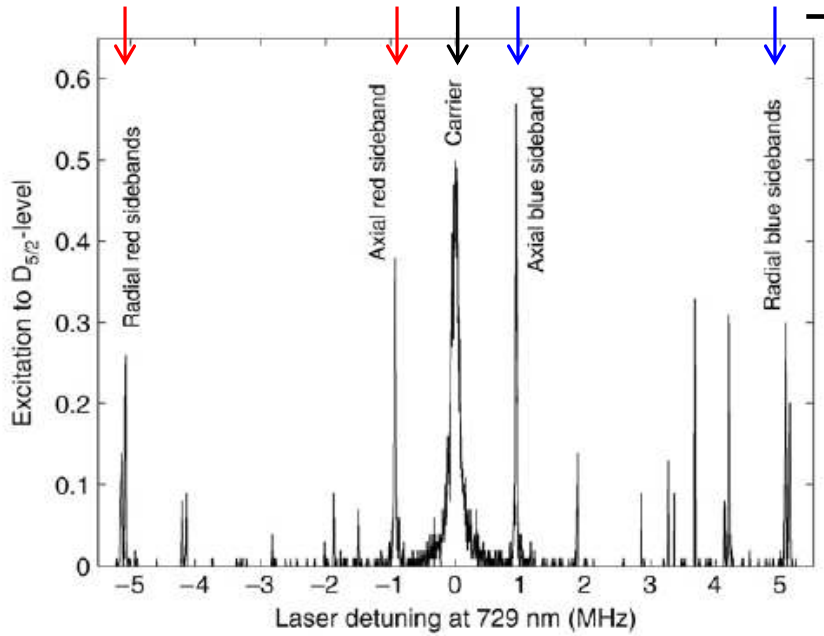
Outline

- Quantum mechanics with trapped ions
- Why wire-up trapped ions
- Coupling via wire
- Coupling via LC resonator
- Experimental status
  - -experimental system
  - -influence of coupling wire
- Outlook

Quantum mechanics with trapped ions

Two-level system ⊗ Motional state ladder



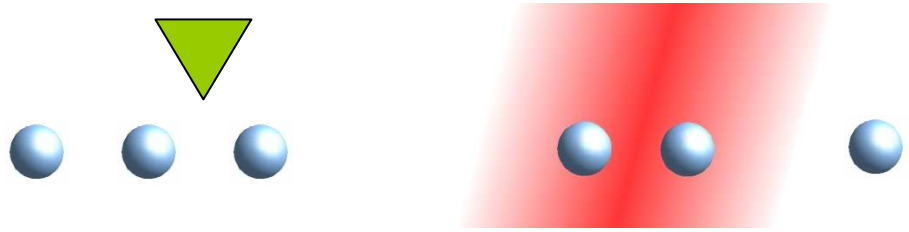


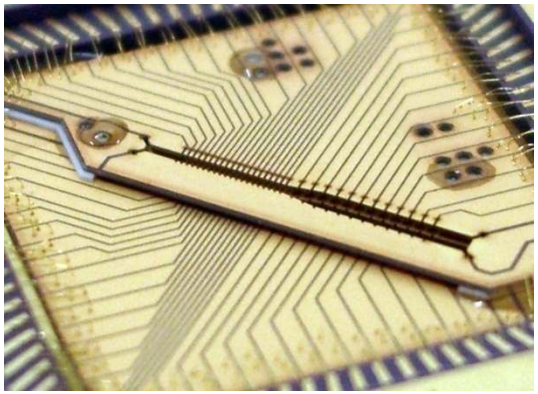
Graph from H. Häffner *et al.*

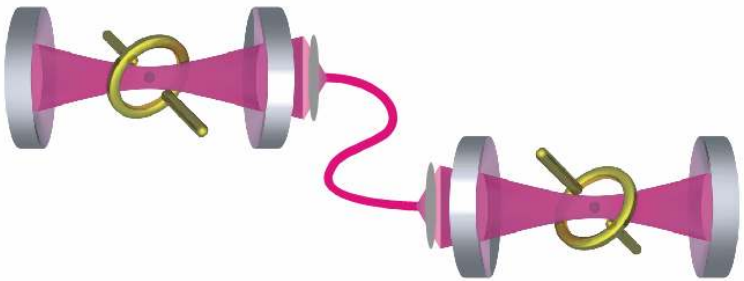
Phys. Rep. **469** 155 (2008)

Scaling ion traps

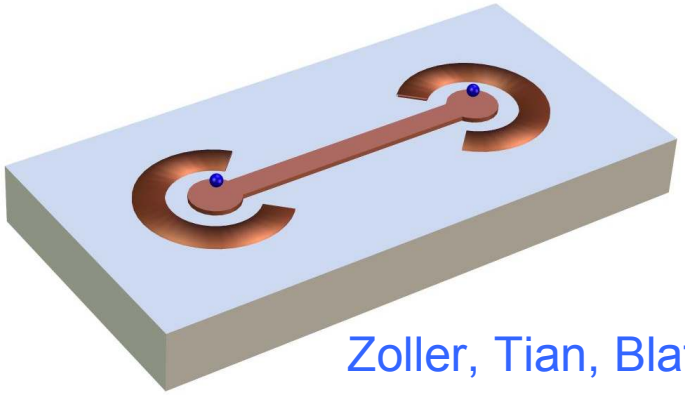
Kielpinski, Monroe, Wineland







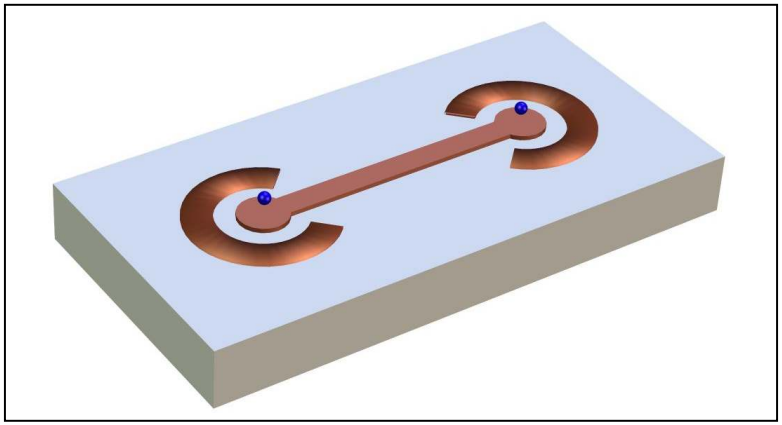
Cirac, Zoller, Kimble, Mabuchi



Zoller, Tian, Blatt

Applications

- Solid-state quantum bus
- Decoherence in charge transport

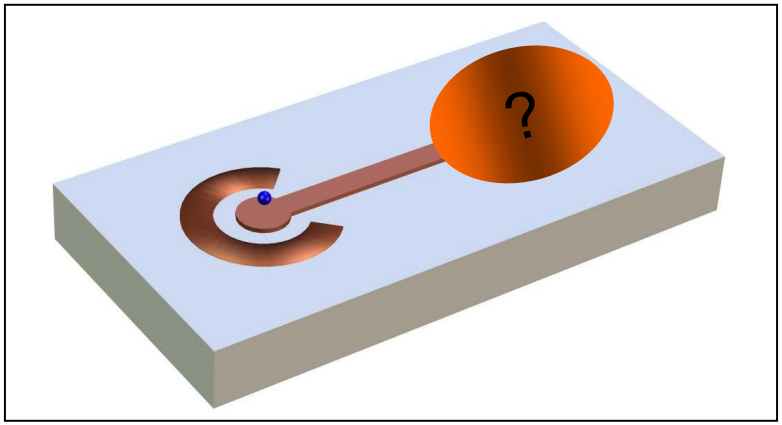


Applications

- Solid-state quantum bus
- Decoherence in charge transport

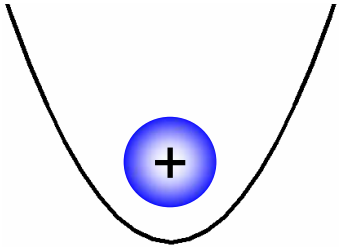
- Laser cooling of LC resonators (Heinzen & Wineland, PRA **47**, 2977)
- AMO - Solid state interface
- Trapped-ion detectors

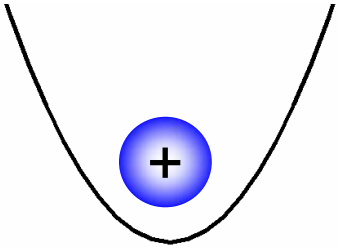
…



Coupling concept

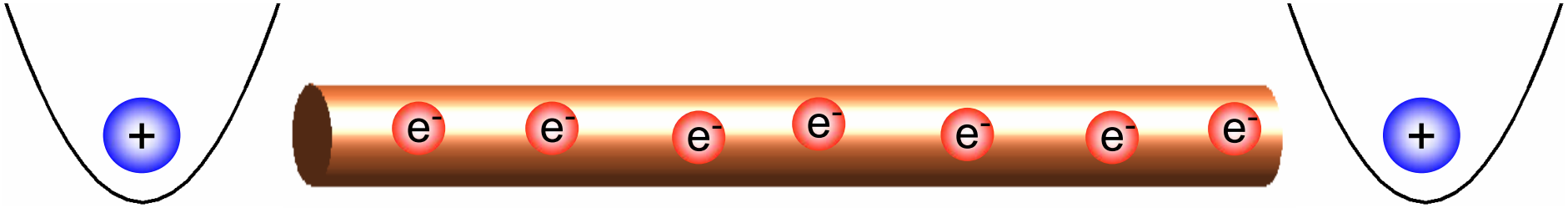
Two trapped ions …



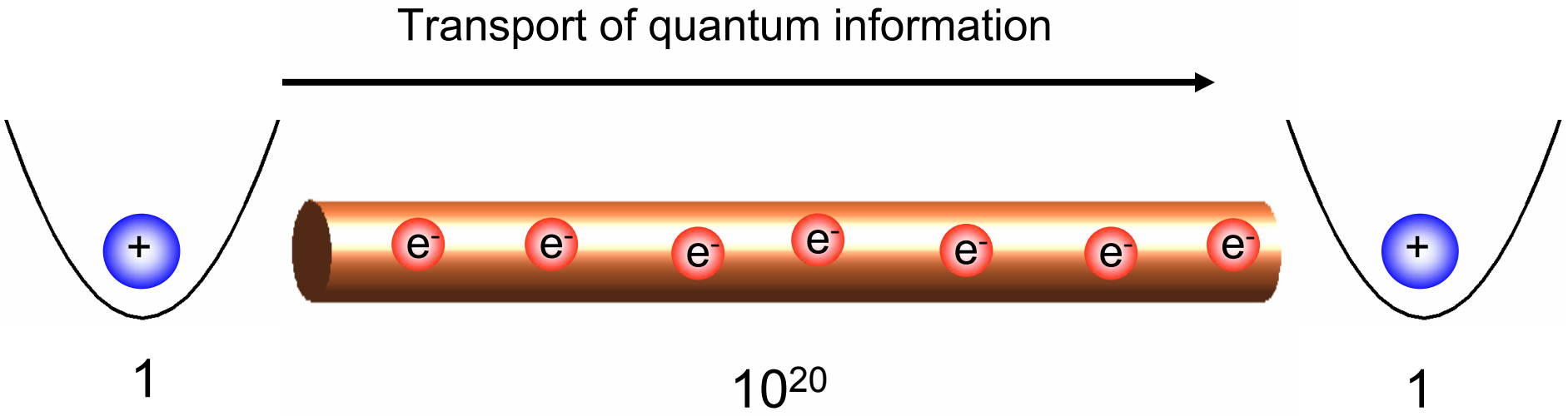


Coupling concept

Two trapped ions + a wire

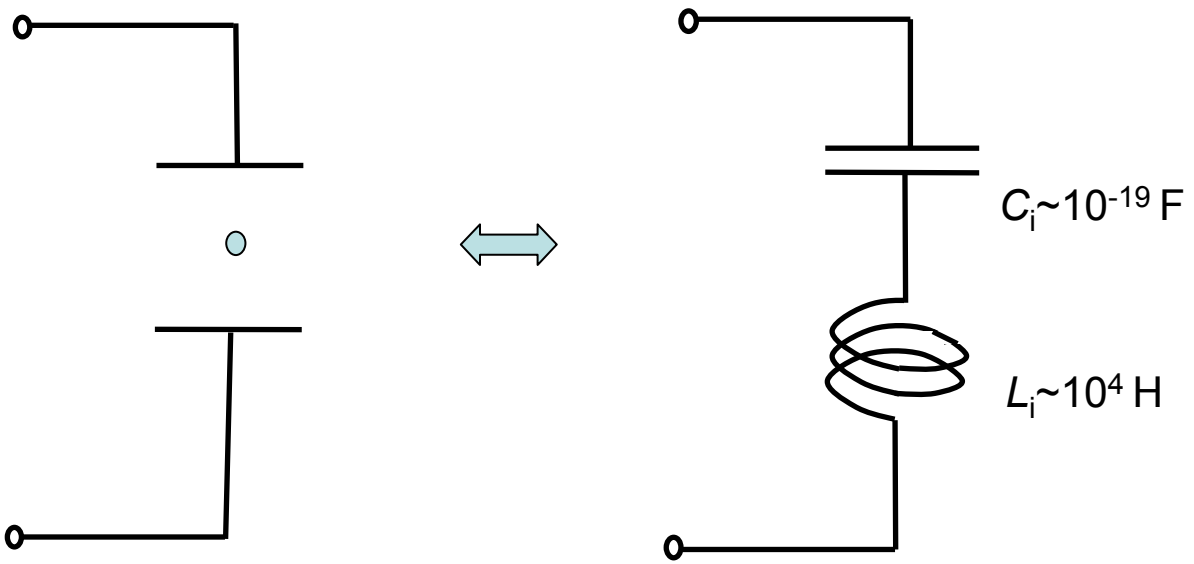


Coupling concept



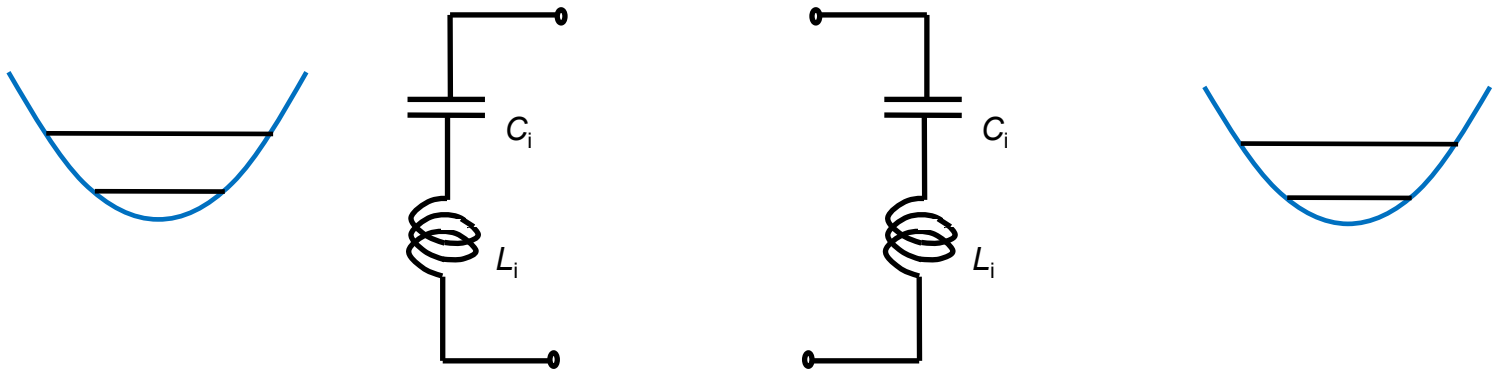
Quantum coherence in the wire?

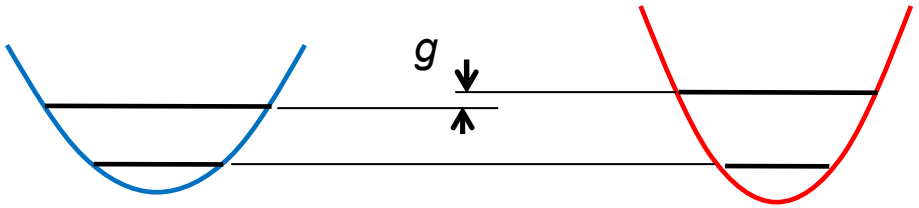
Ion- LC equivalence



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 mechanism

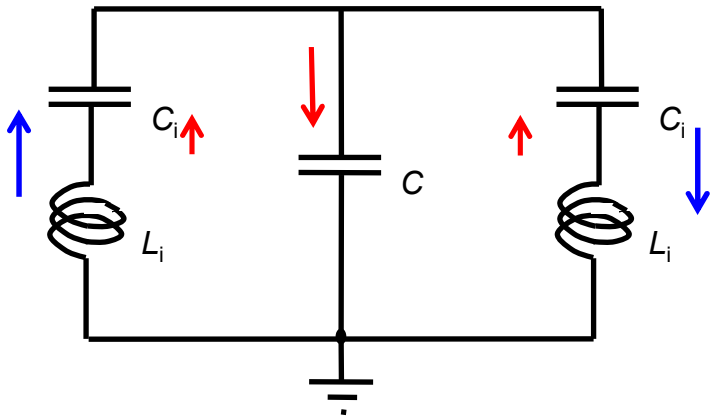




$$g \propto \frac{C_\mathrm{i}}{C} \propto \frac{1}{f_\mathrm{i}\, l\, D^2}$$

$g \approx 10\,\mathrm{Hz} \quad (200\,\mu\mathrm{m} \ \text{height})$

$g \approx 1\,\mathrm{kHz} \quad (50\,\mu\mathrm{m} \ \text{height})$



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 (2009)

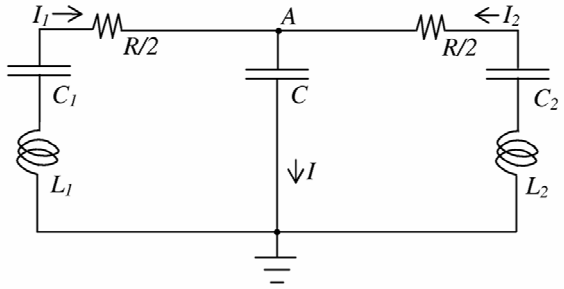
Decoherernce

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: $I \approx 10^{-16}\,A$

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



Johnson noise heating

$\gamma_J = \frac{k_B T \Delta f}{\hbar\omega_i} = \frac{2\pi k_B T}{\hbar Q_i} \approx 3 \cdot 10^{-3}\,\frac{1}{s}$ $\qquad T = 4\,\mathrm{K}$

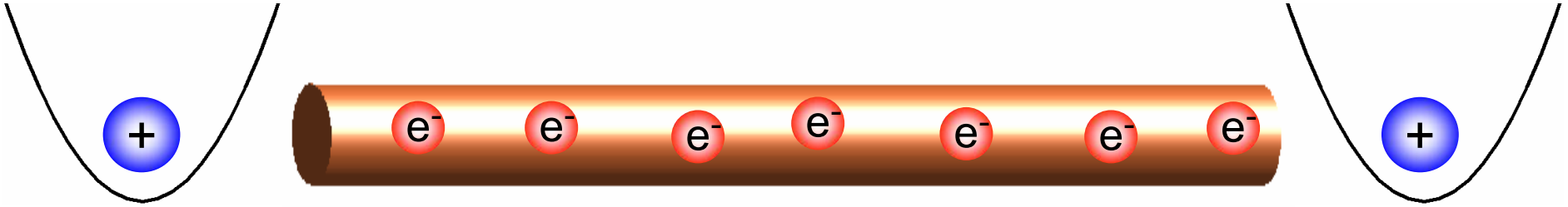
Anomalous Heating?

Cool apparatus to cryogenic temperatures

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

State transfer

Off-resonant

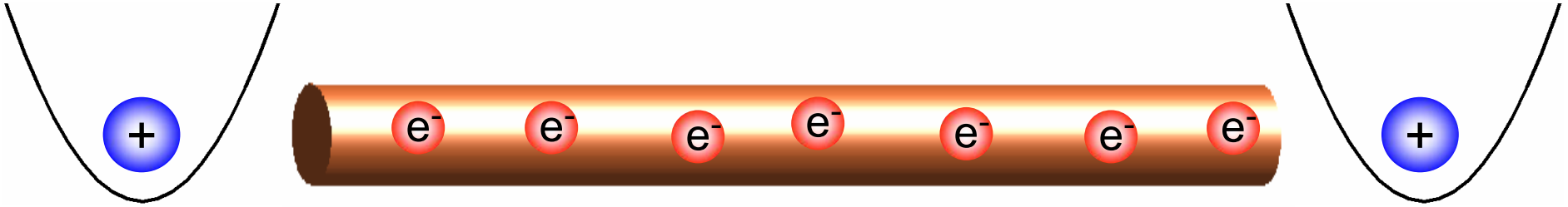


$$\frac{|0\rangle + |n\rangle}{\sqrt{2}}$$

$$|0\rangle$$

State transfer

Resonant

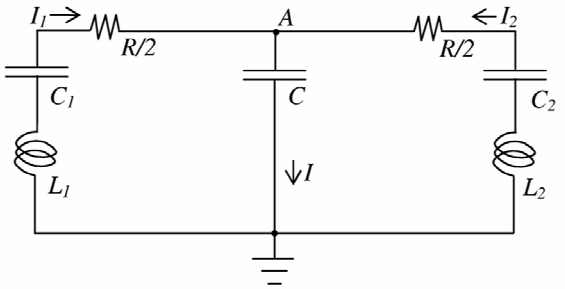


$|0\rangle$

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

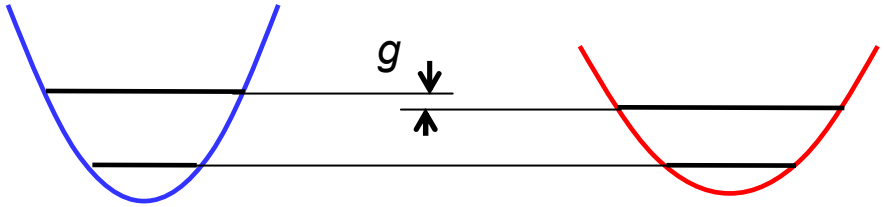
Floating wire requirements

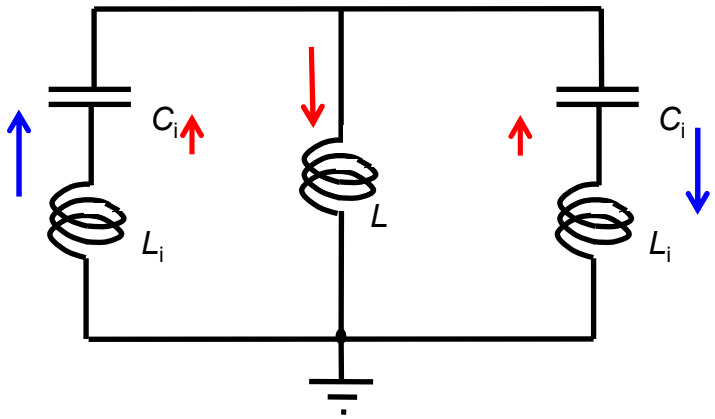
- Miniaturize trap
- Minimize C
- Minimize f_1
- Stray charges?
- Stray calcium?



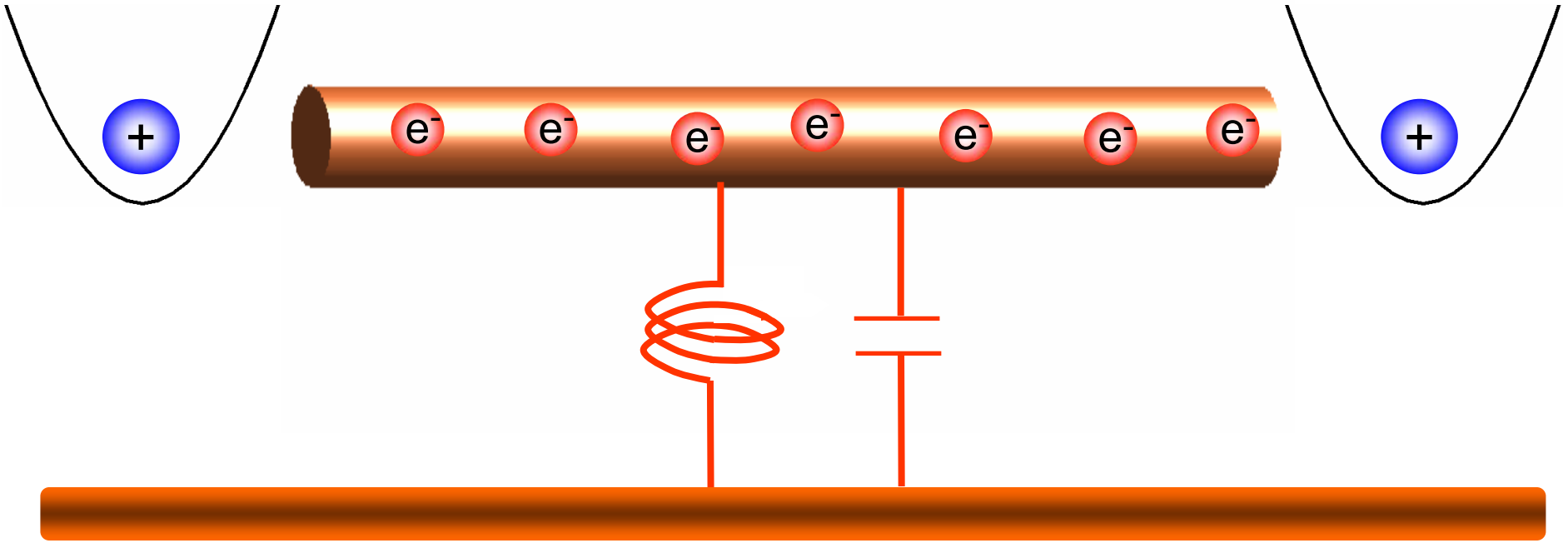
Coupling via a coil

$$g \propto f_{\mathrm{i}} \frac{L}{L_{\mathrm{i}}} \propto \frac{f_{\mathrm{i}} L}{D^2}$$

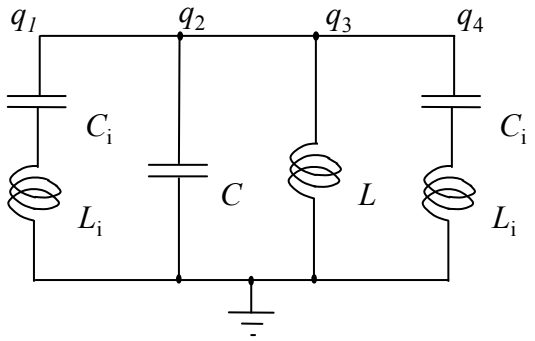




Coupling via a resonator?



Coupling via a resonator



$L = 10\,\mathrm{mH}$ $\quad L_i = 40000\,\mathrm{H}$

$C \approx 2.5\,\mathrm{pF}$ $\quad C_i \approx 6 \cdot 10^{-19}\mathrm{F}$

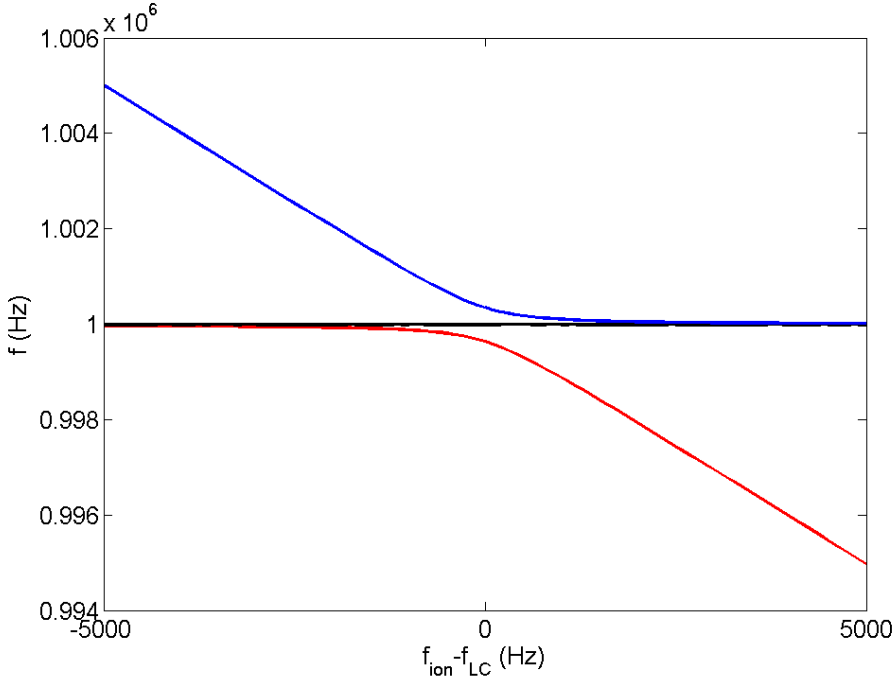
$f \approx 1\,\mathrm{MHz}$

$g_1 \approx 2\pi \cdot 250\ \mathrm{sec}^{-1}$

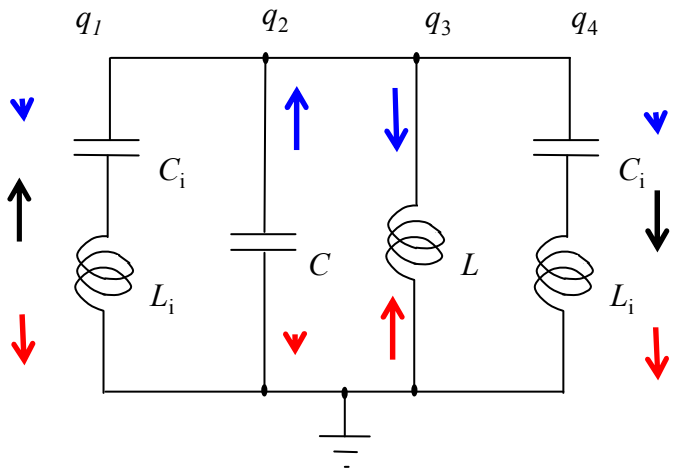
$g \approx 2\pi \cdot 0.12\ \mathrm{sec}^{-1}$

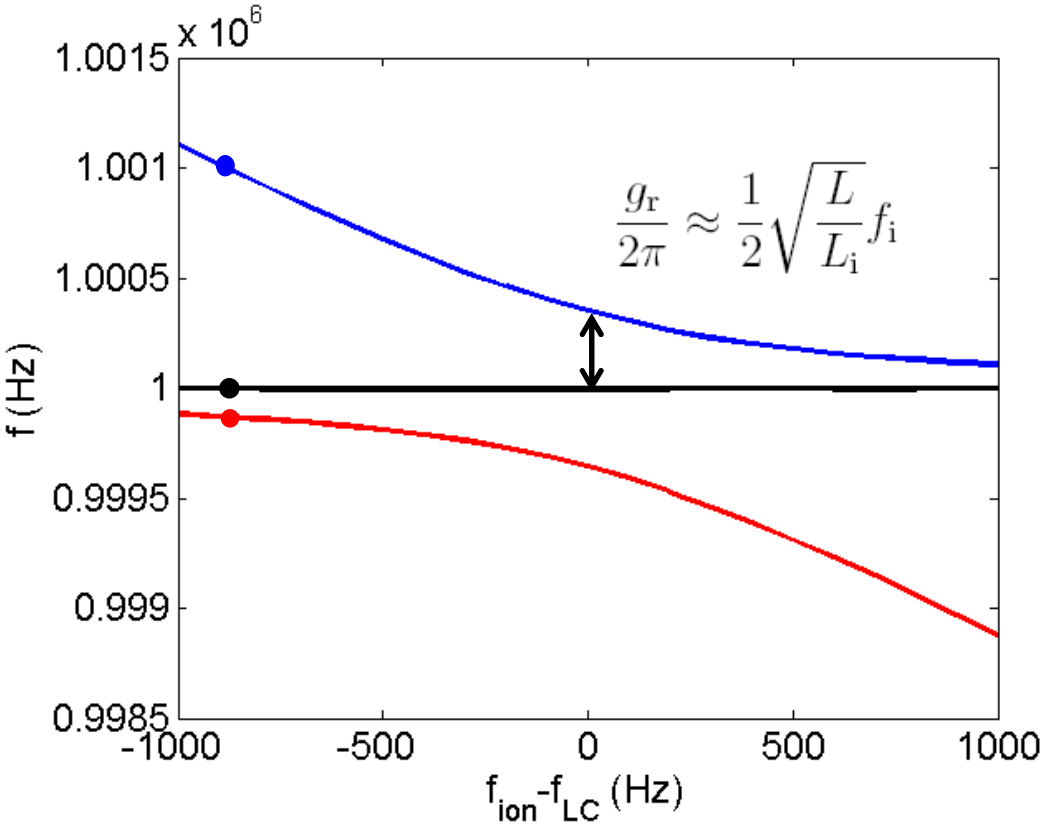
Hamiltonian (RWA)

$$H = \hbar \begin{pmatrix} a_1^+ & a_2^+ & a_3^+ \end{pmatrix} \begin{pmatrix} \omega_i & g_1 & g \\ g_1 & \omega_{LC} & g_1 \\ g & g_1 & \omega_i \end{pmatrix} \begin{pmatrix} a_1 \\ a_2 \\ a_3 \end{pmatrix}$$

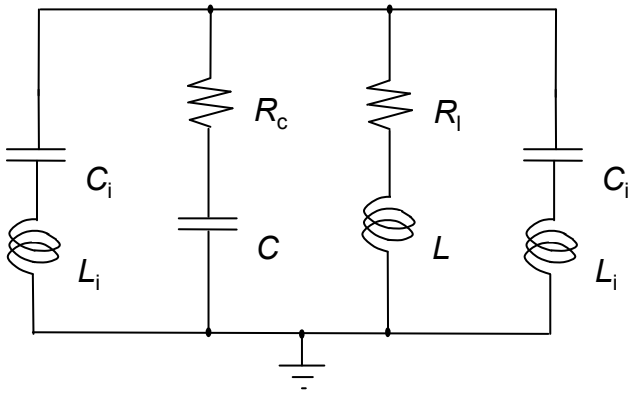


Normal modes





Decoherence



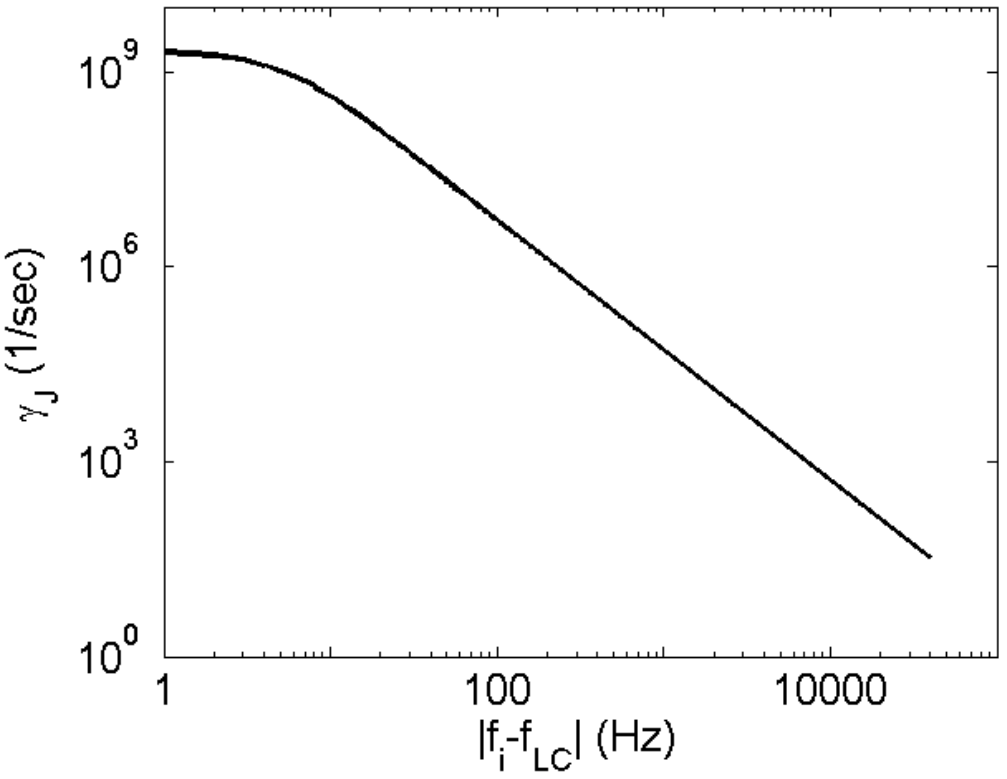
$$L = 10\,\mathrm{mH} \quad L_\mathrm{i} = 40000\,\mathrm{H}$$

$$C \approx 2.5\,\mathrm{pF} \quad C_\mathrm{i} \approx 6 \cdot 10^{-19}\mathrm{F}$$

$$Q_\mathrm{LC} = 10^5 \quad f \approx 1\,\mathrm{MHz}$$

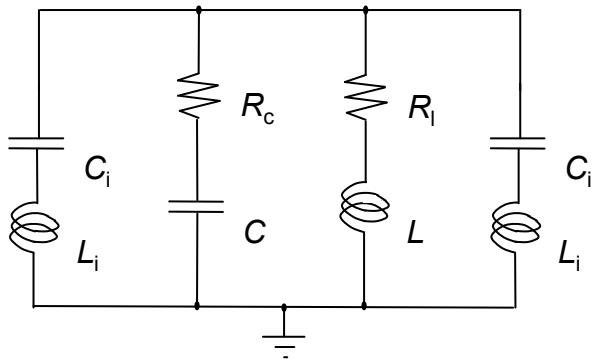
$$T = 4\,\mathrm{K}$$

$$\gamma_\mathrm{J} = \frac{k_\mathrm{B}\,T}{h\,Q_\mathrm{i}} \qquad (\mathrm{phonons/sec})$$

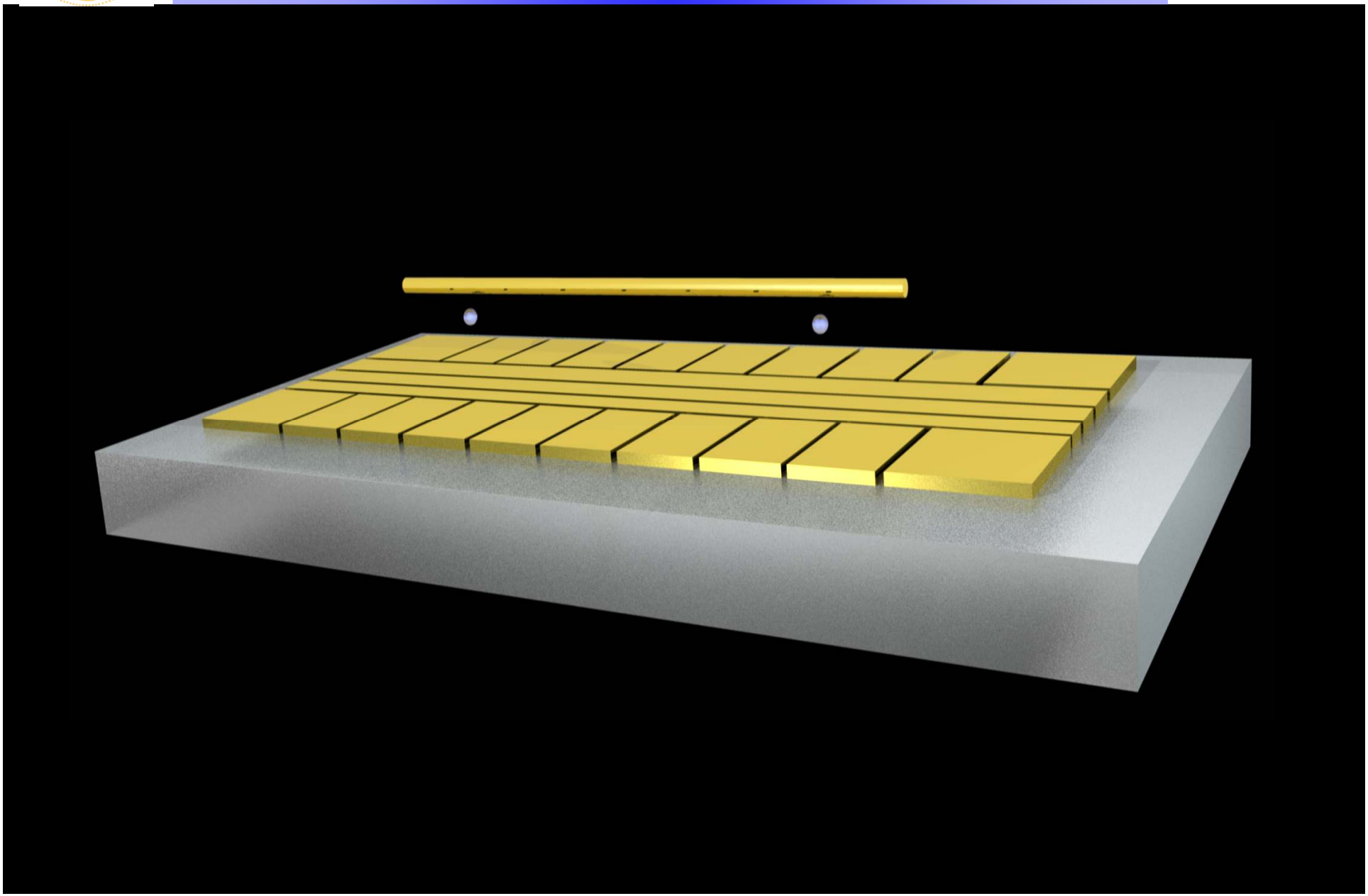


Resonator requirements

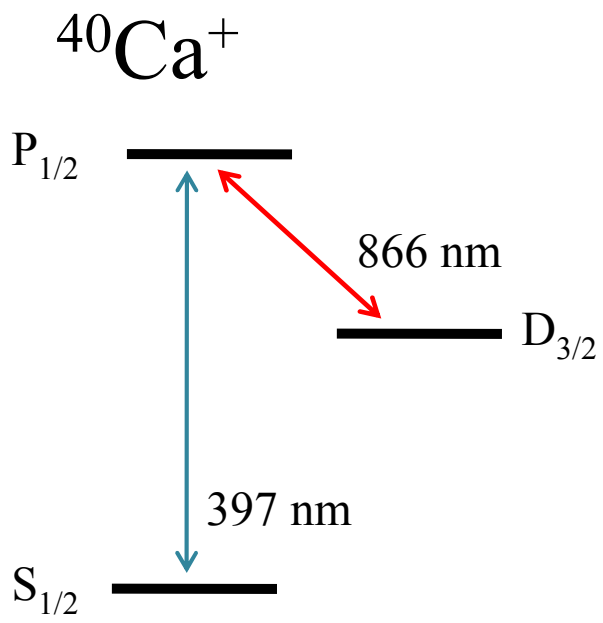
- Miniaturize trap
- Maximize L
- Maximize f_{i}
- Maximize Q
- Engineer detuning



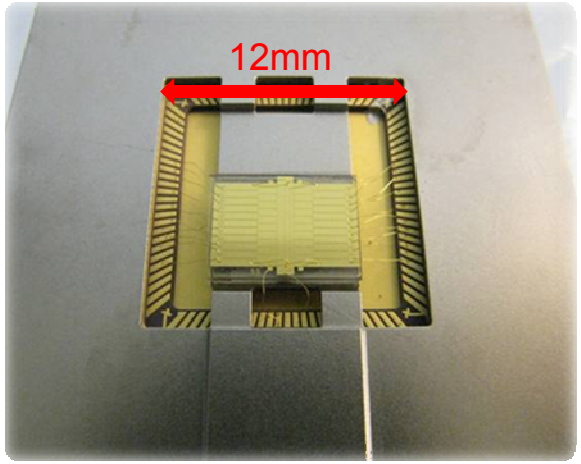
Experimental approach



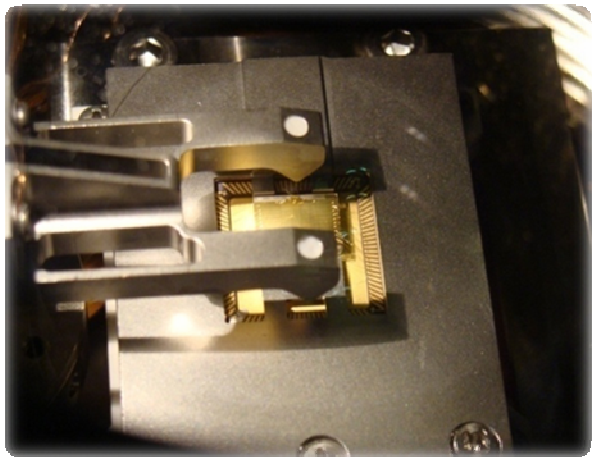
Experimental system



Laser cooling and detection:
397nm and 866nm laser

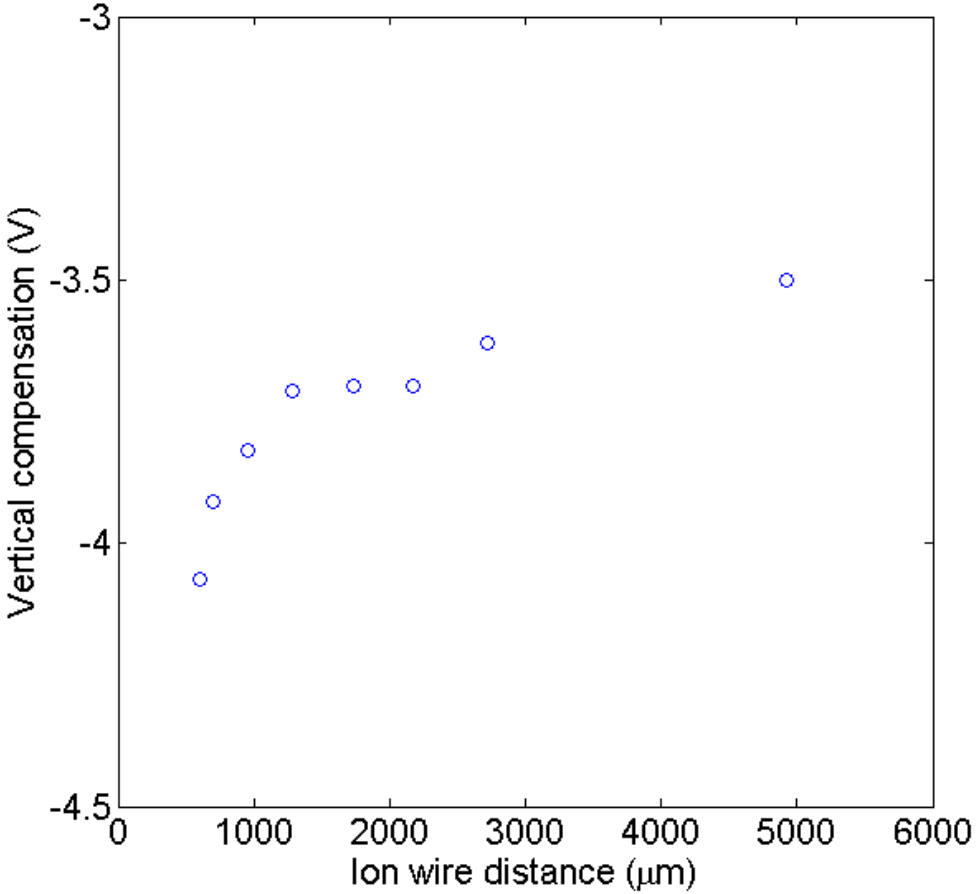


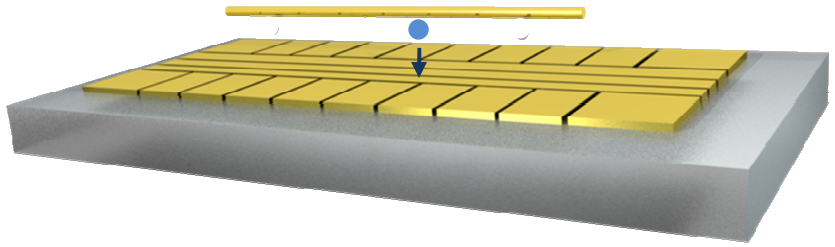
Gold on sapphire microfabricated trap



Wire on translation stage

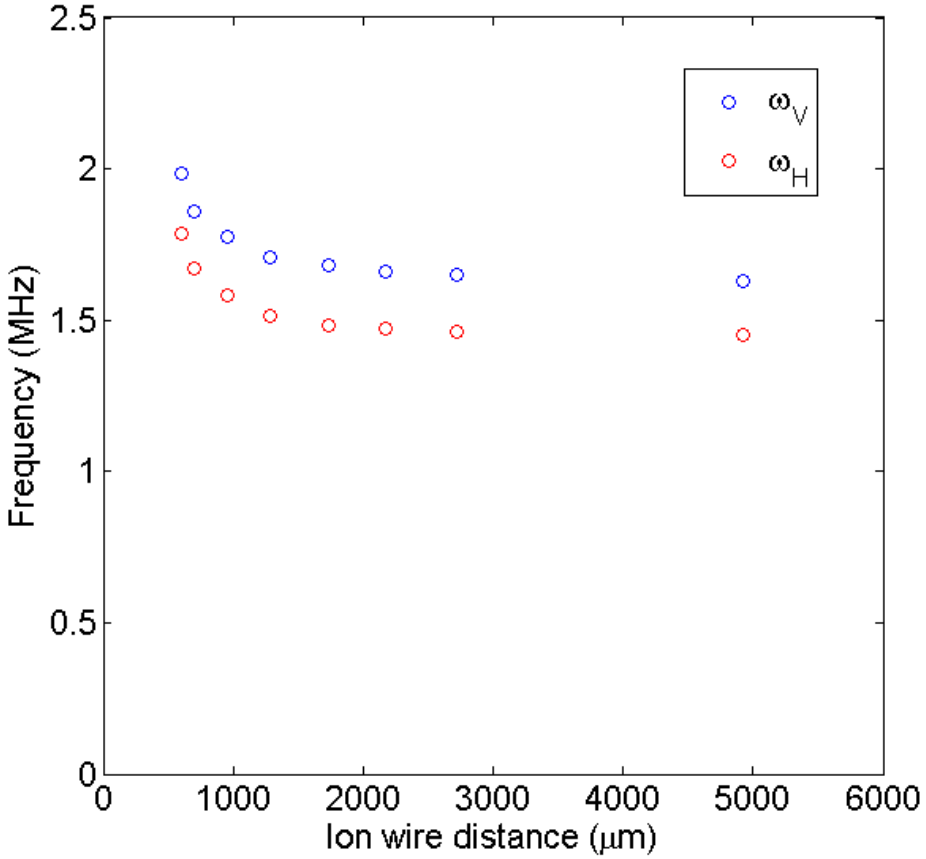
Influence of the wire

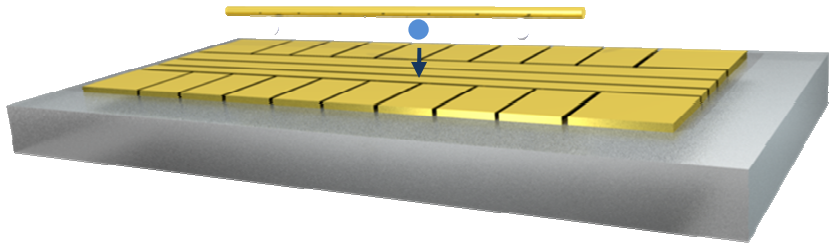




Ion pushed down as wire approaches

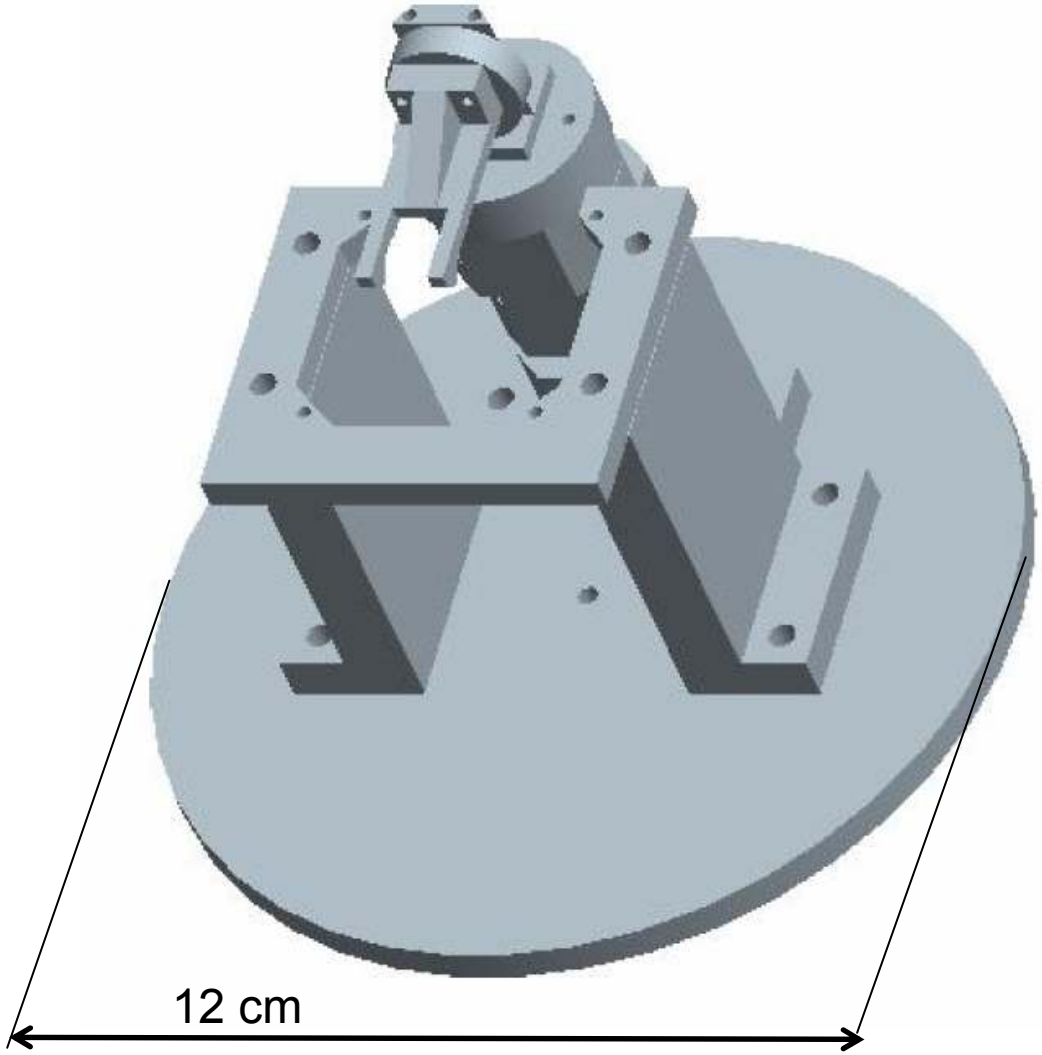
Influence of the wire



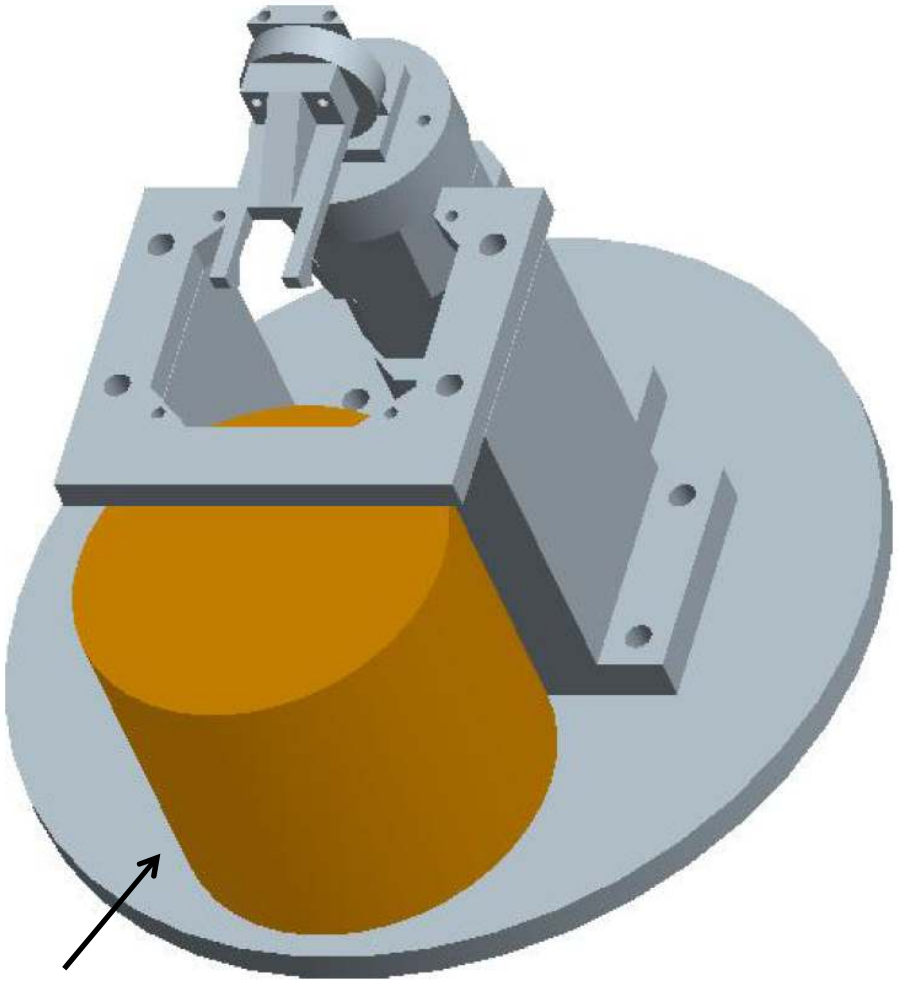


Wire acts as an additional electrode

Cryogenic setup



Cryogenic setup



Where we are

- Two possible coupling schemes
- Optimize geometry/miniaturize traps
- Coherent ion-ion coupling at cryogenic temperature
- Explore ion-resonator system.
- Couple to solid-state devices

People

H. Häffner

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S. Möller

B. Tabakov