Applications of trapped ions to nanotribology

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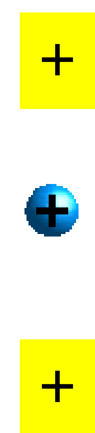
Department of Physics, University of California, Berkeley

- Introduction to ion trapping
- A single ion electric field probe
- Emulating physics of friction
- Conclusions

Trieste, Sep 15th 2011

Trapping ions



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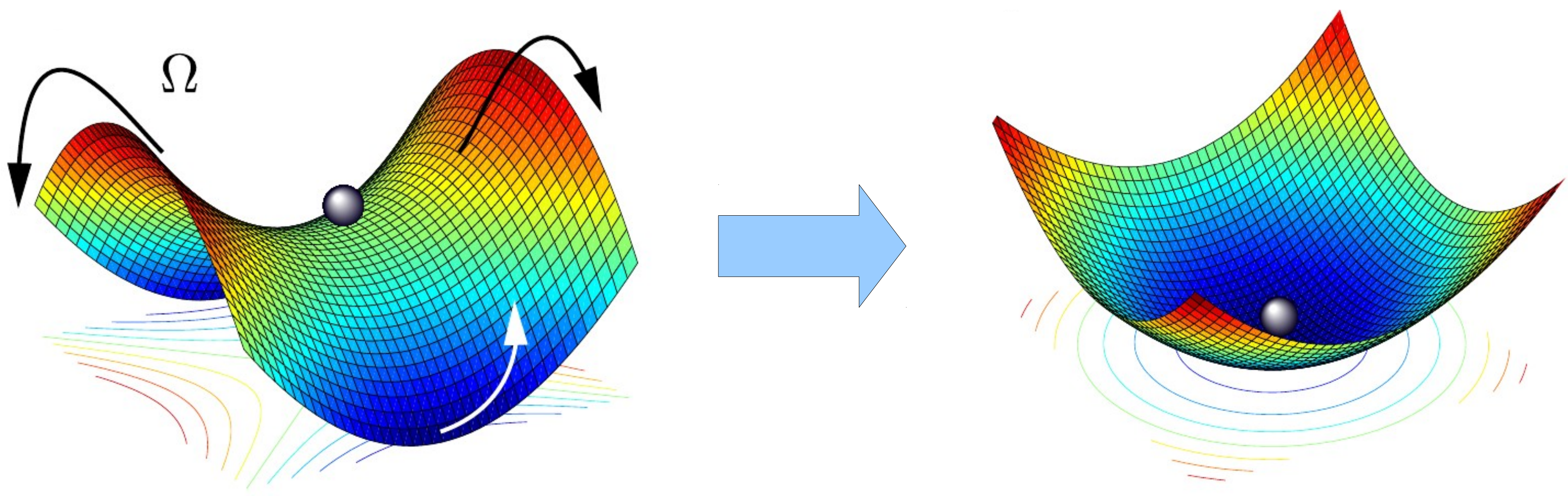
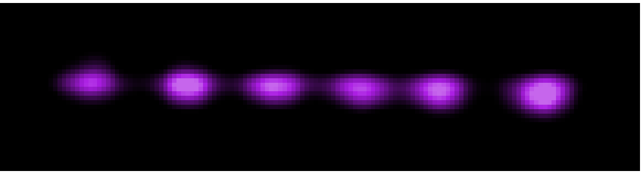
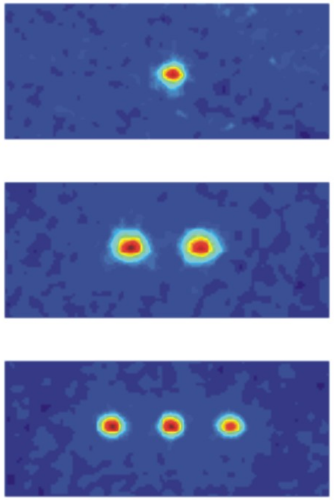
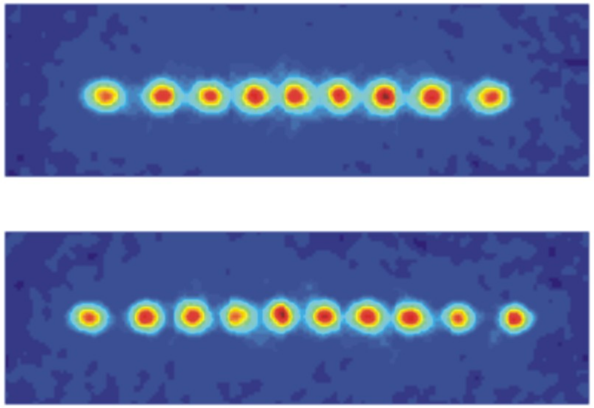


Cold ion crystals



Oxford, England: $^{40}Ca^+$





Innsbruck, Austria: $^{40}Ca^+$

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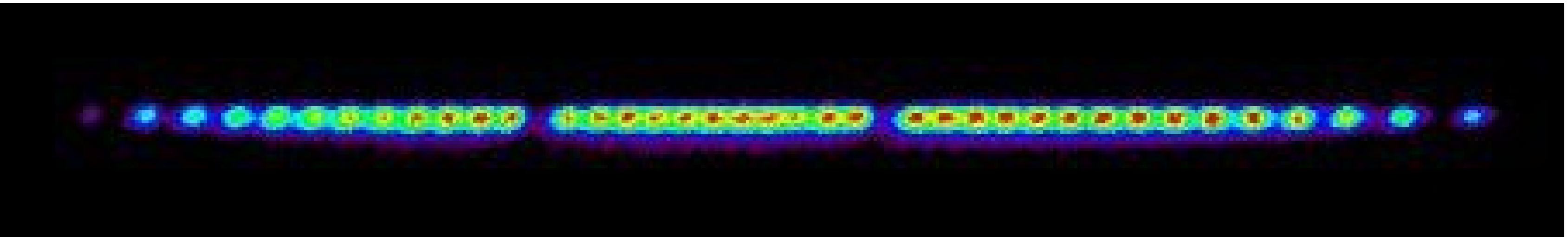
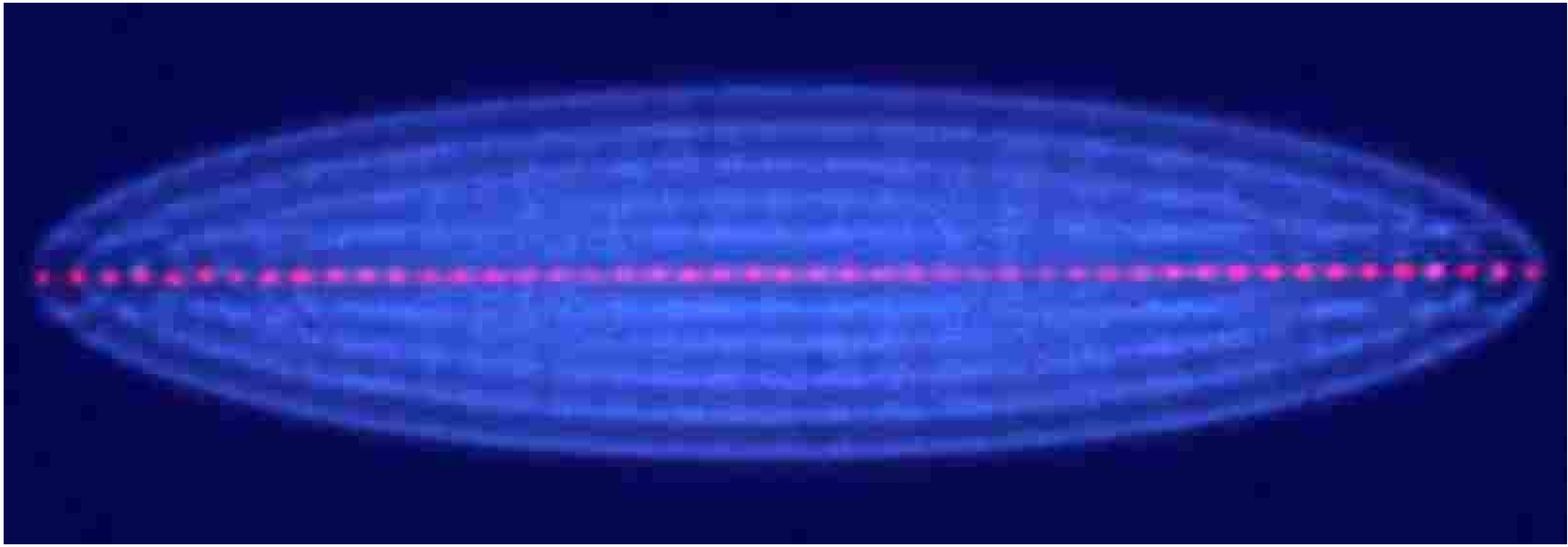
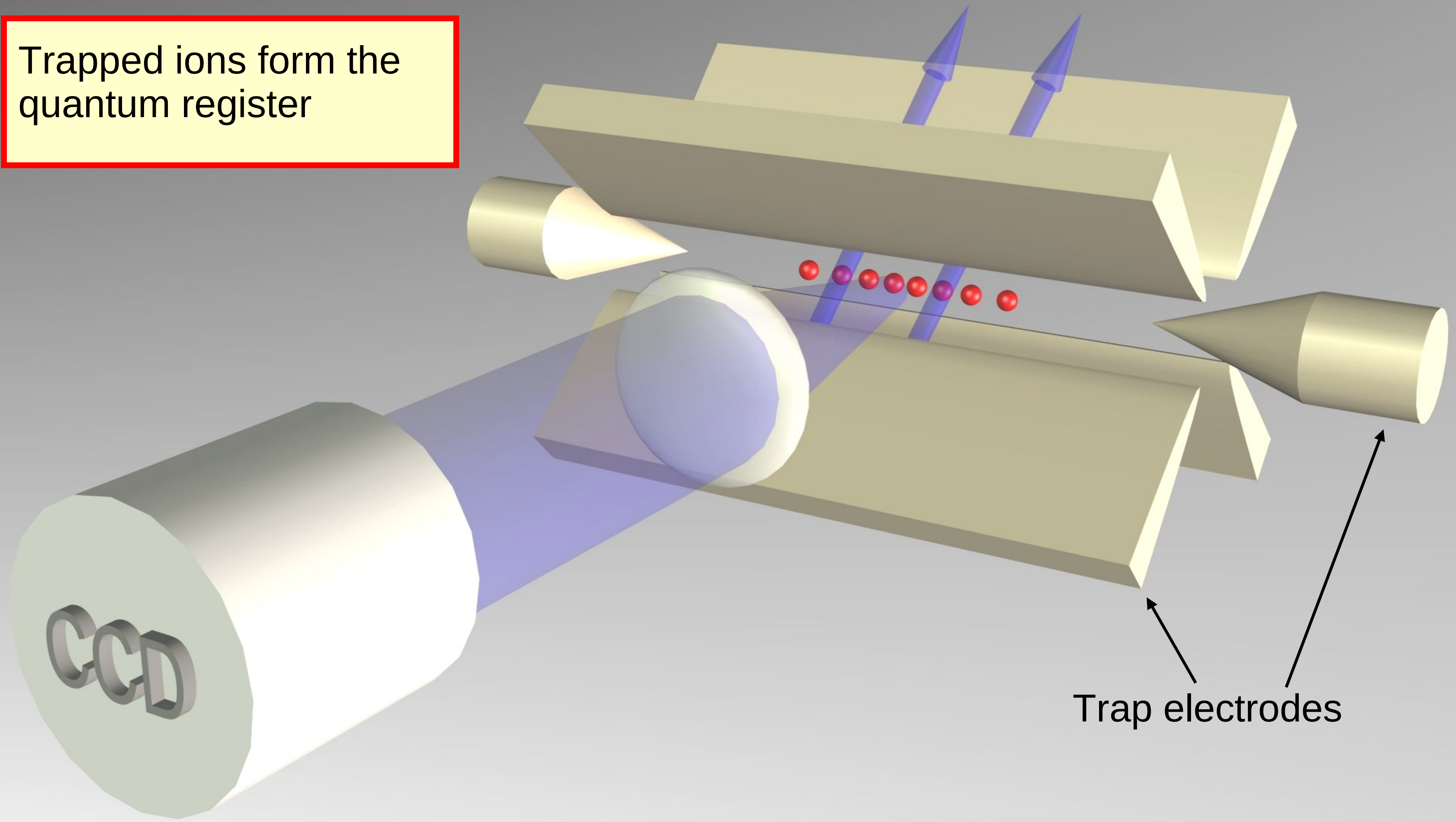




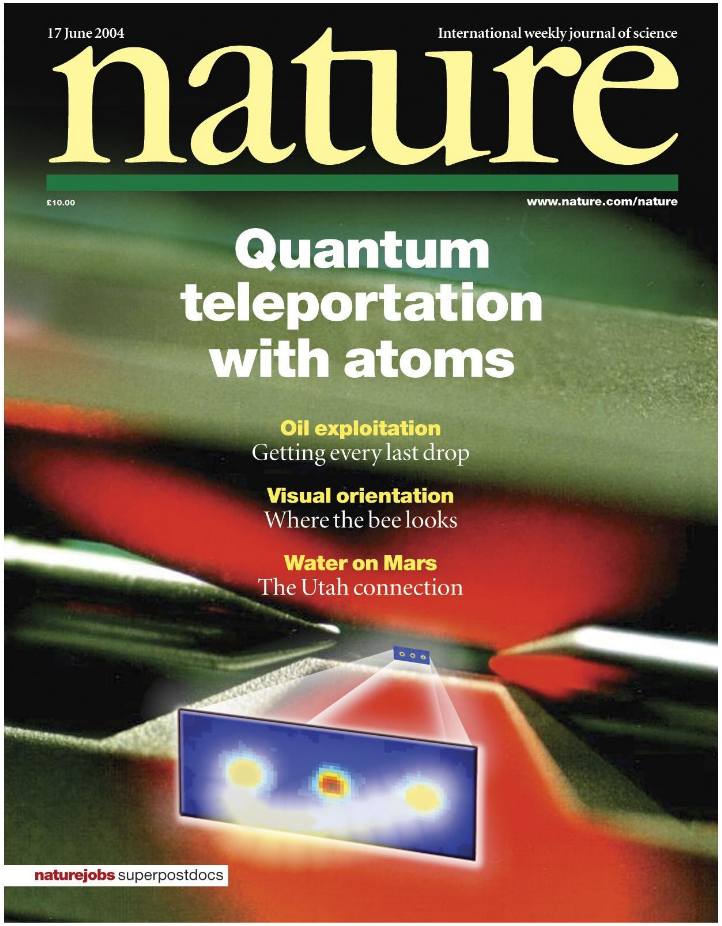
Aarhus, Denmark: $^{40}Ca^+$ (red) and $^{24}Mg^+$ (blue)

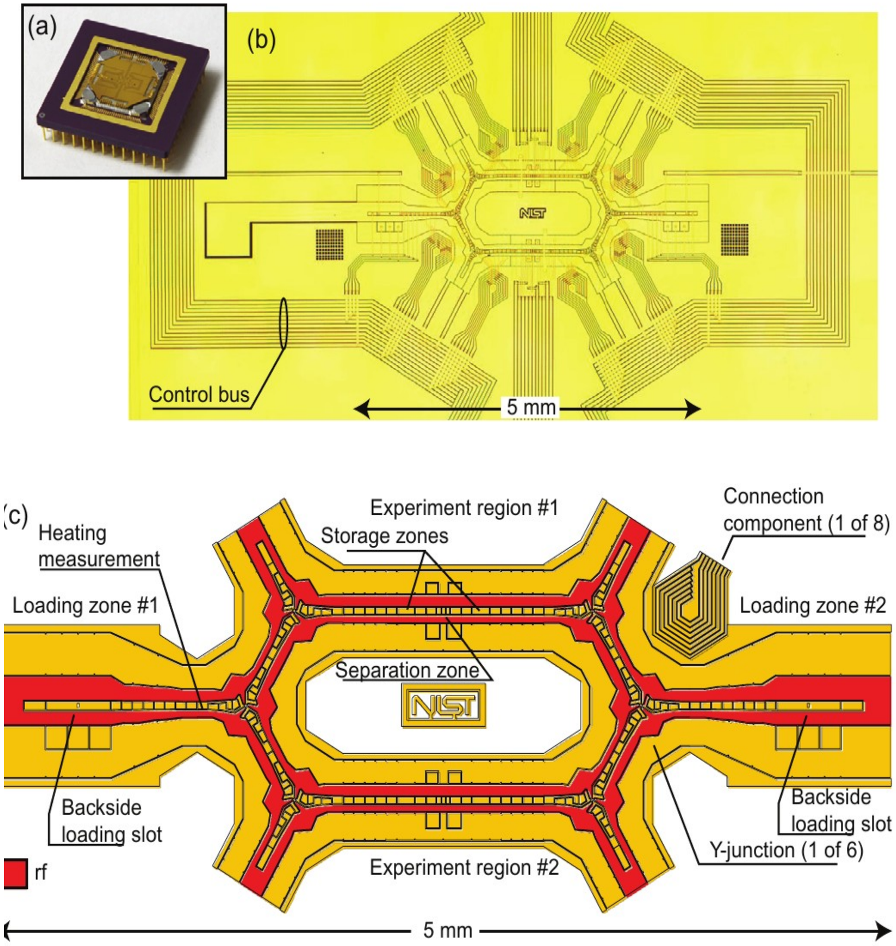
Ion trap quantum computing

Trapped ions form the quantum register



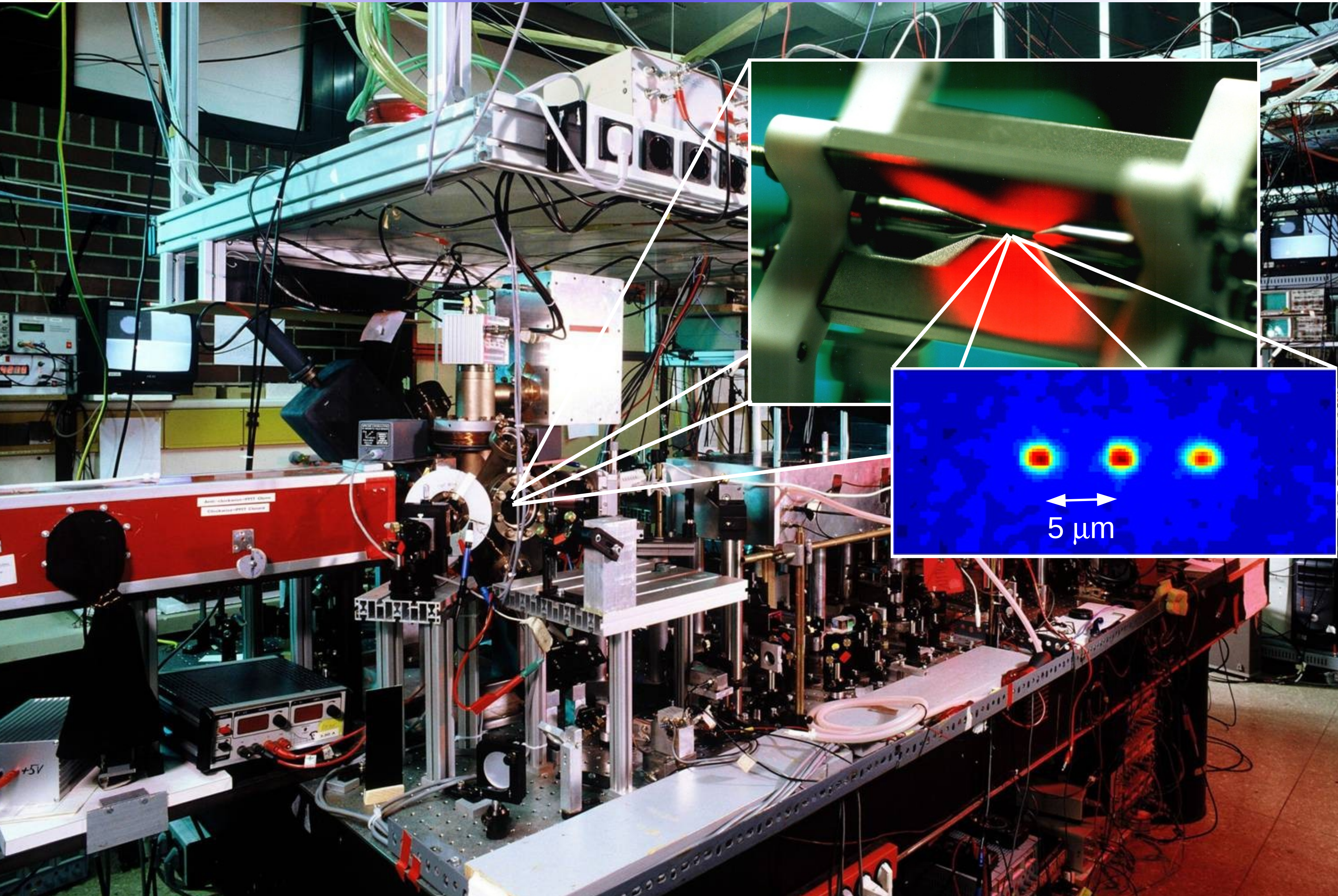
Ion trap quantum computing





From: Amini et al, NJP033031 (2010)

The hardware



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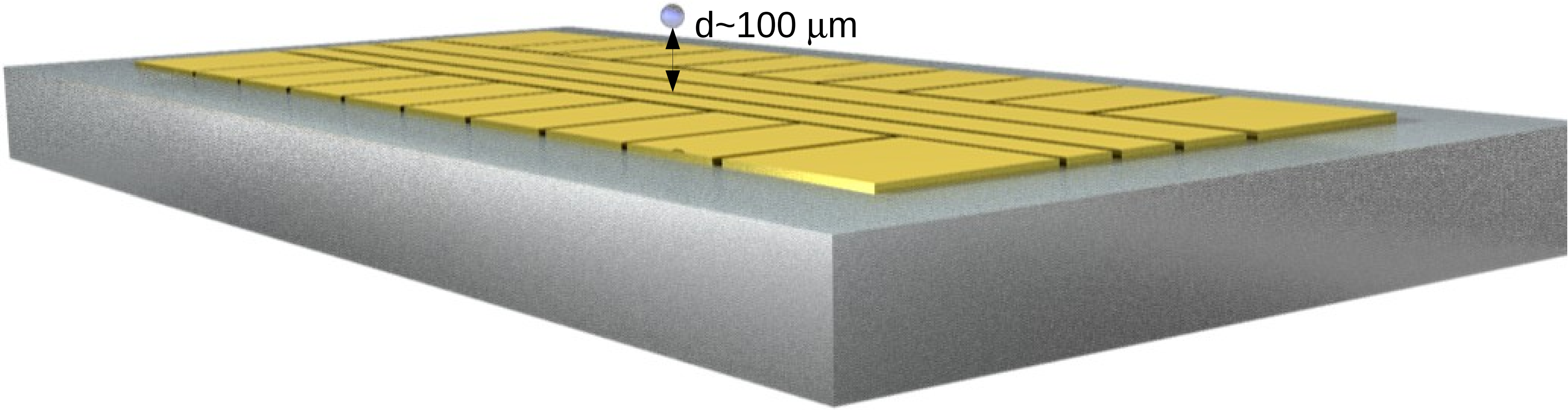
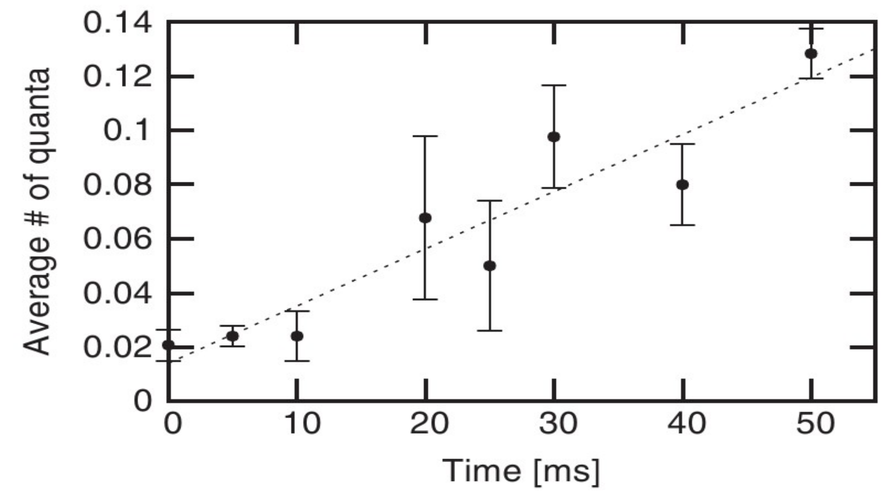
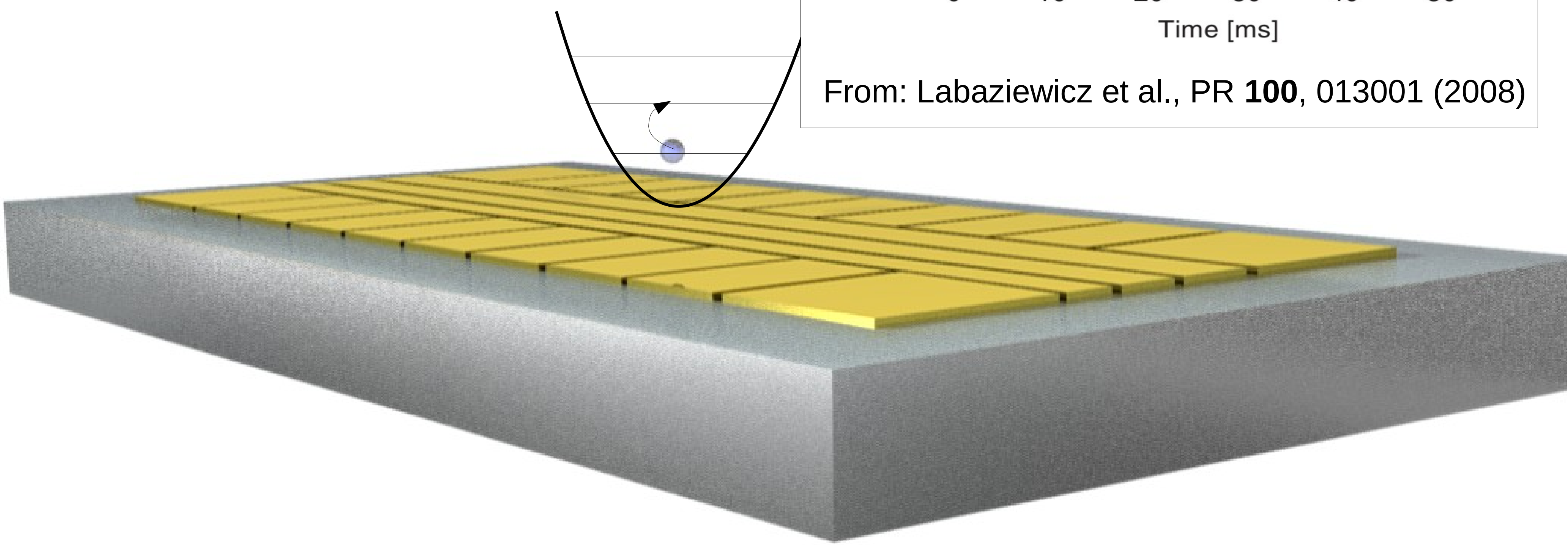
Field sensing



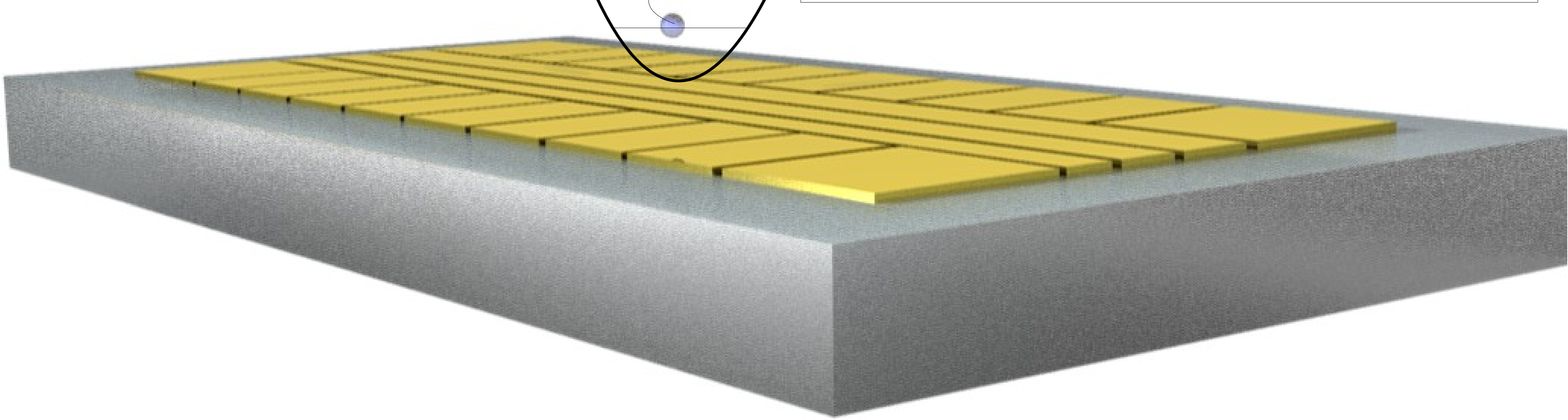
Field sensing

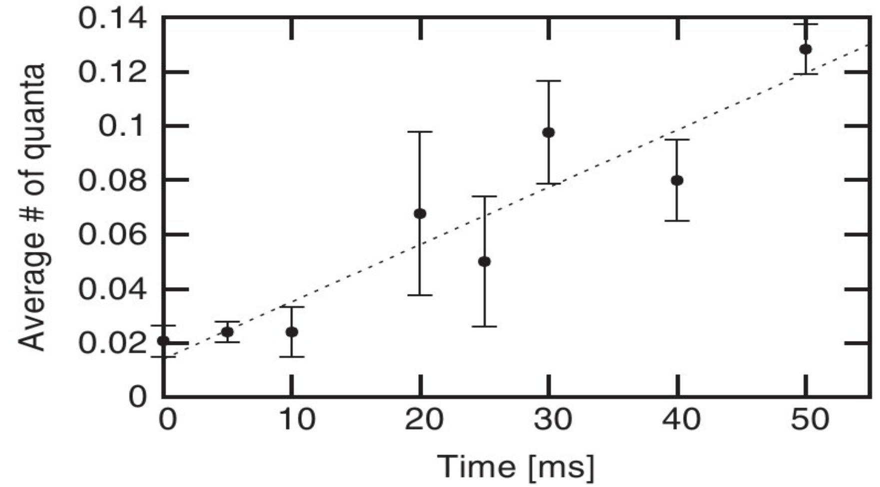


From: Labaziewicz et al., PR **100**, 013001 (2008)



Field sensing

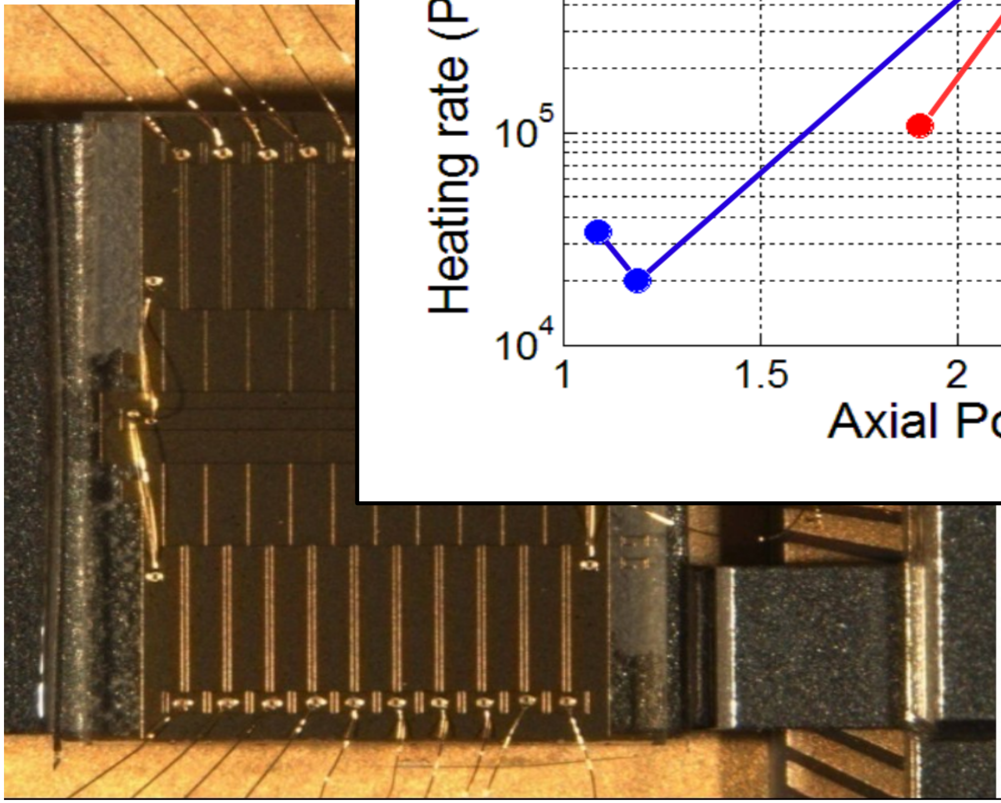


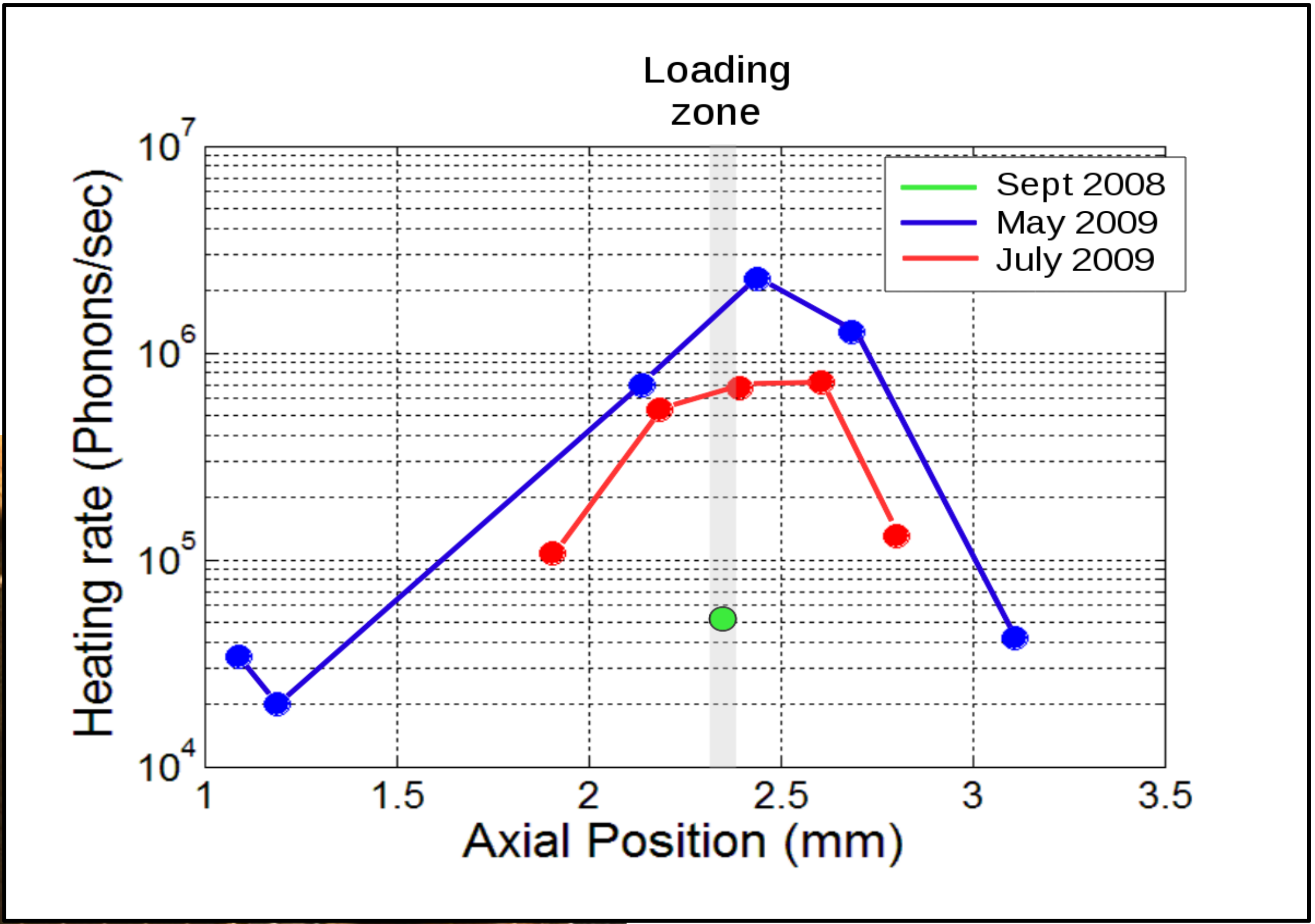


From: Labaziewicz et al., PR **100**, 013001 (2008)

Unknown source for heating

Gold on Sapphire





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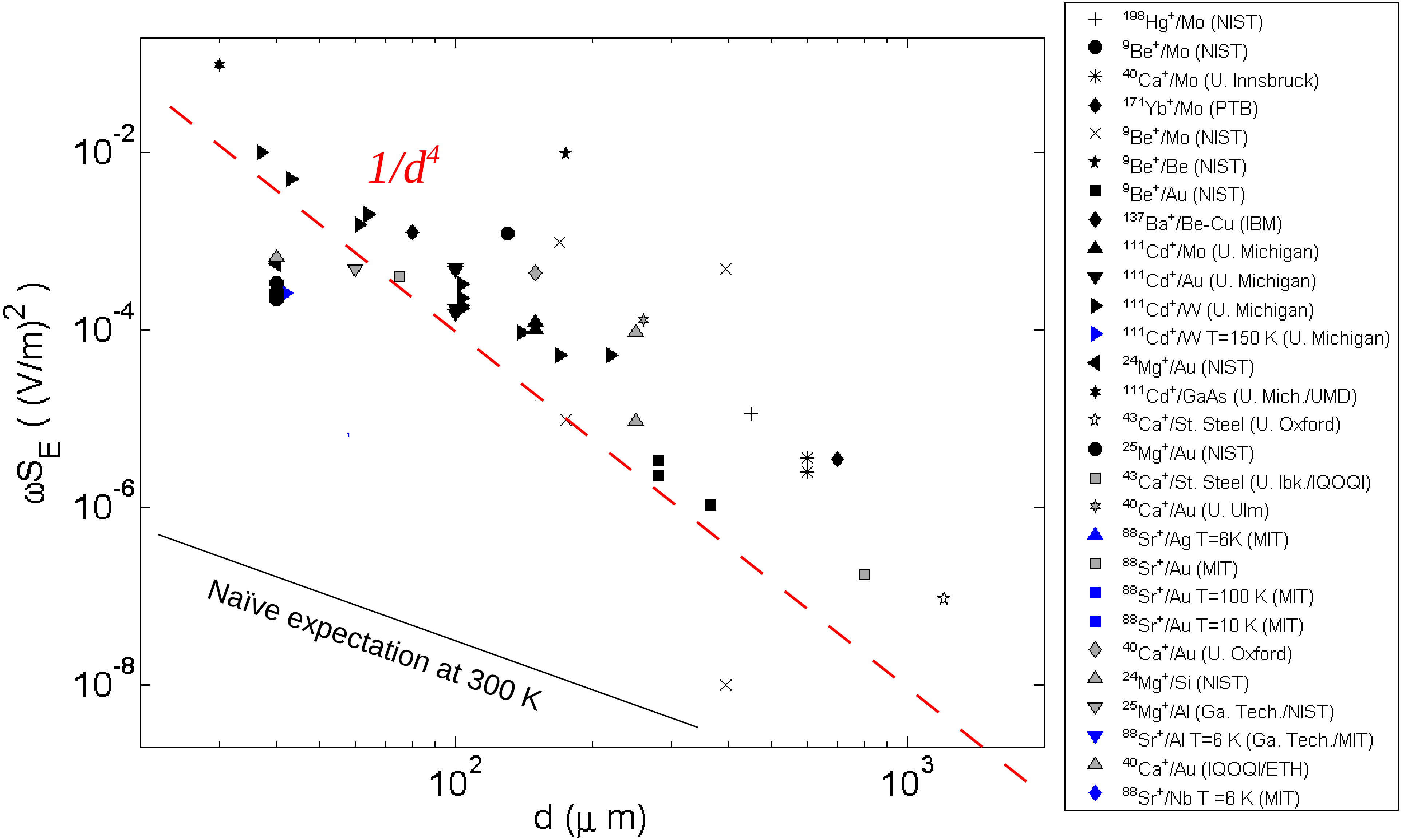

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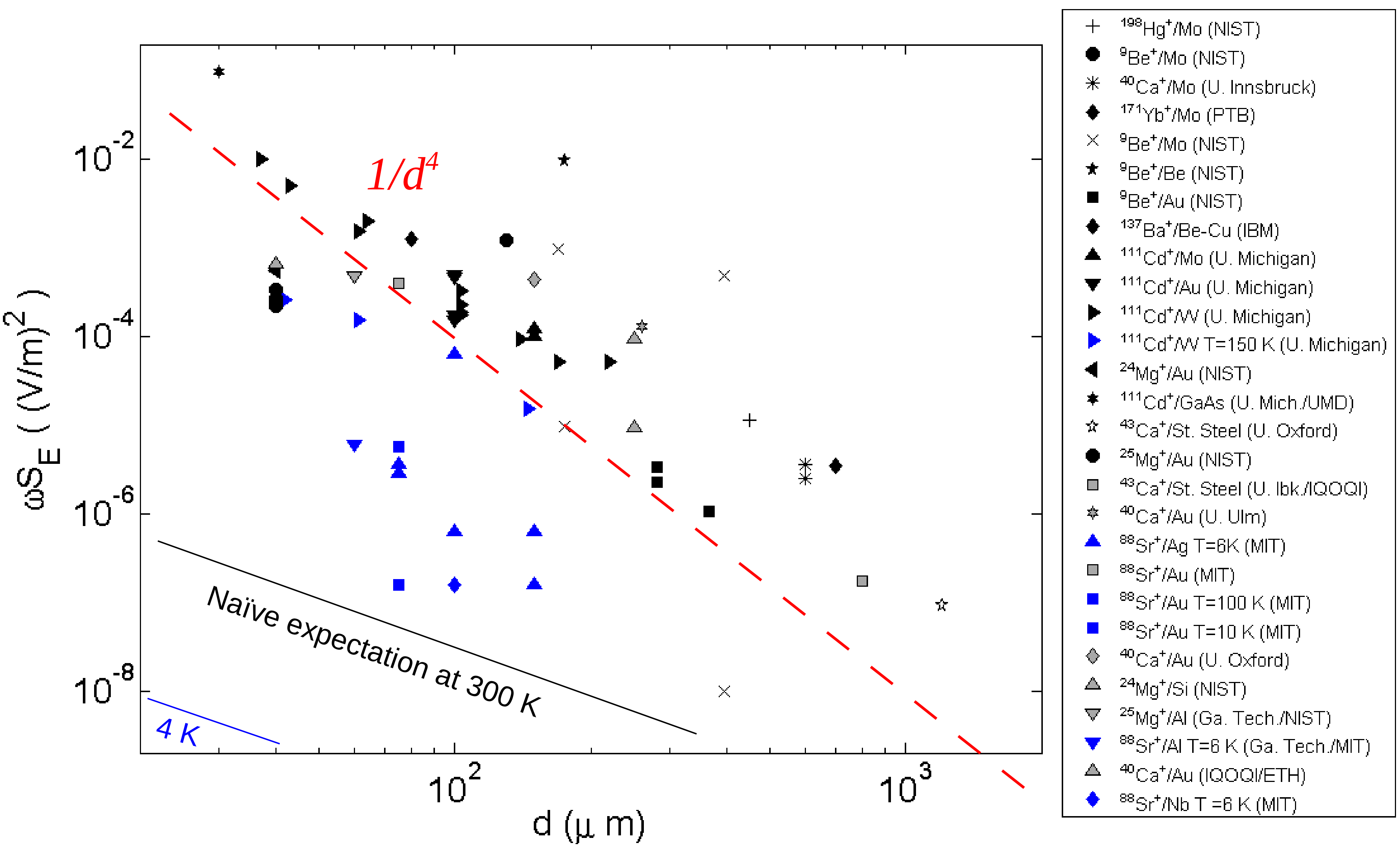
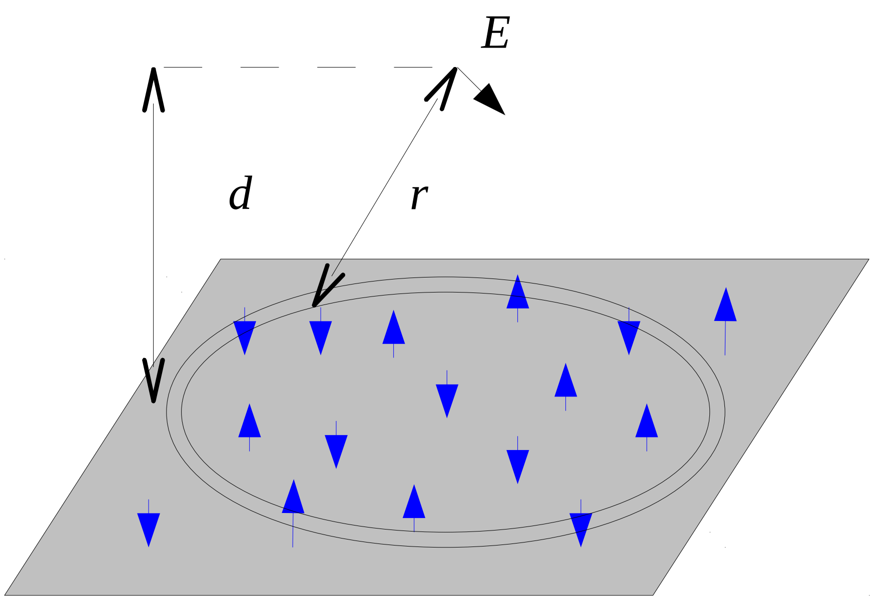


What could cause the field noise?



Other possible noise mechanisms:

- step edge mobility
- ad/desorbtion
- moving grain boundaries
- ???

Random dipole orientation and strength

$$E_N(r) \sim \sqrt{N}\frac{\mu}{r^3}$$

Noise spectral density over trap surface

$$S_{\mathrm{E}} \sim \int_{\mathrm{surf}} n_{\mathrm{s}}(r) \left(\frac{\mu}{r^3}\right)^2 S_\mu \, d\alpha \sim \frac{n_{\mathrm{s}}\mu^2}{d^4} S_\mu$$

Turchette *et al.*, Phys. Rev. A **61** 63418 (2000)

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

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

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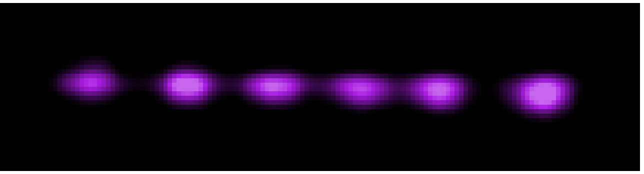
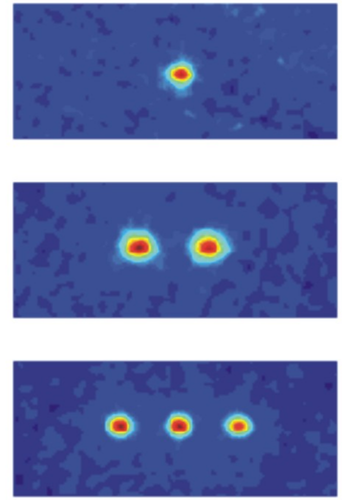
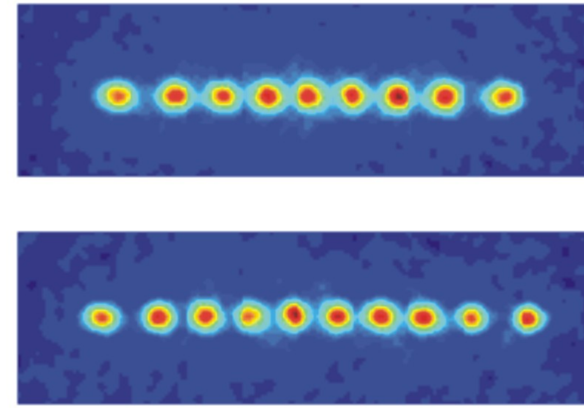
Cold ion crystals



Oxford, England: $^{40}Ca^{+}$





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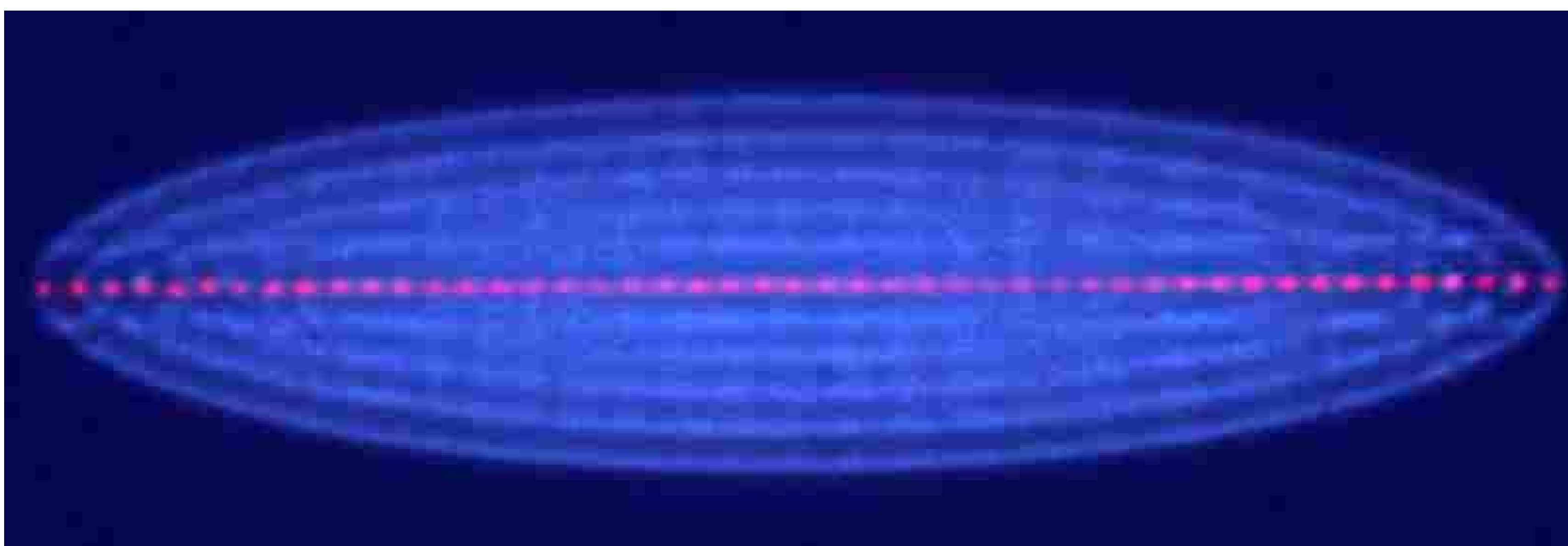
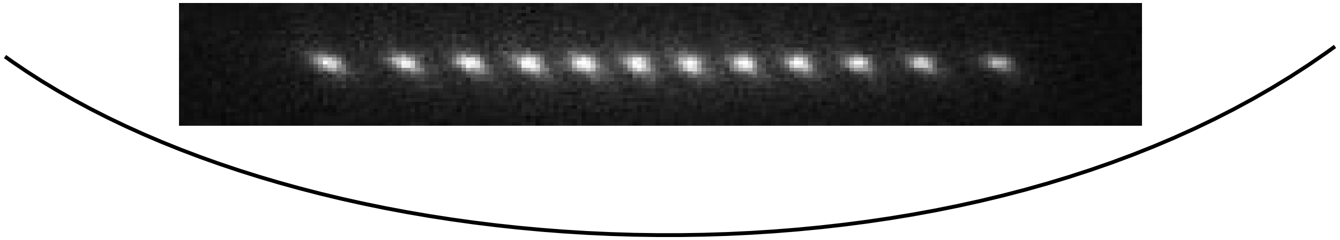
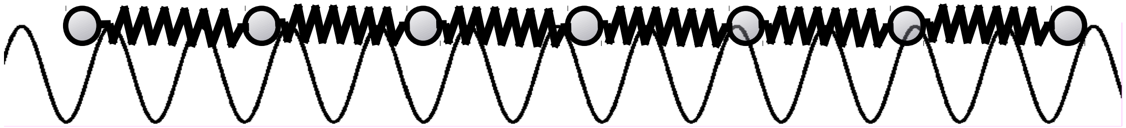


Aarhus, Denmark: $^{40}Ca^{+}$ (red) and $^{24}Mg^{+}$ (blue)

Quantum emulation

General idea: ions in microtraps to emulate quantum many-body physics





Questions:

- friction in the quantum/nano regime?
- how does energy flow at the nano-scale?
- thermal equilibrium of quantum systems?

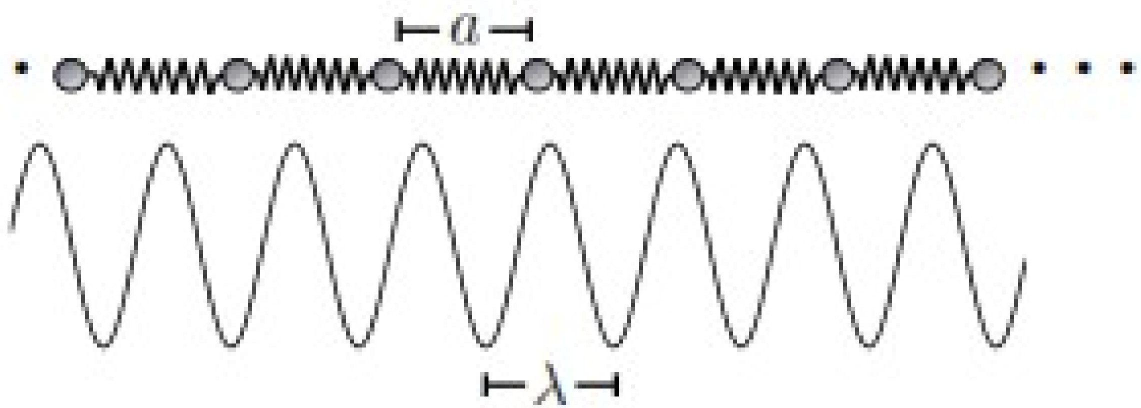
Benassi *et al.*, Nature Commun. **2** 236 (2011)
T. Pruttivarasin et al., New J. Phys. **13**, 075012 (2011)

Quantum emulation of dry friction

A linear trap in an optical cavity: an ion string in a periodic potential

Crystal I

Crystal II



Frenkel-Kontorova model

$$\mathcal{H} = \sum_{i=1}^{N} \left(\frac{P_i^2}{2} + \frac{\omega^2}{2} x_i^2 - K \cos x_i \right) + \sum_{i>j} \frac{1}{|x_i - x_j|}$$

Features:

- quantum phase transition
- non-analytic breaking of KAM surfaces

Garcia-Mata *et al.*, EPJ D, **41** 325 (2007)
Benassi *et al.*, Nature Commun. **2** 236 (2011)

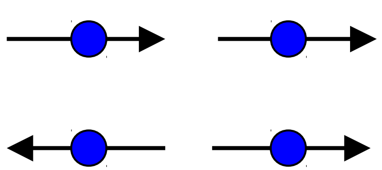
Normal modes

At low temperatures, ions oscillate around their equilibrium positions

Coulomb interaction: coupling of ion motion

$\longrightarrow$ small excitations : collective normal modes

2 ions:

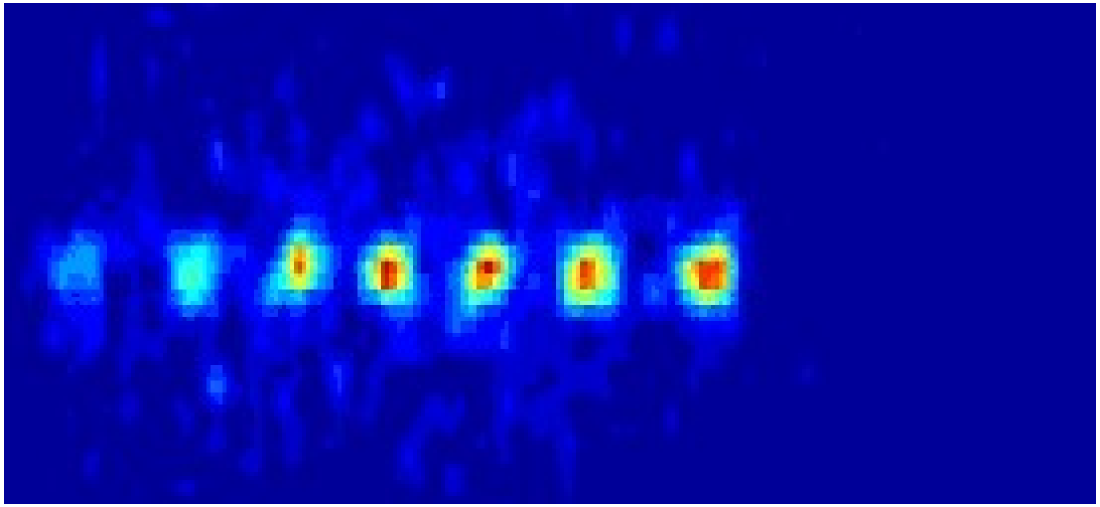


center of mass mode $\nu_1 = \nu_z$

breathing mode $\nu_2 = \sqrt{3}\nu_z$

Center-of-mass and breathing mode excitation

„center-of-mass mode“



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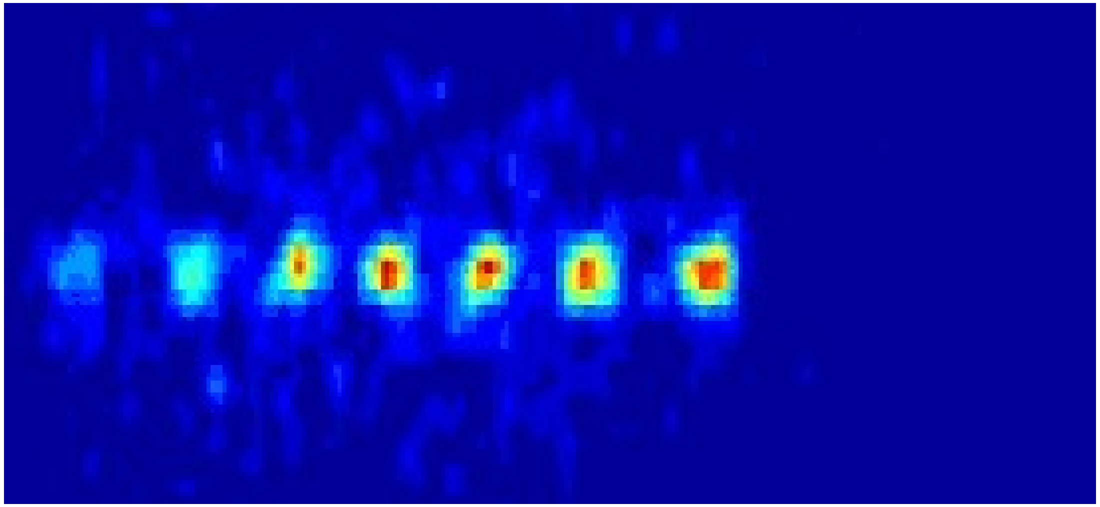
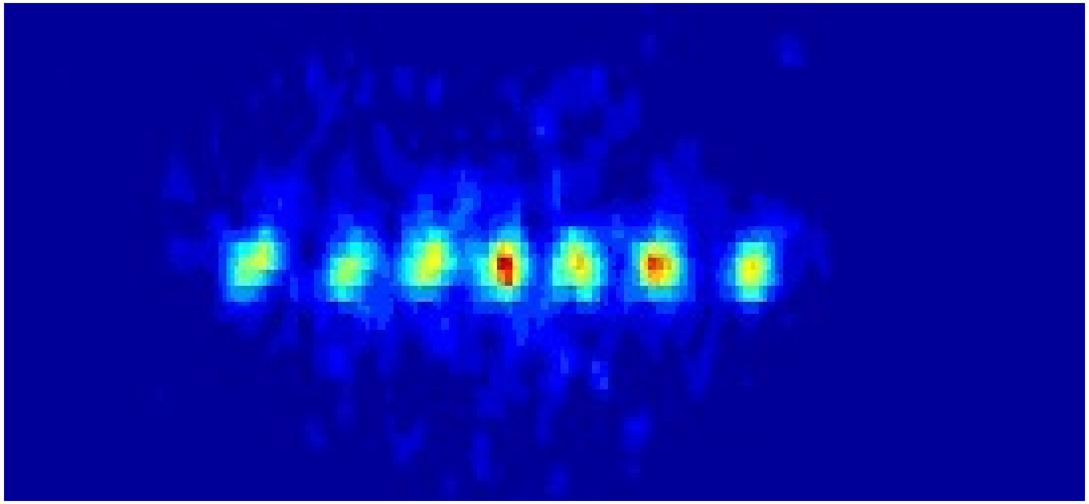


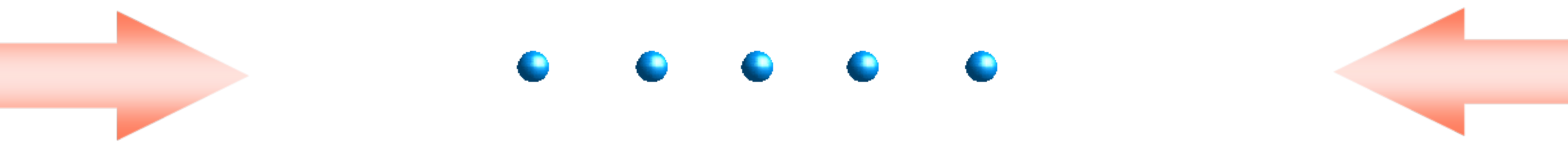
„stretch mode“



Emulation of friction

Frenkel-Kontorova model:

How does a chain of ions move in a periodic potential ?



Ions move collectively

Emulation of friction

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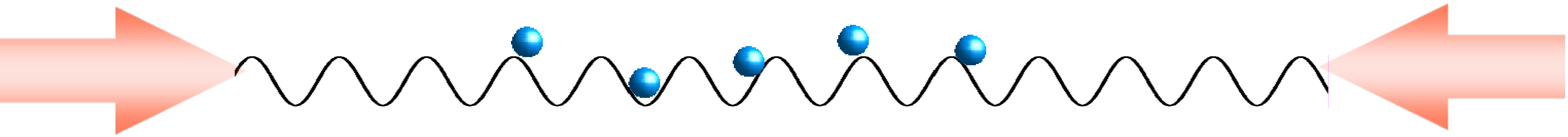

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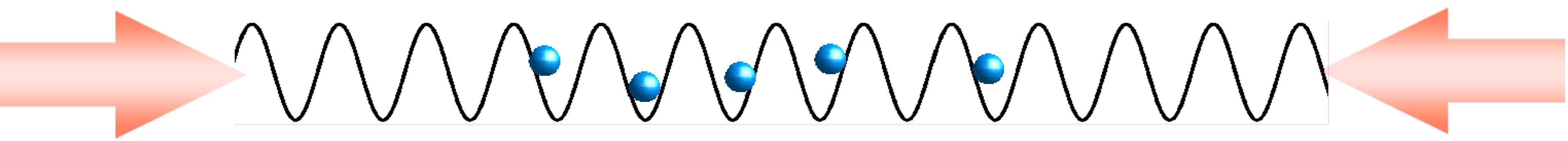

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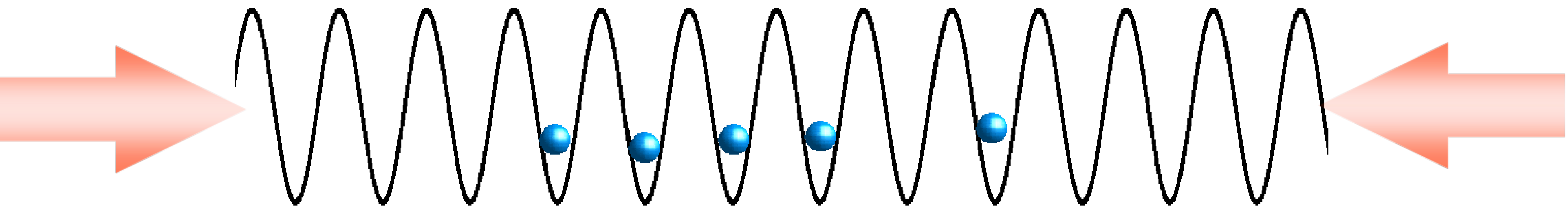
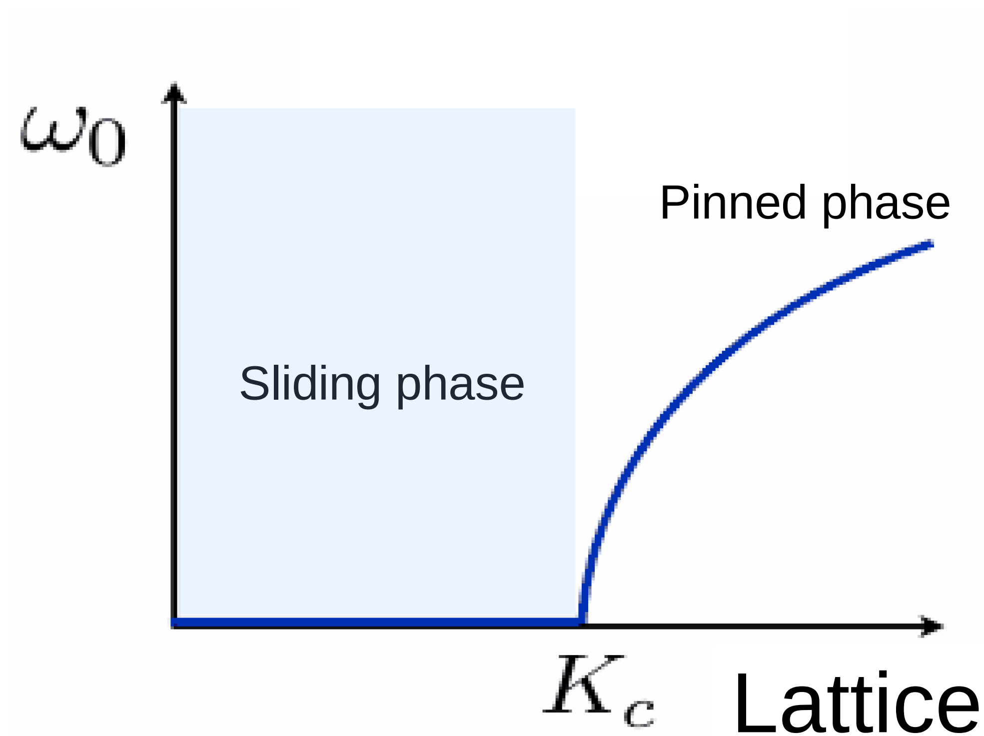


Ions are pinned

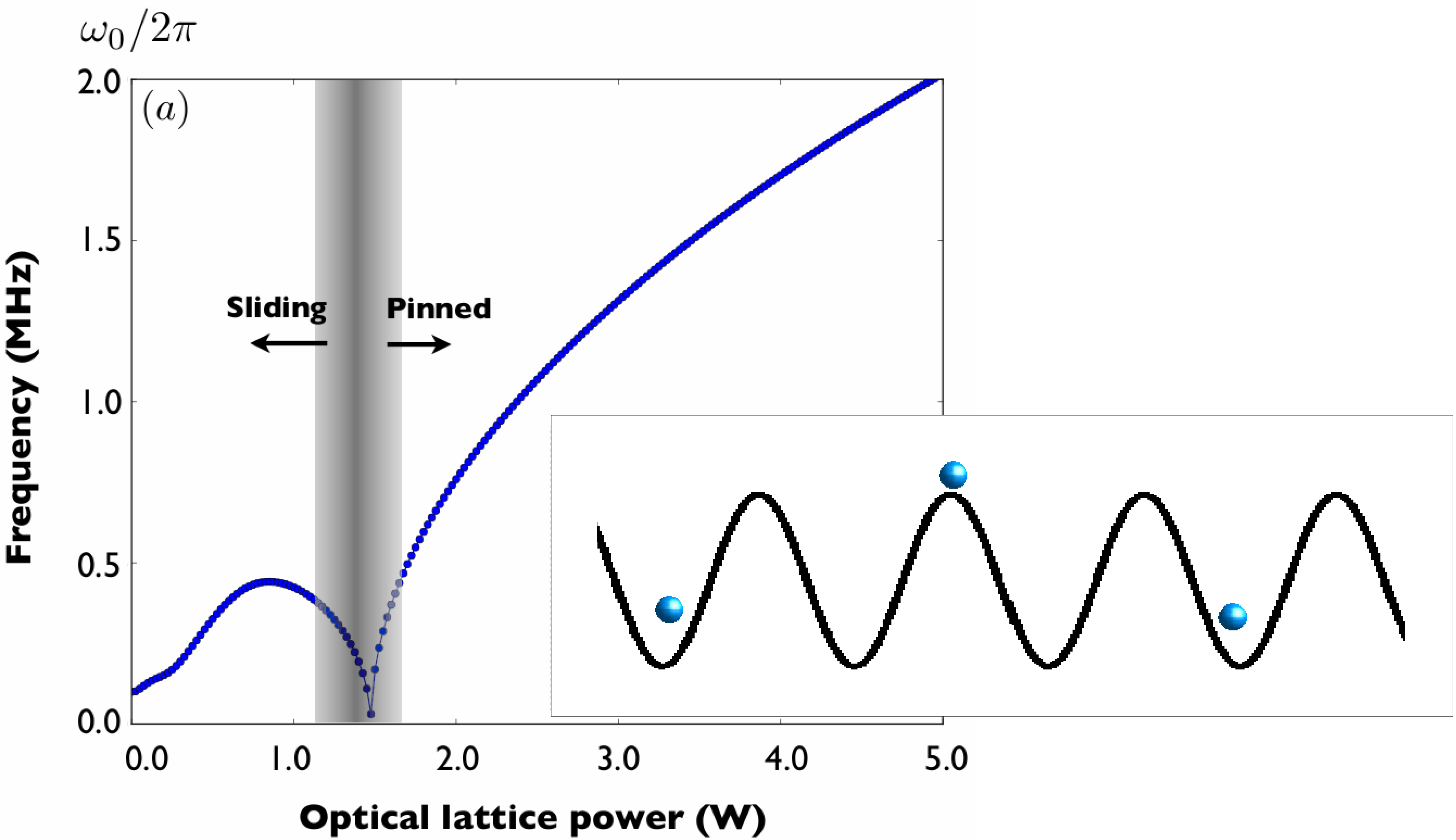
Quantum phase transition ?

Ideal Frenkel-Kontorova model

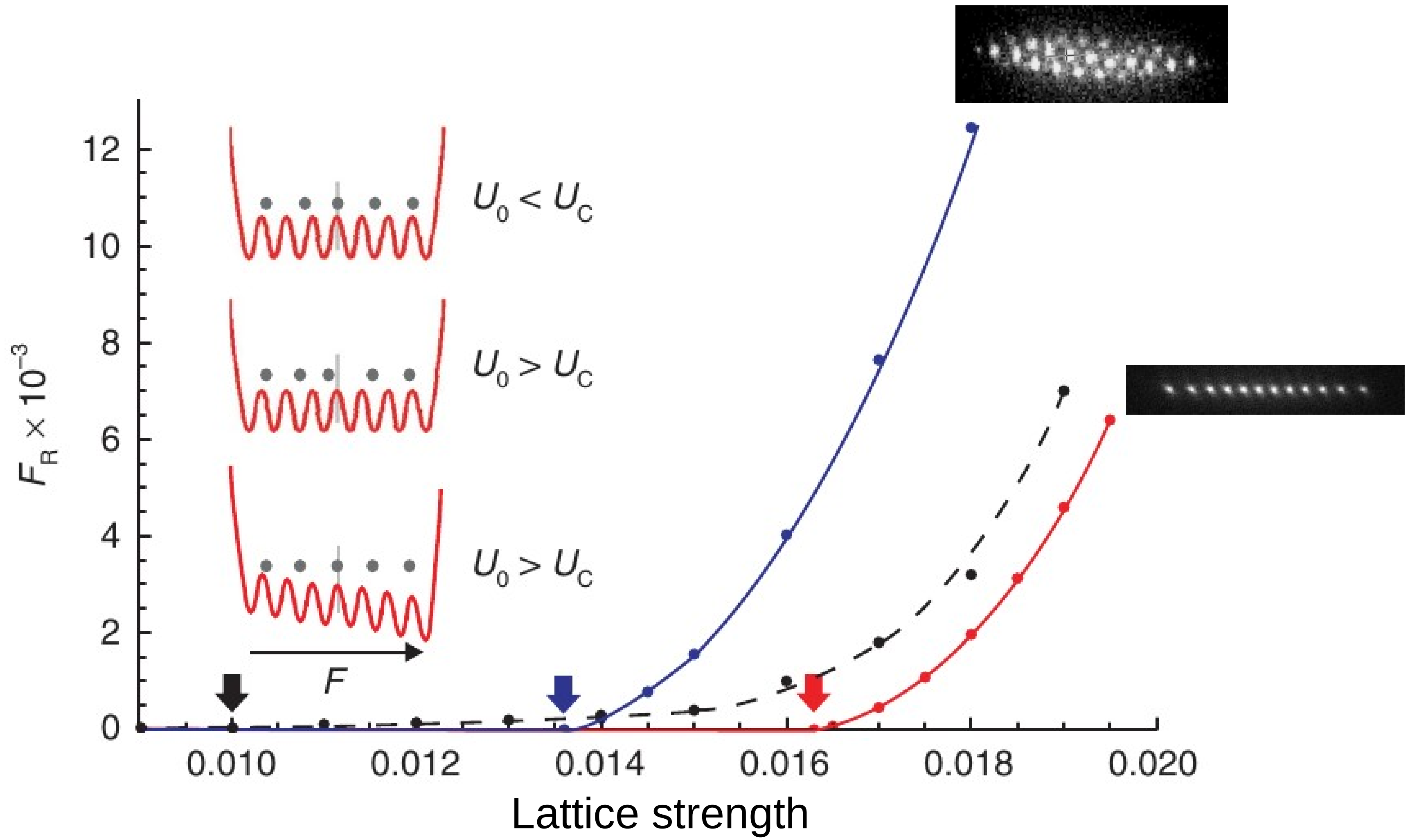


Lattice strength

Quantum simulation: Observables



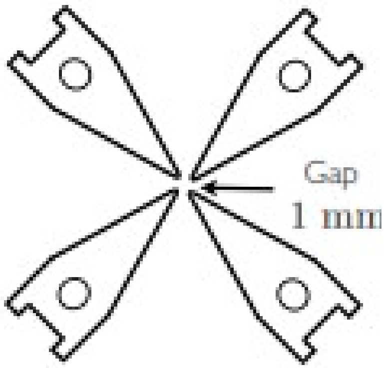
Finding an order parameter

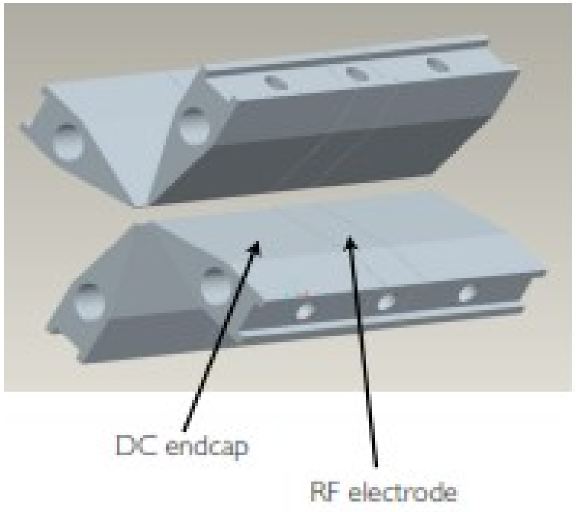


Idea and illustration from Benassi, Vanossi, Tosatti, Nature Commun. **2** 236 (2011)

Experimental set-up

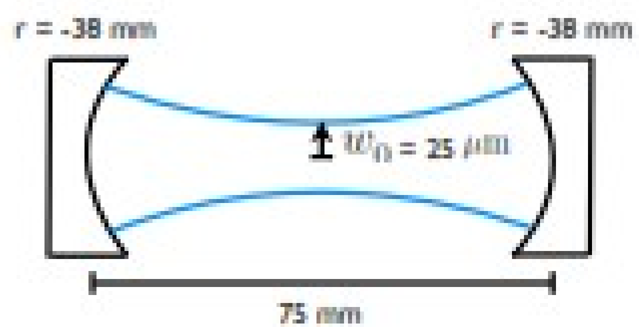
Linear Paul trap:





Trap frequencies:

radial: ~3 MHz radially
axial: 50 kHz to 1 MHz

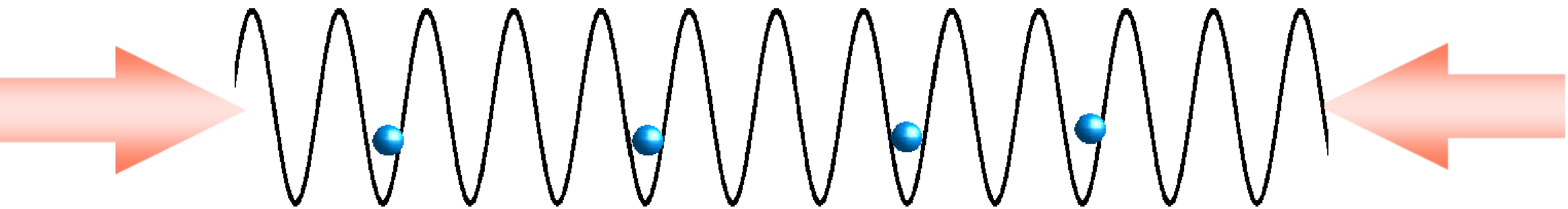


Optical trapping

Experimental challenge: optical force need to be stronger than the electrical forces

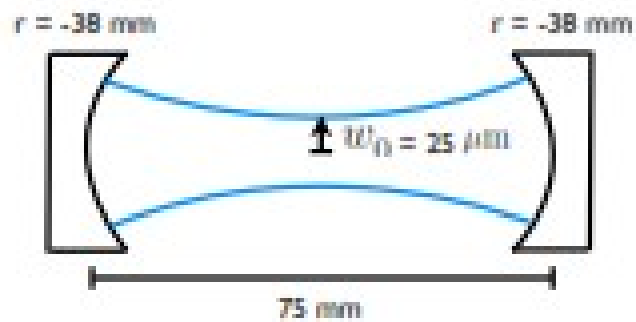
Schneider *et al.*, Nature Photonics **4** (2010)

Schmied *et al.*, NJP **10** (2008)

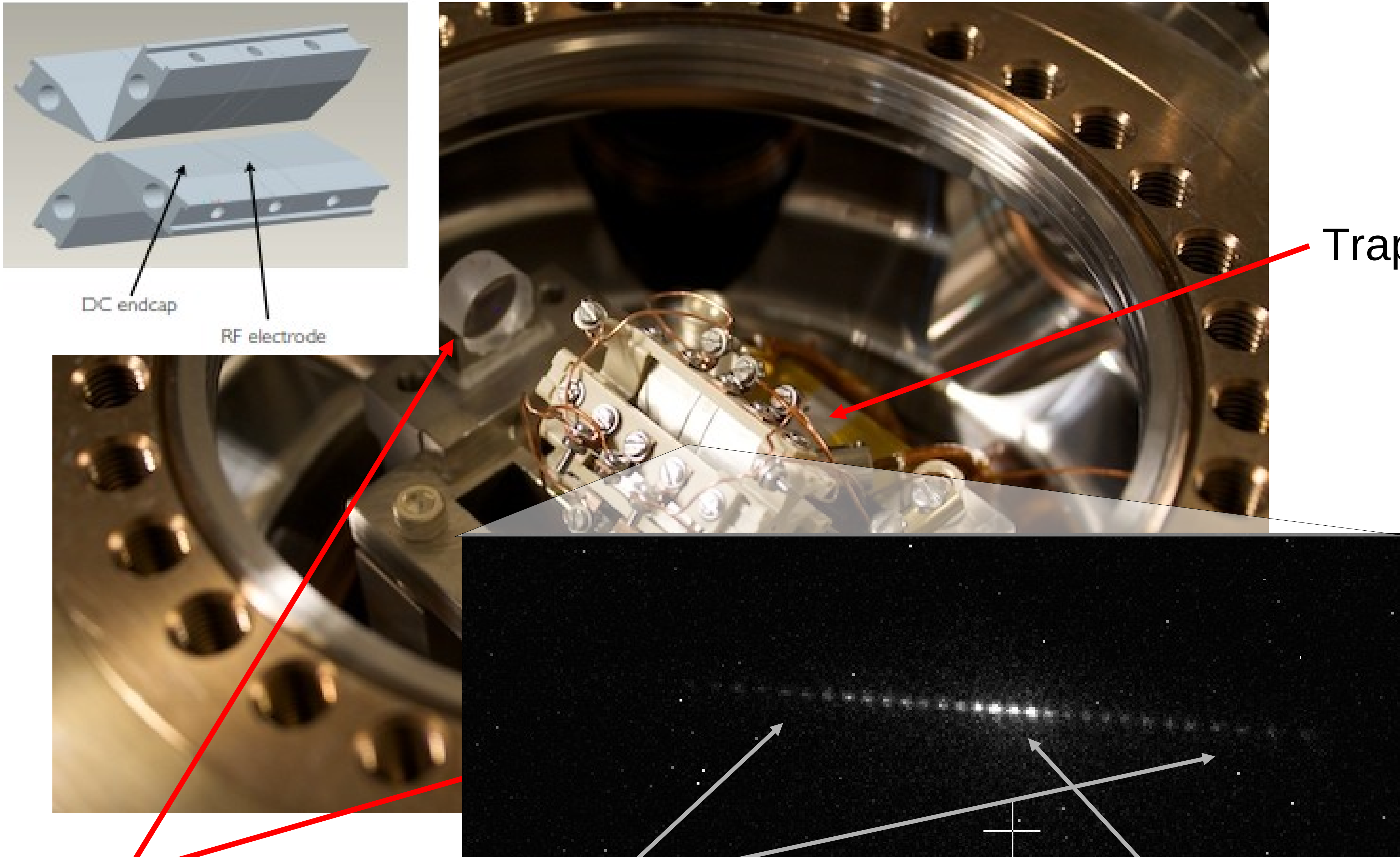


Parameters for Ca^+:
- waist: 25 μm
- power at 405 nm: 2 W
- detuning: 8 nm

→ - optical trap frequency: 1 MHz
- scatter events: 40 / s

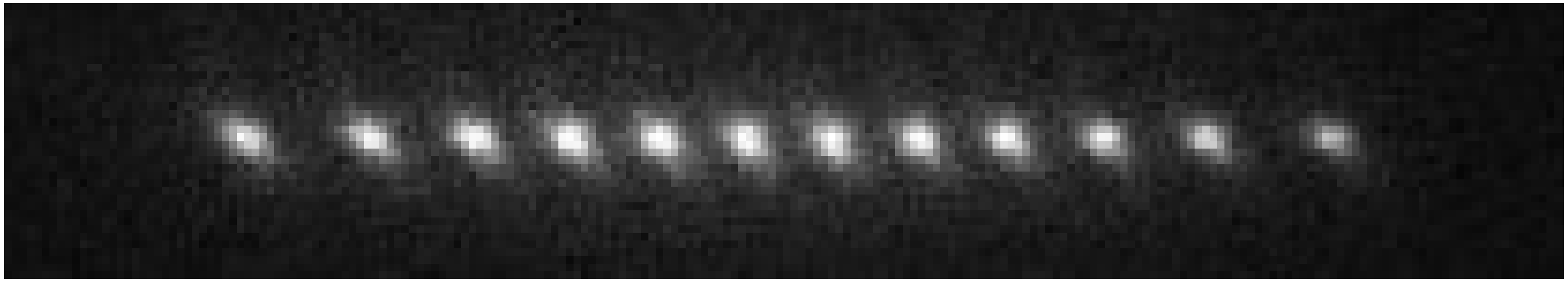


Experimental set-up

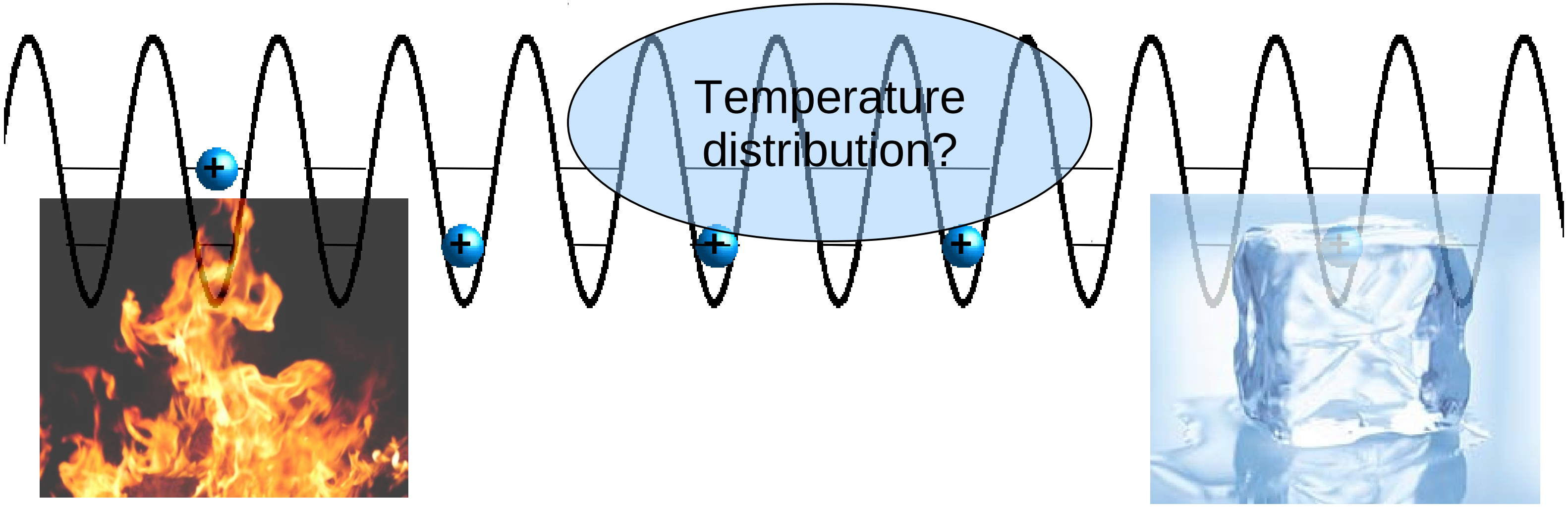


Heat transport

Wigner crystal of trapped ions ...

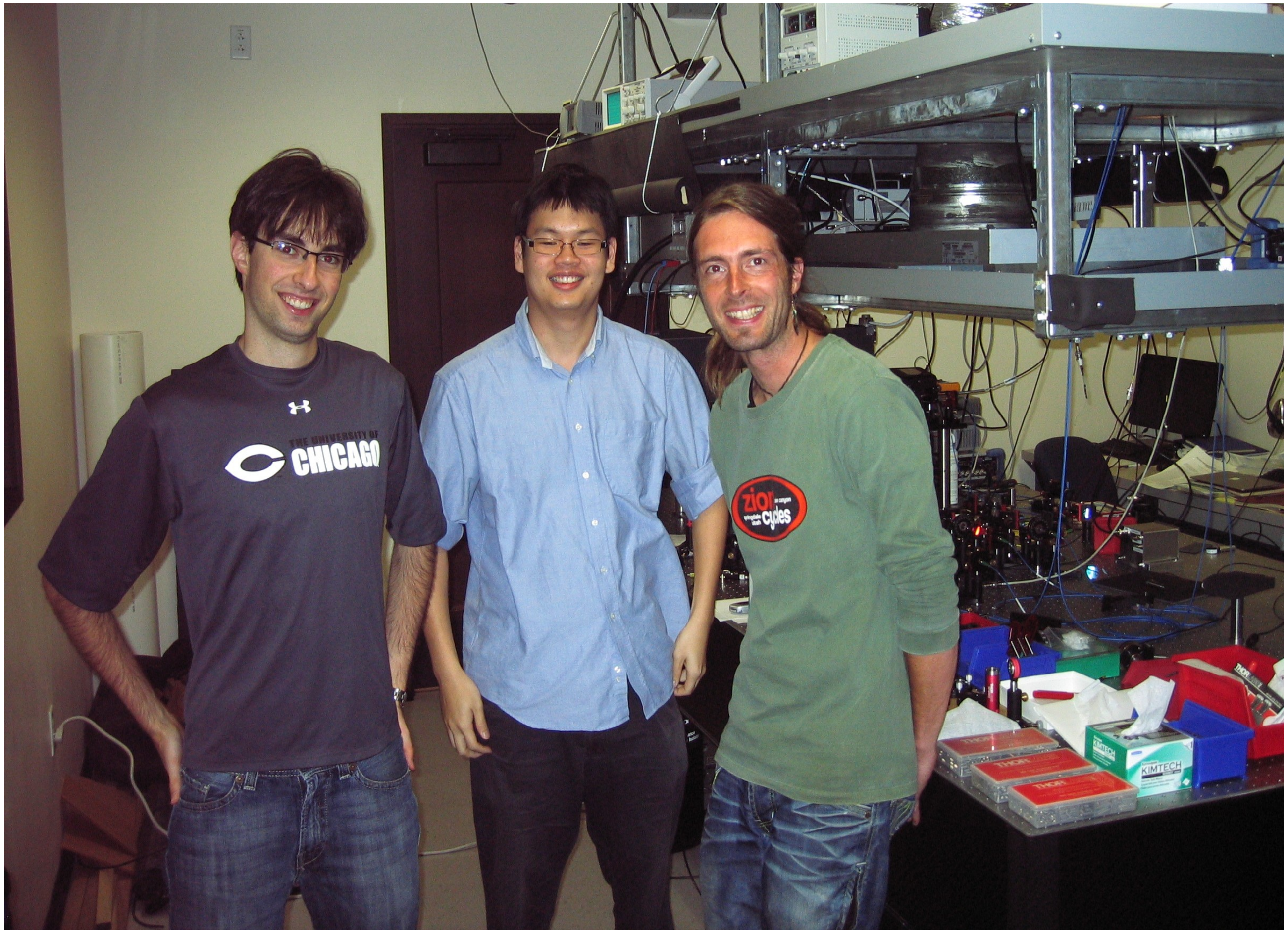


… forms a chain of contrallable oscillators.



The team

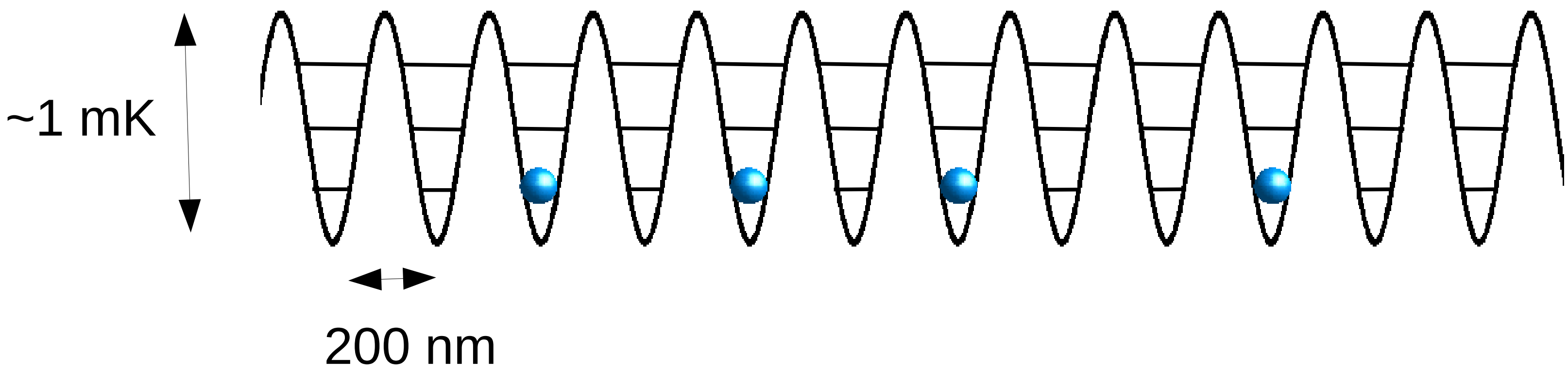
Thaned (Hong) Pruttivarasin
Michael Ramm
Axel Kreuter
Ishan Talukdar



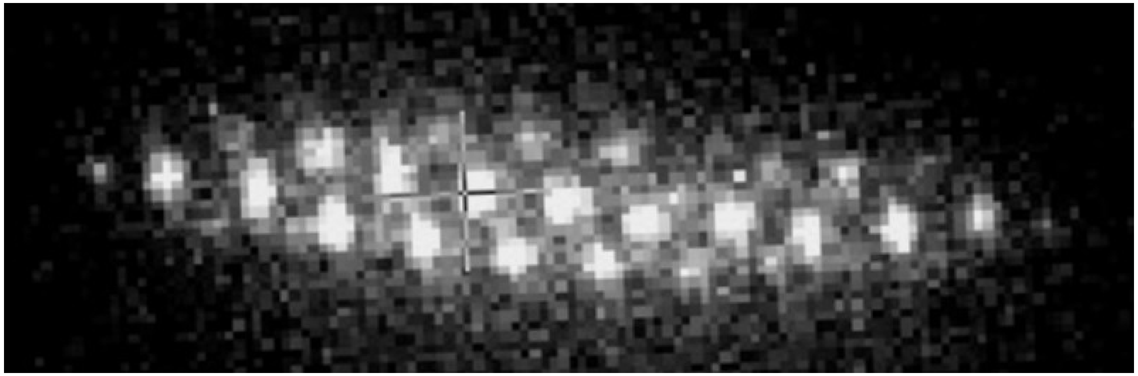
T. Pruttivarasin et al., New J. Phys. **13**, 075012 (2011)

Chances

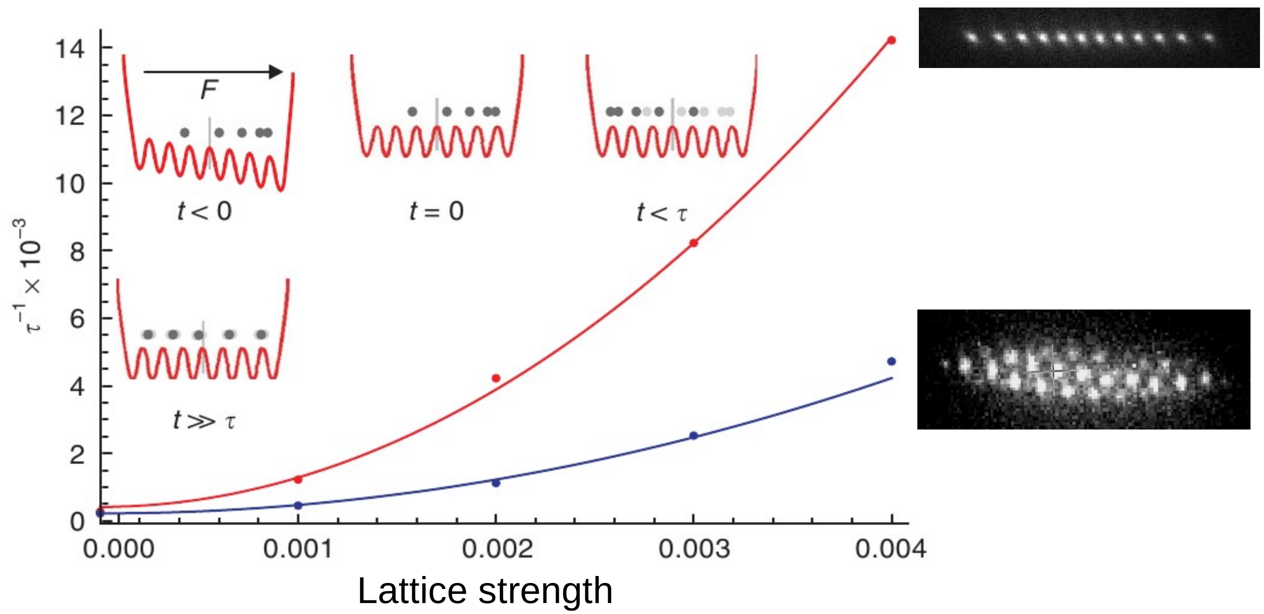
- probe physics related to friction in the quantum regime



- 1-D, 2-D crystals, see Benassi *et al.*, Nature Commun. **2** 236 (2011)

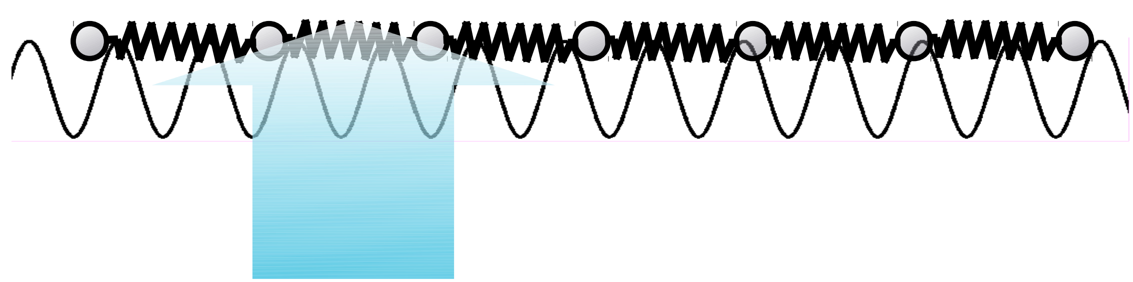


- probe dynamics



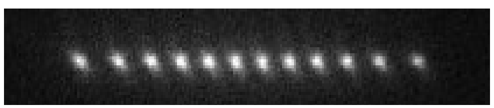
From: Benassi *et al.*, Nature Commun. **2** 236 (2011)

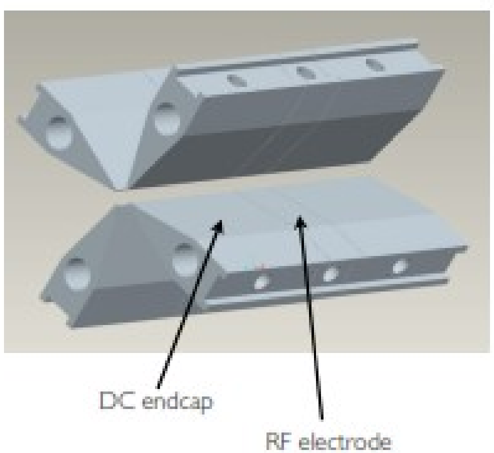
- engineer local dissipation



Conclusion

Trapped ions

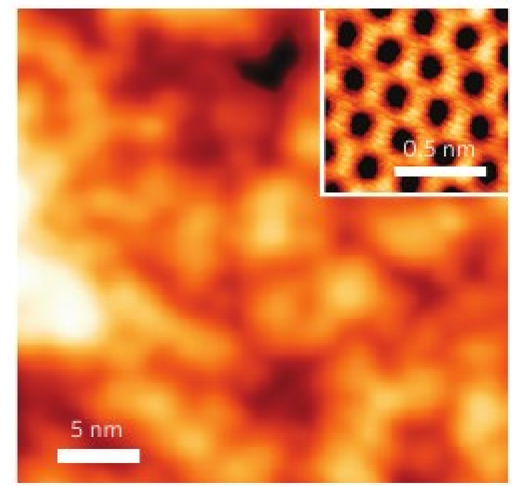




Emulation

Better traps

Surface science



From Zhang et al., Nat. Phys. **5**, 722

People

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Oliver Neitzke

Thaned (Hong) Pruttivarasin

Michael Ramm

Ishan Taludkar