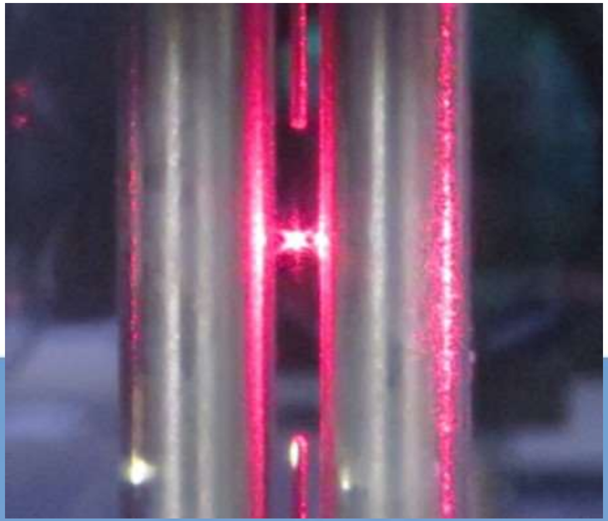
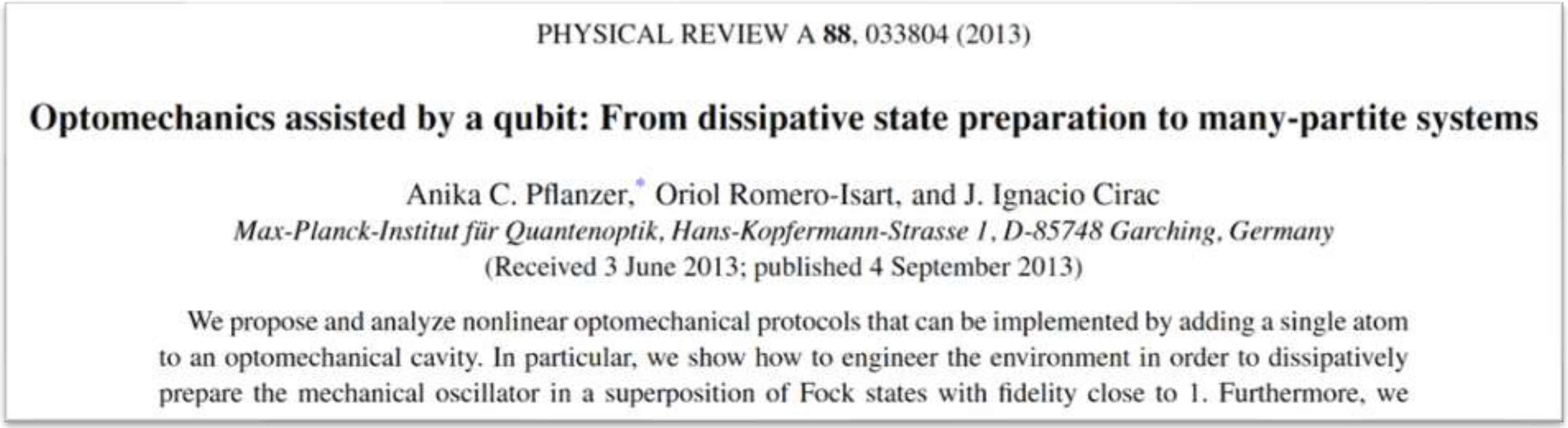
universität
innsbruck



An ultra-high-Q mechanical oscillator in a Paul trap

Tracy Northup, Institute for Experimental Physics, University of Innsbruck

QUANTUM
INTERFACES
GROUP



PHYSICAL REVIEW A **88**, 033804 (2013)

Optomechanics assisted by a qubit: From dissipative state preparation to many-partite systems

Anika C. Pflanzer,* Oriol Romero-Isart, and J. Ignacio Cirac
Max-Planck-Institut für Quantenoptik, Hans-Kopfermann-Strasse 1, D-85748 Garching, Germany
(Received 3 June 2013; published 4 September 2013)

We propose and analyze nonlinear optomechanical protocols that can be implemented by adding a single atom to an optomechanical cavity. In particular, we show how to engineer the environment in order to dissipatively prepare the mechanical oscillator in a superposition of Fock states with fidelity close to 1. Furthermore, we

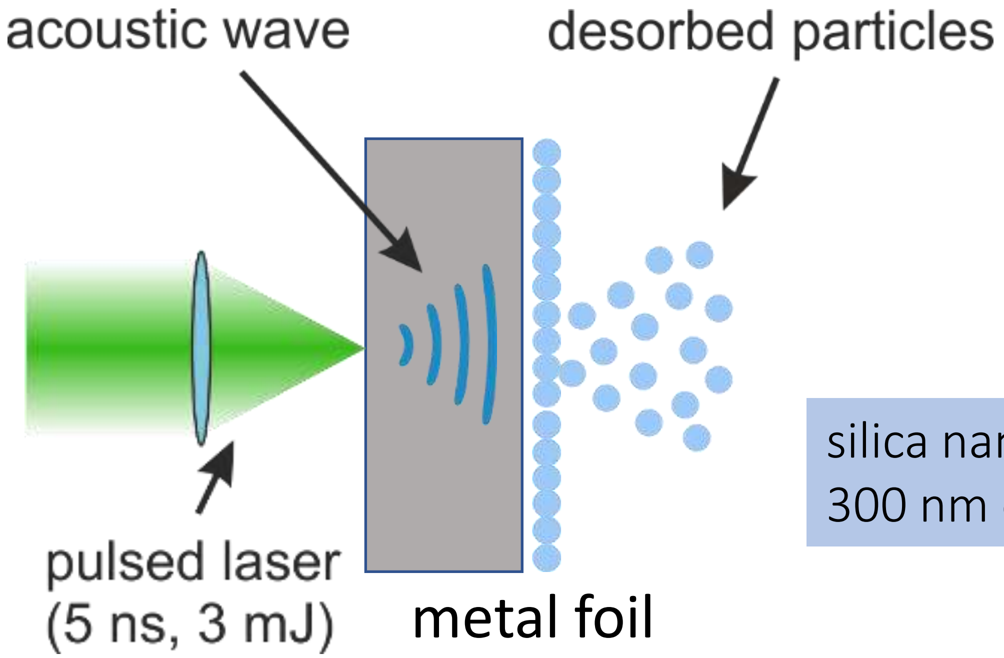
Could you do this with an ion?

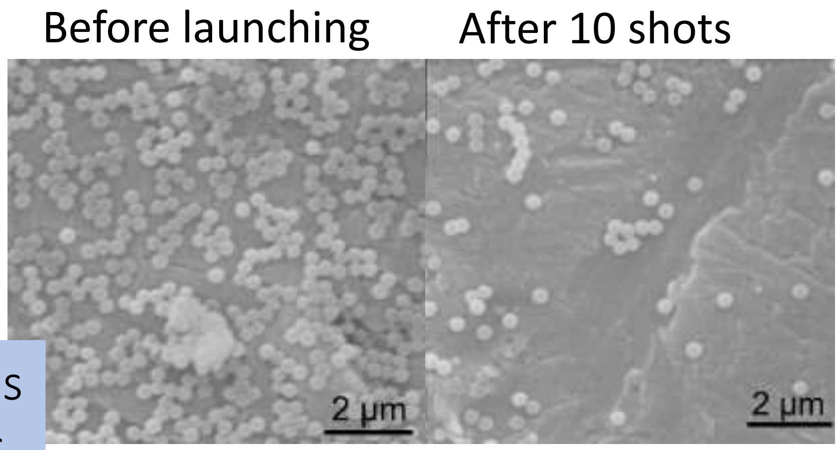
How can ion traps and trapped ions help us prepare quantum states of levitated mechanical systems?

An ultra-high-Q mechanical oscillator in a Paul trap

- We can load & cool silica nanoparticles in an ultra-high vacuum (UHV) environment at room temperature.
- In an ion trap, it’s possible to detect and cool particles without illuminating them optically.
- We measure a quality factor of $1.6(4)\cdot 10^{10}$, enabled by UHV and by the absence of light-induced decoherence.
- An ion and a nanoparticle can be confined in the same Paul trap, despite their very different charge-to-mass ratios.

Laser Induced Acoustic Desorption

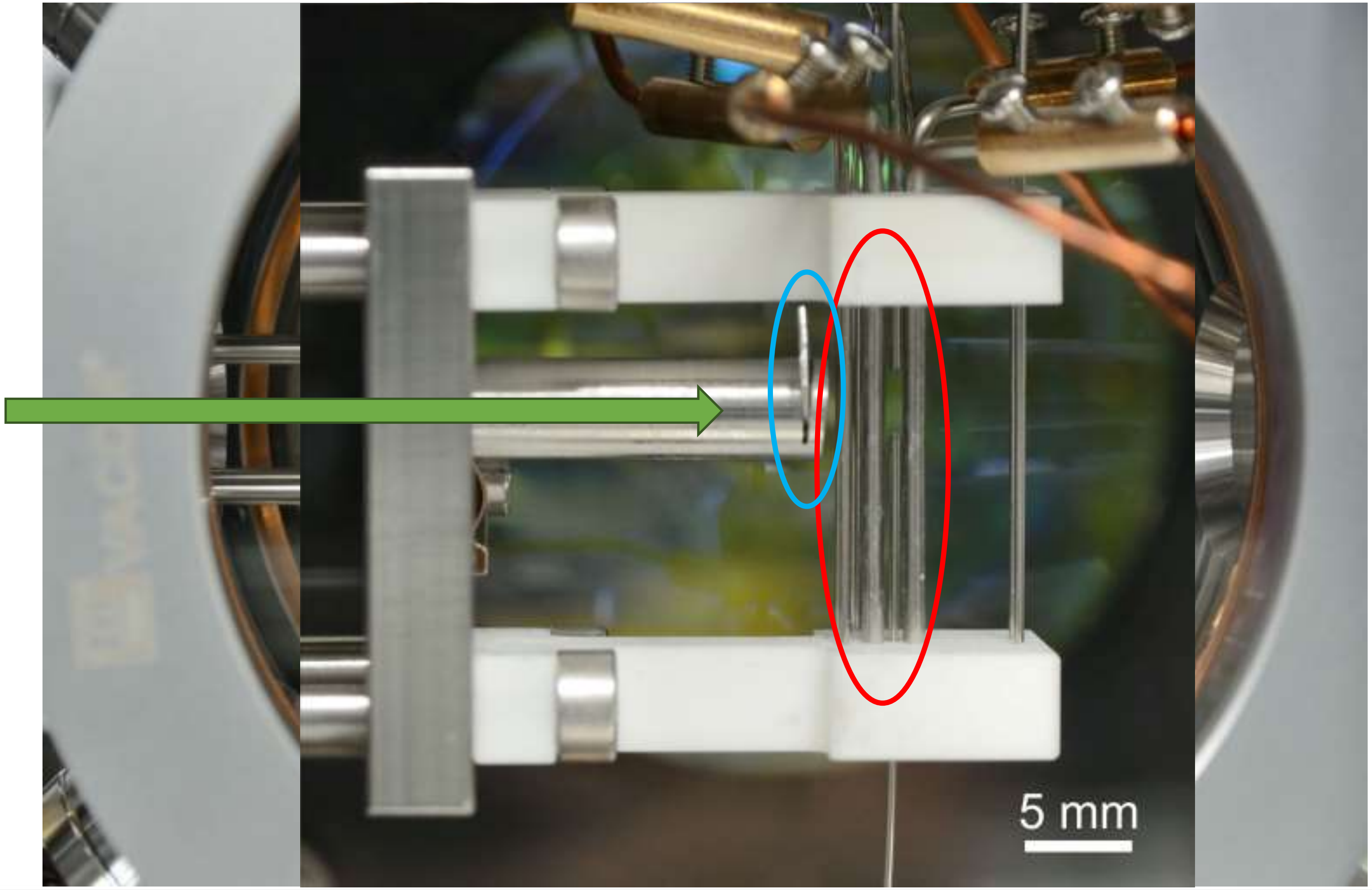


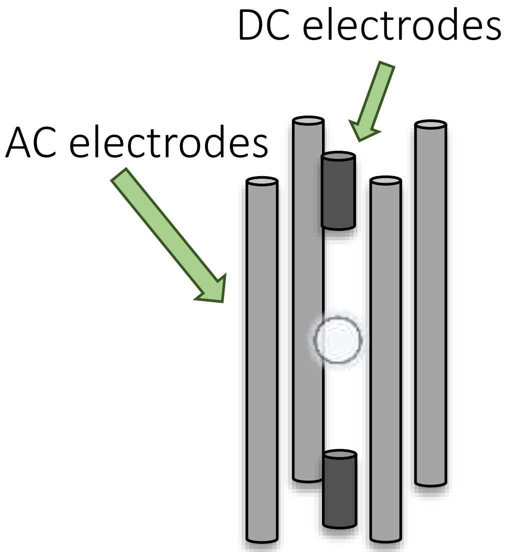


silica nanospheres
300 nm diameter

P. Asenbaum et al., *Nat Commun.* **4**, 2743 (2013)
S. Kuhn et al., *Appl. Phys. Lett.* **111**, 253107 (2017)
D. S. Bykov, P. Mestres, L. Dania, L. Schmöger, T. E. Northup, *Appl. Phys. Lett.* **115**, 034101 (2019)

Experimental setup

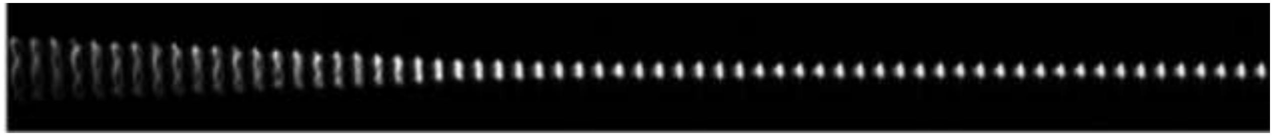




- secular motion at frequency of effective potential (~kHz)
- micromotion at AC drive frequency (~10 kHz)

Nanoparticles are caught within the trap.

We turn on the trap as nanoparticles traverse the trap region.



Damping of oscillations consistent with background gas cooling.

Nanoparticles in UHV:

buffer-gas cooling with N_2, followed by vacuum pumping…

…or trapping in UHV & feedback cooling

localized particles @ $7 \cdot 10^{-11}$ mbar

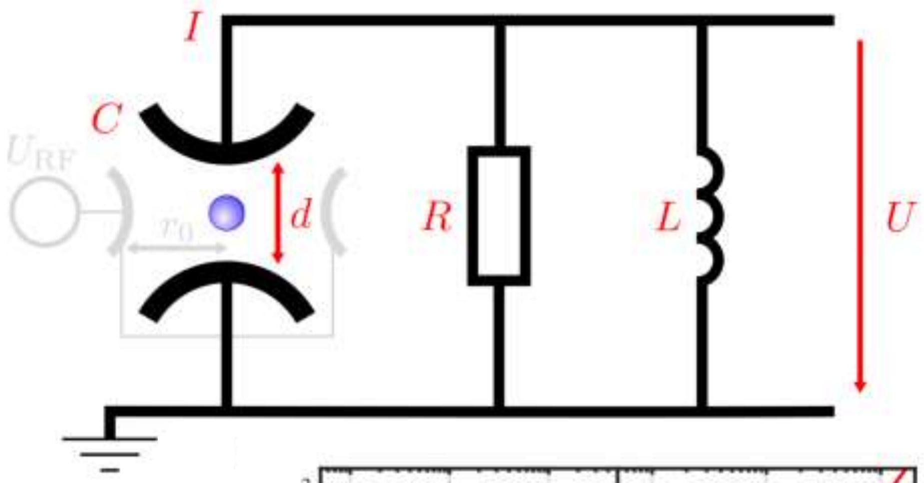
L. Dania, D. S. Bykov, F. Goschin, M. Teller, T. E. Northup, arXiv:2304.02408

D. S. Bykov, P. Mestres, L. Dania, L. Schmöger, T. E. Northup, *Appl. Phys. Lett.* **115**, 034101 (2019)

An ultra-high-Q mechanical oscillator in a Paul trap

- We can load & cool silica nanoparticles in an ultra-high vacuum (UHV) environment at room temperature.
- In an ion trap, it's possible to detect and cool particles without illuminating them optically.
- We measure a quality factor of $1.6(4)\cdot 10^{10}$, enabled by UHV and by the absence of light-induced decoherence.
- An ion and a nanoparticle can be confined in the same Paul trap, despite their very different charge-to-mass ratios.

Electrical detection offers an alternative to optical detection

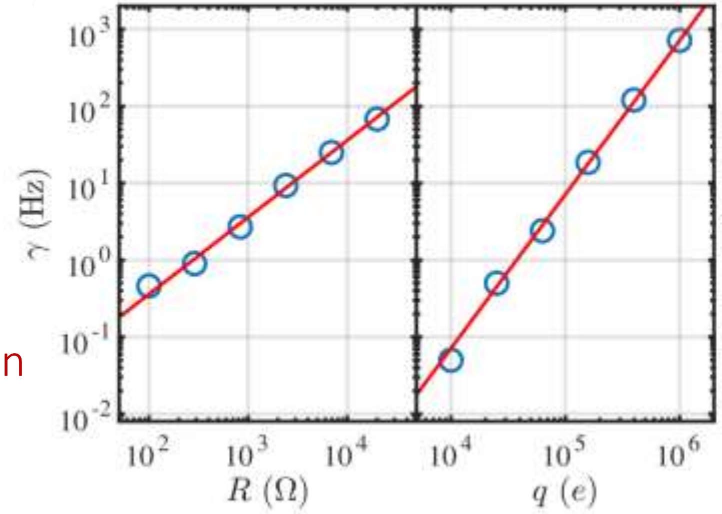


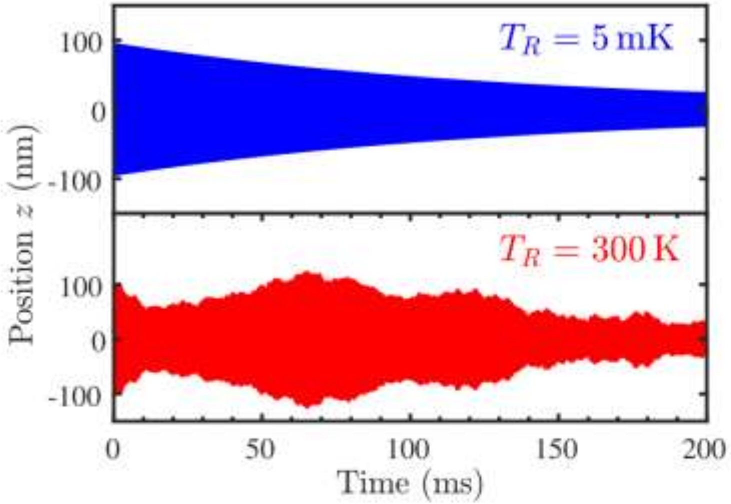
The motion of a charged particle induces a current in the circuit, which can be detected, e.g., with a tuned RLC circuit…

…providing a signal for resistive cooling or feedback cooling.

H. G. Dehmelt, *Adv. At. Mol. Phys.* **5**, 109 (1969)

feedback gain

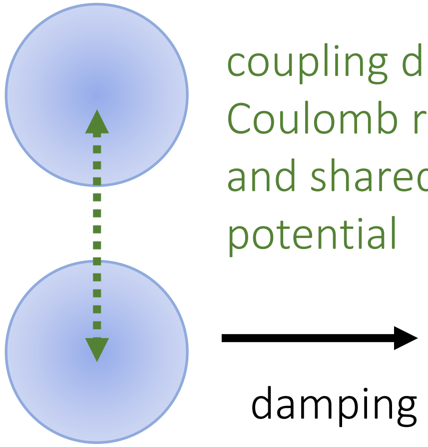




simulations of electrical detection & resistive cooling

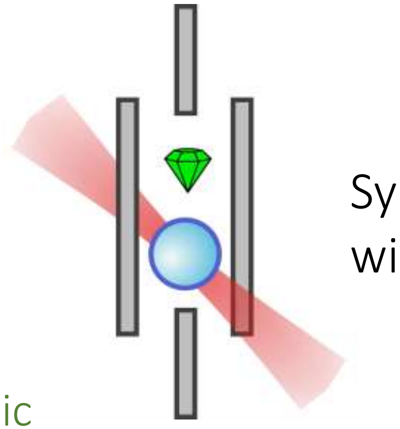
D. Goldwater, B. A. Stickler, L. Martinetz, T. E. Northup, K. Hornberger, J. Millen, *Quantum Sci. Technol.* **4**, 024003 (2019)

Sympathetic cooling: how to cool a particle without illumination



coupling due to Coulomb repulsion and shared harmonic potential

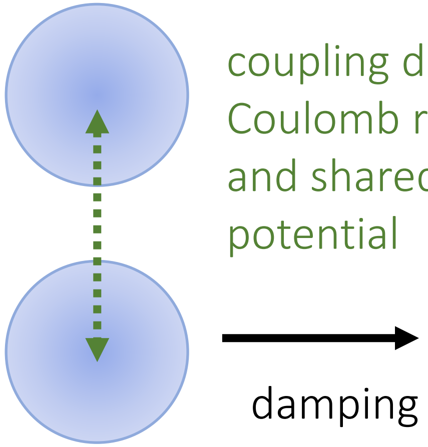
damping force
acts on one particle



Sympathetic cooling allows us to cool particles without illuminating them directly with a laser field.

Sympathetic cooling provides a route to cool multiple nanoparticles in the same trap.

Sympathetic cooling: two coupled oscillators + damping



coupling due to Coulomb repulsion and shared harmonic potential

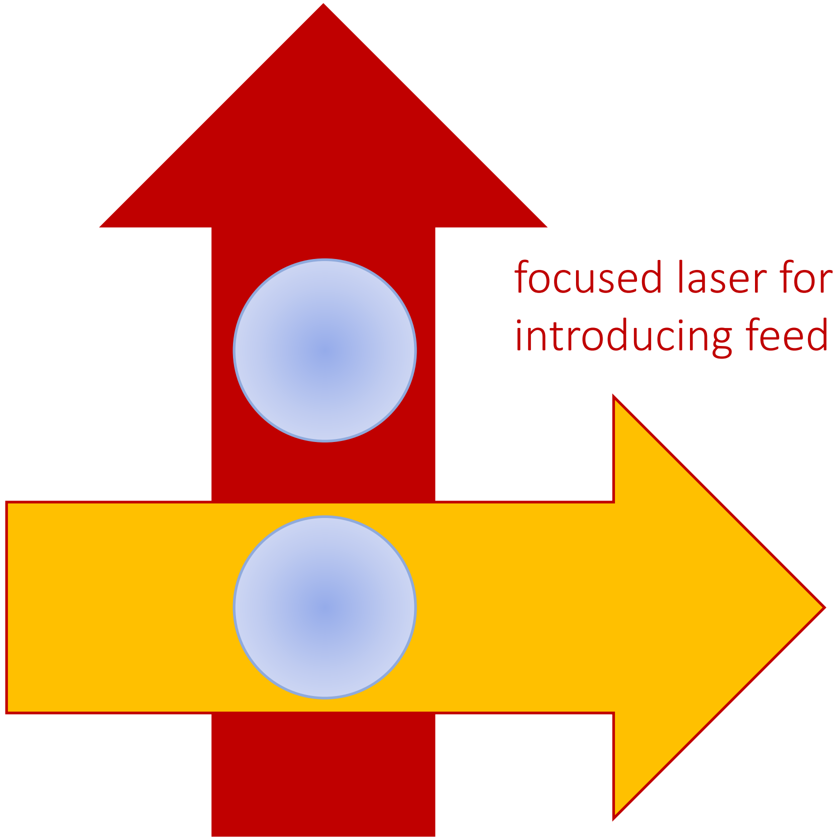
damping force acts on one particle

In ion-trap quantum computing, sympathetic cooling allows computation and cooling to happen in parallel.

- one ion species for computation
- a second species for cooling
- lasers used for one species are not resonant with the transitions of the other species

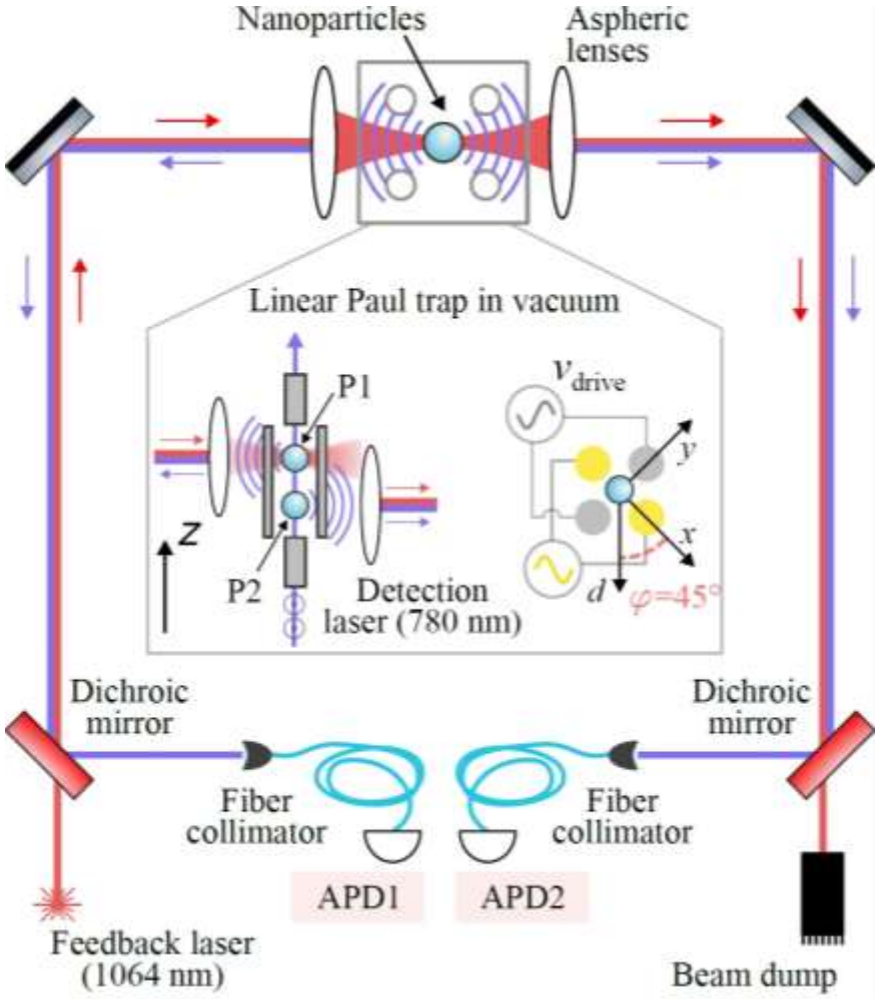
Quantum metrology: sympathetic cooling allows us to choose species that are well suited as sensors or clocks, even if we can't cool them well.

Trapping and detection of a two-particle Coulomb crystal



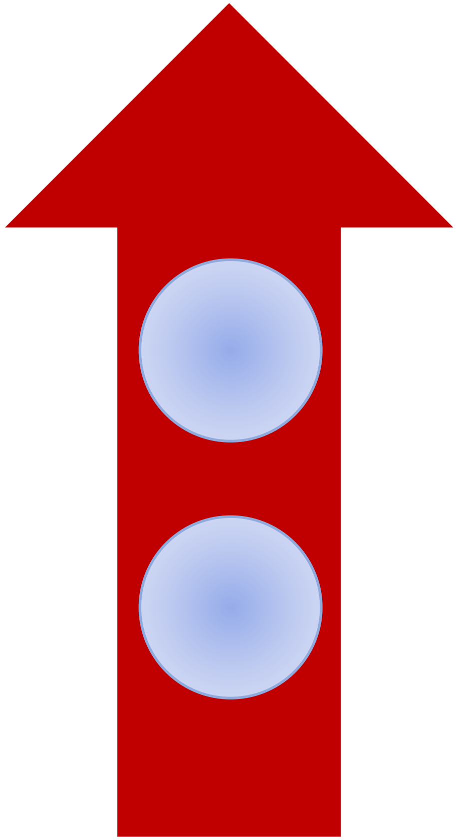
focused laser for
introducing feedback

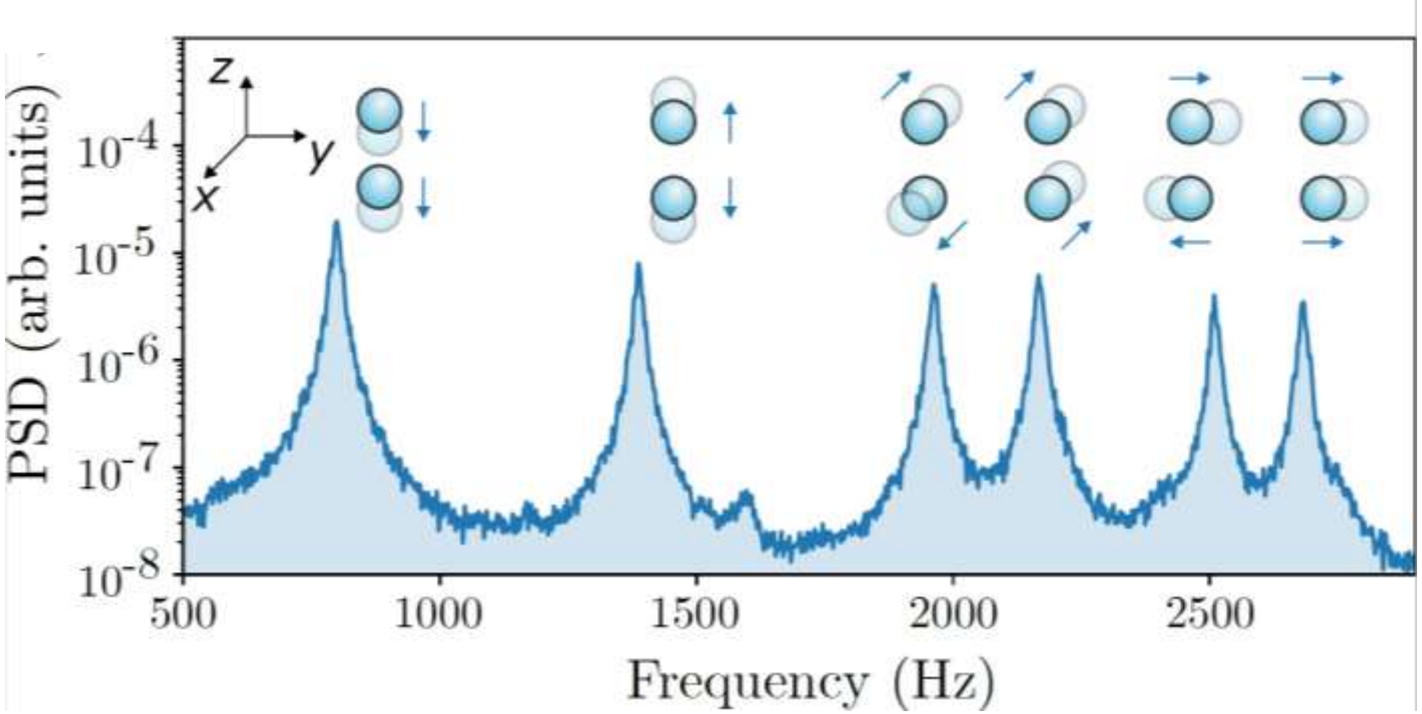
collective laser field for detecting
the motion of each nanoparticle



D. S. Bykov, L. Dania, F. Goschin, T. E. Northup, *Optica* **10**, 438 (2023)

Trapping and detection of a two-particle Coulomb crystal

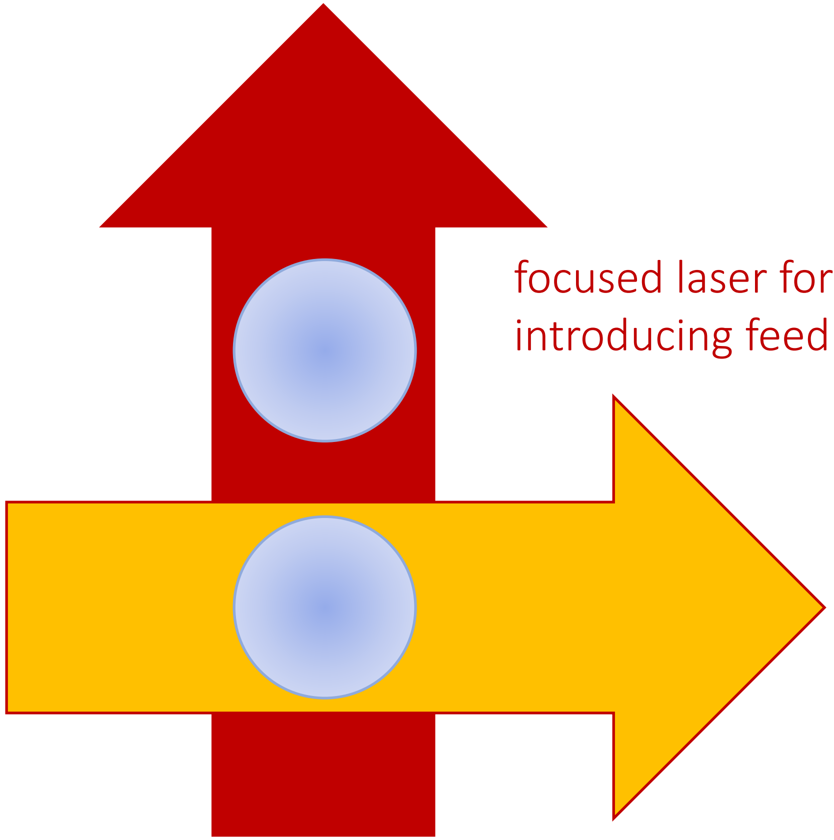




collective laser field for detecting the motion of each nanoparticle

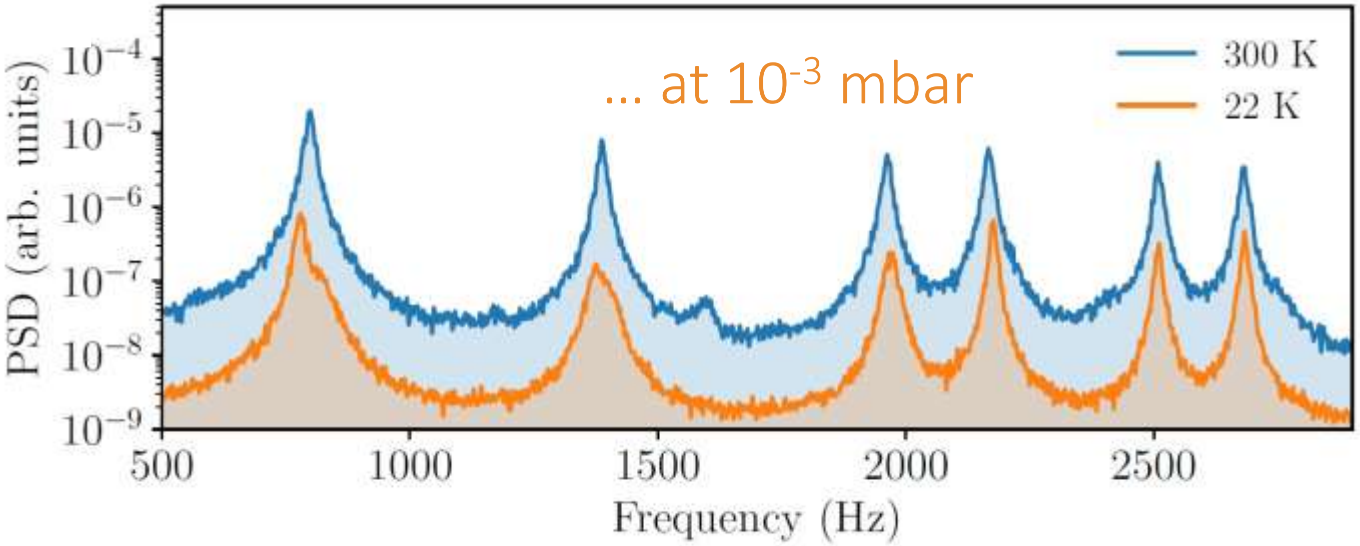
D. S. Bykov, L. Dania, F. Goschin, T. E. Northup, *Optica* **10**, 438 (2023)

Trapping and detection of a two-particle Coulomb crystal



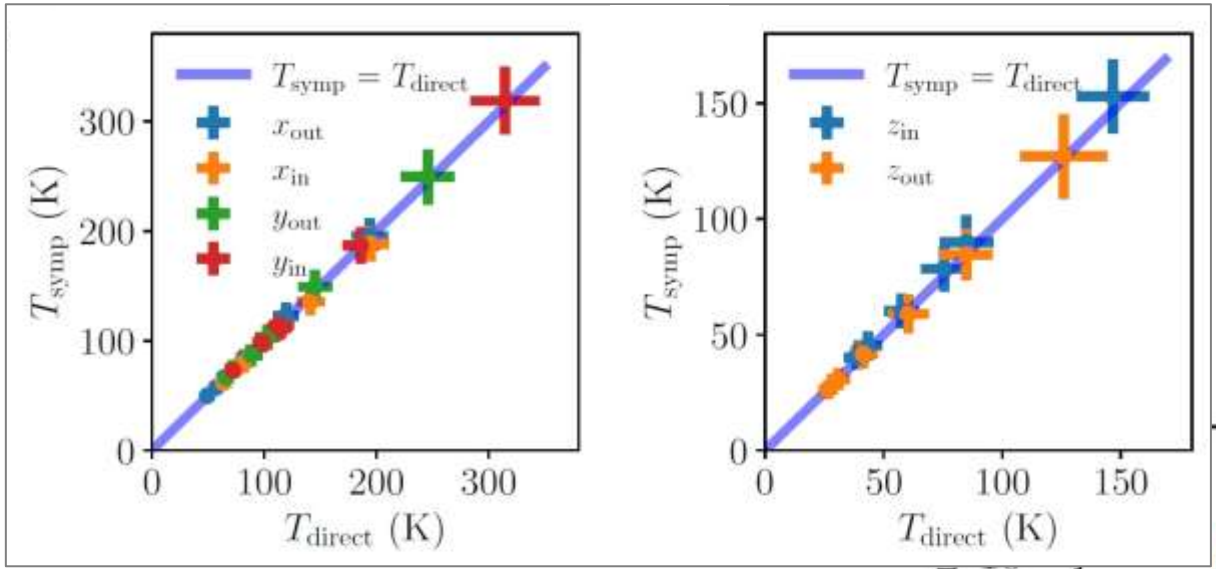
focused laser for introducing feedback

collective laser field for detecting the motion of each nanoparticle



D. S. Bykov, L. Dania, F. Goschin, T. E. Northup, *Optica* **10**, 438 (2023)

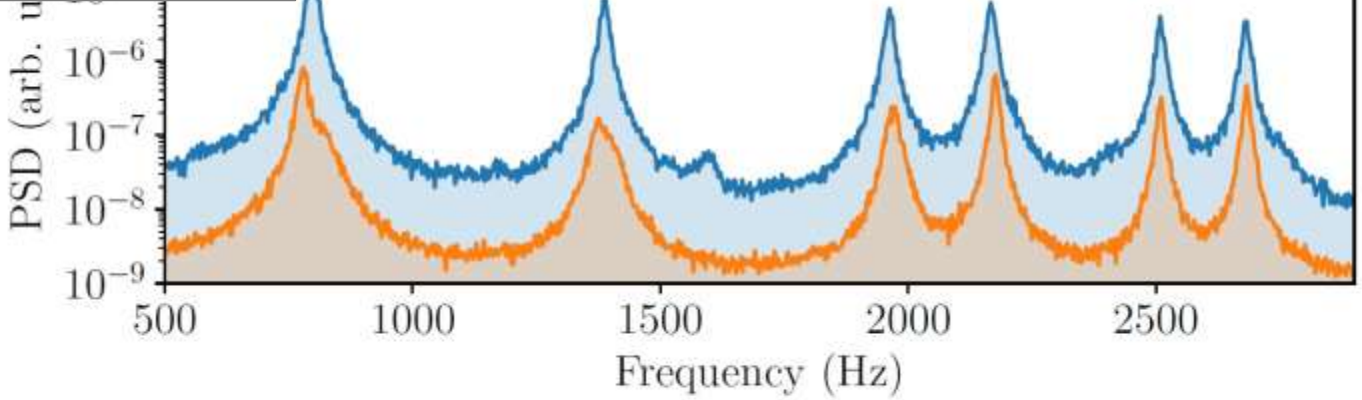
Trapping and detection of a two-particle Coulomb crystal



For each mode, we increase the feedback (cooling rate) to bring the directly cooled particle to lower and lower temperatures.

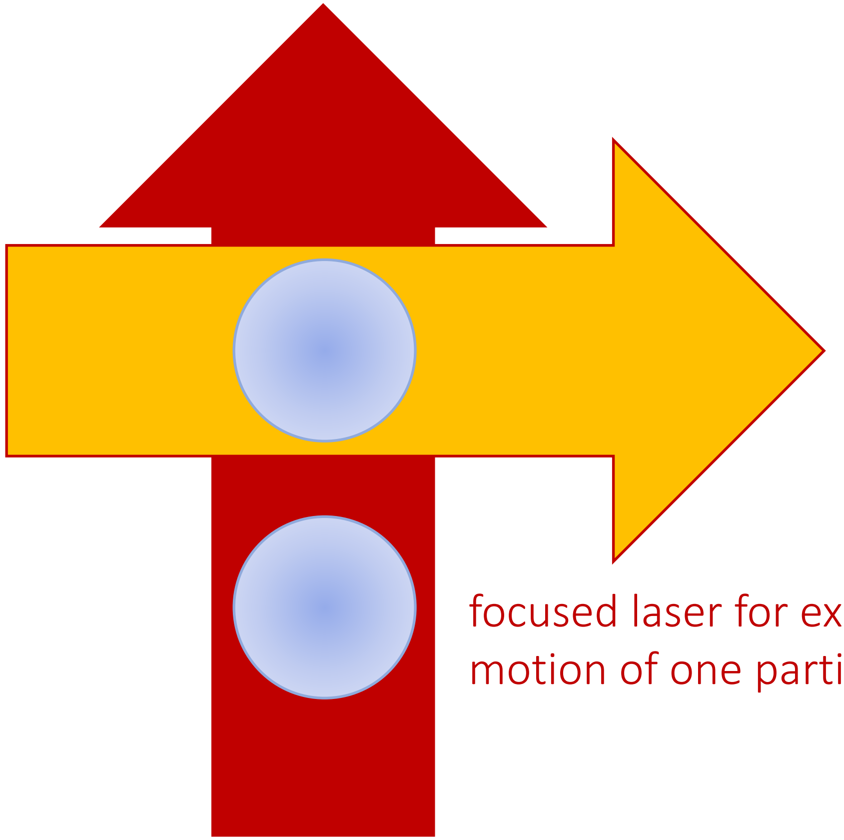
The temperature of the second particle matches the temperature of the first.

… at 10^{-3} mbar



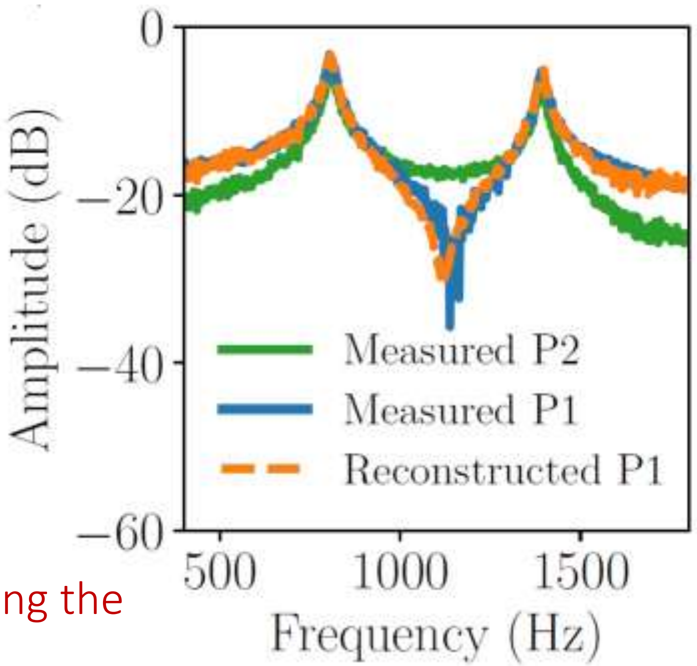
D. S. Bykov, L. Dania, F. Goschin, T. E. Northup, *Optica* **10**, 438 (2023)

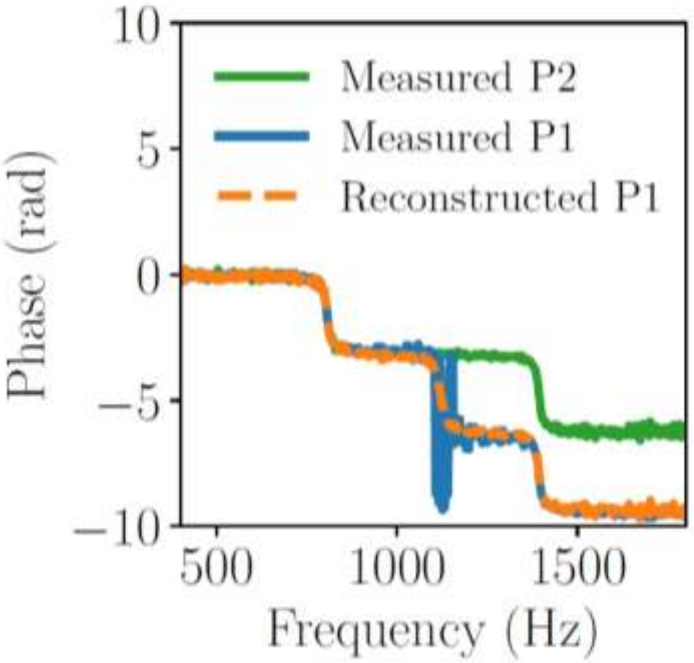
Sympathetic detection: one particle detects the motion of the other



focused laser for exciting the motion of one particle

collective laser field for detecting the motion of each nanoparticle

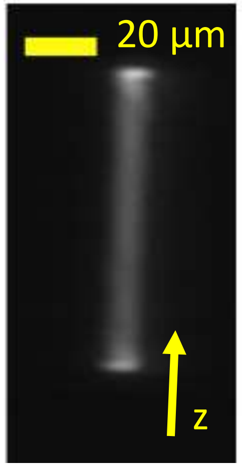




An ultra-high-Q mechanical oscillator in a Paul trap

- We can load & cool silica nanoparticles in an ultra-high vacuum (UHV) environment at room temperature.
- In an ion trap, it’s possible to detect and cool particles without illuminating them optically.
- We measure a quality factor of $1.6(4) \cdot 10^{10}$, enabled by UHV and by the absence of light-induced decoherence.
- An ion and a nanoparticle can be confined in the same Paul trap, despite their very different charge-to-mass ratios.

What happens if we give the particle a kick?



$$\ddot{z} + \gamma \dot{z} + \Omega_z^2 z = \frac{\mathcal{F}_{\mathrm{th}}}{m} \longrightarrow \langle z(t)^2 \rangle = \langle z(0)^2 \rangle e^{-\gamma t}$$

stochastic force: thermalization with environment

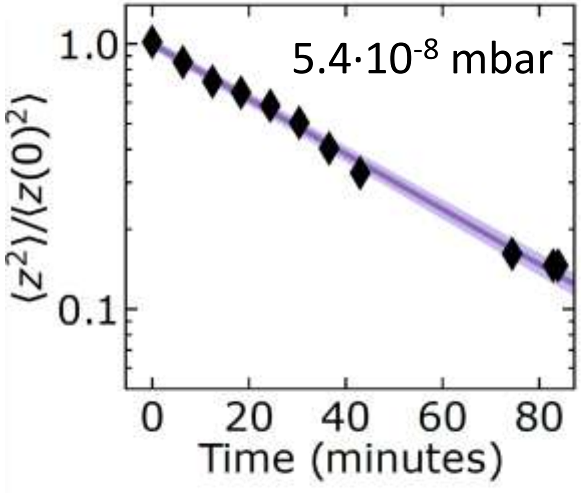
damping rate ∝ pressure

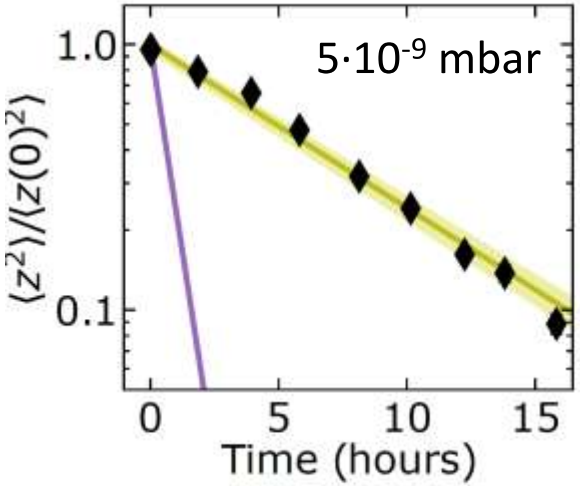
oscillation frequency

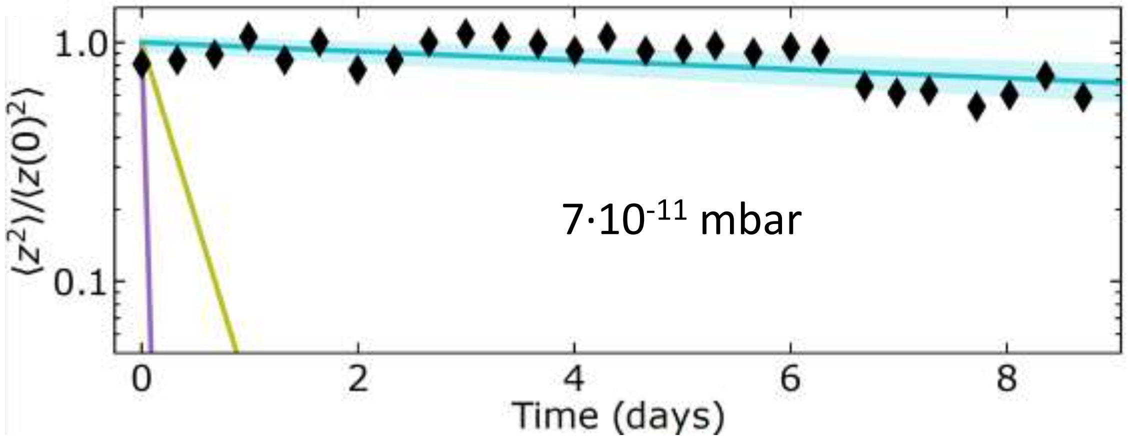
mass

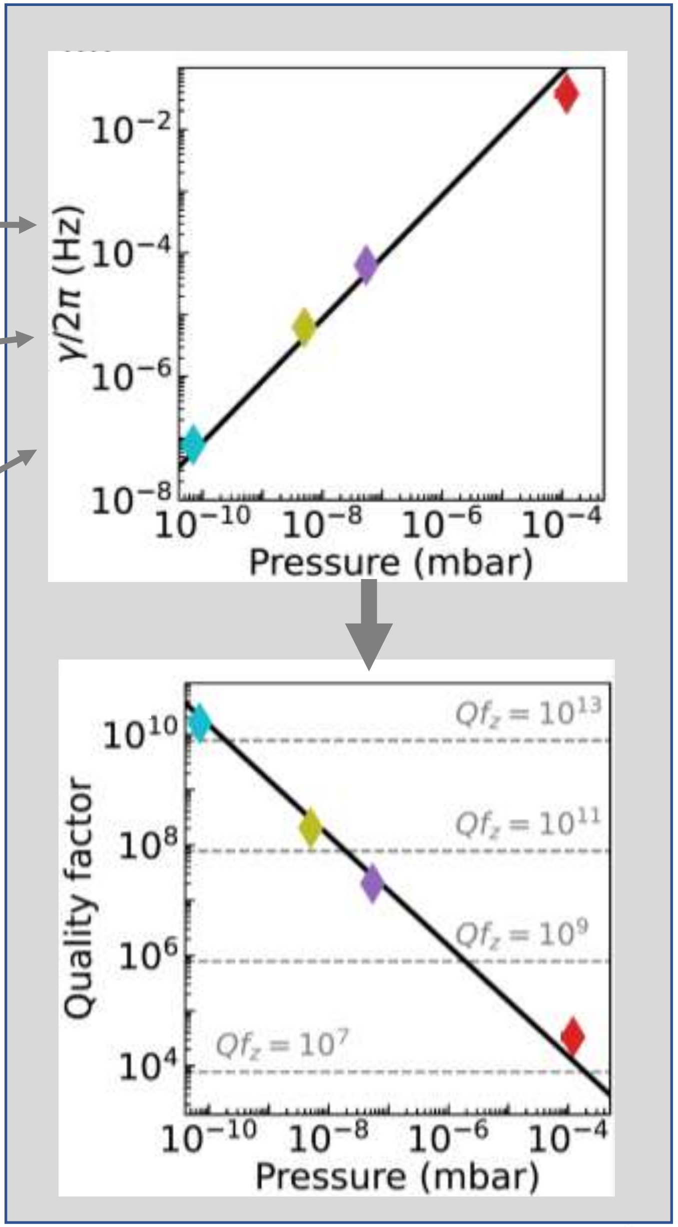
L. Dania, D. S. Bykov, F. Goschin, M. Teller, T. E. Northup, arXiv:2304.02408

Q = 1.6(4)·10^{10} at 7·10^{-11} mbar









L. Dania, D. S. Bykov, F. Goschin, M. Teller, T. E. Northup, arXiv:2304.02408

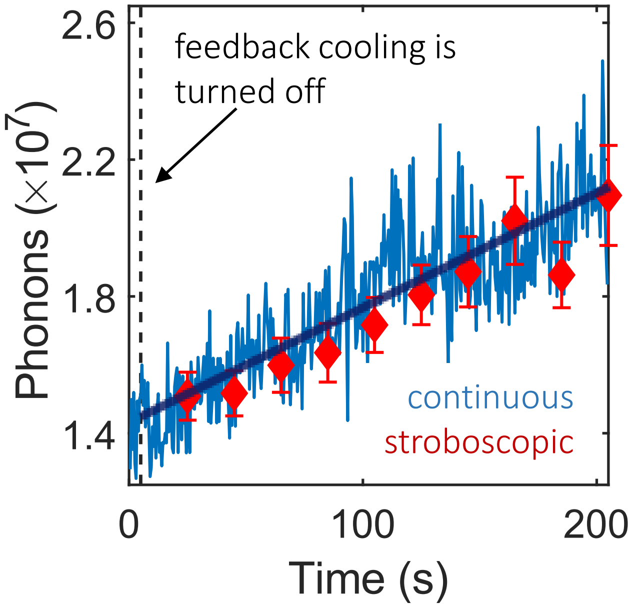
We investigate other noise sources via reheating

Cool the particle and watch it rethermalize:

$$\langle E(t)\rangle = k_B T_0 + k_B(T_{\mathrm{cool}} - T_0)e^{-\gamma t}$$

J. Gieseler, R. Quidant, C. Dellago, L. Novotny, *Nat. Nanotechnol.* **9**, 358 (2014)

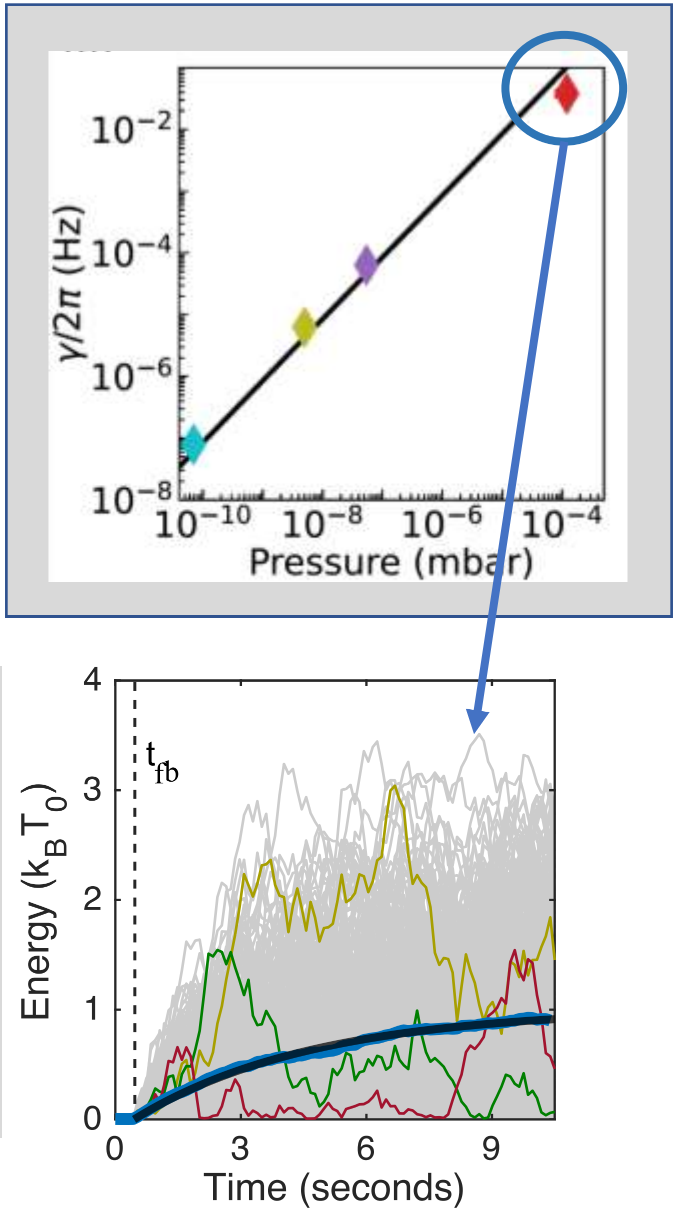
At $7{\cdot}10^{-11}$ mbar:



This heating rate is 12 times higher than predicted from our ringdown measurements!

In contrast to ringdown, ring-up measurements are affected by non-thermal noise sources at UHV.

Possible culprits: electronics noise, vibrations.



L. Dania, D. S. Bykov, F. Goschin, M. Teller, T. E. Northup, arXiv:2304.02408

A nanoparticle as an ultra-high-Q mechanical oscillator

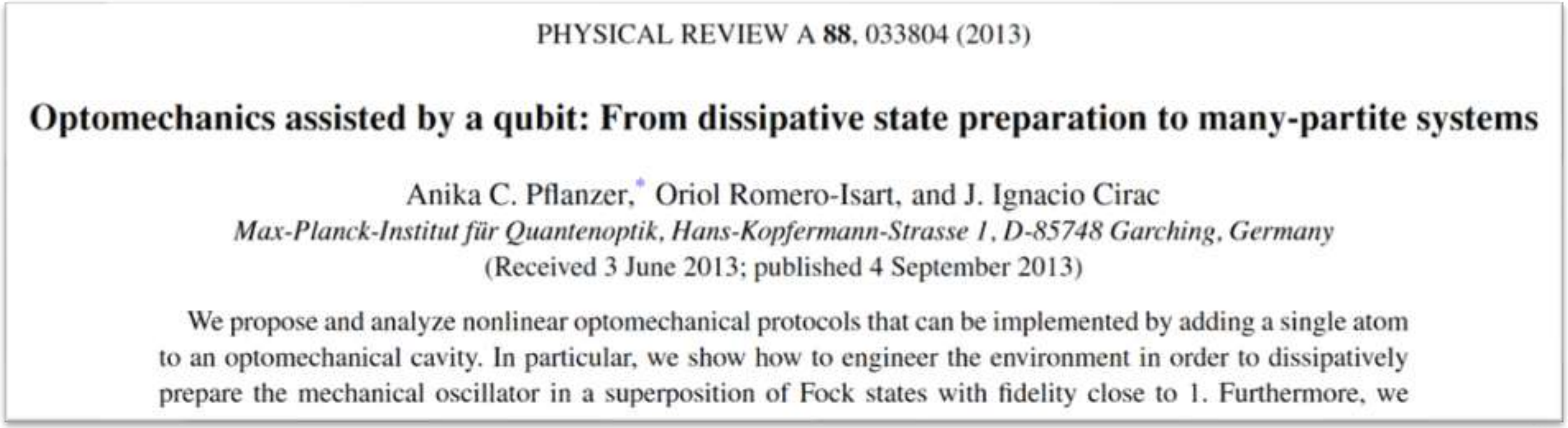
- Q factor more than two orders of magnitude higher than previous measurements with levitated nanoparticles
- Enabling factors: ultra-high vacuum & ion trap
- One molecule collides with the particle every 1.2 oscillation cycles!
- Applications: ultrasensitive force & mass detection
- Allows us to analyze remaining noise sources, which will be crucial for quantum state preparation

L. Dania, D. S. Bykov, F. Goschin, M. Teller, T. E. Northup, arXiv:2304.02408

An ultra-high-Q mechanical oscillator in a Paul trap

- We can load & cool silica nanoparticles in an ultra-high vacuum (UHV) environment at room temperature.
- In an ion trap, it’s possible to detect and cool particles without illuminating them optically.
- We measure a quality factor of $1.6(4)\cdot10^{10}$, enabled by UHV and by the absence of light-induced decoherence.
- An ion and a nanoparticle can be confined in the same Paul trap, despite their very different charge-to-mass ratios.

A trapped ion can act as a nonlinear element



PHYSICAL REVIEW A **88**, 033804 (2013)

Optomechanics assisted by a qubit: From dissipative state preparation to many-partite systems

Anika C. Pflanzer,* Oriol Romero-Isart, and J. Ignacio Cirac
Max-Planck-Institut für Quantenoptik, Hans-Kopfermann-Strasse 1, D-85748 Garching, Germany

(Received 3 June 2013; published 4 September 2013)

We propose and analyze nonlinear optomechanical protocols that can be implemented by adding a single atom to an optomechanical cavity. In particular, we show how to engineer the environment in order to dissipatively prepare the mechanical oscillator in a superposition of Fock states with fidelity close to 1. Furthermore, we

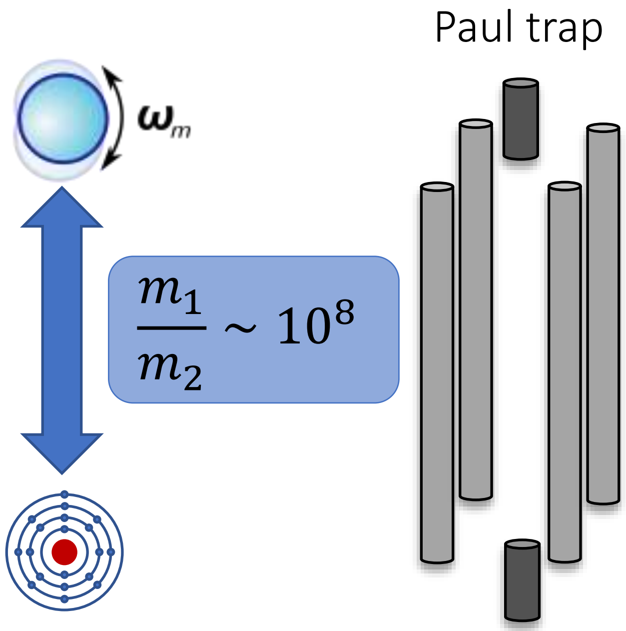
A nanoparticle cooled to the quantum ground state is still a harmonic oscillator in a thermal state.

We need to introduce a nonlinearity to prepare non-Gaussian (quantum) states.

A qubit (two-level system) provides such a nonlinearity.

The plan: co-trap two (very different) charged particles

levitated nanoparticle + calcium ion



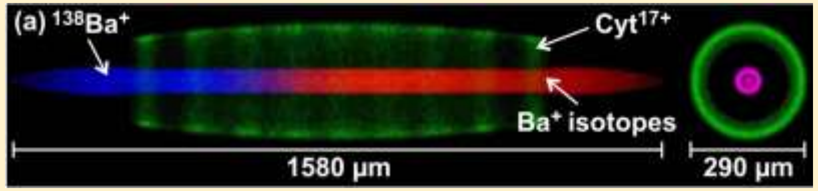
$$\frac{m_1}{m_2} \sim 10^8$$

Prior work:

- Atomic ions + big molecules for sympathetic cooling
  Offenberg et al., *Phys. Rev. A* **78**, 061401(R) (2008)

$$\frac{m_1}{m_2} \sim 10^2$$

Cyt^{17+}	^{138}Ba$^+$
12 390 amu	138 amu



- Proposed: positrons + antiprotons for antihydrogen synthesis
  Dehmelt, *Phys. Scr.* **1995,** 423 (1995)

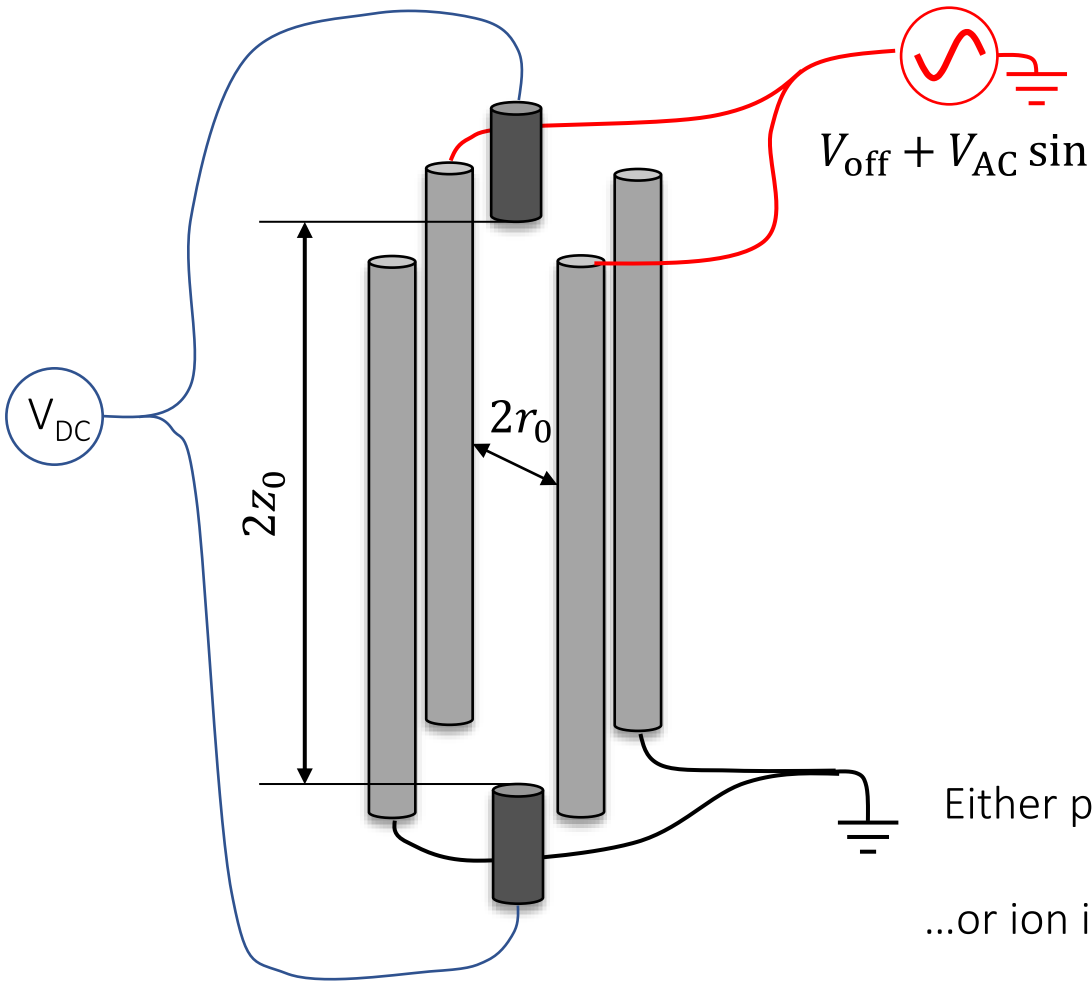
$$\frac{m_1}{m_2} \sim 10^3$$

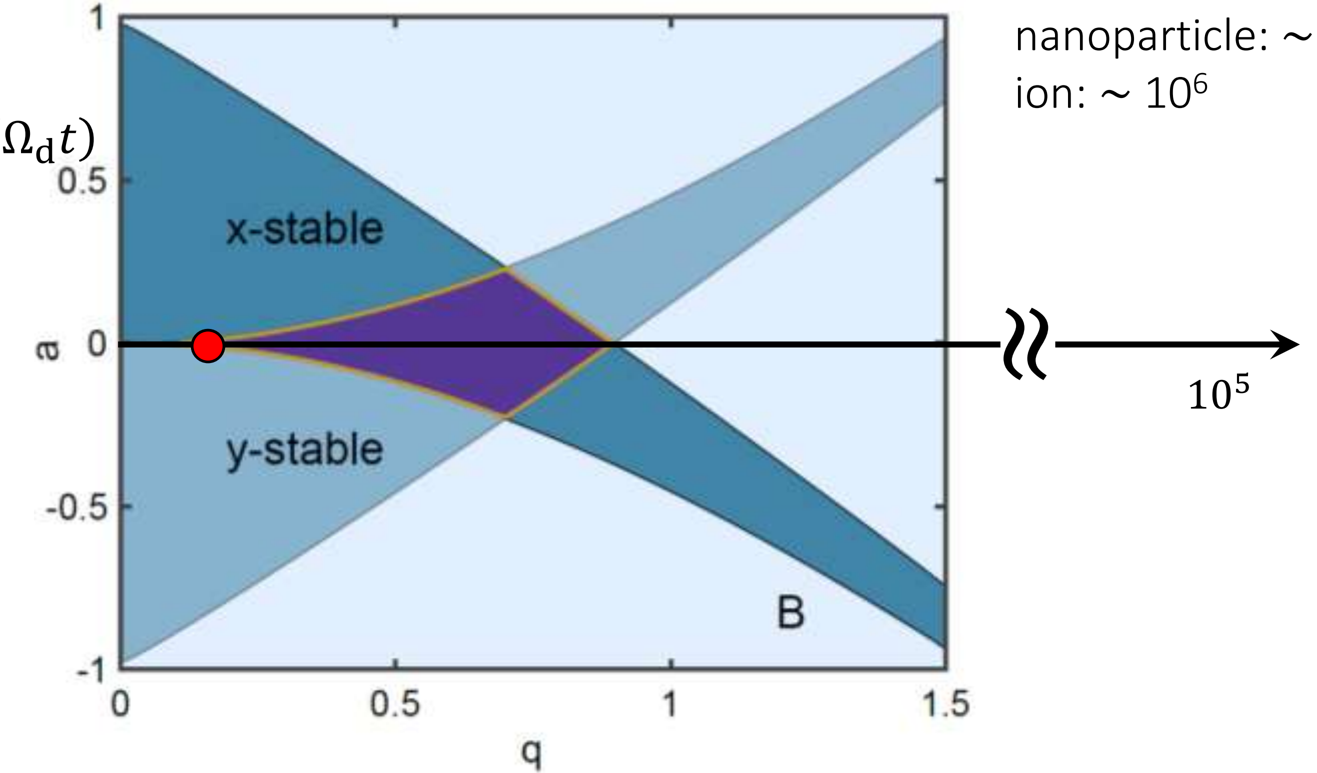
The challenge: stability conditions for a Paul trap

charge

mass

$$a = \frac{Q}{m}\frac{4V_{\mathrm{off}}}{\Omega_{\mathrm{d}}^2 z_0^2} \qquad q = \frac{Q}{m}\frac{4V_{\mathrm{AC}}}{\Omega_{\mathrm{d}}^2 r_0^2}$$





nanoparticle: ~1
ion: ~ 10^6

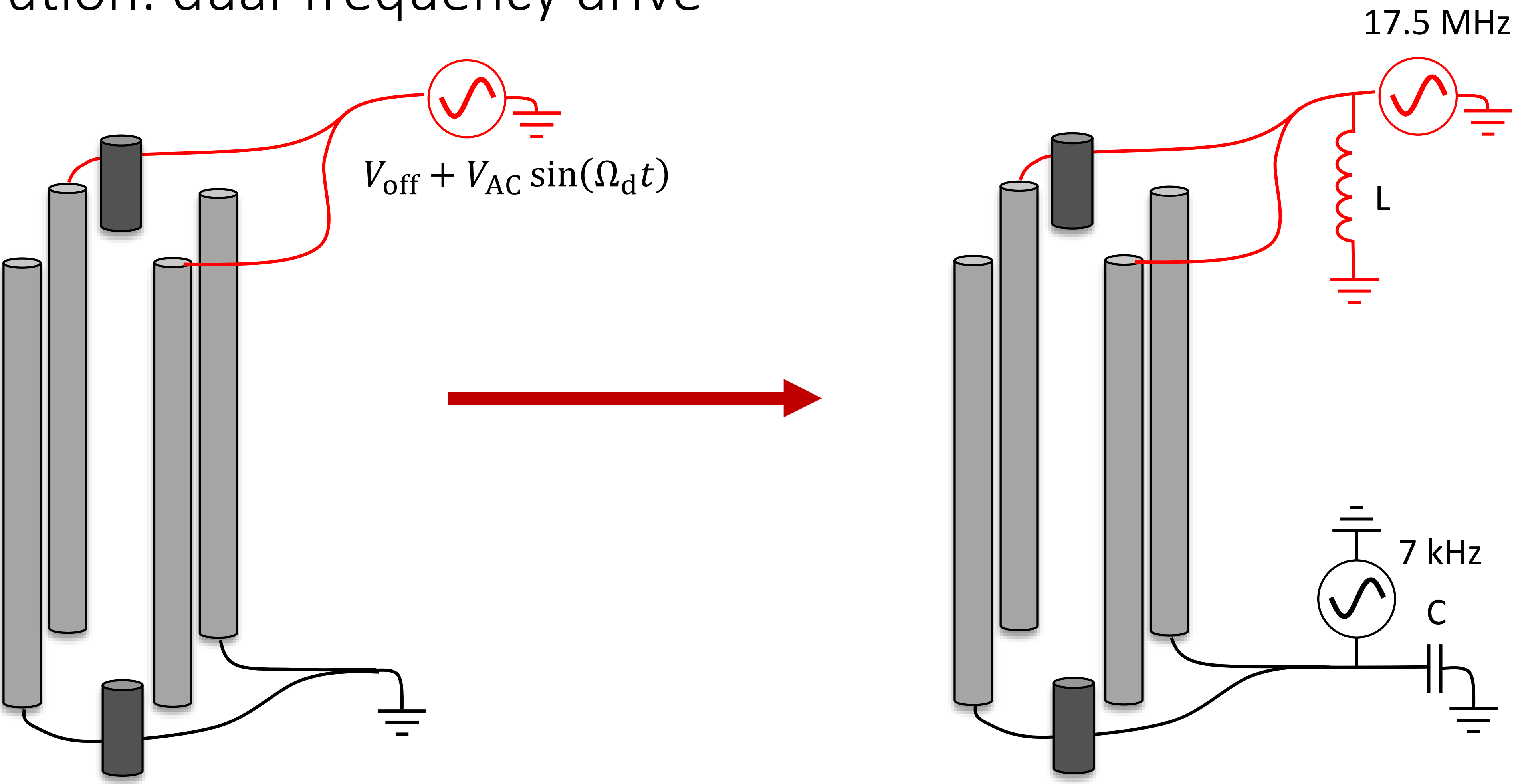
Either particle is trapped but ion is unstable…

$q_{\mathrm{particle}} = 0.1 \Rightarrow q_{\mathrm{ion}} = 10^5$

…or ion is trapped but particle confinement is weak.

$q_{\mathrm{particle}} = 10^{-7} \Leftarrow q_{\mathrm{ion}} = 0.1$

The solution: dual-frequency drive



Dehmelt, Phys. Scr. **1995** 423 (1995)
D. Trypogeorgos et al., Phys. Rev. A **94**, 023609 (2016)

Co-trapping an ion and a nanoparticle

trap a nanoparticle

↓

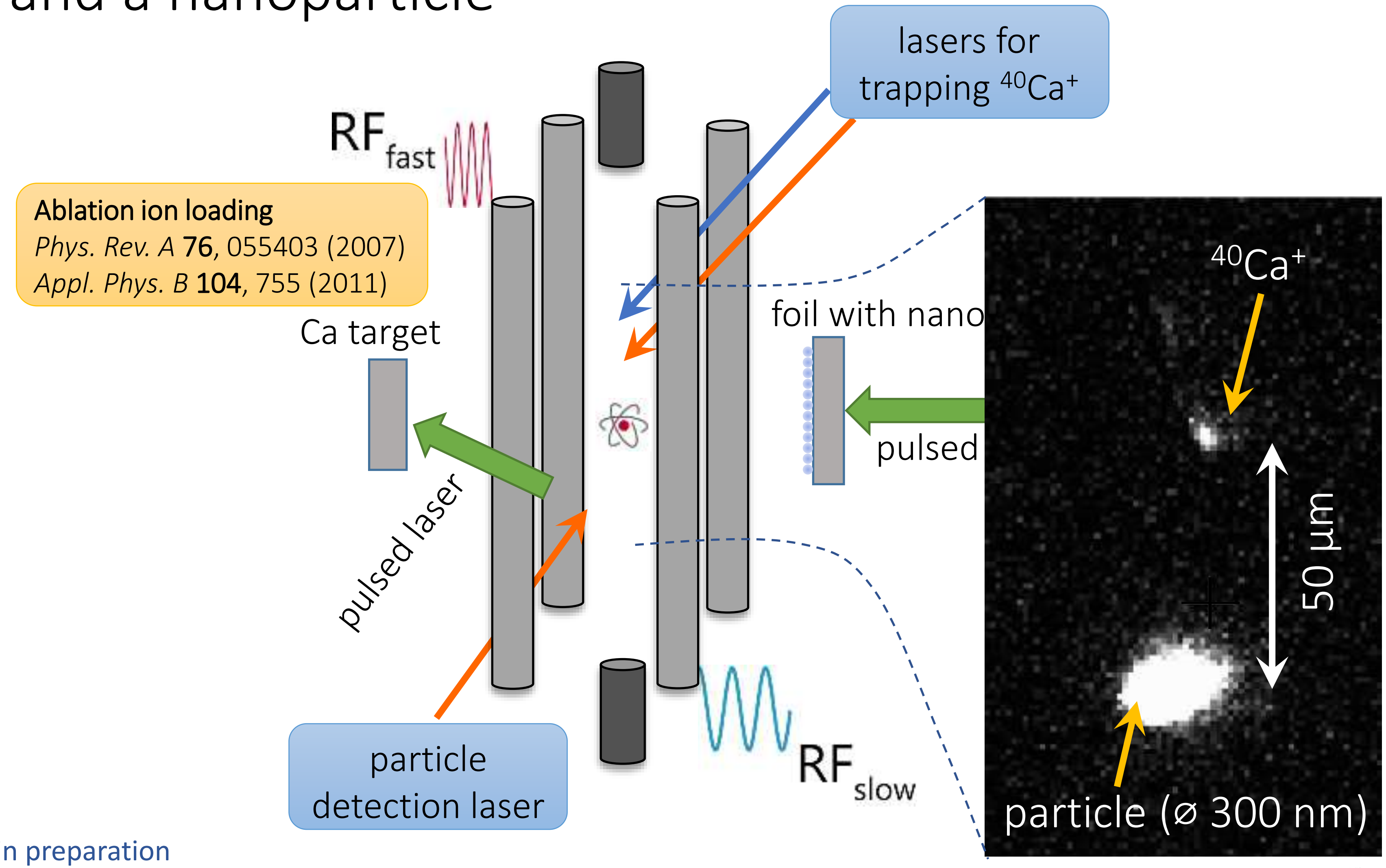
lower the “slow” voltage

↓

displace the particle from the trap center

↓

trap an ion



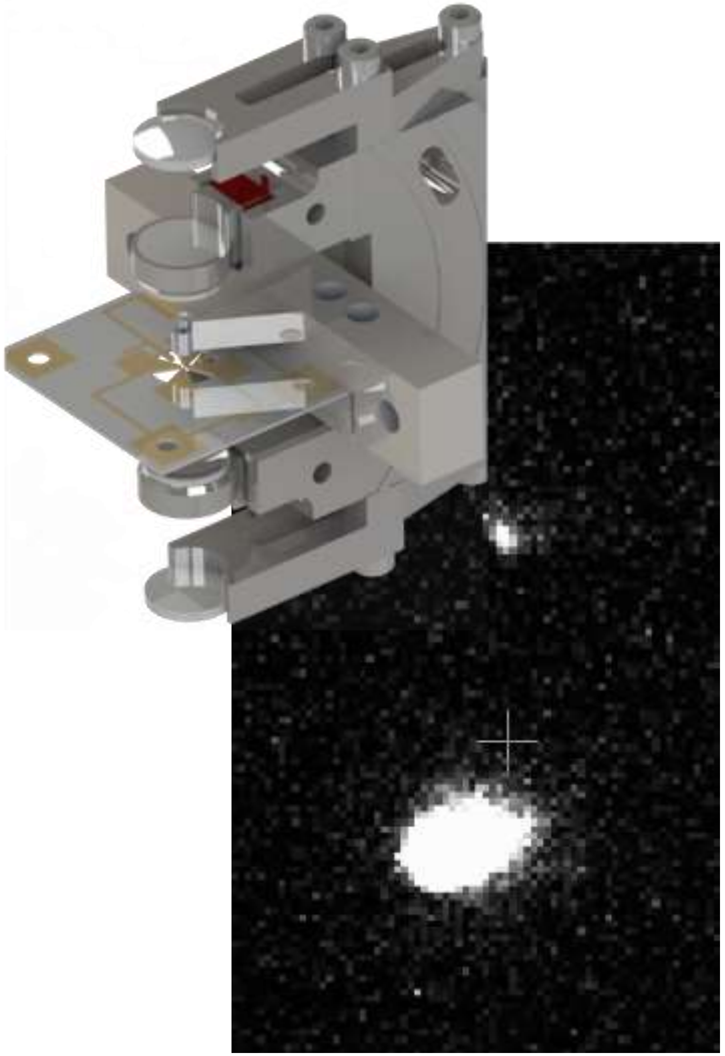
lasers for trapping $^{40}Ca^+$

Ablation ion loading
Phys. Rev. A **76**, 055403 (2007)
Appl. Phys. B **104**, 755 (2011)

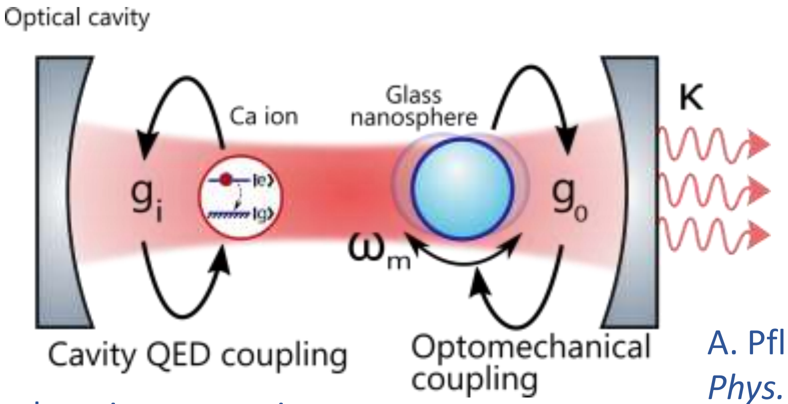
particle detection laser

L. Dania, D. S. Bykov, F. Goschin, T. E. Northup, in preparation

An ion and a nanoparticle in a Paul trap



- First demonstration of dual-frequency trapping
- Dual-frequency trapping has been proposed for antihydrogen synthesis
  Dehmelt, *Phys. Scr.* **1995,** 423 (1995); Leefer et al., *Hyperfine Interact.* **238**, 12 (2017)
- Outlook #1: ion as sensor for the nanoparticle
- Outlook #2: ion + nanoparticle coupled to an optical cavity



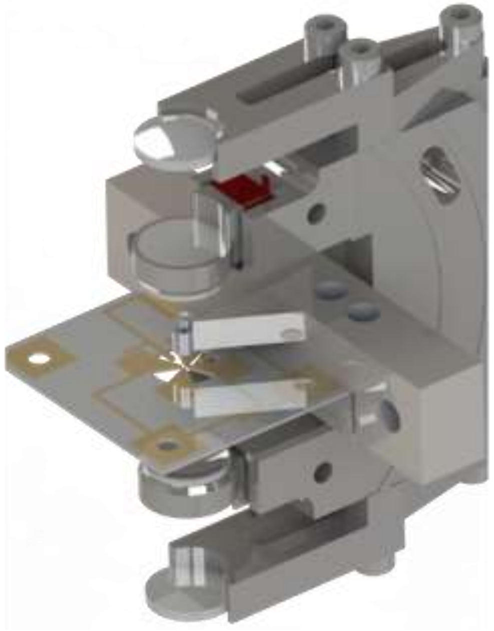
A. Pflanzer, O. Romero-Isart, J. I. Cirac, *Phys. Rev. A* **88**, 033804 (2013)

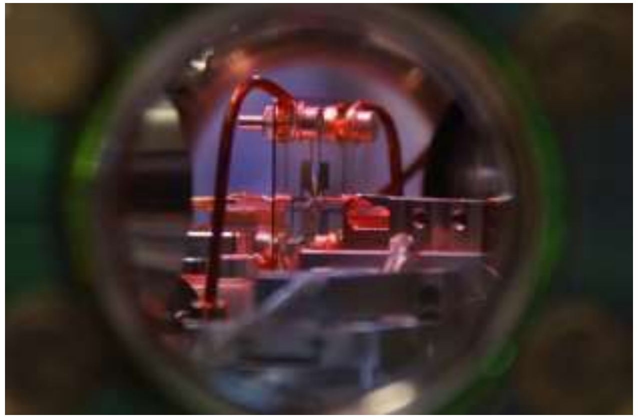
L. Dania, D. S. Bykov, F. Goschin, T. E. Northup, in preparation

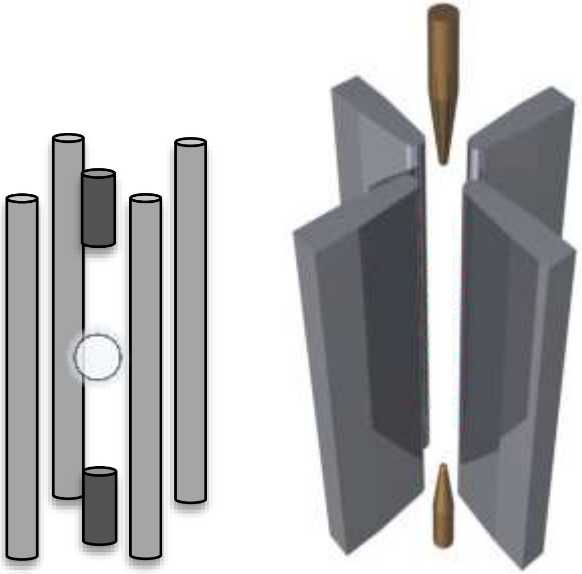
What is a “wheel trap,” anyway?

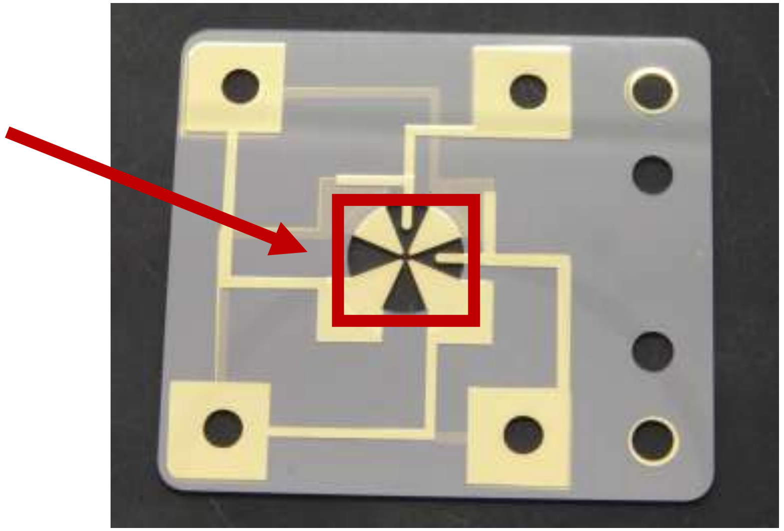
It’s a linear Paul trap.

- Introduced at NIST for Al$^+$ clock
  J.-S. Chen et al., *Phys. Rev. Lett.* **118**, 053002 (2017)
- Adapted in our group for integration with (fiber) cavities
  M. Teller et al., *AVS Quantum Sci.* **5**, 012001 (2023)
- Advantages for nanoparticles:
  optical access for high NA
  cavities with high cooperativity









An ultra-high-Q mechanical oscillator in a Paul trap

- We can load & cool silica nanoparticles in an ultra-high vacuum (UHV) environment at room temperature.

laser-induced acoustic desorption

- In an ion trap, it's possible to detect and cool particles without illuminating them optically.

sympathetic cooling

- We measure a quality factor of $1.6(4)\cdot10^{10}$, enabled by UHV and by the absence of light-induced decoherence.

ring-down & ring-up → insights into decoherence

- An ion and a nanoparticle can be confined in the same Paul trap, despite their very different charge-to-mass ratios.

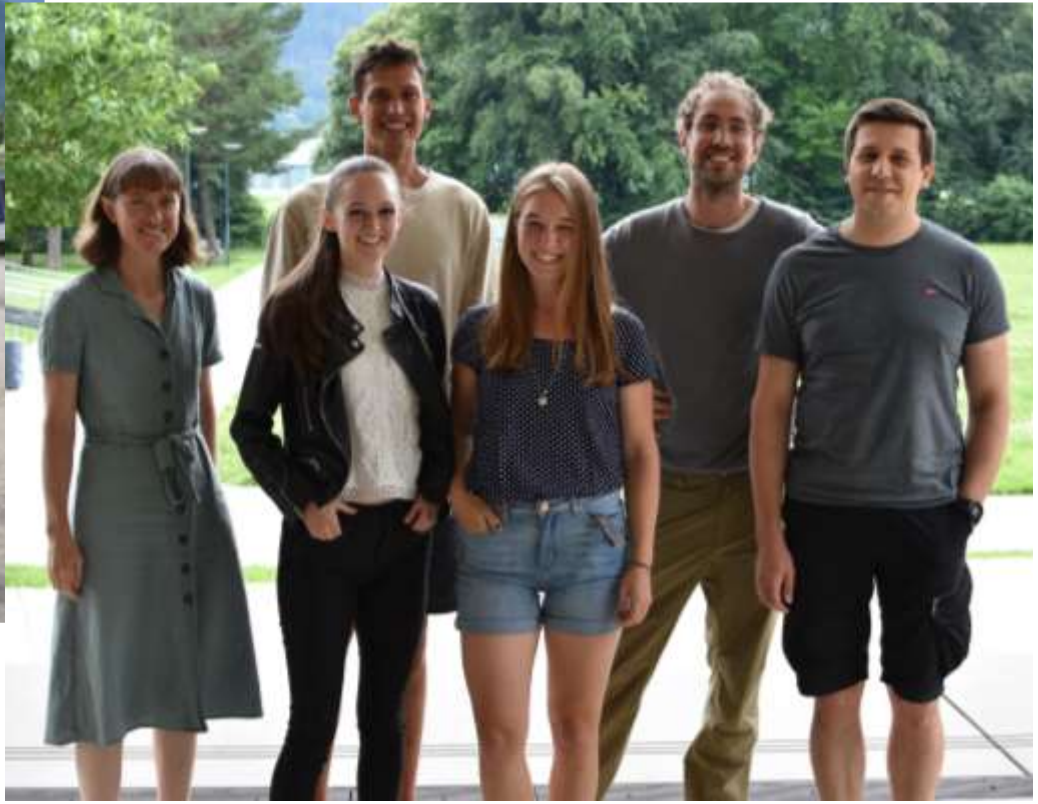
a route to ion-assisted quantum state preparation

Quantum Interfaces Group

QUANTUM INTERFACES GROUP

FWF Der Wissenschaftsfonds.

ÖAW ÖSTERREICHISCHE AKADEMIE DER WISSENSCHAFTEN



universität innsbruck