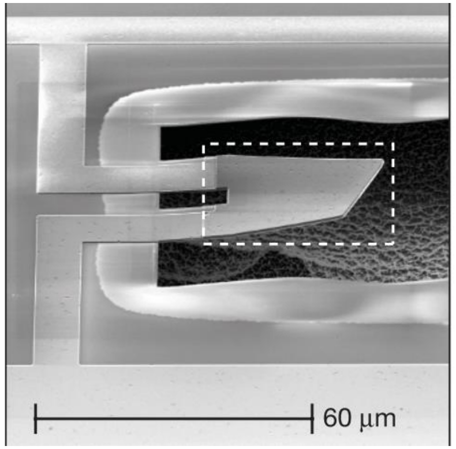
Lecture 3: Levitated mechanical systems for experiments at the quantum level

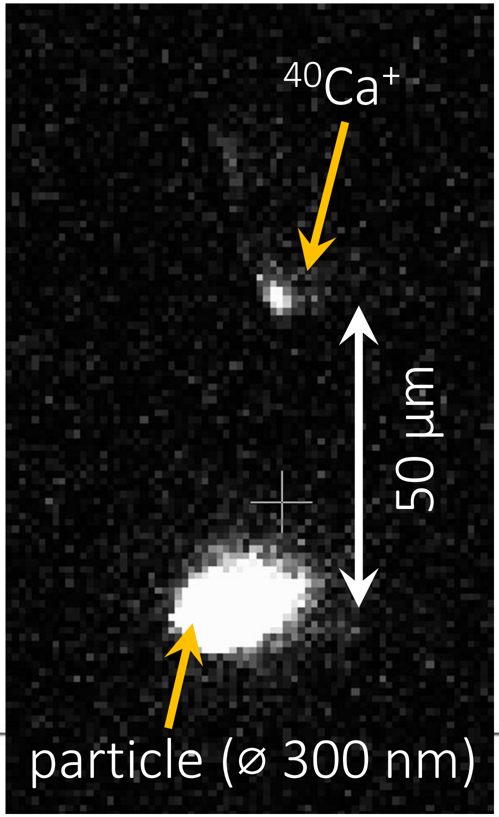
Tracy Northup, Institute for Experimental Physics, University of Innsbruck

Introducing a spin as a nonlinear element



mechanical oscillator
+
superconducting qubit

silica nanoparticle
+
trapped ion



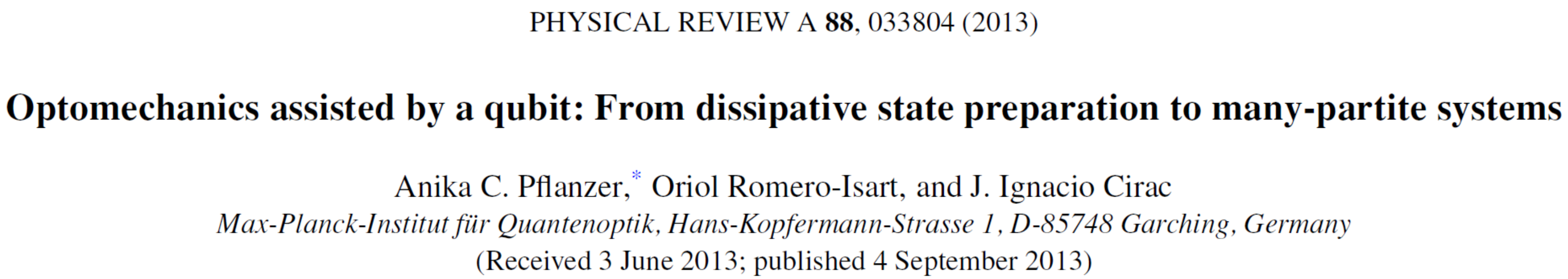
Other approaches:

- levitated particles with internal spin (e.g., NV centers in nanodiamonds)
- without an additional spin: non-Gaussian state preparation via potential engineering
  L. Neumeier et al., *Proc. Natl. Acad. Sci. U.S.A.* **121**, e2306953121 (2024)

Topics: Lecture 3

1. Ions as spins… and as mechanical oscillators
2. Confining an ion and a nanomechanical oscillator in the same trap
3. Levitated mechanical systems: next (experimental) steps

An ion as an auxiliary qubit

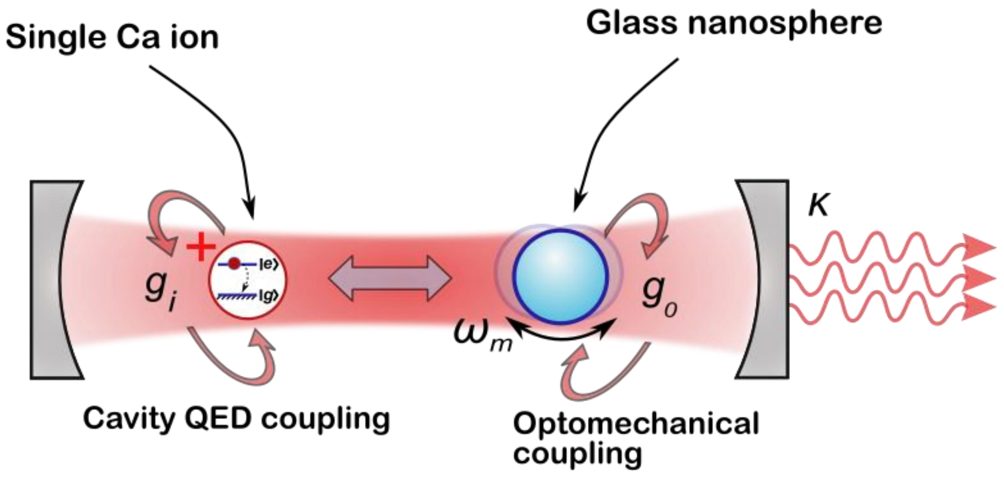


PHYSICAL REVIEW A **88**, 033804 (2013)

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

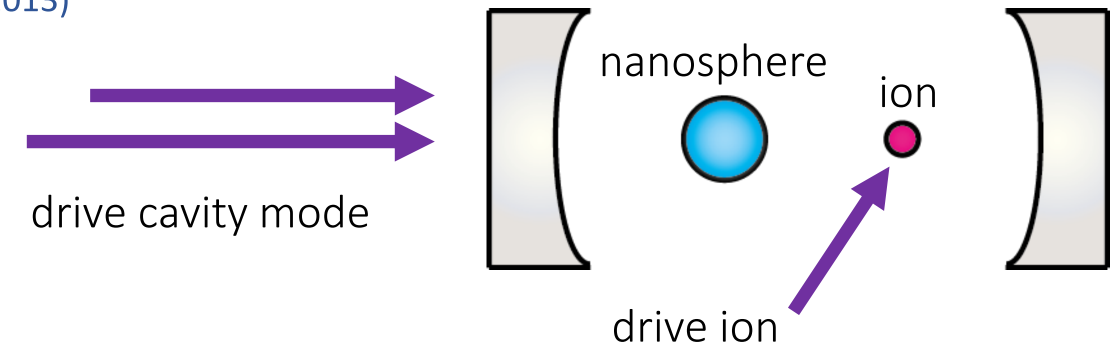
Anika C. Pflanzer,* Oriol Romero-Isart, and J. Ignacio Cirac
Max-Planck-Institut für Quantenoptik, Hans-Kopfermann-Strasse 1, D-85748 Garching, Germany
(Received 3 June 2013; published 4 September 2013)

An auxiliary qubit system enables the preparation of non-Gaussian states.



Dissipative preparation of a Fock-state superposition

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



photon

ion

nanosphere phonon

enhanced via cavity drive

$$H = \Delta \hat{a}_1^\dagger \hat{a}_1 + \frac{\delta}{2}\hat{\sigma}_z + \omega \hat{b}^\dagger \hat{b} + g_\mathrm{m}(\hat{a}_1^\dagger \hat{b} + \hat{a}_1 \hat{b}^\dagger)$$

only two of four interaction terms: laser is red detuned

detuning between laser and cavity

$$- g_\mathrm{q}(\hat{a}_1 \hat{\sigma}^+ + \hat{a}_1^\dagger \hat{\sigma}^-) + \Omega(\hat{\sigma}^+ + \hat{\sigma}^-) + H_\mathrm{aux}$$

ion-cavity coupling

ion drive

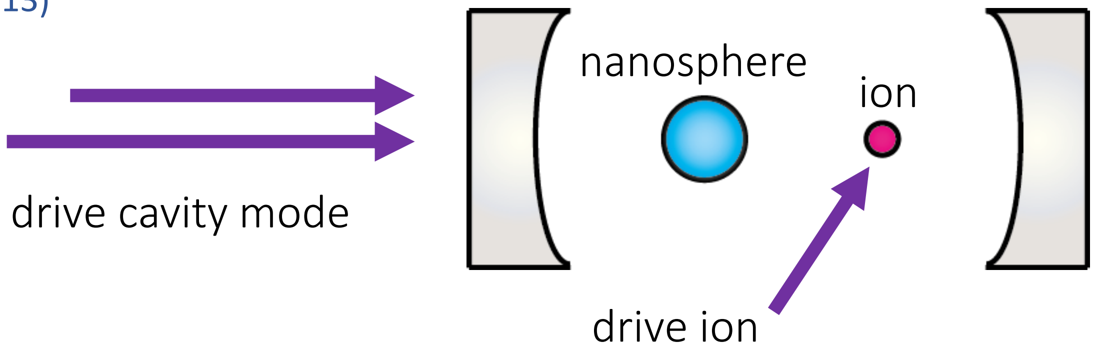
$$H_\mathrm{aux} = \Delta^\mathrm{aux} \hat{a}_2^\dagger \hat{a}_2 - g_\mathrm{m}^\mathrm{aux}(\hat{a}_2^\dagger \hat{b}^\dagger + \hat{a}_2 \hat{b}) + g_\mathrm{q}^\mathrm{aux}(\hat{a}_2^\dagger \hat{\sigma}^+ + \hat{a}_2 \hat{\sigma}^-)$$

only two of four interaction terms: laser is blue detuned

detuning between laser and cavity

Dissipative preparation of a Fock-state superposition

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



dissipative system has two steady states:

$$|g,1\rangle + |e,0|\rangle$$

$$|g,0\rangle$$

the interesting one!

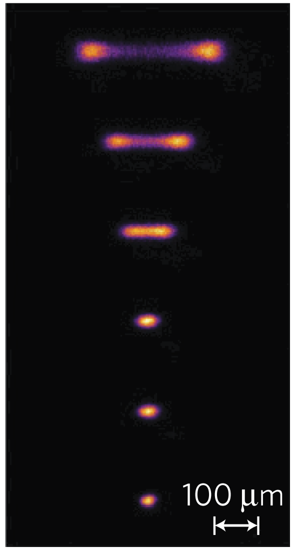
degeneracy lifted with:

- atomic spontaneous decay, nanosphere decoherence
- additional coupling to a second cavity mode, driven blue-detuned

Given system parameters,
engineer dissipation so that first state predominates.

Trapped ions as auxiliary qubits

- Ions are a highly controlled two-level system…
  - hyperfine and optical qubits with long coherence times
  - internal state readout via electron shelving
  - coupling between qubits and motion
  - deterministic, high-fidelity, coherent manipulation
- …well-suited to optomechanics

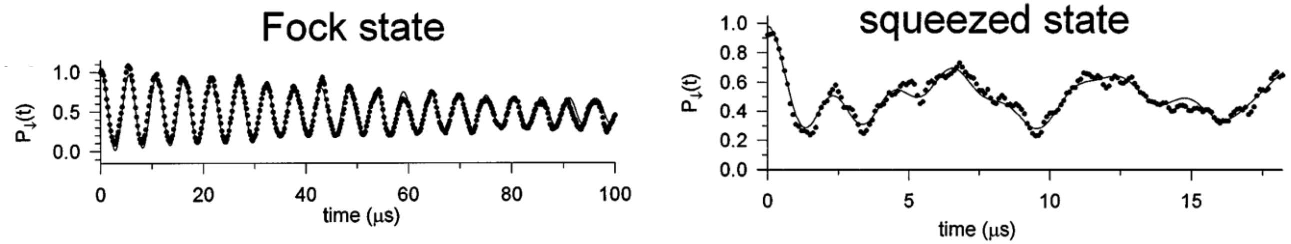


Phonon laser

K. Vahala et al., *Nat. Phys.* **5**, 682 (2009)

Generation of nonclassical states

D. M. Meekhof et al., *Phys. Rev. Lett.* **76**, 1796 (1996)



Entanglement of mechanical oscillators

J. D. Jost et al., *Nature* **459**, 683 (2009)

Trapped ions as auxiliary qubits

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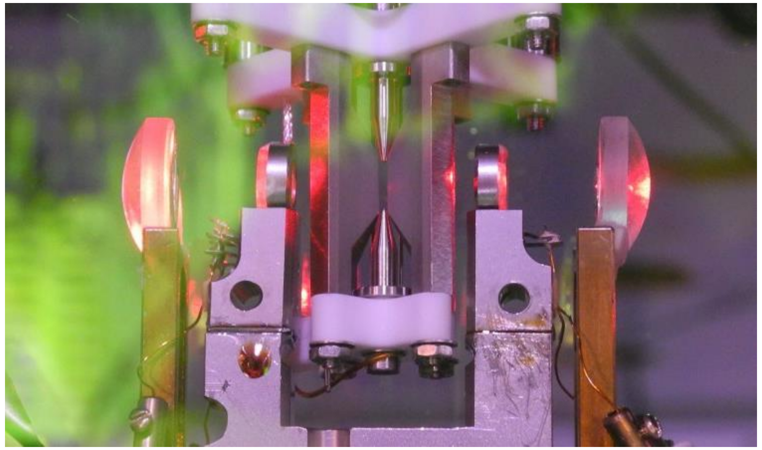
  - cavity coupling to qubit demonstrated at infrared wavelengths



Jaynes-Cummings interaction:

$$H_{\text{int}} = \hbar g(a\sigma^{+} + a^{\dagger}\sigma^{-})$$

Example:

Quantum state transfer from an ion to a photon

A. Stute et al., *Nature Photon.* **7**, 219 (2013)

B. Casabone et al., *Phys. Rev. Lett.* **114**, 023602 (2015)

Trapped ions as auxiliary qubits

» Ions are a highly controlled two-level system...

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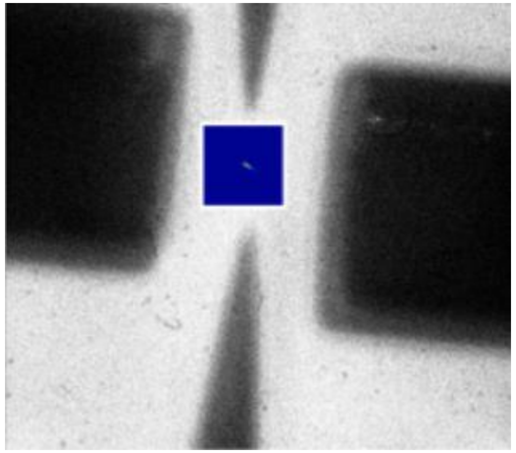
- cavity coupling to qubit demonstrated at infrared wavelengths
- strong coupling on the horizon



Ions in fiber-based cavities

M. Steiner et al., *Phys. Rev. Lett.* **110**, 043003 (2013)

Trapped ions as auxiliary qubits

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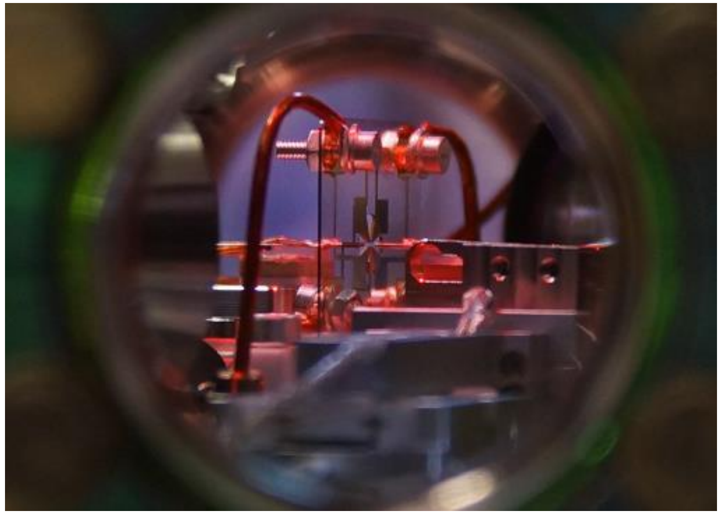

Ions in fiber-based cavities

M. Teller et al., *AVS Quantum Sci.* **5**, 012002 (2023)

Trapped ions as auxiliary qubits

- Ions are a highly controlled two-level system...
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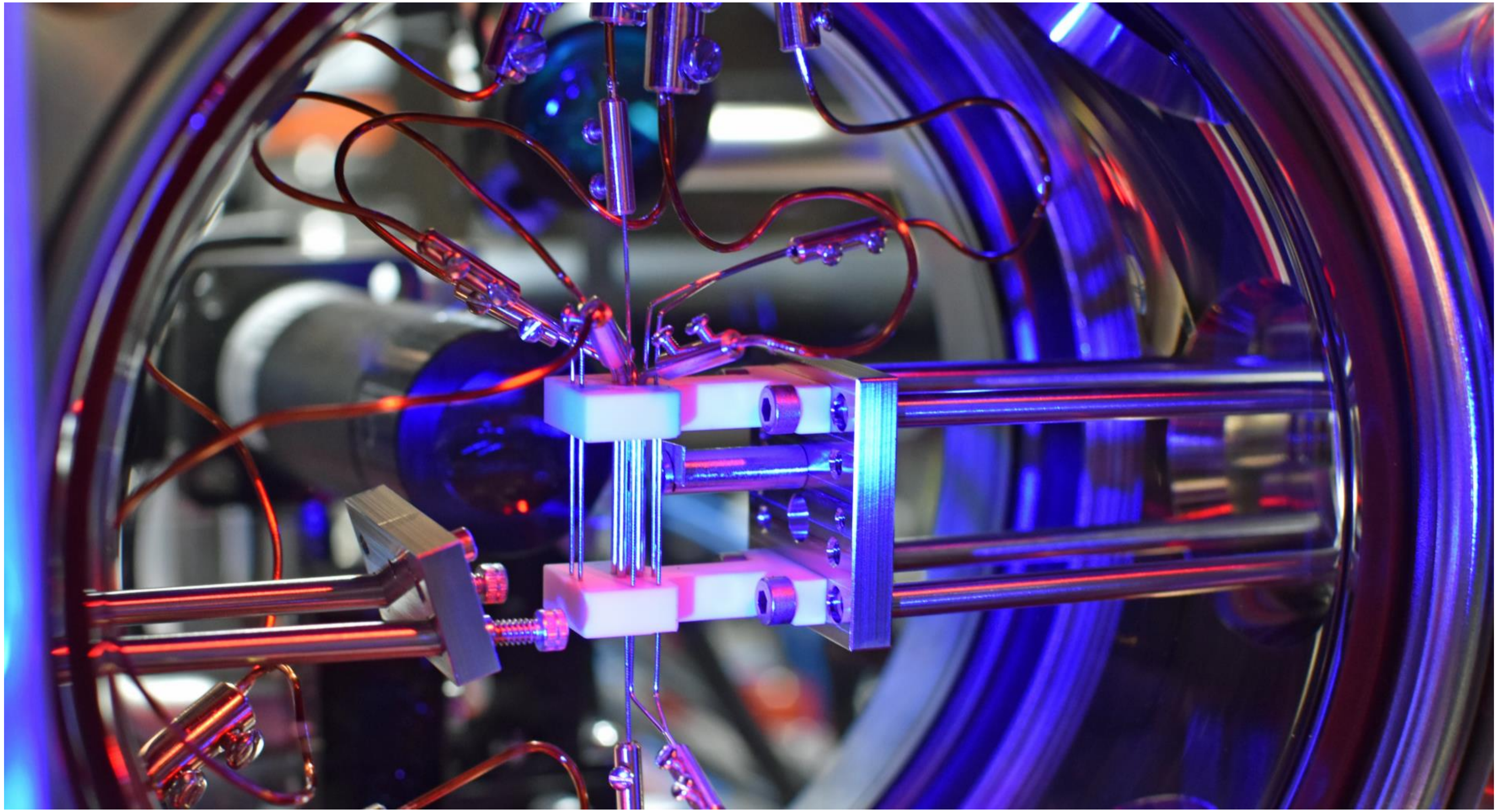
  - internal state readout via electron shelving
  - coupling between qubits and motion
  - deterministic, high-fidelity, coherent manipulation
- ...well-suited to optomechanics
  - cavity coupling to qubit demonstrated at infrared wavelengths
  - strong coupling on the horizon
- ion traps provide a deep confining potential
  - decoupled from heating from optical fields
  - possibility for electrical detection and cooling
- ions as probes for nanospheres

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

Topics: Lecture 3

1. Ions as spins… and as mechanical oscillators
2. Confining an ion and a nanomechanical oscillator in the same trap
3. Levitated mechanical systems: next (experimental) steps

Nanoparticles are confined in a linear Paul trap



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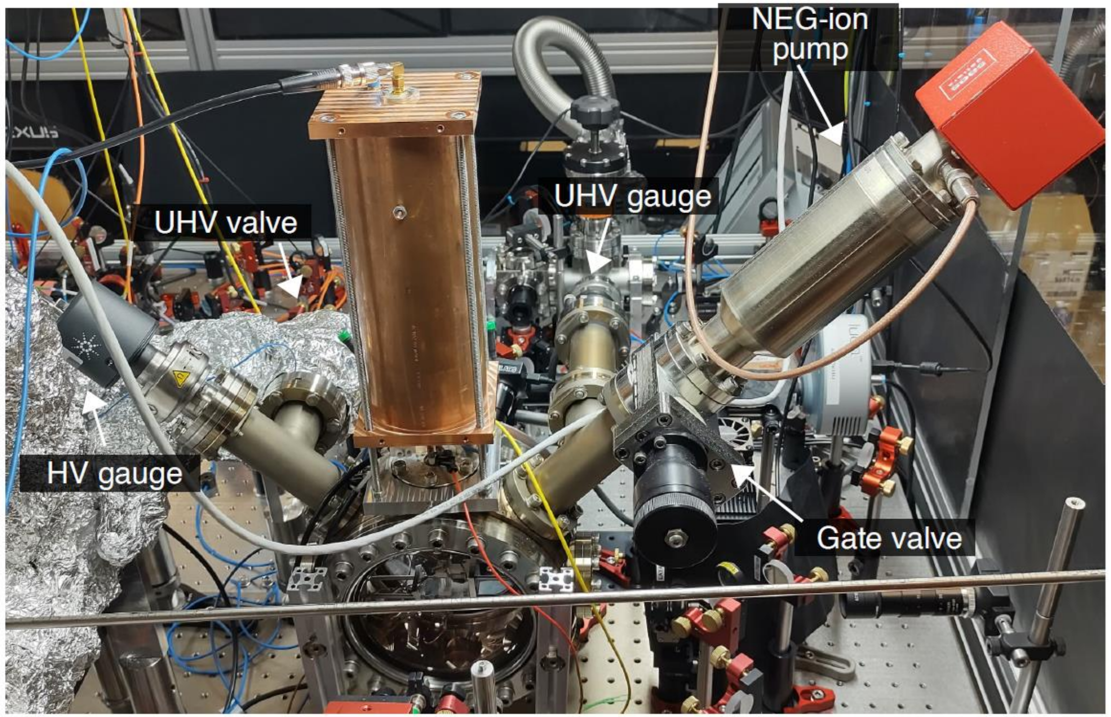
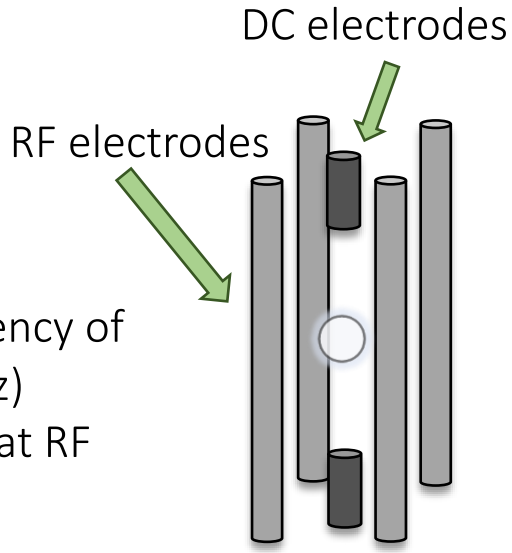
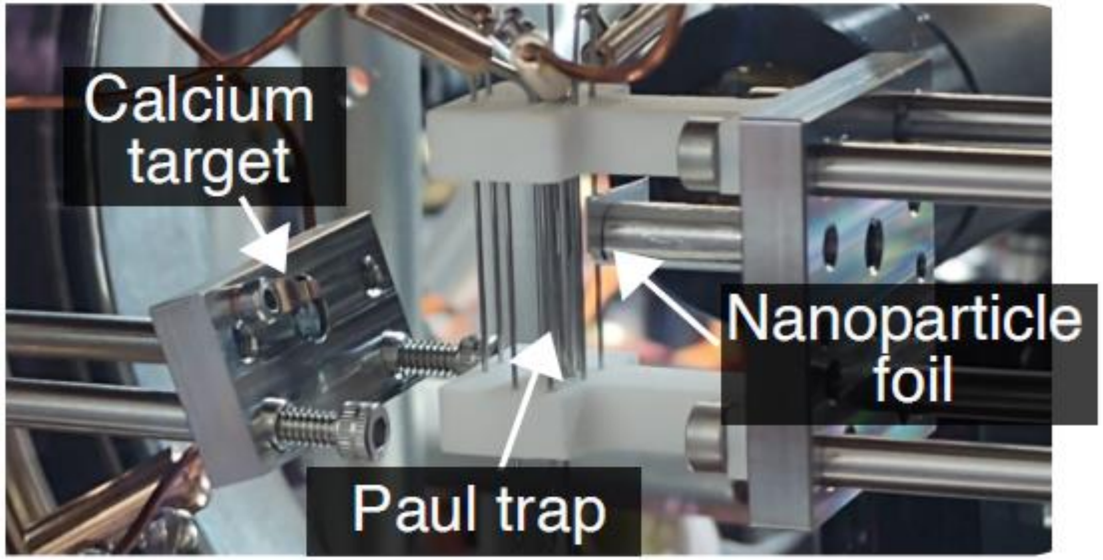


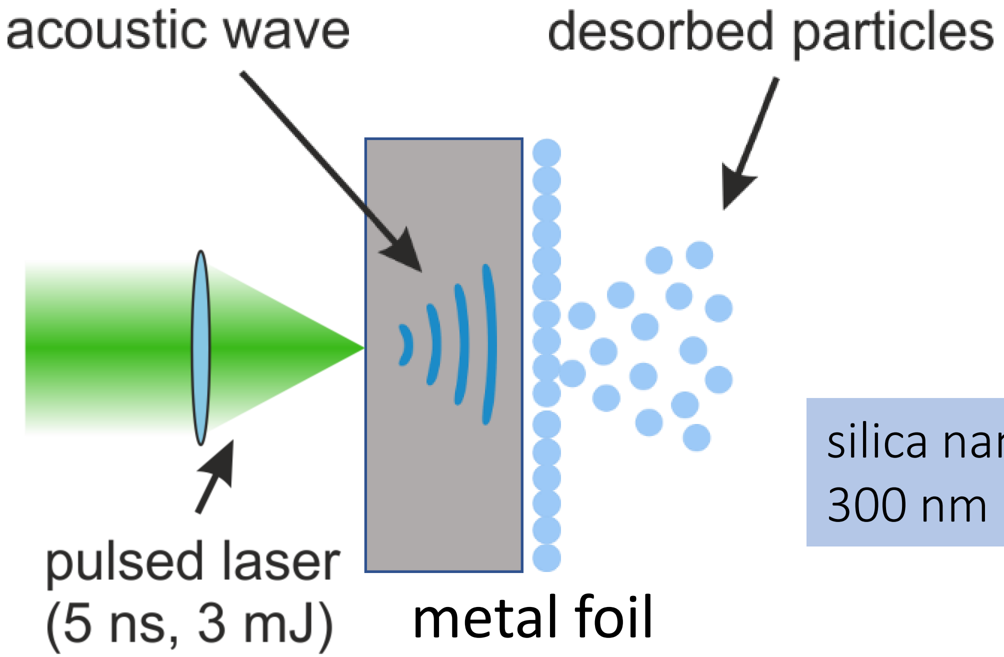
L. Dania, PhD thesis, University of Innsbruck (2023)

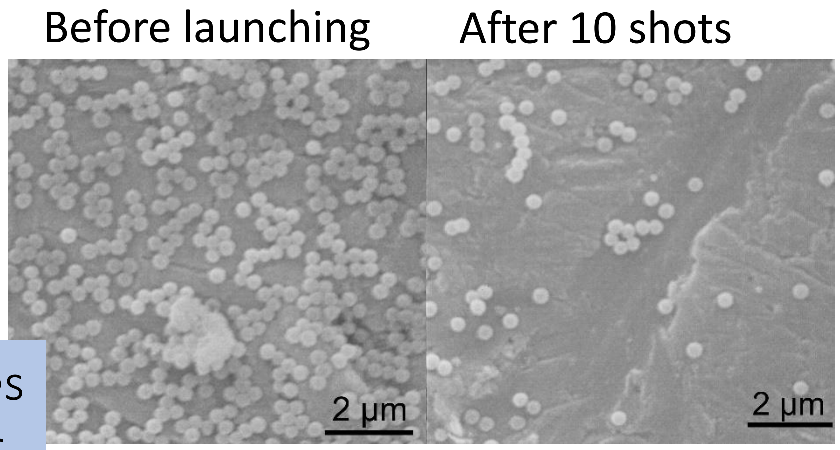
- RF drive (~10 kHz)
- secular motion at frequency of effective potential (~kHz)
- residual "micromotion" at RF frequency





Nanoparticles are loaded via laser-induced acoustic desorption



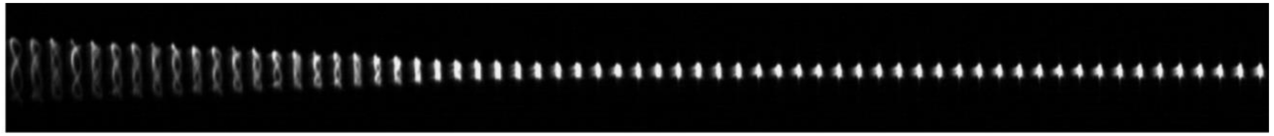


silica nanospheres
300 nm diameter

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)

Nanoparticles are caught within the trap

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



Particle charge can be measured and controlled at the single-charge level.

Damping of oscillations consistent with background gas cooling.

1. Trap nanoparticle in UHV (with large amplitude).
2. Feedback-cool the nanoparticle to millikelvin temperatures in 3D (optical detection, electrical feedback).
   L. Dania, D. S. Bykov, M. Knoll, P. Mestres, T. E. Northup, *Phys. Rev. Research* 3, 013018 (2021)
   L. Dania, K. Heidegger, D. S. Bykov, G. Cerchiari, G. Araneda, T. E. Northup, *Phys. Rev. Lett.* 129, 013601 (2022)
3. To operate at higher pressures: close the gate valve that provides access to the vacuum pump.

→ Tunable operation across eight orders of magnitude in pressure.

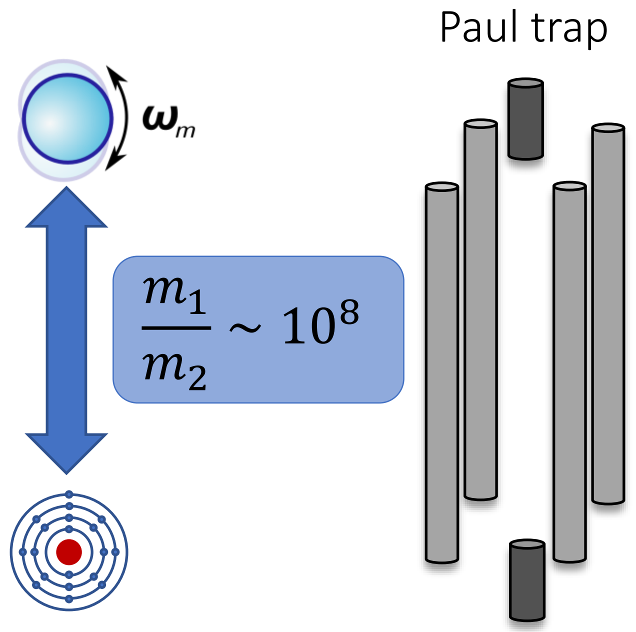
Pressure 2.4e-3 mbar

Pressure 1e-6 mbar

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

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

levitated nanoparticle + calcium ion



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

$$\frac{Q_2/m_2}{Q_1/m_1} \sim 10^6$$

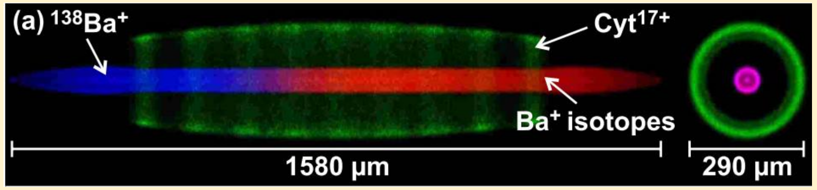
Prior work:

- 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+}	$^{138}\mathrm{Ba}^{+}$
12 390 amu	138 amu



- Proposed: positrons + antiprotons for antihydrogen synthesis

  Dehmelt, *Phys. Scr.* **1995,** 423 (1995)

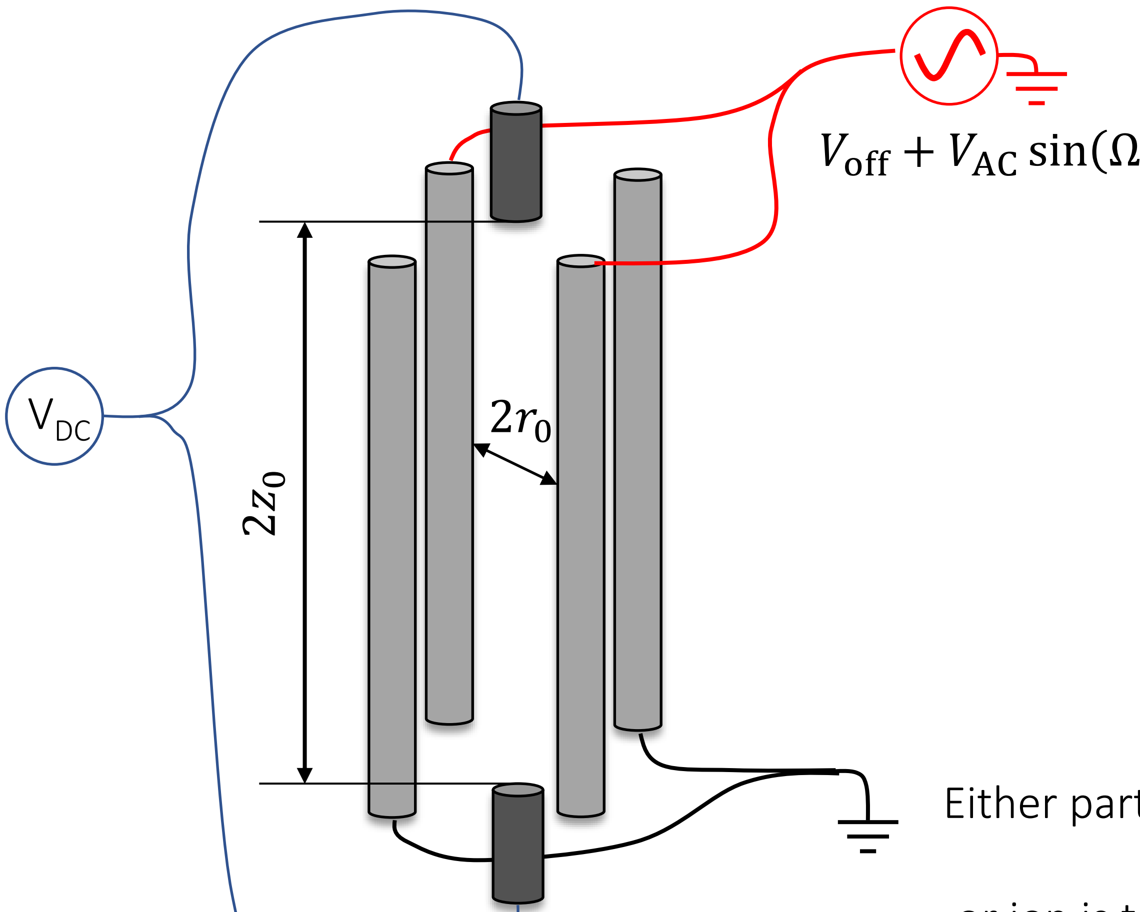
$$\frac{m_1}{m_2} \sim 10^3$$

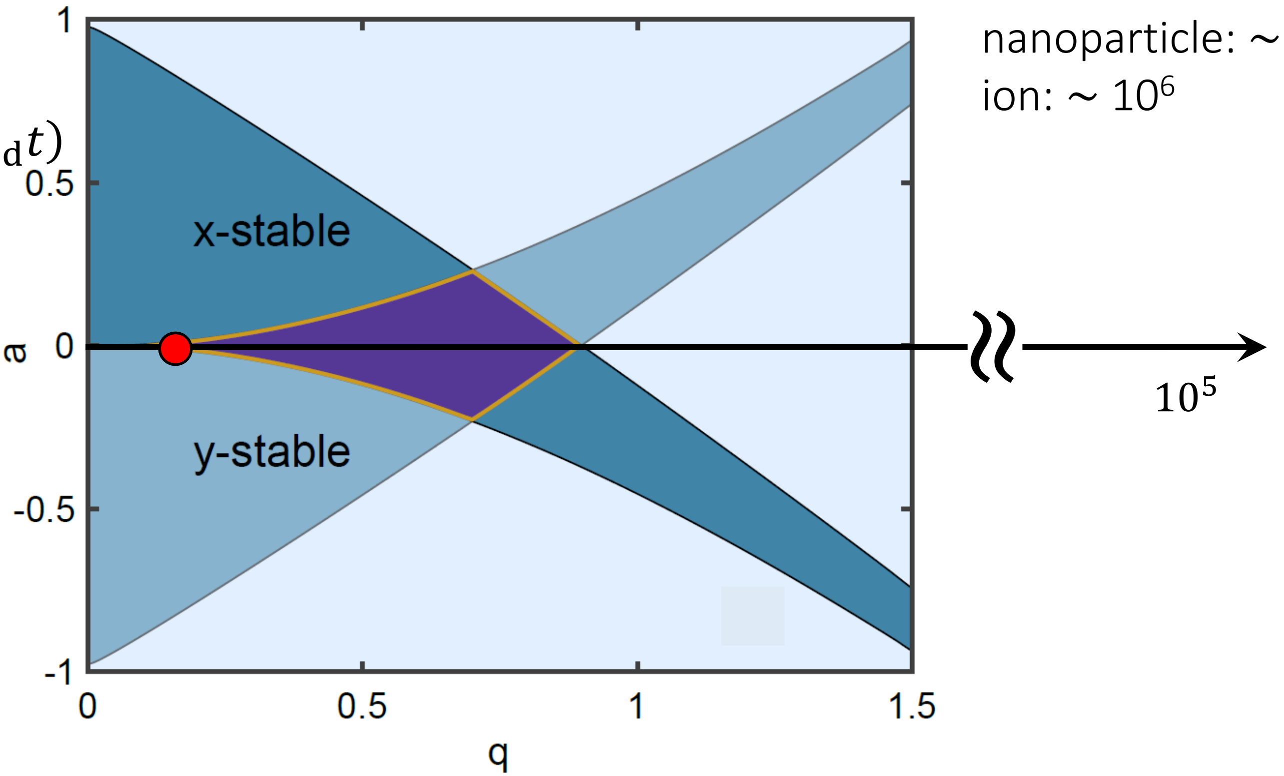
The challenge: stability conditions for a Paul trap

charge

mass

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





nanoparticle: ~1

ion: ~ 10^6

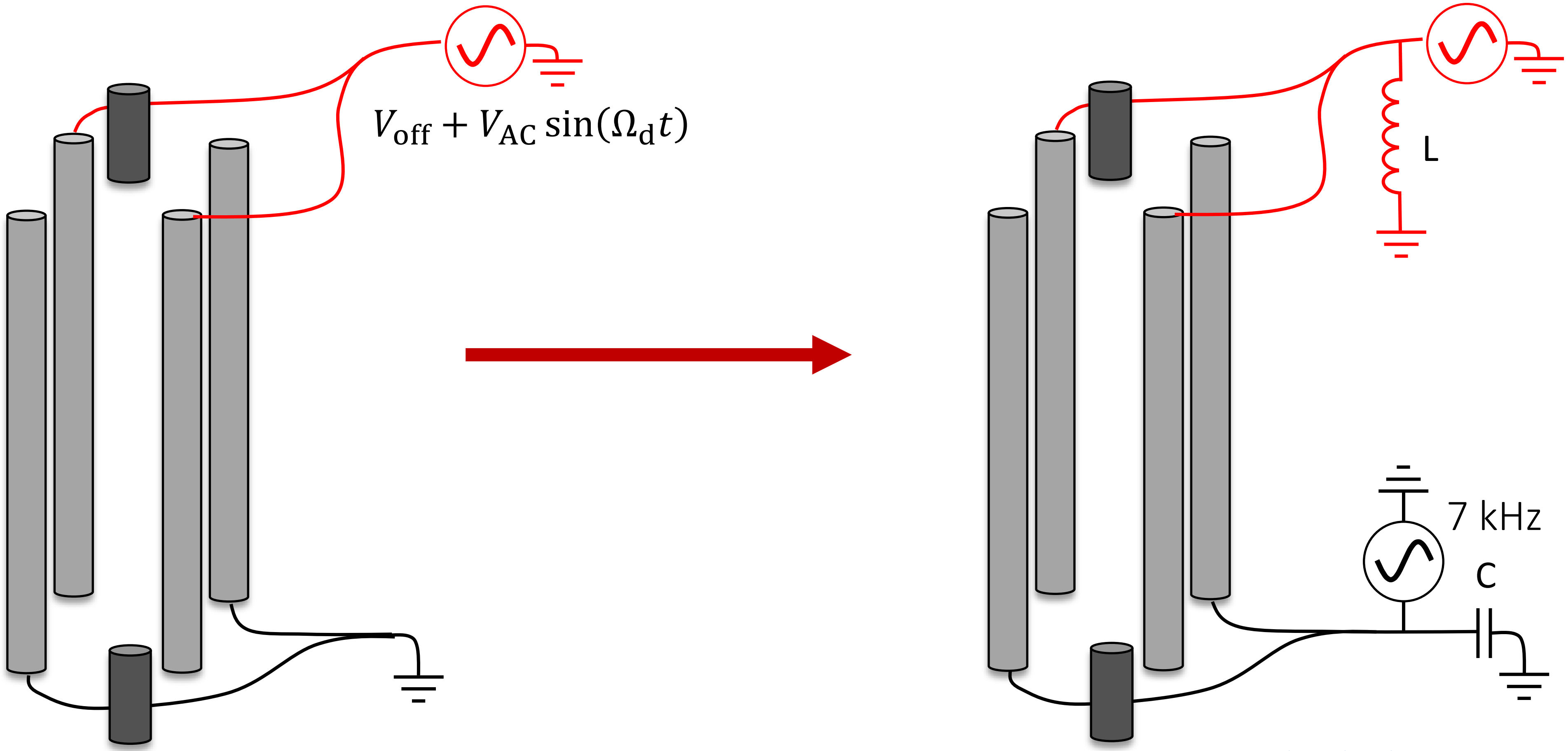
Either particle is trapped but ion is unstable...

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

...or ion is trapped but particle confinement is weak.

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

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 & cool a nanoparticle

↓

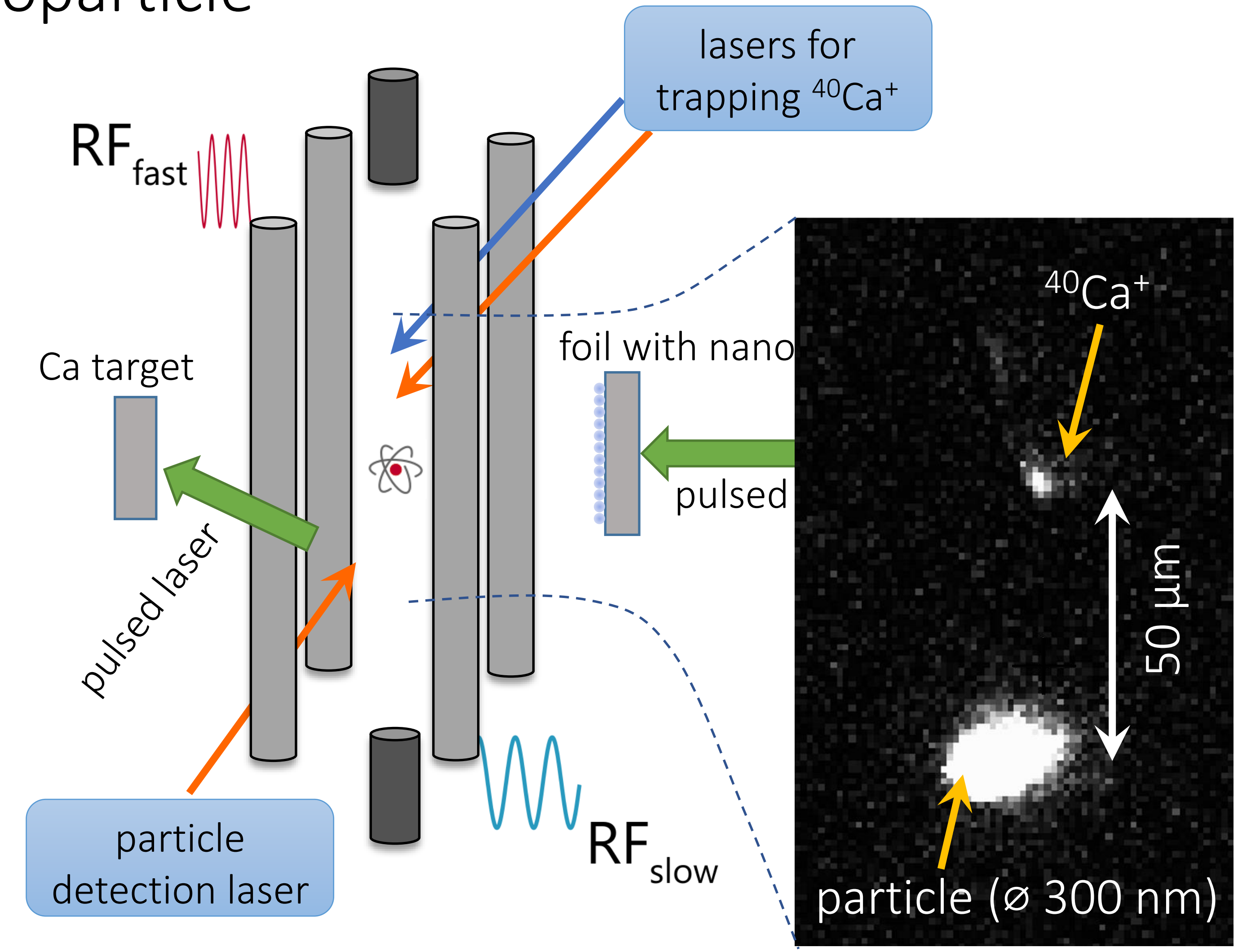
increase nanoparticle charge,
reduce the slow amplitude

↓

displace the particle
from the trap center

↓

trap an ion



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

RF_{fast}

Ca target

pulsed laser

foil with nano

pulsed

RF_{slow}

particle detection laser

$^{40}Ca^+$

50 µm

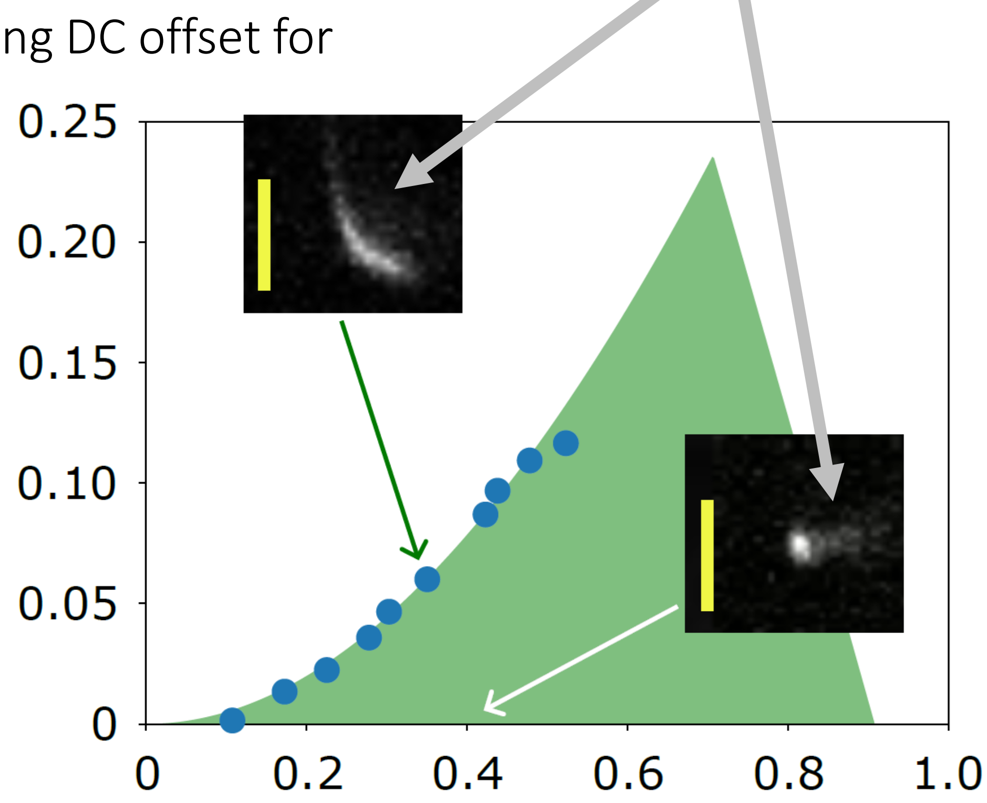
particle (⌀ 300 nm)

D. S. Bykov, L. Dania, F. Goschin, T. E. Northup, arXiv:2403.02034

Properties of a co-trapped ion and nanoparticle

- The fast “ion” field does not perturb the nanoparticle.
- The slow “nanoparticle” field acts as a slowly varying DC offset for the ion & imposes a new stability condition.

camera images of ion
(scale bar: 10 µm)



trap stiffness for nanoparticle

trap stiffness for ion

It will be important to account for the role of slow-field micromotion when engineering interactions between the particles.

D. S. Bykov, L. Dania, F. Goschin, T. E. Northup, arXiv:2403.02034

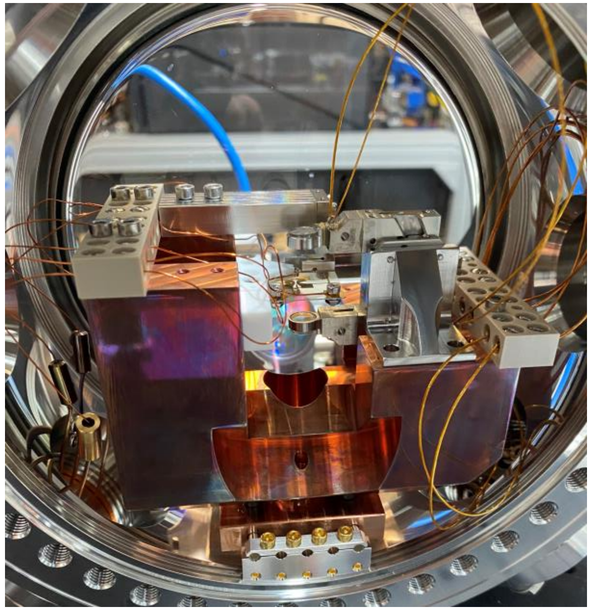
Topics: Lecture 3

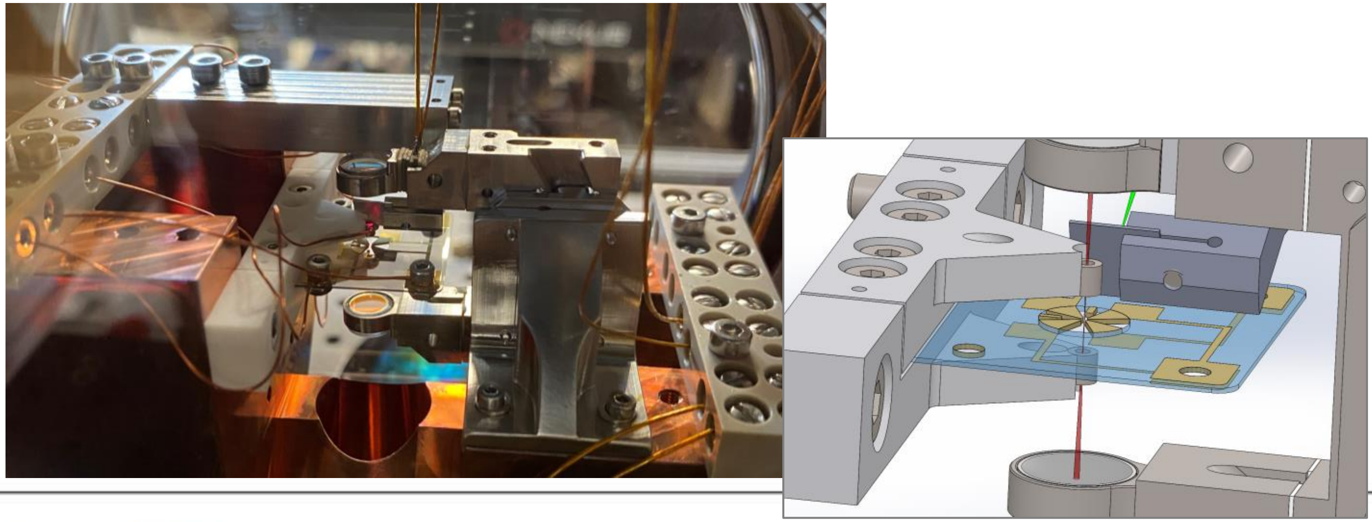
1. Ions as spins… and as mechanical oscillators
2. Confining an ion and a nanomechanical oscillator in the same trap
3. Levitated mechanical systems: next (experimental) steps

Ongoing work: coupling trapped ions to a nanoparticle

C. Gonzalez-Ballestero, A. Deutschmann-Olek, N. Kiesel, M. Aspelmeyer, O. Romero-Isart

- How can we use the ion(s) to cool the nanoparticle?
- How can we use the ion as sensor for the nanoparticle?
- Vision: use the ion qubit to prepare non-Gaussian states of the nanoparticle's motion, mediated by an optical cavity
  A. Pflanzer, O. Romero-Isart, J. I. Cirac, *Phys. Rev. A* **88**, 033804 (2013)



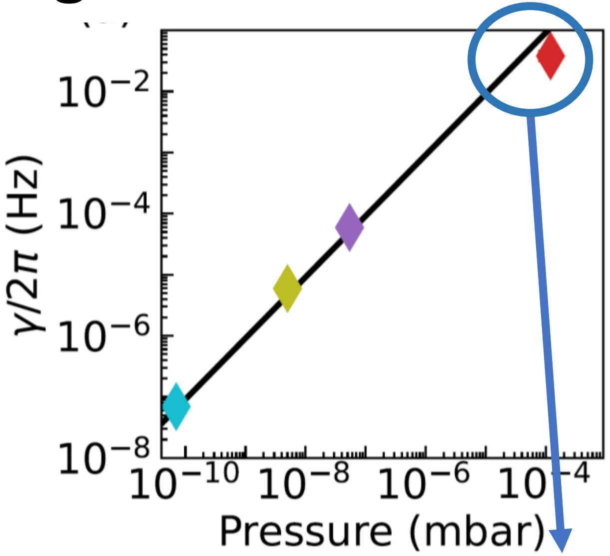


Ongoing work: characterizing noise sources at ultra-high vacuum

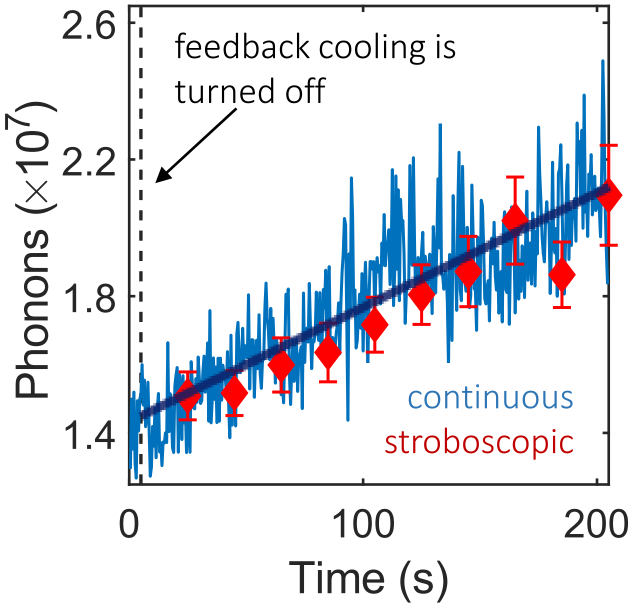
Cool the particle and watch it rethermalize:

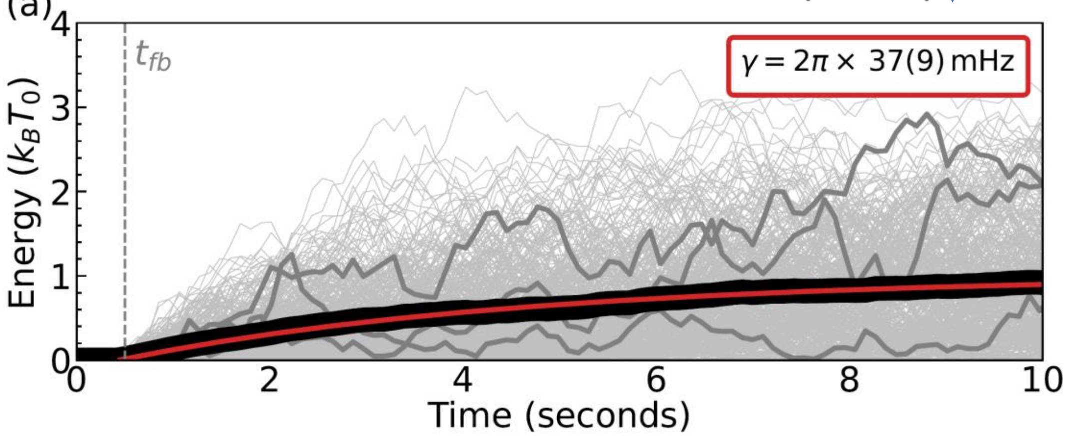
$$\langle E(t)\rangle = k_\mathrm{B}T_0 + k_\mathrm{B}(T_\mathrm{cool} - T_0)e^{-\gamma t}$$

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



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

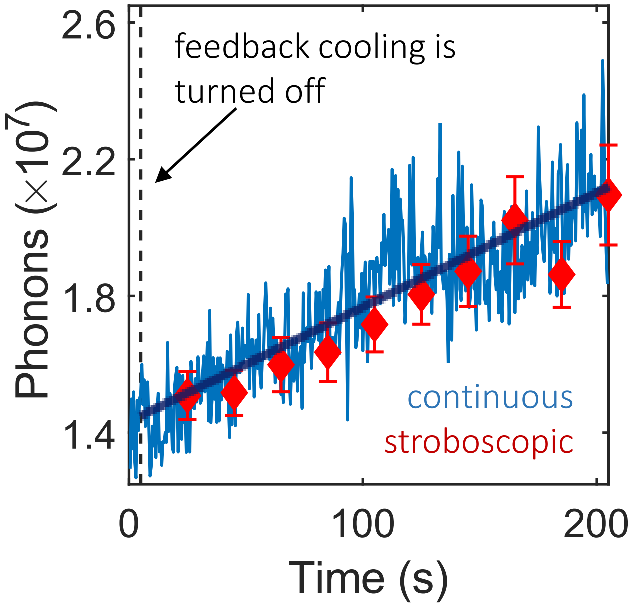




L. Dania, D. S. Bykov, F. Goschin, M. Teller, A. Kassid, T. E. Northup, *Phys. Rev. Lett.* **132**, 133602 (2024)

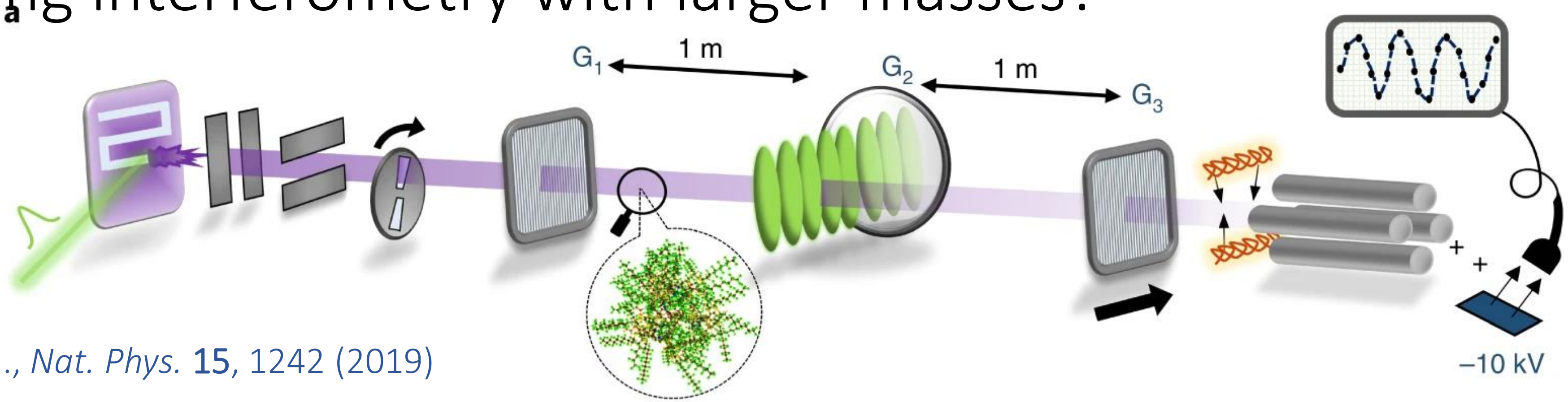
Ongoing work: characterizing noise sources at ultra-high vacuum

At 7·10^{-11} mbar:



- How does the particle rethermalization depend on the trap frequency? Does this correlate with independently measured vibrations?
- How does the particle rethermalization depend on charge? A dependence would point to voltage noise on the electrodes.
- Can we observe energy transfer between the particle's rotation and center-of-mass motion? Such a coupling would be a decoherence channel.

Ongoing work: can we detect smaller levitated particles, enabling interferometry with larger masses?



Y. Y. Fein et al., *Nat. Phys.* **15**, 1242 (2019)

As mass increases, one needs increasingly long interaction times & coherence times. The velocity distribution of particles in a beam becomes a liability.

An alternate approach: trap the particles.

Jean Paul Louys Sanso
Collaboration: R. Wester, M. Arndt

Quantum Interfaces Group

QUANTUM INTERFACES GROUP

FWF
Der Wissenschaftsfonds.

ÖAW ÖSTERREICHISCHE AKADEMIE DER WISSENSCHAFTEN

quantA

Topics: Lecture 3

Ions have a number of strengths that recommend them as auxiliary qubits for preparing non-Gaussian states.

1. Ions as spins… and as mechanical oscillators
2. Confining an ion and a nanomechanical oscillator in the same trap
3. Levitated mechanical systems: next (experimental) steps

We have confined a nanoparticle and ion(s) in the same linear Paul trap, enabled by a dual-frequency drive.

There are a number of challenging and compelling problems to tackle on our way to the quantum regime.

- M. Aspelmeyer, T. J. Kippenberg, F. Marquardt, *Rev. Mod. Phys.* **86**, 1391 (2014)
- L. P. Neukirch, A. N. Vamivakas, *Contemp. Phys.* **56**, 48 (2015)
- J. Millen, T. S. Monteiro, R. Pettit, A. N. Vamivakas, *Rep. Prog. Phys.* **83**, 026401 (2020)
- D. C. Moore, A. A. Geraci, *Quant. Sci. Technol.* **6**, 014008 (2021)
- C. Gonzalez-Ballestero, M. Aspelmeyer, L. Novotny, R. Quidant, O. Romero-Isart, *Science* **374**, 168 (2021)

Let's bring optomechanical systems into the quantum realm.

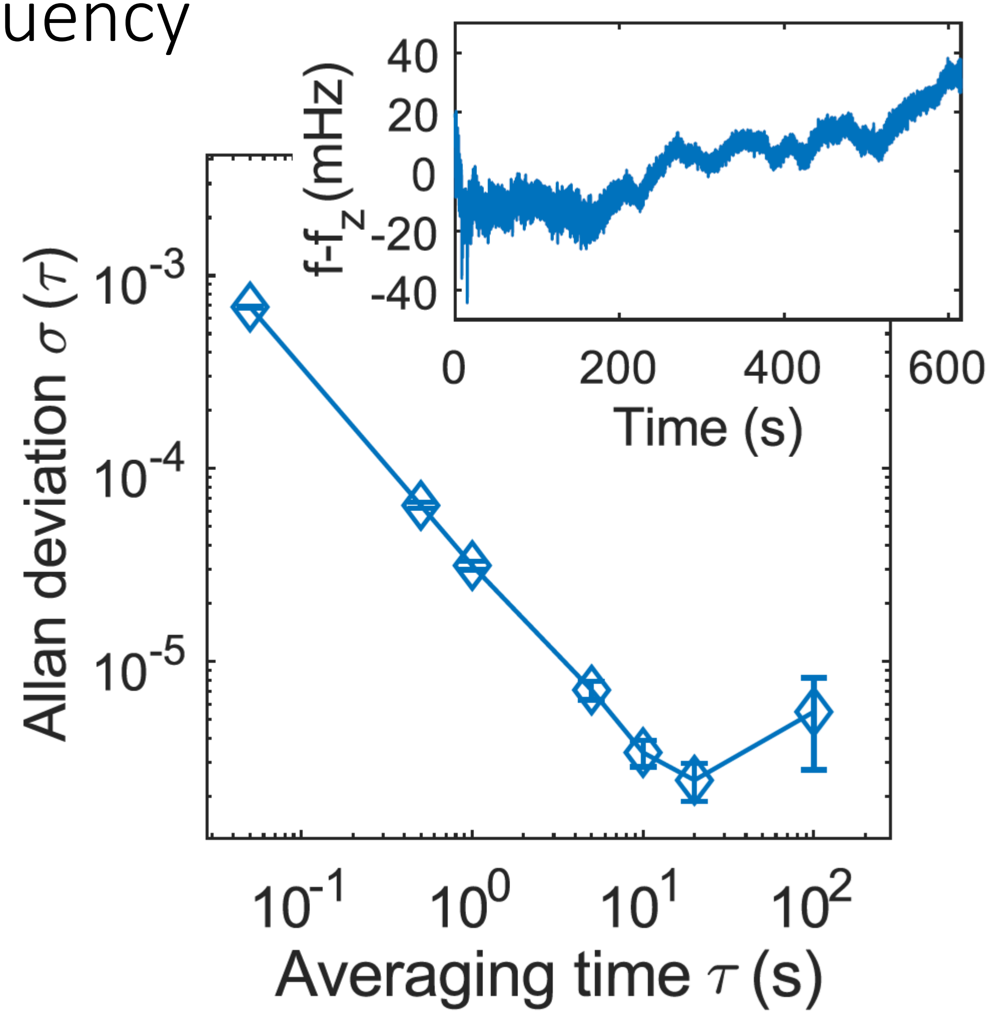
Let's extend quantum control of atoms and photons to mesoscopic systems.

www.uibk.ac.at

We measure amplitude, not frequency

We would need to actively stabilize the RF frequency source of our linear Paul trap for it to be stable at the nanohertz level.

The ring-down method is also insensitive to trap anharmonicities.



L. Dania, D. S. Bykov, F. Goschin, M. Teller, A. Kassid, T. E. Northup, *Phys. Rev. Lett.* **132**, 122602 (2024)