Lecture 2: Levitated mechanical systems for experiments at the quantum level

Tracy Northup, Institute for Experimental Physics, University of Innsbruck

Topics: Lecture 1

1. Quantum optomechanics:
   interactions between light and motion in the quantum regime
2. Why *levitated* optomechanics?
3. What objects should we levitate? And how can we levitate them?
4. Cooling mechanical motion to the quantum ground state
5. Outlook: into the quantum regime

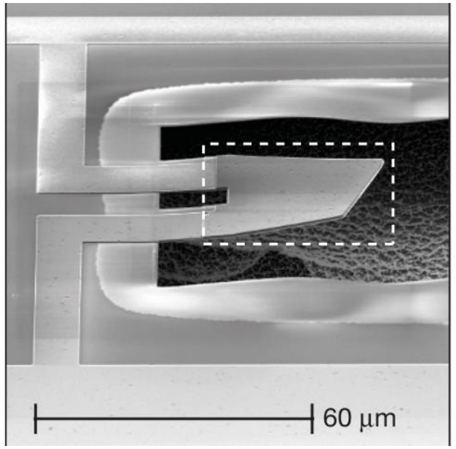
Let's bring optomechanical systems into the quantum realm.

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

Topics: Lecture 1

Interactions between light and motion have already enabled the preparation of quantum states of macroscopic mechanical oscillators.

1. Quantum optomechanics:
   interactions between light and motion in the quantum regime
2. Why *levitated* optomechanics?
3. What objects should we levitate? And how can we levitate them?
4. Cooling mechanical motion to the quantum ground state
5. Outlook: into the quantum regime



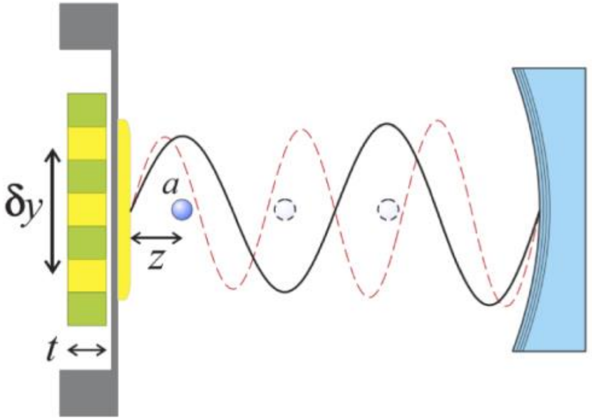
Topics: Lecture 1

Interactions between light and motion have already enabled the preparation of quantum states of macroscopic mechanical oscillators.

1. Quantum optomechanics:
   interactions between light and motion in the quantum regime
2. Why *levitated* optomechanics?

Levitated optomechanical systems offer extreme isolation from the environment at room temperature.

3. What objects should we levitate? And how can we levitate them?
4. Cooling mechanical motion to the quantum ground state
5. Outlook: into the quantum regime



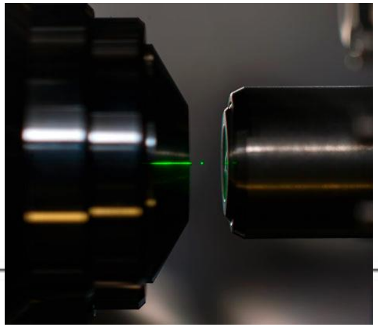
Topics: Lecture 1

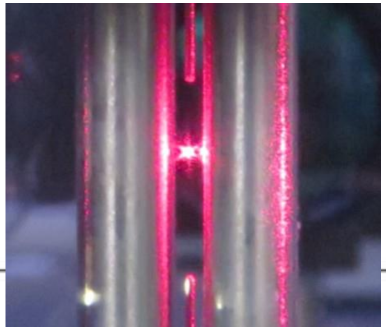
Interactions between light and motion have already enabled the preparation of quantum states of macroscopic mechanical oscillators.

1. Quantum optomechanics:
   interactions between light and motion in the quantum regime
2. Why *levitated* optomechanics?
3. What objects should we levitate? And how can we levitate them?
4. Cooling mechanical motion to the quantum ground state
5. Outlook: into the quantum regime

Levitated optomechanical systems offer extreme isolation from the environment at room temperature.

A wide range of objects can be levitated in optical, electrical, and magnetic traps.





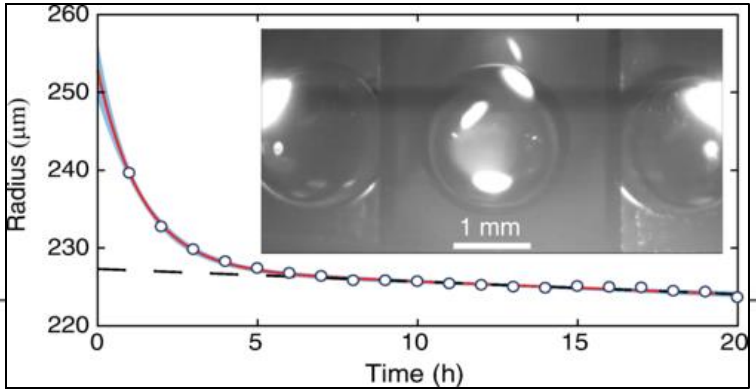
Topics: Lecture 1

Interactions between light and motion have already enabled the preparation of quantum states of macroscopic mechanical oscillators.

1. Quantum optomechanics:
   interactions between light and motion in the quantum regime
2. Why *levitated* optomechanics?
3. What objects should we levitate? And how can we levitate them?
4. Cooling mechanical motion to the quantum ground state
5. Outlook: into the quantum regime

Levitated optomechanical systems offer extreme isolation from the environment at room temperature.

A wide range of objects can be levitated in optical, electrical, and magnetic traps.



magnetically levitated superfluid helium droplets

C. D. Brown et al., *Phys. Rev. Lett.* **130**, 216001 (2023)

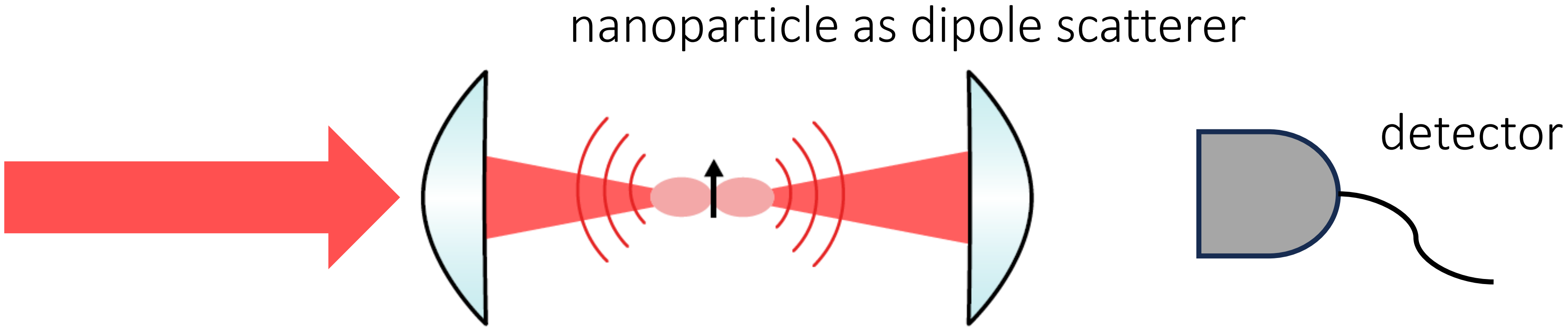
Topics: Lecture 2

1. Efficient detection of a levitated object’s motion
2. Cooling mechanical motion to the quantum ground state
3. Into the quantum regime

Optical interference enables position detection

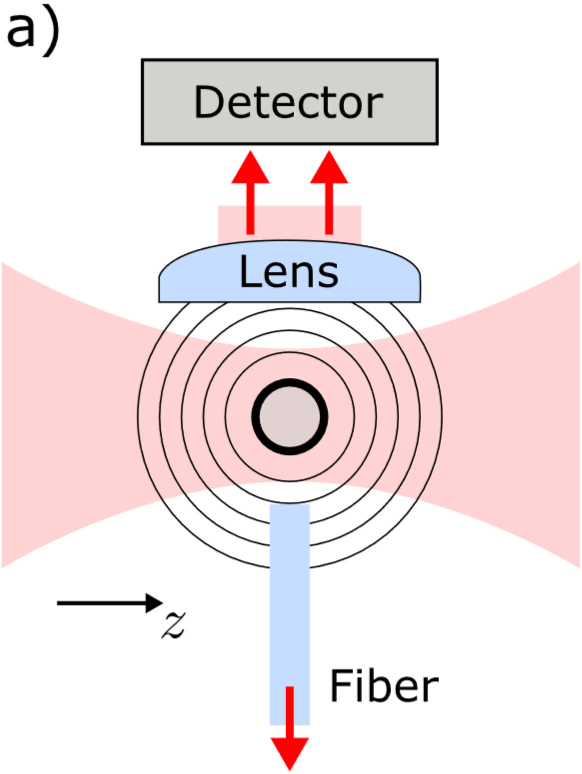
In general, nanoparticle detection is based on optical interference between

1. an illuminating light field, and
2. the light scattered by the particle.



Cameras also provide information about the particle's motion,
but are generally too slow to track its oscillation in a confining potential.

Optical interference enables position detection



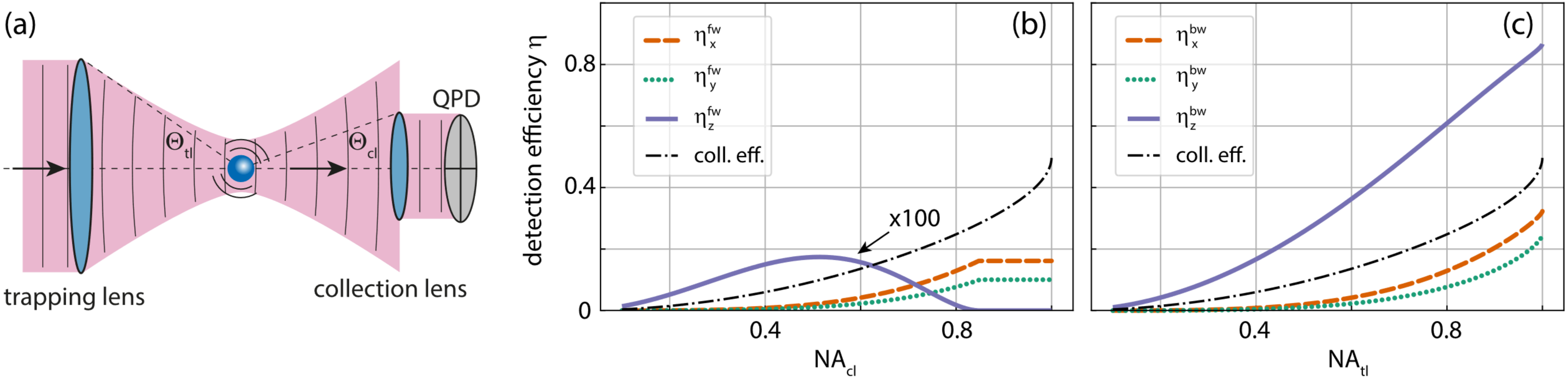
J. Millen, T. S. Monteiro, R. Pettit, A. N. Vamivakas, *Rep. Prog. Phys.* **83**, 026401 (2020)

Efficiency depends on detector position and the motional axis

z axis: propagation axis
x axis: polarization axis

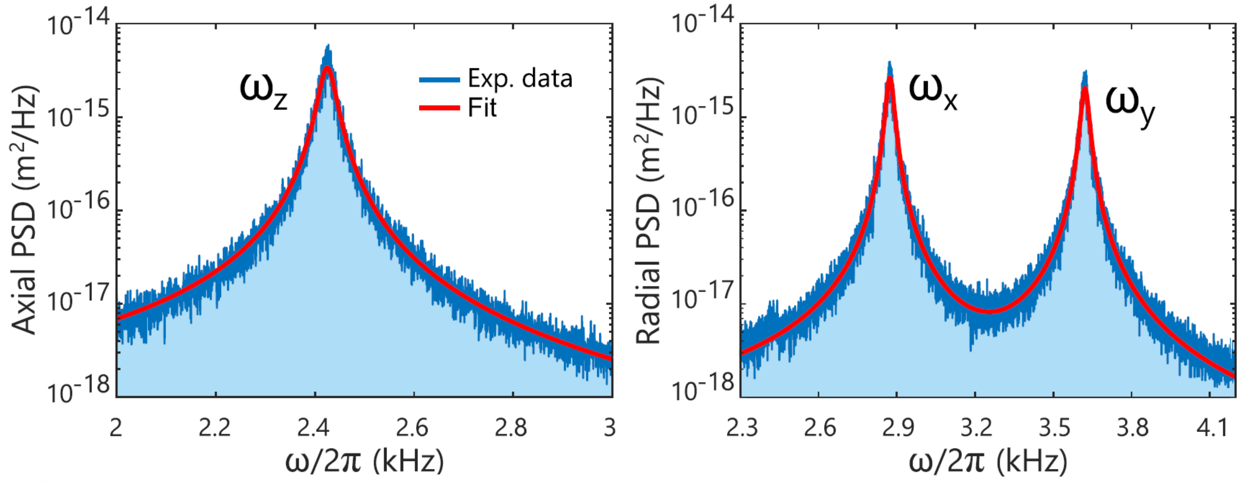
“forward”

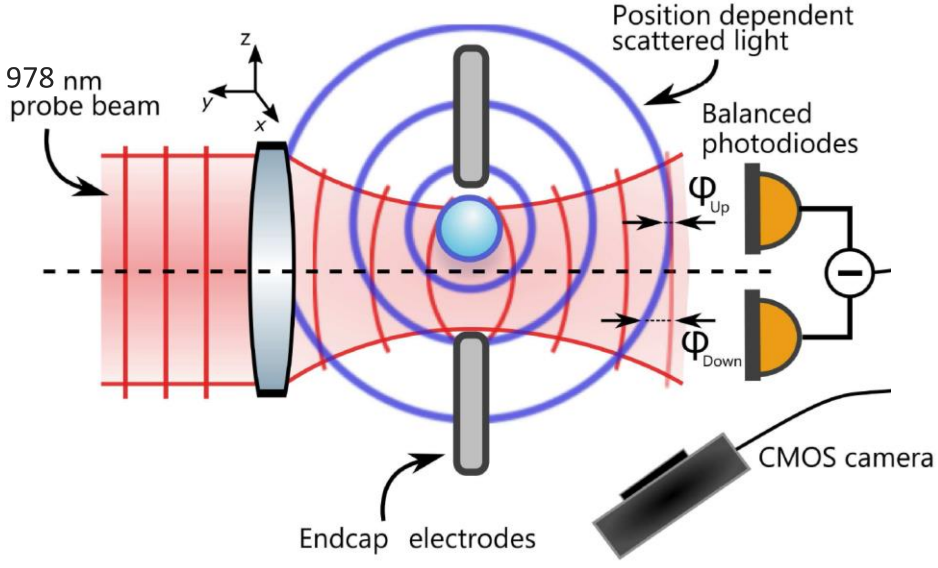
“backward”

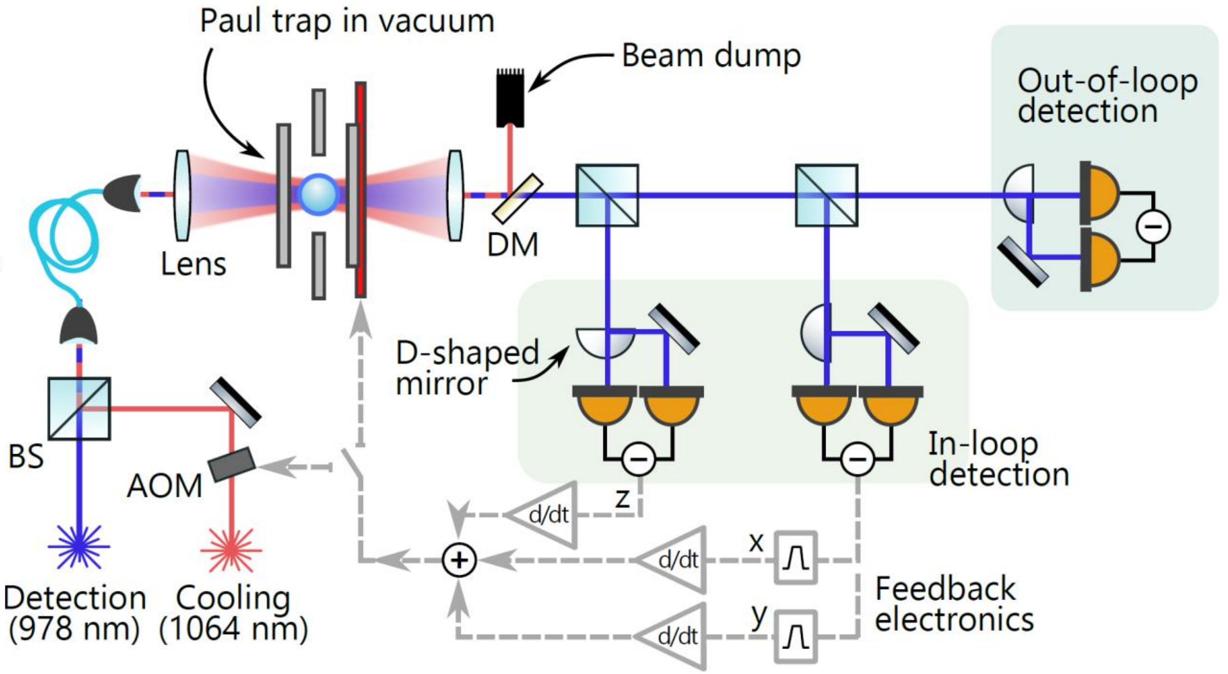


F. Tebbenjohanns, M. Frimmer, L. Novotny, *Phys. Rev. A* **100**, 043821 (2019)

A Fourier transform yields motional signatures

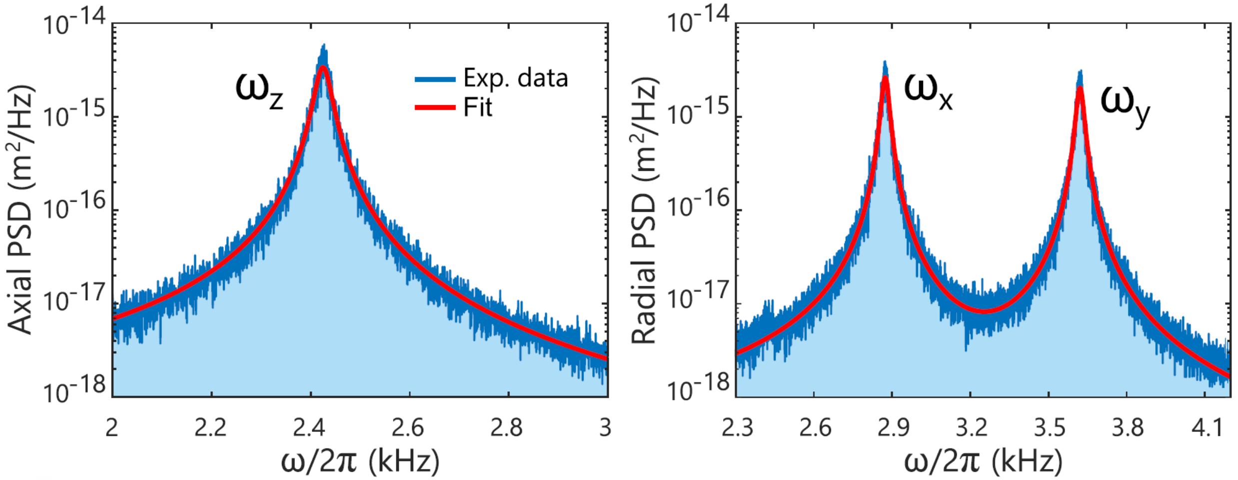


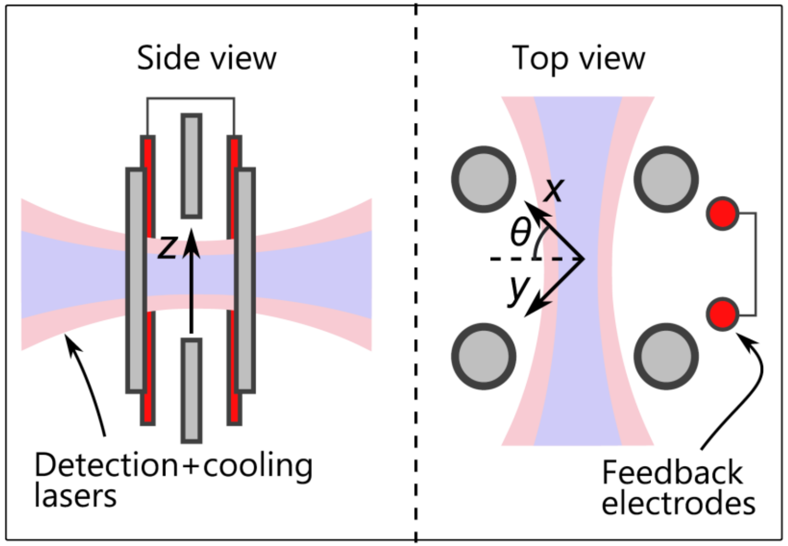


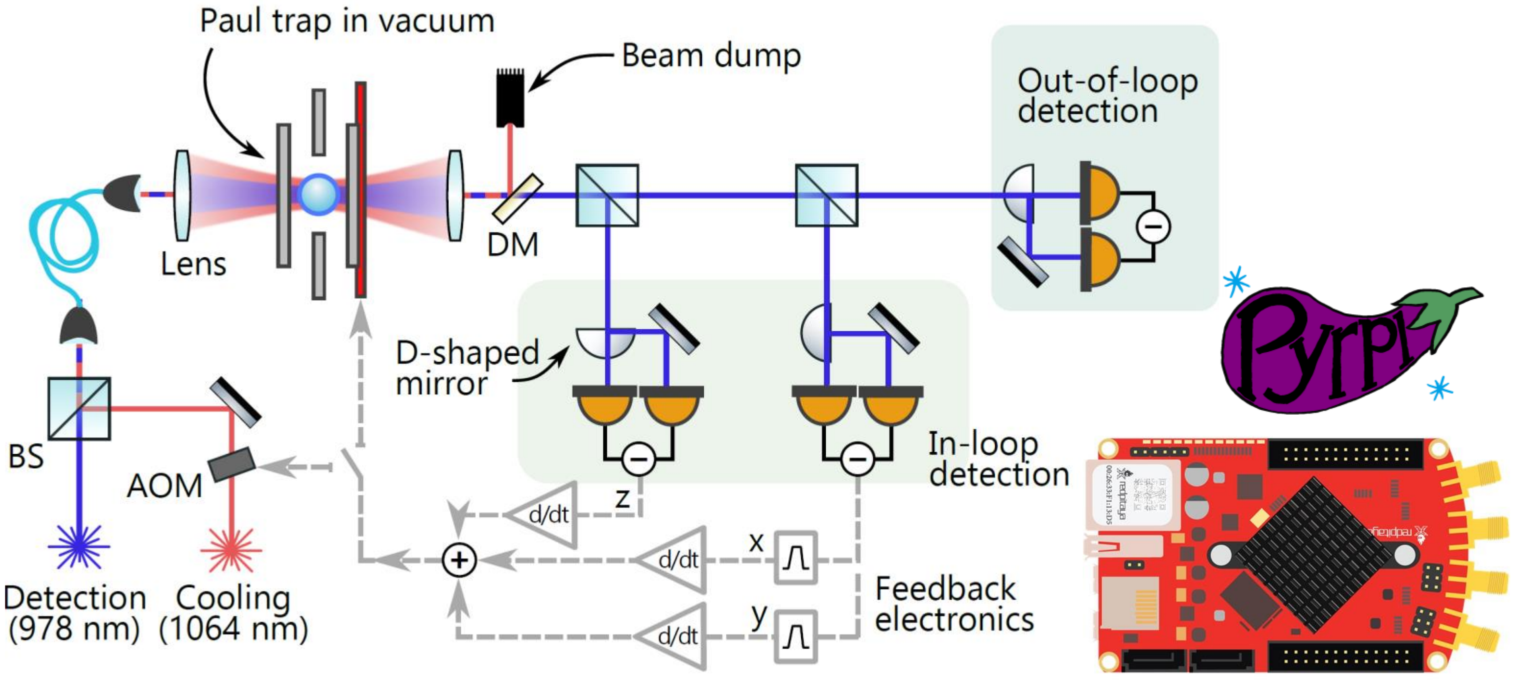


L. Dania, D. S. Bykov, M. Knoll, P. Mestres, T. E. Northup, *Phys. Rev. Res.* **3**, 013018 (2021)

Feedback allows us to damp the particle’s motion





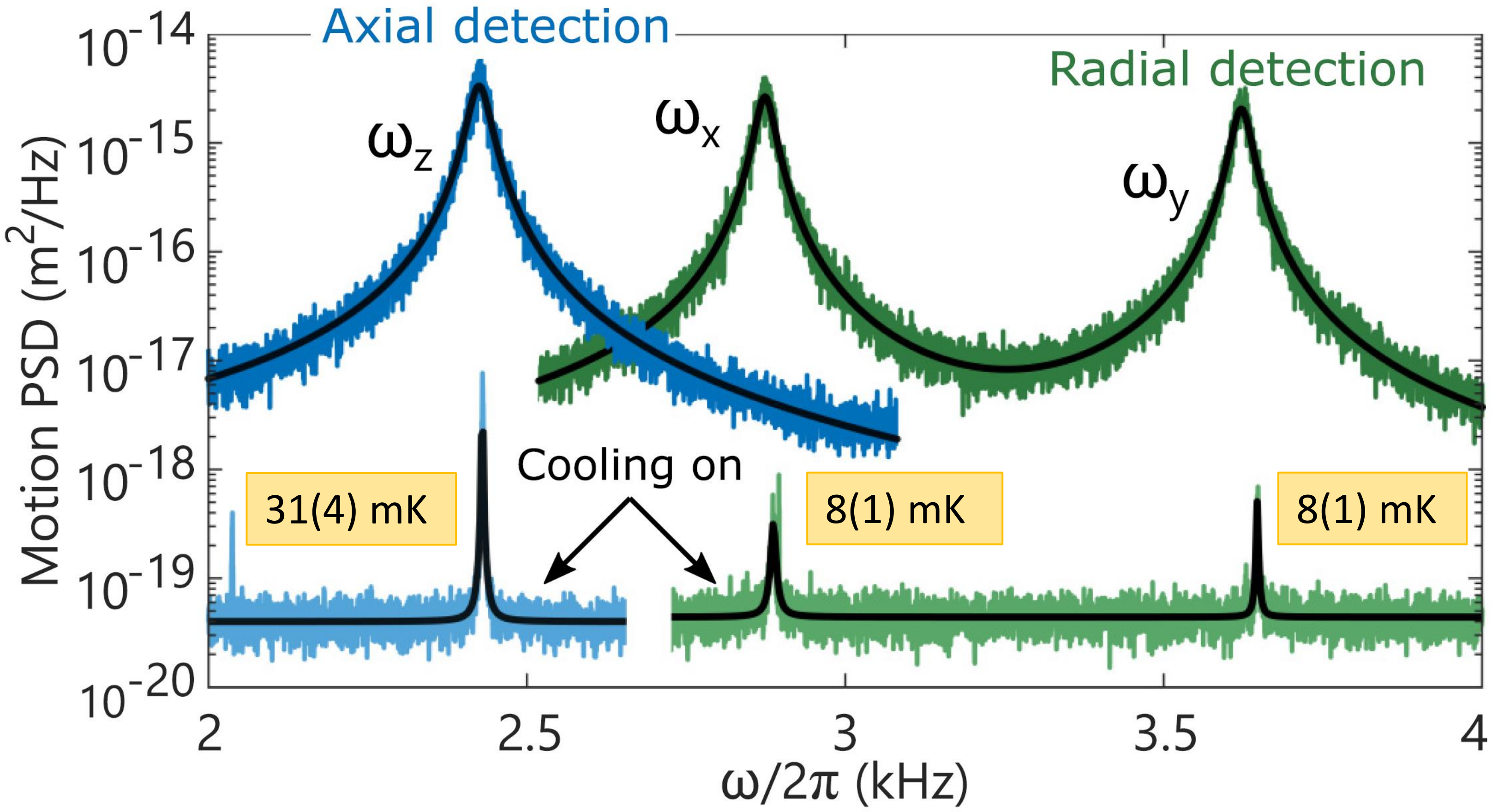


L. Dania, D. S. Bykov, M. Knoll, P. Mestres, T. E. Northup, *Phys. Rev. Res.* **3**, 013018 (2021)

field-programmable gate array

Feedback cooling along three axes

- Optical cooling; electric results are similar
- Both electric and optical feedback fields overlap with all three axes



L. Dania, D. S. Bykov, M. Knoll, P. Mestres, T. E. Northup, *Phys. Rev. Res.* **3**, 013018 (2021)

How far can we cool?

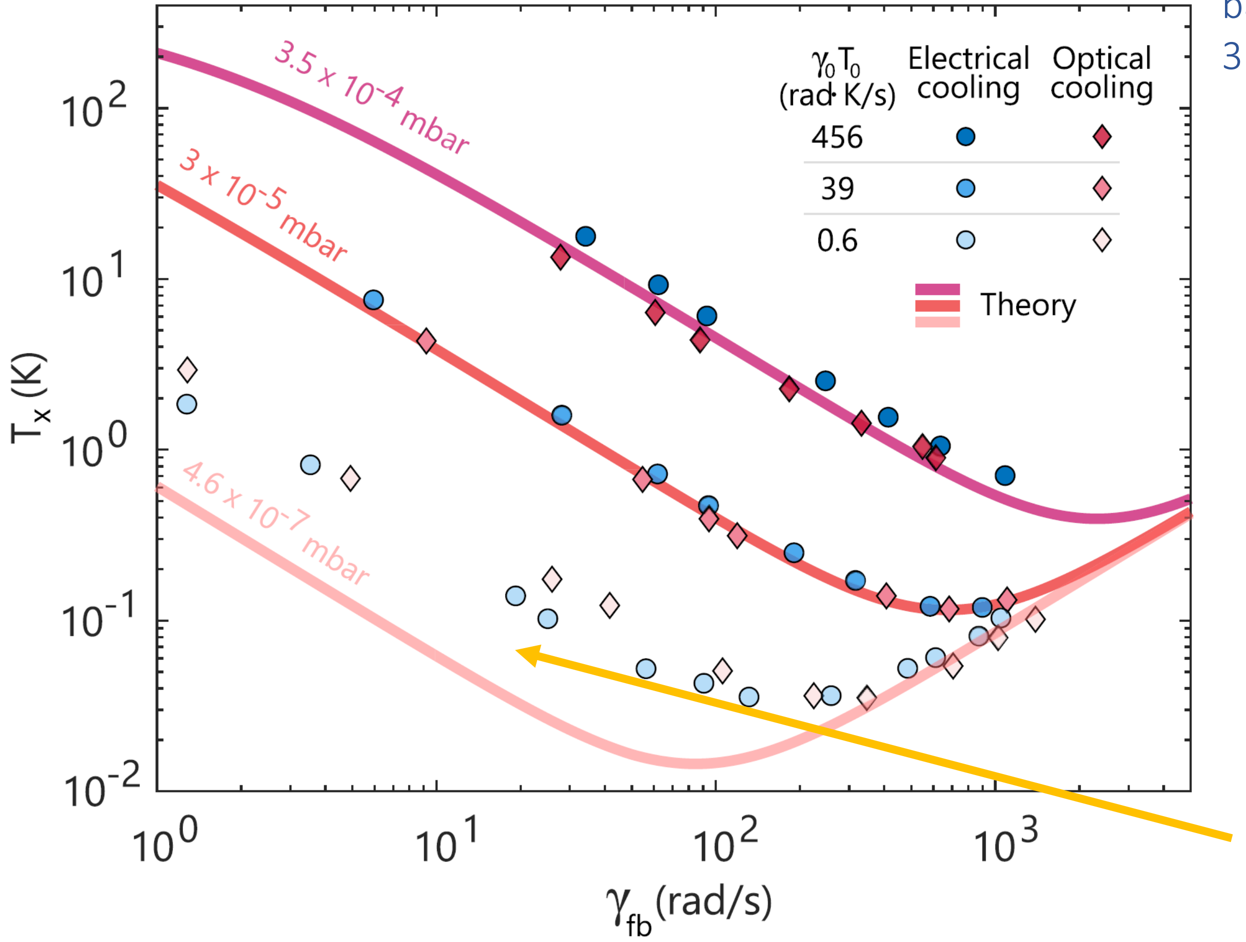
If we turn up the gain of the feedback cooling, the particle’s motional amplitude (“temperature”) gets smaller and smaller…

…until it doesn’t.

We run into the limits of back-action: due to noise on our position measurement, we are heating the particle more than we are cooling it.

Pressure dependence of feedback cooling (x axis)

L. Dania, D. S. Bykov, M. Knoll, P. Mestres, T. E. Northup,
Phys. Rev. Res. **3**, 013018 (2021)



background gas damping; directly measured at $3 \cdot 10^{-2}$ mbar and scaled linearly with pressure

PSD of in-loop motion detection noise

$$T_x = \frac{\gamma_0 T_0}{\gamma_0 + \gamma_{\mathrm{fb}}} + \frac{\pi m \omega_x^2}{2 k_B} \frac{\gamma_{\mathrm{fb}}^2}{\gamma_0 + \gamma_{\mathrm{fb}}} S_{\delta x_{\mathrm{il}}}$$

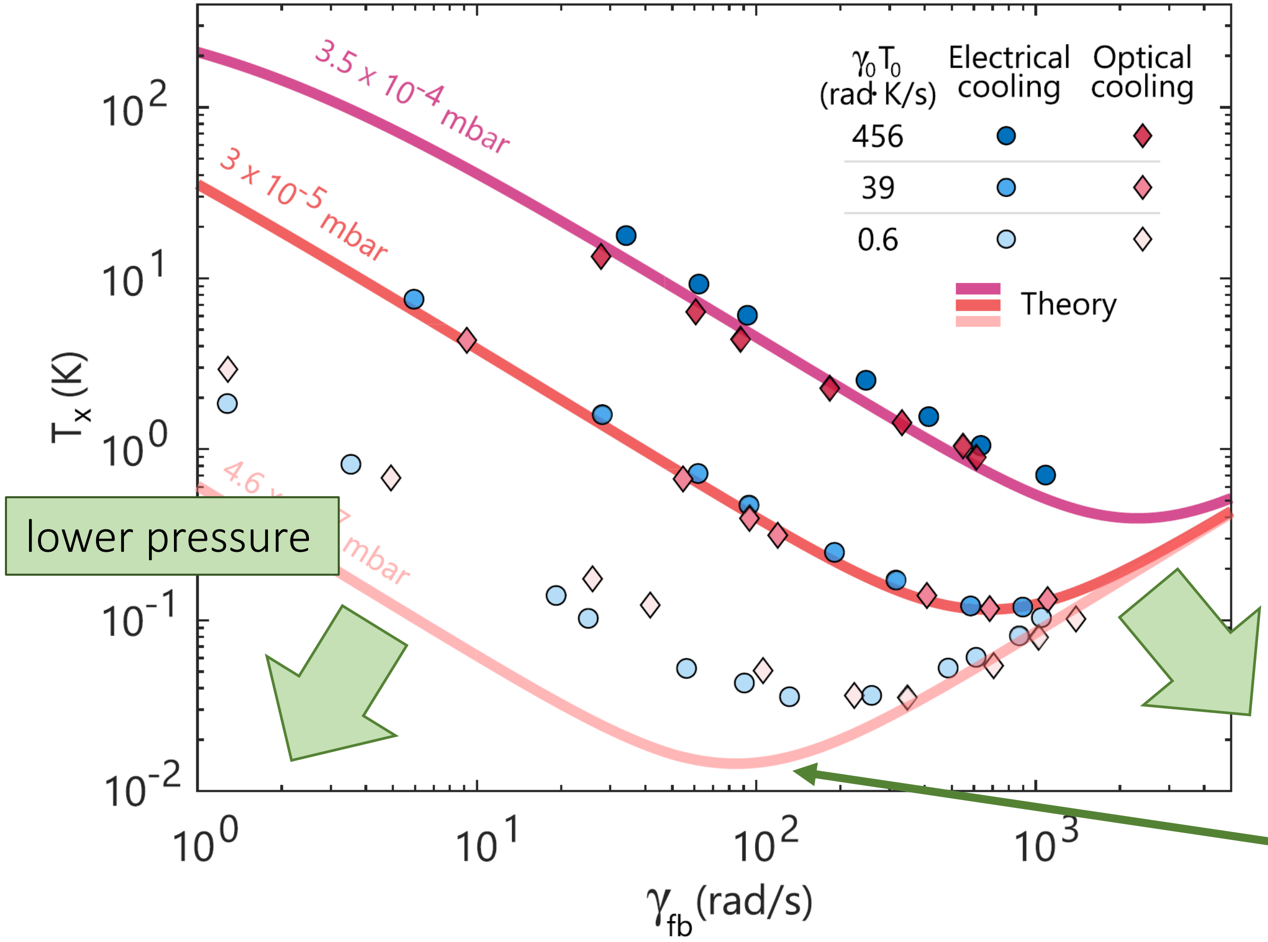
cooling rate; extracted from linewidth of PSD

F. Tebbenjohanns, M. Frimmer, A. Militaru, V. Jain, L. Novotny,
Phys. Rev. Lett. **122**, 223601 (2019)

Subsequent measurements indicate that this discrepancy is position-dependent; we suspect radiofrequency noise of the Paul trap.

Pressure dependence of feedback cooling (x axis)

L. Dania, D. S. Bykov, M. Knoll, P. Mestres, T. E. Northup,
Phys. Rev. Res. **3**, 013018 (2021)



lower pressure

$$T_x = \frac{\gamma_0 T_0}{\gamma_0 + \gamma_{\mathrm{fb}}} + \frac{\pi m \omega_x^2}{2k_B} \frac{\gamma_{\mathrm{fb}}^2}{\gamma_0 + \gamma_{\mathrm{fb}}} S_{\delta x_{\mathrm{il}}}$$

F. Tebbenjohanns, M. Frimmer, A. Militaru, V. Jain, L. Novotny,
Phys. Rev. Lett. **122**, 223601 (2019)

more efficient detection

This is the coldest we can get for a given pressure and detection efficiency.

Topics: Lecture 2

1. Efficient detection of a levitated object’s motion
2. Cooling mechanical motion to the quantum ground state
3. Into the quantum regime

Here, we see the quantized character of the particle’s motion.

In the quantum ground state, a nanoparticle is still in a thermal state…

… but this is a starting point for preparing superpositions & entanglement.

Two routes to cooling: passive and active

Passive: cavity cooling

- nanoparticle is coupled to an optical cavity
- the cavity field carries away energy lost by the particle

Active: feedback cooling

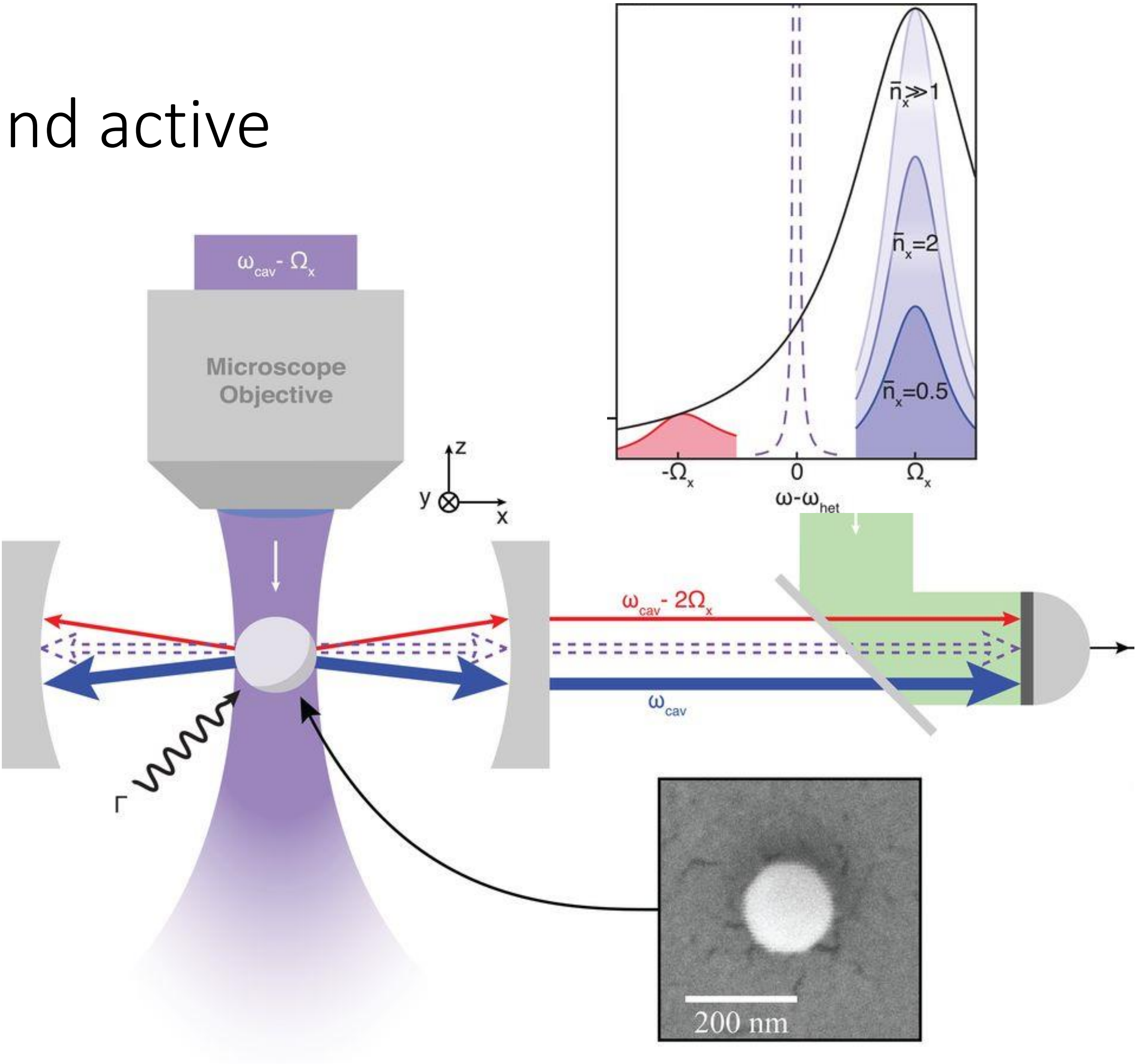
- the position and velocity of the nanoparticle are monitored
- a feedback force (electrical or optical) is applied to counteract the motion of the particle

Two routes to cooling: passive and active

Passive: cavity cooling

- nanoparticle is coupled to an optical cavity
- the cavity field carries away energy lost by the particle
    - tweezer traps a particle at a cavity node → scattering into the cavity is suppressed at the trap frequency
    - scattering at the cavity frequency (blue sideband) is enhanced

mean thermal occupation: 0.43±0.03 phonons (12 µK)



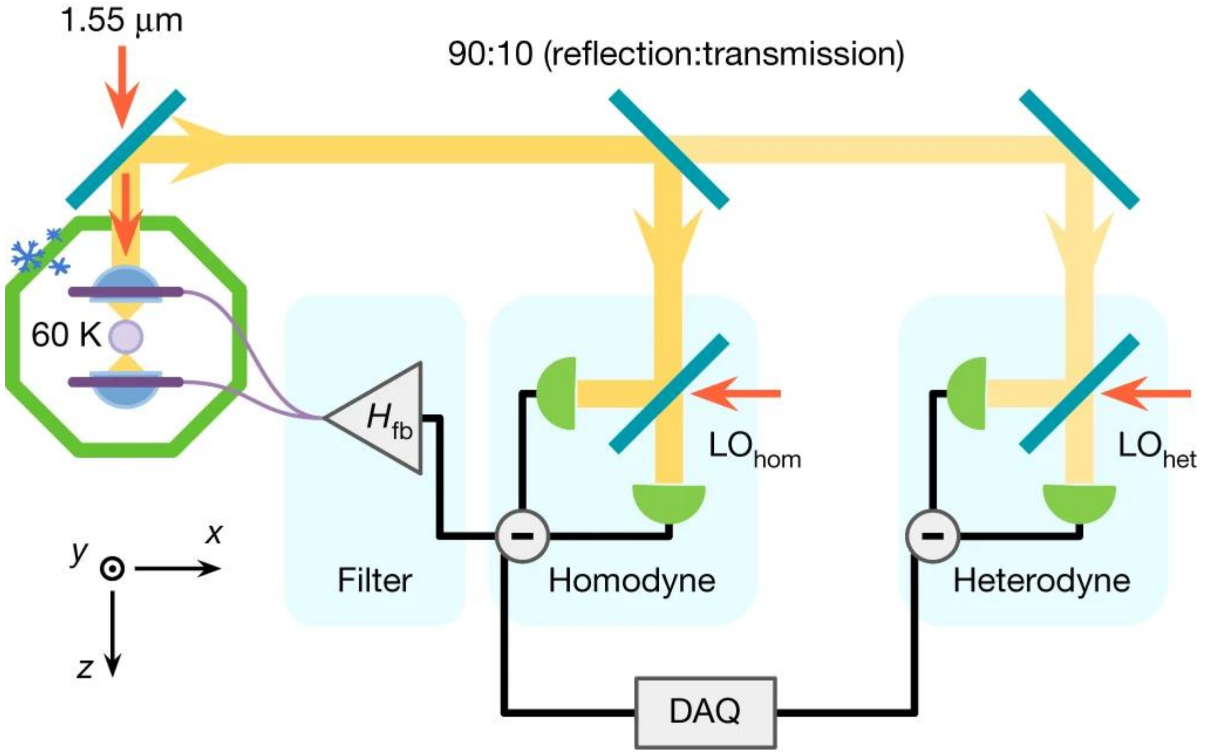
U. Delic, M. Reisenbauer, K. Dare, D. Grass, V. Vuletic, N. Kiesel, M. Aspelmeyer, *Science* **367**, 892 (2020)

Two routes to cooling: passive and active

Active: feedback cooling

- the position and velocity of the nanoparticle are monitored
- a feedback force (electrical or optical) is applied to counteract the motion of the particle
    - interference between back-scattered light from nanoparticle in tweezer and local oscillator
    - feedback applied to electrodes (particle is charged)

mean thermal occupation: 0.65±0.04 phonons



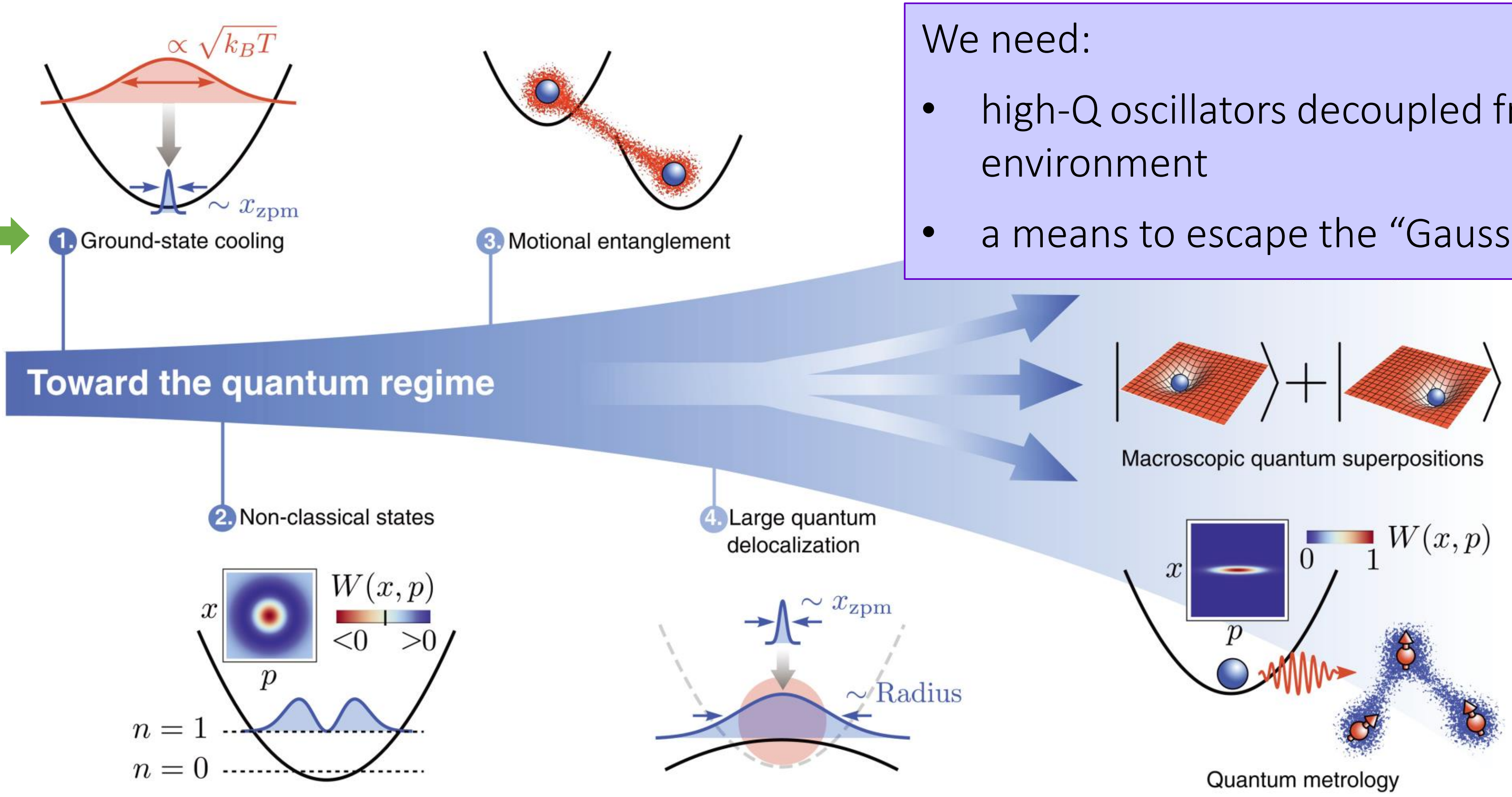
F. Tebbenjohanns, M. L. Mattana, M. Rossi, M. Frimmer, L. Novotny, *Nature* **595**, 378 (2021)

Topics: Lecture 2

1. Efficient detection of a levitated object’s motion
2. Cooling mechanical motion to the quantum ground state
3. Into the quantum regime

Levitated optomechanics: the quantum vision (2021)

state of the art

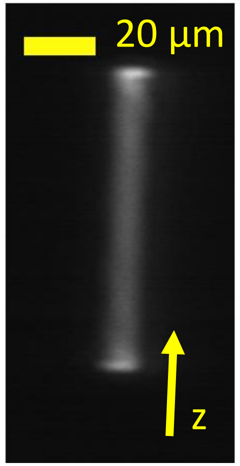


We need:

- high-Q oscillators decoupled from their environment
- a means to escape the "Gaussian prison"

C. Gonzalez-Ballestero, M. Aspelmeyer, L. Novotny, R. Quidant, O. Romero-Isart, *Science* **374**, 168 (2021)

A high-Q levitated nanomechanical oscillator



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

stochastic force: thermalization with environment

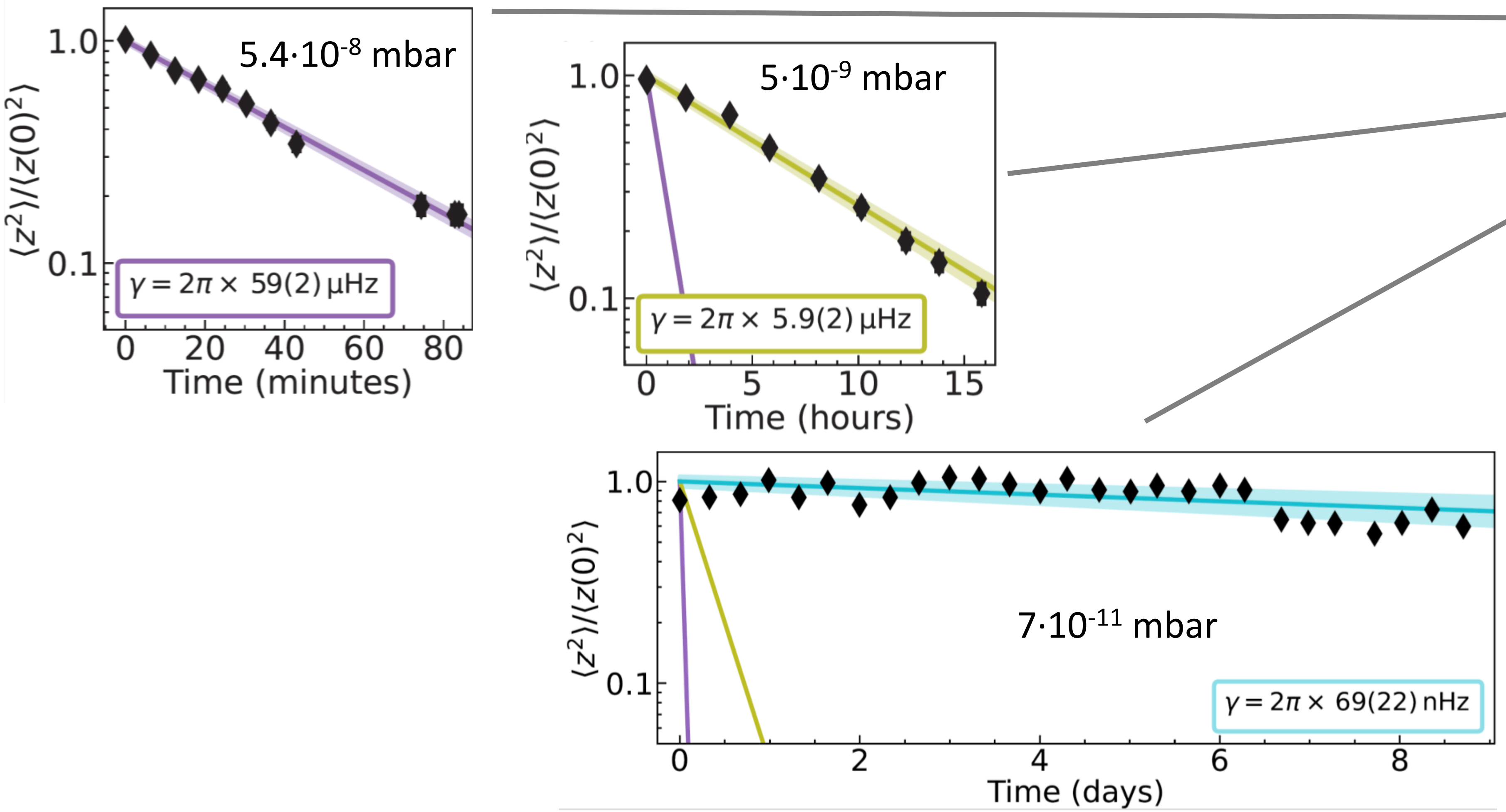
damping rate ∝ pressure

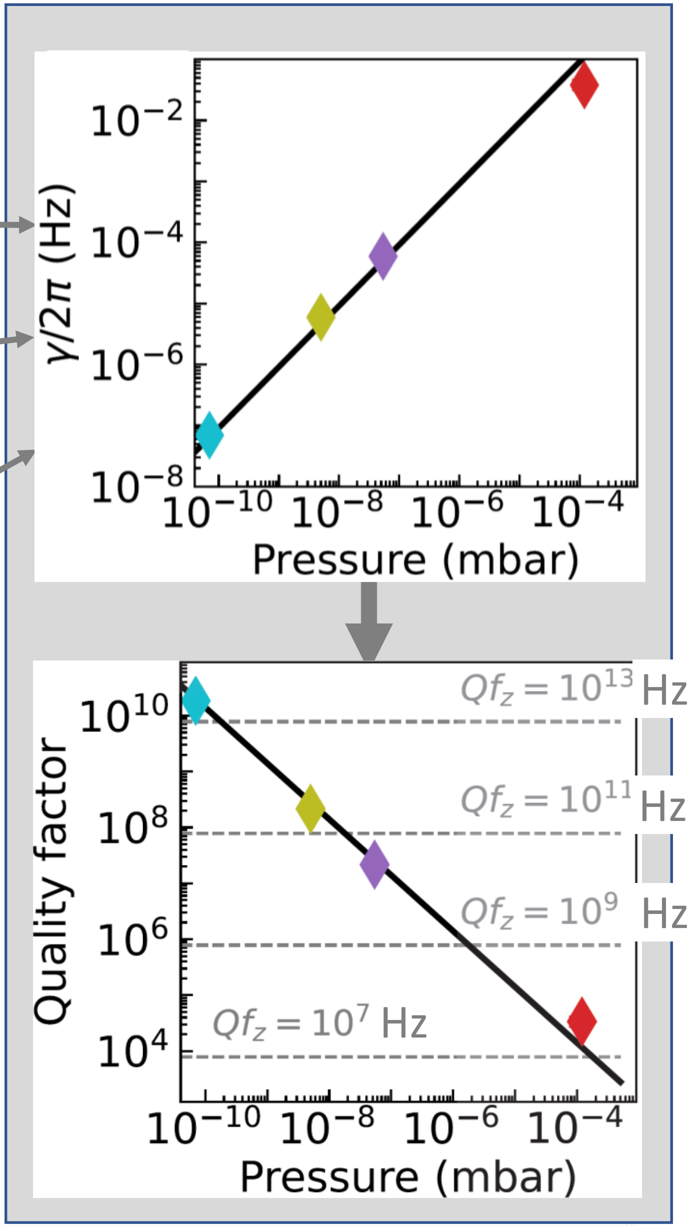
oscillation frequency

mass

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

A high-Q levitated nanomechanical oscillator



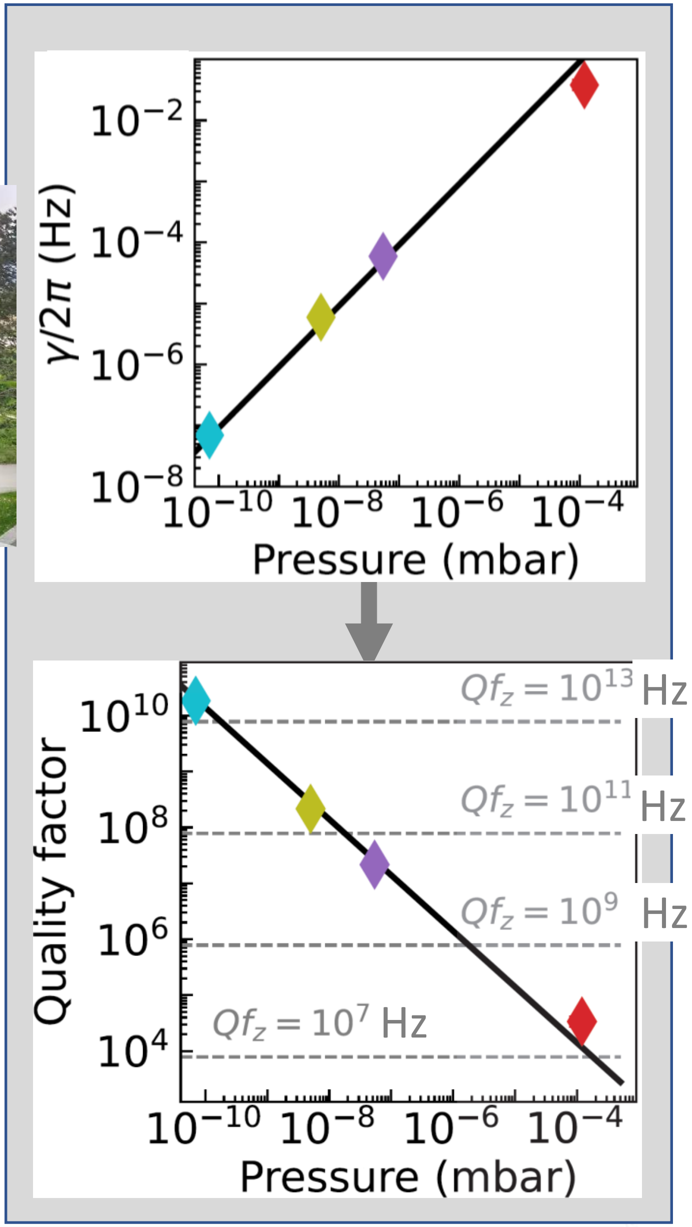


L. Dania, D. S. Bykov, F. Goschin, M. Teller, A. Kassid, T. E. Northup, *Phys. Rev. Lett.* **132**, 133602 (2024)

A high-Q levitated nanomechanical oscillator

talk to Santiago Gliosca!

- Q = 1.8(6)·10^{10}
- Enabling factors: ultra-high vacuum & ion trap
- One molecule collides with the particle every 1.2 oscillation cycles!

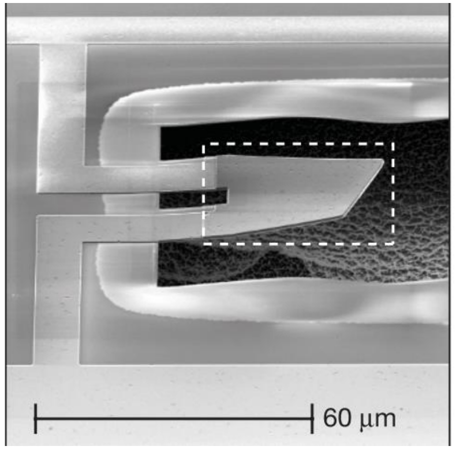


Optical trapping is an enabling technology for nanomechanical systems, but also presents challenges due to photon recoil and heating.

Hybrid traps are a promising approach for future experiments in the quantum regime.

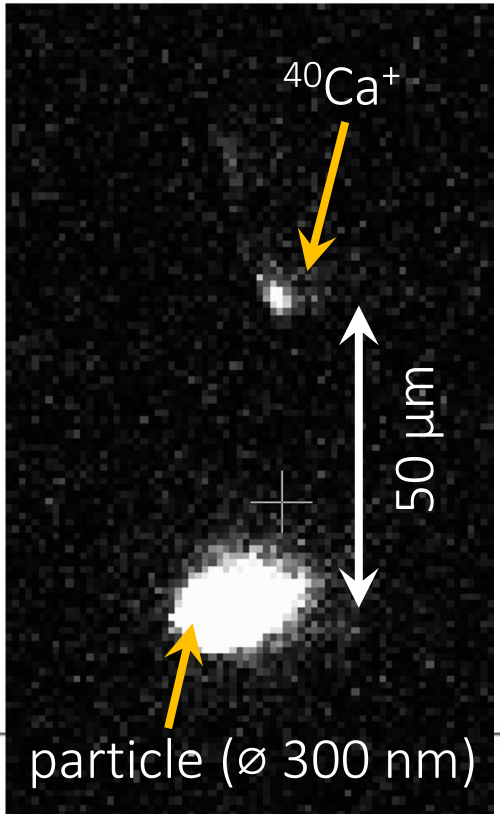
L. Dania, D. S. Bykov, F. Goschin, M. Teller, A. Kassid, T. E. Northup, *Phys. Rev. Lett.* **132**, 133602 (2024)

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 1

Interactions between light and motion have already enabled the preparation of quantum states of macroscopic mechanical oscillators.

1. Quantum optomechanics:
   interactions between light and motion in the quantum regime
2. Why *levitated* optomechanics?
3. What objects should we levitate? And how can we levitate them?
4. Cooling mechanical motion to the quantum ground state
5. Outlook: into the quantum regime

Levitated optomechanical systems offer extreme isolation from the environment at room temperature.

A wide range of objects can be levitated in optical, electrical, and magnetic traps.

Both passive and active optical cooling have been used to bring nanomechanical motion to the quantum ground state.

The motional ground state is the starting point for preparing nonclassical states, which may enable novel sensors & tests of new physics.

- 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