EXPLORING MACROSCOPIC QUANTUM MECHANICS WITH THE LEVITATED OPTOMECHANICS TOOLBOX

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Quantum sensing and fundamental physics with levitated mechanical systems
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Outline

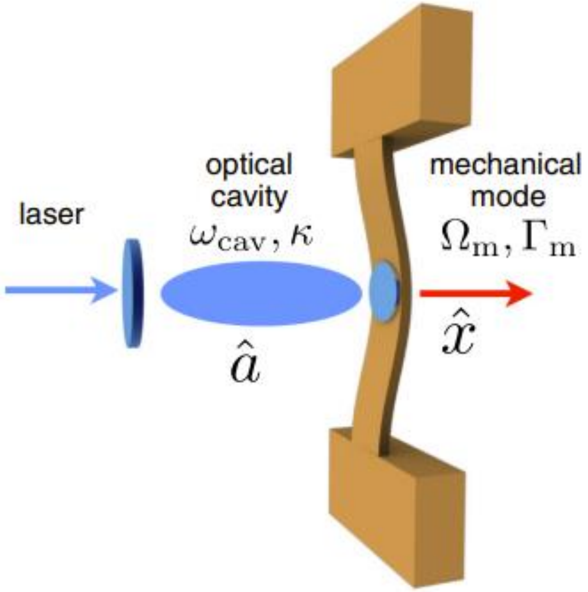
- Levitated optomechanics: the platform of choice
- Overview of group activities
- Levitated optomechanics for macroscopic superpositions
  - *Protocol and experimental implementation*
  - *UHV loading*
  - *The role of internal temperature*
  - *Pulse control and stabilization*
- Outlook and summary

Quantum control of optomechanical systems

Macroscopic **clamped oscillators** have been manipulated into the quantum regime for over a decade[1]

- Can engineer high f_m to achieve "thermal freeze-out" in cryo[2]
- Ground state via resolved-sideband cooling also demonstrated[3,4]
  - *… but challenging at room temperature:*

$$Q_m f_m \gtrsim \frac{k_B T_{bath}}{h} \approx 6 \times 10^{12}$$

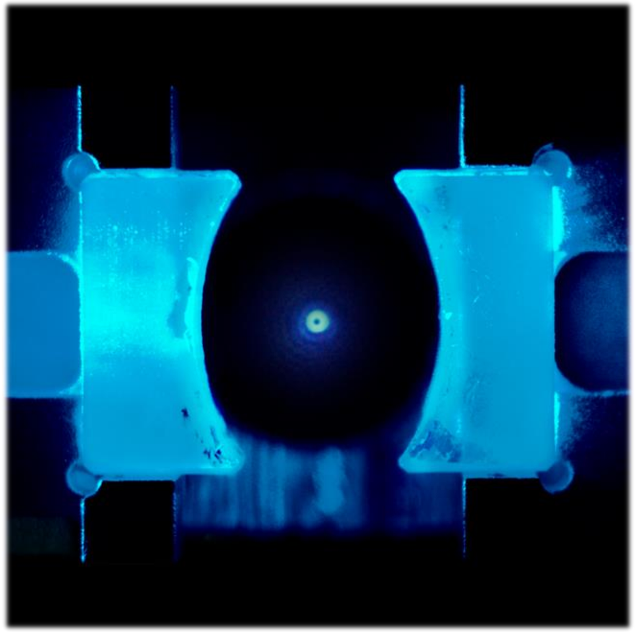


1. Aspelmeyer et al., Rev. Mod. Phys. **86**, 1391 (2014)
2. O'Connell et al., Nature **464**, 697 (2010)
3. Teufel et al., Nature **475**, 359 (2011)
4. Chan et al., Nature **478**, 89 (2011)

Levitated systems

For studying macroscopic quantum mechanics, **levitated systems** area particularly promising[1]

- Freedom from substrate dramatically increases **coherence**
  - *Extremely high quality factors possible*[2]
- Flexible **potential landscapes**
- Flexible **platforms**: optical, electric, magnetic- and combinations thereof

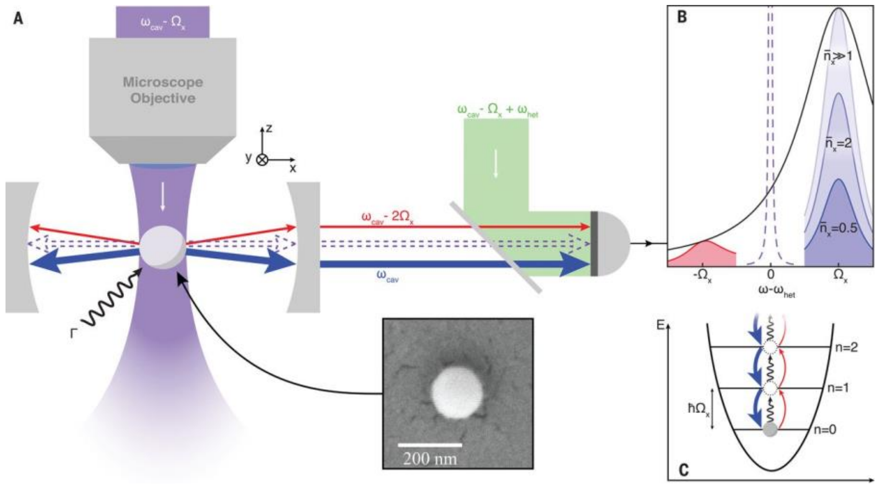


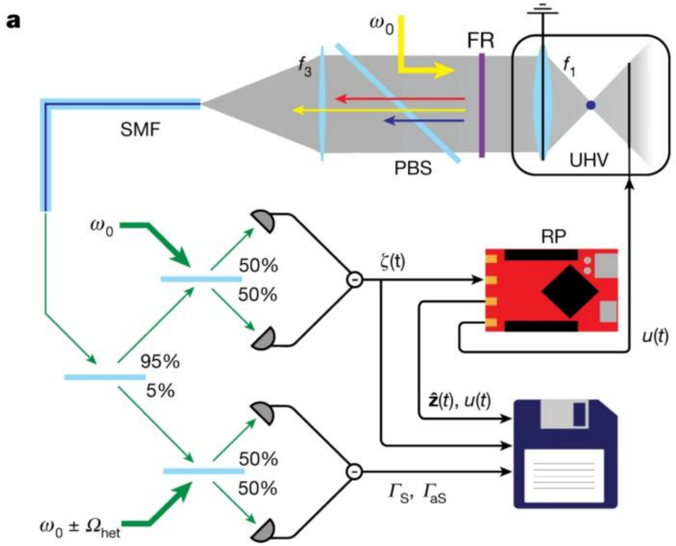
1. Gonzalez-Ballestero et al., Science **374**, 6564 (2021)
2. Dania et al., https://arxiv.org/abs/2304.02408v1 (2023)

Cooling techniques

Generating "interesting" quantum states often requires a pure starting state → **ground-state cooling**

- **Passive:** Resolved-sideband cooling
  - *Red-detuned drive in resolved-sideband regime*
  - *Coherent scattering avoids laser phase noise, co-trapping*





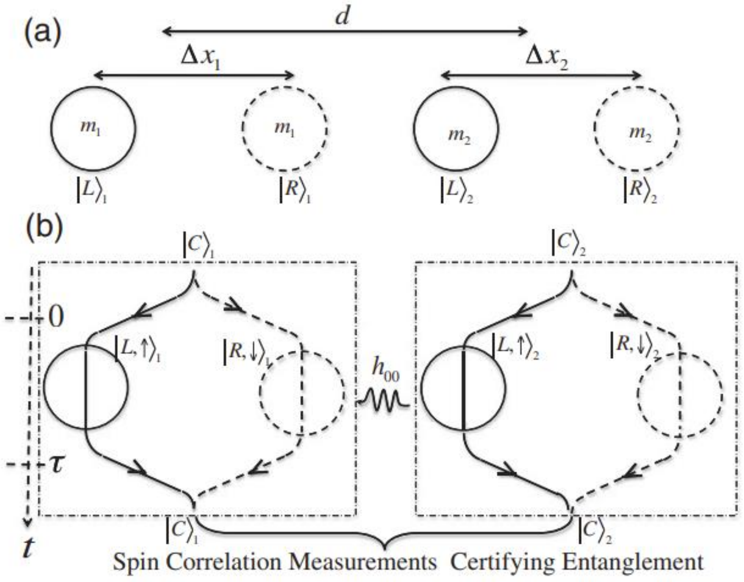
- **Active:** feedback
  - *Measure near Heisenberg limit and provide feedback to particle motion*
  - *Kalman filter for optimal control*
  - *No cavity required*

Gonzalez-Ballestero et al., Science **374**, 6564 (2021)

Fundamental goals

We now have mesoscopic systems in their quantum ground states... what can we do with them?

- **Macroscopic quantum superpositions**
  - *New mass regime to probe linearity of QM*
  - *Robustly rule out modifications (collapse, etc.)*
- **Quantum gravity**
  - *What is the spacetime metric of a superposed object?*
  - *Can masses be entangled by gravity?*



Bose et al., Phys. Rev. Lett. **119**, 240401 (2017)
Mareltto and Vedral, Phys. Rev. Lett. **119**, 240402 (2017)

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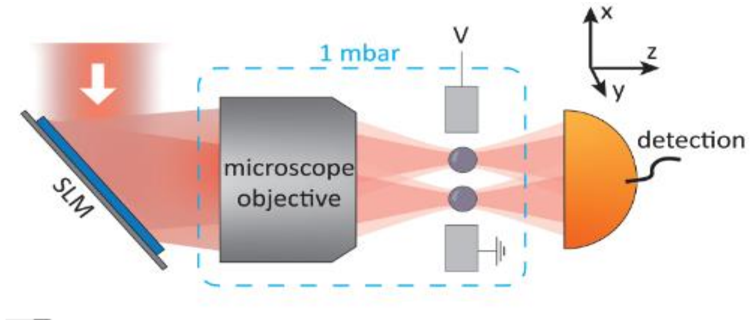
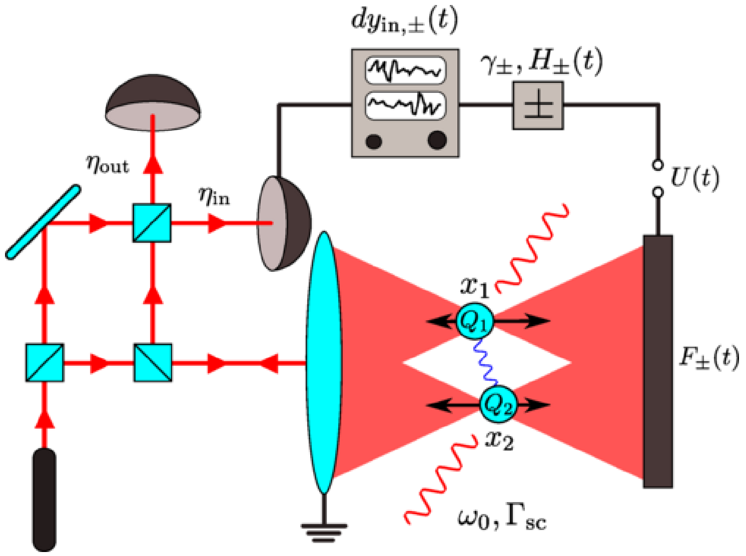
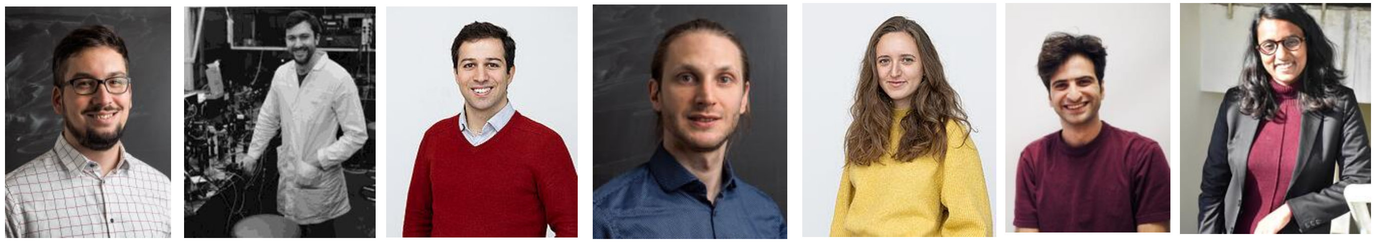
Trap arrays

Goal: explore richer physics beyond single nanoparticles in harmonic traps

- Tunable dipole-dipole coupling[1] and collective states from nonequilibrium dynamics
- Coulomb entanglement between charged nanoparticles[2]





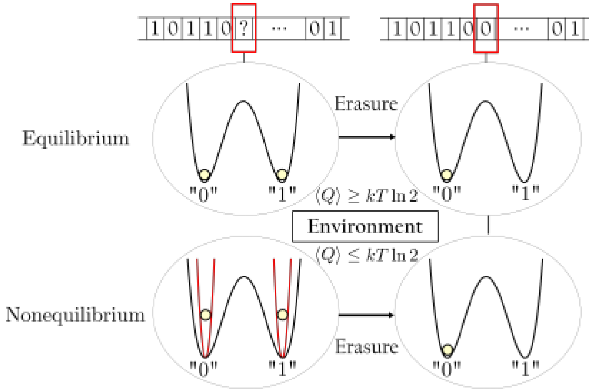


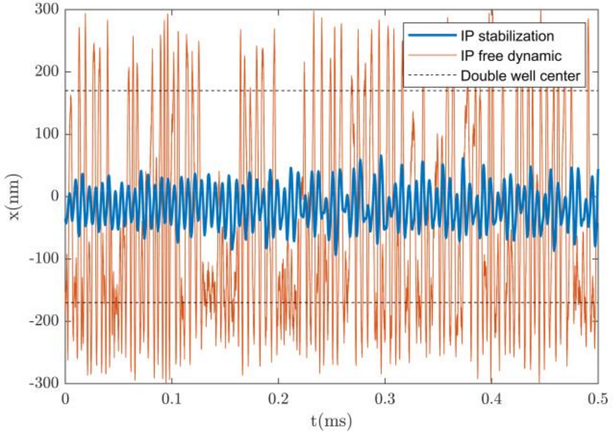
1. Rieser et al., Science **377** (2022)
2. Rudolph et al., Phys. Rev. Lett. **129**, 193602 (2022)

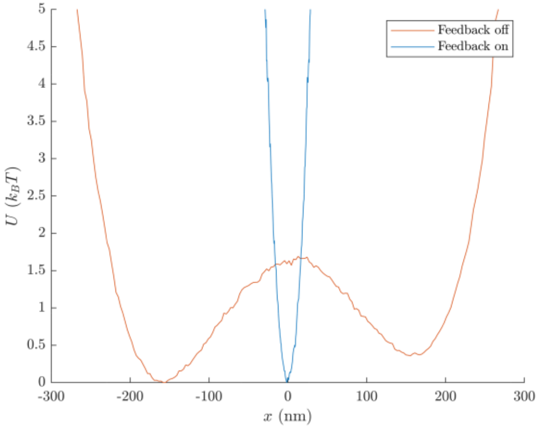
Potential landscape engineering

Goal: Exploit non-quadratic optical potential landscapes in levitated experiments

- **Double well**: out-of-equilibrium thermodynamics
- **Inverted harmonic**: “dark trapping” to avoid internal heating



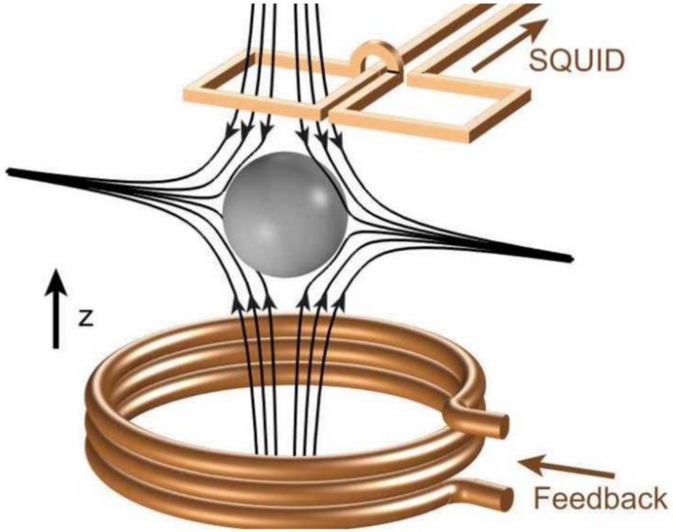




Ciampini et al., arXiv:2107.04429v1 (2021)

Maglev

Goal: develop magnetic levitation of superconductors for quantum experiments

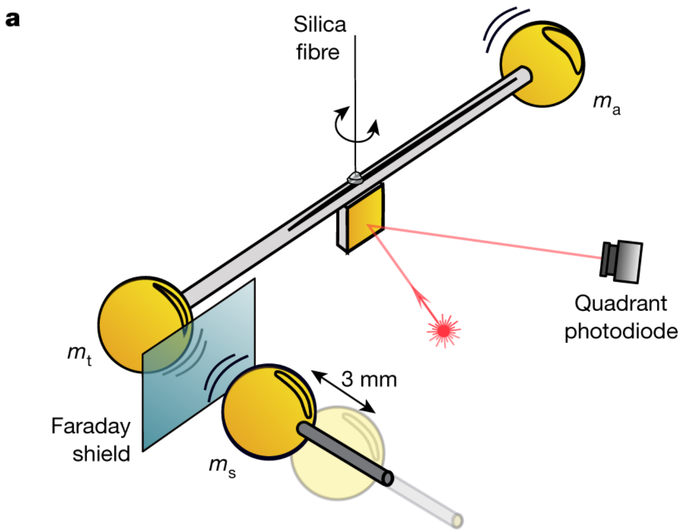


- Larger masses than optical levitation schemes (µg vs fg)
- Cryo environment
- Readout schemes: optical, DC/microwave SQUIDs

Hofer et al., Phys. Rev. Lett. **131**, 043603 (2023)

Classical gravity experiments

Goal: top-down approach to isolate gravitational force at unprecedented scales



- **“Milli-g”:** scaled-down Cavendish experiment
  - *Smallest measured gravitational source mass (92 mg)*
- **“ISLE”:** probe gravity at 10 µm separations
  - *Probe existence of a gravitational extra dimension*

Westphal et al., Nature **591**, 225 (2021)

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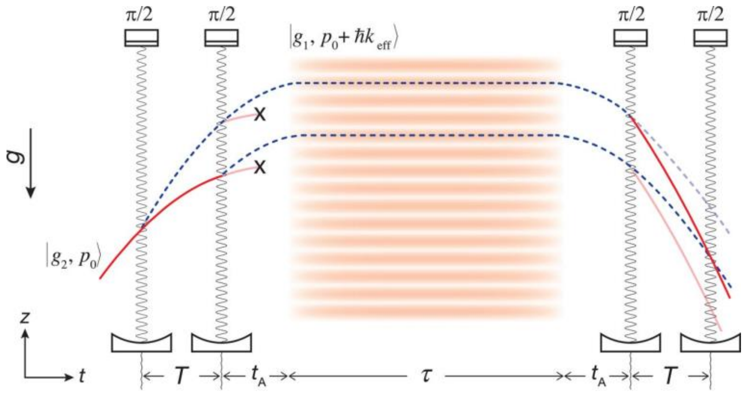
State of the art

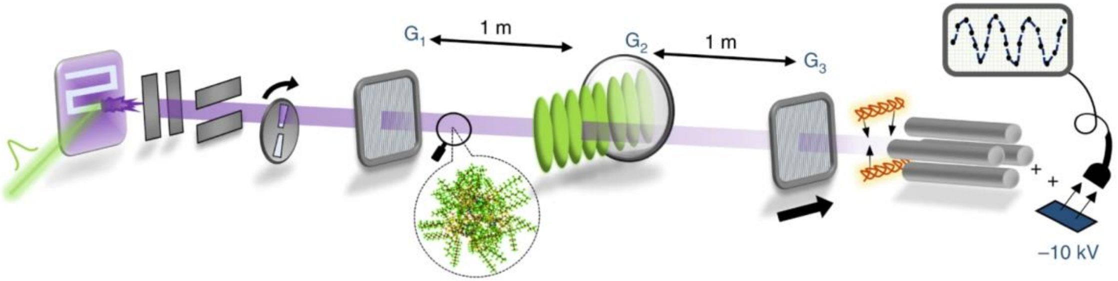
COM:

- **Heaviest:** 25,000 amu, beam of organic molecules in Talbot-Lau configuration[1]
- **Longest hold time:** 70 s, in lattice atom interferometer[2]
- **Largest separation:** 54 cm in 10-m atomic fountain[3]



Non-COM:

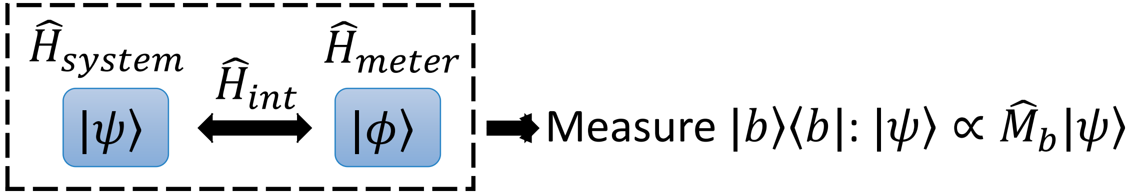
- **Most atoms:** 10^{17} atoms in vibrational state of µg resonator[4]
- **Biggest current:** 2-3 µA of 10^9 Cooper pairs in SQUID[5]



1. Fein et al., Nature Physics **15**, 1242 (2019)
2. Panda et al., https://arxiv.org/abs/2210.07289v2 (2022)
3. Kovachy et al., Nature **528**, 530 (2015)
4. Bild et al., Science **380**, 274 (2023)
5. Friedman et al., Nature **406**, 43 (2000)

Options to create non-Gaussian states

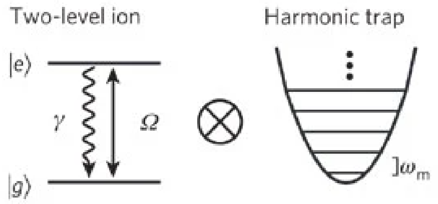
How to do this with 10^9 amu?

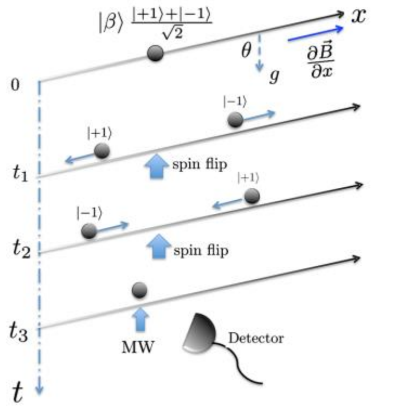


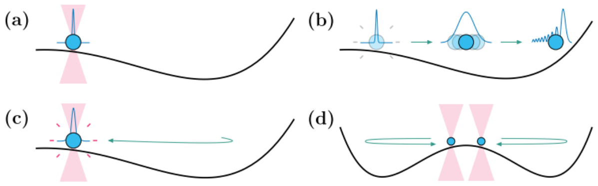
$\hat{H}_{system}$ $\hat{H}_{int}$ $\hat{H}_{meter}$

$|\psi\rangle$ $\longleftrightarrow$ $|\phi\rangle$ $\Rightarrow$ Measure $|b\rangle\langle b|$: $|\psi\rangle \propto \hat{M}_b|\psi\rangle$

- **Nonlinear measurement**
  - $\hat{M}_b = \langle b|U_{int}|\phi\,\rangle$ *nonlinear*
  - *e.g.,* $\hat{x}^2$ *measurement*[1]: $|x\rangle + |-x\rangle$
- **Coupling to auxiliary nonlinear system**
  - *e.g., coupling motional states to a two level system*[2]: $|\psi\rangle\otimes|\mathrm{qubit}\rangle$
  - *Can combine them in the particle (e.g., spin-dependent force*[3]*)*
- **Non-quadratic potential**
  - *Manipulate* $\hat{H}_{system}$
  - *Levitodynamics offers a possible route*[4]







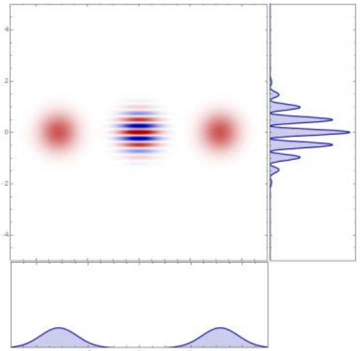
1. Romero-Isart et al., Phys. Rev. Lett. **107**, 020405 (2011)
2. Blatt and Wineland, Nature **453**, 1008 (2008)
3. Wan et al., Phys. Rev. Lett. **117**, 143003 (2016)
4. Roda-Llordes et al., arXiv:2303.07959v1 (2023)

Macroscopic superpositions

The goal: prepare COM non-Gaussian state of a macroscopic object via non-quadratic potential

The requirements:

1. Pure starting state
2. Non-quadratic potential
3. σ_x large enough to “see” the potential (1 and 3 → ξ)
4. $\sigma_p < \Delta p_{\text{fringes}}$



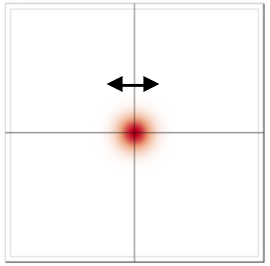
$W(x,p) < 0$

⬇

non-Gaussian

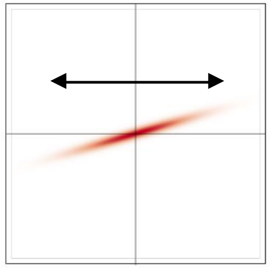
Image: Emilio Pisanty, CC BY-SA 4.0

$\sigma_x = x_{zp} = \sqrt{\hbar/2\boldsymbol{m}\Omega_m}$



… τ …

$\sigma_x = x_{zp}\sqrt{1 + \Omega_m^2\tau^2}$

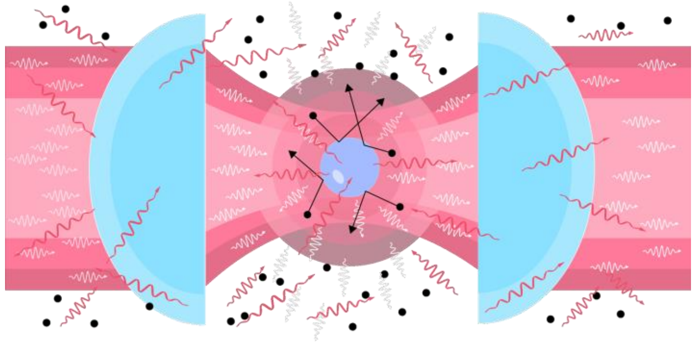


The challenge: time

- Free expansion takes time
- Mapping fringes from p to x takes time
- **Decoherence** gives a time budget

Decoherence mechanisms

Levitated nanoparticles in vacuum are perfectly isolated, right…?



- **Gas collisions**
  - *Source: single gas collision “localizes” particle*
  - *Solution: UHV*
- **Photon recoil**
  - *Source: photons scattering from nanoparticle provide COM information*
  - *Solution: limit light, increase λ (rate $\propto \lambda^{-3}$)*
- **Blackbody radiation**
  - *Source: Blackbody photons from environment **and** from the particle itself*
  - *Solution: avoid internal heating*

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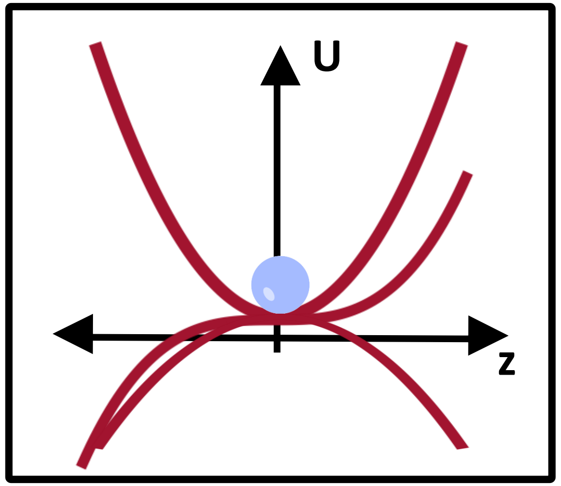
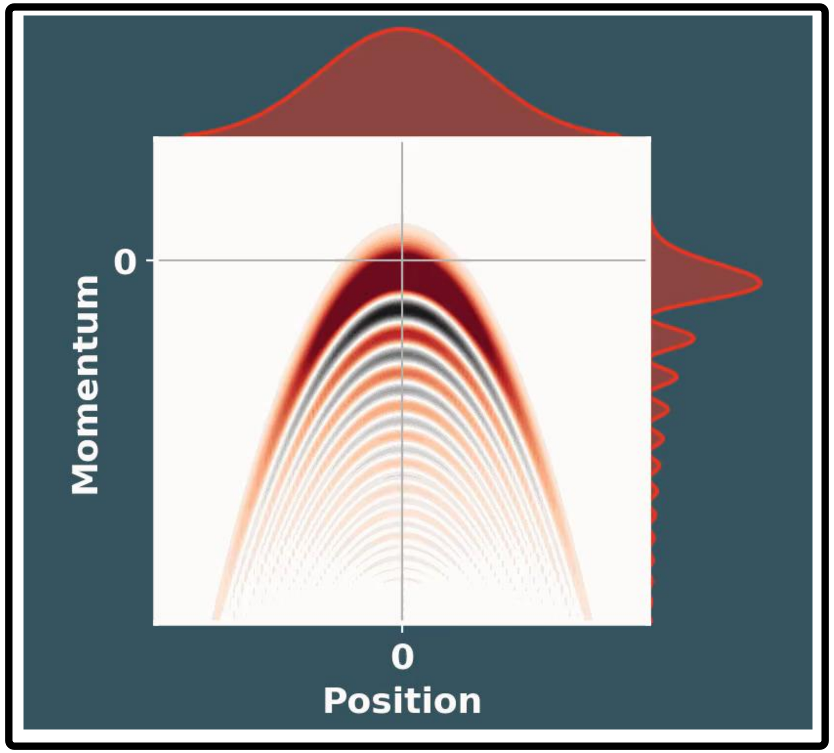
The protocol[1]

Step [illegible] potential

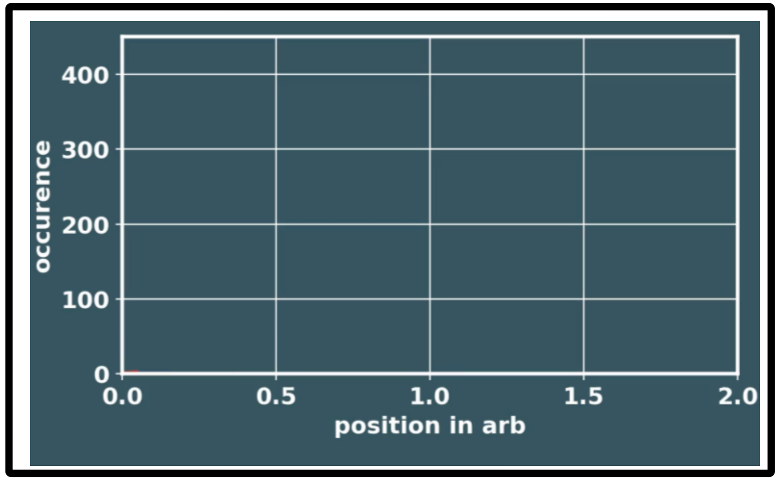
Potential:



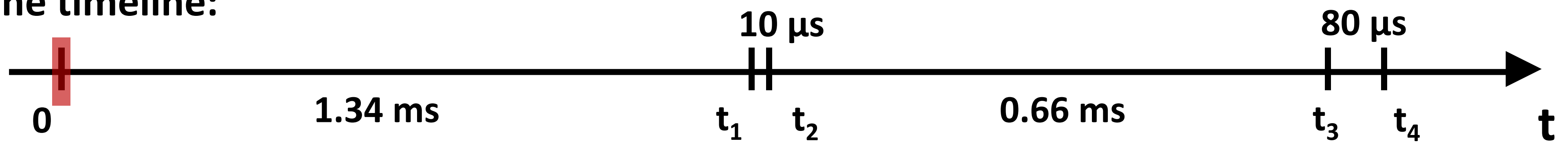
Wigner function:



Measurement:

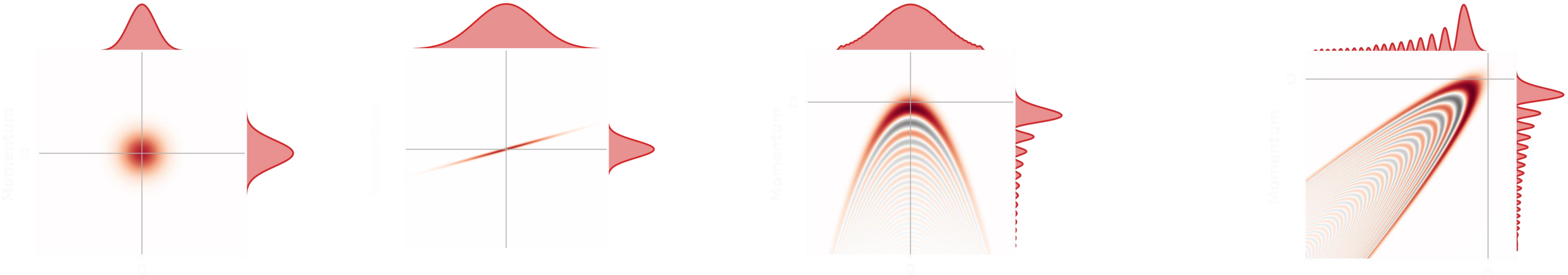


The timeline:



Neumeier et al., arXiv:2207.12539v1 (2022)

Requirements



Harmonic (2 ms)	**Free evolution** (1.34 ms)	**Cubic** (10 µs)	**Free evolution** (0.66 ms)	**Inv. harmonic** (87 µs)

Ground-state cooling

Gravity comp. during free evolutions

Three potential landscapes

1. Harmonic
2. Cubic
3. Inverted harmonic

(4. Free evolutions: *really* no light!)

Repeatability and stability

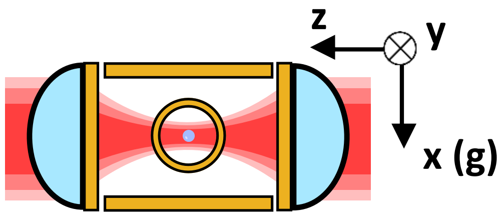
a) Sequence timing
b) Intensity of pulses

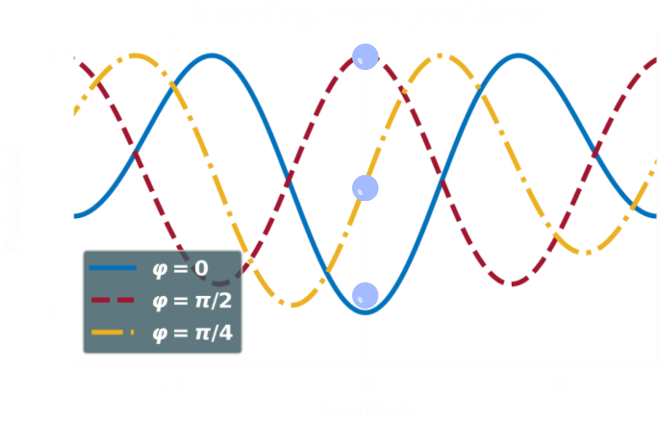
Coherence for $\sim$ 2ms

Potential landscapes

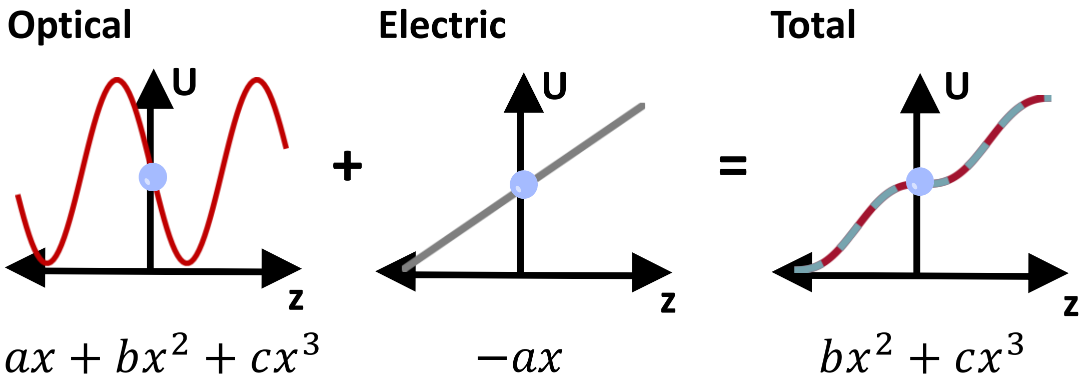
3 pulsed potentials: Harmonic, cubic, inverted harmonic

- Implement as **phases of an optical standing wave**
- Combine with **3d electrodes** for full control

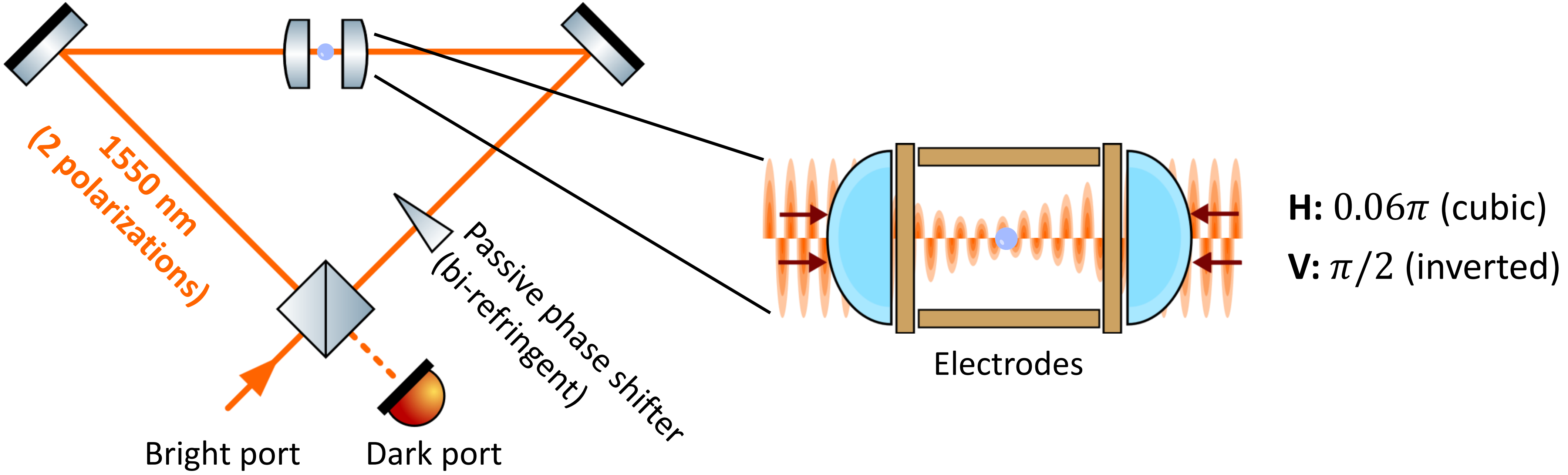




1. ***Linear compensation** of cubic pulse (z)*
2. ***Linear feedback cooling** (x, y, z)*
    - Axially: $\bar{n} \approx 0.5$
    - Radially: $\bar{n} \approx 100$
3. ***Gravity compensation** (x)*



Sagnac configuration



- Phase noise suppression, high SNR dark-port detection
- Low trapping power: good for internal heating
- Potential control

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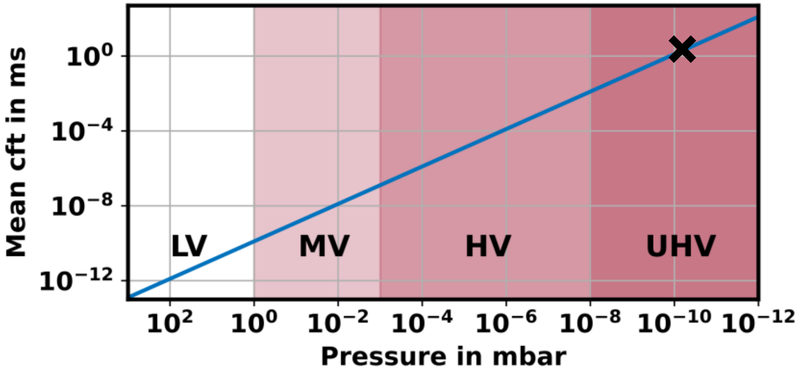
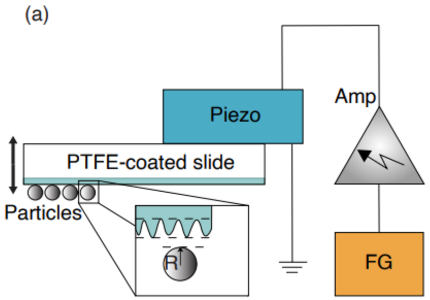
The UHV challenge

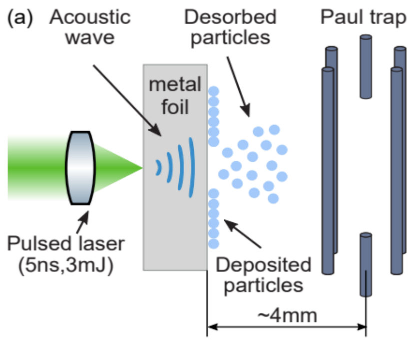
Avoid gas collisions to stay coherent: ms protocols require $\mathrm{p} \leq 10^{-10}$ mbar (no collisions for 90% of runs)

→ Avoid direct nebulizing



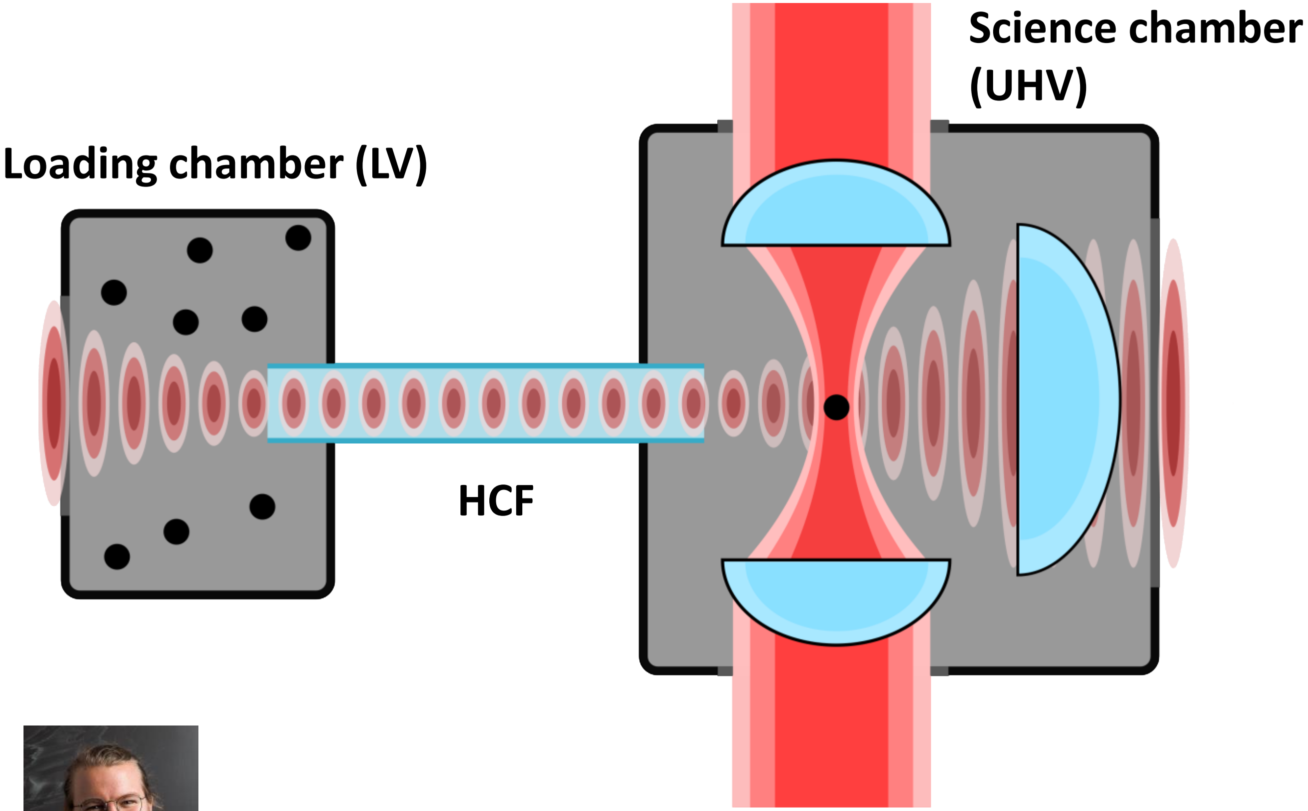
- **Load-lock**
  - *Load into bad vacuum and transfer to UHV*[1]
  - ***Pros:*** *can use established loading methods*
  - ***Cons:*** *moving parts, complexity, slow*
- **Dry loading**
  - *Piezo shaking*[2]*, LIAD*[3]
  - ***Pros:*** *clean, can be direct*
  - ***Cons:*** *inefficient, high launch speeds, not universal*

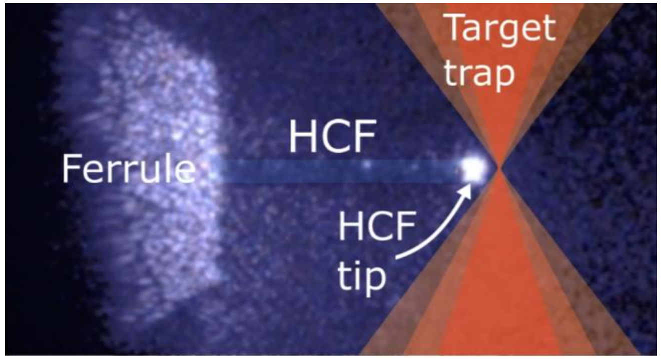


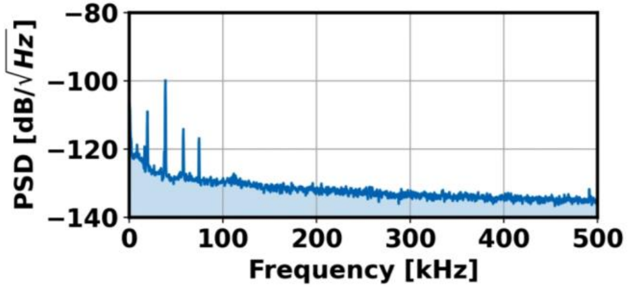


1. Mestres et al., App. Phys. Lett. **107**, 151102 (2015); Calamai et al., AIP Advances **11**, 025246 (2021)
2. Weisman et al., Rev. Sci. Instrum. **93**, 115115 (2022); Khodaee et al., AIP Advances **12**, 125023 (2022)
3. Kuhn et al., Nano Lett. **15**, 5604 (2015); Bykov et al., APL **115**, 034101 (2019)

Hollow-core fiber loading



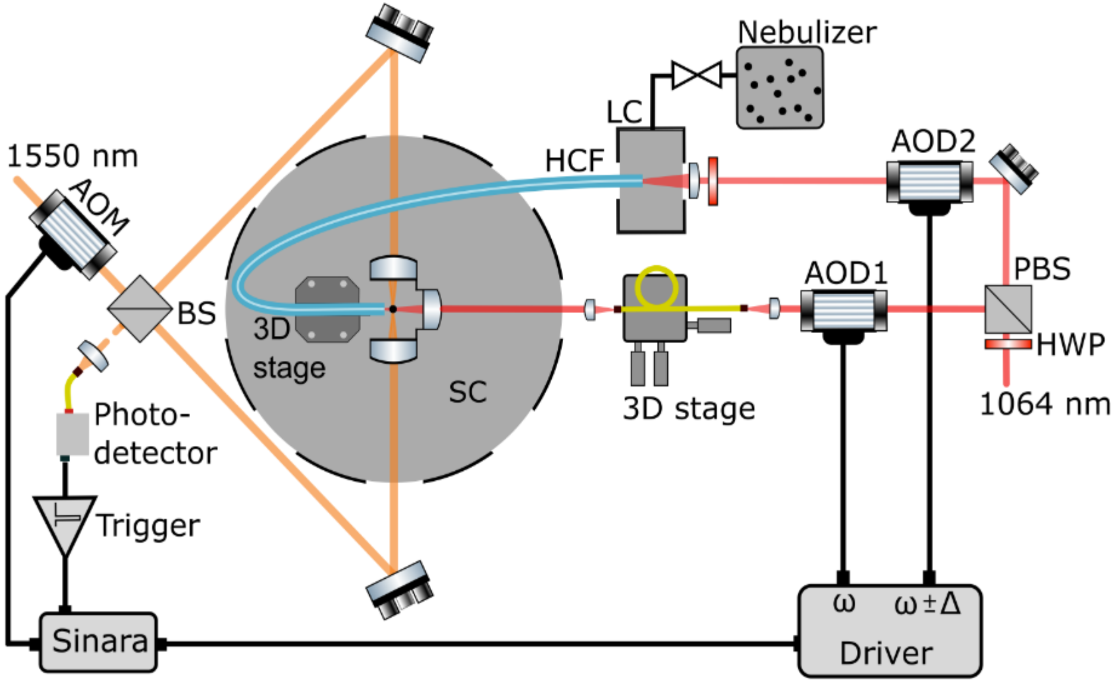




Stefan Lindner

Grass et al., App. Phys. Lett. **108**, 221103 (2016)
Lindner et al., in preparation

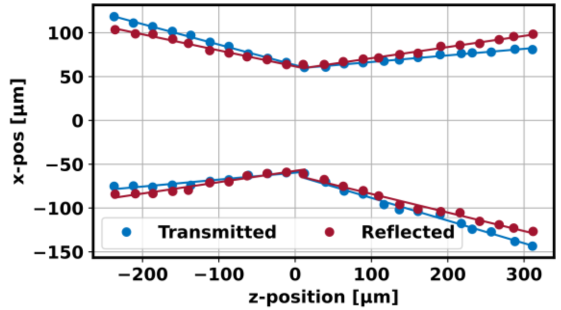
Experimental integration



Lowest-pressure handover to date: $\mathbf{8 \times 10^{-10}}$ **mbar**

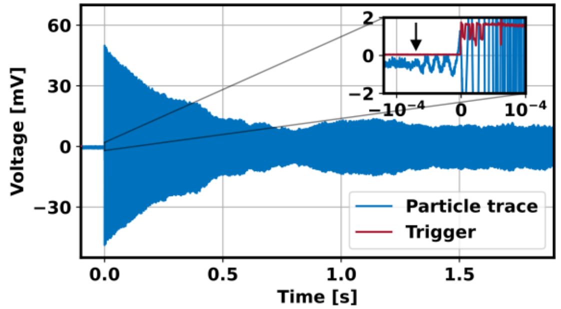
Trap alignment

- Grazing measurements with HCF



In UHV: Triggering

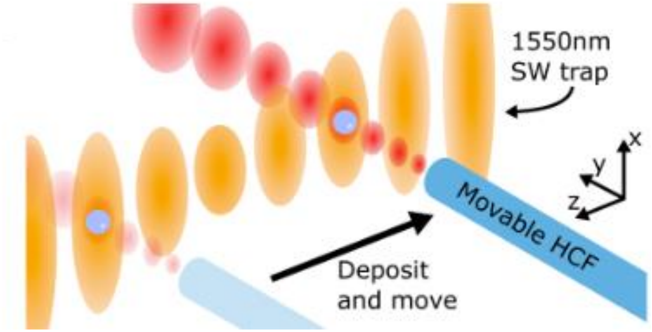
- Gradient force conservative, pulse Sagnac

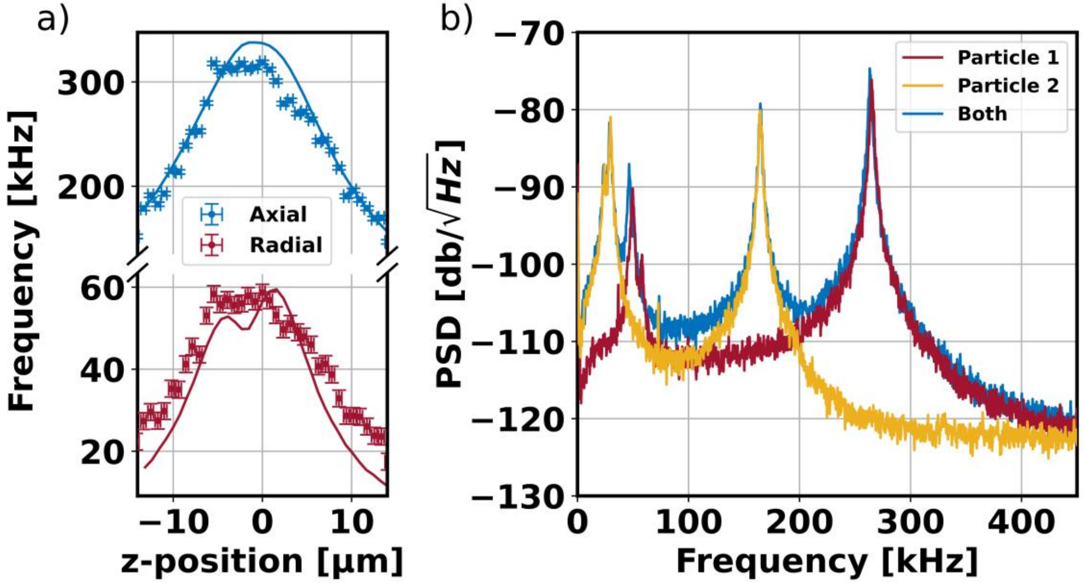


Spatial resolution

The HCF loading technique also enables deterministic loading with **high spatial resolution:**

- Can load specific particles into desired trap sites
- µm-level resolution





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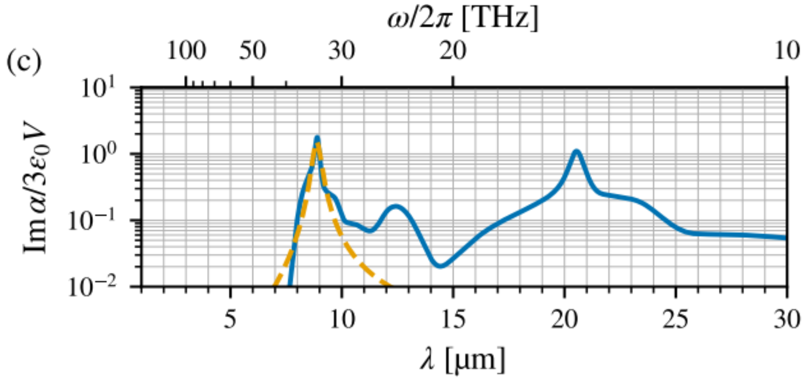
Blackbody decoherence

After gas collisions, photon recoil and **blackbody** remain dominant decoherence mechanisms

- Blackbody contributions:
  - *300 K* ***environment***
  - ***Nanoparticle*** *itself, which can be far hotter*
- Blackbody rates difficult to model due to unknown material properties[1]

$$\text{Rate} \propto \int_0^\infty d\lambda \frac{\mathrm{Im}[\alpha(\lambda)]}{\lambda^7\left[\exp\left(\frac{hc}{\lambda k_\mathrm{B} T_\mathrm{int}}\right)-1\right]}$$

  - $\mathrm{Im}[\alpha(\lambda)]$ *at relevant* λ
  - T_int *of nanoparticle*



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1. Agrenius et al., Phys. Rev. Lett. **130**, 093601 (2023)

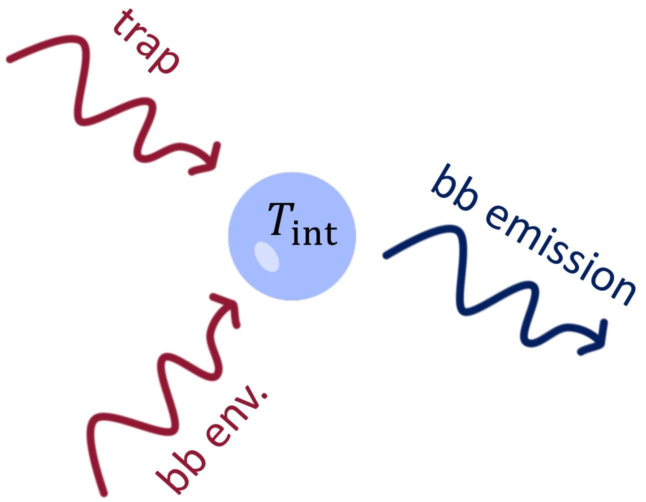
Estimating T_{int}

T_{int} determined via heat balance:

$$\frac{dT_{\mathrm{int}}}{dt} \propto P_{\mathrm{trap}}^{\mathrm{abs}} + P_{\mathrm{bb}}^{\mathrm{abs}}(T_{\mathrm{env}}) - P_{\mathrm{bb}}^{\mathrm{em}}(T_{\mathrm{int}}) - P_{\mathrm{gas}}$$

$$\swarrow \qquad\qquad \searrow \qquad\qquad \searrow$$

$$f\left(\mathrm{Im}\left[n\left(\lambda_{trap}\right)\right]\right) \qquad f(\mathrm{Im}[n(\lambda)]) \qquad f(\mathrm{Im}[n(\lambda)])$$

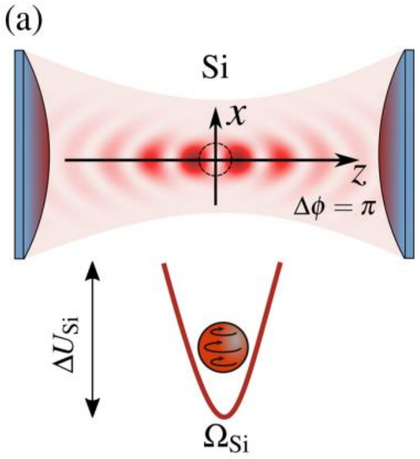


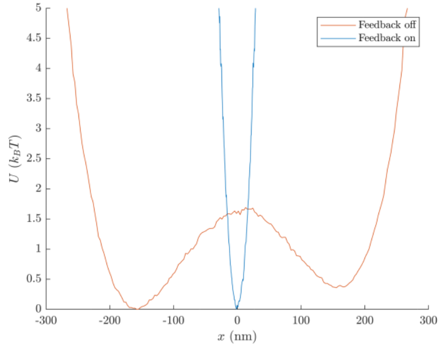
- Need $\mathrm{Im}\left[n\left(\lambda_{trap}\right)\right]$ *and* the spectrum $\mathrm{Im}[n(\lambda)]$[1] , but literature values vary
  - *Likely to depend strongly on surface termination, impurities*
- Can be extracted via reheating measurements[2]

1. Agrenius et al., Phys. Rev. Lett. **130**, 093601 (2023)
2. Hebestreit et al., Phys. Rev. A **97**, 043803 (2018)

Strategies to mitigate BB

- Keep experiments short
- Reduce T_{int}
    - *Standing wave trap (e.g., Sagnac configuration)*
    - *Dark trapping*[1,2]
- Choose low-emissivity particle like silicon[2,3]
    - *T_{int} may be higher, but bb emission reduced*
- Go to cryo environment



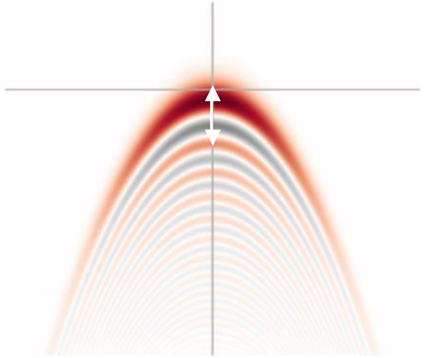


1. Almeida et al., arXiv:2302.01953v1 (2023)
2. Bateman et al., Nature Commun. **5**, 4788 (2014)
3. Lepeshov et al., Phys. Rev. Lett. **130**, 233601 (2023)

Outline

- Levitated optomechanics: the platform of choice
- Overview of group activities
- Levitated optomechanics for macroscopic superpositions
    - *Protocol and experimental implementation*
    - *UHV loading*
    - *The role of internal temperature*
    - ***Pulse control and stabilization***
- Outlook and summary

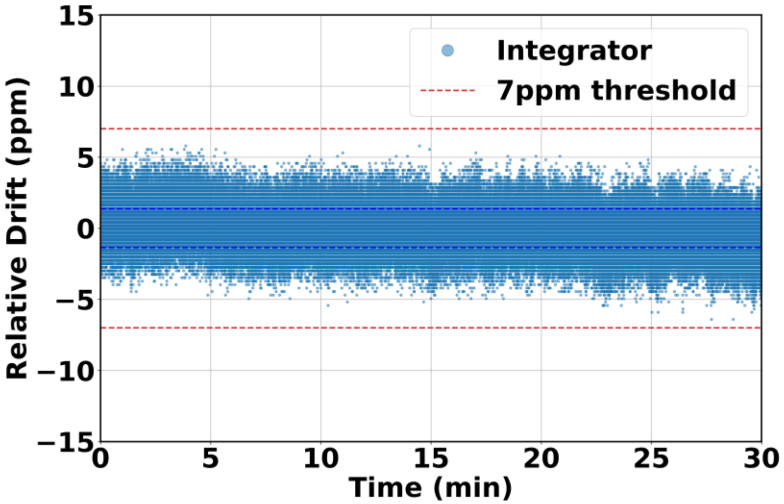
Pulse requirements



- Momentum variations in cubic pulse should be less than the $\Delta p_{\text{fringes}}$:

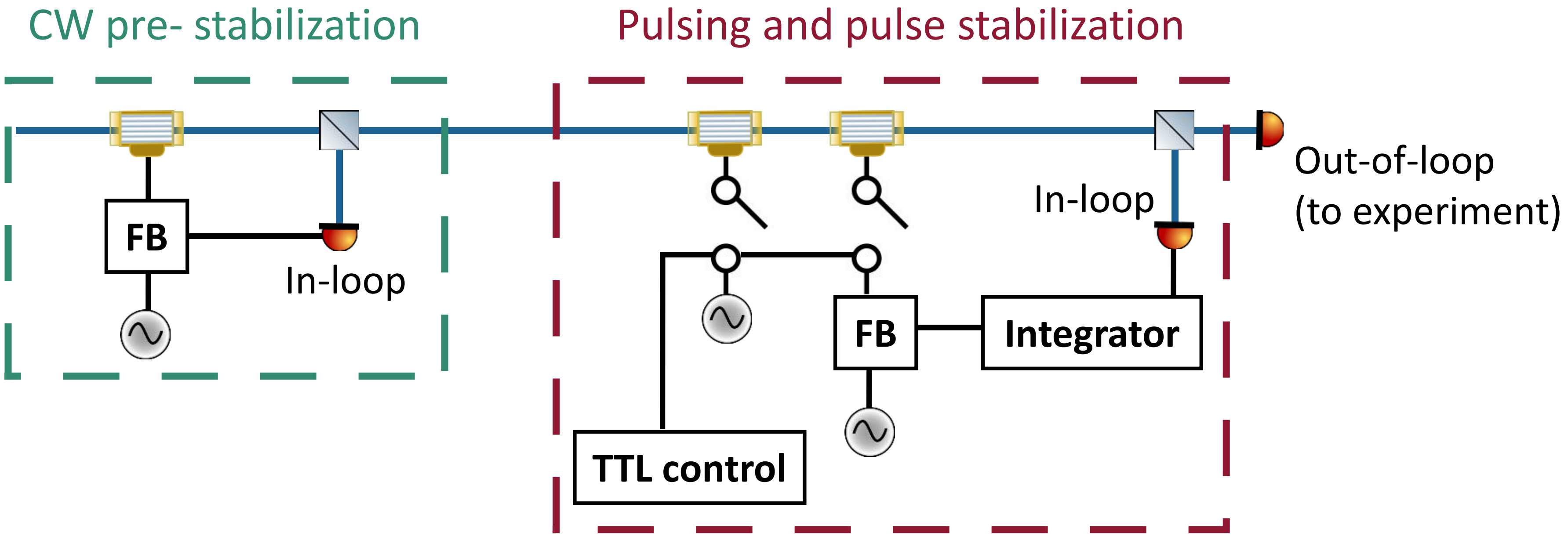
$$\boldsymbol{\Delta A/A < 7 \times 10^{-6}}$$

- Also: High extinction ratio (up to 100 dB), precise timing, phase stability, etc.



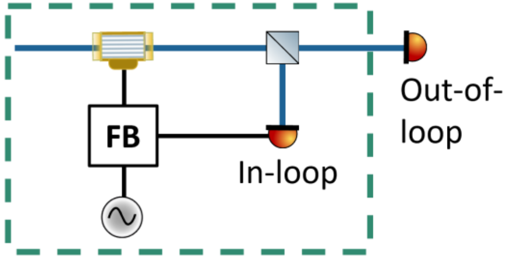
- Must **measure** pulse area with high precision
  - *Analog circuit to **integrate** pulses and **hold** the value*
  - *24 bit ADC to read out*
  - *Noise floor < 10 µV RMS (including detection noise)*

Stabilized optical pulsing



Gregor Meier

Continuous pre-stabilization

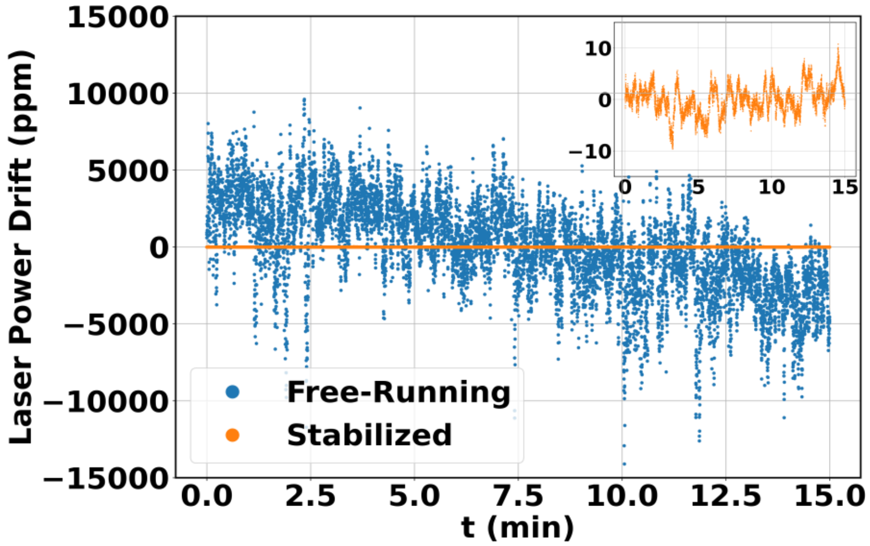


Feedback for CW stabilization

- Analog PID stabilizes to ultra-stable voltage reference[1]
- Temperature drift = polarization drift = power drift
  - *Actively stabilized to < 10 mK*

Performance characterization

- Out-of-loop measurement
- $\Delta P/P < 7 \times 10^{-6}$ up to 1 hour
- Precursor for pulsing, sufficient for GS cooling[2]



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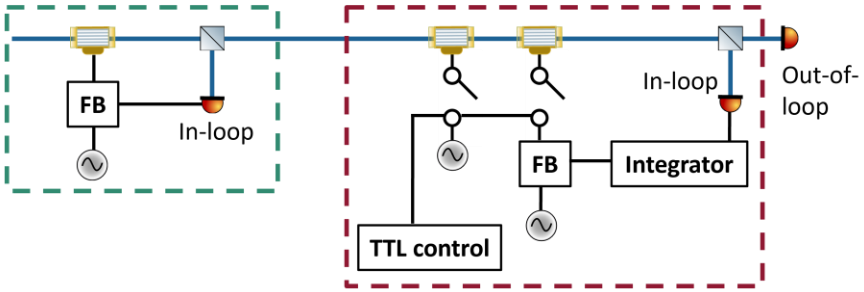
1. Tricot et al., Rev. Sci. Instrum. **89**, 113112 (2018)
2. Kamba et al., Opt. Express **30**, 26716 (2022)

Pulse stabilization

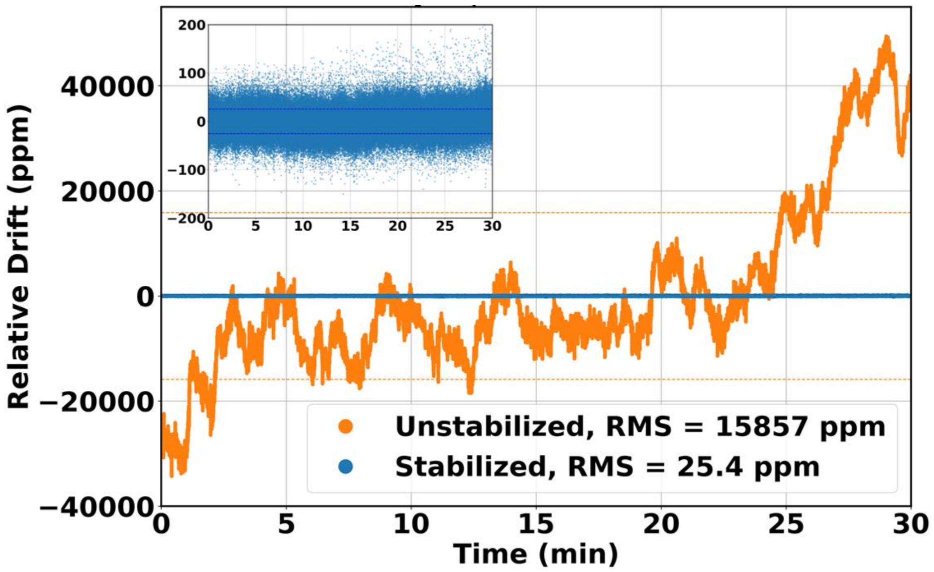


Control and feedback for pulsing

- FPGA for sub-ns timing
- Analog PID on integrator signal

Preliminary results

- In-loop measurement with pre-stabilization
- 10 µs pulses, 200 Hz stabilized to **25 ppm** rms



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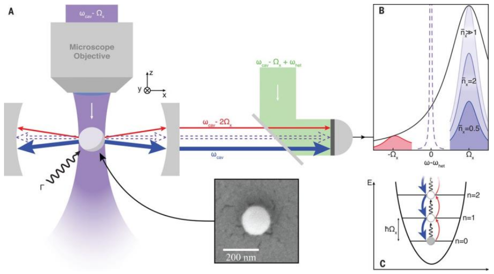
Outlook

Immediate goals:

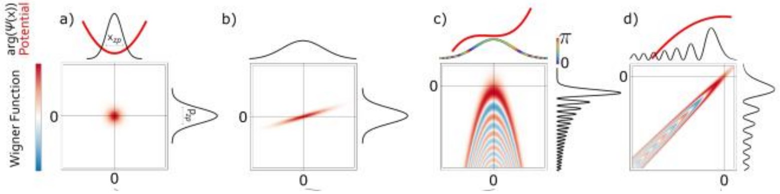
- Pulse stabilization below 7 ppm
  - *Almost there in test setup, currently being implemented in Sagnac*
- Gravity compensation- and confirm coherence
  - *Single-tweezer setup for testing*
- Ground-state cooling of 100 nm particles in Sagnac configuration
  - *Ongoing work*

Summary

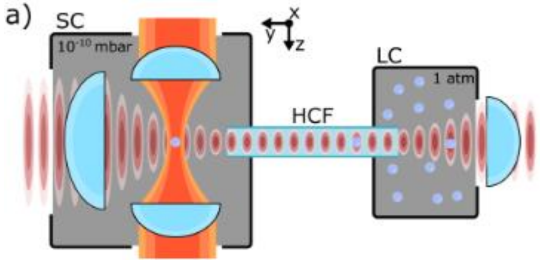
Levitodynamics is a near-ideal platform for macroscopic quantum mechanics



COM interference of nanoparticles is challenging but within reach



Eliminating the role of **decoherence** is key: fast and UHV



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Theory: Lukas Neumeier, Oriol Romero-Isart

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VCQ
Vienna Center for Quantum Science and Technology

Q-XTREME
Macroscopic Quantum Superpositions

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THANK YOU!

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