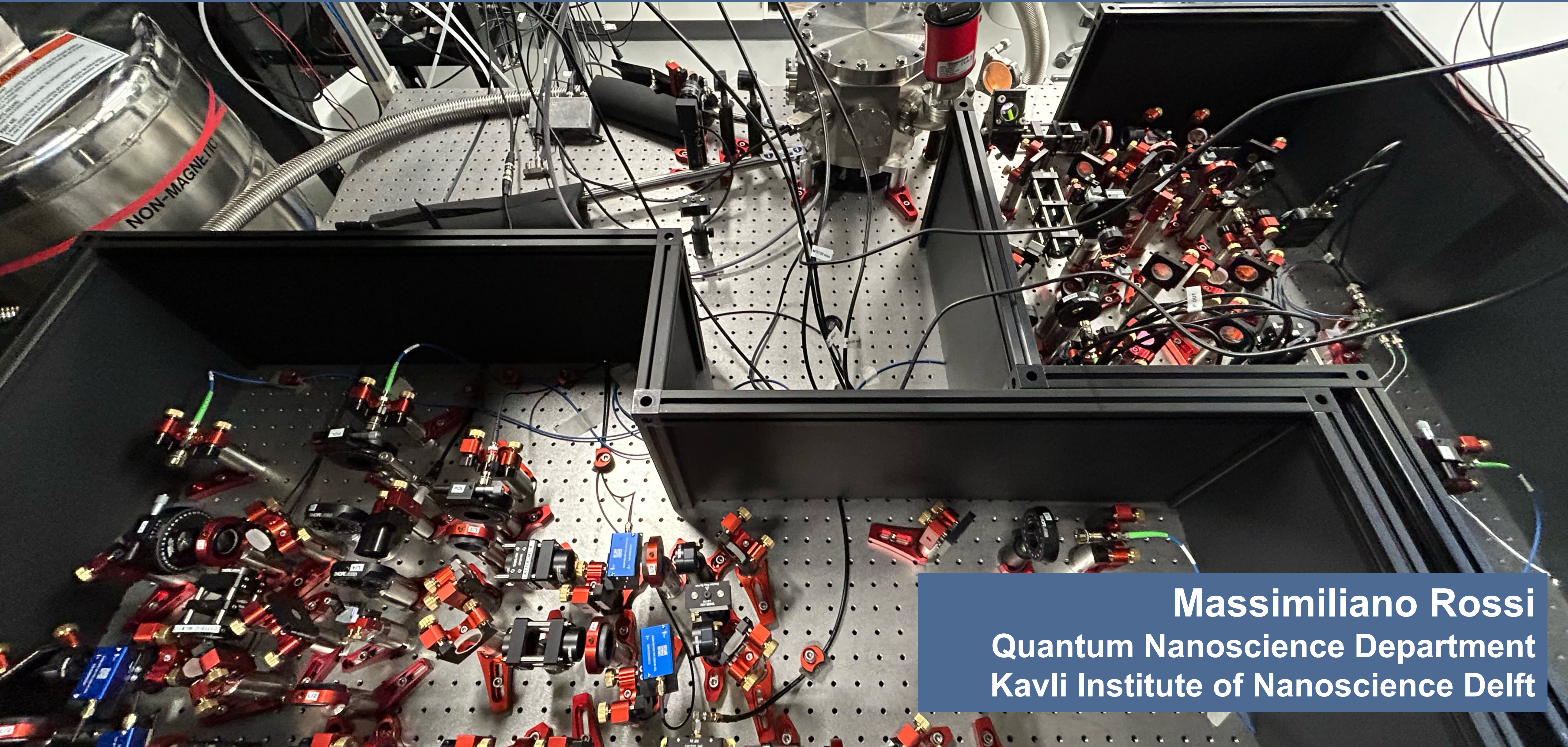
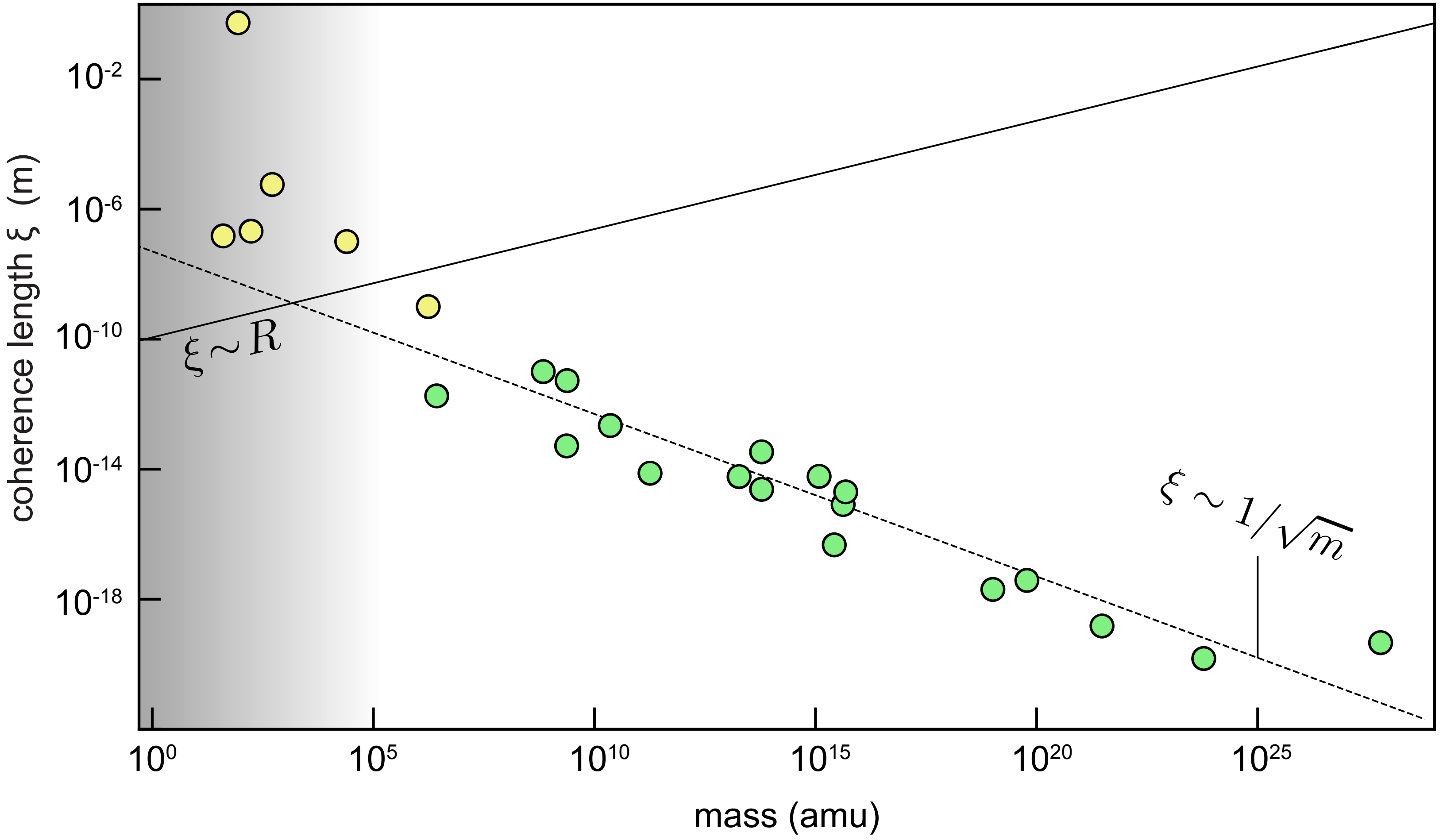
A quantum-limited levitated sensor

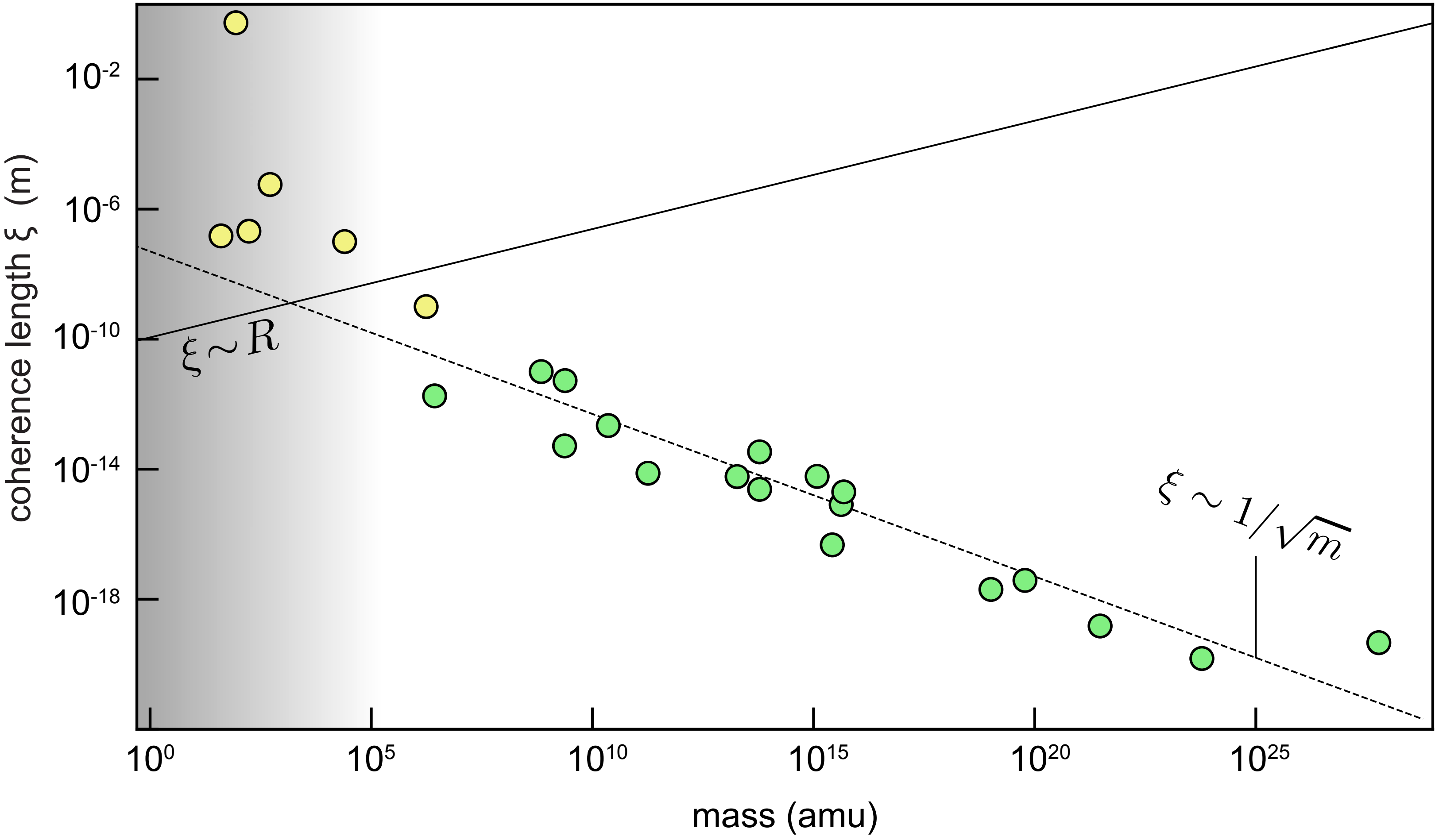


Massimiliano Rossi
Quantum Nanoscience Department
Kavli Institute of Nanoscience Delft

Macroscopic quantum physics

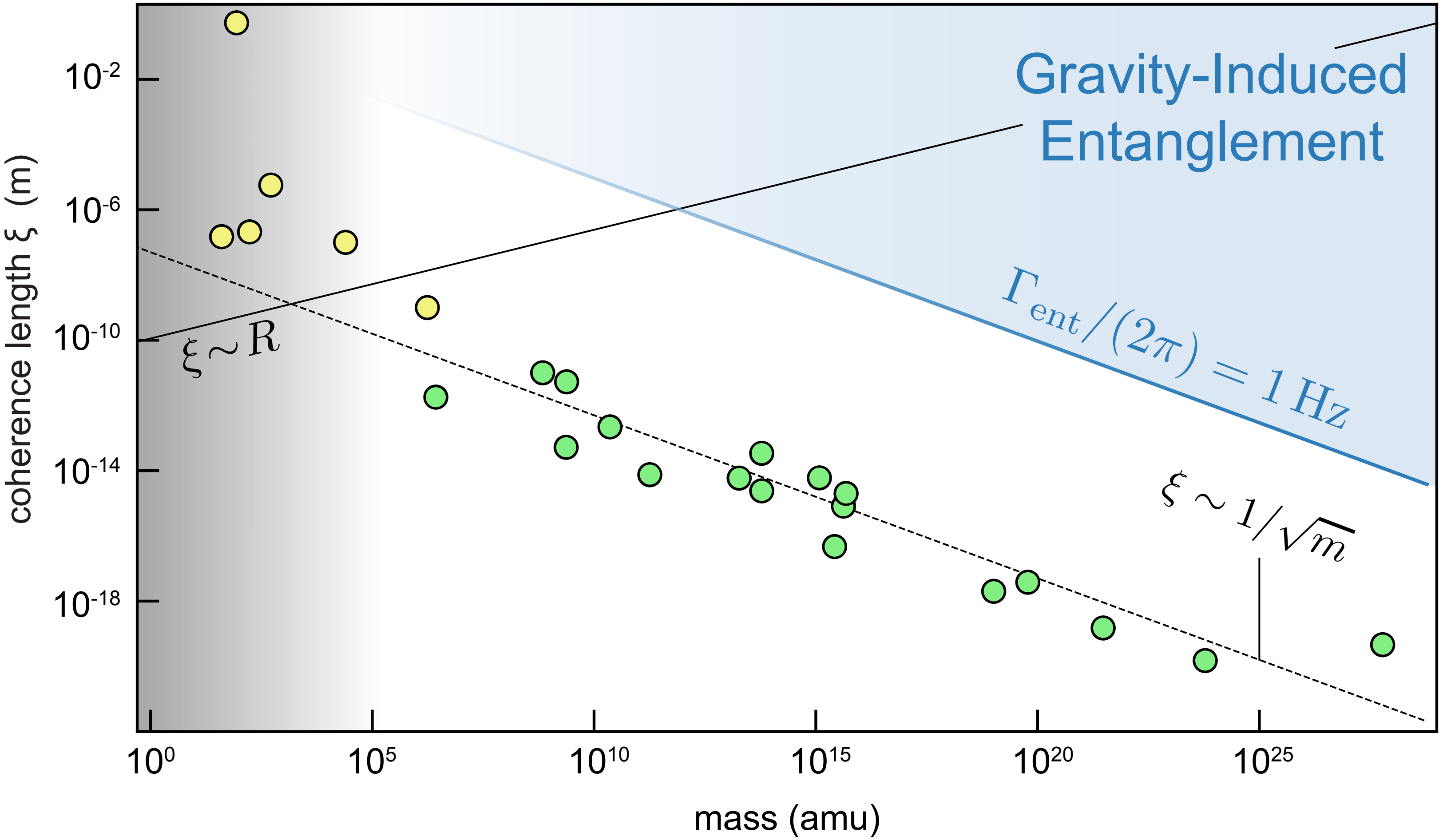


Macroscopic quantum physics



quantum-to-classical transition

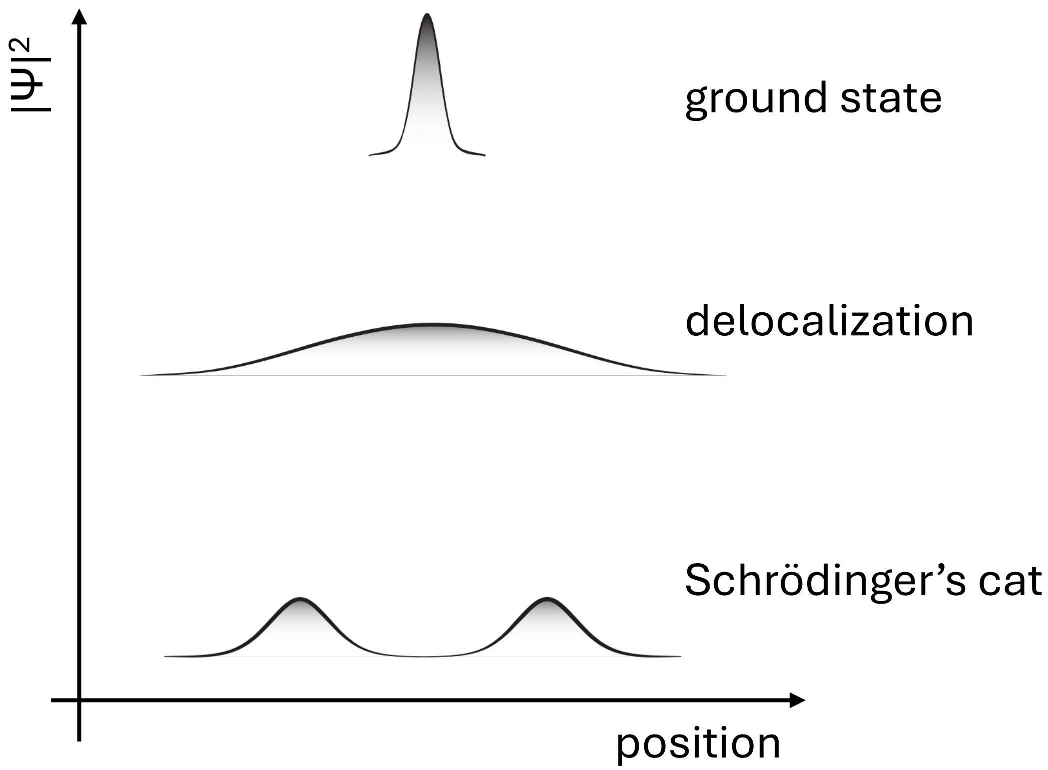
Macroscopic quantum physics



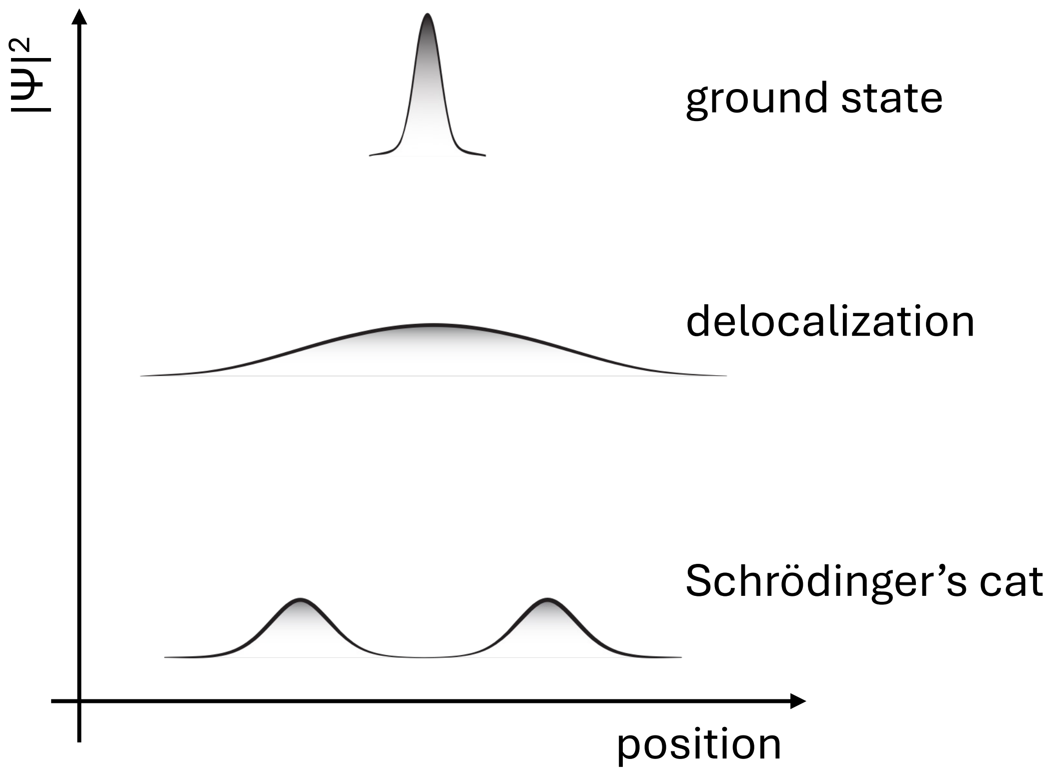
quantum-to-classical transition

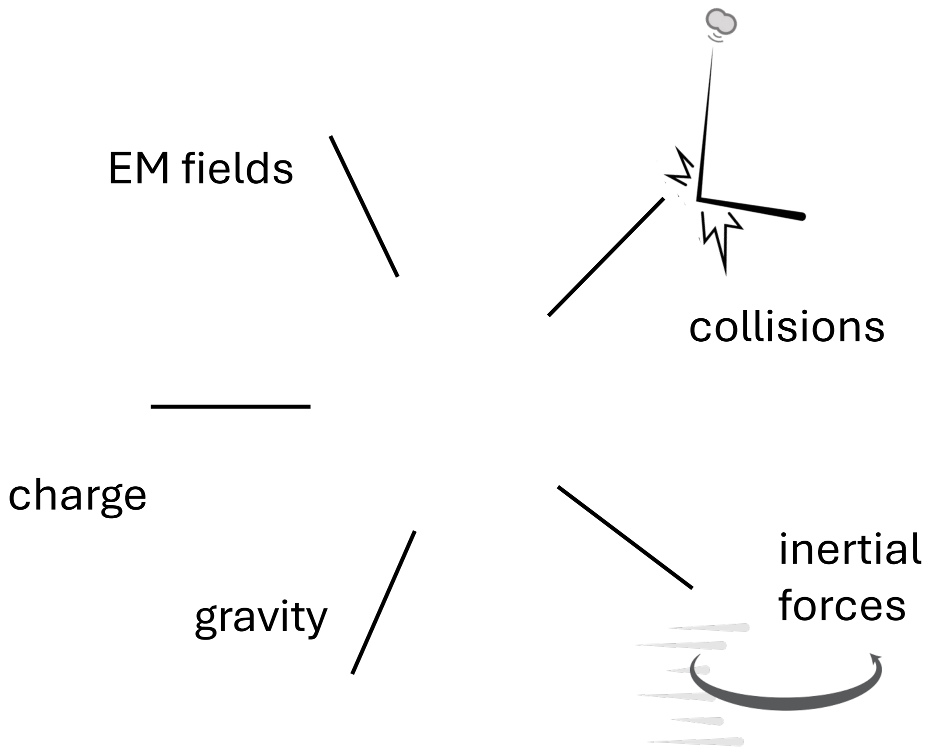
quantum nature of gravity

Quantum physics and sensing

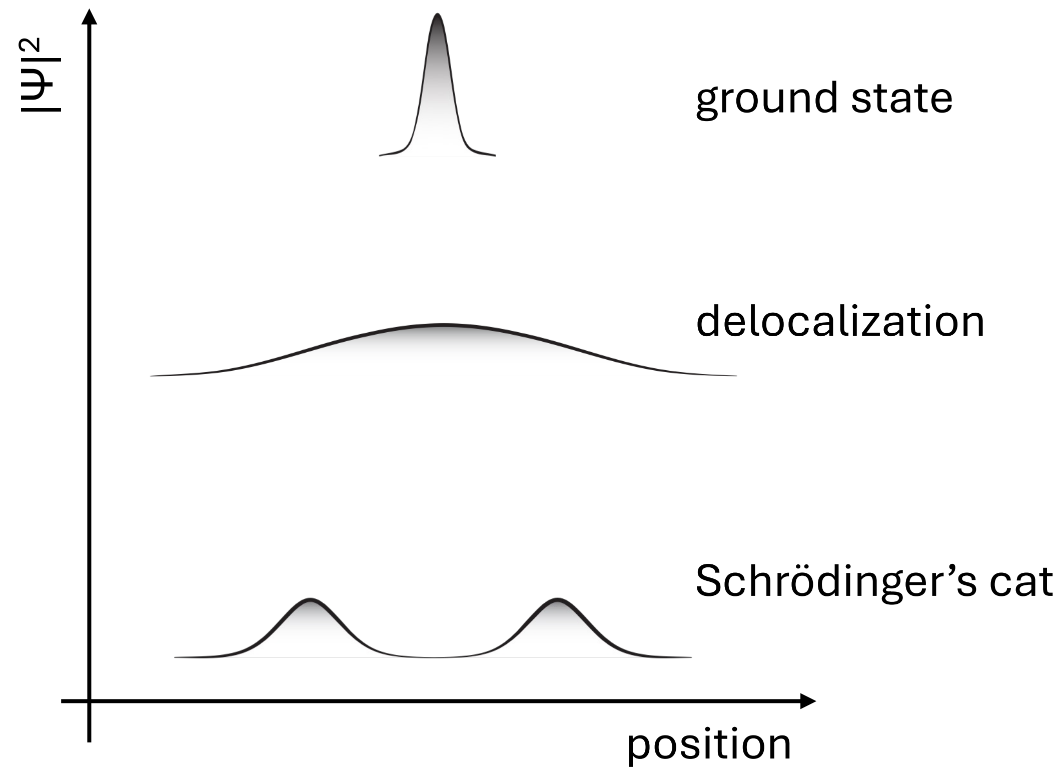


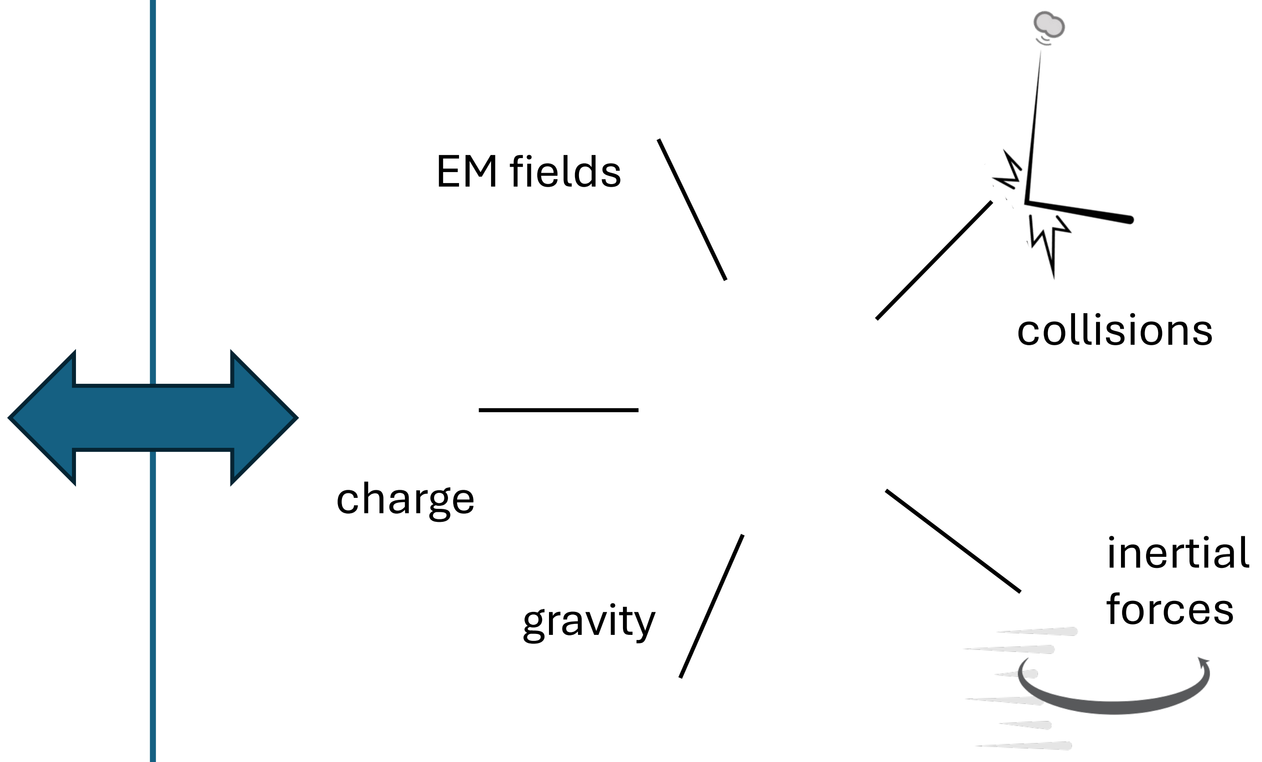
Quantum physics and sensing



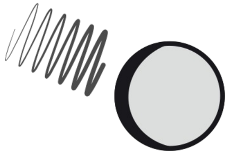


Quantum physics and sensing

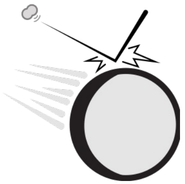




Outline



continuous force sensor



recoil sensing

outlook

Acknowledgements

A. Militaru

N. Carlon Zambon

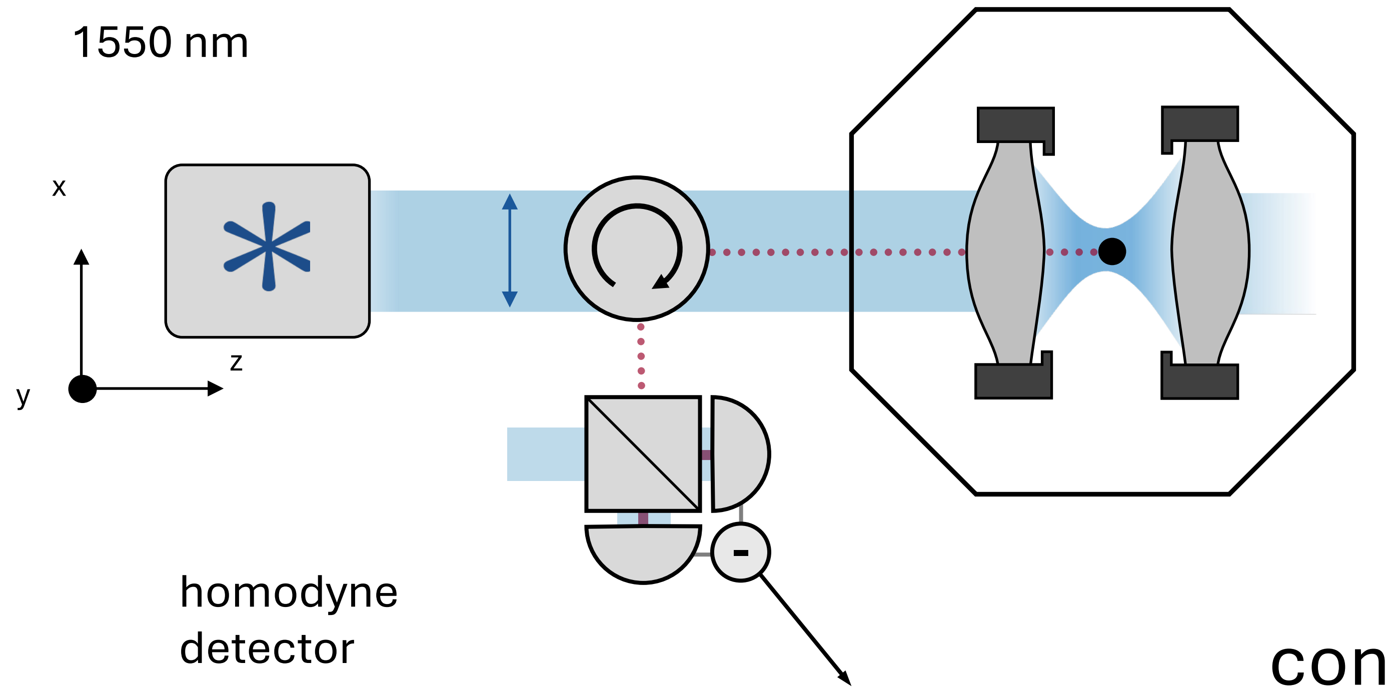
M. Skrabulis

L. Novotny

F. Tebbenjohanns
M. L. Mattana
M. S. Colombano
M. Frimmer

Theory collaborators:
- O. Romero-Isart
- C. Gonzalez-Ballestero
- A. Riera-Campeny

Quantum-limited position measurements

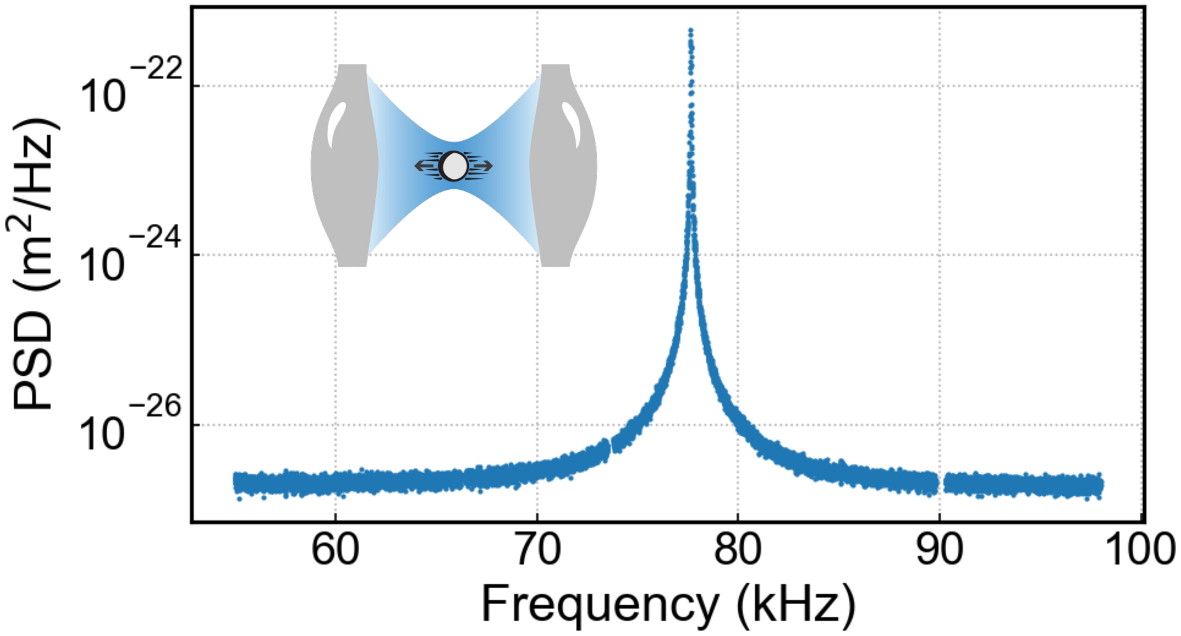


"Heisenberg" microscope

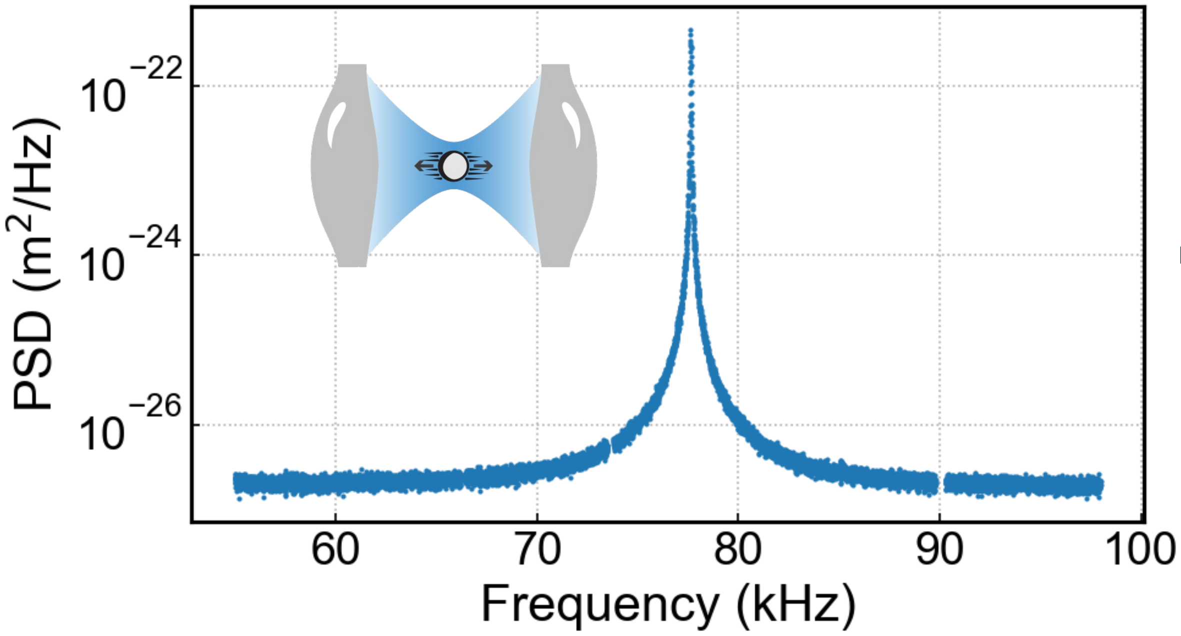
$$x_s + x_n$$

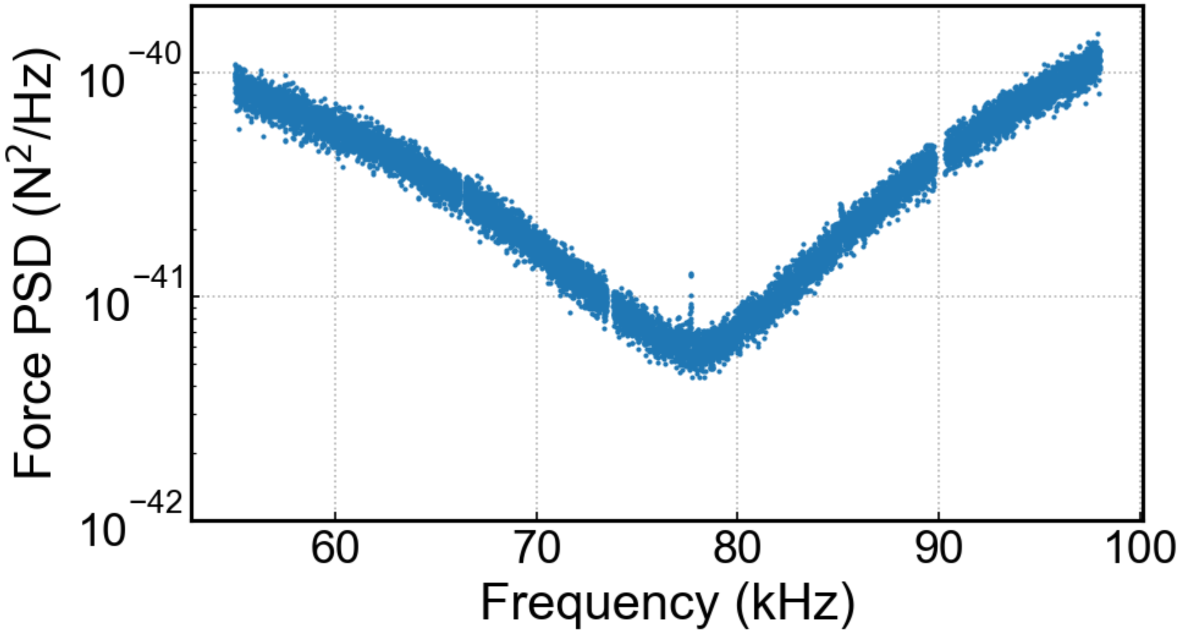
continuous
position measurement

Quantum-limited position measurements

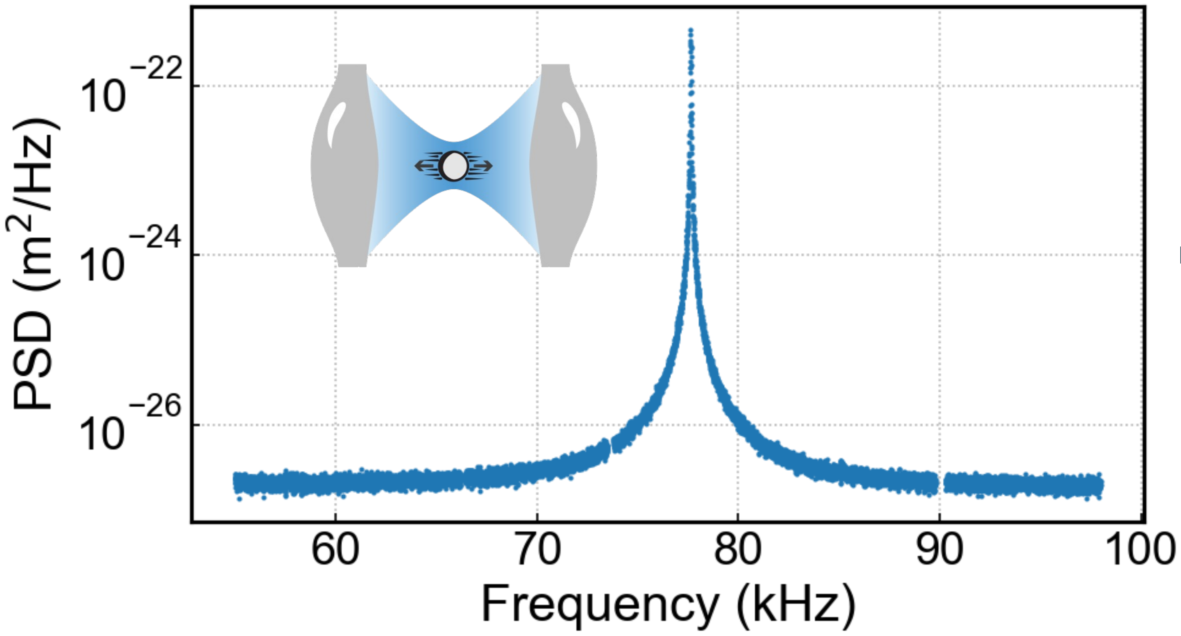


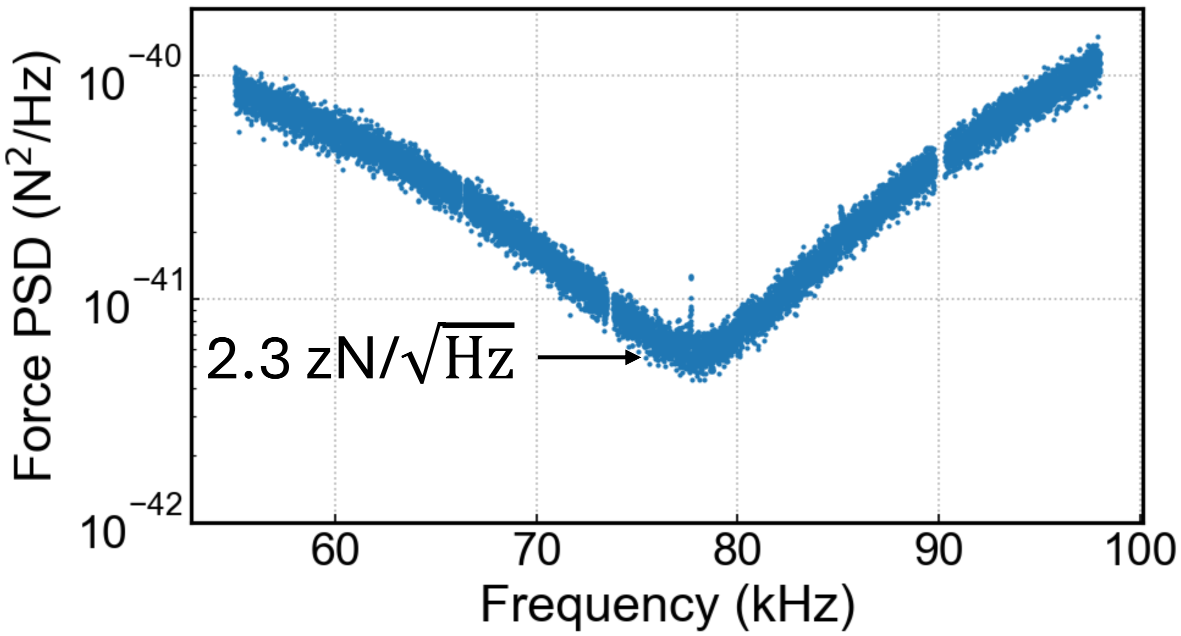
Quantum-limited position measurements



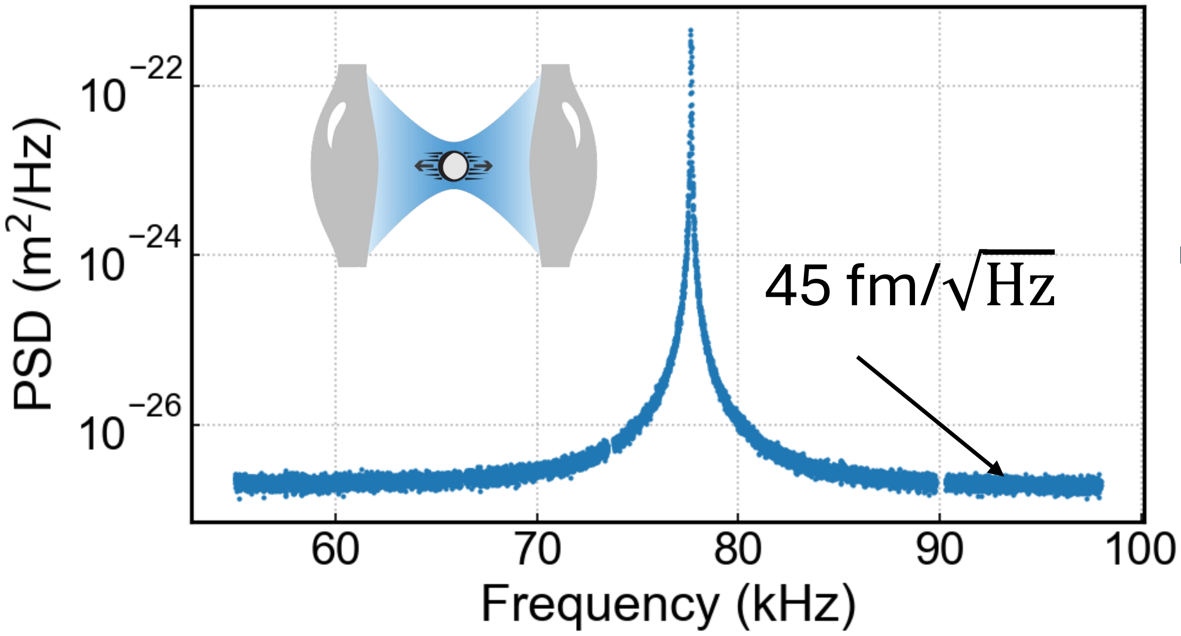


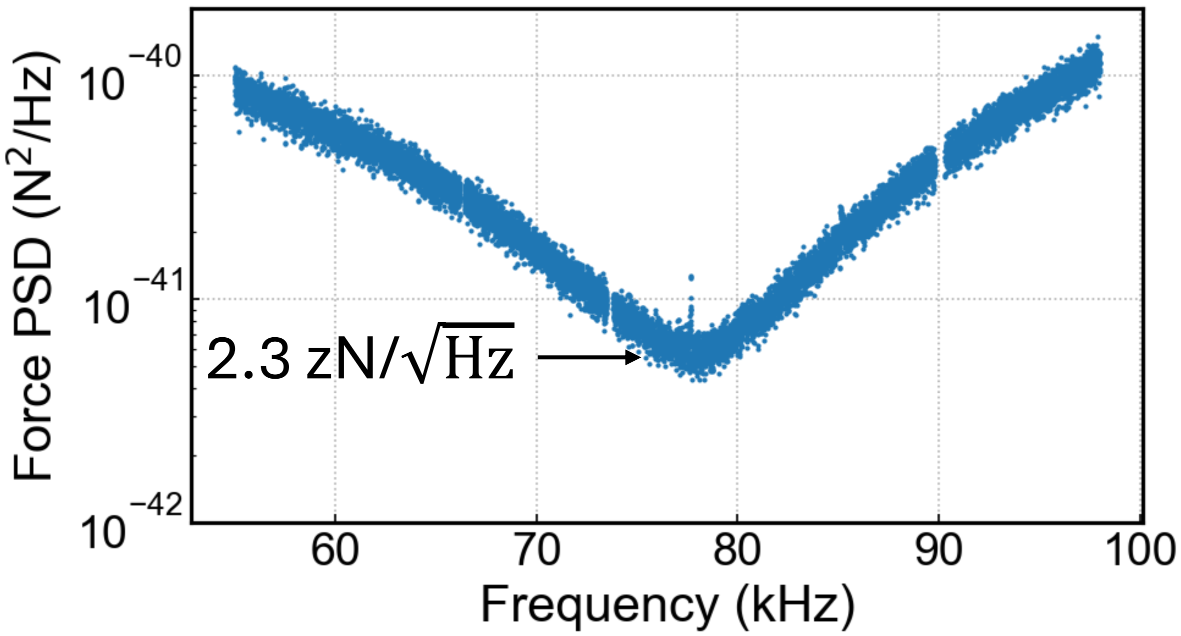
Quantum-limited position measurements



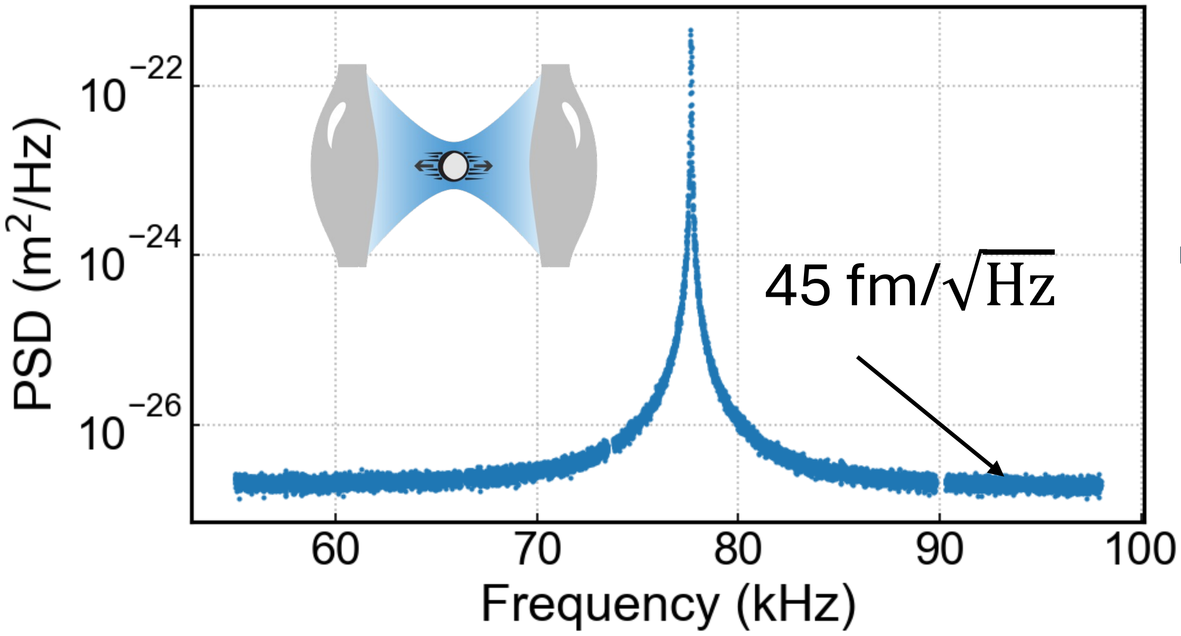


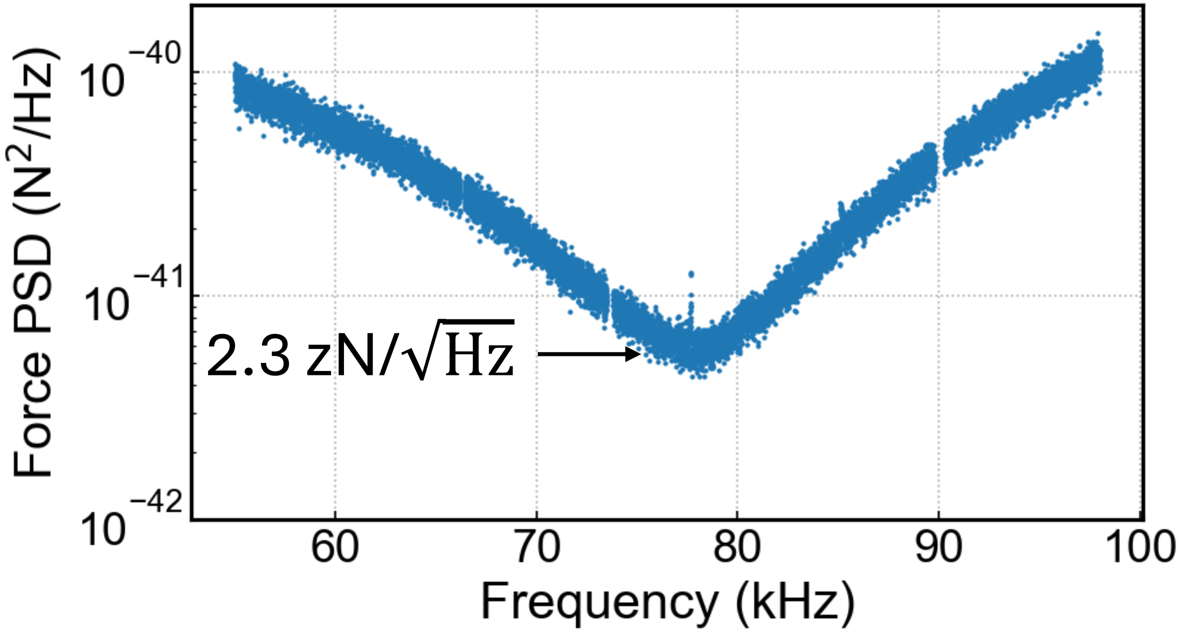
Quantum-limited position measurements





Quantum-limited position measurements

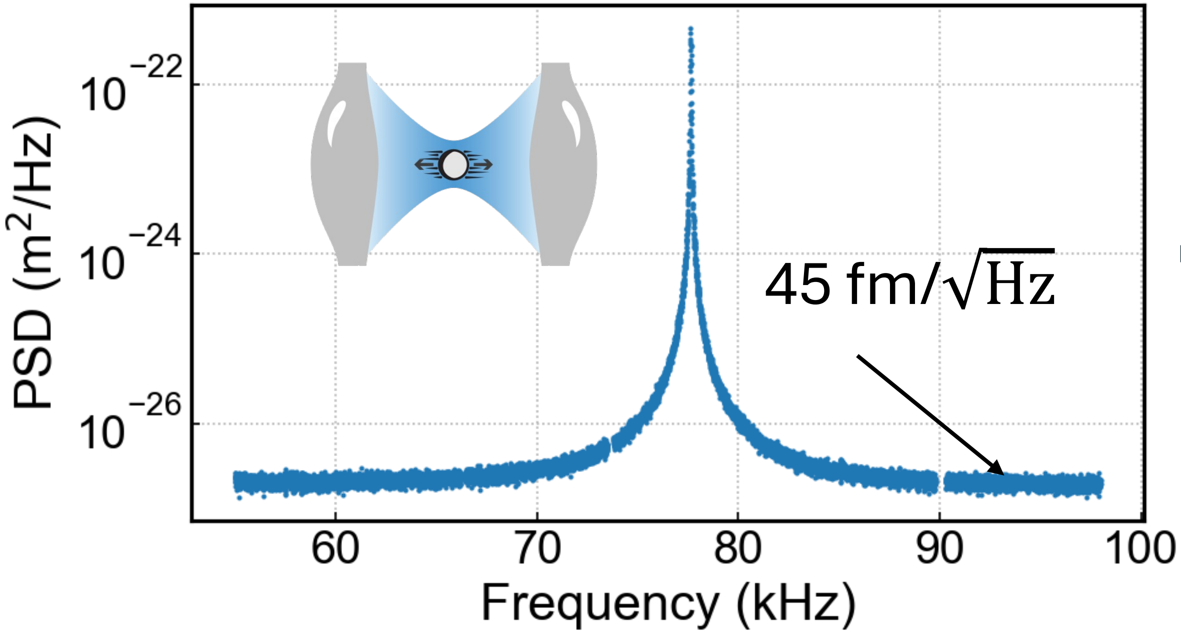


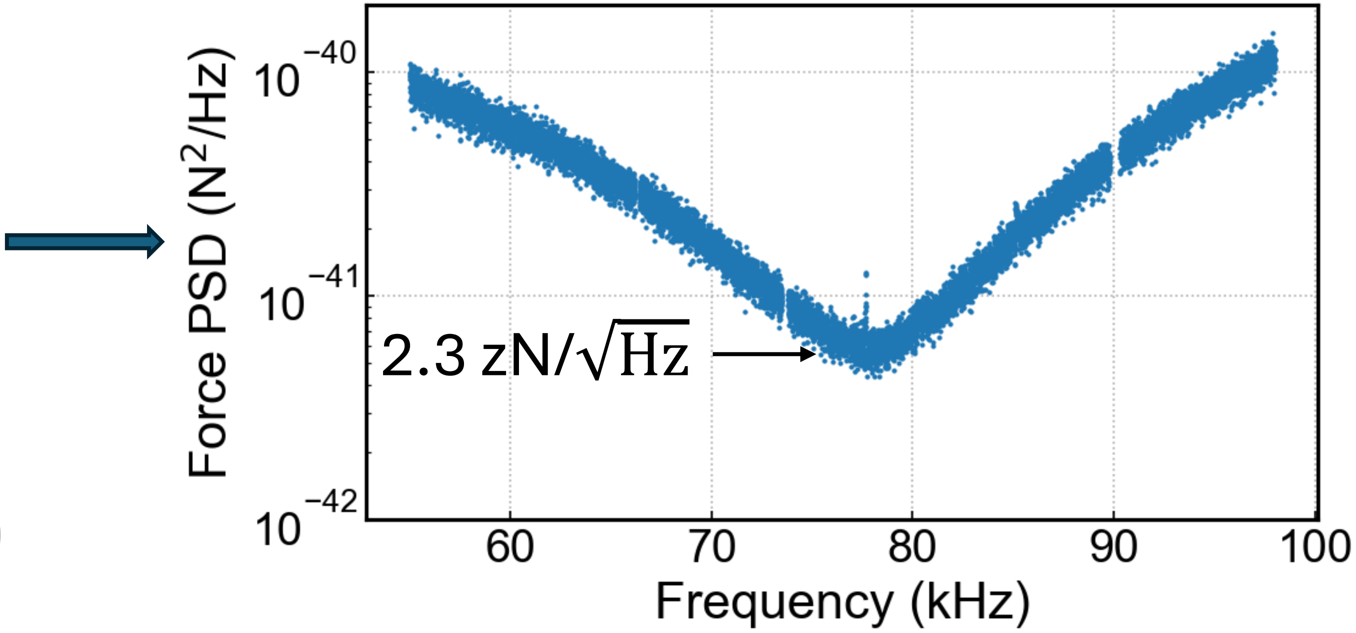


$$\sqrt{S_{FF}^{tot} \cdot S_{imp}} = \frac{1}{\sqrt{\eta}}\frac{\hbar}{2}$$

$$\eta \approx 25\%$$

Quantum-limited position measurements





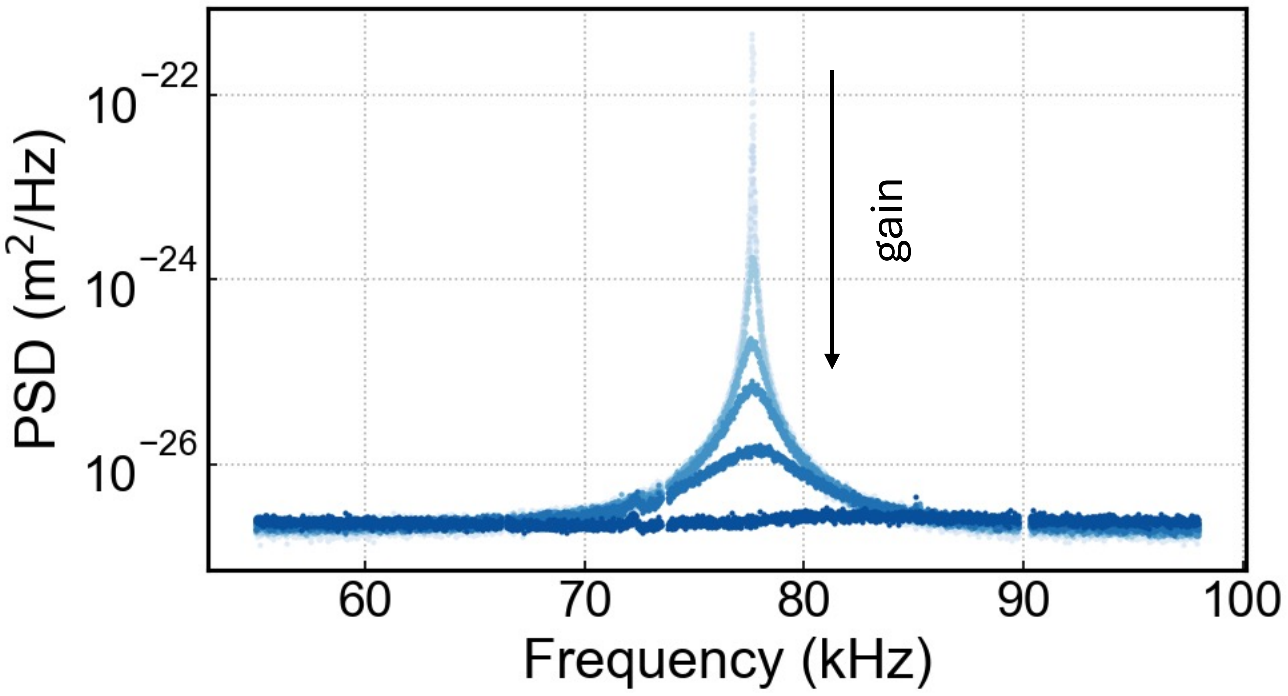
$$\sqrt{S_{FF}^{tot} \cdot S_{imp}} = \frac{1}{\sqrt{\eta}} \frac{\hbar}{2}$$

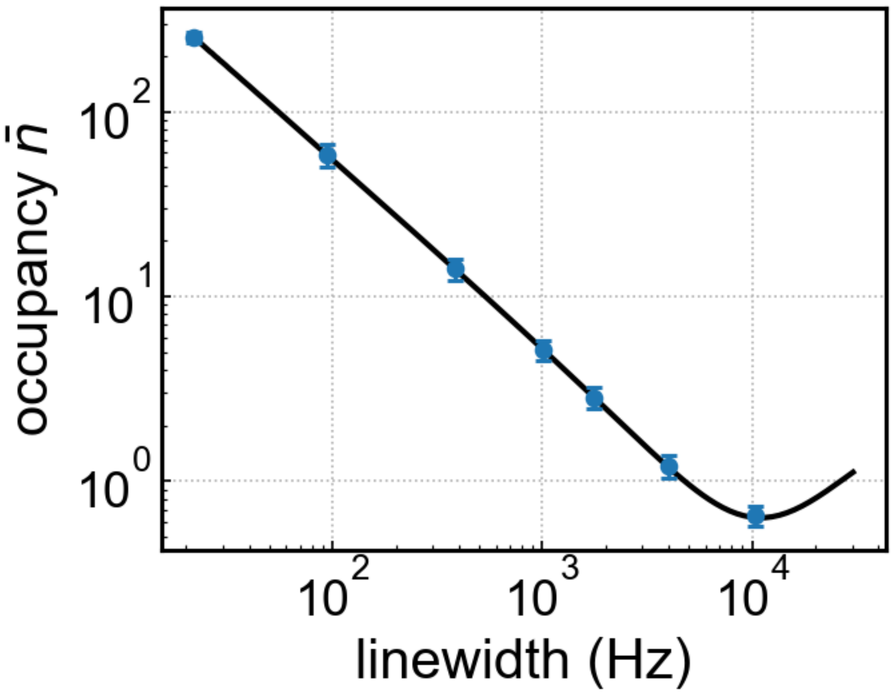
$$\eta \approx 25\%$$

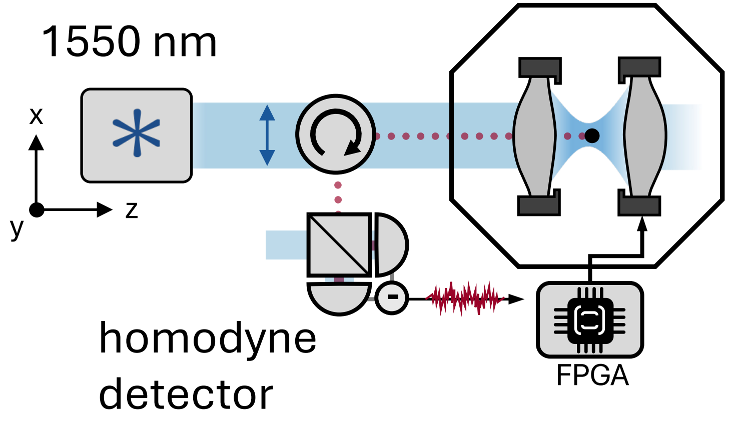
Position estimation accuracy

$$\frac{z_{zpf}}{\sqrt{\eta}} \sim 2z_{zpf}$$

Measurement—based ground state cooling





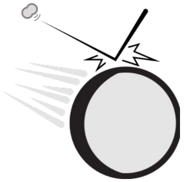


Minimum average energy 0.65 ± 0.08 phonons

Tebbenjohanns et al., Nature 595 (2021)

Outline

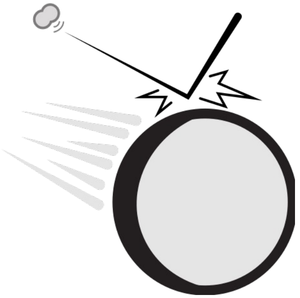
continuous force sensor

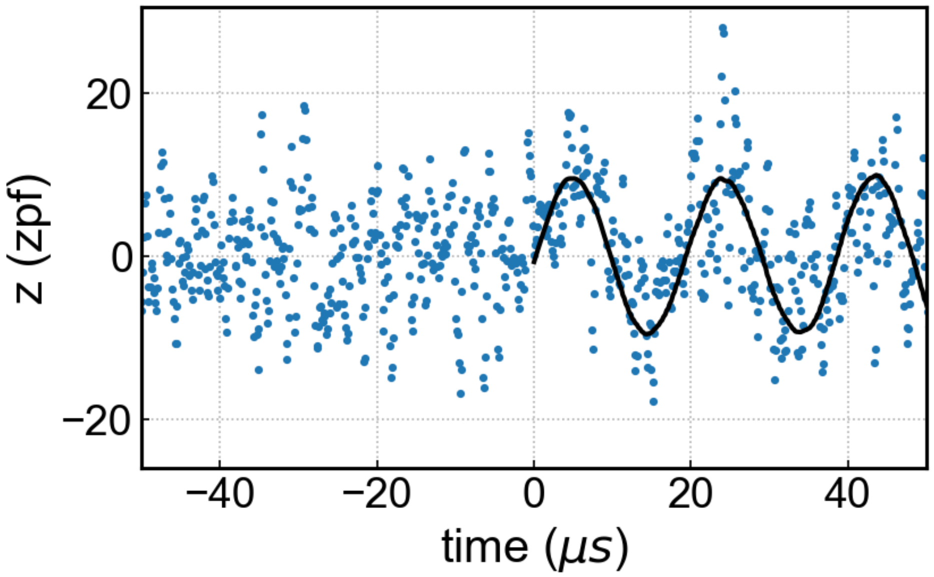


recoil sensing

outlook

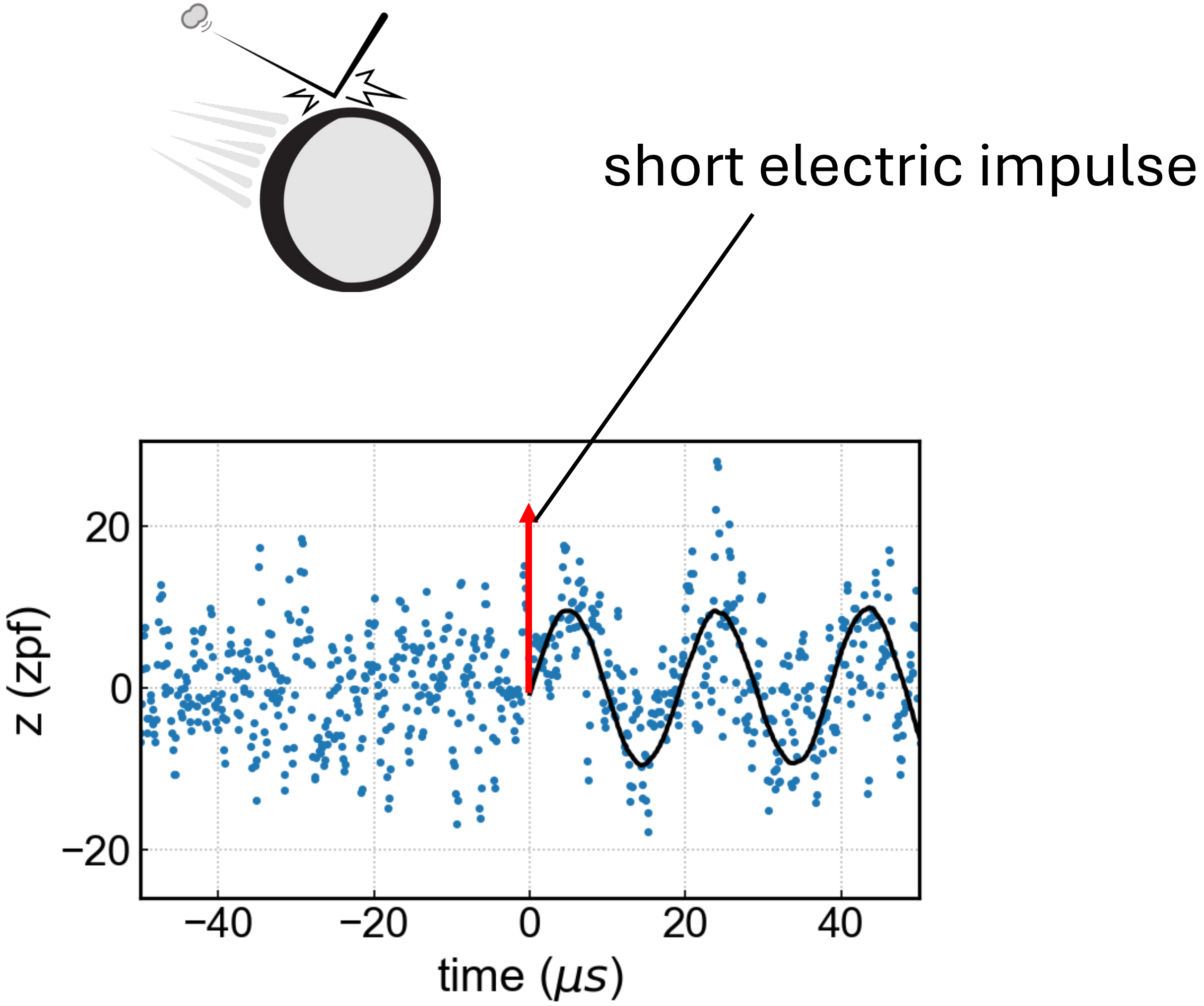
Recoil sensing





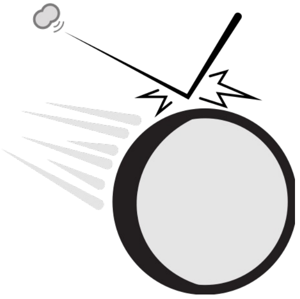
Skrabulis et al., PRL 136, 233604 (2026)

Recoil sensing

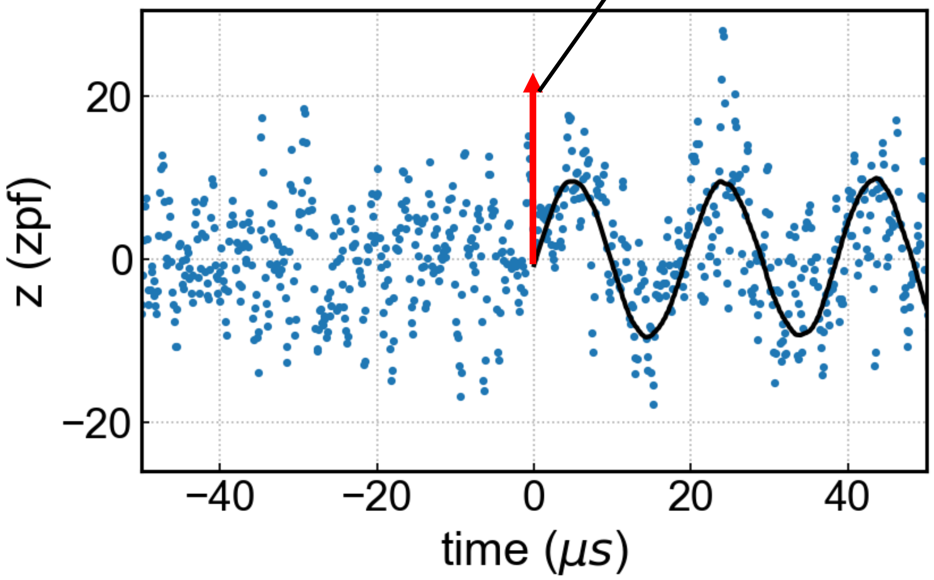


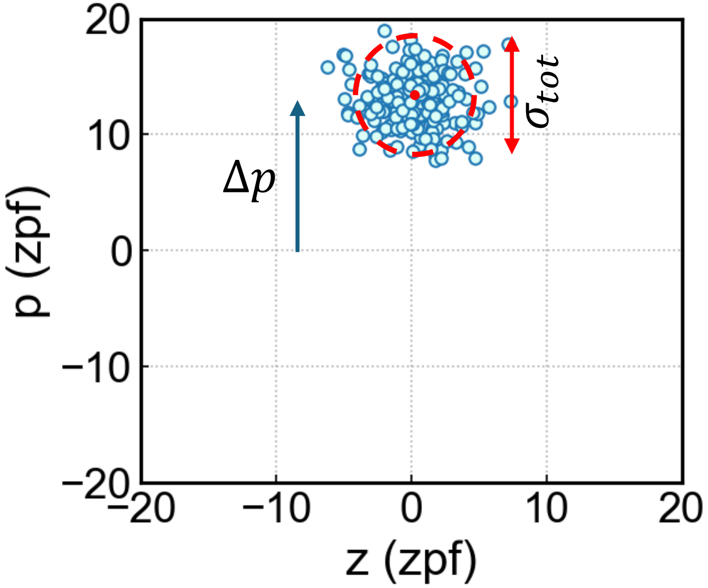
Skrabulis et al., PRL 136, 233604 (2026)

Recoil sensing



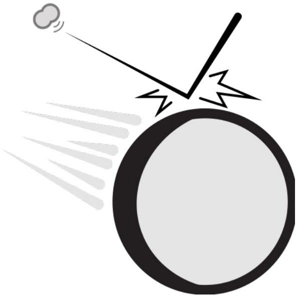
short electric impulse



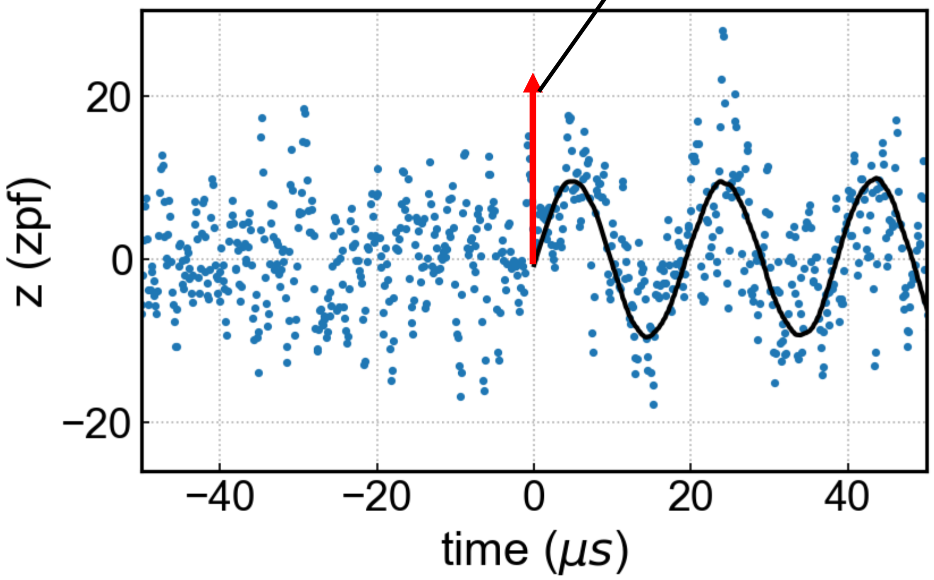


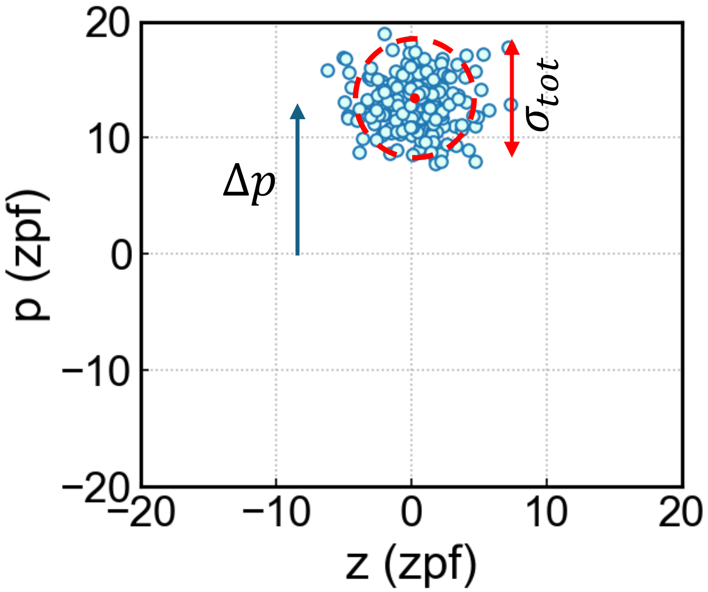
Skrabulis et al., PRL 136, 233604 (2026)

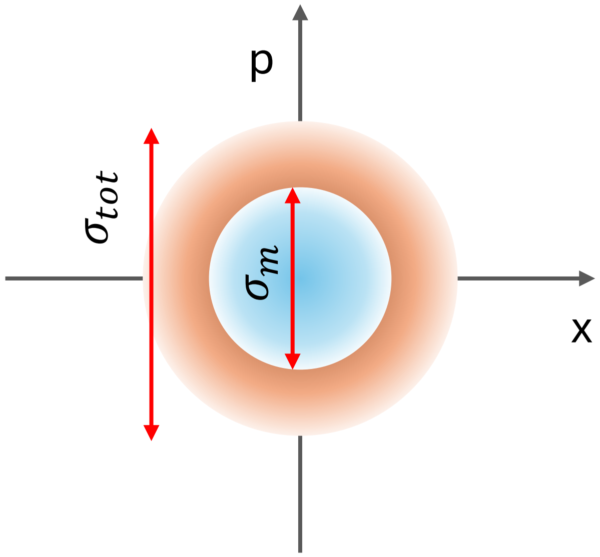
Recoil sensing



short electric impulse







$$\mathrm{SNR} \sim \frac{\Delta p}{\sqrt{\sigma_m^2 + \sigma_r^2}} \leq \frac{\Delta p}{\sqrt{2}\, p_{zpf}}$$

Skrabulis et al., PRL 136, 233604 (2026)

Recoil sensing

coherent signal amplification

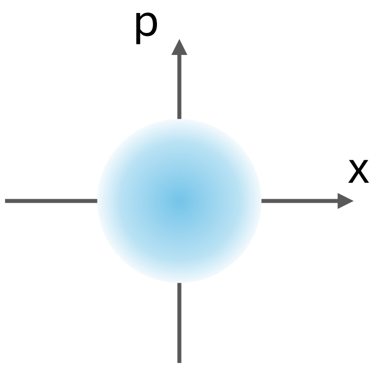
$$\text{SNR} \sim \frac{\Delta p}{\sqrt{\sigma_m^2+\sigma_r^2}} \longrightarrow \frac{\boldsymbol{r}\Delta p}{\sqrt{\sigma_m^2+\sigma_r^2}}$$

Burd et al., Science 364 (2019)

Recoil sensing

coherent signal amplification

$$\text{SNR} \sim \frac{\Delta p}{\sqrt{\sigma_m^2+\sigma_r^2}} \longrightarrow \frac{\boldsymbol{r}\Delta p}{\sqrt{\sigma_m^2+\sigma_r^2}}$$

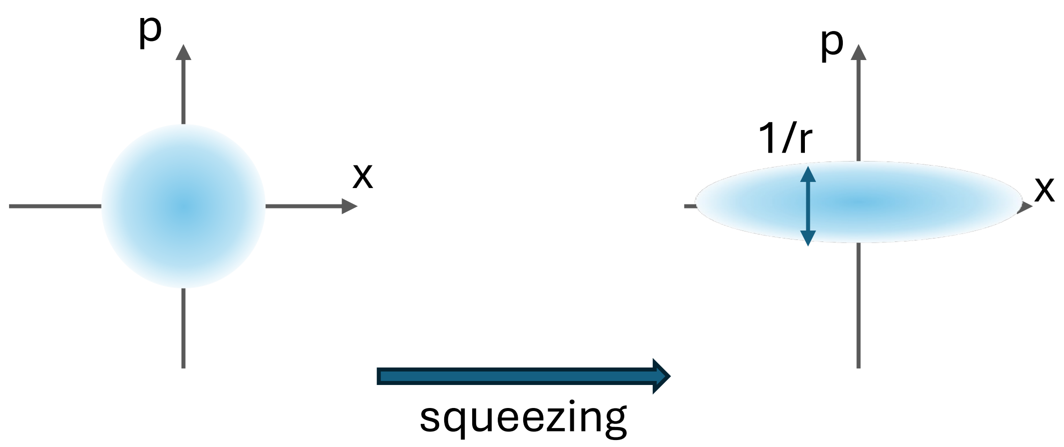


Burd et al., Science 364 (2019)

Recoil sensing

coherent signal amplification

$$\text{SNR} \sim \frac{\Delta p}{\sqrt{\sigma_m^2+\sigma_r^2}} \longrightarrow \frac{\boldsymbol{r}\Delta p}{\sqrt{\sigma_m^2+\sigma_r^2}}$$

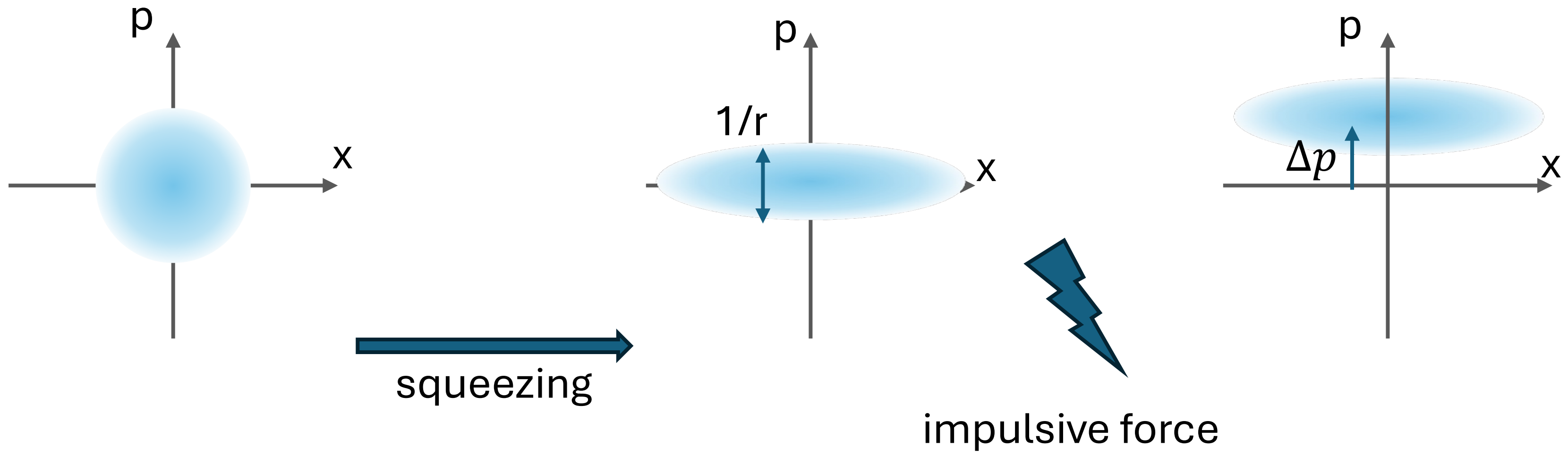


Burd et al., Science 364 (2019)

Recoil sensing

coherent signal amplification

$$\text{SNR} \sim \frac{\Delta p}{\sqrt{\sigma_m^2+\sigma_r^2}} \longrightarrow \frac{\boldsymbol{r}\Delta p}{\sqrt{\sigma_m^2+\sigma_r^2}}$$

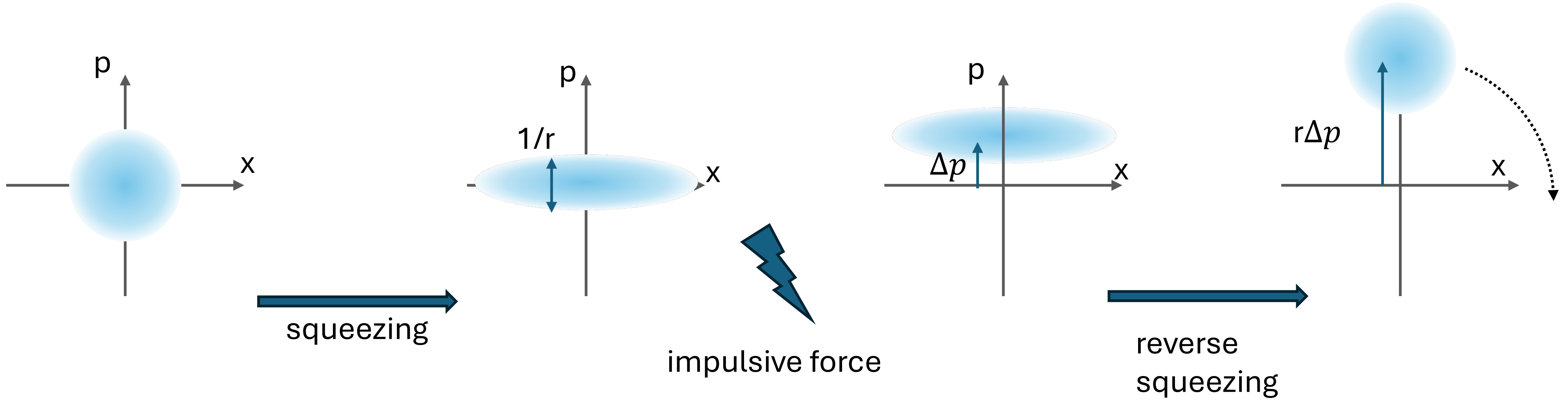


Burd et al., Science 364 (2019)

Recoil sensing

coherent signal amplification

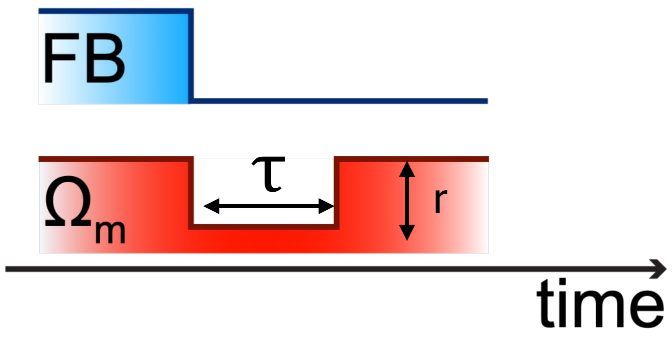
$$\mathrm{SNR} \sim \frac{\Delta p}{\sqrt{\sigma_m^2+\sigma_r^2}} \longrightarrow \frac{\boldsymbol{r}\Delta p}{\sqrt{\sigma_m^2+\sigma_r^2}}$$



Burd et al., Science 364 (2019)

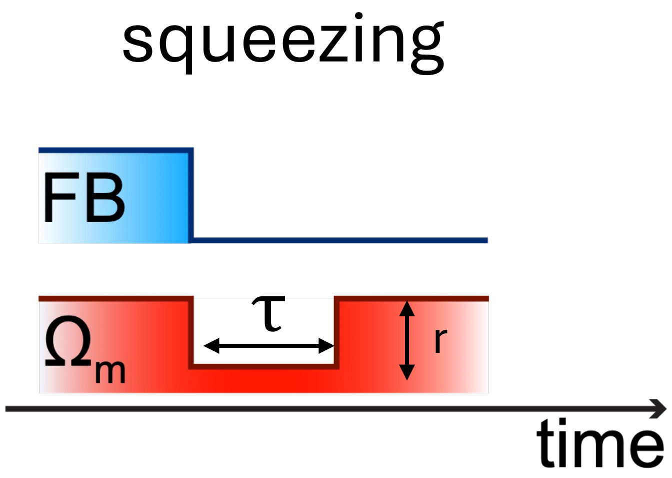
Quantum squeezing of motion

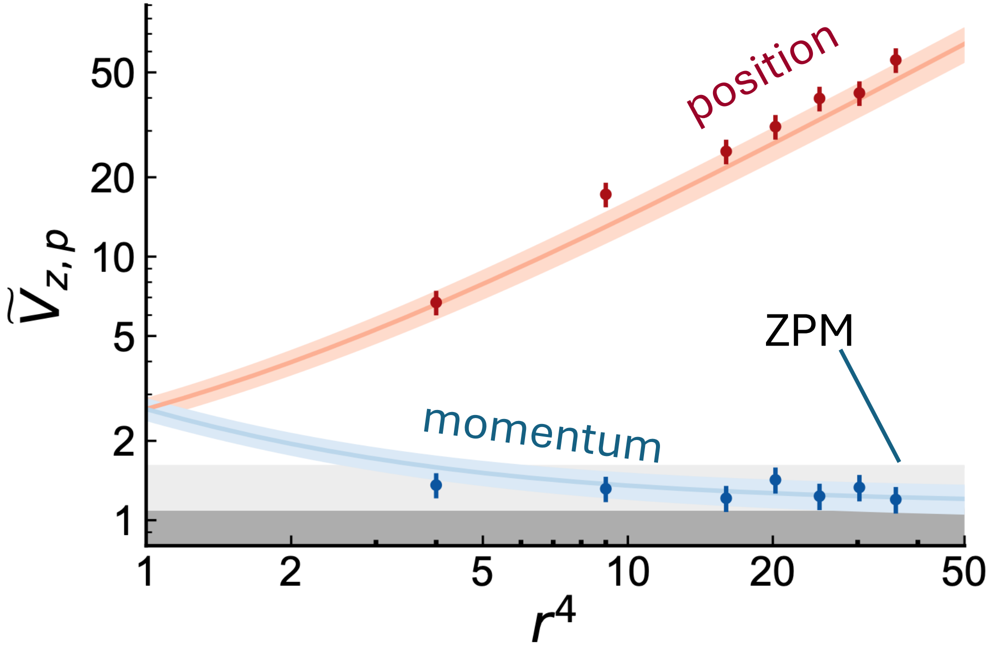
squeezing



Rossi et al., PRL 135, 083601 (2025)

Quantum squeezing of motion

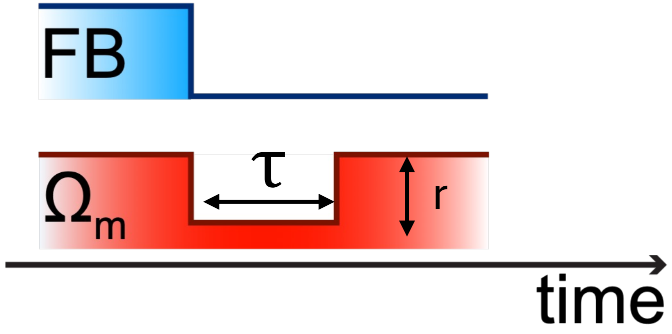


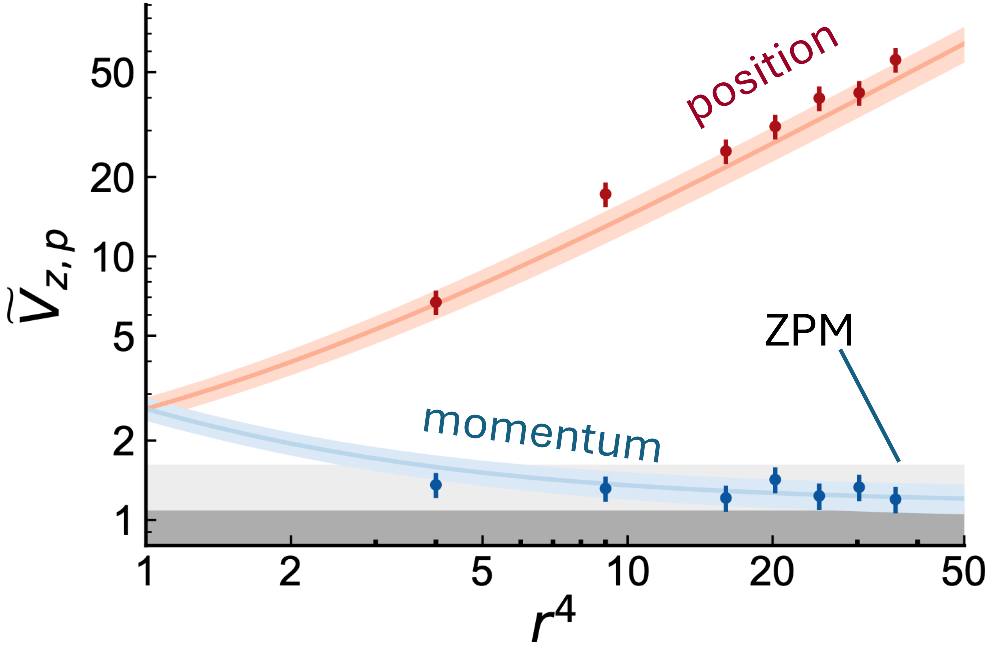


Rossi et al., PRL 135, 083601 (2025)

Quantum squeezing of motion

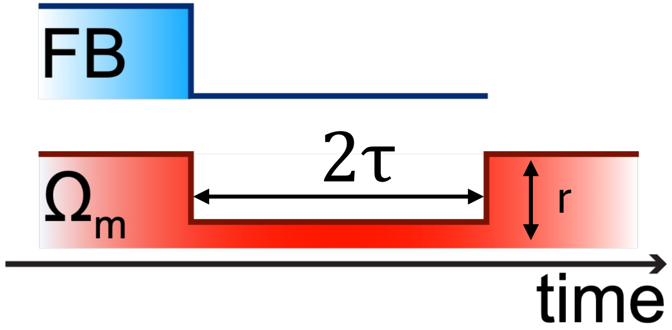
squeezing





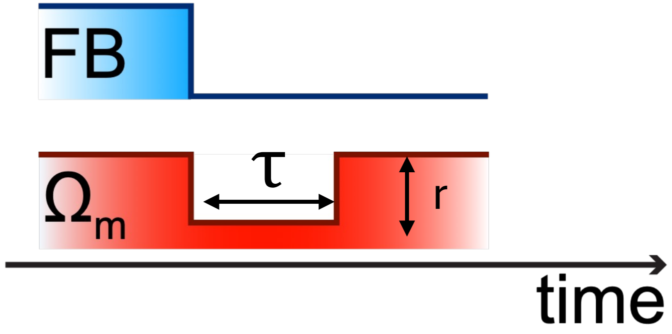
Rossi et al., PRL 135, 083601 (2025)

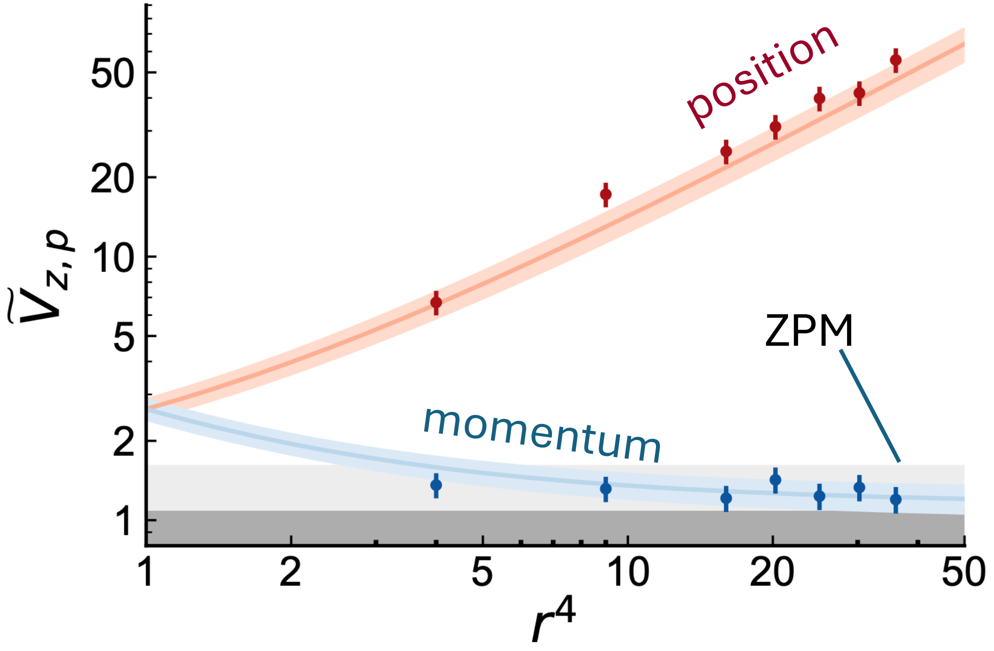
squeezing + anti-squeezing



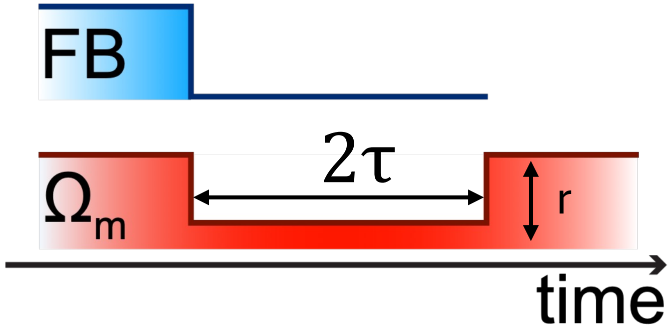
Quantum squeezing of motion

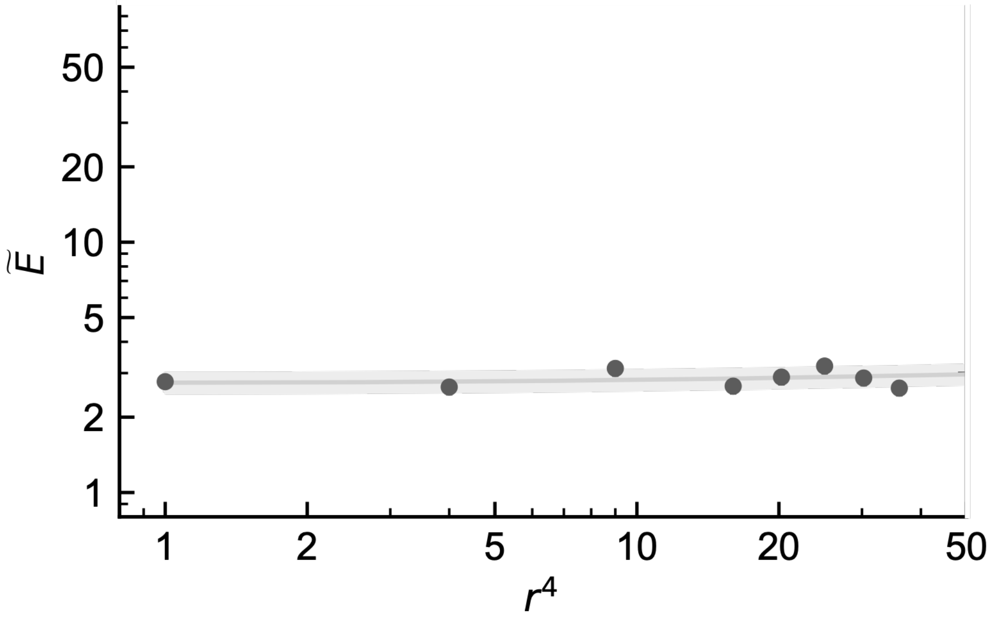
squeezing





squeezing + anti-squeezing

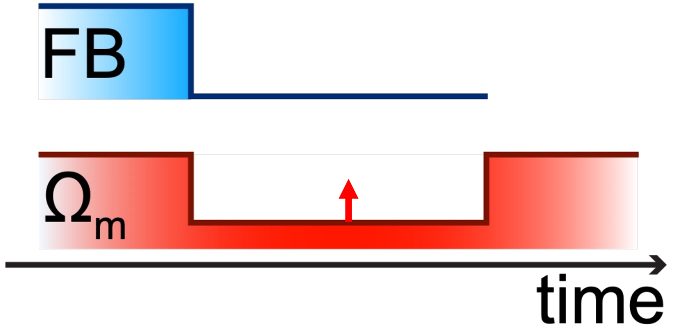




Rossi et al., PRL 135, 083601 (2025)

Recoil sensing below the zero-point motion

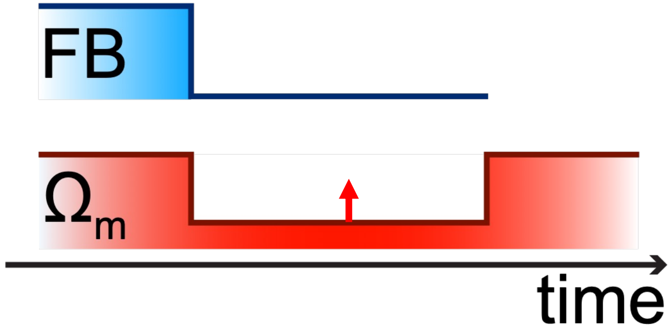
coherent amplification

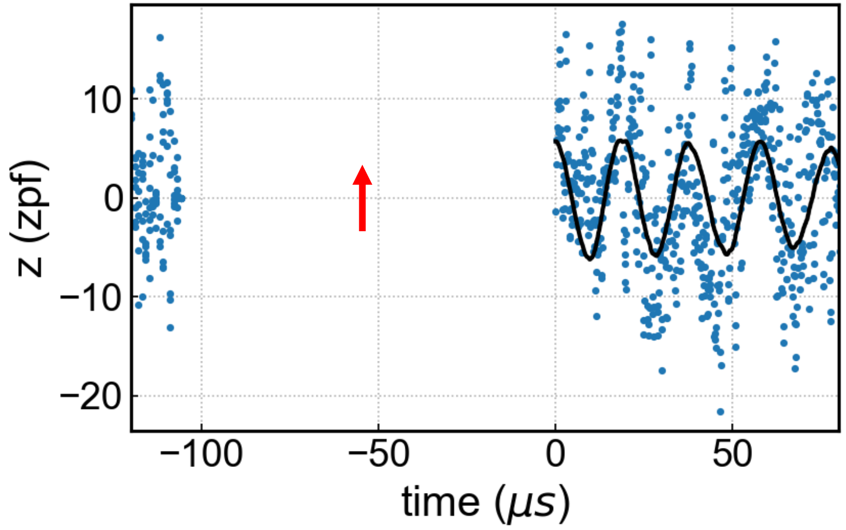


Skrabulis et al., PRL 136, 233604 (2026)

Recoil sensing below the zero-point motion

coherent amplification

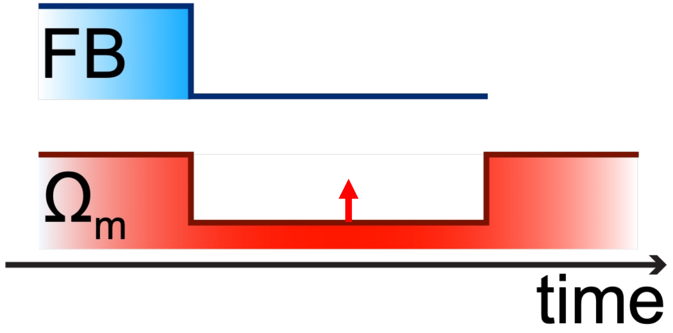


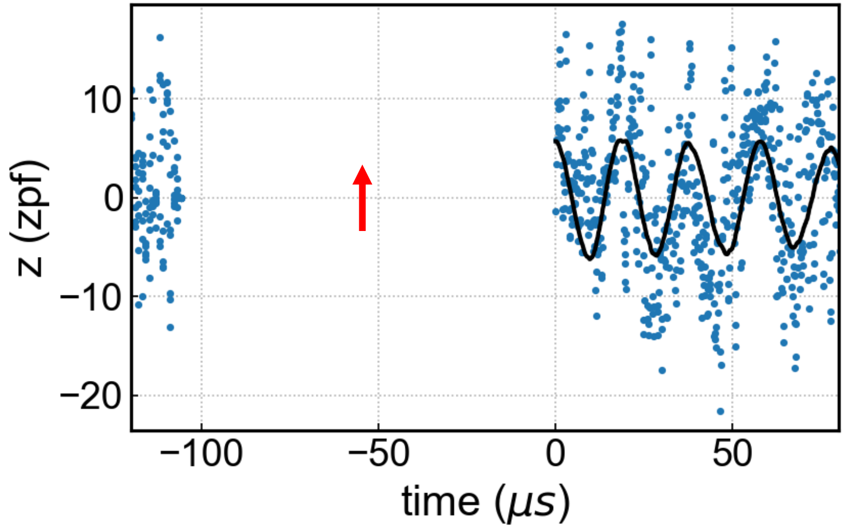


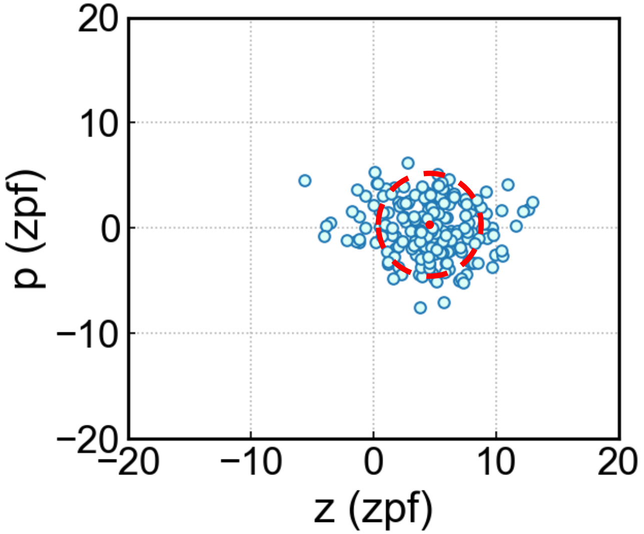
Skrabulis et al., PRL 136, 233604 (2026)

Recoil sensing below the zero-point motion

coherent amplification



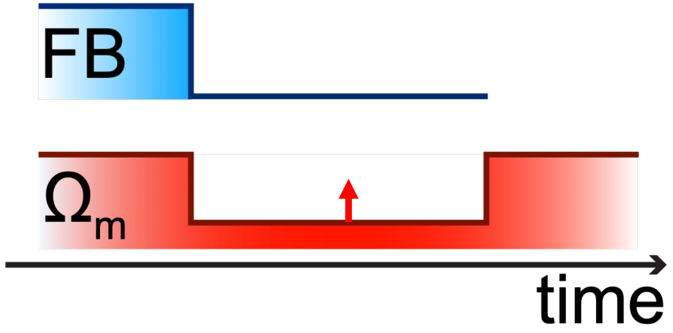




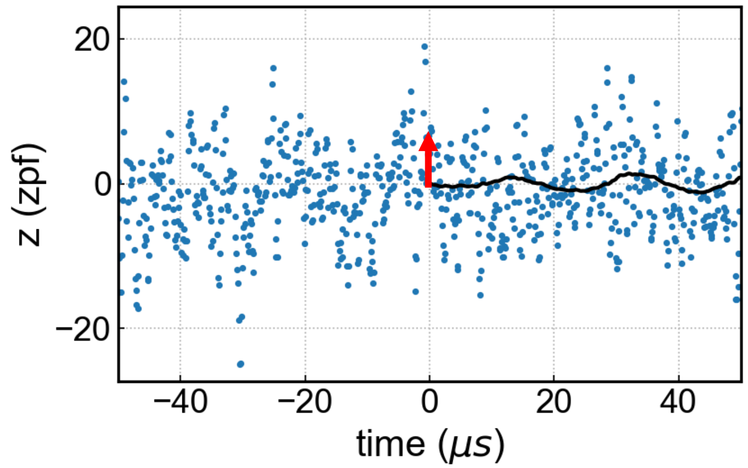
Skrabulis et al., PRL 136, 233604 (2026)

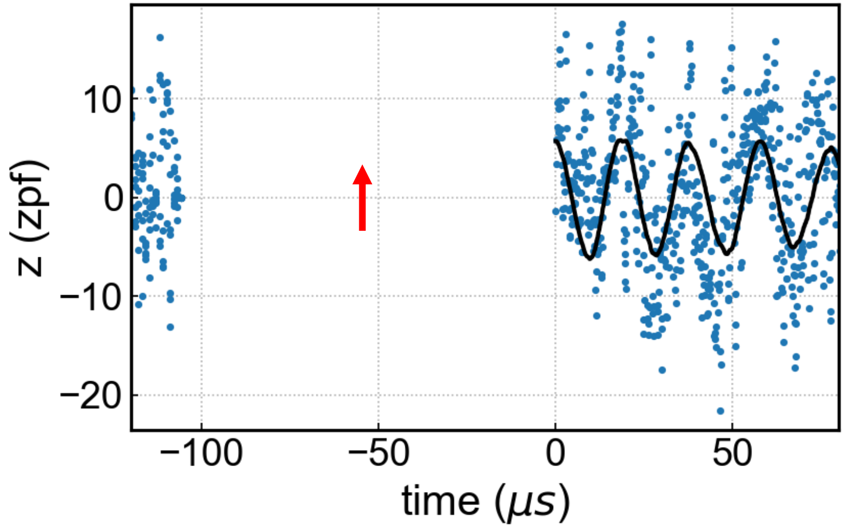
Recoil sensing below the zero-point motion

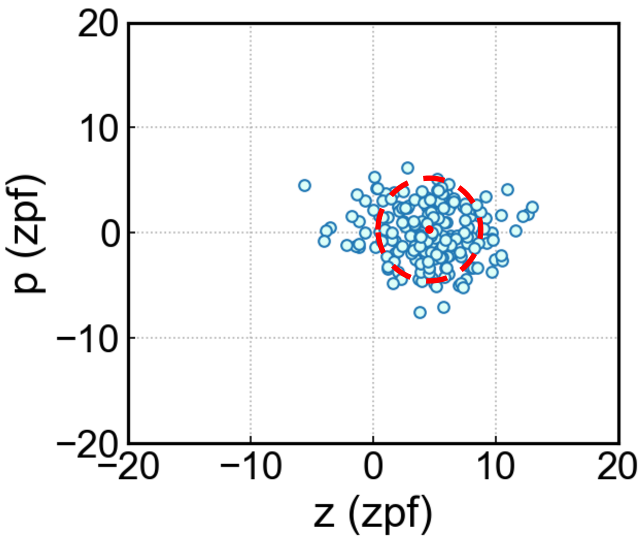
coherent amplification

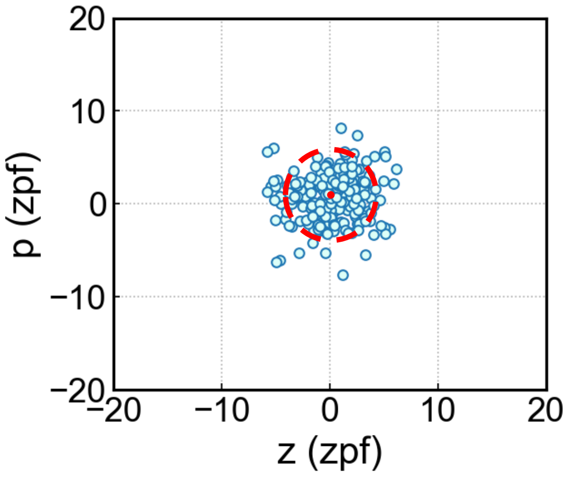


no squeezing



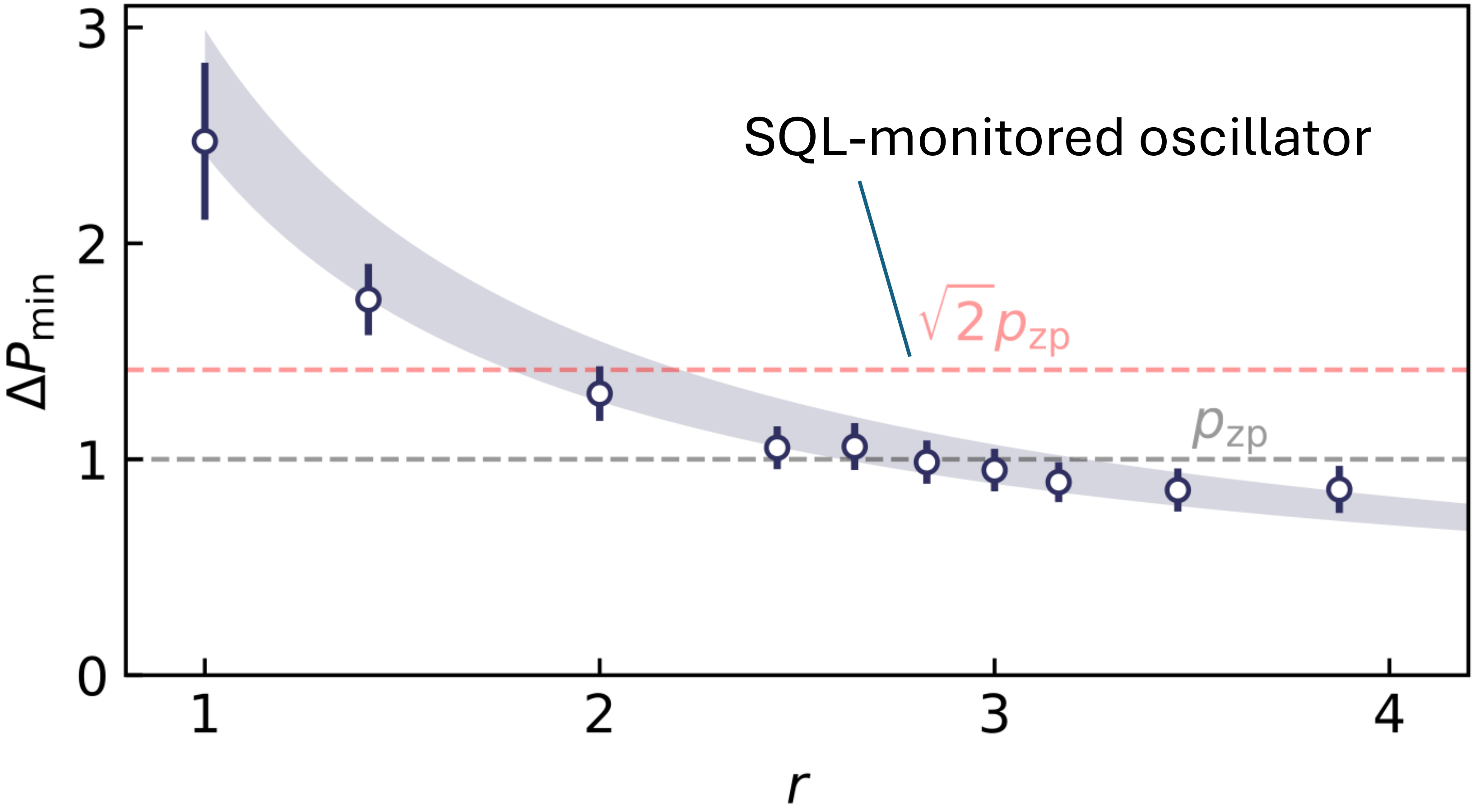






Skrabulis et al., PRL 136, 233604 (2026)

Recoil sensing below the zero-point motion



from total measured noise

$$\Delta p_{min} = \sigma_x / r$$

minimum recoil

6.9 ± 0.8 keV/c

Skrabulis et al., PRL 136, 233604 (2026)

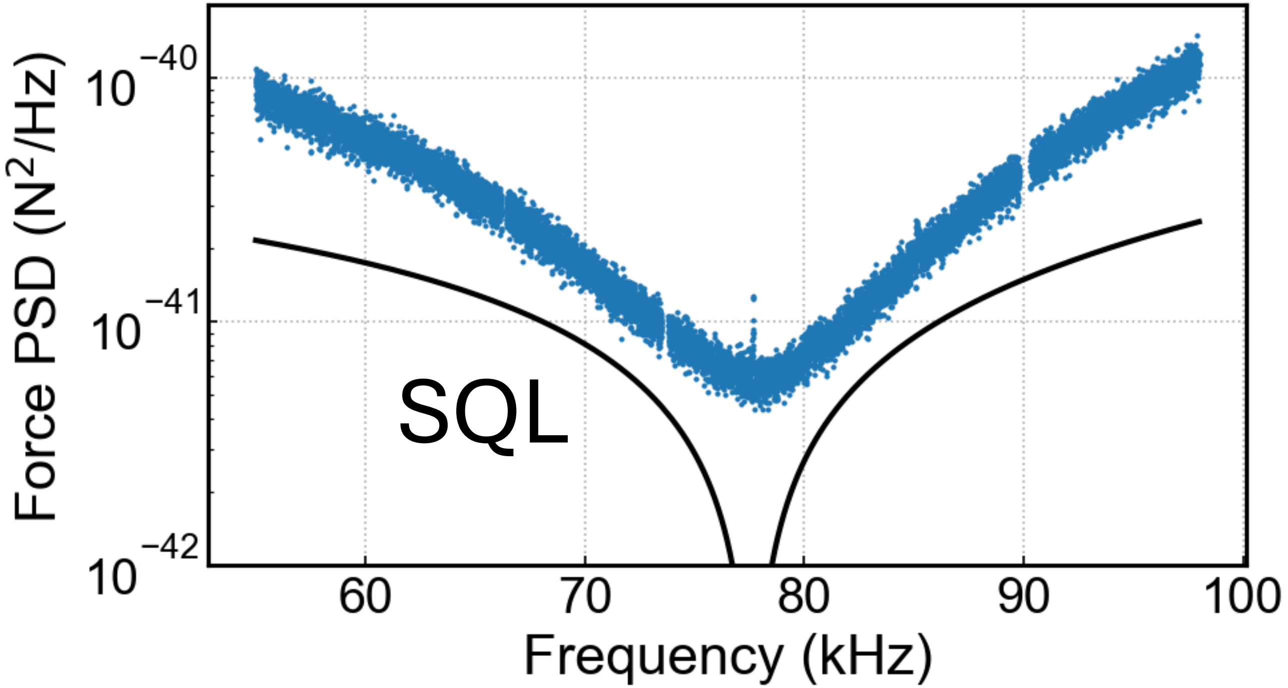
Outline

continuous force sensor

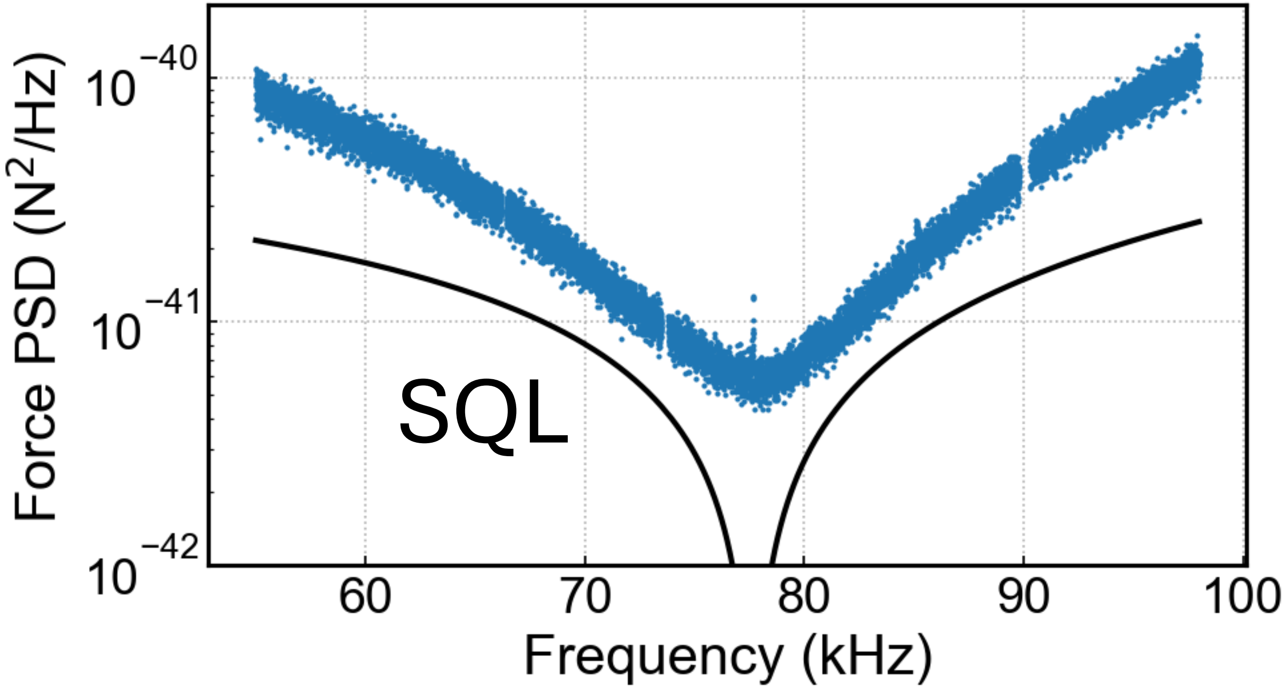
recoil sensing

outlook

Outlook – sub-SQL readout

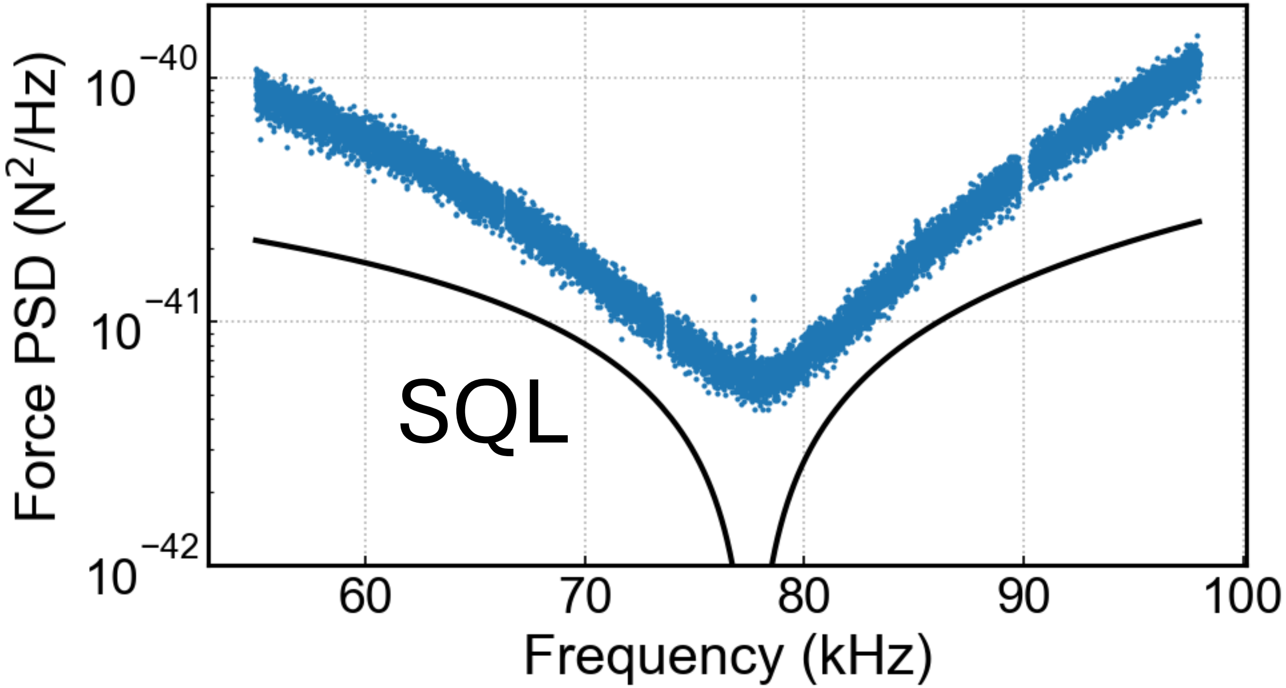


Outlook – sub-SQL readout

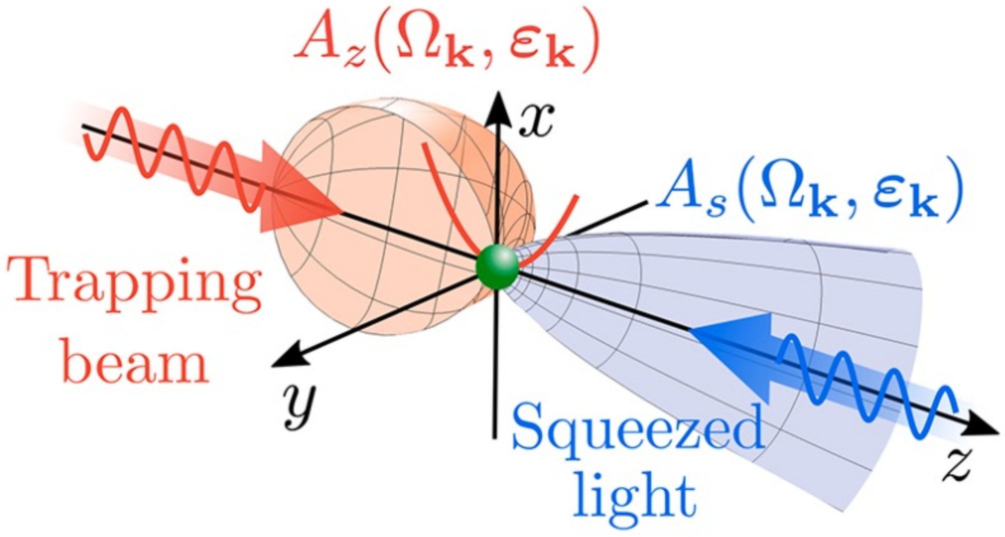


Inject squeezing for sub-SQL readout

Outlook – sub-SQL readout



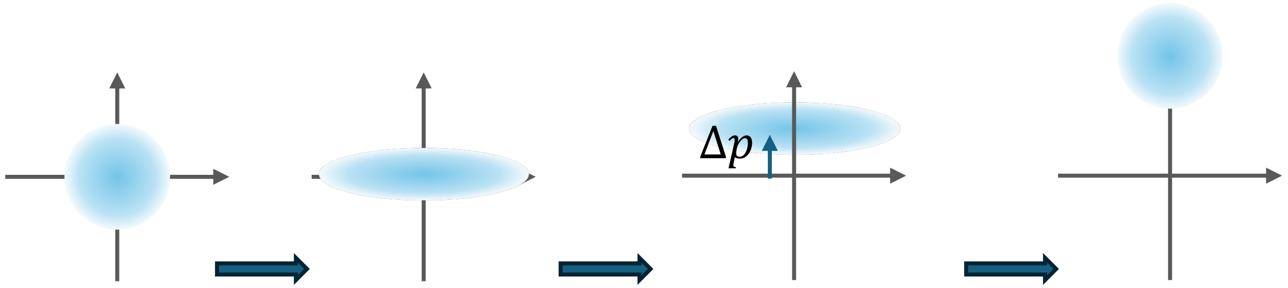
Inject squeezing for sub-SQL readout



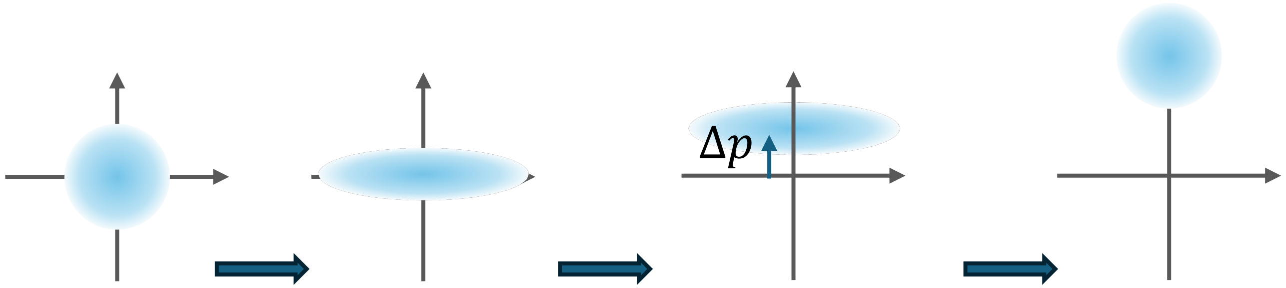
Noise reduction from overlap with information radiation mode

Gonzalez-Ballestero et al. PRX Quantum 4 (2023)

Outlook – amplification of nonlinear forces

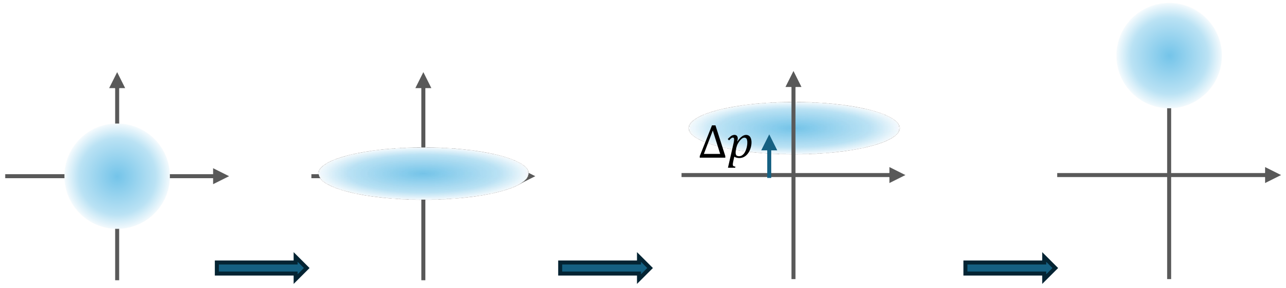


Outlook – amplification of nonlinear forces



$$e^{\frac{i}{\hbar}\Delta \mathrm{p}\ \hat{x}}$$

Outlook – amplification of nonlinear forces



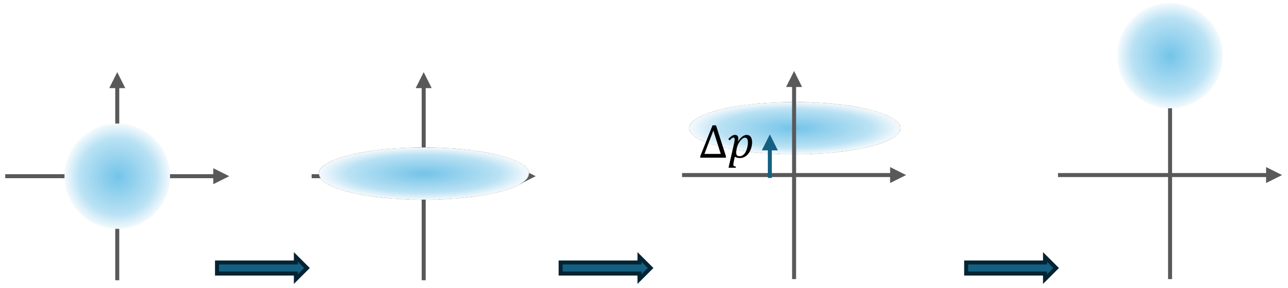
$$e^{\frac{i}{\hbar}\Delta \mathrm{p}\,\hat{x}}$$

Amplifying non-linear phases
from anharmonic forces:

cubic phase $e^{\frac{i}{\hbar}\beta\hat{x}^3}$

Kerr phase $e^{\frac{i}{\hbar}\gamma\hat{x}^4}$

Outlook – amplification of nonlinear forces

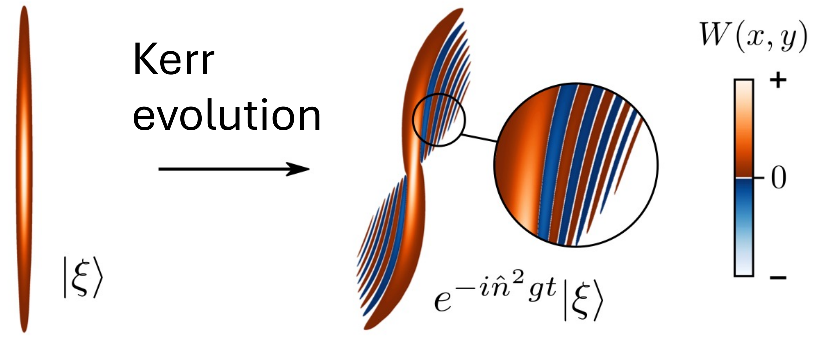


$$e^{\frac{i}{\hbar}\Delta \mathrm{p}\,\hat{x}}$$

Amplifying non-linear phases
from anharmonic forces:

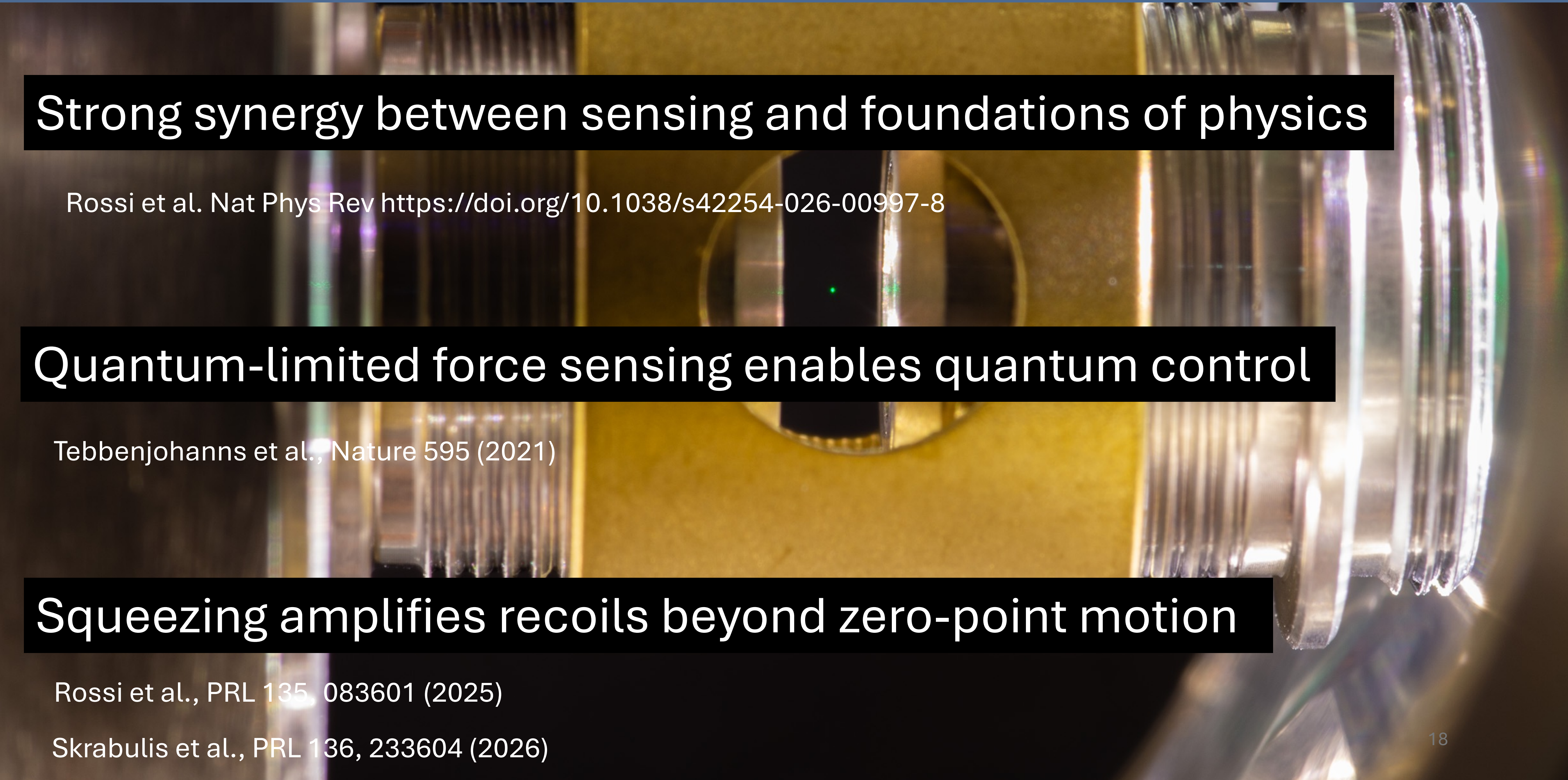
cubic phase $e^{\frac{i}{\hbar}\beta\hat{x}^3}$

Kerr phase $e^{\frac{i}{\hbar}\gamma\hat{x}^4}$



Rosiek et al., PRX Quantum 5, 030312 (2024)
Neumeier et al., PNAS 121 (2024)
Roda-Llordes et al., PRL 132, 023601 (2024)

Summary



Strong synergy between sensing and foundations of physics

Rossi et al. Nat Phys Rev https://doi.org/10.1038/s42254-026-00997-8

Quantum-limited force sensing enables quantum control

Tebbenjohanns et al., Nature 595 (2021)

Squeezing amplifies recoils beyond zero-point motion

Rossi et al., PRL 135, 083601 (2025)

Skrabulis et al., PRL 136, 233604 (2026)