Optimal quantum control of mechanical motion at room temperature: ground state cooling

Lucas Mendicino

Director: Christian Schmiegelow

LIAF

Panorama actual del enfriamiento de nanopartículas en busca de observar efectos cuánticos en objetos macroscópicos

Optimal quantum control of mechanical motion at room temperature: ground state cooling

Panorama del enfriamiento de nanopartículas

Método de atrapado

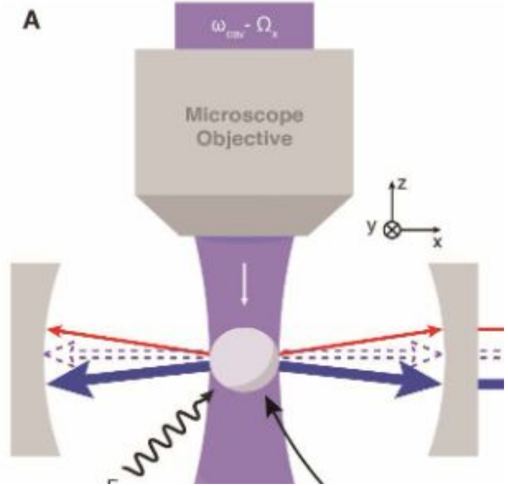
Pinzas ópticas

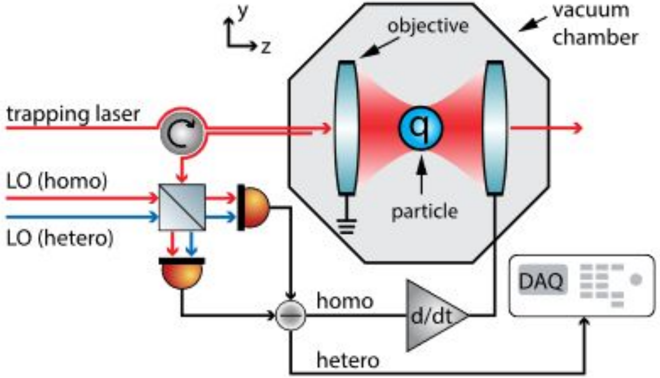
Trampas de Paul

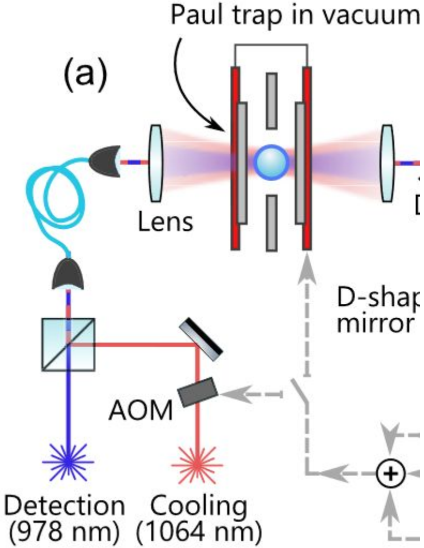
Método de enfriado

Cavity cooling

feedback cooling







Panorama del enfriamiento de nanopartículas

Cooling of a levitated nanoparticle to the motional quantum ground state

First release: 30 January 2020

Uroš Delić[1,2]*, Manuel Reisenbauer[1], Kahan Dare[1,2], David Grass[1]†, Vladan Vuletić[3], Nikolai Kiesel[1], Markus Aspelmeyer[1,2]*

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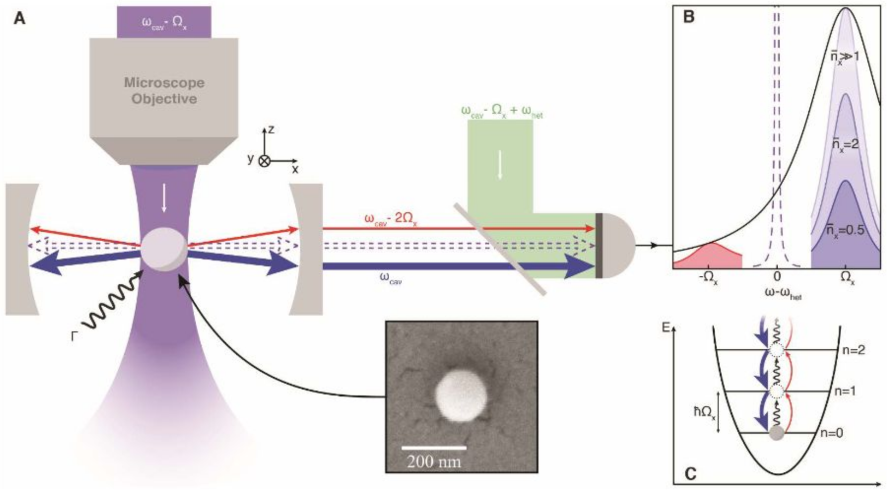
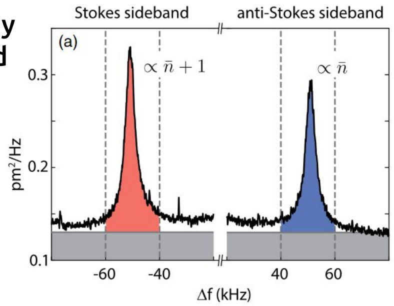


Si hay cavidad

Si no hay cavidad



$$\overline{n}_x = 0.43 \pm 0.03$$

Panorama del enfriamiento de nanopartículas

Motional Sideband Asymmetry of a Nanoparticle Optically Levitated in Free Space

Felix Tebbenjohanns, Martin Frimmer, Vijay Jain, Dominik Windey, and Lukas Novotny
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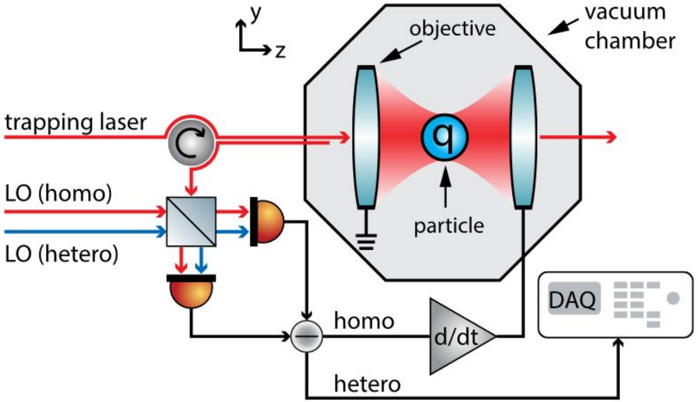
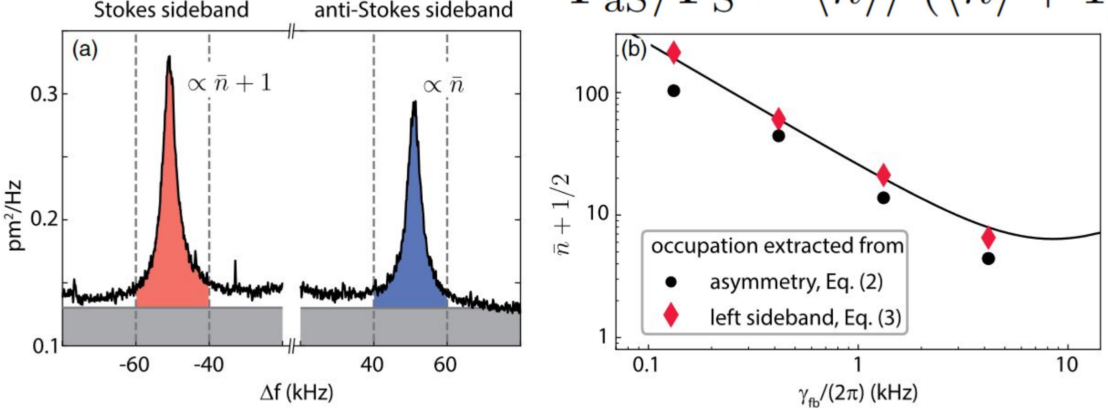
(Received 14 August 2019; published 8 January 2020)



$$\Gamma_{aS}/\Gamma_{S} = \langle n \rangle / (\langle n \rangle + 1)$$



$$\bar{n} = 4$$

Panorama del enfriamiento de nanopartículas

Quantum control of a nanoparticle optically levitated in cryogenic free space

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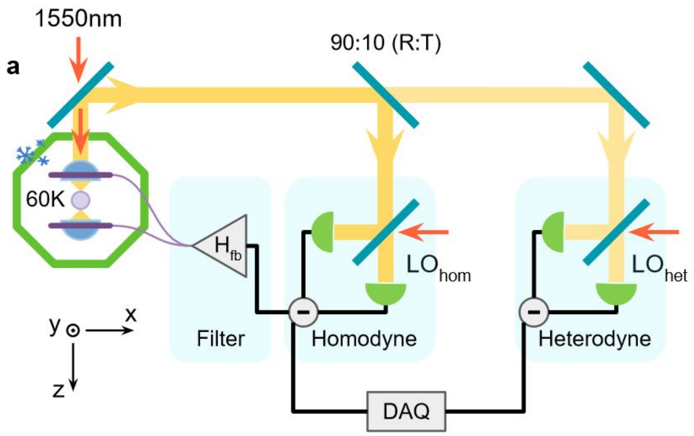
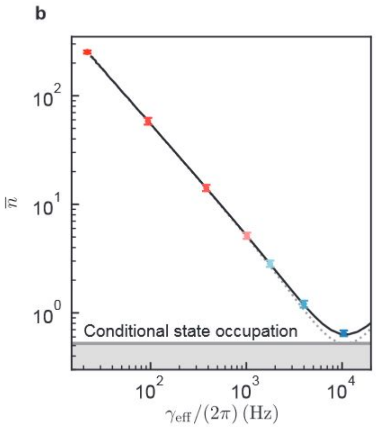
Photonics Laboratory, ETH Zürich, CH-8093 Zürich, Switzerland
(Dated: April 26, 2021)





$$\bar{n} = (0.65 \pm 0.04)$$

Panorama del enfriamiento de nanopartículas

Optical and electrical feedback cooling of a silica nanoparticle levitated in a Paul trap

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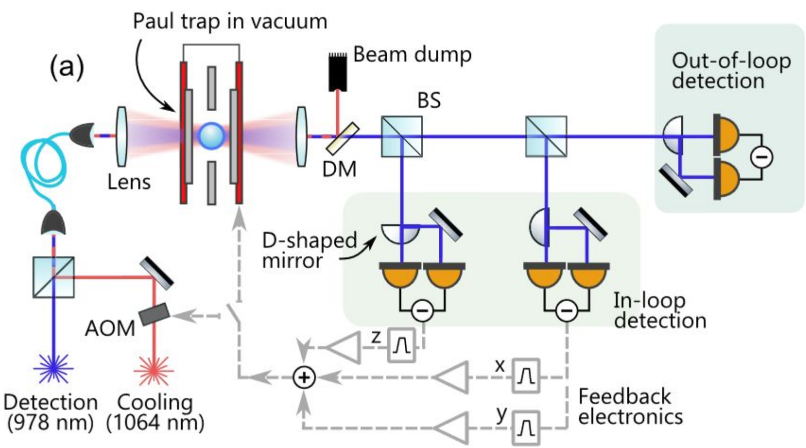
(Received 7 July 2020; accepted 23 November 2020; published 8 January 2021)



2. *Minimum temperature*

The results in Sec. III A correspond to mean phonon occupation numbers $\bar{n}_i = k_B T_i/\hbar\omega_i$ between $4.6(8) \times 10^4$ and $3.4(4) \times 10^5$, where $i \in \{x, y, z\}$ and $\hbar$ is the reduced Planck constant. Given the recent cooling of nanoparticles to the quantum regime [23,24], it is important to understand what limits further cooling in this setup.

Minimizing T_x in Eq. (2) with respect to γ_{fb}, we see that the minimum temperature scales as $T_x^{min} \propto \sqrt{\gamma_0 T_0 S_{\delta x_{il}}}$. Replacing lossy optics in the detection path and substituting a single quadrant photodetector for the three balanced detectors would improve $S_{\delta x_{il}}$ by a factor of 10^2 and $\bar{n}_i$ by a factor of 10. Moreover, we calculate that switching from detection of forward-scattered light to a scheme based on self-interference detection [44] would provide another two orders of magnitude improvement in $S_{\delta x_{il}}$ [45]. To reduce the occupation number even further at room temperature, one could reduce the background pressure γ_0 or increase the trap frequency ω_i. In the latter case, increasing the number of charges on the nanoparticle or decreasing the particle's mass will allow us to trap stably at higher frequencies. Finally, one could introduce cryogenic buffer gas to reduce T_0 and, therefore, the minimum temperature.

Optimal quantum control of mechanical motion at room temperature: ground state cooling

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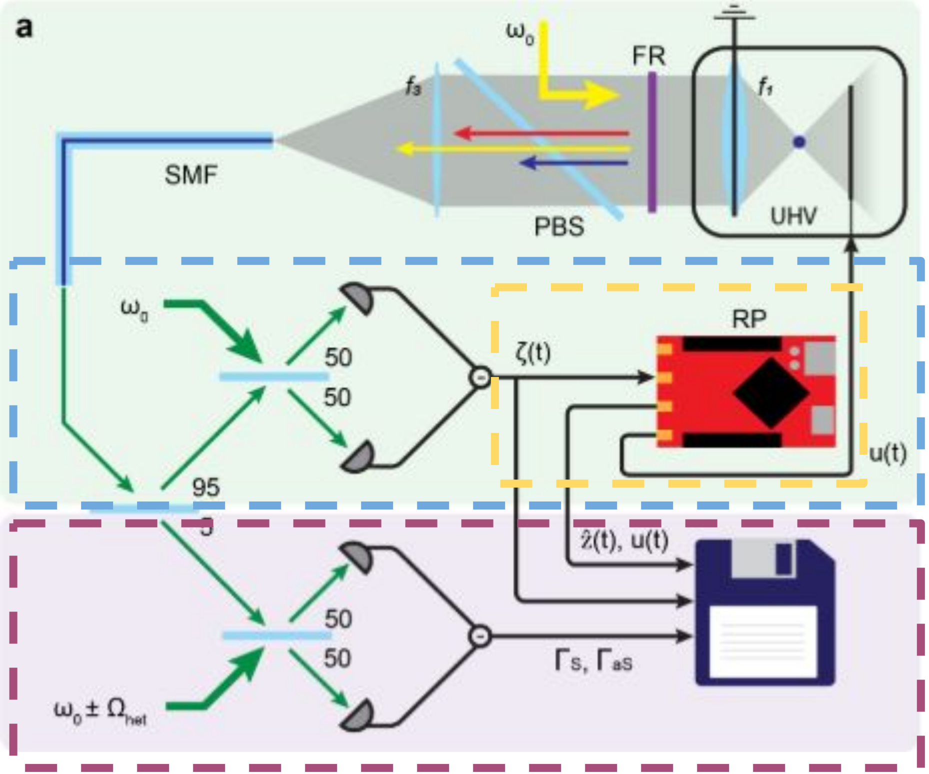
Optimal quantum control of mechanical motion at room temperature: ground state cooling

Resumen

The ability to accurately control the dynamics of physical systems by measurement and feedback is a pillar of modern engineering [1, 2]. Today, the increasing demand for applied quantum technologies requires to adapt this level of control to individual quantum systems [3, 4]. Achieving this in an optimal way is a challenging task that relies on both quantum-limited measurements and specifically tailored algorithms for state estimation and feedback [5]. Successful implementations thus far include experiments on the level of optical and atomic systems [6–8]. Here we demonstrate real-time optimal control of the quantum trajectory [9] of an optically trapped nanoparticle. We combine confocal position sensing close to the Heisenberg limit with optimal state estimation via Kalman filtering to track the particle motion in phase space in real time with a position uncertainty of 1.3 times the zero point fluctuation. Optimal feedback allows us to stabilize the quantum harmonic oscillator to a mean occupation of $n = 0.56 \pm 0.02$ quanta, realizing quantum ground state cooling from room temperature. Our work establishes quantum Kalman filtering as a method to achieve quantum control of mechanical motion, with potential implications for sensing on all scales.

Optimal quantum control of mechanical motion at room temperature: ground state cooling

Medición



single mode fiber (SMF) in a confocal arrangement. It is then split into two paths: an in-loop homodyne detection and an out-of-loop heterodyne detection. The homodyne detection is used for the efficient position measurement ($\zeta(t)$), and is directed to the Red-Pitaya (RP) board, where the LQG is implemented in real time. Both the state estimate ($\hat{\mathbf{z}}(t)$) the and control signal ($u(t)$) can be recorded. The control signal is applied to the electrode in the vacuum chamber. The heterodyne detection (local oscillator at a frequency of $omega_0 \pm \Omega_{\mathrm{het}}$) employs only 5% of the light and performs an out-of-loop measurement of the particle's energy via Raman scattering thermometry by measurement of the ratio of the Stokes and anti-Stokes scattering rates (Γ_{S}, Γ_{aS}). **b**, Contri-

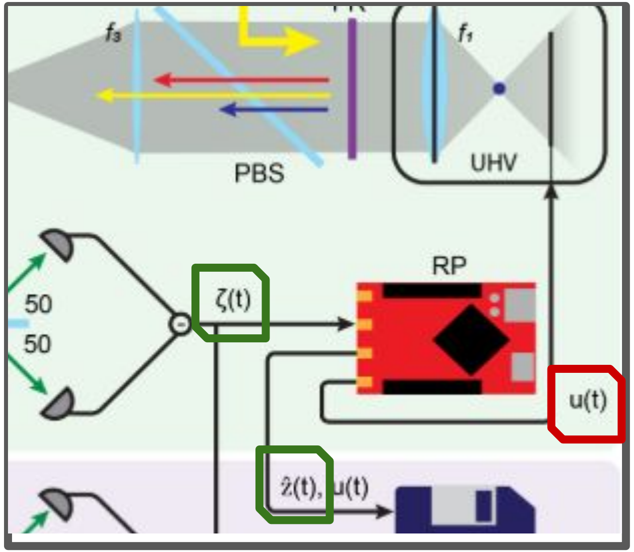
Optimal quantum control of mechanical motion at room temperature: ground state cooling

Real-time Optimal quantum control

Sistema cuántico lineal forzado por ruido blanco gaussiano → **Problema de control lineal-cuadrático-gaussiano (LQG)** → **feedback de salida óptimo**

=

Regulador lineal-cuadrático (LQR) + **Filtro Kalman**

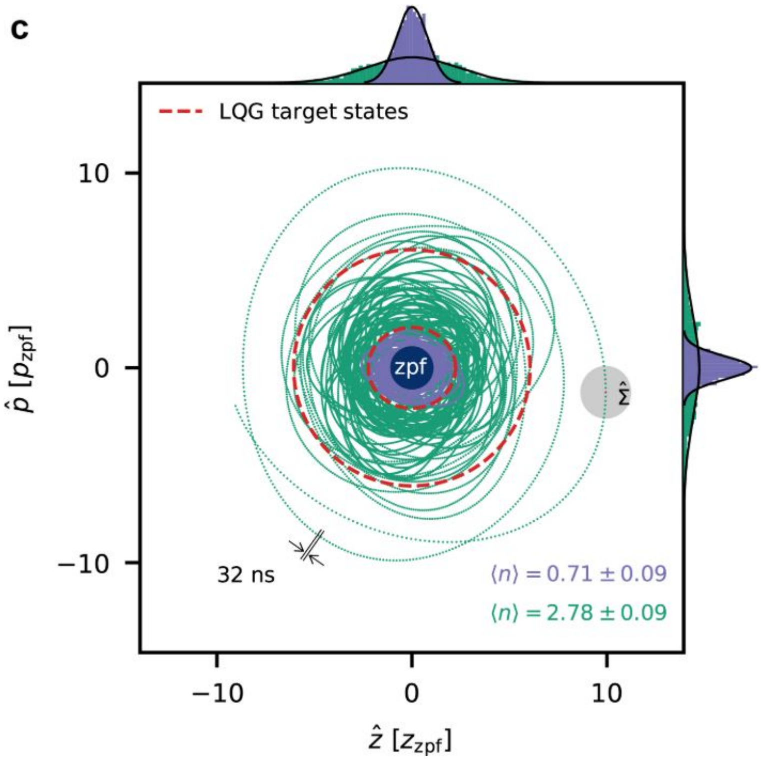


Cálculo del feedback óptimo para un dado estado resolviendo un problema de optimización para minimizar la energía

Como el sistema no es completamente medible, el filtro Kalman se diseña para proveer una estimación basada en medidas con ruido

Optimal quantum control of mechanical motion at room temperature: ground state cooling

Resultados: espacio de fases de la trayectoria cuántica



$$\sigma_z = \sqrt{\hat{\Sigma}^{ss}_{zz}} = 1.30\, z_{zpf}$$

$$\sigma_p = \sqrt{\hat{\Sigma}^{ss}_{pp}} = 1.35\, p_{zpf}$$

$$z_{zpf} = \sqrt{\hbar/(2m\Omega_z)}$$

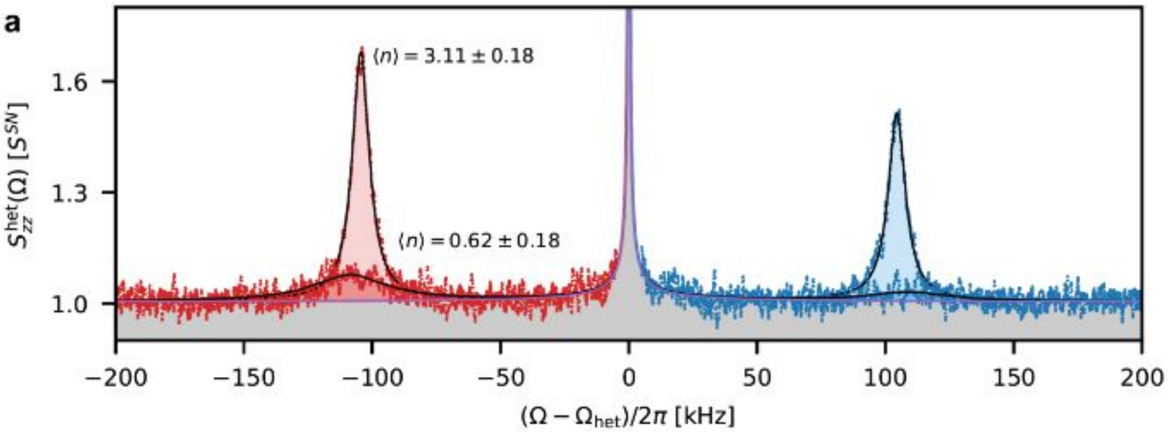
$$p_{zpf} = \sqrt{\hbar m\Omega_z/2}$$

Optimal quantum control of mechanical motion
at room temperature: ground state cooling

Resultados: Asimetría de bandas laterales

Stokes

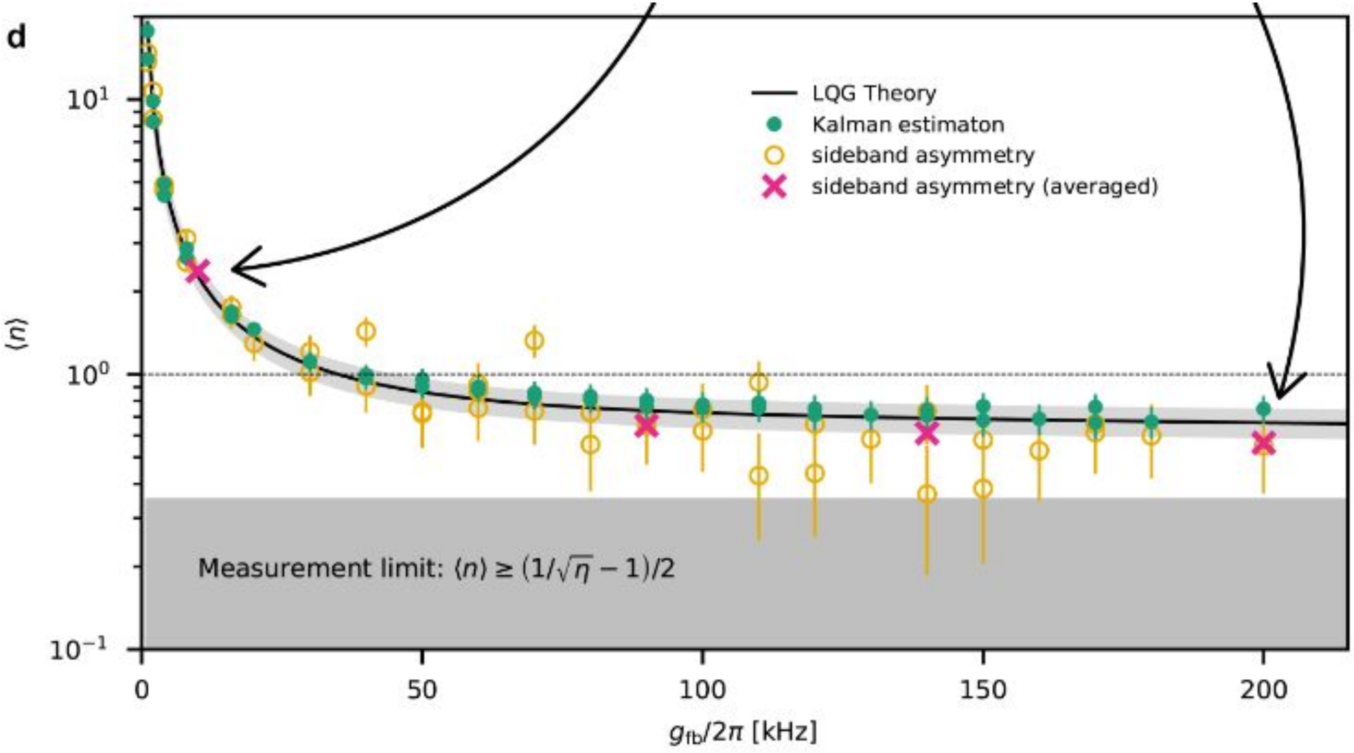
Anti-Stokes



$$\Gamma_{\mathrm{aS}}/\Gamma_{\mathrm{S}} = \langle n\rangle / \left(\langle n\rangle + 1\right)$$

Optimal quantum control of mechanical motion at room temperature: ground state cooling

Resultados: número de ocupación



Conclusiones

- Control cuántico óptimo en tiempo real de una nanopartícula levitada

- Características relevantes:
  - Condiciones experimentales tal que las propiedades mecánico-cuánticas no pueden ser despreciadas
  - Implementación en tiempo real de un filtro Kalman y un regulador lineal-cuadrático que provee los algoritmos requeridos para la estimación del estado óptima y una señal de feedback para el control

- Se alcanza un enfriado por medio de feedback al estado fundamental de movimiento ($\langle n \rangle = 0.56 \pm 0.02$) desde temperatura ambiente.

Panorama del enfriamiento de nanopartículas

Grupo	Atrapado	Enfriamiento	Temp. externa	<n>
Novotny	Óptico	Feedback	Ambiente	4
Novotny	Óptico	Feedback	60K	0.65±0.04
Aspelmeyer	Óptico	Cavidad	Ambiente	0.43±0.03
Aspelmeyer	Óptico	Feedback	Ambiente	0.56±0.02
Northup	Trampa de Paul	Feedback	Ambiente	$>4.6(8)\times10^4$

Felix, Martin, Vijay, Dominik, Lukas, Luisa, Massimiliano, Uros, Manuel, Kahan, David, Vladan, Nikolai, Markus, Lorenzo, Dmitry, Matthias, Pau, Tracy, Lorenzo, Philipp, Constanze, Andreas, Sebastian, Sungkun.

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Extra: fuentes de pérdida de eficiencia

Loss source	η^*	η
Microscope collection (d)	0.375	0.84
Microcope transimissivity (d)	0.84	0.84
Confocal mode-matching (d)	0.71	0.71
Heterodyne split (d)	0.95	0.95
Homodyne balancing (d)	0.99	0.99
Detector efficiency (d)	0.85	0.85
Detector dark-noise (d)	-	0.92
Kalman digital noise (d)	-	0.98
Environmental information loss (e)	-	0.96
Total	0.178	0.347

Table A1. **Measurement efficiency**. The total efficiency budget for photon and information loss. All loss sources are considered in both the detection and electronic line (d), and information loss to the environment (e).

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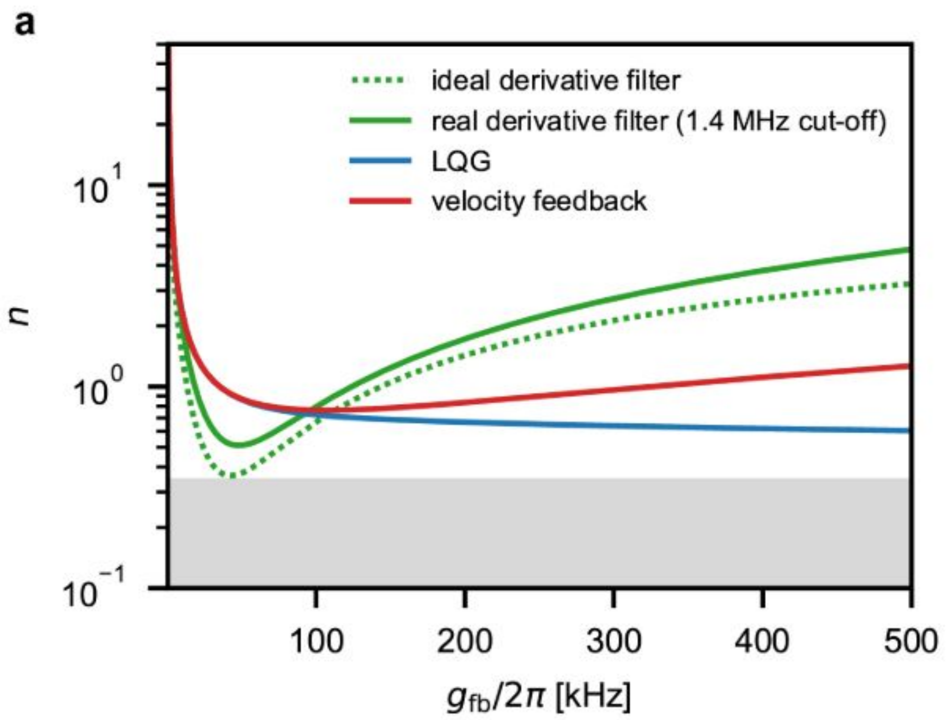
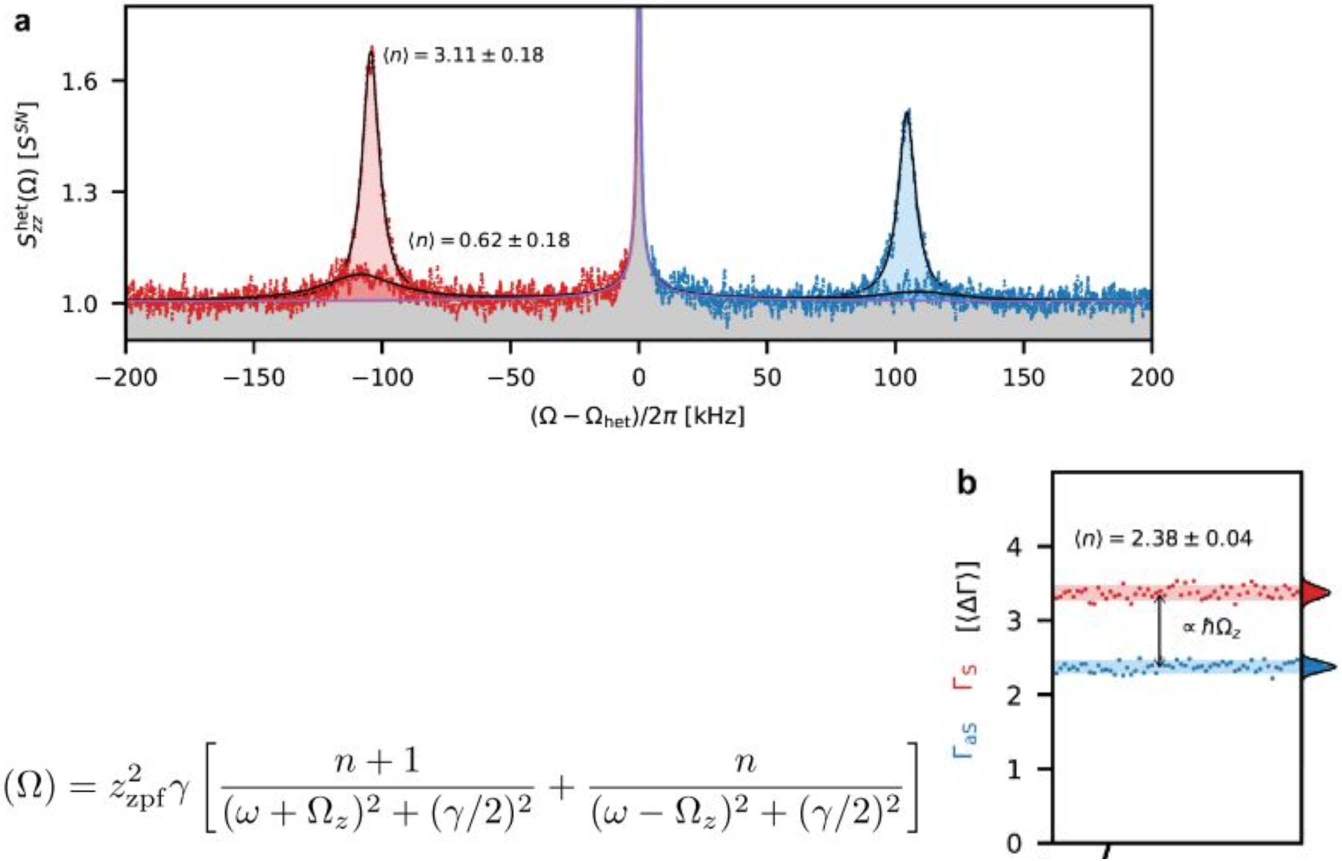
Extra: comparación entre métodos de feedback



Stokes Anti-Stokes



$$S_{zz}(\Omega) = z_{\mathrm{zpf}}^2 \gamma \left[\frac{n+1}{(\omega+\Omega_z)^2 + (\gamma/2)^2} + \frac{n}{(\omega-\Omega_z)^2 + (\gamma/2)^2} \right]$$