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Probing Non-Standard Physics with Levitated Optomechanics

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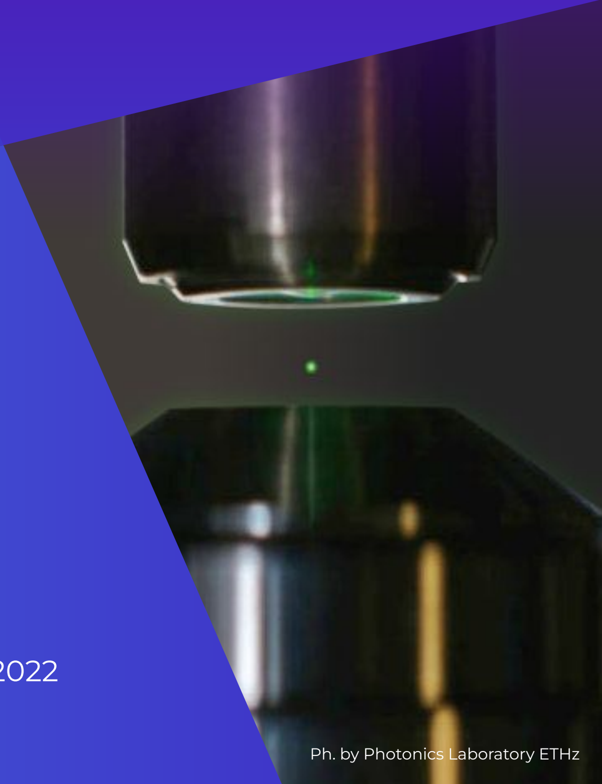


Ph. by Photonics Laboratory ETHz

Searching for New Physics at the Quantum Technology Frontier - Zurich 2022

What is levitated optomechanics?

Optomechanics:
interaction between light and mechanical systems.

Levitated:
the object is captured by fields, in air or vacuum.

Electric	Coulomb force
Magnetic	Meissner effect
Optic	Dipole forces

Ω_0 d $V(q)$ m e^-

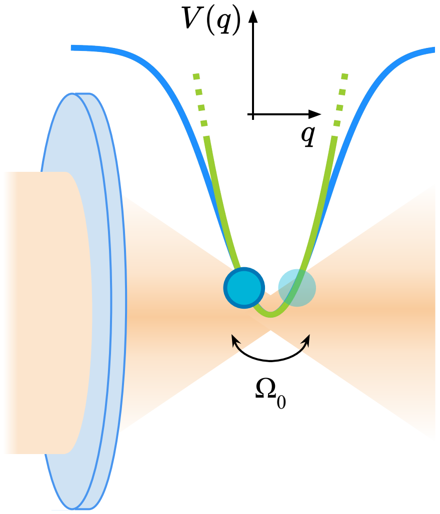
Degrees of freedom

3D damped harmonic oscillator

Decoherence

Measure

Control



$$m\ddot{q}(t) + m\gamma\dot{q}(t) + m\Omega_0^2 q(t) = F_{\mathrm{fluct}}(t) + F_{\mathrm{el}}(t)$$

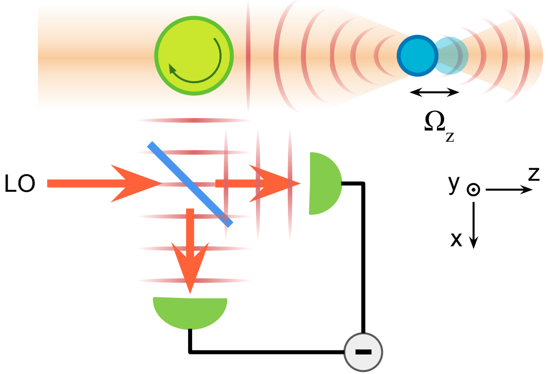
Optical levitation of a nanoparticle

Optical tweezer
Silica nanoparticle.
Photons exchange momentum; net force pushes the particle towards the focus.

Dipolar scatterer
Charged particle in EM field: scatters like a dipole.
Information on the position is encoded on the phase of the scattered field.

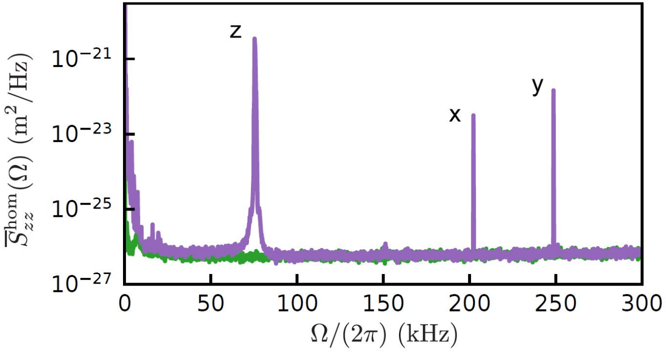
$$I(t) \propto \cos(\phi_{\mathrm{LO}} - \phi_{\mathrm{sc}}(t)) \propto \sin(\phi_{\mathrm{sc}}) \approx 2k\Delta z(t)$$

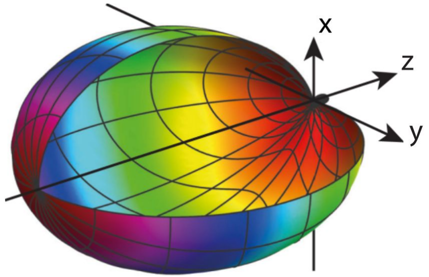
with $\phi_{\mathrm{LO}} = -\pi/2$



Some quantities:

- 100nm Ø silica nanoparticle
- 10^6 AMU
- 1W laser power; 1550nm
- Ω_z ~ 70kHz



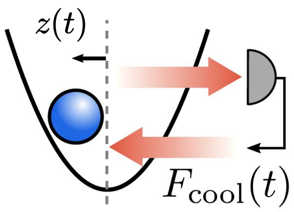


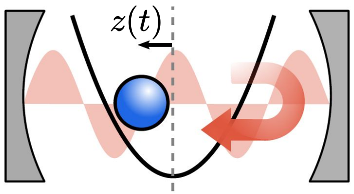
Tebbenjohanns *et al.*, PRA 2019

Controlling the dynamics of the trapped objects

C. Gonzalez-Ballestero *et al.*, Science 2021

Passive feedback
Dissipation of energy through interaction with a cavity.





Active feedback
Generation of damping force tailored on the movement of the object.
→ Requires detection of the movement

- **parametric feedback**: at twice the resonance frequency

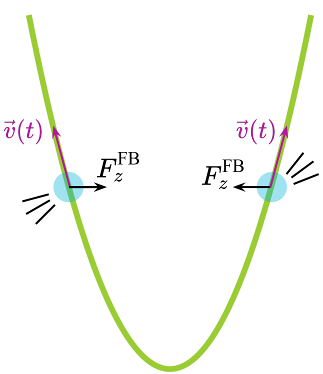
$$V(t) = \frac{1}{2}(\,\bar{k} + k(t))z$$

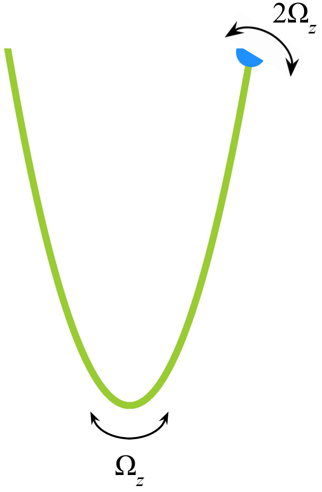
$$\bar{k} = \Omega_z^2 m \;\; ; \;\; k(t) = A_0 \cos(2\Omega_z t + 2\theta_z + \phi)$$

- **linear feedback**: simulates a drag; at the resonance frequency

$$E(t) \propto n_{\mathrm{hot}} e^{-\gamma_{\mathrm{FB}} t} + n_{\mathrm{cool}}$$

$$\langle E \rangle \propto \frac{\Gamma_{\mathrm{bath}}}{\gamma_{\mathrm{FB}}} + \gamma_{\mathrm{FB}} \frac{S_{\mathrm{imp}}}{4}$$

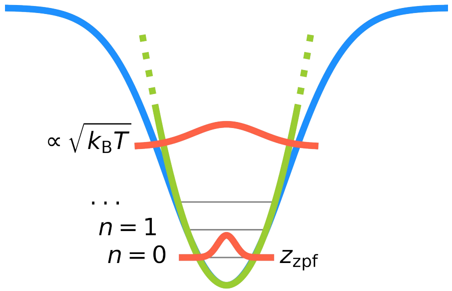


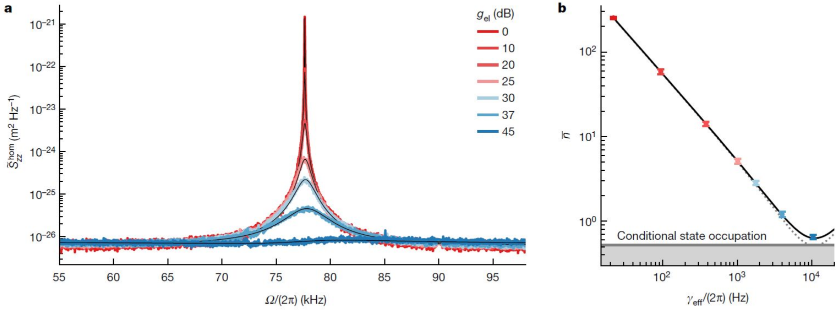


Cooling a nanoparticle to its motional quantum ground state

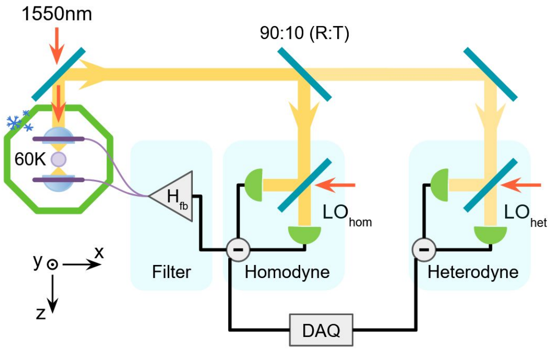
- Trapping in a cryostat
- High efficiency interferometer

$$n = \frac{1}{2}\left(\frac{1}{\sqrt{\eta}} - 1\right)$$



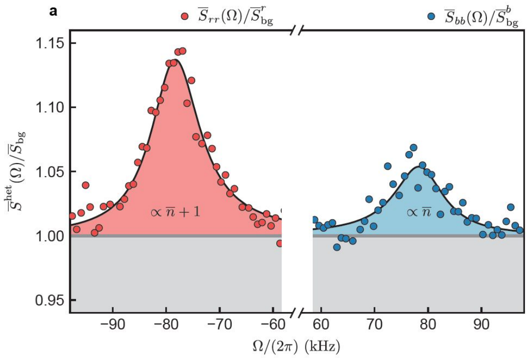


Tebbenjohanns, Mattana, Rossi *et al.*, Nature 2021

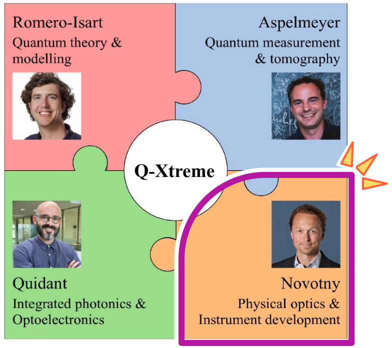


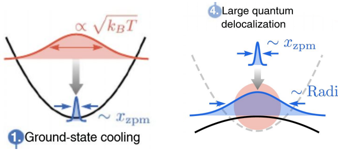
Some quantities:

- $T = 60\text{K};\ P = 3 \cdot 10^{-9}$ mbar
- $n = 0.65$ mean occupation
- state purity 43%
- $\eta = 0.24$

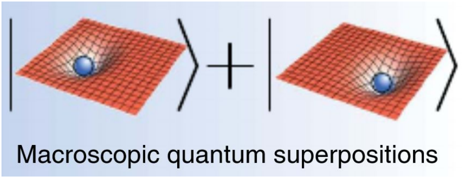


A versatile platform

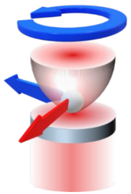


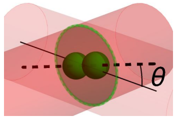


Gonzalez-Ballestero *et al.*, Science 2021



Applied Physics & Sensing

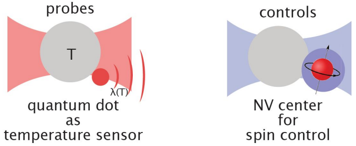


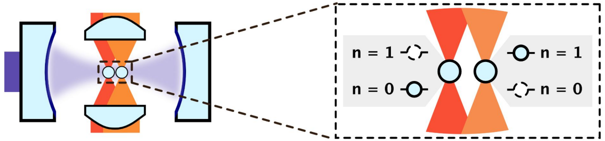


Fundamental Physics

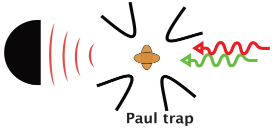
Inter-disciplinary

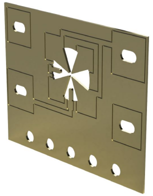
promising systems: hybrid particles





levitated spectroscopy





Test bench for semiclassical gravity

A. Grossardt *et al.*, PRD 2016

Problem: perturbative quantization of the gravitational field

Try: semiclassical theory $$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = \frac{8\pi G}{c^4} \langle \Psi | \hat{T}_{\mu\nu} | \Psi \rangle$$

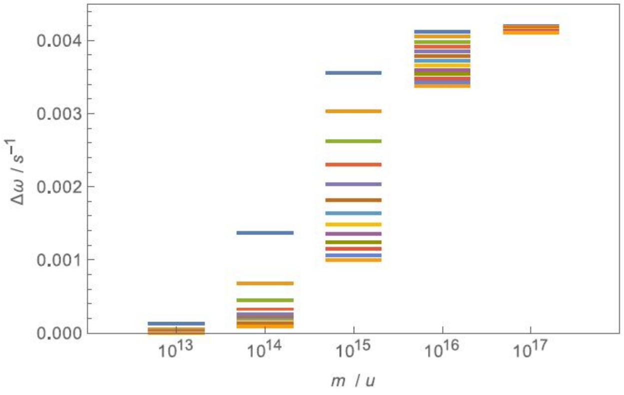
Schrödinger-Newton equation

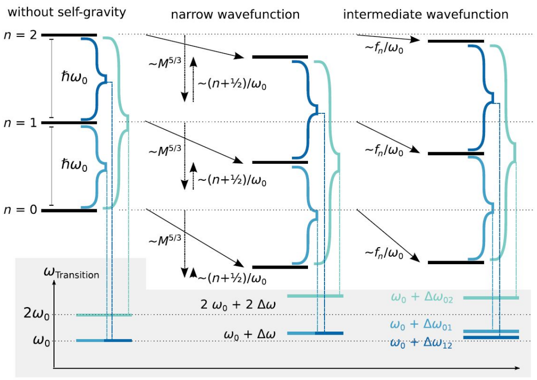
$$i\hbar \frac{\partial}{\partial t} \psi(t, \mathbf{r}) = \left(-\frac{\hbar^2}{2M} \nabla^2 + V_{\text{ext}} + V_g[\psi] \right) \psi(t, \mathbf{r})$$

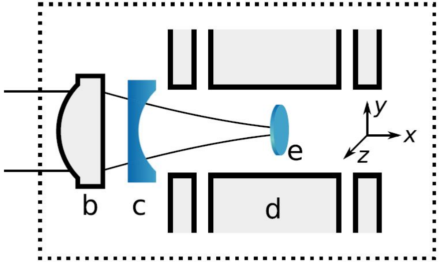
$$\Delta E_n = -\frac{G\hbar m}{4\sigma^3 \omega_0} f_n(\alpha)$$

$$\alpha = 2\sigma \sqrt{M\omega_0/\hbar}$$

$$\Delta\omega_{n_1 n_2}^{\text{interm}} = \Delta\omega_{\text{SN}} g_{n_1 n_2}(\alpha)$$







Some quantities:

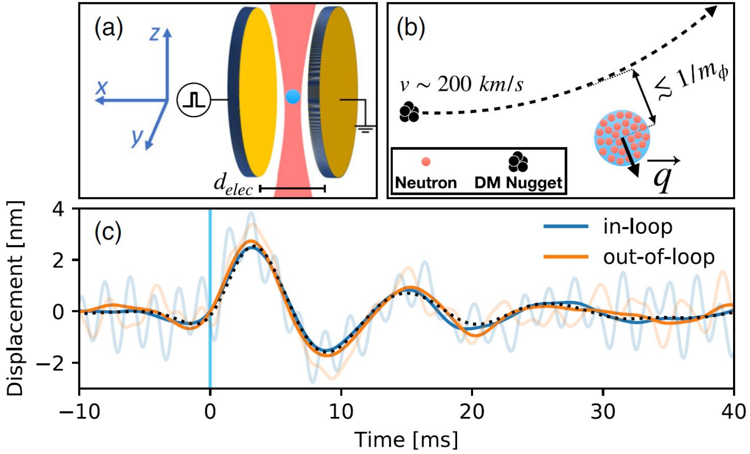
- $\omega_0 \sim 2\pi \cdot 10\text{Hz}$
- dimensions ~ 5 µm
- M ~ 10^{15} AMU (osmium)
- $\Delta f \sim 0.1$ mHz

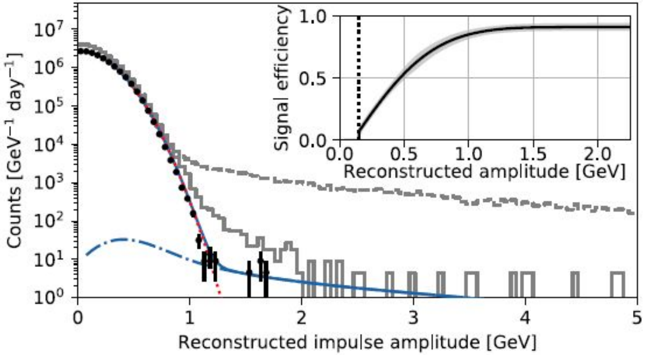
Levitodynamics for dark matter sensors

F. Monteiro *et al.*, PRL 2020

Problem: detecting dark matter with massive detectors is difficult
Try: use macroscopic force sensors

$$V(r) = \frac{\alpha}{r} e^{-r/\lambda}$$





Some quantities:

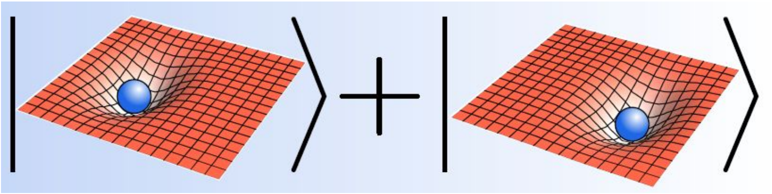
- 10 µm Ø silica nanoparticle
- COM cooled to 200 µK
- P ~ 10^{-7} mbar
- Sensitivity down to 0.3GeV

Macroscopic quantum superpositions

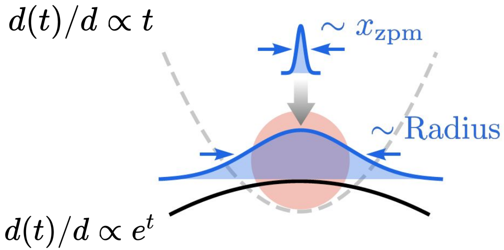
Problem: expanding quantum mechanic description to the macroscopic world

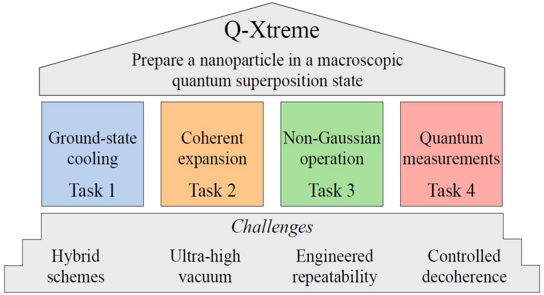
Try: prepare massive objects in spatial quantum superposition state
-> delocalization must be bigger than object's size

C. Gonzalez-Ballestero *et al.*, Science 2021



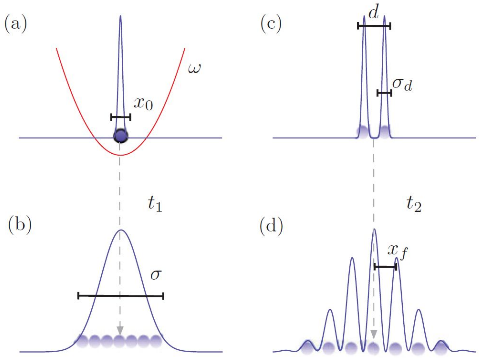
$$d = x_0\sqrt{8\mathcal{P}}$$
$$x_0 = \sqrt{\hbar/(2M\omega_x)}$$
$$\mathcal{P} = \mathrm{tr}[\hat{\rho}^2] = 1/(2\bar{n}+1)$$

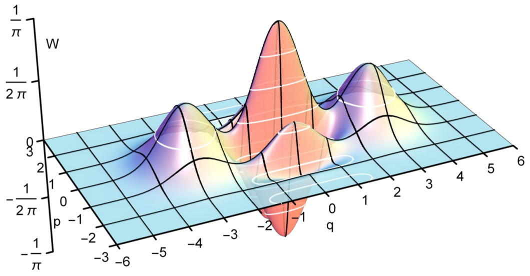




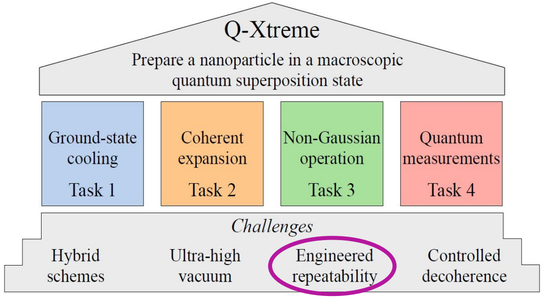
Macroscopic quantum superpositions

O. Romero-Isart, PRA 2011





By Geek3 - Own work This diagram was created with Mathematica., CC BY-SA 4.0, https://commons.wikimedia.org/w/index.php?curid=79089559



Some quantities:

- Target mass: >10^9AMU
- particle dimensions: 10^{-6}m
- $x_{zpf} = 10^{-2}$m

Outlook

- Founding principles of levitated optomechanics
- Levitated optomechanics as a tool for quantum control of motion
- Applications in non-standard physics