Manipulation of levitated optomechanics to test fundamental physics

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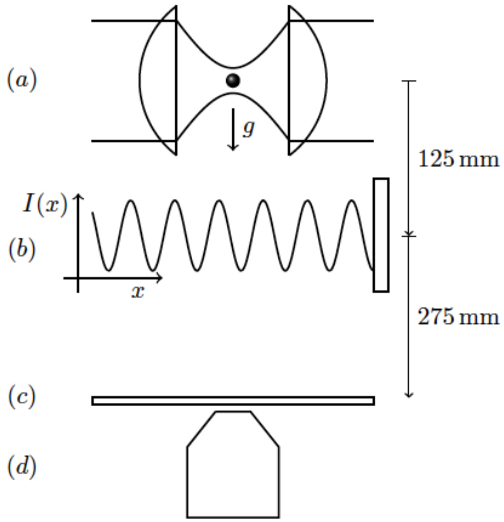
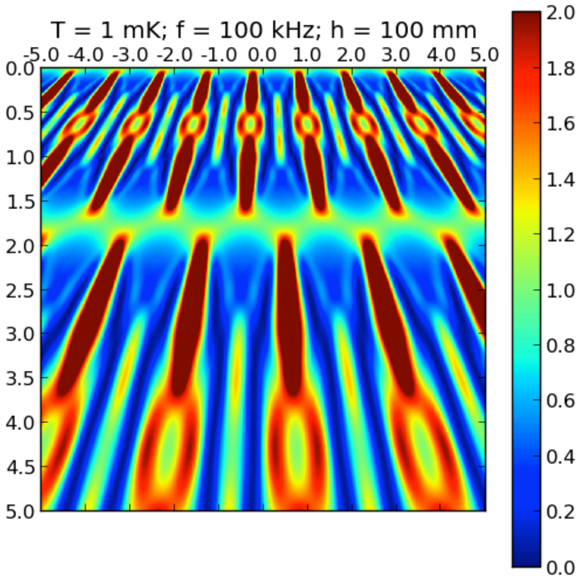
Nanoparticle Talbot Interferometer: NaTalI



Talbot interferometer with particle of mass: 10^6 - 10^7 amu (~20nm diameter)

- **Wigner function model of interference pattern**
- **Dominating decoherence effect:** Blackbody emission and absorption.
- **Mass of particle is limited by Earth's gravity ... future experiment in space?**

Quantum carpet:



Collimation/Preparation of spatial coherence translates to cooling of the particle in the trap.

Advantage compared to other schemes:
We don't need ground state of trapped particle before the drop.

Bateman, J., S. Nimmrichter, K. Hornberger, and H. Ulbricht
Near-field interferometry of a free-falling nanoparticle from a point-like source
Nature Communications 4, 4788 (2014).

LEVITATED OPTOMECHANICS

Subkelvin Parametric Feedback Cooling of a Laser-Trapped Nanoparticle

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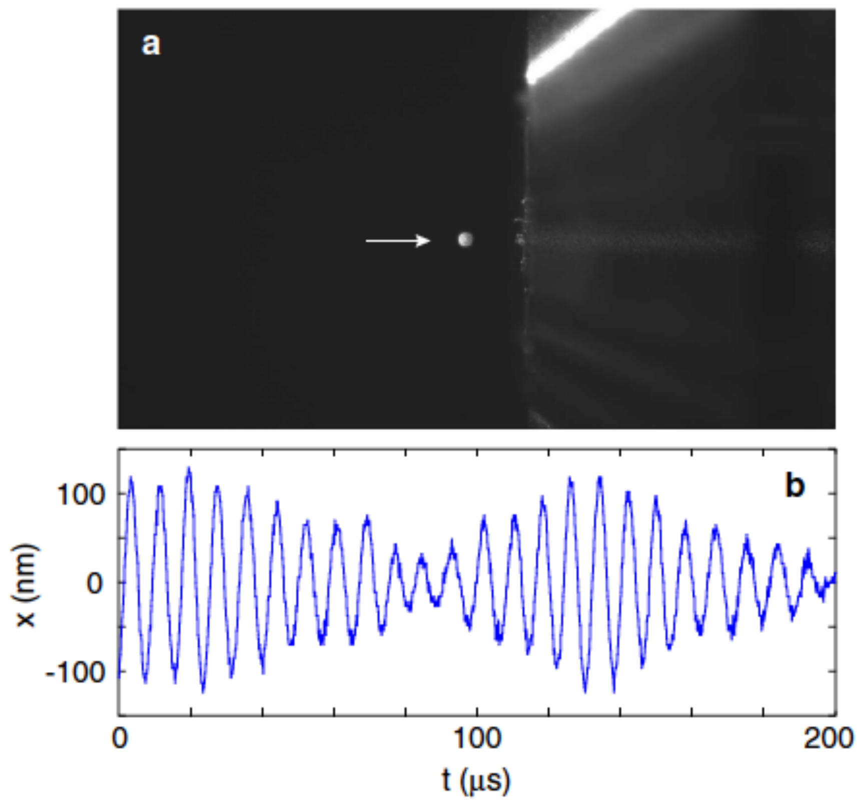

Cavity cooling of an optically levitated submicron particle

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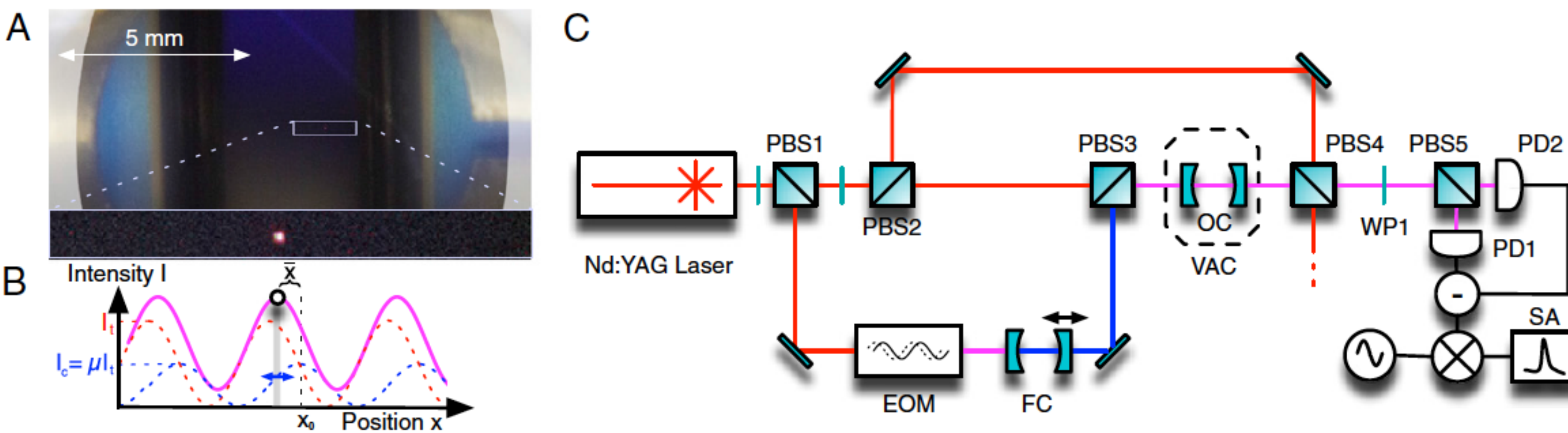

Cavity Cooling a Single Charged Levitated Nanosphere

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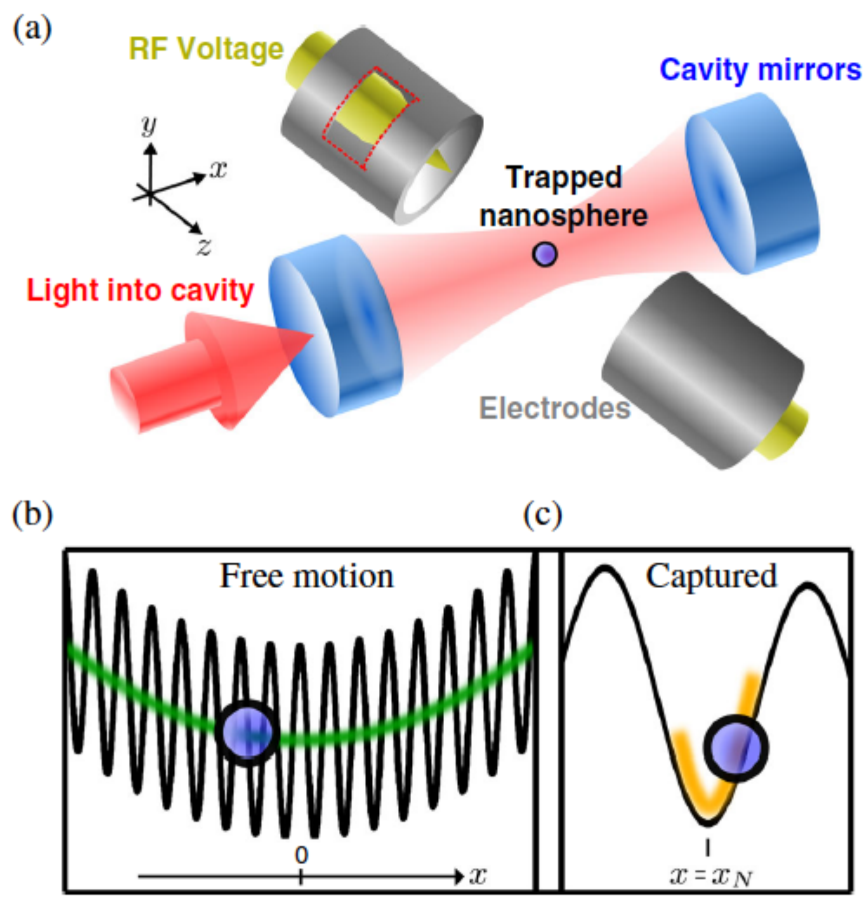
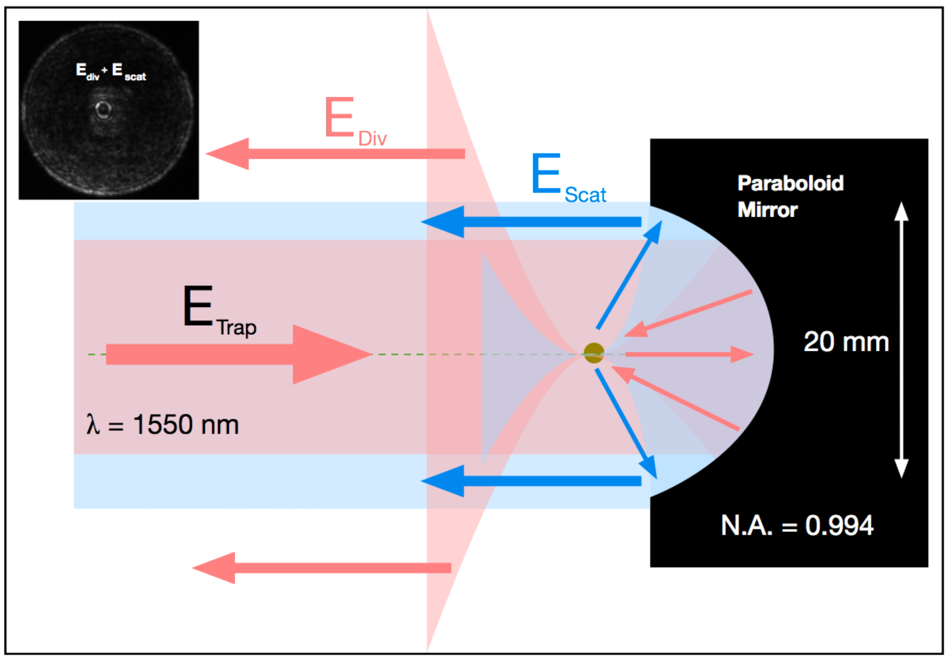
(Received 31 December 2014; published 27 March 2015)



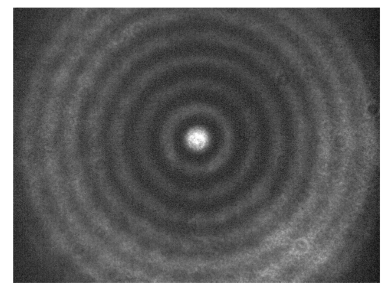
Experiments with nanoparticles: the particle optical trap

- **Trap a single particle in vacuum**
- **Optical parametric feedback to cool the centre of mass motion**

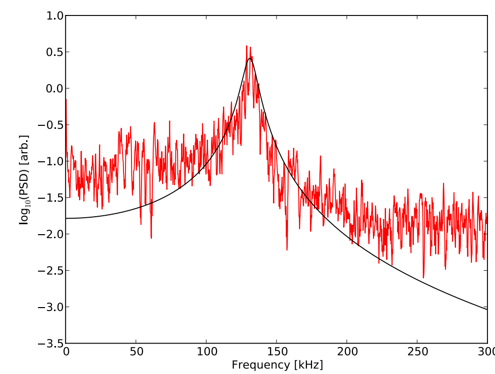
Setup schematics:



Particle in the trap:
42 nm – 150 nm diameter SiO_2, <100 mW, NA=0.9, down to **$1x10^{-6}$ mbar**

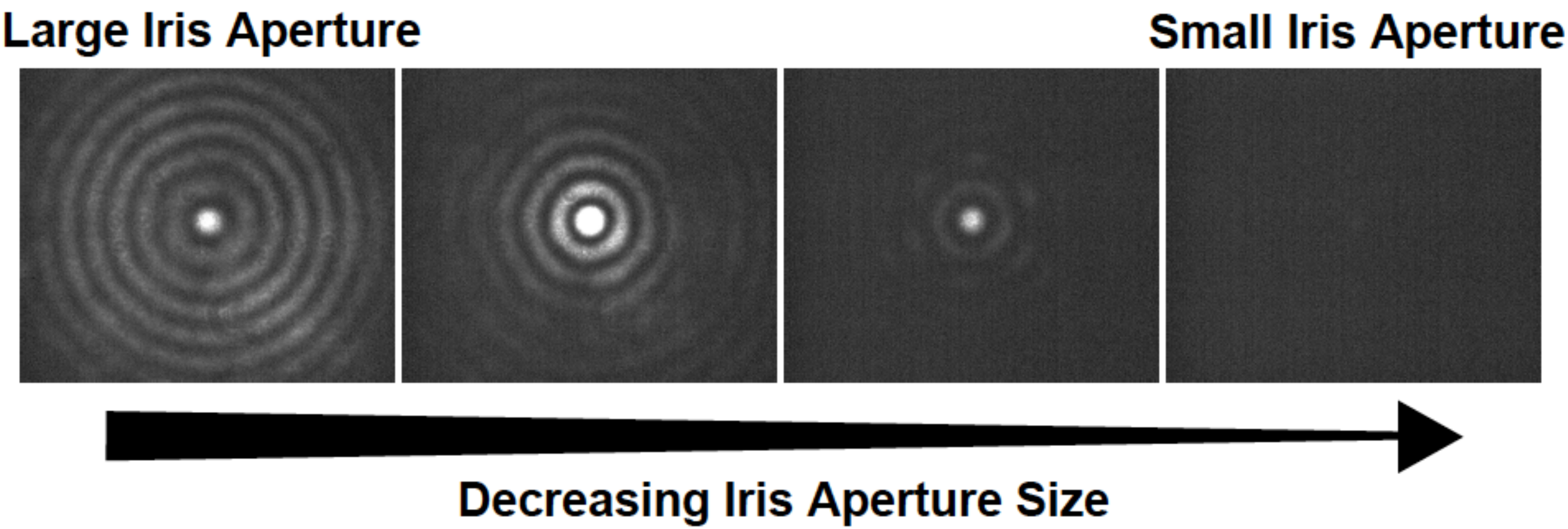


Mechanical frequency measurement:

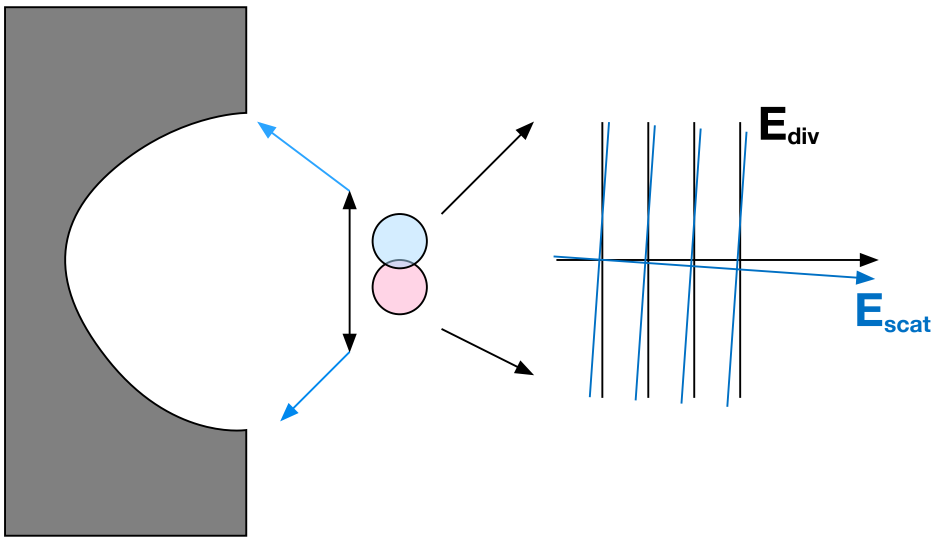


Trapping, 3d imaging, and 3d cooling done with a single beam of 1550nm light.

Signal for detection of motion of particle: optical interference pattern



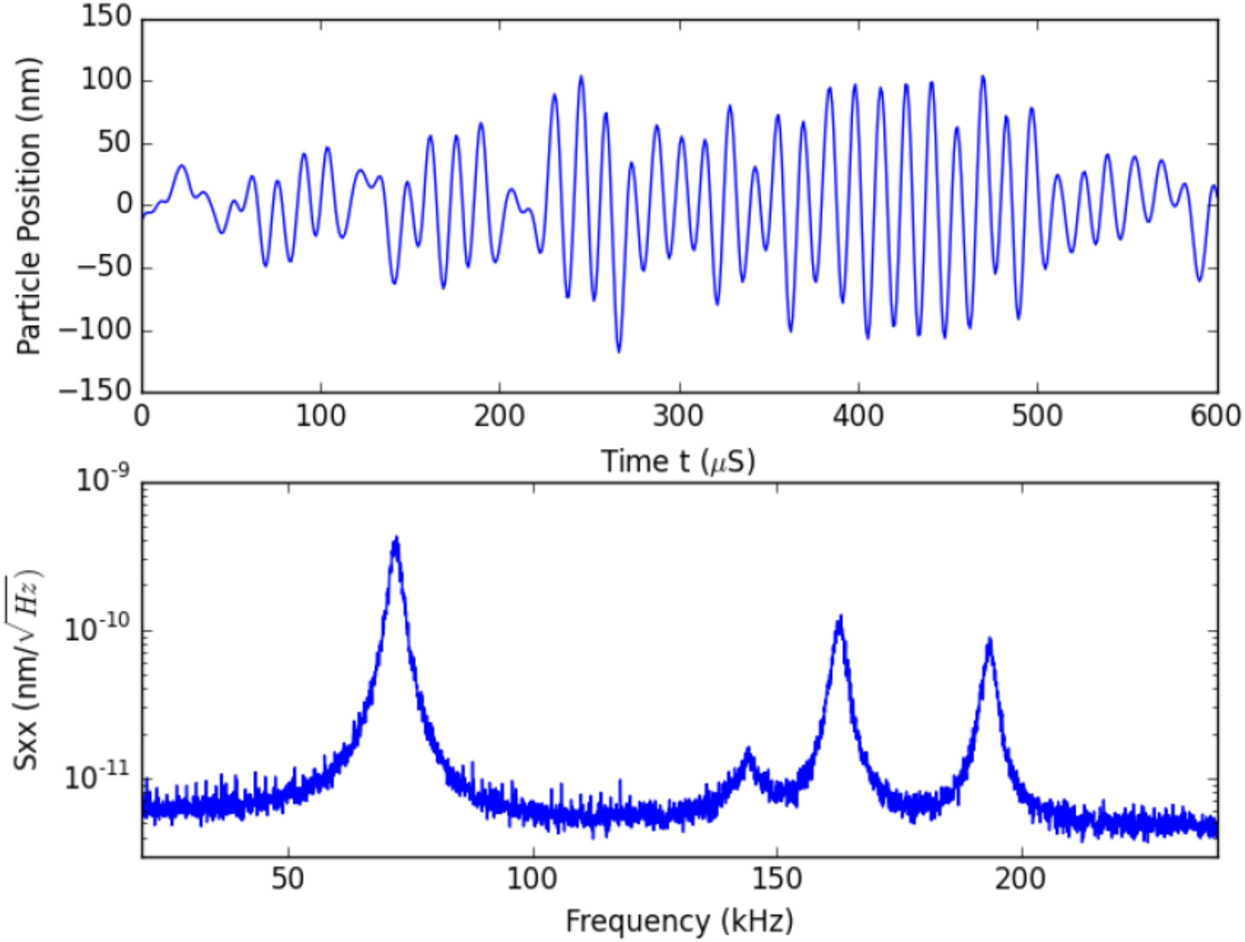
Light Interferometry for Particle Detection of x,y motion:



The total intensity at the detector is:

$$I \propto |E_{total}|^2 = |E_{div} + E_{scat}|^2 = E_{div}^2 + 2E_{div}E_{scat}\sin(\phi_{scat}) + E_{scat}^2$$

See the mechanical oscillation ….

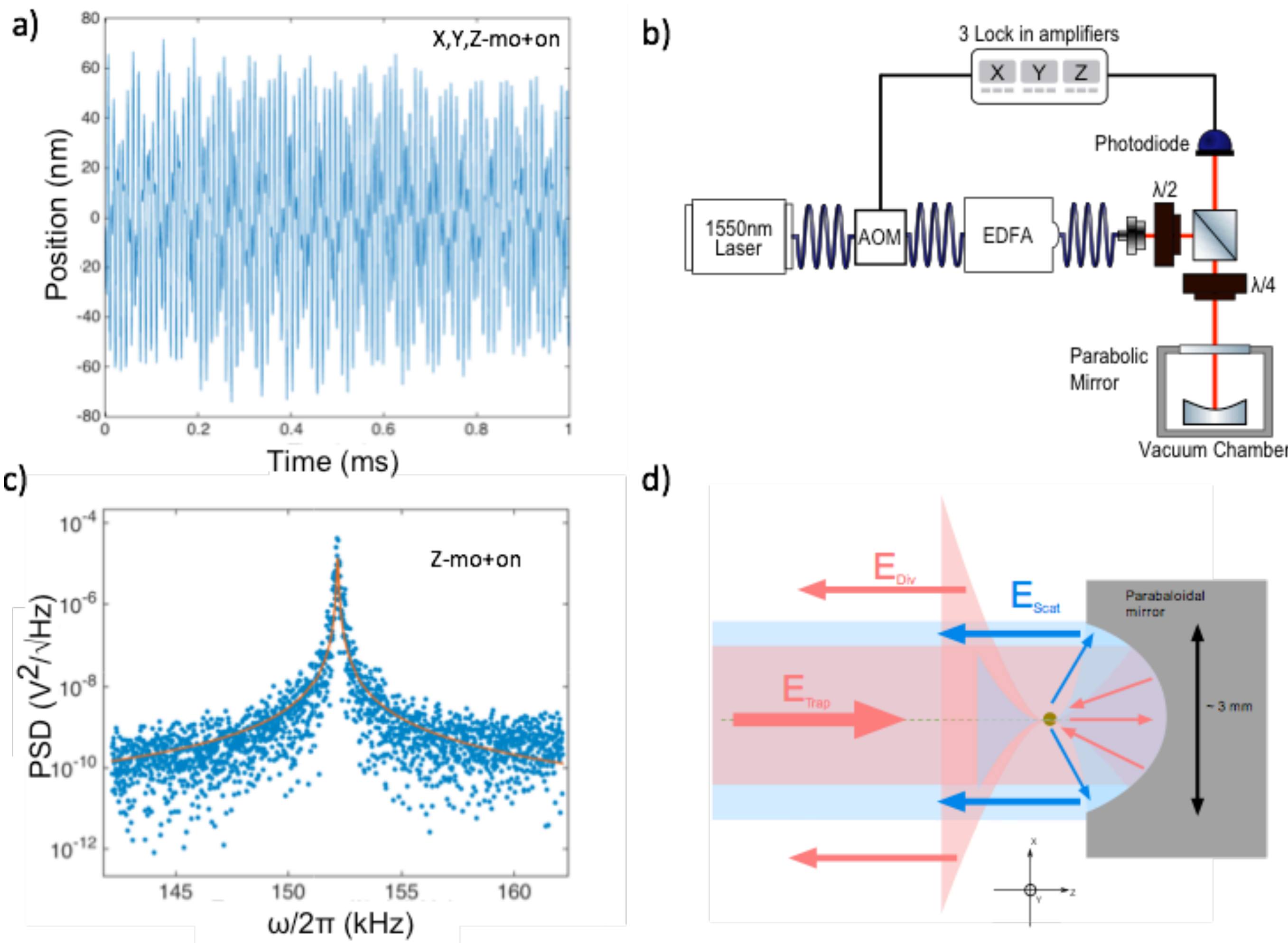


$$\omega_0 = \sqrt{k_0/m}$$, with $$k_0 = 8\alpha P/(c\pi\epsilon_0 \mathrm{w_f^4})$$

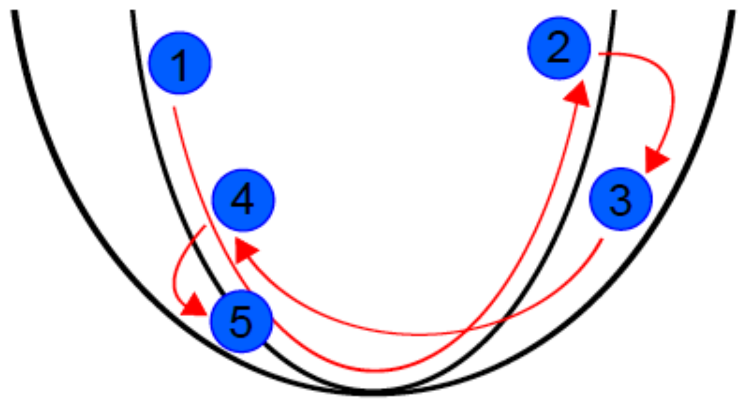
Trap and measure position …

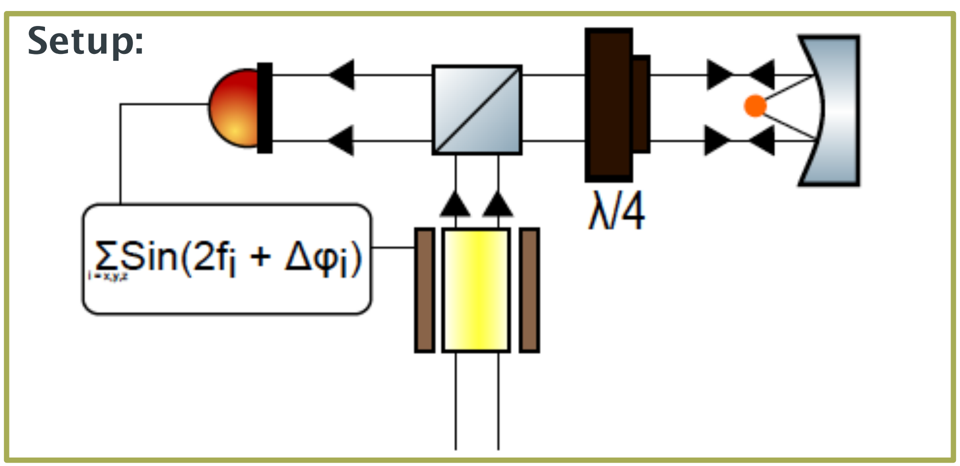
Equation of motion: $\ddot{x}(t) + \Gamma_0 \dot{x}(t) + \omega_0^2 x(t) = \frac{1}{m}[F_{\text{fluct}}(t) + F_{\text{feed}}(t)]$

Power spectral density: $$S_x(\omega) = \frac{k_B T_0}{\pi m} \frac{\Gamma_0}{([\omega_0 + \delta\omega]^2 - \omega^2)^2 + \omega^2[\Gamma_0 + \delta\Gamma]^2}$$



Parametric Feedback Cooling: use the interference signal to modulate the trapping laser light intensity



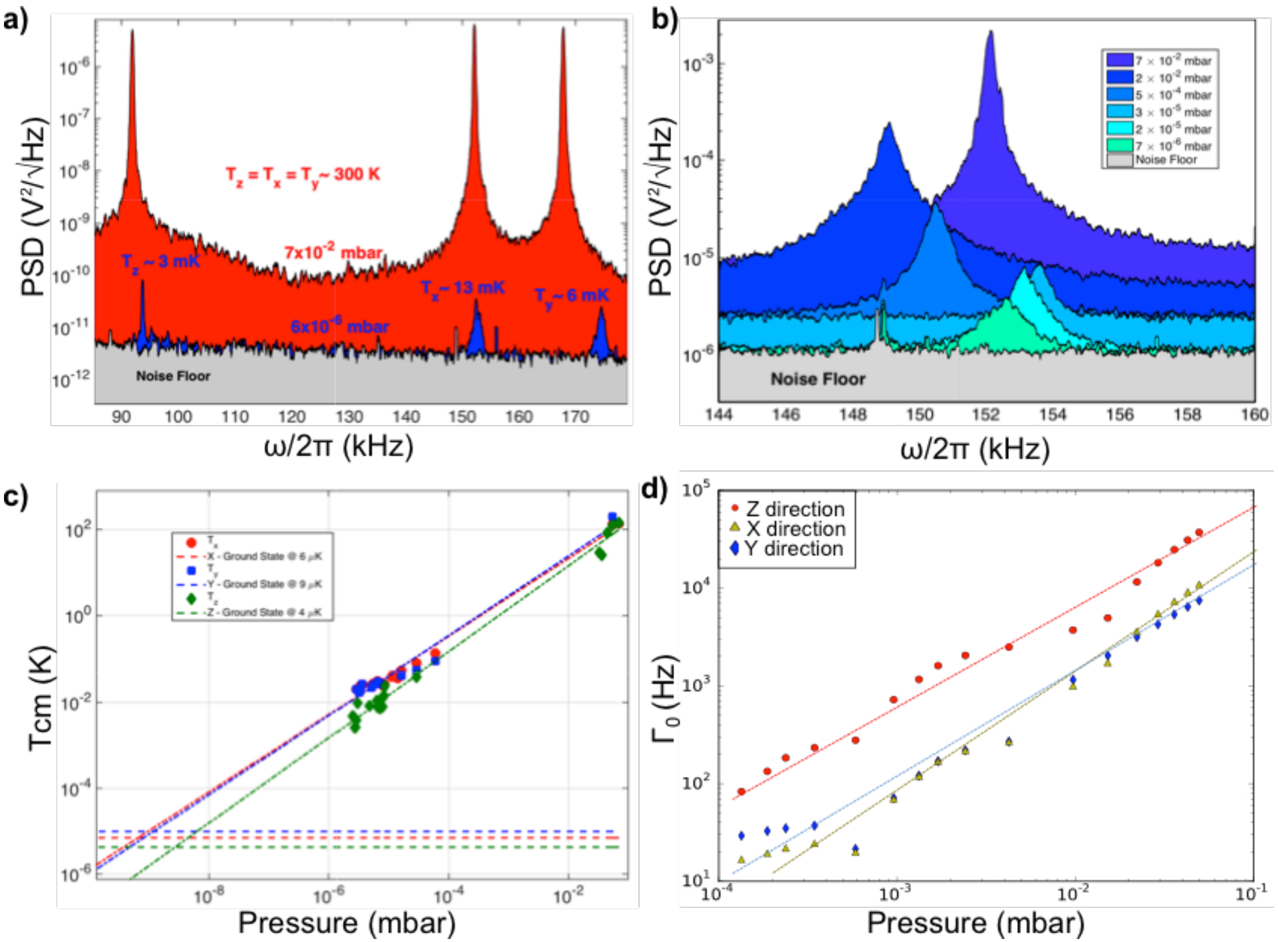


- Cooling the COM motion of the particle by modulation of the trap depth => trapping laser power modulation
  - Increase trap depth when particle is moving away from center.
  - Decrease trap depth when particle is moving towards the depth.
- Feedback signal in the form of:

$$\propto \sin(2\omega_0 t + \phi)$$

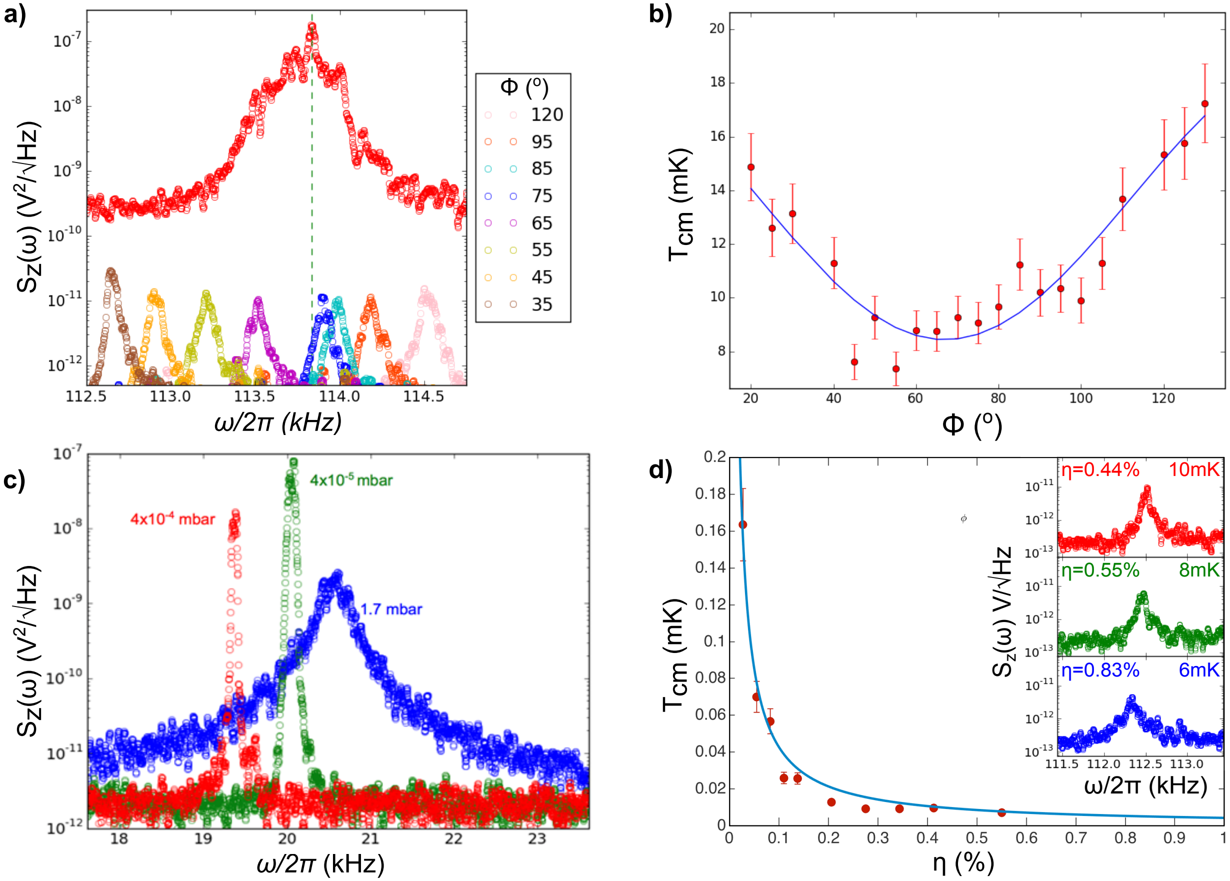
Studying the dynamics of the trapped particle …

Power spectral density: $$S_x(\omega) = \frac{k_B T_0}{\pi m} \frac{\Gamma_0}{([\omega_0 + \delta\omega]^2 - \omega^2)^2 + \omega^2 [\Gamma_0 + \delta\Gamma]^2}$$



- 26nm to 150nm particle
- X,y,z cooled to ~1 mK
- Q = 10^7 measured @10^{-5} mbar
- Damping by gas collision
- 200fm/sqrt{Hz} position resolution of detection

The effect of the parametric feedback …

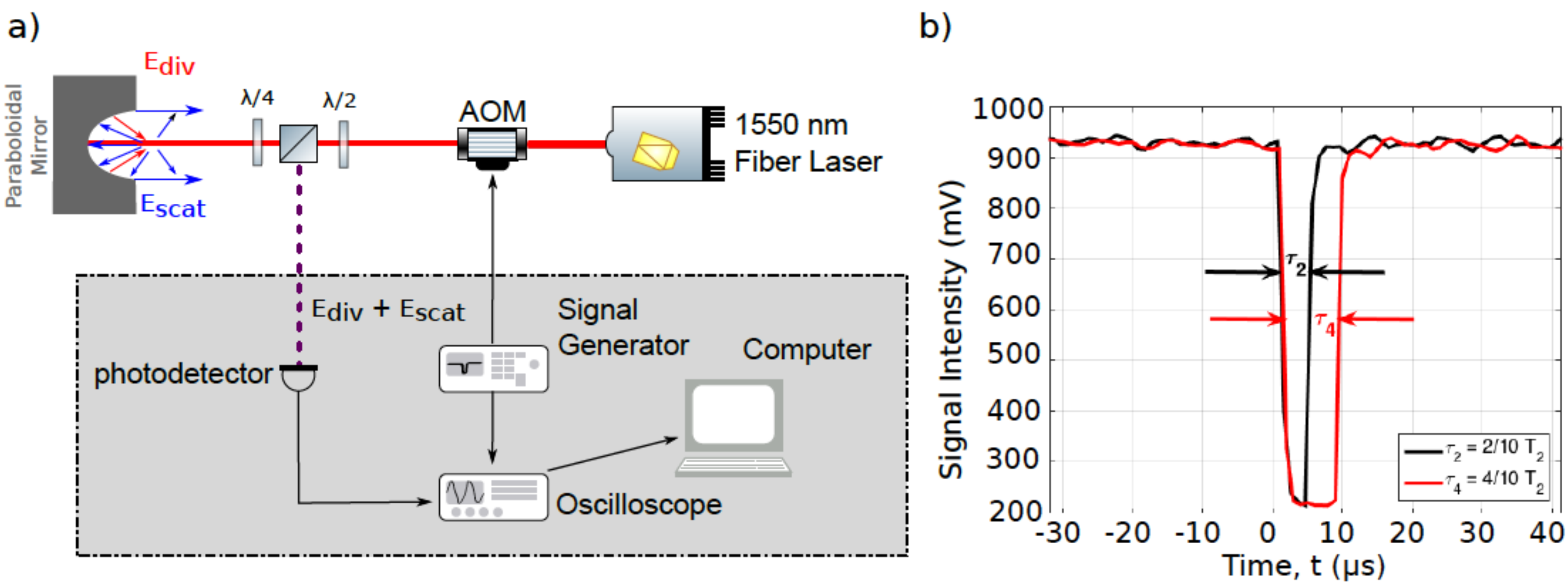


- **Result: We have a source, now we build the Talbot Interferometer to test the superposition principle in a new mass range!**
- **To cool further we need to overcome the present limit by the noise of the elecgronics.**

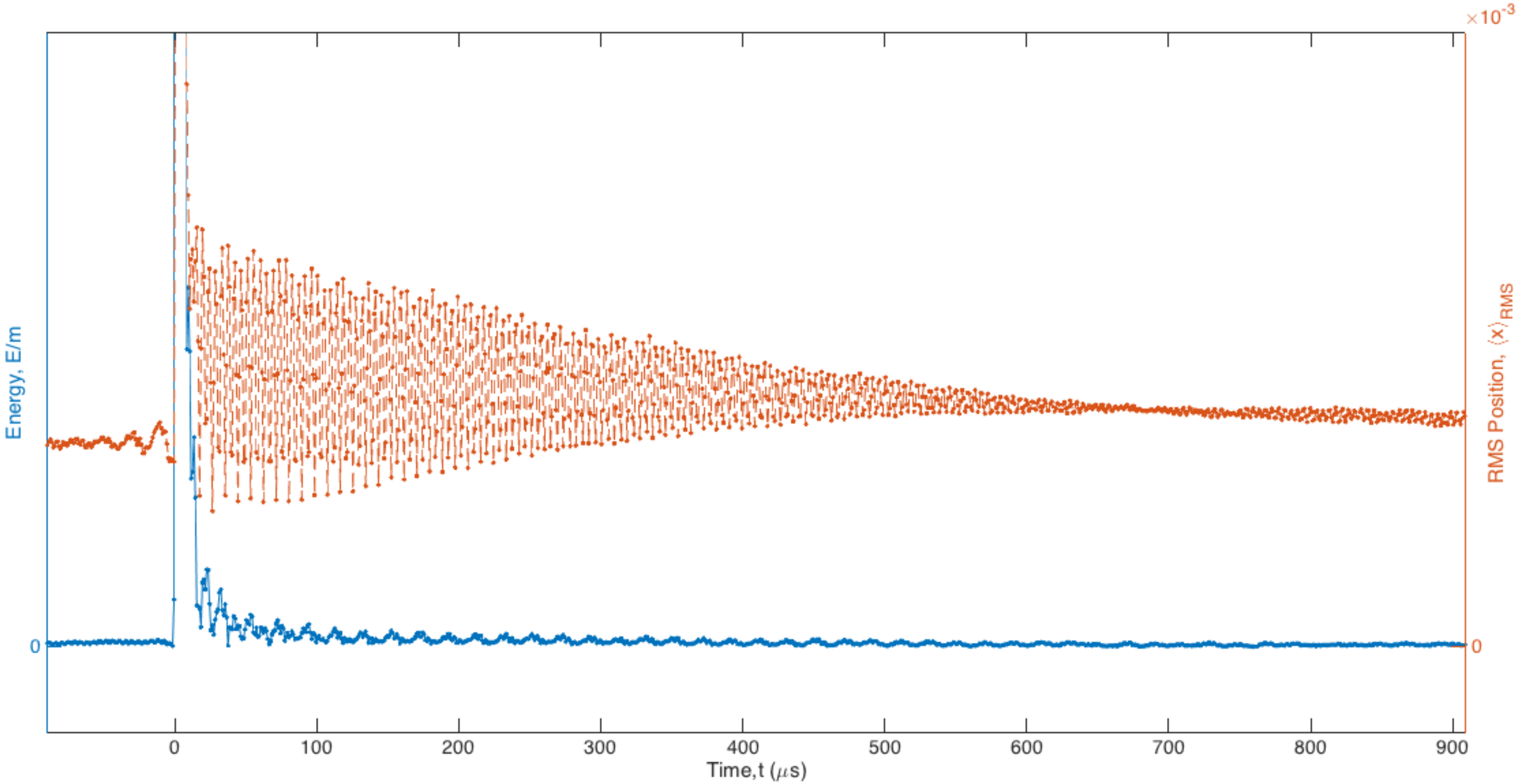
Vovrosh, J., M. Rashid, D. Hempston, J. Bateman, and H. Ulbricht, ***Controlling the Motion of a Nanoparticle Trapped in Vacuum***, arXiv:1603.02917 (2016).

LEVITATED OPTOMECHANICS: SQUEEZING/SQUASHING

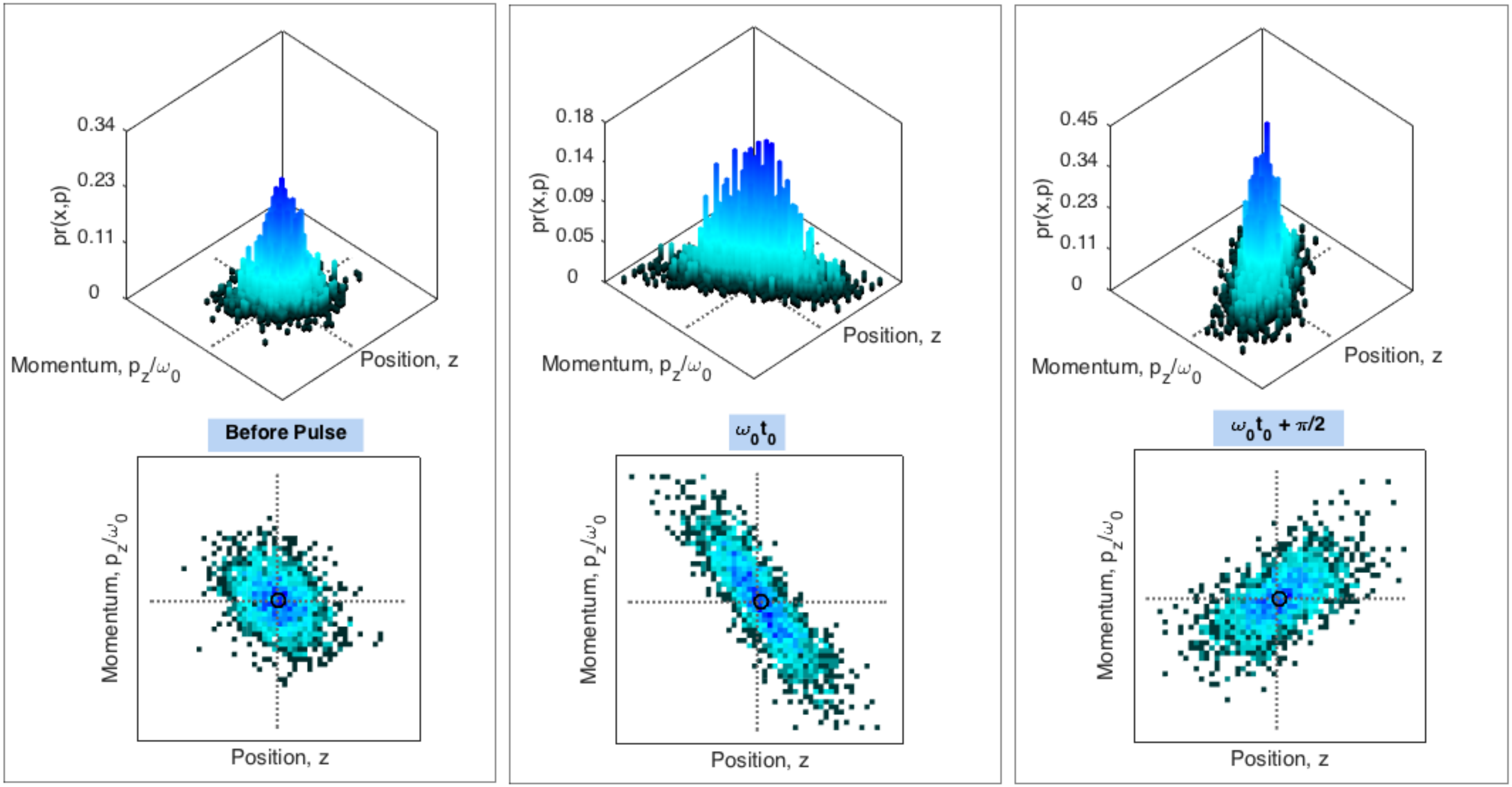
Squeezing/Squashing: by fast switching the trap frequency



RMS position vs time



Squeezing the thermal motion



Rashid, M., T. Tufarelli, J. Bateman, J. Vovrosh, D. Hempston, M. S. Kim, and H. Ulbricht, ***Experimental Realisation of a Thermal Squeezed State of Levitated Optomechanics***, arXiv:1607.05509 (2016).

NOW FOR SOMETHING COMPLETELY DIFFERENT… SEMICLASSICAL GRAVITY

Schroedinger-Newton (SN): semi-classical gravity

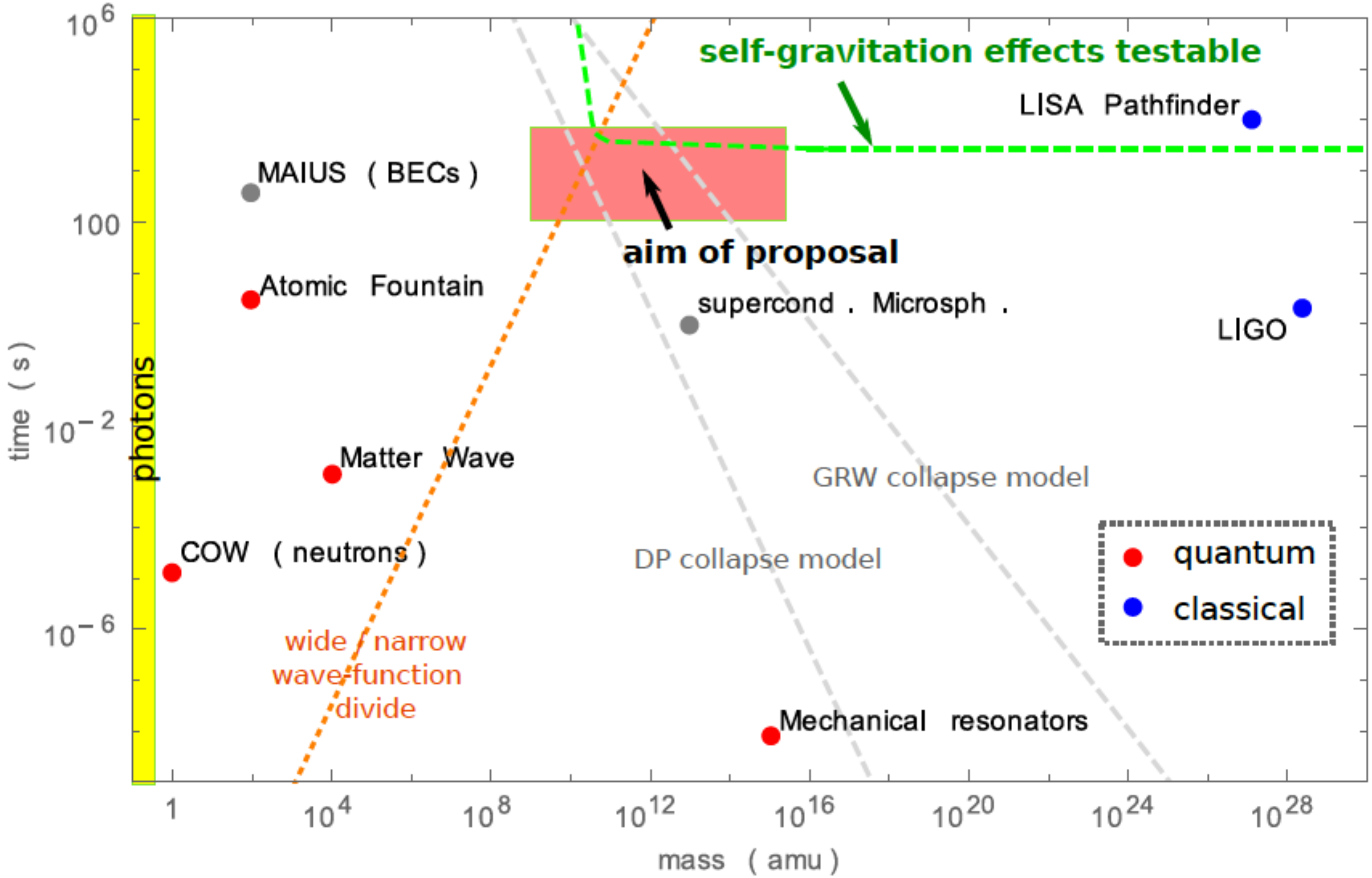
$$R_{\mu\nu} + \frac{1}{2} g_{\mu\nu} R = \frac{8\pi G}{c^4} \langle \Psi | \hat{T}_{\mu\nu} | \Psi \rangle \,.$$

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

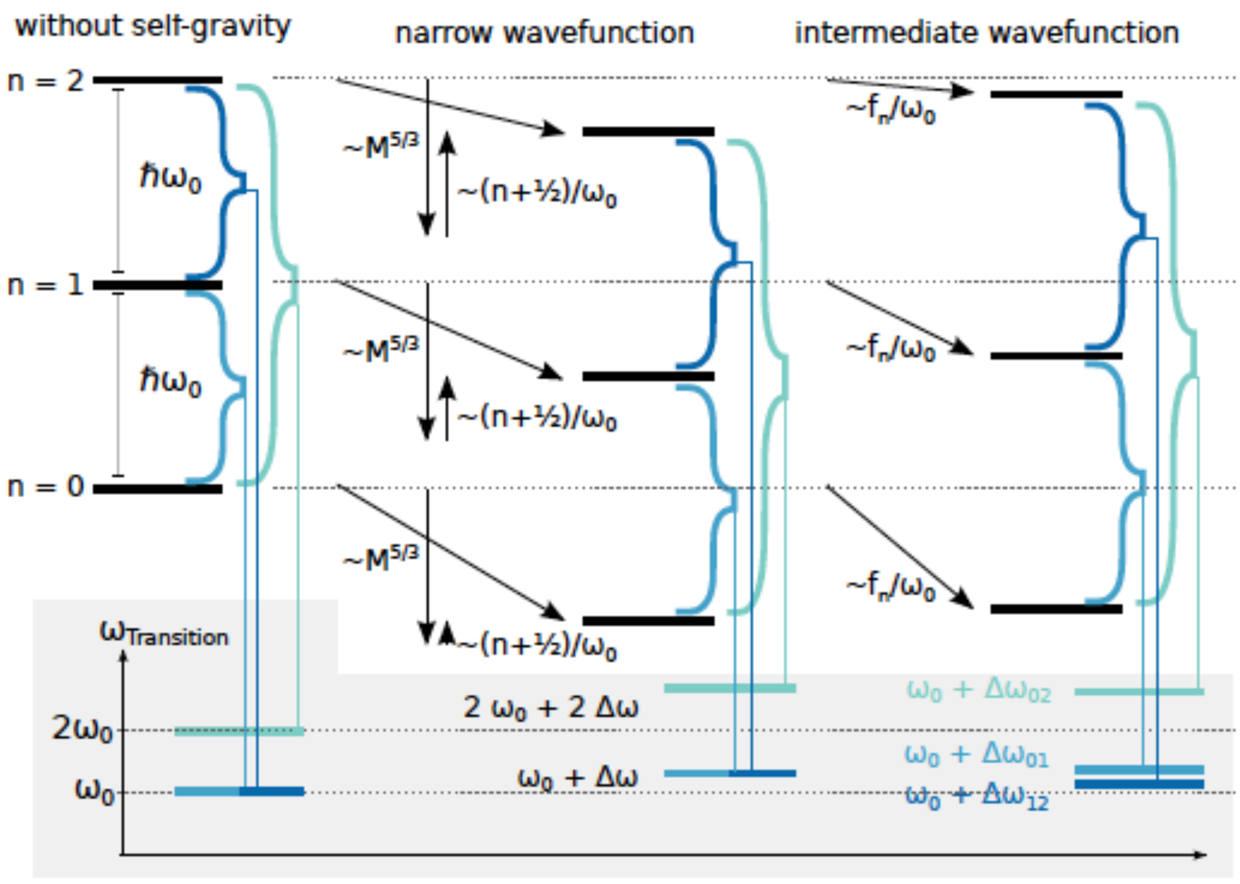
$$V_g[\psi](t, \mathbf{r}) = -G \int \mathrm{d}^3 r' \, |\psi(t, \mathbf{r}')|^2 \, I_{\rho_c}(\mathbf{r} - \mathbf{r}') \,.$$

Obvious option for test: study free wavefunction expansion

Wave function expansion: a case for space



Our proposal: Predicted shifts of energy levels according to SN



- SN shift of energy levels of mechanical harmonic oscillator
- Feasible for a test With existing tech

A Großardt, J Bateman, H Ulbricht, A Bassi, ***Optomechanical test of the Schrodinger-Newton equation,*** arXiv:1510.01696 (2015)

Thanks to …

- **Group at Southampton:** Muddassar Rashid, David Hempston, Jamie Vovrosh, Ashley Setter, George Winstone, Chris Timberlake, Marko Toros.
- **Quantum Optics Theory:** Mauro Paternostro, Myungshik Kim, Sougato Bose, Tommaso Tufarelli.
- **Matter-wave Interferometry and Experiments:** Klaus Hornberger, Peter Barker, Markus Aspelmeyer, Nikolai Kiesel.
- **Foundations of Physics:** Angelo Bassi & group, Tejinder P Singh, Andre Grossardt.

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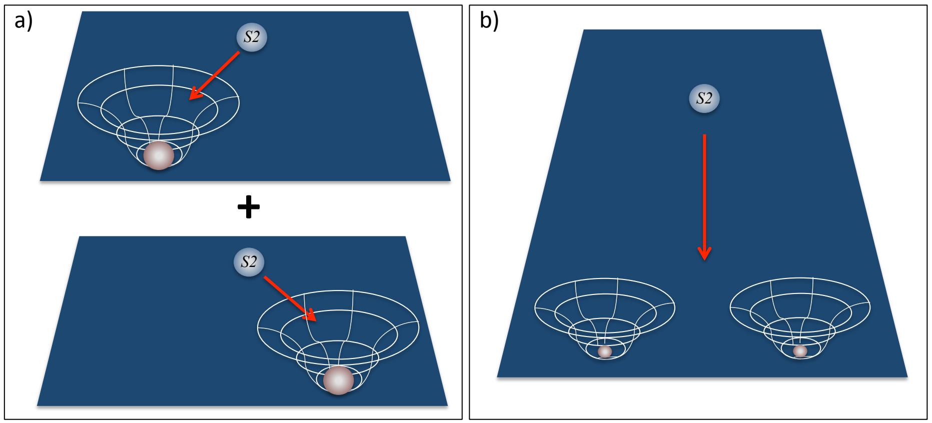
Application: Experimental test of gravity

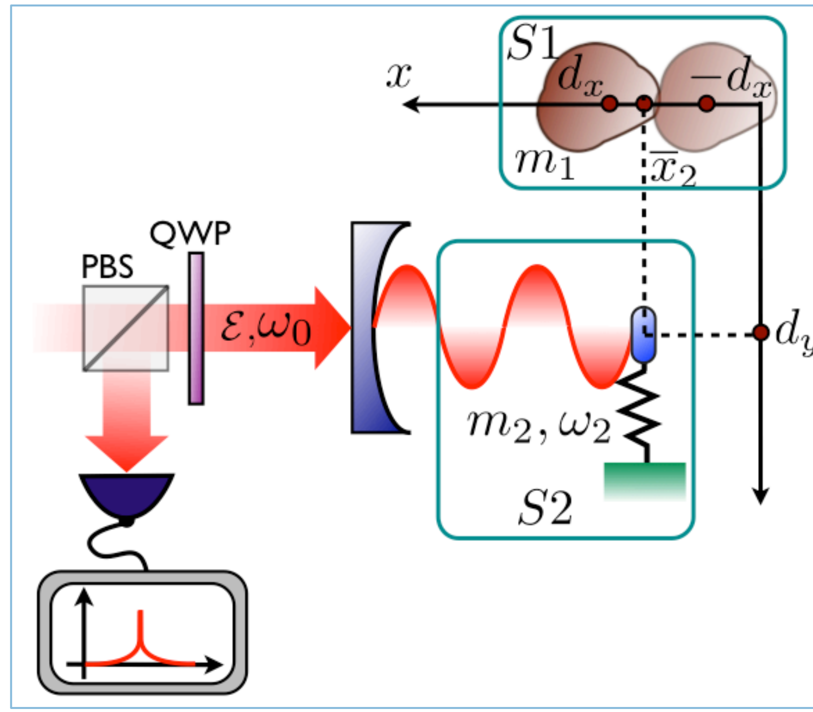
How does the gravitational field of a spatial quantum superposition state look like?

Is Gravity Quantum?



This test seems to be feasible with todays optomechanics devices and technology.

Idea for the experimental setup



M. Bahrami, A. Bassi, S. McMillen, M. Paternostro, H. Ulbricht, **Is Gravity Quantum?,** arXiv:1507.05733 (2015).